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How We Learned to Drill the Pressurized Shale in the Gulf of Mexico: One Person's Recollection

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ABSTRACT:

"High" pressure wells in the Gulf of Mexico in the 1950-60's were the result of some unknown source and were treated with very ad-hoc solutions. This paper discusses the resolution of the high pressure drilling problems in the 1960-70's and the various people who championed the solutions that are still the basis of drilling high pressure wells.

INTRODUCTION

This is not an engineering or scientific study, but a history of the decade in which we finally figured out how to drill the plastic pressured marine shale in the Mississippi River Delta. It involved classical Geological Engineering although due to the influence of Shell Oil we called it Petrophysics.

I was involved in this work between about 1960 and 1972. While I had some small original parts and considerable operational influence, for the most part I stood on the shoulders (and ideas) of much bigger men. So this discussion is from the viewpoint of one of the players and as such is a bit of personal history.

While there were papers as far back as 1927 (Ruby 1927;Athy, 1930; Dickenson 1953; Thomeer and Bottema 1961) describing some of the basic problems of geopressures and shale water expulsion, Drilling Engineers, Geologists, Seismologists, and Academia were not talking to each other and were for the most part unaware of the problems or activities of the other disciplines. The Miocene shale of the GOM was just a big black pile of gumbo mud 20,000feet thick (as far as the drillers knew)

(Figure 1. GOM Shale)

EARLY GOM MUD and CASING PLAN

It all starts with the 1950 original Gulf of Mexico (GOM) mud program: (Figure 2)

● native mud with a SpG of 1.08 to 1.2 (9-10pounds per gallon (ppg) to 10, 000'of depth

●increase the mud density 1ppg (or .12 SpG) every 1000 feet of depth.

●break-over the native mud to a lime mud

●set casing with 1.5 SpG, (12.5ppg mud)

●drill ahead increasing the mud density 1ppg every 1000 feet

●at 12.5ppg, the drill rig went from footage to day work

This worked in general, but there were a lot of well bore stability problems; gas or salt water kicks, slow drilling rate, and stuck drill pipe. The general program was too general but it worked better than any other program we tried. There was a lot of non-productive down time trying to control salt water or gas flows (well kicks) and unstick drill pipe. We need to note at this point, the major problem wasn't the spectacular blowout, while there were some of those, the big problem was the high expense of lost time due to trying to control salt water flows, gas flows, and to free the stuck drill pipe that came with the saltwater and gas flow problems.

THE WELL CONTROL BREAKTHROUGH

The first clear clue to the solution of the drilling problems was with the publication on Blowout and Well Control by OBrien and Goins in 1960 In subsequent technical meetings the subject was discussed at length by the authors and in informal meetings by other operators, notably Frank Priebe with Cities Service Oil Company.

I entered the problem in 1962 as the Magcobar (drilling mud) Staff Technical Service Engineer in Southwest Louisiana. Another service company was loud in criticizing our drilling mud technology and testing..

I proposed that the most effective (and profitable) way to solve the problem of the criticism, was to bypass the entire problem and have the mud engineer kill the well kick using a well choke. A series of twelve correspondent courses was developed on the "new" theory of how to kill a well kick and one was sent out every two weeks to all the local company mud engineers with the proviso that their expense account would not be paid until the finished lesson was turned in. The principle worked very well – everyone turned in the lessons on time.

(Figure 3 We Learned to Control Salt Water and Gas Flows)

About half way through the series, I had a phone call about 2:00AM. On the 23rd of December. The Mud Engineer on an offshore drilling rig said that they had a well kick. The problem was that it usually took four or five days to get back to drilling if the drill pipe didn't get struck as the result of the well kick. The real problem was that both the Tool Pusher and the Mud Engineer were married with small children and had promised to be home for Christmas. So the Mud Engineer asked if I thought he could kill the well according to our correspondence course. I said, "Go to it".

