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# Pore Pressure Variation Within the Tuscaloosa Trend: Morganza and Moore-Sams Fields, Louisiana Gulf Coast

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Repeat formation tester (RFT, mark of Schlumberger) pore pressure data from the lower Tuscaloosa Formation (Upper Cretaceous) are analyzed across a pressure transition zone in two gas fields of the Tuscaloosa trend, Louisiana, documenting a pressure seal within a sandstone-dominated interval that maintains a pressure anomaly of ~20 MPa. Pressure measurements within the formation span a depth interval of 5500-6060 m and are limited to the crests of rollover structures associated with growth faults; the onset of overpressure occurs at a depth between 5620 m and 5690 m in two fault blocks, while the strata are displaced across the fault by 100 to 120 m, suggesting that the pressure seal may be near-horizontal, crosscutting stratigraphic boundaries. The pressure seal zone is as thin as 38 m and occurs within interbedded sandstones and shales. Overpressures in all wells of the Moore-Sams Field and in two wells of the Morganza Field follow local hydrostatic gradients, indicating that portions of the overpressured zone are in fluid communication though isolated from shallower, normally pressured fluids. In other wells, overpressures increase with depth in a stair-step manner to 117 MPa at depths of 5.9 km. The occurrence of the pressure seal in interbedded sandstones and shales where higher permeability is expected suggests that the sandstones of the seal zone are unusually tight. A companion petrographic study of sandstones near the pressure seal suggests that extreme compaction of the sandstones after dissolution of grain-supporting cements may have contributed to the low permeability of the seal zone.

## INTRODUCTION

Nearly all of the hypotheses proposed to explain the generation and maintenance of abnormally high fluid pressures in sedimentary basins attempt to account for one or more of three processes: pore volume reduction, pore fluid volume increase, and/or permeability barrier (pressure seal) formation (see *Gretener and Feng* [1985] for a review). Unless there is an escape path of reasonable permeability, pore pressure in sedimentary rocks will increase above hydrostatic pressure as either the pore volume is reduced or the volume of pore fluid (water, oil, gas, or their combinations) is increased. Overpressuring may occur by fluid or gas released from hydrocarbon generation and clay diagenesis, by differential heating of rocks and fluid, or by compaction of grains at a rate that exceeds dewatering of pores. Additionally, the maintenance of abnormal pressures over geologic time requires either rocks of extremely low permeability, the recharging of pressures by continued subsidence (compaction and heating), or the continued addition of fluids [*Bradley*, 1975; *Gretener and Feng*, 1985; *Hunt*, 1990].

Several two-dimensional fluid flow models combine Darcy's law for fluid flow through porous media with shale compaction to predict pore pressures in subsiding basins such as the Gulf Coast [e.g., *Bethke*, 1986; *Bethke et al.*, 1988; *Harrison and Summa*, 1991] and the North Sea [e.g., *England et al.*, 1987; *Ungerer et al.*, 1987; *Mann and Mackinzie*, 1990]. In each of these models the pressure-generating mechanism is attributed to the disequilibrium compaction of shales [*Dickinson*, 1953; *Magara*, 1971, 1978], which is controlled by the sedimentation, or loading, rates of the overlying sediments. Permeabilitiy barriers required to maintain overpressures in vertically flowing pore waters typically require permeabilities in the nanodarcy range [*Ungerer et al.*, 1987; *Harrison and Summa*, 1991; L. Cathles, personal communication, 1991], which for shales may require burial depths of at least 3 km [*Gretener and Feng*, 1985], and would exclude most siltstones and sandstones.

If disequilibrium compaction in shales is the predominant pressure-generating mechanism in subsiding, shale-rich basins such as the Gulf Coast or the North Sea as *Bethke* [1986] and *England et al.* [1987] and others argue, then the overpressured pore fluids must have flowed from the shales into the sandstones where they are measured. During flow the overpressured fluids are trapped by permeability barriers such as shales, tight sandstones, carbonates, and/or evaporites. While shales are apparently the most common permeability barrier in the subsurface, especially in the Gulf Coast basin where shales comprise 85% of the sediments [*Bethke*, 1986], cases of evaporite pressure seals have been described [*Parker*, 1974], as well as seals within carbonates (D. Powley, unpublished lecture notes, 1989). Far less is known about pressure seals within sandstones or sandstone-dominated sections [*Hunt*, 1990; *Jansa and Noguera Urrea*, 1990; *Powley*, 1990; *Tigert and Al-Shaieb*, 1990; *Drzewieki et al.*, 1991; *Moline et al.*, 1991; *Weedman et al.*, 1991*a,b*, 1992], situations that may occur more frequently in Mesozoic and older rocks.

Our objective is to describe closely spaced repeat formation tester (RFT, mark of Schlumberger) pore pressure measurements that constrain the geometry of the pressure seal in the lower Tuscaloosa Formation in the Moore-Sams and Morganza fields and to consider several hypotheses on pressure generation and seal formation mechanisms. The term "pressure seal" is used to mean a zone in the subsurface of inferred extremely low permeability that maintains a measurable water pressure anomaly, and is used synonymously with pressure transition zone. Low permeability may be due to primary textures in shales, carbonates, and evaporites or to diagenetic processes that reduce porosity or permeability in a variety of

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rock types. Work is in progress on analyzing samples above and below the pressure seal within the lower Tuscaloosa Formation described in this paper [*Albrecht et al.*, 1991; *Weedman et al.*, 1991*a*,*b*, 1992] to further constrain its genesis and time of formation.

## GEOLOGIC SETTING

The very porous (>25%) sandstones of the deep lower Tuscaloosa Formation (Upper Cretaceous) produce gas and condensate in the approximate depth range of 5000 to 6400 m south of the Early Cretaceous shelf margin (Figure 1) where the formation exhibits a basinward sixfold increase in sandstone thickness over a distance of <30 km [*Funkhouser et al.*, 1980; *Smith*, 1985]. In the Moore-Sams and Morganza fields, the formation is cut by several east-west trending, southward dipping growth faults (Figure 2), and comprises shales and both fining- and coarsening-upward sandbodies interpreted as distributary channels, distributary-mouth bars, and offshore bars [*Smith*, 1985]. A transition to overpressure occurs within the lower Tuscaloosa Formation in these two fields. Reservoirs within the lower Tuscaloosa Formation <10 km to the north of the study area are normally pressured while reservoirs in the same formation <10 km to the south are entirely overpressured [*McCulloh and Purcell*, 1983; *McCulloh*, 1985], indicating that the top of overpressure must crosscut stratigraphic boundaries. However, the topography of the top of overpressure "surface" remains elusive because high-resolution pressure data are not widely available.

