GEOLOGIC AND HYDROLOGIC CONTROLS

ON FLOW AT VENDOME WELL,

SULPHUR, OK

By

JASON DARYL NORD

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

1996

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
Master of Science
July, 2000

GEOLOGIC AND HYDROLOGIC CONTROLS

ON FLOW AT VENDOME WELL,

SULPHUR, OK

Thesis Approved:

Thesis Advisor

Dean of the Graduate College

ACKNOWLEDGEMENTS

In the long and arduous road of completing this thesis, many people helped me along the way. However, before I can thank everyone, I unfortunately have to begin this on a sad note. Prior to the completion of this thesis, a well-known local from the Sulphur area, Mrs. Opal Brown, was killed in a car wreck. Mrs. Brown was a Vendome Well historian whom helped me immensely on the historical section of this thesis. She went out of her way by sending me photos of the well, and even spending an entire afternoon with me at the Sulphur library one summer day. Her spirit and kindness made quite an impression on me and for that reason I wish to dedicate this thesis to her.

I would like to begin this by thanking Dr. Nicholl for his guidance along the way. Although I often got "lost", he was always there to encourage and then nudge me back into the right direction. Also, since this thesis was unfunded, his ingenuity came in extremely handy at numerous points throughout this endeavor, especially in helping to create the apparatus used to measure the flow rate at Vendome Well. Lastly, I would like to thank Dr. Nicholl for all the time and effort that he put into helping shape this thesis into what is seen today, for I know that that takes its toll. Dr. Nicholl, I wish you nothing but the best of luck in the future!

I would also like to thank my other two thesis committee members. I have known Dr. Vitek for many years and have really appreciated his input in this thesis. I have long respected Dr. Vitek and I feel extremely privileged to have had him on my committee. I also wish to thank Dr. Wikle, whom is from the Geography department. I had the pleasure to meet and work with Dr. Wikle on a two year long National Park Service project for Chickasaw National Recreation Area. Since meeting him, Dr. Wikle has helped me out numerous times and for that I am grateful. I appreciate his willingness to sit on my committee and for all the advice that he has provided along the way.

Several other professors have also helped me out tremendously. First of all, I want to thank Dr. Al-Shaieb for everything that he did to help me. Whether it was allowing me to use the x-ray diffractor or there to just answer a few of my questions, he was always encouraging me. A special thanks also goes out to Dr. Puckette, who so generously spent time fielding my questions and offering his advice on the well cuttings section. Without the help of these two professors, my thesis would not have been complete.

My thesis definitely would not have been attainable without the cooperation of Chickasaw National Recreation Area management. In particular, I would like to extend my gratitude to Ron Parker, who has helped me out extensively for the past few years. Also, I wish to thank Paul Christensen for all the assistance that he provided in the early stages of this thesis.

During my education at Oklahoma State University, I have had the pleasure to meet many people and forge numerous friendships. In particular, I would like to acknowledge my good friend and fellow Geology graduate student, Phebe Deyhim. I want to thank her for her support during this thesis, but more importantly for just being a trusting friend to talk and hang out with.

Last, but definitely not least, I would like to express my thanks to my family. To my parents, I wish to express my gratitude for all of the support and sacrifices that were made for me in order to succeed not only in this thesis, but also more importantly in life. Mom and dad, you will never know how much I appreciate all that you have done for me! They patiently waited as I took what essentially was the "ten year plan" to graduate. I can not count how many times my dad asked me "when are you going to graduate?" Well dad, this one is for you....I FINALLY did it! Thanks also goes out to my two sisters, Rebecca and Audrey, and my little brother Nicholas. As with most siblings, growing up with them has made life much more interesting and fulfilling. Lastly, this acknowledgement would not be complete without also thanking my step-mom, Jeretta.

I would like to conclude this by once again thanking all these people above for helping make this thesis attainable. I wish everyone the best of luck, as I sadly close one chapter of my life and anxiously await to begin another.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

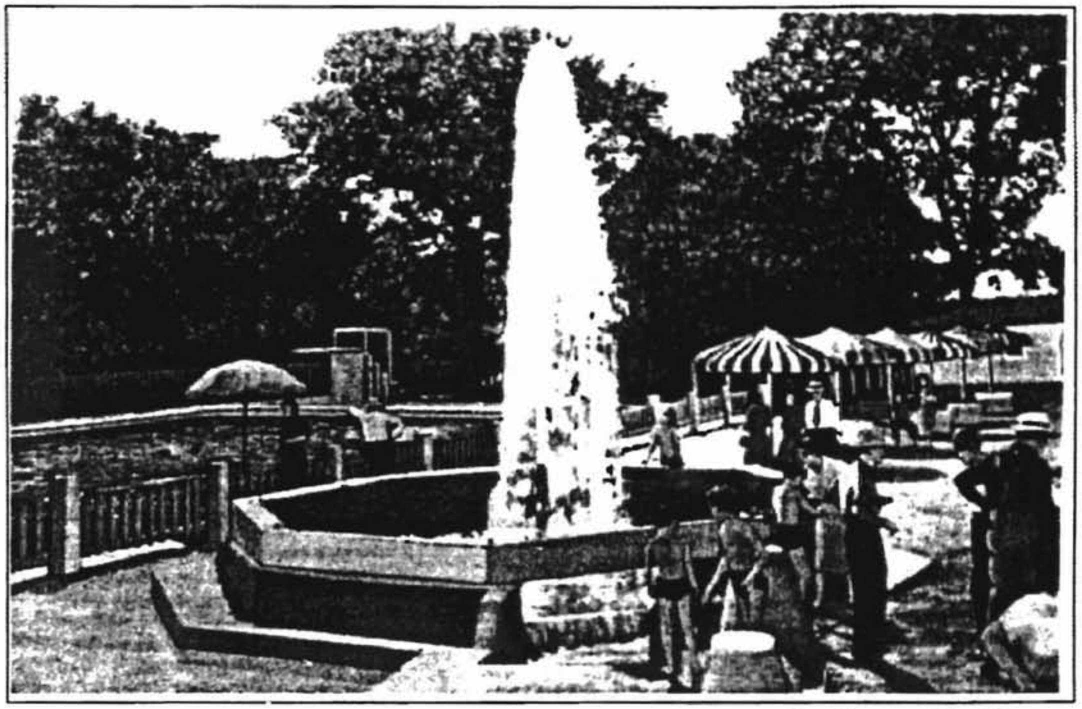
Vendome Well is a historically and culturally significant artesian well located in south-central Oklahoma. Presently, Vendome is owned by the United States government. It is located within Chickasaw National Recreation Area (CNRA), which is managed by the National Park Service (NPS). Discharge from this free-flowing well has shown a declining trend since it was first drilled in 1922. This change in flow suggests that the resource is being depleted. This thesis will evaluate existing data to assist in developing a better understanding of the geologic and hydrologic mechanisms that control flow at Vendome. This interpretation may be used to assist in the management of this resource.

Reasons for this thesis

Over the past half-century, studies of discharge have suggested that springs and wells in and around Chickasaw National Recreation Area (CNRA) have shown a trend of declining flow (Hanson and Cates, 1994). Vendome is one such well that is thought to be affected. It is believed to have had a discharge rate of 3,500 gallons per minute around the time it was drilled in 1922; however, in 1985, discharge was measured at only 900 gallons per minute

(Hanson and Cates, 1994). Vendome discharges through a vertical fountain; photographs of the well taken at various times (see Figures 1 and 2) seem to show an apparent decline in discharge with time. Although lowering of the water column could be attributed to other causes such as a change in a well nozzle or clogging of the well, the drop is likely explained by a decline in aquifer pressure. The exact reasons for the apparent decrease in flow are presently unknown; however, it is suspected that human intervention is a primary cause (Hanson and Cates, 1994). One reason behind this belief is that the observed decline has been concurrent with the growth of the population of the area. It is during this time of increased settlement that additional artesian and pumping wells were drilled within the area surrounding Vendome. With this increase in the number of wells, an increase in the amount of water removed from the aquifer probably occurred. Resultant decreases in water pressure within the aquifer may be responsible for reduced discharge to the springs and wells in the area.

Mindful of the increasing importance of water conservation, the National Park Service (NPS) had Vendome Well re-drilled and re-routed in the fall of 1997. The new well was drilled approximately 35 feet to the west of the old well (see Figure 3); to retain the historic values of the well, flow was routed to the old fountain. According to an article in the local newspaper (Sulphur Times-Democrat dated December 4th, 1997), the drilling of Vendome Well was done in three phases. The first phase was to drill down as far as needed to achieve a minimum desired water flow of at least 500 gallons per minute. During the initial drilling to 402 feet, the water flow was measured at only 60 gallons per minute.



Compliments of Opal Brown

Figure 1
Vendome Well, early 1950's

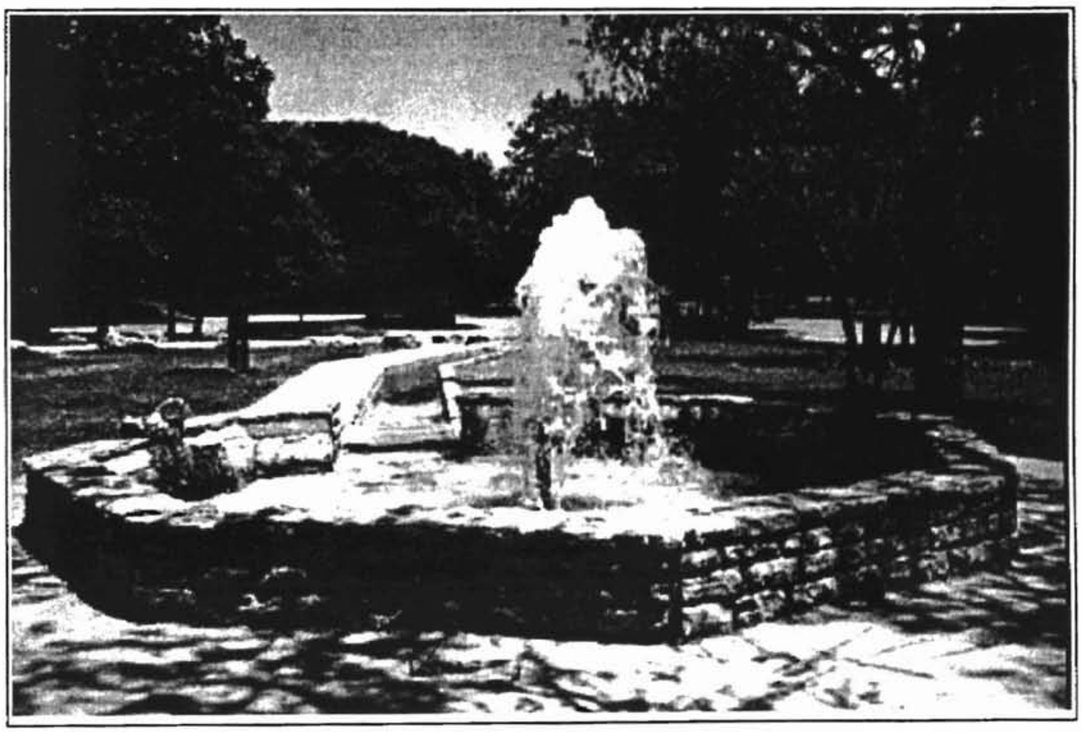


Photo by J. Nord

Figure 2
Vendome Well, 1998

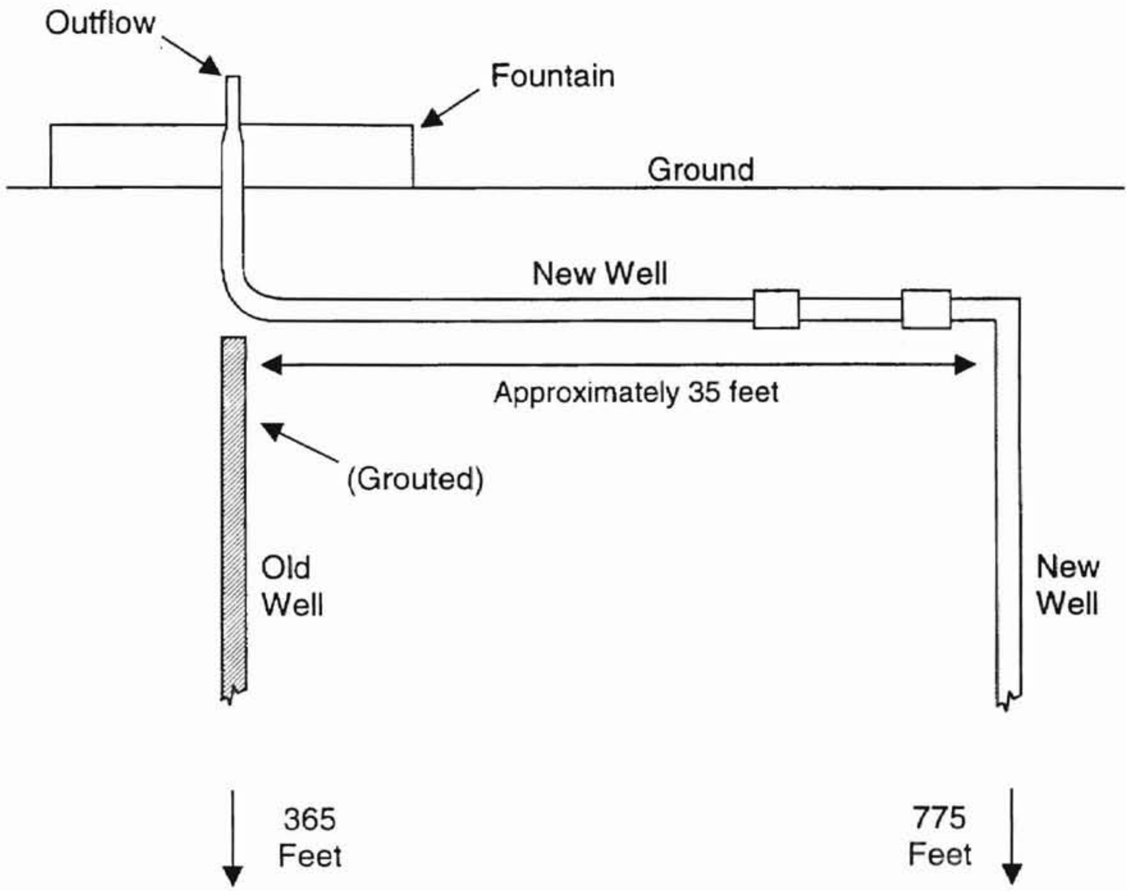


Figure 3
Cross-sectional diagram of the old and new piping
system at Vendome Well
(not to scale)

After reaching a depth of 775 feet, water flow of between 900 and 1000 gallons per minute was measured and thus drilling was ceased. The second phase of the drilling operation was to plug the old well. The final phase involved routing flow from the newly drilled well to the existing fountain.

This drilling operation attempted to solve two problems. First of all, portions of the old well casing were rusted out and leaking leading to possible mixing between deep and shallow groundwater. Secondly, a lack of control valves prevented management from controlling discharge. As a result of the three phases of drilling, CNRA staff can now more easily manage the flow of Vendome.

Although numerous studies have been conducted on the adjacent Arbuckle Mountains (e.g., Decker and Merritt, 1931; Ham, 1955, 1969, 1973; Johnson et al., 1984), very few geologic studies have been completed within CNRA and subsequently, little is known about the geology of CNRA. Even less information is available concerning the geologic parameters that control flow from the numerous springs and wells in the area. Lack of knowledge regarding the local aquifer system limits the ability to explain why flow from wells and springs in the area has been decreasing throughout recent time. This study provides information that is intended to improve our understanding of the local mechanics of the aquifer system, which in turn may help determine the reasons for decrease in flow from springs and wells in the area.

Location

Vendome Well is located within Chickasaw National Recreation Area (CNRA), which is in south-central Oklahoma, approximately 100 miles south of Oklahoma City. Once known as Platt National Park, the area was re-designated in 1976 as CNRA, and covers a region of 9,888 acres (see Figure 4) located to the south and southwest of the City of Sulphur. Two lakes, Lake of the Arbuckles and Veterans Lake are within the boundaries of CNRA (see Figure 5). One of the principal reasons that CNRA was originally created was to protect the unique hydrologic environment located in the area surrounding Vendome. To this day, numerous wells and springs (including Vendome) cover the landscape of CNRA and the surrounding area (see Figure 6).

General Background

The water which flows from Vendome Well is derived from an aquifer located in geologic units beneath the well. An aquifer may be defined as "a geologic unit that can store and transmit water at rates fast enough to supply reasonable amounts to wells" (Fetter, 1994). Unconsolidated sands and gravels, sandstones, limestones, dolomites, various metamorphic, and igneous rocks are examples of lithologic units known to act as aquifers (Fetter, 1994). Aquifers are located in the subsurface in almost all geographic locations throughout the world, and in environments ranging from rain forests to deserts. It has been estimated that approximately 65 times more water is stored in the subsurface (aquifers) as

