SUBSURFACE GEOLOGY OF ARSENIC-BEARING PERMIAN SEDIMENTARY ROCKS IN THE GARBER-WELLINGTON INTERVAL OF THE CENTRAL OKLAHOMA AQUIFER, CLEVELAND COUNTY, OKLAHOMA

By

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I.

INTRODUCTION

As an important source of drinking water in central Oklahoma, the Central Oklahoma Aquifer (COA) has been the focus of much attention in recent years because of elevated levels of naturally occurring arsenic. The City of Norman, located in Cleveland County, Oklahoma (Figure 1), obtains its groundwater from the Garber-Wellington portion of the Central Oklahoma Aquifer; Norman has the second highest levels of naturally occurring arsenic in drinking water in the United States, exceeded only by Albuquerque, NM. In 2006, the Environmental Protection Agency (EPA) will lower the maximum allowable limit of arsenic in drinking water from the current level of 50 ppb to 10 ppb; numerous wells currently producing from the Central Oklahoma Aquifer will not meet the new standard. The City of Norman would like to remediate the arsenic-in-drinking-water-problem so that city wells will not have to be taken off line. The city is also trying to avoid the expense of surface treatment techniques. OSU, in conjunction with the EPA and the United States Geological Survey (USGS), is evaluating remediation techniques and preparing preventative guidelines to the City of Norman and other municipalities that obtain their drinking water from the Central Oklahoma Aquifer. Previous work by the USGS has indicated that arsenic concentration may be proportional to the volume of shale in a wellbore (Schlottmann et al., 1998). Therefore, some approaches to achieving the goal of lowered arsenic levels are: 1) selective production

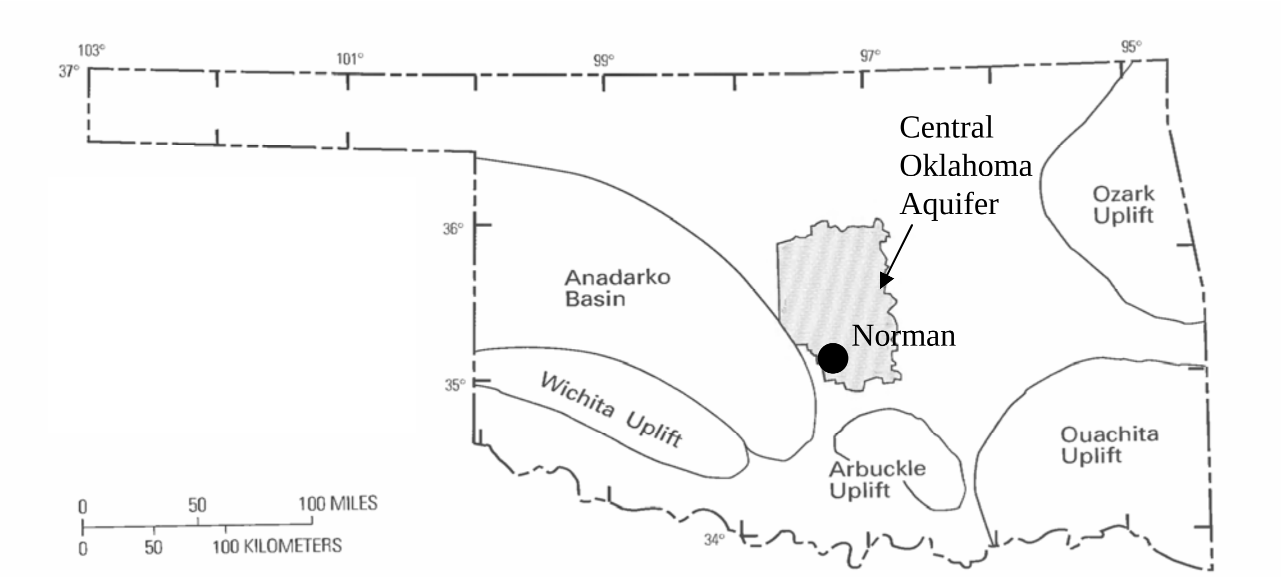


Figure 1. Location map of the Central Oklahoma Aquifer and surrounding geologic features (modified after George N. Breit, *The Diagenetic History of Permian Rocks in the Central Oklahoma Aquifer*, in USGS Water-Supply Paper 2357-A)

of water from low arsenic stratigraphic intervals; 2) squeezing off high-arsenic intervals in existing wells; and 3) drilling new wells in areas with low arsenic potential. In order to implement these approaches, the need arises for subsurface mapping of the Garber-Wellington Aquifer, in terms of lithofacies (sandstone, shale, shaly sandstone) and sediment packages. This work should provide a better understanding of the Garber Sandstone and Wellington Formation not only with respect to arsenic, but also with respect to the depositional system from which the rocks originated. To fulfill the need for better definition of the geology of the Garber-Wellington Aquifer, this study, along with two other OSU graduate theses, begins to establish a geologic-stratigraphic framework for this part of the COA.

With the exception of Quaternary fluvial terrace deposits, all rocks in the Central Oklahoma Aquifer are Permian (Artinskian, formerly Leonardian) aged. The Garber Sandstone and the Wellington Formation are the most significant water-bearing units in the Central Oklahoma Aquifer; other formations in the COA are the underlying Council Grove, Chase, and Admire Groups. The aquifer is overlain and in some places confined by the Hennessey Shale and underlain by the Pennsylvanian Vanoss Formation (Figure 2). The Garber Sandstone and the underlying Wellington Formation consist of amalgamated lenticular fluvial sandstones interbedded with mudstones, siltstones, and some conglomerates (Breit et al., 1990). Previous work by the U.S. Geological Survey has shown that arsenic content in the Garber-Wellington Aquifer is a function of grain-size, i.e., arsenic concentration is higher where the rocks are finer-grained (Schlottmann et al., 1998). It has also been suggested by the USGS that arsenic is elevated in sandstones isolated by finer-grained rocks, due to a lack of flushing-out of these rocks.

In this study, the Garber-Wellington Aquifer was analyzed in terms of the geometry, continuity, and spatial distribution of different lithofacies. The two other OSU theses focus on the physical properties of the rocks, especially outcrop gamma-ray measurements, grain size analyses, and whole-rock geochemistry (Gregory Gromadzki), and outcrop description and mapping (Kathy Kenney). These three studies are intended to complement each other and enhance understanding of arsenic distribution in the Garber-Wellington Aquifer through integration of both surface and subsurface work.

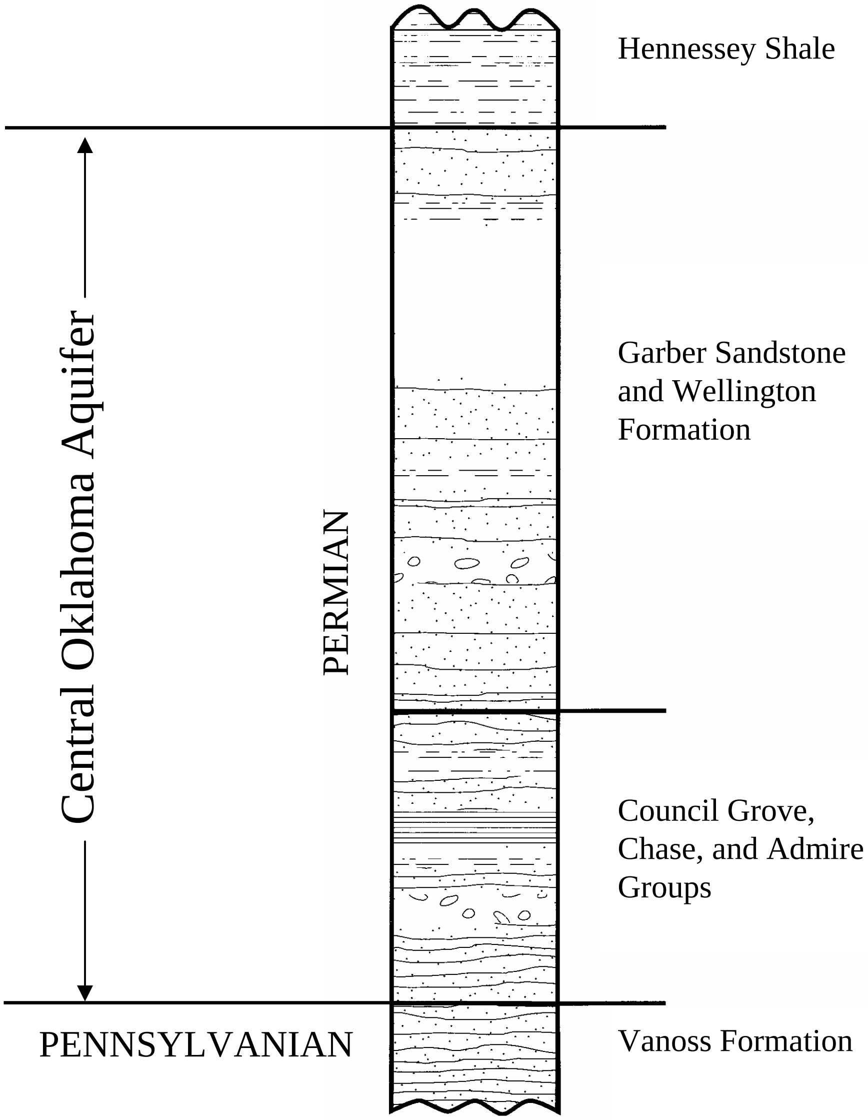


Figure 2. Stratigraphic column of the Central Oklahoma Aquifer (modified after George N. Breit, *The Diagenetic History of Permian Rocks in the Central Oklahoma Aquifer*, in USGS Water-Supply Paper 2357-A)

II.

PURPOSE AND OBJECTIVES

The primary goal of this study is to provide a geologic and stratigraphic framework to be used by the USGS and EPA to help remediate the arsenic problem in the Norman, OK area. These agencies will be able to use the results of this study and its two counterpart studies as a guideline for selection of new drilling locations, as a means of possibly locating and isolating arsenic-rich zones, and as input into fluid flow modeling to be conducted by the USGS. For this study to be helpful in this manner, the Garber-Wellington aquifer was mapped in terms of structure, thickness, and lithofacies. Subsurface well logs were the primary source of data, although a minor amount of core data was also used. From the well logs, cross-sections and maps were constructed to provide a picture of the subsurface character of the Garber-Wellington Aquifer, especially with respect to unit continuity and gradations from one lithofacies into another.

The Garber Wellington aquifer is composed of three primary lithofacies as represented by wireline logs: sandstone, shale, and shaly sandstone. There are also minor amounts of conglomerates, but these are not mapped in this study because of the difficulty associated with identifying them using well logs (they are usually too thin). If arsenic occurrence is associated with finer-grained lithofacies (shaly sandstone and shale), then mapping the distribution of these lithofacies should provide valuable insight into the relationship between arsenic occurrence and rock type in the Garber-Wellington Aquifer. Briefly, the objectives of this thesis are to:

1) Construct cross sections through the Garber Sandstone and to use the cross sections to determine if the rocks of the Garber Sandstone can be correlated (the units do not contain regional stratigraphic markers),
2) Identify, from the cross sections, continuous sediment packages or units,
3) Map the subsurface structural relief of the upper and lower surfaces of the Garber Sandstone and any identifiable units within it,
4) Determine and map the amounts of clean sandstone, shaly sandstone, and shale in the Garber Sandstone (and in its mappable components), in terms of net thickness, percent lithology, and/or ratios of various lithofacies,
5) Identify areas of prospective low and high arsenic concentration based on the above maps,
6) Estimate the location and orientation of the main depo-center responsible for the Garber sediments in the Norman area, and to attempt to track changes in the system through time (migration of the channel fairway) based on the maps, and
7) Recommend possible remediation strategies based on our understanding of the geology and stratigraphic framework.

III.

BACKGROUND AND PREVIOUS WORK

The Garber-Wellington Aquifer makes up most of the thickness of the Central Oklahoma Aquifer (COA) and contains most of the aquifer’s fresh water. The COA also is overlain by the Hennessey Shale and Quaternary alluvium, and underlain by the Chase, Council Grove, and Admire Groups. In Cleveland County, the Garber-Wellington Aquifer is confined by the Hennessey Shale to the west, and is unconfined to the east. The USGS has done much work on the COA; among the conclusions reached from their investigations is that arsenic is mobilized under high pH conditions, and that high pH conditions in the COA occur at depth, below the city of Norman. The USGS has also concluded that the arsenic is contained in the Permian siltstones and mudstones of the aquifer. Most of this work has focused more on the geochemical aspect of the problem rather than on the sedimentary framework that makes up the aquifer. The USGS work will be discussed later in more detail.

General Geology

The study area is located to the south of the Oklahoma City Anticline, a structure whose development is associated with the Nemaha Ridge and the Anadarko Basin. The units of the Garber-Wellington dip to the west and are relatively flat lying. However, several known fault zones surround the study area at depth. The Oklahoma

City Anticline is an elongate, anticlinal feature trending north 30 degrees west in southern Oklahoma County, and is bounded to the east by the Nemaha Fault Zone (Foley, 1934).

In order to show the evolution of our understanding and conception of the Garber Sandstone and Wellington Formation, the literature will be discussed chronologically. The earliest papers, from the 1930's, were written with respect to Permian red beds as possible oil and gas reservoirs. The earliest work to treat the Garber and Wellington as an aquifer came in the 1960's. Most of the modern research (post-1950's) focuses on the geochemistry and hydrologic properties of the aquifer.

Some of the earliest work on the Permian in Oklahoma is found in *The Subdivision of the Enid Formation* by Aurin, et al. (1926). The Enid Formation was a term used to describe a sequence of rocks that included much of the Permian section. As the result of a field conference attended by the Aurin, Officer, Gould, and several other geologists, the Enid Formation was subdivided into six distinct formations. These formations, from oldest to youngest, were the Stillwater, Wellington, Garber, Hennessey, Duncan, and Chickasha. Aurin et al. (1926) give a detailed account of the conclusions reached at the field conference, and describe each of the formations in detail.

At the time the Aurin et al. (1926) paper was written, the name "Garber Sandstone" was primarily a local term, and the authors proposed that the name be formally adopted as a formation name, to describe "a series of red clay shales, red sandy shales, and red sandstones lying above the Wellington" (p. 794). The authors also state that the Garber is about 600 feet thick. Also proposed is the usage of *Lucien Shale Member* and *Hayward Sandstone Member* to describe the lower and upper intervals of the Garber. However, these units do not persist from the area of description (Garfield, western Noble, and western Logan counties) into Cleveland County. The lower Garber, or Lucien Shale Member, is described as being mostly red shales with a few sandstone units. In the Norman area, however, the current author found that the lower Garber contains as much sandstone as the upper Garber.

The Wellington Formation is described by Aurin, et al., in its type locality (Wellington, KS), as consisting of “drab or gray shale with numerous thin beds of gray ‘mud-stone,’ scattered impure limestones, and clay conglomerates”. Aurin, et al. also recognize the southward gradation of the Wellington into red beds, stating that as one moves south, the shales become red, followed by the appearance of sandstones. South of the Cimarron River, the Wellington has completely changed from its character at the type locality, consisting there of interbedded red siliciclastic mudstone and sandstone. The top of the Wellington is given as “the base of the lowest heavy sandstone of the Garber formation,” and the base of the Wellington is the top of the Herington Limestone. The thickness of the Wellington is about 600 feet in the northern part of the state.

The name “Stillwater Formation” is used by Aurin, et al. as a collective term, encompassing what are now referred to as the Council Grove, Chase, and Admire Groups. The top of the Stillwater Formation is the Herington Limestone and its base is the Cottonwood Limestone. The authors report a facies change from limestone/shale dominated to sandstone/shale dominated, as well as a general thickening, as one moves south from Kansas. Some of the major formation names and divisions described by Aurin, et al. (1926) are still in use, except for “Stillwater Formation.” Their Garber and Wellington subunit names are also uncommon.

Another of the early papers dealing with Permian rocks in Oklahoma was *Lower Permian Correlations in Cleveland, McClain, and Garvin Counties, Oklahoma*, by Robert H. Dott (1932). Dott's work was focused mainly on continuing and developing the work of Aurin, et al. (1926), and he proposed several changes to their subdivision of the Enid Group. His correlations were based on "lithologic similarity, the sequence of beds, similar thicknesses" (p. 119). Interestingly, he also mentions the use of zones of barite roses as regional markers, but this is later refuted by Lloyd Gatewood (1968), who reported that they do not occur in discrete zones. Dott reports 600 feet of Hennessey Shale, 200 feet of Garber Sandstone, and 400 feet of Wellington Formation.

Another follow-up to the paper by Aurin, et al. (1926) was Joseph M. Patterson's *Permian of Logan and Lincoln Counties* (1933). He proposed that the red beds of these counties, including the Garber and Wellington, were deposited in a deltaic environment. Patterson reports the dip as west-southwest at thirty-five feet per mile. Patterson also may have been the first to discuss the dolomitic conglomerates found at the bases of the red bed sandstones. He proposed that the dolomite came from deposits formed by evaporative conditions in playa lakes, perhaps on an "old delta" during dry periods. These deposits were ripped up and reworked by stronger currents. Another note of interest is Patterson's statement that muscovite flakes up to 5mm long are common in the Garber and Wellington. Muscovite, he says, is nearly ubiquitous in the Garber, but is not detectable until the sample is crushed and treated with acid. The Wellington Formation, as described by Patterson, includes the lower Fallis Sandstone member and the upper Iconium Shale member. Patterson agrees with Aurin et al. (1926) that the base of the Wellington is located approximately at the top of the Herington zone, but points out that the Herington cannot be traced south of T.22N.-R.2E. Regarding the top of the aquifer, Patterson states that the Garber-Hennessey contact occurs at the most drastic change from sand deposition to shale deposition. Patterson reports that the Garber is 90% sandstone, also stating that in Logan County, the upper 20-30 feet of Garber is quite consistent. One assertion by Patterson that has been perpetuated in more recent works is that the sediments comprising the Permian units in Logan and Lincoln Counties were transported by a large fluvial system flowing west at "about the latitude of central Oklahoma County" (p. 255).

One of the earlier papers that focused on the structural geology of the Permian units was *Tectonics of Oklahoma City Anticline* (1934) by Lyndon L. Foley. Foley gives the location of the Oklahoma City Anticline as Townships 10, 11, and 12 North, and Ranges 2 and 3 West. As mentioned above, the axis of the fold trends N30W, and the structure is steeper on the eastern side. The dip of the fold axial plane is about 53 degrees to the east. This structure was well developed as early as the beginning of the Pennsylvanian, when a Nemaha-associated fault to the east of the structure had caused vertical movement of 2000 feet. Deformation continued as late as the beginning of Hennessey deposition; by this time, it was considerably less dramatic, although "spasmodic and frequent" (p. 261).

In a later paper, Darsie A. Green (1936), reports the results of detailed structural mapping as they pertain to formations from the Belle City Limestone to the Quartermaster Formation. At the time this paper was written, the Pennsylvanian-Permian contact was placed at the top of the Herington Limestone. It has since been moved down considerably, to the top of the Vanoss Formation. Green also states in his abstract that the Garber and Wellington cannot be differentiated south of northern Oklahoma County. Green also states that the Garber-Wellington interval in T.9N. (Cleveland County) is about 900 feet thick and 90% sandstone, and grades southward into shale.

Tanner (1959) presents his interpretation of various lithofacies in Noble, Cleveland, and Seminole Counties in terms of shoreline location and orientation in the late Pennsylvanian and early Permian. He maintains that the sea at this time was probably epeiric, being very shallow (less than 200 feet deep) and with little slope. This could have caused wide fluctuations in the shoreline, but he presents in this paper a shoreline, trending roughly northeast-southwest, that retreated to the northwest. Regarding Cleveland County, Tanner states, similarly to earlier writers, that strike is north-northwest and dip is to the west at 30 feet per mile. In Seminole County, according to Tanner (1959), Upper Wellington (Fallis) and Garber sandstones exhibit characteristics of lagoon/barrier island facies, but in Cleveland County, there are no such characteristics; this has contributed to the interpretation of the rocks in Cleveland County as deltaic. Tanner’s cross-bedding studies suggest that Garber and Upper Wellington sandstones are at least partly littoral in origin. In central Cleveland County, cross-bedding trends west to west-southwest, and there are fainter, secondary sets of crossbeds trending north and east. This direction of secondary cross bedding is thought to point toward the sedimentary source more so than the dominant crossbeds. These secondary modes trend about south 25 degrees east. However, he also states that the data is not conclusive enough to allow diagnosis of the depositional environment. On one of his paleogeographic maps, Tanner shows his post-Wellington shoreline passing just south of Oklahoma City. Regarding tectonically active areas as possible sediment sources, Tanner maintains that although the

Wichitas, Arbuckles, Ozarks, and Ouachitas were all active to some degree during early Permian deposition, the Wichitas and Arbuckles were probably the most significant contributors.

Lloyd Gatewood (1968) is a good source of information about the structural evolution of the study area, and is relevant to this study even though the paper mostly deals with pre-Permian strata. The Oklahoma City Field is located in southern Oklahoma County, just north of the Cleveland County line. It lies at the southern end of the Nemaha Ridge and on the northeast rim of the Anadarko Basin. Residing at the intersection of these two structural entities is a large, faulted anticline, which is the predominant producing structure of the Oklahoma City Field. The Oklahoma City Anticline is bounded on the east by a nearly vertical normal fault, which at the level of the Skinner Sandstone has a displacement of about 2,000 feet. Faulting, folding, and erosion were the prevailing processes that shaped the Oklahoma City Field, and they occurred more or less contemporaneously. The faulting probably occurred before the anticline had fully developed, because the full interval of rocks from the Hunton Group through the Simpson is preserved on the fault's downthrown side. Many of the Pennsylvanian formations thin over the top of the anticline. Concerning Permian rocks, Gatewood states that the structure seen in surface strata probably reflects periodic Permian or post-Permian deformation (Figures 3 and 4).

In more recent years, several papers have been written about Upper Paleozoic environmental conditions in western equatorial Pangea, where Oklahoma was probably located. In their 2001 paper *Equatorial Aridity in Western Pangea: Lower Permian Loessite and Dolomitic Paleosols in Northeastern New Mexico, USA*, Kessler et al.

describe the depositional environments and climatic conditions that were dominant during early Wolfcampian to early Leonardian (Artinskian) time. The interval studied was deposited at equatorial latitudes; its lower part contains mostly fluvial facies, while loessite is prevalent in the upper part, and paleosols are found throughout the interval. This stratigraphy, according to the Kessler et al. (2001), reflects a long term climate shift from wetter to drier conditions, because of northward continental drift and monsoonal circulation. Pedogenic evidence suggests that higher-frequency fluctuations between wet and arid conditions were occurring at the same time; possibly because of low-latitude glacial-interglacial settings.

Similar research was carried further by G.S. and M.J. Soreghan in 2002. Their paper *Atmospheric Dust and Algal Dominance in the Late Paleozoic; a Hypothesis* attempts to explain the “close temporal and spatial relationship” between Late Paleozoic eolian siltstone and algal bioherms. The authors suggest that large amounts of atmospheric dust could have caused wide fluctuations in oceanic oxygen and carbon dioxide, as well as pH, which would have affected the ecosystems’ biogeochemical environment. In another 2002 paper, *Paleowinds inferred from detrital-zircon geochronology of upper Paleozoic loessite, western equatorial Pangea,* M.J. Soreghan et al. use uranium-lead dating techniques to study changes in atmospheric wind conditions from middle Pennsylvanian to early Permian time. Four eolian siltstones were studied using detrital-zircon geochronology, and the results point to changing sediment sources caused by shifting winds. Their work suggests that during Wolfcampian time, winds across present-day Oklahoma were predominantly easterly, picking up sediments from the Wichita and Ouachita Mountains and depositing them to the west.

Hydrogeology

In the 1968 Oklahoma Geological Survey publication *Ground-Water Resources of Cleveland and Oklahoma Counties*, P.R. Wood and L.C. Burton state that because of the comparable lithology of the Garber and Wellington, the two formations constitute a single aquifer. The research described in this 1968 publication was conducted cooperatively by the USGS and the Oklahoma Geological Survey, to describe the hydrogeology of the Garber Sandstone and Wellington Formation and to appraise the aquifer's potential with respect to future development. According to Burton and Wood, the beds strike north-south in Oklahoma County and north-northwest in Cleveland County, with a regional dip of 30 to 35 feet per mile west and southwest toward the Anadarko Basin.

The outcrop area of the Garber Sandstone encompasses most of the eastern two-thirds of Cleveland County, and its topography is typified by rounded, generally steep hills covered by scrub oaks and similar vegetation. The contact between the Garber Sandstone and the Wellington Formation is conformable and sometimes gradational. The upper surface of the Garber, where it contacts the Hennessey Shale, is also conformable and locally gradational, and is identifiable from a geomorphologic standpoint by the transition from the Garber-type of topography into smooth, grassy prairies; the authors also state that in places there is a twenty to thirty feet thick zone where the Garber and Hennessey interfinger.

The Garber and Wellington are both described as fine or very fine-grained sandstone that is loosely cemented, lenticular, cross-bedded, and interbedded with shale, which is often sandy or silty. The grains within the sandstones are almost exclusively subangular to subrounded quartz. The sandstone units of the Garber are often made up of several stacked cross-bedded units, whose foreset directions can vary considerably. Garber sandstones are usually cemented by iron-rich clay, though calcite, dolomite, and barite cements are not uncommon. Also present in Garber sands are concretions of calcite, dolomite, hematite, and barite, as well as rare wood fragment impressions and some petrified wood. Thin beds of chert conglomerate or dolomitic conglomerate sometimes occur at the bases of the sandstones. The amount of sandstone relative to shale is greatest in northeastern Cleveland County, decreasing to the south and west; furthermore, as one travels south and west, the highest quantities of sandstone are found at progressively deeper intervals. Thickness of sandstone beds, which can change rapidly over short distances, can range from as little as a few inches up to fifty feet. In central Cleveland County, the Garber is reportedly about 400 feet thick, and the Wellington can be as thick as 700 feet.

The surface of the base of fresh water across Oklahoma and Cleveland Counties gives the impression of an elongate trough trending parallel to geologic strike. The base of freshwater is influenced by local structure, so the shallowest freshwater is located over the Oklahoma City anticline. Furthermore, the gradient of the base of freshwater becomes very steep west of Norman and forms a northward trending line that extends into Oklahoma County. This line may represent the limit to which Garber and Wellington sandstones have been flushed with freshwater, and may also be related to a change in sediment character. Wood and Burton (1968) also state that while the beds are relatively homoclinal, local flexures in both the Garber and Wellington do exist and are primarily the result of the presence of the Oklahoma City Structure.

In a 1988 USGS publication by Mosier and Bullock, *Review of the General Geology and Solid-Phase Geochemical Studies in the Vicinity of the Central Oklahoma Aquife*r, the depositional environment of the Garber and Wellington is described as deltaic. Although these formations contribute most of the groundwater to the system, the Hennessey Group and Chase, Council Grove, and Admire Groups are part of the same flow system, hence they are all grouped together as the Central Oklahoma Aquifer. In this paper, regional dip of the aquifer units is reported as 50 feet per mile, as opposed to the typical 30 or 35 feet per mile of the earlier work. The fluvial system that deposited the Permian sediments, according to the authors, flowed from east to west, and a delta was located in present-day central Oklahoma County. This is consistent with the comments of Patterson, made in the 1930's. Mosier and Bullock give the Garber and Wellington a combined thickness of 330-890 ft. Citing Carr and Marcher (1977), the authors report Garber-Wellington sand content of 25-75% in Oklahoma and Logan Counties, with an average of 50%. They also state that while 5-10 ft. sandstone beds are the most common thickness, they may be as thick as 40 feet.

In the abstract for Scott Christenson's 1992 paper *Geohydrology and Ground-Water Flow Simulation of the Central Oklahoma Aquifer*, the author says that percent sand is 70% in the central part of the aquifer and it decreases in all directions, down to about 40%. The central area of higher sand content is thought to be the center of deltaic deposition. He also states that the combined thickness of the Garber and Wellington is 1,165to 1,600 feet- a much different range of values than the 330- 890 feet reported by

Mosier and Bullock. Freshwater in the Garber-Wellington Aquifer is underlain by brines, and the thickness of the freshwater interval is about 900 ft near the aquifer's center. According to Christenson, vertical flow is also significant.

In the 1990 study *Mineralogy and Petrography of the Central Oklahoma Aquifer,* Breit, Rice, and Esposito report the results of their study of rock samples from the USGS NOTS (Naturally Occurring Trace Substances) wells. All but one of the NOTS wells, which are discussed in more detail below, were located in areas with water-quality problems. The sandstones are quartz arenites to sublitharenites, comprised mainly of quartz and illite-rich clays. Also present as detritus, in minor amounts, are feldspar, chert, metamorphic rock fragments, and chlorite. Authigenic minerals consist of dolomite, barite, calcite, hematite, goethite, kaolinite, and quartz overgrowths. Breit et al. say that while micas are minor to trace constituents, muscovite is ubiquitous, and the grains are silt-sized or smaller, but occasionally as large as medium-grained sand. The rocks also contain an illite-rich matrix. All samples contained similar mineral assemblages that varied little; however, the well located in the area of better water quality had lesser amounts of dolomite, chlorite, and plagioclase feldspar.

According to Breit et al., the boundaries of the COA are the Canadian River to the south, the Cimarron River to the north, the limit of freshwater circulation on the west (Oklahoma-Canadian and Lincoln-Kingfisher County lines) and the Permian-Pennsylvanian (Vanoss Formation) contact to the east. (Freshwater is defined as water containing less than 5000 mg/L total dissolved solids, and the depth to the base of freshwater ranges from 100 to 1000 feet below the land's surface.) The difficulty inherent in distinguishing the Garber from the Wellington has resulted in the grouping of these formations into a single hydrogeologic unit, the Garber-Wellington Aquifer. The combined thickness of Garber and Wellington is given by Breit et al. as 800-1000 feet. Both formations are truncated by erosion to the east, and the beds dip west-southwest at 50 feet per mile and thicken towards the Anadarko Basin. According to these authors, the environment of deposition was a combination of marginal marine and fluvial environments. The authors state that the sediment source for these rocks was probably the Arbuckle and Ouachita Mountains.

In order to address concerns about unsafe drinking water from the Central Oklahoma Aquifer, the USGS, in cooperation with the Association of Central Oklahoma Governments (ACOG), conducted the NOTS project, and published the results in 1991's *Chemical Analyses of Water Samples and Geophysical Logs from Cored Test Holes Drilled in the Central Oklahoma Aquifer, Oklahoma.* Written by J.L. Schlottmann and R.A. Funkhouser, this publication details the drilling of nine test wells, called the NOTS (Naturally Occurring Trace Substances) wells, in Cleveland, Oklahoma, Logan, Lincoln, and Pottawatomie Counties. The project was designed to study the groundwater-aquifer system of the Central Oklahoma Aquifer as it relates to increased levels of potentially toxic naturally occurring contaminants. The substances of concern were arsenic, selenium, uranium, chromium, and residual alpha-particle activity. No detailed attempts at interpreting the data are presented in this particular publication. Of the nine test holes

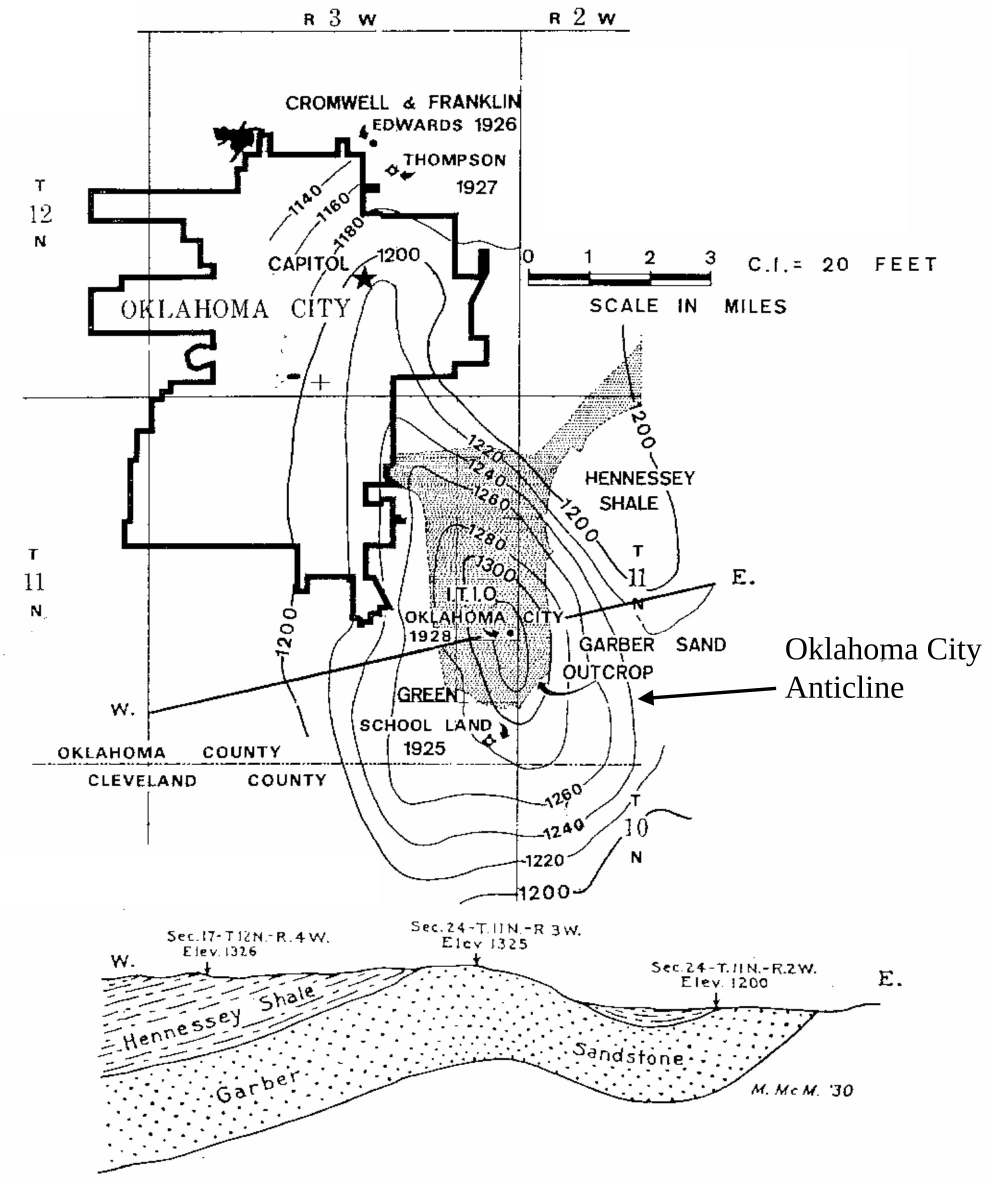


Figure 3. Cross section and structure map on the Garber Sandstone in the Oklahoma City Field. The map was made in 1928 for the Indian Territory Illuminating Oil Company and shows flexure in the Garber Sandstone due to the Oklahoma City Anticline (modified after Lloyd E. Gatewood, *Oklahoma City Field– Anatomy of a Giant*, in AAPG Bulletin, vol. 52, no. 3)

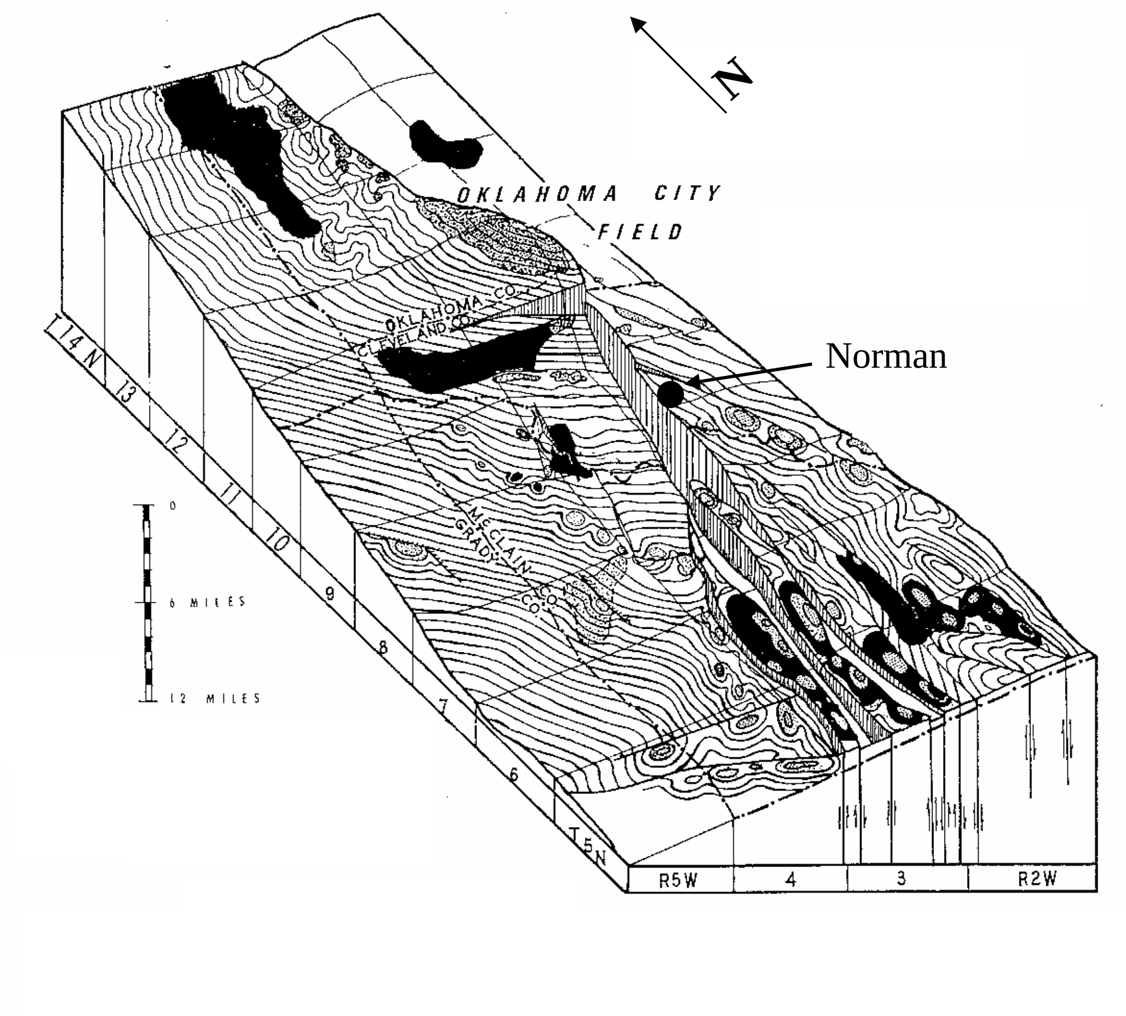


Figure 4. Location of the Oklahoma City Anticline and associated faults, mapped on the Siluro-Devonian Hunton Limestone (modified after Lloyd E. Gatewood, 1968; *Oklahoma City Field– Anatomy of a Giant*, AAPG Bulletin, vol. 52, no. 3)

drilled, eight were cored and sampled for hydrochemical analysis, and all nine were logged with down-hole logging tools. Water was sampled from water-bearing units in each borehole by using inflatable packers to isolate sandstone layers. In terms of chemical analysis, the water samples were tested for density, pH, conductivity, major cations and anions, nitrogen and phosphorous, organic carbon, trace metals, radiation and radionuclides, and stable isotopes. Logs from the three NOTS wells in Cleveland County (NOTS 4, NOTS 7, and NOTS 7A) have been used in this thesis. NOTS 7 and 7A are included in cross section E-E', and NOTS 4 is in cross section X-X'. Furthermore, the core from NOTS 7A was used in conjunction with its accompanying log to help determine proper placement of gamma ray cutoff lines for sand and shale.