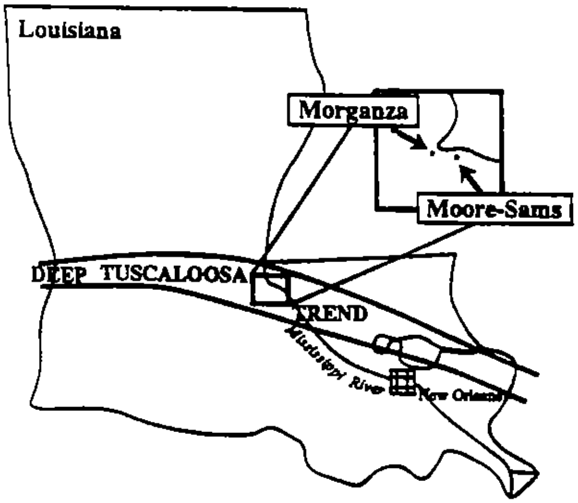

Fig. 1. Map of Louisiana showing the study area in the Moore-Sams and Morganza fields (expanded block) in the Tuscaloosa trend.

The pressure transition in the lower Tuscaloosa Formation differs in several ways from the typical pressure transition in the Tertiary section of the Gulf Coast basin which occurs within laterally extensive marine shales that isolate more porous sandbodies [e.g., *Dickinson*, 1953; *Wallace et al.*, 1979; *Bruce*, 1984], although as additional RFT data are released, more variablity may be recognized. First, there are two overpressured zones in the study area, an upper one at approximately 4.5 km depth in the Midway shale and a lower one within the lower Tuscaloosa Formation, at about 5.6 km [*Matheny*, 1979; *Pankonien*, 1979; this study]. Second, the lithology at the transition zone, as indicated by combining gamma ray logs with RFT pressure data, is not a thick shale but is interbedded sandstones and shales (~3 m thick) that do not appear to be laterally continuous along strike or downdip. There is a thick (~50 m) laterally extensive shale near the base of the formation, however, that forms the pressure seal in one well. Third, the high sand/shale ratio of the formation, estimated from gamma ray logs to be as about 4:1, suggests there should be nearly complete sandstone connectivity within the formation [*King*, 1990]; in which case, overpressured fluids should flow into the normally pressured zone through sandstone conduits. *Wallace et al.* [1979] show that the pressure transition zone typically occurs within the lithologic transition from deltaic sandstone to massive marine shale characterized by 15-35% sandstone interbedded with shale. Fourth, the abrupt pressure transition to overpressure is as thin as 38 m in one well; a thin transition zone has been associated in other parts of the basin with chemical or diagenetic seals [*Parker*, 1974]. Fifth, the apparent horizontal nature of the transition zone at the field scale, as well as at the regional scale of tens of kilometers, suggests a depth rather than

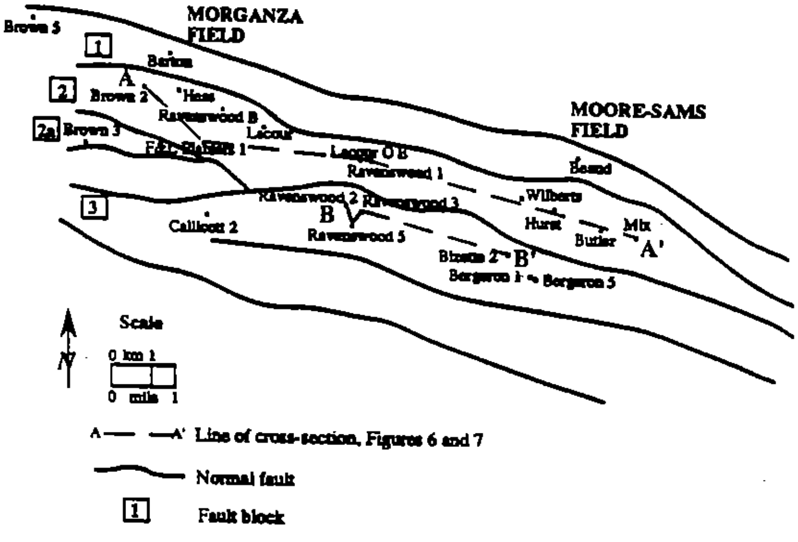

Fig. 2. Map of the Morganza and Moore-Sams fields showing well locations and listric normal faults that subdivide the fields into fault blocks. Lines of cross section, A-A' and B-B', are shown for Figures 6 and 7 (after AMOCO map).

sedimentologic control. While many of these seal zone characteristics suggest that diagenetic processes may be controlling the pressure seal depth, clearly none is diagnostic of diagenetic seals.

## METHODS

RFT pressure data were taken during the course of drilling and producing wells in the Moore-Sams and Morganza fields in the early 1980s. A probe 15 cm in diameter on the RFT tool is injected into sandstone beds in the wall of the borehole, a seal is established, and pore fluid from the sandstone is allowed to flow into two chambers past a pressure gauge, at two different flow rates [*Smolen*, 1977]. The pressure changes in the flow path detected by the gauge are recorded at the wellhead as a pressure versus time plot. Quality control is maintained by examination of pressure build-up plots eliminating faulty tests due to mud leakage or insufficient permeability. The value of the RFT tool is that its pressure gauge is accurate to within ±29 psi (± ~0.2 Mpa) and that the measurements are made in discrete sandstone beds [*Smolen*, 1977]. However, in this study, pressure measurements at the same depths varied as much as 2 MPa.

Depths to formation tops were taken from logs; the top of the lower Tuscaloosa Formation is marked by a distinctive calcareous shale marker bed known as the Pilot, or Bain marker, and is used to correlate the top of the formation from one fault block to another [*Billingsley*, 1980]. Sand/shale ratios were estimated from gamma ray logs by defining the 100% sandstone and 100% shale lines and considering sandstone intervals any unit registering 30% to the left of the shale line on the gamma ray trace. Ratios were calculated every 100 feet (30.5 m) and averaged over the entire formation in the producing wells. Maps of fault blocks were provided by AMOCO Research Center.

## RESULTS

Pressures are given in megapascals and reflect water pressures. The term "overpressure" is used here to denote pore pressures above normal, that is, greater than the hydrostatic pressure indicated by $\rho gh$, where $\rho$ is the density of the pore fluid, $g$ is gravity, and $h$ is depth. "Overpressure" is sometimes used, though not here, to refer to the portion of the pore pressure that exceeds hydrostatic [e.g., *Mann and Mackenzie*, 1990]. Pressure gradients are given in megapascals per kilometer or kilopascals per meter, which are the same number, and are calculated from the surface by dividing pore pressure by depth. Use of the term "pressure gradient" does not imply that such a gradient exists for the significant intervals unless the gradient is a hydrostatic gradient. The term "local hydrostatic gradient" is used in the text to describe pore pressures within the overpressured interval that increase with depth at a rate that is parallel to the hydrostatic gradient to the ground surface. The presence of a local hydrostatic gradient is interpreted to mean that the fluids in that interval are in hydraulic communication despite being overpressured. Because the pressures at such depths far exceed those developed by flow of meteroic waters driven from local topography or by compactional flow, pore water movement is not a reasonable control on pressure gradients in these fields.

