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Analysis of Seal Integrity in Matagorda Island Field for Drilling Optimization

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Abstract

Study focuses on formation evaluation of Miocene gas bearing reservoirs in Matagorda Island field (GOM 519-18); and developing some advanced interpretation techniques that could improve drilling and well performance in other parts of Gulf of Mexico. Semi-consolidated sediments found in the offshore Gulf of Mexico presents a particularly challenging problem because of the lack of many conventional core information, extremely complex geological settings and high--cost drilling in the overpressured zones. Two different events were recognized in shales at Matagorda Island area. Faulting that enhances the seal capacity, and faulting that cause seal damage through micro-fracturing. Both scenarios were noticed on wireline logs and in seismic, and accounted for in subsequent well planning. These analyses have been used to predict pressure compartmentalization and position of casing points in eight wells drilled.

Introduction

Abnormally-high formation pressures or overpressures are observed world-wide in many types of sedimentary basins and tectonic environments. A seal is required to preserve overpressured zone; its "transition" from normally (hydrostatic) pressured to overpressured section depend upon properties or "perfection" of the seal. Excellent seal will have a relatively small "transition zone" as all excessive pressure generated below will be handled steeply by its lower portion. On the contrary seals of poor quality require much thicker section to keep the same amount of pressure and will result in well developed gradual transition, and even may lead to leaking into upper formations.

Shales and claystones form excellent seals to regional fluid migration; and their capacity to do so depends upon their capillary properties. Capillary pressure in rocks is controlled by interfacial tension, wettability of the rock surfaces, and the pore distribution, especially pore throat interconnection (9). B. Sneider defines a seal as a sediment, rock or immobile fluid with a high capillary entry pressure, which will dam or trap hydrocarbons. In order to be effective, pressure seals must be continuous and homogeneous (10). Typical shales and claystones in the Gulf-of-Mexico meet these requirements and present a very good seals.

In the Gulf-of-Mexico basin, sequences are commonly deposited throughout the area that is now a structure zone between salt and/or mud diapirs. Such active tectonics can influence seal integrity and composition, resulting in unexpected changes in overpressure compartmentalization. The sealing capacity along a fault is not constant. Several processes may increase or reduce sealing properties of a fault: clay smearing, deformation, secondary cementation, pressure solution etc. Previous work performed by Castillo et. al., (2000) discusses how an inactive reservoir sealing fault become a leaking "pressure conductor" after re-activation; similar observations have been made by Finkbeiner et.al., (1998). It is critically important to incorporate all information available and decide if every fault we are drilling through could possibly damage or add to pressure seal integrity.

Early recognition of presence of long transitional zones associated with disrupted pressure seals is a key to success in safe and efficient drilling. Pore pressure and fracture gradient trends were analyzed in seven wells to provide recommendations and control over development drilling in the Matagorda Island 519/18 blocks. The goal was to predict and characterize overpressure compartments, aid to well design and optimize completion.

1. Geology and Regional Settings

MI519/18 Field is located approximately 9 miles offshore from Matagorda Island, middle Texas coast, northwest Gulf of Mexico. The area is actually composed of three acreage blocks, numbers 519, 518 and 487 with 519 block sharing the majority of proven reserves. The Matagorda Island 519 Field is a part of an expanded lower Miocene decollement complex and produces from two overpressured zones. The structure consists of an expanded section that is rotated along a normal fault system with a thinning sedimentary section in the upstructure. This development creates a complex structural/stratigraphic trap over the crest of a deep seated shale diapir that runs perpendicular to coast parallel expansion faults. Stratigraphycally, the productive section is found within the lower Miocene Discorbis (B) Consistent (III) zone.

Major depositional sequences in the area are most affected by the middle Moulton/Pointbank system, and are characterized by extremely high sedimentation rates. Galloway (1985) describes this section as consisting of sand rich inner-coastal “microtidal” barrier island sequences transacted by numerous small streams. Deposition along the MI 519 area takes place in what Reading (1978) describes as a destructive deltaic depositional phase. During this phase, the depositional rates were equivalent to subsidence rates, allowing strike-oriented (coastal parallel) sand bodies to form downthrown to glide-plane expansion faults. Because there was no one major depositional outlet but instead a series of small coastal systems, slight sedimentation changes could cause rapid switching of depositional sites. These small systems were dominated by beach ridges, shallow shore face with local channels, and channel mouth bars with strike-oriented shallow shelf bar development during regression phases. Continued subsidence combined with the switching of depocenters allowed for preservation of some of the transgressive facies.

