USGS - REDBOOK WORKSHOP

The Nature of High Fluid Pressure in Sedimentary Basins

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Any study of the mechanical involvement of fluids in faulting will undoubtedly consider the effect of high fluid pressure. While measurements of fluid pressure about faults are rare, some of the best data come from oil and natural gas fields in sedimentary basins (e.g., the Gulf of Mexico). Such detailed pressure data give an in sight into the distribution of abnormal pressure in and around fault zones where high fluid pressures are quasi-static relative to the earthquake cycle. For quasi-static fluid pressures, the nature of the pressure seal is an issue. The purpose of this paper is to describe the change in fluid pressure when abnormal pressure is encountered in sedimentary basins. In particular, focus is on the question of whether or not high fluid pressures are any different along fault zones than within intact rock at some distance from the fault zones.

Geopressure profiles were constructed largely from original shut in bottom hole pressure (BHP) measurements recorded in numerous wells within various oil and gas fields of a sedimentary basin. Such pressure data were recorded by the operators during the completion and production phases of each well and is 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.

Early compilations of fluid pressure data from the Gulf of Mexico suggest that abnormal pressure increases in a rather nonsystematic manner at a depth where shales become more common in the stratigraphic column. In the literature (e.g., Magara, 1978; Chapman, 1980), a common model for pressure increase in Tertiary rocks is well expressed by a figure from Wallace et al (1979) which shows that below the hydrostatically pressured zone, pore pressure increases with depth so that the geopressure profile is a concave curve that grades into a lower convex curve. The result is a geopressure profile with the shape of a "lazy S". Such geopressure profiles are characterized by lack of sharp boundaries, in contrast to geopressure profiles drawn through seals bounding pressure compartments (e.g., Hunt, 1990; Weedman et al., 1992). In fact, Chapman (1980) cites the "lazy S" shape of the geopressure profiles as evidence that there are no seals (i.e., distinct low permeability horizons relative to rocks above and below) at the top of overpressure in thick shale sections of the Gulf Coast.

Construction of a geopressure profile assumes that high quality data from each well in individual fault blocks follow the same general trend and that differences in original pressures due to rollover anticlines were relatively small. Special care was used to select original pressures and exclude low pressures taken after a particular zone had experienced some production drawdown which is indicated by data falling off of a geopressure profile by more than 2 MPa. Pressure points that were determined to be faulty or drawn down were left off of the final plots. Detailed pressure records were not available for any of the BHP data, therefore evaluating the quality of each test was not possible.

<u>Tuscaloosa Trend</u> The first example of abnormal pressure about fault zones is taken from the Tuscaloosa trend in Louisiana (Weedman et al., 1992). The very porous sandstones of the lower Tuscaloosa Formation (Upper Cretaceous) produce gas in the depth range of 5400 to 6400 meters south of the Lower Cretaceous shelf margin (Fig.1). In the **Moore-Sams** and **Morganza** fields, the formation is cut by several east-west trending, southward dipping growth faults (Fig-

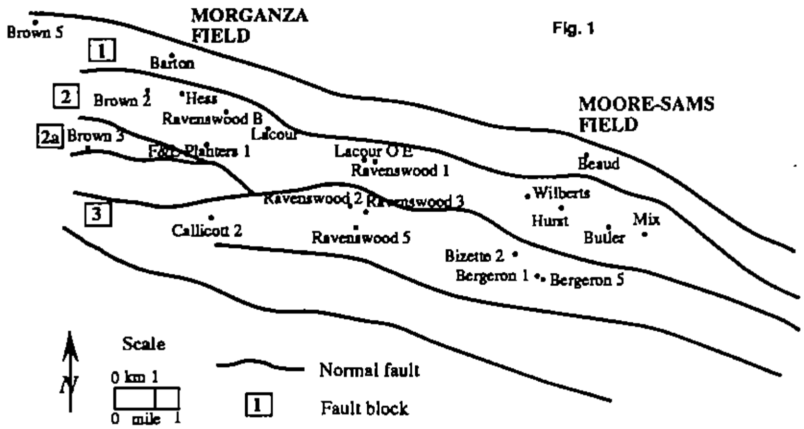

Fig. 1

ure 1), and comprises shales and both fining- and coarsening-upward sand bodies interpreted as distributary channels, distributary-mouth bars, and offshore bars. 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 are normally pressured while reservoirs in the same formation < 10 km to the south are entirely overpressured (McCulloh and Purcell , 1983).