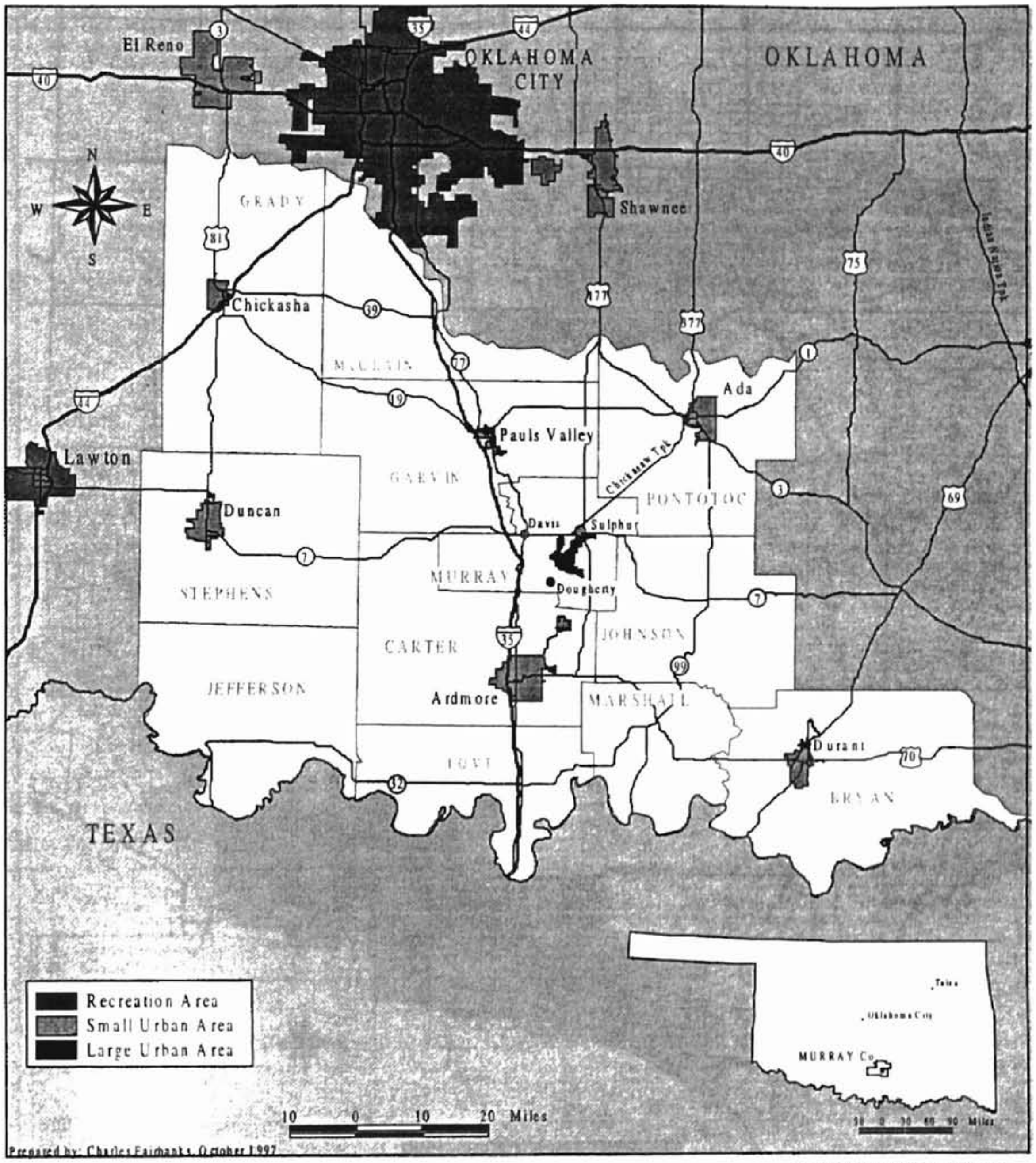


Figure 4
Regional Map

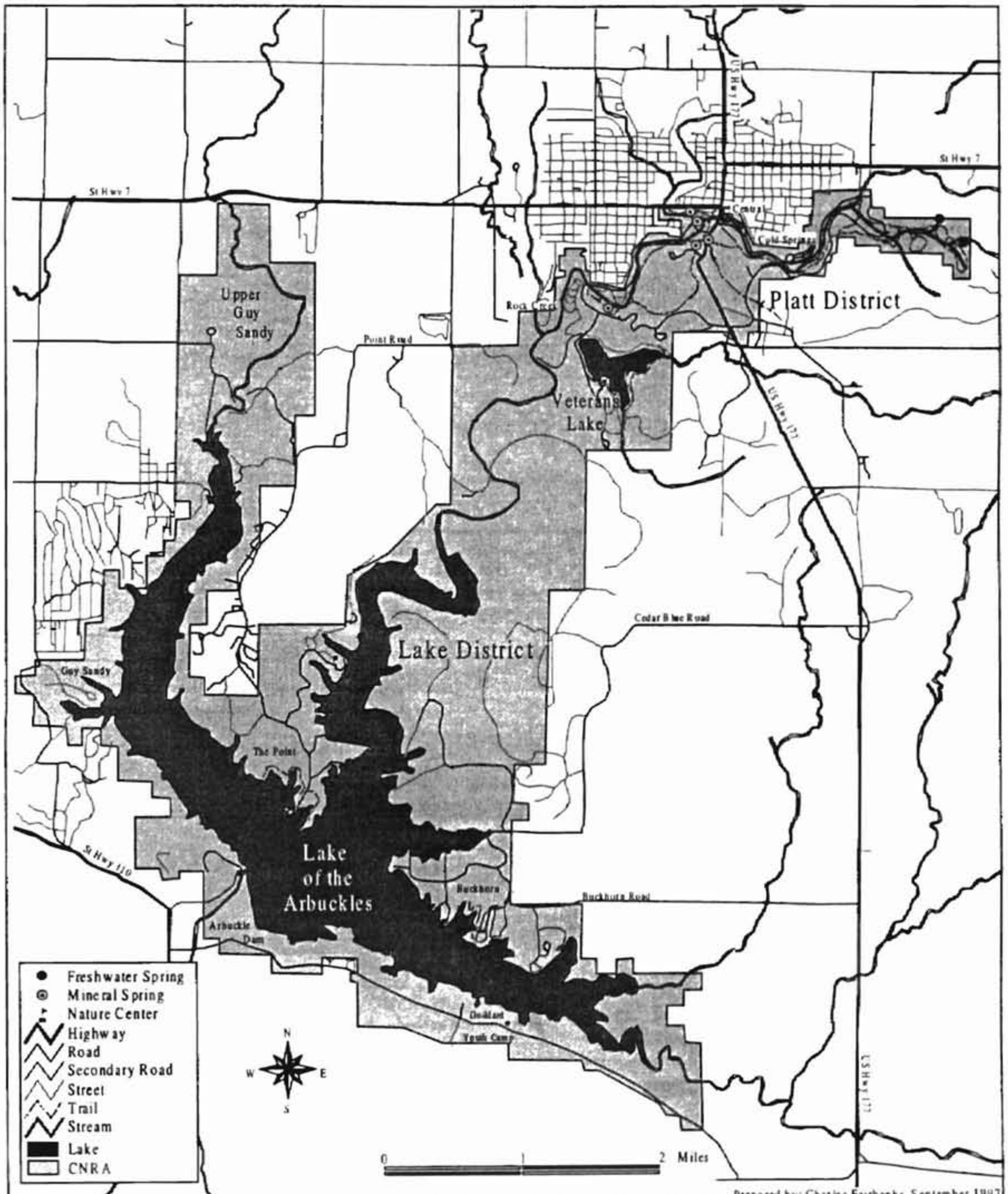


Figure 5
Chickasaw National Recreation Area

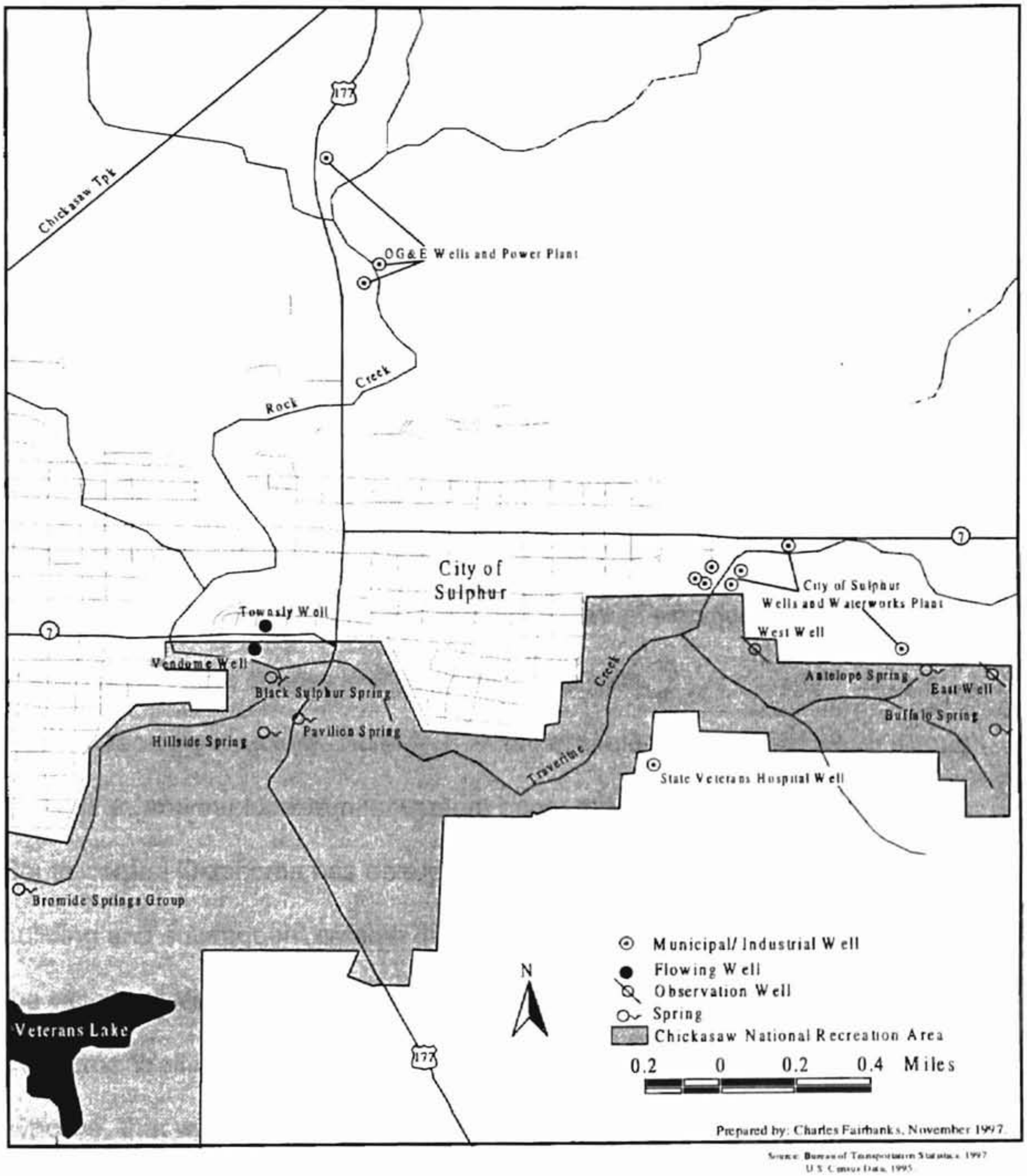


Figure 6
Well and Spring
Locations at CNRA

compared to that stored in fresh water surface bodies, such as lakes and rivers (Fetter, 1994).

The origins and nature of water derived at the springs and wells in CNRA (including Vendome) are a classic textbook model (Barker and Jameson, 1975). The predominant surface rock at Vendome belongs to a tight, well-cemented limestone conglomerate known as the Vanoss Formation. This formation is highly impervious to the flow of water, and thus acts as a confining layer. Rock units that are impervious to water are known as confining layers because they restrict the flow of water to the underlying aquifer (Fetter, 1994). Underlying the surface rocks at Vendome are two geologic groups of rocks known as the Arbuckle and Simpson Groups. These two primarily carbonate geologic groups comprise the aquifer, and allow for the movement of significant quantities of water through pore spaces and fractures in the rock.

Geologic structure can play a prominent role in the flow of water through an aquifer, and the local aquifer system beneath Vendome is no exception. South-central Oklahoma has a very complex geologic history because of the building and subsequent erosion of the Arbuckle Mountains. Thus, the rocks in the vicinity of Vendome Well show a great deal of structural complexity. Vendome Well is situated on the lower northern slope of a massive downfold, or syncline, that was formed during the Permian period (250 to 300 Million Years Ago). Massive folding within the region occurred in conjunction with the uplift of the Arbuckle Mountains (Barker and Jameson, 1975). In the time since this mountain building event, erosional processes have truncated the syncline to expose the porous Arbuckle and Simpson Groups in areas to the east-southeast of Vendome. As rain falls onto the outcrops of these formations, it percolates downward into the aquifer. From this outcrop area, the Arbuckle and Simpson Groups dip at an angle beneath the Vanoss Formation. Similar to water flowing through a pipe, water in confined aquifers is under pressure (Fetter, 1994). In the confined Arbuckle and Simpson Aquifers, there is sufficient water pressure such that any cracks in the confining layer (Vanoss Formation) will yield water at the surface. Likewise, wells drilled through the confining Vanoss Formation yield water without the need of a pump. These free-flowing wells such as Vendome are referred to as artesian wells, and are an indication that the water in the Arbuckle-Simpson aquifer is under significant pressure. The amount of water that flows from artesian wells at any given time is a direct function of the pressure within the aquifer. Thus, as the pressure increases, so too does the flow rate, and vice-versa (Nicholl et al., 1999). A simplified illustrative example of an artesian aquifer, such as the system that yields Vendome Well is shown in Figure 7.

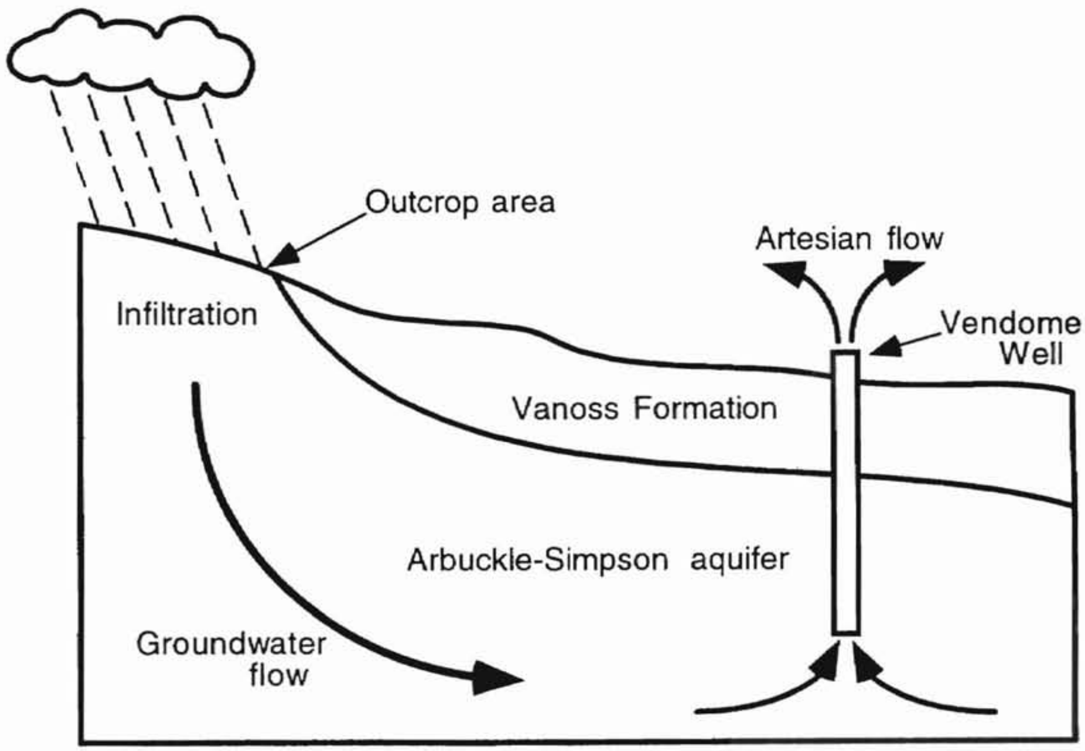


Figure 7
Simplified cross-section of the Arbuckle-Simpson aquifer system (Modified after Nicholl et al., 1999)

Objectives

The main objective of this thesis is to create a better understanding of the aquifer at Vendome Well.

The primary objectives of this investigation are:

1. Identify the geologic units lying beneath Vendome Well by analyzing rock cuttings and other pertinent data.
2. Infer source rocks from water quality data of Vendome Well.
3. Infer hydrologic characteristics (transmissivity and storativity) of the aquifer at Vendome Well.
4. Conclude the most likely subsurface scenario (both geologic and hydrologic) at Vendome Well.

Methods of Investigation

Integration of numerous types of information was essential in determining the aquifer characteristics of Vendome Well. A literature search was conducted on the geology of the Arbuckle Uplift in Southern Oklahoma to establish the tectonic and depositional background of the region. Other literature searches were also implemented to determine the history of the well and the geologic history of the region. Valuable information was also obtained from a historian native to the Sulphur area (Mrs. Opal Brown).

Drill cuttings from the re-drilling of Vendome Well in October 1997, were obtained from Chickasaw National Recreation Area. The cuttings, which spanned to a depth of over 750 feet, were examined and described thoroughly in five-foot increments. This information was then used to piece together a stratigraphic profile at Vendome Well, so as to better understand how water is delivered to Vendome.

Regional correlation of the geology of the area to that of Vendome was done primarily through the use of a geologic study performed by a University of Oklahoma Master's student, Steven Cates. This thesis, entitled *Fault Distribution in the Sulphur, Oklahoma area based on Gravity, Magnetic, and Structural data*, concentrated on the location of faults in the area surrounding Vendome. In this study, numerous data sources were used to determine the locales of faults that are covered by an outcropping formation in the area. These same data sources, which included surface and subsurface geologic data, Bouguer gravity maps, and cross-sections designed from a computer program, were also used to correlate the stratigraphic section at Vendome with the local geology of the region.

Outline

Following this introduction, the next chapter provides a historical perspective of Vendome Well to understand the importance of the well. A geologic history of the Arbuckle Mountain region is presented in Chapter Three. Chapter Four presents the primary stratigraphic units lying in the subsurface of Vendome. Chapter Five introduces water chemistry data, which was used to help infer the source rocks providing water to Vendome. Cuttings obtained during the re-drilling of Vendome are described within Chapter Six, so as to better determine the geology beneath Vendome. The geologic data provided from these cuttings is then correlated to the geology of the area in Chapter Seven. Chapter Eight describes a constant drawdown aquifer test performed on Vendome. This chapter also details the procedure used to take data from the aquifer test, and estimate aquifer characteristics, such as transmissivity and storativity. Finally, conclusions and recommendations are provided in Chapter Nine.

CHAPTER II

HISTORY OF VENDOME WELL AND CNRA

Vendome Well is a cultural resource currently owned by the United States government and managed by Chickasaw National Recreation Area (CNRA), which is an entity of the National Park Service (NPS). The mission of the NPS regarding water resources at CNRA is specifically stated in the *1996 Strategic Plan* that the area is preserved "...to provide for the protection of CNRA's unique resources, springs, streams, lakes, and other natural features..." (NPS, 1996). To discern the significance of Vendome, the history of CNRA and the surrounding region must be understood.

History of CNRA

The region surrounding Vendome has been important to inhabitants (humans, animals, and plant species) for thousands of years. The numerous natural springs found on the landscape provided these inhabitants with a critical water resource in an area that at certain times of the year can be relatively dry. Archaeological evidence suggests that human use of the springs dates as far back as 7,000 years (Boeger, 1987). Lands in the vicinity of CNRA, and hence Vendome, were first inhabited by Native American tribes who valued the springwater for its medicinal uses, and viewed the springs as sacred places (Boeger, 1987; National Parks and Conservation Association, 1993). They also valued the area because the springs were a reliable source of water. As a result, wild game, fish, and plants migrated to the area because the springs helped to provide abundant shelter and water sources. The wild game that was attracted to the area was a source of food for local tribes.

In the late 1800's, an influx of white settlers migrated to the area after word spread that the bromide and sulfur springs had a medicinal value. As development increased, Native Americans living in the region realized that increased development posed a threat to the springs. Fearing permanent damage, or loss of the spring waters, representatives of the Chickasaw and Choctaw Nations petitioned for federal government protection of the land that included the springs. An ally for their cause was a United States Congressman from Connecticut, Orville H. Platt, who realized the importance of protecting spring waters in the area (Cunningham, 1941). With support from Platt, 640 acres of land owned by several Native Americans tribes was set aside by Congress on July 1, 1902. This land was known as Sulphur Springs Reservation and put under the supervision of the Department of the Interior (Boeger, 1987).

On June 29, 1906, the Sulphur Springs Reservation was re-designated as Platt National Park in honor of the Connecticut Congressman. The park was unique for two reasons. First, Platt was the smallest national park in the country and secondly, it was established through a voluntary conveyance of property from two Native American Nations (Boeger, 1987). In 1916, the NPS was established as a separate entity within the Department of Interior, and control of the land was passed to the new agency.

In the years during the "Great Depression" (late 1920's to mid-1930's), the economy of the United States was in shambles (NPS, 1985). By March of 1933, over 25% of the United States population (13 million people) were unemployed. In response to this crisis, President Franklin Delanore Roosevelt called a meeting of high government officials to create a Civilian Conservation Corps (CCC). The plan was to put 500,000 unemployed young persons to work improving forests, parks, and rangelands (NPS, 1985). Platt National Park was the focus of one such CCC camp that carried out projects that included planting trees and the construction of roads, bridges, and trails (Boeger, 1987; NPS, 1996; Sallee and Schoneweis, 1997; Wikle et al., 1998).

Water was the primary attraction at Platt Park, therefore improvements made by the CCC concentrated on the springs and streams in the area (see Figure 8). Improvements included such projects as the construction of pavilions, a pool at Buffalo Springs, and outflow channels (Boeger, 1987). Stream improvements included the construction of small dams along Travertine Creek to improve the swimming areas, which subsequently created many of the popular "swimming holes" (Brown, 1998). The work done at Platt Park by the CCC in the early 1930's had a large impact on the landscape, which can be seen today, as many of the structures still serve the original purposes. This notion was confirmed by a 1997 Cultural Landscape Inventory (Sallee and Schoneweis, 1997), which determined that CNRA's (formerly Platt Park) landscape largely

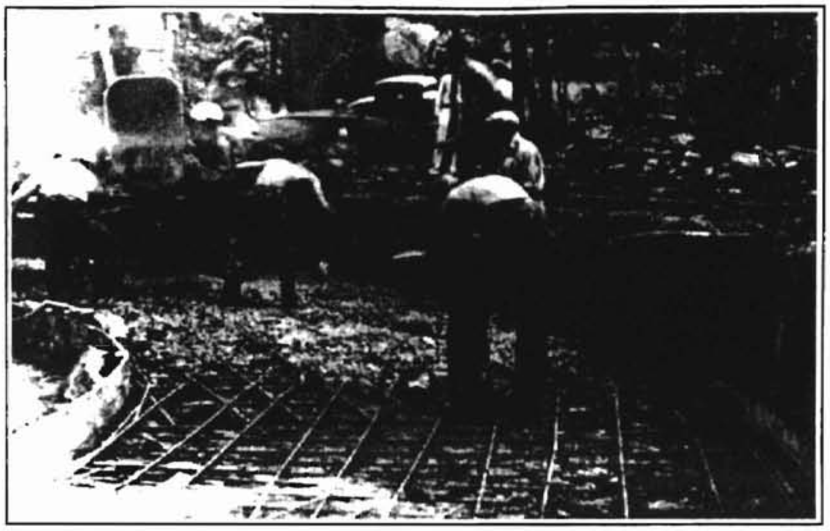


Figure 8
CCC workers constructing the Buffalo Springs pool, 1930's

Figure 9
CCC Tree Surgeon, 1930's

reflects the era from 1933-1940. During this time interval, the CCC built structures with rustic designs (Sallee and Schoneweis, 1997). The CCC's influence can also be seen in the biological community, particularly the dominance of certain tree species, such as the Red Cedar (Boeger, 1987). More than 550,000 trees and plants were transplanted within Platt Park by the CCC (see Figure 9).

In the early 1960's, land south of Platt Park was developed into Lake of the Arbuckles Reservoir (see Figure 5). This reservoir, under the authority of the Bureau of Reclamation, was constructed to facilitate flood control and to serve as a municipal water supply (Brown, 1998). Lake of the Arbuckles was created by the damming of Rock Creek, but also receives water from several spring-fed local creeks that flow directly into the reservoir.

Park officials realized at this time that the interests of visitors to the park were changing from merely collecting mineral water, to recreational pursuits. Based on this, it seemed that Lake of the Arbuckles and Platt Park would compliment one another well (Boeger, 1987). In 1970, NPS officials made a proposal to purchase land located between Lake of the Arbuckles and the park. At this same time, because of the changing interests of the visitors to the park, it was suggested that Platt National Park be re-designated as a National Recreational Area. It was recommended that this newly combined land (the original Platt National Park and Lake of the Arbuckles) be re-named Chickasaw National Recreation Area, in honor of those who initiated the conveyance of the original tract of land (Boeger, 1987). On March 17, 1976, Chickasaw National

Recreation Area was officially established, and the new land surrounding Lake of the Arbuckles was subsequently added.

The final addition to CNRA came on November 14, 1983 when the NPS obtained a quit claim deed from the City of Sulphur. In this deed, CNRA received land on the southern fringe of the City of Sulphur, which included Veterans Lake, and a historically and culturally important feature, Vendome Well. Major boundary changes at CNRA are shown in Figure 10.

History of Vendome

The area surrounding Vendome Well has a colorful history, even prior to the well being drilled. The area, which was known simply as "The Vendome", began initially with the excavation of the Vendome Amusement Pool in May 1906 (Brown, 1977). At that time, arrangements were made to pipe water from the Park Hotel Artesian Well, which was located across the street (currently Highway 7) from where the pool was being built (Brown, 1977). In October of that same year, the Electric Theatre opened at "The Vendome" with much anticipation, as 300 tickets were purchased for the event. This theatre was re-named "Electric Auditorium" and was showing new moving pictures three times a week (Brown, 1977). Shortly thereafter, on May 1st, 1907, the Vendome Pool was completed in time for the onslaught of summer visitors. "The Vendome" soon became a popular "hangout" and sometimes featured a street carnival which included a Ferris wheel, merry-go-round, cane rack, prize wheel, glass blowers, acrobats, and other attractions (Brown, 1977). Large crowds soon began flocking to the

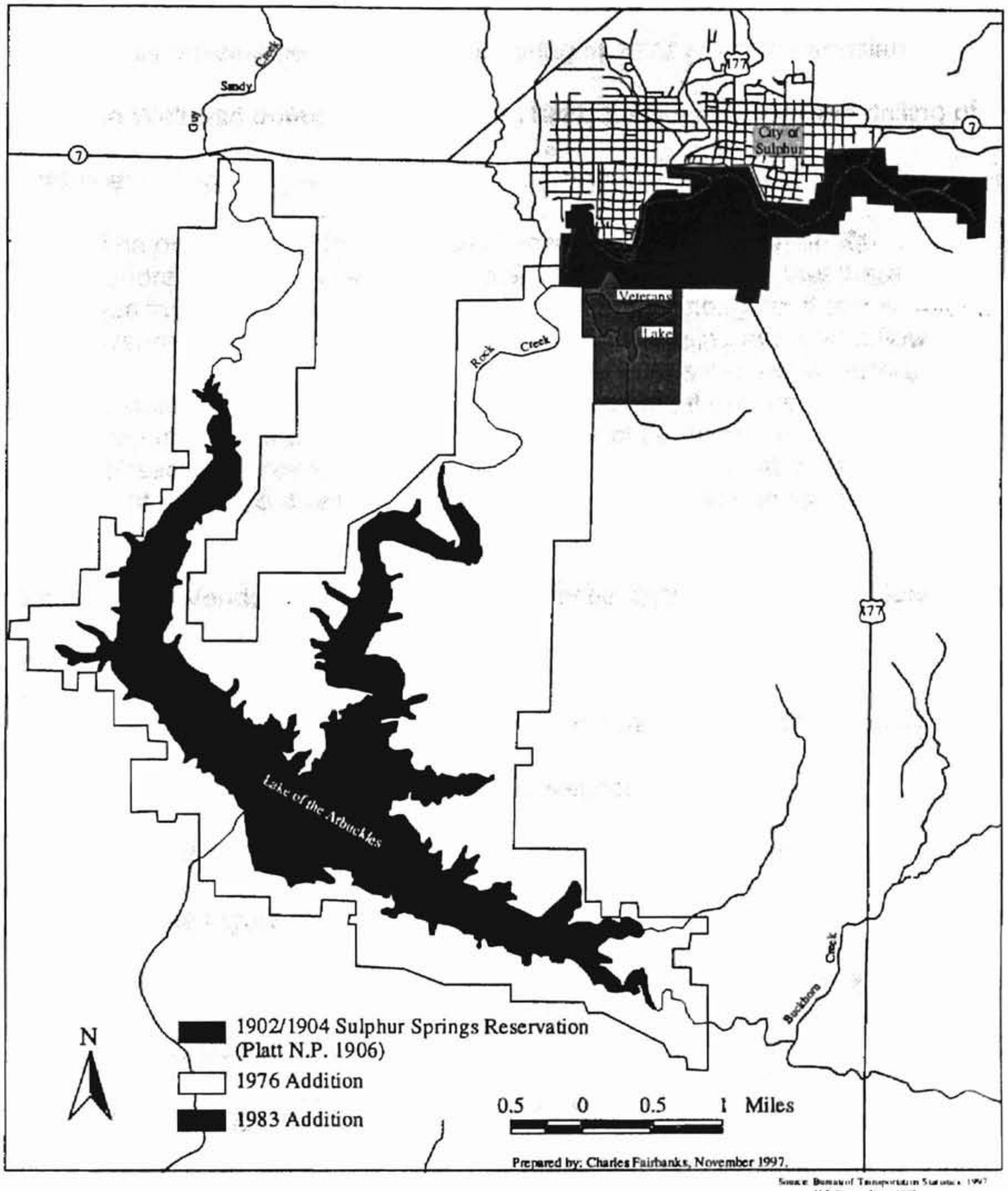


Figure 10
Boundary changes at
Chickasaw National Recreation Area

area each summer. Realizing the increased popularity of "The Vendome", the two owners, John Townsley and Frank Lewis, decided to develop the area even further. This development began in the spring of 1922 when the artesian Vendome Well was drilled. Cunningham (1941) briefly described the drilling of Vendome:

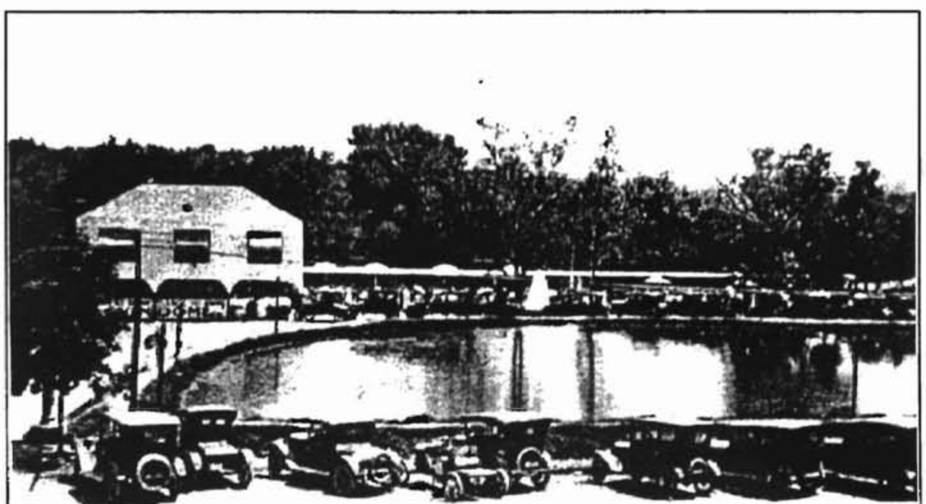
> "The owners had planned to drill (Vendome) to the depth of 500 hundred feet to insure a strong flow of water, but at 360 feet there was tapped a current of sulfur water with force enough to throw a stream of water 50 feet into the air above the casing and with a flow of 3,500 gallons of water per minute. The drillers had not expected to strike water for at least another hundred feet, therefore no preparations had been made to take care of the overflow. As a consequence, everything was flooded, and workmen labored all night digging a drainage ditch to Rock Creek (Cunningham, 1941, p. 29-30)."