Several models could be used to describe a series of interrelated facies of Matagorda Island Field. A regressive or basinward migrating barrier island sequence was described by Davis, et al. (1971) and P. Weimer (1971). These regressive models describe beach facies, channels and shelf bar relationships and are well related to productive reservoir sands. Modern analogs with a detailed description of subenvironments at a distributary mouth in a river – dominated delta are presented in Coleman and Gagliano work (1980). Very useful outcrop examples were found within a Frewens Formation outcrops in Powder River, Wyoming (11).

Two key lithofacies were recognized within predominantely shayly sediments: delta front and pro-delta. The delta front consists of silty claystones which are gray to greenish gray, laminated or lenticular bedded, with a few gray horizontal and ripple stratified sands. Small sand-filled burrows are present in the claystones and most commonly occur near the contacts with interbedded sands. The overall degree of bioturbation decreases upwards. Contacts are gradational and often unclear. The claystones are dark gray, horizontally laminated; with light gray and low-angle parallel silt and sand interbeds. Some deformation and possible loading of isolated sandy lenses occurs. They are produced by alternations of no flow to lower flow regime in a sand starving system. The pro-delta claystones are dark gray to black and non-burrowed, occasionally with some silt material that is randomly dispersed and support low amplitude ripple laminae (minor to absent) and horizontal laminations. They are gradationally deposited in very slightly coarsening upward sequences, during very low current flow, possible under anoxic conditions.

2. Matagorda Island Case Study

Pore and fracture pressure trends were analyzed in seven wells to support future drilling activity in the Matagorda Island area, blocks 519/18 (fig. 1). The goal was to characterize existing seal pressures, assess existing compartmentalization and aid to well design and safe drilling. The data collected included direct pressure measurements from drill stem test (DST) and repeat-formation (RFT) tester and pressure-bombs, with equivalent mud weights and associated leak-off/integrity tests (LOT). In addition, pressure estimates from resistivity and acoustic logs in shales were applied using empirical relationships (1,5,13). Mineralogical composition have been studied using X-ray diffraction and SEM (electron microscopy) photographs on core samples from MI487 L2 and sidewalls from MI518 #1 wells.

One of the features we had to account for, while drilling into overpressured zones is the decrease of shale density, consequent increase of porosity and associated lower water salinity in contrast to shales that had been buried under hydropressure regime. Compaction of sediments with increasing depth of burial believed to be the main source of abnormal pressure (2,6). Shales could become undercompacted (and overpressured) if the rate of burial is higher that the rate of water expulsion. In this case certain part of water is “trapped” within the shale. With the increasing of depth of burial, pore pressure and fracture gradient increase at different rates. In the younger (normally pressured) Miocene section the rate of pore pressure increase is lower then the increase in fracture pressure. In the deeper section there is a gradual transition into pressured compartments were the gradient in pore pressure exceeded the fracture gradient. Both trends converge at the mud line (fig. 2 and 3) and set a physical limit to the length of open hole that can be maintained before setting an additional casing string (13). "Safe Window" for drilling could be determined between the calculated pore and fracture pressures. For the well to be stable and under control, the mud pressure gradient must always be in between.

Based on previous studies (Djafarov et.al., 2001) several stages of shale compaction could be recognized on porosity logs. 1) Initial compaction and formation of claly mud (30-100’); were new minerals are formed under oxidation and later under deoxidization environment. 2) Free compaction and formation of soft clay (100-4000’) and compaction of loose (non-cemented) particles under conditions of physically connected water removing (drainage). 3) “Labored” (4600 - 9800’); with compaction of partially cemented rocks under connected pores condition. 4)“Seriously labored” (<9800’); occurs under isolated pores conditions, when water removing is possible only due to natural hydro-fractures, osmosis (diffusion exchange) or incorporating water into crystal structure of minerals. Tops of these zones are denoted on figures (fig. 2, 3 & 4) as M – mud line; G- free compaction, B – labored compaction, and A- for overpressured sections.

3. Seal Composition and Diagenesis

When the clay minerals were originally deposited, the associated water compose from 65 to 80% of the total bulk volume (9,12). In the process of subsequent burial and compaction, a portion of this volume of water is expelled out of the sediments leaving a pore volume that is related to compressive stress on the framework. Overpressure may also develop in rocks undergoing progressive diagenetic alterations due to release of water by mineral dehydration. During alteration clay minerals are transformed from low density highly disordered products of weathering/reworking into dense chlorite (10). In Matagorda Island area the average log-derived density of shales increases from about 1.70 g/cm^3 to 2.72 g/cm^3 with the depth of burial. After the initial effect of compaction causing expulsion of interpore water from the shaly rocks, diagenetic changes become more important. Clay minerals are changed with the depth of burial: montmorillonite altered into mixed-layer illite-chlorite-montmorillonite; also the "regularity" of mixed-layered components tends to increase with the depth (Weaver and Beck). It was stated that in GOM there is a close regional relationship between overpressure and smectite-to-illite transformation (1, 14).

