A RECONNAISSANCE STUDY OF CONTROLS ON AQUIFER QUALITY IN THE CENTRAL OKLAHOMA AQUIFER, OKLAHOMA

By

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NOMENCLATURE

COA	Central Oklahoma Aquifer
mg/l	milligram per liter
mm	millimeter
NAWQA	National Water Quality Assessment
NOTS	Naturally Occurring Trace Substances
SAS	Statistical Analysis System (Computer program)
TDS	Total Dissolved Solids
U.S.G.S.	United States Geological Survey

CHAPTER I

INTRODUCTION

The Central Oklahoma Aquifer (COA) is an important source of water for Oklahoma City and the surrounding areas. Fig. 1 shows the geographic boundaries of the Central Oklahoma Aquifer. It extends over an area of about 8,000 sq. km (Christenson, 1998). Water from the aquifer is used extensively for municipal, industrial, commercial, and domestic purposes. In fact, the aquifer is the major source of water for most of the municipalities in central Oklahoma. Therefore, the COA is central to the economy of Oklahoma City and its surroundings (Christenson, 1998). In 1985, the aquifer supplied drinking water to about 50% of people living in Cleveland County and 20% of people living in Oklahoma County. Most of the wells drilled into the COA vary in depths between 150 and 300 feet (Grelen, 2000).

The quality of water from the COA is an important environmental issue (Parkhurst and others, 1989). Water from the COA is found to contain large concentrations of arsenic, chromium, selenium, and uranium (Breit and others, 1990). A team from the U.S.G.S. conducted a study for the Oklahoma Planning and Resources Board and concluded that there is a strong relationship between the structure and character of the rocks in the aquifer and the quantity, occurrence, and quality of the water supplies (U.S.G.S-anonymous, 1945).

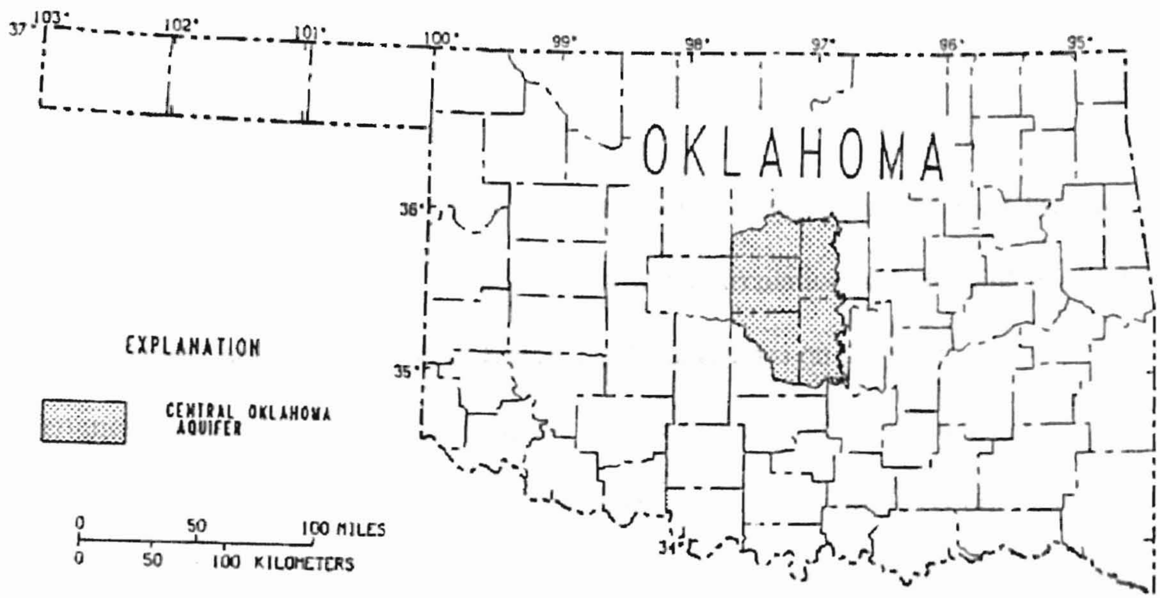

Fig. 1: Location map of the Central Oklahoma Aquifer (Schlottmann and Funkhouser, 1991).

Hence, the geology of the COA needs to be more fully described so that this resource can be better managed. Among the important stratigraphic units producing water from the COA system is the Permian-age Garber Sandstone, which constitutes the principal interest of this study. The Garber Sandstone is generally characterized as a red, cross-bedded to massive, lenticular sandstone that is locally conglomeratic. It is interstratified with beds of red fissile shale and sandy shale (Suneson and Hemish, 1998).

Study Area

The COA extends from the Canadian River on the south to approximately the Cimarron River on the north, and to the depth limit of freshwater circulation, which coincides with the Oklahoma-Canadian and Lincoln-Kingfisher County lines on the west. The easternmost extent of the aquifer is along the contact of the Pennsylvanian Vanoss Formation with the Permian Chase, Council-Grove, and Admire Groups (Purkhurst and others, 1989). The area of interest for the present study encompasses Logan, Oklahoma, and Cleveland Counties (Fig. 2). This geographic area of study is chosen because of the availability and the reliability of the data.

Data Sources

George N. Breit of the U.S. Geological Survey (U.S.G.S.) collected some of the data used in this study from five wells drilled into the COA in the year of 1990. These wells were drilled and cored as part of the National Aquifer and Water Quality Analysis program (NAWQA). The wells are referred to by the USGS as Naturally Occurring Trace Substances Wells (or NOTS Wells). General summary information about these wells is provided in Appendix A.

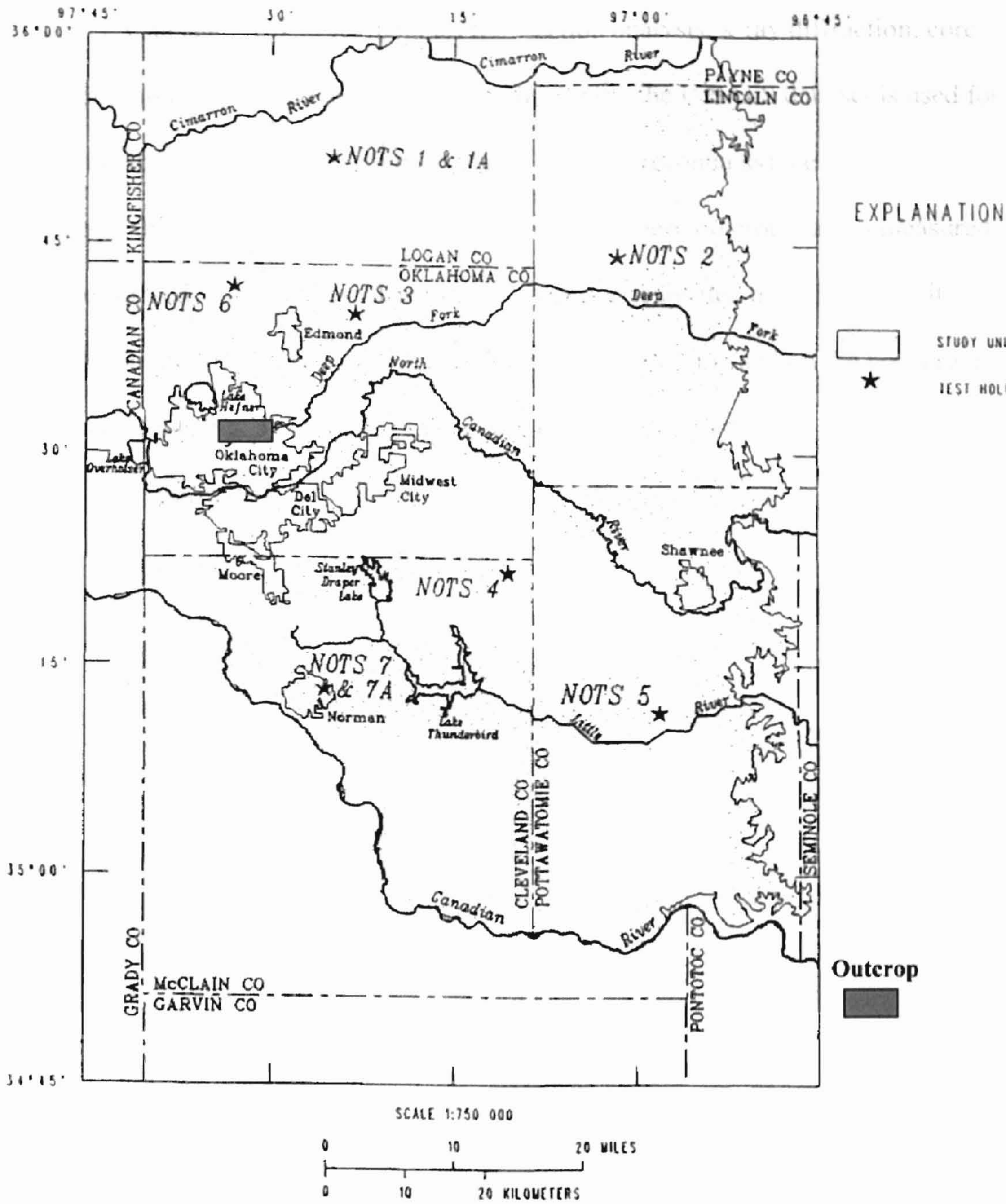

Fig. 2: Index map of the USGS-NOTS Wells: 1a, 3, 4, 6, and 7a are in this study (Schlotmann and Funkhouser, 1991).

This U.S.G.S subsurface data set includes thin section analysis, x-ray diffraction, core descriptions, and gamma-ray log profiles. In this thesis, the U.S.G.S data set is used for analysis and interpretation and is supplemented by some reconnaissance outcrop descriptions, thin section descriptions for samples from these outcrops, and a measured section performed by the author. The measured section is located in Oklahoma City, Oklahoma, on the southwest corner of the Cowboy Hall of Fame and on the north side of the interstate I-44 (Fig. 3). Details of the entire data set used to conduct this study are provided in Appendix B.

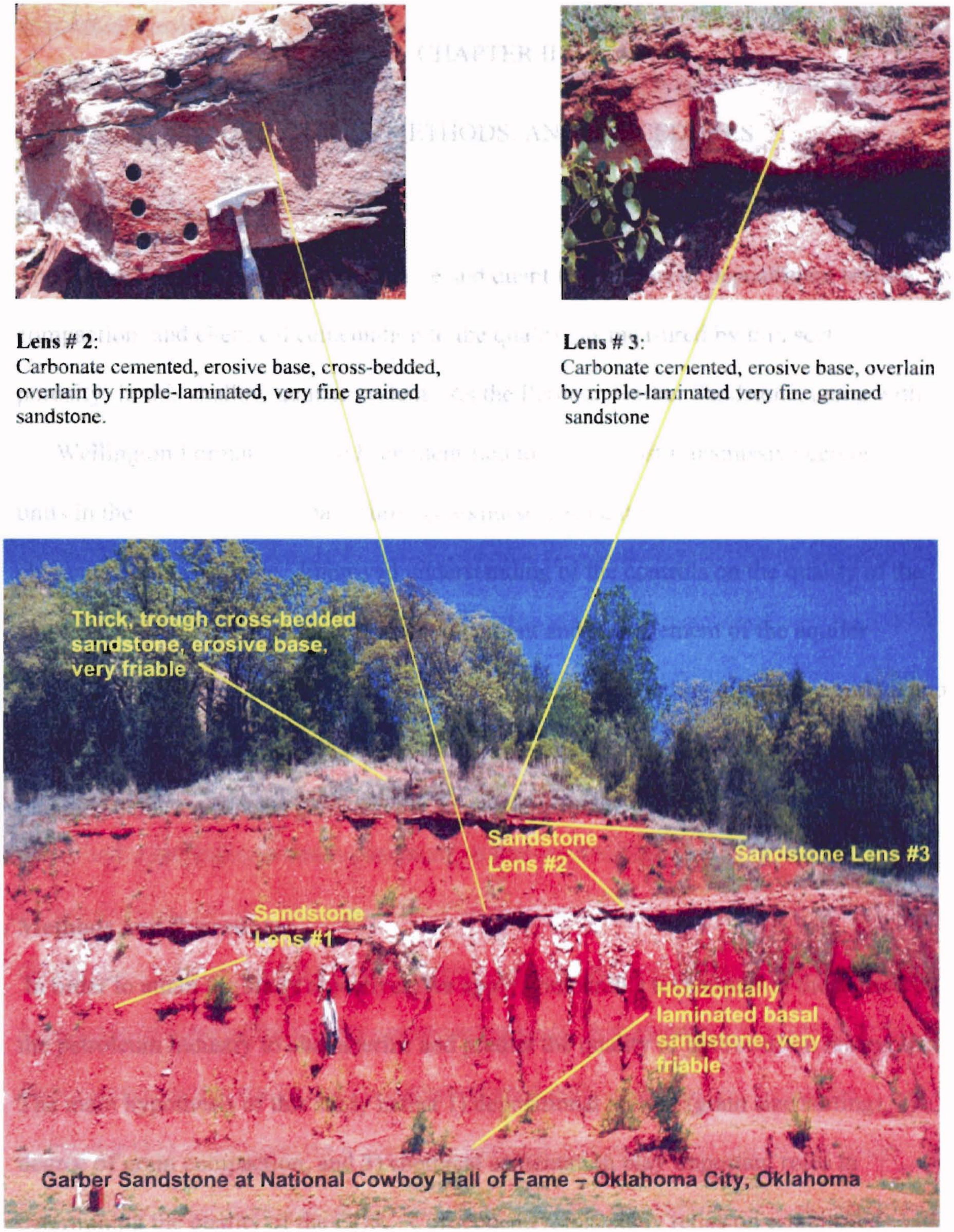

Fig. 3: General view and sedimentary features of the Permian Garber Sandstone at the National Cowboy Hall of Fame outcrop.

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CHAPTER II

OBJECTIVES, METHODS, AND PROCEDURES

Study Objectives

The purpose of this study is to determine and quantify the roles of depositional texture, compaction, and chemical cementation to the quality (as measured by thin section porosity) in this shallow aquifer system. As the Permian Garber Sandstone, along with the Wellington Formation, have been identified to be the most transmissive geologic units in the Central Oklahoma Aquifer (Parkhurst, 1997), it is prudent to better characterize this package. Improved understanding of the controls on the quality of the aquifer can result in better long-term development and management of the aquifer system. In addition, the data collected in this study can be used by others to correlate and map the aquifer quality on a regional basis. Municipalities for the purpose of economic planning can use products generated by subsequent studies.

Methods and Procedures

In order to attain the study objectives, we apply comparable techniques to those used by the petroleum industry to characterize and predict the quality of hydrocarbon reservoirs. The main hypothesis of this study is that 1) depositional texture (grain size/sorting), 2) degree of grain compaction, and 3) chemical cementation play important roles in determining the quality of the COA. Consequently, this study relies on established techniques and tools such as outcrop and core descriptions, thin section analysis, gamma-ray logs, and x-ray diffraction data. Once the data are collected and quality controlled, the data were analyzed with the Statistical Analysis System (SAS). The results of this analysis are summarized in Table 1. The SAS program helps to describe the Garber Sandstone so that the characteristics of the unit can be spatially generalized throughout the study area.

The author proposes that the aquifer is likely to perform better in zones or areas in which the sandstone has the following characteristics:

1) The aquifer is relatively uncemented and contains coarser-grained sands, which will result in higher permeability.

2) The aquifer contains uniformly sized grains (moderately well to well sorted), resulting in higher porosity (or storativity).

3) The aquifer occurring shallow in burial will have higher porosity and permeability due to less burial compaction than more deeply buried portions of the aquifer.

4) The aquifer interval contains thicker sand packages and high net to gross, resulting in better continuity or interconnectivity of the sand bodies.

Gamma-ray profiles from the NOTS Wells were helpful for documenting the vertical expression of some of the Garber sandstone intervals. It is proposed, though not demonstrated in this study, that the degree of sand body interconnectivity can be correlated to bed thickness for a given depositional system. We do test in this study, however, the roles of aquifer characteristics #1, 2, and 3 cited above.

The Garber Sandstone samples analyzed in this study were selected for analysis based on variations in sedimentary features seen in outcrop at National Cowboy Hall of Fame. This outcrop was measured and described from the base to the top and significant variations in texture and cementation patterns noted. Representative hand specimen and core plug samples were taken from the sandy portions of the vertical section. Some samples were obtained in sand beds lateral to the vertical section. Samples were labeled and placed carefully in plastic bags for thin section preparation. Mineralogy, Inc. of Tulsa, Oklahoma prepared twenty-one thin sections. The goal of the thin section preparations was to obtain a well-defined pore system free of artifacts by impregnating all samples at 1500 psi with blue-dye epoxy. The thin sections were also stained for potassium feldspar. The thin sections were cut in a direction perpendicular to the laminations or bedding. The point count and textural data from the USGS thin section data set used in this study was collected in a similar manner to that described above (see Breit, 1990, Open-File Report for details of procedures).

Sandstone Composition and Texture –The composition of the sandstone was collected using a standard point-counting technique of 300 points per thin section. Each thin section was point counted using a grid coordinate system. The surface area of each thin section was divided into six (6) equal-spaced horizontal lines or traverse. Each line, in turn, was divided into fifty (50) equal-spaced points. The mineralogical component at each point under the ocular cross hairs was then counted. The grain size of the sandstones was determined in thin section by estimating the size of ten grains in five fields of view as observed down the microscope. The measurements of grains in five fields of view were averaged to determine the grain size for each thin section.

A magnification of 25x was used for grain size. At this power, exactly 35 increments in the field of view corresponds to one millimeter in length. The number of increments for each field of view was multiplied by 0.0286 (1/35 mm) to obtain the grain size. Sorting was determined from standard visual comparitor (Folk, 1980).

The U.S.G.S. data set had verbal estimates of grain size and sorting. These verbal estimates were translated to numeric values by converting the verbal size and sorting estimate for each thin section to a grain size and sorting number that corresponds to midpoint of each textural class (Table 2).

<u>Role of Depositional Texture</u> - The influence of grain size and sorting on the quality of the Garber aquifer was inferred from comparison of the Garber data to the porosity and permeability experiments of Beard and Weyl (1973) for unconsolidated sediment. Their work demonstrates that high porosity sands are better sorted and lower porosity sands are more poorly sorted. Permeability in their data set varies more strongly with grain size than with sorting, however. High permeability sands are commonly coarser-grained (large pore throats) and lower permeability sands are finer grained (smaller pore throats). Taken in combination, therefore, high porosity-high permeability sands are coarse grained and well sorted while low porosity-low permeability sands are poorly sorted and fine-grained. Generalizations in the present study about Garber aquifer quality relative to texture are based on comparison of the Garber data to these experimental findings of Beard and Weyl (1973).

Garber Compaction- The intergranular volume (IGV) of the Garber Sandstone was used to estimate the degree of compaction in the Garber Sandstone. The reason for calculating the degree of compaction in the Garber is to determine where, on a regional basis, the aquifer has undergone less compaction (corresponding to shallower burial depth).

Garber Burial History- In addition, a burial history curve in the study area was constructed. The burial history curve is helpful in understanding the geologic and diagenetic history of the Garber Sandstone.

CHAPTER III

PREVIOUS GARBER INVESTIGATIONS

The Central Oklahoma aquifer is defined by a series of stratigraphic intervals that produce substantial amount of water from an extensive groundwater flow system that occurs in Cleveland, Lincoln, Logan, Oklahoma, Payne, and Pottawatomie Counties. The lower boundary of the aquifer is set not by the stratigraphy, but by the lower limit of groundwater with total dissolved solids less than 5000 milligrams per liter (TDS< 5000 mg/l). The lower limit of groundwater also referred to as the base of fresh water, ranges in depth from 100 to about 1,000 feet (Parkhurst et al., 1989).

Aurin et al., (1926) named the Garber Sandstone after the town of Garber. This small town is located in eastern Garfield County, Oklahoma. The Garber Sandstone was described as a series of red clay shales, red sandy shales, and red sandstones overlying the Wellington. The Garber Sandstone exposed in the southern Logan and northern Oklahoma Counties is mostly orange-brown to reddish-brown, fine-grained sandstone that is irregularly bedded with red-brown shale and some chert and mudstone conglomerate (USGS-anonymous, 1977).

The Garber Sandstone and the Wellington Formation are commonly studied as a single complex. The combination of these two units constitutes a complex of interfingering lenticular beds of sandstone, siltstone, and shale that can change in thickness over very short distances. In general, the sandstone is fine to very fine-grained and friable. The depositional matrix is commonly red mud. The sandstone beds vary in color from white to pink, orange, deep red, or purple. Most beds show rather deep hematitic staining (Mosier and Bullock, 1988). The Garber Sandstone, along with all the other Permian units in the aquifer, dips very shallow to the west-southwest, about 50 feet per mile (10 meters/ kilometer). The depositional environments for these Permian units were characterized as marginal-marine and fluvial environments that thicken westward toward the Anadarko Basin (Breit, 1989).

Lithologic differences in the Garber-Wellington sequence cause the aquifer to change both vertically and horizontally in term of hydraulic behavior. As a result, groundwater in the aquifer occurs under unconfined, semi-artesian, and artesian conditions. Unconfined conditions generally take place at depths of less than 200 feet (60 meters) where the aquifer is exposed at the surface. Artesian conditions occur below 200 feet (60 meters) and in most of the area where the Hennessey Group overlies the aquifer (USGS-anonymous, 1977).

The Ouachita province and adjacent areas were the major sources of sediment supply to the southeast of Oklahoma up to the Wolfcampian time (Johnson and Denison, 1973). The Garber Sandstone deposited during the Leonardian time is believed to inherit most of its sediments from the southern part of the State of Oklahoma as a result of the Wichita uplift. Paleocurrent analysis performed by faculty at Oklahoma State University suggests trend of the Garber channel is North-North-West (NNW) direction based on measurements of cross-bedding.

The present depth of the Garber Sandstone, based on core data in the study area, is a maximum of 630 feet. This depth compares favorably to the depth shown on the burial history curve (Fig. 9). This depth is less in the study area, suggesting that the Garber Sandstone was uplifted within the study area and has undergone significant erosion since its deposition and burial during Permian time.

Turkarslan (1979) conducted a study on the Garber Sandstone outcrop in Cleveland County. He studied the seismic response of the unit. He concluded that the Garber Sandstone is composed of three to four layers depending on the location in Cleveland County. The first layer (upper) is interpreted as a dry, porous soil. The second layer appears to be loose, unconsolidated, dry, and porous sandstone. Finally, the third layer is made of unconsolidated sediments; this layer is highly porous and it is slightly water-saturated. Turkarslan (1979) suggests that the Garber Sandstone may comprise several stratigraphic intervals. However, without age control and regional mapping, one cannot be certain that the variations observed in Cleveland County are due to fluvial stacking patterns within a single stratigraphic interval or due to amalgamation of different stratigraphic intervals.

CHAPTER IV

STRUCTURAL AND STRATIGRAPHIC FRAMEWORKS

Structure

The Permian Garber Sandstone was deposited after the tectonic uplift of the Wichita block located in southern Oklahoma. This event ended by early Permian time (Wolfcampian). With respect to deposition of the Garber Sandstone, the formation has accumulated in a structurally stable zone. The Garber Sandstone deposited during the Leonardian time is believed to inherit most of its sediments from the southern part of the State of Oklahoma as a result of the Wichita uplift. Paleocurrent analysis performed by faculty at Oklahoma State University suggests trend of the Garber channel is North-North-West (NNW) direction based on measurements of cross-bedding.

The present depth of the Garber Sandstone, based on core data in the study area, is a maximum of 630 feet. This depth compares favorably to the depth shown on the burial history curve (Fig. 8). This depth is less in the study area, suggesting that the Garber Sandstone was uplifted and has undergone significant erosion since its deposition and burial during the Leonardian time.