The next morning he called back and said the well had killed just like the lessons said it would. (The real truth was that it was a small salt water well kick, and almost anything would have worked). The word spread among the other mud engineers like wildfire, and there was no stopping them. From then on we were the group that could kill a well kick and business improved and everyone was a hero.

This was an important breakthrough in the Gulf Drilling and it was picked up over the next few years by all the operators. There were the usual teething problems with a new technology, but the original technique was sound and glitches in everyone's understanding worked their way out, (Rehm, 1969).

The interesting thing to note here was that this was done on a field level with no "headquarters" permission or support.

KILLING WELL FLOWS (KICKS) CHANGED OUR PERSPECTIVE ON DRILLING IN THE GULF

Beyond an immediate improvement in drilling costs, the well kill was important because it opened the door to confidence in us that we could control some of these drilling problems and minimize lost time. But most important it promoted new thinking. How do we deal with this new the well control idea or technology?

Under the leadership of the Shell Petrophysics Group in New Orleans, Shell started drilling from kick to kick, controlling the mud density in such a way the well kicks were small and easy to control and avoiding the large catastrophic well kicks. This procedure increased drilling rate and decreased lost time. I have never found documentation on this process, but it was common knowledge.

There were other activities based on well control that were growing by the month; more and different well chokes, discussions of practice and theory, and the reduction of all of the well control ideas into practice

PORE PRESSURE FROM ELECTRIC LOGS

The next big breakthrough in understanding, came about two years later, (1963-4). At an earlier Well Log Interpreters Meeting in Lafayette, Louisiana, Harold Hamm of Schlumberger (Hamm 1966) noted that, ' the 16" short normal electric log readout of shale resistivity seemed to point to areas were we had well kick problems.' I don't know who else caught that statement but I heard it loud and clear.

I went to the local electric log library and picked up a few well logs from areas where we were having well kicks and hung the logs over the nine foot office door so I could see a long sequence of the hole). After picking shale points and plotting them, it was obvious that a decrease in resistivity in the shale pointed to higher pressure zones. (Figure 4 Typical 1960 IES Log) With a red pencil and a straight edge, the pressure increase plotted in a dramatic manner.

A short series of correspondence lessons followed along with a trip along the Gulf Coast for show and tell. By this time, the Mud Engineers and their contacts were ready to listen. Could we really calculate pore pressures from the logs of offset wells? Since this was a period of intense platform drilling, offset well data was readily available on board the drill rig in the form of the standard IES log or Induction Electric Survey

In this period we used two cycle semi-log paper for a lot of our calculations and pads of it were readily available. It became evident that if we plotted depth on the linear axis and resistivity on the semilog axis, that mud weight change could be read directly. Likewise if we plotted depth vs resistivity on a coordinate scale, mud weight change could be read directly from a log scale overlay. The same was true of the new Sonic™ or acoustic log. In general sonic or acoustic logs were a lot clearer, but not nearly as common as the standard IES log. (Figure 6 Sonic Log Pressure Plot)

The same pattern followed as with the well control. A telephone call from an offshore platform, "We are drilling very slowly and the offset data shows our mud weight is 4ppg too high. Can I cut the mud weight?" I was at home in bed and he was on the rig in 200 feet of water. So they cut the mud weight and the drilling rate returned to its normal one ft/minute. The news passed around like lightening. Electric Log calculations for mud weight really worked!!

You have had to have been in that period to realize what profound influence that had on mud densities and on the mud engineers themselves. All of a sudden we really knew something that was vital to the drilling operation.

Fifty years later, it is not clear how the log technology spread from one Mud Company to the others, but the Operators Engineers and Log Analysts quickly picked up on the technology, It is not clear exactly who did what, but was certainly not from a single source. ,(Timco, 1965; Foster & Whalen, 1965; Wallace, 1966). .

Schlumberger and the other logging companies were aware of the breakthrough and pointing it out to the operators. At any rate along with the increase in well control practices, there was an almost explosive grasp of the potential of the electric, and sonic or acoustic log as a drilling and casing point tool.