Illite & mixed layered illite/smectite are very common minerals in Matagorda shales (MI518 #1 & MI487 L2 XRD). Smectite initially contains abundant interlayer water in its crystal structure. When the interlayer water is expelled due to overpressuring, it becomes pore water. As a result we have the increase in volume and forming an abnormal pressure in the system. Illite appears in fibers and sheets; microporosity associated with illite mixed layered illite/smectite minerals will retain high amount of irreducible water and suppress resistivity log response (11). That’s especially related to a secondary illite with web-like microtexture, which appears as a pseudomatrix in a several cases. Release of structurally bound water from smectite also can occur during its transformation to illite by the addition of Al and K ions, and the release of Na, Ca, Mg, Fe and Si ions plus water. A number of authors described a water source at depth through a diagenetic change of clay minerals (12). The discharge of interlayer water is a temperature-dependent process with the dehydration reaction beginning in the 200 to 240 F (93 to 110 C) range. It was previously established (8,14) that at areas with moderate to high geothermal gradients this complete transformation occurs at the depth of approximately 15,000'.

4. Tectonic Activity

In Gulf-of-Mexico area, were sediments are progressively buried and compacted, abnormally high formation pressure (AFP) develops if the permeability of pressure seals, is sufficiently low. It may also result from faulting, folding, lateral sliding and slipping or squeezing, diapiric shale or salt movements, volcanism etc. (1,7). Pressure compartments often associated with active faulting because reservoir rocks may be displaced and juxtaposed against the shaly sections. In Caspian Sea area such events were observed and a close connection between mud volcanoes and overpressured zones was established by P. Avdusin. Depending on subsidence rate, the shale permeability must be as low as 10-21 – 10-22 m^2, (Knut Bjorlykke, 2001) to maintain generated overpressures. Faults are mostly act as seals playing an important role in preservation of the overpressured sections, but if re-activated, they can destroy or damage the seal. Such faults may allow fluid to leak from deep overpressured compartments, and thus produce overpressure in rocks at shallower depths. With time, the faults usually become healed mostly by carbonate or by quartz material (2); and during the progressive subsidence tend to be less permeable than the rock matrix due to filling with very fine particles.

All the data was analyzed using Presgraph a PC-based program that allows processing and graphical presentation of pressure information of various types. After establishing an overburden trend, measured formation pressure, mud weight profiles and LOT results were used to set up boundary conditions and provide reference points on subsequent calculations of sealing pore pressures from logging data.

Two different effects of faulting presence were observed in a Matagorda Island Field. Faults may act as a seal and enhance the shale sealing. Changes in pore pressure calculated from sonic/resistivity logs are steep, “transitional” zone is about a 100 - 150‘ thick and almost invisible at a whole well scale. Because of such sharp changes these zones are hard to recognize on logs, however typically one casing point is required to separate it from upper normally pressured section. An example of sealing fault is shown on figure 3, were the overpressured formation is separated into two compartments: A1 and A2. Very short transitional zones at the top of both compartments were noticed. Another option is when fault causes partial damage, possibly through micro-fractures in shales. Shale sealing properties are decreased, pore pressure in reservoir sands is lower than in neighboring blocks (fig 5). Sealing zone possess gradual changes in pore pressure with lower values that expected. Such zones are up to 2000' thick and could be observed on LWD as well as on conventional log diagrams. Several casing points are required in order to drill through such zone. An example of complex combination of fault influence is set forth on the figure 5 (fig.5). Although long transitional zone have been observed, overpressure from AFP formation did not decrease due to second fault (marked "B" on fig. 1) sealing its compartment. Zones with reduced sealing capacities will fracture much easier and allow "pressure migration" to upper zones. As a result upper zone will become unexpectedly overpressured; also such faults may cause forming of the shallow gas zone. To avoid drilling surprises during sidetracking in well MI519 F2, the calibrated model based on wireline logs was applied to evaluate pore-pressure using LWD GR and resistivity measurements. Real-time analysis (fig. 5) allows identifying of the exact position of transitional zone and overpressured seal and aid in optimizing of casing point.

Conclusions and Recommendations

Most of well documented faults (seismic, well-log correlation, paleo data) in Matagorda Island area are pressure sealing. However, there are few examples when faulting results in partial destruction of pressure seal integrity and thus produces unexpected long "transitional zone". Such areas lead to additional complexities in drilling, require real-time pore-pressure analysis using LWD/MWD data and may result in changes of casing program. By incorporating pore pressure trends from sealing sections into the reservoir model, one can predict whether the fault will act as a pressure-formation liquids "semi-conductor" or as a good seal. Transitional zones with reduced sealing capacity could frac, allowing vertical migration and lead to shallow gas/overpressue forming. It is recommended to map such faults and to avoid drilling through damaged seals when possible.