The present depth of the Garber Sandstone, based on core data in the study area, is a maximum of 630 feet. This depth compares favorably to the depth shown on the burial history curve. The cumulatively total thickness of the Garber-Wellington sequence is estimated from 800 to 1000 feet. The Garber-Wellington shows erosional truncation to the east (Breit et al., 1990). Erosional surfaces internal to the Garber Sandstone are commonly observed in outcrops and at the Cowboy Hall of Fame location.

Stratigraphy

Stratigraphic units of the COA include Quaternary alluvial and terrace deposits and Permian sedimentary rocks (Breit et al., 1990). These Permian rocks, beginning at the base include the Admire Group, Council Group, Chase Group, Wellington Formation, Garber Sandstone, Hennessey Group, and El Reno Group (Fig. 4). The Permian Hennessey Group overlies the Garber Sandstone. The contact between Wellington Formation and Garber Sandstone as well as the contact between Garber Sandstone and Hennessey Group are still controversial. The Hennessey Group is described as being composed of massive reddish-brown mudstone with lesser amount of orange-brown to greenish siltstone and reddish-brown, fine-grained sandstone (Breit et al, 1990). Sometimes, the lithologic appearance is typical to a locality. For instance Aurin et al. (1926) characterized the Hennessey group in Kingfisher County, Oklahoma as rusty, blocky, rarely fissile shales and siltstones showing white- or light- green bands, streaks, and spots with a conchoidal fracture. They also characterized the Garber sandstone as cross-bedded, more or less lenticular, conglomeratic, massive, red sandstone, containing strata with beds of red fissile shale and sandy shale. Cragin (1896) described the Wellington Formation as bluish-gray, greenish, and reddish shale, with thin beds of sandstones.

Erathem	System	Geologic unit
Cenozoic	Quaternary	Alluvium
		Terrace deposits
Paleozoic	Permian	El Reno Group
		Hennessey Group
		Garber Sandstone
		Wellington Formation
		Chase Group
		Council Grove Group
		Admire Group
	Pennsylvanian	Vanoss Formation

Fig. 4: Major stratigraphic units of the Central Oklahoma Aquifer (Parkhurst et al., 1989)

CHAPTER V

RESULTS

Outcrop and Core Descriptions

The main Garber Sandstone outcrop described in this study is located in Oklahoma City area, on the north side of Interstate I-44, and on the southwest side of the Cowboy Hall of Fame property. The reason for studying this particular Garber Sandstone outcrop is because it contains a variety of sedimentary features. Among these features are some highly carbonate cemented intervals, some trough cross-bedded units, some channelized sandstone lenses with erosional bases, and some poorly consolidated sandstone that would serve as a good aquifer if projected into the subsurface.

The outcrop is generally reddish in color and the vertical section is about 95 feet (30 meters) in thickness. The outcrop can be divided into five parts: the basal sand (referred to as "B"), three lenses (referred to as L1, L2, L3), and a sandy and poorly consolidated top layer, T. Between each of the layers starting above B, there is a relatively thick interval of mudstone. The measured section of the outcrop is illustrated in Fig. 5.

The thickness of the base of the outcrop is indeterminable. This basal sand is off-white to gray in color, matrix free, and very friable. The very top of the basal sand is greenish and contains thin, horizontal laminations. Sand grains range from fine to very fine, and are

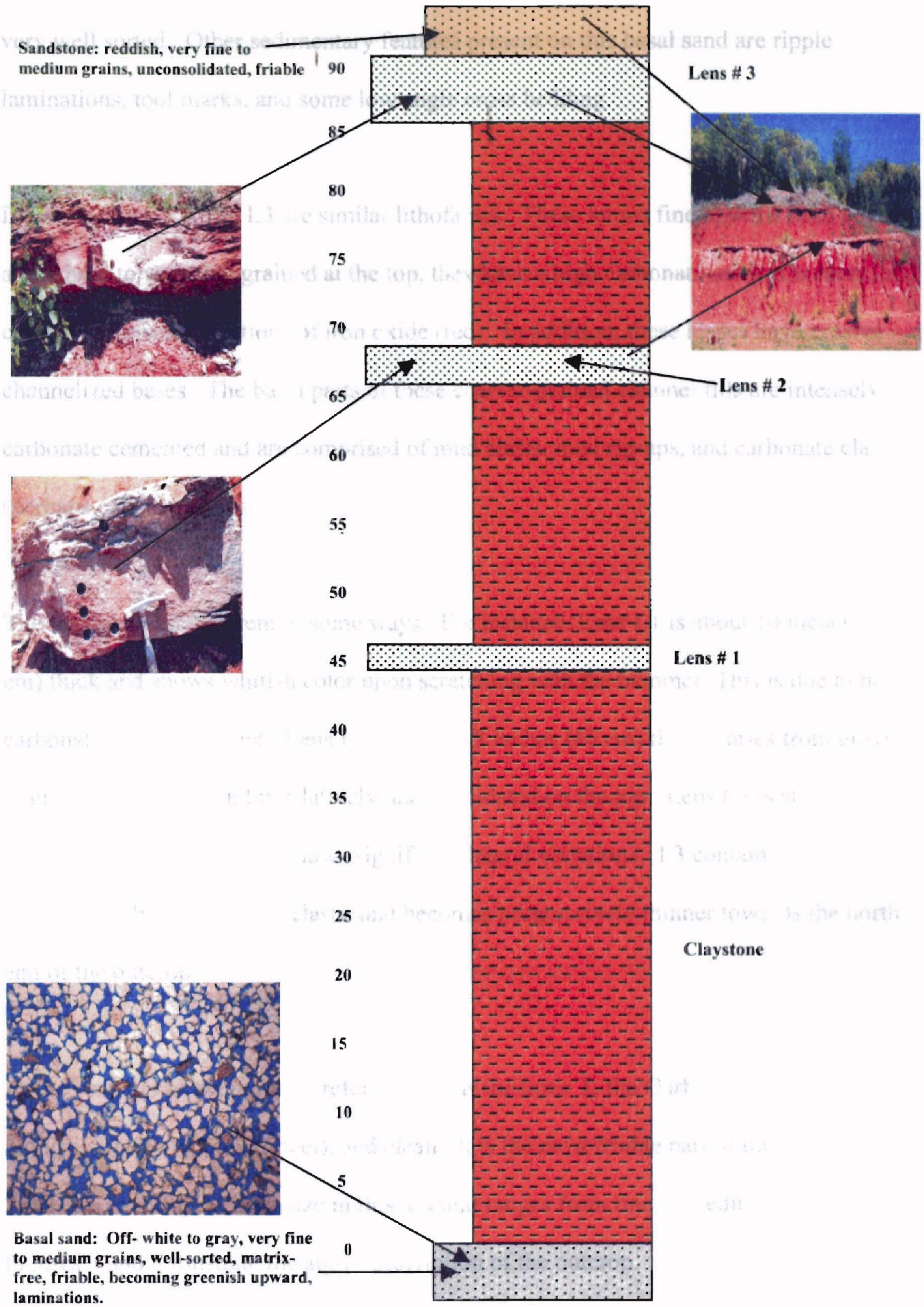

Fig. 5: Stratigraphic column of the measured section of the Cowboy Hall Fame outcrop.

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very well sorted. Other sedimentary features present on this basal sand are ripple laminations, tool marks, and some low angle cross bedding.

Layers (lenses) L1, L2, L3 are similar lithofacies. These lenses fine upward from coarse at the base to very fine grained at the top, they have a high carbonate-cement content, and contain large concentrations of iron oxide (red). In addition, these lenses have erosive channelized bases. The basal parts of these coarser-grained channel fills are intensely carbonate cemented and are comprised of mud clasts, mud rip-ups, and carbonate clasts (perhaps caliche rip-ups).

The lenses are all different in some ways. For instance, Lens L1 is about 10 inches (25 cm) thick and shows whitish color upon scratching with the hammer. This is due to high carbonate cement content. Lens L2 is about 18 inches (46 cm) thick, varies from grayish to greenish in color, and is relatively unconsolidated on the top. Lens L3 is about 25 inches (63 cm) thick and it shows significant lateral variations. L3 contains some trough crossed-bedding, carbonate clasts, and becomes progressively thinner towards the north end of the outcrop.

At the very top of the outcrop, referred also as the layer T, the Garber Sandstone is reddish, relatively thick (5 feet), and clean. It is the most friable part of this Garber Sandstone outcrop. Grain size in this top unit ranges from fine to medium sand. Figures 3 and 5 illustrate the above description of the outcrop.

Among the five NOTS Wells involved in this present study, only the core of the NOTS Well 1a was fully described. The core was described from the base to the surface for a total interval thickness of 268 feet.

The major sedimentary and geologic features that characterize the core are summarized here. The core includes horizontal and parallel laminations, small-scale ripples, low angle cross bedding, disruption by rooting, intraclasts, calcite nodules, and concretions.
A detailed description of the core from the NOTS Well 1a is provided in Fig. 6a.

Generally, the core examined shows a series of fining upward sands (Fig. 6b). The base of the core is made of fine to medium grained quartz sandstone with small scale ripples. The middle section of the core is red, purple, locally calcitic, and clayey. It contains carbonate concretions. Above this portion of the core, there is a zone of significant iron-oxide content. It is also pebble rich and has low angle cross-bedding and horizontal parallel bedding. A conglomeratic sandstone lies just above. Near the surface, from 30 feet to 20.5 feet, the section becomes rooting mudstone. Evidence of root prints filled with dolomite cement suggests soil horizon development in the floodplain.

The top section of the core 1a, from 20.5 feet to 15 feet, shows a fining upward sequence with pebble conglomerates. The sandstone varies from very fine-to-fine grained sand, with some pebbles and clay matrix.

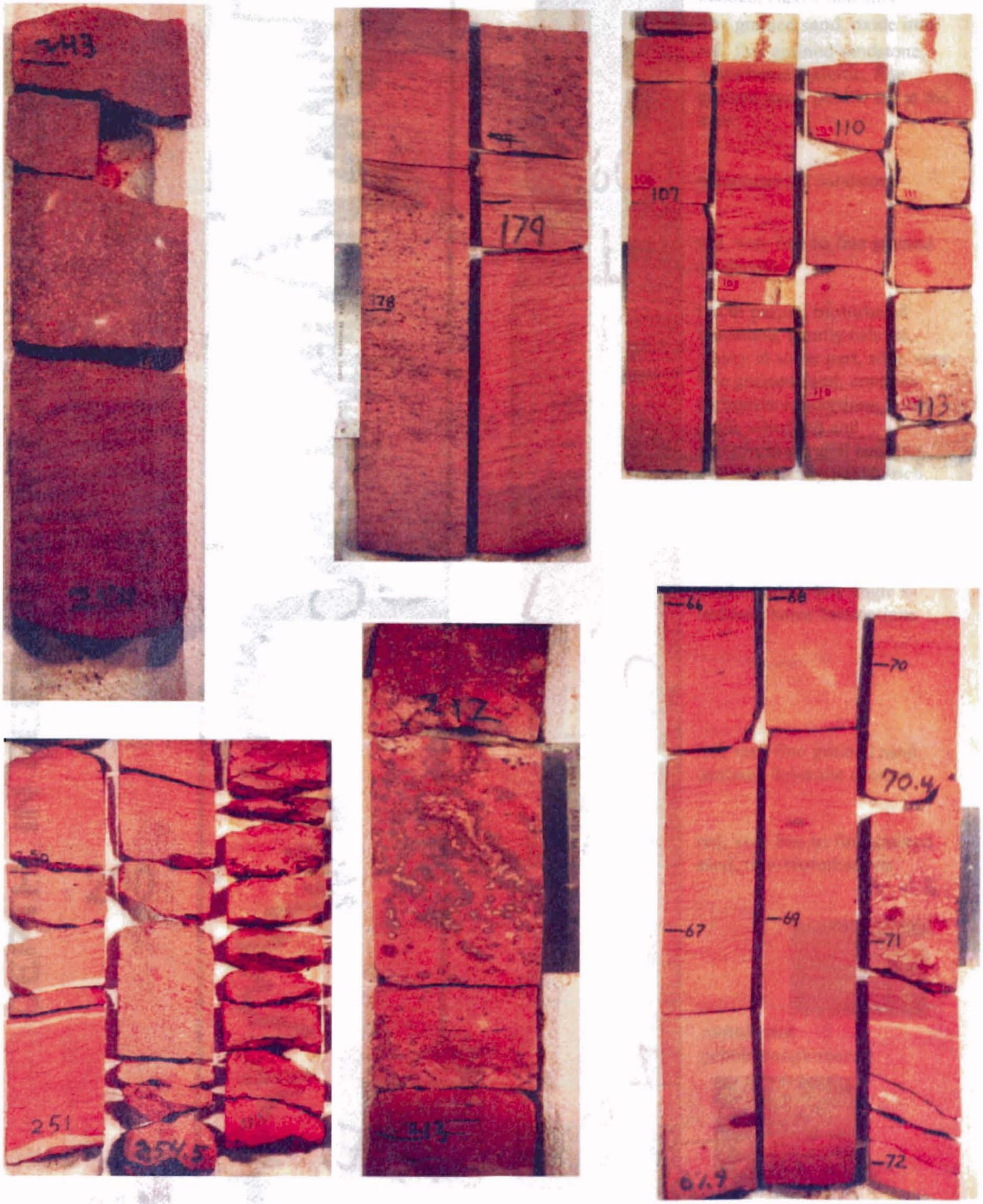

Fig. 6: The described Core from NOTS Well 1a shows sedimentary features such as fining upward sequence, lamination, carbonate and mud clasts, mud rip-ups, concretions, calcite nodules, conglomeratic and cement zones.

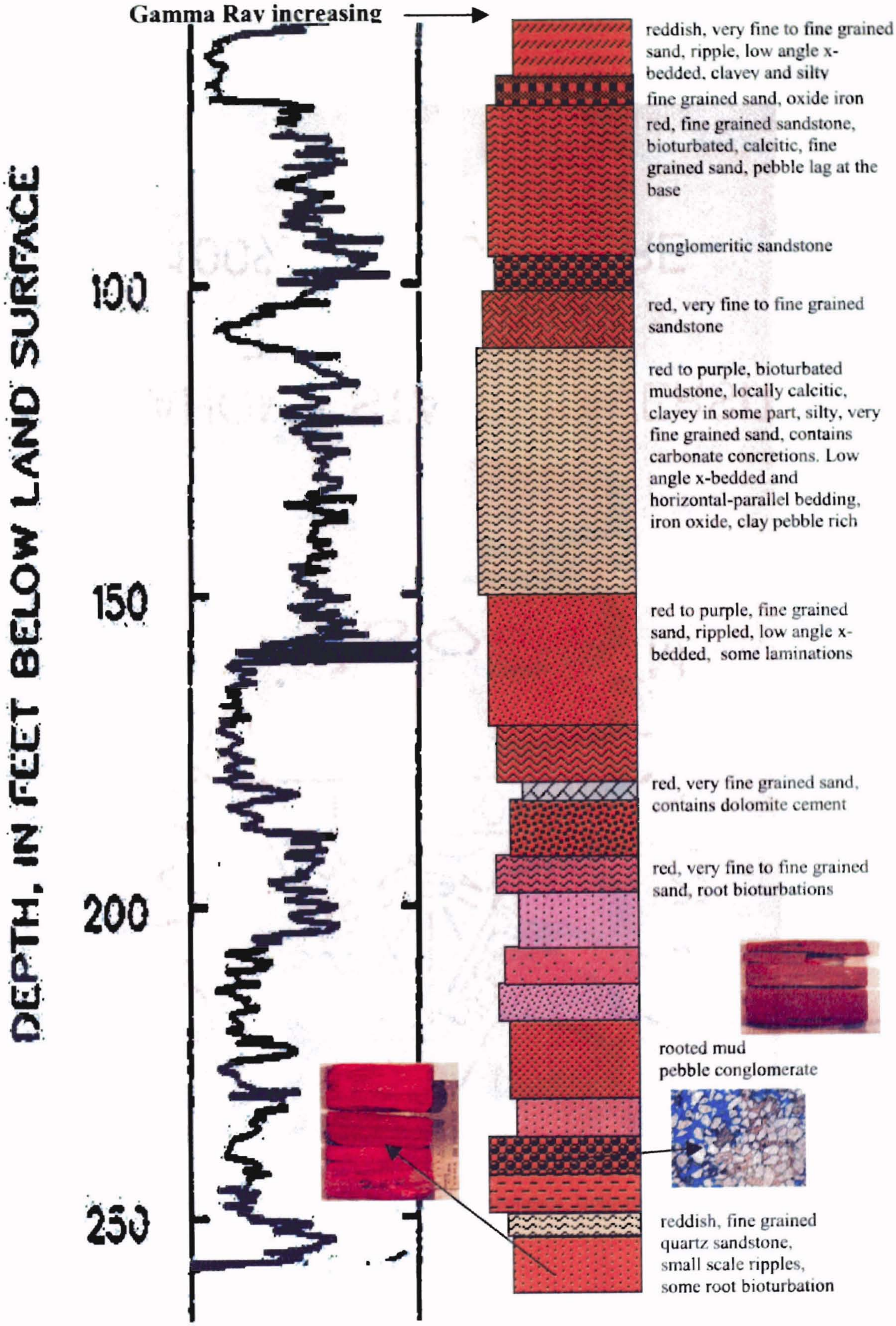

Fig. 6a: USGS-NOTS Well 1a, Core description and Gamma ray response.

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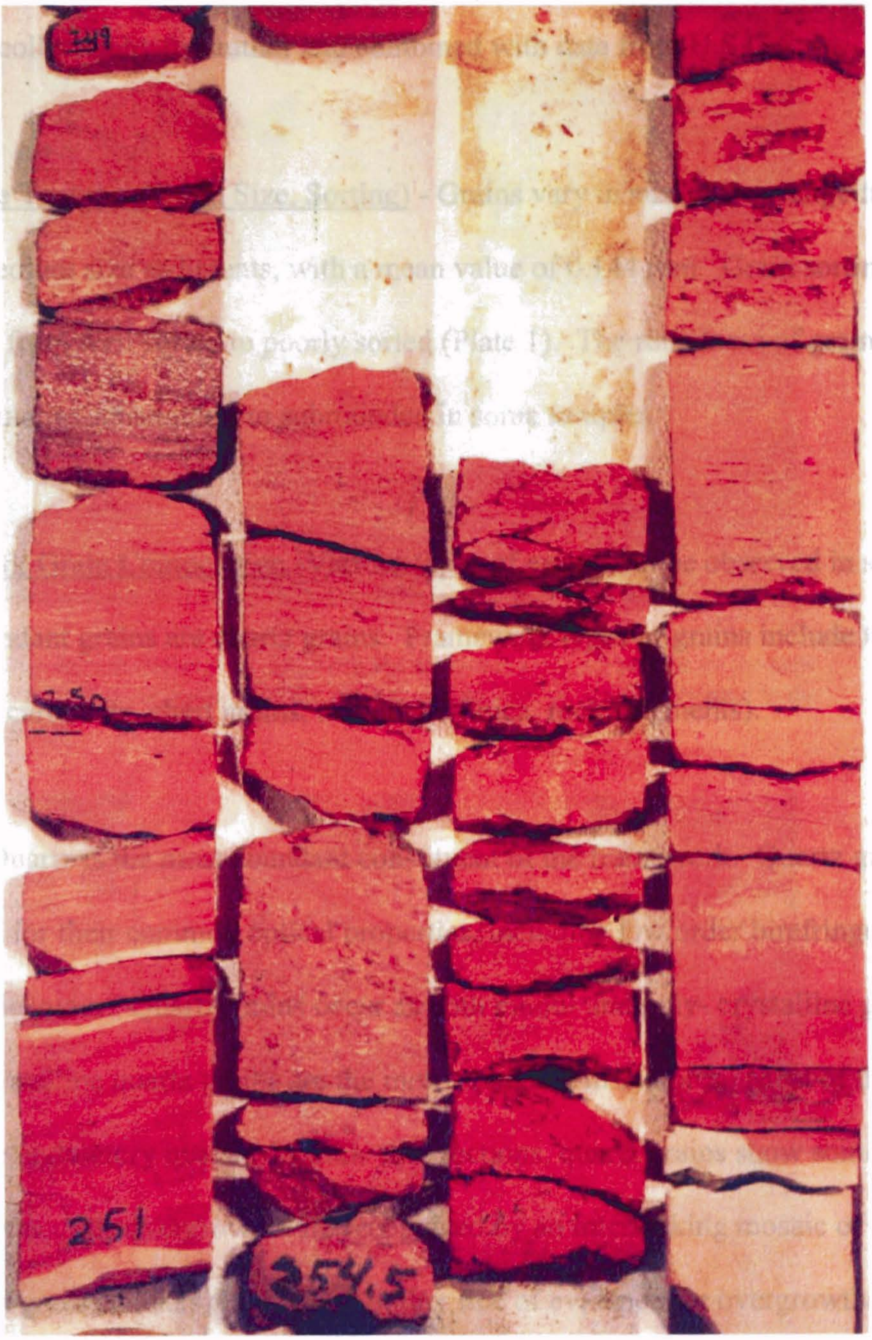

Fig. 6b: Core 1a shows a fining upward sequence, laminations, conglomerate

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Petrographic Examinations

The petrography investigation of this study is summarized the following discussion. The data was collected by the author and combined with data from U.S.G.S.

Sandstone Textures (Grain Size, Sorting) - Grains vary in size. They range from very fine to medium size sediments, with a mean value of 0.144 mm. Grain sorting varies generally from well sorted to poorly sorted (Plate 1). The roundness of grains varies from angular to subangular, to subrounded in some samples.

Framework Grain Composition -Various types of grains can be observed in samples. The most abundant grains are quartz grains. Framework types of grains include feldspar (Plate 2), carbonate, chert grains, and others (mica, rock fragments).

Quartz- Quartz is the most abundant constituent of the framework. Quartz grains are identified for their common optical properties, including low order birefringence and uniaxial behavior. Quartz grains occur as both mono- and poly- crystalline grains. Mono-crystalline quartz grains are the more abundant in samples. Most of the quartz grains are undulatory quartz. In some thin sections, quartz grains show some overgrowths. The overgrowths are recognized by an interlocking mosaic of thin quartz crystals at grain contacts (Plate 3). Another line of evidence for overgrowths is that the thickness of numerous overgrowths in a field of view is uniform. This would not be expected where the overgrowths were inherited on detrital grains. There is also evidence

NOTS 1a-14 (141.6')

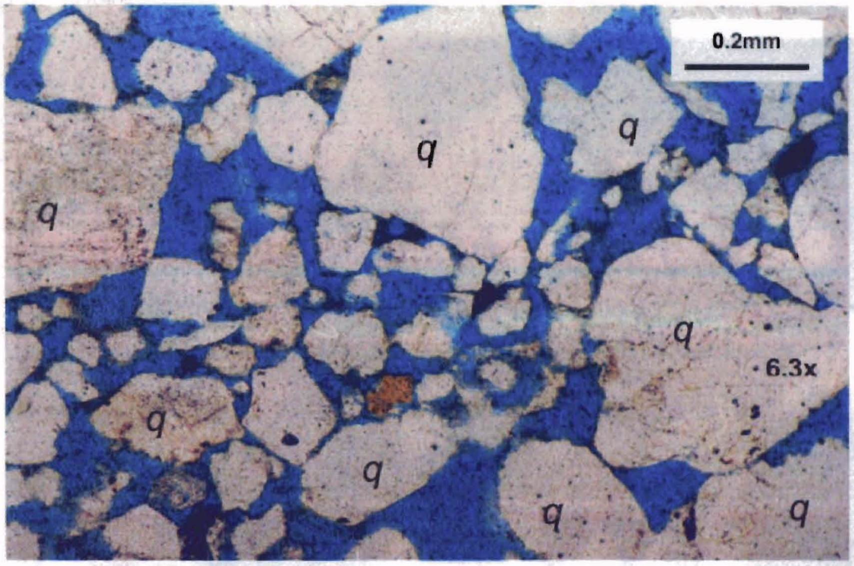

Plate 1: Thin section shows poor sorting in the shallower (141.6') portion of the core 1a reducing the porosity of the section. Quartz grains are predominant in the sample.