DRILLING DATA - THE "d" EXPONENT

About two years later, while we were all digesting this technology, Jorden and Shirley (1966) of Shell Oil Company in New Orleans published a rather academic paper based on some field data, and referenced previous micro-drilling. They proposed a drilling equation (Figure 7 "General Drilling Equation) and noted that if the equation was solved for exponent to the 'bit weight / diameter' expression, it would tend to predict differential pressure between the well bore and the pore pressure. The term for formation drillability "a" would drop out when a thick formation of a single age and lithology were considered – such as in Offshore Louisiana. However they noted that this was lab work and probably shouldn't be tried in the field. .(Fig 8 Scatter from Jorden and Shirley Data)

I don't know who tried it first, but despite the published scatter curve from Jorden and Shirley, the trend was very reliable. Drillability could be related to differential pressure at the bit, and in turn calculate pore pressure.

Here was a real time tool that could tell us differential pressure at the drill bit and knowing the mud density, in real time we knew the pore pressure. The idea was grabbed by the Mud Engineers and Well Site Geologists (Mud Loggers) as the tool we had always been looking for, (Rehm & McClendon 1971)

While I don't know who did what with this technology, I know how our group with Magcobar jumped on the "d" exponent idea. Again the idea was passed along by a combination of lessons in log reading, plotting, and calculation along with Show and Tell. Our main tool for the math was our little six inch slide rules or four inch circular slide rule, but Jorden and Shirley had provided a nomograph that helped the more mathematically challenged field people. The plotting in real time of the "d" was an immediate success and along with electric log calculations was a real predictive tool. It also helped that we were no longer afraid of well kicks and were quite willing to take a small influx of salt water or gas to verify the actual pore pressure. Within several months, all the offshore mud engineers and most of Louisiana marsh country mud engineers were routinely using the "d" exponent to control mud density and avoid well kicks and stuck pipe.

We applied the semi-log overlay to the "d" trend and were able to develop the proper scaling to read mud density directly. This was the same approach that was used with well log plots and everyone was comfortable with it.(Figure 5 "d" Solution Plot)

Mario Zomarra with 'IMC'in the middle and late 1970's pushed "d" exponent use. He modified it and plotted it on semilog paper. In his peer review of this paper he commented that we did it wrong. It should have been a semi-log plot. He is probably correct

Over the next two years the "d" system was improved by the observation that if the "d" was multiplied by "the normal mud density/the actual mud density", this "normalized" the effect of any mud density changes while drilling. This was the "dc" which was actually named after a Mud Engineer named Cesmirosky who made the observation, so "dc" actually meant "d" with the Cesmirosky correction.

Another improvement was made by field observation, (by Wiley Bishop) that if the mud density were increased to keep the 'dc" on trend line, the borehole differential pressure would remain the same and you could drill ahead safely until the mud density indicated a casing point.

A very interesting predictive tool was presented for our group by Hebert (Hebert et.al. 1972) who showed that the effect of drillability on the pressure cap could be used to predict the ultimate pressure contained within that pressure cell. (Figure 5 "d" Solution Plot Showing Seal)

PRESSURE SEAL AND DIAGENESIS

Diagenesis is one of the geological terms that describes the compaction of sediments into shale. As sediments were continually deposited in the Delta, the lower material was compressed by the increasing load from above. The fine grained sediments – clays-formed into a semi-permeable membrane that allowed water to migrate up and retained salty water in the pores of the clay-shale. This action provided a pressure gradient in the shale pores that was equal to a column of water to the surface.

During periods of drought or changes in river flow, finer limey sediments were deposited which acted as a barrier and not as an impermeable membrane. Below them the water could no longer migrate up and as pressure from sedimentation increased, the pore water in the shale started to pick up the weight of the overburden.

The pressure gradient then became equal to a column of salty water down to the seal, but below the seal the gradient increased to that of overburden.