Compaction is the main porosity reduction agent and it leads to restricting of pore throats and increasing of pore system tortuosity. Mineralogical changes result in density increasing of new-formed minerals; they can not be responsible for porosity decreasing. In separate pressured compartments with vary "transitional zones" we observe no difference in shale mineralogy. In Matagorda Island we have a random distribution of kaolinite/illite/mixed layered components, and observe no dependence in clay minerals distribution vs. depth (for the study interval 8500-17200').

Conventional porosity methods in streaks (interbeds) of shales within reservoir sections cannot be used for pore pressure analysis. Shales contain certain amount of silty material due to high sedimentation rates and may exhibit more random fabric orientation. If additional complications occur due to changes in lithology or micro-fracturing a spectral porosity method: NMR (nuclear magnetic resonance) is a preferred technique. For real-time pore-pressure estimate in this case a measurements of longitudal relaxation time (T_1) would have an advantage over more common T_2 measurements.

In overpressured formations, the seal quality could be described by the high of "transitional zone". Good quality pressure seals will result in steep pore pressure changes, whether damaged seals will lead to long transition and possible pressure leaks. During drilling operations, properly calibrated LWD resistivity data could be used to evaluate seal quality in real time. Complex cases with mixed/unknown lithology and/or salt mass presence require a combination of resistivity and full-wave sonic logs. Future research should be aimed at understanding of shale and claystone sealing integrity and their recognition on logging diagrams.

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Nomenclature

DST = drill stem test
EMW = equivalent mud weight
LOT= leak-of-test
RFT = repeat formation test
SEM = scanning electron microscopy
T_1 *– longitudal relaxation time*
T_2 *– transverse relaxation time*
TVD=true vertical depth
XRD = X-ray diffraction

References

1. Bourgoyne Adam T. et.al., 1991. Applied Drilling Engineering. SPE textbook series.
2. Castillo, D.A., Bishop, D.J., Donaldson, I., Kuek, D., de Ruig, M., Trupp, M., and Shuster, M.W. "Trap integrity in the Laminaria High-Nancar Trough region, Timor Sea: Prediction of fault seal failure using well-constrained stress tensors and fault surfaces interpreted from 3D seismic" APPEA, Journal 2000, p. 151–173.
3. Djafarov I.S. Khafizov S.F. and Syngaevsky P. E. "Advanced Formation Evaluation for Prediction and Characterization of Overpressured Zones". AAPG 2nd International Regional Conference, Sankt-Petersburg, Russia 15-18 July, 2001.

4. Finkbeiner, T., Zoback, M.D., Stump, B., and Flemings, P., "In situ stress, pore pressure, and hydrocarbon migration in the South Eugene Island Field, Gulf of Mexico", in Mitchell, A., and Grauls, D., eds., "Overpressures in petroleum exploration, workshop proceedings", 1998, Pau, France, Elf Aquitaine Memoir 72, p. 103–110.
5. Heppard Philip D. and Traugott Martin O. "Use of Seal, Structural, and Centroid Information in Pore Pressure Prediction", Amoco Exploration and Production Technology Group, Houston, Texas, AAPG materials 1999.
6. Lee Stan, Shaw Jesse, and Ho Rachel. "Detecting Reservoir Seal Integrity Using Seismic Methods". Mobil Technology Company, SEG, 1999.
7. Mildren S.D., Hills R.R. and Kaldi J. "Calibrating Predictions of Fault Seal Reactivation in the Timor Sea" Materials of National Centre for Petroleum Geology and Geophysics, University of Adelaide, Australia, 2002.
8. Richard J. H. Jolly and Lidia Lonergan "Mechanisms and controls on the formation of sand intrusions". Journal of the Geological Society, London, Vol. 159, 2002, pp. 605–617.
9. Roger M. Slatt, " Significance of Shales and Mudrocks in Oil and Gas Exploration and Reservoir Development" School of Geology and Geophysics, University of Oklahoma, Course Notes, 2000.
10. Sneider, Robert M., Surdam Ronald and Varva Charles. "Seals - a Critical Element to Successful Exploration and Production". PTTC workshop materials. Jackson, Mississippi, March 29, 2000.
11. Syngaevsky Pavel E. "Formation Evaluation of the Siphonina Davisi Section at Matagorda Island Field. Offshore Texas, Gulf of Mexico: 622/623 and 519 blocks". Louisiana State University, The Craft and Hawkins Department of Petroleum Engineering, April 2000 (Post-doctoral study).
12. Tingay Mark, Hills Richard, Morley Chris, Swabrick Richard and Okpere Eugene. "Overpressure, In-situ Stress and Mobile Shale Features in the Baram Delta, Brunei Darussalam", University of Adelaide, Australia, APCRC presentation, 2001.
13. Wagner, Bruce E. "Pressure Trends in Lower Viosca Knoll and Mississippi Canyon, Gulf of Mexico Deep Water: Implications for Seals, Column Heights and Hydrocarbon Migration", AAPG Annual Meeting, May 17-20, 1998.
14. Yassir N.A. and Bell J.S. “Abnormally High Fluid Pressures and Associated Porosities and Stress Regimes in Sedimentary Basins”, SPE Formation Evaluation, March 1996.