The drilling of Vendome served several purposes. Although the Park Hotel Well across the street continued to flow, Townsley and Lewis wanted the deeper well to fill the pool during the summer. Also, the new well was used for display purposes, as yet another attraction to "The Vendome" (Brown, 1977). At the time it was drilled, Vendome was touted as being the "largest flowing mineral well in the world" (see Figure 11).

In coordination with the drilling of Vendome Well, the two owners (Townsley and Lewis) also had the swimming pool enlarged, and built a warming pool, dance pavilion, and restaurant (Brown, 1977). The heated pool was located to the north of the pool and right next to a two-story building (see Figure 12). On the bottom floor of this building was the restaurant, and directly above it the dance hall. These three facilities became known as the "Vendome Complex" (Brown, personal communication, 1999). The addition of the new facilities

Compliments of Opal Brown

Figure 11
Swimmers enjoying Vendome, 1920's



Compliments of Opal Brown

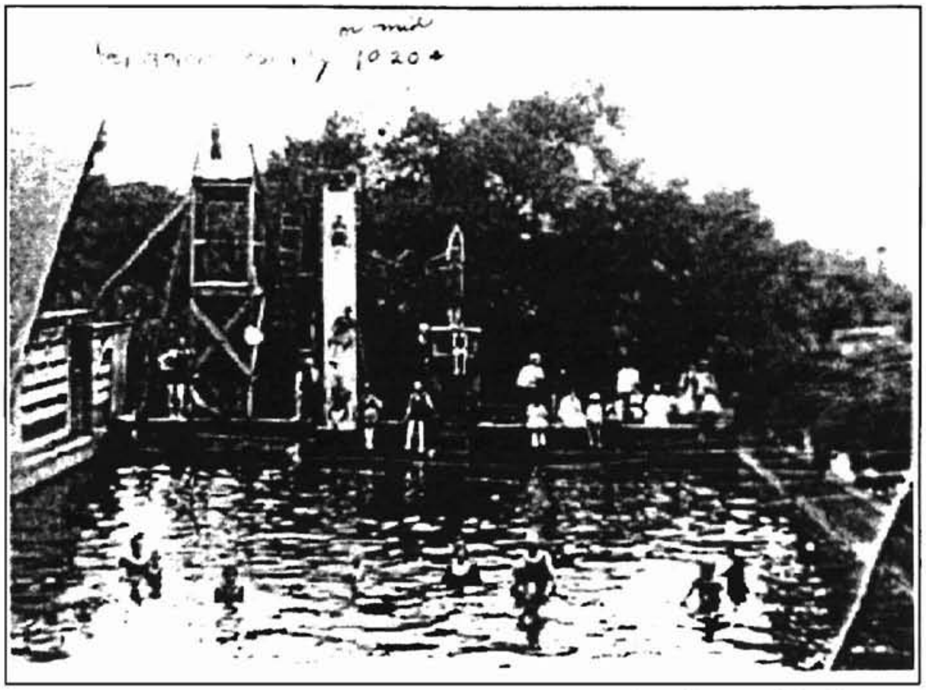
Figure 12
The Vendome Complex, 1920's

became an instant success, as large crowds soon patronized the "Vendome Complex" during the summer months (see Figure 13). The complex provided swimming activities during the day, while at night the owners brought in orchestras to play for the dances (Brown, personal communication, 1999). The "Vendome Complex" remained a popular place for much of the 1920's and continued to exist through the 1950's.

Then, sometime during the 1950's, the "Vendome Complex" burned down and was never rebuilt (Brown, personal communication, 1999). This was the beginning of the end for "The Vendome" area as a place that large crowds would frequent. Soon after the fire, the Vendome Pool was also closed down (see Figure 14). Interest in the pool subsided primarily because people realized that local creeks such as Rock Creek provided numerous swimming holes that were free of charge (Brown, personal communication, 1999). Also, at about this time, Lake of the Arbuckles was built south of "The Vendome", and undoubtedly many visitors now viewed the lake as a new area for recreation.

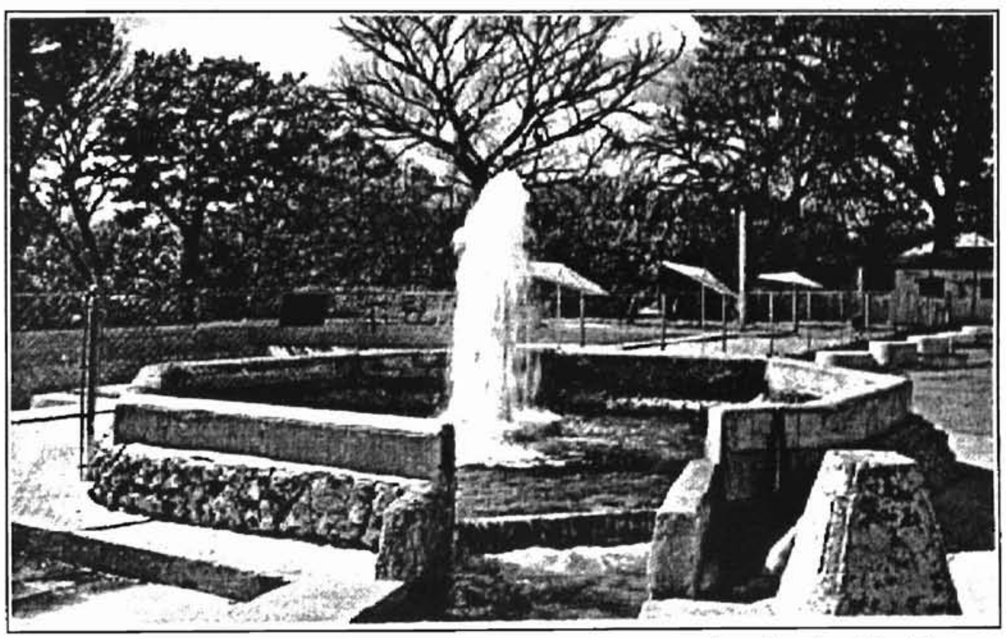
After the closing of the Vendome Complex as a social attraction, the history of "The Vendome" has been relatively quiet. Two important dates occurred in the years following the closing of the Vendome Complex. In 1983, the City of Sulphur relinquished Vendome Well and the surrounding land to the NPS. The second occurred in 1997, when Vendome Well was re-drilled and re-routed to better control the flow of water.

Today, one would not recognize "The Vendome" as a place that large crowds once frequented for entertainment. Long gone are the pool, restaurant,



Compliments of Opal Brown

Figure 13
Visitors having fun at Vendome Pool, 1920's



Compliments of Opal Brown

Figure 14
Vendome Well, 1960's

dance hall, and carnival-type atmosphere that persisted there so long ago. Although the landscape has changed quite frequently over the years, one constant has remained. Vendome Well continues to discharge its mineralized water, although at a lower flow rate, just as it did some 75 years ago. Thus, Vendome Well has become a symbolically important landmark to the local population, one which links the history and culture of the past to the present.

CHAPTER III

GEOLOGIC SETTING

Vendome Well is situated on the northern flank of the Arbuckle Uplift region, a roughly triangular uplift feature that covers approximately 720 square miles (1800 square kilometers) of south-central Oklahoma midway between Oklahoma City, Oklahoma and Dallas, Texas (Booth, 1981; Barker and Jameson, 1975). Physiographically speaking, the Arbuckle Uplift is situated between the Anadarko Basin to the northwest, Ouachita Uplift to the southeast, Ardmore Basin to the south-southwest, and the Cherokee Platform to the north (see Figure 15). Containing as much as 15,000 feet (4,500 meters) of folded and faulted sediments, the Arbuckle Uplift region preserves one of the thickest accumulations of Paleozoic sediments in the central United States (Tapp, 1997). The 1.28 billion years of geologic history preserved in the region extends from basement Precambrian granites, which make up the continental crust of the mid-continent, to relatively modern deposits in streams and rivers (Tapp, 1997).

Regional structural setting and tectonics

The Arbuckle Uplift consists of an inlier of folded and faulted Paleozoic and Precambrian rocks. Booth (1981) describes this structurally complex

Figure 15
Generalized map showing the physiographic provinces of Oklahoma (After Tapp, 1997)

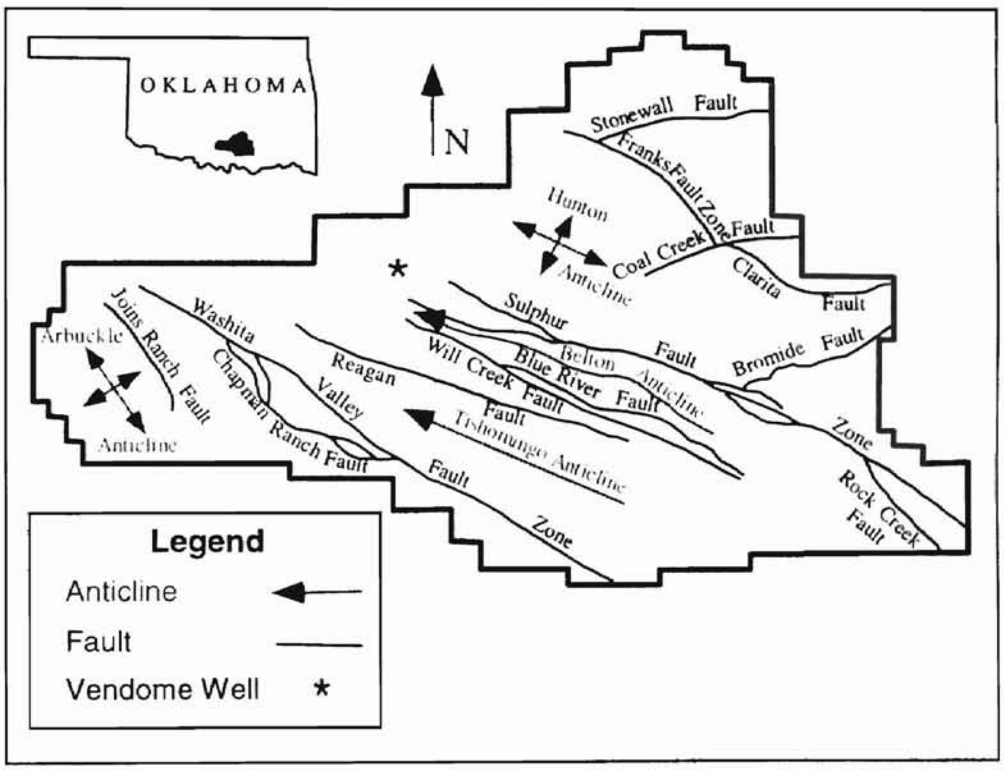


Figure 16
Tectonic map of major structural features within the Arbuckle Uplift Region (Modified after Ham, 1954)

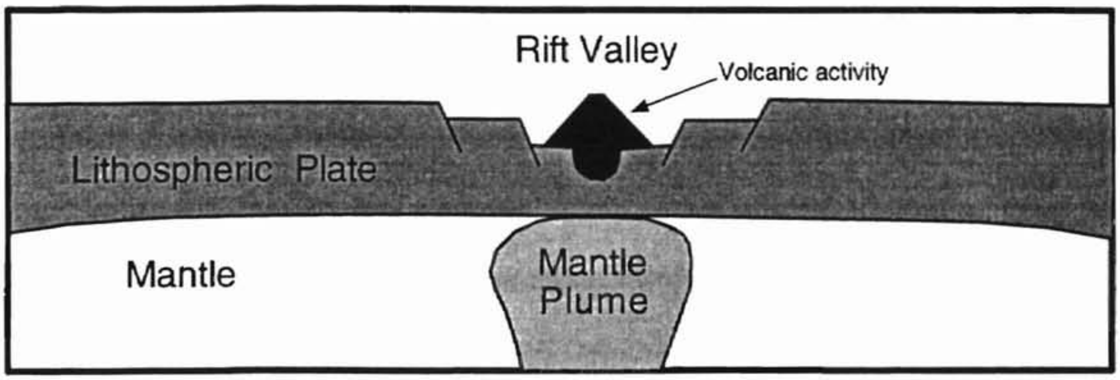
region as a prevalent northwest-southeast trending alignment of folds and faults (see Figure 16). Four major anticlines dominate folding in the region: the Arbuckle, Tishmingo, Belton, and Hunton anticlines. These anticlinal structures are separated by major faults, and three synclinal structures: the Washita Valley, Sulphur-Wapanucka, and Mill Creek synclines (Booth, 1981).

On a larger scale, the uplifted region is a major structural feature located in a series of west-northwesterly trending basins and uplifts (McConnell et al., 1990). The term Southern Oklahoma Aulacogen (SOA) was given to this alignment of uplifts and basins which span from southern Oklahoma to northern Texas (Hoffman et al., 1974). The SOA extends west-northwest from the Ouachita foldbelt, which is located in southeast Oklahoma, for approximately 435 miles (700 kilometers) into the mid-continent, through southwestern Oklahoma and northern Texas (Feinstein, 1981). Although probably a single depositional trough through Paleozoic time, the aulacogen was broken up into a series of basins and uplifts that are present today (Webster, 1980).

Aulacogens

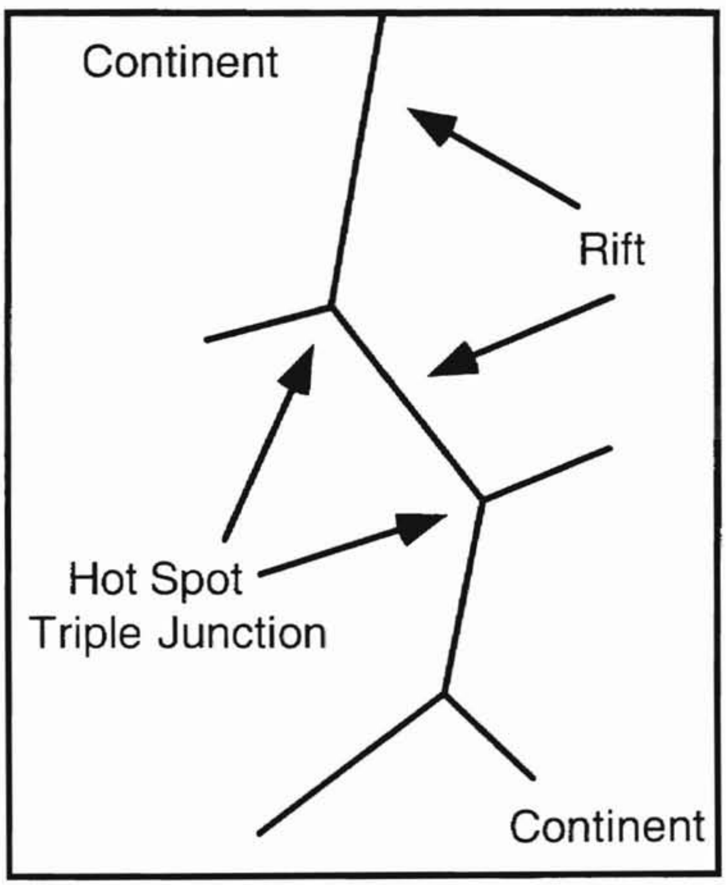
According to Hoffman, et al. (1974), Russian geologist Nikolai Shatski (1946) was the first to recognize the importance of aulacogens as tectonic structures. Shatski (1946) generally described aulacogens as a long lived, fault bounded trough in an otherwise stable platform that intersects a deformed belt or a continental margin at a high angle and contains an abnormally thick and usually undeformed section of terrestrial and marine sediments. Shatski also pointed out that the most obvious example of an aulacogen was the northwest trending Paleozoic trough that extended across southern Oklahoma (Hoffman, et al., 1974). An aulacogen within a cratonic platform is generally considered to be linked to the opening and closing of an associated oceanic basin (Hoffman, et al., 1974).

One theory for the development of aulacogens is through the concept of rift-rift-rift triple junction (Kearey and Vine, 1990). Hoffman, et al. (1974) stated that aulacogens begin as a narrow fault bound graben or rift, which extends into the craton, or stable portion of the continent, from a re-entrant or bend in a newly formed continental margin. Burke and Dewey (1973) and Hoffman et al. (1974) have suggested that continental lithosphere that is stationary with respect to the mantle, will respond in the following manner to an underlying mantle plume. Increased heat flow from the plume (hot spot) causes uplift and extension (see Figure 17). Blocks fall down along normal faults creating three rifts, which typically meet at 120-degree angles, forming a triple junction near the center of the uplift (see Figure 18). This rifting process is commonly accompanied by alkalic igneous activity. Typically, two of the three rifts continue to spread and form oceanic crust along their axes. If the sea floor continues to spread, the margins of the two rifts develop into passive continental margins. The third rift ceases to spread at an early stage, preventing the development of oceanic crust and a subsequent basin. This third arm, which is known as a failed rift, typically extends into the craton at a high angle to the developing passive continental margin, and may lead to the formation of a failed rift.



After Kearey and Vine, 1990

Figure 17
The formation of a Rift Valley



After Kearey and Vine, 1990

Figure 18
The formation of a triple-junction aulacogen

The aulacogen and passive continental margin begin to subside because of the cooling of the crust of the rift as they each move further away from the hot, spreading center. As subsidence continues, marine transgression occurs across the continental margin. Because the failed rift is a weak zone in the lithosphere, the aulacogen subsides faster than the surrounding craton, and therefore receives more sediment. These sediments typically consist of marine carbonates and sandstones, followed by marine and non-marine shale, sandstone, and conglomerate (Haas, 1981).

A number of authors (e.g., Ham et al., 1964; Ham, 1969; Prautt, 1975; Wickham, 1978; and Thompson, 1976; 1978) identified three primary stages that occur in the evolution of an aulacogen (see Figure 19). The first is a rifting stage, when uplift and graben form in association with intrusive and extrusive igneous activity. The next event is a subsiding stage, which involves rapid subsidence of the aulacogen and simultaneous accumulation of a thick sedimentary sequence. The final evolutionary event is a deformational stage, where local basins and uplifts form within the aulacogen; erosion of the uplifted areas leads to an accumulation of orogenic conglomerates. Strikingly similar present-day examples occur of each of these three stages, including the Afar region of east Africa (rifting stage), the Niger Delta region of western Africa (subsiding stage), and a deformational stage occurring in the Timor Sea between Australia and Indonesia (Thompson, 1978).

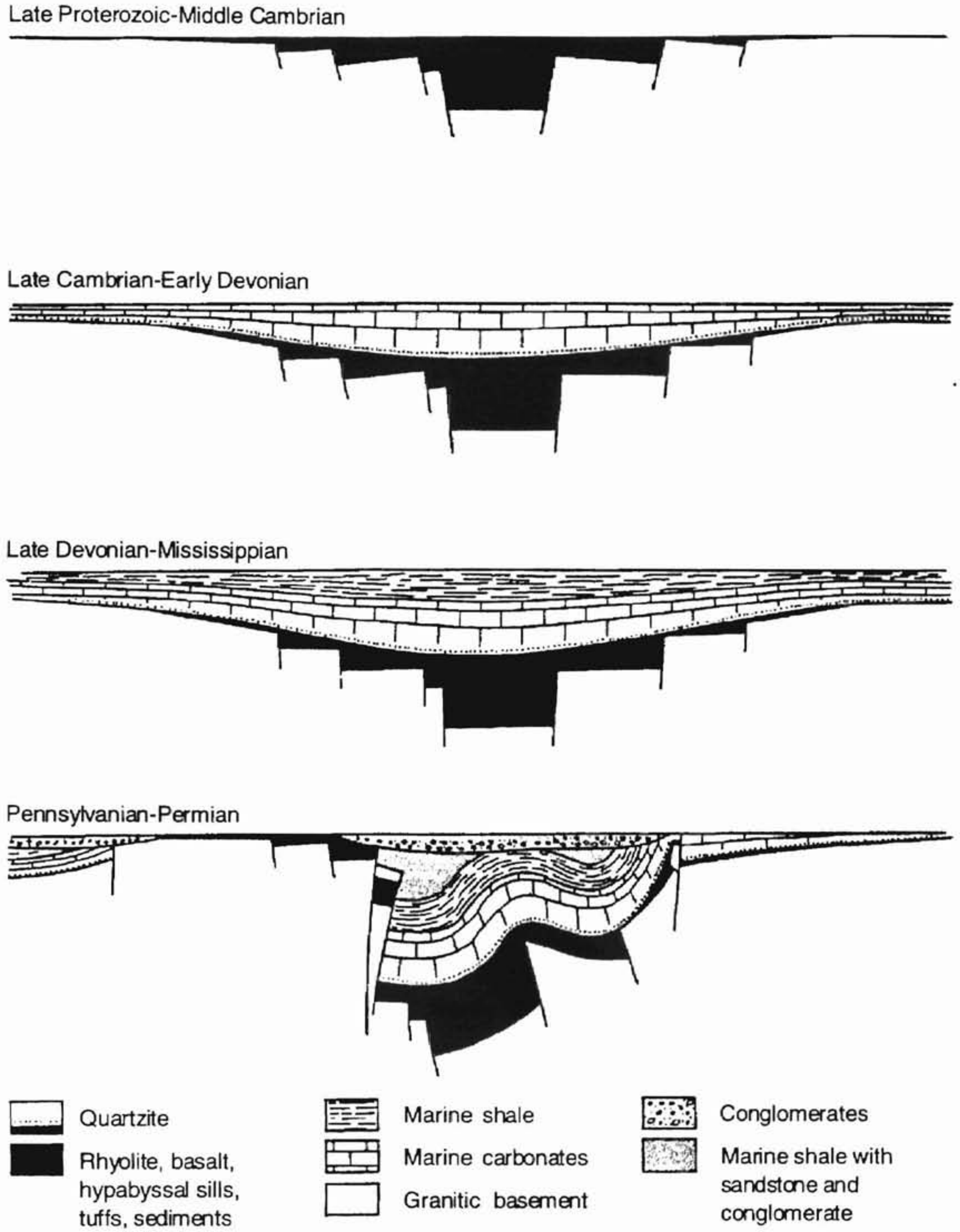


Figure 19
Schematic transverse sections illustrating the evolution of the southern Oklahoma aulacogen (after Ham, 1969)

Evolution of the Southern Oklahoma Aulacogen

The evolution of the Southern Oklahoma Aulacogen can be interpreted in terms of the three previously described stages of aulacogen development (Wickham, 1978). The first stage occurred about 565 million years ago (MYA) during the Late Precambrian to Early Cambrian and involved the formation of a fault bound rift valley, or failed arm of a triple junction (Burke and Dewey, 1973; Prautt, 1975; and Wickham, 1978). Rifting was followed during the early to middle Cambrian (525 MYA) by rhyolitic volcanism that lined the newly formed valley floors in the rifted region (Tapp, 1997). Massive rhyolite extrusions accumulated to thicknesses of as much as 4500 feet (1350 meters) in portions of the rift (Haas, 1981).