It is not clear who was the pressure seal champion or champions, probably W.A. Boatman of United Core (1967) , Jim Gill of Baroid,(1968) and Dick Louden of Magcobar,(1972), had as much to do with discussing and using the pressure seal as anyone. The pressure seal, it turned out, was the key to everything. Once we understood the seal, we started to understand the concept of Diagenesis

During the depositional period, there were occasional droughts or climate changes that caused finer grained limey materials to be deposited in the Delta. This denser deposit upset the normal (diagenesis) compression of the semi-permiable membrane of the clay/shale that allowed water to escape upward. The changed depositional zone was a barrier to normalizing pressure by blocking the shale water escape. The result was that with continued deposition the water in the shale started to pick up the overburden load instead of the shale structure. So to the normal pressure, equal to a column of water to the surface, below the seal was added the overburden load from that depth on to some other depth.

However, this was only if the seal didn't leak. (Stuart 1970). Many or most of the seals leaked and so the extra load was not overburden or normal pressure, but something in between.

At this point in the technological change, we understood the basic seal concept. Most of the seals were on the order of six to ten feet thick and were pretty obvious. It was easy to see the seal from well logs or mud cuttings, and a slower drilling rate always occurred within the seal.

TEMPERATURE CHANGE BELOW THE SEAL

In the Miocene formations, the temperature gradient was very consistent until a pressure seal was reached. The gradient then broke, the seal was hotter, but the gradient below it was less.

This showed up clearly on temperature logs, but also showed up in mud line temperature as measured by the on site geological sample logging units.(Mud Loggers) (Gill, 1968; Wilson & Bush 1972). Temperature plots showed the onset of abnormal pressures and could used to determine the mud density increase needed. Boatman(1967) and Gill(1968) with their geologists and Mud Logging units championed using temperature logs as one of their primary pressure prediction tools.

SHALE DENSITY CHANGE BELOW THE SEAL

The same condition occurred with shale density. Shale density increased at a constant rate until a pressure seal was reached. The seal had a greater density and below it, the shale density decreased in proportion to pressure increase, (Boatman, 1967). This was one of the favorite mud logging tools. A simple balance was all that was required. Shale density was also used by the mud engineers who we taught how to calculate shale density from the mud balance.

SALINITY CHANGE

One of the big problems in drilling was saturated or near saturated salt water flows. One of the semi-permeable membrane effects of the massive shale was to concentrate the salt in the pore space and thence to the local sand layers,(Overton & Timko, 1969). The mud logging people learned how to plot salinity increase in the normal pressured zones, and then note the decreased salinity in the abnormal pressure zones, and this become one of their pressure prediction tools,(Gill, 1968).

(Figure 9 Comparison of Plot Sources)

GEOLOGICAL SAMPLE UNITS - MUD LOGGING

Baroid with their mud logging units (Gill 1968) became especially aggressive in promoting the value of the mud logging unit in geopressures which in turn forced Magcobar to start a semi-computerized mud logging system which lead to the Analysts Logging system (Later purchased by Schlumberger)

The reviving of the mud logging business was a significant step in controlling high bottom hole pressures since it put a geologist on the front line of the drilling operation. In addition to sample catching and lithologic descriptions, the mud loggers monitored the "d" exponent, flow line temperature, gas volume and type, salinity, shale density, pore pressure and plotted the results in close to real time.

SEISMIC VELOCITY

It was evident from the acoustic wire line logs that we should be able to see the pressure variations from seismic records. (Pennebaker 1968.) The problem was that 'interval velocity' interpretation was still done by hand and some of the migration techniques were not fully developed. On top of that with a few exceptions, exploration and drilling were not on the same wave length. (Figure 10 Seismic Plot)

FRACTURE GRADIENT.