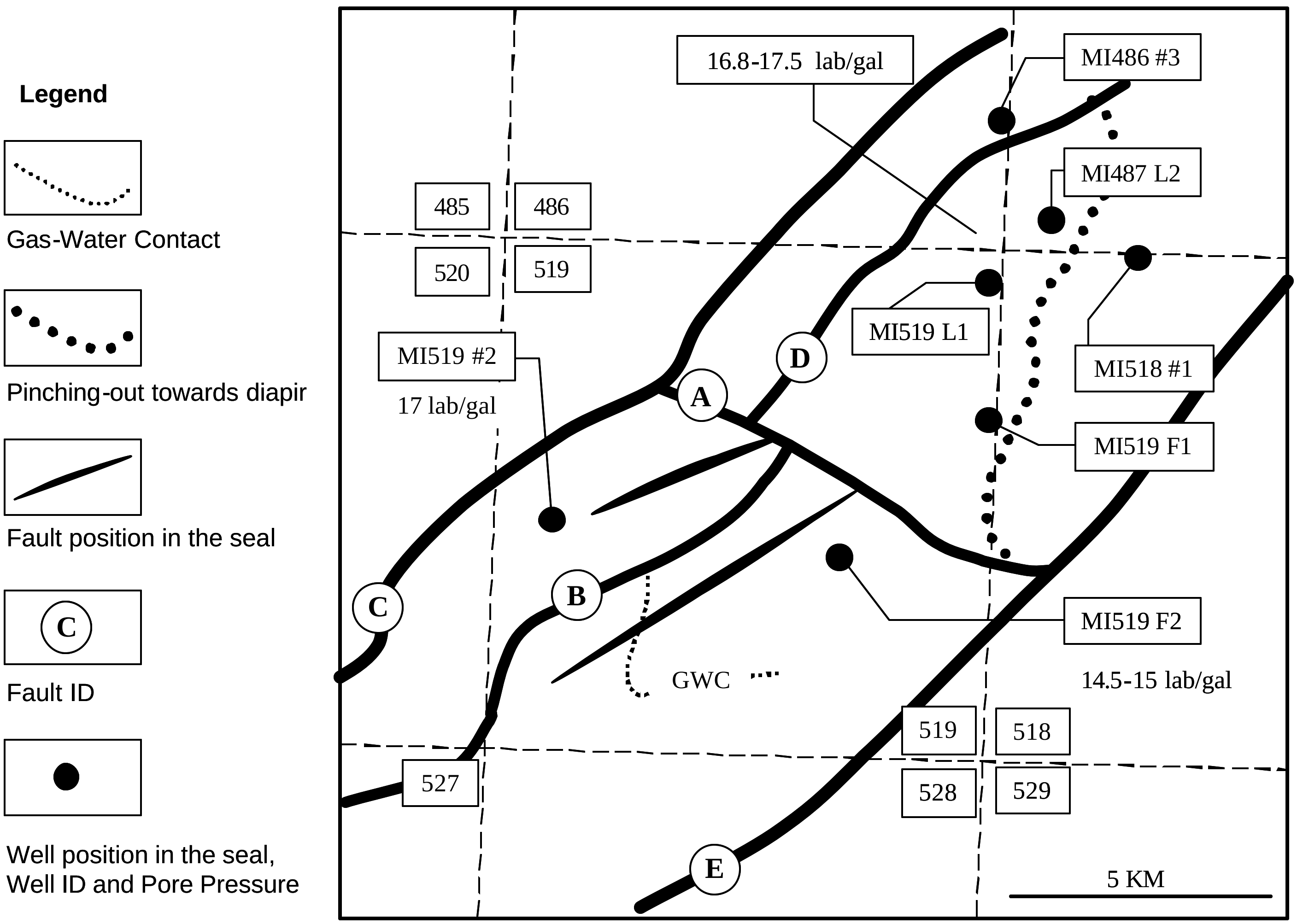

Figure 1. Matagorda Island Field acreage and well location.