Following the initial rifting event, continued extension and cooling of the area during the Late Cambrian (500 MYA) led to subsidence of the failed rift (Axtmann, 1983). Early in the subsidence stage, the granite and rhyolite located on the floor of the rift was eroded and re-deposited. The resulting accumulation of arkosic sand (Reagan Sandstone) represents the first clastic rocks of the SOA (Price, 1997). As subsidence continued, the area sank below sea level, forming a large marine embayment, which eventually developed into a broad epicontinental sea, commonly known as the Oklahoma Basin (Wickham, 1978).

During subsidence, the aulacogen accumulated five to ten times more marine sediment than adjacent areas (Thompson, 1978). Initially, carbonate rocks dominated clastics by a ratio of six to one, as seen in the Timber Hills and Arbuckle Groups of the Upper Cambrian period (Haas, 1981). Carbonate rocks account for a large portion (80%) of the sedimentary rocks found in the region (Johnson and McCasland, 1971). Based on subsidence curves by Feinstein (1981), most of the subsidence in the aulacogen occurred during the Ordovician (460 MYA), but continued through the Devonian (400 MYA). This subsidence is preserved in the massive Cambrian-Ordovician aged Arbuckle Group, which is over a mile thick in many locales throughout the Arbuckle Uplift region. Fauna and algal plumes within the Arbuckle point towards it never being at great depths, which implies that sedimentation within the aulacogen kept pace with subsidence (Wickham, 1978). Following deposition of the Arbuckle Group, the accumulation of limestones and dolomites was occasionally interrupted by influxes of clastic materials (shale and sandstone) that can be seen in the Late Ordovician (440 MYA) aged Simpson Group. The final stages of subsidence, which occurred during the Devonian (400 MYA), were characterized by a change in sedimentation from predominantly carbonates, to the clastic dominated Woodford and Springer Formations (Booth, 1981).

The deformational stage, which consisted of two main pulses of intense deformation that occurred during the Pennsylvanian (300 MYA), had a profound effect on the SOA, and especially the Arbuckle Uplift region (Perry, 1989). Deformation may have been activated by a continent-continent collision during the Early Pennsylvanian (310 MYA) that resulted in the creation of the Ouachita foldbelt (Wickham et al., 1976). The first of these two pulses was the Wichita Orogeny of Morrowan through Desmoinesian age, which was marked by the rise of the Amarillo-Wichita Mountain horst block (Webster, 1980). Evidence of this event can be found in the present-day Wichita Mountains of southwestern Oklahoma, which are located west of the Arbuckle Uplift region in an area known as the Wichita-Criner Uplift (see Figure 15). Faulting caused by the orogeny, began, and proceeded throughout the Pennsylvanian until it ceased in the Early Permian.

The second pulse of deformation commenced during Virgilian time, and resulted in the uplifting of the Arbuckle Mountains. The Arbuckle Orogeny was characterized by large-scale strike slip faulting along pre-existing normal fault zones. This activity created strong folding, thrusting, and uplifting of fault blocks (Burke, 1977). The area was uplifted thousands of feet during the formation of the Arbuckle anticline and associated structures (Fay, 1989). A massive graben (downfallen block) developed along the northern flank of the Arbuckle anticline; large amounts of material eroded from the mountains were then deposited within the graben. The erosion of the uplifted area, which contained thousands of feet of older carbonates, resulted in a change of the Pennsylvanian (300 MYA) depositional lithology to one that was dominated by limestone conglomerates. Four principal conglomerate sequences occur within, and contiguous with the Arbuckle Mountains, and each represents erosional products derived from differing periods of the uplift (Ham, 1978).

Following the orogenic period of the Pennsylvanian (300 MYA), the Arbuckle Uplift region was emergent above sea level. Continuous erosion and weathering has slowly worn the area from the once seven thousand foot mountains into the low, rolling hills of today (Faye, 1989). Because of the uplift and deep erosional processes in the area, rocks that would normally be deeply buried are exposed at the surface (Ham, 1978). The apparent simplicity of the rolling hills belies the underlying complexity of the subsurface. This complexity includes twisted rocks, numerous faults, and other structural features such as anticlines and synclines.

Local Structural Geology

Events during Pennsylvanian time (300 MYA) resulted in severe deformation of the stratigraphy within the Arbuckle Mountains. Local geologic maps indicate that extensive deformation also occurred within the vicinity of Vendome Well (Hanson and Cates, 1994). Left-lateral strike-slip faulting is considered to have been the dominant mechanism of this deformation (Ham et al., 1964; Carter, 1979; and Haas, 1981). Geologic structure in the vicinity of Vendome Well is dominated by several northwest trending strike-slip faults. Numerous faults have been mapped in outcrops of the Arbuckle and Simpson Groups within the study area, of which there are two main faults: the North and South Sulphur Faults (Hanson and Cates, 1994). The dominant fault is the North Sulphur Fault, which can be traced from eight miles south of the City of Sulphur to about one and a quarter miles east of CNRA (Hanson and Cates, 1994). The other fault, South Sulphur, can be tracked from two and a half miles southeast of CNRA until it parallels the North Sulphur Fault (Hanson and Cates, 1994). The South Sulphur Fault, which outcrops at section 13 of township 1N-3E, can be recognized at the surface by the steeply northern dipping beds on the north side and gently dipping beds on the south side of the fault (Cates, 1989). Numerous other faults are known to exist, although fault orientation within the local subsurface is unknown (Cates, 1989).

Undoubtedly, smaller networks of fracturing (minor faults and joints) are commonly associated with major fault zones; however, the locations of these fractured areas are also unknown. Barthel's (1985) examination of lineament orientations in rocks east of Vendome Well indicated that more extensive fracturing occurred within the Arbuckle rocks as opposed to the Simpson rocks. Nonetheless, more subsurface studies will need to be conducted to get a better understanding of the overall structural complexity of the local geology.

CHAPTER IV

HYDRO-STRATIGRAPHY

Of the numerous geologic units found in the region, three principal units (Vanoss Formation, Simpson Group, and Arbuckle Group; see Table 1) are believed to dominate subsurface flow in the vicinity of Vendome Well (Cates, 1989; Hanson and Cates, 1994). The aquifer which supplies water to Vendome and the surrounding area, known as the Arbuckle-Simpson aquifer, derives its name from the two geologic units of which it is comprised (Hanson and Cates, 1994). The primary permeable layers of interest include the carbonate-dominated Arbuckle and Simpson Groups, which are thought to be tilted in the subsurface beneath Vendome Well (see Figure 7). The area surrounding Vendome is capped by a limestone conglomerate with alternating strata of shale and sandstone, known as the Vanoss Formation. This chapter summarizes existing information on the lithologic and hydrologic properties of the three stratigraphic units that are believed to make up the aquifer system located beneath Vendome.

Table 1
Geologic Formations

Rock Unit	Age (MYA)	Description
Vanoss Formation	Pennsylvanian (320-280 MYA)	Limestone conglomerate
Simpson Group	Ordovician (500-430 MYA)	Limestone, sandstone, and shale
Arbuckle Group	Cambrian-Ordovician (4600-500 MYA)	Dolomite, limestone, and sandstone

Hanson and Cates, 1994

Vanoss Formation

The Vanoss Formation is the predominant surface rock in the area surrounding, and including Vendome Well. This low conductivity unit acts as a cap rock or confining layer to the underlying aquifer. The Vanoss Formation consists of a lower conglomerate member and an upper shale member (Ham, 1954). The conglomerate member has low permeability, and is resistant to weathering. It is commonly described as a gray limestone boulder and cobble conglomerate containing thin lenses of pebbles and granules that allow the massive bedding to appear (Dunham, 1955). The upper shale unit is described as "dull red or light green, blocky, and calcareous, with its color varying from one location to the next" (Dunham, 1955). The moderately thick formation ranges up to a thickness of 1550 feet; the maximum thickness of the conglomerate member of the formation generally is about 650 feet (Barthel, 1985).

The locally restricted Vanoss Formation, found on the northern edge of the Arbuckle Mountains, was formed as a result of orogenic processes that occurred during the middle and late Virgilian (Pennsylvanian) aged Arbuckle Orogeny

(Ham, 1978). Following the uplift, long-term erosion occurred in the uplifted area, and much of the eroded sediment was deposited into the lower lying elevations. Although most of the Vanoss stones and cobbles are derived from the carbonate Arbuckle Group, the formation does contain feldspar and granite fragments, with the oldest fragments found within the unit being derived from the Cambrian Reagan Sandstone (Dunham, 1955).

The importance of the Vanoss Formation to the aquifer system is primarily as a confining layer to the Arbuckle-Simpson aquifer located beneath the formation. The Vanoss acts as a cap rock to the aquifer because it is relatively impervious. This formation is much less permeable than the underlying units because it is relatively unfractured (therefore it has less secondary porosity). Its unfractured nature is presumably a result of being deposited during the Arbuckle Orogeny (Pennsylvanian time), and hence it was subjected to less post-depositional tectonic activity than the older units (Arbuckle and Simpson Groups).

Simpson Group

This carbonate-dominated group of Ordovician age is located beneath the Vanoss Formation, and makes up the upper portion of the Arbuckle-Simpson aquifer. The group is recognized as an extremely variable formation and consists not only of many large limestone, sandstone, and shale members, but also of large bodies of rock with thin successions of alternating shales, limestones, and sandstones (Decker and Merritt, 1931). The Simpson is officially considered to be comprised of five divisions, which include in ascending order, the Joins, Oil Creek, McLish, Tulip Creek, and Bromide Formations (Bauer, 1990). Each of the five formations represents a complete sedimentary cycle (Decker and Merritt, 1931). These five formations are each described as having a basal sandstone, ranging from 50 to 350 foot intervals, located at the bottom of the four upper formations and a conglomerate at the base of the lowest formation (Decker and Merritt, 1931). These basal sandstones represent the largest single influx of clastics during this time (Haas, 1981). Thickness estimates of the Simpson Group by Barthel (1985) generally vary from 600 to 1600 feet; however Ham (1978) indicated that some outcrops of the Simpson have a thickness of as much as 2300 feet.

The Simpson Group represents a time during the Ordovician when clastics were introduced intermittently between times of carbonate deposition within the oceanic trough known as the Southern Oklahoma Aulacogen. Sedimentation consisted of limestone that was interbedded with periods of shales and sandstones on the aulacogen margin and craton, and graded into deeper water limestone with interbedded shale and sandstone toward the aulacogen trough (Haas, 1981).

Arbuckle Group

This Group, which is of Upper Cambrian to Middle Ordovician age, is the oldest of the three strata discussed, and comprises the lower portion of the Arbuckle-Simpson aquifer. The Arbuckle Group is another highly variable group with stratigraphic characteristics that change from formation to formation. Six formations that are recognized within the Arbuckle Group, which include in ascending order: the Fort Sill, Signal Mountain, McKenzie Hill, Cool Creek, Kindblade, and West Spring Creek (Ragland and Donovan, 1991; Wilson et al., 1991). For the most part, the Arbuckle is dominated by carbonates (both limestones and dolomites). Hanson and Cates (1994) describe the Arbuckle Group as extensively folded and faulted dolomitic limestone and some sandstone. The Arbuckle Group is a massive unit that is estimated to be over a mile (5280 feet) thick, and as much as 8,000 feet in some locales (Gould, 1925; Decker 1939; and Wilson et al., 1991).

The Arbuckle Group and its equivalents (names of the Group vary regionally) underlie a broad range of area throughout Oklahoma and surrounding states; however, most of its outcroppings and enormous thickness occur within the Arbuckle Uplift region (Johnson, 1991; Wilson et al., 1991). The Arbuckle Group represents a depositional environment of the Late Cambrian to Middle Ordovician in which enormous amounts of shallow marine carbonates were deposited within a deep subsiding trough (known as the Southern Oklahoma Aulacogen) on the southern edge of the North American craton.

Characteristics of carbonate aquifers

The Arbuckle and Simpson Groups are the two geologic units in the local subsurface that act as a conduit to the flow of water. To be considered an aquifer, a geological formation must be both porous and permeable (Manning, 1997). Porosity refers to the voids in a rock, expressed as a fraction or percentage of the bulk volume. Permeability is the capacity of the rock to transmit water (Jennings, 1971). Thus, the degree of porosity and permeability in an aquifer is important in the storage of water within the aquifer, and in determining the ability for water to flow, the direction it will flow, and how fast it will move through the aquifer. In large part, these factors are determined by the lithologic and structural characteristics of the geological units that make-up the aquifer (Fairchild et al., 1990).

Aquifers can occur in almost any earthen material, provided that the material is porous and permeable to water. Aquifers are commonly found in sedimentary rocks, which are formed when sediment or chemical precipitates are deposited, buried, and then compacted into consolidated rock. Following sandstones, carbonates (limestones and dolomites) are the most valuable water-bearing formations among the consolidated rocks (Kazmann, 1972). The majority of the permeable material for the aquifer is located in the carbonate rocks of these two localized rock units (Arbuckle and Simpson Groups).

When clastic sediments are compacted and formed into consolidated rock, void spaces occur between the packing of the sediment grains. These initial void spaces are known as primary porosity (see Figure 20a-d). Void space can also be created after the rock has already been lithified. This void space, which is known as secondary porosity (see Figure 20e-f), usually results from the formation of structural features such as fractures, or through removal of minerals by solution (Bates and Jackson, 1984). Secondary porosity commonly

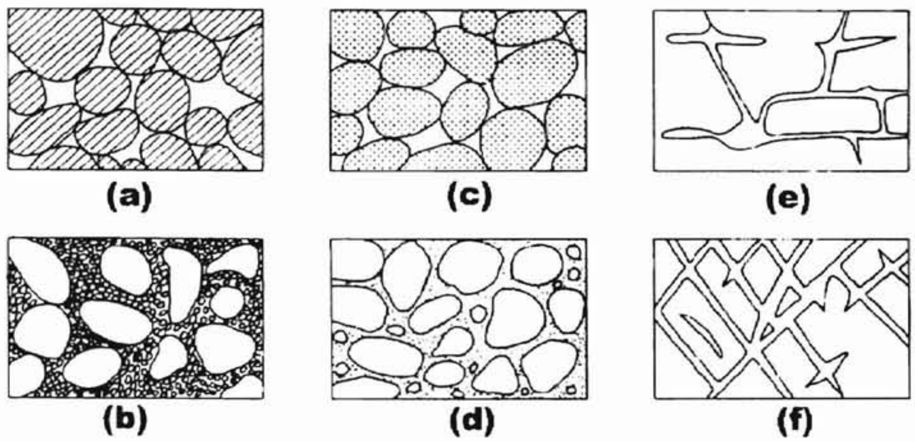


Figure 20
Primary vs. Secondary porosity.

(a-d) Primary porosities. (e-f) Secondary porosities.

(a) Well-sorted sedimentary deposit having high porosity; (b) poorly sorted sedimentary deposit having low porosity; (c)well-sorted sedimentary consisting of pebbles that are themselves porous, so that the deposit as a whole has a very high porosity; (d) well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices; (e) rock rendered porous by solution; (f) rock rendered porous by fracturing (after Meinzer, 1923) determines the water-bearing characteristics of carbonate aquifers, such as the Arbuckle-Simpson.

Limestone is composed mainly of calcium carbonate ($CaCO_3$), which is formed by precipitation from natural waters, or by organic processes involving lime-secreting animals such as plankton, algae, corals, and shellfish (Manning, 1997). Limey deposits often have high original porosities (primary porosity), but as they are changed to sedimentary rock during compaction, the rock often becomes more dense and hence less porous. Limestone usually has a low primary porosity; therefore, this lithology owes most of its hydrologic properties to secondary porosity, which can be increased through the solubility of $CaCO_3$ into water.

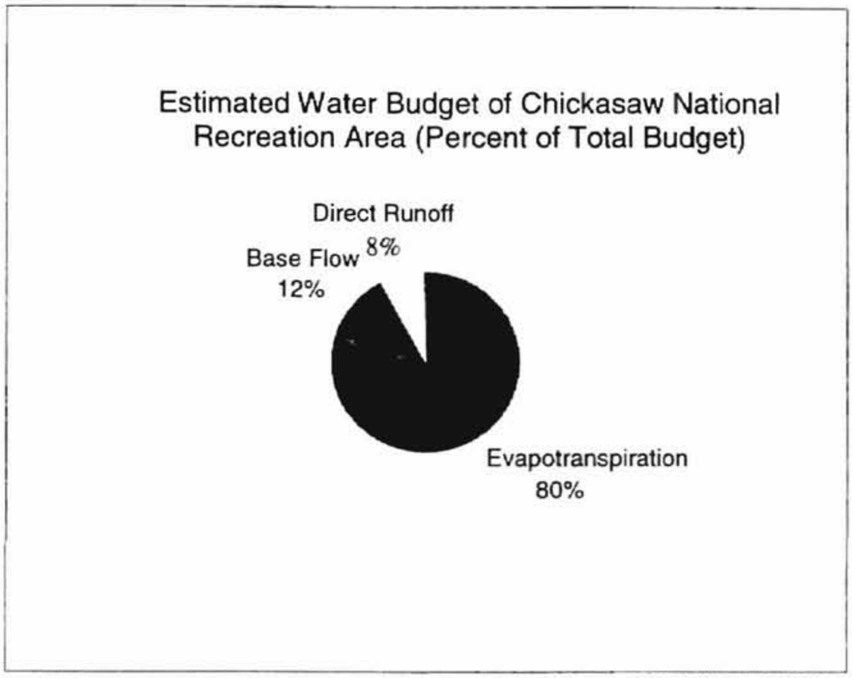
The other prominent carbonate rock is dolostone, which is commonly referred to as dolomite and has a variable formula of: $(Ca, Mg)_2 (CO_3)_2$. Under certain conditions, some of the calcium in limestone is replaced by magnesium from seawater, occurring either during deposition, or after the rock has been deposited (Driscoll, 1986). It is not known with certainty how this process (dolomitization) transpires; however, the addition of small amounts of magnesium causes a pronounced toughening (tightening) of the rock (Driscoll, 1986). Like limestone, flow within dolomite is also primarily through secondary porosity, however, dolomite is less soluble in water than limestone.

The dissolution of $CaCO_3$ in a carbonate aquifer such as the Arbuckle-Simpson would occur as follows. The process begins when precipitation seeps into the aquifer outcrop area (recharge zone) and then moves down into cracks within the carbonate rocks. Cracks typically form in carbonate rock as a result of folding and faulting such as that occurring during the Arbuckle Uplift (Fairchild et al., 1990). Rainwater nearly always carries Carbon Dioxide (CO_2) that is derived from the atmosphere, soil, and vegetation (Manning, 1997). Because of its CO_2 content, the slightly acidic groundwater dissolves some of the $CaCO_3$ as it passes through the rock, thus enlarging the water pathways. Over long periods of time, large volumes of rock can be removed and carried away by the groundwater (Fairchild et al., 1990). Water derived from a carbonate aquifer is typically "hard", or in other words, it contains significant amounts of bicarbonate ions dissolved from the host rock. The water that flows from Vendome displays a mineralized content which is typical of water that is derived from a carbonate source, such as the Arbuckle and Simpson Groups (Hanson and Cates, 1994).

Site Specific

The Arbuckle region has been subjected in the past to periods of faulting and folding. In the vicinity of Vendome Well, early geologic evidence suggested that the two primary hydrologic units, the Arbuckle and Simpson Groups, were dipping beneath Vendome (Cates, 1989). These two hydrologic units are covered in the area surrounding Vendome by the conglomeratic Vanoss Formation, although evidence from Cates (1989) and this study suggest that only the Arbuckle resides beneath the Vanoss at Vendome. Nonetheless, in the area to the east and southeast of Vendome, the Vanoss Formation has been eroded (truncated) leaving the porous Arbuckle and Simpson Groups exposed at the surface. This outcrop area is believed to be the source for inflows to the Arbuckle-Simpson aquifer system, whereby acting as a recharge zone to the aquifer as precipitation hits the outcropped area and infiltrates down into the aquifer (Fairchild et al., 1981). Not all precipitation hitting the outcrop actually permeates into the Arbuckle-Simpson aquifer. A local hydrologic budget, prepared by Fairchild et al. (1981) estimated that of the 38.4 inches of average annual precipitation, 80% is lost to evapotranspiration, which is the loss of water from evaporation or plants (see Figure 21). Of the remaining 20% that hits the outcrop area, 12% goes to recharging the aquifer, while the remaining 8% consists of direct runoff into streams following precipitation events (Fairchild et al., 1981).

Because of the diversity of rock forms and the subsequent differing susceptibleness to erosion, the area surrounding Vendome is commonly regarded as "hilly". Generally speaking, the erosion-resistant sandstone rocks form topographic highs, while the less resistant carbonates and clays form topographic lows (Sallee and Schoneweis, 1997). Local topography is important to understanding the Arbuckle-Simpson aquifer system. In general, inflows to the aquifer occur in recharge areas that are topographically high and outflows persist in discharge areas that are topographically low (Fairchild, et al., 1981). For instance, topographically low discharge areas primarily occur at locales of creeks and streams, which are sustained throughout the year by groundwater discharge from springs (Fairchild et al., 1981).



Source: Fairchild et al., 1981

Figure 21
Hydrologic Budget

Once water infiltrates into the Arbuckle-Simpson aquifer, it is believed to flow primarily along a network of faults and fractures (Fairchild et al., 1990). The period of time it takes for water to pass through the Arbuckle-Simpson aquifer system is presently unknown. Water in a typical aquifer system can take a fairly long period of time (decades) to move through the system. This time period is dependent on many complicated factors such as lithology, interconnectiveness of the flow network, pore space, and hydraulic gradient.

Just as water flows into the Arbuckle-Simpson aquifer system, it must eventually be released. Outflows from the Arbuckle-Simpson aquifer occur wherever a fissure (fracture or fault) occurs that reaches vertically through the cap rock (Vanoss Formation) to the surface (Fairchild et al., 1981). The pressure on the water in the aquifer is great enough that at many locations water will flow freely up to the surface through these fissures. Evidence of this outflow from the Arbuckle-Simpson aquifer can be witnessed by the numerous flowing natural springs and wells that dot the landscape in the area.

The occurrence and movement of groundwater in the Arbuckle-Simpson aquifer are strongly controlled by lithology and structure (Fairchild et al., 1990). Associated with major fault zones in the region are numerous minor faults and joints that occur in the more dense beds, such as the Arbuckle Group carbonate (limestone and dolomite) rocks (Fairchild et al., 1990). This results in an irregular network of openings of all sizes and shapes, making the prediction of water flow quite difficult. Thus, a well such as Vendome, must hit one of these vertical or lateral water-bearing channels to produce water (Kazmann, 1972). Evidence proves that such is the case at Vendome, as both times the well has been drilled (1922 and 1997), the well remained essentially dry until a productive zone was encountered, and water immediately gushed to the surface. When Vendome was re-drilled in 1997, evidence of the importance of vertical or lateral water-bearing channels to the well were documented in notes (see Appendix A) taken by an on-site NPS hydrogeologist, Mr. Paul Christensen.

