CORRELATING PETROPHYSICAL AND FLOOD PERFORMANCE IN THE LEVELLAND SLAUGHTER FIELD

Marshall Watson
ACT Operating Company/Texas Tech University

FIELD HISTORY AND DEVELOPMENT

The Permian Basin is located in West Texas and Southeast New Mexico. It is one of the largest oil producing regions in the United States. The Levelland Slaughter Field is on the Northwestern Shelf of the Permian Basin and is part of a chain of San Andres Fields which extends westward through the Chavaroo field area in Roosevelt County, New Mexico and southwest to the Wasson field in Gaines/Yoakum County, Texas. The Levelland Slaughter field, which produces from the San Andres member of the Permian section, is located for the most part in Cochran and Hockley counties, Texas, about 40 miles west of Lubbock. The field produces sour crude with an API gravity of 29 –31˚ at a depth of 4900 ft. The Levelland Slaughter field was discovered in 1937 followed by a rapid development program. Initial primary production was via depletion and solution gas drive mechanism. Secondary recovery operations were implemented, for the most part, in the early 1960's through the early 1970's. Several infill drilling programs were implemented as a result of the rapid oil price increases in the 1970's. The field has over 6000 wells, including producers, shut in producers, injectors, water supply and disposal wells.[18] CO_2 flooding was commenced in the early 1980's in some of the southeastern, more prolific units and leases, of the Slaughter field. According to the Oil & Gas Journal in 2004, of the 15 active CO_2 flood projects in Texas, seven of them are in the Levelland Slaughter field and all have been termed profitable.

BACKGROUND DISCUSSION

To characterize the reservoir, one must understand the depositional environment and the rock fabric. Once the fore going is accomplished you can understand and formulate reservoir continuity and distribution of permeability which are two of the most important items in assessing a waterflood. From core data one can develop a relationship between porosity and permeability, given knowledge of the rock fabric. Lucia has developed transforms for relating interparticle porosity to permeability for given rock fabrics.[20] The larger the rock fabric number, the larger the representative grains sizes. Lucia petrophysical classification system is as follows:

Class 1: grainstones, dolograinstones and large crystalline dolostones

Class 2: grain dominated packstones, fine and medium crystalline grain-dominated dolopackstone and medium crystalline mud-dominated dolostones

Class 3; mud-dominated limestones and fine crystalline mud-dominated dolostones

An example of rock classification would be grainstones, normally found in shoaling or ramp crest areas, having a larger rock fabric or grain size, are classified as a Class 1 rock fabric. Also large crystalline mud-dominated dolostones also plot in the field of large rock fabric, but are closer to a Class 2. Lucia developed the following global transform based on multiple linear regressions as shown in equation 1:

$$Log(k) = (A - B\log(class)) + (C - D\log(class))\log(\phi_{ip}) \qquad (1)$$

Where A=9.7982, B=12.0838, C=8.6711 and D=8.2065. The class is the rock fabric number ranging from 0.5 – 4, and ϕ_{ip} is the fractional interparticle porosity. A plot of the transforms is shown in Figure 1. In Figure 1, graph A is the porosity permeability transforms continuum plotted for rock fabric class numbers ranging from 0.5 to 4.0. In Graph B and C, in Figure 1, are the rock classifications for non-vuggy limestone and non-vuggy dolomite respectively.

Vug porosity is usually not connected and adds little to the permeability of the rock because the vugs are connected through the interparticle pore space. Lucia has developed a method for calculating interparticle and separate-vug porosity, ϕ_{sv}, in the following equation 2:[32]

$$\phi_{sv} = 10^{a - b(\Delta t - 141.5\phi_t)}. \qquad (2)$$

Where ϕ_t is the total porosity measured with neutron-density logs and, for anhydritic dolomite, a=4.4419 and b=0.1529. It also follows that the interparticle porosity ϕ_{ip} can be calculated with the following equation 3:

$$\phi_{ip} = \phi_t - \phi_{sv}. \tag{3}$$

Calculations from logs require a neutron density for ϕ_t calculation and a sonic log for calculation of ϕ_{sv}.

Water saturation, S_w, is calculated using resistivity and porosity log data in Archie's equation in the following equation 4:[2]

$$S_w = (\frac{FR_w}{R_t})^{1/n}. \tag{4}$$

Where

$$F = \frac{a}{\phi^m}. \tag{5}$$

Where F is the formation factor, R_w is the resistivity of the formation water, R_t is the resistivity of the rock containing the hydrocarbons, n is the saturation exponent and m is the cementation exponent. The coefficient *a* is an empirically derived number and is general accepted as 1.0. Lucia reports that interparticle porosity can exhibit cementation exponents, m, ranging from 1.8 to 2.0.[20, 32] The value of m can be calculated from wet zones via a Pickett plot[24, 25]. Given very low to no separate vug porosity, m approaches a value of 1.8.

Another important rock characteristic is the variation or distribution of permeability. Dykstra and Parsons developed the use of a coefficient termed "coefficient of permeability variation" (*V*) defined in the following equation 6:[14]

$$V = \frac{\bar{k} - k_\sigma}{\bar{k}} \tag{6}$$

Where $\bar{k} =$ permeability at the 50th percentile of the cumulative sample and $k_\sigma =$ permeability at 84.1 percent of the cumulative sample. A completely homogenous system would have a *V* of 0, while an extremely heterogeneous systems approach a *V* of 1. The majority of Permian Basin carbonates have a *V* ranging from 0.60 to 0.95.

GEOLOGICAL OVERVIEW

The San Andres is characterized as a restricted platform carbonate play.[13] Oil is trapped in an up dip porosity pinch out on a gentle monoclinal structure. The San Andres reservoir was formed by a regressive series of cyclic deposits that prograded south, southeast across a broad, low relief, shallow water shelf.[15] The Levelland Slaughter field is one of several San Andres oil fields that produce on the North and Northwest shelf (hereafter termed collectively as Northwest Shelf). The noted meteoric water effects both the dolomitization and leaching process post deposition as well as, in more modern times, the hydrodynamic tilting of the oil columns. The San Andres is divided informally into the upper and lower San Andres by a regional siltstone marker that is 2 to 10 feet thick, labeled as the Pi (π) marker.[15, 27] The lower San Andres is the portion that is productive on the Northwest shelf. A structure map of the top of the lower San Andres or Pi marker, is shown in Figure 2.[27] Generally, the San Andres is deposited in the following manner from an offshore point going inland as follows[10, 20]

1. Open-marine, subtidal limestone
2. Shoaling area, subtidal and subaerial exposed dolostones (reservoir rock)
2. Restricted-marine, subtidal dolostones (reservoir rock)
3. Intertidal and supra tidal dolostones
4. Salina, brine pan, sabkha, and mud flat anhydrites

A generalized block diagram of a carbonate ramp is shown in Figure 3. The development of a carbonate high frequency sequence is detailed in Figure 4. As seen in Figure 4, the porous members within the San Andres pay general offset to the south-southeast (toward the sea) as they prograde into the Midland Basin. That is, the shallower, younger, productive horizons within the lower San Andres formation progressively shift to the south from the productive deeper, older San Andres productive horizons. The entire depositional cycle is capped by a tight, intertidal and supratidal anhydrite and dolomite. Within the porous members, anhydrite usually fills the larger vuggy and moldic pores, thus, the remaining porosity is the lower porosity. The lower porosity is the intercrystalline pores of the mud dominated fabric dolostones.[19] Average porosity is usually 10% with a permeability of less than

10 mD.[16, 19] It is important to note that the coastline is not a simple linear system. There are channels, lagoons, re-entrant areas, and peninsulas.

PARTITIONING LEVELLAND SLAUGHTER RESERVOIR

The Levelland and Slaughter field is basically one geologic feature; however, the Levelland field is an area that generally produces from older, deeper portion of the lower San Andres while the Slaughter field generally produces from a younger shallower section in the lower San Andres. Figure 5 shows the relationship of the pay members in the central and western portions of Levelland Slaughter field. While the diagram is simplified, the actual porosity pinch out of the Slaughter field extends far into the Levelland portion of the field and is gas productive. The Levelland Slaughter reservoir is subdivided into four porosity units termed in this paper as the Mallet, P1, P2, P3 and P4.[12] A type log of the lower San Andres is shown in the Levelland field cross section, Figure 6, and is representative of Levelland field. Given the P2 is inconsistent, it was not noted on logs. Also, the Mallet is only present in the far southeastern portion of the field and thus, is also not noted on the logs.

For the purpose of this investigation, partitioning of the field will focus on P3 through P1 San Andres time. It understood that in the far southeastern portions of the field, given it is in the closest proximity to the sea, will be the area of the last reservoir quality deposition. The last portion of the deposition will be poorer in reservoir quality being intertidal - near shore type of environment such as the P3 in the western portion of the field discussed later in this report. The Levelland Slaughter productive area of the field can be partitioned into three depositional areas. From outer marine toward inland the depositional areas are:

1. Shoaling area, or ramp crest, furthest east and south edge of the field
2. Lagoonal area in the middle ramp, located further north and west, and,
3. Near shore mixed with intertidal and supratidal further to the west and north.