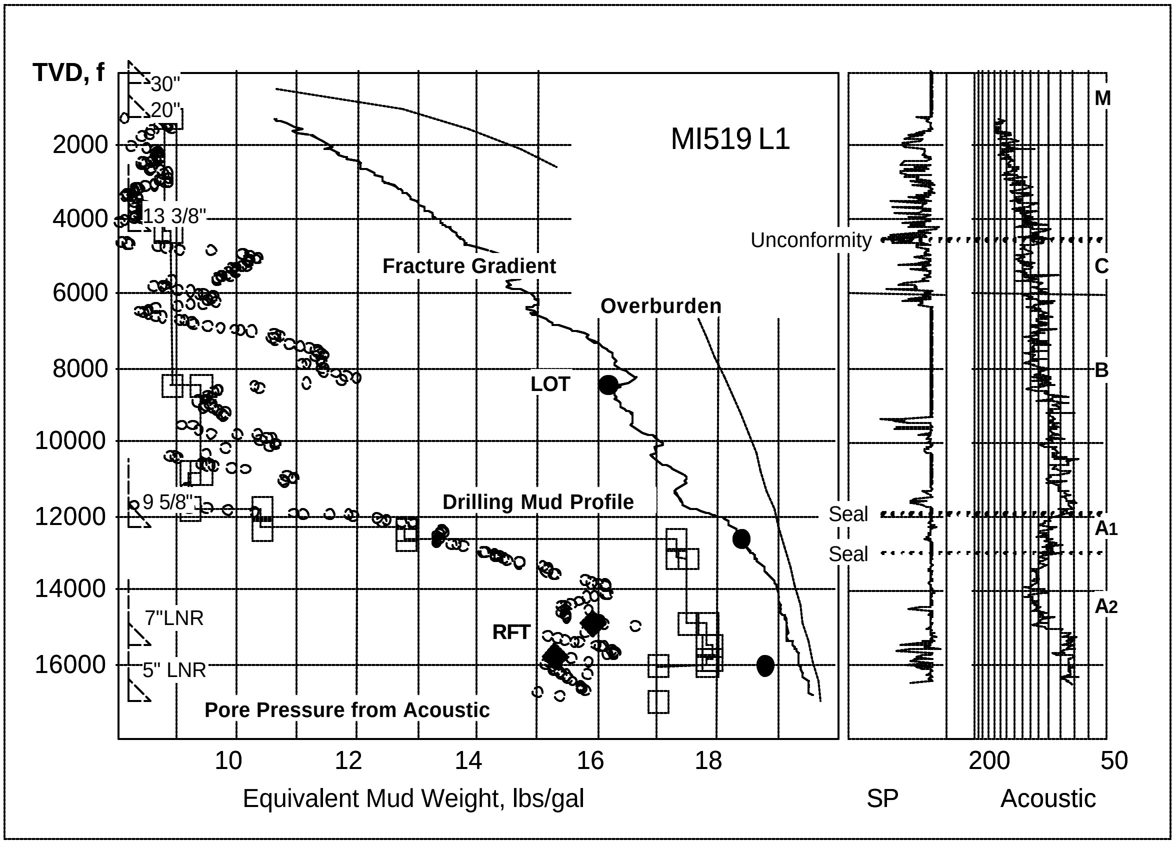

Figure 2. Wel MI519 L1. Two pressure seals of good quality with small transitional zones.