As mentioned, lithology also plays an important role in the movement of water in the Arbuckle-Simpson aquifer. Although the aquifer is primarily (approximately two-thirds) composed of carbonate rock, the two groups (especially the Simpson Group) are interbedded with sandstones and shales as well (Fairchild et al., 1990). These interbedded lithologies have different porosity and permeability characteristics than the surrounding carbonate rock, which may also influence groundwater movement in the aquifer. Shale usually has a much lower permeability than sandstones and carbonates; thus, interbedded layers of shale in the aquifer may restrict groundwater flow. When you combine the complexities of the lithology with that of the structure, it makes it very difficult to determine the exact mechanism for water movement within the aquifer system.

CHAPTER V

INFERENCE OF SOURCE ROCKS

As groundwater passes through an aquifer, solid materials may dissolve into the water. Most of the dissolved matter in water originates from solution of the rocks through which the water has moved (Fairchild et al., 1990). The amount of dissolved matter in the water depends on the physical and chemical characteristics of the original water, the petrologic make up of the rocks, and the length of time that the water has been in contact with the rocks (Fairchild et al., 1981).

Background

The initial composition of groundwater originates from rainfall, which may be considered to be diluted seawater (Hounslow, 1995). During its return path to the sea, water composition is altered by rock weathering, evaporation, biological activity, and aeration. During weathering, differing amounts of Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sulfate (SO_4^{2-}), Bicarbonate (HCO_3^-), Silicate (SiO_2), and other substances are dissolved into the water (Hounslow, 1995). The amount and types of dissolved ions is directly dependent on the mineralogy of the rocks that come into contact with the water. In many cases, the minerals from source rocks may be deduced from the water composition, a technique which is known as source-rock deduction (Hounslow, 1995). Using this technique, dissolved minerals found in water flowing from Vendome Well lend support to the type of geologic setting from which the water originates.

Regional Evidence

Numerous springs and wells dot the landscape surrounding Vendome, all of which are believed to receive flow from the Arbuckle-Simpson aquifer. To better understand the origin of the groundwater in the area, several previous studies have investigated the water-quality characteristics of local streams, lakes, springs, and wells (Gould, 1906; Gould and Schoff, 1939; Cumiford, et al., 1968; Streebin and Harp, 1977).

A study performed by D.L. Hart was of particular interest. Fairchild et al. (1981) summarized water-quality data collected from several springs and wells in the area using a report that had been prepared by D.L. Hart. Hart plotted hydrochemical data from springs and wells on Piper and Stiff diagrams, which are graphical methods used to show the relative amounts of anions and cations in solution. He observed that several groups of springs and wells displayed nearly identical water-quality characteristics (see Figures 22-27). Based on similarities in water-quality, Hart placed the springs and wells into three groups. Using information on the geological make-up of the Arbuckle and Simpson Groups, Hart was able to identify likely source rocks for each of the three groups.

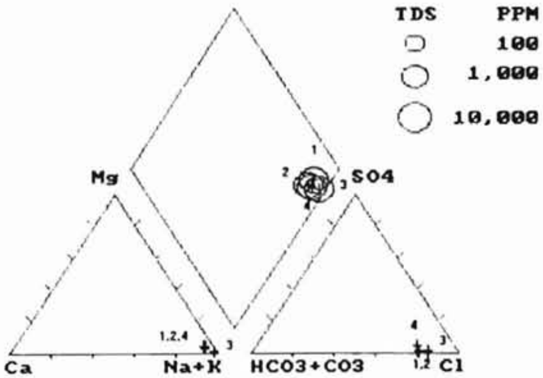


Figure 22
Piper Diagram
of the Simpson Group

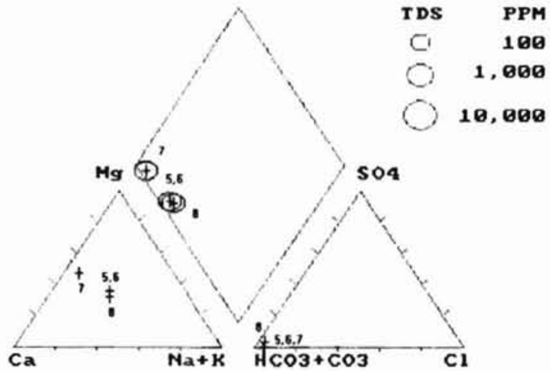


Figure 23
Piper Diagram
of the Arbuckle Group

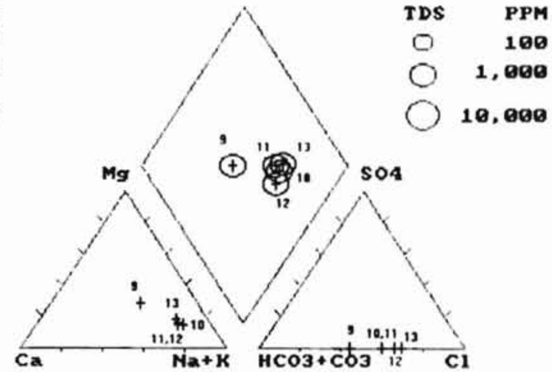


Figure 24
Piper Diagram
of the Arbuckle-Simpson Mixture

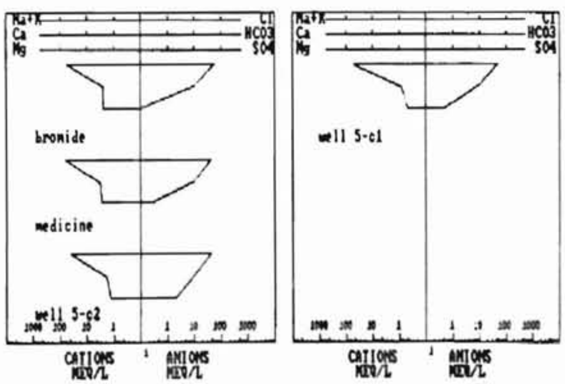


Figure 25
Stiff Diagram
of the Simpson Group

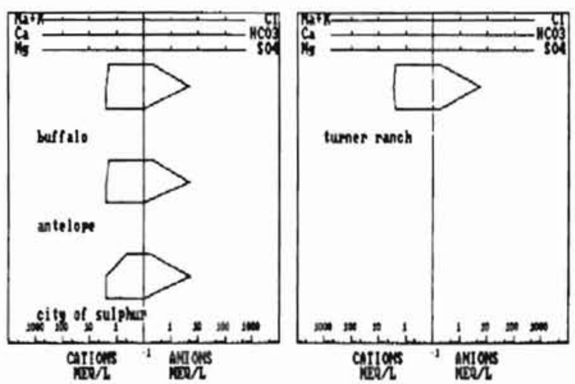


Figure 26
Stiff Diagram
of the Arbuckle Group

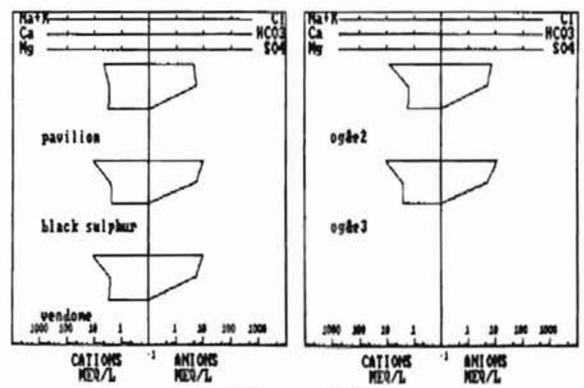


Figure 27
Stiff Diagram
of the Arbuckle-Simpson Mixture

Source of diagrams. Hanson and Cates, 1994.

The first group of springs and wells is thought to be derived from the Simpson Group (Hanson and Cates, 1992). This groundwater is generally described as being "highly mineralized", with a Total Dissolved Solids (TDS) content that is characterized as very high, having more than 4000 milligrams per liter (Mg/L). The high TDS content and high levels of bicarbonate, sodium, calcium, and sulfate indicate that the water is derived from a carbonate aquifer. Chloride and sodium concentrations are high enough to suggest that a saline source, which is presently unknown, exists.

The second group of springs and wells is thought to be derived from the Arbuckle Group (Hanson and Cates, 1992). This group contains water that is characterized as being "extremely clean", meaning that it has a low TDS content as compared to other springs and wells in the area (Hanson and Cates, 1992). The water is a calcium-magnesium-bicarbonate type and has a TDS content of approximately 300 mg/L. This suggests that the water is derived from the Arbuckle Group, because the group is composed primarily of limestone and dolomite rocks (Hanson and Cates, 1992).

The last group of springs and wells (including Vendome) with similar water chemistries is thought to be derived from a mixture of the Arbuckle and Simpson Groups (Hanson and Cates, 1992). A primary reason that this group is considered to be a mixture of waters from the Arbuckle and Simpson Groups is that the group displays water-quality characteristics that are intermediate to the levels seen from the other two groups, with a TDS falling between that of the Simpson Group and that of the Arbuckle Group. Members of this group have moderate TDS contents ranging from 600-1200 mg/L, which is between the TDS value of approximately 300 mg/L for the Arbuckle characteristic water and approximately 4000 mg/L for Simpson water. Also, the presence of bicarbonate, calcium, and magnesium ions indicate carbonate dissolution, which would be consistent with water derived from an Arbuckle-Simpson mixture. Because of the lack of geological studies in the area, the mechanism for the mixing of water between the two source rocks is presently unknown. One possibility, however, could be as a result of fault(s) that transverse the two units in the subsurface and allow for mixing of the groundwater (Hanson and Cates, 1994).

Vendome Well

In the Fall of 1993, water quality samples were collected for numerous springs and wells in the area by the Environmental Protection Agency (EPA). The samples were sent to ManTech Environmental Technology for measurement of ion chemistry; data from Vendome Well (Table 2), suggest that the water is derived from a carbonate source.

The first type of evidence from the analysis pertains to the conductivity of the water. Conductivity is the reciprocal of the resistance in ohms between the opposite faces of a 1-cm cube of an aqueous solution at a specified temperature (usually 25 degrees Celsius) and has units that are called mhos (Hounslow, 1995). In the 1993 analysis done by ManTech Environmental Technology a TDS reading was not taken, but instead a conductivity of 2330 micromhos was

Table 2
Selected water quality data from Vendome

Water Quality Test	Measurement
pH	7.42
Conductivity	2330 μmhos
Bicarbonate	394 mg/L
Calcium	86.1 mg/L
Chloride	572 mg/L
Magnesium	39.3 mg/L
Sodium	323 mg/L

determined, which is considered to be a high reading. According to Hounslow (1995) conductivity is a good estimator of TDS because TDS in mg/L is proportional to conductivity in micromhos. It seems logical that some of the high conductivity reading results from carbonate dissolution, however, a large portion must be attributed to the high sodium chloride concentrations found in the water.

The next type of evidence from the analysis pertains to the types and amounts of ions that were found in the water. Of particular interest are the high concentrations of calcium, magnesium, and bicarbonate, which indicates that the water is of a calcium-magnesium-bicarbonate type (Fairchild et al., 1981). These concentrations are important because such ions usually indicate a carbonate source. Water from Vendome showed a high concentration of calcium (86.1 mg/L), which suggests that the water passed through limestone rocks. Magnesium also showed a high concentration (39.3 mg/L), indicating that the water came into contact with a magnesium source on its journey to the surface. Hounslow (1995) notes that the most common source of large quantities of magnesium in natural waters is dolomite $(Ca, Mg)_2 (CO_3)_2$. According to Ham (1955), rocks of the Arbuckle Group are mostly limestone in the western portions of the Arbuckle Mountains, but mostly dolomite in the east and northeast parts of this area (the locale of Vendome Well). Another ion that showed a high concentration was bicarbonate (394 mg/L). Bicarbonate is formed when carbon dioxide and water react with various minerals in a process called acid hydrolysis (Hounslow, 1995). When considerable amounts of bicarbonate is found dissolved in water, such as in the case at Vendome, the likely source is carbonate rock.

Other evidence from the water quality analysis performed in 1993 can be used to examine acidity. The pH scale for acidity (see Figure 28) ranges from 0 (maximum acidity) to 14 (maximum alkalinity), or from highly acidic to highly basic. The water sample taken from Vendome Well indicated a pH of 7.42. This is significant when the following is considered. First, normal rain has a pH of 5.6, which is slightly acidic as a result of the carbon dioxide picked up in the atmosphere of Earth (LeMay et al., 1990). It can be logically assumed that the water derived from Vendome falls directly onto the outcrop and subsequently flows through the aquifer. Therefore, something from within the aquifer must be dissolving into the water, causing the rise in pH from 5.6 to 7.42 as it flows from Vendome (see Figure 29). This increase of nearly two integers on the pH scale is significant because the pH scale is logarithmic, meaning that an increase of two indicates a pH that is nearly 100 times more basic (see Figure 29). A likely source for this rise in the pH level would be a high concentration of bicarbonate

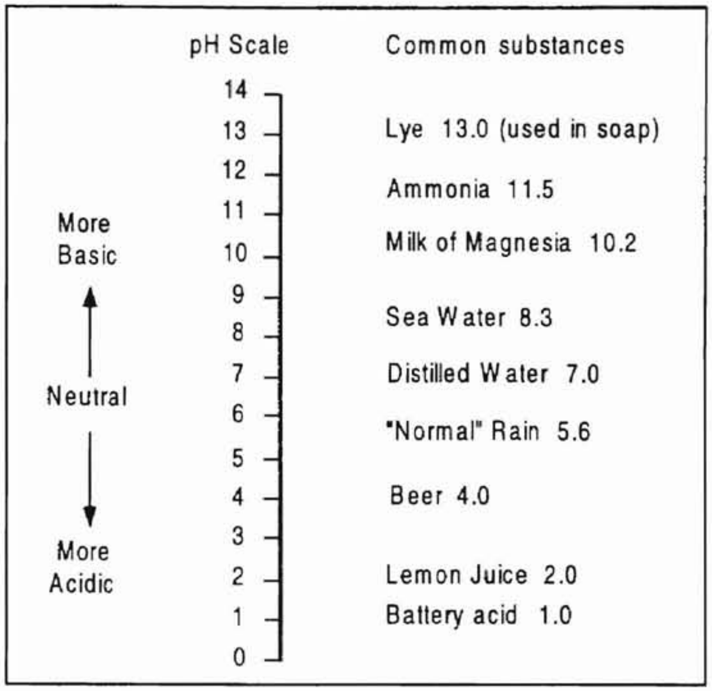


Figure 28
pH scale and correspnding values of common substances

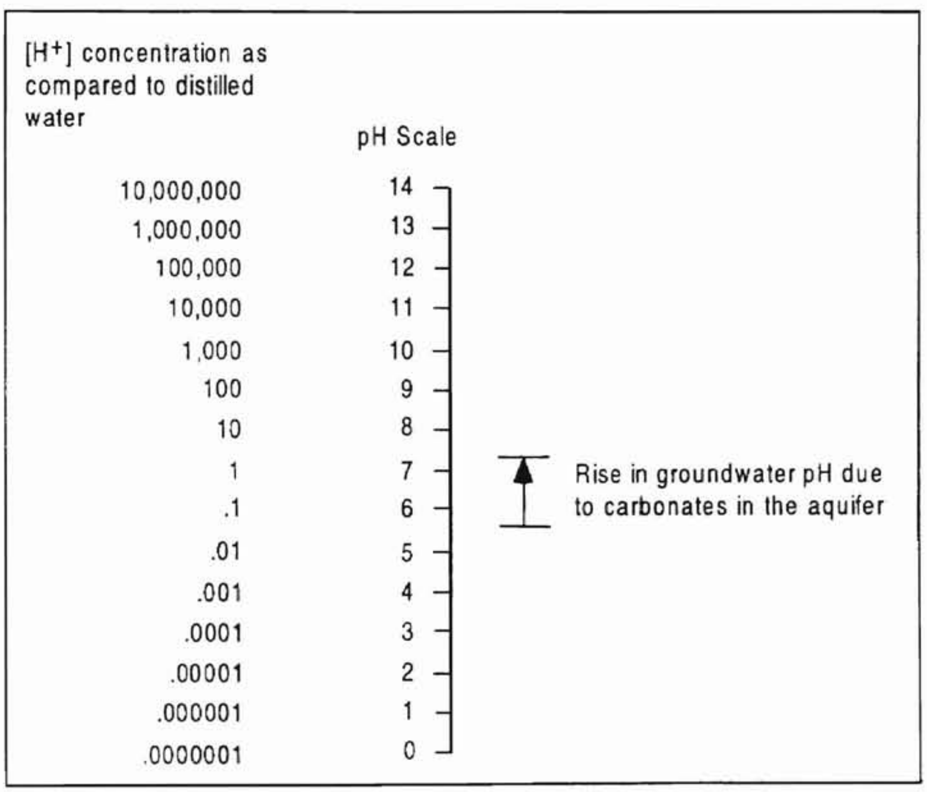


Figure 29
pH scale and comparitive hydrogen ion concentrations

(HCO_3^-) ions that have been dissolved into the water. Carbonate is highly basic, and acts to neutralize acids (Hydrogen ions) in water, thus raising the pH of the water. The most likely source of the HCO_3^- in the subsurface would be as a result of water flowing through a carbonate aquifer.

The final evidence to indicate the origins of the water at Vendome are Total Dissolved Solids (TDS). TDS is the total amount of ions that are dissolved into the water sample (Hounslow, 1995). TDS is calculated by adding the mass of ions plus silicate (SiO_2) and is usually measured in milligrams per liter (mg/L). From previous samples collected at Vendome the water had a TDS of 1200 mg/L (Hanson and Cates, 1994). According to source-rock deductions done by Hounslow (1995), a water sample that is higher than 500 mg/L indicates "carbonate weathering, brine, and/or seawater". Although a carbonate source undoubtedly contributes to the high TDS levels, it does not account for such a high amount. This fact, along with the high sodium (Na^+) and chloride (Cl^-) concentrations found in the water, indicates that a sodium chloride source exists, which at this time is presently unknown.

The water quality evidence provided in this section, when combined, suggests a likely source of the water derived from Vendome. The water is believed to be from a carbonate source, which most likely would be from the Arbuckle and Simpson Groups. The relatively low amount of TDS with respect to other springs in the area and the presence of magnesium would be consistent with water from dolomitic rocks of the Arbuckle Group.

CHAPTER VI

WELL CUTTINGS

In the Fall of 1997, the NPS authorized the re-drilling and re-routing of Vendome Well. During the re-drilling process, two primary sources of geologic information were collected. The first was well cuttings, which are the fragmental rock samples broken or torn from the rock penetrated during drilling. These fragmental pieces of rock were collected by the drilling company and stored by CNRA Management in sample bags for future study. With the cooperation of CNRA and the NPS, I was able to obtain these samples in the Spring of 1999. The second source of data was from Paul Christensen, a NPS hydrogeologist who observed and took notes at the time of the drilling (see Appendix A). This chapter focuses on lithologic information obtained from the well cuttings.

Preparation of the well cuttings

Once the well cuttings were obtained from CNRA, organization became the first objective. First, the bags needed to be laid out and organized by depth; cuttings were originally collected over five foot intervals, i.e. 0-5, 5-10, 10-15....and so on. The cuttings, which were approximately 1/8 of an inch in diameter, were then placed into black sample trays, each of which had ten compartments. A total of 16 trays were required to hold the entire section of 775 feet. Because many of the samples were covered in drilling mud, each sample was cleaned by placing it in a mesh strainer and rinsing it with water.

Limitations

Prior to describing the well cuttings, it was important to consider some of the limitations that can occur when using well cuttings to describe the lithology of a section. In the petroleum industry, a geologist normally has a core (fully intact section of rock) from which to describe a particular zone of interest. When drilling water wells, however, it is uncommon to take core because cuttings are much cheaper to obtain.

Interpretations of cuttings are limiting for various reasons. Cuttings do not give an accurate visual representation of a borehole like a core would provide. Characteristics such as sedimentary structures are destroyed when the rock is broken up. Secondly, cuttings make it difficult to determine some of the petrologic characteristics of the rocks. Larger petrologic features are broken up during the drilling process and can no longer be witnessed. This makes it difficult to determine the depositional environment using cuttings. Especially pertinent to this investigation was that the size of the cuttings made it infeasible to find allochems (fossils, peloids, ooliths, limecasts) within the carbonate samples. This is significant because allochems can be used to more accurately describe carbonates.

The last few limitations of cuttings arise from problems that can occur during the drilling process. Because cuttings are not intact like core, the reliability of the section is only as good as the accuracy in which the cuttings are brought to the surface, and subsequently stored. One source of error to consider is the lag time (of at least 10 minutes) between when a section of rock is drilled, and when the chips come to the surface. This "lag time" can result in confusion as to the actual depths of the cuttings (Silver, 1978). Another problem occurs with the mixing of cuttings from different depths. This can occur in many ways such as during the caving-in of rock from higher sections. Conversely, sections of rock can be lost to underground caves connected to the drilled hole (Silver, 1978). Also, cutting density and shape can affect transport to the surface, which may lead to mixing. One last possible source of problems relates to human errors, such as mis-marked samples. Some of the limitations of cuttings may be overcome through correlation to well logs. It was determined that mechanical logs were performed once on Vendome Well, however, it was performed on the original pipe system and only to a minimal depth. These logs will be discussed later in this chapter.

Description of the well cuttings

After considering all the limitations and restrictions of describing well cuttings, the two main objectives to be derived from the well cuttings were to:

1) Determine the lithology of the section beneath Vendome
2) Identify the stratigraphic formations present

The following paragraphs are a general description of the well cuttings from Vendome. A more detailed summary of the lithology of the section can be found within a petrologic log located in Appendix B.

The soil zone has a depth of approximately five feet; immediately below, one encounters the hard conglomerate of the Vanoss Formation. The Pennsylvanian-aged Vanoss Formation was a chief depositional product of the Arbuckle Orogeny. Following the uplifting of the area during this orogenic event, carbonates were eroded into low-lying areas (Ham, 1969). Such was the case with the Vanoss, whose limestone cobbles and boulders were derived from the erosion of the Arbuckle Group.

Encountering the Vanoss Formation at the top of the section was anticipated considering that this limestone conglomerate is the dominant surface rock at Vendome Well, and in the surrounding area. The majority of the well cuttings in the top 325 feet were gray subangular limestone cobbles, which is a tell-tale characteristic of the Vanoss Formation because it is an erosional by-product of the Arbuckle Group. Clay and sandstone layers, however, were also recorded throughout the top 325 feet. Viewed in the cuttings at foot depths of 70-95, 100-110, 125-135, 190-195, 255-265, and 310-325 was a gray friable clay. Also, at 145-170 and 270-275 was a red friable clay. All of the clay within this formation reacted strongly with hydrochloric acid, which suggests a carbonate origin.

The existence of clay layers seems to be verified by mechanical logs performed on the original Vendome Well pipe system over 20 years ago. On April 6, 1978, the United States Geological Survey obtained temperature, resistivity, flow direction, spontaneous potential, and gamma-gamma logs of the well to a depth of 245 feet (Hanson and Cates, 1992). The gamma log and the resistivity log suggest that clay lenses occur at several intervals throughout the logged depth (Hanson and Cates, 1992). Because no logs have been performed on the new well hole as of the date of this study, correlation must be used between the two well holes. Although the lithology of these two holes could be different, it is unlikely given the relative close proximity (35 feet). Therefore, it can be assumed that the clay lenses viewed in the log of the old well are the same units viewed in the well cuttings from the new well.

Several small layers of sandstone also occur within the Vanoss Formation at depths of 25-30, 65-70, 95-100, 135-140, 170-175, 220-225, 265-270, and 275-280 feet. These sandstones were primarily brown, fine to medium grained, and sometimes included sequences of siltstone. It is probable that these layers are the arkosic sandstone that is known to exist within the Vanoss. Ham (1969) states that the presence of this arkose within the Vanoss Formation records the first unroofing of the Precambrian granite in the Arbuckle Mountains, which occurred during Late Pennsylvanian time.

At a depth of 325 feet, an abrupt change in lithology occurred from a limestone conglomerate to that of a fairly uniform looking carbonate. Choosing this depth for the base of the conglomerate appears to be consistent with an isopach map of the Vanoss Conglomerate that places the base of the Vanoss near Vendome Well at 189 meters (614 feet) above mean sea level (Cates, 1989). Because the surface elevation at Vendome Well is 976 feet, this would put the estimated thickness of the Vanoss Formation at 362 feet, according to Cates. This is fairly close to the determined thickness from the well cuttings (within 40 feet), especially when you consider that within the area, the Vanoss can vary from 200 to 1500 feet thick.