Ramondetta developed a facies map of the Northern Shelf, as shown in Figure 7, and is based on core descriptions.[28] Note the shoaling area on his map is denoted as "Dolomite," whereas the lagoonal and intertidal areas are noted as "Dolomite intercalated with clastics and anhydrite." Based on further log analysis and flood performance, a modified shoal area is noted in Figure 7. As a matter of detail, the shoaling area probably shifted towards and away from the shore line through various early San Andres periods.

The shoaling areas are characterized by the lack of anhydrite and anhydrite layers (in P1 – P3 zones) as this portion of the carbonate ramp was adjacent to open marine and high energy environment as seen in the Figure 3 and was never supratidal during P3 – P1 time. The highest net pays and best primary oil recoveries are in the shoaling area. There is evidence of sub aerial exposure of the shoaling areas during times of large sea level drops. This resulted in leaching of unstable carbonates by meteoric waters.[28] The shoaling areas are laterally discontinuous reservoirs and very difficult to correlate. Often the porous members are miscorrelated due to the image that the zones are similar in nature and depth; however, the grainstone-oolitic bars are overlapping one another as shown in Figure 8.[29] Infill and horizontal drilling are required to connect the discontinuous porosity members in order for a waterflood to be effective, such as in the Sundown Unit.

The lagoonal areas are also good reservoirs, however the pay is not as thick and there are distinct cycle tops of tight intertidal, supratidal dolomites and anhydrites. Referring back to Figure 4, one can see that the tidal flats are more prominent further inland. The tidal flats are represented by the cycle tops of anhydrite, as seen in the Figure 4, which finger out toward the sea then pinch out. The tidal flats or anhydrite caps represent the end of high frequency cycles. At the end of the major cycle the entire sequence is capped by a thick tidal flat due to sea regression. The lagoonal area is noted in the North Central Levelland Unit No. 533 in Figure 6. Here the high frequency P3 anhydrite cap is 30 feet thick as opposed to the thinner anhydrite caps further to the west which are approaching the P3 San Andres time shoreline. In arid climates, such as in Permian San Andres time, evaporate deposits may form by precipitation from standing bodies of marine water isolated from the ocean by tidal floats or grainstone-oolitic bars, such as that mentioned above.[21, 22] A hypersaline lagoon which is restricted from the ocean by a discontinuous barrier is the depositional model most commonly used to explain evaporite deposits. When sea level is up, this area is a good subtidal depositional environment, thus explaining the favorable petrophysical properties resulting in good oil recoveries in this region. In addition, reservoir continuity is much better in the lagoon area than the shoal areas due to lower energies than the ramp crest with the grainstone-oolitic bars. And, as opposed to the shoal area, infill drilling is not required to a great extent other than for reserve acceleration. Infill drilling will be discussed later in the report.

The near shore - intertidal areas are the poorest reservoir areas. However, this is the last area to be fully developed in the Levelland Slaughter field. There is potential in this area due to the reentrants which developed subtidal deposits. This area is also characterized by very high degree of vertical heterogeneity. Often pay and non-pay rock are only a couple of feet thick. Lateral reservoir continuity is excellent in this portion of the carbonate ramp due to extremely low energy environment. Exceptions are the re-entrants and tidal channels discussed below. Porous zones can be correlated over large areas.[27] The area far to the west around the Starnes, XIT and F. O. Masten units, are examples of the near shore environments.

In the near shore environment, slight changes in sea level cause an area to go from subtidal to supratidal, thus giving this area its high vertical heterogeneity. Geological mapping of reservoir rock is much more difficult to project in this area. Reservoir quality can change abruptly going from a slight positive into a low caused by re-entrants or tidal channels. This can be seen in the western areas of the field in the J. M. Wright Unit and Starnes Unit. Still, the reservoir is very continuous as seen in the depletion encountered in the development drilling in the 1960's and 1970's where well initial rates were substantially less due to depletion.

All reservoir quality rock at Levelland Slaughter was formed in subtidal environment and furthermore most, if not all pay is intercrystalline porosity.[12] Two types of subtidal rock exist, open marine and restricted marine. Without modern logs, it is difficult to clearly distinguish between the two types of subtidal facies.[12] Both types of rock have the same porosity permeability relationship, however open marine will have higher porosity and permeability.[12] As a general rule, the open marine is the dominant environment in the shoaling area where the restricted marine is dominant in the near shore – intertidal area. The lagoon area consist of a mix of the two fore mentioned environments, with an assumed dominance of open marine with periods of restricted marine. To demonstrate the three different depositional environments, representative logs, each from a separate type of environment, have been analyzed and put into an east west cross section shown in Figure 6. From east to west the following logs are presented from their respective depositional areas:

Central Levelland Unit No. 162A and Southeast Levelland Unit No. 305 – shoaling area
North Central Levelland Unit No. 533 and Whiteface Unit No. 102 RW – lagoon area
D. S. Wright No. 29 and JMWU No. 62 – near shore – intertidal

Figures 9, 10 and 11 are more detailed logs of each. The key to the assessment is anhydrite content and thickness in the cycle top. Note in Figure 11 that the shoaling area has minimal anhydrite and has very thick pay members with little apparent tight laminations within the thick members. Moving east toward the shoreline, the lagoonal environment, Figure 9, where much more anhydrite has appeared and cycle tops are marked with a thick anhydrite layers. However, minimal anhydrite is seen in the main pay, but the lamination or tighter porosity streaks within the pay are more apparent than the Levelland Unit well. Moving still further east towards the shoreline, in Figure 10, the anhydrite content within the pay has increased and the porosity has decreased due to the anhydrite inclusions as compared to the lagoon area. Also note that the vugular porosity present in the Whiteface well in Figure 9 is not present in near shore well in Figure 10. The lack of vugs in the near shore area is due to anhydrite filled moldic pores and vugs. Unfortunately, the higher porosity rock in the near shore area is also filled with anhydrite thus reducing the overall porosity and permeability. In the lagoon, during deposition and high sea levels, this area would be continually sub-tidal as a result of its deeper water as oppose to the near shore area becoming intertidal and supratidal during slight sea level fluctuations.

In the shoaling area, it is difficult to correlate the P1, P2, P3 and P4. This has been discussed previously regarding this area was never supratidal. Figure 11 shows an example of a shoal area well, CLU 162A. Based on log analysis, it appears that the lower units, P3 and P4, were fully developed all across the Levelland Slaughter field. At the end of P3 time there was a substantial sea level drop leaving behind large brine pan areas in the lagoon and some intertidal areas, thus the reason for the consistent anhydrite cap across the western portion of the Levelland Slaughter field behind the shoaling area.

RESERVOIR DESCRIPTION

The best rock for flooding must have the intercrystalline porosity, and even though it has low porosity and permeability, it is well connected. In contrast, the vugs and leached out or moldic pores are not well connected, although they exhibit good porosity. The permeability distribution in the Levelland Slaughter field varies both aerially and vertically. The San Andres formation in the Levelland Slaughter field is similar to many West Texas Permian carbonate reservoirs because it is heterogeneous and consists of individual pay stringers. Although the reservoir properties change across the field, the span of values is not that great. The generalized or average reservoir properties across Levelland Slaughter field are shown in Table 1.[6, 33] The major differences are net pay and permeability in the near shore - intertidal areas.

To classify rock types, Lucia style plots were constructed to classify rock fabric. An example of this plot is shown in Figure 12 of the Oxy Levelland Unit No. 742. One can see that the rock fabric class (RF) is equal to 1.5. It is important to reiterate that the Lucia plot uses ϕ_{ip} versus core or neutron density calculated ϕ_t. A plot using ϕ_t for the same Levelland Unit well is shown in Figure 13. Note for Levelland Unit No. 742 the rock fabric number is 2.5 – 3. The same plots were prepared for the Whiteface Unit and JMWU wells located in the lagoon and near shore - intertidal areas respectively. Both of the aforementioned wells had a rock fabric number of 1.5. All the plots correlated very well with Class 1 and 2 rock types in the pay zones when using ϕ_{ip}. In the near shore - intertidal areas, where there is no vuggy porosity, the rock fabric numbers are the same in both the core porosity, or ϕ_t, and the ϕ_{ip} plots. In order to sort out the rock fabric, given that multiple types are represented in the plots on a given well, it is convenient to plot the permeability transforms on a log plot as shown in Figures 9, 10 and 11. In addition to the permeability transforms, interparticle and separate vug porosity is calculated and presented on the logs. With few exceptions, separate
vug porosity, ϕ_{sv} was 0 to 2 porosity points or approximately 0 to 16% of the total porosity, ϕ_t. In the near shore - intertidal area, ϕ_{sv} is negligible since vugs and moldic porosity was often filled with anhydrite inclusions.