<u>Moore-Sams Field</u> All pore pressures measured in fault block 1 fall on a hydrostatic gradient to the ground surface; the abnormal pressures in blocks 2 and 3 of this field follow a local hydrostatic gradient (Figure 2). The overpressures of blocks 2 and 3 follow a local hydrostatic gradient down to depths of 5850 m reaching magnitudes of 82.6 MPa. The top of the transition zone from normal to overpressure occurs in the depth range of 5620 m to 5683 m, while the top of the lower Tuscaloosa Formation is displaced down by 105 meters from block 2 to 3. Therefore, the variation in the depth to the top of overpressure between fault blocks 2 and 3 is considerably less than the displacement of the strata across the fault.

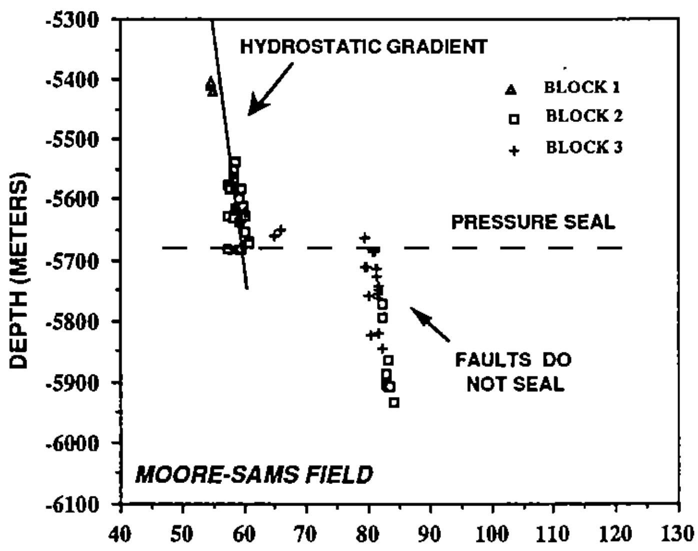

Fig. 2

It is important to note that the magnitude and gradient of abnormal pressures in blocks 2 and 3 are very similar, even though stratigraphy differs across the fault as indicated by the displacement of both the top of the lower Tuscaloosa Formation (by ~105 m) and the shale break at the base of the formation (by ~180 m), as well as in the basinward thickening (~ 78 m) of the formation. The fault that separates the two blocks, therefore, does not act as a pressure seal, because overpressures are nearly equal on both sides of the fault at the same depths. There is apparent fluid communication across the fault and within the overpressured sandstones of this field. Communication through the fault zone indicates that the effective stress within the fault zone is the same as found within intact rock on either side of the fault.

<u>Morganza Field</u> Overpressures in the Morganza Field wells reach magnitudes as great as 117 MPa at depths of 5975 meters (Figure 3). 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 up the reservoir into at least five blocks; four of them have wells with RFT pressure data. As in the

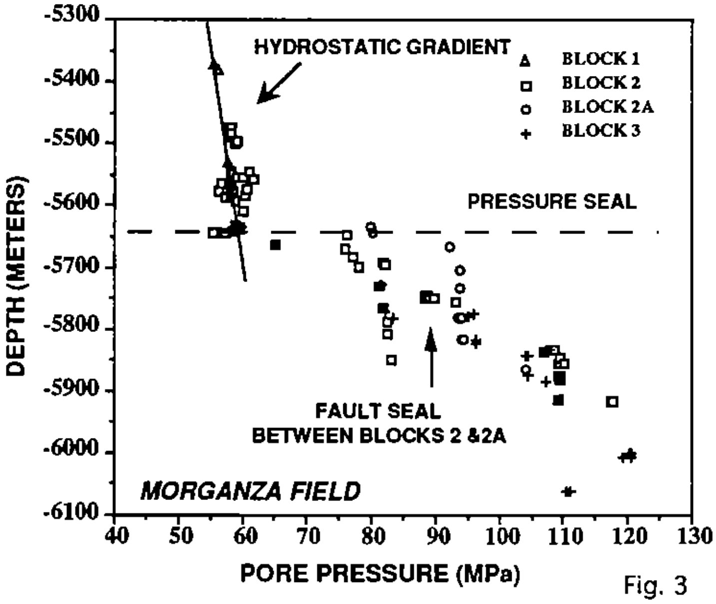

Fig. 3

Moore-Sams Field, all pore pressure data from fault block 1 are normal, i.e., they lie on a hydrostatic gradient to the ground surface, while the overpressures encountered 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 magnitudes of 83 MPa and 94 MPa, respectively, at depths of about 5800 meters, while pore pressures in the Brown 2 well follow a series of stair-step local hydrostatic gradients, reaching magnitudes as great as 117 MPa at depths of 5975 meters.