Massive carbonate rocks dominated the section beneath the Vanoss Formation. Because the two groups expected to underlie the Vanoss differ in that the Simpson is primarily limestone and the Arbuckle primarily dolomite, it was necessary to differentiate between these two carbonates. Dolomite resembles limestone so closely that it is usually impossible to distinguish the two rock types without a chemical test (Klein and Hurlbut, 1993). Typically, limestone is differentiated from dolomite because limestone will react vigorously when put into contact with hydrochloric acid, whereas dolomite must be ground into a powder before it will react. Dolomite is usually the result of alteration of limestone, in which part of the calcium is replaced by magnesium (Klein and Hurlbut, 1993). Under some instances if the ratio of calcium-magnesium is in a transition stage between limestone and dolomite, it can be difficult to differentiate the two rocks even with a chemical test. This seems to be the case with the carbonate rocks beneath Vendome, therefore an x-ray diffraction test was performed on several samples in the bottom 450 feet of the well cuttings.

Ten samples were taken from various depths of the carbonate (350, 365, 375, 395, 460, 530, 545, 635, 650, and 660 feet). Each sample was chosen based on the belief that it represented a separate unit within the formation, because of its unique texture and color. These ten samples were each ground separately into fine powders, and examined by the x-ray diffractometer located in a lab at the Oklahoma State University School of Geology. The x-ray diffractometer identifies the mineralogical composition of a sample. Graphs of each of the ten samples are located in Appendix C. The 100% peak on each graph occurs in the same area (at approximately 31°). This signifies a uniform lithology throughout the carbonate section. According to Moore and Reynolds (1997), the locations of these peaks indicate a dolomitic lithology.

The bottom 450 feet of the well cuttings were a fairly uniform, very fine-grained crystalline dolomite. Although fairly unvaried lithologically, the color did vary throughout the section. Green-colored dolomite with noticeable pyrite crystals was found in the upper portions of the section at an approximate depth of 335-350 feet. One other green-colored dolomite was found at a depth of 365-375 feet. Beneath this green dolomite, the section begins as a gray color, but changes to a brown at 470 feet. This brown dolomite continues until the final 80 feet of the hole, when it then switches back to a gray dolomite. Slightly larger grains were found within the brown as opposed to the gray dolomite, which is noted in the petrologic log in Appendix B. The gray dolomite is primarily a very fine crystalline rock, which suggests that it was formed in a low energy environment, whereas some sections of the brown dolomite contain slightly larger crystals. This would be an indication that it was formed in a higher energy environment. Lastly, at various depths in the carbonate section, small calcite-filled fractures were spotted within the cuttings, and were noted within the remarks column of Appendix B. These small fractures would seem to help support the notion that this carbonate group is fractured.

Although it is often difficult to differentiate between the Arbuckle and Simpson Groups, several clues from the well cuttings pointed to the Arbuckle Group. First, the section was a massive dolomite with no major interruptions in the lithology. This was important for numerous reasons. The Simpson Group consists of several units, each of which represents a complete sedimentary cycle of a marine environment (Hanson and Cates, 1992). Consequently, each unit has an upper shale member underlain by limey shale, sandy lime, and a basal sand (Hanson and Cates, 1992). This was critical because none of these cycles were seen within the well cuttings at Vendome; conversely, the unit was of a very uniform lithology. Because the well cuttings beneath 325 feet were dolomitic also points to the Arbuckle. Rocks from the Arbuckle Group consist of limestone and dolomite, whereas the Simpson contains primarily limestone, shales, and sandstones (Hanson and Cates, 1992). Of these two carbonate rock groups, the Arbuckle is the only stratum that contains significant dolomite. Although the Arbuckle Group can occur as either limestone or dolomite in the area, according to Smith and Wilson (1983) this group is mostly dolomite to the east and north of the Arbuckle Anticline. Figure 16 shows that Vendome Well is located to the northeast of the Arbuckle Anticline. This supports the idea that these rocks are from the Arbuckle Group because they are dolomitic, and not likely to be from the other prominent carbonate unit in the area, the Simpson Group. While the descriptions from these well cuttings can not be entirely conclusive, other evidence seems to also support the notion that these rocks are from the Arbuckle Group. In the following chapter, literary evidence will be provided in support of this belief.

CHAPTER VII

CORRELATION TO REGIONAL GEOLOGY

Correlation can be defined as the determination of structural or stratigraphic units that are equivalent in time, age, or stratigraphic position (Tearpock and Bischke, 1991). Essentially, correlation is the linking of geologic data from numerous data sources (wells, field studies, etc.) to better understand the overall geologic "picture"; i.e., geologic trends in an area or region. In this study, a local subsurface study by Cates (1989) helped support the lithologic information interpreted from the rock cuttings at Vendome Well.

Reasons for regional correlation in this thesis

Regional correlation provides additional insight from the limited geologic data available for the area surrounding Vendome Well. The two lithologic groups of primary concern, the Arbuckle (Ordovician-Cambrian Age) and Simpson Groups (Ordovician Age), outcrop within a few miles to the southeast of Vendome, where structural and stratigraphic trends can be seen. In the immediate vicinity of Vendome, however, a relatively undeformed Pennsylvanian-aged conglomerate (Vanoss Formation) obscures the geology beneath it (Cates, 1989).

A stratigraphic column (see Figure 30) typical of the subsurface beneath CNRA clearly indicates this notion that the Vanoss lies on top of the Simpson, followed by the Arbuckle (Cates, 1989). Also, outcrops southeast of CNRA (and Vendome) provide evidence that the Sulphur anticline plunges beneath CNRA and the city of Sulphur (Cates, 1989). Therefore, it would be expected that the Simpson Group would be encountered beneath the Vanoss in the Vendome cuttings. The cuttings suggest, however, that in the subsurface beneath Vendome Well, the Vanoss is lying unconformably on top of the Arbuckle. As the Simpson Group constitutes a significant portion of the column, with an approximate localized thickness of 2000 feet (Cates, 1989), it is surprising that this group would be missing at Vendome.

Proving this idea is especially difficult since the Vanoss covers a substantial area surrounding Vendome and obscures the underlying strata. Also, subsurface complexities resulting from the Pennsylvanian-aged Arbuckle Orogeny reduces the utility of stratigraphic and structural relationships observed further away from Vendome. Therefore, alternate geologic methods must be employed, as opposed to simply relying on information obtained from visual and field reconnaissance of the local outcrops. A study performed by Cates (1989) suggests that the Simpson Group has been removed from the localized subsurface around Vendome Well. The rest of this chapter will discuss observations from the well cuttings with respect to the various investigations carried out by Cates (well data, Gravity maps, and modeling techniques).

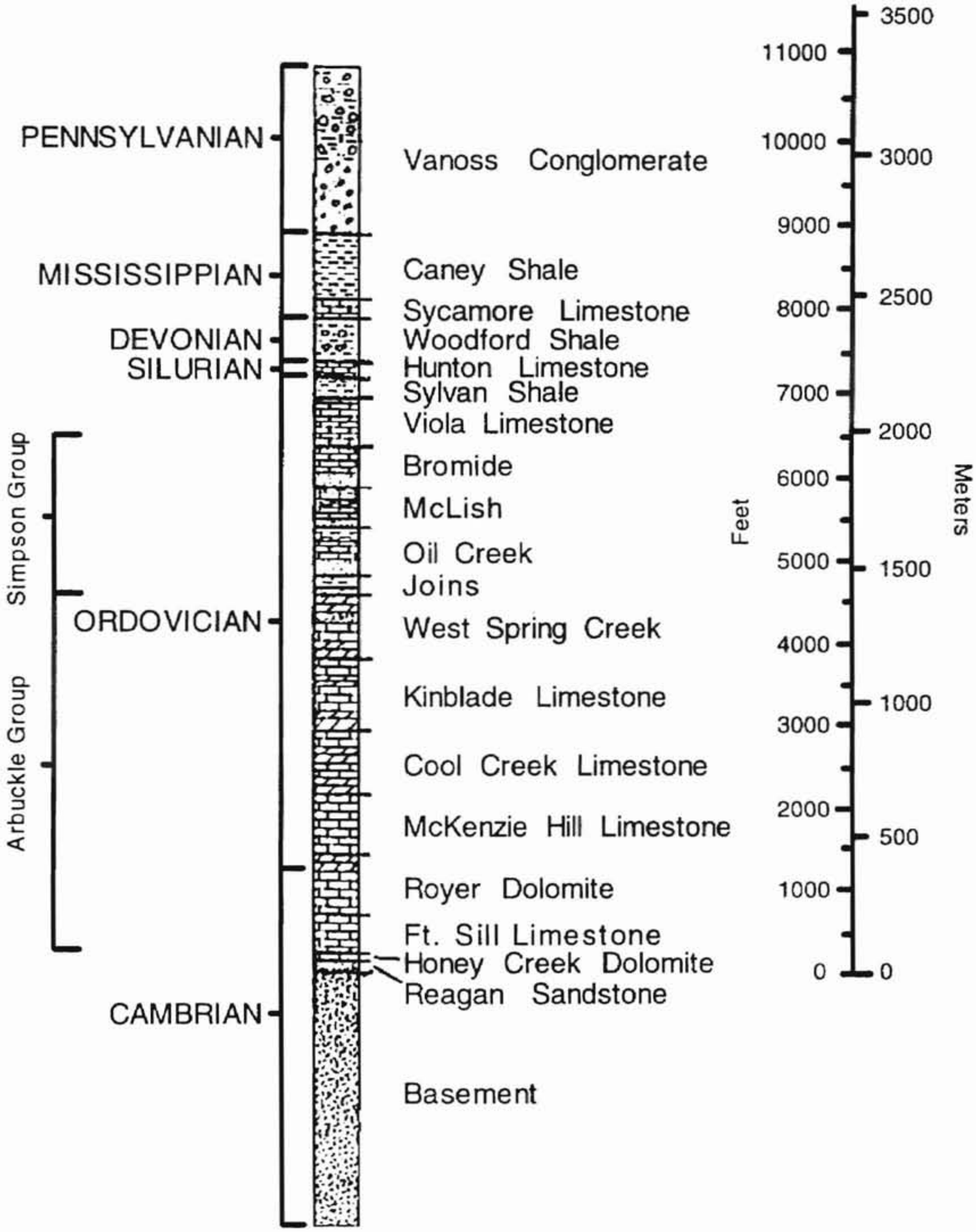


Figure 30
Stratigraphic column at CNRA (Modified after Cates, 1989)

Evidence

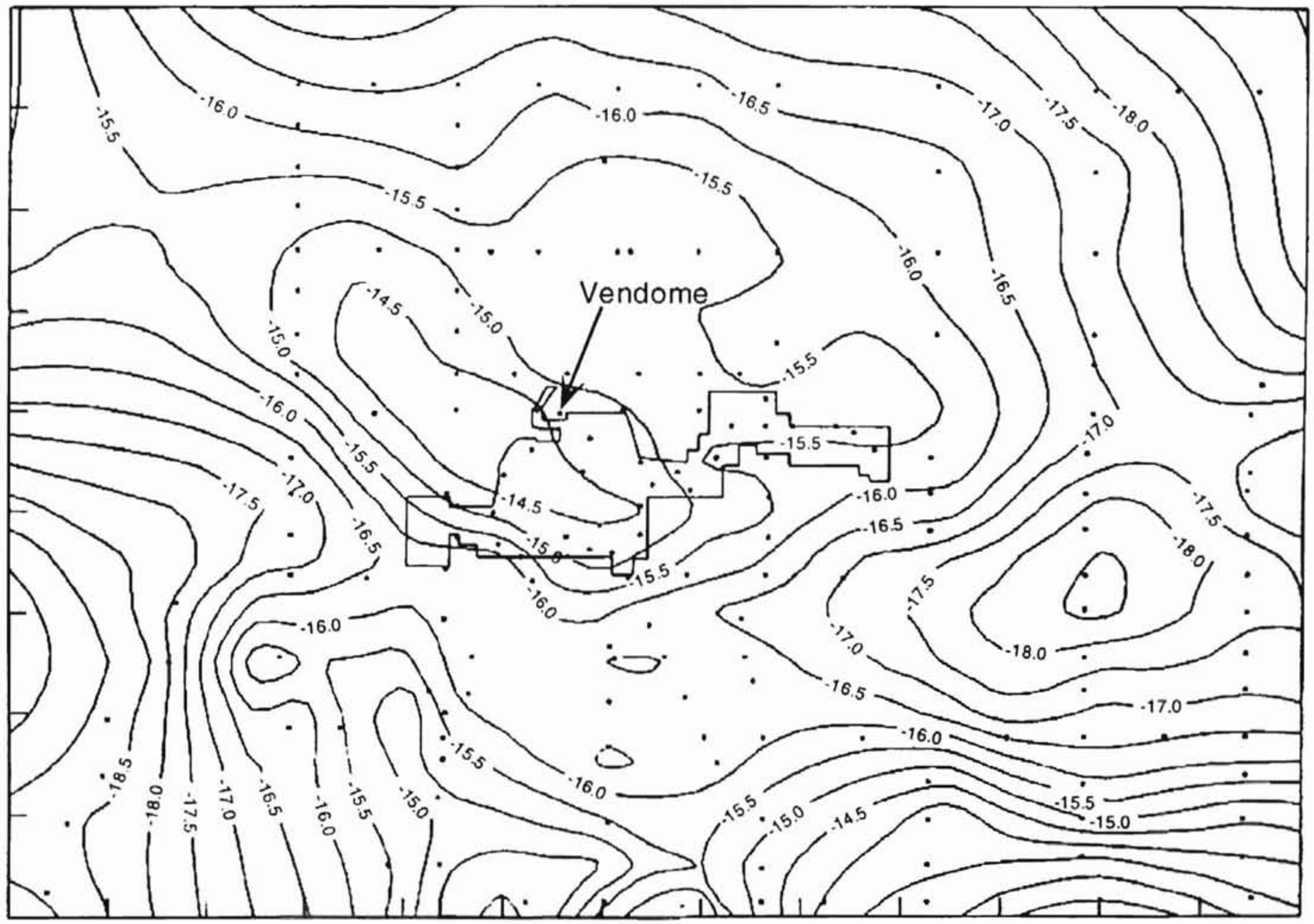
Cates used well data to estimate the probable locations of numerous faults in the Sulphur area; however, the North and South Sulphur Faults are of particular interest because they likely affect the geology and hydrology at Vendome. Cates suggests that Vendome is located on an upthrown block, commonly referred to as a *horst*. He postulates that to the north of these two faults, a block of earth has been upthrown in relation to the area to the south, which is considered to be a downthrown block. These upthrown and downthrown blocks, known as horsts and grabens respectively, are usually associated with normal faulting due to extensional forces (Davis, 1984).

Numerous oil well data is available several miles to the west of CNRA and Vendome; Cates (1989) used this data to estimate the location of the South Sulphur Fault as it trends northwest to areas west of CNRA and Vendome. Normal faulting raises one block with respect to the other; hence the stratigraphy of wells on opposite sides of the fault will be vertically offset. This "offset", which ranged from as little as 750 feet to as much as 2800 feet, is important because it would most likely be the indicator of a fault cutting between the two well locations. From each pair of wells that provided this "offset" evidence, the fault was simply interpolated to the locale of the next set of wells that showed "offset". Because little subsurface data was located within CNRA, the location of the fault beneath CNRA is less certain.

While subsurface data is sparse within, and adjacent to CNRA, limited well data lends support to the belief that the Arbuckle Group lies unconformably beneath the Vanoss Formation in the area surrounding Vendome. The first set of data is from several OG&E power plant wells located a few miles north of Vendome (See Figure 6). Microscopic analysis of drill cuttings from these wells by W. Ham and M. E. McKinley of the Oklahoma Geological Survey suggested that the Arbuckle Group lies unconformably beneath the Vanoss Formation in two of these wells (Cates, 1989). Outcrop areas to the southeast of CNRA suggest that the Sulphur Syncline plunges beneath CNRA and Vendome. If this syncline were to continue to plunge below these well sites, however, the Arbuckle Group would be expected at a much greater depth than is actually observed (Cates, 1989). This result could be explained by a fault located between the outcrop area southeast of CNRA and these wells located north of Vendome. Also, the entire stratigraphic section of the Simpson Group is missing at these wells, which indicates that the area has likely been upthrown and subsequently eroded.

The second set of localized subsurface data comes from two wells, known as the East and West Well, that are located in the eastern portion of CNRA (see Figure 6). At a location approximately two miles to the east of Vendome, these two wells provide the closest available subsurface data. Following the drilling of these two wells, they were subsequently analyzed stratigraphically by James Irwin of the United States Geological Survey. In both wells, the Vanoss Formation was found to be lying unconformably on top of the upper member of the Arbuckle Group (West Spring Creek Formation) at a depth of between 120 to 150 feet. If, as previously stated, the Sulphur Syncline continues to plunge beneath CNRA, then these two wells should be completed stratigraphically above the Viola limestone rather than the West Spring Creek (Cates, 1989). Data indicates that at least 1600 feet of section is missing relative to nearby outcrop located to the south. This is best accounted for by the inference of a fault (North Sulphur Fault) between the two wells in CNRA and the Simpson Group outcrop within the Sulphur Syncline to the southeast (Cates, 1989). These wells are believed to be located on the same upthrown block as Vendome because of their location north of the two localized faults, and the close proximity to Vendome. Therefore, a correlation can be made between the similarities of the subsurface stratigraphy of Vendome to those of the two wells that lie just to the east.

Cates also gathered magnetic and gravity data from 180 sites in a 125 square mile area surrounding, and including Vendome. Data was used to prepare a Bouguer anomaly map, showing the difference between observed and theoretical gravity, which corresponds to differences in rock density (Coruh and Robinson, 1988). Mapped Bouguer gravity is low over areas where average rock density is relatively low; conversely, higher values indicate areas of relatively high average density (Coruh and Robinson, 1988). Cates (1989) computed weighted average densities for each of the localized formations (see Table 3) using density logs taken from four wells in the area. Of particular interest is the large difference in the density values between the Arbuckle (2.73 g/cm^3) and Simpson Group formations (2.4 - 2.5 g/cm^3). In the Bouguer gravity map developed by Cates (see Figure 31), a gravity high (indicated by the less



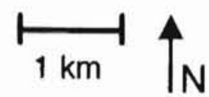


Figure 31
Bouguer anomaly map of Platt National Park and the surrounding area (Modified after Cates, 1989)

Table 3
Formation names, thicknesses, and densities

Formation Name	Thickness (meters)	Density (g/cc)
Hunton Limestone	61	2.63
Sylvan Shale	69	2.44
Viola Limestone	168	2.57
Simpson Formations		
Bromide	107	2.45
Upper McLish	113	2.60
Lower McLish	40	2.30
Oil Creek Shale	98	2.50
Oil Creek Limey Sand	55	2.40
Oil Creek Sandstone	22	2.30
Joins	67	2.40
Arbuckle Group	1344	2.73

Cates, 1989

negative values of −14 to −15) occurs in the subsurface of Vendome. Because the highest density rock in the local subsurface is the Arbuckle Group, it is likely to be lying uncomformably beneath the Vanoss Formation at Vendome. Cates summarized his data by stating: "the oblong positive anomaly in the western half of CNRA correlates well with the Arbuckle Group horst block that was discovered from subsurface well data located to the northwest of CNRA. It seems highly possible that this feature and the anomaly on the Bouguer gravity map are related."

Cates also used a two-dimensional (2-D) gravity and magnetic inversion model known as SAKI (Webring, 1985) to develop density models based on gravity data collected over an area of known geology. The model was used to interpret geologic relationships in areas of limited surface or subsurface control (Cates, 1989). A cross-section (see Figure 32) of the subsurface beneath Vendome was constructed using a Bouguer gravity profile (top of figure), and a

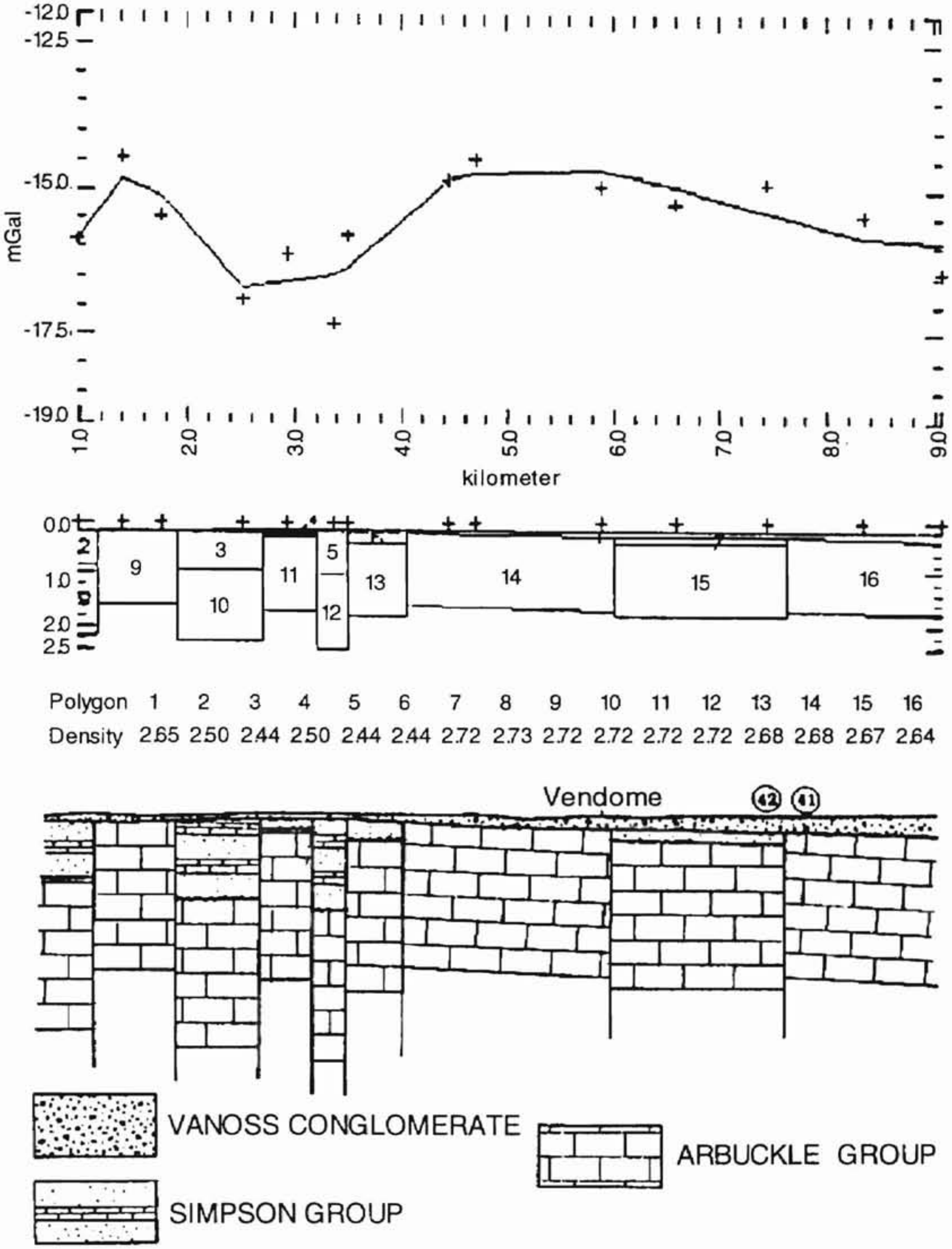


Figure 32
Cross-section of the stratigraphy beneath Vendome Well
(Modified after Cates, 1989)

polygon density model (middle of figure). The cross-section was also aided through the use of geologic constraints from two outcrop locations, the Vendome Well, and two OG&E wells (#41 and #42). Of particular interest is the subsurface directly beneath Vendome. In the simulated cross-section, a vertical hole beneath Vendome would cut initially through the Vanoss Formation, followed by the Arbuckle Group lying unconformably beneath; the Simpson Group is missing. The cross-section explains this stratigraphic sequence by faults that occurred when the section beneath Vendome and the surrounding area was upthrown.