There was one further development needed in this period, and that was a understanding that lost circulation was a function of the fracture pressure or fracture gradient. There was no clear field understanding of the fracture pressure/stress relationship prior to 1957. Hubert and Willis (1957) gave us a generalized stress, pore pressure-overburden pressure relationship which when translated into mud weight terms:

Fracture Gradient ppg = 1/3 x (19.6ppg - PP) + PP

Where:

1/3 = ratio between maximum and minimum stress in a normal shale depositional environment

19.6ppg = Overburden gradient expressed as a mud density

PP = pore pressure gradient expressed as a mud density

This sort of worked, and it gave a justification to the fracture gradient and casing points that had already been observed. In 1963 Ben Eaton further discussed fracturing as a completion or stimulating technique, but the ideas did not resound in the drilling operations

Bob Mathews and John Kelly of Mobil Oil Co finally published their landmark paper in the Oil and Gas Journal in 1967 although Mathews and Kelly had been working on it for several years. It got immediate attention from drilling operations,

$$F = P/D + k_i \times \sigma/D$$

Where:

F = Fracture Gradient, psi/ft

P =Formation Pressure,(Pore Pressure), psi

D = depth, ft

ki = matrix stress coefficient, for the depth at which the value of σ would be the normal matrix stress

σ = normal matrix stress, dimensionless

The method required some input from experience, but the stress curves were easy to develop and the whole system worked well.

Later, the Mathews and Kelly procedure was replaced by the concept of infinite thick walled cylinders modified by stress. That particular idea first proposed in a general way by Ben Eaton (1963). It took another ten years to finally work its way into operations. The problem of fracture gradients went from a general statement by Hubert and Willis in 1957 to a final more engineering approach in about 15 years. Work on stress related problems with the well bore is still evolving and is particularly critical in horizontal and high angle drilling.

THE SOLUTIONS WERE NOT ALWAYS SIMPLE

Not all of the indicators were always accurate. The geology of the Mississippi Delta is structurally complex with dipping fore set beds and many small slump faults. (Figure 11 Delta Section) This was a little confusing at first until we realized the trend was important and that trend lines would sometimes be displaced, Jim Gill (1968) published a great deal of information on the offsets of trend lines. Faults, dipping beds, percent of shale and sand, and seals all had their effect on our understanding. Fortunately for all of that, the Northern Gulf of Mexico is geologically consistent over many miles and thousands of feet of sediments.

THE SEMINARS

In April of 1967, the Louisiana State University (LSU) School of Geology and Department of Petroleum Engineering lead by Dr Farrell, and Dr. Hise held the first of three biannual Symposiums on “Abnormal Subsurface Pressure” The second Symposium was held in January of 1970, and the final or Third Symposium was held in May of 1972. The exceptional papers presented in these Symposiums captured the history and development of the abnormal subsurface pressure, theory, and drilling procedures during the decade of the 1960’s. The papers indicated that most of the ideas and practices were in place by 1967 and were further refined into the 1970’s.

It should be noted when looking at the time line, most processes had been in use for one to several years before they were presented as a paper.

CONCLUSION

The decade of the 1960’s was an eye opener to the drilling industry. The insular efforts of drilling vs. geology vs. seismic vs. academia and research started to come together to define and solve some of the many drilling problems. This slow confluence still continues today with better communication between those who have the problem, those who can define the problem, and finally those who can suggest a solution.

This discussion showed how the whole concept of pore pressure related to well control and the prediction of abnormal wellbore pressures. What is here-in covered is only a small part of that technology explosion. There were also significant advances in drill bits and sealed bearing, in casing design in drilling fluids, offshore drilling operations and other drilling and completion fields.

Each decade, including the present, has experienced this type of expansion. Wells are being drilling and produced today that were considered

impossible even 10 years ago. Last year wells were drilled to a vertical depth of 6 1/2 miles. In the horizontal area a well was drilled with a horizontal length of 7miles in just two months.
We are now producing oil from shale that a few years ago was considered just a nuisance to the driller.

LESSONS TO BE LEARNED

New ideas and technologies need a Champion. The technology can be pushed by a company, but it still needs a dedicated individual champion. If you see a process that needs a champion or see a champion leading a process, grab on to it and be a champion yourself.

ACKNOWLEDGEMENT:

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Dr Leon Robinson, now retired from EPR, helped with a clearer understanding of the Jorden and Shirley drilling equation and the problems with the scatter of their original data.