A plot of all pressure data in Table 1 from successful RFT tests for both fields is shown in Figure 3; stratigraphic data are given in Table 2. A transition from normal to overpressure occurs at about 5640 m. Unfortunately, RFT pressure data from shallower depths in these two fields are sparse, though the few pressure measurements that are available suggest that there are two overpressured zones in these two fields, separated by a zone of normally pressured pore fluids: the top of the upper zone is at ~4300 m depth, perhaps in the Midway Shale, and the top of the lower one is at ~5640 m depth within the lower Tuscaloosa Formation. Several other studies of indirect pressure indicators such as shale resistivity, sonic travel time, and mud weight changes with depth document the upper transition zone in other Tuscaloosa trend fields as well [*Matheny*, 1979; *Pankonien*, 1979; *Gill*, 1980; *McCulloh and Purcell*, 1983; *McCulloh*, 1985].

### *Moore-Sams Field*

All pore pressures measured in fault block 1 fall on the hydrostatic gradient to the surface; the abnormal pressures in blocks 2 and 3 of this field follow a local hydrostatic gradient down to depths of 5850 m reaching 82.6 MPa (Figure 4). The top of a transition zone from normal to overpressure occurs in the depth range of 5620 m (Bizette 2) to 5683 m (Mix), while the top of the formation is displaced by ~105 m from blocks 2 to 3. Therefore the variation in the depth to the top of overpressure between fault blocks 2 and 3 is less than the approximated displacement of the strata across the fault, suggesting, though not confirming, that it may be horizontal. Pressure measurements were taken from wells drilled on or near the crests of rollover structures associated with the growth faults; the depth to the top of overpressure is unknown away from the crests or near the faults. However, the occurrence of the transition zone at different depths within the formation on either side of the fault suggests that the pressure seal must crosscut stratigraphy at some location.

It is important to note that the magnitude and gradient of abnormal pressures in blocks 2 and 3 are very similar, even though the stratigraphy differs across the fault as indicated by the displacement of the top of the lower Tuscaloosa Formation (by ~105 m), of the shale break near the base of the formation (by ~180 m), and in the basinward thickening (~ 78 m) of the formation (Table 2). The fault that separates the two blocks does not act as a pressure seal, because overpressures are nearly equal on both sides of the fault at the same depths, strongly suggesting that there is fluid communication across the fault and among the overpressured sandstones of this field.

### *Morganza Field*

Pore pressures in the Morganza Field are plotted versus depth in Figure 5. The pore pressures through overpressured sandstone-dominated intervals in the Morganza Field generally follow local hydrostatic gradients but jump as much as 26 MPa across certain shaley intervals. The growth faults in this field divide it into at least five blocks; four of them have wells with RFT pressure data. As in the Moore-Sams Field, all pore pressure data from fault block 1 are normal; that is, they lie on a hydrostatic gradient to the surface, while the overpressures encountered in wells in fault blocks 2 and 3 are of a much greater magnitude than in the Moore-Sams Field. The pore pressures in the OE Lacour well and in part of Brown 3 well reach 83 MPa and 104 MPa, respectively, at depths of about 5850 m, while pore pressures in the Brown 2 well follow a

