Geological and depositional characterization of a fluvial channel sand in the Chanac Formation: Kern Front field, San Joaquin Basin, California

By

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Dedicated to my wife Kaitlin....my predestined...
Acknowledgements

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ABSTRACT

The Kern Front oil field is the site of an enhanced oil recovery (EOR) project by means of steam injection located in the Southern San Joaquin Basin of California. There are a number of fundamental challenges associated with this type of project, namely the architecture of the fluvial system that makes up the producing Chanac Formation. The Chanac Formation is a late Miocene fluvial system that is stratigraphically located at the base of a multi-million year hiatus. The Chanac Formation is comprised of fine to coarse grained friable sand units separated by mudstone or claystone intervals. Previous models have classified this system as that of a meandering fluvial system. Using the facies analysis approach presented by Miall (1985) and with the availability of recent petrophysical data, it is suggested that at least part of the Chanac Formation, namely the interval evaluated within this research, is not a meandering fluvial system, but instead that of a low sinuosity stable anastomosing system. The nearby Kern River Formation is defined as a braided fluvial system, but was deposited during a time of significant uplift in the Sierra Nevada mountain range which would have greatly changed the slope, accommodation space, and depositional energy compared to the timing of the Chanac deposition. The understanding of this system and further analysis will allow optimization of current field operations and ensure the future success of planned field development.
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INTRODUCTION

Fluvial systems are those which are associated with rivers and streams. Sediments are transported in these systems as either bedload (those close to the bottom of the river bed) or suspended load (those suspended within the water). These systems are made up of numerous deposits and landforms which can be used to help identify flow characteristics. The two most well-known fluvial channel designations are meandering and braided. Meandering systems are typically recognized as a highly sinuous singular channel on a shallow sloping plain that don’t have significant amounts of discharge. Braided systems on the other hand are usually comprised of multiple low to intermediate sinuosity channels on a slightly steeper slope with increased discharge rate. Depth to width ratios are also typically different between these two systems, braided typically exhibiting shallower channels and wide channel edges.

In addition to Braided and Meandering channel designations, other channel designations have been the focus of additional research in recent years, specifically Straight channel systems (Wang & Ni, 2002) and Anastomosing systems (Makaske, 2001). Straight channel (or river) systems were designated by Rust (1978) as a single channel system having a sinuosity ratio of lower than 1.5. Wang & Ni (2002) concluded in their research that these rivers are much too complex and unstable to classify as a channel system and that it should not be regarded as a channel designation but more of an intermittent stage of channel development. Anastomosing channel systems are mentioned in Miall (1985), and have recently been reviewed by Wang et al. (2000) and Makaske (2001). Makaske (2001) takes the stance that Anastomosing systems are actually a combination of straight, braided, and meandering channels and are typically the result of Avulsions.

Fluvial deposits are a common source of hydrocarbons and can be excellent targets for hydrocarbon recovery by Enhanced Oil Recovery (EOR) methods such as steam injection (Figure 1). Gaining a greater understanding of these systems has been topic of interest, especially over the last decade when it was realized how economic they could be (Flores, 1985). Unfortunately fluvial systems can be a challenge when it comes to addressing the key uncertainties associated with these methods.

Steam injection is an Enhanced Oil Recovery (EOR) method by which steam is forced into the subsurface either through a production or specialized injection well. The associated heat in the steam helps to reduce the viscosity of the oil present, allowing it to flow easier to production wells (Hong,
1994). The two most common methods of steam injection practice are by cyclic steam injection and steamflood pattern-based injection (Figure 1). When undertaking a steamflood development there are a number of key geological uncertainties that need to be addressed. These include 1) reservoir quality, 2) reservoir architecture, 3) local/regional faulting, and 4) structural dip. More specifically there are key uncertainties regarding the reservoir quality and architecture that can affect the injection of steam, such as 1) porosity / permeability distribution, 2) reservoir connectivity, 3) reservoir thickness, and 4) pore-fluid properties.

Reservoir heterogeneity can affect steam flood in both vertical and aerial aspects. Faults or other vertical changes such as sand pinchouts can reduce the ability for heated oil and steam to travel from an injection well to a production well. Steam injection rates will vary between channel and bar sands due to their variations in grain sizes and grain distribution, which will influence the effectiveness of the hydrocarbon sweep. Steam injection can also benefit from an understanding of the depositional environment, for example, a multi sand reservoir separated by a shale interval might benefit from first steaming the lower sand and allowing the shale to act as a “hot plate” to heat the oil above the shale (Hong, 1994).

Fluvial systems are an appealing target for steam injection and other EOR practices because they typically are made up of coarser grained material with higher permeability values. These characteristics allow steam to travel easier through the subsurface and create an effective sweep of hydrocarbons within the sand body. Both meandering and braided systems can be exceptional targets but different approaches will need to be taken depending on the system. As mentioned before, channel width and thickness will be variable in these systems and this will affect pattern configuration as injection rates and well spacing will need to be optimized for vertical and aerial sand connectivity. For example, if there is a narrow channel, it’s not appropriate to place a large steam pattern over it because only a number of the wells would fall outside of the main channel sand, which could create an issue with continuity, and in the end affect the pattern efficiency and ultimate hydrocarbon recovery.

The Kern Front oil field (Figure 2) was discovered in 1912 by the Standard Oil Company of California (Hendrickson, 1928). The first commercial well had an initial production rate of 500 barrels of oil per day (BOPD) while the field itself reached a plateau of 11,000 BOPD in 1930 via means of primary depletion (Edwards, 1941). The field has since been re-developed and expanded both aerially and vertically. Kern Front has since surpassed its highest production levels in recent years by the use of steam injection practices. The gravity of oil in the field, which ranges from 12-17° API (specific gravity of
0.986 - 0.953) has made it an exceptional target for steam injection, which has been used throughout the field since 1969.