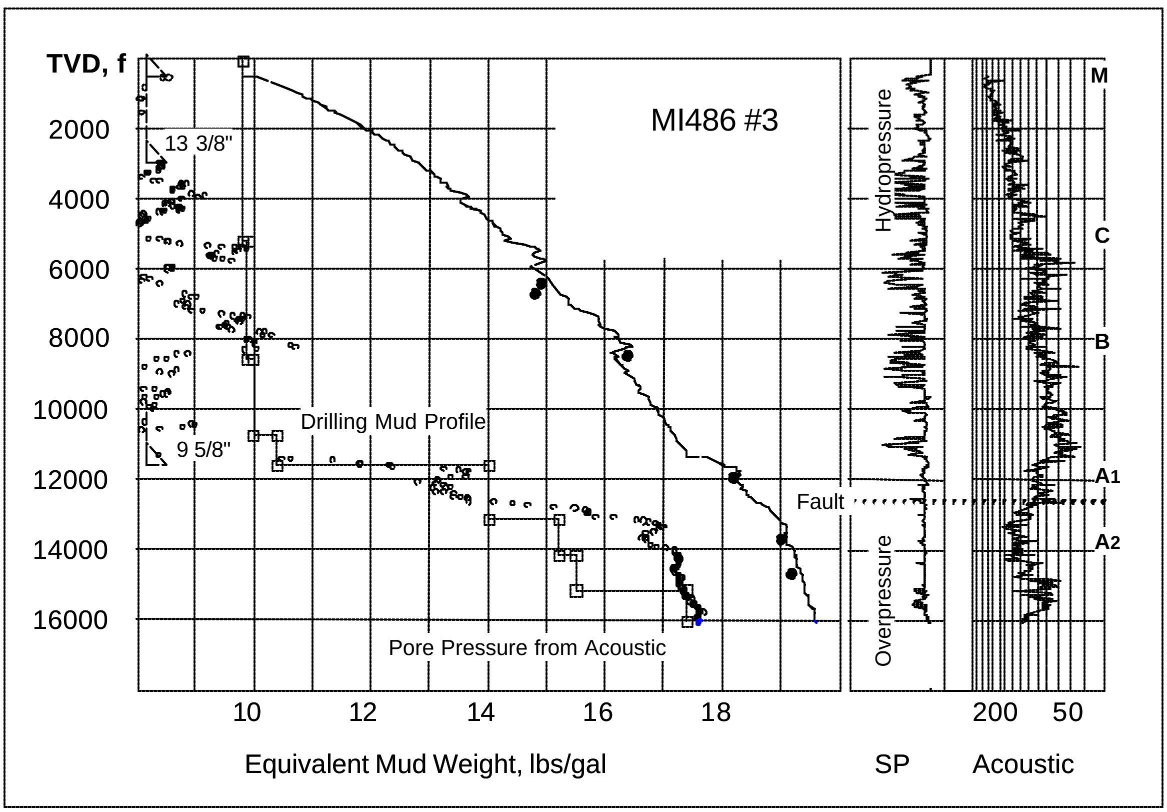

Figure 3. Wel MI486 #3. Two pressure compartments separated with fault.

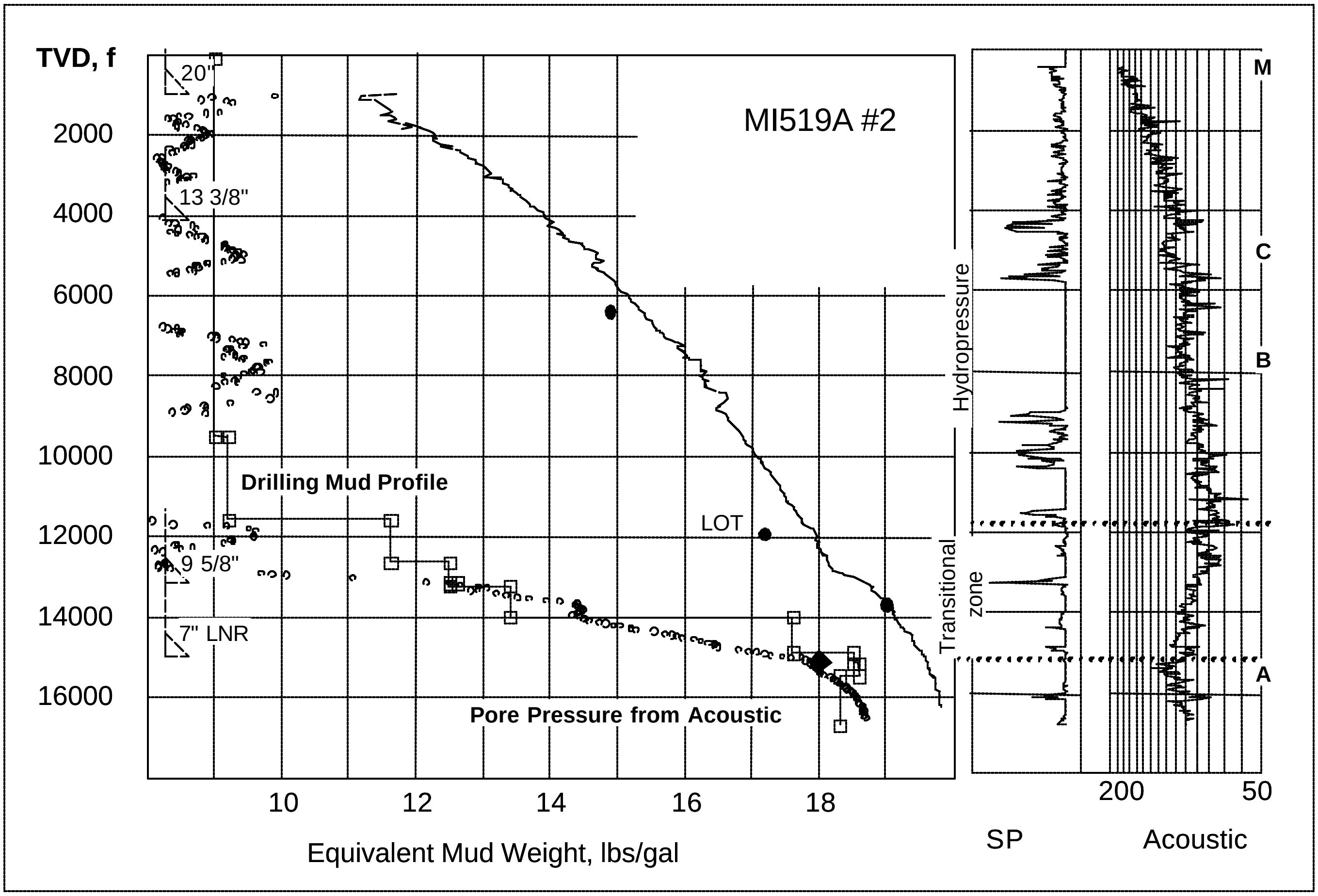

Figure 4. Wel MI519A #2. Long transitional zone – result of pressure seal damage.