Because of the small pore throats the reservoir rock exhibits thick transition zones due to capillary effects.[19] Also, because of the fore going capillary effect, Levelland Slaughter San Andres reservoirs have high irreducible water saturations (S_{wirr}) generally 40 - 60% at 6% porosity and 60 - 100% at 4% porosity.[4] At any given height above the free water level, fluid saturations will vary with rock type and pore throat size.[1, 31] And of course, pore throat size is directly related to permeability. Thus, below a certain value of permeability, the lower permeability will translate into higher water saturations. In other words, differences in capillary pressure curves imply that different rocks will produce water free hydrocarbons at different heights above the free water level.[1, 3] This is an important aspect both in primary and secondary production. Typically through the 1950's, while reservoir pressure was still high in the higher permeability zones, wells would initially produce at near 100% oil cuts. After a few years of production, water cuts would start to increase to a level of about 20 – 50%, depending on the depositional area of the field. It is theorized that the increasing water cuts are due to the concept that tighter zones do not contribute significantly to production initially, but after the high permeability zones deplete, the lower permeability zones start producing greater percentages of the total rate. The lower permeability zones, as discussed above, have higher water saturations, thus have favorable relative permeability to water. In cases were there is substantial amounts of low permeable rock, such as the far western portion (near shore - intertidal), water cuts during primary production can reach 50% and sometimes higher.

It appears generally from the data that for the mud-dominated dolostone that a permeability to air of 0.2 - 0.5 mD or greater is required for significant oil movement in the primary production mode. To arrive at a cut off porosity, the Lucia porosity – permeability transforms are used. To use the transforms one must have knowledge of rock fabric. This can be accomplished by correlation of flow units near wells with core data. Without the core data, one needs general knowledge of reservoir location relative to the fore mentioned defined geologic environments. In the case of Levelland Slaughter it has been shown that the rock fabric number is 1.5, thus the cut off porosity for 0.3 mD would be approximately 7%. Usually the only data available is total porosity, ϕ_t; therefore, it is important to know what deposition environment is present. In a near shore - intertidal area ϕ_t is equal to ϕ_{ip}, thus the 7.0% holds true on the log calculated porosity using a neutron density or cased hole neutron with good porosity transforms. In the lagoon and shoal areas, the rock fabric has been shown to be 1 to 1.5 class values greater when plotting ϕ_t rather than utilizing ϕ_{ip}; thus, using a rock fabric number of 2 – 2.5 and a permeability limit of 0.3 mD, the cut off porosity is 9%. This appears reasonable when qualitatively assessing the pay in the Levelland Unit log utilizing different porosity cut off values.

Induced fracturing was investigated using FMI logs and evidence of early water breakthrough from adjacent injectors and producers. In areas other than the shoaling area, the overwhelming indication was generally a NW-SE fracture azimuth. This agreed with former studies in the literature.[17] FMI logs identified the average fracture azimuth to be 280˚. Two specific wells in the J. M. Wright Unit experienced immediate breakthrough were both on an azimuth of 280˚ from an offset offending wells. One offending well was a water injection well that communicated with a producer in one week. The other offending well was a producer that was hydraulically fracture treated with large volume/high rate "slick water" treatments.

GENERAL PERFORMANCE OVERVIEW

Generally the waterflood performance of the Levelland Slaughter field can be considered excellent. The rock is relatively continuous and the crude is moderately low shrinkage oil with low viscosities. Reservoir pressure had dropped from its original pressure of 1710 psi to 300 - 700 psi. before secondary (waterflood) recovery operations were introduced. Oil properties are outlined in Table 1. Typical recoveries are 10% OOIP on primary, an incremental 20% on secondary, and for the few CO_2 floods installed, it would appear that tertiary recovery will amount to another 10 - 20% OOIP.

METHODS OF EOR DEVELOPMENT

Several leases and units underwent multiple phases of infill drilling, usually from 40 to 20 acre spacing. A substantial amount of infill drilling occurred in the 1970's when oil prices were rapidly increasing. Several floods were infill drilled while the flood was still maturing, thus making it impossible to estimate the benefits of infill drilling. From floods that underwent infill drilling after the flood had matured and had established a decline, an assessment of the impact of infill drilling was made. Infill drilling was successful in the shoaling area, such as the Oxy Sundown Unit, Bass's leases just west of the Sundown Unit and Oxy's Northeast Levelland Unit. An example of the infill incremental recovery in Oxy's sundown unit is shown in Figure 14. On the other hand, infill drilling in the lagoonal and intertidal areas to the west resulted only in reserve acceleration. An infill project example in the lagoon area is the Whiteface Unit shown in Figure 15. In the Whiteface example it can be seen how infill drilling in 1988 – 1989 resulted only in a small amount of acceleration.

The three major flood patterns utilized in the Levelland Slaughter field are the 5-spot, staggered line drive and chicken wire pattern. Bass has used a skewed 4-spot in the eastern area (shoal area) near Sundown. Predominately, the injection wells are aligned NW-SE everywhere except the in the southeast potion of the shoaling area where injectors are aligned NE-SW. As previously mentioned, the induced fractures are oriented WNW-ESE, thus the reasoning for that alignment in most of the field. It is unknown if the fracture azimuth changes in the shoaling area E – W due to a change in tectonic stress. Literature suggest that a fracture less than 10% of the distance between wells has minimal affect on pattern performance.[5, 17]

WATERFLOOD PERFORMANCE ANALYSIS

An analysis was made of as many leases/units as possible where sufficient data was available. A map presenting S:P ratios across the field is shown in Figure16. Primary recovery data was gathered from the Railroad Commission of Texas[26] which is based on information furnished by operators when submitting injection permits. The S:P data is a good tool for predicting flood's EUR. Discrepancies in local areas of like petrophysical properties could be due to pattern alignment and completion methods.

As previously discussed, several of the units have undergone multiple infill drilling episodes. Of the 19 projects assessed, only five had positive indicators of increased reserves due to infill drilling. All those five were in the southeast portion of the Levelland Slaughter field, Hockley County. The rest of the infill programs resulted in reserve acceleration or infill drilling took place while the unit was undergoing reservoir fill up. Infill drilling could not be assessed during fillup because production was increasing prior to and during infill drilling.

Producing GOR's reached a low after fillup, then increased in several units. This could be due in part to recompletion in P1 and P2 gas zones in the Levelland field to take advantage of high gas prices. This GOR increasing phenomenon was noted in the Whiteface and West Levelland Units in the Levelland field. In the Slaughter field, 10 of the 24 units evaluated saw the same increasing producing GOR phenomena. Given the Slaughter field is located primarily in the shoal area, crossflow allowing vertical phase segregation could be the reason for the increased GOR's. It was previously mentioned that the Mallet unit saw increase in GOR with shallower depths.[6]

PETROPHYSICAL AND FLOOD PERFORMANCE

A detail summary of flood statistics and petrophysical characteristics by lease is shown in Table 2 respectively. It can be concluded that the performance across the field is consistent except for the near shore - intertidal areas. The map shown in Figure 16 exhibit the same point. Based on the foregoing, an attempt was made to characterize the different environments in Figure16. This geological environment assessment also considers geology based on geologic cross sections constructed across the field with particular emphasis on anhydrite characteristics discussed earlier.

Another aspect in determining primary and secondary net pay is the relation of permeability and initial water saturation (S_{wi}). Because of the lower permeability in the near shore – intertidal areas, S_{wi} is higher than that of the shoal and lagoon areas. At a given critical S_{wi}, an oil bank cannot be formed.[8, 11] Data from area core work was assessed and the critical S_{wi} is 42%. Several flow units within the primary pay intervals in the near shore – intertidal area have a S_{wi} greater than the critical S_{wi}. The fore going results in negligible secondary recovery for two reasons: 1) the low permeability in contrast to the high permeability, given a large permeability distribution[9] and 2) the fact that an oil bank cannot be created in that particular flow unit. Thus, secondary pay is less than primary pay because in primary production, the fore mention flow units with S_{wi} greater than the critical S_{wi} will still contribute to production. Other studies have also suggested a S_{wi} cut off value of 40%.[12] The only time critical S_{wi} comes into play in the shoaling area is in the transition zone. Large vertical transition zones are present due to the lack of vertical flow barriers in the shoaling area. Recently operators have reported successful attempts to complete deeper in the productive zone. The deeper portions of the productive reservoir are in the transition zone; however, the S_{wi} is low enough to allow economic oil flow rates with acceptable water cuts. While not a great waterflood target, the transition zone is excellent for CO_2 miscible flooding. Unlike the near shore – intertidal area, the transition zone in the shoaling area has good permeability.

As previously discussed, a cut off permeability of 0.3 mD was used for primary recovery. For secondary waterflood, a permeability cut off 1.0 mD was derived based on the fore going critical S_{wi} discussion. The secondary recovery permeability cut off is based on capillary pressure and relative permeability data. Given the fore going, ϕ_t cut off values for secondary recovery were derived from the Lucia plots for shoal/lagoon and near shore areas of 10.5% and 8.0% for respectively. Generally there is no difference in primary and secondary net pay in the shoal and lagoon area; however, the secondary pay in the near shore – intertidal area is approximately 60 – 70 % of primary net pay. This is the reason that S:P ratio in the near shore – intertidal area are in the range of 1.0 as compared to the S:P values near 2.0 or more in the lagoon and shoaling areas.