There have been numerous wells drilled within the Kern Front oil field, and hundreds of core samples taken, yet few significant studies have been done within the Kern Front oil field (Hendrickson, 1928; Edwards, 1941; Link et al. 1990). Studies from the neighboring Kern River oil field (Bartow and Pittman, 1983; Kuespert and Sanford, 1990; Ginger et al., 1995; and Coburn and Gillespie, 2002) can provide some information in an attempt to fill in the gaps for some of the formations that are present in both fields.

Hendrickson (1928) identified the Kern Front field as a monocline dipping to the southwest and discusses two identifiable faults within the field. He also interpreted the Temblor formation and the Walker formation, which are now known as the Etchegoin and Chanac formations respectively. He also made some key observations within the field, namely that it is not possible to define a sharp contact between the two formations due to an unconformity, and that there is a shift between depositional environments, noting a variation between marine and terrestrial indicators.

Edwards (1941) built on the work of Hendrickson (1928) identifying the Etchegoin and Chanac formations and briefly describing them both along with the other formations present down to what is considered the pre-cretaceous basement complex. He recorded a trend of sands increasing in overall percentage to the SW. He also identified the Chanac as the primary oil bearing zone throughout the field. Like Hendrickson (1928), Edwards (1941) grouped hydrocarbon occurrences into three groups, known as the Tegeler, Lehnhardt, and Wonder zones.

Link et al. (1990) were more thorough in describing both the formation architecture and depositional environment within Kern Front. Link et al. (1990) has conducted full core descriptions for the northern part of Kern Front, mostly focusing on Sections 2 and 11. Additional testing was also completed in the Etchegoin and Chanac formations including grain size and XRD analyses. Importantly Link et al. (1990) identified the Etchegoin as a North to South trending deltaic shore facies. He also identifies one of the Chanac units as a moderately to highly sinuous meandering channel. In a word, Link et al. (1990) gave a great glimpse of the Kern Front oil field, specifically the northernmost sections of the field and the shallower sand units.
Unfortunately, none of these studies have focused on the characterization of the deeper sand bodies within the producing Chanac formation. They are also all lacking in a comprehensive look into the depositional facies and features within a fluvial environment. Therefore, in this research, I use subsurface log data, in conjunction with rock properties in the form of core data to create a representative model of a single channel sand within the Chanac Formation. The results of this study give insight into the regional geology at the time of deposition by helping to indicate channel direction and architecture during a time of fluvial deposition. The channel architecture revealed in this study provides strategic references to ensure that future steam injection strategies are undertaken in an efficient manner.
Figure 1. The two most common methods of oil recovery by means of Steam Injection, which is a type of Enhanced Oil Recovery (EOR). The first method known as cyclic steam injection (left) utilizes a single wellbore where steam is injected, the well is shut in, and then after a soak period the heated oil and water is produced at the surface. The second method known as a steamflood (right) utilizes multiple wellbores with a steam injector that has the purpose of constantly injecting heated steam into the subsurface. This constant steam produces a sweep much like a piston and moves the heated oil towards production well(s). Taken from Shah et al. (2010).
Figure 2. Location map of the Southern San Joaquin Basin. Kern Front field is highlighted in green. Modified from Reid (1995.)
GEOLOGIC SETTING & STUDY AREA

Regional Geology

The San Joaquin Basin is located in the southern portion of the Great Valley of California (Figure 3). The San Joaquin Basin is bounded by the Coast Ranges to the west and by the Sierra Nevada mountain range to the east. The southernmost portion of the San Joaquin Basin is bounded by the San Emigdio Range and Tehachapi Mountains (Nilsen, 1996). The San Joaquin Basin was originally formed in the late Mesozoic as a forearc basin, resting above an eastward dipping subduction zone (Dickinson 1974; Ingersoll 1978, 1983; Dickson and Seely 1979; Nilsen 1986, 1996; Moxon, 1988). The San Joaquin Basin then went through a series of tectonic cycles of uplift and subsidence during the Paleogene (Reid, 1988). The west side of the basin was uplifted in the Eocene and extensional deformation followed during the Oligocene (Nilsen, 1996). During the Neogene the basin was subjected to subsidence and deformation due to tectonic rotation from strike-slip faulting (Bartow, 1991). During this time significant oil prone source rocks were created in the southern San Joaquin Basin (Ziegler and Spotts, 1978). A major source of sediment for the basin came from the Sierra Nevada range which fed sediment westward into the deepening basin (Reid, 1988).

Localized Geology

The Kern Front oil field is located in the south eastern portion of the San Joaquin Basin (Figure 2) approximately 10 miles (16km) northwest of Bakersfield. Kern Front is separated from the nearby Kern River oil field by a large north to sound trending normal fault with approximately 200ft (61m) of vertical throw known as the Kern Front Fault (Appendix 1). The hydrocarbon producing intervals within the field are Upper Miocene to Pliocene in age (12Mya – 5 Mya) and are known as the Etchegoin and Chanac Formations (Figure 4).

The primary unit of study, the Chanac Formation, is an Upper Miocene age (12Mya to 9Mya) fluvial sandstone that has gross thickness values that reach over 400ft (122m) and is the non-marine equivalent of the Santa Margarita Formation which underlies it in the Kern Front field. It consists of a sequence of alternating fine-to-coarse-grained friable sands and mudstone or claystone units with formation depths ranging from -1200ft (366m) to -1600ft (488m) TVDSS (True Vertical Depth Subsea). The sandstone units are feldspar rich with moderate amounts of mica, which would be expected due to the position of the field relative to the Sierra Nevada range. Link et al. (1990) interpreted the Chanac Formation as a meandering channel system deposited on a coastal-plain comprised mostly of mud. The
deposits themselves being interpreted as sheetflood deposits. They also identified that the Chanac consists of east-west trending channels that form narrow sand bodies.