TABLE 1. RFT Pressure Data

| Well Name | Depth, m | Pressure, MPa |
|---|---|---|
| *Moore-Sams Field* | | |
| Mix | 5536 | 58.5 |
| | 5536 | 58.5 |
| | 5536 | 58.6 |
| | 5628 | 57.3 |
| | 5629 | 59.4 |
| | 5682 | 59.4 |
| | 5683 | 57.3 |
| | 5683 | 59.3 |
| | 5773 | 82.1 |
| | 5794 | 82.3 |
| | 5865 | 83.1 |
| | 5887 | 82.9 |
| | 5904 | 82.9 |
| | 5909 | 83.5 |
| | 5909 | 83.1 |
| | 5909 | 83.1 |
| | 5935 | 84.1 |
| Bergeron 1 | 3446 | 35.2 |
| | 3447 | 35.2 |
| | 3448 | 35.2 |
| | 3448 | 35.3 |
| | 3449 | 35.3 |
| Wilberts | 5568 | 58.2 |
| | 5571 | 58.4 |
| | 5630 | 58.3 |
| Hurst | 5550 | 58.1 |
| | 5576 | 57.4 |
| | 5577 | 57.4 |
| | 5582 | 57.5 |
| | 5582 | 58.5 |
| | 5614 | 58.6 |
| | 5615 | 58.8 |
| | 5639 | 59.1 |
| Bizette 2 | 5620 | 60.0 |
| | 5650 | 65.7 |
| | 5659 | 64.9 |
| | 5687 | 80.6 |
| | 5712 | 79.4 |
| | 5712 | 79.6 |
| | 5822 | 80.3 |
| | 5847 | 82.2 |
| Beaud | 5405 | 54.9 |
| | 5413 | 54.9 |
| | 5423 | 55.0 |
| Butler | 5582 | 59.4 |
| | 5599 | 59.2 |
| | 5613 | 59.8 |
| | 5614 | 56.7 |
| | 5626 | 60.2 |
| | 5653 | 60.3 |
| | 5663 | 60.2 |
| | 5670 | 60.7 |
| | 5671 | 60.7 |
| Bergeron 5 | 5664 | 79.3 |
| | 5684 | 81.0 |
| | 5716 | 81.3 |
| | 5728 | 81.3 |
| | 5742 | 81.4 |
| | 5751 | 81.5 |
| | 5757 | 81.5 |
| | 5758 | 80.0 |
| | 5762 | 81.6 |
| | 5762 | 81.6 |
| *Morganza Field* | | |
| Hess | 5475 | 58.1 |
| | 5475 | 58.1 |
| | 5483 | 58.3 |
| Brown 5 | 4528 | 76.2 |
| | 4528 | 76.5 |
| | 4530 | 76.4 |
| | 5530 | 58.0 |
| | 5530 | 58.0 |
| | 5531 | 58.1 |
| Barton | 5375 | 55.8 |
| | 5375 | 55.9 |
| | 5382 | 56.5 |
| Brown 2 | 5495 | 59.0 |
| | 5496 | 59.1 |
| | 5496 | 59.1 |
| | 5497 | 59.0 |
| | 5498 | 59.0 |
| | 5499 | 59.1 |
| | 5592 | 58.8 |
| | 5630 | 58.7 |
| | 5632 | 58.8 |
| | 5639 | 59.5 |
| | 5642 | 58.7 |
| | 5695 | 82.3 |
| | 5745 | 88.4 |
| | 5745 | 88.8 |
| | 5745 | 88.9 |
| | 5750 | 88.5 |
| | 5750 | 89.0 |
| | 5750 | 89.8 |
| | 5750 | 89.7 |
| | 5751 | 89.8 |
| | 5751 | 89.8 |
| | 5758 | 93.2 |
| | 5835 | 108.6 |
| | 5847 | 109.7 |
| | 5857 | 109.1 |
| | 5857 | 109.1 |
| | 5857 | 109.6 |
| | 5857 | 110.1 |
| | 5916 | 117.3 |
| | 5916 | 117.4 |
| | 5916 | 117.7 |
| Ravenswood /B/ | 5486 | 57.9 |
| | 5486 | 57.9 |
| | 5489 | 58.4 |
| | 5580 | 58.5 |
| | 5580 | 58.6 |
| | 5581 | 58.6 |
| | 5585 | 58.6 |
| | 5585 | 58.7 |
| F&L Planters | 5555 | 59.2 |
| | 5555 | 60.1 |
| | 5692 | 81.8 |
| | 5692 | 81.9 |
| Lacour et al. | 5585 | 57.2 |
| | 5645 | 55.3 |
| | 5645 | 57.0 |
| | 5645 | 57.3 |
| Ravenswood 1 | 5546 | 58.2 |
| | 5547 | 58.3 |
| | 5560 | 58.1 |
| | 5563 | 56.7 |
| | 5575 | 56.5 |
| | 5575 | 58.1 |
| | 5575 | 58.4 |
| | 5578 | 58.4 |
| | 5585 | 58.2 |
| | 5585 | 58.4 |
| | 5585 | 58.6 |
| | 5585 | 58.7 |
| | 5587 | 58.4 |
| O E Lacour | 5545 | 61.0 |
| | 5557 | 61.8 |
| | 5573 | 60.6 |
| | 5573 | 60.7 |
| | 5583 | 60.5 |
| | 5609 | 60.0 |
| | 5647 | 76.3 |
| | 5669 | 76.0 |
| | 5683 | 77.2 |
| | 5698 | 78.0 |
| | 5790 | 82.5 |
| | 5809 | 82.5 |
| | 5851 | 83.1 |
| Ravenswood 5 | 5641 | 59.3 |
| | 5772 | 82.2 |
| | 5842 | 104.1 |
| | 5842 | 104.1 |
| | 5842 | 104.5 |
| | 5875 | 104.5 |
| | 6061 | 110.5 |
| | 6061 | 111.0 |
| Brown 3 | 5635 | 80.1 |
| | 5645 | 80.2 |
| | 5668 | 92.1 |
| | 5704 | 93.7 |
| | 5704 | 93.9 |
| | 5734 | 93.7 |
| | 5781 | 93.6 |
| | 5781 | 93.7 |
| | 5781 | 94.2 |
| | 5817 | 94.0 |
| | 5817 | 94.1 |
| | 5817 | 94.5 |
| | 5865 | 104.2 |
| Callicott | 5775 | 96.1 |
| | 5775 | 96.1 |
| | 5776 | 96.0 |
| | 5776 | 96.1 |
| | 5778 | 95.1 |
| | 5818 | 96.4 |
| | 5822 | 96.4 |
| | 5822 | 96.5 |
| | 5886 | 107.5 |
| | 5999 | 120.2 |
| | 5999 | 120.3 |
| | 5999 | 120.6 |
| | 6007 | 119.4 |
| | 6007 | 120.6 |
| Ravenswood 2 | 5634 | 59.3 |
| | 5634 | 59.4 |
| | 5635 | 59.3 |
| | 5664 | 65.1 |
| | 5730 | 81.1 |
| | 5765 | 82.0 |
| | 5834 | 108.0 |
| | 5838 | 107.0 |
| | 5875 | 110.0 |
| | 5877 | 109.1 |
| | 5881 | 110.0 |
| | 5882 | 110.0 |
| | 5915 | 109.1 |
| | 5915 | 109.2 |
| Ravenswood 3 | 5633 | 59.7 |
| | 5634 | 59.8 |
| | 5635 | 59.9 |
| | 5636 | 59.4 |
| | 5729 | 81.4 |
| | 5782 | 83.5 |

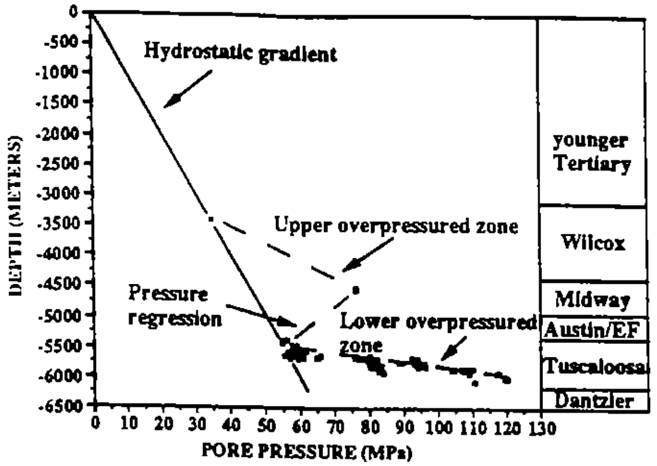

Fig. 3. Plot of pore pressure versus depth of all successful RFT tests from the Morganza and Moore-Sams fields. Data indicate two overpressured zones separated by at least 300 m of normally pressured fluids. Approximate depths to formation tops shown at right; EF (Eagle Ford).

TABLE 2. Stratigraphic Data for the Lower Tuscaloosa Formation

| Fault Block | Well Name | Depth to Top of Lower Tuscaloosa Formation, m | Thickness of Lower Tuscaloosa Formation,* m |
|---|---|---|---|
| | | *Moore-Sams Field* | |
| 1 | Beand | 5365 | 232 |
| 2 | Wilberts | 5516 | 268 |
| | Hurst | 5480 | 268 |
| | Mix | 5496 | 268 |
| | Butler | 5480 | - |
| 3 | Bizette 2 | 5614 | 346 |
| | Bergeron 1 | 5590 | - |
| | Bergeron 5 | 5596 | - |
| | | *Morganza Field* | |
| 1 | Brown 5 | 5403 | - |
| | Barton | 5335 | 181 |
| 2 | Brown 2 | 5458 | 343 |
| | Hess | 5437 | - |
| | Ravenswood /B/ | 5435 | - |
| | Ravenswood 1 | 5483 | 287 |
| | F&L Planters | 5465 | 335 |
| | OE Lacour | 5474 | 293 |
| 2a | Brown 3 | 5578 | - |
| 3 | Ravenswood 2 | 5577 | - |
| | Ravenswood 3 | 5581 | 424 |
| | Ravenswood 5 | 5589 | - |

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* Formation boundaries are based on lithologic changes in logs in the absence of paleontologic data; thicknesses should be considered minimums. The underlying formation (Dantzler) is lithologically similar, and seismic resolution is limited at such depths. Dashes indicate that the well did not penetrate the entire formation.

series of stair-step local hydrostatic gradients reaching 117 MPa at depths of 5916 m.