After using the permeability cut off of 1 mD, one must still use a second step of determining a second permeability cut off based on water cut.[9] A simple multilayered waterflood model, such as the Stiles method will suffice. The Stiles method of predicting waterflood performance is targeted towards those reservoir with a high degree of vertical heterogeneity with no crossflow.[11, 30] The method also assumes unit mobility, which in the case of Levelland Slaughter is a valid assumption. The advantage over the Dykstra Parson method is that it does not require an exact log normal distribution of permeability. This is especially true with the shoaling areas that had a dramatic turn up in the permeability variation curve at the high end of permeability. Unfortunately, there is high probability that crossflow is a problem in the shoal areas due to its good vertical reservoir permeability. Given a concern for crossflow, the Stiles method may have some limitations in the shoal area.

CO_2 miscible flooding may work better in the lagoon and near shore area given the layered effect combined with low heterogeneity or permeability variation. The layering effect inhibits crossflow, thus preventing CO_2 from overriding the flood front. The problem with the lagoon and near shore areas is that there is less net pay as compared to the shoaling areas, which is where all the CO_2 floods have been installed to date. The smaller net pays translates into less OOIP; however, given the current oil prices, these areas may now be economic. Other problems mentioned previously regarding the near shore – intertidal area are the losses of injectant out of zone and the low rates. Again, these problems can be potentially overcome to a certain degree, and also, with high oil prices, may be economical to CO_2 flood.

CONCLUSIONS

A study was performed to investigate the geological, petrophysical and reservoir flood performance of the Levelland Slaughter field. The geology of the Levelland field was assessed with the aid of literature review associated with assessment of log and core data. In the process of the assessment, three distinct areas were defined as follows: the shoaling area, located in the eastern and south eastern area of the field; the lagoon area, located in the northwestern portion; and the near shore - intertidal area, located in the western portion of the field.

Petrophysical parameters, derived from methods suggested by Lucia and others were defined in each of fore mentioned geological environments. Critical parameters were rock fabrics which, for the most part, were a class 2 throughout the field except for some of the zones in the shoaling areas having a class 1. The fore mention exception greatly effected the permeability distribution creating more heterogeneity.

Reservoir evaluation proceeded with the aid of the geological, petrophysical and fluid defined parameters. Classification of reservoir rock was based on both direct measurements of petrophysical parameters and inferred parameters based on production and injection performance. Net pay criterion was also studied. Net pay permeability cut offs for primary and secondary recovery were 0.3 and 1.0 mD respectively. Permeability cut offs considered relative permeability and fractional flow curves with a derived critical S_{wi} of 42%. Porosity cut offs depended on whether ϕ_{ip} or ϕ_t were used and the type of Lucia rock class.

Infill and horizontal drilling were examined for each of the geological defined areas. It appeared that infill drilling added reserves in the shoaling area only and resulted in acceleration in other areas. Horizontal drilling appeared to be successful in the shoaling area and was not yet determined to be successful in the lagoon and near shore areas. Improvements in stimulation methods for horizontal wells may help in this regard.

NOMENCLATURE

a	= Archie a – empirical number normally = 1.0
API	= American Petroleum Institute
B_o	= Oil formation volume factor, reservoir barrels/stock tank barrel
B_{oi}	= Initial oil formation volume factor, reservoir barrels/stock tank barrel
B_{vw}	= Bulk volume water, percent
EOR	= Enhanced oil recovery
EUR	= Estimated ultimate recovery
F	= Formation factor, dimensionless
GOR	= Gas oil ratio, scf/bbl
h	= pay thickness, ft.
IPPHI	= ϕ_{ip} = Interparticle porosity, fraction
k	= Permeability, mD
k_{ro}	= Relative permeability to oil, fraction
k_{rw}	= Relative permeability to water, fraction
$\bar{k}$	= Permeability at the 50th percentile of the cumulative sample, mD
k_σ	= Permeability at the 84.1 percentile of the cumulative sample, mD
KLUC1	= Permeability Lucia class 1 rock transform, mD
KLUC2	= Permeability Lucia class 2 rock transform, mD
KLUC3	= Permeability Lucia class 3 rock transform, mD
KLUC4	= Permeability Lucia class 4 rock transform, mD
LUCPHI	= ϕ_{sv} = Separate vug porosity, fraction
MBO	= Thousands of barrels of oil
MBW	= Thousands of barrels of water
MMBO	= Millions of barrels of oil
MMBW	= Millions of barrels of water
MMP	= Minimum miscibility pressure, psi
m	= Archie cementation exponent
N	= Oil in place, stock tank barrels
N_p	= Oil produced, stock tank barrels
n	= Archie saturation exponent
OOIP	= Orignal Oil in Place
p	= pressure, psi
p_b	= bubble point pressure, psi
PhiND	= Weighted neutron density porosity, percent
PU	= Porosity units
PV	= Pore volume, fraction
PVT	= Pressure, volume, temperature
PXND	= Cross plot porosity, percent
R_t	= Formation Resistivity, ohm-meters
R_w	= Formation Water Resistivity, ohm-meters
RF	= Rock fabric class
stb	= Stock tank barrels
S_o	= Oil saturation, fraction
S_w	= Water saturation, fraction
S_g	= Gas saturation, fraction
S:P	= secondary oil recover: primary oil recovery ratio
TD	= Total depth, ft.
T:S	= Tertiary oil recovery: Secondary oil recovery ratio
V	= Permeability variation
WOR	= Water oil ratio
Δt	= Sonic travel time, μsec/ft

ϕ = Porosity, fraction

ϕ_{sv} = Separate vug porosity, fraction

ϕ_t = Total porosity

ϕ_{ip} = Interparticle porosity, fraction

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Table1
Levelland Slaughter Reservoir/Petrophysical Data.[6, 33]

Area	Shoal	Lagoon	Near Shore
Depth	4900	4900	4900
Net Pay Primary (feet)	70	30	25
Net Pay Secondary (feet)	70	30	17
Gross Pay (feet)	120	60	60
Porosity Range (fraction)	0.08 – 0.18	0.08 – 0.16	0.08 – 0.11
Average Porosity (fraction)	0.12	0.11	0.09
Water saturation – Initial (frac)	0.28	0.20	0.30
Permeability – Range (md)	1.0 – 40	0.1 - 30	0.1 - 30
Permeability Geo Mean (md)	2.5	1.5	0.5
k_{ro} @ Swi (frac)	0.57	0.57	0.57
S_{ro} (frac)	0.28	0.28	0.28
k_{rw} @ Sor (mD)	0.21	0.21	0.21
S_{wi} (frac)	0.21	0.25	0.35
Oil Saturation – At start of flood (frac)	0.6	0.6	0.6
Gas Saturation – At start of flood (frac)	0.08	0.08	0.08
Oil Gravity (degrees API)	32	33	29
Reservoir Temperature ˚F	110	105	110
Saturation Pressure @ 110^o F (psi)	1710	472	1710
Formation Volume Factor – Initial	1.3241	1.090	1.3241
Initial Pressure (psi)	1710	1710	1710
Pressure start of flood (psi)	300 - 600	100 - 300	100 - 600
Initial GOR (scf/stb)	623	159	623
Oil Viscosity at Saturation Pressure (cP)	1.078	2.12	1.078
Current Reservoir Pressure	2500	2000 - 3000	2500
Formation Volume Factor – Current	1.20	1.088	1.20
Current Producing GOR (scf/stb)	300	149	300
Oil Viscosity @ 110^o F (cP) – Current	1.5	2.37	1.5
Water Viscosity @ 110^o F (cP)	0.67	0.67	0.67
Producing GOR @ start of flood (scf/stb)	3000	3000	2500-8000(c)
Formation Volume factor @ start of flood	1.15	1.08	1.15
Mobility Ratio	0.82	1.30	0.82

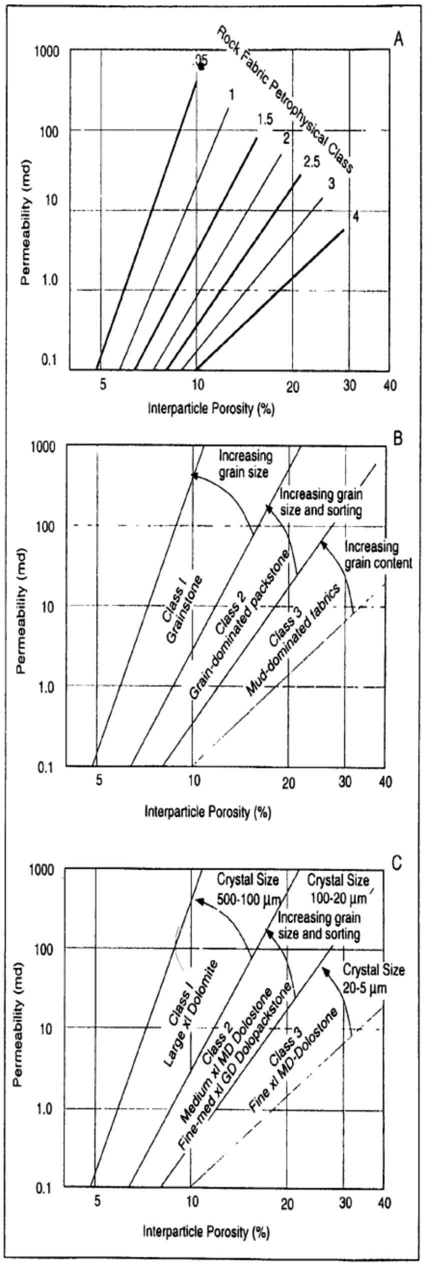
(a) Higher GOR's are due to P1 gas cap commingled production.