Figure 3. A representation of the Great Valley of California. The San Joaquin Basin is outlined in Green. Numbers and colors represent tectonic units within California. Latitude and Longitude values are shown along the edges. Modified from Irwin (1990).
Figure 4. Depiction of age, stratigraphy, lithology, and probable environments of deposition for units in the Bakersfield area. Highlighted unit represents the focus of this study. Modified from Olsen et al. (1986).
To the east of Kern Front is the Kern River field, the major productive interval there is the Kern River Formation. There is not much agreement on the contact between the Kern River Formation and the Chanac Formation, but there appears to be an outcrop showing the Kern River Formation uncomformably overlies the Chanac Formation (Bartow, 1983) while in the study area the Kern River Formation overlies the Etchegoin Formation. The Chanac Formation, like the Kern River formation is sourced from the western flank of the Southern Sierra Nevada mountain range and was deposited in an E-W direction, though unlike the Kern River Formation it also appears further south along the San Emigdio Highlands (Reid, 1995).

In Kern Front the Chanac Formation is uncomformably overlain by the Etchegoin Formation (Edwards, 1941), the unconformity between the two formations is considered to be a hiatus of 2-3My. The sands of the Etchegoin are made up of medium-to-coarse grained sandstones exhibiting poor to moderate sorting, grains are subangular to angular (Link et al., 1990). The Etchegoin Formation is interpreted as a shallow marine sand which was deposited trending N-S along the shelf system of the basin. To the east in the Kern River field these sands thin and eventually pinch out completely as the basin continues beyond the extent of shelfal deposits. The Etchegoin sand is identified as a basal Pliocene transgressive sand that underwent rapid deposition due to its age varying very little from location to location throughout the San Joaquin Valley (Foss, 1971).

Study Area

The area of study for this research covers approximately 320 acres (1.3 KM²) and is located in the lower half of the Kern Front oil field (Figure 5). This area has been under development for over 85 years and is currently undergoing the processes of steam injection which began in 2001. This area was chosen because of well depth and the density of wells available for study. This area has also been the location of several whole core recoveries. In terms of research this area is also one that has not been studied in comparison to the papers of Hendrickson (1928), Edwards (1941), and Link et al. (1990), which all focused in the northern part of the field.
Study area showing surrounding topography and surficial geology.

Figure 5. Study area location within Kern Front oil field, numbers represent sections. Outlines provided from Department of Oil, Gas, and Geothermal Resources, Surficial Geology provided from the USGS, and U.S. Topographic background provided from ESRI.
DATA & METHODOLOGY

Log Interpretation

Petrophysical logs are the primary data source for this research. Spontaneous Potential (SP) logs and Deep Resistivity logs were the most widespread throughout the data set and were used to identify the unit of interest for this project and to help identify the location within the fluvial system. Gamma Ray logs were used if SP logs proved to be unreliable, but their usage was limited.

Spontaneous Potential logs are one of the earliest log types that were used for petroleum exploration. They are used primarily for distinguishing permeable units (sands) from impermeable units (shales). SP logs work by measuring the direct current (DC) that develops between an electrode in the wellbore and an electrode that is affixed to the surface (Figure 6) (Doll, 1948; Asquith and Krygowski, 2004). SP log measurements are recorded in millivolts (mV) and accordingly do not have an absolute scale, therefore the best use of these logs is observing trends and shifts from the shale baseline SP value to identify permeable sand bodies (Halliburton, 1991).

Resistivity logs are one of the most common types of electrical logs used in modern logging suites. Resistivity logs work by producing an electrical current within the formation and measuring the resistivity present between two points. These logs are typically used to identify wet (water filled) or hydrocarbon bearing zones due to the resistivity variations within the formation that are associated with fluid content. There are two versions that are primarily used, one has an electrode on the surface (similar to that of Figure 7) that emits current through the formation where a detector in the wellbore receives the measurements, the second uses an internal coil to induce a current within the formation and measure its conductivity (Asquith and Krygowski, 2004). The reference to deep resistivity is an indication of the Depth of Investigation of the tool itself. Deep resistivity tools allow accurate measurements of the formation further away from the wellbore, bypassing zones that may be flushed or invaded by drilling fluids. Modern tools reach depths of investigation of up to 90” (228.6cm) into the formation (Schlumberger, 2010).

Gamma ray logs measure natural radioactivity that is emitted from formations. They are mostly used for correlation of sand and shale units because shale typically contains more radioactive material than sands. The most common type used in modern logging suites uses a sodium iodide (NaI) crystal to detect the impact of a gamma ray particle that is emitted by a naturally occurring radioactive element, e.g. potassium, and then uses a photocathode to produce electrons which creates a measurable voltage
Gamma ray logs can be deceiving in areas that contain high amounts of potassium feldspars, micas, or glauconite because these materials have a high level of naturally occurring radioactivity and can make a permeable sand body produce a signature similar to that of a shale or other impermeable body (Asquith and Krygowski, 2004).

Using petrophysical logs, sand bodies can be correlated across great distances by using trends in SP, Resistivity, and Gamma Ray log signatures. Table 1 shows an example of idealized log trends that were observed and correlated using petrophysical logs and gives explanations of what these trends can symbolize in terms of environment of deposition.

![Figure 6. Representation of a downhole wireline logging tool known as Spontaneous Potential (SP). Voltage is measured between the Ground Electrode and SP Electrode to provide an indication of lithology. Taken from Halliburton (1991).](image-url)
<table>
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<th><strong>Gamma ray</strong></th>
<th><strong>SP</strong></th>
<th><strong>Res</strong></th>
<th><strong>CLEANING-UP TREND (or funnel trend)</strong></th>
<th><strong>Represents a gradual upward change in clay-mineral content. Defined by either a progressive change in lithology or proportions of thinly interbedded units.</strong></th>
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<td><strong>DIRTYING-UP TREND (or bell trend)</strong></td>
<td><strong>Gradual upward change in clay-mineral content. Can also represent a lithology change such as an upward thinning sand bed or a transition from sand to shale. Mostly seen within meandering or tidal channel deposits, representing an upward decrease in fluid velocity or energy like those seen in coarse grained fluvial successions.</strong></td>
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<td></td>
<td><strong>BOXCAR TREND (or cylindrical trend)</strong></td>
<td><strong>Low gamma unit set within a high gamma background unit, indicates an abrupt switch from one unit to the other. Typical in Turbidites, some fluvial channel sands, and aeolian sand units.</strong></td>
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<td></td>
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<td></td>
<td><strong>BOW TREND (or symmetrical trend)</strong></td>
<td><strong>Generally the result of waxing and waning of clastic sedimentation rate in a basinal setting.</strong></td>
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<td></td>
<td></td>
<td><strong>IRREGULAR TREND</strong></td>
<td><strong>Represent the aggradation of shaley or silty lithology, typical of a shelfal or deep water environment. Muddy alluvial overbank facies can also show this sort of trend.</strong></td>
</tr>
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**Key:**
* Resistivity assumes water-fill