The article *Arsenic, Chromium, Selenium, and Uranium in the Central Oklahoma Aquifer*, by Schlottman, Mosier, and Breit (1998) explains why toxic substance concentration is related to mudstone distribution. The behavior of dissolved arsenic, chromium, selenium, and uranium is affected by cation-exchange reactions, permeability, and redox conditions. These conditions are affected by the distribution of mudstone in the aquifer. Cation-exchange reactions are affected because of the clay minerals in the mudstone; reactions involving the exchange of sodium (bound to mixed-layer illite-smectite clays) for calcium and magnesium (in solution) result in the dissolution of dolomite, which raises the pH and alkalinity in shalier parts of the aquifer. Permeability affects contaminant levels because shalier rocks are less permeable, so less groundwater flows through the rocks in a given amount of time than flows through cleaner rocks. This impedes the flushing-out of trace substances. Redox conditions mainly affect the occurrence of selenium, chromium, and uranium; in general, clay-rich soils develop which leach oxygen out of the recharge water. This results in groundwater low in dissolved oxygen, which inhibits oxidation of chromium and selenium.

The net sand and percent sand maps in Schlottmann et al. were made using sand and shale. That is, they drew a line halfway between the clean sand line and the shale baseline; this assumes only two lithologies and does not account for shaly sand. The range they found for sandstone thickness in the Garber-Wellington Aquifer was 20-60 feet, but in south-central Oklahoma County, as thick as 300 feet. The authors say that the greatest thicknesses of sandstone are located in central and south-central Oklahoma County. Percent sand, with respect to the entire COA interval, apparently decreases outward from central Oklahoma County, and shale content increases to the east as well as with depth. Their maps of sandstone thickness and percent sand for the COA are on a much wider scale than the maps presented in this thesis; furthermore, they encompass the entire COA rather than just the Garber Sandstone and the Wellington Formation.

In a recently completed OSU graduate thesis (2004), Greg Gromadzki has quantified the relationship of arsenic to finer grained lithofacies, and has also demonstrated that gamma ray measurements can serve as a rough proxy for arsenic content in the rocks.

In George Breit’s 1998 paper *The Diagenetic History of Permian Rocks in the Central Oklahoma Aquifer,* it is reported that Garber-Wellington sand content ranges from 24-75% and that the sediments were transported to an epeiric sea to the west and north. The sediment source was Paleozoic sandstone, shale, and chert in the Ouachita uplift, with minor amounts from the Arbuckle and Ozark Mountains. Bedded limestone and evaporites are the basin equivalent of Garber-Wellington rocks. Central Oklahoma at the time of deposition (early Permian) was near the equator and experienced alternate wet and dry periods during the time when the sediments forming these rocks were deposited. By late Permian, the climate had changed, becoming increasingly and more steadily arid.

Related work in Oklahoma has been completed by Jim Roberts for Enercon Services, Inc., of Oklahoma City. Roberts summarizes his work in *Characterizing and Mapping the Regional Base of an Underground Source of Drinking Water in Central Oklahoma Using Open-Hole Geophysical Logs and Water Quality Data* (2001). His study focuses on the quantification of total dissolved solids (TDS) from well logs in freshwater portions of the Garber-Wellington Aquifer in Cleveland, Oklahoma, and Logan Counties. This work was done primarily to aid in depth-setting requirements for surface casing in oil and gas wells. This work is significant to the arsenic problem because of the relationship of arsenic occurrence to water type.

Some indirectly related work can be found in the Texas Bureau of Economic Geology publication, *Hydrogeologic Significance of Depositional Systems and Facies in Lower Cretaceous Sandstones, North-Central Texas*, written by W. Douglas Hall (1976). Hall focuses on the hydrogeology of the Hosston and Hensel Sandstones, two important groundwater-bearing units in North-Central Texas. The Hosston and Hensel are quite different from the Garber and Wellington. However, the author's descriptions of fluvial depositional environments as they relate to outcrop morphology and well log signatures are considered relevant to this thesis. Hall describes several types of fluvial facies and facies models: meanderbelt facies, flood-basin facies, the coarse-grained meanderbelt fluvial model, and the mixed coarse-grained/fine grained meanderbelt fluvial model.

Sandstones associated with meanderbelt facies, Hall says, contain channel lag, lower point-bar deposits, and erosional bases. On well logs, these characteristics translate to sharp basal contacts and abbreviated fining upward sequences, and vertical stacking is common. On outcrop, this type of deposit contains channel lag deposits and large-scale trough crossbeds overlain by smaller-scale trough and tabular crossbeds. He also states that "although individual meanderbelt facies are poorly defined, maximum net sandstone axes within the multilateral sandstone body are oriented subparallel to paleoslope." The sandstone packages are separated by finer-grained overbank deposits. Grading laterally into the meanderbelt sandstones are the flood-basin facies, which consist of overbank mudstones and siltstones. These units may be interbedded with thin sandstones (possibly crevasse-splay sediments). Hall (1976) then discusses the coarse-grained meanderbelt fluvial model, which is halfway between braided and fine-grained fluvial systems. This type of depositional system is characterized by a moderate slope, medium-coarse grained sand, and lower-middle point bar deposits. With this type of environment, partially developed point bars merge to form larger sand packages. Furthermore, entire point-bar sequences are not common; upper point bar facies are usually truncated by chute channel-fill and chute bar deposits. Truncation occurs as a result of severe flooding, when channels break through levees and scour the streambed, eroding the upper point bar and replacing it with chute bar sediments. Lastly, Hall discusses the mixed coarse-grained/fine-grained meanderbelt fluvial model. The distinction between the two models can be found in the flood-basin facies, which consist of thin, discontinuous mudstones and siltstones in the first model, and thicker, more expansive mudstones and siltstones in the second model. It should also be mentioned that the coarse-grained model lacks consistent fining upward sequences and has a high sand to mud ratio, i.e., it has many complete point bar deposits, and extensive overbank muds.

IV.

METHODOLOGY

Well logs were the primary source of data for this project. Logs were analyzed and correlated using the Geoplus Petra software package, which is a common software package used in the petroleum industry; however, this software is practical for any project dealing with well logs and/or mapping. The approach was to first correlate major formation boundaries, i.e. the top and base of the Garber Sandstone and the base of the Wellington Formation. Once this was completed, the next step was to determine the thickness of clean sandstone, shaly sandstone, and shale for each well log. The thickness of each of these lithofacies was then mapped, either as net thickness or as percent of the entire interval. More detailed discussion follows.

Data Acquisition and Interpretation

Well logs were obtained from the Association of Central Oklahoma Governments (ACOG), the Oklahoma University Physical Plant, and the City of Norman. The logs had various combinations of curves, but the most common curves were gamma ray, SP, resistivity, and neutron logs. Each well's location and other header information is given in Appendix A. Two categories of well logs were used: oil/gas well logs and water well logs. The oil and gas well logs were usually open hole logs, consisting of an SP curve and a resistivity curve; since these wells usually have several hundred feet of surface casing, they were not particularly helpful in studying the Garber Sandstone, although they were occasionally used to pick the Garber-Wellington contact or the base of the Wellington Formation. Since these deeper wells provided the best coverage on a countywide basis, they were useful for constructing large-scale cross sections of the major formations (cross sections X-X’ and Y-Y’). The water wells typically penetrate from the surface down to about 600-700 feet and show most if not all of the Garber Sandstone. These wells typically have a more comprehensive logging suite, making them easier to interpret since the SP log alone is often difficult to interpret because of the presence of fresh water. Hence, water wells logs were better suited to picking the Garber-Wellington contact, calculating thickness of various lithofacies, and correlating within the Garber-Wellington. Appendix B lists the locations for each Norman and OU well used in the project, as well as each borehole’s total depth, datum elevation, elevation of formation tops, and arsenic concentration, where available. This table also contains information about the thickness of the various lithofacies in each unit within the Garber.

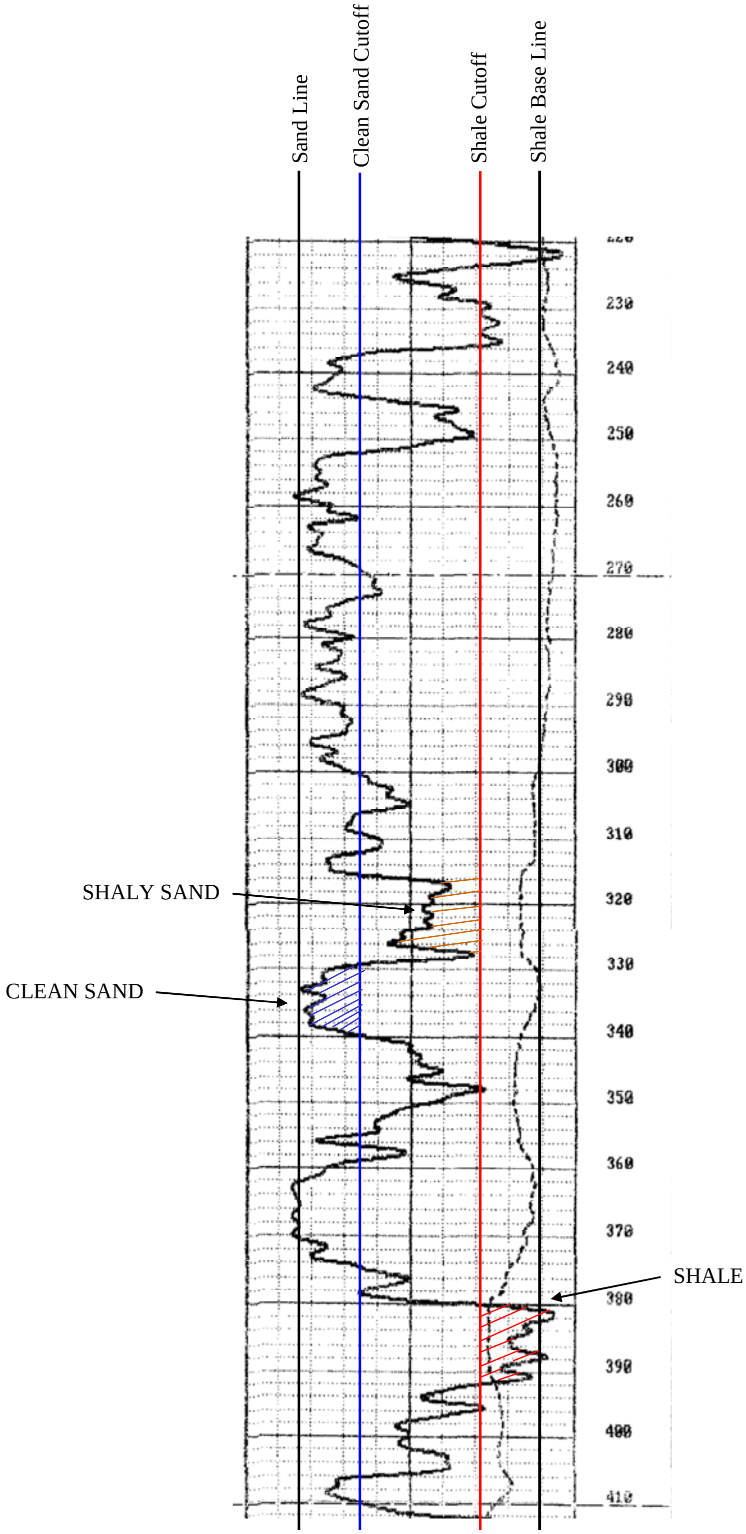
Since many of the water well logs had no unit scale on the gamma ray curves (i.e., no API units), they were scaled in arbitrary units, ranging from 0 at the clean sand line to 100 at the shale base line. The core from NOTS Well 7A, located in central Cleveland County, was used in conjunction with the NOTS 7A well log to help determine proper placement of cutoff lines. For instance, to determine the clean sand cutoff line, a clean sandstone interval was found both on the log (scaled from zero to 100) and on the core. Then, the cutoff line was moved either left or right until the top of the clean sand zone on the log was at the same depth as the top of the same clean sand zone on the core. This process was repeated for several different sandstone and shale intervals, until it was determined that 25 and 75 were the best cutoff values for clean sand and shale, respectively (Figure 5).

The cumulative thickness of sandstone less than 25 units (total thickness to the left of the clean sand line) was divided by the thickness of the logged interval to obtain percent clean sand for a particular well. If h_{sd} is the combined thickness of clean sandstone in a well, and h_{gw} is the overall thickness of the Garber-Wellington section in the well, then

$$h_{sd} / h_{gw} = z$$

where z is the percentage of Garber-Wellington that is made up of clean sandstone for that particular well. Percentages of shale and shaly sandstone were calculated in a similar manner. Since these values apply to the entire wellbore with no consideration of stratigraphic interval (other than the exclusion of Hennessey Shale), the percent values are probably more appropriate for mapping than the gross thickness values (h_{sd}) alone, because gross values are more directly affected by variations in the wells' depth of penetration. Hence, the clean sand and shale cutoff lines were used to calculate and produce maps of percent clean sand, percent shaly sand, percent shale, clean sand to shale ratio, and clean sand to shaly sand ratio. Shaly sand thickness was calculated by subtracting the combined thickness of clean sand and shale from the logged interval thickness; of course, this method assumes that anything that is not clean sand or shale is either sandy shale or shaly sand. These maps were completed the immediate Norman area, since this is the focus area of the study. There are few wells suitable for this purpose outside this area (see Plate 1). Three Garber subunits, Units A, B, and C, were

Figure 5. Gamma ray curve showing the positions of the cutoff lines for clean sand and shale



identifiable on 48 wells in the Norman area, and these wells were used to construct similar maps for the subunits.

Logs from about 300 wells were used in the study to correlate Garber and Wellington formation boundaries. The Herington Limestone, which underlies the Wellington, was used as a rough guide to finding the base of the Wellington. The Garber-Wellington contact was picked based on regional dip, lithologic differences (more shale in the Wellington), and decreased shale resistivity in shales of the upper Wellington compared to sands of the lower Garber (see Appendix E). Known depths of the contact were also used, primarily from NOTS Well 4 and previous work done by Jim Roberts (2001) in Oklahoma County. The top of the Garber Sandstone was the simplest to identify, since it is overlain by the Hennessey Shale. Refer to Figure 6 for a type log of the Garber-Wellington Aquifer. Following is a more detailed account of major formation boundaries in the study area.

The Garber-Wellington Aquifer is bounded above by the Hennessey Shale and below by the Council Grove, Chase, and Admire Groups. The contact between the Garber and the Hennessey is usually easy to identify, although this contact is occasionally gradational, so the presence of thin sandstones near the base of the Hennessey can make the top of the Garber a little harder to pinpoint. The Garber is also occasionally overlain by alluvial deposits, which further complicate matters since the well log signatures of these units are similar to those of the Garber. In fact, they were probably deposited in similar environments.

The contact between the Garber Sandstone and the Wellington Formation is somewhat problematical. It is recognized that the Garber is generally sandier than the

Wellington, and two reliable picks of the Garber-Wellington contact were available, in NOTS Well 4 and in Adam #1, which was analyzed by Jim Roberts. However, neither of these wells is close to Norman, and the indistinct nature of the contact made it difficult to extrapolate the contact to the Norman area. In the heart of the study area, however, the base of the Garber is often underlain by a thick shale unit. This, and the higher sand content in the Garber, has allowed for better correlation in this area. It has also been suggested that the Garber-Wellington contact could be picked based on a decrease in shale resistivity in the Wellington. This decrease seems to exist for most sections, and using it as a guideline usually produced acceptable results, even though there can be multiple decreases in shale resistivity throughout an interval.

The contact between the Wellington Formation and the underlying units was apparent only on oil/gas well logs; although on some logs it was obvious, it was obscured on other logs due to a very flat SP curve. There is a limey zone near the top of the Council Grove that is most likely the equivalent of the Herington Limestone; in some areas, the most reliable method for locating the base of the Wellington was to find this zone, and pick the first sandstone above it as the base of the Wellington. Although the character of the Herington zone changes somewhat, and on some logs is not visible at all, this method yielded fairly consistent results with regard to the base of the Wellington. However, on many logs, the SP curve is too flat to allow confident identification of the base of the Wellington.

Within the Garber Sandstone, the units between the surfaces which could be correlated through the study area on cross sections were arbitrarily called A, B, and C. Units A, B, and C were mapped by simple pattern recognition and correlation of sediment

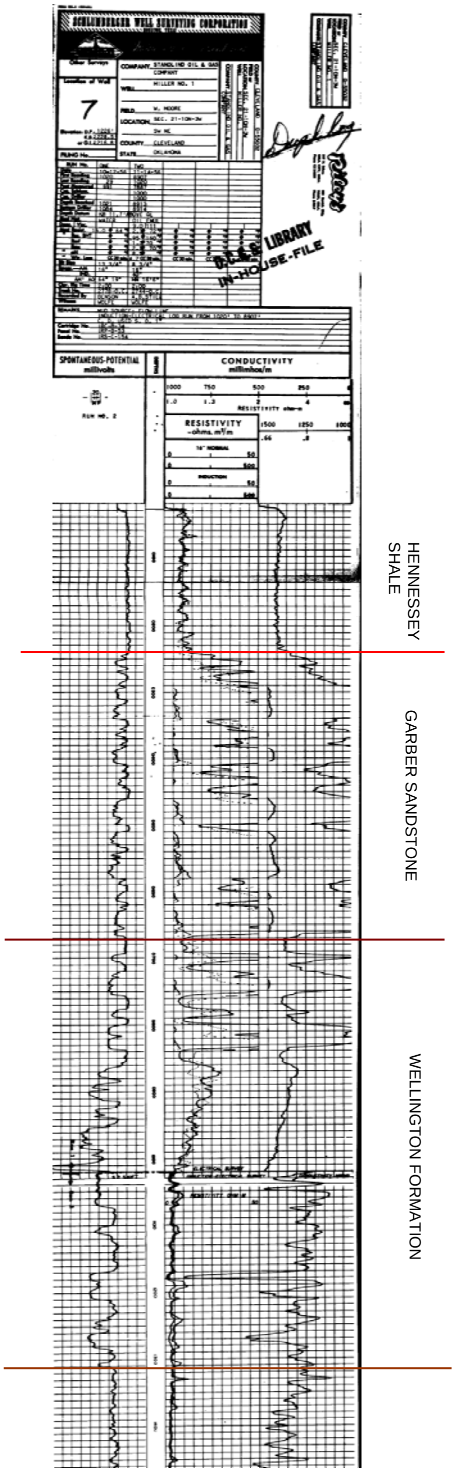


Figure 6. Type log of the Garber-Wellington section from the Miller #1 in northwestern Cleveland County

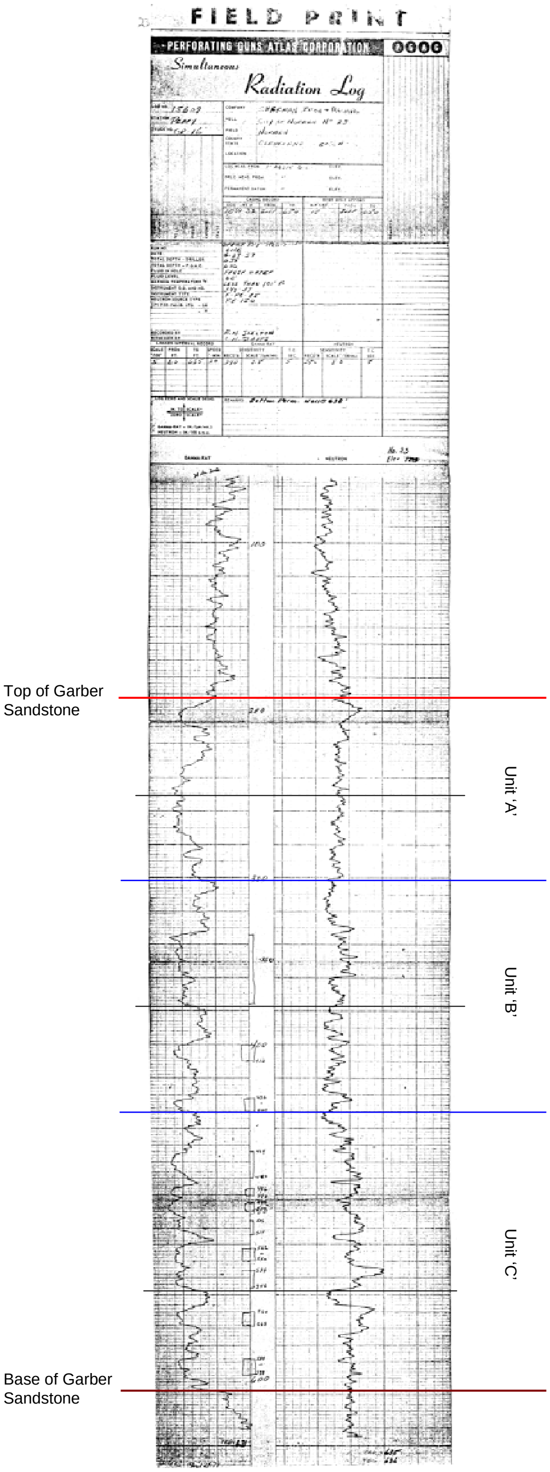


Figure 7. Type log of the Garber Sandstone from Norman Water Well #23

packages from log to log. Loop ties were used in the correlation process to insure accurate picks. There are two subunits each in A, B, and C, but these were not mapped individually because these subunits were not always distinct. A type log for the Garber Sandstone and Units A, B, and C is shown in Figure 7.

Construction of Maps and Cross Sections

The top of the Garber Sandstone, easily recognizable due to the contrast in composition compared with the overlying Hennessey Shale, was mapped in terms of its structure. Since the Garber outcrops just east of Norman, the structure map could only be carried that far. Structure maps were also created for the bases of units A, B, and C (the base of unit C is the base of the Garber.) These surfaces were mapped as a trend residual surface, which is made by calculating the regional trend (regional dip) and subtracting it from the true structure of the surface. This was done to enhance interpretation of sedimentation patterns in these units.

Because of the rapid lateral changes within both the Garber and Wellington, a constant stratigraphic interval could not be defined for the entire area of quality well coverage. Therefore, percent lithology maps were made by finding the total thickness of the desired lithology and dividing it by the thickness of Garber-Wellington logged in the well. As previously discussed, the core from NOTS Well 7A, in conjunction with its log, was used to select appropriate cutoff lines for sand and shale. This technique was used to map percent clean sand, shale, and shaly sand. The percentage of clean sandstones thicker than four feet and thicker than eight feet was also calculated and mapped, to determine if one area was more dominated by massive sandstones than another. These maps did not vary much from the maps of the unfiltered data, so they are not presented here, although the data can be found in the appendices.

The map of arsenic distribution (Plate 3B) was made using data taken from the report by CH2MHill. The map of potentially high and low arsenic zones (Figure 16) was made by inspecting the clean sand/shaly sand/shale maps in conjunction with the arsenic distribution map, and conservatively outlining favorable and unfavorable areas based on both lithofacies distribution and existing arsenic data.

In the area for which a constant stratigraphic interval could be defined (i.e. units A, B, and C), gross interval thickness and net sand were mapped in addition to percent clean sand and percent shaly sand. Frequency distributions were also constructed for Units A, B, and C. For each unit, a histogram was constructed for net clean sand thickness, percent clean sand, and percent shaly sand. These charts allow visual interpretation of the relative amounts of the various lithofacies of which each unit is comprised.

Two structural cross sections were constructed on a countywide scale. Only major formational contacts were picked on these cross sections, and their purpose is to show the structural trend of the strata across the entire county. Eight cross sections were constructed in the Norman area. The top and base of the Garber Sandstone were picked, as well as the units A, B, and C. The purpose of these cross sections is to illustrate that while individual sands rapidly grade into shales and vice versa, packages of sediments can be relatively continuous and their correlation is possible throughout a limited area. These cross sections are also intended for closer examination of the log signatures typical of Garber rocks. On the cross sections of A, B, and C, each unit is divided into two subunits, shown by black lines, while the upper and lower surfaces of A, B, and C are shown with blue lines. The subunits are not mapped but are included to illustrate some of the geometric relationships between sediment packages of the Garber. These more detailed, smaller-scale cross sections are hung stratigraphically on the top of the Garber Sandstone; if this surface does not appear on all the logs in the cross section, then it is presented structurally, i.e., the datum is sea-level.

V.

RESULTS AND DISCUSSION

Most of the results of this study are presented in the form of maps and cross sections. In this section, there is a general summary of the log data, after which the maps will be discussed, followed by the cross sections. The cross sections are discussed in two groups, large scale and small scale. There are two large scale cross sections, X-X' and Y-Y'; these are on a county-sized scale. The eight small scale cross sections are focused around the Norman area. The maps and cross sections discussed here are presented as plates, located at the back of the thesis.

Well Log Data Summary

Comparison of summary statistics for OU and Norman water wells (Table 1 and Figure 8) shows that the OU wells, in general, are higher in arsenic concentration, shale content, and shaly sand content, and lower in clean sand content. Frequency distributions of net clean sand content, percent clean sand, and percent shaly sand for each of the three main Garber packages were constructed and are presented as Figures 9, 10, and 11, respectively. In terms of net clean sand thickness (in feet), Unit C was the sandiest, averaging 61 feet of clean sand per well, and Unit A was the shaliest, averaging 43 feet of clean sand per well. Units B and C appear to have fairly normal distributions, but Unit A looks much more irregular. Unit C also has the highest average percent clean sand, averaging 43% clean sand in each well, while Units A and B both average about 40% clean sand in each well. These percentages are about the same, but the frequency distributions for each unit look quite different, especially Unit B, which does not appear to have a normal distribution. Both Units A and B seem to have more samples towards the low end of the scale than Unit C. Unit A has the highest percent shaly sand, averaging 51%. Units B and C are similar, averaging 45% and 43%, respectively. Units A and B have more values on the higher end of the scale than does Unit C. From the summary statistics and collection of histograms, it appears that in general, Unit C is the sandiest package and Unit A is the shaliest unit, that is, sand content in the Garber decreases upward. From visual evaluation of the histograms, it also appears that normality of the sample population increases with depth. T-tests were not performed to test for statistical significance.

In her 2005 OSU master's thesis, Kathy Kenny reports similar results regarding grain size and stratigraphic interval. She has found that the outcrops lower in the section are the coarsest-grained, and that grain size decreases upward through the study interval. These findings independently corroborate the findings based on well logs presented in the preceding paragraph.

Maps

Well locations and major structural features near Norman and its surrounding vicinity are shown on Plate 1. The structure map of the top of the Garber Sandstone (Plate 2, top) shows that the units are dipping to the west, and that the strike is variable but generally to the northwest. The map shows a change in strike of the Garber because of the presence of the Oklahoma City structure to the north of the study area. Also on Plate 2 is an isopach map of the Garber Sandstone, which shows thickening to the east up to the outcrop edge.

Several of the maps constructed for this study (shown on Plate 3A) were based on the total amount of sandstone and shale in each well bore, irrespective of what part of the section the well penetrated. This was done to identify any trends present over an area for which continuous units could not be identified. Maps constructed in this manner include percent sand, percent shale, and percent shaly sand maps, as well as a clean sand to shale ratio map and a clean sand to shaly sand ratio map. Generally speaking, each of these maps show a transition from high sand content to low sand content from east to west. The most predominant and recurring anomalies on these maps are two prominent high-sand content areas east of Norman and one prominent low-sand content area west of Norman. Although these maps could have some shortcomings because the thickness of the sampled interval is decreasing to the west (because of the regional dip), the presence of recurring anomalies on different maps suggests the observations and interpretations are valid.

One concern with these maps was due to the increasing depth of penetration into the Garber-Wellington Aquifer to the east as a result of the westward dip of the strata. That is, wells to the east of the study area generally contained a thicker section of Garber-Wellington because the aquifer is dipping to the west. Therefore, it was a possibility that the eastward increase in sand percentage might actually be an artifact of the mapping technique, that is, the presence of a sandier interval in the lower Garber in the east that was not logged in wells to the west. To test whether or not this was the case, a map was constructed of net thickness of clean sand in the upper 300 feet of the Garber. Three-hundred feet was the approximate minimum thickness of Garber penetrated in the western wells, and therefore was the thickest interval common to all the wells being used on the percent lithofacies maps. Since the same trend (decreasing sand content westward) was detected in the upper 300 feet of Garber in these wells, it seemed reasonable to conclude that the occurrence of more sandstone to the east was not due solely to the effects of a lower, sandier interval having not been penetrated in the western wells.

To investigate the relationship between lithofacies and arsenic distribution, a bubble map of arsenic concentration was created. This was done by plotting a colored circle around a well symbol; the radius of each circle is proportional to the arsenic concentration in that particular well. This is similar to production maps in the petroleum industry. The bubble map was then drawn on top of the Norman area lithofacies maps, and the resulting overlay (Plate 3B) was examined to see if high arsenic areas corresponded to high shale or shaly sand areas, and if low arsenic areas corresponded to areas high in clean sand content. Although a relationship is visible on all the overlays, it appears to be strongest on the shaly sand map. Arsenic concentration may be more closely related to shaly sand content rather that shale or clean sand content because the mixture of clays and sand grains could result in an aquifer permeable enough to yield water, yet not permeable enough to permit thorough flushing. There are a few outliers, particularly to the west, where OU Well #9 has a relatively high arsenic concentration but is relatively low in shaly sand content. The outliers could be because of secondary mobilization of the arsenic (Gromadzki, 2004) or due to differences in water chemistry.

Perhaps more robust are the maps of Units A, B, and C, the three subunits of the Garber. The maps of these units are complementary and reveal more about depositional processes in the study area. Interval isopach maps and clean sand isolith maps were constructed for each of the three units, as were percent clean sand and percent shaly sand maps. Additionally, by mapping the structure of the base of these units and subtracting a residual trend surface, the local relief of the upper and lower surfaces of A, B, and C were mapped, allowing further delineation of the units' geometry. By examining all of the maps for each unit concurrently, a better picture of the depositional character of the units and changes in depositional character with time was obtained. These maps will be discussed starting with Unit C and moving upward to Unit A, so that the maps are discussed chronologically. The residual trend maps are shown on Plate 4; Plate 5 shows the interval isopach, clean sand isopach, percent clean sand map, and percent shaly sand map for Unit A. Plates 6 and 7 show these maps for Units B and C.

From the residual trend map of the structure of Unit C (base of Garber), it is evident that Unit C has a convex base, with a wide, elongate, NW-SE trending low dominating the map, possibly indicating incision by the overlying unit. Relief on this surface ranges from zero up to about thirty feet. Both the isopach map and net clean sand map of Unit C show that the majority of sedimentation occurred within this low, i.e., C is thickest in the depositional low, especially at the southeastern end. In terms of percent clean sand, there seems to be no correspondence with the trough. In fact, the only trend suggested by the percent clean sand map is an area of high percent sand that runs down into the trough from a higher area to the northeast. The percent shaly sand map shows two lobes of higher percent shaly sand that may or may not be connected, but trend along the same position as the low. Additionally, an elongate area of lower percent shaly sand rests along the northeast edge of the trough, and trends up onto it, similar to the high percent clean sand body on the other map. This same geometry occurs on the high area to the southwest; the percentage of shaly sand decreases as one moves up onto the high area. These maps show that Unit C first filled in the low area, and that high percent clean sand and low percent shaly sand do not necessarily coincide with the area of highest net clean sand or net overall thickness. Perhaps this is because although the main part of the channel system occupied the trough, the cleanest areas in terms of percent lithofacies occur mostly on the highs. This may mean that Unit C started out as a deeper water deposit and by the time the low had been mostly filled up, the environment was more conducive to cleaner sediments and/or winnowing out of fines.

Relief on the upper surface of Unit C (also the lower surface of Unit B) ranges from zero to about sixty feet. This surface is characterized by a high that is almost identical to the position of the low at the base of Unit C. It makes sense that the base of B would be higher here since it corresponds to the area of highest sedimentation in Unit C. Furthermore, the low areas at the base of B correspond to the high areas at the base of C. A low to the southwest in the map area has the highest isopach thickness for Unit B, again indicating filling in of low areas. However, Unit B is very thin over a low in the northeast of the map area; this suggests either erosion of Unit B by Unit A, or decreased sedimentation to the northeast, which would indicate a shift of the main depositional system to the west. Across the top of the high at the base of the unit, the isopach thickness of B decreases from west to east, again suggesting decreased sedimentation to the east. However, the net clean sand map, percent clean sand map, and percent shaly sand map show that the thickest, cleanest sands were deposited in a north-northeast trending strip that runs from the central high into the northeast low. The percent clean sand map and net clean sand map also show decreased occurrence of sand to the west of the map area. Therefore, it appears that total stratigraphic thickness increases to the west, but clean sand content increases to the east. The percent shaly sand map, similar to the corresponding map for Unit C, shows that an area of higher percent shaly sand lies northeast of and adjacent to the area of lower shaly sand content. So for Unit B, it appears that overall sedimentation rates were higher to the west, but deposition of cleaner lithofacies was occurring in the eastern part of the mapped area. Perhaps this means that Unit B first started to fill in the low to the northeast, but the main fairway of sedimentation began to shift to the west and subsequently spread out over the map area.

The base of Unit A/top of Unit B is very similar to the base of Unit B/top of Unit C. Relief ranges from zero to about 50 feet. This suggests that the high established by the lobate feature of Unit C persisted through the section. So, although Unit B is thickest in the southwest, this area remains a low at the top of B, relative to the central ridge.