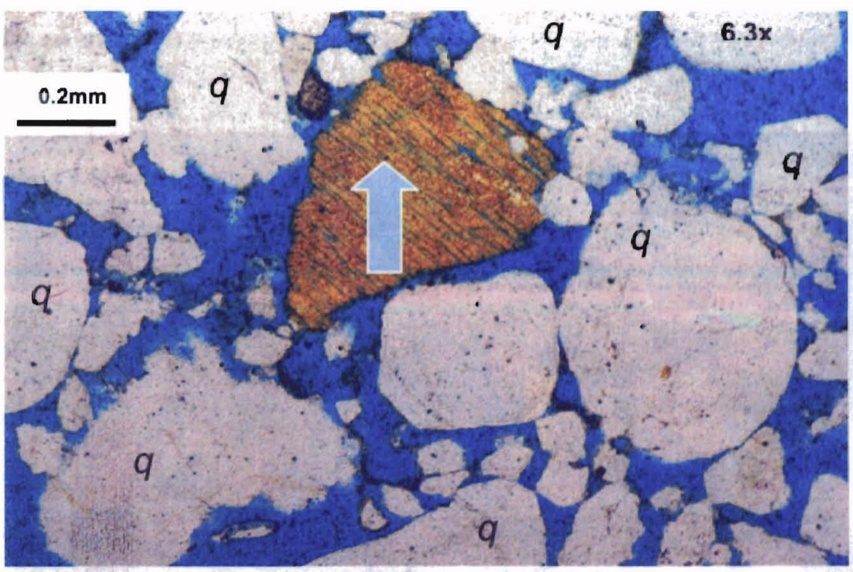

Plate 2: Poor sorting, K-feldspar grain (light blue arrow) among quartz grains.

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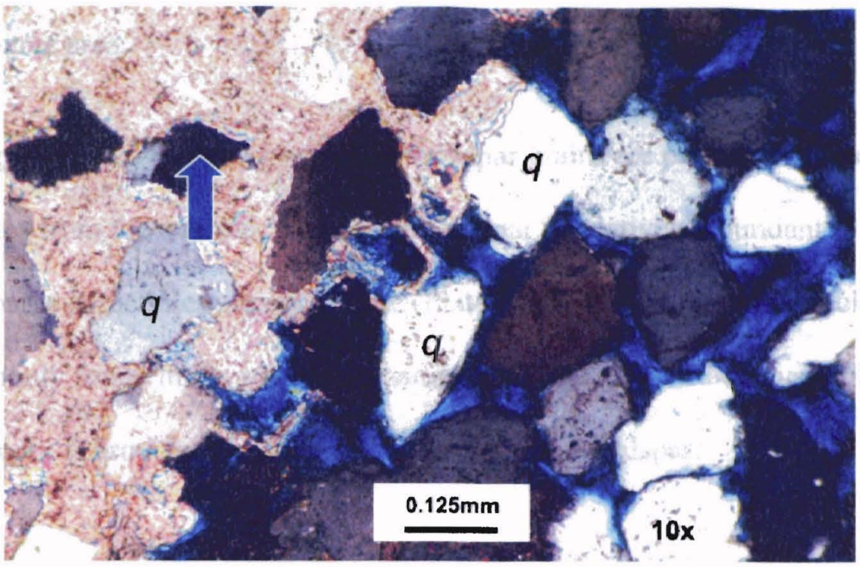

q = quartz grain

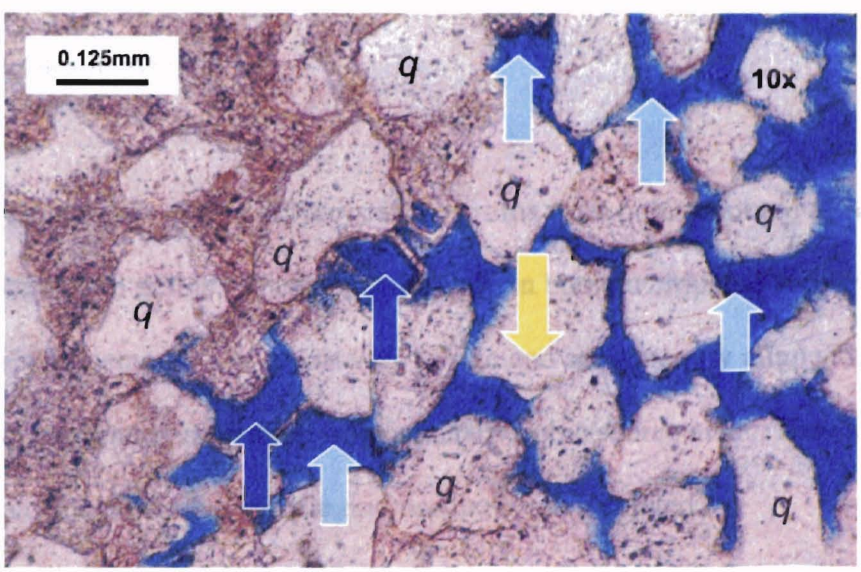

Plate 3: Sample shows, dolomite cement, quartz overgrowths (gold arrow), intergranular primary porosity (light blue arrows) and intergranular secondary porosity (blue arrows).

that some quartz grains with overgrowths were inherited from the source area or provenance. Quartz grain overgrowths appear partially eroded or truncated. The truncated overgrowths are likely to be related to the transport of quartz grains from the source area.

Feldspar- K-feldspar and plagioclase feldspar grains are present in some samples. In samples from the outcrop, plagioclase feldspar is relatively abundant (5%). Plagioclase feldspar is sometimes altered to illite (Plate 8). K-feldspar and plagioclase feldspar are commonly found in the subsurface samples. The data set made available in Appendix B provides percentages for each type of feldspar.

Hematite – It is the common oxide-iron mineral present in samples. Hematite is responsible for the red color of the Garber Sandstone. It is characterized by red streaks and it appears as massive, opaque, and pore filling material. It is also disseminated in the matrix and is sometimes encased by ferroan dolomite cement. It constitutes about 4% of the samples in average.

Rock Fragments – Some polycrystalline grains were point-counted as rock fragments (metaquartzite) grains. They are commonly in both outcrop and subsurface samples. Crystals in metaquartzite grains vary in size and are generally aligned in a parallel manner suggesting derivation from a metamorphic source area. They show high andulatory extinction when the microscope stage is rotated.

Carbonate grains are particularly abundant in the L1-1 (55%) and L3-1 (66%) samples from the outcrop. This high amount of carbonate grains is caused by the presence of large size of carbonate clasts in these samples. Carbonate grain types were not separated during the point-counting procedure. Optically, carbonate grains are recognizable by their high relief (commonly containing iron) and very high order birefringence. Some low grade metamorphic grains contain both quartz and muscovite.

Sublitharenite Sandstone – Composition of the sandstones within the study area suggests that the Garber is a sublitharenite sandstone (Folk, 1980). The sandstone is dominated by quartz grain, but rock fragments are greater in abundance than feldspar. Based on data set, the mean normalized quartz content (Q-F-R) is about 92%, normalized feldspar is about 3%, and normalized rock fragment is about 5% in the Garber Sandstone.

Depositional Matrix- Matrix is composed of mixture of clays (illite, very fine muscovite, and kaolinite).

Cement- The most common type of cement present in the samples is dolomite cement. Dolomite cement is poikilotopic and highly pleochroic (Plate 4a). The pleochroic behavior is probably due to iron in the cement. Some cement was also calcite (red stain in some thin sections). Quartz cement occurred in very small volumes. One thin section had a trace of barite cement. Although cementation is very common in the study area, it occurs about less than 1% of the outcrop area.

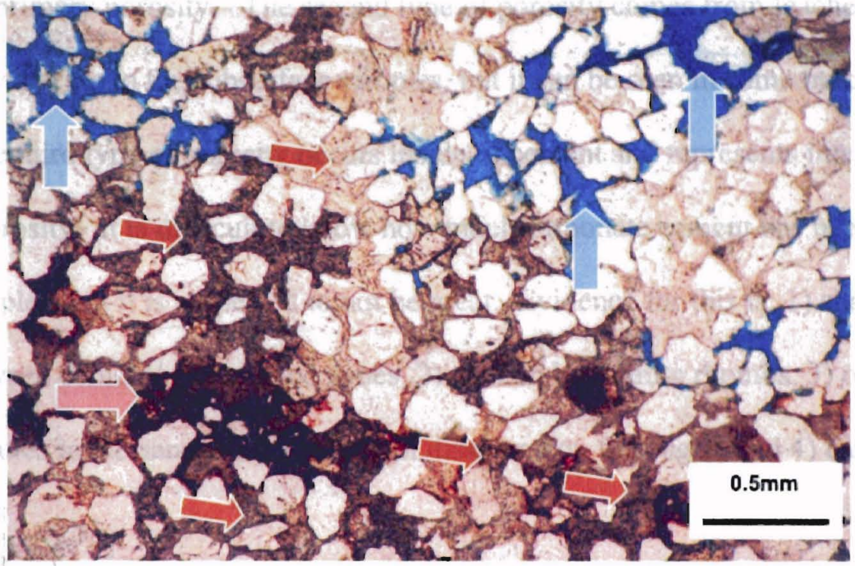

Plate 4a: - Iron (hematite, pink arrows), ferroan dolomite cement (brown arrows), and porosity (blue arrows) in a sample from the Cowboy Hall of Fame outcrop (Layer L3-2). Note that hematite is encased by the ferroan dolomite cement. The brown arrows are positioned on poikilotopic crystals of dolomite. Based on the optical properties, this field of view has at least seven crystals (as indicated by the arrows).

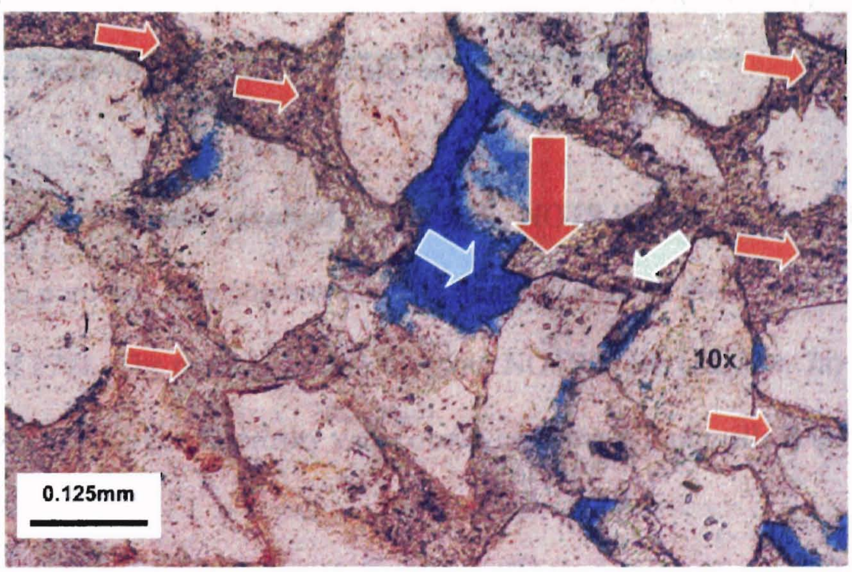

Plate 4b: - Ferroan dolomite cement (brown arrows) and porosity (blue arrow) in a sample from the Cowboy Hall of Fame outcrop (Layer L3-2). The large brown arrow indicates a euhedral crystal that is growing into a pore of the sandstone. A trace of rhombohedral cleavage is visible in the crystal (light green arrow).

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Porosity- Three types of pore space were identified in samples. The common type is intergranular porosity, which is mostly the result of a loosely arranged framework of quartz grains. In this case, intergranular porosity is depositional; as such it can be classified as primary porosity. The second type of porosity comes from leached grains. This is relatively rare in the subsurface samples, but it can be seen in some outcrop samples. The third type of porosity occurs inside of cement and represents intergranular secondary porosity. It is difficult to know how much carbonate cement has been leached from the samples, but it is suspected to not be great. Evidence for this is: 1) sharp contacts between cement/uncemented zones, 2) euhedral dolomite rhombs, 3) occurrence of round nodules in the sandstone that are not dissolved on the edges, and 4) carbonate grains.

Comparison of NOTS Wells Petrographic Data

Al though wells are not stratigraphically correlated, the comparison of NOTS Wells petrographic data is a convenient way to identify obvious differences in aquifer quality across the study area. This study has not been performed within a detail stratigraphic framework. The framework does not currently exist.

Porosity - Among the five wells involved in this study, NOTS Well 6 has the highest mean thin section porosity. The porosity range in this well is about 4% to 44%, with a mean porosity of 27%. The porosity in the other four NOTS Wells (1a, 3, 4, 7a) ranges from 16% to 19%. The highest porosity value observed in these four wells is about 41%.

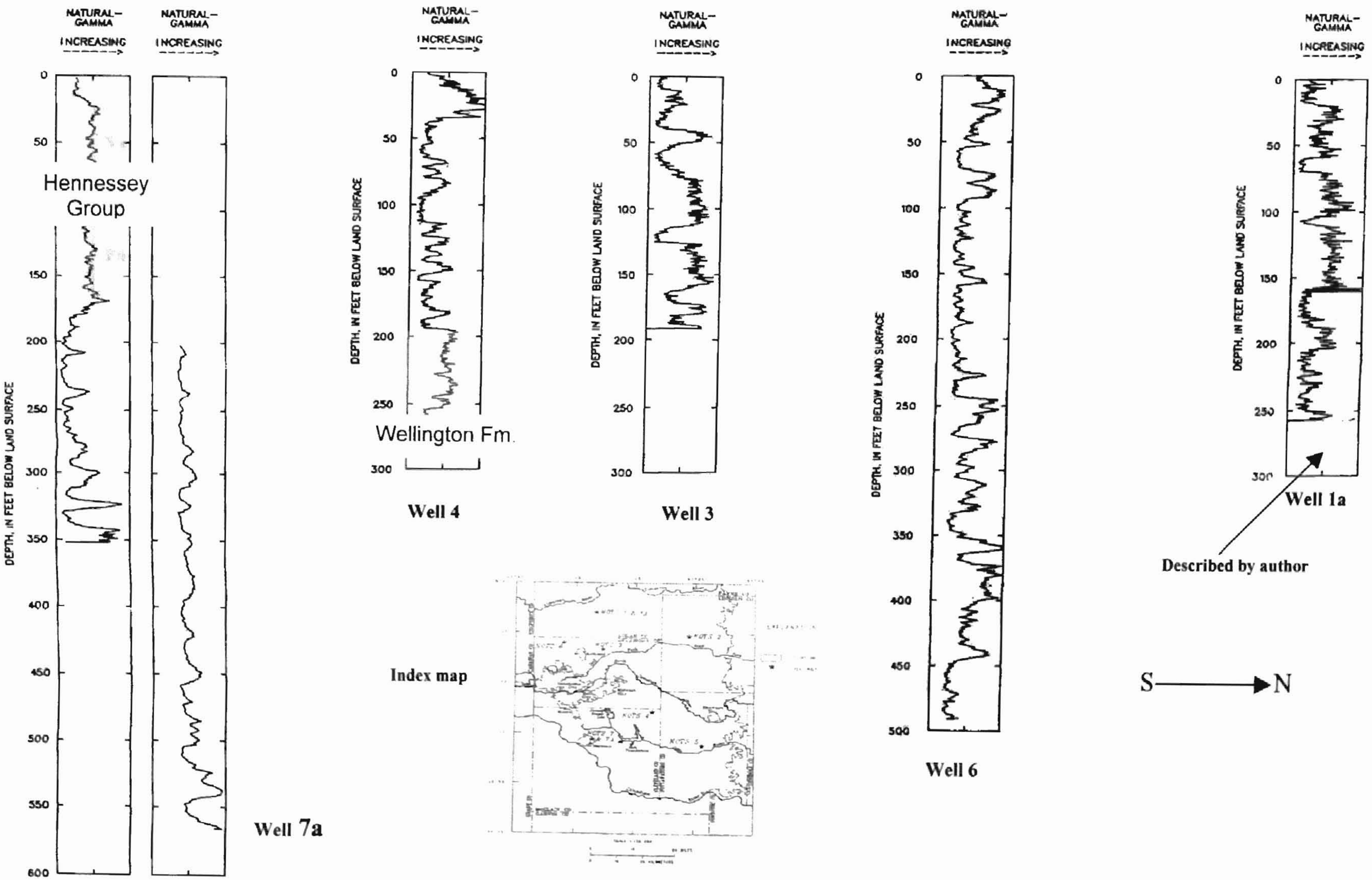
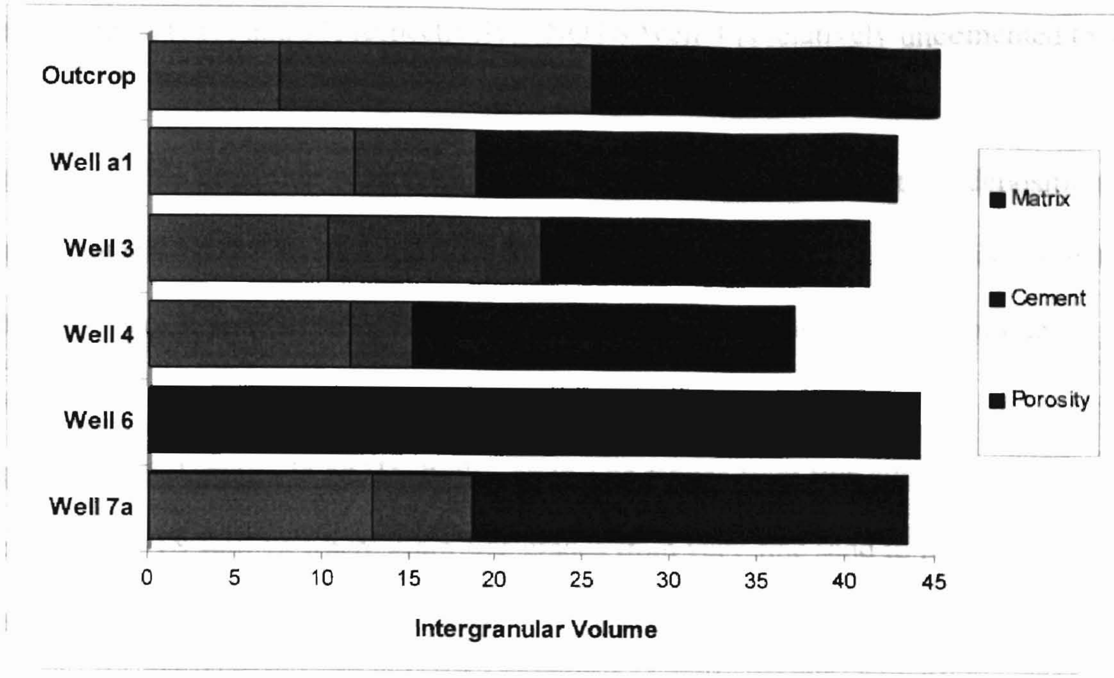


Fig. 7: USGS-NOTS Wells: Gamma Ray response on the Permian Garber Sandstone.

Variable	NOTS Wells + Outcrop	NOTS Wells	Outcrop	Well 1a	Well 3	Well 4	Well 6	Well 7a
Porosity	19.6 **(1)** 0 - 43.7 **(2)**	20.4 0 - 43.7	14.2 1 - 34.1	17.8 0 - 35	16.4 .3 - 36.9	18.9 1.6 - 37.5	26.7 3.7 - 43.7	18.6 .7 - 40.7
Cement	12.3 0 - 88.7	11.3 0 - 88.7	19.5 0 - 54	18.1 .3 - 88.7	15.8 0 - 60.0	4.8 0 - 8.7	10.5 0 - 66.7	8.9 .6 - 46.5
Matrix	13.9 0 - 55.8	14.1 0 - 55.8	12.5 0 - 39.3	14.4 1.5 - 38	11.8 .5 - 34.3	17.7 1.6 - 36.7	9.5 0 - 55.8	20.8 1.8 - 42.5
Grain Size	0.2 1 - 0.4	0.155 .0625 - .375	0.1347 .033 - 0.1843	0.118 .094 - .188	0.144 .094 -.375	0.184 .0625 - .375	0.17 .094 - .375	0.14 .063 - .25
Sorting	0.8 .3 - 2.0	0.89 0.425 – 1.5	0.41 .25 - 2	.93 .6 - 1.5	0.88 .425 - 1.5	0.85 .425 - 1.5	0.86 .43 - 1.5	0.99 .43 -1.5
Normalized Tot. Qrtz	91.2	92.5	84.8	92.1	89.1	93.1	94.2	94.0

Table 1: Summary statistics- table of results

(1) Mean value (%) **(2)** Range (%)



Intergranular Volume (IGV), Summary for each NOTS Well and Outcrop in the study area.

Variable	Outcrop	Well 1a	Well 3	Well 4	Well 6	Well 7a
Porosity	19.0	23.9	18.6	21.8	29.7	24.7
Matrix	7.8	11.8	10.3	11.6	6.4	12.8
Cement	17.5	7.0	12.3	3.6	7.9	5.8
IGV	40.5	42.7	41.2	37.0	44.0	43.3

Table 1a: IGV-summary data. Data set includes only samples with less than 26% total matrix and those with less than 40% cement.

Cement - NOTS Wells 1a, and 3 are highly cemented (18% and 16%) compared to NOTS Wells 6 and 7a (11% and 9% respectively). NOTS Well 4 is relatively uncemented (5%).

Matrix - Another important observation regarding the control on porosity is depositional matrix content. NOTS Wells 4 and 7a (18% and 21%) have the highest matrix content. NOTS Wells 6, 3, and 1a (10%, 12% and 14%) have relatively low matrix volumes.

Grain Size and Sorting - In NOTS Wells, grain size ranges from fine silt to medium sand, except for NOTS well 1a where grain size grades from very-fine sand to fine sand. Sorting shows a more uniform trend in all NOTS wells. The Garber ranges from well to poorly sorted sand in each of the wells. Generally, grain size and sorting ranges are almost identical for NOTS Wells.

Comparison of Outcrop and Subsurface Samples

Texture (grain size, sorting), cement volume, and matrix volume are the most important variables for determining the character of porosity in aquifers and reservoirs. These variables are summarized in Table 1. The table and cross-plots compare thin section data from outcrop samples collected by the author and thin section data collected from the subsurface (Breit et al., 1990). This comparison will help to establish the similarity and differences in the two sample sets. Comparison of the data sets is one step in trying to assess the regional changes in porosity, matrix and cement contents, and grain size and sorting in the Garber. The outcrop data is used to establish relationships between the lithofacies and depositional setting. The Breit's subsurface data set does not contain depositional setting or bedform designations. Consequently, it is difficult to directly compare petrography of the data sets. However, analysis suggests that the petrography between the two data sets are very similar. Therefore, it was decided to combine the data into one data set for analysis. By combining the data sets, one can better evaluate the relationship between the petrology and the geology.

Porosity

Inspection of Table 1 shows that there is a difference in porosity between outcrop and subsurface data. The mean porosity values are 14% and 20% respectively. The highest porosity occurring in outcrop is about 34% and highest in the subsurface is 44%.