Table 2
Detail Lease Petrophysical Characteristics

Unit/Lease Name	Area	Rock Fabric in Pay (a)	Average Core Porosity (%)	Permeability Geometric Mean (mD)	Coefficient of Permeability Variation
Walsh JMWU	Intertidal	1.5	6.7	0.4	0.86
Oxy Sundown	Shoal	2.0	8.0	2.6	0.98
Oxy Levelland	Shoal	2.5	10.7	1.9	(b)
Energen Whiteface	Lagoonal	2.5	10.7	1.2	0.88
Apache Coons	Shoal	2.0	11.8	2.1	0.85
Walsh Starnes	Intertidal	1.5	6.3	0.4	0.88
Walsh Starnes	Near Shore	2.0	10.0	1.5	0.87
Oxy Central Levelland	Lagoonal	1.5	10.2	4.0	0.85

(a) using ϕ_t

(b) Bimodal system, cannot calculate.



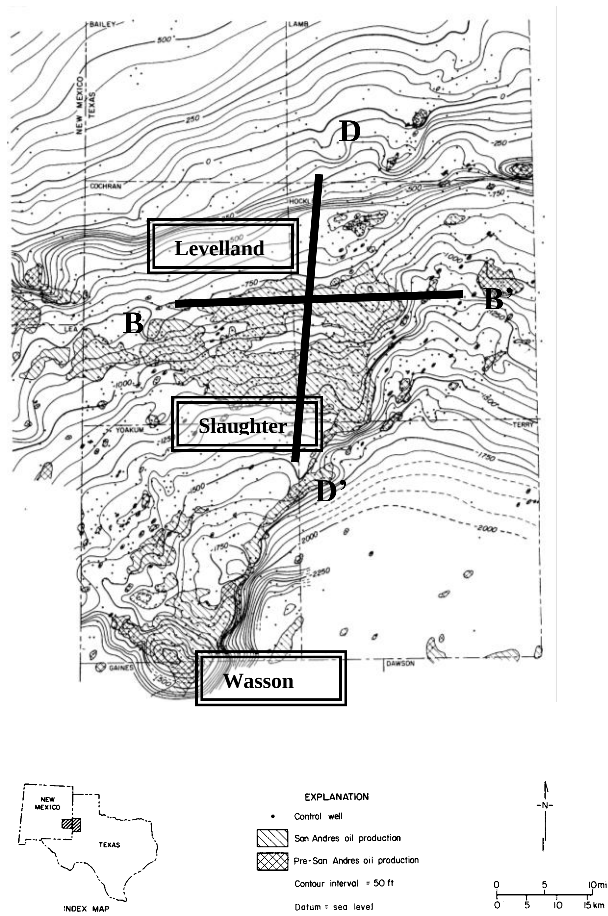


Figure 2 - Northwest Shelf Structure Map on the San Andres π Marker.[27]

Figure 1- Lucia's Porosity Permeability Transforms[20]

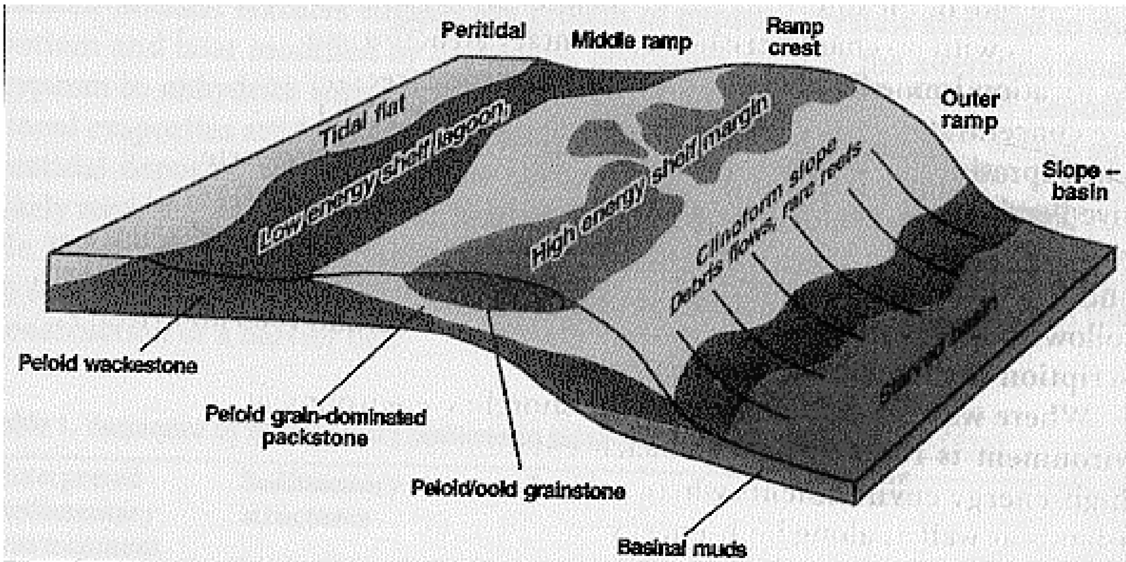


Figure 3 - Carbonate Ramp Block Diagram[20]

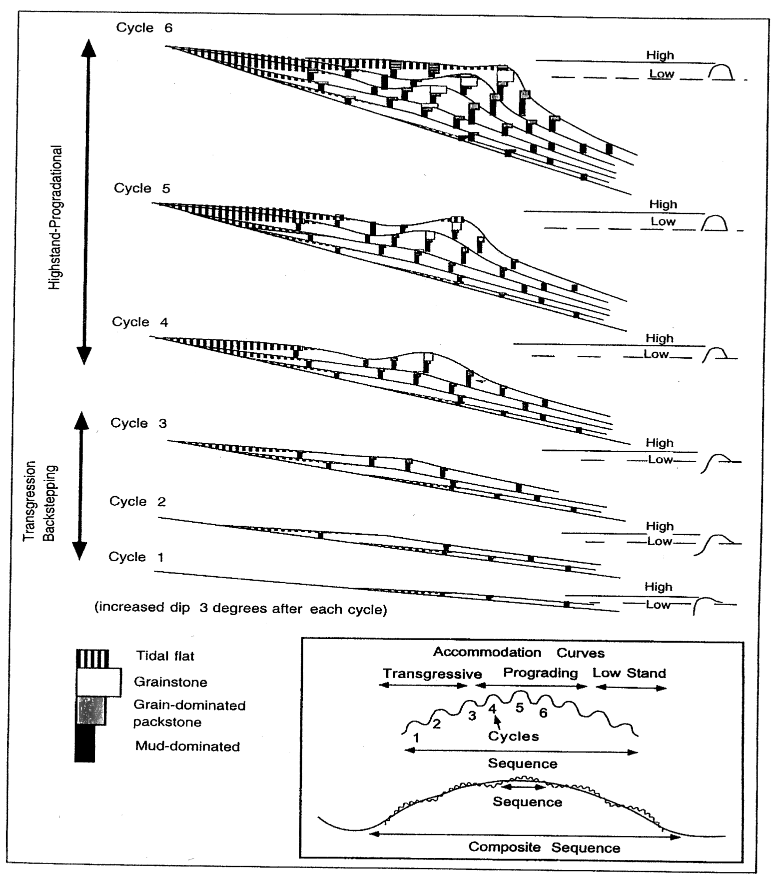


Figure 4 - Development of a Carbonate High-Frequency Sequence[20]

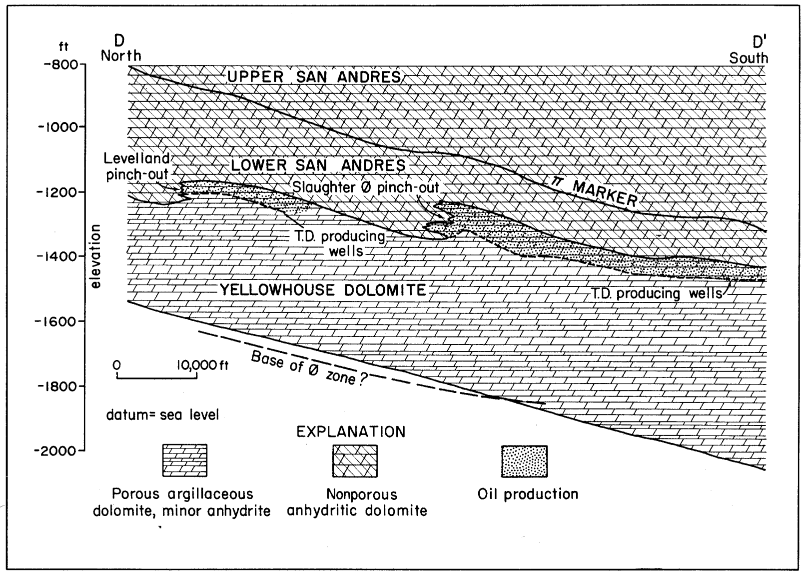


Figure 5 - North South Cross Sction (see Figure 2) Through the Center of the Levelland Slaughter Field[27]