Unit A is thickest in the low to the northeast. The thickest portion of Unit A overlies the thinnest area of Unit B, which is to the northeast and coincides with the region of greatest sand content in B. The net clean sand, percent clean sand, and percent shaly sand are all highest in this area also (to the east and northeast). Therefore, it may be the case that Unit A filled in the low next to the high created by C and perpetuated by B, because the greatest quantity of sediments and the percent clean sand are greatest in the low. Unit A is the only unit for which thickest sediment package and cleanest sediment package are coincident. The residual trend map of the top of Unit A (top of

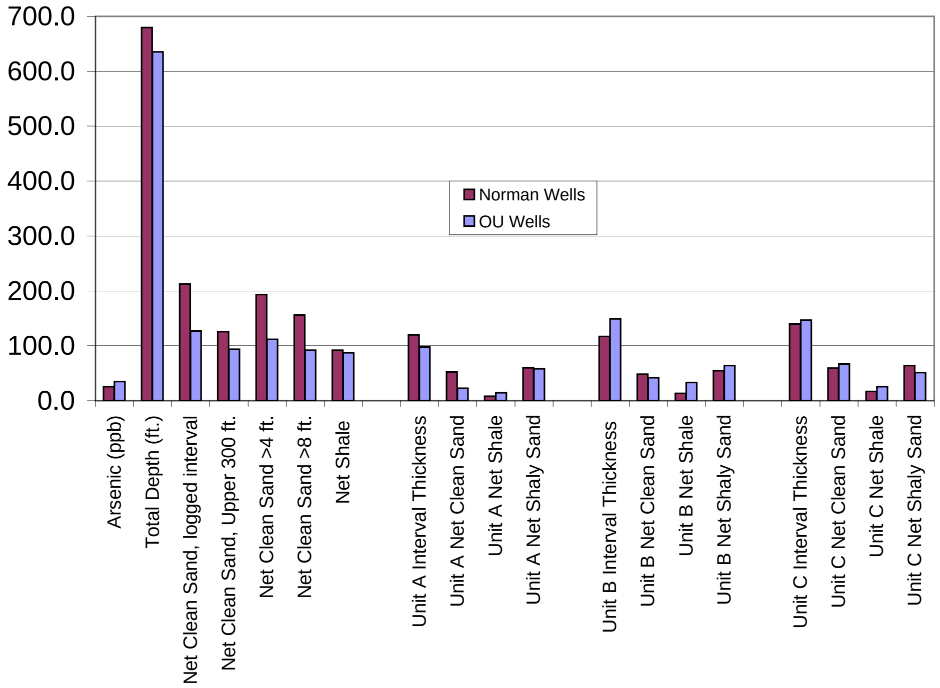
Garber Sandstone) shows a high, with relief up to 20-30 feet. This high corresponds to the area of thickest sedimentation in Unit A, indicating that the ridge created by Unit C and also present at the top of Unit B has influenced sedimentation on either side of it. By the time we move up to the top of Unit A, the highs are located on either side of where the original trough was, with a depositional low running down the middle.

The well log signatures, maps, and cross sections suggest that the depositional environment for the Garber Sandstone was fluvial, most likely meandering. This conclusion has also been reached by Kathy Kenney in her 2005 OSU thesis, in which she reports outcrop evidence for a meandering fluvial environment. Features she has observed on outcrops, such as lateral facies changes and compensatory stacking, are also evident on the cross sections and maps. She has also observed fluvial characteristics such as point bar deposits and erosional contacts, which are also evident on well log signatures.

Table 1. Summary statistics for various parameters in OU and Norman water wells. All net thickness values are in feet.

	Average		Median		Standard Deviation	
	Norman	OU	Norman	OU	Norman	OU
Arsenic (ppb)	25.8	34.7	10.7	26.5	43.1	20.8
Total Depth (ft.)	679.4	635.4	690.0	629.0	89.4	78.5
Net Clean Sand, logged interval	212.8	126.8	215.3	122.2	53.7	33.9
Net Clean Sand, Upper 300 ft.	125.9	93.8	114.7	93.7	40.1	28.6
Net Clean Sand >4 ft.	193.5	112.0	197.0	116.2	49.2	33.8
Net Clean Sand >8 ft.	156.2	91.8	153.9	101.0	48.6	38.8
Net Shale	92.2	87.4	97.0	89.0	49.8	39.1
Unit A Interval Thickness	120.0	97.8	103.8	96.0	43.5	12.5
Unit A Net Clean Sand	52.7	22.9	47.0	16.2	25.9	17.6
Unit A Net Shale	8.4	14.6	5.3	5.8	10.5	17.6
Unit A Net Shaly Sand	60.2	58.0	54.1	57.0	29.4	14.4
Unit B Interval Thickness	116.9	148.9	118.5	145.0	18.0	15.3
Unit B Net Clean Sand	48.4	42.1	50.7	40.3	14.0	13.9
Unit B Net Shale	13.6	33.4	10.4	35.5	10.7	17.6
Unit B Net Shaly Sand	54.8	64.3	53.7	63.3	21.8	17.3
Unit C Interval Thickness	139.7	146.5	119.0	142.0	37.3	13.5
Unit C Net Clean Sand	59.2	66.7	59.0	67.1	22.2	13.3
Unit C Net Shale	16.8	25.5	12.8	24.9	15.1	19.1
Unit C Net Shaly Sand	64.0	51.0	65.5	51.1	19.7	12.6

Figure 8. Comparison of Average Values for OU and Norman Water Wells (units are feet except where noted)



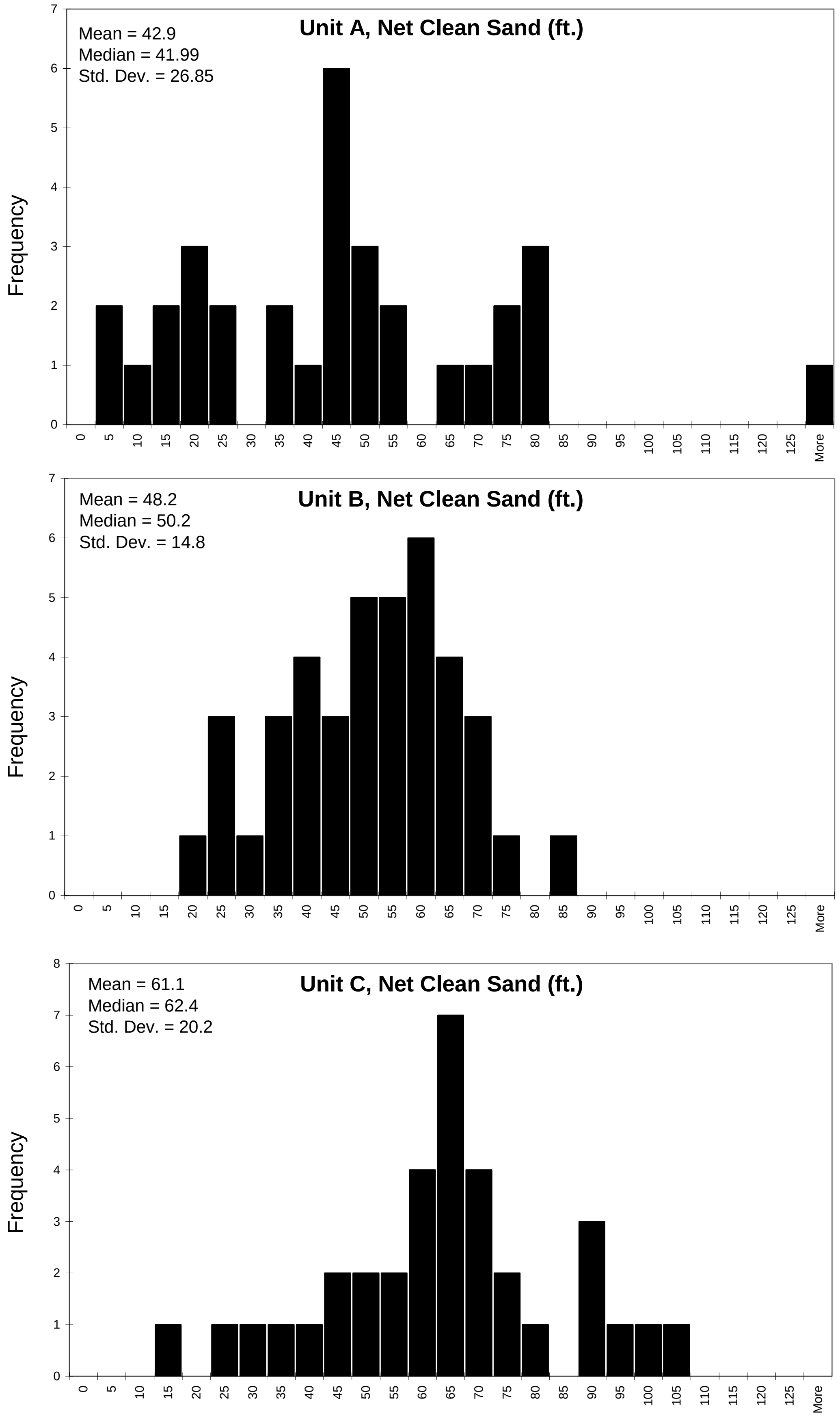


Figure 9. Net Clean Sandstone Content, Garber Sandstone Units A, B, and C

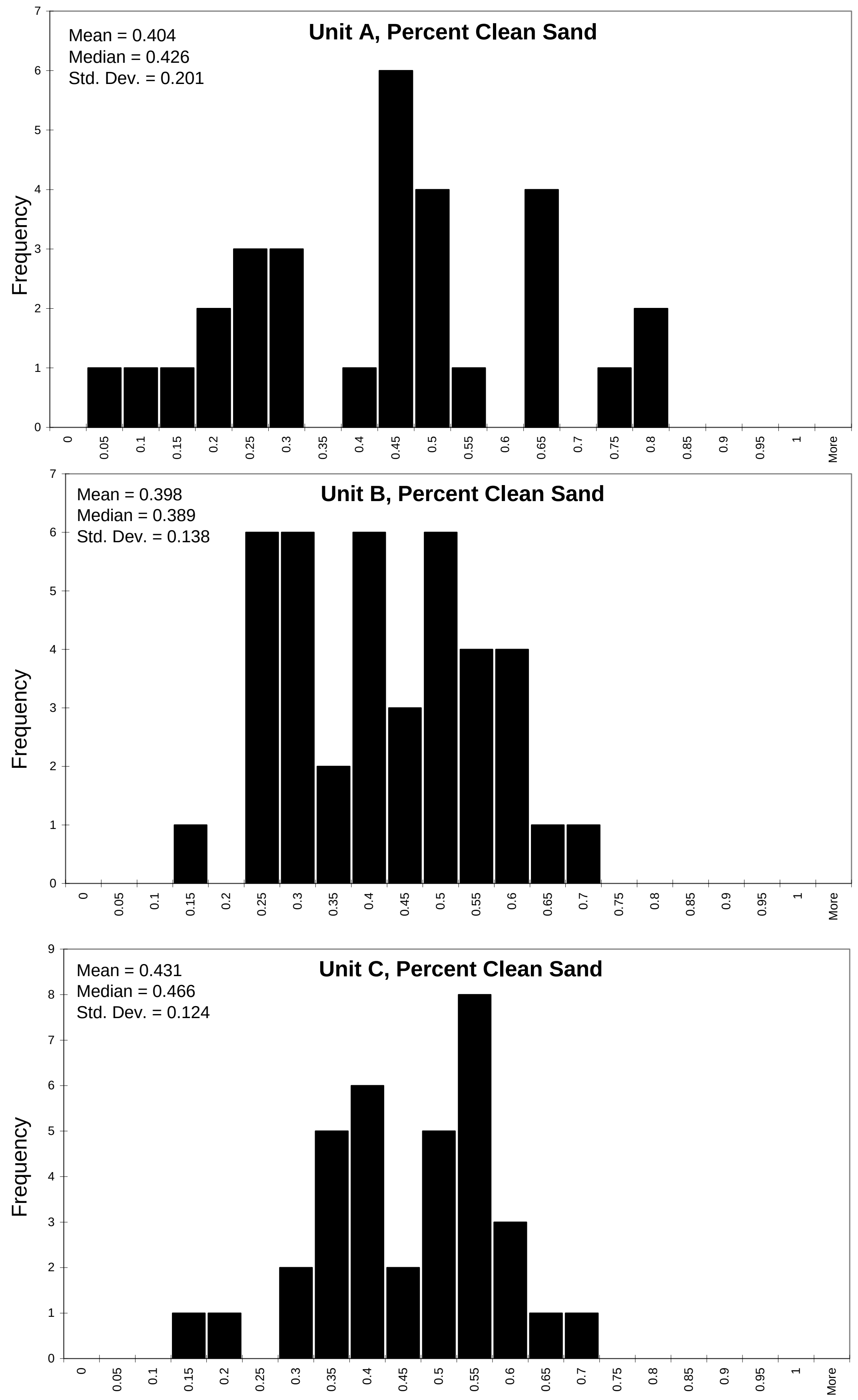


Figure 10. Percent Clean Sandstone Content, Garber Sandstone Units A, B, and C

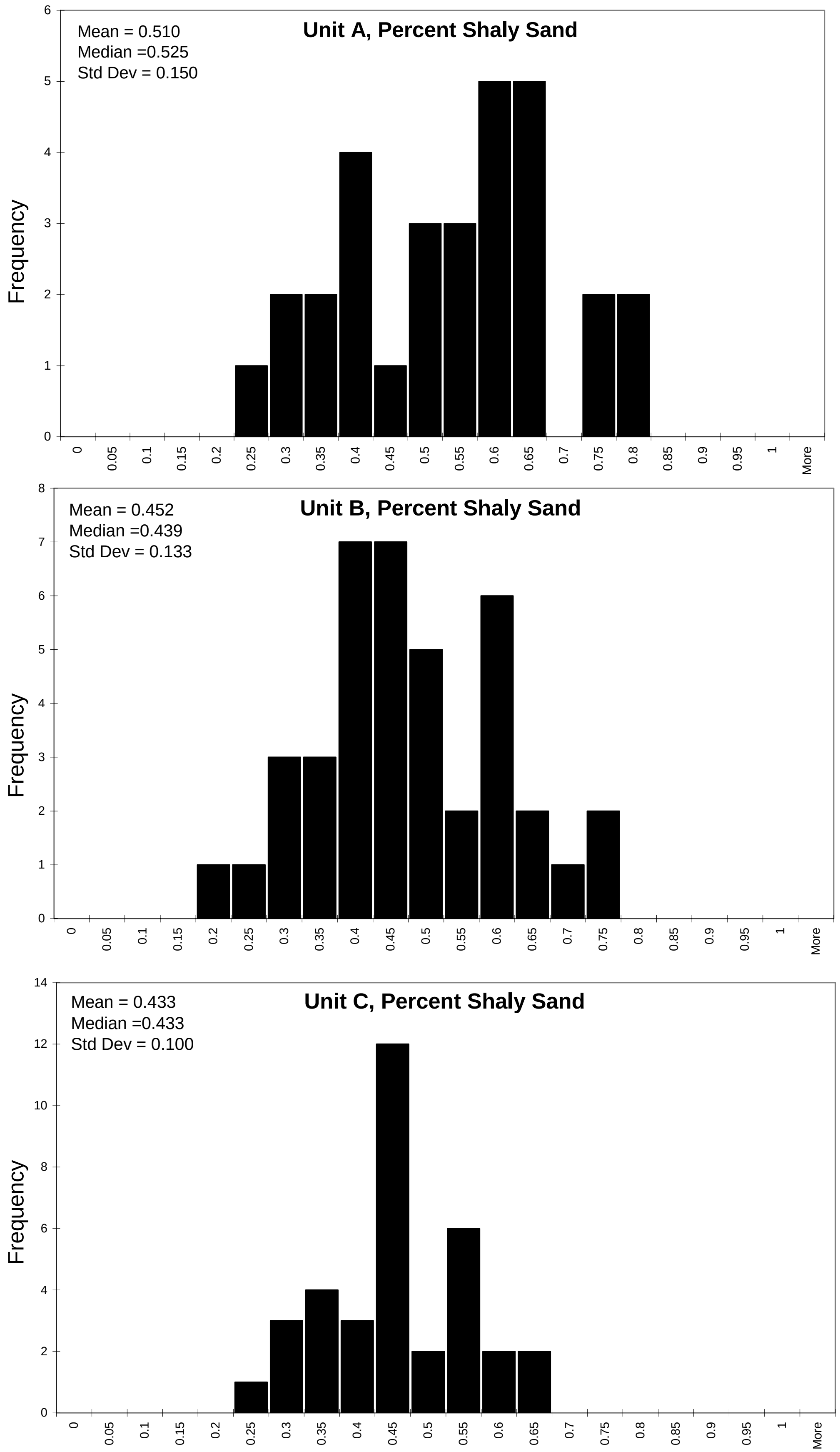


Figure 11. Percent Shaly Sandstone Content, Garber Sandstone Units A, B, and C

Large Scale Cross Sections

The location of these cross section lines, X-X’ and Y-Y’, are shown on Figure 12 as well as Plate 8. Structural cross section X-X’ shows the regional dip in the east-west direction, south of the Oklahoma County/Cleveland County line. On this cross section, the top of the Garber dips to the west at about 30 feet per mile, and the underlying surfaces have similar dips. The inferred Garber-Wellington contact on the east side of the cross section is because of a lack of wells for which this contact was logged in the eastern half of Cleveland County. The cross section also shows the facies transition of the Herington Limestone to a shale section.

Structural cross section Y-Y’ shows the regional dip in a north-south direction in the western part of Cleveland County and southern Oklahoma County. The cross section shows that the beds are striking more or less north-south in Oklahoma County, and they begin to dip slightly to the south in northern Cleveland County, before flattening out just north of Norman and then rising slightly between Norman and Noble. The cross section suggests the presence of a subtle depression or low area between the north line of T9N R3W and the Noble vicinity.

Small Scale Cross Sections and Well Log Response Patterns

The discussion of the small scale cross sections (A-A’ through H-H’) consists of some general information about each cross section, such as a brief description of the orientation of the cross section line and some of the features seen on that particular cross section. The location of these cross section lines can be found on Figure 13, and also on

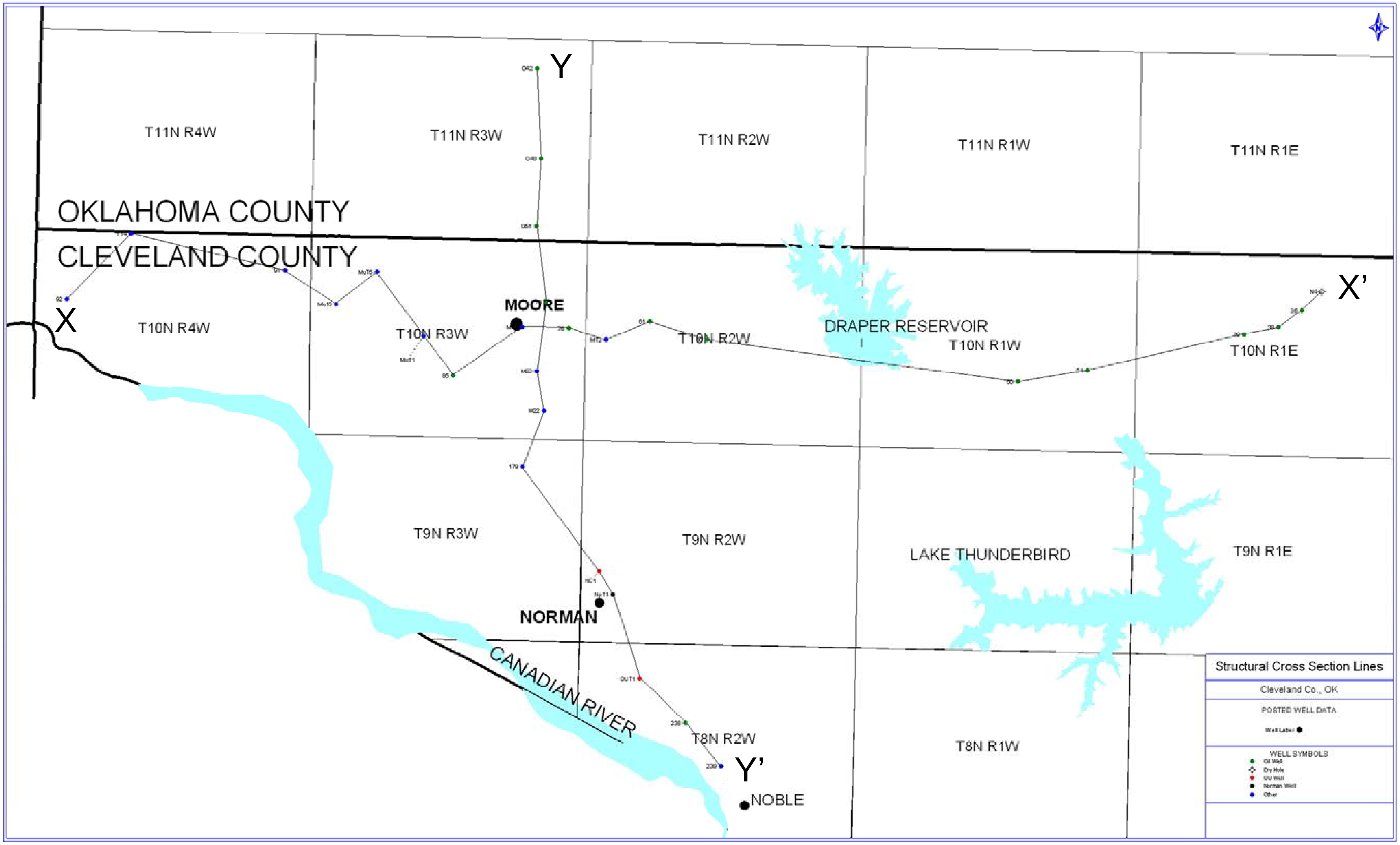


Figure 12. Map showing location of cross sections X-X' and Y-Y'

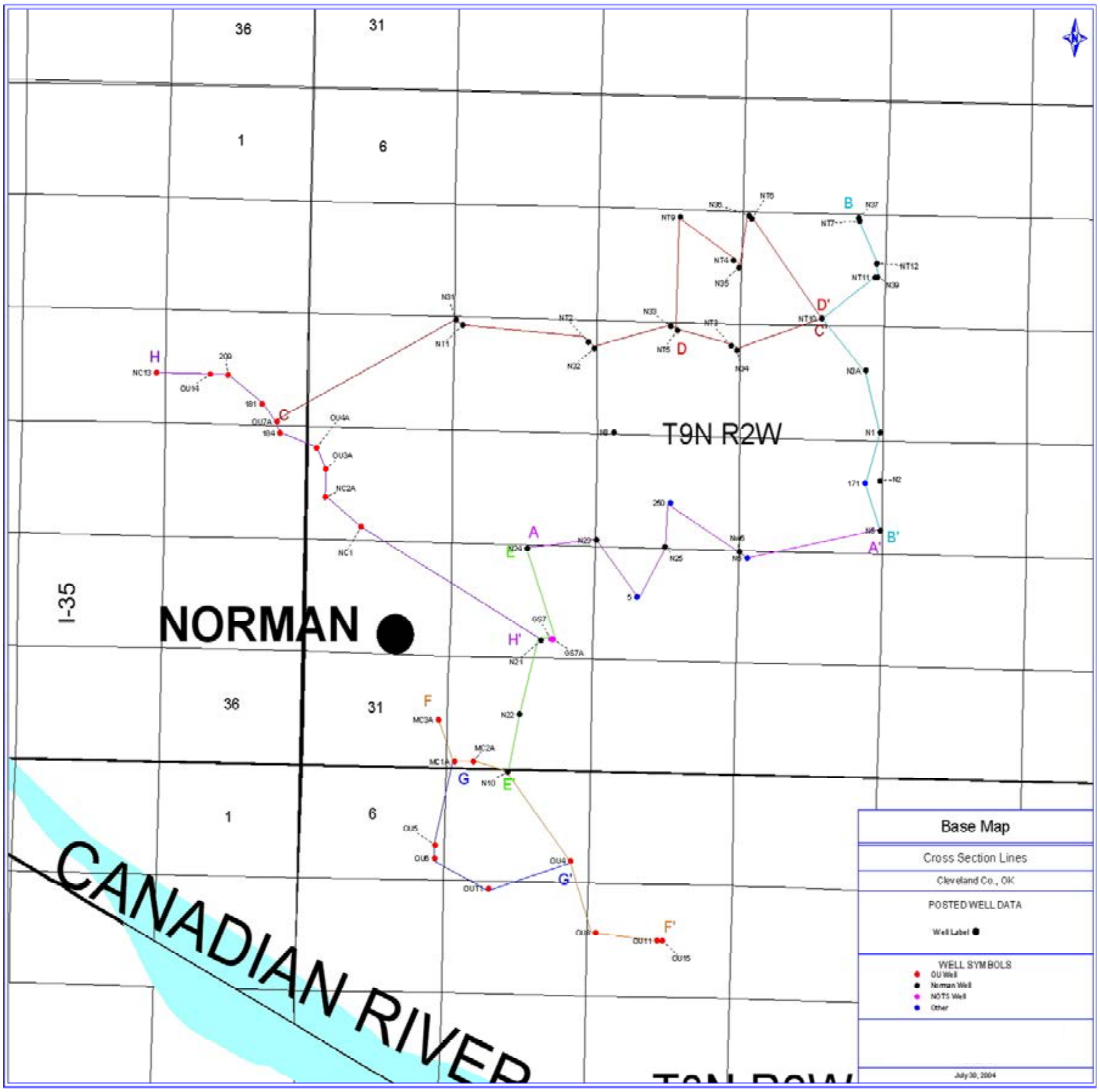


Figure 13. Map Showing location of cross sections A-A’ through H-H’

Plate 8. The cross sections can be found on Plates 10, 11, 12, and 13.

Cross section A-A’ runs approximately east-west, except for a portion of the line which runs more north-south. A-A’ is hung stratigraphically on the top of the Garber, and is tied into cross section B-B’ by well N5. Among the characteristics seen on this cross section are fining upward intervals which probably represent point bar deposits. Also seen are relatively clean, thick sandstones developing shale breaks and grading into thinly bedded sands and shales. Individual sandstones on well logs can be as thick as fifty feet. Also present is a continuous sandstone at the base of Unit B. This sandstone is blocky in places and is about thirty feet thick, except in the two westernmost wells, where it is thinner. This sandstone is present in quite a few wells used in the cross section. Figure 14 is a detail from Cross Section H-H’ showing the typical log signature of this sandstone. Figure 15 is a detail from Cross Section D-D’ showing typical gradation of shale and blocky sandstones into more thinly bedded sandstones.

Cross section B-B’ is a north-south line, hung structurally (datum = MSL) because the top of the Garber is not found on some of the logs. The section is more or less on strike in the northern end of the line, and the units begin to dip to the south towards the southern end. This cross section shows the gradation of thick sandstones into fining upward series, and the development of thin shale breaks within thick sands. Truncation is also present, as are stacked fining upward intervals.

Cross section C-C’ is hung on the top of the Garber and runs in an east-west direction. Except for the two end wells, the wells in this cross section occur in very

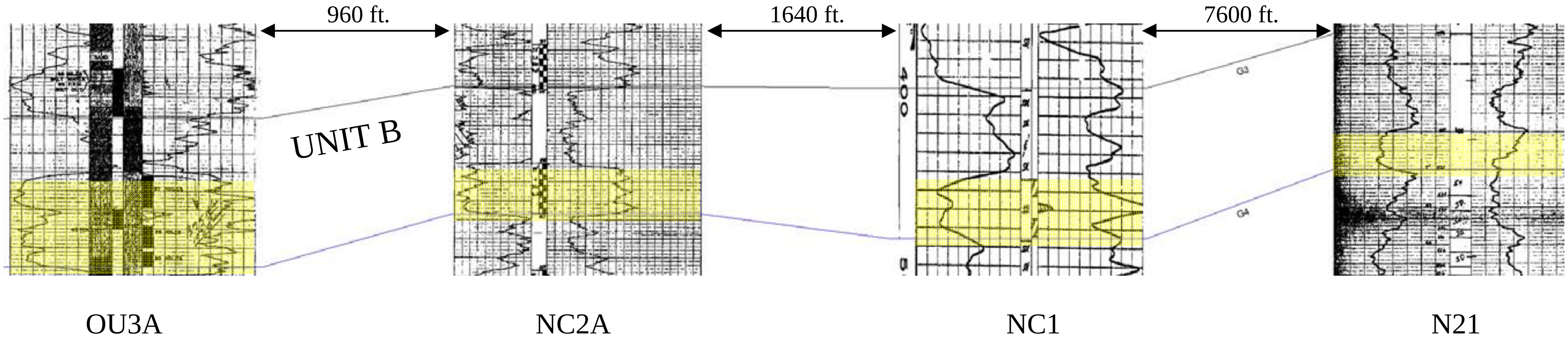


Figure 14. Detail of cross section H-H', showing the persistent sandstone at the base of Garber Unit B.

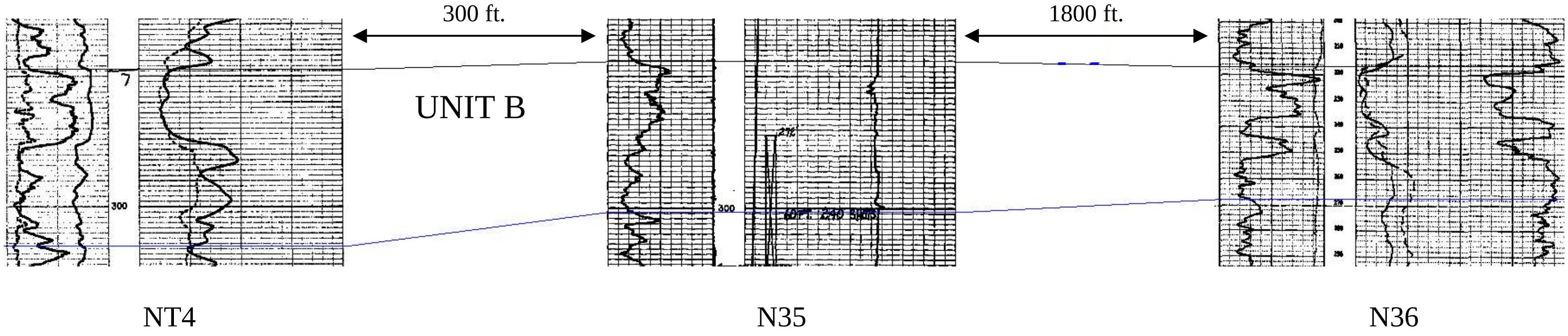


Figure 15. Detail of cross section D-D', showing the typical lateral gradation of sandstone to shale in the Garber. Note the fining-upward character in well N35.

closely spaced pairs. The major unit boundaries on this cross section are sometimes rather subtle, but the author believes the boundaries are in the correct position since they were carried through from other cross sections where they are more apparent. Similar to cross sections A-A' and B-B', this section shows thick sandstones grading into more thinly bedded sandstones and shales over distances of several hundred feet, and the interbedded sandstones and shales grading into fining upward intervals. Persistent sandstone units are present at the top of Unit A and at the base of Unit B. A thick shale unit is also present in Unit B.

Cross section D-D' is a structural cross section, with the top of the Garber projected across several wells where it cannot be seen on the logs. The base of the Garber is relatively flat lying. This cross section is more or less a loop, going north, turning east, and then heading back south, as it ties into cross section C-C' at both ends. Some of the features seen on this cross section include stacked sandstones, rapid thickening and thinning of shales, and once again, lateral gradation of thick sandstones into interbedded sandstone and shale, over distances of less than a mile. Unit B contains a continuous sandstone at its base.

Cross section E-E' is a stratigraphic section hung on the top of the Garber; this cross section goes through the two NOTS wells in the Norman area, NOTS 7 and 7A. These two wells are very close together, and the top of the Garber can be seen easily on both logs, as well as the upper and lower surfaces of Unit B. Only two wells in this cross section penetrate the base of the Garber. E-E' is a north-south cross section, connecting cross sections A-A', F-F', and H-H'. This cross section exhibits the characteristic lateral gradation of sandstone to shale seen on each of the preceding cross sections, as well as stacked clean sandstones, fining upward series, thick shales, and continuous sandstone beds at the bases of Unit B and upper Unit C.

Cross section F-F’ trends northwest-southeast, and is a structural cross section due to the absence of the top of the Garber in the northwestern most well (MC10). The top of the Garber as well as the bases and tops of the Garber units have an undulating character, and units’ thickness is fairly consistent. The four wells to the southeast are old OU water wells, and the logs date from the 1940’s, hence stratigraphic resolution based on these logs is difficult; the packages are identifiable on these logs, but they (the logs) only penetrate through the top of Unit C. The sediment package boundaries on this cross section exhibit an erosional character not seen on the preceding cross sections, but the units do display some fining upward intervals and persistent basal sandstones.

Stratigraphic cross section G-G’, hung on the top of the Garber, is another loop, connecting to F-F’ at both ends. This cross section has only five wells, but the erosional character seen on F-F’ is nonetheless apparent. For the most part, the units of G-G’ are quite comparable to those of F-F’. Particularly striking is the sixty-foot thick, somewhat blocky sandstone of upper Unit C in well OU6.

Cross section H-H’, which runs northwest-southeast, has the greatest number of wells (11) of all the small-scale cross sections that were constructed. However, several of the wells were not logged over a very thick interval, which necessitates the projection of some of the surfaces across the cross section. All of the wells on H-H’ are OU wells except for Norman Well #21 at the southeast end, which connects H-H’ to E-E’; H-H’ is also connected to cross section C-C’ by OU7A, the fifth well from the left. This cross section contains the typical lateral gradation and fining upward series seen in the other cross sections, as well as a thick shale unit and a thick, continuous sandstone at the base of Unit B. There is also a prominent coarsening upward interval in OU7A in upper Unit B.

All of the cross sections exhibit several instances of fining upward intervals, which are probably point bar deposits. Many of these deposits are incomplete; that is, the upper part of the point bar deposits have been removed or were never deposited. All of the cross sections also show prominent lateral gradation of thick, clean sandstones into thinner, interbedded sandstones and shales and also into the point bar deposits. There are few coarsening upward sequences. Frequently, especially in Unit B, there is a relatively clean sandstone at the base of a unit that is continuous across an entire cross section. This suggests that water depth and energy was fairly consistent at the beginning of deposition of these units. These characteristics suggest that the rocks of the Garber Sandstone are similar to the “meanderbelt facies” discussed in the paper by Hall (1976).

From the literature, it appears that Norman is situated in an area of the aquifer with lower sand content relative to areas to its north and east. Burton and Wood assert that the sandstone to shale ratio is highest in northeastern Cleveland County and decreases to the southwest, while other authors maintain that sand content is highest in central Oklahoma County and decreases outward in all directions. In the immediate Norman area, however, there are trends that suggest the presence of areas of locally low and high sand content. In general, clean sand seems to be more abundant to the east and at deeper intervals within the Garber (i.e., Unit C is sandier than Units A and B- refer to Figures 9, 10, and 11). The areal variations are probably more significant than the vertical variations, because it is not uncommon to find a thick, clean sandstone at any given interval within the Garber. That is, although sand content may increase from Unit A downward, the difference is not very large from one unit to the next when compared with the differences from one well location to the next. Neither does it appear that arsenic occurrence can be linked to any one unit or individual sediment layer, since they usually grade into something else relatively rapidly. Therefore, it is recommended that wells be drilled in areas with high clean sand and low shaly sand (Figure 16).

VI.

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

The primary source of data for this study was well logs, which were used to construct various maps and cross sections. After examining this data, the following conclusions can be drawn.

1.) The Garber Sandstone in Cleveland County ranges from about 400-600 feet thick, and dips to the west at approximately 35 feet per mile, except where the regional dip is influenced by deeper structure

2.) Sediment packages exist within the Garber Sandstone that can be correlated from well to well over moderate distances. Three locally continuous sediment packages have been identified in the Garber (Units A, B, and C).