Summary

In light of Cates study, the most likely scenario seems to be that Vendome is located on an upthrown block (horst). As the Arbuckle Orogeny uplifted the area, wide-scale faulting occurred, which likely resulted in the fault block being thrown up. As the block was thrown up higher, subsequent erosional processes led to the localized removal of the Simpson Group. Also, during this orogeny portions of the Arbuckle Group were eroded into lower lying areas, forming the Vanoss Conglomerate, which now covers the Arbuckle at Vendome. This scenario would account for the present-day geology beneath Vendome, one in which the Arbuckle Group lies unconformably underneath that of the Vanoss Formation.

CHAPTER VIII

INFERENCE OF AQUIFER PROPERTIES AT VENDOME WELL

The primary objective of this study is to postulate how water is delivered to Vendome Well. In addition to the geologic and hydrologic setting, estimates of hydraulic characteristics of the Arbuckle-Simpson aquifer beneath Vendome were needed. According to Fairchild et al. (1990), the hydraulic characteristics (also known as aquifer properties) describe the ability of an aquifer to store and transmit water. These parameters are commonly expressed in terms of the storativity (S) and transmissivity (T). Brown et al. (1962) confirmed the value of using T and S in describing an aquifer: "the worth of an aquifer as a fully developed source of water depends largely on two inherent characteristics: its ability to store (storativity) and transmit water (transmissivity)". Combining geologic data with estimated hydraulic characteristics of the aquifer will increase the understanding of how water is delivered to Vendome Well.

Definitions

To fully understand this section, the following terms need to be defined: head, drawdown, potentiometric surface, transmissivity, and storativity. The difference between primary and secondary porosity is also important. Head, also known as hydraulic head, represents the total mechanical energy per unit weight of water at any point within a fluid (Fetter, 1994). A practical definition of head is the elevation above datum to which fluid will rise in an open tube inserted into the aquifer. Head is measured over that portion of the aquifer to which the tube is open. The potentiometric surface is defined as an imaginary surface representing the spatial variation of head within an aquifer (Lohman, 1972). This surface may be located either above or below the land surface, and is often used to infer the direction of flow, which occurs from areas of high to low head.

Removal of water from a well causes a change in the potentiometric surface around the well. For water to flow towards a well, it must be a localized low in the potentiometric surface. At any given time and place, drawdown is defined as the vertical change in the potentiometric surface that results from flow to the well; that is, the difference between the unperturbed potentiometric surface (no flow to the well), and the perturbed condition (well is flowing).

Transmissivity of an aquifer is defined as the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient (Fairchild et al., 1990). Simply put, transmissivity describes the ease with which water flows through the aquifer in the horizontal direction. Transmissivity has units of L^2/T and is proportional to hydraulic conductivity (K) and aquifer thickness ($T = Kb$). Hydraulic conductivity is a coefficient used to describe the rate at which water can move through a porous medium irrespective of media dimensions, and is a function of properties of both the porous medium and the fluid passing through it (Fetter, 1994).

Another hydraulic characteristic to define is storativity (S), which is related to aquifer compression. Head partially supports the aquifer; thus, when the head in a saturated aquifer or confining unit changes, water will either be stored or expelled. When head is lowered, the aquifer contracts vertically; conversely an increase in head would expand the aquifer. This dimensionless unit gives the volume of water that a permeable unit will absorb or expel from storage per unit surface area per unit change in head (Fetter, 1994). Like T, S increases with aquifer thickness. Typically, storativity of a confined aquifer ranges from 10^{-5} to 10^{-3}.

Hydraulic characteristics of an aquifer are normally controlled by the intergranular connection of pore spaces, or primary porosity of the rock unit. This type of porosity is commonly found in sandstone aquifers. Flow can also occur in spaces created after the deposition of the rock units, commonly known as secondary porosity. It is believed that secondary porosity dominates flow within the Arbuckle-Simpson aquifer. This notion is supported by the statement "rocks of the Arbuckle Group have little or no intergranular porosity; all void space is in the form of secondary porosity such as joints, fractures, and solution channels" (Fairchild et al., 1990). If the hydraulic characteristics of the aquifer can be estimated, then the dominant type of aquifer porosity will be better understood.

Measuring Hydraulic Characteristics

Prior to estimating the hydraulic characteristics of an aquifer, pertinent data on the aquifer must be collected. One way to acquire such data is by performing an aquifer test, as suggested by a Department of Interior Study (1995) that stated: "a better understanding of the influence of geologic structure upon the hydrologic system within CNRA could be obtained by capping the Vendome Well and other nearby flowing wells and conducting a shut in aquifer test". The study went on further to say that "a shut in test could also provide estimates of the local hydraulic characteristics of the aquifer, which presently are not well known in the immediate CNRA vicinity" (DOI, 1995). Since there have been no known aquifer tests on Vendome Well, therefore a constant drawdown test was conducted for this study as an alternative to a shut in test.

Constant Drawdown Test

Pumping tests are commonly used to estimate specific capacity of a well, which is the rate of discharge divided by the drawdown of water level within the well (Fairchild et al., 1981). However, the nature of artesian wells such as Vendome (i.e. water rises to the surface) makes it difficult to determine aquifer characteristics by pumping the well. Artesian wells are typically assessed by measuring the flow rate, which does not provide data on transmissivity and storativity. One can estimate T and S of artesian aquifers, however, by employing the constant drawdown analysis (Merritt, 1997).

Jacob and Lohman (1952) derived equations for determining T and S from constant drawdown tests in which the drawdown varies with time. The term "constant drawdown" applied to this test is actually misleading, because the head in the aquifer varies with time (Merritt, 1997). Mathematically, drawdown within the well itself is assumed to remain constant following initiation of flow, hence the name "constant drawdown". This test may be performed when a naturally flowing well in a confined aquifer is shut in for a period long enough for the head to recover (Merritt, 1997). The well is then opened and allowed to flow for a period of roughly two to four hours, during which timed measurements are made of the declining rate of flow (Lohman, 1972). The overall time that data are collected can vary, and is dependent upon how quickly the aquifer reaches an equilibrium state that includes discharge from the well. Aquifer transmissivity can be estimated from the variation in discharge following uncapping of the well.

Initially, before the well is shut in, the aquifer is at equilibrium with the well, which yields a fairly constant flow rate (see Figure 33a). From the figure, notice how the potentiometric surface curves down towards the well. This occurs because the well must have a lower hydraulic head than the surrounding area for water to flow. Darcy's Law ($Q = -K A\, dh/dx$) states that flow in an aquifer moves from an area of high to low hydraulic head. The constant drawdown test begins when the well is capped or shut in (see Figure 33b). At such time, the potentiometric surface recovers to a condition that reflects lateral flow in the aquifer under natural gradient. After the well is subsequently uncapped, head in the well drops quickly from the formation head to that of the well outlet (see Figure 33c). As seen in this figure, initially a large head difference (drawdown) occurs between the well and the adjacent aquifer. Assuming that the conductivity (K) and cross-sectional area (A) of the aquifer are constant, Darcy's equation indicates that flow will be proportional to the hydraulic gradient (dh/dx).

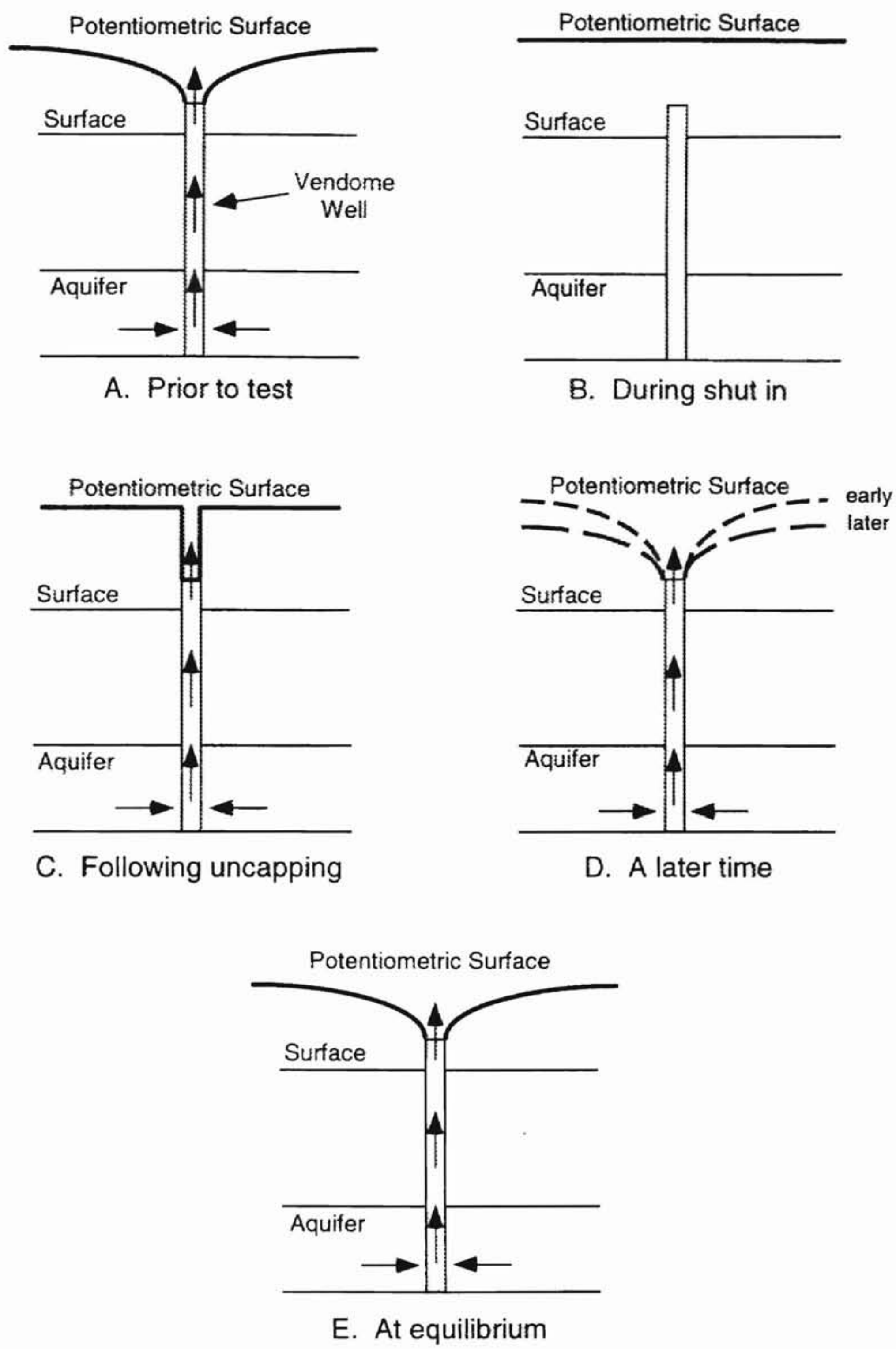


Figure 33 (a-e)
Cross-sectional view of Vendome Well displaying the Potentiometric surface at various times before, during, and following the aquifer test

Because dh/dx will be greatest following the uncapping, flow should be the highest during this time. After the initial stages following the uncapping, water flows to the well from a greater distance, and a cone of depression develops in the potentiometric surface (see Figure 33d). This change in shape of the potentiometric surface represents a decrease in the head difference between the surrounding area and the well. Hence, the gradient (dh/dx) term in Darcy's equation becomes smaller, which indicates the flow from the well will decrease. The development of a cone of depression is represented in Figure 33d by the lines labeled "early" and "later". The cone of depression grows outward until head in the formation returns to an equilibrium (see Figure 33e) condition (flow rate and potentiometric surface) which is normal for the flowing well.

The time needed for a well to reach an equilibrium state following uncapping can be used to estimate hydraulic characteristics of the aquifer. Essentially, this recovery time reflects the availability of water within the aquifer to the well. Jacob and Lohman (1952) showed that transmissivity and storativity can be estimated by using data (time versus discharge rate) obtained during a constant drawdown test. Assuming that the aquifer is homogeneous, isotropic, extensive laterally, and that T and S are constant at all places in time (Lohman, 1972) leads to the following relations for flow during a constant drawdown test:

$$Q = T\, 2\pi\, G(\alpha)\, Sw \qquad (1)$$

$$\alpha = Tt/(S\, rw^2) \qquad (2)$$

where T is transmissivity, Q is flow rate, π is pi, $G(\alpha)$ is a non-linear function of alpha, Sw is the drawdown in the well, S is storativity, t is time, and rw is the radius of the discharging well (Lohman, 1972). Note that π, $G(\alpha)$, α, and S are dimensionless; consistent units must be used for the remaining parameters. Values for $G(\alpha)$ are obtained from published tables (i.e. *Water Hydraulics* page 24, Lohman, 1972).

In a constant drawdown test, flow is measured as a function of time. Values for Q/Sw and t/rw^2 are obtained at different stages (times) of the test and cross-plotted on a log-log scale. This curve is then matched to a known curve relating $G(\alpha)$ to (α). Equations 1 and 2 can then be used to estimate T and S.

Constant Drawdown at Vendome

At approximately 8 a.m. on March 17, 2000, a constant drawdown test was performed at Vendome Well. At 4 p.m. on the day before the test, Vendome Well was shut off by Chickasaw National Recreation Area management. The aquifer was then allowed to equilibrate to natural gradient conditions for a period of approximately 16 hours prior to the test.

To understand how the test was set up, first it is important to assess the physical layout of Vendome Well. Flow from Vendome initially empties into a circular shaped fountain from a vertical pipe. Leading out of the east end of the fountain is a two foot deep rectangular channel that carries flow from the well. Located within the channel, approximately 65 feet downstream from the well, is a rectangular weir with an inactive gaging station. The water in the channel then continues its course for several hundred feet downstream until it empties into Rock Creek. A map view of Vendome Well can be found on the left side of Figure 34.

The data required for this test is drawdown in the well, and discharge as a function of time. Drawdown in the well is the distance between head under natural gradient and the elevation of the outlet. Ideally, the best way to ascertain the hydraulic head would have been through the use of a pressure valve tapped into the well casing, such as was done in an artesian flow test performed by Wyrick and Floyd (1961). No such valve, however, was included in the new plumbing of Vendome. Because of the cultural importance of the well, it was not practical to enact any physical modifications to the plumbing. Therefore, the hydraulic head was estimated using the *Bernoulli equation*, which will be discussed later in this section.

The other required data are discharge as a function of time. On wells that have small flow rates, it is common to estimate discharge by manually catching discharge in buckets. The rate of flow of Vendome (approximately 650 Gallons Per Minute), however, makes it nearly impossible to catch all the discharge and maintain a reasonable degree of accuracy.

Discharge at Vendome was measured by using the existing weir. A weir is a vertical baffle (dam) that restricts the total flow of water in an open or closed channel, and is the simplest device used to measure flow (Driscoll, 1986). The weir is placed flush against the flowing stream and sits within the channel, acting to restrict flow. A rectangular notch is cut into the weir at Vendome (rectangular

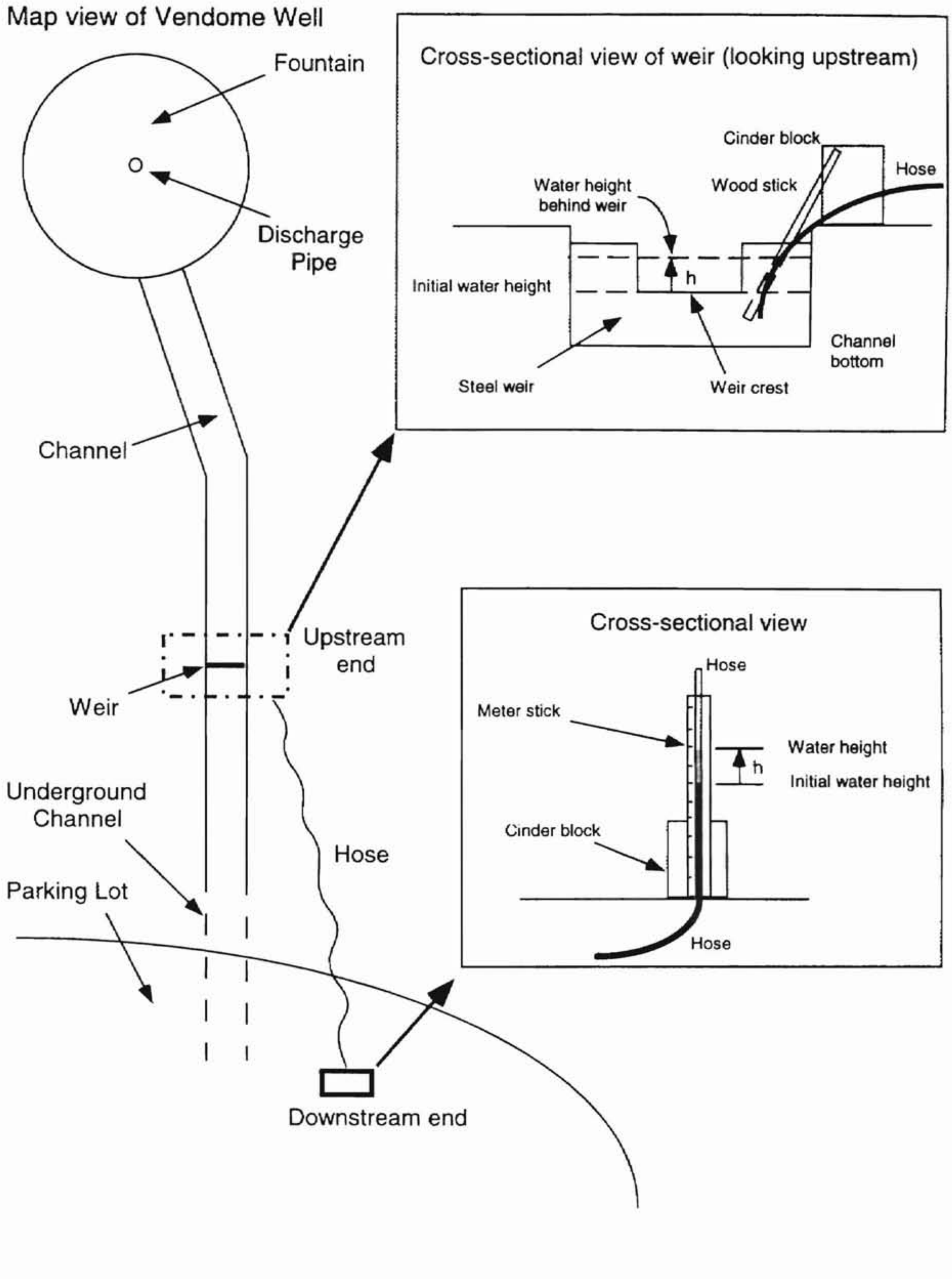


Figure 34
Map view of Vendome Well and schematic drawing of the water level apparatus

weir with end contractions). The crest of the weir is defined as the bottom of the notch, and is the level to which the water must rise before it spills over (Driscoll, 1986). Once the dimension and shape of the weir notch are known, then the only other variable needed to determine discharge is the water height above the crest of the weir, which is represented by the variable "h" in Figure 34. These discharge values were obtained from weir data by using *The Francis Equation* (Driscoll, 1986):

$$Q = 3.33\,(L - 0.2H)\,H^{1.5} \qquad (3)$$

where Q is the flow rate, L is the length of the weir opening, and H is the water height above the notch in the weir.

Although water height above the crest could have simply been read directly at the weir, one serious problem would have arisen. Flow from Vendome exhibited significant turbulence, causing fluctuation of the water level on the upstream portion of the weir where the height measurement would have been taken. This fluctuation of the water level would have undoubtedly compromised the accuracy of the data measurements. Therefore, an apparatus needed to be developed that could dampen out this water level fluctuation problem, while also being able to accurately measure the water height above the weir crest throughout the test.

It was hypothesized that the head near the channel bottom fluctuates less than near the surface, therefore a water level apparatus was employed to accomplish this task (Figure 34). Rigid 3/8" vinyl tubing was used for the water level so that pressure changes were transmitted correctly. One end of the hose was pointed into the channel just in front of the upstream side of the weir. A ½ inch diameter wood stick anchored to a cinder block was used to provide stability so that the hose would not move around as flow passed it in the channel. The hose was then extended approximately 50 feet downstream from the weir and secured to a meter stick attached to a second cinder block. This end of the hose was used to measure water above the crest height throughout the constant drawdown test; therefore, a length of clear hose was attached to facilitate reading water levels. A stopwatch was placed next to the meter stick to make it easier to track changes in water height as a function of time.

The plan for the original test included video taping the water height, while also timing the test with a stopwatch. The video taping was intended to act as a backup, in order to document this information should anything have gone wrong with manual measurements. Because water levels typically change rapidly in the initial stages of the test, a visual recording could have been used to help measure the water level more precisely (Wyrick and Floyd, 1961). Unfortunately, persistent rain precluded use of the video system, and because of institutional constraints, the test could not be postponed.

Theory of the apparatus

This water level apparatus relies on the most basic of hydrologic principles, in which the height of the water in the upstream end of the hose will reflect the same height in the downstream end of the hose. If the channel behind the weir is filled to the crest of the weir, then this initial water level in the upstream end of the hose will be transmitted to the downstream end, giving a baseline value for taking measurements during the test. Because the channel was initially filled to the crest of the weir prior to the test, any discharge from the well will cause water to flow over the crest. As increased discharge is released from the well, more water will spill over the crest of the weir and water height above the crest will subsequently increase. Hydraulic principles tell us that as the water height rises/falls in the channel (upstream end of the hose), the height will rise/fall in the same proportion at the downstream end of the hose. This concept is depicted on the right side of Figure 34. Notice that the water height above the crest (denoted by the letter "h") at the upstream end of the apparatus is equal to the level read at the downstream end, which is also denoted by the letter "h".

Head Loss

To estimate drawdown at Vendome (Sw in equation 1), head in the aquifer under natural gradient conditions must first be estimated. As discussed earlier, it was not possible to directly measure this quantity. As an alternative, an estimate was made of a lower bound based on head at the bottom of the well under flowing conditions. Head loss within the plumbing system can represent the lower bound of the aquifer head because an artesian aquifer must have *at least* this much head to flow to the surface.

As water flows through a pipe, it loses head (energy). Pipe friction is a key factor, but head is also lost to components within the plumbing system such as elbows, tees, reducers, valves, and filters (Munson et al., 1990). One method to estimate these head losses is through the use of the *Bernoulli equation*. This equation:

$$p/\gamma + z + V^2/2g = \text{constant} \qquad (4)$$

where p is the fluid pressure, γ is specific weight of the fluid, z is elevation head, V is the velocity of the fluid in the pipe, and g is gravity. The equation can be applied in two different conditions. First of all, when the fluid is not moving, *Bernoulli's equation* describes how pressure varies with depth. When the fluid moves, however, this equation describes how pressure and speed must change together with depth in the fluid (Munson et al., 1990). The *Bernoulli equation* is only valid in a system where: 1) viscous effects are negligible; 2) flow is steady; 3) the fluid is incompressible; and 4) the equation is only applicable along a streamline (Munson et al., 1990). Essentially, the *Bernoulli equation* tells us that if one knows head at point A (H_A) and head losses that occur between point A and B (H_L), then one can estimate head at point B (H_B) by use of: $H_B = H_A - H_L$. Therefore, the equation is a valid means to estimate head loss between the outlet and the producing part of the formation.

After obtaining a blueprint of the plumbing plan from CNRA management, the system was subdivided into sections, then head loss in each section was estimated. Each section in the Vendome Well pipe system (see Figure 35) is represented by a number from one to thirteen, with one being the bottom section and thirteen the outlet. Sections can be grouped into two categories: pipe friction and component losses. The following paragraphs are an explanation of how head loss was estimated for each of the thirteen different sections; results are summarized in Table 4, with all units in feet and seconds.