Table 1. Trends standardly used to correlate lithological units between wellbores. Possible inferences that can be made from these trends are indicated on the right. Modified from Milton and Emery, 1996.
Core Analysis & Description

Both Sidewall and Conventional core data was available within the study area and was used to provide an insight on in-situ rock conditions including porosity, permeability, and fluid saturations. Conventional core was made available to interpret either by means of high resolution photography or hands on analysis.

Sidewall cores are samples taken from the formation in an orientation perpendicular to the wellbore and are usually recovered by the means of a wireline tool, which is similar to downhole logging tools (Figure 7). The most commonly used method of sidewall core recovery, the same type that are used for this study, is by use of hollow bullets fired into the formation using an explosive charge, these are known as percussion sidewalls (Agarwal et al., 2014).

Conventional core samples are captured by the use of a special coring bit, which is essentially a hollow drill bit in which the core is pulled up into long tubes (usually 30ft) known as core barrels. The drill bit continues to circulate and cut its way through the formation as it drills deeper into the formation, allowing more core to be captured inside the barrel. Once the coring interval is completed (or the core barrel is full) a special mechanism known as a core catcher traps the core in place and allows it to be brought to surface (Figure 8). After reaching the surface the core is cut into manageable 3ft (1m) sections and it is then capped and transported to the core analysis lab, or kept chilled until the rest of the coring operation is completed (Dacy and Potter, 2010).

Upon delivery to the laboratory the process for analysis of sidewall core and conventional core becomes fairly similar as the conventional core is slabbed using a nitrogen cooled saw blade into 1/3 and 2/3 sections. The 1/3 sections are used for photography and core display/description, while the 2/3 sections are usually taken and used for routine analysis of porosity, permeability, and saturations, or special core analysis samples are taken for XRD, thin sections, and advanced testing such as residual saturations or steamflood analysis. Routine analysis is performed by drilling into the 2/3 section using a nitrogen cooled bit and recovering a small plug (around 1” in diameter), similar to the size of a sidewall core sample. For routine analysis the rocks are wrapped and compressed in an attempt to simulate in situ conditions and then they are subjected to routine core analysis testing (Dacy and Potter, 2010).

Core descriptions were completed on the 1/3 sections that were available for the unit of interest in either photographic or physical form. Descriptions were completed in 1ft increments and significant features were recorded.
Figure 7. Simplification of a Percussion sidewall tool and how it recovers core from the formation. Taken from Crain’s Petrophysical Handbook.

Figure 8. Showing a typical coring bit and barrel orientation for a conventional coring tool. Taken from Crain’s Petrophysical Handbook.
Net Sand & Structure Maps

After the unit of interest was correlated by the use of petrophysical logs, Net Sand and structure maps were generated by the use of Decision Space Desktop™ a product from Halliburton Industries.

Upon establishing top and base picks for the formation and unit of interest a structure map was constructed for both the top and base of the unit of study using existing well locations as data points. These maps were created using a Kriging algorithm and using a grid cell size of 40ft (12.2m) and containing a total of 6384 individual cells. Net sand values were calculated over the unit of interest and summed within the software. These summed values were plotted on each of the projects well locations and contours were hand drawn based on these values.

Fluvial Classification

There has been quite a bit of work over the years in classifying fluvial architectures and environments. Shulits (1959) noted that a high sinuosity is not conductive to efficient bedload transport. Schuum (1963) discovered that there is supporting evidence linking an increase in total bedload transport to the amount of coarser grained sediment around a channels perimeter. Building on this Schuum (1963) derived a model linking the mode of sediment transport (suspended load, mixed load, or bed load) to channel stability.

Friend (1983) built upon the work from Schuum (1963), agreeing that while sediment load was a good indicator for channel stability, it wasn’t possible to reliably summarize fluctuations that occur in sediment load over the lifetime of a river. Friend (1983) suggested that additional resources must be used to identify channel patterns. The suggestion is to incorporate microforms, mesoforms, and macroforms based on the work of Jackson (1975). These features can be preserved in ancient facies and analyzed to assist in channel definition. The classes he defines for channel classification are sheet floods, fixed channels, and mobile channels.

Miall (1985) built on these previous works, but indicated there are a number of controls that govern fluvial sedimentation and deposition, a stream typically isn’t just assigned to be braided, meandering, anastomosing, or straight, but can be a gradation between any of these. While previous works had grouped channels together, Miall (1985) indicated that there were variations to every rule, for example 1) high sinuosity meandering river systems can still contain numerous bars and islands, making them appear similar to that of a braided river, 2) sediment load may be not only an indicator of
surrounding perimeter sediment, but also a result of variations in sediment availability due to source rock weathering and erodibility or provenance. Miall (1985) broke down the previously established microforms, mesoforms, and macroforms, indicating that not all of them are diagnostic of fluvial architecture. Microforms for example are so small scale that they are essentially identical in all environments dominated by clastic sediments, and therefore cannot be reliable indicators of the systems architecture. Mesoforms are typically generated by dynamic events, such as flood events, and while they can show variation within a system they are not a good identifier for the overall architecture. Macroforms on the other hand can reflect periods of tens to thousands of years, these macroforms are what Miall bases his Major architectural elements on.

Eventually, Miall (1985) divided major architectural elements into eight categories 1) Channels, 2) Gravelly bars and bedforms, 3) Sandy bed forms, 4) Foreset macroforms, 5) Lateral accretion deposits, 6) Sediment gravity flow deposits, 7) Laminated sheet sands, and 8) Overbank fines (Figure 9). Upon investigating these eight elements a system can be classified into one of Miall’s twelve models or even appear as a combination of more than one.