The pressure data from the Morganza Field are more complex than the data from the Moore-Sams; a great deal of variation in pore pressure exists in the depth range of 5675 to 5850 m, suggesting that several pressure seals may exist, not only along certain faults (between blocks 2 and 2a), but even within fault blocks (i.e., 2 and 3). Here faults serve as pressure seals which are zones of sufficiently low permeability to maintain a measurable vertical or lateral pressure anomaly. Effective normal stress within such sealed fault zone can be sizable.

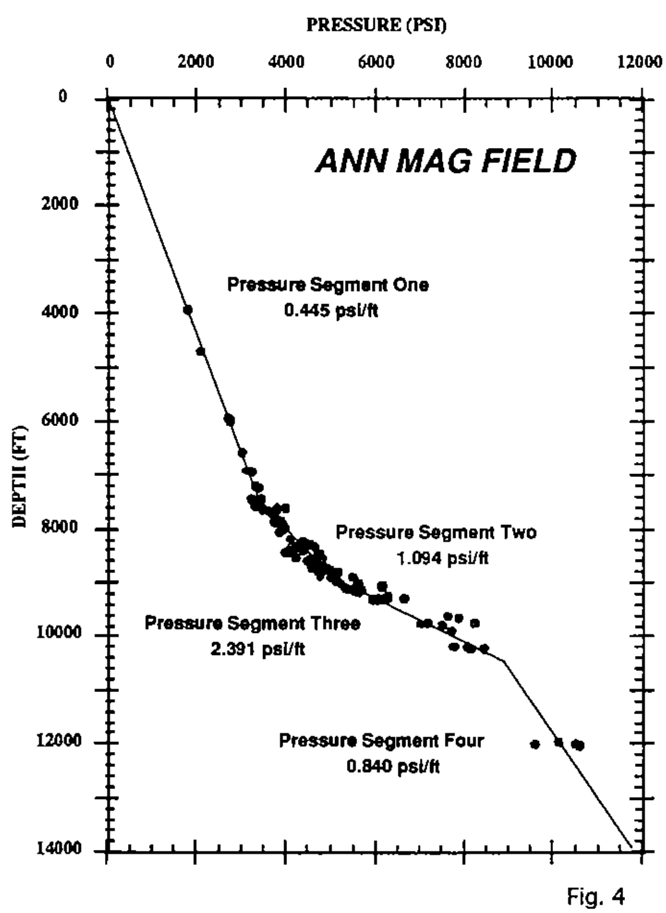

Fig. 4

South Texas Geopressure profiles for many fields in South Texas 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 geopressure profiles.

A geopressure profile constructed for the **Ann Mag** field allows us to identify the top of abnormal pressure at a depth of approximately 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 4). A normal pressure gradient of 0.445 psi/ft (10.1 MPa/km) is found down to the top of abnormal pressure. 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