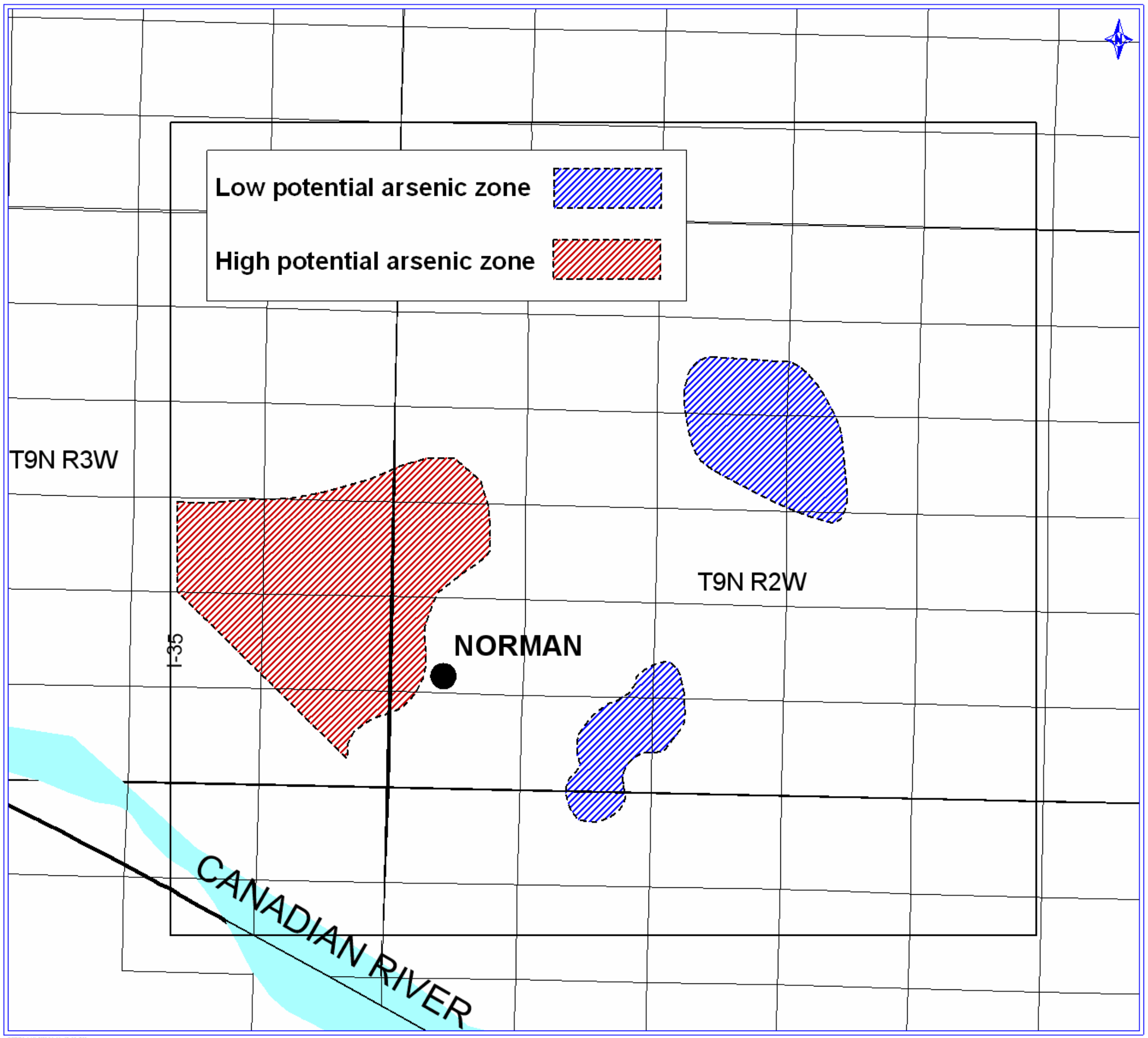
3.) Similar to what is seen in outcrops, individual sandstone bodies within these packages pinch out or grade laterally into shale over shorter distances. Clean sandstone units often grade into more thinly bedded sandstone and shale, or into fining upward intervals.

4.) The maps of Units A, B, and C suggest that the dominant style of deposition has resulted in the formation of depositional highs followed by increased sedimentation in the adjacent low areas.

5.) Variations in arsenic distribution coincide reasonably well with lithofacies, especially shaly sandstone, though there are some outliers.

One focus for future work could be to attempt linking arsenic distribution with various parts of the fluvial system, such as overbank deposits, channel mouth bars, etc. There is also potential for this work to be carried northward into Oklahoma County, especially the Tinker Air Force Base area. The same units mapped here (A, B, and C) may not be present, but most likely similar or equivalent units can be identified and mapped. Regarding more detailed stratigraphic analysis, chemostratigraphy and FMI and micro-resistivity logs would be extremely informative but immediate availability is unlikely due to analytical cost. However, detailed studies of well log signatures could be used to reconstruct the various parts of the channel system in terms of their paleogeomorphology.

Figure 16. Potentially high and low arsenic zones in the Norman area



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APPENDICES

APPENDIX A

WELL HEADER DATA

Well Header Information

Well Label	Well Name	Latitude	Longitude	Township	Range	Section	Quarter	County	Datum Elevation
2	Washington School Test Well #2	35.212736	-97.372814	9N	2W	35	SE NE	Cleveland	1130
5	Griffin Memorial Hospital #5	35.226475	-97.418133	9N	2W	28	SW SE NW	Cleveland	1199
30	NormanWWNW36th	No info.						Cleveland	
31	NormanWW#8A	No info.						Cleveland	
32	Ada Flemming #A-1	35.370688	-97.207287	10N	1E	4	C SW SE NW	Cleveland	1195
33	Hirsche #1	35.376271	-97.247101	10N	1E	6	NW NW NW	Cleveland	1155
34	Wodkins #1	35.359703	-97.196162	10N	1E	9	SE NE NE	Cleveland	1225
35	Coley #1	35.353341	-97.183996	10N	1E	10	C NW SE	Cleveland	1191
36	R. E. Wilson #1	35.343183	-97.158594	10N	1E	13	NW SW NW	Cleveland	1160
37	Foster 'B' #1	35.346892	-97.162948	10N	1E	14	NW NE NE	Cleveland	1162
38	Franklin #1	35.346088	-97.192842	10N	1E	15	NW NW	Cleveland	1238
39	State Land #1	35.342593	-97.206033	10N	1E	16	C SE NW	Cleveland	1209
40	Barton #1	35.323408	-97.187187	10N	1E	22	SE NE SW	Cleveland	1177
41	Wilson Estate #1	35.317953	-97.182632	10N	1E	27	NE NW NE	Cleveland	1145
42	Wilson #1	35.310851	-97.202525	10N	1E	28	NW NW SE	Cleveland	1142
43	Gunter #1	35.307236	-97.229131	10N	1E	29	NW SW SW	Cleveland	1149
44	Parr #1	35.299015	-97.201249	10N	1E	33	C SW NE	Cleveland	1185
45	Helen Anderson #1	35.363657	-97.24866	10N	1W	1	SE SE SE	Cleveland	1176
46	Pringle #1	35.363677	-97.26823	10N	1W	2	SW SE SE	Cleveland	1142
47	Maree Lewinsohn #1	35.354666	-97.297006	10N	1W	10		Cleveland	1215
48	Northcott #1	35.358329	-97.270445	10N	1W	11	NE SW NE	Cleveland	1167
49	Hayes #1	35.334623	-97.262001	10N	1W	13	SE SW SW	Cleveland	1150
50	Little #1	35.320367	-97.29261	10N	1W	22	SE SE SW	Cleveland	1187
51	Owenbey #1	35.325788	-97.266009	10N	1W	23	NE NE SE	Cleveland	1188
52	Lucas #1	35.311201	-97.279314	10N	1W	26	NE NW SW	Cleveland	1173
53	Hall #1	35.306003	-97.33696	10N	1W	30	SE SE SE	Cleveland	1158
54	Zimmerman #1	35.291566	-97.34811	10N	1W	31	SW SE SW	Cleveland	1077
55	Sublett #1	35.302394	-97.325982	10N	1W	32	SW NW NE	Cleveland	1147
56	Quiett #1	35.30205	-97.266129	10N	1W	35	SE NE NE	Cleveland	1133
57	Conley #1	35.367439	-97.378718	10N	2W	2	SW NW SE	Cleveland	1184
58	Rice #2	35.374825	-97.400442	10N	2W	3	SW NE NW	Cleveland	1260
59	Shroyer #1	35.360343	-97.39169	10N	2W	10	SW NE NE	Cleveland	1195
60	State #5	35.33597	-97.412443	10N	2W	16	NE SW SW SE	Cleveland	1164
61	Lindsay #3	35.343204	-97.434638	10N	2W	17	C SE NW	Cleveland	1235
64	Cook #1	35.307116	-97.372952	10N	2W	26	C SE SE	Cleveland	1157
65	Young #4	35.306084	-97.433522	10N	2W	29	SE SE SW	Cleveland	1160
66	Keller #1	35.292555	-97.412593	10N	2W	33	SW SE	Cleveland	1155
67	Fox #1	35.297063	-97.395946	10N	2W	34	NW NW SE	Cleveland	1115
68	Shelburg #1	35.292546	-97.386251	10N	2W	35	C SW SW	Cleveland	1112
69	State #36-1	35.304256	-97.358597	10N	2W	36	NE NW NE	Cleveland	1108
70	School Land #1-B	35.297027	-97.365239	10N	2W	36	NW NE SW	Cleveland	1162

Well Label	Well Name	Latitude	Longitude	Township	Range	Section	Quarter	County	Datum Elevation
75	Nail #1	35.350419	-97.474732	10N	3W	12	SW SW	Cleveland	1257
76	Steinmeyer #1	35.339621	-97.465846	10N	3W	13	C NW SE	Cleveland	1210
82	Kysela #4	35.328703	-97.549864	10N	3W	19	C SE NE	Cleveland	1213
83	Miller #1	35.328858	-97.518801	10N	3W	21	SW NE	Cleveland	1229
84	Perry Jury #1	35.317903	-97.466844	10N	3W	25	W/2 NW NE	Cleveland	1189
85	Sullivan #2	35.317945	-97.50987	10N	3W	27	NW NW	Cleveland	1217
89	McBride #1	35.350099	-97.646805	10N	4W	8	SE SW	Cleveland	1277
91	SE Wheatland WSW	35.362037	-97.575388	10N	4W	12	NE NE NW	Cleveland	1208
92	Test Hole #1	35.347245	-97.659044	10N	4W	18	NE NW NE	Grady	1312
93	Russell Butler #3	35.328534	-97.598457	10N	4W	23	C SW NW	Cleveland	1220
96	Foster #1	35.276327	-97.162719	9N	1E	2	SW SE SE	Cleveland	1136
97	Hoover #1	35.281928	-97.195713	9N	1E	4	NE NE SE	Cleveland	1137
98	Williams #1	35.27407	-97.232008	9N	1E	7	NE NE	Cleveland	1058
99	Go-do-pea-se #1	35.262112	-97.195551	9N	1E	9	SE SE SE	Cleveland	1107
100	Rookstool #1	35.273727	-97.192374	9N	1E	10	C NW NW	Cleveland	1138
101	Wilson #1	35.273593	-97.152742	9N	1E	12	C NE NW	Cleveland	1051
102	Pah Koh Nay #1	35.256309	-97.158243	9N	1E	13	NW SW NW	Cleveland	1118
103	Citizens Nat'l Bank #1	35.247451	-97.192372	9N	1E	15	C S/2 SW SW	Cleveland	1110
104	Citizens Nat'l Bank #A-1	35.253066	-97.195437	9N	1E	16	C NE NE SE	Cleveland	1138
105	Godopease #1	35.259393	-97.218637	9N	1E	17	C NW NE	Cleveland	1141
106	Benard #1	35.252214	-97.24085	9N	1E	18	C NE SW	Cleveland	1026
107	Little Axe School Dist. #4	35.244048	-97.195393	9N	1E	21	SE NE NE	Cleveland	1100
108	Warmack #1	35.233206	-97.204243	9N	1E	21	SE SE SW	Cleveland	1071
109	White #2	35.244852	-97.187945	9N	1E	22	C E NE NW	Cleveland	1037
110	Mack #1	35.236537	-97.144964	9N	1E	24	SW NE SE	Cleveland	1049
111	Essary #1	35.230207	-97.152629	9N	1E	25	C NE NW	Cleveland	1107
112	Little Fish Unit #1	35.220268	-97.155947	9N	1E	25	NE SW SW	Cleveland	1041
113	Joe Brendle #1	35.222143	-97.160403	9N	1E	26	SE NE SE	Cleveland	1086
114	Little Jim #2	35.227565	-97.191302	9N	1E	27	NE SW NW	Cleveland	1037
115	Edna Hall #1	35.230295	-97.196498	9N	1E	28	C NE NE	Cleveland	1026
116	Goodin #1	35.207894	-97.213073	9N	1E	32	SE NE SE	Cleveland	1041
117	King #1	35.207668	-97.208744	9N	1E	33	SE NW SW	Cleveland	992
118	Austin Estate #1	35.213078	-97.18683	9N	1E	34	NE SE NW	Cleveland	992
119	Billy Williams #1	35.213058	-97.166553	9N	1E	35	200' W of C N/2 SW NE	Cleveland	1049
120	McCalmon #1	35.204738	-97.152585	9N	1E	36	C SE SW	Cleveland	980
121	Banning #1	35.205642	-97.142632	9N	1E	36	NE SE SE	Cleveland	980
122	Le Master #1	35.284259	-97.292689	9N	1W	3	SE SE NW	Cleveland	1179
123	Blackburn #1	35.282591	-97.33034	9N	1W	5	NW NE SW	Cleveland	1100
124	King #1	35.286205	-97.343428	9N	1W	6	NW SW NE	Cleveland	1116
125	Maddox #1	35.275283	-97.338933	9N	1W	7	NW NE NE	Cleveland	1067
126	Johnson #1	35.273476	-97.328045	9N	1W	8	SE NE NW	Cleveland	1065
127	Kelley #1	35.26785	-97.272856	9N	1W	11	NW NW SE	Cleveland	1173
128	Titus McCoy #1	35.270561	-97.24983	9N	1W	12	SE NE	Cleveland	1162

Well Label	Well Name	Latitude	Longitude	Township	Range	Section	Quarter	County	Datum Elevation
129	McCoy #1	35.254995	-97.248532	9N	1W	13	SE SE NE	Cleveland	1123
130	Nora Todd #1	35.253574	-97.317035	9N	1W	16	NW NW SW	Cleveland	1060
131	Forrest Mouser #6	35.25172	-97.319191	9N	1W	17	SE NE SE	Cleveland	1118
132	Matlock #1	35.256238	-97.346678	9N	1W	18	SE NW	Cleveland	1117
133	Smith #1	35.23903	-97.347819	9N	1W	19	NW NE SW	Cleveland	1173
134	R.E. Connelly #1	35.23903	-97.321359	9N	1W	20	NW NE SE	Cleveland	1072
135	Briggs #1	35.239021	-97.312597	9N	1W	21	NW NE SW	Cleveland	1044
136	Rohart #1	35.246251	-97.290574	9N	1W	22	NW NW NE	Cleveland	1101
137	Brehm #1	35.240739	-97.268573	9N	1W	23	SW SE NE	Cleveland	1118
138	Wilson #1	35.241474	-97.262914	9N	1W	24	C SW NW	Cleveland	1155
139	Walker #1	35.23152	-97.261899	9N	1W	25	NE NW NW	Cleveland	1096
140	Clark #1	35.231699	-97.266227	9N	1W	26	NE NE NE	Cleveland	1073
141	Otto Heims #1	35.228084	-97.290382	9N	1W	27	NW SW NE	Cleveland	1184
142	Birkhead #1	35.231799	-97.317019	9N	1W	28	NW NW NW	Cleveland	1138
143	Schonwald #1	35.223699	-97.320211	9N	1W	29	NE SE	Cleveland	1144
144	Russell #1	35.219124	-97.347704	9N	1W	30	SW SE SW	Cleveland	1193
145	Lula Vaughn #1	35.212766	-97.350849	9N	1W	31	C SW NW	Cleveland	1154
146	M.B. Fulkerson #1	35.211712	-97.268317	9N	1W	35	SW SE NE	Cleveland	1071
147	Holstein #1	35.209905	-97.261896	9N	1W	36	NE NW SW	Cleveland	1104
148	Nelson #1	35.282605	-97.356382	9N	2W	1	NW NE SE	Cleveland	1106
149	Williams #B-1	35.28527	-97.399295	9N	2W	3	C SE NW	Cleveland	1145
150	Kuhlman #1	35.281656	-97.39044	9N	2W	3	C NE SE	Cleveland	1090
151	Jennings #1	35.278955	-97.418126	9N	2W	4	NW SE SW	Cleveland	1146
154	Lessly #2-A	35.266349	-97.4093	9N	2W	9	SW NE SE	Cleveland	1134
156	Oliphant #1	35.27177	-97.389449	9N	2W	10	NE SE NE	Cleveland	1142
161	Strong #1	35.259847	-97.364175	9N	2W	13	C NE NW	Cleveland	1148
162	Ray Howell #1	35.259839	-97.377387	9N	2W	14	C NW NE	Cleveland	1169
163	Hansmeyer #1	35.253514	-97.387345	9N	2W	14	NW NW SW	Cleveland	1179
167	Boggs #1	35.253592	-97.40718	9N	2W	16	NE NE SE	Cleveland	1198
170	Rucker #1	35.249136	-97.430258	9N	2W	17	C SW SE	Cleveland	1186
171	Norman Well #2-A	35.241716	-97.39038	9N	2W	22	SE NE	Cleveland	1124
172	Klement #1	35.240841	-97.358602	9N	2W	24	SE SW NE	Cleveland	1163
173	Graves #1	35.239034	-97.363028	9N	2W	24	NE NE SW	Cleveland	1177
174	Boesken #1	35.227277	-97.394742	9N	2W	27	SW NE	Cleveland	1181
178	Core Hole #23	35.203982	-97.386049	9N	2W	35	C SL SW SW	Cleveland	1199
179	ACOG MW OK-3	35.279176	-97.482331	9N	3W	2	NE SW SE	Cleveland	1170
180	Gross #1	35.275471	-97.528528	9N	3W	9	NW NW NW	Cleveland	1142
181	OU Naval Base Well #7	35.250124	-97.464675	9N	3W	13	NE SW SE	Cleveland	1160
182	Helen Hamm #1	35.248218	-97.504316	9N	3W	15	SE SE SW	Cleveland	1188
184	OU Naval Base Well #6	35.246503	-97.462421	9N	3W	24	NW NE NE	Cleveland	1175
185	Westport Golf Club Test #1	35.22746	-97.483306	9N	3W	26	SW NE	Cleveland	1155
192	EW Harris #1	35.3080336	-97.5396357	10N	3W	29	NE SE SW	Cleveland	1190
193	Test Well #1	35.3015374	-97.5961615	10N	4W	35	NW	Cleveland	1190

Well Label	Well Name	Latitude	Longitude	Township	Range	Section	Quarter	County	Datum Elevation
209	OU Navy Well #5	35.2537747	-97.4689342	9N	3W	13	NE NE SW	Cleveland	1170
215	Cox #1	35.19012	-97.254069	8N	1W	1	C S/2 SW SE	Cleveland	1132
216	Stanford #1	35.202904	-97.277159	8N	1W	2	NW NE NW	Cleveland	1150
217	Sullivant #1	35.202785	-97.308077	8N	1W	4	NW NW NE	Cleveland	1118
218	Hoffman #2	35.193654	-97.319049	8N	1W	5	SE NE SE	Cleveland	1124
219	Brown #1	35.175675	-97.345358	8N	1W	7	SE SE SW	Cleveland	1130
220	Ralph Caddell #1	35.187421	-97.333278	8N	1W	8	NW NW	Cleveland	1136
221	H. Berman #2	35.177586	-97.297192	8N	1W	10	NE SW SW	Cleveland	1179
222	Deaver #1	35.180297	-97.267207	8N	1W	11	NE SE	Cleveland	1108
223	Witt #1	35.166686	-97.274909	8N	1W	14	NE NE SW	Cleveland	1140
224	F. Cook Jr. #2	35.170411	-97.288262	8N	1W	15	1650 SNL, 1650 WEL	Cleveland	1192
225	Black #1	35.172959	-97.350821	8N	1W	18	NW NW	Cleveland	1141
226	Cities Service Oil Company #1	35.159523	-97.283964	8N	1W	22	85' W NE NE NE	Cleveland	1165
227	Ellis #1	35.152128	-97.259665	8N	1W	24	NW NE SW	Cleveland	1180
228	Demand #1	35.14314	-97.290403	8N	1W	27	SW NW NE	Cleveland	1246
229	Schock #1	35.123067	-97.308135	8N	1W	33	NW NW SE	Cleveland	1189
230	Patterson #1	35.125712	-97.263106	8N	1W	36	SW NW	Cleveland	1232
231	Core Hole #22	35.195607	-97.369573	8N	2W	1	NW NW SW	Cleveland	1145
232	Core Hole #24	35.191341	-97.403569	8N	2W	3	SW SW	Cleveland	1183
235	Core Hole #19	35.176725	-97.381733	8N	2W	11	SE SW	Cleveland	1156
236	Valouch #1	35.173116	-97.386153	8N	2W	14	NW NW	Cleveland	1184
237	Core Hole #20	35.173239	-97.394839	8N	2W	15	NW NE	Cleveland	1177
238	Tullius #4	35.169753	-97.417805	8N	2W	16	1990 FNL, 1770 FWL	Cleveland	1175
239	Core Hole #18	35.151457	-97.40382	8N	2W	22	NW SW	Cleveland	1100
241	Taylor #1	35.157782	-97.380717	8N	2W	23	SE NE NW	Cleveland	1167
243	Core Hole #16	35.151361	-97.368559	8N	2W	24	NW SW	Cleveland	1183
245	Core Hole #15	35.140489	-97.368557	8N	2W	25	SW NW	Cleveland	1193
246	Core Hole #13	35.131446	-97.393086	8N	2W	27	C SL SE	Cleveland	1133
250	Hall Park Well #4	35.238609	-97.414263	9N	2W	21	SW NW NW SE	Cleveland	1228
257	Noble Pollack #1	35.1149944	-97.3159557	7N	1W	4	NW NW	Cleveland	1100
GS7	NOTS 7	35.2208333	-97.4286111					Cleveland	1172
GS7A	NOTS 7A	35.2208333	-97.4283333					Cleveland	1172
M21	City of Moore Well #21	35.3207275	-97.51096	10N	3W	22	SW SW SW	Cleveland	1210
M22	City of Moore #22	35.303515	-97.4746	10N	3W	36	NW NW	Cleveland	1215
M23	City of Moore Well #23	35.3206462	-97.4778247	10N	3W	23	SE SE SE	Cleveland	1225
M24	City of Moore Well #24	35.332466	-97.4614039	10N	3W	24	NE NE	Cleveland	1199
M26	City of Moore Well #26	35.3690343	-97.4975738	10N	3W	3	SE NW NE SE	Cleveland	1307
M36	City of Moore #36	35.346818	-97.44802	10N	2W	18	C NW NE	Cleveland	1245
MC1A	OU MC Well #1-A	35.2048257	-97.4401572	9N	2W	31	SE SE	Cleveland	1163
MC2A	OU MC Well #2-A	35.2048777	-97.4378563	9N	2W	32	SE SW SW	Cleveland	1152
MC3A	OU MC Well #3A	35.2101285	-97.4422384	9N	2W	31	NE NE SE	Cleveland	1175
MT1	City of Moore #1 Test Hole	35.364055	-97.462546	10N	3W	1	SW SE SE	Cleveland	1275
MT2	City of Moore #2 Test Hole	35.335072	-97.451343	10N	2W	18	SE SE SW	Cleveland	1198

Well Label	Well Name	Latitude	Longitude	Township	Range	Section	Quarter	County	Datum Elevation
MTA2	City of Moore Test Well #A-2	35.361392	-97.492263	10N	3W	11	NW NW	Cleveland	1280
MTB	City of Moore Test Well B	35.33969	-97.483493	10N	3W	14	NW SE	Cleveland	1230
Mu10	City of Mustang Well #10	35.340573	-97.5288416	10N	3W	16	NW NW SW	Cleveland	1208
Mu11	City of Mustang #11	35.334789	-97.521578	10N	3W	16	SE SE SE SW	Cleveland	1217
Mu13	City of Mustang #13	35.347731	-97.555403	10N	3W	18	NW NW NE	Cleveland	1205
Mu2	City of Mustang M-II	35.335273	-97.533304	10N	3W	17		Cleveland	1200
Mu9	City of Mustang #9	35.344246	-97.531078	10N	3W	17	NE SE NE	Cleveland	1222
Mu9B	City of Mustang Test #9B	35.3433551	-97.5322115	10N	3W	17	SE NE	Cleveland	1223
MuT4	City of Mustang Test Hole M-IV	35.318563	-97.590637	10N	4W	26	NW NW NE	Cleveland	1159
MuT5	City of Mustang Test Well #5	35.362275	-97.539997	10N	3W	8	NE NE NW	Cleveland	1250
MuT7	City of Mustang Test Well #7	35.370756	-97.548304	10N	3W	6	SE SE SE NE	Cleveland	1271
MuTh5	City of Mustang Test Hole M-V	35.314058	-97.616101	10N	4W	27	SW NW	Cleveland	1162
MuY	City of Mustang M-Y	35.357446	-97.59853	10N	4W	11	SW NW	Oklahoma	1240
N1	NormanWW#1	35.2482789	-97.3886414	9N	2W	15	SESE	Cleveland	1160
N10	NormanWW#10	35.2036319	-97.4336075	N	W			Cleveland	1150
N11	NormanWW#11	35.2605336	-97.4733075	9N	3W	13	NENWNW	Cleveland	1178
N12	NormanWW#12	35.2661306	-97.4780467	N	W			Cleveland	1170
N15	NormanWW#15	35.2745903	-97.4809875	9N	3W	11		Cleveland	1148
N16	NormanWW#16	35.2800061	-97.4825181	9N	3W	2		Cleveland	1171
N17	NormanWW#17	35.283628	-97.485502	9N	3W	2		Cleveland	1170
N18	NormanWW#18	35.2906653	-97.4864367	9N	3W	2		Cleveland	1179
N19	NormanWW#19	35.2956683	-97.4887847	10N	3W	35		Cleveland	1160
N2	NormanWW#2	35.2420375	-97.3885517	9N	2W	22		Cleveland	1130
N20	NormanWW#20	35.3011089	-97.4895678	10N	3W	35		Cleveland	1186
N21	NormanWW#21	35.2206233	-97.4298467	N	W			Cleveland	1167
N22	NormanWW#22	35.211079	-97.432307	9N	2W	32		Cleveland	1147
N23	NormanWW#23	35.2336994	-97.4232622	N	W			Cleveland	1216
N24	NormanWW#24	35.232395	-97.431752	9N	2W	29	NW NW NW NE	Cleveland	1190
N25	NormanWW#25	35.2329933	-97.4148281	9N	2W	21	SESESW	Cleveland	1209
N31	NormanWW#31	35.2615289	-97.4410297	9N	2W	17	NWNW	Cleveland	1165
N32	NormanWW#32	35.2582472	-97.4239925	9N	2W	17	SENENE	Cleveland	1180
N33	NormanWW#33	35.2613281	-97.4146481	9N	2W	16	NWNWNWNE	Cleveland	1182
N34	NormanWW#34	35.2584403	-97.4064608	9N	2W	16	SESENENE	Cleveland	1160
N35	NormanWW#35	35.2690617	-97.4063978	9N	2W	9	SESESENE	Cleveland	1113
N36	NormanWW#36	35.2757519	-97.40529	9N	2W	10	NWNWNW	Cleveland	1084
N37	NormanWW#37	35.2757694	-97.3917789	9N	2W	18	NWNENE	Cleveland	1081
N39	NormanWW#39	35.2681965	-97.3893596	9N	2W	10	NENESE	Cleveland	1163
N3A	Norman Well #3-A	35.256225	-97.390562	9N	2W	15	SE NE	Cleveland	1180
N4	NOTS 4	35.3616667	-97.1763889	10N	1E	11	NW NW NW	Cleveland	1145
N40	NormanWW#40	35.2614928	-97.3795986	9N	2W	14	NWNWNWNE	Cleveland	1174
N5	NormanWW#5	35.235665	-97.3884106	9N	2W	22		Cleveland	1161
N6	Norman Well #6	35.231794	-97.404697	9N	2W	27	NW NW NW	Cleveland	1190
N7A	Norman Well #7-A	35.241022	-97.493072	9N	3W	23		Cleveland	1164

Well Label	Well Name	Latitude	Longitude	Township	Range	Section	Quarter	County	Datum Elevation
N8	NormanWW#8	35.2475392	-97.4213728	9N	2W	16		Cleveland	1213
Nb11	Noble Well #11	35.145006	-97.363032	8N	2W	25	NE NE NW	Cleveland	1200
Nb3	Noble Well #3	35.146939	-97.380717	8N	2W	23	SE SE SW	Cleveland	1204
NbT1	Noble Test Well #1	35.1322762	-97.3214219	8N	1W	29	SW SE SE	Cleveland	1155
NbT2	Noble Test Well #2	35.132237	-97.334599	8N	1W	29	SW SW SW	Cleveland	1140
NbT3	Noble Test Well #3	35.130363	-97.354465	8N	2W	36	NE NE NE	Cleveland	1160
NbT4	Noble Test Well #4	35.141631	-97.391886	8N	2W	27	NW SE NE	Cleveland	1185
NbT5	Noble Test Well #5	35.152934	-97.3888027	8N	2W	22	NE NE NE SE	Cleveland	1195
NbTW1	Noble Test Well #1	35.1356958	-97.3958631	8N	2W	27	NW SE	Cleveland	1182
NbTW2	Noble Test Well #2	35.1319068	-97.3791453	8N	2W	26	SW SW SW SE	Cleveland	1201
NC1	OU North Campus Well #1	35.2347073	-97.452224	9N	2W	19	SE SW	Cleveland	1186
NC11	OU NC Well #11	35.2447537	-97.4643934	9N	3W	24	SE NW NE	Cleveland	1177
NC13	OU NC Well #13	35.2538746	-97.477742	9N	3W	14		Cleveland	1181
NC1A	OU North Campus Well #1A	35.2347114	-97.4520538	9N	2W	19	SE SW	Cleveland	1187
NC2A	OU North Campus Well #2A	35.238394	-97.4566835	9N	2W	19	NE NW SE SW	Cleveland	1190
NL1	Norman WW#14	35.2692382	-97.4799881					Cleveland	
NL2	NormanWW #13	35.2634576	-97.4771637					Cleveland	
NL3	NormanWW#4	35.2499146	-97.4296475					Cleveland	
NL4	NormanWW#38	35.2720894	-97.3894361					Cleveland	
NL5	OU N.C. #8	35.2520528	-97.4670431					Cleveland	
NoSM	Noble Southern Mea	35.137663	-97.325638	8N	1W	29	NW NW SE	Cleveland	1170
NpT1	City of Norman Andrews Park Test Well #1	35.2246766	-97.4466139	9N	2W	30	NE NW SE	Cleveland	1173
NT1	City of Norman Test Well #1	35.260883	-97.440217	9N	2W	17	NW NW NW	Cleveland	1160
NT10	City of Norman Test #10	35.262735	-97.396089	9N	2W	10	SW SW SE	Cleveland	1150
NT11	City of Norman Test #11	35.2681571	-97.3896501	9N	2W	10	NE NE SE	Cleveland	1160
NT12	City of Norman Test #12	35.269963	-97.389449	9N	2W	10	SE SE NE	Cleveland	1145
NT13	City of Norman Test #13	35.260837	-97.378521	9N	2W	14	NWNWNE	Cleveland	1173
NT2	City of Norman Test Well #2	35.259076	-97.424726	9N	2W	17	SE NE NE	Cleveland	1180
NT3	City of Norman Test Well #3	35.259014	-97.40718	9N	2W	16	SE SE NE NE	Cleveland	1160
NT4	City of Norman Test #4	35.269963	-97.407087	9N	2W	9	SE SE SE NE	Cleveland	1113
NT5	City of Norman Test Well #5	35.260821	-97.413819	9N	2W	16	NW NW NW NE	Cleveland	1183
NT6	City of Norman Test #6	35.275384	-97.404943	9N	2W	10	NW NW NW NW	Cleveland	1084
NT7	City of Norman Test #7	35.275384	-97.391663	9N	2W	10	NW NE NE	Cleveland	1081
NT8	City of Norman Test Well #8	35.26095	-97.451262	9N	2W	18	NE NE NW	Cleveland	1080
NT9	City of Norman Test #9	35.275384	-97.413727	9N	2W	9	NW NW NE	Cleveland	1093
Nw6	NormanWW#6	35.2326069	-97.4056578	9N	2W	27		Cleveland	1192
O1	Adam #1	35.5821046	-97.4314891	13N	2W	20	SW/SE	Oklahoma	1045
O17	Sante Fe RR #1-30	35.393039	-97.339929	11N	2W	30		Oklahoma	1317
O18	Marathon MW-17	35.407069	-97.584383	11N	4W	23	SE SE SE	Oklahoma	1270
O19	Marathon MW-18	35.411667	-97.576673	11N	4W	24	NE SW	Oklahoma	1251
O2	Leonard #1	35.567555	-97.4404451	13N	2W	29	SW SW	Oklahoma	1047
O20	Marathon MW-16	35.397141	-97.576671	11N	4W	25	NE SW	Oklahoma	1271
O21	Garrett #1	35.456553	-97.150172	11N	1E	1	NE SW	Oklahoma	1148

Well Label	Well Name	Latitude	Longitude	Township	Range	Section	Quarter	County	Datum Elevation
O22	Kusek #1	35.460296	-97.1614	11N	1E	2	1420 SNL 660 WEL	Oklahoma	1121
O23	Lowry #1	35.456882	-97.239142	11N	1E	6	NE SE	Oklahoma	1189
O24	Cooper #1	35.431427	-97.190291	11N	1E	15	NW NW NE	Oklahoma	1220
O25	Singer #1	35.417018	-97.208189	11N	1E	21	NW NW NE	Oklahoma	1182
O26	Skelton #1	35.402429	-97.172845	11N	1E	26	NW SW SE	Oklahoma	1146
O27	Tickle #1	35.3953	-97.199436	11N	1E	28	SE SE SW	Oklahoma	1139
O28	Claudine #1	35.380874	-97.234959	11N	1E	31	SE NE NE	Oklahoma	1233
O29	Guthrie #1	35.380748	-97.190641	11N	1E	34	SW SW NW	Oklahoma	1192
O3	Jesse #1	35.596524	-97.4316111	13N	2W	17	SW SE	Oklahoma	1108
O30	Whitehead #1	35.460764	-97.295929	11N	1W	3	NW SE SE	Oklahoma	1187
O31	Larkin #1	35.442485	-97.344499	11N	1W	7	NE SE	Oklahoma	1309
O32	Carrier #1	35.392711	-97.248578	11N	1W	25	SE SE SE	Oklahoma	1175
O33	Test Well #21	35.399073	-97.326725	11N	1W	29		Oklahoma	1279
O34	Divacky #1	35.397303	-97.412641	11N	2W	28	NW SE	Oklahoma	1268
O35	Little #1	35.40179	-97.437968	11N	2W	29	NE SW NW	Oklahoma	1283
O36	Stamper #7	35.399983	-97.451294	11N	2W	30	SE SE NW	Oklahoma	1297
O37	Emerson #13	35.398176	-97.455727	11N	2W	30	NE NW SW	Oklahoma	1307
O38	Vencl #18	35.381898	-97.444606	11N	2W	31	SW NE SE	Oklahoma	1286
O39	Salsman #6	35.386408	-97.439082	11N	2W	32	SW NW	Oklahoma	1277
O4	Tinker #1	35.41581	-97.359316	11N	2W	24	SW NE SW NE	Oklahoma	1252
O40	Test Well #1L	35.379082	-97.373179	11N	2W	35	SE SE	Oklahoma	1220
O41	Theimer #9	35.454303	-97.464685	11N	3W	1	SE NW SE	Oklahoma	1214
O42	Theimer #1	35.451693	-97.480172	11N	3W	2	W/2 SE SE	Oklahoma	1217
O43	ACOG MW	35.453397	-97.499055	11N	3W	3	SE	Oklahoma	1180
O44	OKC Stockyards	35.45596	-97.555737	11N	3W	6	NW NW SE	Oklahoma	1195
O45	Trospar Park #37	35.443424	-97.471478	11N	3W	12	SW SE NW	Oklahoma	1229
O46	Trosper #14	35.428047	-97.467955	11N	3W	13	NO SPOT	Oklahoma	1236
O47	Surbeck #A-1	35.410786	-97.504716	11N	3W	22	SE NE SW	Oklahoma	1250
O48	Werner Farley SWD #4	35.412712	-97.477902	11N	3W	23	NE NE SE	Oklahoma	1242
O49	ACOG MW OK-5	35.398186	-97.460348	11N	3W	25	NE NE SE	Oklahoma	1330
O5	Harvest #1	35.43876	-97.208047	11N	1E	9	SW	Oklahoma	1180
O50	Billen #1	35.400015	-97.477902	11N	3W	26	SE SE NE	Oklahoma	1265
O51	Lord #1	35.383533	-97.479128	11N	3W	35	N/2 NE SE	Oklahoma	1287
O52	Fuson #1	35.462285	-97.567852	11N	4W	1	NE NE	Oklahoma	1195
O55	Hayes #1	35.447898	-97.651721	11N	4W	8	NW NW	Oklahoma	1242
O58	Zurline #1	35.429744	-97.629892	11N	4W	16	SE NW	Oklahoma	1287
O6	Echo #1-13	35.43301	-97.143742	11N	1E	13	NE NE	Oklahoma	1125
O61	Cermak #1	35.418868	-97.664856	11N	4W	19	NE NW	Oklahoma	1298
O7	City of Choctaw Well #8	35.441552	-97.248554	11N	1W	12	NE NE SE	Oklahoma	1243
O8	Test Well #1	35.402709	-97.340051	11N	1W	30	NE	Oklahoma	1250
OU10	OU Well #10	35.2338487	-97.4820235	9N	3W	23	SE SW SE	Cleveland	1177
OU11	OU Navy Well #11	35.1823927	-97.4148781	8N	2W	9		Cleveland	1147
OU12	OU Well #12	35.2392994	-97.4644444	9N	3W	24	NE NW SE	Cleveland	1171