Cement

A comparison of the amount of cement occurring in outcrop and in the subsurface shows a difference as well. The mean cement values are 20% in outcrop and 11% in the subsurface. These results lead to a tentative conclusion that less cement is found within the subsurface than is found in the outcrop. This result is just the opposite of what one would expect if near surface sandstone was being leached of carbonate cement due to surface weathering. However, this finding is exactly what one would expect if the outcrop samples are biased towards cemented zones that are resistant to weathering. The more friable, unconsolidated sands in outcrop cannot be sampled effectively. Consequently, they are under-represented in outcrop sampling relative to the subsurface continuous core.

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Wentworth Size Class	Size (in Millimeters)
Medium Sand	0.375
Fine Sand	0.188
Very Fine Sand	0.094
Fine Silt	0.008
Very fine Silt	0.004

Verbal Scale	Phi Standard Deviation
Very Well sorted	0.175
Well Sorted	0.425
Moderately Sorted	0.75
Poorly sorted	1.50
Very Poorly Sorted	3.0

Table 2: Charts for determination of Grain size and Sorting (Folk, 1980, pp. 23, 103)

Matrix

Another important control on the porosity is the depositional matrix. The mean matrix values for outcrop and subsurface sandstone data are 13% and 14% respectively. The maximum value estimated in outcrop is about 39%, and 56% is the maximum value for one of the subsurface siltstones. However, on total, the data indicate that no difference exists in matrix volume between the outcrop and subsurface sandstones.

Grain Size and Sorting

Grain size estimated from the outcrop samples varies from 0.1 mm to 0.4 mm, with a mean value of 0.14 mm. These grain size estimates suggest that the Garber outcrop sandstone varies from very-fine sand to medium-sand size. Sorting values range from 0.25 to 2.0ϕ, with a mean value of 0.41ϕ. Consequently, based on the Folk's (1980) classification scheme, the Garber sandstone ranges from very well to poorly sorted. The Folk's chart is provided in Table 2.

The Garber subsurface samples exhibit a wider range in grain size than the outcrop samples. Grain size ranges between 0.0625 mm and 0.375 mm, with a mean grain size of 0.155 mm. This suggests the Garber subsurface data set contains siltstones and can range up to medium grained sandstone. Sorting ranges from 0.425 to 1.5ϕ, with a mean sorting of 0.89ϕ. This suggests that the Garber in the subsurface varies from well sorted to poorly sorted sand according to Folk's (1980) classification. Therefore, the outcrop sandstone is better sorted and contains fine-grained sands.

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Comparison of outcrop and surface data on well basis shows similarities between outcrop and NOTS Well 3, which is the closest well to the outcrop location. They present similar patterns in term of porosity, matrix, and cement. Frequency distributions are provided in Appendix C.

The above summaries for texture, cement, and matrix volume and controls on thin section porosity are supported by the analysis of cross plots (Fig. 8a-e). These plots show trends in each of these parameters for each individual well with burial depth. The graphs reveal significant geological information. Based on these cross-plot data, the Central Oklahoma Aquifer can be divided into two depth intervals. At depths greater than 320 feet (98 meters), many porosity values in the COA range from 20% to 40%. The mean porosity for depths greater than 320 feet is about 25%. However, for data occurring shallower than 320 feet, excluding the outcrop samples, it is observed a larger range in porosity (0% to 44%) than what is observed for the deeper samples. The shallower samples (0 to 320 feet) have a much lower mean porosity (about 19%) than the deeper samples (below 320 feet). Table 3 is a summary of these results.

In terms of porosity controls, most of the sample matrix volumes at depths > 320 feet varies from 1% to 25 %. The mean matrix value is about 13%. In contrast, matrix varies from 0.5% to about 40% at depths < 320 feet. The mean value is about 14.3%. Also, the amount of cement is less at depths > 320 feet, varying from 0.7% to 20%. The mean value is about 10%. The volume of cement is much higher at depths shallower than 320 feet; it ranges from 0% to about 40%. The mean value is about 20%. Based on data, the

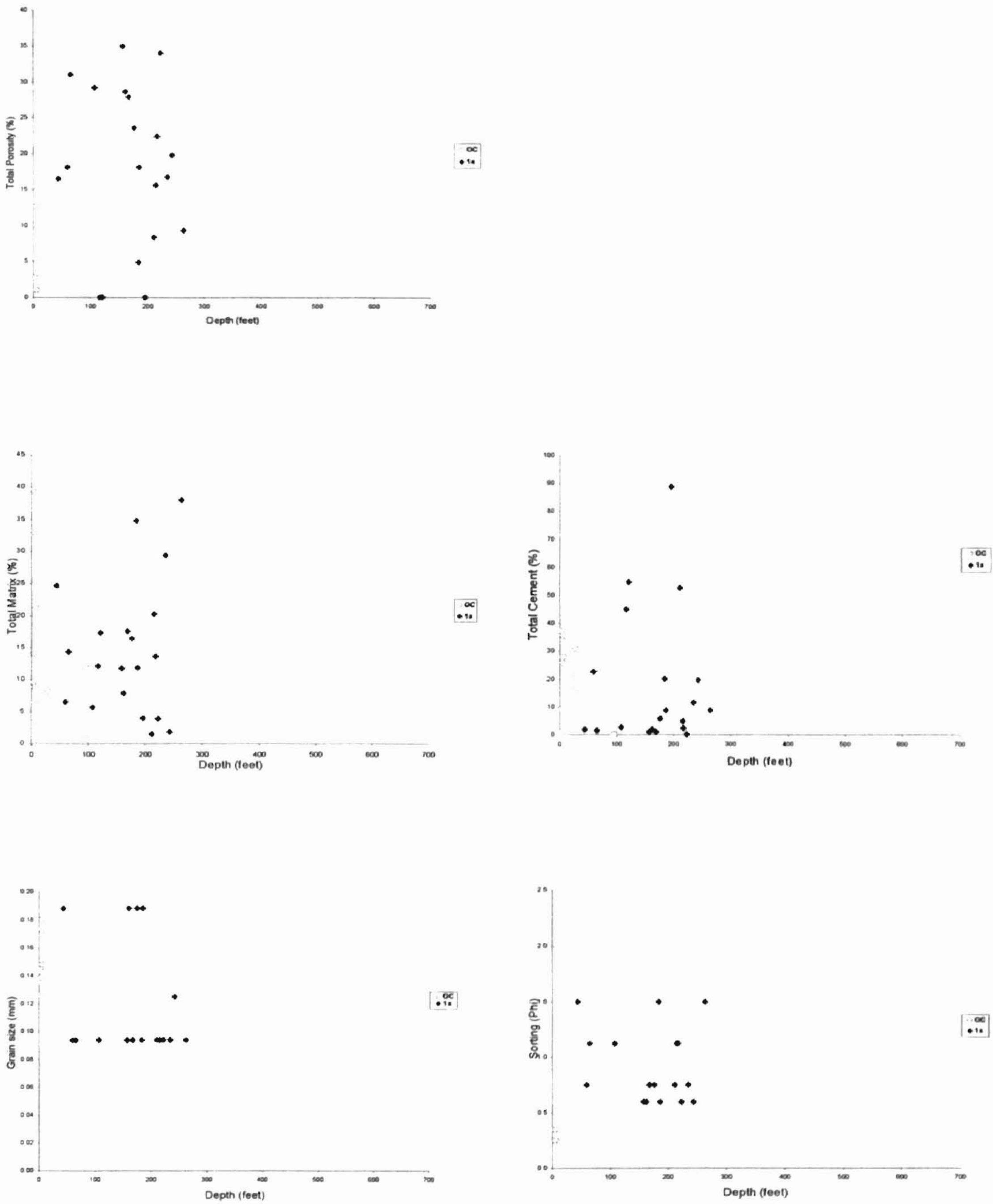

Fig. 8a: Cross-Plots showing comparison for Outcrop versus U.S.G.S. NOTS Well 1a data.

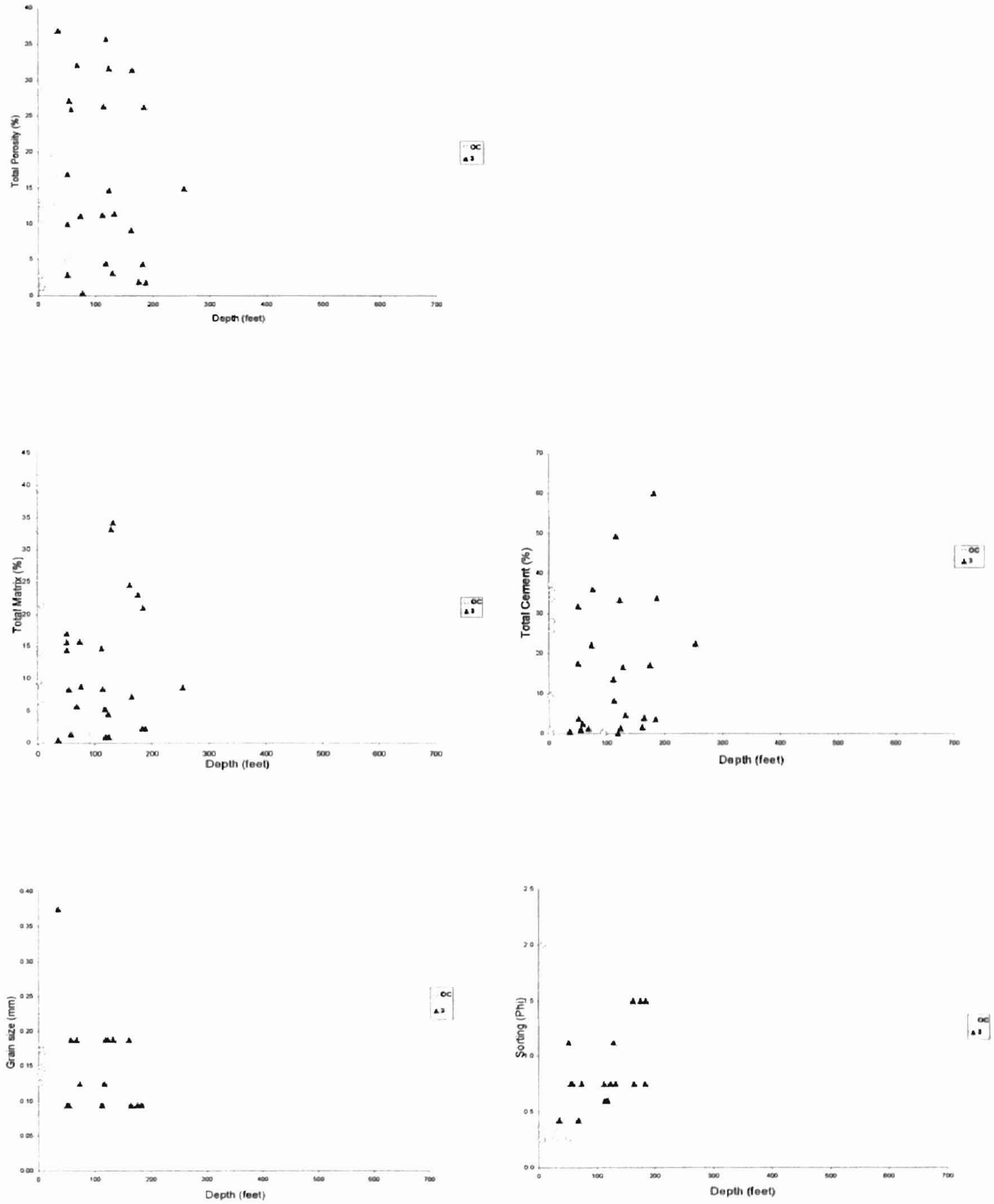

Fig. 8b: Cross-plots showing comparison for Outcrop versus U.S.G.S. NOTS Well 3 data.

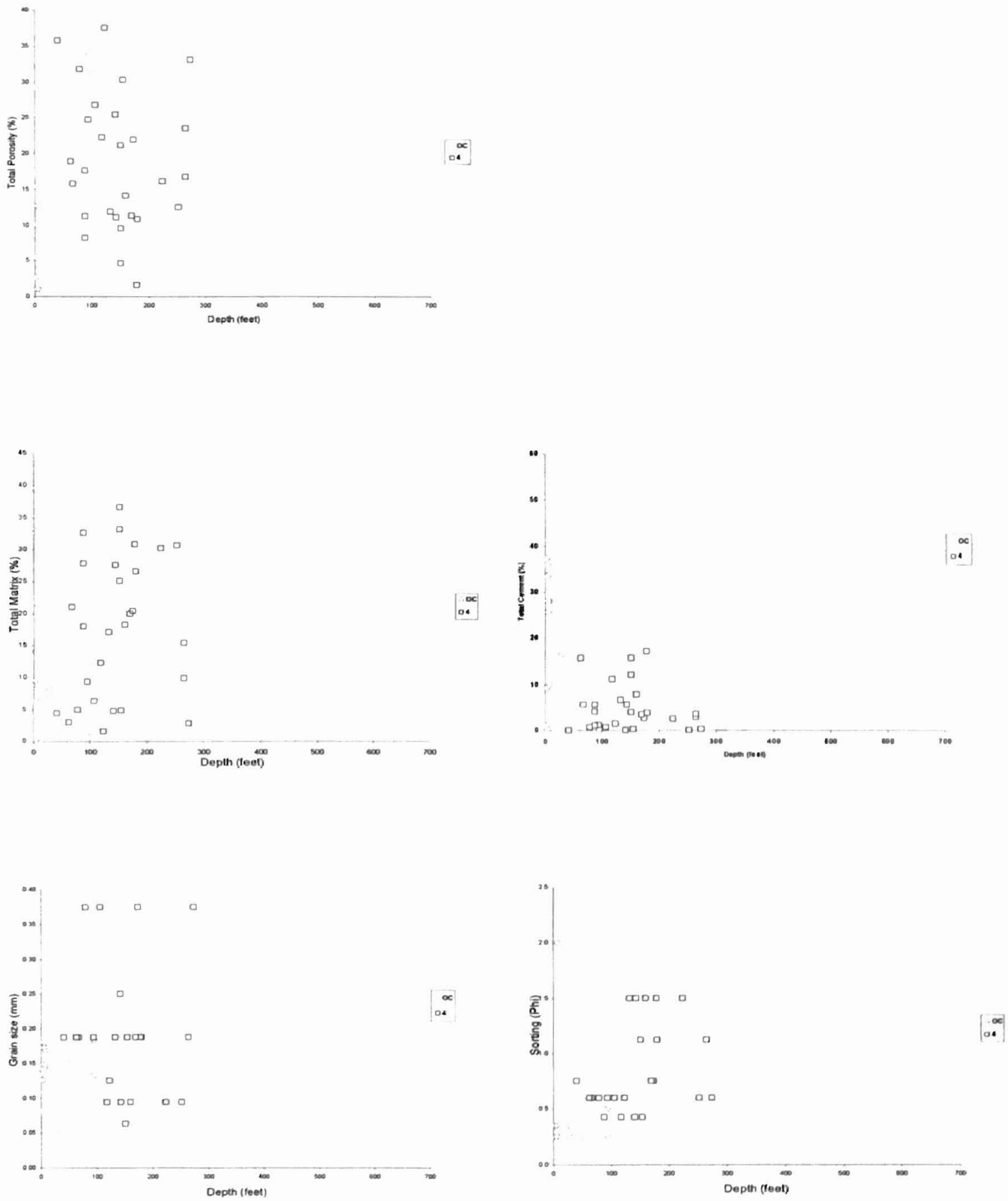

Fig. 8c: Cross-plots showing comparison for Outcrop versus U.S.G.S. NOTS Well 4 data.

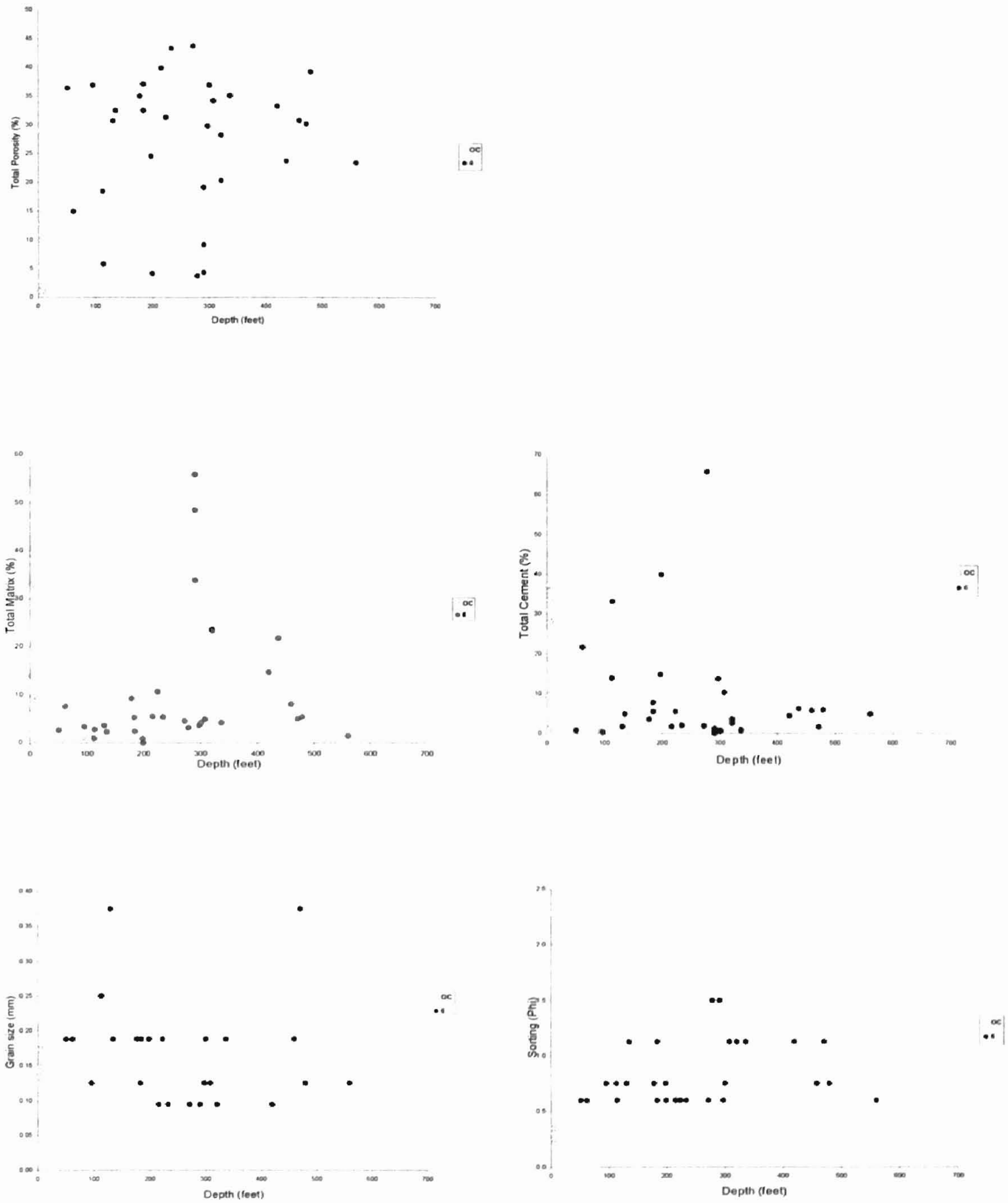

Fig. 8d: Cross-plots showing comparison for Outcrop versus U.S.G.S. NOTS Well 6 data.

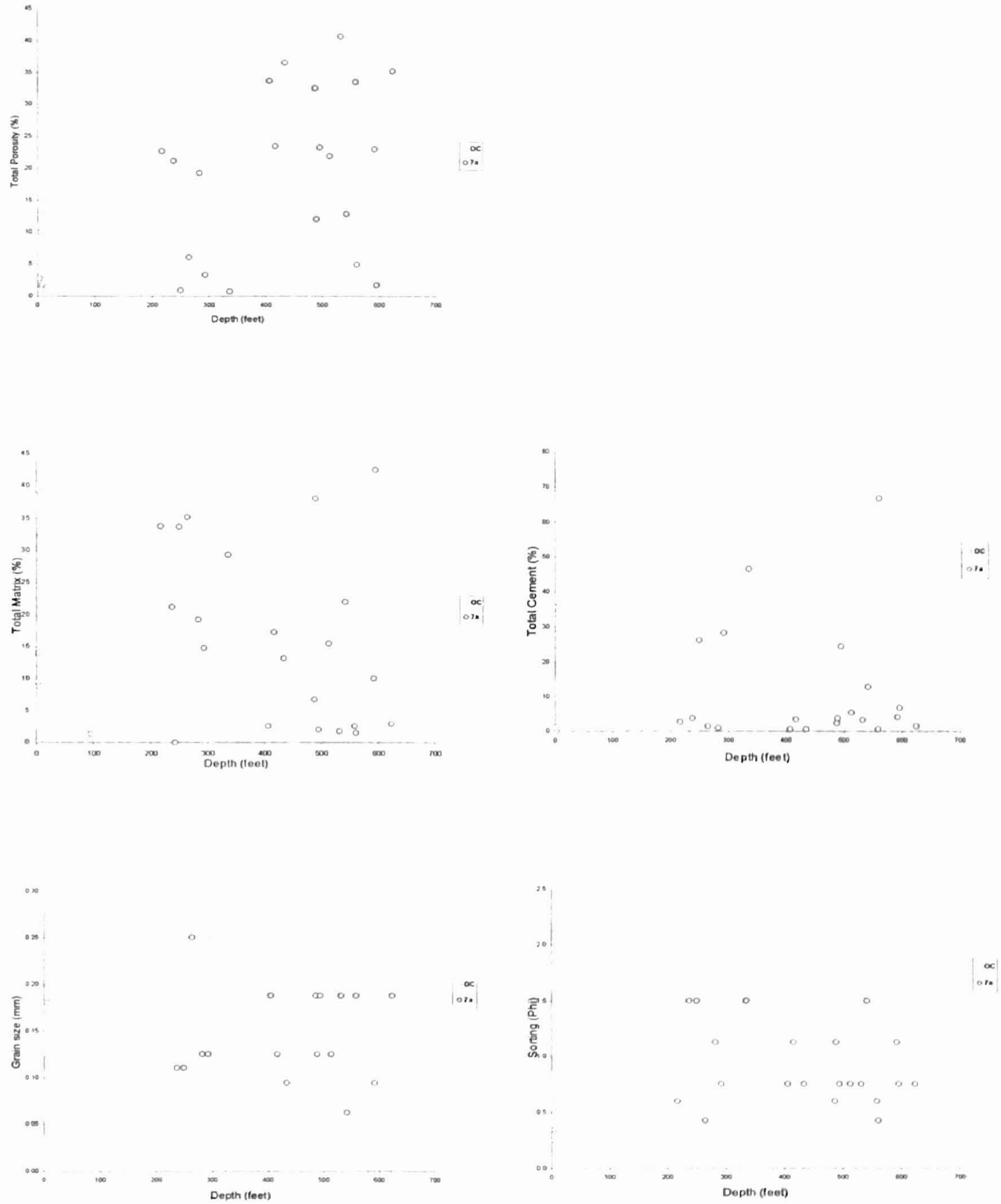

Fig. 8e: Cross-plots showing comparison for Outcrop versus U.S.G.S. NOTS Well 7a data.

deeper section (> 320') of the Garber Sandstone has slightly lower matrix than the upper section (< 320') in the study area. The deeper section of the Garber Sandstone also contains slightly less cement than the shallow section (Fig. 11). These observations are assisted by the frequency distribution comparing the two depth intervals (fig. 8f).