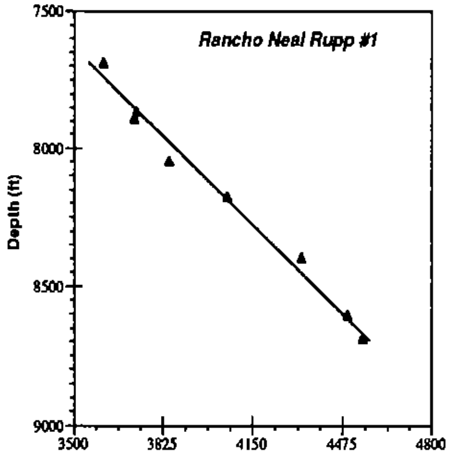

Fig. 5

undercompaction is a section with a high gradient of 2.391 psi/ft (54.1 MPa/km) down to a depth of approximately 10500 ft (3200 m). The deepest section has a pressure gradient of about 0.84 psi/ft (18.9 MPa/km) which is poorly constrained because of the small number of data points. When encountering these linear pressure-depth segments in other fields, they are labeled ONE through FOUR moving downward in a field. 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 4 follows a curve more like the "lazy S" of Chapman (1980). However, figure 4 is compilation over an entire field where fault zones do not act as seals. Pressure data from single wells serve as the best evidence for linear segments in pressure-depth profiles as opposed to nonlinear pressure increases. Pressure segment TWO for the Rupp 1 well is particularly well defined (Figure 5). A computer calculated curve fit to the data points comprising this segment indicates a linear curve fit with a regression coefficient of 0.993. The abrupt change in pressure gradient that occurs in going from the normally pressured section to abnormally pressured section is also consistent with linear pressure-depth segments. Observations also indicate that the change from normal compaction to undercompaction occurs abruptly, rather than gradually and that this abrupt change is accompanied by an abrupt change in abnormal pressure gradient as seen in going from pressure segment TWO to pressure segment THREE in the Ann Mag field (Leftwich and Engelder, 1993).

In the **Alazan** field 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 field. Segments in the Alazan field are equivalent to segments ONE, THREE, and FOUR in the Ann Mag and field. Segment TWO is missing because the top of abnormal pressure and the top of undercompaction are coincident.

In summary, the Ann Mag field shows four linear pressure segments with the top of undercompaction defining the boundary between segments TWO and THREE. Although segment FOUR is poorly constrained in the Ann Mag field due to lack of data, a linear segment FOUR is well constrained in other Tertiary fields. A field with four pressure segments is called the Ann Mag-type field. In contrast the Alazan field had three pressure segments so, fields with three pressure segments are called Alazan-type fields (Leftwich and Engelder, 1993).

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., 1992). 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 (~ 20 m) (i.e., a pressure seal a la Powley, 1990) where the local pressure gradient is as much as 0.43 MPa/m (pressure segment B of Figure 6). We know less about the shallower Tertiary geopressure profile above the Tuscaloosa trend, but, we know that it is overpressured at depths of ~4,200 m, 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 0.01 MPa/m which is

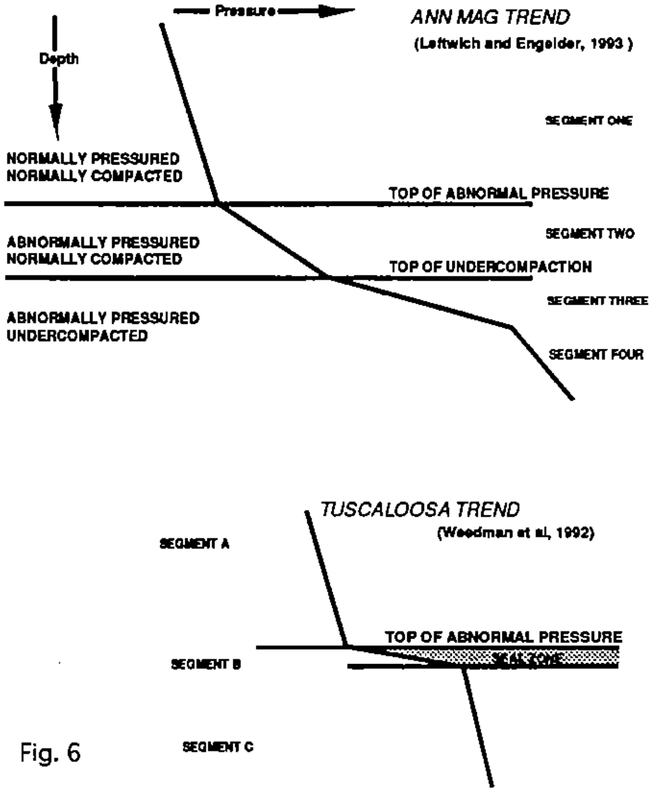

Fig. 6

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 which could be characterized by either an Ann-Mag or Alazan geopressure profile. The present data is 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 6). Thus, we have recognized that geopressures within the Gulf of Mexico are characterized by at least six different pressure segments. The following table gives ranges for pressure gradients for each of the six pressure segments in terms of kPa/m:

Segment:	ONE & A	TWO	THREE	FOUR	B	C
Gradient :	10.1-10.2	20 - 34	45 - 100	19 - 21	450 +	10.1-10.2

In conclusion, one interpretation of the pressure data is that in non-sealing fault zones effective stress is about the same as that in the country rock whereas, in sealing fault zones, the effective stress can be considerably higher.

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