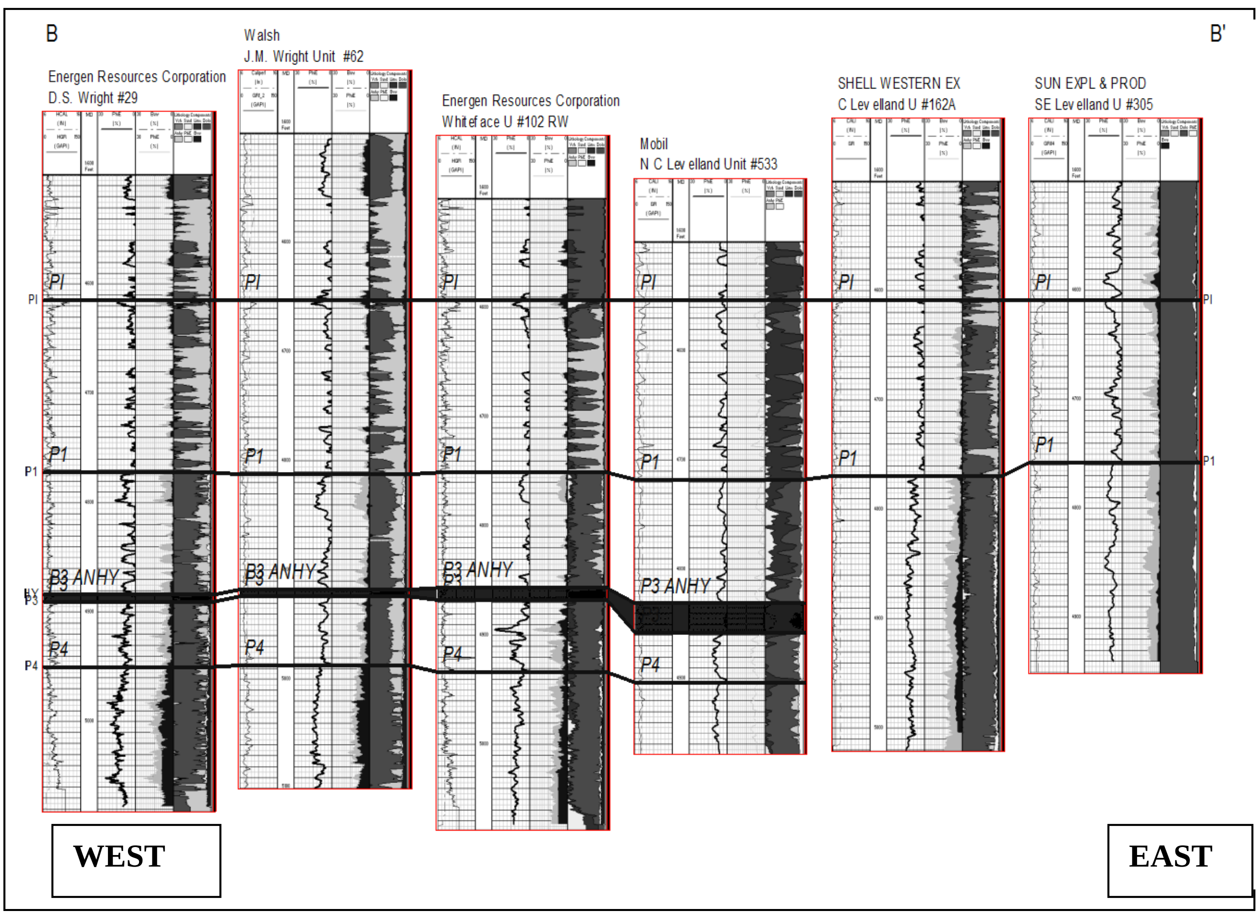
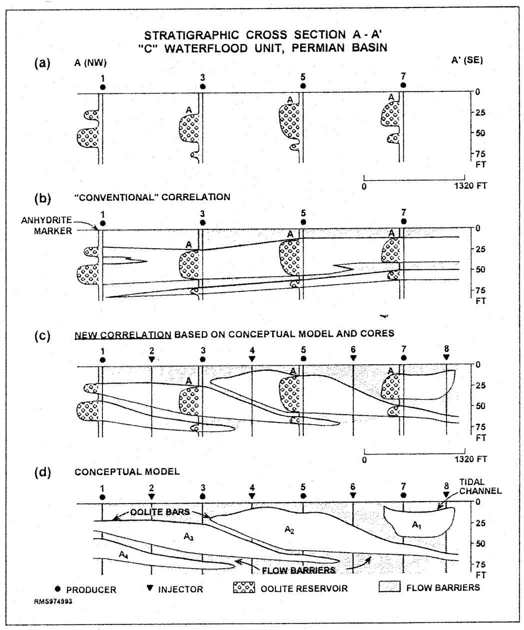


Figure 6 - East West Cross Section for Northern Levelland Area (see Figure 2 for Section Location)



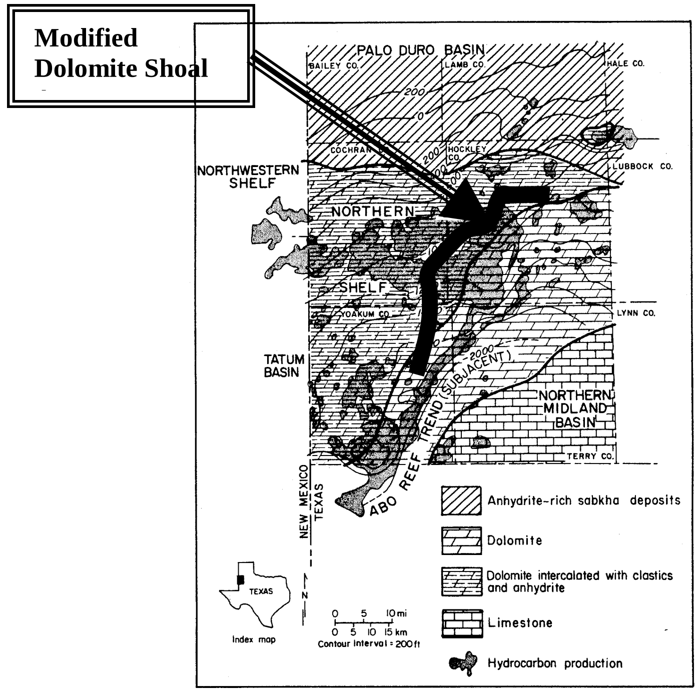


Figure 8 - Example of Lateral Discontinuity in Shoal Area[29]

Figure 7 - Northwest Shelf Facies Map[28]