Well Label	Well Name	Latitude	Longitude	Township	Range	Section	Quarter	County	Datum Elevation
OU14	OU Navy Well #14	35.2538518	-97.4711318	9N	3W	13	NW NE SW	Cleveland	1177
OU15	OU Navy Well #15	35.1823943	-97.4142296	8N	2W	9		Cleveland	1150
OU3A	OU Well #3A	35.2420301	-97.4567115	9N	2W	19	SE NW	Cleveland	1185
OU4	OU Naval Well #4	35.1923856	-97.4256883	8N	2W	9		Cleveland	1145
OU4A	OU Well #4-A	35.2446956	-97.4578885	9N	2W	19	NW NW	Cleveland	1175
OU5	OU Navy #5	35.1940099	-97.4423506	8N	2W	6	SE NE SE	Cleveland	1170
OU6	OU Navy Well #6	35.1923062	-97.4423709	8N	2W	6	NE SE SE	Cleveland	1150
OU7A	OU Naval Base Well #7A	35.247945	-97.4628	9N	3W	13	SW SW SE SE	Cleveland	1175
OU8	OU Navy Well #8	35.1831931	-97.4224242	8N	2W	9	SE SW NW	Cleveland	1154
OU9	OU Well #9	35.2374462	-97.4820225	9N	3W	23	SE NW SE	Cleveland	1181
OUT1	OU Test Well #1	35.188591	-97.4356946	8N	2W	8	NW NE NW	Cleveland	1143
T30	TAFB Well #30	35.430693	-97.420388	11N	2W	16	NE SW NW	Oklahoma	1201
T31	TAFB Water Well #31	35.419823	-97.416023	11N	2W	21	NE NE NW	Oklahoma	1214
T32	TAFB Test Well #32	35.433386	-97.390588	11N	2W	15	NE NE	Oklahoma	1250
T33	TAFB Water Well #33	35.416182	-97.36761	11N	2W	24	NE SW NW	Oklahoma	1284
TT34	TAFB Water Well Test #33	35.416247	-97.369774	11N	2W	24	NW SE NW	Oklahoma	1285
Y13	Yukon Well #13	35.377624	-97.575054	11N	4W	36	SE SE SE SW	Oklahoma	1280
Y5	Yukon Well Y-V	35.420228	-97.648883	11N	4W	20	NW NW NE NW	Oklahoma	1258
Y6	Yukon Well Y-VI	35.428362	-97.671001	11N	4W	18	SW SW SW NW	Oklahoma	1310
Y8	Yukon Well Y-VIII	35.421612	-97.619912	11N	4W	16	SE SE SE	Oklahoma	1254
YP6	Yukon Well Y-P-6	35.421625	-97.600021	11N	4W	14	SW SW SW	Oklahoma	1283
YT1	City of Yukon Test Well #1	35.372082	-97.576579	10N	4W	1	SE NW	Cleveland	1270
YT3	Yukon Test Well #2	35.455172	-97.616742	11N	4W	3	NW SW	Oklahoma	1210
YT4	City of Yukon Test Hole #Y-IV	35.376273	-97.634935	10N	4W	4	NW NW NW	Cleveland	1260
YT7	Yukon Test Well Y-VII	35.434275	-97.602213	11N	4W	15	NE NE NE	Oklahoma	1241
YTY1	Yukon Test Well Y-I	35.440224	-97.65442	11N	4W	7	NE SE NE SE	Oklahoma	1250

APPENDIX B

FORMATION TOP DATA

Well Label	Well Name	Garber Top	Unit B Top	Unit C Top	Garber Base	Wellington Base
5	Griffin Memorial Hospital #5	170	274	409	586	
32	Ada Flemming #A-1					802
33	Hirsche #1				340	821
34	Wodkins #1					805
35	Coley #1					859
36	R. E. Wilson #1					658
37	Foster 'B' #1					672
38	Franklin #1				322	913
39	State Land #1					946
40	Barton #1					760
41	Wilson Estate #1					719
42	Wilson #1				280	762
43	Gunter #1					809
44	Parr #1					784
45	Helen Anderson #1					847
46	Pringle #1					855
47	Maree Lewinsohn #1				532	1009
48	Northcott #1					855
49	Hayes #1					900
50	Little #1					1036
51	Owenbey #1					963
52	Lucas #1					975
53	Hall #1					901
54	Zimmerman #1					836
55	Sublett #1					1011
56	Quiett #1					912
57	Conley #1					988
58	Rice #2					1177
59	Shroyer #1					1107
60	State #5					1021
61	Lindsay #3					1134
64	Cook #1					955
66	Keller #1					1033

Well Label	Well Name	Garber Top	Unit B Top	Unit C Top	Garber Base	Wellington Base
67	Fox #1					976
68	Shelburg #1					944
69	State #36-1				335	882
70	School Land #1-B					950
75	Nail #1	117			569	1156
76	Steinmeyer #1				542	1234
82	Kysela #4					1358
83	Miller #1	240	340		666	1312
84	Perry Jury #1					1176
85	Sullivan #2					1273
89	McBride #1	574				
91	SE Wheatland WSW	325	425	568	784	
92	Test Hole #1	550				
93	Russell Butler #3					1405
96	Foster #1					691
97	Hoover #1					711
98	Williams #1				269	773
99	Go-do-pea-se #1					714
100	Rookstool #1					719
101	Wilson #1					596
102	Pah Koh Nay #1					632
103	Citizens Nat'l Bank #1					683
104	Citizens Nat'l Bank #A-1					750
105	Godopease #1					773
106	Benard #1					775
107	Little Axe School Dist. #4				253	
108	Warmack #1					719
109	White #2					589
110	Mack #1					481
111	Essary #1					565
112	Little Fish Unit #1					501
113	Joe Brendle #1					552
114	Little Jim #2					638

Well Label	Well Name	Garber Top	Unit B Top	Unit C Top	Garber Base	Wellington Base
115	Edna Hall #1					633
116	Goodin #1					726
117	King #1					721
118	Austin Estate #1					587
119	Billy Williams #1					621
120	McCalmon #1					553
121	Banning #1					531
122	Le Master #1				603	1097
123	Blackburn #1					839
124	King #1					881
125	Maddox #1					827
126	Johnson #1					786
127	Kelley #1					980
128	Titus McCoy #1					905
129	McCoy #1					848
130	Nora Todd #1					856
131	Forrest Mouser #6					939
132	Matlock #1					990
133	Smith #1					986
134	R.E. Connelly #1					913
135	Briggs #1					845
136	Rohart #1					837
137	Brehm #1					858
138	Wilson #1					952
139	Walker #1					878
140	Clark #1					843
141	Otto Heims #1					941
142	Birkhead #1					953
143	Schonwald #1					996
144	Russell #1					1034
145	Lula Vaughn #1					1088
146	M.B. Fulkerson #1					888
147	Holstein #1					868

Well Label	Well Name	Garber Top	Unit B Top	Unit C Top	Garber Base	Wellington Base
148	Nelson #1					901
149	Williams #B-1					997
150	Kuhlman #1					928
151	Jennings #1					1055
154	Lessly #2-A					1050
156	Oliphant #1					947
161	Strong #1					1012
162	Ray Howell #1					1037
163	Hansmeyer #1					1043
167	Boggs #1				538	1123
170	Rucker #1					1140
171	Norman Well #2-A		185	323	456	
172	Klement #1					997
173	Graves #1					1019
174	Boesken #1					1053
178	Core Hole #23	130			525	
179	ACOG MW OK-3	226	322		652	
180	Gross #1					1322
181	OU Naval Base Well #7			476		
182	Helen Hamm #1					1322
184	OU Naval Base Well #6			469		
185	Westport Golf Club Test #1	311			746	
192	EW Harris #1					1368
193	Test Well #1	408				
209	OU Navy Well #5		371	504		
217	Sullivant #1					965
218	Hoffman #2					970
219	Brown #1					1070
220	Ralph Caddell #1					1043
221	H. Berman #2					969
223	Witt #1					908
224	F. Cook Jr. #2					980
225	Black #1					1101

Well Label	Well Name	Garber Top	Unit B Top	Unit C Top	Garber Base	Wellington Base
226	Cities Service Oil Company #1					955
227	Ellis #1					923
228	Demand #1					1049
229	Schock #1					1051
230	Patterson #1					972
231	Core Hole #22	40			458	
232	Core Hole #24	201				
235	Core Hole #19	128				
236	Valouch #1					1184
237	Core Hole #20	182				
238	Tullius #4	238			685	1161
239	Core Hole #18	103			545	
241	Taylor #1	163	195		529	
243	Core Hole #16	164	254	397		
245	Core Hole #15	135	303	467		
250	Hall Park Well #4	166	276	420	623	
257	Noble Pollack #1		175	332		
GS7	NOTS 7	183	277	418		
GS7A	NOTS 7A	173	277	418		
M21	City of Moore Well #21	222	328		700	
M22	City of Moore #22	176			621	
M23	City of Moore Well #23	183			592	
M24	City of Moore Well #24	83			496	
M26	City of Moore Well #26	171	435		683	
M36	City of Moore #36	82			499	
MC1A	OU MC Well #1-A	228	339	476	609	
MC2A	OU MC Well #2-A	205	315	454	590	
MC3A	OU MC Well #3A			475	608	
MT1	City of Moore #1 Test Hole	68			529	
MT2	City of Moore #2 Test Hole	76			476	
MTA2	City of Moore Test Well #A-2	138	384		664	
MTB	City of Moore Test Well B	143	325		588	
Mu10	City of Mustang Well #10	232	327		689	

Well Label	Well Name	Garber Top	Unit B Top	Unit C Top	Garber Base	Wellington Base
Mu11	City of Mustang #11	222	334		693	
Mu13	City of Mustang #13	289			748	
Mu2	City of Mustang M-II	214			687	
Mu9	City of Mustang #9	267	361		721	
Mu9B	City of Mustang Test #9B	287	368		708	
MuT4	City of Mustang Test Hole M-IV	328			794	
MuT5	City of Mustang Test Well #5				734	
MuT7	City of Mustang Test Well #7	277			714	
MuTh5	City of Mustang Test Hole M-V	429				
MuY	City of Mustang M-Y	399				
N1	NormanWW#1	56	214	370	490	
N10	NormanWW#10	217	319	452		
N11	NormanWW#11	231	342			
N12	NormanWW#12	234	325		667	
N15	NormanWW#15	217	300	465	640	
N16	NormanWW#16	234	344	487	659	
N17	NormanWW#17	213			640	
N18	NormanWW#18	212	320	462	651	
N19	NormanWW#19	167	285	435	619	
N2	NormanWW#2	42	165	286	493	
N20	NormanWW#20	138	264	404	614	
N21	NormanWW#21	193	277	420	599	
N22	NormanWW#22	207	287	441	615	
N23	NormanWW#23	192	301	439	607	
N24	NormanWW#24	189	286	423		
N25	NormanWW#25	161	279	411	571	
N31	NormanWW#31	170	254	365	543	
N32	NormanWW#32	156	261	373	537	
N33	NormanWW#33	97	260	380	496	
N34	NormanWW#34	42	244	340	457	
N35	NormanWW#35		194	302	400	
N36	NormanWW#36		159	268	380	
N37	NormanWW#37		124	208	328	

Well Label	Well Name	Garber Top	Unit B Top	Unit C Top	Garber Base	Wellington Base
N39	NormanWW#39		193	291	403	
N3A	Norman Well #3-A	51	218	367	487	
N4	NOTS 4				195	
N40	NormanWW#40				418	
N5	NormanWW#5	97	167	286	488	
N6	Norman Well #6	129	221	352	564	
N7A	Norman Well #7-A	298			737	
N8	NormanWW#8	168	271	411	578	
Nb11	Noble Well #11	118	283	365		
Nb3	Noble Well #3	163	350			
NbT1	Noble Test Well #1		222	386		
NbT2	Noble Test Well #2		224	388		
NbT3	Noble Test Well #3	83	254	407		
NbT4	Noble Test Well #4	207	295	392		
NbT5	Noble Test Well #5		341			
NbTW1	Noble Test Well #1	213				
NbTW2	Noble Test Well #2	189	258	411		
NC1	OU North Campus Well #1	234	309	476		
NC11	OU NC Well #11	243	296	453		
NC13	OU NC Well #13	281	370	511		
NC1A	OU North Campus Well #1A		340	482	630	
NC2A	OU North Campus Well #2A	229	337	467	632	
NoSM	Noble Southern Mea		247	423		
NpT1	City of Norman Andrews Park Test Well #1	286	386	514	686	
NT1	City of Norman Test Well #1	163	248	374	537	
NT10	City of Norman Test #10	10	201	321	419	
NT11	City of Norman Test #11		197	287	403	
NT12	City of Norman Test #12		185	283	400	
NT13	City of Norman Test #13				414	
NT2	City of Norman Test Well #2	156	261	372	536	
NT3	City of Norman Test Well #3	48	244	343	461	
NT4	City of Norman Test #4		193	315	410	
NT5	City of Norman Test Well #5	98	265	383	499	

Well Label	Well Name	Garber Top	Unit B Top	Unit C Top	Garber Base	Wellington Base
NT6	City of Norman Test #6		163	272	378	
NT7	City of Norman Test #7		118	207	329	
NT8	City of Norman Test Well #8	82	118			
NT9	City of Norman Test #9		169	302	397	
Nw6	NormanWW#6	128	221	356	566	
O1	Adam #1				223	1059
O17	Sante Fe RR #1-30		184	454		1232
O18	Marathon MW-17	356	451	644		
O19	Marathon MW-18	317			733	
O2	Leonard #1					963
O20	Marathon MW-16	351	433	592	775	
O21	Garrett #1					720
O22	Kusek #1					709
O23	Lowry #1				292	772
O24	Cooper #1				233	779
O25	Singer #1				232	772
O26	Skelton #1					704
O27	Tickle #1				229	745
O28	Claudine #1				391	882
O29	Guthrie #1					766
O3	Jesse #1					1202
O30	Whitehead #1				314	836
O31	Larkin #1					1096
O32	Carrier #1					843
O33	Test Well #21			368		
O34	Divacky #1					1059
O35	Little #1				422	1086
O36	Stamper #7				440	1204
O37	Emerson #13				467	1198
O38	Vencl #18				500	
O39	Salsman #6				751	1077
O4	Tinker #1					1060
O41	Theimer #9				428	1158

Well Label	Well Name	Garber Top	Unit B Top	Unit C Top	Garber Base	Wellington Base
O42	Theimer #1				555	1106
O43	ACOG MW	75			480	
O44	OKC Stockyards	150			610	
O45	Trospar Park #37				412	1014
O46	Trosper #14				456	1000
O47	Surbeck #A-1					1114
O48	Werner Farley SWD #4	69			561	1102
O49	ACOG MW OK-5				504	
O5	Harvest #1					744
O50	Billen #1				502	
O51	Lord #1	101			582	1154
O52	Fuson #1	188			706	1298
O55	Hayes #1	468			911	1586
O58	Zurline #1	399			911	1592
O6	Echo #1-13					687
O61	Cermak #1	589			1075	1696
O7	City of Choctaw Well #8				387	
O8	Test Well #1		90			
OU10	OU Well #10	301				
OU11	OU Navy Well #11	205	300	474		
OU12	OU Well #12	242	288	456		
OU14	OU Navy Well #14	264	383	505	649	
OU15	OU Navy Well #15	197	302	438		
OU3A	OU Well #3A	228	324	490		
OU4	OU Naval Well #4	199	290	457		
OU4A	OU Well #4-A	225		473	632	
OU5	OU Navy #5	247	339	484	630	
OU6	OU Navy Well #6	228	331	482	621	
OU7A	OU Naval Base Well #7A	232	339	484	624	
OU8	OU Navy Well #8	220	305	459		
OU9	OU Well #9	298			737	
OUT1	OU Test Well #1	215	296	455	625	
T30	TAFB Well #30		248	498	400	

Well Label	Well Name	Garber Top	Unit B Top	Unit C Top	Garber Base	Wellington Base
T31	TAFB Water Well #31		264	514	412	
T32	TAFB Test Well #32		189	414	413	
T33	TAFB Water Well #33		155	421		
TT34	TAFB Water Well Test #33		165	430		
Y13	Yukon Well #13	352	436	597	792	
Y5	Yukon Well Y-V	426			937	
Y6	Yukon Well Y-VI	660				
Y8	Yukon Well Y-VIII	328			845	
YP6	Yukon Well Y-P-6	322		578	801	
YT1	City of Yukon Test Well #1	346	443	591	808	
YT3	Yukon Test Well #2	265			764	
YT4	City of Yukon Test Hole #Y-IV	422			897	
YT7	Yukon Test Well Y-VII	270		525	775	
YTY1	Yukon Test Well Y-I	498			930	

APPENDIX C

NORMAN WATER WELL DATA

Well Label	Well Name	Arsenic (ppb)	TD	Garber Top
30	Norman Well NW36th		850	
31	Norman Well #8A		685	
171	Norman Well #2-A		732	
N1	Norman Well #1	0.85	684	56
N10	Norman Well #10	4.59	600	217
N11	Norman Well #11	40.06	630	231
N12	Norman Well #12	52.82	670	234
N15	Norman Well #15	22.88	670	217
N16	Norman Well #16	25.2	676	234
N17	Norman Well #17		720	213
N18	Norman Well #18	10.85	691	212
N19	Norman Well #19	7.23	688	167
N2	Norman Well #2	10.61	740	42
N20	Norman Well #20	3.68	694	138
N21	Norman Well #21	38.35	638	193
N22	Norman Well #22		624	207
N23	Norman Well #23	93.4	631	192
N24	Norman Well #24	231	560	189
N25	Norman Well #25	59.33	625	161
N31	Norman Well #31	30	655	170
N32	Norman Well #32	23.57	600	156
N33	Norman Well #33	1.97	635	97
N34	Norman Well #34	6.25	602	42
N35	Norman Well #35	1.03	514	
N36	Norman Well #36	17.81	710	
N37	Norman Well #37	1.48	710	
N39	Norman Well #39	5.05	695	
N3A	Norman Well #3-A	0.83	766	51
N40	Norman Well #40	1.08	698	
N5	Norman Well #5	11.85	677	97
N6	Norman Well #6		602	129
N7A	Norman Well #7-A	20.34	850	298
N8	Norman Well #8	2.02	760	168
NL1	Norman Well #14	42.2		
NL2	Norman Well #13	10.08		
NL3	Norman Well #4	40.73		
NL4	Norman Well #38	0.81		
NpT1	City of Norman Andrews Park Test Well #1		830	286
NT1	City of Norman Test Well #1		743	163
NT10	City of Norman Test #10		696	10
NT11	City of Norman Test #11		700	
NT12	City of Norman Test #12		700	
NT13	City of Norman Test #13		786	
NT2	City of Norman Test Well #2		749	156
NT3	City of Norman Test Well #3		745	48
NT4	City of Norman Test #4		735	
NT5	City of Norman Test Well #5		737	98
NT6	City of Norman Test #6		590	
NT7	City of Norman Test #7		644	
NT8	City of Norman Test Well #8		296	82
NT9	City of Norman Test #9		690	
Nw6	Norman Well #6	7.98	690	128

Well Label	Unit B Top	Unit C Top	Garber Base	Net Clean Sand (ft.)	Net Clean Sand, Upper 300 ft.
30					
31				696	262.8
171	185	323	456	700	241.5
N1	214	370	490	700	242.6
N10	319	452		786	288.9
N11	342			735	284.2
N12	325		667	590	202.5
N15	300	465	640	644	223.4
N16	344	487	659	690	257.9
N17			640	580	224
N18	320	462	651	593	187.9
N19	285	435	619	697	248.1
N2	165	286	493	639	228.5
N20	264	404	614	214	80.5
N21	277	420	599		
N22	287	441	615		
N23	301	439	607		
N24	286	423			
N25	279	411	571		
N31	254	365	543		
N32	261	373	537	628	251
N33	260	380	496	383	193.8
N34	244	340	457	399	174
N35	194	302	400	436	171.8
N36	159	268	380	453	182.5
N37	124	208	328	442	127.4
N39	193	291	403	507	190.7
N3A	218	367	487	479	201.9
N40			418	525	201.1
N5	167	286	488	698	260.8
N6	221	352	564	556	192.9
N7A			737	445	124.7
N8	271	411	578	417	172
NL1				439	185.5
NL2				371	130.9
NL3				464	101.8
NL4				485	188.9
NpT1	386	514	686	444	138.7
NT1	248	374	537	538	272.7
NT10	201	321	419	560	273.9
NT11	197	287	403	514	207.5
NT12	185	283	400	710	247
NT13			414	710	277
NT2	261	372	536		
NT3	244	343	461	695	287.1
NT4	193	315	410		
NT5	265	383	499	698	271.4
NT6	163	272	378	619	215.3
NT7	118	207	329	562	279.7
NT8	118			592	228.8
NT9	169	302	397		
Nw6	221	356	566		

Well Label	Net Clean Sands >4 ft.	Net Clean Sands >8 ft.	Shale Thickness	Unit A Isopach Thickness
30				
31		219.89	189.21	133.1
171		197	166.35	142.5
N1		207.26	153.86	136
N10		244.84	145.25	176.4
N11		252.01	192.2	201.3
N12		164.39	129.26	100.3
N15		182.39	127.65	105.6
N16		211.69	183.49	148.7
N17	110.8	219.68	198.93	119.3
N18	114.7	179.9	134.23	132.6
N19	95.8	238.2	221.52	184.5
N2		206.72	179.45	98.5
N20		67.98	46.33	47.5
N21				
N22				
N23				
N24				
N25				
N31				
N32	90.8	233.09	191.69	106
N33	153.8	189.04	154.71	29
N34	142.7	169	169	42
N35	106.9	170.79	159	27
N36	121.8	181.18	152.17	43
N37	92.7	117.16	93.96	59
N39	91.7	185.96	155.87	50.2
N3A	106.2	190.79	152.48	21
N40	119.3	197.91	175.01	47
N5	209.9	227	152.91	133
N6	115.3	172.45	151.98	42
N7A	90	113.22	87.17	61
N8	111.2	166.85	138.55	26.5
NL1	143.2	172.09	146.91	29
NL2	111.1	91.56	36.59	22.9
NL3	52.9	92.2	68.07	111
NL4	113.8	172.57	153.3	46
NpT1	119.6	137.27	99.68	97
NT1	178.4	246.67	204.3	74
NT10	187.4	272.87	264.72	73.7
NT11		184.48	138	69
NT12		211.01	121.04	169.5
NT13		254.12	197.28	146.8
NT2				
NT3		281.9	242.13	90.8
NT4				
NT5		241.11	205.32	142.7
NT6		200.5	127.25	118.6
NT7	228.8	255	234.54	75.3
NT8	139.8	212.65	161.4	100.4
NT9				
Nw6				

Well Label	Unit A Net Clean Sand (ft.)	Unit A Shale Thickness	Unit A Shaly Sand Thickness
30			
31	191	67.21	36.3
171			
N1			
N10			
N11			
N12			
N15			
N16			
N17	85	22.21	0
N18	105.1	49.03	9.7
N19	196.3	42.07	30
N2	167.2	40.58	8.9
N20			
N21			
N22			
N23			
N24			
N25			
N31			
N32			
N33	102	74.97	0
N34			
N35			
N36			
N37			
N39			
N3A			
N40			
N5	123	76.24	3.6
N6			
N7A	84.4	33.97	3.9
N8	80	16.08	15.7
NL1	108.7	50.46	0
NL2	97	40.55	6.6
NL3			
NL4	84	23.5	0
NpT1	105	52.81	10.9
NT1	163.5	75.18	13.8
NT10	202.3	125.02	0
NT11			
NT12			
NT13			
NT2			
NT3			
NT4			
NT5			
NT6	70	45	0.4
NT7	93.4	71.63	11.7
NT8	102.5	41.9	0
NT9			
Nw6			

Well Label	Unit B Isopach Thickness	Unit B Net Clean Sand (ft.)	Unit B Shale Thickness
30			
31	87.5	120	58.82
171		90	41.88
N1		98	56.44
N10			
N11		122	53.92
N12		109	55.1
N15		89	48
N16		133	65.43
N17	62.8	126	38.38
N18	46.4	111	24.4
N19	124.2	99	49.18
N2	126.6	118	45.11
N20			
N21			
N22			
N23			
N24			
N25			
N31			
N32			
N33	27	133	50.88
N34			
N35			
N36			
N37			
N39			
N3A			
N40			
N5	43.1	121	24.66
N6			
N7A	46.4	143	31.16
N8	48.2	154	65.53
NL1	58.3	138	50.61
NL2	49.9	137	36.45
NL3			
NL4	60.5	111	30.91
NpT1	41.3	112	24.14
NT1	74.4	120	70.08
NT10	77.3	96	62.42
NT11		108	64.37
NT12		109	56.13
NT13		84	55.03
NT2			
NT3		98	52.44
NT4			
NT5			
NT6	24.6	119	27.27
NT7	23.8	135	67.2
NT8	60.6	140	50.55
NT9			
Nw6			

Well Label	Unit B Shaly Sand Thickness	Unit C Isopach Thickness	Unit C Net Clean Sand (ft.)
30			
31	14.5	46.7	98
171	16.1	32	115.76
N1	10.6	30.9	116.82
N10			
N11	23.1	45	95
N12	11.7	42.2	106.3
N15	10.4	30.6	122.21
N16	10.2	57.4	95
N17	39.1	48.5	163
N18	6.9	79.7	164
N19	19.1	30.7	118
N2	0	72.9	116
N20			
N21			
N22			
N23			
N24			
N25			
N31			
N32			
N33	23.3	58.8	
N34			
N35			
N36			
N37			
N39			
N3A			
N40			
N5	37.8	58.5	207
N6			
N7A	21.5	90.3	179
N8	3.6	84.9	174
NL1	4.9	82.5	167.68
NL2	10.4	90.2	
NL3			
NL4	15.2	64.9	178
NpT1	4.5	83.3	164
NT1	0	49.9	116
NT10	5.9	27.6	117
NT11	3	40.7	98
NT12	32.9	20	111.9
NT13	5.9	23	120
NT2			
NT3	4.9	40.6	111.58
NT4			
NT5			
NT6	25.5	66.2	202
NT7	9.9	57.9	210
NT8	9.7	79.8	167
NT9			
Nw6			

Well Label	Unit C Shale Thickness	Unit C Shaly Sand Thickness
30		
31	34.58	11.1
171	45.15	5.7
N1	42.94	14.5
N10		
N11	47.59	15.7
N12	58.95	2.2
N15	23.27	23.9
N16	25.33	20.8
N17	67.07	10.2
N18	53.86	38.7
N19	63.3	21.2
N2	64.73	6.8
N20		
N21		
N22		
N23		
N24		
N25		
N31		
N32		
N33		
N34		
N35		
N36		
N37		
N39		
N3A		
N40		
N5	64.12	56.5
N6		
N7A	59.14	20.1
N8	89.97	7.3
NL1	85.58	0.7
NL2		
NL3		
NL4	85.35	1.1
NpT1	55.42	37.6
NT1	76.86	2.4
NT10	62.26	4.8
NT11	52.95	3
NT12	56.68	5.5
NT13	13.49	40.5
NT2		
NT3	39.96	0
NT4		
NT5		
NT6	74.7	32.2
NT7	100.2	31.3
NT8	96.34	22
NT9		
Nw6		

APPENDIX D

UNIVERSITY OF OKLAHOMA WATER WELL DATA

Well Label	Well Name	Arsenic (ppb)	TD	Garber Top	Unit B Top
181	OU Naval Base Well #7	18	615		
184	OU Naval Base Well #6	16	623		
209	OU Navy Well #5	16	598		371
MC1A	OU Main Campus Well #1-A		642	228	339
MC2A	OU Main Campus Well #2-A		632	205	315
MC3A	OU Main Campus Well #3A		647		
NC1	OU North Campus Well #1		608	234	309
NC11	OU North Campus Well #11		629	243	296
NC13	OU North Campus Well #13	47	671	281	370
NC1A	OU North Campus Well #1A		630		340
NC2A	OU North Campus Well #2A	57	634	229	337
NL5	OU North Campus Well #8	20			
OU10	OU Well #10		610	301	
OU11	OU Navy Well #11		510	205	300
OU12	OU Well #12	81	624	242	288
OU14	OU Navy Well #14	37	752	264	383
OU15	OU Navy Well #15		522	197	302
OU3A	OU Well #3A	24	629	228	324
OU4	OU Naval Well #4		469	199	290
OU4A	OU Well #4-A	29	634	225	
OU5	OU Navy #5		759	247	339
OU6	OU Navy Well #6		744	228	331
OU7A	OU Naval Base Well #7A	18	618	232	339
OU8	OU Navy Well #8		546	220	305
OU9	OU Well #9	53	795	298	
OUT1	OU Test Well #1		745	215	296

Well Label	Unit C Top	Garber Base	G/W Logged Thickness	Net Clean Sand (ft.)
181	476			
184	469			
209	504			
MC1A	476	609	414	97.2
MC2A	454	590	427	88.6
MC3A	475	608	283	98.3
NC1	476		383	125.2
NC11	453		386	112.9
NC13	511		390	175.5
NC1A	482	630	380	148.7
NC2A	467	632	405	99.2
NL5				
OU10			260	85.7
OU11	474		305	109.2
OU12	456		382	100.8
OU14	505	649	488	133.9
OU15	438		325	124.8
OU3A	490		329	87.1
OU4	457		270	119.6
OU4A	473	632	634	134.6
OU5	484	630	512	172.8
OU6	482	621	516	204.3
OU7A	484	624	382	143.7
OU8	459		326	93.7
OU9		737	497	172.4
OUT1	455	625	530	161.6

Well Label	Net Clean Sand, Upper 300 ft.	Net Clean Sands >4 ft.	Net Clean Sands >8 ft.
181			
184			
209			
MC1A	45.6	84.05	51.87
MC2A	57.7	79.16	51.25
MC3A		90.21	48.49
NC1	119.1	122.19	104.86
NC11	89	83.16	50.24
NC13	108	166.19	137.07
NC1A		142.37	129.38
NC2A	65.6	71.52	41.87
NL5			
OU10		37.13	10.7
OU11	101.6	105.92	101.58
OU12	67	85.22	66.13
OU14	72.9	125.01	69.06
OU15	124.2	112.77	112.77
OU3A		82.65	71.32
OU4	119.6	119.6	100.48
OU4A		131.41	117.98
OU5	121.3	156.31	142.65
OU6	155.1	155.91	141.11
OU7A	74.5	127.27	113.25
OU8	93.7	89.18	89.18
OU9	84.7	154.92	142.28
OUT1	94.5	141.43	125.45

Well Label	Shale Thickness	Unit A Isopach Thickness	Unit A Net Clean Sand (ft.)
181			
184			
209			
MC1A	150	111	1.99
MC2A	93.5	110	47.78
MC3A			
NC1	71.4	75	
NC11	89		
NC13	54.5	89	38.73
NC1A	97.8		
NC2A	160.1	108	13.61
NL5			
OU10	86.3		
OU11	35.2	95	3.8
OU12	102		
OU14	114.1	119	20
OU15	72.3	105	11.5
OU3A	109.3	96	
OU4	38.7	91	
OU4A	60.5		
OU5	105.5	92	43.6
OU6	35.4	103	46
OU7A	49.8	107	9.2
OU8	39.2	85	
OU9	113.6		
OUT1	157.7	81	16.2

Well Label	Unit A Shale Thickness	Unit A Shaly Sand Thickness	Unit B Isopach Thickness
181			
184			
209			
MC1A	44.6	64.4	137
MC2A	0	62.2	139
MC3A			
NC1	0		167
NC11			
NC13	5.8	44.4	141
NC1A			
NC2A	53.7	40.6	130
NL5			
OU10			
OU11	29.6		174
OU12			
OU14	26.7	72.3	122
OU15	25.2		136
OU3A	0		166
OU4	3.2		167
OU4A			
OU5	2	46.4	145
OU6	0	57	151
OU7A	13.2	84.6	145
OU8	0		154
OU9			
OUT1	14.5	50.3	159

Well Label	Unit B Net Clean Sand (ft.)	Unit B Shale Thickness	Unit B Shaly Sand Thickness
181			
184			
209			
MC1A	17.84	59.6	59.6
MC2A	33.16	56.8	49
MC3A			
NC1		46.4	
NC11			
NC13	63.81	13.9	63.3
NC1A			
NC2A	40.33	55.8	33.8
NL5			
OU10			
OU11		5.6	
OU12			
OU14	35.22	30.6	56.2
OU15		43.3	
OU3A		42.5	
OU4		35.5	
OU4A			
OU5	38.18	22.1	84.7
OU6	59.67	8.3	83.1
OU7A	43.15	35.8	66
OU8		15.7	
OU9			
OUT1	47.4	28.4	83.2

Well Label	Unit C Isopach Thickness	Unit C Net Clean Sand (ft.)
181		
184		
209		
MC1A	133	62.37
MC2A	136	61.17
MC3A	133	
NC1		
NC11		
NC13		
NC1A		
NC2A	165	43.13
NL5		
OU10		
OU11		
OU12		
OU14	144	67.15
OU15		
OU3A		
OU4		
OU4A	159	
OU5	146	71.98
OU6	139	69.7
OU7A	140	91.3
OU8		
OU9		
OUT1	170	67.05

Well Label	Unit C Shale Thickness	Unit C Shaly Sand Thickness
181		
184		
209		
MC1A	33.1	37.5
MC2A	18.1	56.7
MC3A	0	
NC1		
NC11		
NC13		
NC1A		
NC2A	50.5	71.3
NL5		
OU10		
OU11		
OU12		
OU14	25.9	51
OU15		
OU3A		
OU4		
OU4A	23.9	
OU5	42.3	31.7
OU6	8.3	61
OU7A	0.8	47.9
OU8		
OU9		
OUT1	51.8	51.2

APPENDIX E

GARBER-WELLINGTON CONTACT STUDY

During the earlier stages of this thesis, it became apparent that deciding where to pick the Garber-Wellington contact on well logs may be problematical. The two formations have similar log characteristics, and there are virtually no regional marker beds. Jim Roberts, a geological consultant who has done some impressive work on the Garber and Wellington, shared how he approached the problem. He explained that the shale beds in the Wellington had lower resistivity on average than the shale beds in the Garber, and therefore the contact would occur at a point in the section where a general decrease in shale resistivity was observed. He also stated that the Wellington Formation generally contains more shale than the Garber Sandstone. Figure E1 shows the log from the City of Moore Test Well #1, and where the Garber-Wellington contact would be placed based on Mr. Roberts' theory. The red dashed line was added as a reference line for shale resistivity. On this log, most of the shale beds below 530' have lower resistivity than those above 530', so the contact was placed at 530', the depth where the decrease occurs.

To test this idea, 28 well logs were digitized and analyzed statistically using *SAS* (the wells used are listed in Table E1). Four curves for each well were digitized and sampled at a rate of 3 samples per foot. It was necessary to assume that the technique was effective and pick the contact on the logs based on the criteria discussed above, so that there would be two groups of samples to compare. If the data above where the contact was picked were markedly different from the data below, i.e., if the section below the datum was shalier than the section above, then it would be assumed that the contact was probably in the right place. Since the aim of this project was to prove or disprove that the methodology for picking the Garber-Wellington contact was valid, the terms “Garber” and “Wellington” are used in the discussion below only to differentiate between the interval above the proposed contact depth and the interval below it.

Simple univariate analysis of the data shows that the mean gamma ray value for the interval above the chosen datum (proposed Garber-Wellington contact) is lower than the interval below, i.e., the upper section is, on average, “cleaner” than the lower interval. The mean long normal and short normal are lower for the lower interval; from Mr. Roberts’ theory, lower resistivity in the Wellington would be expected, although this could be partially due to increasingly saline water with depth. The SP curve on average has lower deflection in the upper interval, which would normally indicate lower shale content. However, this could be because of the presence of freshwater causing a suppressed SP response over much of the interval. Table E2 shows a comparison of summary statistics for the two populations.