A great deal of variation in pore pressure exists in the depth range of 5675 to 5850 m in different wells of the Morganza Field, suggesting that several minor pressure seals may exist there, not only along certain faults (between blocks 2 and 2a) but also within fault blocks as well (i.e., 2 and 3). "Pressure seal" is used here to mean a zone of sufficiently low permeability to maintain a measurable vertical or lateral pressure anomaly; low permeability may be due to either primary textures or diagenetic alteration.

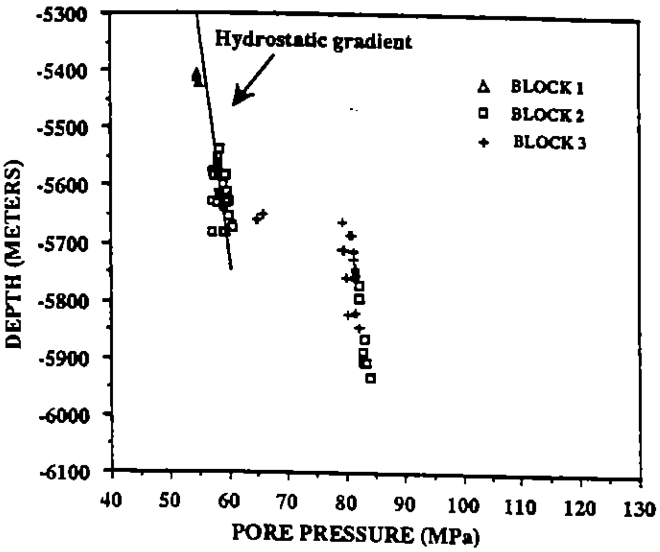


Fig. 4. Plot of pressure versus depth of RFT data from the Moore-Sams Field. Data are from fault blocks listed at right. The hydrostatic gradient to the surface is shown for reference.

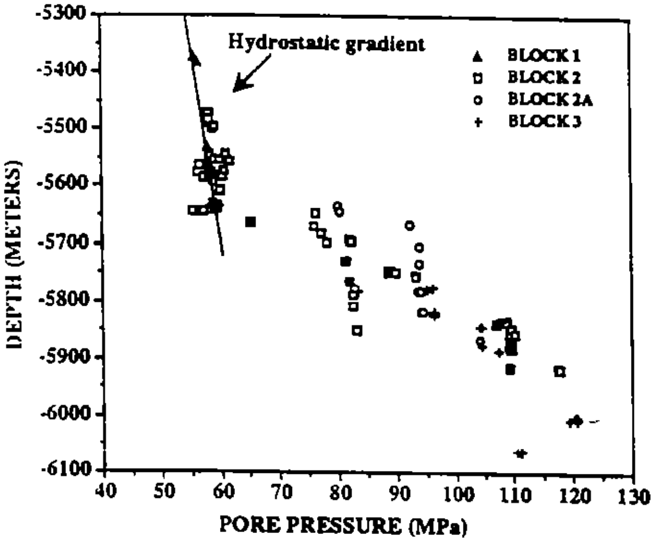
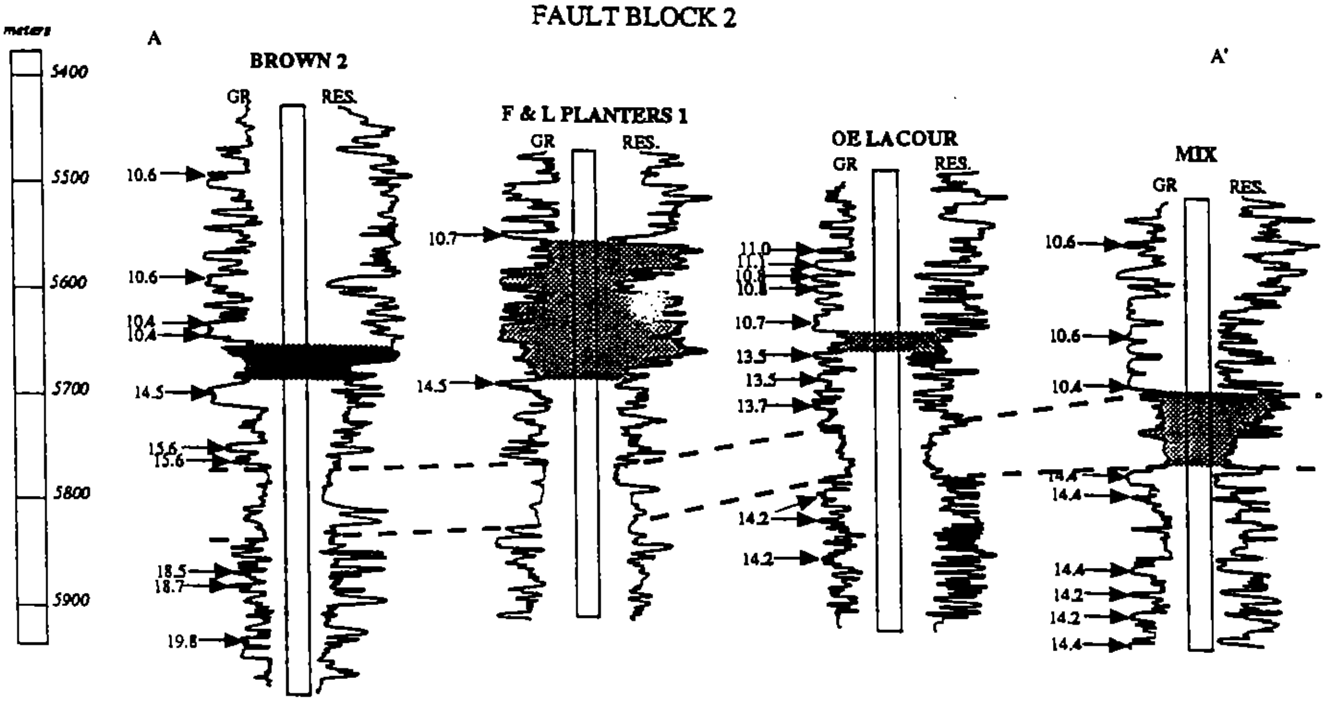


Fig. 5. Plot of pressure versus depth of RFT data from the Morganza Field. Data come from fault blocks listed at right. The hydrostatic gradient to the surface is shown for reference.