In this study, I use the methodology presented by Miall (1985) in conjunction with log trends and core descriptions to identify and classify the fluvial architecture of the Chanac Formation.
RESULTS

Petrophysical Log Results

For this study 191 wells were correlated throughout the study area with associated cross sections made through them. After more data refinement the number of wells used for this project was reduced to 61 due to the potential steam and depletion influence on the log curve signatures. This type of influence can suppress log signatures and create an inaccurate representation of the petrophysical log data.

Formations were first identified, there were a number of Etchegoin and Chanac surface picks indicated in both data available from the Department of Oil, Gas, and Geothermal Resources (DOGGR) and from geologic studies previously mentioned within this paper. Once these formations were established the study unit was identified due to its fair sand continuity in the unit of interest, current development interest, and availability of other prospective data. Figure 10 shows a type log of the area, including key geologic indicators and identifying the unit of study.

Wells were correlated in a grid including both north to south and east west cross sections. Top and base picks were made for Unit J, they were designated J and J2 respectively. Unit J mostly consists of sandstone with the occasional silt or shale break within the sand body, some wells had additional sand bodies that were attached to the base of Unit J, they were excluded because they did not fit into the typical blocky Unit J signature identified. A typical Unit J sand had a thickness that varied from 20-50ft (6-15m).

Unit J exhibits a blocky SP signature throughout most of the study area, there are a couple variations from this with a few wells showing an almost completely flat trend and a few blocky signatures which could be interpreted as bowed. Resistivity logs are variable, typically coarsening up towards to the top of the unit, some exhibit a blocky signature as well, and occasionally a fining upwards trend is seen. Wells were double checked to make sure there were no signs of depletion or steam influence from cyclic steaming and early steamflooding.
Figure 10. A representative type log of the study area. Well known formations are indicated as well as the designated interval of study “Unit J”.
Core Analysis & Description

Percussion sidewall Core analysis was available for a total of 48 wells within the study area that penetrated into Unit J. Most wells contained between 1-3 samples, the limited number of samples is likely due to the fact they were used for determining saturations for well completions. Sands in the unit are described as dark brown in color, ranging from very fine-to-very coarse grained with occasional samples containing granules or pebbles. Slight traces of silt in the samples were noted as were indication of micaceous minerals.

In sidewall samples permeability values ranged from 100-3500 millidarcies (md) with porosity values between 25 and 35 percent. Averages for all the sidewall core data can be seen in Table 2. For Unit J oil saturations vary slightly.

A total of four wells with whole core data residing in the study area were available for data analysis and photographic review. One of these wells had poor quality photos and it was not reviewed beyond the data values. The three higher quality core wells appear in Appendix 2 and are presented in 3 or 5ft core increments with descriptions for each of them. The first two wells, 22R and 28i were described using only core photography while the third well 346 was described using both photographic data and a hands on analysis of the 1/3 core sections (Appendices 2a-2h).

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</thead>
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<tr>
<td>Average Grain Density (g/cm³)</td>
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<tr>
<td>Average Oil Saturation (%)</td>
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<td>Average Oil Saturation (%)</td>
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*Porosity and Permeability values based only on Horizontal Plug samples

Table 2. Average values taken from routine core analysis of all available core taken in Unit J. Vertical samples were excluded from these averages. Md represents millidarcies.
Stratigraphic Sections

Stratigraphic sections were created for the cored intervals available within Unit J to give a glimpse of stratigraphic framework and sedimentary features visible within Unit J (Figures 11-13).

In well 22R Unit J appears to be a dark brown oil saturated sand that consists of a medium to coarse grained sand fining upwards into a siltstone or claystone layer at the top of the cored interval. The bottom of the unit shows a sub rounded fractured cobble that is approximately 3 inches (7.62cm) in diameter. Possible water escape structures can be seen at about 6.6ft (2m) from the bottom of the cored interval.

In well 28i Unit J shows a medium to coarse grained light brown sand, the bottom of the cored unit shows ripples and possible scour surfaces, moving upwards in the section the sand appears to transition to a darker brown sand. A calcification or dissolution of a rock fragment can be seen at ~5ft (1.5m) from the top of the interval. The top of the sand quickly transitions into a fine grained sand with evidence of cross-bedding.

In well 346 Unit J is a medium to coarse grained tan sand showing cross-bedding and reworked calcareous material towards the bottom of the stratigraphic interval, moving up the stratigraphic unit the sand appears a darker brown color that is very unconsolidated with no identifiable structures. It then fines upwards until a sharp change in grain size is seen that is associated with a change in color to a lighter brown sand. Approximately 13ft (4m) from the bottom of the core interval, just above the previously mentioned color shift, the sand appears to shift into a conglomerate with a coarse sand matrix. The fragments are large enough that a feldspar clast could easily be identified. Moving upwards the amount of rock fragments appears to decrease into a friable fine to medium grained sandstone. A sharp shift in grain size appears again ~3.5ft (1m) from the top of the unit and a shift to coarse sand with subrounded pebbles is seen that is similar to the lower shift in grain size.
Figure 11. Stratigraphic Section of Unit J in well 22R, not all of the unit was cored or recovered. Legend of units and structures appears to the upper right.
Figure 12. Stratigraphic Section of Unit J in well 28i. Approximately half of the unit was cored and/or recovered. Legend appears to the right.
Figure 13. Stratigraphic Section of Unit J in well 346. A majority (80%) of the core was recovered. Legend appears to the upper right of the page.
Net Sand & Structure Mapping

Net sand calculations were made in each well by evaluating the log signatures of Unit J and identifying the intervals that were sand, these intervals were summed and the results of these calculations appear in Table 3. Channel thicknesses are fairly consistent with an average sand thickness of approximately 28ft. Some wells exhibited no sand at all, instead showing an interval with extremely suppressed spontaneous potential and resistivity curves. Both of the wells that showed this lack of sand appeared at the NW extents of the study area. Net sand values were then plotted on a blank location map encompassing the study area (Figure 14) and contours were created from these values. Sand thicknesses decrease towards both the NW and SW parts of the study area with a general increase in sand thickness towards the center of the area. Overall the sand thickness stays fairly consistent with an average sand thickness of 28ft (8.5m) throughout the study area. Thicker sands averaging from 30-45ft (9-14m) dominate the NE of the study area, these sands gradually decrease to the SE to less than 25ft (8m). Sand thickness decreases abruptly in the NW corner going from an area of 40ft (12m) thickness to 0ft where the area appears to be mud dominated.