	“Garber”		“Wellington”	
Log Type	Mean	Std Dev	Mean	Std Dev
Gamma Ray	81.5	23.1	93.4	27.9
SP	-2.1	17.97	-6.5	15.8
Long Normal	34.9	22.1	28.8	19.2
Short Normal	42.6	30.9	30.9	23.4

Table E2, Comparison of mean and standard deviation the 2 groups of log curves.

The easiest way to examine the differences between the two groups of data was to plot all the samples of a given log type on the same chart, with the proposed Garber-

Wellington contact used as the datum. For instance, all the gamma ray curves for all 28 wells were plotted on the same chart, with API units on the x-axis and depth on the y-axis. However, the depth axis cannot be subsea depth or measured depth, but rather depth relative to the proposed Garber-Wellington contact. In other words, for each well, the depth where the contact was picked was given a value of zero, with positive depth above and negative depth below. This removes any smearing of the data that would occur because of the dip of the beds.

The resulting log data comparison charts, which can be seen in Figure E2, make clear several differences between the interval above the datum and the interval below, as do frequency distributions of the log data, shown in Figures E3 and E4. On Figure E2, the section above the datum is shown in red, and the section below is shown in blue. The gamma ray curve comparison (Figure E2) shows that there are more data points with high gamma ray values below the contact, indicating increased shale content. This observation fits well with what was expected in terms of Garber Sandstone versus Wellington Formation. The histograms of gamma ray values (Figure E3) also show that the Wellington is more heavily weighted towards higher gamma ray values than the Garber, also indicating a higher abundance of shale and clays. The SP curve comparison shows that the Garber has larger SP deflections, both positive and negative, than the Wellington. This may indicate a higher percentage of well-developed sandstones in the Garber. The SP frequency distributions show a similar result, with the histogram for Garber SP values being wider at the base than that of the Wellington, indicating a higher frequency of sandstones with larger deflections. Both the long normal and short normal figures show lower resistivity below the proposed contact, which may be partly because of lower shale resistivity, but is probably also caused by increasingly saline water in the sandstones with depth. The histograms of Garber versus Wellington show that both the long normal and the short normal are more heavily skewed towards low-resistivity values in the Wellington than in the Garber.

The gamma ray chart on Figure E2 and the gamma ray frequency distributions are the most revealing about the differences between the two populations of data, since effects of water chemistry on the measurements are minimal. There is a larger percentage of shale below the datum than above it, and the increase in shale is quite abrupt. If it is true that the Garber Sandstone contains less shale than the Wellington Formation, then the contact was probably placed at or very close to the correct depth. If it were placed at the wrong depth, then one would not expect to see any obvious differences between the two groups of data. Furthermore, although the gamma ray data may be the most definitive, a marked change in the shape of the plots on Figure E2 occurs on the log data vs. depth charts for all four log types.

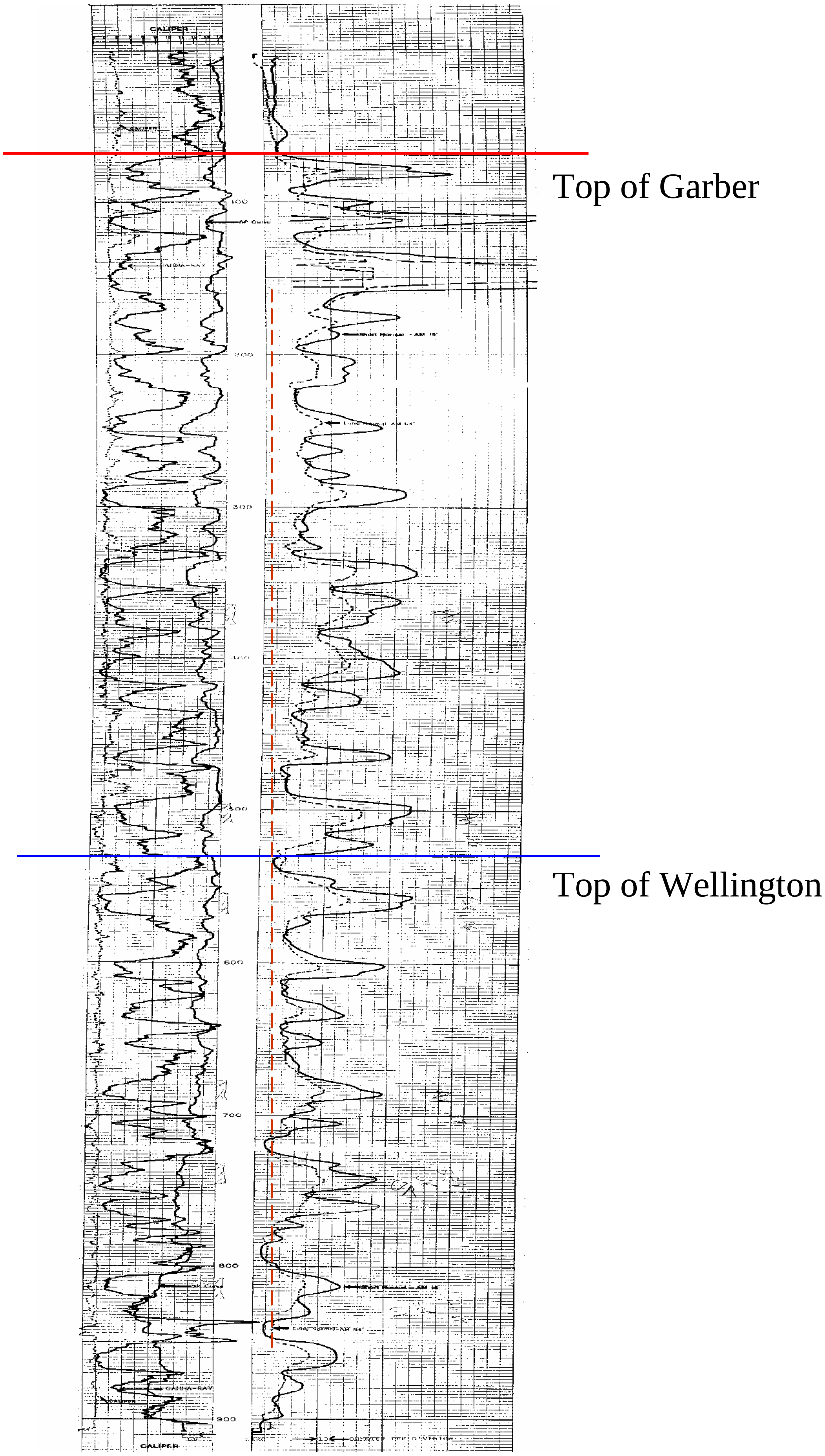


Figure E1. City of Moore Test Well #11, showing lower shale resistivity in the Wellington Formation

Table E1. List of wells used in Appendix E

UWI	Well Name	Surf Lat	Surf Lon	Datum	Township	Range	Section	Spot Call	Top Garb	Top Well
9	City of Norman Test #13	35.26084	-97.3785	1173	9N	2W	14	NWNWNE		456
26	NormanWW#36	35.27575	-97.4053	1084	9N	2W	10	NWNWNW		380
27	NormanWW#37	35.27577	-97.3918	1081	9N	2W	18	NWNENE		331
62	City of Moore #36	35.34682	-97.448	1245	10N	2W	18	C NW NE	82	499
63	City of Moore #2 Test Hole	35.33507	-97.4513	1198	10N	2W	18	SE SE SW	78	476
71	City of Moore #1 Test Hole	35.36406	-97.4625	1275	10N	3W	1	SW SE SE	68	529
72	City of Mustang Test Well #7	35.37076	-97.5483	1271	10N	3W	6	SE SE SE NE	276	682
78	City of Mustang #11	35.33479	-97.5216	1217	10N	3W	16	SE SE SE SW	228	694
79	City of Mustang #9	35.34425	-97.5311	1222	10N	3W	17	NE SE NE	270	659
81	City of Mustang #13	35.34773	-97.5554	1205	10N	3W	18	NW NW NE	289	708
89	McBride #1	35.3501	-97.6468	1277	10N	4W	8	SE SW	573	
152	City of Norman Test #9	35.27538	-97.4137	1093	9N	2W	9	NW NW NE		348
153	City of Norman Test #4	35.26996	-97.4071	1113	9N	2W	9	SE SE SE NE		410
155	City of Norman Test #7	35.27538	-97.3917	1081	9N	2W	10	NW NE NE		329
157	City of Norman Test #12	35.26996	-97.3894	1145	9N	2W	10	SE SE NE		400
158	City of Norman Test #6	35.27538	-97.4049	1084	9N	2W	10	NW NW NW NW		378
159	City of Norman Test #11	35.26816	-97.3894	1160	9N	2W	10	NE NE SE		403
160	City of Norman Test #10	35.26274	-97.3961	1150	9N	2W	10	SW SW SE		419
165	City of Norman Test Well #5	35.26082	-97.4138	1183	9N	2W	16	NW NW NW NE	98	531
166	City of Norman Test Well #3	35.25901	-97.4072	1160	9N	2W	16	SE SE NE NE	48	461
168	City of Norman Test Well #2	35.25908	-97.4247	1180	9N	2W	17	SE NE NE	156	537
169	City of Norman Test Well #1	35.26088	-97.4402	1160	9N	2W	17	NW NW NW	163	535
177	Washington School Test Well #2	35.21274	-97.3728	1130	9N	2W	35	SE NE		
183	City of Norman Well #7-A	35.24102	-97.4931	1164	9N	3W	23		298	737
185	Westport Golf Club Test #1	35.22746	-97.4833	1155	9N	3W	26	SW NE	311	744
187	City of Mustang Well #10	35.34057	-97.5288	1208	10N	3W	16	NW NW SW	230	649
188	City of Mustang Test #9B	35.34336	-97.5322	1223	10N	3W	17	SE NE	287	708
193	Test Well #1	35.30154	-97.5962	1190	10N	4W	35	NW	408	

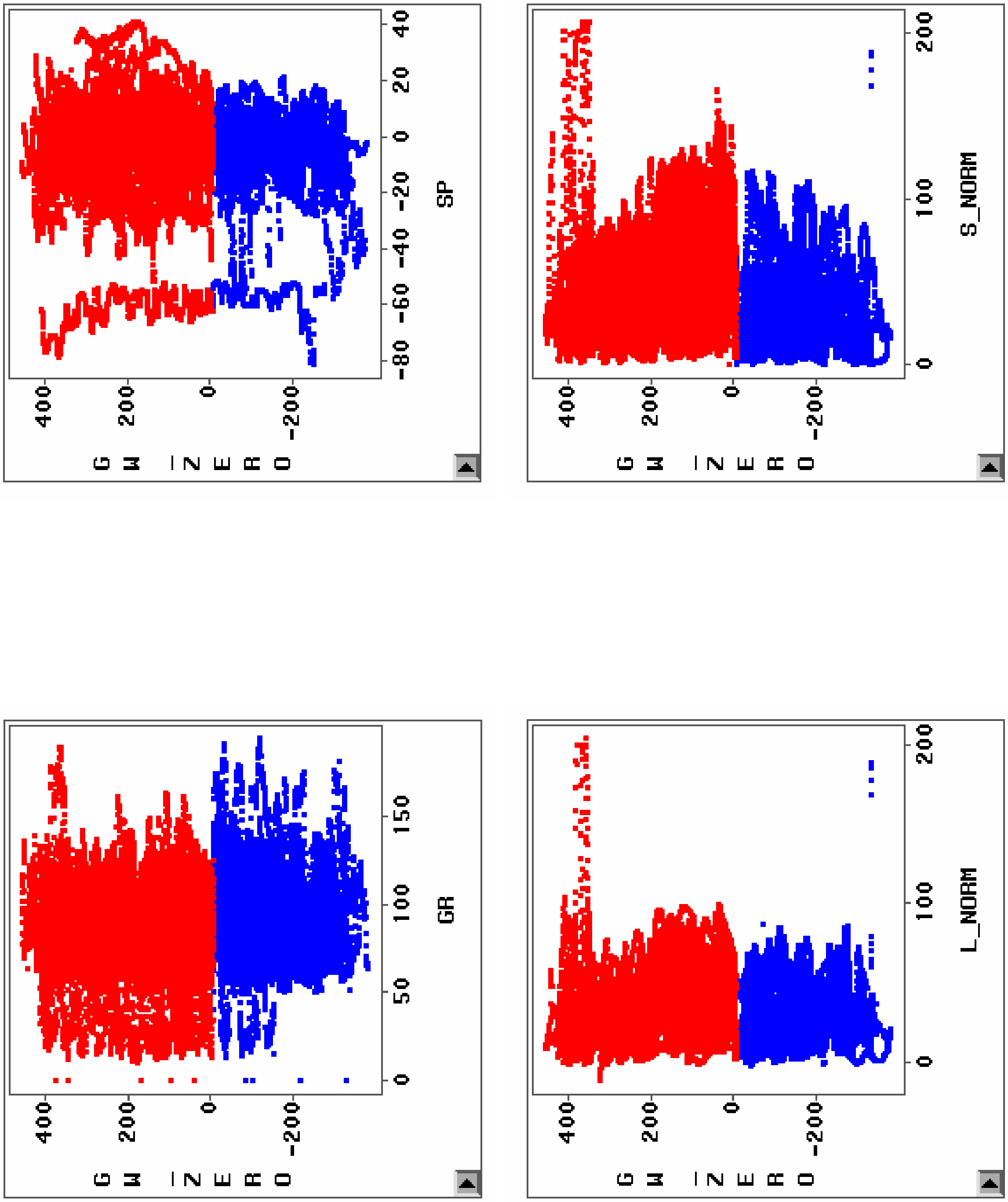


Figure E2. Cross plots of digital log data vs. depth. Zero on the y-axis is the proposed contact depth.

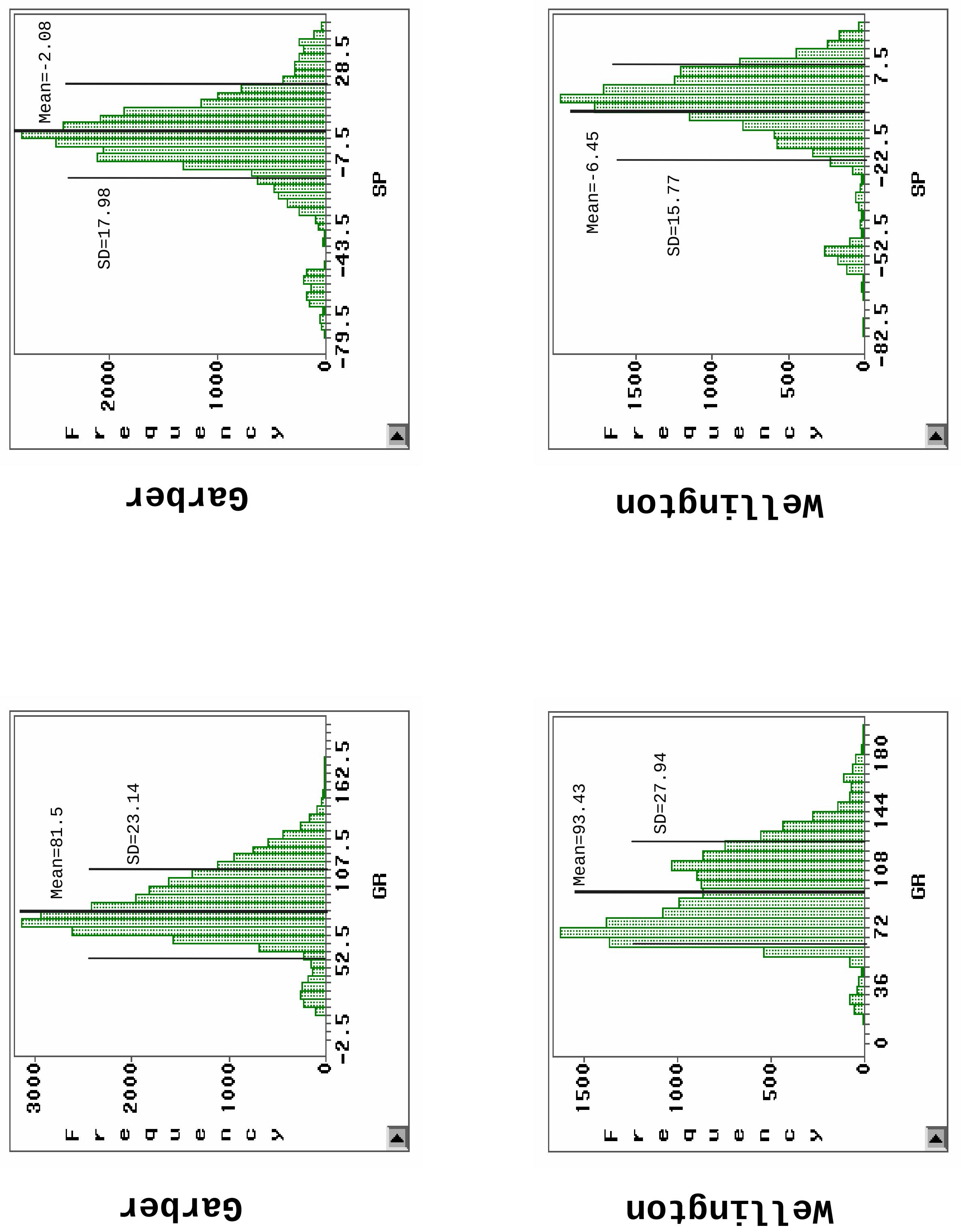


Figure E3. Frequency distribution comparisons for Garber (top) and Wellington (bottom), gamma ray data (left) and SP data (right)

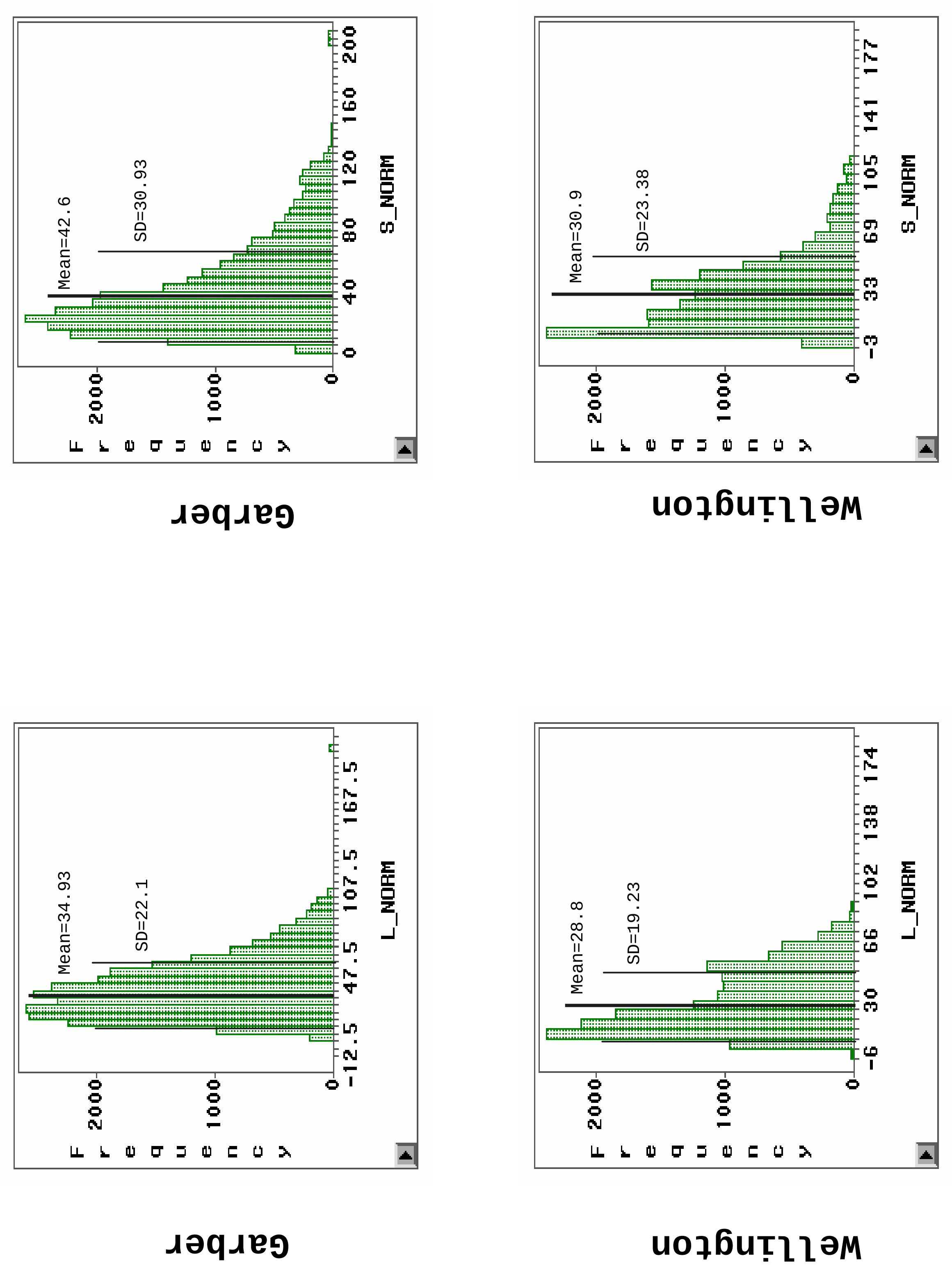


Figure E4. Frequency distribution comparisons for Garber (top) and Wellington (bottom), long normal data (left) and short normal data (right)

Plate 1. Base Map, Cleveland County and southern Oklahoma County (strucural features from Luza and Lawson, 1981).

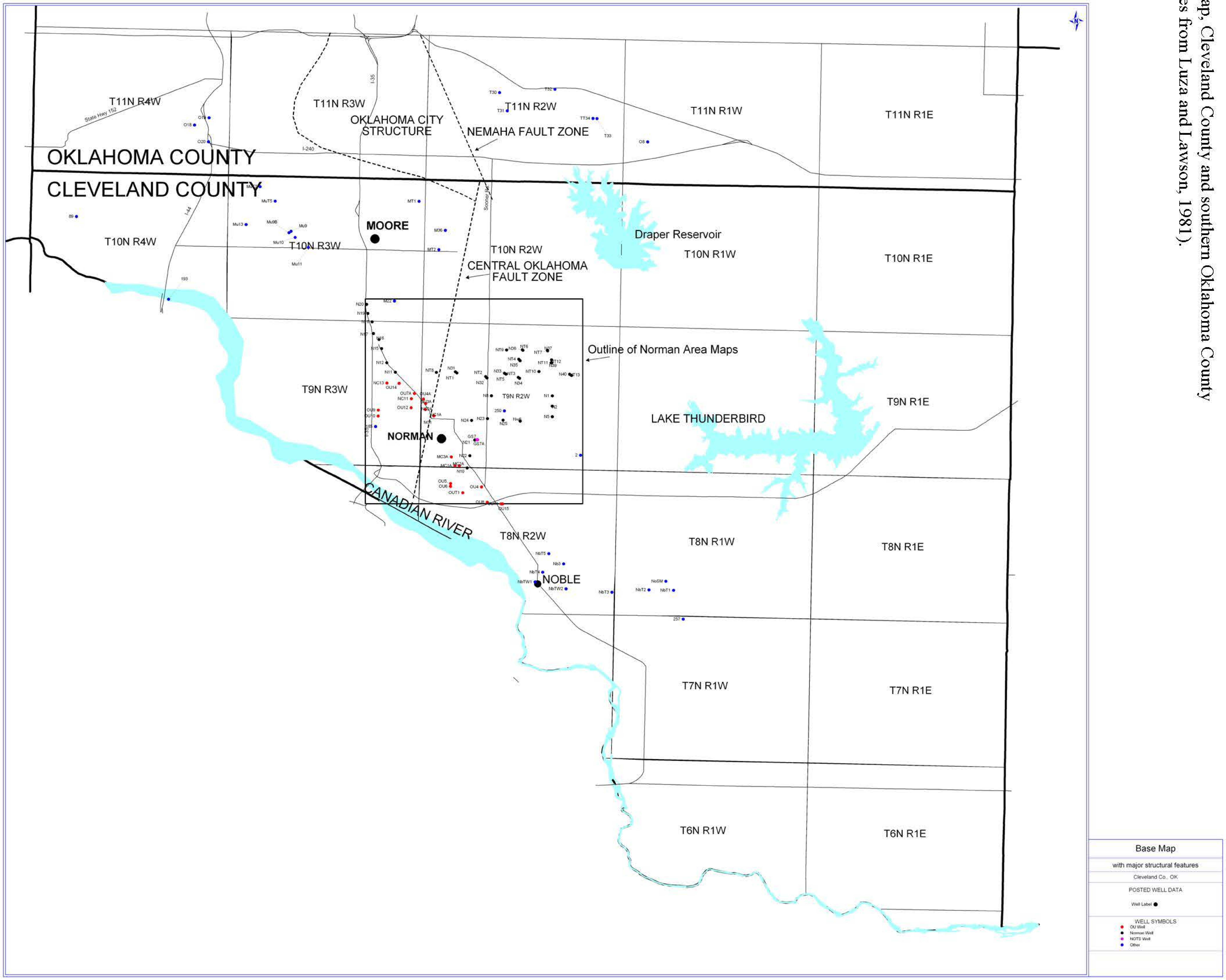
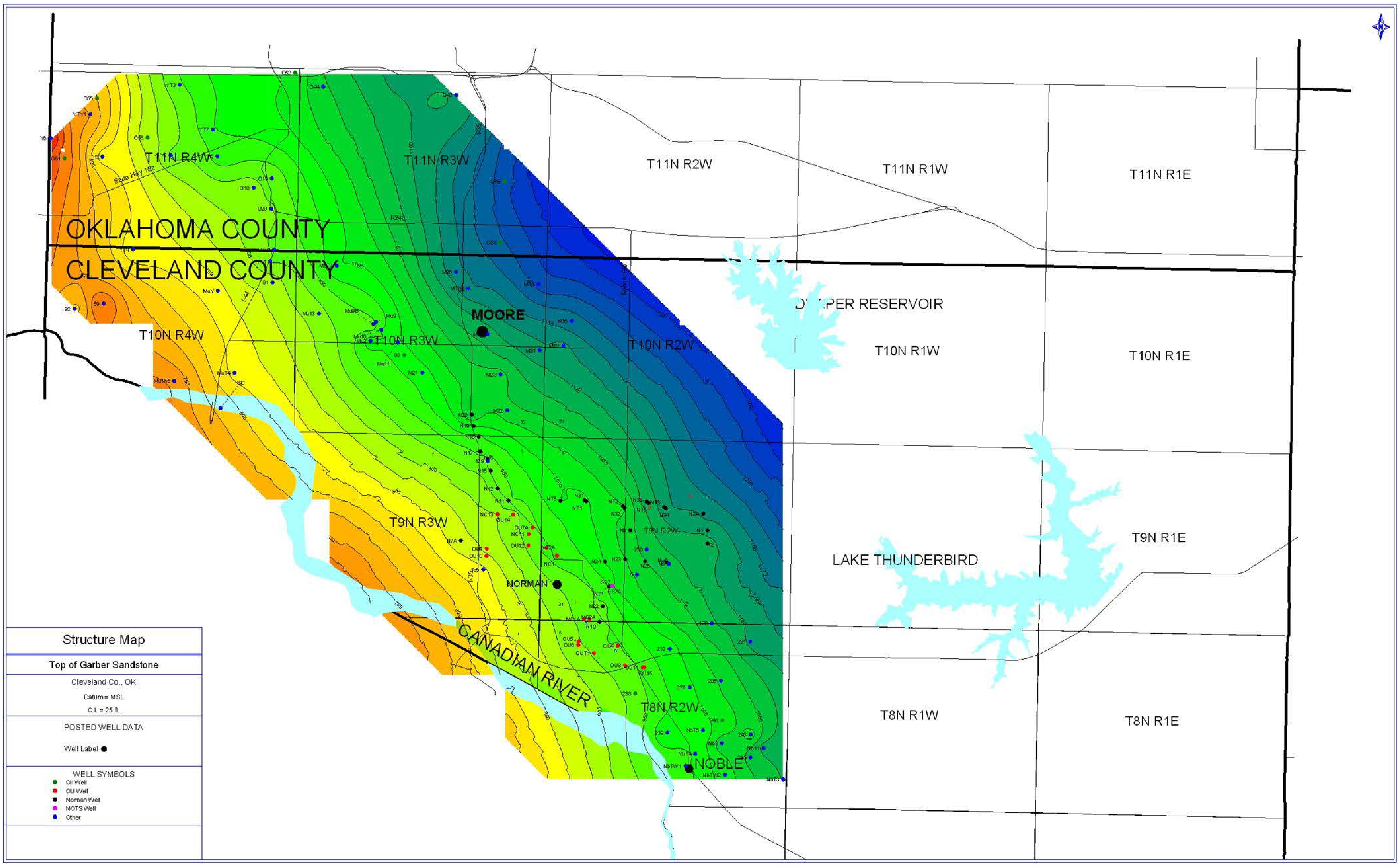


Plate 2: Structure Map, Top of Garber Sandstone, and Garber Sandstone Isopach Map