## *Pressure Seal Geometry*

Both normal and overpressure RFT measurements are available for eight wells which constrain the depth and thickness of the pressure seal in the two fields. Cross sections of those wells from fault blocks 2 and 3 are shown in Figures 6 and 7, respectively. The locations of RFT measurements are shown with arrows to the left of the gamma ray log, and the pressure gradients (to the surface), read as either megapascals per kilometer (MPa/km) or kilopascals per meter (kPa/m), are shown to the left of each arrow. In these units, normal pressures are about 10.5 but may vary slightly with the salinity of the pore water. The depth interval between the deepest normal pressure and the shallowest overpressure



Pressure gradient units = MPa/km or KPa/m

Fig. 6. Cross section A-A' of wells in fault block 2 for which normal and abnormal pressures were measured. Line of cross section is shown in Figure 2. Arrows indicate measurement location, numbers are pressure gradients (in megapascals per kilometer) to the surface. The logs are gamma ray on the left and resistivity on the right. The logs begin at the top of the lower Tuscaloosa Formation at the Bain marker bed and extend to the bottom of the well. The depth interval between the deepest normal pressure measurement and the shallowest overpressure measurement is shaded; the pressure seal must occur within this interval. One shale bed is correlated (dashed line) that may be the only laterally extensive shale in the two fields.

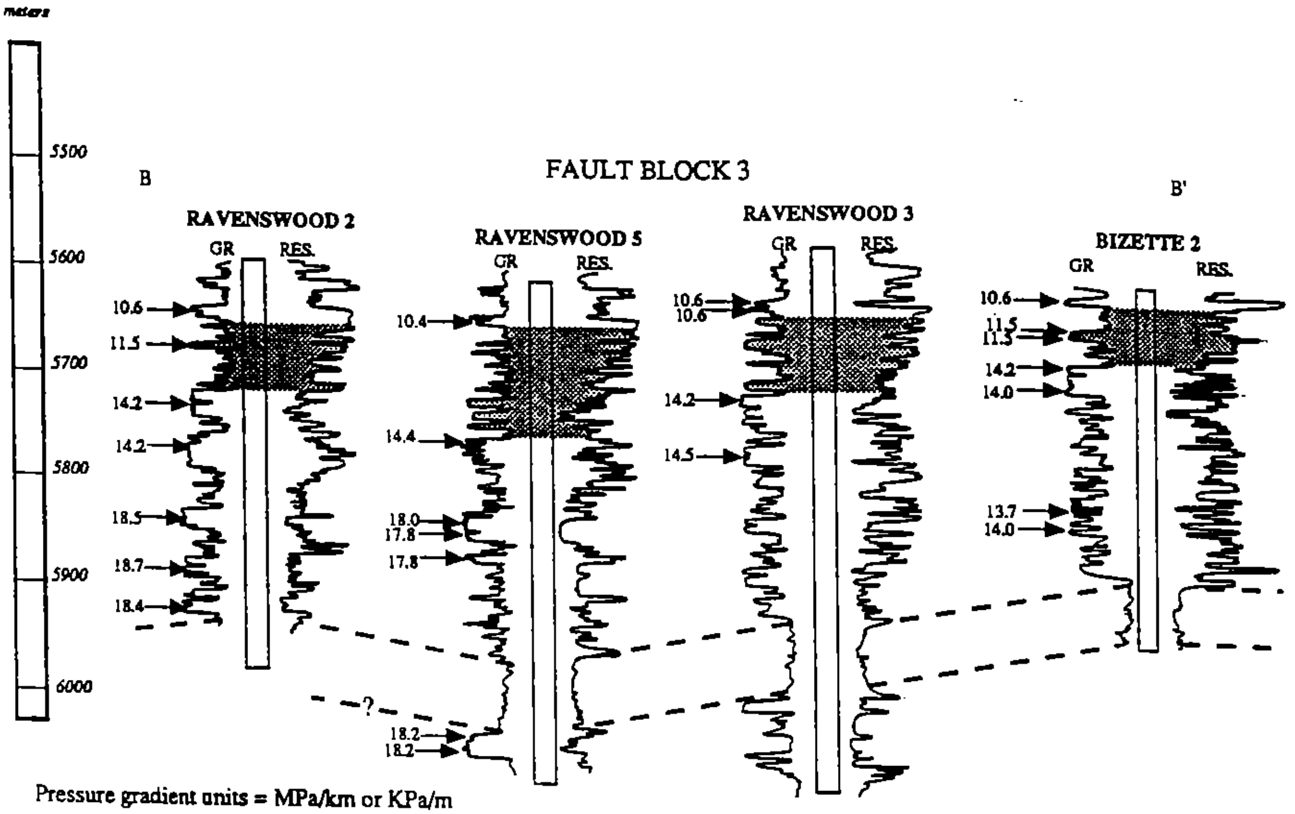
(>10.5 kPa/m) measurements is shaded and indicates the maximum thickness of the pressure seal, which is as thin as 38 m in one well (O E Lacour well). This interval is characterized lithologically by interbedded sandstone and shale and is upward coarsening, as least in part, in most wells examined (Figures 6 and 7). The upward coarsening trend is determined in a qualitative sense from gamma ray logs.

Comparison of wells from fault blocks 2 and 3 (Figures 6 and 7) shows that the pressure seal is in the middle part of the lower Tuscaloosa Formation in fault block 2 and in the upper part of the formation in fault block 3. In the Mix well the pressure seal is deeper than in the other wells; additionally, the seal there is within the thick shale break observed in all wells, the only shale that correlates across the fields along strike and perhaps basinward. These pressure data show that the laterally extensive shale, indicated in Figures 6 and 7 as a dashed line of correlation, is not the pressure seal in the other wells. The depth to the pressure seal in fault block 2 occurs between 5609 and 5642 m in the OE Lacour and Brown 2 wells, while in the Mix well is about 5683 m, perhaps due to the presence of some very thick sandstones between 5600 and 5680 m. The maximum possible thickness of the pressure seal in block 2 varies from 38 m (OE Lacour) to 137 m (F&L Planters). In fault block 3 of both fields, the deepest normal pessure is consistent along strike from well to well varying from 5635 m (Ravenswood 2) to 5659 m (Bizette 2); maximum possible thickness of the pressure seal in block 3 varies from 67 m (Bizette 2) to 131 m (Ravenswood 5).