Mario Zamora, Manager of Applied Engineering with MI-SWACO, a Schlumberger Company, was a significant source of information about the limits and extremes of the “d” equation in field use and how trend lines could be predicted.

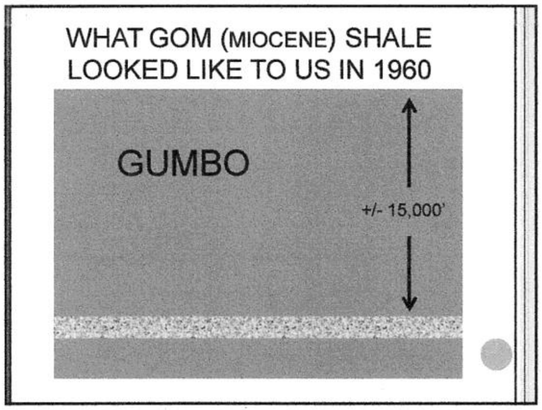

Figure 1

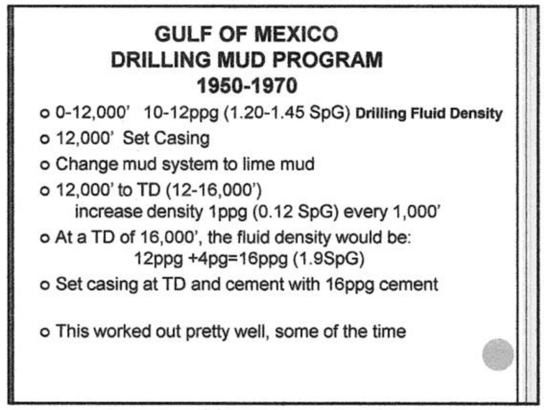

Figure 2

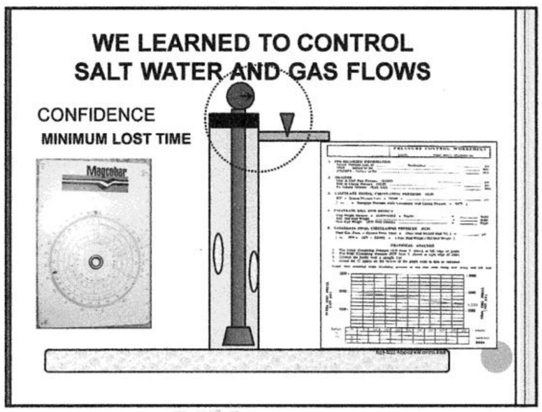

Figure 3

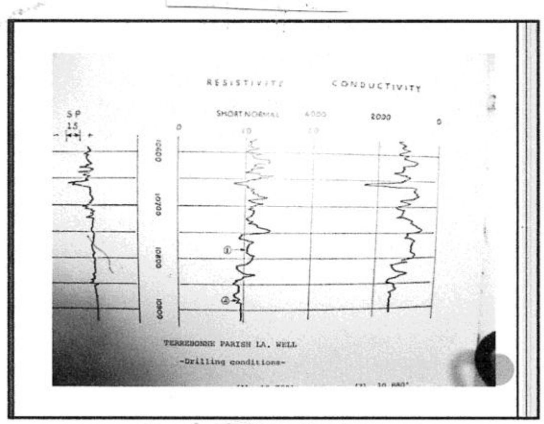

Figure 4
Typical 1960 IES Log

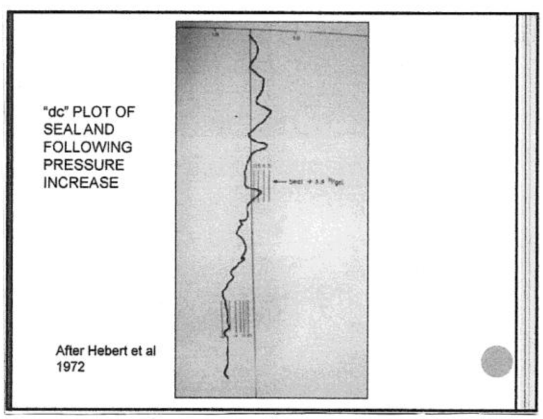