Grain size range is consistent within this aquifer. Grain size varies from very fine to medium grained sands. But, sorting occurs differently between shallow and deep intervals. At the outcrop, sediments vary from well to moderately sorted. Down to about 320 feet deep, sorting values vary from well to poorly sorted. Sorting varies from very to well sorted at depth greater than 320 feet. A summary of the results is provided in Tables 1 and 3.

The intergranular volume (IGV) of the Garber Sandstone is used to estimate the degree of compaction in the Garber Sandstone (Fig. 10 and Fig. 11). The reason for calculating the degree of compaction in the Garber is to determine where, on a regional basis, the aquifer has undergone less compaction (corresponding to shallower burial depth).
The IGV (= intergranular porosity + depositional matrix + pore-filling cement, Paxton et al., 2002) is a valuable and underutilized indicator of grain compaction in granular materials. The IGV compaction curve of Paxton et al. (2002) serves as a standard for comparison. The mean IGV in the Paxton work was determined by removing from the data set all samples that have more 5% matrix. A summary of IGV for samples from NOTS Wells and outcrop is represented in Table 4. Similarly, this was constructed taking into account only samples with less than 40% cement and 26% matrix.

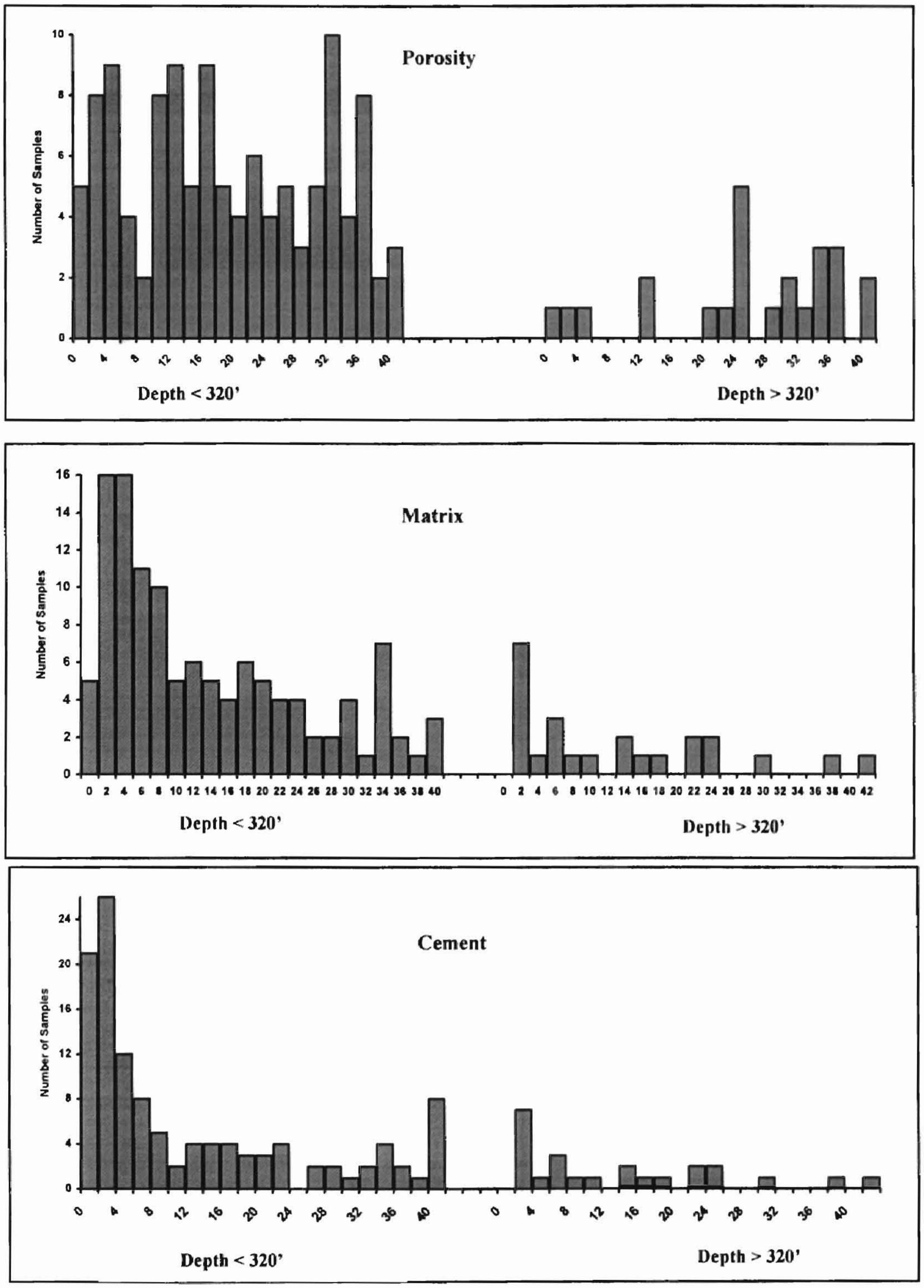

Fig. 8f: Interval depth comparison for porosity, matrix, and cement.

Depth...	Grain size (mm)	Sorting (ϕ)	Porosity (%)	Matrix (%)	Cement (%)
N	17	17	17	17	17
Outcrop	0.1347	0.41	14.2	12.5	19.5
N	90	94	101	101	101
< 320'	0.1538	0.89	19.4	14.3	11.8
N	20	23	24	24	24
> 320'	0.1518	0.91	25	13.2	9.1

Table 3: Summary table of mean porosity, matrix, and cement by depth interval. * *N* = Sample size

A burial history curve in the study area is provided (Fig. 9). The burial history curve is helpful in understanding the geologic and diagenetic history of the Garber Sandstone. A Time-Depth or Time-Temperature curve allows us to tie the petrographic data to the degree of compaction and cementation. Generation of these curves were possible by converting Schmoker's (1986) data using the equation that relates the geothermal gradient of the study area, surface temperature, formation temperature, and depth (Asquith, 1982, and Bassiouni, 1994). A complete interpreted data set is provided in Appendix D.

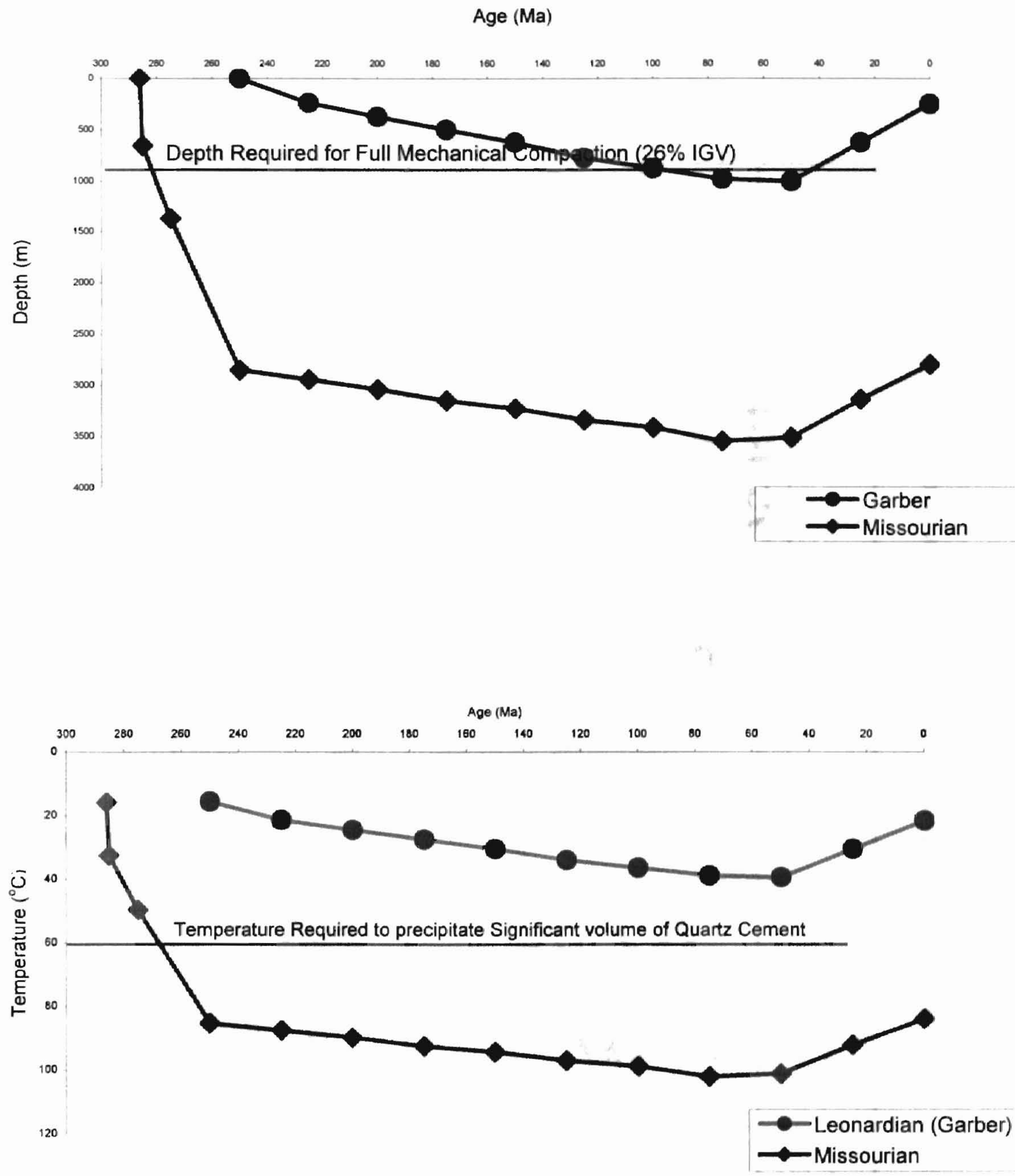

Fig. 9: Burial history reconstruction of the study area, after Schmoker (1986).

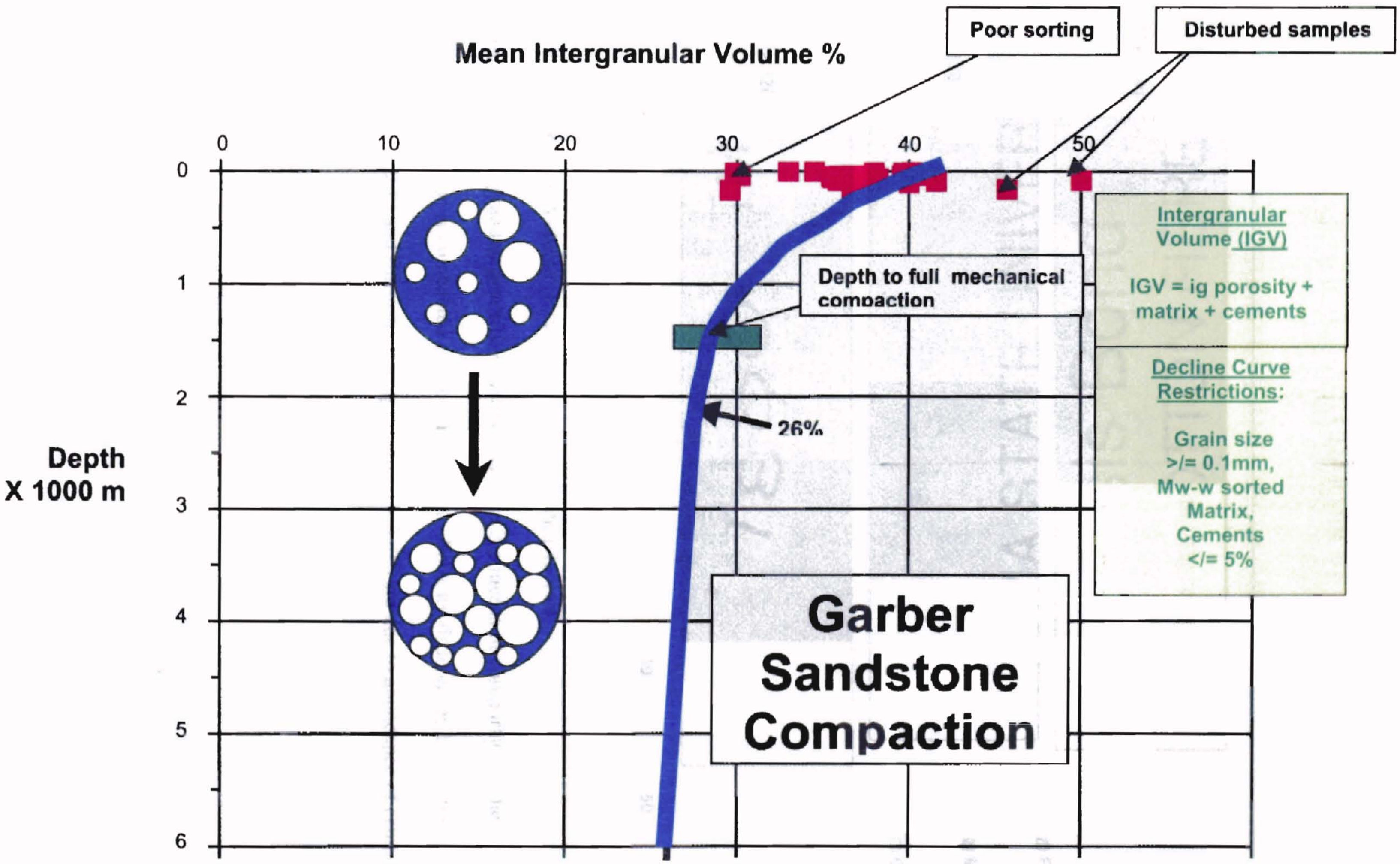

Fig. 10: Compaction State of Sandstone, after Paxton et al. (2002)

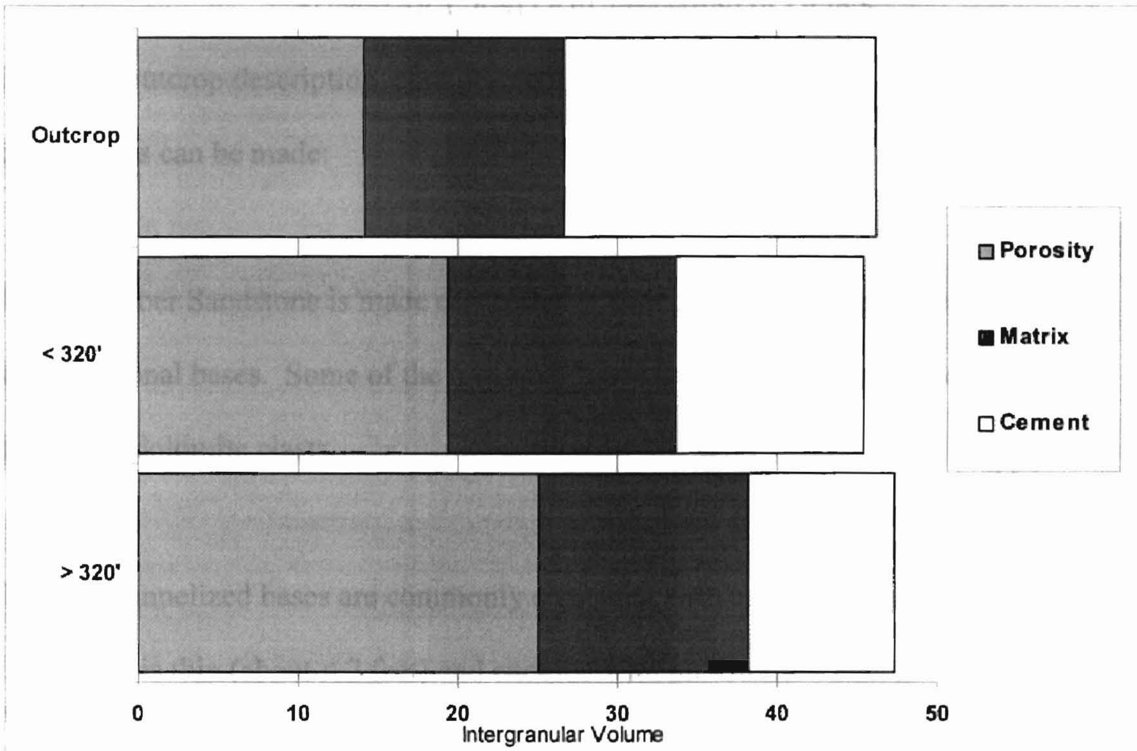

Fig. 11: Intergranular Volume (IGV) as function of depth intervals.

The sum of the intergranular porosity + matrix + cement is a means of comparison. The comparison above shows that the Garber is compacted to the same extent. Porosity differences between outcrop-subsurface samples (depth < 320') and subsurface samples (depth > 320') are due to abundance of cement and matrix.

CHAPTER VI

SUMMARY AND RECOMMENDATIONS

Based on outcrop description, core description, thin sections, and well logs the following conclusions can be made:

1. The Garber Sandstone is made of a series of fining-upward, channelized sandstones with erosional bases. Some of the erosional bases are conglomeritic and contain mud-clasts and dolomite clasts.

2. The channelized bases are commonly cemented with calcite and dolomite, particularly if the sand is thin (about < 2 feet) and encased with mudstone.

3. The most porous intervals in the Garber tend to be thickly bedded (10 to 20 feet and greater) sandstones, that contain low angle trough cross-bedding. The sandstone contains fine to medium grains.

4. Based on framework grain composition, the Garber Sandstones is a sublitheranite sandstone.

5. Burial history reconstruction (Schmoker, 1986) suggests that the Garber has not been buried more than 3300 feet (1000 meters) and has not been subjected to temperatures greater than 70 - 90° F (> 20 -32° C).

6. Some intervals in the Garber contain very small discontinuous euhedral quartz overgrowths. This suggests that the Permian Garber Sandstone has not been heated to temperatures greater than 176° F (> 80° C), and is compatible with the burial history work of Schmoker. The volume of quartz cement would be much greater had higher temperatures been achieved.

7. Based on intergranular volume (IGV) carbonate cementation in the Garber Sandstone occurred at shallow burial depth, and probably soon after deposition.

8. Analysis of a large petrographic data set indicates that the porosity and aquifer quality of deeper (>320 feet) Garber Sandstones is greater than the shallower (< 320 feet) Garber Sandstones,

  a. Shallower (< 320 feet) Garber Sandstones contain slightly more depositional matrix and carbonate cement.
  b. Deeper (> 320 feet) Garber Sandstones contain less depositional matrix and carbonate cement, with intergranular porosities ranging up about 47%.

9. The intergranular volume (IGV) of the Garber Sandstones fits relatively well within the window expected for established compaction curves. The degree of compaction, based on IGV, suggests that the Garber Sandstone has not been deeply buried. Moreover, Schmoker's burial history reconstruction suggests that the Garber should not be fully compacted, which the data support. However, the IGV data indicate that the Garber

samples used in this study have not been buried as deeply as indicated by the Schmoker's burial history reconstruction.

10. Because carbonate cement in the Garber Sandstone is commonly associated with thin channelized sandstone with shaley interbeds, the deep porous portions of the Garber may represent thick amalgamated channel deposits with few shaley interbeds.

11. In order to more effectively explore for the best aquifer potential in the Garber Sandstone in the COA, additional studies must be conducted to better define and map the stratigraphy and depositional environments of the Garber Sandstone throughout Central Oklahoma. A major challenge of the mapping program is to determine whether or not the thick, porous portions of the Garber Sandstone occur in a sand transport fairway(s) within a single stratigraphic interval or if the sand transport fairway(s) occur(s) in different stratigraphic intervals defined by regional erosional surfaces (or sequence boundaries).

12. Since this present study only deals with two deeper (> 320') wells, it is suggested to drill or observe more deeper wells to test the role of depth to the quality of the COA.

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Well (NOTS)	Formation	Total Depth (feet)	Depth Range (feet)	Operator	Location	County
1a	Garber	268	15-268	USGS	21- 16N- 2W NE NE NW	Logan
3	Garber	195	15-195	USGS	23- 14N- 2W NE SW SW	Oklahoma
4	Garber	291	15–260	USGS	11- 10N- 1E NW NW NW	Cleveland
6	Garber	587	20-587	USGS	7- 14N- 3W NE NE SE	Oklahoma
7a	Garber	631	175-630	USGS	29- 9N- 2W NE SW SE	Cleveland

Appendix A: USGS NOTS-Wells, Summary Information (modified after Breit et al., 1990)