The upper part of the seal zone in nearly all wells in Figures 6 and 7 is characterized by high resistivity in both the sandstones and shales. High resistivity may be due to the presence of hydrocarbons or extremely low porosity, or perhaps both. Below the resistivity maximum, but in the seal zone, is a sharp decline in resistivity of shales and sandstones, indicating increased porosity or more conductive pore fluids, or both. This resistivity signature of the top of overpressure was first described by *Hottman and Johnson* [1965] and is used in the Tuscaloosa trend with other log indicators, as well as in most of the Gulf Coast, to anticipate the onset of overpressure during drilling [*Gill*, 1980].

## DISCUSSION

Several generalizations can be made from a survey of these pressure data, keeping in mind that the data come from wells aligned with the crests of rollover structures related to syndepositional growth faults; this distribution, which prohibits construction of a dip-oriented cross section of more than two wells. The depth to the transition from normal to abnormal pressures in wells of the Moore-Sams and Morganza fields occurs at about the same depth in two fault blocks, while the strata in the same wells are displaced by about 100-120 m perpendicular to strike (Figures 6 and 7). All pore pressures measured in the lower Tuscaloosa Formation in block 1 are normal. However, in block 2 of both fields, a pressure transition occurs near the middle of the lower Tuscaloosa Formation, while in block 3, in both fields, only the uppermost sandstone beds of the lower Tuscaloosa Formation



Pressure gradient units = MPa/km or KPa/m

Fig. 7. Cross section B-B' of wells in fault block 3 for which normal and abnormal pressures were measured. Line of cross section is shown in Figure 2. Arrows indicate measurement location, numbers are pressure gradients (in megapascals per kilometer) from the surface. The logs are gamma ray on the left and resistivity on the right. The logs begin at the top of the lower Tuscaloosa Formation at the Bain marker bed and extend to the bottom of the well. The depth interval between the deepest normal pressure measurement and the shallowest overpressure measurement is shaded; the pressure seal must occur within this interval. One shale bed is correlated (dashed line) that may be the only laterally extensive shale in the two fields.

are normally pressured, and the rest of the formation is abnormally pressured to a different magnitude in different parts of each field.

The raw pressure and lithologic data can be interpreted in several ways. First, the top of overpressure may be nearly horizontal, crosscutting strata from one fault block to the next. This interpretation would be consistent with the geometry of pressure seals and compartments proposed by *Bradley* [1975] and *Powley* [1990] and further discussed by *Hunt* [1990]. Second, the transition zone may follow the same strata across the rollover structures in each fault block but be offset at the fault. Apparent horizontality would be controlled by the greatest depth at which normally pressured sandstones are juxtaposed at faults and the relative structural relief of the rollovers associated with the fault. Third, the top of overpressure may follow a nonconformable but tortuous horizon and simply by coincidence be at approximately the same depths in the two fault blocks.

For case two to be valid, a laterally extensive shale is required that reaches from fault to fault, in the absence of a diagenetic permeability barrier, to vertically isolate normal from overpressured sandstones in all three fault blocks; that is, a pressure seal is required. A shale bed can be a pressure seal only if it vertically isolates hydraulically conductive rocks, typically sandstones, above and below. If the conductive rocks are connected in the third dimension, shales may form baffles to flow, but they should not be capable of maintaining pressure anomalies over geologic time. Differentiating sealing from nonsealing shales, as well as the recognition of other permeability barriers operating in a reservoir, requires knowledge of shale geometry or sandstone connectivity [*Begg and King*, 1985; *King*, 1990]. Evidence available from logs suggests that the only shale that might extend from fault to fault, the shale break at 5700 m in block 2 and at 5900 m in block 3, is clearly not the seal in most of the wells. Additionally, *Weber's* [1982] investigation of shale length as a function of depositional environment suggests that in the delta front environment laterally continuous shales typically have a shale length that is smaller than the distance from fault to fault in the Moore-Sams and Morganza fields (2-5 km), suggesting further that a shale bed is an unlikely candidate for a pressure seal in these fields.

If case one or three is valid, the pressure seal must crosscut inferred stratigraphic boundaries. We have no paleontologic data that demonstrate that the pressure seal is in slightly older rocks in fault block 2 than in fault block 3; our argument is based on the assumption that the top of the lower Tuscaloosa, the Bain marker horizon, is time equivalent in each fault block, and that sedimentation rates in fault block three were probably greater than in fault block 2.

There is some degree of lithologic control on the location of the pressure seal, in that the seal appears to occur within interbedded sandstones and shales that typically are upward coarsening. A correlative shale is near the base of the formation and may be, at least in fault block 3, the prodelta deposits over which the deltas prograded. While a thick shale in fault block 2 appears to form the seal in the Mix well, it clearly does not form the seal in the other wells. Therefore the seal does not occur at, what in this case may be, the contact between deltaic sandstones and marine shales as generally expected in the Gulf Coast [*Dickinson*, 1953; *Wallace et al.*, 1979] but within the overlying sandstone-rich delta front sediments.

A parallel study of sandstone diagenesis above and below the pressure seal in three wells in the study area (Ravenswood /B/, Butler, and Fontaine wells) demonstrates that the pressure transition zone separates sandstone strata of unusually high secondary porosity of up to 26% [*Weedman et al.*, 1991*a,b*, 1992]. A packing analysis of the sandstones above and below the pressure seal indicates that compaction of high-porosity (secondary porosity) sandstones below the seal has been inhibited by overpressured pore fluid, while similar high-porosity sandstones above the seal have compacted as much as 20% since the dissolution of grain-supporting calcite cement, referred to as secondary compaction [*Weedman et al.*, 1992]. Compaction to this degree requires grain crushing of rock fragments and pressure solution of quartz grains, processes which are documented above the pressure seal zone in the study area, though nearly absent below. Samples of cuttings taken from within the seal zone show extensive pressure solution and fitted textures that would, if as laterally extensive as suspected, provide permeability barriers within the thin sandstones of the seal interval [*Albrecht et al.*, 1991; *Weedman et al.*, 1992]. These observations suggest that the pressure seal may have become effective in isolating porous sandstones during or soon after the dissolution of grain-supporting calcite cement and that a process analogous to shale undercompaction exists in overpressured sandstones as well.

Therefore petrographic analysis links pressure seal formation to the dissolution of grain-supporting calcite cements and may provide timing constraints on the process. In the Gulf Coast Tertiary, calcite cements are thought to have partially dissolved in many reservoirs at temperatures between 75° and 125°C [*Franks and Forester*, 1984]. Assuming a constant geothermal gradient of 25°C/km for the study area, that depth range would be 2.4 km to 4 km. Superimposing that depth interval on a simple burial history curve for a well in the Moore-Sams Field, Figure 8 indicates that the pressure seal could be as old as 30-60 million years. *Bethke* [1989] calculates that the onset of overpressures in late Cretaceous rocks at similar depths, though farther to the west of the study area, commenced in about Oligocene time, which is consistent with the above estimate based on petrography.