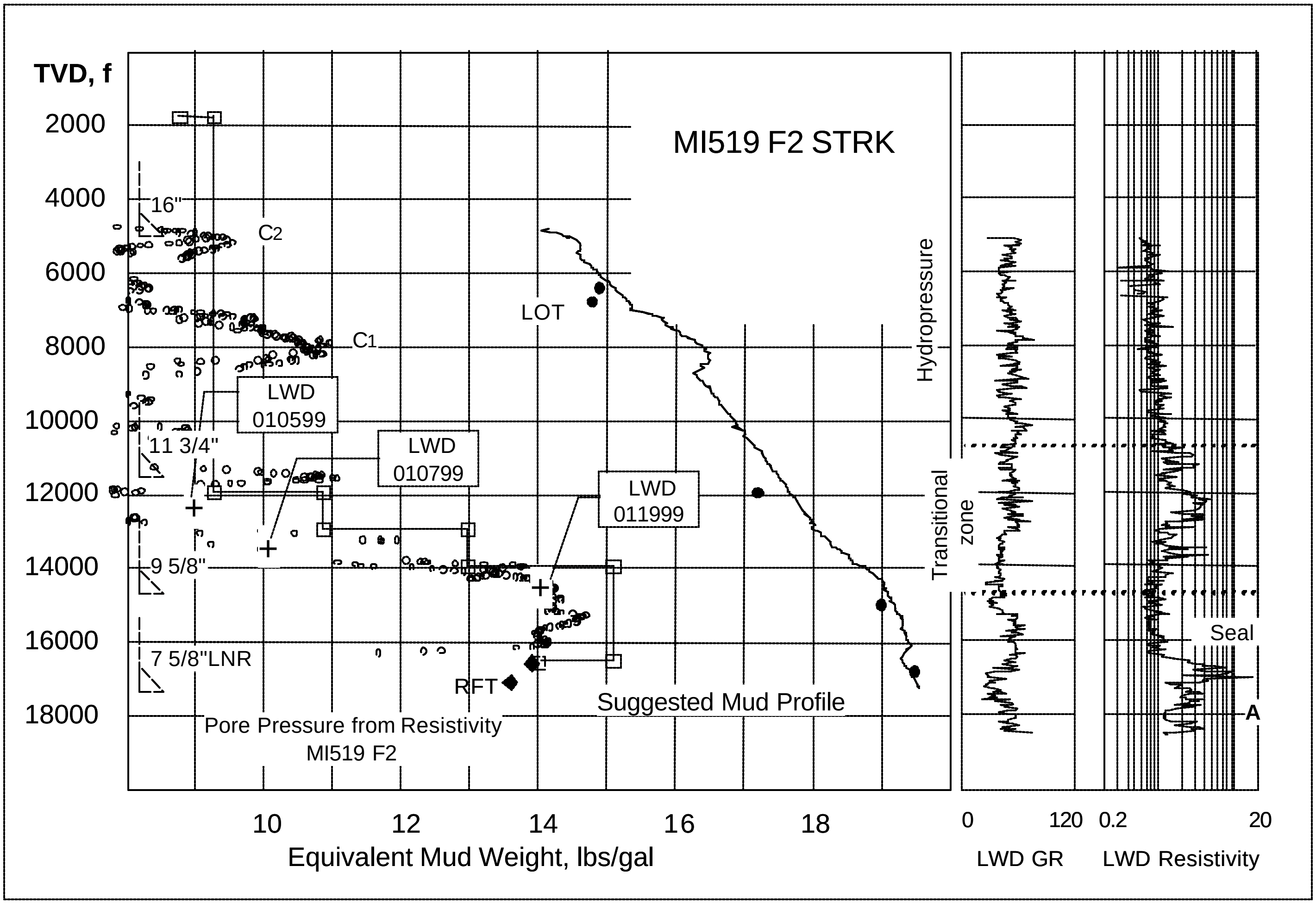

Figure 5. Wel MI519 F2 sidetrack. Real-time pore pressure analysis using LWD alow to optimize casing program in long transition zone (damaged seal).