Sample	Lithology	Depth (ft)	EGrainSize	GSmicron	Esorting	IGporosity	Leachedpor	totporosity	mQuartz	pQuartz	Plagiocl	K-spar	GMtx	Rmtx	totmtrx	Mica	RFcarb	RFother	RFtotal	Micritdolo	Hematite	Kaolinite	Calcite	Spardolom	totcem	totQuartz	TotFeld	Total	NQtz	NFeld	NRF	IGV
B-1	sandstone	85.0	0.1805	180.5	0.5	23.9	10.0	34.1	53.0	9.1	0.0	1.4	xxxxx	xxxxx	0.0	0.3	2.4	0.0	2.4	0.0	0.0	0.0	0.0	0.3	0.3	61.6	1.4	99.95	94.2	2.1	3.87	24.4
B-2	sandstone	95.0	0.1843	184.3	0.5	28	3.7	31.7	58.3	7.3	0.0	0.0	xxxxx	xxxxx	1.3	0.3	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	65.6	0.0	99.90	98.5	0.0	1.50	29.3
B-3	sandstone	95.0	0.133	133	0.25	25.7	6.3	32.0	53.3	1.3	0.0	0.0	xxxxx	xxxxx	13.0	0.3	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	54.6	0.0	99.90	98.2	0.0	1.80	37.7
L1-1	sandstone	51.0	0.1482	148.2	0.25	4.4	0.7	5.0	15.3	0.0	0.0	0.0	xxxxx	xxxxx	24.8	0.0	54.4	1.0	55.4	0.0	0.0	0.0	0.0	0.0	0.0	15.4	0.0	100.70	22.1	0.0	77.94	83.0
L2-1	sandstone	28.0	0.0333	33.3	0.25	11	2.7	13.1	30.1	4.6	0.0	0.0	xxxxx	xxxxx	7.3	7.3	15.7	1.0	16.7	0.0	0.0	0.0	0.0	20.7	20.7	35.0	0.0	100.70	69.0	0.0	30.97	38.4
L2-2	sandstone	28.0	0.0523	52.3	0.25	8.3	8.3	16.6	27.0	2.7	0.0	0.0	xxxxx	xxxxx	8.3	1.3	9.0	3.7	12.7	0.0	0.0	0.0	0.0	31.0	31.0	29.7	0.0	99.80	76.7	0.0	23.28	47.7
L2-3	sandstone	28.0	0.056	56	0.35	8.7	10.7	19.3	27.3	5.0	0.0	0.0	xxxxx	xxxxx	22.3	3.3	4.0	2.3	6.3	0.0	0.0	0.0	0.0	16.3	16.3	32.3	0.0	99.90	89.0	0.0	11.02	47.3
L3-1	sandstone	8.0	0.1691	169.1	2.0	1.0	0.0	1.0	15.3	2.0	0.0	0.0	xxxxx	xxxxx	3.7	0.0	66.0	0.0	66.0	0.0	0.0	0.0	0.0	11.0	11.0	17.3	0.0	99.00	20.8	0.0	79.23	14.7
L3-2	sandstone	8.0	0.1463	146.3	0.25	12.3	1.7	1.7	45.3	1.0	0.0	0.0	xxxxx	xxxxx	10.0	0.3	1.3	0.0	1.3	0.0	0.0	0.0	0.0	28.0	28.0	46.3	0.0	99.90	97.3	0.0	2.73	49.3
T-1	sandstone	3.0	0.1254	125.4	0.25	25.7	1.0	1.0	53.0	1.7	0.0	0.0	xxxxx	xxxxx	8.3	0.3	0.0	0.7	0.7	0.0	0.0	0.0	0.0	9.3	9.3	54.7	0.0	100.00	100.0	0.0	0.00	42.2
T-2	sandstone	3.0	0.1444	144.4	0.35	18.7	5.3	5.3	52.0	0.3	0.0	0.0	xxxxx	xxxxx	20.0	0.7	1.3	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	52.3	0.0	99.30	97.6	0.0	2.43	39.3
T-3	sandstone	3.0	0.1387	138.7	0.35	24	5.0	29.0	50.0	4.3	0.0	0.0	xxxxx	xxxxx	12.3	0.3	1.0	0.3	1.3	0.0	0.0	0.0	0.0	1.0	1.0	55.6	0.0	99.50	98.2	0.0	1.77	39.0
T-4	sandstone	3.0	0.1349	134.9	0.25	9.3	2.7	2.7	42.0	1.3	0.0	0.0	xxxxx	xxxxx	5.3	0.0	1.0	0.3	1.3	0.0	0.0	0.0	0.0	37.3	37.3	43.3	0.0	99.20	97.7	0.0	2.28	52.0
P-1	sandstone	6.0	0.1425	142.5	0.25	10	0.0	10.0	47.7	6.0	0.0	0.0	xxxxx	xxxxx	6.3	0.3	0.3	0.0	0.3	0.0	0.0	0.0	0.0	29.6	29.6	53.5	0.0	100.00	99.4	0.0	0.56	44.7
P-2	sandstone	6.0	0.1729	172.9	0.25	14.7	1.0	15.3	48.0	9.0	0.0	0.0	xxxxx	xxxxx	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.7	25.7	57.0	0.0	99.70	100.0	0.0	0.00	41.3
P-3	sandstone	6.0	0.1482	148.2	0.35	12	0.7	12.7	38.0	5.0	0.0	5.3	xxxxx	xxxxx	2.0	0.0	1.3	0.0	1.3	0.0	0.0	0.0	0.0	35.7	35.7	43.0	6.3	100.00	86.7	10.7	2.62	48.7
P-4	sandstone	6.0	0.1805	180.5	0.25	9	1.0	10.0	45.0	4.7	0.0	0.0	xxxxx	xxxxx	4.0	0.3	2.3	0.0	2.3	0.0	0.0	0.0	0.0	33.7	33.7	49.7	0.0	100.00	95.6	0.0	4.42	46.6
p1a-01	sandstone	243.2	0.094	94	1.5	xxxx	xxxx	9.3	35.4	4.5	1.2	0.3	3.8	34.2	38.0	xxxxx	2.4	xxxxx	2.4	0.0	8.0	0.3	0.0	0.6	8.9	39.9	1.5	100.00	91.1	3.4	5.46	56.2
p1a-02	sandstone	243.2	0.125	125	0.6	xxxx	xxxx	19.8	52.7	4.6	0.9	0.0	0.4	1.5	1.9	xxxxx	0.3	xxxxx	0.3	0.0	6.7	0.0	1.5	11.6	19.8	57.3	0.9	100.00	97.8	1.5	0.51	41.5
p1a-03	silty sandst	235.3	0.094	94	0.75	xxxx	xxxx	16.7	38.7	2.3	1.0	0.0	10.4	19.0	29.4	xxxxx	0.5	xxxxx	0.5	0.0	11.6	0.0	0.0	0.0	11.6	41.0	1.0	100.00	98.9	2.4	0.71	57.7
p1a-04	sandstone	222.9	0.094	94	0.6	xxxx	xxxx	34.0	52.1	5.2	1.6	0.0	1.3	2.6	3.9	xxxxx	2.6	xxxxx	2.6	0.0	0.3	0.0	0.0	0.0	0.3	57.3	1.6	99.70	93.2	2.6	4.23	38.2
p1a-05	sandstone	215.4	0.094	94	1.125	xxxx	xxxx	15.6	50.6	7.5	0.6	0.0	2.6	17.6	20.2	xxxxx	0.3	xxxxx	0.3	0.0	4.7	0.3	0.0	0.0	5.0	58.1	0.6	99.80	98.5	1.0	0.51	40.8
p1a-06	sandstone	217.2	0.094	94	1.125	xxxx	xxxx	22.4	54.1	4.2	1.6	0.0	3.3	10.4	13.7	xxxxx	1.6	xxxxx	1.6	0.0	2.0	0.3	0.0	0.0	2.3	58.3	1.6	99.90	94.8	2.6	2.60	38.4
p1a-07	sandstone	211.7	0.094	94	0.75	xxxx	xxxx	8.4	35.0	0.3	1.3	0.0	1.5	0.0	1.5	xxxxx	1.0	xxxxx	1.0	8.6	27.1	0.7	0.0	16.2	52.6	35.3	1.3	100.10	93.9	3.5	2.66	62.5
p1a-08	sandstone	186.3	0.188	188	0.6	xxxx	xxxx	18.1	52.4	6.0	0.9	0.0	3.9	8.0	11.9	xxxxx	1.8	xxxxx	1.8	0.0	6.8	1.8	0.3	0.0	8.9	58.4	0.9	100.00	95.6	1.5	2.95	38.8
p1a-09	silty sandst	184.3	0.094	94	1.5	xxxx	xxxx	4.9	35.5	3.6	0.7	0.0	3.9	30.9	34.8	xxxxx	0.3	xxxxx	0.3	0.0	19.1	1.0	0.0	0.0	20.1	39.1	0.7	99.80	97.5	1.7	0.75	59.8
p1a-10	sandstone	178.5	0.188	188	0.75	xxxx	xxxx	23.6	49.5	3.3	0.7	0.0	2.2	14.2	16.4	xxxxx	0.7	xxxxx	0.7	0.0	5.6	0.3	0.0	0.0	5.9	52.8	0.7	100.10	97.4	1.3	1.29	45.9
p1a-11	sandstone	188.0	0.094	94	0.75	xxxx	xxxx	27.9	43.8	7.5	0.7	0.0	3.2	14.4	17.6	xxxxx	1.3	xxxxx	1.3	0.0	0.0	1.0	0.0	0.0	1.0	51.4	0.7	99.80	96.3	1.3	2.43	46.5
p1a-12	sandstone	161.5	0.188	188	0.6	xxxx	xxxx	28.8	58.1	3.7	0.3	0.0	1.8	6.1	7.9	xxxxx	1.4	xxxxx	1.4	0.0	2.0	0.0	0.0	0.0	2.0	59.6	0.3	100.00	97.2	0.5	2.28	38.5
p1a-13	silty sandst	157.7	0.094	94	0.6	xxxx	xxxx	35.0	45.5	3.9	1.3	0.0	10.5	1.3	11.8	xxxxx	1.6	xxxxx	1.6	0.0	0.0	1.0	0.0	0.0	1.0	49.4	1.3	100.10	94.5	2.5	3.06	47.6
p1a-14	siltstone	121.5	xxxxx	xxxxx	xxxxx	xxxx	xxxx	0.0	27.2	0.3	0.0	0.0	10.3	7.0	17.3	xxxxx	0.3	xxxxx	0.3	10.0	14.6	0.0	0.0	30.2	54.8	27.5	0.0	99.80	98.9	0.0	1.08	72.1
p1a-15	siltstone	116.9	xxxxx	xxxxx	xxxxx	xxxx	xxxx	0.0	15.6	0.0	0.0	1.1	3.4	8.8	12.2	xxxxx	25.9	xxxxx	25.9	26.1	9.9	0.0	0.0	9.1	45.1	15.6	1.1	99.80	38.6	2.6	60.80	67.3
p1a-16	sandstone	108.0	0.094	94	1.125	xxxx	xxxx	28.2	47.7	8.7	0.9	0.0	1.3	4.4	5.7	xxxxx	4.0	xxxxx	4.0	0.0	0.3	1.6	0.0	0.9	2.8	57.4	0.9	100.00	92.1	1.4	6.42	37.7
p1a-17	conglomer	196.0	xxxxx	xxxxx	xxxxx	xxxx	xxxx	0.0	6.3	0.7	0.3	0.0	0.0	4.0	4.0	xxxxx	0.0	xxxxx	0.0	4.3	27.6	0.0	0.0	56.8	88.7	7.0	0.3	100.00	95.9	4.1	0.00	92.7
p1a-18	sandstone	59.8	0.094	94	0.75	xxxx	xxxx	18.1	47.1	3.2	0.6	0.0	3.7	2.9	6.6	xxxxx	1.6	xxxxx	1.6	0.0	21.8	1.0	0.0	0.0	22.8	50.3	0.6	100.00	95.8	1.1	3.05	47.5
p1a-19	sandstone	65.4	0.094	94	1.125	xxxx	xxxx	31.0	41.6	7.7	1.0	0.0	2.5	11.9	14.4	xxxxx	2.6	xxxxx	2.6	0.0	1.0	0.6	0.0	0.0	1.6	49.3	1.0	99.80	93.2	1.9	4.91	47.0
p1a-20	sandstone	44.0	0.188	188	1.5	xxxx	xxxx	18.5	51.0	3.4	1.0	1.0	5.6	19.1	24.7	xxxxx	0.5	xxxxx	0.5	0.0	1.0	1.0	0.0	0.0	2.0	54.4	2.0	100.10	95.6	3.5	0.88	43.2
p1a-21	conglomer	250.0	xxxxx	xxxxx	xxxxx	xxxx	xxxx	14.9	41.2	2.9	0.6	0.0	1.9	6.8	8.7	xxxxx	9.4	xxxxx	9.4	5.0	5.9	0.6	1.8	9.1	22.4	44.1	0.6	100.10	81.5	1.1	17.38	46.0
p3-01	sandstone	51.5	0.094	94	1.125	xxxx	xxxx	10.0	47.2	3.6	0.3	2.3	11.1	4.6	15.7	xxxxx	3.3	xxxxx	3.3	0.0	15.3	1.3	0.0	1.0	17.6	50.6	2.6	100.00	89.6	4.6	5.82	45.5
p3-01red	sandstone	51.5	0.094	94	1.125	xxxx	xxxx	2.9	52.6	4.5	0.6	1.9	14.5	0.0	14.5	xxxxx	5.1	xxxxx	5.1	0.0	0.0	1.9	0.0	1.9	3.8	57.1	2.5	99.80	88.3	3.9	7.86	21.2
p3-01green	sandstone	51.5	0.094	94	1.125	xxxx	xxxx	16.9	41.7	2.6	0.0	2.6	7.7	9.3	17.0	xxxxx	1.3	xxxxx	1.3	0.0	31.1	0.7	0.0	0.0	31.8	44.3	2.6	99.80	91.9	5.4	2.70	65.7
p3-02	sandstone	54.9	0.094	94	0.75	xxxx	xxxx	27.1	52.2	6.0	2.3	0.3	5.1	3.3	8.4	xxxxx	2.7	xxxxx	2.7	0.0	0.7	0.3	0.0	0.0	1.0	58.2	2.6	100.00	91.7	4.1	4.25	36.5
p3-03	sandstone	68.0	0.188	188	0.425	xxxx	xxxx	32.1	46.5	6.3	2.3	0.0	2.5	3.3	5.8	xxxxx	2.7	xxxxx	2.7	0.0	1.0	0.3	0.0	0.0	1.3	55.8	2.3	100.00	91.6	3.6	4.44	39.2
p3-04	sandstone	74.1	0.125	125	0.75	xxxx	xxxx	11.1	39.6	8.9	0.3	0.0	10.7	5.1	15.8	xxxxx	2.2	xxxxx	2.2	0.0	17.9	2.6	0.0	1.6	22.1	48.5	0.3	100.00	95.1	0.6	4.31	49.0
p3-05	conglomer	78.5	xxxxx	xxxxx	xxxxx	xxxx	xxxx	0.3	14.2	1.0	0.3	1.0	3.3	5.6	8.9	xxxxx	38.1	xxxxx	38.1	2.0	4.3	0.0	0.0	29.8	36.1	15.2	1.3	99.90	27.6	3.4	69.78	45.3
p3-06	sandstone	112.4	0.094	94	0.75	xxxx	xxxx	11.2	48.1	8.4	2.0	0.3	14.7	0.0	14.7	xxxxx	1.7	xxxxx	1.7	0.0	0.3	0.0	0.0	13.3	13.6	56.5	2.3	100.00	93.4	3.8	2.81	39.5
p3-07	sandstone	113.9	0.094	94	0.6	xxxx	xxxx	26.3	46.6	6.2	0.3	0.0	5.4	3.1	8.5	xxxxx	1.8	xxxxx	1.8	0.0	0.6	0.3	7.4	0.0	8.3	54.8	0.3	100.00	96.3	0.5	3.18	43.1
p3-08	sandstone	117.4	0.125	125	0.6	xxxx	xxxx	4.5	28.6	13.2	1.3	0.0	5.0	0.3	5.3	xxxxx	0.0	xxxxx	0.0	0.0	44.5	0.0	0.0	4.7	49.2	39.8	1.3	100.00	96.8	3.2	0.00	58.0
p3-09	sandstone	119.2	0.188	188	0.6	xxxx	xxxx	35.7	47.3	13.0	0.3	0.0	1.0	0.0	1.0	xxxxx	2.7	xxxxx	2.7	0.0	0.0	0.0	0.0	0.0	0.0	60.3	0.3	100.00	95.3	0.5	4.27	36.7
p3-10	sandstone	123.0	0.188	188	0.75	xxxx	xxxx	31.8	53.3	7.6	0.7	0.0	3.2	1.3	4.5	xxxxx	1.0	xxxxx	1.0	0.0	0.7	0.3	0.0	0.0	1.3	60.9	0.7	100.00	97.3	1.1	1.60	37.4
p3-11	sandstone	124.0	0.188	188	0.75	xxxx	xxxx	14.7	43.7	5.3	0.0	0.0	1.0	0.0	1.0	xxxxx	1.8	xxxxx	1.8	2.5	9.6	0.0	0.0	21.3	33.4	49.0	0.0	99.90	96.5	0.0	3.54	49.1
p3-12	silty sandst	132.4	0.188	188	0.75	xxxx	xxxx	11.4	44.3	2.3	0.0	0.3	18.0	16.3	34.3	xxxxx	2.7	xxxxx	2.7	0.0	4.7	0.0	0.0	0.0	4.7	46.6	0.3	100.00	94.0	0.6	5.44	50.4
p3-13	sandstone	161.7	0.188	188	1.5	xxxx	xxxx	8.1	52.3	9.0	1.0	0.3	20.6	4.0	24.6	xxxxx	2.0	xxxxx	2.0	0.0	1.7	0.0	0.0	0.0	1.7	61.3	1.3	100.00	94.9	2.0	3.10	35.4
p3-14	sandstone	164.5	0.094	94	0.75	xxxx	xxxx	31.4	46.5	6.5	0.3	0.0	2.1	5.2	7.3	xxxxx	2.0	xxxxx	2.0	0.0	1.6	0.7	0.0	1.6	3.9	55.0	0.3	99.90	95.0	0.5	3.40	42.6
p3-16	sandstone	175.7	0.094	94	1.5	xxxx	xxxx	1.9	39.4	3.3	0.0	0.6	3.3	19.8	23.1	xxxxx	14.3	xxxxx	14.3	0.0	13.5	0.0	0.0	3.6	17.1	42.7	0.6	99.90	73.9	1.4	24.74	42.5
p3-17	sandstone	182.7	0.094	94	0.75	xxxx	xxxx	4.4	32.0	0.7	0.0	0.3	0.3	2.0	2.3	xxxxx	0.3	xxxxx	0.3	0.0	33.0	0.0	0.0	27.0	60.0	32.7	0.3	100.00	98.2	0.9	0.90	66.1
p3-18	sandstone	184.6	0.094	94	1.5	xxxx	xxxx	26.2	41.9	5.3	0.7	0.0	5.5	15.5	21.0	xxxxx	1.3	xxxxx	1.3	0.0	3.3	0.3	0.0	0.0	3.6	47.2	0.7	100.00	95.8	1.4	2.64	50.6
p3-19	sandstone	35.4	0.375	375	0.425	xxxx	xxxx	38.9	55.6	5.6	0.3	0.0	0.6	0.0	0.6	xxxxx	0.3	xxxxx	0.3	0.0	0.3	0.3	0.0	0.0	0.6	61.2	0.3	99.80	99.0	0.5	0.49	38.0
p3-20	conglomer	186.3	xxxxx	xxxxx	xxxxx	xxxx	xxxx	1.8	28.3	3.4	0.3	1.2	0.4	1.9	2.3	xxxxx	28.9	xxxxx	28.8	0.0	21.7	0.0	0.0	12.1	33.8	31.7	1.5	100.00	51.0	2.4	46.54	37.8
p3-21	sandstone	58.0	0.188	188	0.75	xxxx	xxxx	25.9	61.1	7.9	1.0	0.0	1.1	0.3	1.4	xxxxx	0.0	xxxxx	0.0	0.0	2.6	0.0	0.0	0.0	2.6	69.0	1.0	99.90	98.6	1.4	0.00	29.9
p3-22	siltstone	129.0	xxxxx	xxxxx	1.125	xxxx	xxxx	3.1	41.2	3.7	0.3	1.3	11.9	21.3	33.2	xxxxx	0.7	xxxxx	0.7	0.0	15.3	0.0	0.0	1.3	16.6	44.9	1.6	100.10	95.1	3.4	1.48	52.9
p4-01	sandstone	274.2	0.375	375	0.6	xxxx	xxxx	33.1	54.5	6.6	1.7	0.3	2.8	0.0	2.8	xxxxx	0.7	xxxxx	0.7	0.0	0.0	0.3	0.0	0.0	0.3	61.1	2.0	100.00	95.8	3.1	1.10	36.2
p4-02	sandstone	265.3	0.188	188	1.125	xxxx	xxxx	23.5	54.2	5.4	1.6	1.3	8.9	1.0	9.9	xxxxx	1.3	xxxxx	1.3	0.0	2.6	0.3	0.0	0.0	2.9	59.6	2.9	100.10	93.4	4.5	2.04	36.3
p4-03	sandstone	284.8	0.188	188	1.125	xxxx	xxxx	16.7	59.0	2.6	1.3	1.3	9.6	5.8	15.4	xxxxx	0.3	xxxxx	0.3	0.0	3.5	0.0	0.0	0.0	3.5	61.6	2.6	100.10	95.5	4.0	0.47	35.6
p4-04	sandstone	252.1	0.094	94	0.6	xxxx	xxxx	12.5	48.8	4.7	1.0	2.0	23.7	7.0	30.7	xxxxx	0.3	xxxxx	0.3	0.0	0.0	0.0	0.0	0.0	0.0	53.5	3.0	100.00	94.2	5.3	0.53	43.2
p4-05	siltstone	224.1	0.094	94	1.5	xxxx	xxxx	18.1	36.8	6.3	3.8	1.9	9.3	21.0	30.3	xxxxx	2.2	xxxxx	2.2	0.0	1.9	0.6	0.0	0.0	2.5	43.1	5.7	99.90	84.5	11.2	4.31	48.8
p4-06	sandstone	179.6	0.188	188	1.125	xxxx	xxxx	10.8	46.3	6.7	2.6	2.9	26.3	0.3	26.6	xxxxx	0.3	xxxxx	0.3	0.0	0.0	3.8	0.0	0.0	3.8	53.0	5.5	100.00	90.1	9.4	0.51	41.2
p4-07	sandstone	176.4	0.188	188	1.5	xxxx	xxxx	1.9	44.3	2.8	2.8	0.0	21.1	8.8	30.9	xxxxx	0.3	xxxxx	0.3	0.0	16.8	0.3	0.0	0.0	17.1	47.1	2.8	99.80	93.8	5.6	0.60	49.6
p4-08	sandstone	173.6	0.375	375	0.75	xxxx	xxxx	21.9	43.8	6.7	3.2	0.0	3.7	16.7	20.4	xxxxx	1.3	xxxxx	1.3	0.0	1.8	1.0	0.0	0.0	2.8	50.6	3.2	100.00	91.8	5.8	2.56	44.9
p4-09	sandstone	169.7	0.188	188	0.75	xxxx	xxxx	11.3	57.6	2.5	2.8	0.6	11.5	8.5	20.0	xxxxx	1.6	xxxxx	1.6	0.0	2.8	0.6	0.0	0.0	3.4	60.1	3.4	99.80	92.3	5.2	2.46	34.7
p4-10	sandstone	159.9	0.094	94	1.5	xxxx	xxxx	14.1	49.5	3.6	3.0	2.1	9.5	8.8	18.3	xxxxx	1.5	xxxxx	1.5	0.0	7.3	0.6	0.0	0.0	7.9	53.1	5.1	100.00	88.8	8.5	2.51	40.5

Appendix B: Index table for data used in this study.