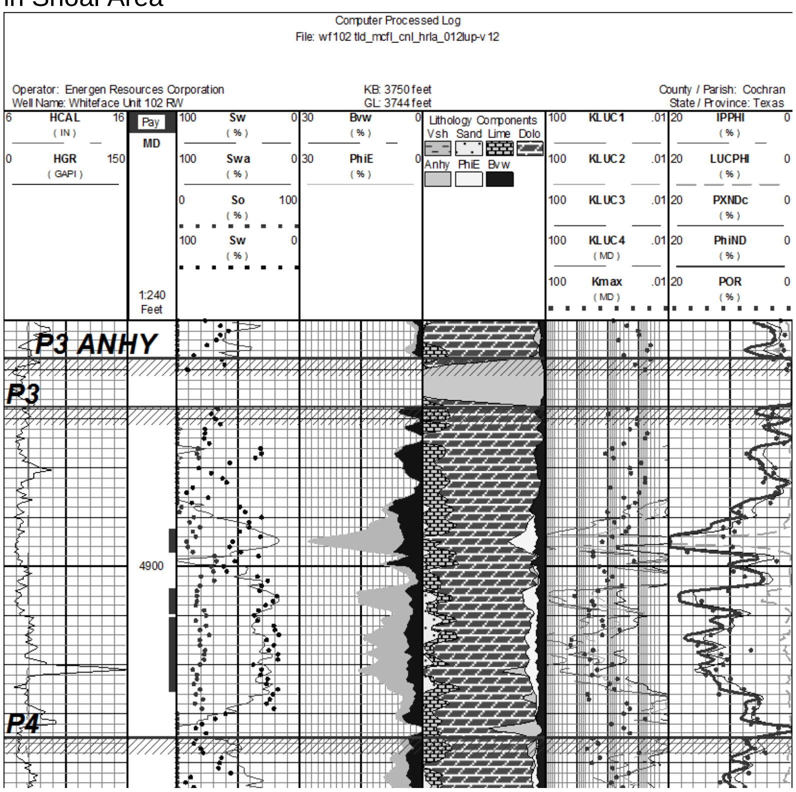
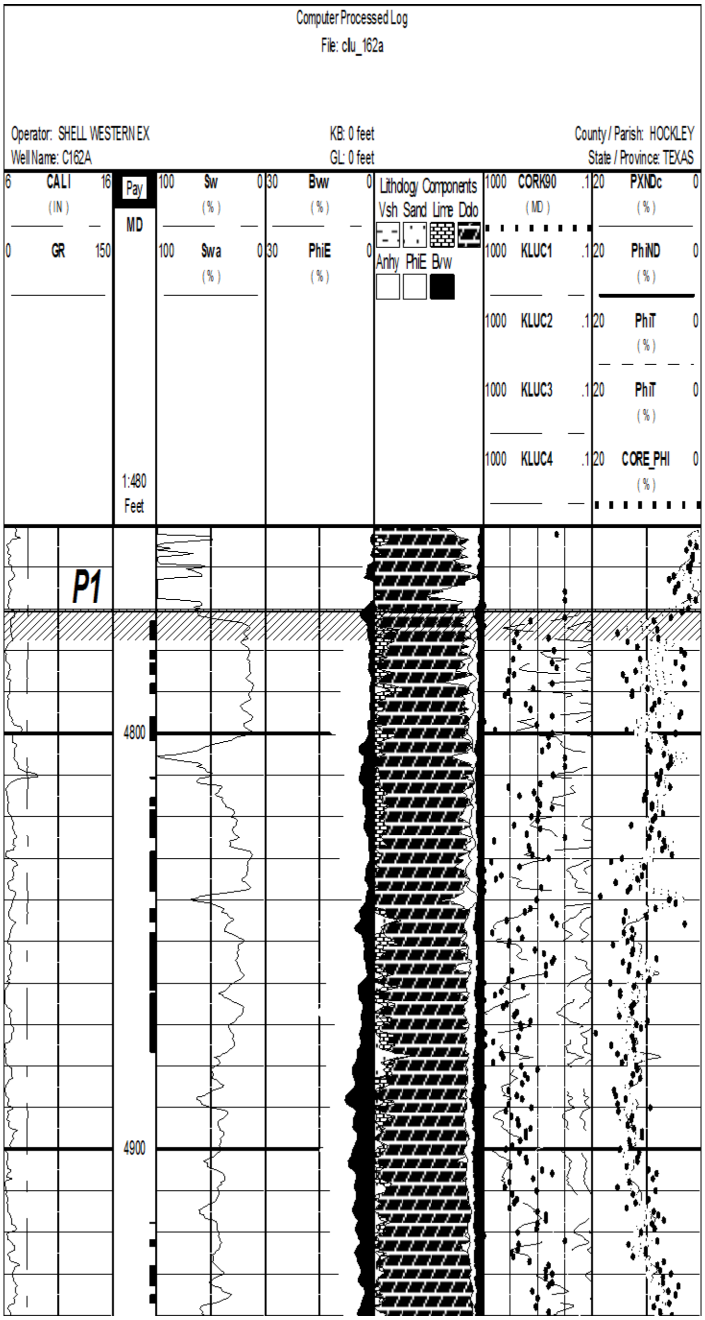


Figure 9 - Whiteface Unit No. 102 RW Processed Log



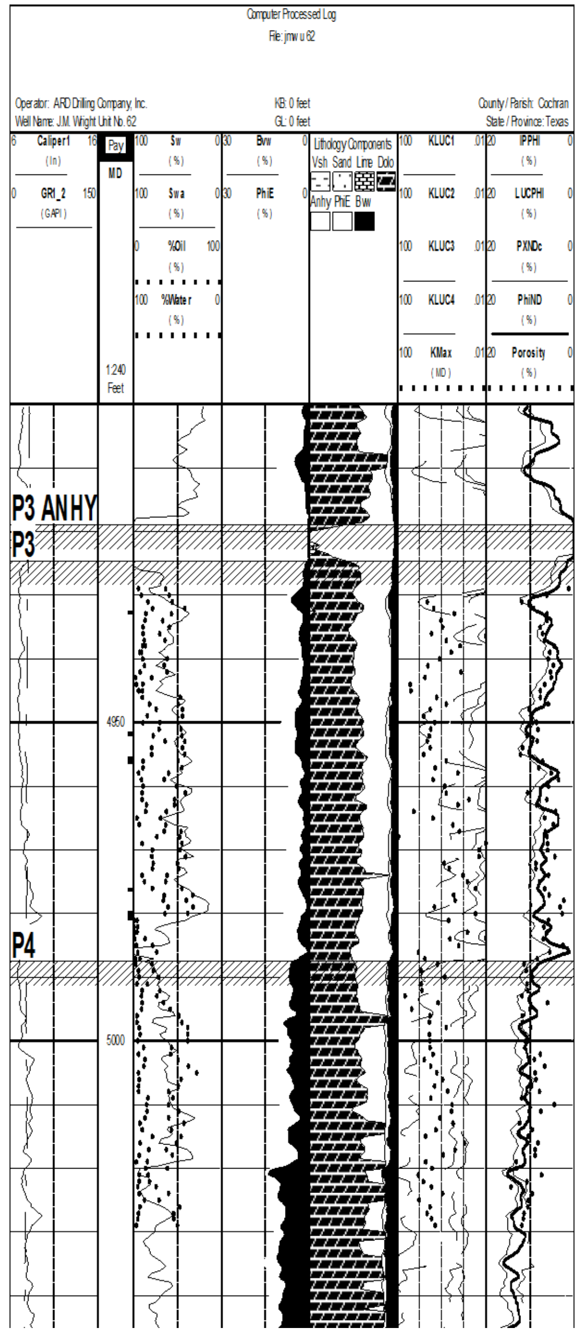


Figure 11 - Central Levelland Unit No. 162A Processed Log
Figure 10- JM Wright No. 62 Processed Log