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<th>63</th>
<th>64</th>
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<th>67</th>
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<td>23'</td>
<td>42'</td>
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<td>23'</td>
<td>26'</td>
<td>29'</td>
<td>37'</td>
<td>32'</td>
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<td>26'</td>
<td>22'</td>
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<th>160</th>
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<th>301</th>
<th>457</th>
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<td>51'</td>
<td>30'</td>
<td>34'</td>
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<td>0'</td>
<td>51'</td>
<td>25'</td>
<td>30'</td>
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<th>711</th>
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<th>728</th>
<th>860</th>
<th>11R</th>
<th>22R</th>
<th>29R</th>
<th>2i</th>
<th>30R</th>
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<td>33'</td>
<td>24'</td>
<td>29'</td>
<td>33'</td>
<td>35'</td>
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<td>39'</td>
<td>51'</td>
<td>27'</td>
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<th>37R</th>
<th>3i</th>
<th>4i</th>
<th>62R</th>
<th>Gi</th>
<th>7i</th>
<th>82R</th>
<th>86R</th>
<th>8i</th>
<th>9iR</th>
<th>TO-1</th>
</tr>
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<tbody>
<tr>
<td>Net Sand Value (ft)</td>
<td>31'</td>
<td>21'</td>
<td>34'</td>
<td>26'</td>
<td>31'</td>
<td>32'</td>
<td>31'</td>
<td>9'</td>
<td>31'</td>
<td>29'</td>
<td>17'</td>
<td>29'</td>
</tr>
</tbody>
</table>

| Average Net Sand (ft): | 27.62ft | P10: 27R |
| Standard Deviation: | 5.19 | P50: 29ft |

Table 3. Table representing the results of calculating Net Sand values for the study area wells.
After net sand calculations were completed, cross sections were created parallel to the apparent direction of thinning (Appendices 3a-3d). These cross sections are lithologically filled to indicate the trend of net sand throughout the study area. The cross sections show a trend that appears to support the thought of thinning to the NW and SE and thickening along the center. Sands along the NW appear to be thin or non-existent through the cross sections. There appear to be thinner and thicker trends that can be correlated from the NE to the SW portion of the study interval.

Structure maps were created on both the top and base of Unit J (Figure 15 & 16). Unit J appears to be a SW dipping monocline with a gentle dip of approximately 5°. The top of Unit J gently dips from the NE to the SW from -1220ft (372m) to -1570ft (479m) TVDSS throughout the study area while the base of Unit J dips from -1270ft (387m) to -1610ft (490m) TVDSS. There appears to be at least one identifiable fault in the area towards the western side of the study area, but due to the timing of regional uplift the faults should be identified as post depositional (Graham et al. 1988, Jones et al. 2004, and Cecil et al. 2014).
Figure 14. Contour map showing Net Sand values plotted on study area well locations. Contours were hand contoured at a 5ft contour interval and represent net thickness. Color fills represent like contour intervals. Red markings indicate well locations and their associated net sand thickness values.
Figure 15. Structure map generated in Decision Space Desktop™ representing the top of Unit J. Orange letters indicate well numbers. Black numbers indicate TVDSS values.
Figure 16. Structure map generated in Decision Space Desktop™ representing the base of Unit J. Orange letters indicate well numbers. Black numbers indicate TVDSS values.
DISCUSSION

Fluvial Facies Analysis

The four identified channel systems existing in fluvial classifications (straight, meandering, braided, anastomosing) are useful but these are just key members and there can be any number of gradations between them when identifying fluvial architecture (Miall, 1985). Miall (1985) identified eight key architectural elements in his paper (Figure 9). Unfortunately only some of these elements can be identified within the study area. This could be because they simply don’t exist or more likely due to limitations within the data set.

In this study concave up Channel (CH) elements are very prominent and easily identified with the use of the available subsurface log data and the lithologic cross sections discussed earlier in this paper (Appendices 3a-3d). Within the study area a good example of mud-dominated Overbank Fines (OF) is seen in the NW portion of the study area where a steep channel edge cuts into these mud dominated sediments. Gravely (GB) and Sandy (SB) bedforms, or bars, were interpreted by coarsening upwards sequences via spontaneous potential or resistivity logs. Due to the sand dominance within the study area these are interpreted as Sandy mid-channel bars elongated in the direction of flow from NE to SW, this coarsening upwards sequence can also be an indication of linguoid or transverse bars associated with high stage conditions, but due to dataset limitations it isn’t possible to identify the exact type of bar, so they are labeled as a generic bar term in this study (Miall, 2006; Charlton, 2008). Lateral Accretions (LA) are seen in the SE part of the study area, identified by their fining upwards sequences in subsurface log data. All of these elements are labeled and seen in Figure 17.

Elements identified by Miall (1985) that don’t appear in the study area are Laminated Sands (LS), Sediment Gravity Flows (SG), or Foreset Macroforms (FM). Foreset Macroforms are notoriously hard to identify by use of vertical profile analysis except in areas of very close well spacing (Miall, 1985). Foreset Macroforms can be over a kilometer across and contain complex internal geometry therefore needing a three dimensional approach to review them. Identification of these deposits typically requires exposed surfaces such as road cuts, natural cliffs, open pit mines.