Figure 5
"d" Solution Plot

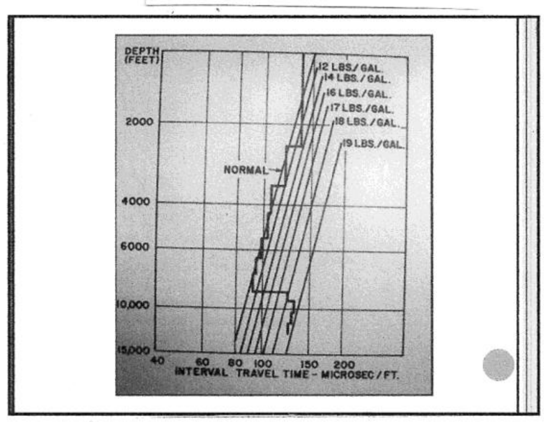

Figure 6
'Sonic' Log Pressure Plot

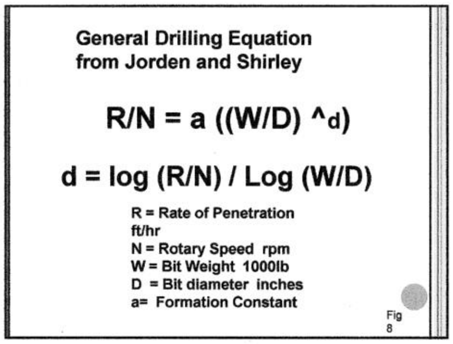

Figure 7

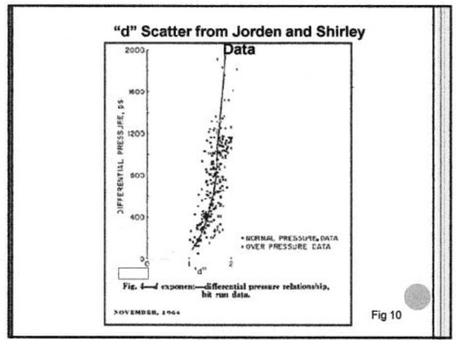

Figure 8

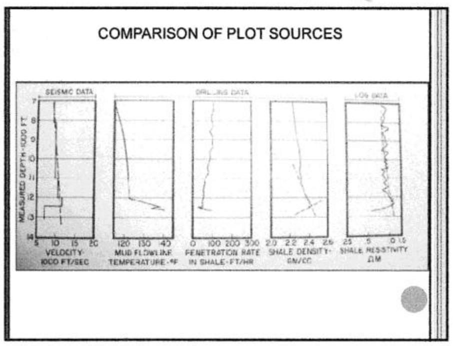

Figure 9

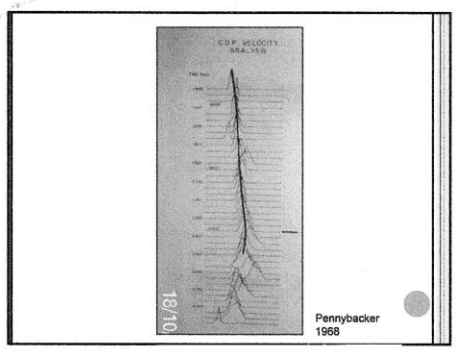

Figure 10
Seismic Pressure Plot

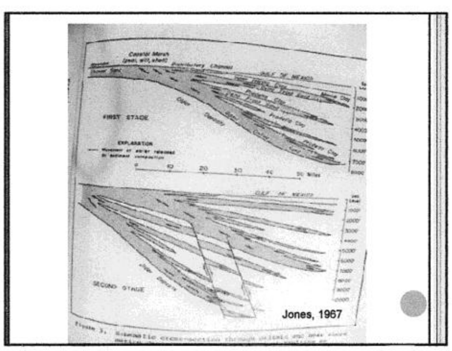

Figure 11
Gulf of Mexico Section

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