An unusual aspect of the pressure transition in these fields is that sandstone porosity above and below the pressure seal is very high, up to 26% [*Weedman et al.*, 1992]. Pressure data suggest that sandstones above the seal are in hydraulic continuity, as are many of the sandstones below the seal. In addition, the only laterally extensive shale that can be correlated across the fields that may reach from fault to fault clearly is not the seal in most wells examined. The rocks that do form the seal and maintain a pressure difference of ~20 MPa over a depth range of 38 to 137 m, are interbedded thin (~3 m) sandstones and shales. *King* [1990] has shown by three-dimensional modeling of a hypothetical random network of cuboidal sandbodies in shale that within an interval where the net to gross sand ratio (sand: sand + shale) is 0.8 (equivalent to a sand/shale ratio of 4:1, as in the study area) the connected sandstone fraction approaches 100%. This observation suggests to us that while the thin sandstones in the seal zone were probably interconnected with sandstones above and below when deposited, they are now very tight with a sufficiently low permeability to act with the shales as a pressure seal that can maintain a significant pressure anomaly for tens of millions of years.

In the absence of direct pore pressure measurements, the onset of overpressure while drilling is estimated with the shale resistivity log [*Hottman and Johnson*, 1965; *Bredehoeft et al.*, 1988]. A relatively low shale resistivity, compared to higher resistivities of shallower shales is often attributed to undercompaction; that is, the shales have not compacted to the degree that is expected for their depth, compared to the trend established in shallower shales. Overpressured pore fluids from undercompacted shales should flow into adjacent sandstones until the pressures in both rock types equilibrate or until the dewatered shales fully compact. In the study area, thick normally pressured sandstones overlie low-resistivity shales within and below the seal zone, while thin overpressured sandstones are interbedded within them.

Several pressure generating mechanisms have been proposed for overpressures in sandstones such as thermal cracking of oil to gas [*Hedberg*, 1974], the flow of overpressured pore fluids from shales that are undercompacted [*Dickinson*, 1953] or have additional pore water from the smectite to illite conversion [*Powers*, 1967; *Perry and Hower*, 1970, 1972] and aquathermal pressuring [*Barker*, 1972]. Organic rich shales in the lower Tuscaloosa Formation, thought to be the source rocks for the reservoirs [*Sassen*, 1990], are clearly deep enough to produce gas [*Hunt*, 1990]. In addition, the shale

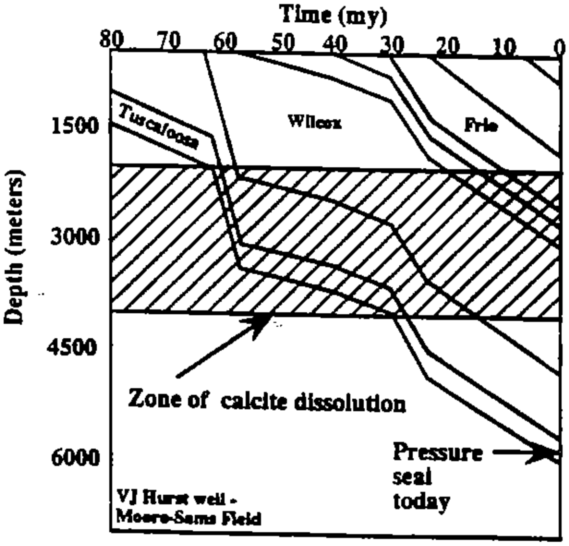


Fig. 8. Simple burial curve for the V.J. Hurst well in the Moore-Sams Field from the present to approximately 80 m.y. ago (compaction has been neglected). Lower Tuscaloosa (Upper Cretaceous), Wilcox (Eocene), and Frio (Oligocene) clastic wedges are identified. The depth interval at which temperatures range from 75° to 125°C (the temperature range of calcite dissolution in the Tertiary of the Gulf Coast according to data from *Franks and Forester* [1984]) is indicated with diagonal lines; a temperature gradient of 25°C/km is assumed. The lower Tuscaloosa Formation passed through this temperature range approximately 30 to 60 m.y. ago. If pressure seal formation coincided with dissolution of grain-supporting carbonate cements, it could be tens of millions of years old.

resistivity decline across the pressure seal zone suggests that the overpressured shales are now undercompacted and could be a source of overpressured fluids to the sandstones. If the pressure seal formed at a depth several kilometers shallower than it is today, as suggested by petrography of sandstones in the vicinity of the seal, a portion of the overpressure could be attributed to aquathermal pressuring or to trapped pore fluids generated by clay diagenesis and hydrocarbon generation at shallower depths.

However, none of the proposed pressure generation mechanisms account for a sealing mechanism. Additional insight into the origin and trapping of overpressured fluids in the Tuscaloosa trend will be examined by collecting more pressure data from updip and downdip and along strike to define the regional geometry and the controls on the unusual pressure regression along the northern margin of the trend [*McCulloh and Purcell*, 1983], as well as to further test the hypothesis of diagenetic controls on permeability barriers within the reservoirs.

## CONCLUSIONS

The top of overpressure in the Tertiary section of Gulf Coast typically is placed at the contact of the major deltaic sandstones and the underlying marine shales [*Dickinson*, 1953; *Bruce*, 1984]. A transition to overpressure occurs within a sand-rich portion of delta front sediments of the lower Tuscaloosa Formation in the study area, though <10 km to the north, the formation is normally pressured and <10 km to the south, it is entirely overpressured. Here, in the Moore-Sams and Morganza fields, the pressure transition zone is characterized by thin (~3 m) upward coarsening interbedded sandstones and shales that are underlain by similar upward coarsening, but clearly interconnected sandstones. The similar depth to the top of overpressure in two fault blocks suggests that the pressure seal may be nearly flat, though an irregular topography can not be discounted. The only laterally extensive shale in the formation clearly does not form the pressure seal, a claim that would not be possible without high-resolution RFT pressure data.

Pressure seals are unexpected in sand-rich intervals. Petrographic data from a companion study of sandstones above and below the pressure seal in Morganza and Moore-Sams fields strongly suggest that it has been effective for tens of millions of years, requiring horizons of extremely low permeability. A permeability reduction mechanism has been proposed of renewed compaction after cement-dissolution secondary porosity in sandstones involving grain crushing and extensive pressure solution. This process may be concentrated in the sandstones of the seal zone where interbedded tight sandstones and shales maintain the pressure anomaly.

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