xxxxx data non- available

Sample	Lithology	Depth (ft)	EGrainSize	GSmicron	Esorting	IGporosity	Leachedpor	totporosity	mQuartz	pQuartz	Plagiocl	K-spar	GMtx	Rmtx	totmtx	Mica	RFcarb	RFother	RFtotal	Microdolo	Hematite	Kaolinite	Calcite	Spardolom	totcem	totQuartz	TotFeld	Total	NQtz	NFeld	NRF	IGV
p4-11	sandstone	154.8	0.188	188	0.425	xxxxx	xxxxx	30.3	53.3	8.2	1.6	0.0	2.6	2.3	4.9	xxxxx	1.3	xxxxx	1.3	0.0	0.3	0.0	0.0	0.0	0.3	61.5	1.6	99.90	95.5	2.5	2.02	35.5
p4-12	sandstone	151.1	0.0625	62.5	1.125	xxxxx	xxxxx	9.6	41.3	0.0	1.2	1.4	9.2	24.0	33.2	xxxxx	1.2	xxxxx	1.2	0.0	9.8	0.3	0.0	2.0	12.1	41.3	2.6	100.00	91.6	5.8	2.66	54.9
p4-12red	sandstone	151.1	0.0625	62.5	1.125	xxxxx	xxxxx	4.6	47.1	0.0	1.9	1.0	24.1	1.0	25.1	xxxxx	0.0	xxxxx	0.0	0.0	0.0	1.0	0.0	2.9	3.9	47.1	2.9	100.10	94.2	5.8	0.00	33.6
p4-12gm	sandstone	151.1	0.0625	62.5	1.125	xxxxx	xxxxx	21.1	38.8	0.0	0.8	1.7	2.8	33.9	36.7	xxxxx	1.7	xxxxx	1.7	0.0	14.0	0.0	0.0	1.7	15.7	38.8	2.5	100.00	90.2	5.8	3.95	73.5
p4-13	sandstone	143.1	0.094	94	1.5	xxxxx	xxxxx	11.1	47.5	1.3	3.8	2.5	7.0	20.6	27.6	xxxxx	0.6	xxxxx	0.6	0.0	5.0	0.6	0.0	0.0	5.6	48.8	6.3	100.00	87.6	11.3	1.08	44.3
p4-14	sandstone	141.6	0.25	250	0.425	xxxxx	xxxxx	25.4	51.5	15.6	0.7	0.7	2.8	2.0	4.8	xxxxx	1.3	xxxxx	1.3	0.0	0.0	0.0	0.0	0.0	0.0	67.1	1.4	100.00	96.1	2.0	1.86	30.2
p4-15	sandstone	132.4	0.188	188	1.5	xxxxx	xxxxx	11.9	51.8	9.6	2.6	0.0	13.3	3.8	17.1	xxxxx	0.3	xxxxx	0.3	0.0	4.2	0.6	1.3	0.6	6.7	61.4	2.6	100.00	95.5	4.0	0.47	35.7
p4-16	sandstone	118.0	0.094	94	0.425	xxxxx	xxxxx	22.2	39.2	5.4	7.2	1.5	9.3	3.0	12.3	xxxxx	1.2	xxxxx	1.2	0.0	6.9	2.1	2.1	0.0	11.1	44.6	8.7	100.10	81.8	16.0	2.20	45.6
p4-17	sandstone	108.1	0.375	375	0.6	xxxxx	xxxxx	28.8	55.8	4.5	2.9	0.3	2.9	3.5	6.4	xxxxx	2.6	xxxxx	2.6	0.0	0.6	0.0	0.0	0.0	0.6	60.3	3.2	99.90	91.2	4.8	3.93	33.8
p4-18	sandstone	94.0	0.188	188	0.6	xxxxx	xxxxx	24.7	54.9	5.5	1.6	1.3	2.6	6.8	9.4	xxxxx	1.3	xxxxx	1.3	0.0	0.6	0.6	0.0	0.0	1.2	60.4	2.9	99.90	93.5	4.5	2.01	35.3
p4-19	siltstone	88.0	xxxxx	xxxxx	0.425	xxxxx	xxxxx	11.2	52.5	3.5	0.0	0.0	8.8	19.1	27.9	xxxxx	0.6	xxxxx	0.6	0.0	4.1	0.0	0.0	0.0	4.1	56.0	0.0	99.80	98.9	0.0	1.06	43.2
p4-19red	siltstone	88.0	xxxxx	xxxxx	0.425	xxxxx	xxxxx	8.2	55.4	6.9	0.0	0.0	18.0	0.0	18.0	xxxxx	1.0	xxxxx	1.0	0.0	1.0	0.0	0.0	0.0	1.0	62.3	0.0	99.90	98.4	0.0	1.58	27.2
p4-19gm	siltstone	88.0	xxxxx	xxxxx	0.425	xxxxx	xxxxx	17.6	51.2	1.9	0.0	0.0	4.5	28.2	32.7	xxxxx	0.5	xxxxx	0.5	0.0	5.6	0.0	0.0	0.0	5.6	53.1	0.0	100.10	99.1	0.0	0.93	55.9
p4-20	sandstone	79.0	0.375	375	0.6	xxxxx	xxxxx	31.8	52.3	6.5	1.3	0.0	2.7	2.3	5.0	xxxxx	2.6	xxxxx	2.6	0.0	0.3	0.3	0.0	0.0	0.6	58.8	1.3	100.10	93.8	2.1	4.15	37.4
p4-21	sandstone	87.0	0.188	188	0.6	xxxxx	xxxxx	15.8	48.6	5.0	1.6	1.6	5.7	15.3	21.0	xxxxx	0.9	xxxxx	0.9	0.0	3.7	1.9	0.0	0.0	5.6	53.6	3.2	100.10	92.9	5.5	1.56	42.4
p4-22	sandstone	83.1	0.188	188	0.6	xxxxx	xxxxx	18.9	51.8	8.4	1.7	0.3	2.7	0.3	3.0	xxxxx	0.3	xxxxx	0.3	0.0	15.4	0.3	0.0	0.0	15.7	60.2	2.0	100.10	96.3	3.2	0.48	37.6
p4-23	sandstone	41.3	0.188	188	0.75	xxxxx	xxxxx	35.8	48.7	7.5	0.7	1.0	2.8	1.6	4.4	xxxxx	2.0	xxxxx	2.0	0.0	0.0	0.0	0.0	0.0	0.0	56.2	1.7	100.10	93.8	2.8	3.34	40.2
p4-24	sandstone	125.0	0.125	125	0.6	xxxxx	xxxxx	37.5	50.8	5.9	0.0	0.0	1.3	0.3	1.6	xxxxx	2.9	xxxxx	2.9	0.0	0.7	0.7	0.0	0.0	1.4	56.7	0.0	100.10	95.1	0.0	4.87	40.5
p6-01	sandstone	51.6	0.188	188	0.6	xxxxx	xxxxx	36.4	52.8	4.3	0.7	1.6	1.6	1.0	2.6	xxxxx	1.0	xxxxx	1.0	0.0	0.7	0.0	0.0	0.0	0.7	57.1	2.3	100.10	94.5	3.8	1.66	39.7
p6-02	sandstone	62.7	0.188	188	0.8	xxxxx	xxxxx	14.9	46.5	7.6	0.3	0.3	1.9	5.7	7.6	xxxxx	1.0	xxxxx	1.0	0.0	2.2	0.0	1.6	17.8	21.6	54.1	0.6	99.80	97.1	1.1	1.80	44.1
p6-03	sandstone	96.5	0.125	125	0.75	xxxxx	xxxxx	38.9	53.5	4.0	1.7	0.0	2.0	1.3	3.3	xxxxx	0.3	xxxxx	0.3	0.0	0.3	0.0	0.0	0.0	0.3	57.5	1.7	100.00	96.6	2.8	0.50	40.5
p6-04	sandstone	113.8	0.25	250.0	0.75	xxxxx	xxxxx	18.4	57.1	7.3	1.7	0.3	0.2	0.7	0.9	xxxxx	0.3	xxxxx	0.3	0.0	0.0	0.0	0.0	14.0	14.0	64.4	2.0	100.00	96.6	3.0	0.45	33.3
p6-05	sandstone	114.3	0.25	250.0	0.6	xxxxx	xxxxx	5.8	55.8	1.8	0.6	0.3	0.3	2.4	2.7	xxxxx	0.0	xxxxx	0.0	0.0	2.1	0.0	7.0	23.9	33.0	57.6	0.9	100.00	98.5	1.5	0.00	41.5
p6-06	sandstone	131.1	0.375	375.0	0.75	xxxxx	xxxxx	30.7	54.5	7.3	0.7	0.3	3.3	0.3	3.6	xxxxx	1.3	xxxxx	1.3	0.0	0.0	0.0	1.0	0.7	1.7	61.8	1.0	100.10	96.4	1.6	2.03	38.0
p6-07	sandstone	135.6	0.188	188.0	1.125	xxxxx	xxxxx	32.5	53.4	4.5	0.6	1.0	2.0	0.3	2.3	xxxxx	1.0	xxxxx	1.0	0.0	3.2	0.3	1.3	0.0	4.8	57.9	1.6	100.10	95.7	2.6	1.65	39.6
p6-08	sandstone	178.5	0.188	188.0	0.75	xxxxx	xxxxx	35.0	45.5	5.1	0.6	0.0	3.5	5.7	9.2	xxxxx	1.0	xxxxx	1.0	0.0	2.5	0.0	1.0	0.0	3.5	50.6	0.6	99.90	96.9	1.1	1.92	47.7
p6-09	sandstone	184.2	0.125	125.0	1.125	xxxxx	xxxxx	37.1	45.0	1.5	1.5	0.3	2.8	2.4	5.2	xxxxx	1.5	xxxxx	1.5	0.0	3.3	0.6	3.6	0.3	7.8	46.5	1.8	99.90	93.4	3.6	3.01	50.1
p6-10	sandstone	198.4	0.188	188.0	0.75	xxxxx	xxxxx	24.5	53.0	6.6	0.0	0.3	0.8	0.0	0.8	xxxxx	0.0	xxxxx	0.0	0.0	0.0	0.0	1.3	13.5	14.8	59.6	0.3	100.00	99.5	0.5	0.00	40.1
p6-11	sandstone	200.2	0.188	188.0	0.6	xxxxx	xxxxx	4.1	52.8	1.9	0.9	0.3	0.0	0.0	0.0	xxxxx	0.0	xxxxx	0.0	0.0	5.3	0.0	0.0	34.6	39.9	54.7	1.2	99.90	97.9	2.1	0.00	44.0
p6-12	sandstone	216.8	0.094	94.0	0.6	xxxxx	xxxxx	38.8	45.3	5.9	0.7	0.7	2.8	2.6	5.4	xxxxx	0.7	xxxxx	0.7	0.0	1.0	0.0	0.7	0.0	1.7	51.2	1.4	100.20	96.1	2.6	1.31	46.9
p6-13	sandstone	224.2	0.188	188.0	0.6	xxxxx	xxxxx	31.3	48.3	3.5	0.3	0.3	3.7	6.9	10.6	xxxxx	0.3	xxxxx	0.3	0.0	5.4	0.0	0.0	0.0	5.4	51.8	0.6	100.00	98.3	1.1	0.57	47.3
p6-14	sandstone	234.5	0.094	94.0	0.6	xxxxx	xxxxx	43.3	41.2	2.9	2.3	1.6	3.0	2.3	5.3	xxxxx	1.6	xxxxx	1.6	0.0	0.0	1.3	0.6	0.0	1.9	44.1	3.9	100.10	88.9	7.9	3.23	50.5
p6-15	sandstone	273.0	0.094	94.0	0.6	xxxxx	xxxxx	43.7	45.0	2.6	1.0	0.3	3.2	1.3	4.5	xxxxx	1.0	xxxxx	1.0	0.0	0.6	0.6	0.6	0.0	1.8	47.6	1.3	100.00	95.4	2.6	2.00	50.0
p6-16	conglomerate	279.3	xxxxx	xxxxx	1.5	xxxxx	xxxxx	3.7	12.1	0.7	0.0	0.3	0.5	2.6	3.1	xxxxx	14.4	xxxxx	14.4	36.7	14.8	0.0	0.0	14.1	65.6	12.8	0.3	99.90	46.5	1.1	52.38	72.4
p6-17	sandstone	291.1	0.094	94.0	1.5	xxxxx	xxxxx	8.2	37.3	2.9	3.9	1.0	5.4	28.4	33.8	xxxxx	1.0	xxxxx	1.3	0.6	0.0	1.0	0.0	0.0	1.0	40.2	4.9	99.90	87.2	10.6	2.17	44.0
p6-17mud	mudstone	291.1	0.094	94.0	1.5	xxxxx	xxxxx	4.3	31.5	5.9	1.0	0.0	1.6	54.2	55.8	xxxxx	1.5	xxxxx	1.5	0.0	0.0	0.0	0.0	0.0	0.0	37.4	1.0	100.00	93.7	2.5	3.78	60.1
p6-17sand	sandstone	291.1	0.094	94.0	1.5	xxxxx	xxxxx	18.1	33.4	4.9	2.0	0.3	2.9	45.6	48.5	xxxxx	1.3	xxxxx	1.3	0.0	0.0	0.3	0.0	0.0	0.3	38.3	2.3	100.80	91.4	5.5	3.10	67.9
p6-18	sandstone	298.3	0.125	125.0	0.6	xxxxx	xxxxx	28.8	45.8	6.6	0.0	0.0	2.0	1.5	3.5	xxxxx	0.6	xxxxx	0.6	0.0	7.8	0.0	1.8	4.2	13.8	52.4	0.0	100.10	98.9	0.0	1.13	47.1
p6-19	sandstone	301.3	0.188	188.0	0.75	xxxxx	xxxxx	36.8	50.5	5.2	1.0	0.0	1.2	2.9	4.1	xxxxx	1.6	xxxxx	1.6	0.0	0.0	0.3	0.3	0.0	0.6	55.7	1.0	99.90	95.5	1.7	2.74	41.6
p6-20	sandstone	308.6	0.125	125.0	1.125	xxxxx	xxxxx	34.2	41.7	5.4	1.4	0.0	3.2	1.7	4.9	xxxxx	2.0	xxxxx	2.0	0.0	10.3	0.0	0.0	0.0	10.3	47.1	1.4	99.90	93.3	2.8	3.96	49.4
p6-21	sandstone	321.2	0.094	94.0	1.125	xxxxx	xxxxx	28.2	39.2	5.1	0.0	0.3	6.2	17.4	23.6	xxxxx	1.0	xxxxx	1.0	0.0	1.0	0.3	1.3	0.0	2.6	44.3	0.3	100.00	97.1	0.7	2.19	54.4
p6-21*	sandstone	321.2	0.094	94.0	1.125	xxxxx	xxxxx	20.3	46.9	2.3	1.9	0.6	4.9	18.4	23.3	xxxxx	1.0	xxxxx	1.0	0.0	2.6	0.3	0.0	0.6	3.5	49.2	2.5	99.80	93.4	4.7	1.90	47.1
p6-22	sandstone	337.1	0.188	188.0	1.125	xxxxx	xxxxx	35.1	49.2	8.2	1.3	0.0	4.2	0.0	4.2	xxxxx	1.3	xxxxx	1.3	0.0	0.0	0.7	0.0	0.0	0.7	57.4	1.3	100.00	95.7	2.2	2.17	40.0
p6-31	sandstone	184.6	0.188	188.0	0.6	xxxxx	xxxxx	32.5	56.8	1.0	1.0	0.3	1.4	1.0	2.4	xxxxx	0.7	xxxxx	0.7	0.0	0.7	0.0	0.0	4.7	5.4	57.8	1.3	100.10	96.7	2.2	1.17	40.3
p6-25	sandstone	421.0	0.094	94.0	1.125	xxxxx	xxxxx	33.3	41.9	2.6	0.6	0.0	3.8	10.9	14.7	xxxxx	2.6	xxxxx	2.6	0.0	0.6	0.3	0.3	3.2	4.4	44.5	0.6	100.10	93.3	1.3	5.45	52.4
p6-26	sandstone	437.1	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	23.7	40.6	4.6	1.9	0.3	6.9	14.9	21.8	xxxxx	0.9	xxxxx	0.9	0.0	5.9	0.3	0.0	0.0	6.2	45.2	2.2	100.00	93.6	4.6	1.86	51.7
p6-27	sandstone	459.8	0.188	188.0	0.75	xxxxx	xxxxx	30.8	48.9	6.8	0.3	0.0	4.1	3.9	8.0	xxxxx	1.3	xxxxx	1.3	0.0	1.3	0.0	0.0	4.2	5.6	53.7	0.3	99.90	97.1	0.5	2.36	44.6
p6-28	sandstone	471.8	0.375	375.0	1.125	xxxxx	xxxxx	30.2	55.4	6.5	0.7	0.0	1.4	3.6	5.0	xxxxx	0.7	xxxxx	0.7	0.0	1.6	0.0	0.0	0.0	1.6	61.9	0.7	100.10	97.8	1.1	1.11	36.8
p6-29	sandstone	480.2	0.125	125.0	0.75	xxxxx	xxxxx	39.2	42.0	5.6	0.6	0.0	3.1	2.2	5.3	xxxxx	1.5	xxxxx	1.5	0.0	5.9	0.0	0.0	0.0	5.9	47.6	0.6	100.10	95.8	1.2	3.02	50.4
p6-30	sandstone	580.5	0.125	125.0	0.6	xxxxx	xxxxx	23.4	66.3	2.2	0.6	0.0	0.4	1.0	1.4	xxxxx	1.3	xxxxx	1.3	0.0	4.6	0.0	0.0	0.0	4.6	68.5	0.6	100.00	97.3	0.9	1.85	29.8
p6-32	sandstone	486.9	0.188	188.0	0.6	xxxxx	xxxxx	32.6	48.9	8.1	0.7	0.0	6.5	0.3	6.8	xxxxx	0.7	xxxxx	0.7	0.0	0.3	1.3	0.0	0.7	2.3	57.0	0.7	100.00	97.8	1.2	1.20	41.6
p6-33	sandstone	494.8	0.188	188.0	0.75	xxxxx	xxxxx	23.3	45.1	2.9	1.3	0.0	2.0	0.0	2.0	xxxxx	1.0	xxxxx	1.0	0.0	2.3	0.3	0.0	21.8	24.4	48.0	1.3	100.00	95.4	2.6	1.89	49.7
p6-35	sandstone	558.8	0.188	188.0	0.6	xxxxx	xxxxx	33.5	49.0	10.3	1.3	0.0	2.3	0.3	2.6	xxxxx	2.6	xxxxx	2.6	0.0	0.0	0.6	0.0	0.0	0.6	59.3	1.3	99.90	93.8	2.1	4.11	36.7
p6-36	conglomer	580.8	xxxxx	xxxxx	0.425	xxxxx	xxxxx	4.9	24.1	2.1	0.3	0.0	1.5	0.0	1.5	xxxxx	0.3	xxxxx	0.3	58.5	0.0	0.0	0.0	8.2	66.7	26.2	0.3	99.90	97.8	1.1	1.12	73.1
p7a-01	conglomer	624.2	0.188	188.0	0.75	xxxxx	xxxxx	35.2	49.4	9.0	0.0	0.3	1.3	1.6	2.9	xxxxx	1.9	xxxxx	1.9	0.0	0.0	0.3	1.0	0.0	1.3	58.4	0.3	100.00	96.4	0.5	3.14	38.4
p7a-02	sandstone	582.5	0.094	94.0	1.125	xxxxx	xxxxx	23.0	59.3	2.0	1.0	0.0	3.4	6.7	10.1	xxxxx	0.7	xxxxx	0.7	0.0	3.7	0.3	0.0	0.0	4.0	61.3	1.0	100.10	97.3	1.6	1.11	37.1
p7a-03	sandstone	588.3	xxxxx	xxxxx	0.75	xxxxx	xxxxx	1.7	42.2	4.1	0.8	1.6	27.3	15.2	42.5	xxxxx	0.8	xxxxx	0.8	0.0	4.8	0.0	0.0	1.9	6.7	46.3	2.2	100.00	94.3	4.5	1.22	50.9
p7a-04	siltstone	542.4	0.0625	62.5	1.5	xxxxx	xxxxx	12.9	47.4	3.2	0.3	0.6	15.5	6.5	22.0	xxxxx	0.9	xxxxx	0.9	0.0	11.3	0.3	0.0	1.2	12.8	50.6	0.9	100.10	96.6	1.7	1.72	47.7
p7a-05	sandstone	532.2	0.188	188.0	0.75	xxxxx	xxxxx	40.7	46.3	7.0	0.0	0.0	0.9	0.9	1.8	xxxxx	1.0	xxxxx	1.0	0.0	0.6	0.0	2.6	0.0	3.2	53.3	0.0	100.00	98.2	0.0	1.84	45.7
p7a-06	sandstone	513.2	0.125	125.0	0.75	xxxxx	xxxxx	22.0	49.3	3.3	1.6	1.3	5.3	10.2	15.5	xxxxx	1.6	xxxxx	1.6	0.0	4.6	0.7	0.0	0.0	5.3	52.6	2.9	99.90	92.1	5.1	2.80	42.8
p7a-07	sandstone	489.0	0.125	125.0	1.125	xxxxx	xxxxx	12.1	38.1	2.3	2.0	1.6	1.5	36.6	38.1	xxxxx	2.3	xxxxx	2.3	0.0	2.9	0.7	0.0	0.0	3.6	40.4	3.6	100.10	87.3	7.8	4.97	53.8
p7a-08	sandstone	433.6	0.094	94.0	0.75	xxxxx	xxxxx	36.6	40.5	4.8	2.4	0.0	4.2	9.0	13.2	xxxxx	1.8	xxxxx	1.8	0.0	0.0	0.0	0.0	0.6	0.6	45.3	2.4	99.90	91.5	4.8	3.64	50.4
p7a-10	sandstone	416.6	0.125	125.0	1.125	xxxxx	xxxxx	23.5	44.8	5.6	0.7	1.6	15.2	2.1	17.3	xxxxx	3.3	xxxxx	3.3	0.0	0.7	0.0	0.0	2.6	3.3	50.4	2.3	100.10	90.0	4.1	5.88	44.1
p7a-11	sandstone	406.2	0.188	188.0	0.75	xxxxx	xxxxx	33.7	53.0	7.0	1.0	0.0	1.3	1.3	2.6	xxxxx	2.0	xxxxx	2.0	0.0	0.3	0.0	0.0	0.3	0.6	60.0	1.0	99.90	95.2	1.6	3.17	38.6
p7a-13	sandstone	336.0	xxxxx	xxxxx	1.5	xxxxx	xxxxx	0.7	20.8	0.0	0.3	0.0	3.5	25.9	29.4	xxxxx	2.2	xxxxx	2.2	6.5	0.9	0.0	0.0	38.1	46.5	20.8	0.3	99.90	88.3	1.3	9.44	76.6
p7a-14	conglomer	282.9	0.125	125.0	0.75	xxxxx	xxxxx	3.5	48.1	6.3	0.3	0.7	4.3	10.5	14.8	xxxxx	0.3	xxxxx	0.3	0.0	0.3	0.3	0.0	27.6	28.2	52.4	1.0	100.00	97.6	1.9	0.56	46.5
p7a-15	sandstone	383.2	0.125	125.0	1.125	xxxxx	xxxxx	19.3	51.1	7.8	0.6	0.3	2.6	16.7	19.3	xxxxx	0.6	xxxxx	0.6	0.0	0.3	0.6	0.0	0.0	0.9	58.9	0.9	99.90	97.5	1.5	0.99	39.5
p7a-16	sandstone	264.7	0.25	250.0	0.425	xxxxx	xxxxx	6.1	47.5	6.9	0.7	1.3	1.1	34.1	35.2	xxxxx	1.0	xxxxx	1.0	0.0	1.3	0.0	0.0	0.0	1.3	54.4	2.0	100.00	94.8	3.5	1.74	42.6
p7a-17	sandstone	250.3	0.11	110.0	1.5	xxxxx	xxxxx	0.9	36.3	1.3	0.3	0.0	0.2	33.5	33.7	xxxxx	1.3	xxxxx	1.3	1.0	1.6	0.3	0.0	23.2	26.1	37.6	0.3	99.90	95.9	0.8	3.32	60.7
p7a-19	siltstone	237.6	0.11	110.0	1.5	xxxxx	xxxxx	21.2	45.3	4.5	1.6	0.6	2.7	18.5	21.2	xxxxx	1.9	xxxxx	1.9	0.0	1.3	1.0	1.0	0.3	3.6	49.8	2.2	99.90	92.4	4.1	3.53	46.0
p7a-20	siltstone	217.4	xxxxx	xxxxx	0.6	xxxxx	xxxxx	22.7	36.8	0.3	1.3	1.6	2.0	31.8	33.8	xxxxx	0.7	xxxxx	0.7	0.0	1.6	0.3	0.0	0.7	2.8	37.2	2.9	99.90	91.2	7.1	1.72	59.1

Appendix B (continued)

LEONARDIAN				MISSOURIAN		
Age (Ma)	Temp. (°C)	Depth (m)		Age (Ma)	Temp.(°C)	Depth (m)
0	21.49	250		0	83.92	2796.55
25	30.4	625		25	92.05	3134.84
50	39.26	1000		50	101.08	3509.76
75	38.79	980		75	101.98	3547.3
100	36.3	875		100	98.82	3415.92
125	33.93	775		125	97.02	3340.84
150	30.37	625		150	94.31	3228.23
175	27.41	500		175	92.5	3153.15
200	24.45	375		200	89.79	3040.54
225	21.25	240		225	87.53	2946.7
250	15.56	0		250	85.28	2852.85
				275	49.62	1370.12
				285	32.47	656.91
				286	15.83	0

Appendix C: Data used for constructing the burial history curve, after Schmoker (1986, p. 8).