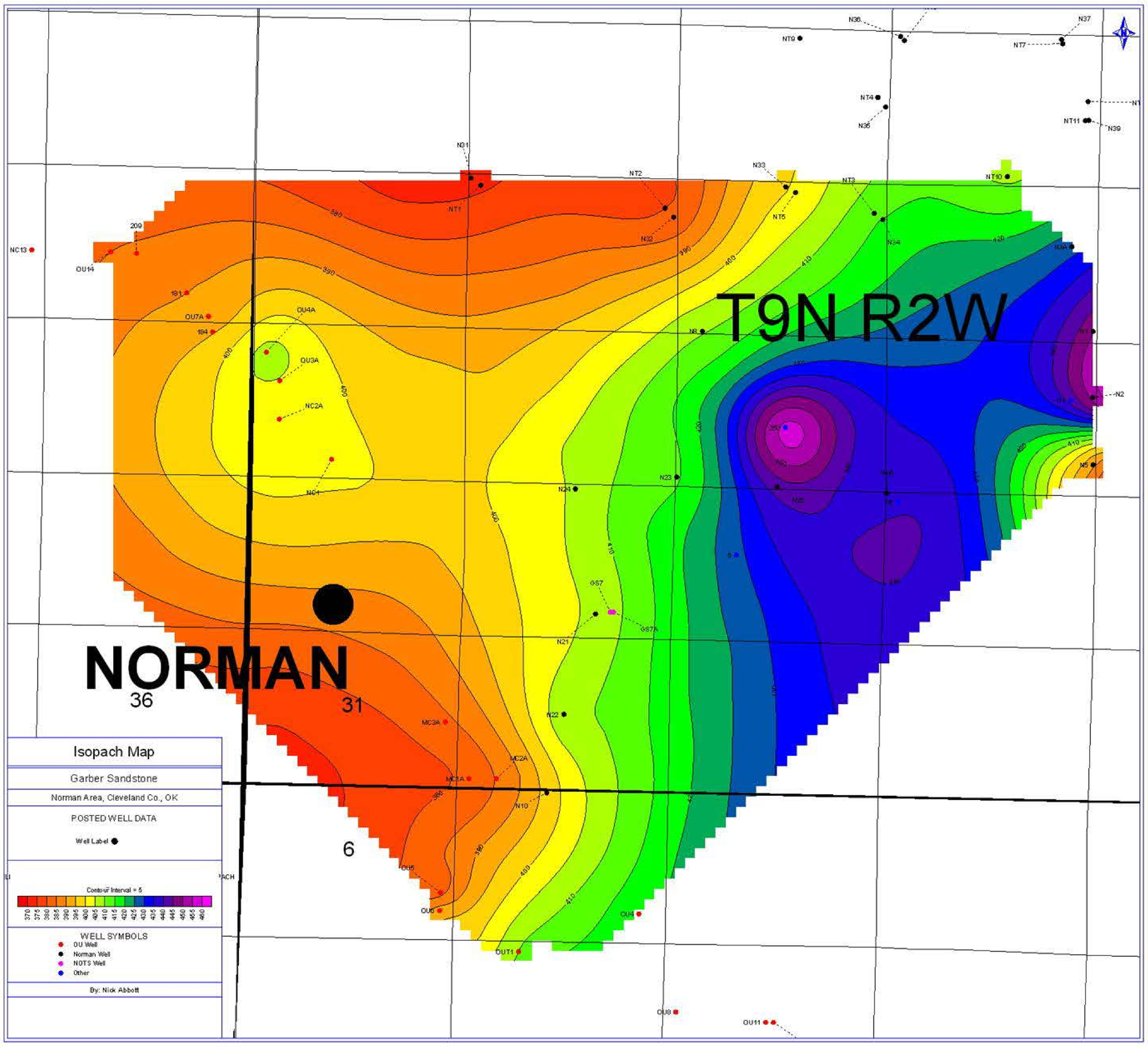
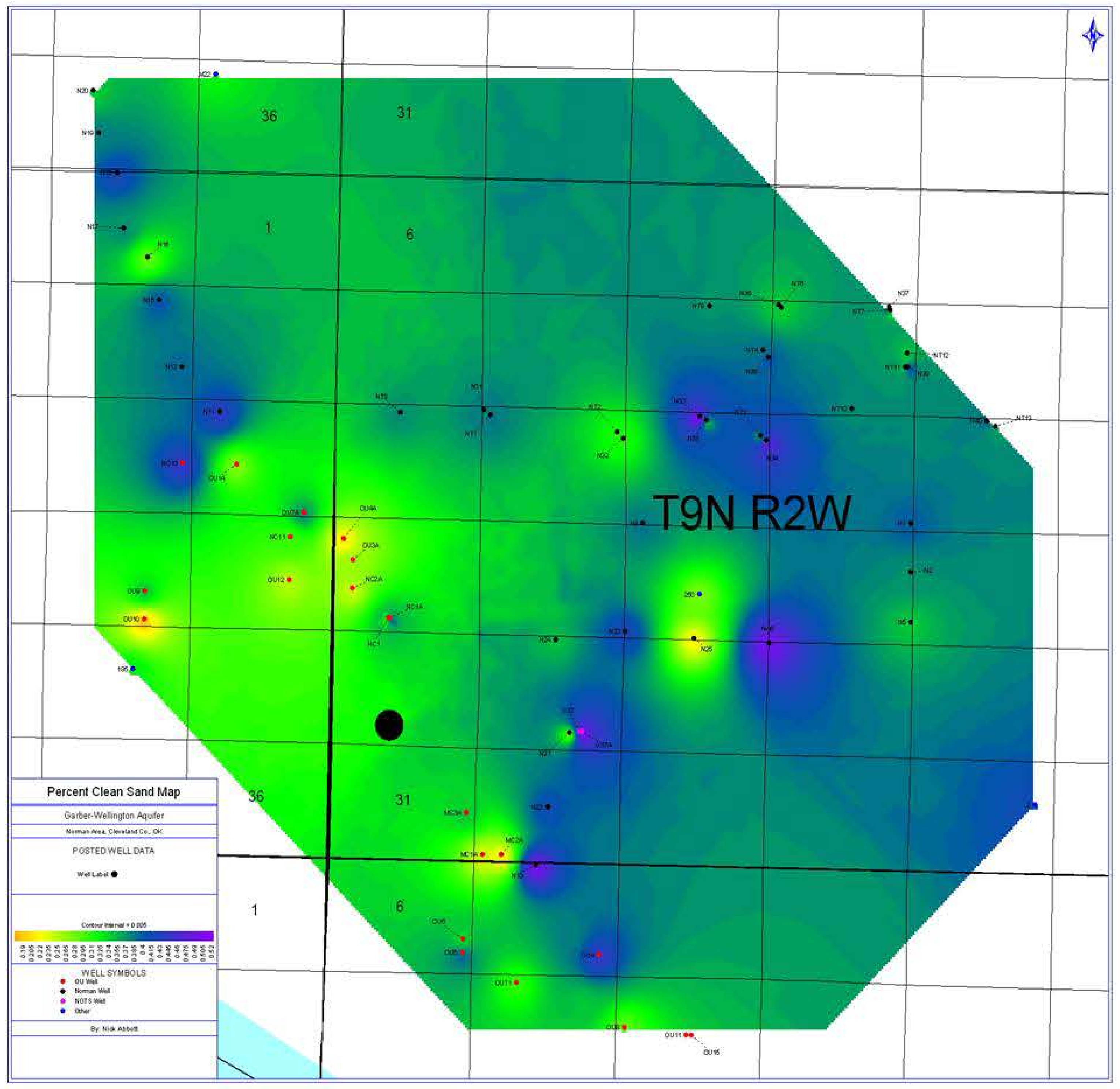
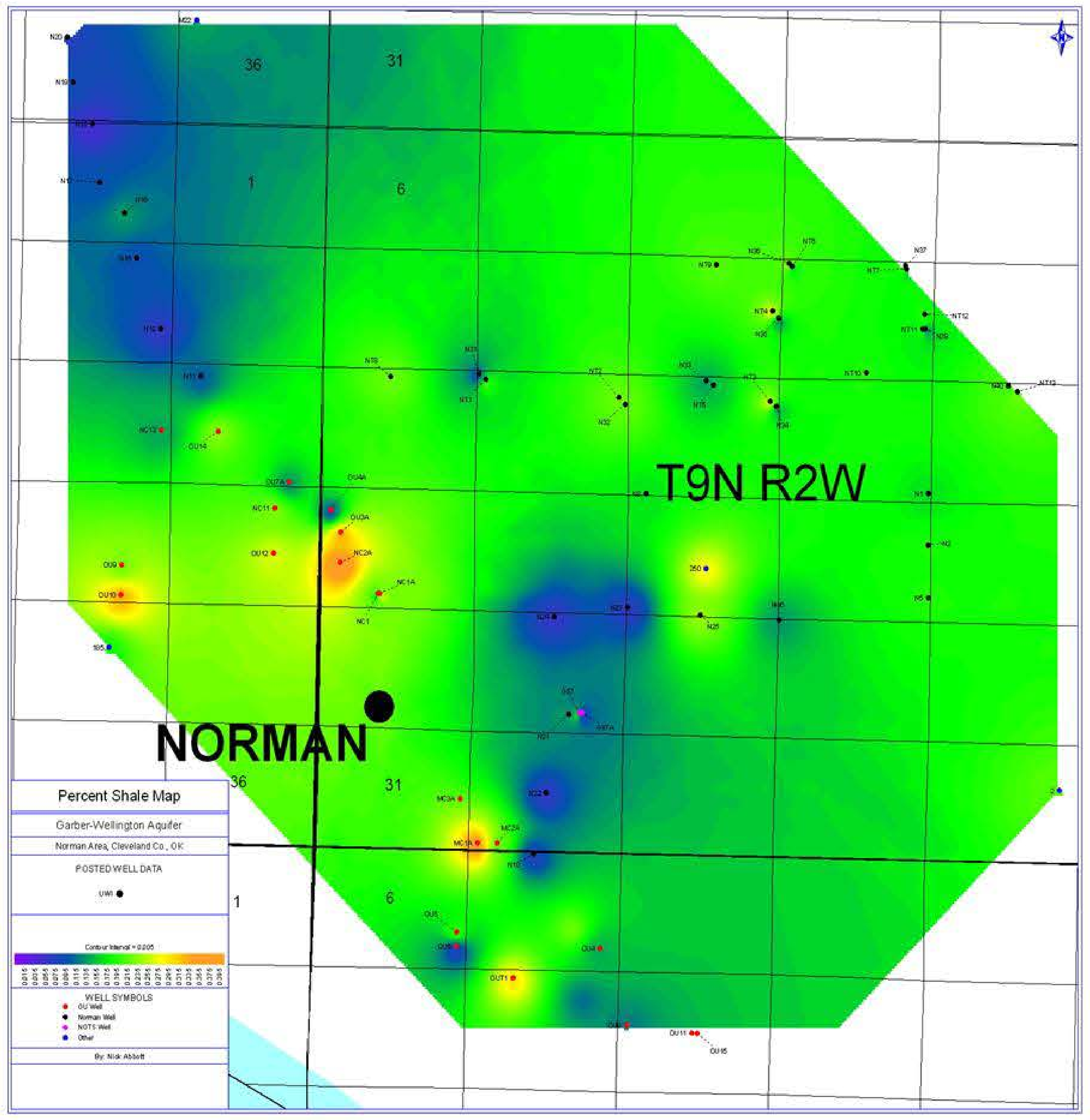
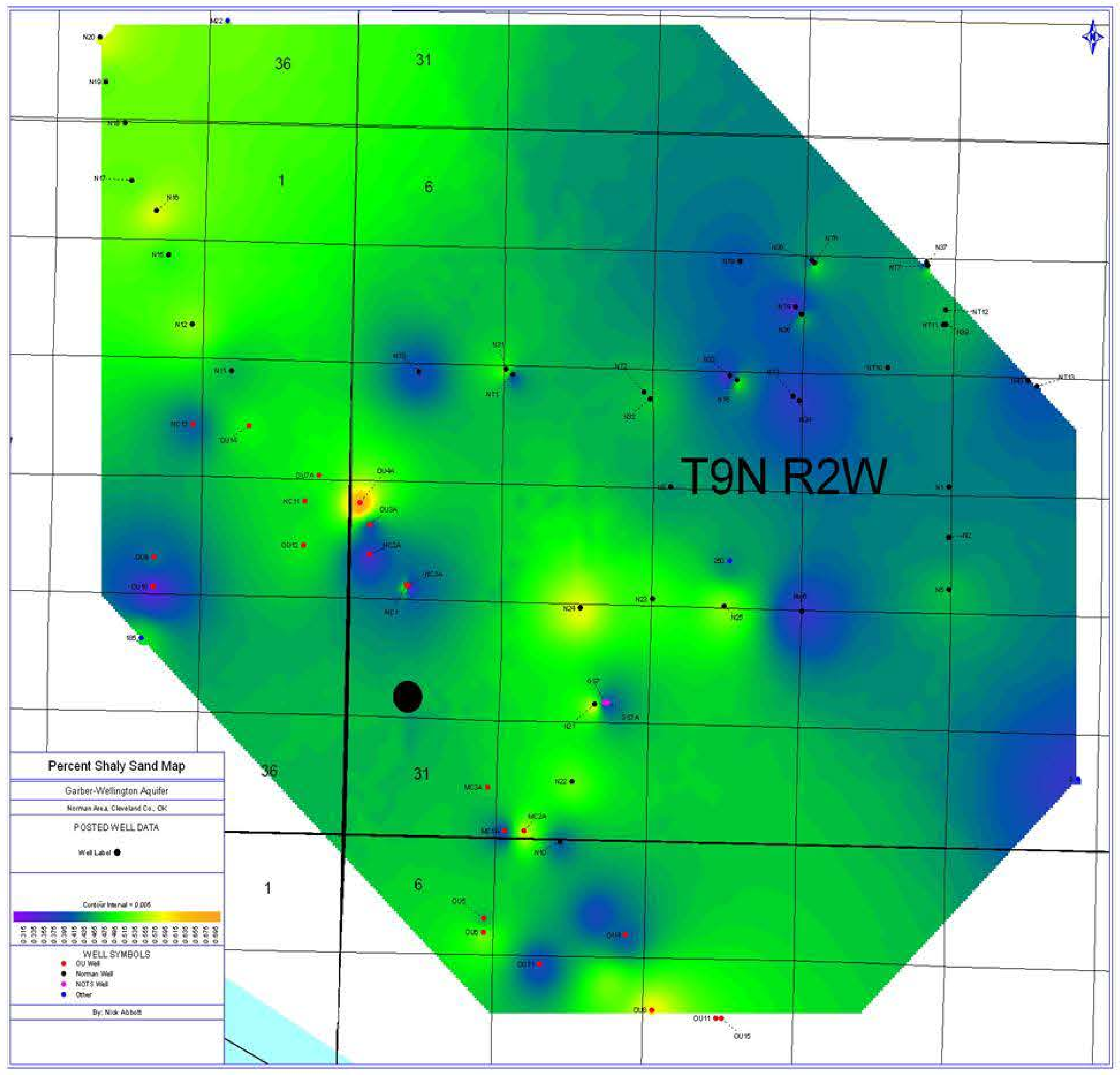
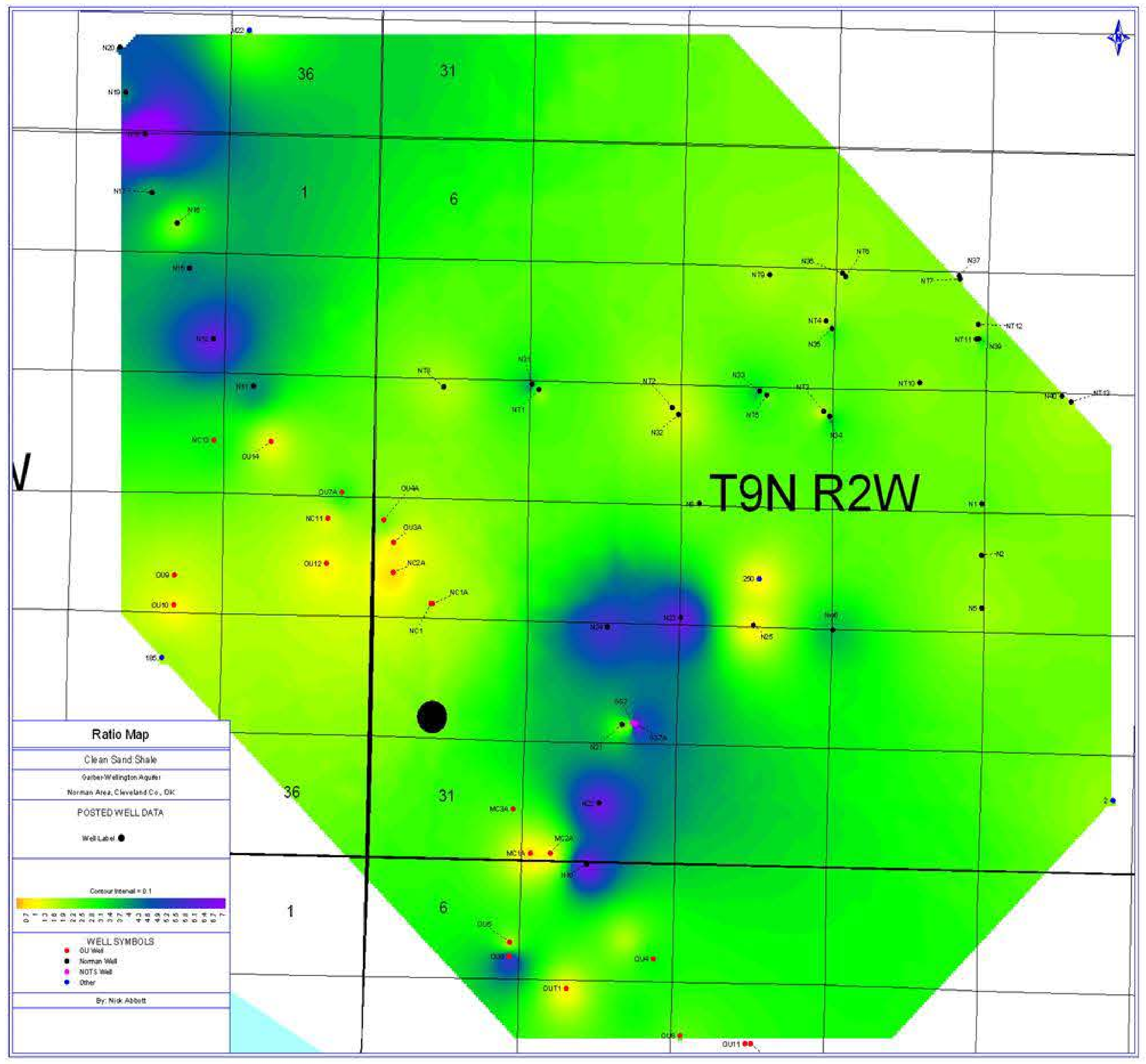


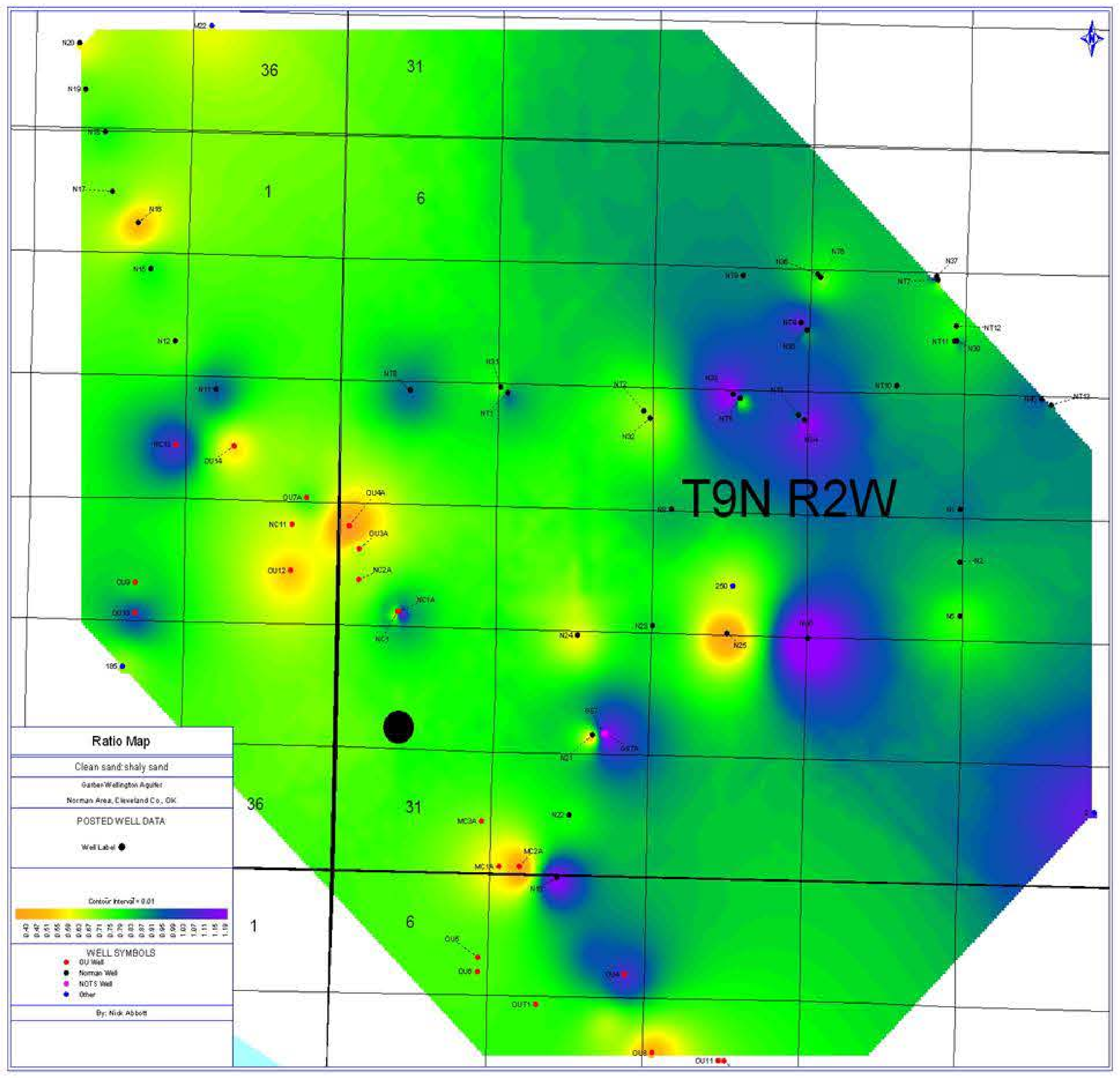
Plate 3: Lithofacies Maps Based on Logged Interval











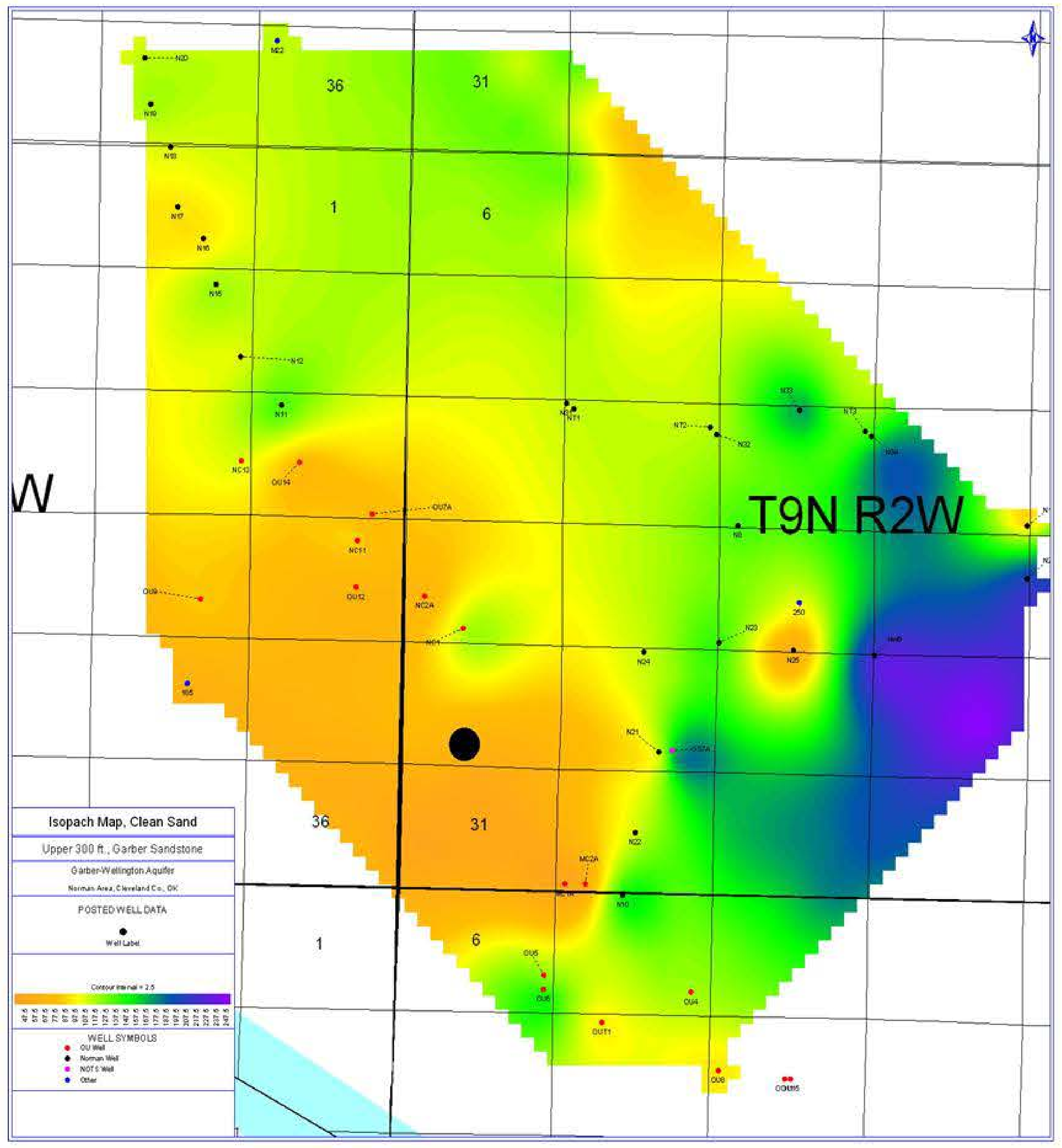
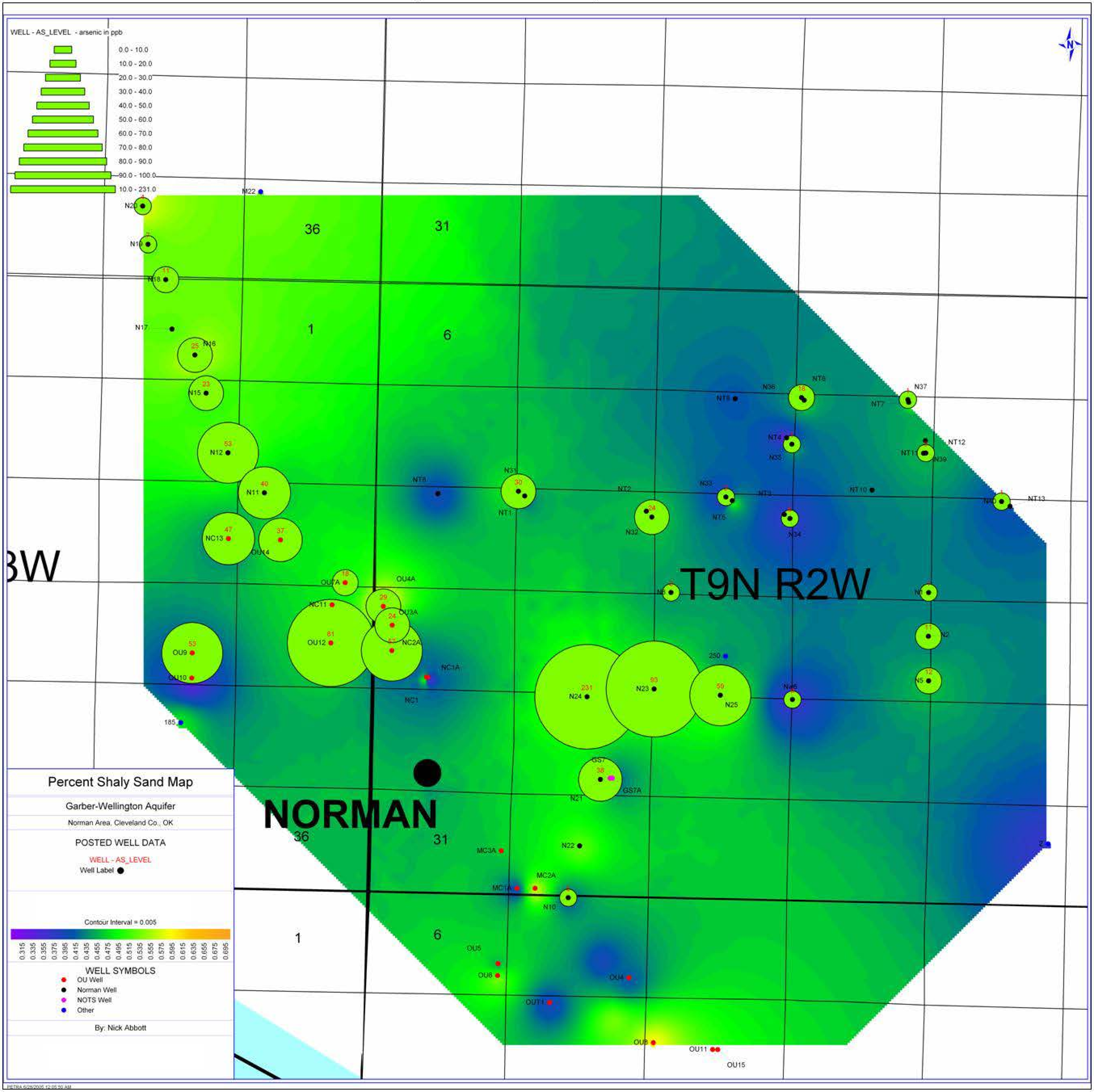


Plate 3B. Percent Shaly Sandstone Map with Arsenic Concentration.



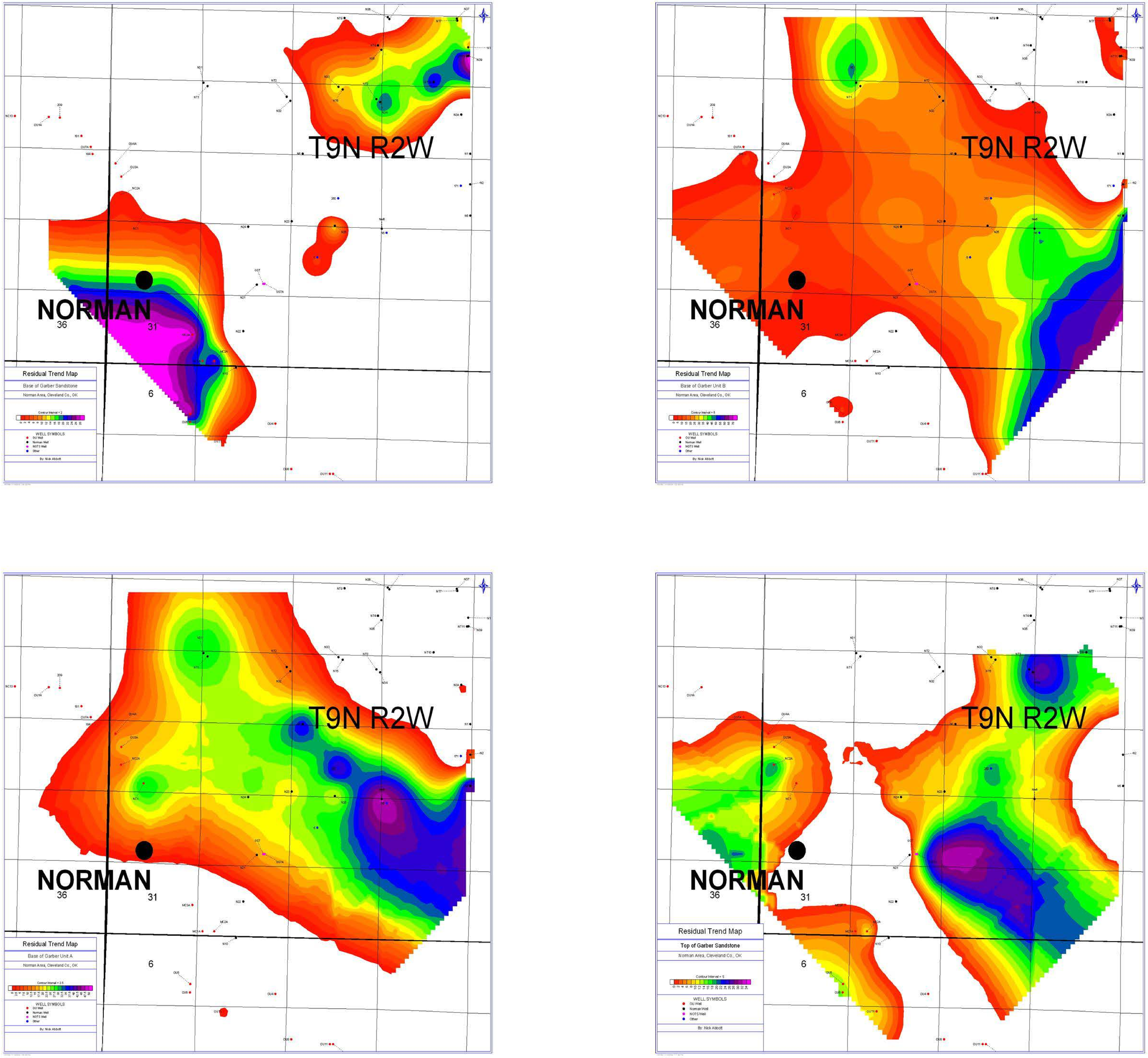


Plate 4. Residual Trend Maps (structure minus regional dip): Units A, B, and C

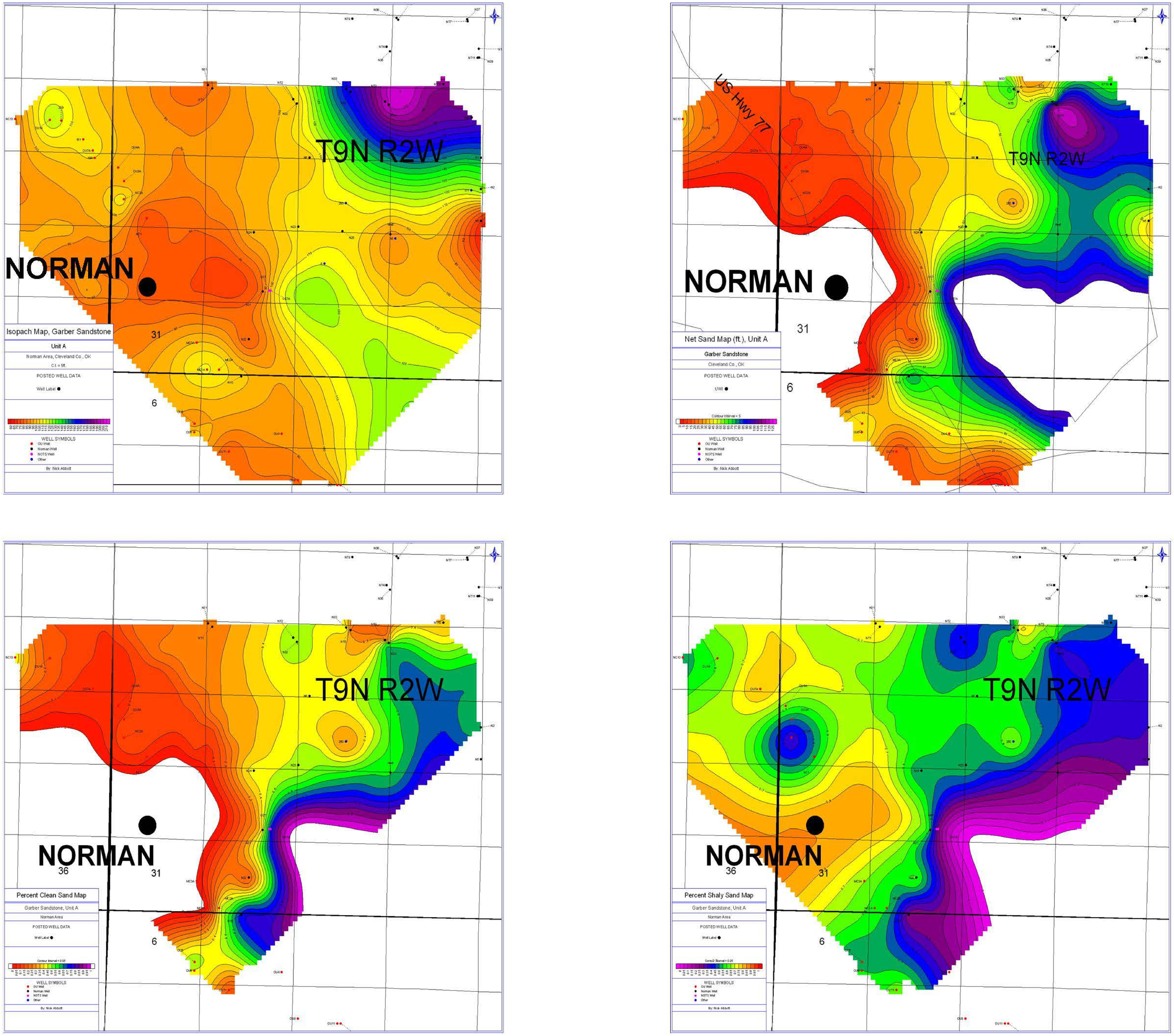


Plate 5. Garber Sandstone Unit A: Isopach Map, Net Clean Sandstone Map, Percent Clean Sandstone Map, Percent Shaly Sandstone Map

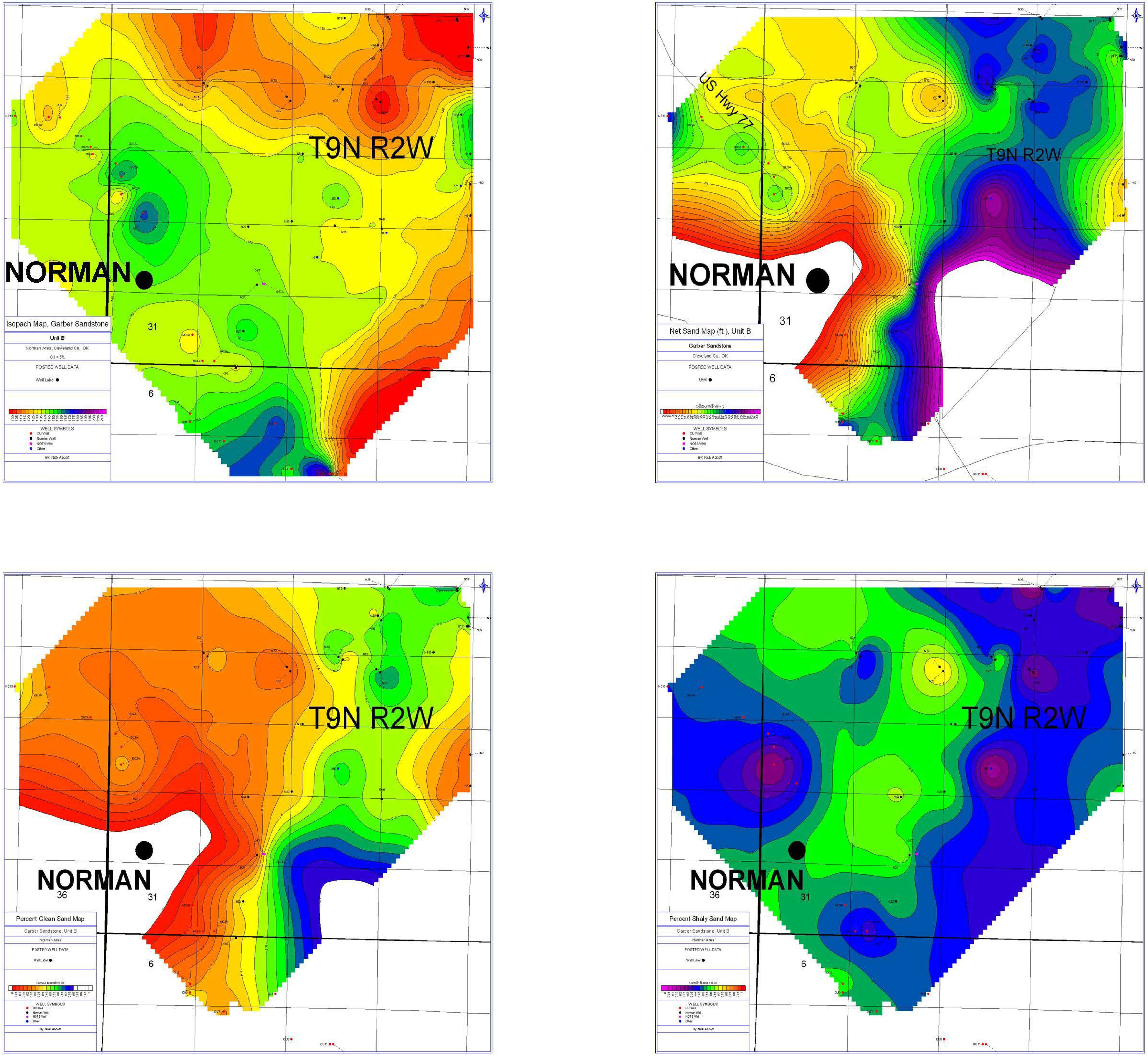


Plate 6. Garber Sandstone Unit A: Isopach Map, Net Clean Sandstone Map, Percent Clean Sandstone Map, Percent Shaly Sandstone Map

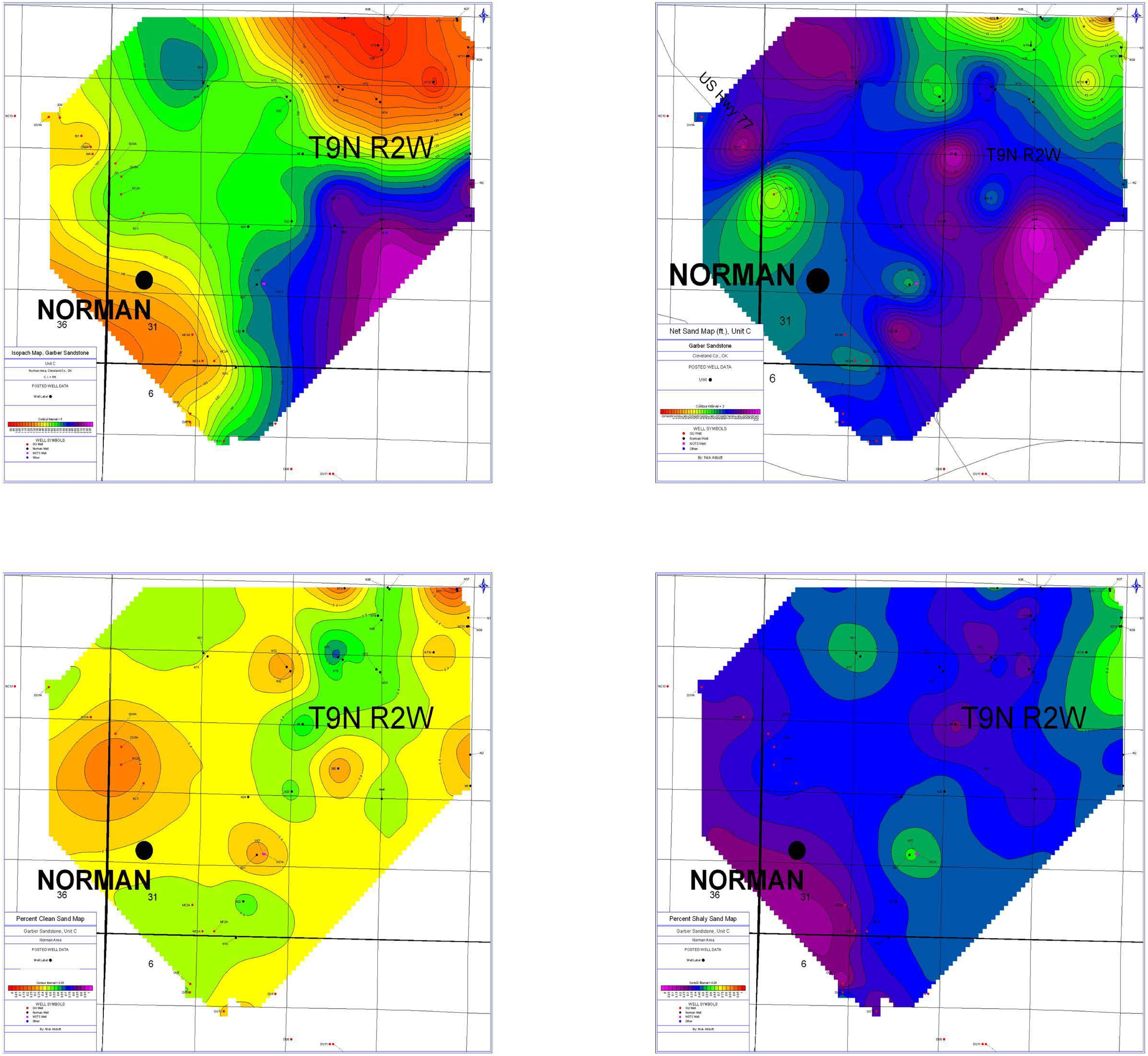


Plate 7. Garber Sandstone Unit A: Isopach Map, Net Clean Sandstone Map, Percent Clean Sandstone Map, Percent Shaly Sandstone Map