When reviewing elements that are present within the study area this system most closely resembles Model 8 presented by Miall (1985), which would reveal this channel to be a variable sinuosity, stable, anastomosed channel system (Table 4). This system could possibly be a gradation of a number of the endmembers and might not perfectly fit into one classification.
Figure 17. Reconstruction of the depositional environment of Unit J. Estimated flow direction is shown by arrows. Contour lines indicate net sand thickness. Elements taken from Miall (1978). CH = Channel, LA = Lateral Accretion (or point bar), BAR = Either Sandy Bed form (SB) or Linguoid Bar element, OF = Overbank Fines.

Contour Interval = 5ft
<table>
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<th>No.</th>
<th>Sinuosity</th>
<th>Braiding parameter</th>
<th>Sediment type</th>
<th>Characteristic elements *1</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>low to high</td>
<td>high</td>
<td>sand, fines</td>
<td>SB, OF (LA)</td>
<td>Rust (1981), Smith (1983)</td>
</tr>
<tr>
<td>11</td>
<td>low</td>
<td>high</td>
<td>sand, minor fines</td>
<td>SB (OF)</td>
<td>Williams (1971), Miall and Gibling (1978)</td>
</tr>
</tbody>
</table>

Table 4. Miall’s common fluvial styles identified by different model numbers. Elements in brackets are minor components. Taken from Miall (1985).
Formation of Anastomosing River System

A look into a nearby fluvial system could help support the interpretation as the Chanac Formation (at least Unit J) as an anastomosing river system. As described earlier the Kern River Formation overlies the Etchegoin Formation in the study area, and possibly even unconformably overlies the Chanac Formation itself in the Kern River field, therefore it has the possibility of giving great insight to our understanding of Unit J. Graham et al. (1988) summarized that the Kern River Formation is a low sinuosity fluvial system comprised of “a thick accumulation of braided stream deposits”. Ginger et al. (1995) also interpreted the Kern River Formation as a set of braided river channels. These interpretations are in contrast to the anastomosing system identified in this research. There are a few fundamental variations that can help to explain why systems in such close proximity have different classifications assigned to them, i.e. geomorphological and tectonic differences.

A common link that helps to explain variations in river systems is Geomorphology. Slope deformation can occur due to regional uplift or subsidence, which also directly relates to a change in accommodation space. Some of the changes occurred to a river system due to slope deformation are identified and listed in Figure 18. With enough subsidence, a meandering river can be changed into an anastomosing river; or vice versa with enough uplift (Richards, 1996; Wang et al., 2000; Makaske, 2001).

Graham et al. (1988) uses the nearby Kern River Formation to address the uplift history of the Southern Sierra Nevada range and they not only established that the Kern River Formation deposition corresponds to the uplift of the Sierra Nevada but that there were numerous glacial advances that occurred at that time as well which could have contributed an increased erosional rate at approximately 8 Ma (Figure 19). Both uplift as well as erosion rates play a significant role in accommodation space, an increase in uplift can be essentially cancelled out by an equal sized erosional event, which would keep the base level consistent and result in no accommodation space changes. Jones et al. (2004) illustrate in their paper that there are multiple models with varying amounts of uplift and erosion that all match the current base level of the Sierra Nevada, though they place uplift more recently than Graham et al. Cecil et al. (2014) uses methods similar to Jones et al. (2004) by analyzing the lithosphere by use of volcanics. Their results indicated that the Sierra Nevada was undergoing rapid subsidence and sedimentation throughout the Cenozoic and then underwent uplift in the late Miocene, this timing would place this event close to the model presented by Graham et al. (1988). Cecil et al. (2014) also uses granulation textures discovered by Link et al. (1990) in the Kern Front field as an indication of rapid uplift, these granulation textures are typically seen at burial depths of >5250 ft (1600 m) yet they currently reside at

35
~1600 ft (500 m), which indicates significant amount of uplift that the Sierra Nevada was undergoing and modifies the uplift dating to around 6 Ma.

This subsidence and uplift history helps to identify possible slope deformations and accommodation space changes within the region. The Chanac formation would have been deposited during a time of subsidence, which would have been a time of decreased slope gradient and accommodation space which would be a favorable depositional situation for an Anastomosing river system. While the Kern River Formation was mostly deposited in a time of uplift and sea level rise, which would have been a big increase in accommodation space. This would have provided a higher gradient and the channel system would have moved away from an Anastomosing system into more of a meandering or braided channel configuration (Coe et al. 2003, Miall 2006).
Figure 18. Response of fluvial systems to uplift and subsidence based on experimental flume studies performed by Ouchi, 1985. Time scale from top to bottom in each diagram. Figure from Richards, M.T., in Emery & Myers (1996).
Figure 19. Summary of tectonic, sedimentary, and climatic events affecting the southern Sierra Nevada and southeastern San Joaquin basin during the last 10 million years. Taken from Graham et al. (1988).
Dataset Limitations

1) As mentioned in the previous section there are some important elements that typically can’t be identified by subsurface log and core data.
2) There aren’t any available exposed outcrops of the Chanac Formation. There is supposed to be the previously mentioned Chanac-Kern River unconformity but this is in opposition to published Dibblee maps and it has not been located by this researcher.
3) Only one whole core was available for physical investigation, and even that core could have been compromised as it has been stored in ambient storage for years before examination.
4) Logs, being one of the key resources for this project, are difficult to deal with due to high feldspar content and potential effects of steam influence and depletion even with dataset scrutiny.
CONCLUSIONS

This research has identified that the fluvial river system represented by Unit J of the Chanac Formation in the study area is that of an Anastomosing system, and its discrepancy from the Kern River Formation is due to variations in accommodation space, mostly influenced by the Chanac Formation’s deposition in a time of subsidence as opposed to the Kern River Formation’s deposition during a time of uplift and higher sea level.

This research has shown that even using subsurface log data, and with a lack of outcrops, that a fluvial architecture can be identified using key elements from the model that Miall (1985) proposed. These similar elements could be used to identify other fluvial systems to assist in economic development of hydrocarbons.

This research has also shown that well logs are a key indicator especially when dealing with a similar fluvial system. An anastomosing system is constantly changing over time even in stable systems, and this could create a problem when attempting to track steam injection and to obtain a successful sweep of hydrocarbons.