Note: Schmoker's data for Time-Depth and Time-Temperature curves were converted to the above data set using the relationship below (Asquith, 1982. Bassiouni, 1994)

Tf = (°C) = gG x Depth (m) + Ts

Tf (°F) = gG x Depth (ft) + Ts

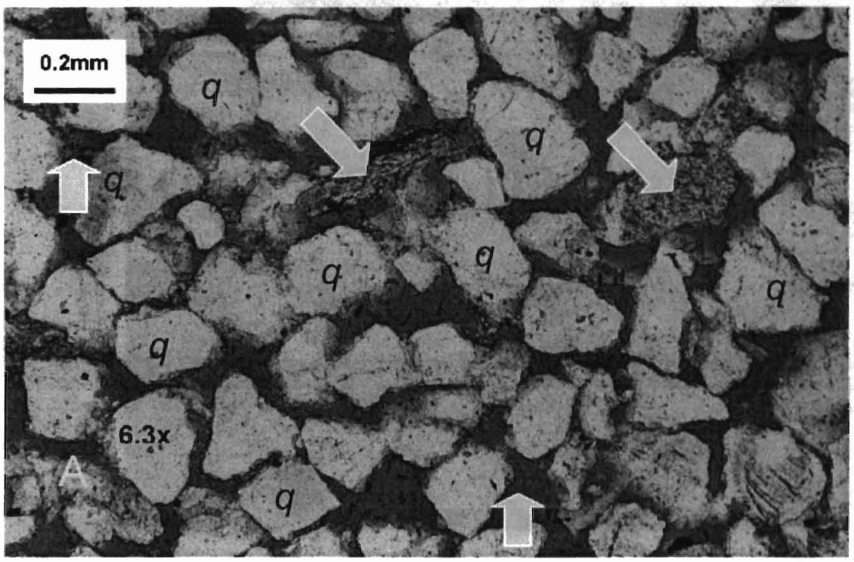
gG = geothermal Gradient = 2.37 /100 (°C / m) ~ (1.3 / 100 °F /ft) in the study area.

Tf = Formation temperature

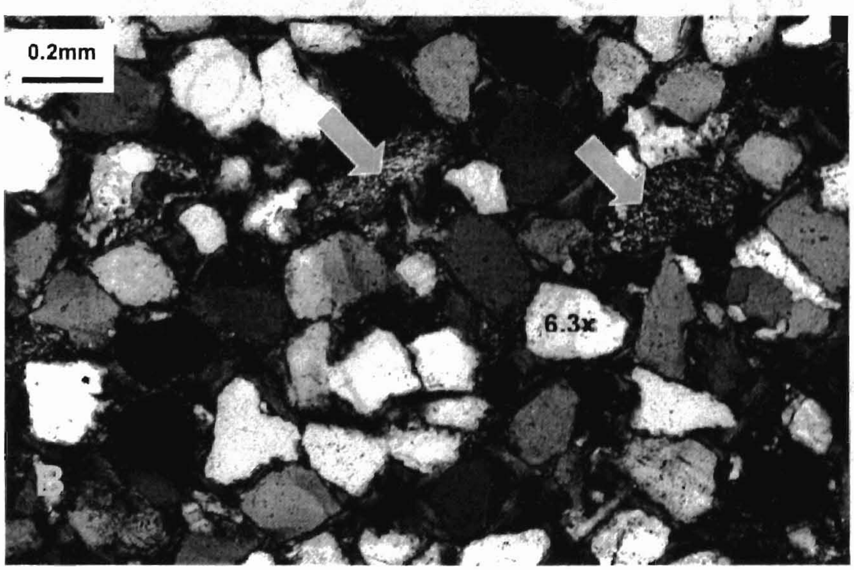
Ts = Surface temperature = 15.56 °C (60 °F) in the study area.

Well	Depth (Feet)	Depth (m)	IGV (%)	Porosity (%)
w3	119.2	0.03633	36.7	35.7
wo	0	0	33	31.7
w4	41.3	0.01259	40.2	35.8
w4	141.6	0.04316	30.2	25.4
w4	274.2	0.08358	35.9	33.1
w6	96.5	0.02941	40.5	36.9
w1	222.9	0.06794	38.2	34
w4	154.8	0.04718	35.5	30.3
wo	0	0	34.5	34.1
w3	35.4	0.01079	38	36.9
w6	558.8	0.17032	36.7	33.5
w7a	406.2	0.12381	36.9	33.7
w6	301.3	0.09184	41.6	36.9
w6	51.6	0.01573	39.7	36.4
w6	337.1	0.10275	40	35.1
w7a	624.2	0.19026	37.1	35.2
w3	123	0.03749	37.4	31.6
w4	123	0.03749	40.5	37.5
w6	131.1	0.03996	36	30.7
w6	273	0.08321	50	43.7
w3	58	0.01768	29.9	25.9
w7a	532.2	0.16222	45.7	40.7
w6	560.5	0.17084	29.6	23.4
w6	135.6	0.04133	39.6	32.5
w6	184.8	0.05633	35.6	32.5

Appendix D: Compaction-Curve data set. This data is for estimating the degree of compaction of the Permian Garber Sandstone and it groups only samples with less than 5% matrix. Wo = outcrop *q = quartz grain*

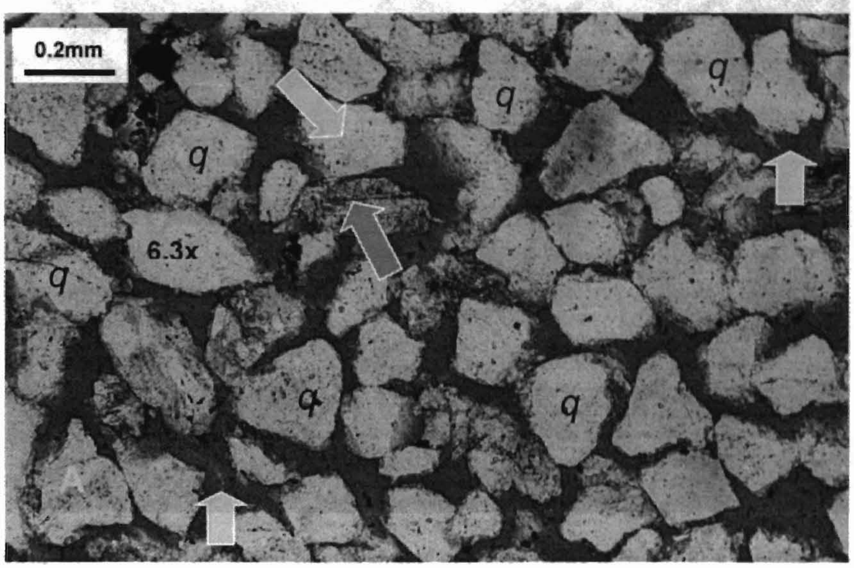


Porosity is indicated by blue arrows in the photograph.

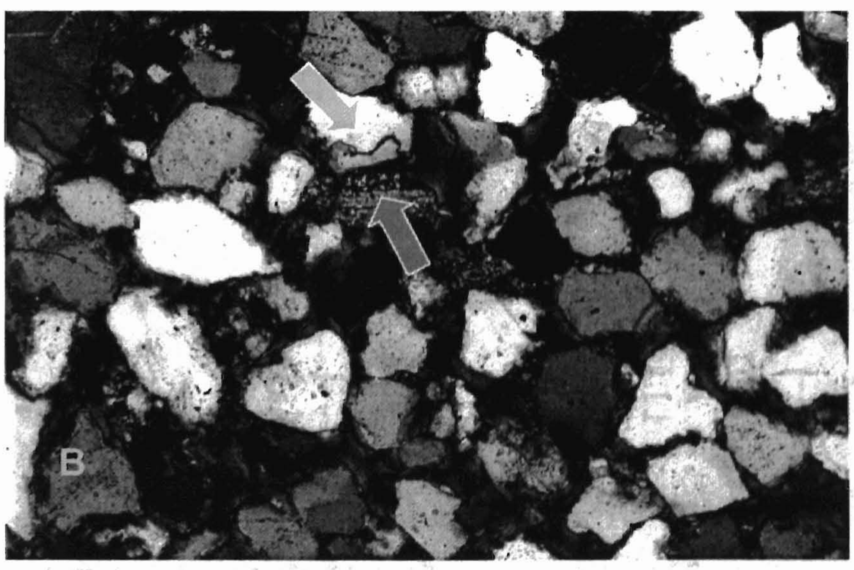


Appendix E1. - Low grade metamorphic micaceous rock fragments in a field of view from sample B-1. Photo B (crossed polars) demonstrates that the rock fragment contains mica (higher order birefringence). Note that most of the quartz grains are monocrystalline.

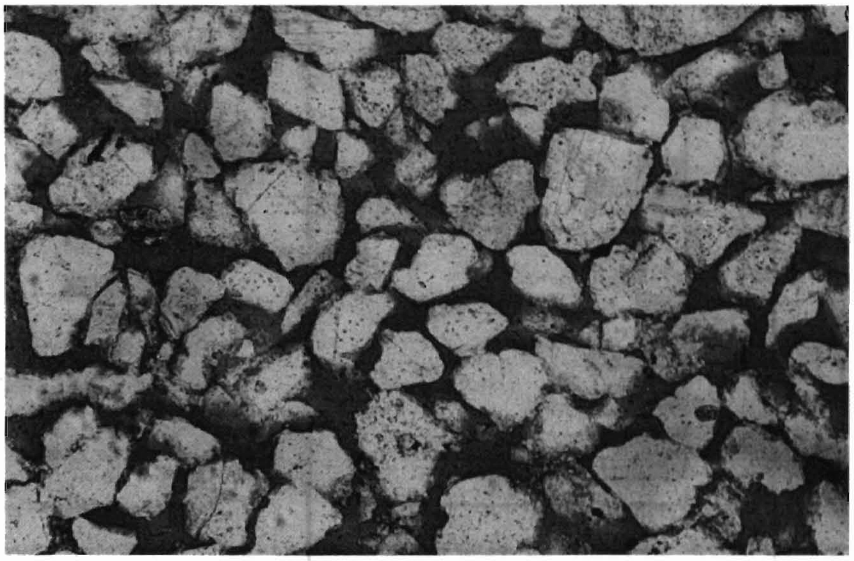
q = quartz grain



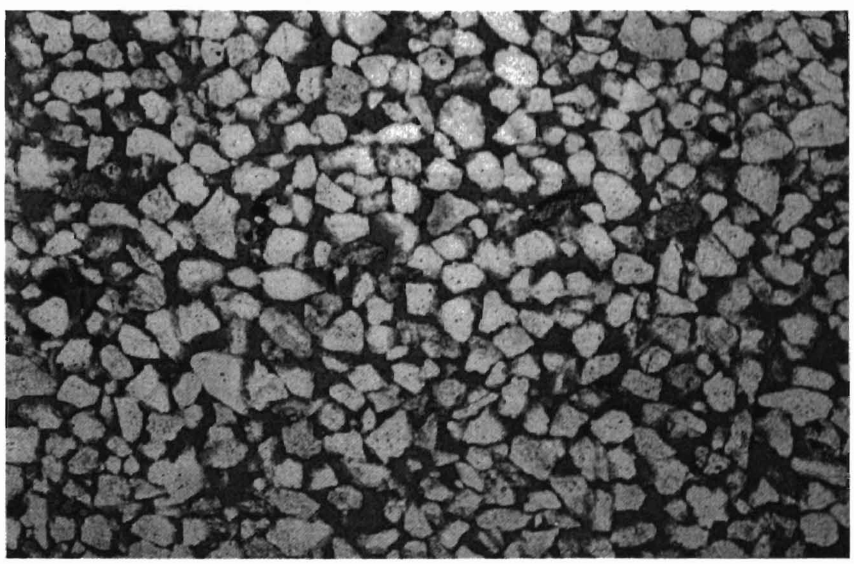
Porosity is indicated by blue arrows in the photograph.



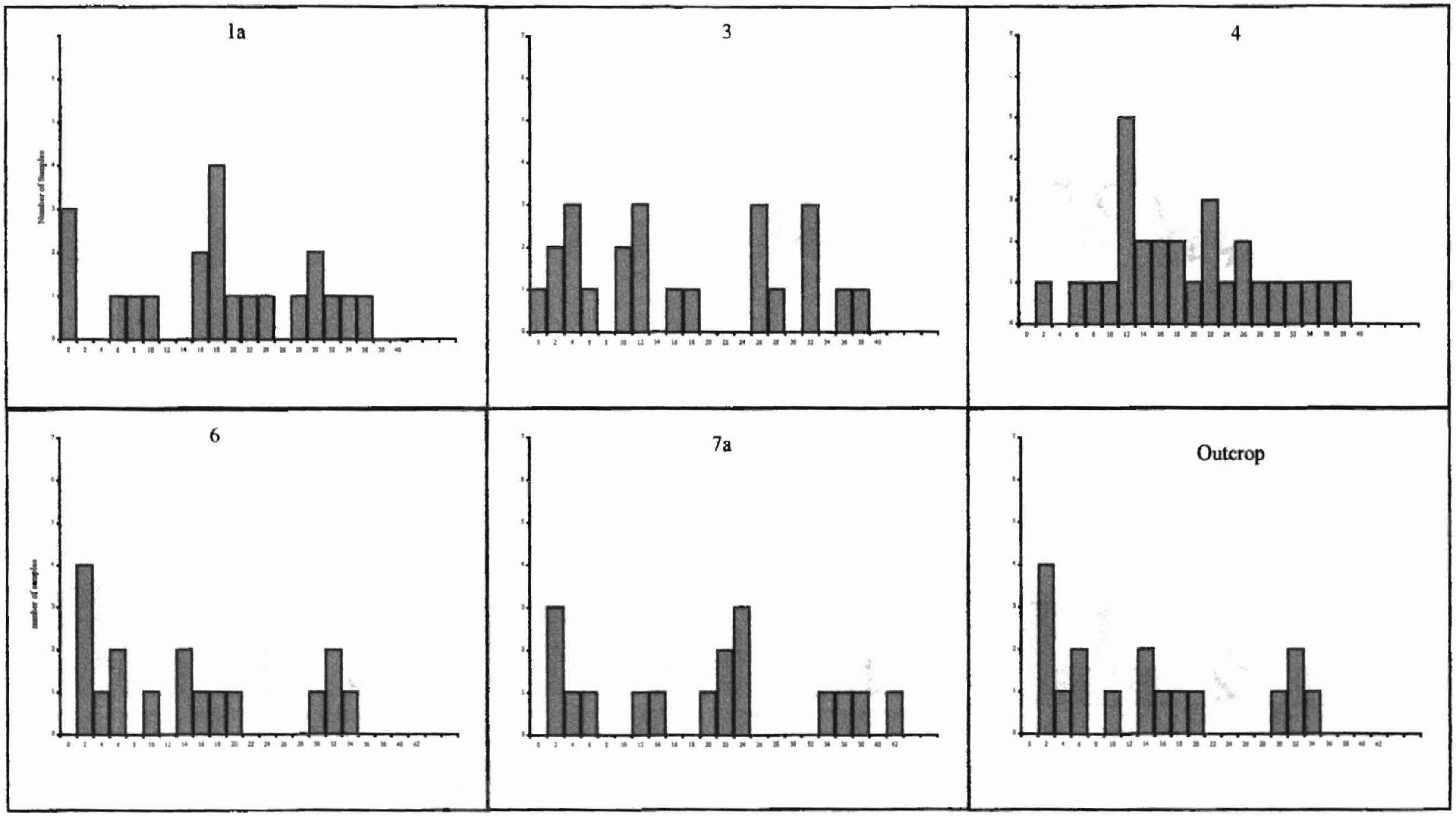
Appendix E2. - General field of view in sample B-1 from the base of the Cowboy Hall of Fame outcrop. A plagioclase grain is indicated by the purple arrow. The plagioclase grain contains some pinpoint centers of higher-order birefringence that corresponds to mica (illite, sometimes referred to as sericite) (purple arrow in Photo B). Note that most of the quartz grains are monocrystalline with exception of the grain at the gray arrow.



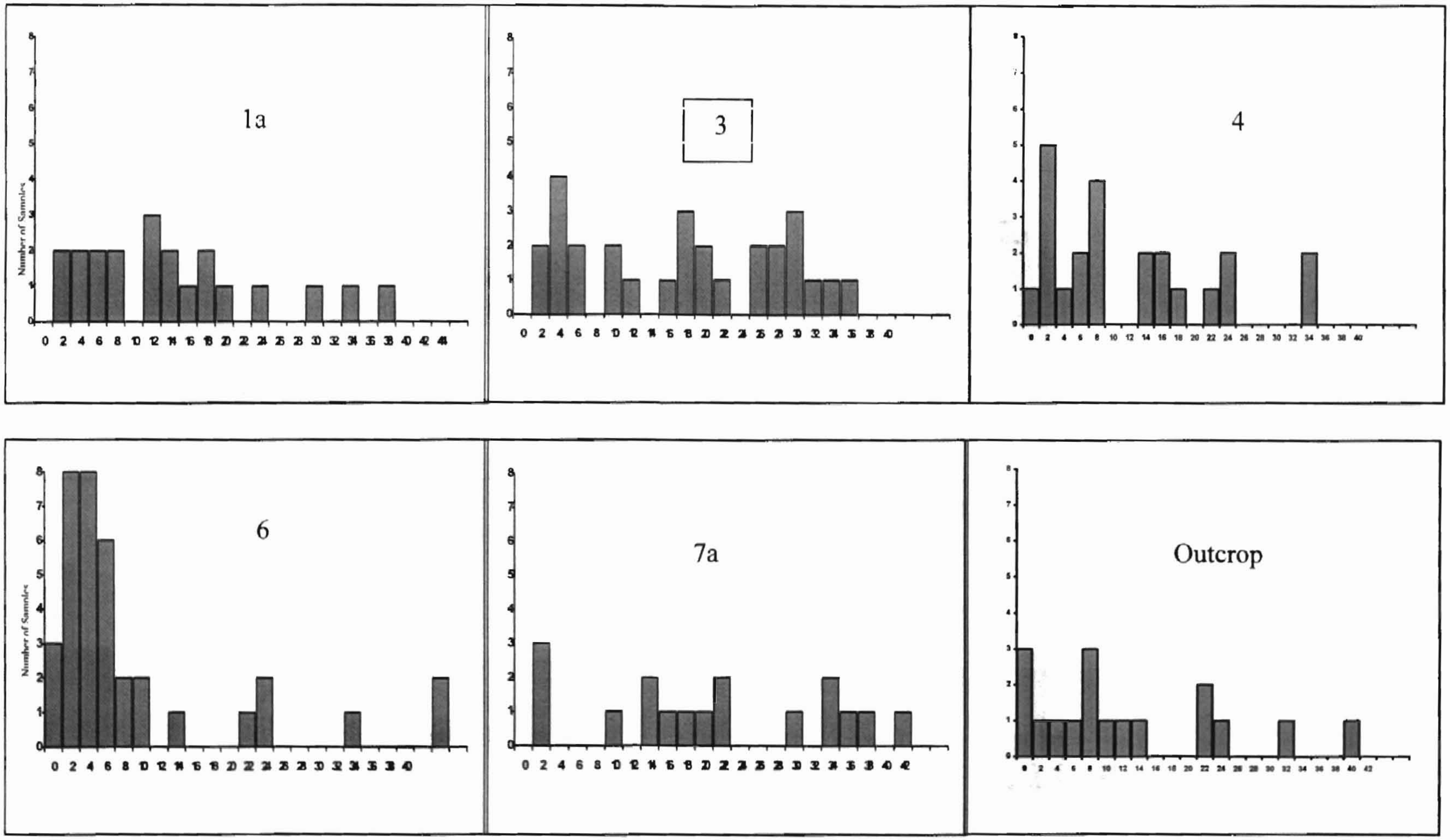
Appendix E3: Well-developed intergranular porosity (blue arrows) in a sample from the Cowboy Hall of Fame outcrop (Layer B-1). This sample has 32% porosity according to point count analysis of the Sandstone. Based on grain roundness, cleavage traces, and the absence of a straw-yellow stain (sodium cobaltinitrate for potassium feldspar), the purple arrow at f is a plagioclase feldspar grain.



Appendix E4: Well developed intergranular porosity (blue arrows) in a sample from Hall of Fame outcrop (Layer B-1). Most of the grains are quartz (62% according to point count analysis). Trace of micaceous rock fragments and plagioclase feldspar (dark green arrows) are also present.



Appendix F-1: Porosity distribution for individual NOTS Well and Outcrop.



Appendix F-2: Matrix Distribution for NOTS Well individually and Outcrop.

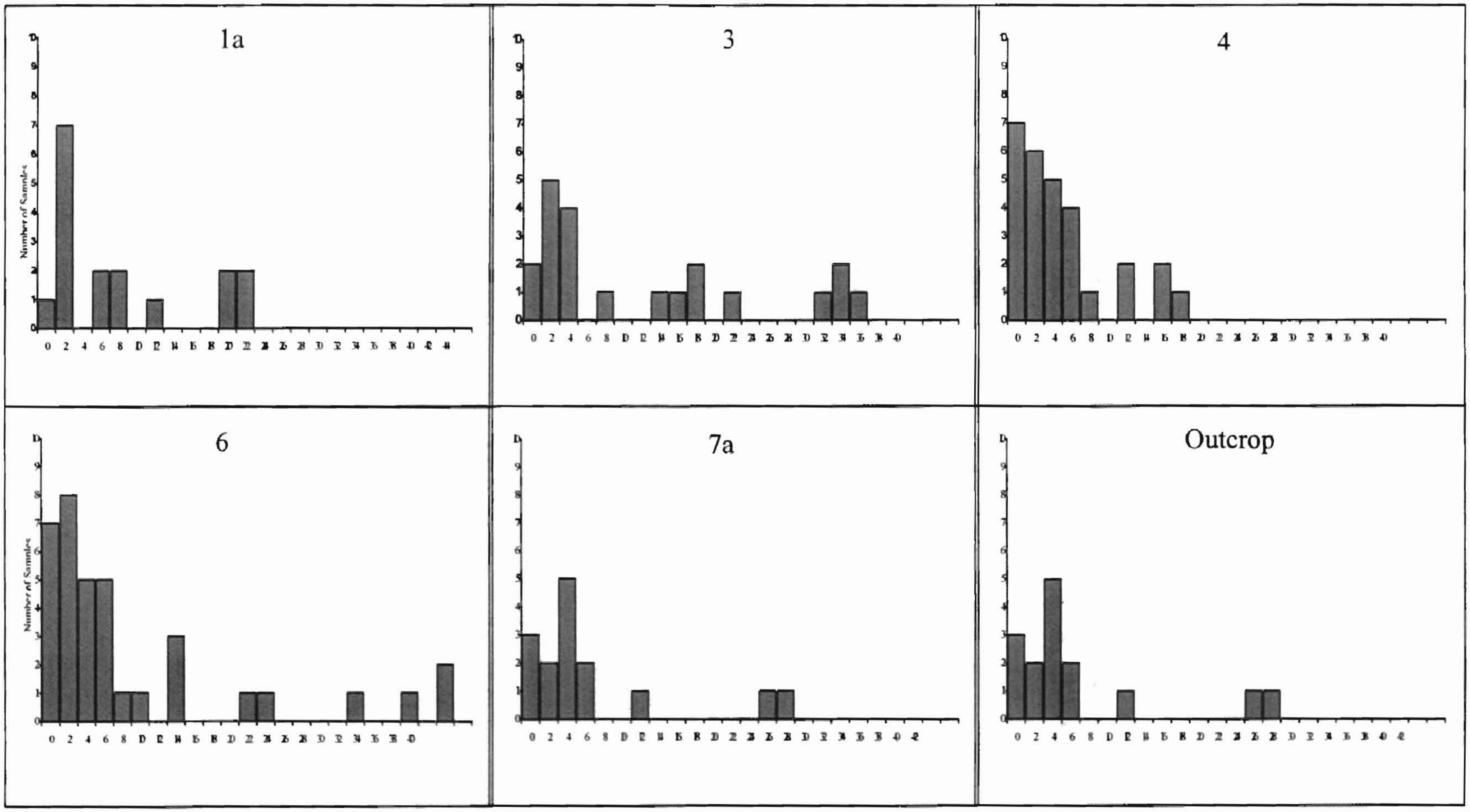


Fig. F-3: Cement Distribution for NOTS Well individually and Outcrop.

VITA

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