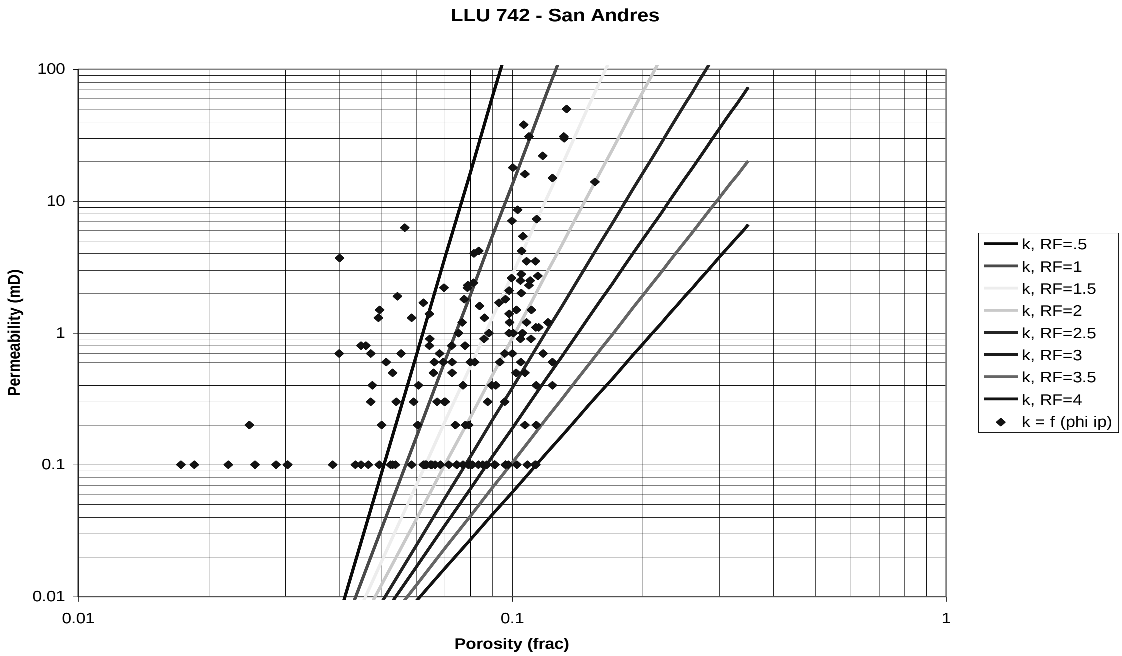


Figure 12 - Lucia Rock Fabric Using ϕ_{ip} Plot for Levelland Unit No. 742

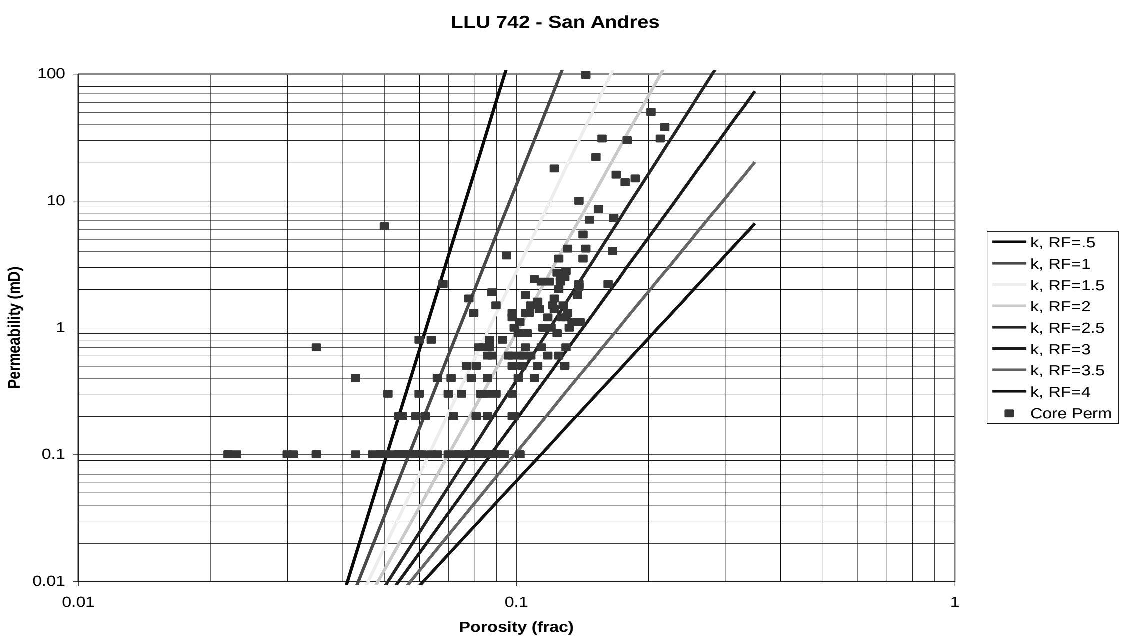


Figure 13 - Lucia Rock Fabric Plot Using ϕ_t for Levelland Unit No. 742

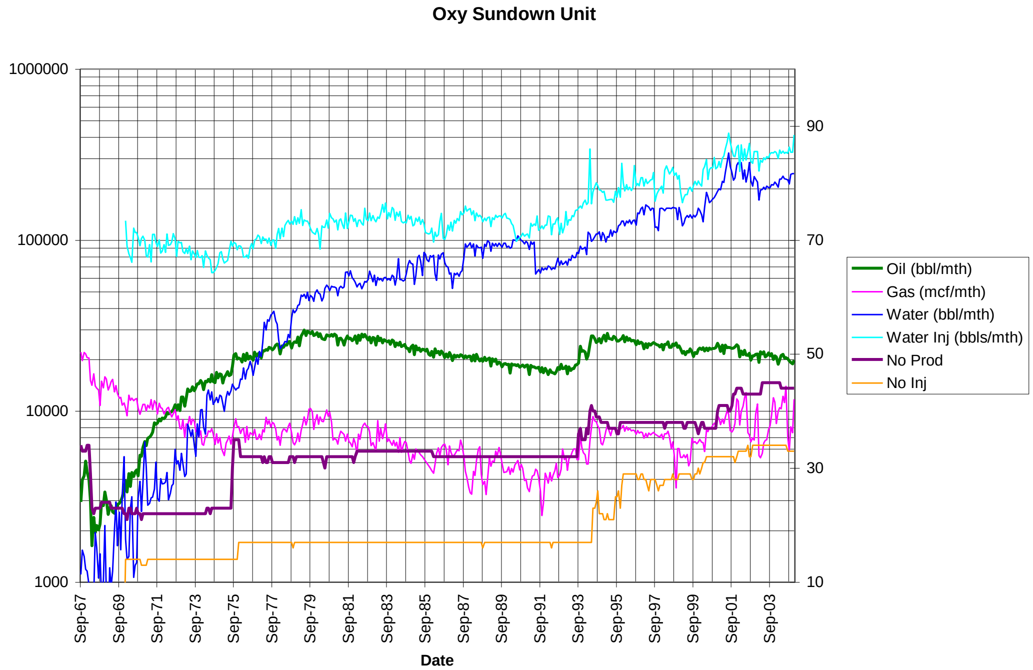
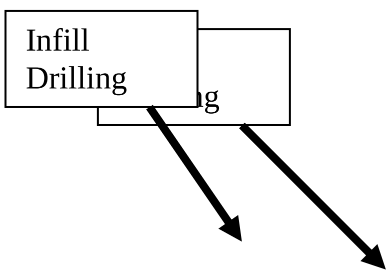


Figure 14 - Oxy Sundown Unit Production/Injection Plot



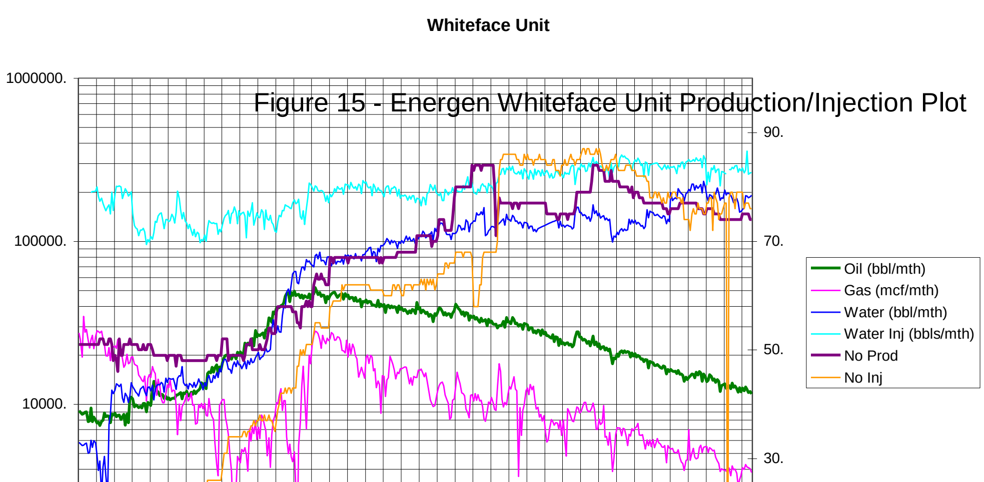


Figure 15 - Energen Whiteface Unit Production/Injection Plot

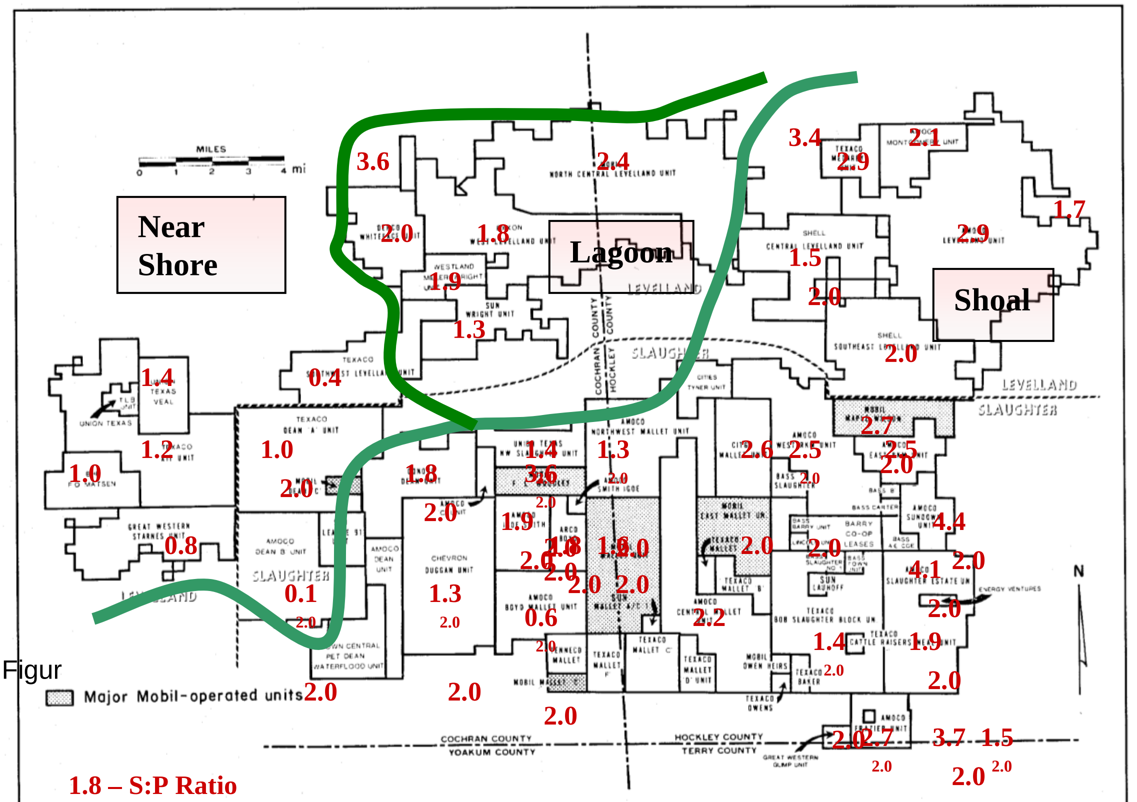


Figure 16 - Levelland Slaughter Field Lease Map with S:P Data