With the advancements in fluvial system identification there should be a number of opportunities to re-evaluate existing fields and apply these models. Especially in areas where there is a high well density and outcrops available for study.
RECOMMENDATIONS FOR FUTURE WORK

1) Expanding the study area, especially to the North and South to see if indeed the system is bounded by channel edges, or if they are part of a bigger system.

2) Expand the project to include units above and below Unit J and completing the same exercise as this research. This could give real insight on how the channel systems may have changed over time in respect to flow direction and fluvial architecture.

3) Map out the system further to the East through Kern River and to the west through Poso Creek to possibly get a full picture of the system as it progresses from proximal to distal. A recently drilled core well is showing signs of a much finer Unit J to the west, this could be a good indication that it is more distal than the study area of this research.

4) Evaluate the most economic and successful means of approaching an anastomosing fluvial system for hydrocarbon development and most efficient practices.
Appendix 1. A rough sketch showing the location of the Kern Front fault and how it offsets the major units between the Kern Front field and the Kern River field. Of note are the unconformable layers and the significant offset of the fault. Modified from Link et al. (1990).
Appendix 2a. Core description of the well 22R from the study area. This well had a limited interval that was cored and only photos were available for interpretation. Blue star indicates well location.

2210’ - 2213’: Poor Core Recovery. Siltstone layers with interbedded coarse grained sands. Consolidating into a cohesive sand around 2213’.

2213’ - 2219’: Appears to be a medium to coarse grained sand, occasional granule or pebble. No identifiable features except for possible water escape structures near 2218.5’. Poor available image quality makes analysis difficult.

2219’ - 2219.6’: Medium to coarse grained sand appears to be coarsening downward into a more pebbly material, large rock from 2219.3’ to 2219.6’.
2155’ - 2160’: Fine to Coarse grained sand. Cross-bedding present from 2155.5 - 2155.8 and then coarses downward to 2156.9. Finer sand from 2156.9 to 2157.2 and then grades into a coarse sand till 2160.

2160’ - 2165’: Medium to Coarse grained sand. Possible repeating flow structures or bioturbation at 2161’, 2162’, and 2162.5’. Calcification or Rock Fragment at 2163.5’.
2165' - 2170': Medium to coarse grained sand, fining downwards to 2166.5. Large rock clast present at 2167.2. Sand appears medium grained till 2170. Slight discoloration at 2168.8, possibly inter-bedded clay. Granules and pebbles visible at from 2169.5 to 2169.8.

2170' - 2174': Medium to coarse grained sand. Structure that appears to be ripples from 2170.5 to 2171.2. Again from 2171.4 to 2171.6, though these appear more planar. 2172 shows a possible scour surface. Sand from 2172 to 2172.6 appears more cohesive and less unconsolidated. Rubble from 2172.7-2173, representative of a core barrel change. Another scour surface and cohesive sand section appears at 2173.65.
Appendix 2d. Core description of the well 346 (Part 1). This well had photographs available and the core was being stored in ambient storage so it was able to be physically investigated. Blue star indicates well location.

2226'-2229': Vf-Vcgr sand, mostly medium to coarse grained sediment. Occasional granule or pebble, very unconsolidated. Poor Recovery.

2229'-2232': Vf-mед grained sand, good oil content. Sharp contact visible at 2229.8 associated with a grain change, possibly a flooding event surface. Occasional linear alignment of coarse grained sediment present.
Appendix 2e. Core description of the well 346 (Part 2). This well had photographs available and the core was being stored in ambient storage so it was able to be physically investigated. Blue star indicates well location.

2232'-2235': Similar grain size to 2226-2229 core. Friable sediment, occasional granule or pebble.

2235'-2238': Med-Coarse grained sand, pebbles becoming more prominent towards bottom of core. Pebbles seem grouped, pebles are subangular to rounded.
Appendix 2f. Core description of the well 346 (Part 3). This well had photographs available and the core was being stored in ambient storage so it was able to be physically investigated. Blue star indicates well location.

2238’-2241’: Coarse sand matrix, pebble sizes increasing from previous interval. Feldspar clast visible at 2240.1.

2241’-2244’: Rounded rock clast towards top of interval, grain size fining downwards to 2242.7. Sharp contact at 2242.7 associated with a color change and shift towards even finer grained sediment. Similar to earlier contact.
Appendix 2g. Core description of the well 346 (Part 4). This well had photographs available and the core was being stored in ambient storage so it was able to be physically investigated. Blue star indicates well location.

2244'-2247': Coarse sand fining downwards towards 2246. Calcified sand present at 2246 and 2246.5. Sand begins to grade toward coarser sand again at bottom of core.

2247'-2250': Vf-Vcgr sands, no identifiable features within, unconsolidated.
Appendix 2h. Core description of the well 346 (Part 5). This well had photographs available and the core was being stored in ambient storage so it was able to be physically investigated. Blue star indicates well location.

2250'-2253': Vf-Vggr sand, small reworked calcaerous mineral or calcified sand located at 2250. Color shift at 2250.8 and 2251.8, possible tighter unit, less saturation (increased clay content?). Cross beds or contact present at 2252.7.

2253'-2254.2': Med-Vggr sands, possible crossbeds at 2253.3. Rubble at the bottom.
Appendix 3. Index map of cross sections created trending NW to SE parallel to the direction of sediment thinning. Red markings indicate well locations and their associated net sand values. Cross Sections can be seen in appendices.
Appendix 3b. Cross section B-B’. Sand lithology indicated using lithological analysis of wellbores. Fill between wellbores based in contour interpretation. Lithological log datum is Unit J top.
Appendix 3c. Cross section C-C'. Sand lithology indicated using lithological analysis of wellbores. Fill between wellbores based in contour interpretation. Lithological log datum is Unit J top.
Appendix 3d. Cross section D-D'. Sand lithology indicated using lithological analysis of wellbores. Fill between wellbores based in contour interpretation. Lithological log datum is Unit J top.
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