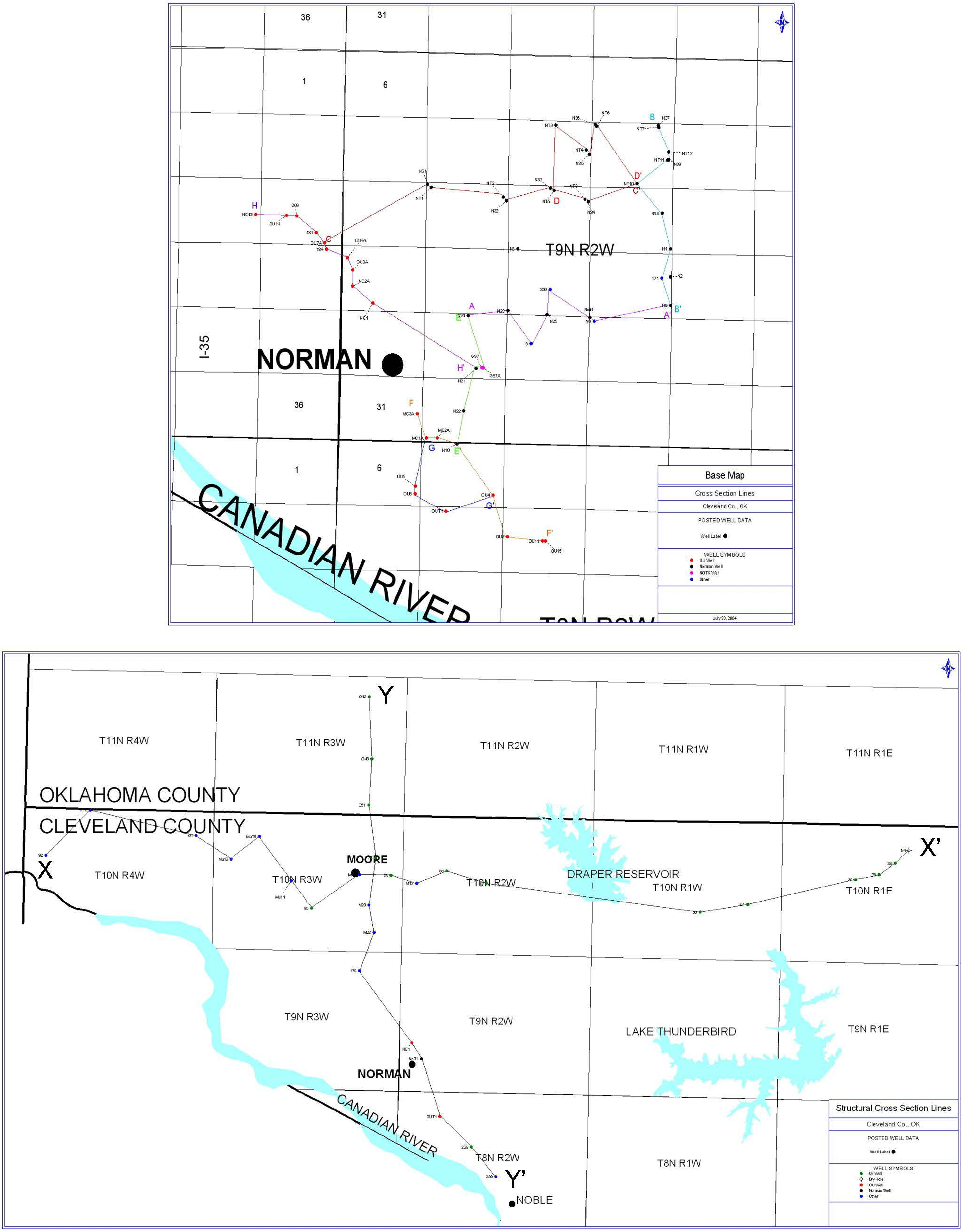


Plate 8. Base Maps with Cross Section Lines.

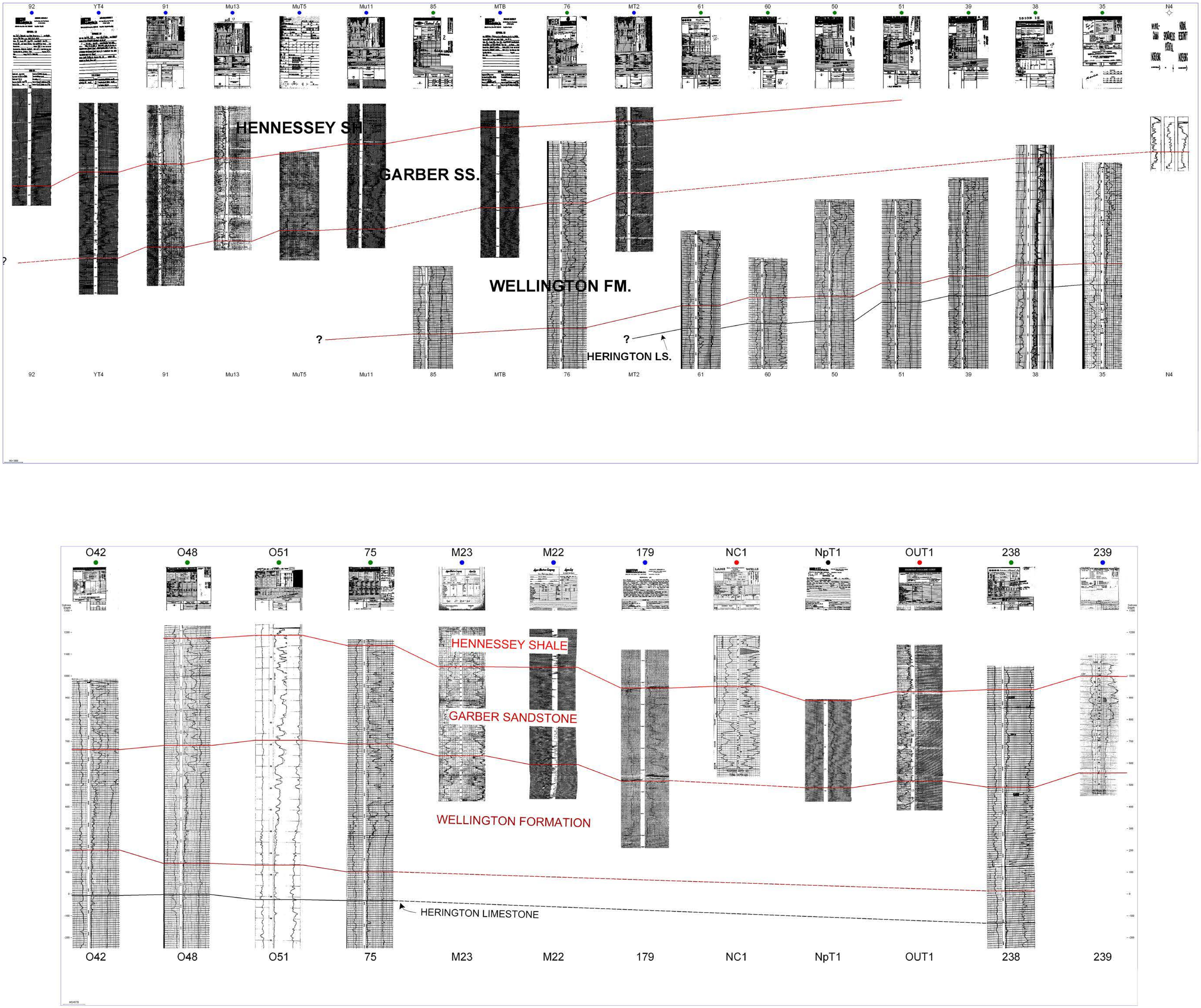
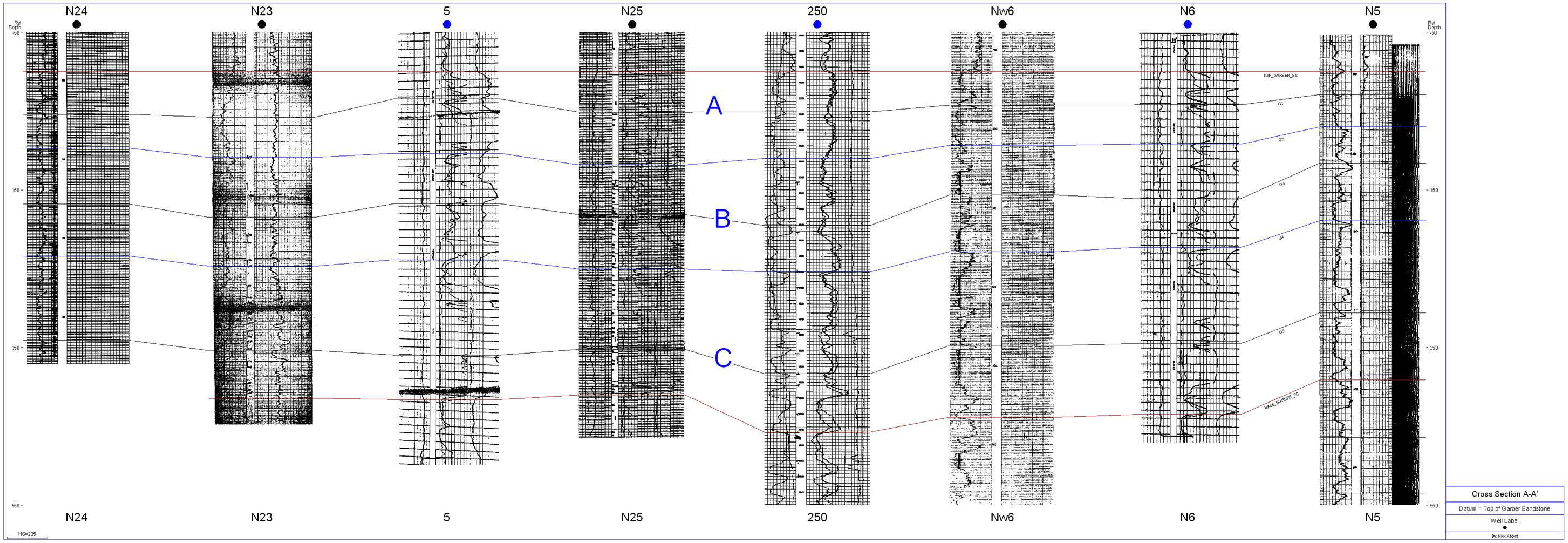


Plate 9. Structural Cross Sections X-X' (top) and Y-Y' (bottom). Datum = MSL.

Plate 10. Cross Section A-A' and B-B'



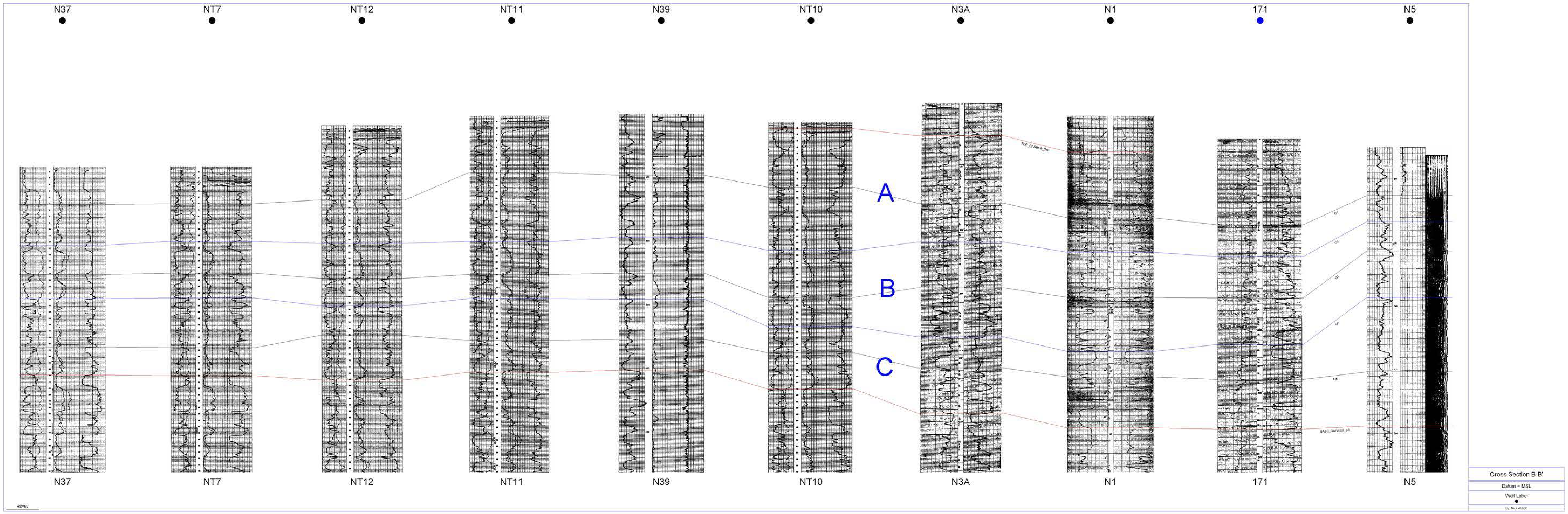
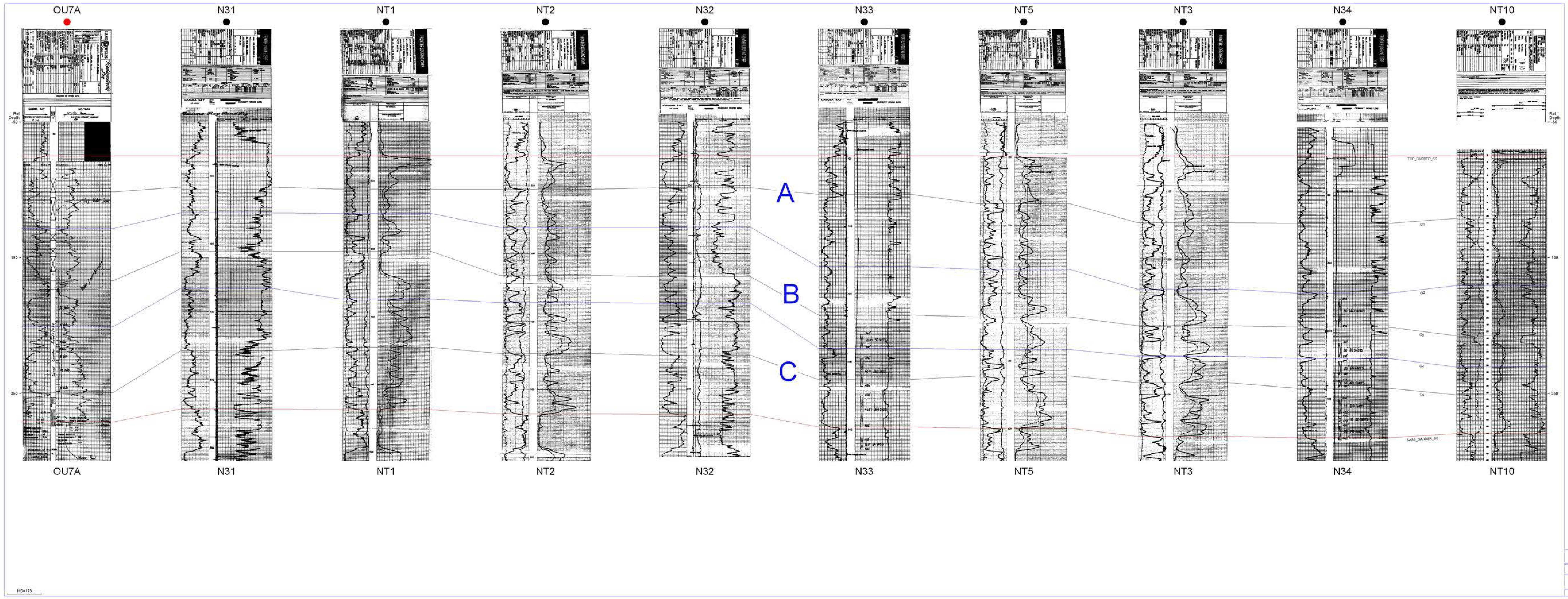


Plate 11. Cross Sections C-C' and D-D'

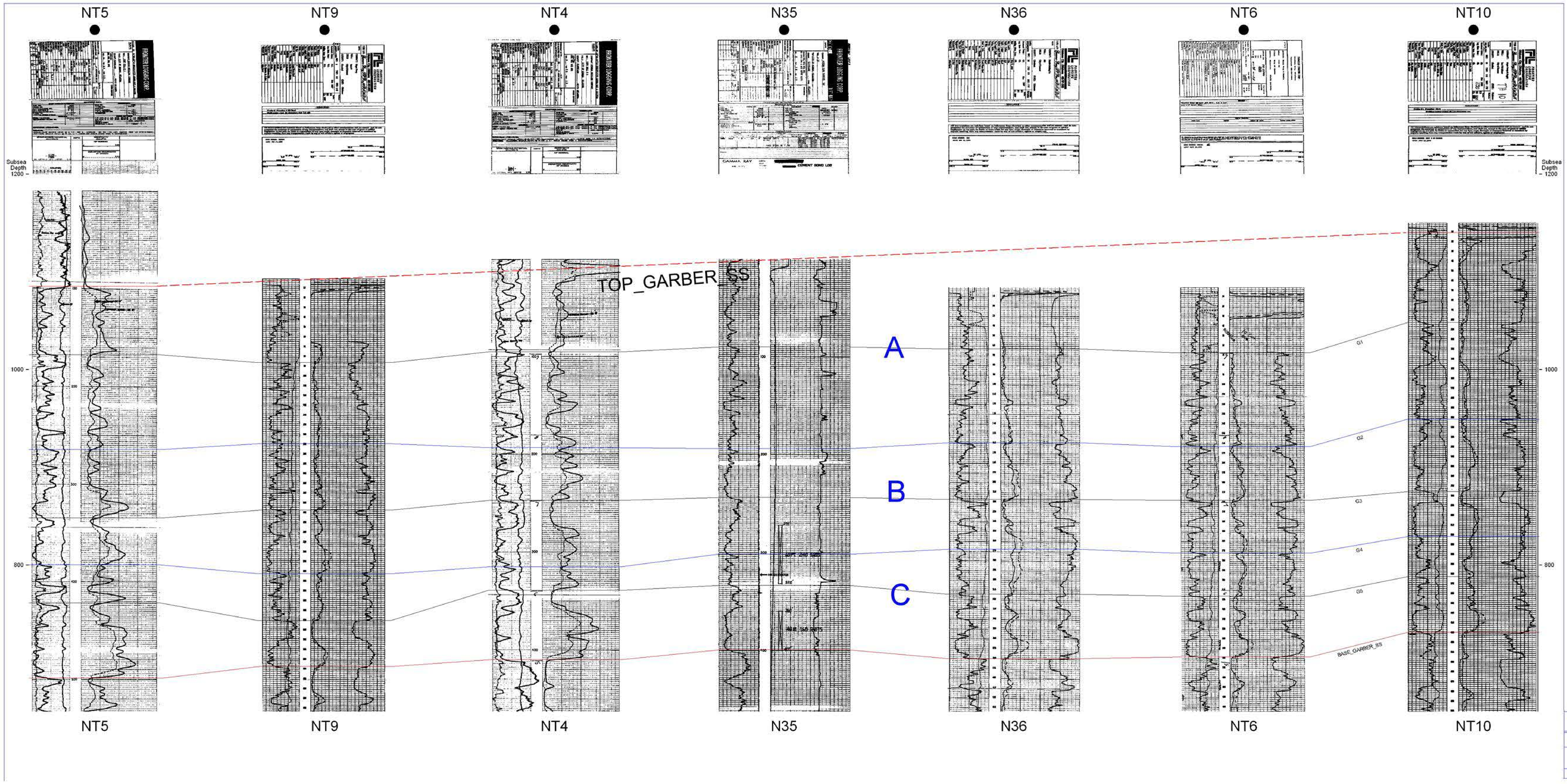


Cross section C-C'

Datum = Top of Garber Sandstone

Well Label ●

By: Nick Abbott



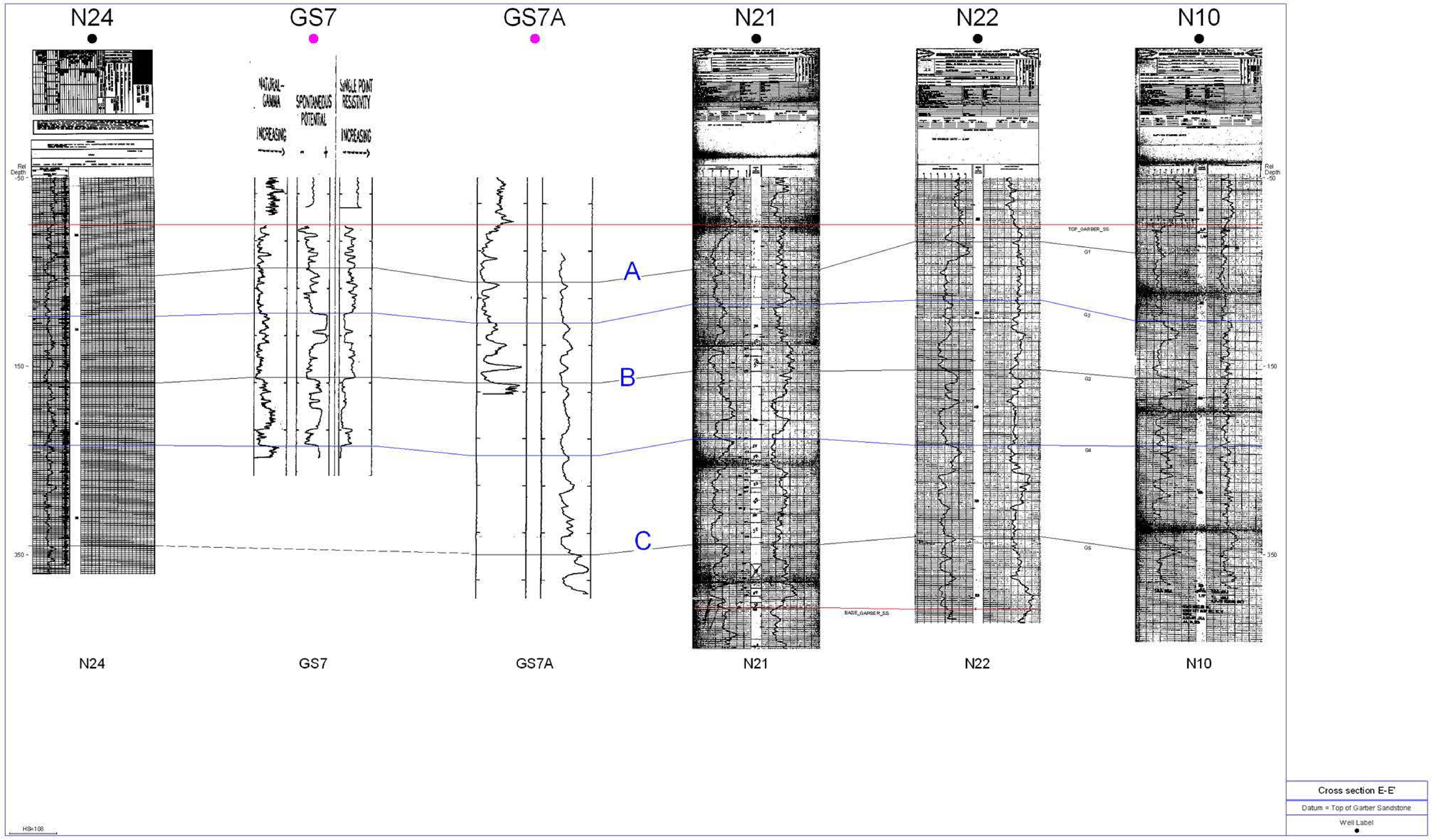
Cross section D-D'

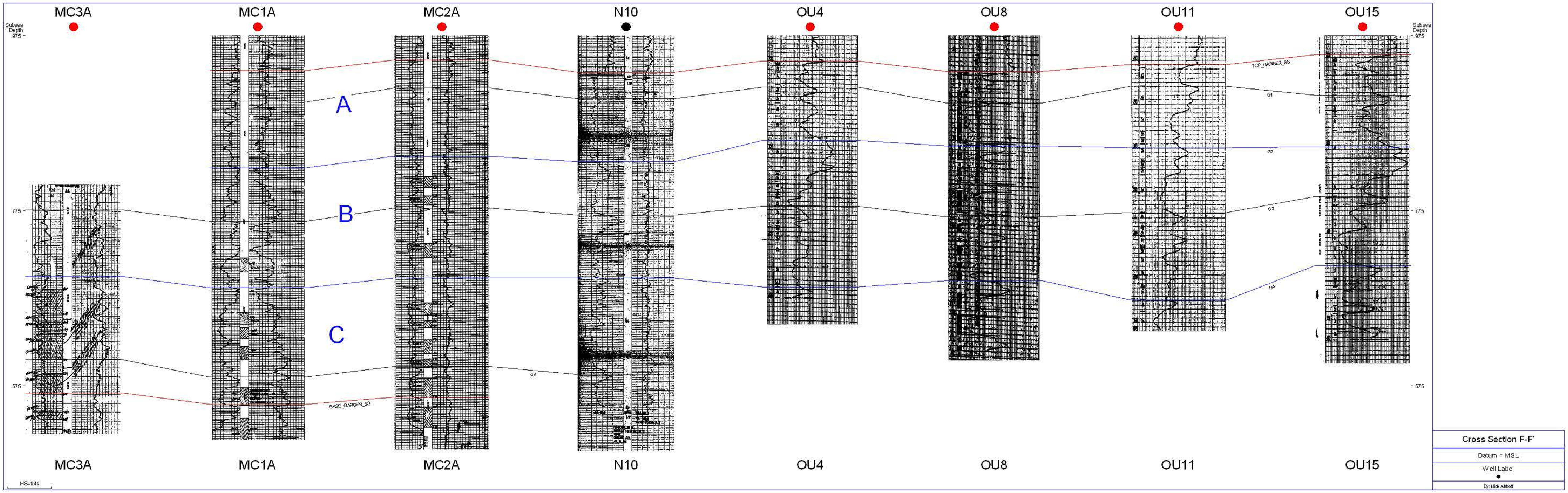
Datum = MSL

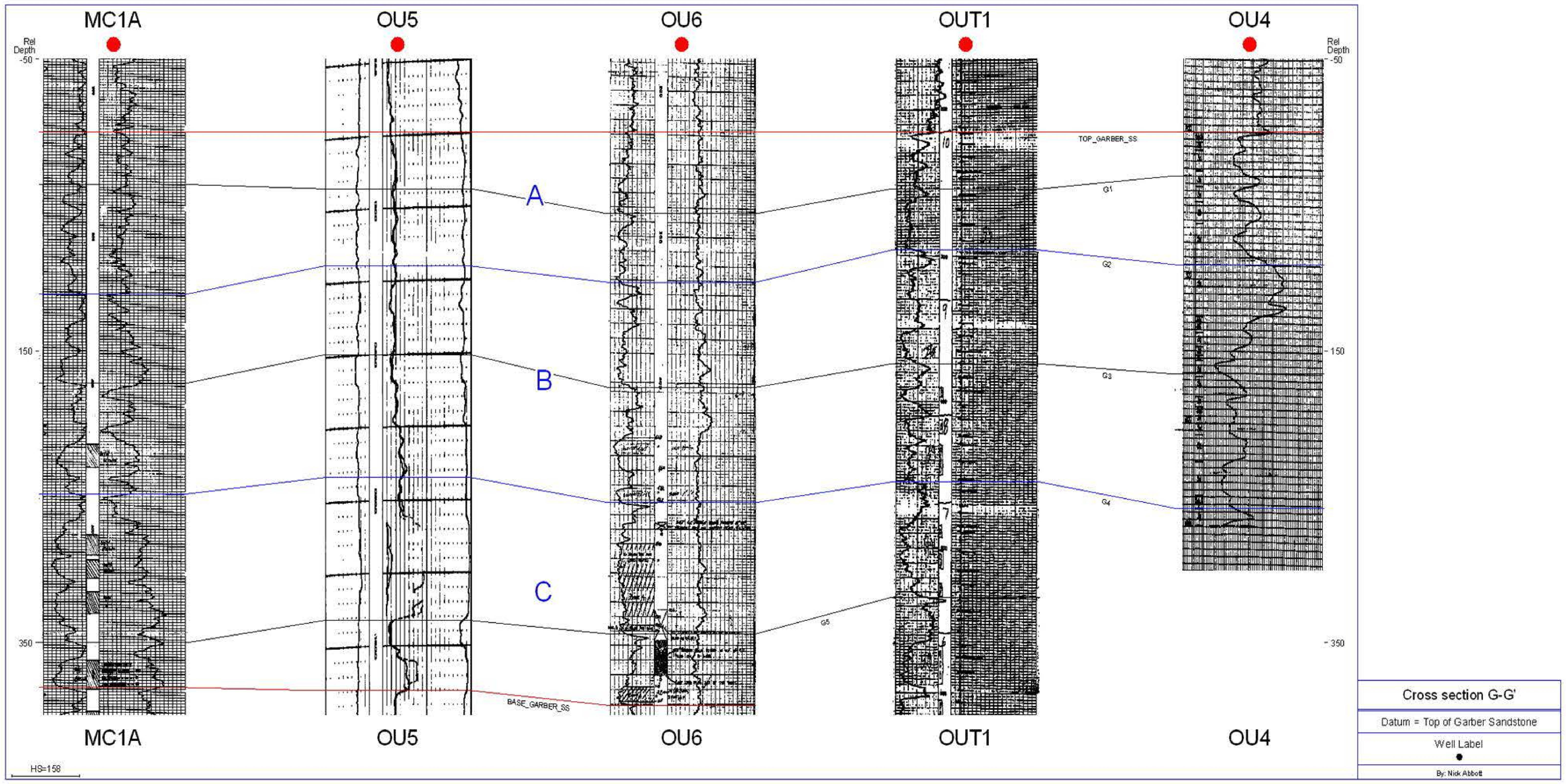
Well Label ●

By: Nick Abbott

Plate 12. Cross Section E-E' and F-F'







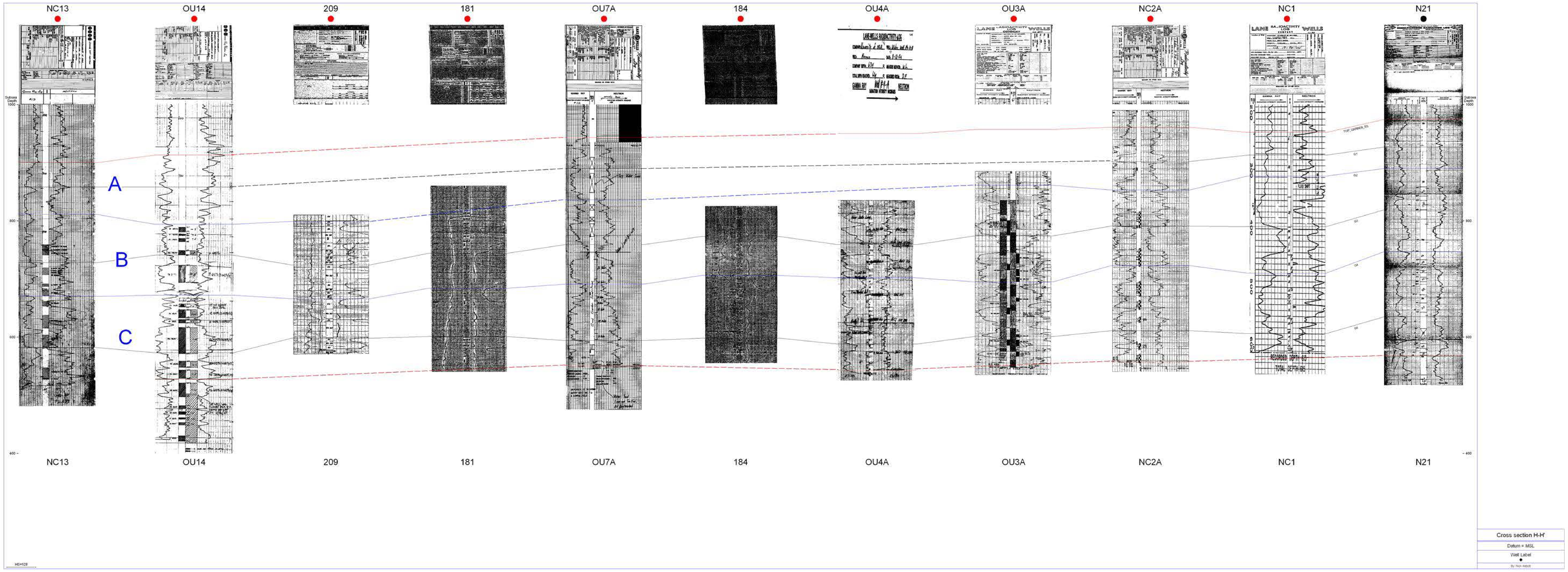


Plate 13. Cross Section G-G' and H-H'

VITA

Ben Nicholas Abbott

Candidate for the Degree of

Master of Science

Thesis: SUBSURFACE GEOLOGY OF ARSENIC-BEARING PERMIAN SEDIMENTARY ROCKS IN THE GARBER-WELLINGTON INTERVAL OF THE CENTRAL OKLAHOMA AQUIFER, CLEVELAND COUNTY, OKLAHOMA

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Professional Memberships: Tulsa Geological Society, American Association of Petroleum Geologists

Name: Ben N. Abbott Date of Degree: December 2005

Institution: Oklahoma State University Location: Stillwater, OK

Title of Study: SUBSURFACE GEOLOGY OF ARSENIC-BEARING PERMIAN SEDIMENTARY ROCKS IN THE GARBER-WELLINGTON INTERVAL OF THE CENTRAL OKLAHOMA AQUIFER, CLEVELAND COUNTY, OKLAHOMA

Pages in Study: 111 Candidate for the Degree of Master of Science

The Central Oklahoma Aquifer is an important source of drinking water in central Oklahoma. The major formations making up the aquifer, the Garber Sandstone and the Wellington Formation, consist of fluvial sandstones interbedded with mudstones, siltstones, and conglomerates. Water from some wells has naturally occurring arsenic levels that exceed federal standards. Past work suggests that the arsenic is concentrated in water produced from sandstones isolated by finer-grained rocks. One strategy for remediation is to selectively produce water from low-arsenic zones and to limit water production from sandstones isolated by finer-grained lithofacies. This requires the development of a stratigraphic framework that defines the lateral and vertical distribution of arsenic-prone lithofacies. Mapping of lithofacies suggests that arsenic concentration is most closely associated with shaly sandstone distribution; based on the maps, there are two favorable areas for new water wells, and at least one area that should be avoided.

Advisor's Approval: Stanley T. Paxton