The system at Vendome contains six significant straight pipe sections (#1, 3, 7, 9, 11, and 13 in Figure 35). Head loss (H_L) within a straight pipe is described by the equation:

$$H_L = f\,(L / D)V^2/(2g) \qquad (5)$$

where f is the friction factor (dimensionless), L is the length of the section of pipe, D is the diameter of the pipe, V is the velocity of the water, and g is gravity (Daugherty and Franzini, 1977).

One of the key components to determining head loss in a straight pipe is the friction factor (f). The first value needed to estimate the friction factor in a pipe is the roughness (ε). As the term would indicate, roughness (units of length) deals with the actual roughness of the pipe walls, and is dependent upon the type of pipe that the water is flowing through. For example, smooth pipes such as plastic have a low ε value, as opposed to riveted steel, which has a high ε. Values of ε for various types of pipe can be found in almost any fluid mechanics

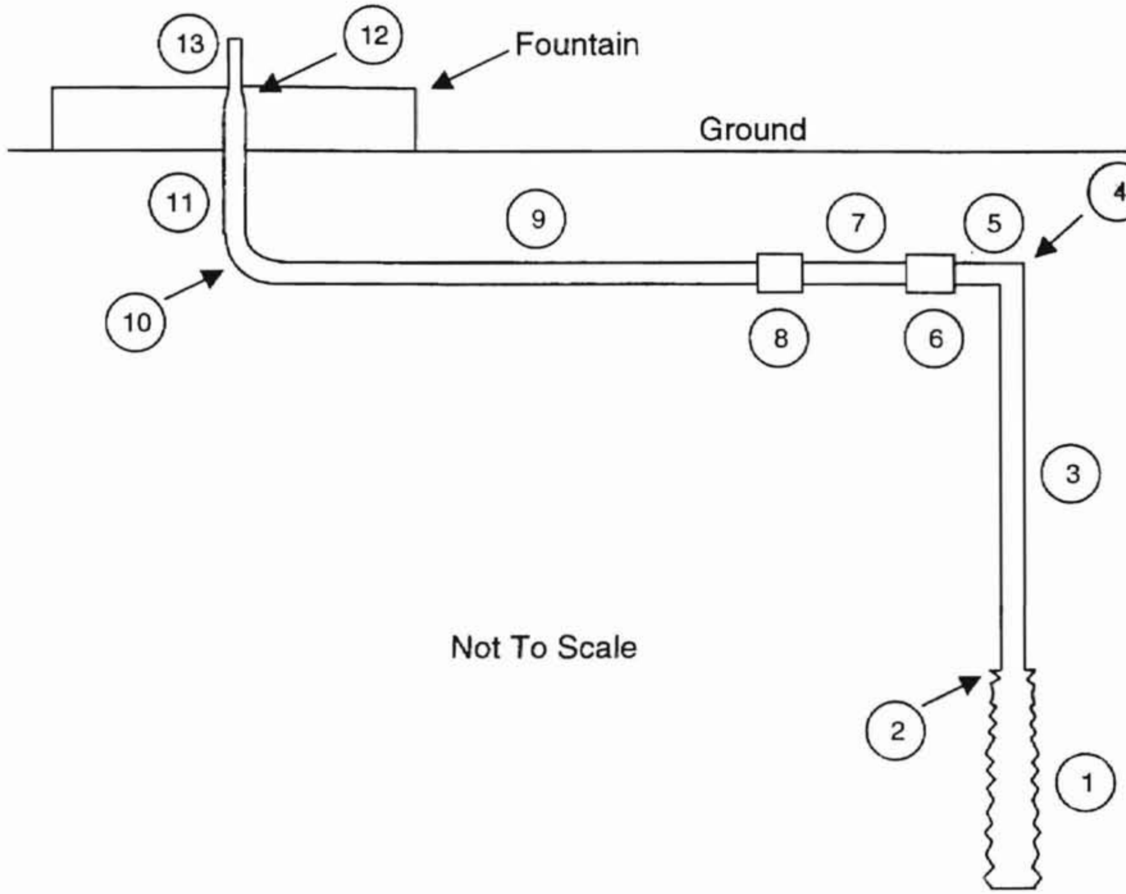


Figure 35
New Vendome pipe system displaying the
thirteen sections of head loss

Table 4
Thirteen sections of head loss within the Vendome pipe system

Section #	Description	Loss factor (ft)	ε/D	Reynolds #	Velocity (ft/sec)	Friction factor	Head loss (ft)
1	Straight pipe (steel) Length: 475 ft Diameter: 0.531 ft	0.0417	0.0785	2.9×10^5	6.666	0.094	58.0
2	Sudden expansion V_1 = 6.666 ft/sec V_2 = 6.173 ft/sec	n/a	n/a	n/a	n/a	n/a	<0.1
3	Straight pipe (steel) Length: 297 ft Diameter: 0.552 ft	0.00015	0.00027	2.8×10^5	6.173	0.017	5.4
4	Sudden contraction Diameter1 = 0.5 ft Diameter2 = 0.552 ft	0.06	n/a	n/a	7.525	n/a	<0.1
5	Tee, branched flow, flanged	1.0	n/a	n/a	7.525	n/a	0.9
6	Gate valve	0.19	n/a	n/a	7.525	n/a	0.2
7	Straight pipe (pvc) Length: 10 ft Diameter: 0.5 ft	n/a	0.0	3.1×10^5	7.525	0.014	0.3
8	Butterfly valve	0.5	n/a	n/a	7.525	n/a	0.4
9	Straight pipe (pvc) Length: 25 ft Diameter: 0.5 ft	n/a	0.0	3.1×10^5	7.525	0.014	0.6
10	Long radius 90° bend, flanged	0.2	n/a	n/a	7.525	n/a	0.2
11	Straight pipe (pvc) Length: 3 ft Diameter: 0.5 ft	n/a	0.0	3.1×10^5	7.525	0.014	0.1
12	Bell Reducer	1.2	n/a	n/a	7.525	n/a	1.0
13	Straight pipe (pvc) Length: 2 ft Diameter: 0.33 ft	0.00015	0.00045	4.6×10^5	16.967	0.0175	0.5
					Estimated total head loss (ft):		67.6

book. For sections of pipe that were steel, a value of 0.00015 for ε was used, and for pvc, a value of 0 (zero) was used (Daugherty and Franzini, 1977).

Once the roughness of a particular section is estimated, it is then divided by the diameter of the pipe (in feet). This value (ε / D) is the first number needed to determine the friction factor (f) for the pipe. The other value needed is the Reynolds number (D * V / v), which is the product of the diameter of the pipe and fluid velocity divided by the fluid viscosity, which was assumed to be that of pure water at 60 degrees Fahrenheit (1.217×10^{-5} ft^2 / sec). Once the Reynolds number (dimensionless) is determined, friction factor can then be estimated by using a Moody chart. The (ε / D) value and Reynolds number are cross-plotted to yield an approximate friction factor for the pipe.

Section #1 is an open hole and not a pipe, therefore a roughness value had to be estimated. When an open hole is drilled, it is not perfectly cut and contains jagged edges, which were estimated at Vendome to be approximately ½ inch. This number was used for the roughness value, and yielded a (ε / D) value (0.0785) that is off of the Moody chart, and thus had to be interpolated. The high value of ε / D is expected, as an open hole will be much rougher than the manufactured pipes for which the Moody diagram was developed. Using a cross-plot of the Reynold's number (2.9×10^{-5}), a friction factor of .094 was estimated. This friction factor is approximately nine times greater than that for a rough concrete pipe (f = .01).

Another source of head loss within the Vendome pipe system results from the sudden expansion from one size pipe to another, which occurs in section #2 (see Figure 35). As water flows from a smaller diameter pipe to that of a larger one (expansion) velocity suddenly decreases causing turbulence, which in turn leads to a loss of energy (Daugherty and Franzini, 1977). Loss of head because of sudden expansion is given by the equation:

$$H_L = (V_1 - V_2)^2/(2g) \qquad (6)$$

where V_1 is the velocity in the small pipe, V_2 is the velocity in the larger pipe, and g is gravity.

In one section of the pipe system flow suddenly contracts (section #4). As flow is suddenly contracted, the velocity of the fluid within the pipe is increased, and a loss of energy occurs because of turbulence (Daugherty and Franzini, 1977). The loss of head in this situation is given by the equation:

$$H_L = K_c V_2^2/(2g) \qquad (7)$$

where V_2^2 is the velocity in the smaller pipe, K_c is a factor dependent on D_2/D_1, D_2 is the diameter of the smaller pipe, and D_1 is the diameter of the larger pipe. K_c for section #4 was estimated (0.06) from Table 8.2 of *Fluid Mechanics with engineering applications* (Daugherty and Franzini, 1977).

Gradual contraction of flow results in less head loss than a sudden contraction, and is accomplished by changing from one diameter to the other by means of a smoothly curved transition, or through the use of the frustum of a cone (Daugherty and Franzini, 1977). Gradual contraction occurs in section #12 of the Vendome plumbing (see Figure 35), in the form of a Bell reducer. In this component, the loss of head is defined by the equation:

$$H_L = K_L V_1^2 /(2g) \qquad (8)$$

where K_L is a loss coefficient based on the angle at which the reducer contracts. V_1 is the velocity within the larger pipe (prior to being forced through the reducer), and g is gravity. With an angle of approximately 60°, Figure 8.33 in *Fundamentals of Fluid Mechanics* determines that K_L is approximately 1.2 (Munson et al., 1990).

Bends in the pipe are yet another component within the Vendome plumbing that causes loss of head. Two bends were required, because the new well was drilled approximately 35 feet west of the existing fountain area and then routed underground back to the fountain. According to the Vendome plumbing plan, this routing required a tee and a 90° bend (respectively sections #5 and 10 of Figure 35). Head loss in both types of bends is given by the equation:

$$H_L = K_L V^2 /(2g) \qquad (9)$$

where K_L is a loss coefficient based on the type of bend used (Munson et al., 1990), V is the velocity of the water, and g is gravity. Section #5 was a form of bend known as a branched flow flanged tee ($K_L = 1.0$). In section #10 the bend was of a type known as a long radius 90° gradual bend ($K_L = 0.2$).

The only remaining significant components within the Vendome Well pipe system are two valves. Section 6 consists of a Gate valve and a Butterfly valve is found in section #8. No matter the type of valve used, head loss is estimated by using the equation:

$$H_L = K_L V^2 /(2g) \qquad (10)$$

where once again K_L is a loss coefficient based on the type of valve used, V is the velocity of the water, and g is gravity. Values of K_L vary depending on the type of valve employed, and how much the valve was opened. At the time of the constant drawdown test, these valves were both fully open. K_L for a fully opened Butterfly valve is 0.5, whereas for a Gate valve 0.19 was appropriate (Munson et al., 1990).

Once the values for head losses were estimated for each of the thirteen different sections (see Table 4), they were added together to obtain total head loss for the Vendome Well pipe system (67.6 feet). The majority of the head loss was generated in sections #1 and 3. The primary reason section #1 had such a high loss resulted from the large roughness value attributed to an open hole, which led to a larger friction factor. Section #1 also occurred across a very long stretch of open hole (475 feet), a factor which helped contribute to the large head loss estimated for this section (58.0 feet). Head loss from section #3 was also relatively large (4.5 feet), which was also primarily a result of the length (244 feet). These two sections comprised over 90% of the total head loss estimated within the system. Also, assumptions made in these sections could drastically change the overall head loss for the system, whereas changes in any of the other eleven sections would have little effect. Lastly, all head loss values are estimates, and while likely imprecise, they serve to provide a rough estimate of the total head loss within the system, and hence formation head.

Vendome Well is located at an elevation of 976 feet above sea level. Head losses within the plumbing system are assumed to be the *minimum* difference between formation head and head at the outlet that would cause the well to flow. Therefore, the sum of the elevation of the outlet (976 feet) and the estimate of head loss within the plumbing (67.6 feet) provides us with an estimated lower bound (see Figure 36) for the formation head (1043.6 feet). Next, an upper bound for the range of head at Vendome needed to be estimated. According to hydrologic principles, the head at Vendome can be no higher than the water table height in its recharge area; thus providing an upper bound on head in the aquifer (see Figure 36). The Arbuckle and Simpson Group outcrops, located to the southeast of Vendome, are presumed to be the recharge area for the well. Using a potentiometric map of the outcrop area, the average water table in the recharge area was determined to be approximately 1075 feet above sea level.

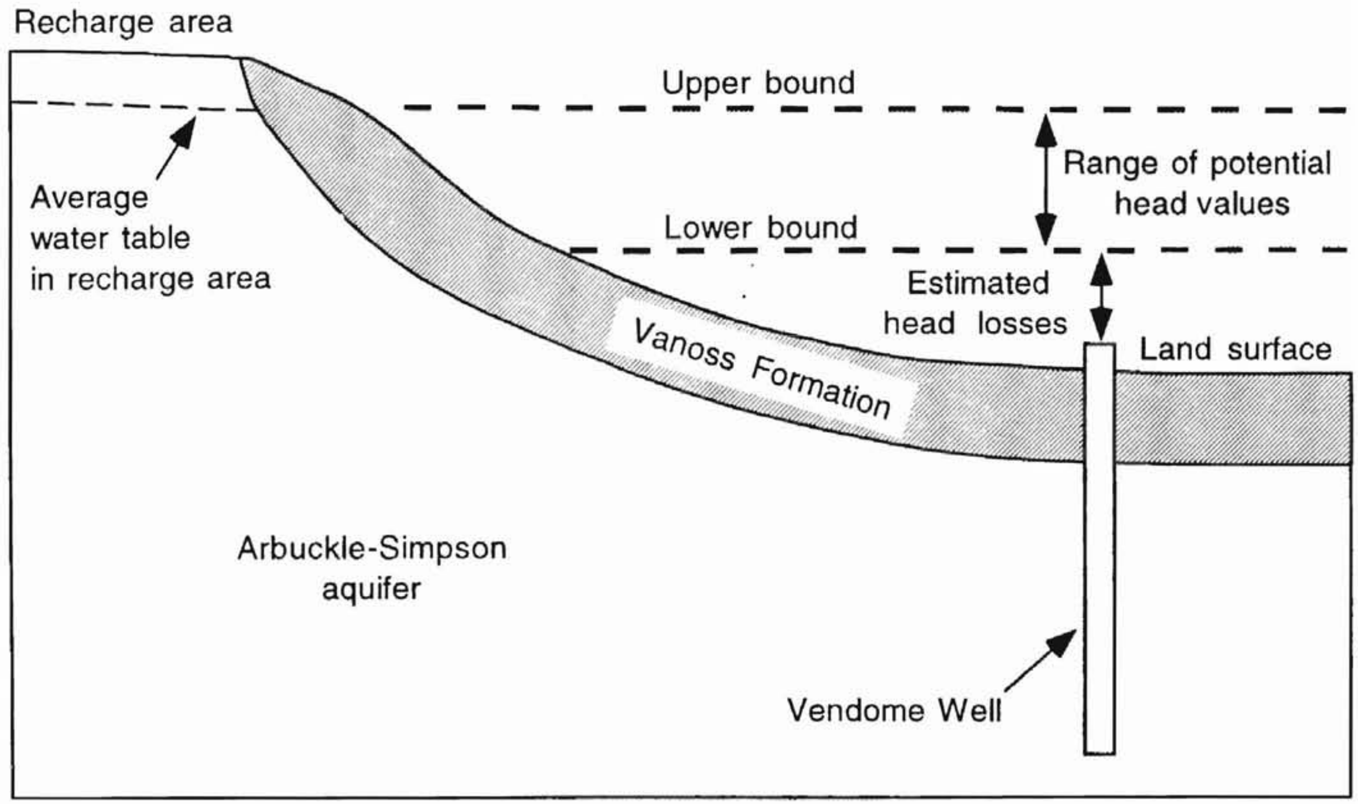
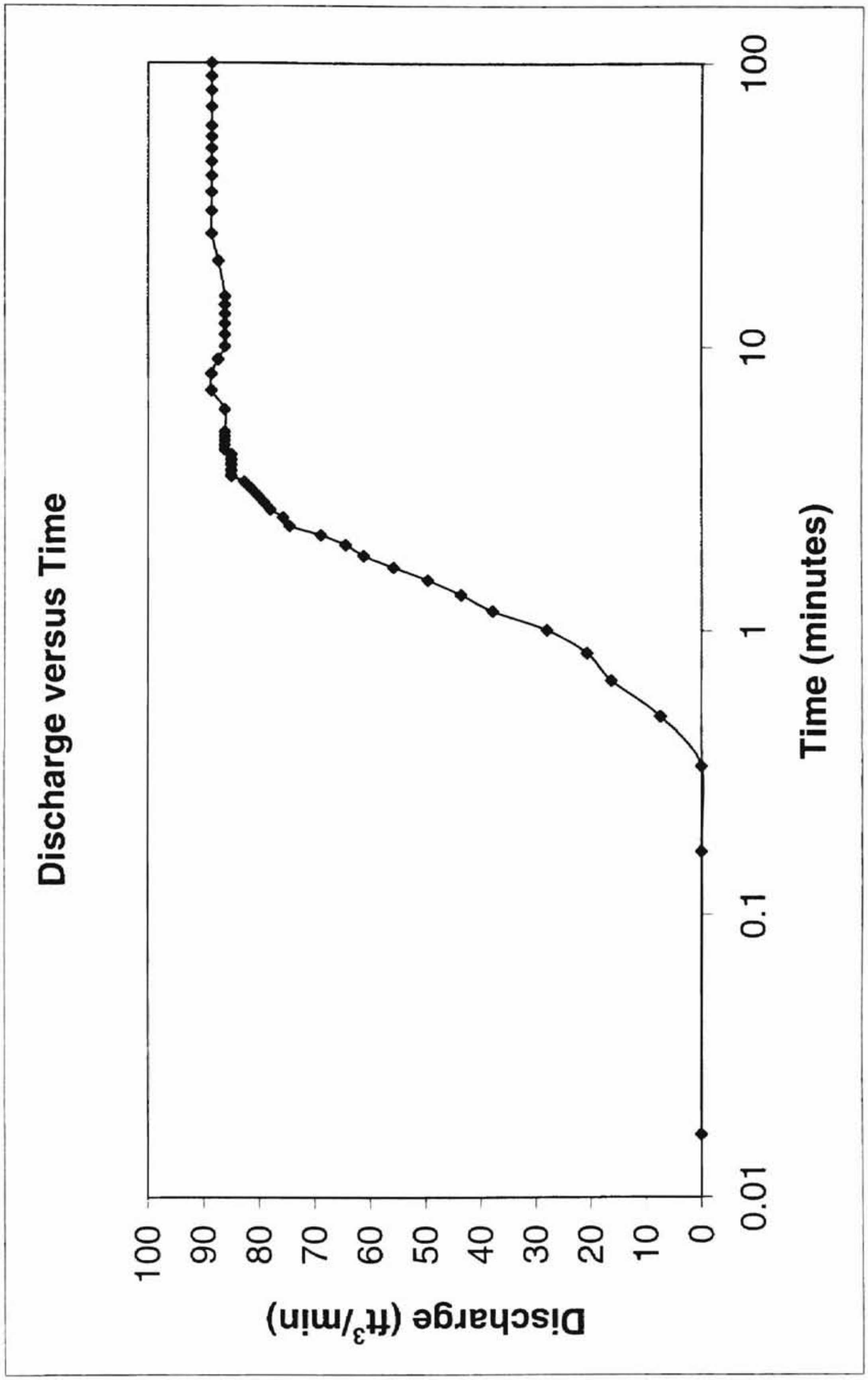


Figure 36
Cross-section of the Arbuckle-Simpson aquifer displaying the estimated head range at Vendome Well
(not to scale)

Estimating Aquifer Parameters

As discussed above, it was necessary to perform a constant drawdown test, which was hypothesized to yield declining flow as a function of time. Prior to the test, it was hypothesized that uncertainty in the early time data would result from open channel flow between the outlet and the measurement point located 65 feet downstream. The data (see Figure 37) show a lag time in flow of approximately fifteen seconds followed by a steady rise until about 3-4 minutes, where flow reaches equilibrium. Note that $t = 0$ is the time that the well was uncapped. Expectations for a constant drawdown test are that flow rate will be initially high, and then decrease until an equilibrium condition is attained. It is believed that this probably occurred during our test, however, the response time of the aquifer was so fast that this expected behavior occurred during the first three minutes of the test, where data are suspect.

Typically, discharge is measured directly at the outlet during a constant drawdown test. No method exists to measure flow at the outlet of Vendome, with the next best option being at the weir, located approximately 65 feet downstream from Vendome. Because of the distance from Vendome, an initial delay occurs in the arrival of water to the weir. Also, open channel flow increases through gradual rising of the water level, which accounts for the progressive increase seen within Figure 37. Despite the biased data, two pertinent facts were obtained from the test. First, an estimate of equilibrium flow from Vendome was obtained. Secondly, the aquifer recovered extremely fast, or in other words, it reached an equilibrium state rapidly. This recovery relates to the hydraulic



Discharge versus Time
Discharge (ft³/min)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
100
Time (minutes)

Figure 37

characteristics of the aquifer at Vendome, and indicates that the aquifer has a high transmissivity, with water being available to the well very quickly.

Because of the skewed flow data, T and S can not be estimated through standard curve matching using equations 1 and 2. Therefore, an alternate means was used to estimate T and S based on the two principal observations that were taken from the test, which was the final flow rate and that the well recovered to equilibrium conditions extremely fast. It was decided that T and S could best be estimated by predicting aquifer response for various values of T and S, and then comparing the results of those predictions to that of these observations.

This method involved plotting flow versus time for varying hydraulic conditions to see which scenario would most closely replicate the results seen in the test at Vendome. To obtain flow (Q) as a function of time, equations 1 and 2 require estimates for T, S, Sw, and rw. Based on well losses (discussed earlier), Sw was assumed to be 67.6 feet. Because the open hole was 6 3/8" in diameter, rw would be 3-3/16" (.2656 feet). Several values of T were considered, recognizing that T = Kb, where K is the hydraulic conductivity and b is the thickness of the aquifer open to the well (475 feet).

At the conclusion of the test (100 minutes), an equilibrium flow rate of 86.2 ft^3/min was estimated. Therefore, all predictions were constrained to recreate this flow. The next step was to select values for transmissivity. It is known that the subsurface material beneath Vendome is consolidated. Also, rapid recovery to equilibrium suggests that the transmissivity of the aquifer is very high. One of the most transmissive consolidated materials is sandstone; therefore, predictions began by using K values representative of consolidated sandstone. The first value chosen for T was 0.5 ft^2/min, which represents the middle to upper range (5×10^{-4} cm/sec) of hydraulic conductivity for a sandstone (Sanders, 1998). Values for $G(\alpha)$ and α at 100 minutes were obtained from equations 1 and 2, which led to the estimation of S for the given transmissivity. Given S, flow values could then be estimated for any prior time. Using this technique, a curve for flow versus time was plotted for T = 0.5 ft^2/min (see Figure 38). The S value for this case was 18.12. According to the definition of S, a lake would have S = 1, and it is unlikely that any physically realistic system could have a higher value; according to Fetter (1994), a confined aquifer has a storativity on the order of 5×10^{-3} or less. Also, after viewing the curve, it is apparent that when T = 0.5 ft^2/min, the head in the well is still recovering at a time much later than witnessed in the test (3 minutes). This suggests that the actual T is higher than our initial assumption.

The second T value chosen was 1 ft^2/min, which represents an upper bound on expected transmissivity for a 475 foot thick consolidated sandstone, because a T = 1 ft^2/min corresponds to the most permeable K (1×10^{-3} cm/sec) for a consolidated sandstone, according to Sanders (1998). The same analysis described for T = 0.5 ft^2/min was repeated and plotted on Figure 38. This curve plotted to the left of the first curve, but recovery was still not as quick as occurred in the aquifer test. Also, for this transmissivity, the storativity was calculated to be 0.2109, which is still much higher than expected for a confined aquifer. It is

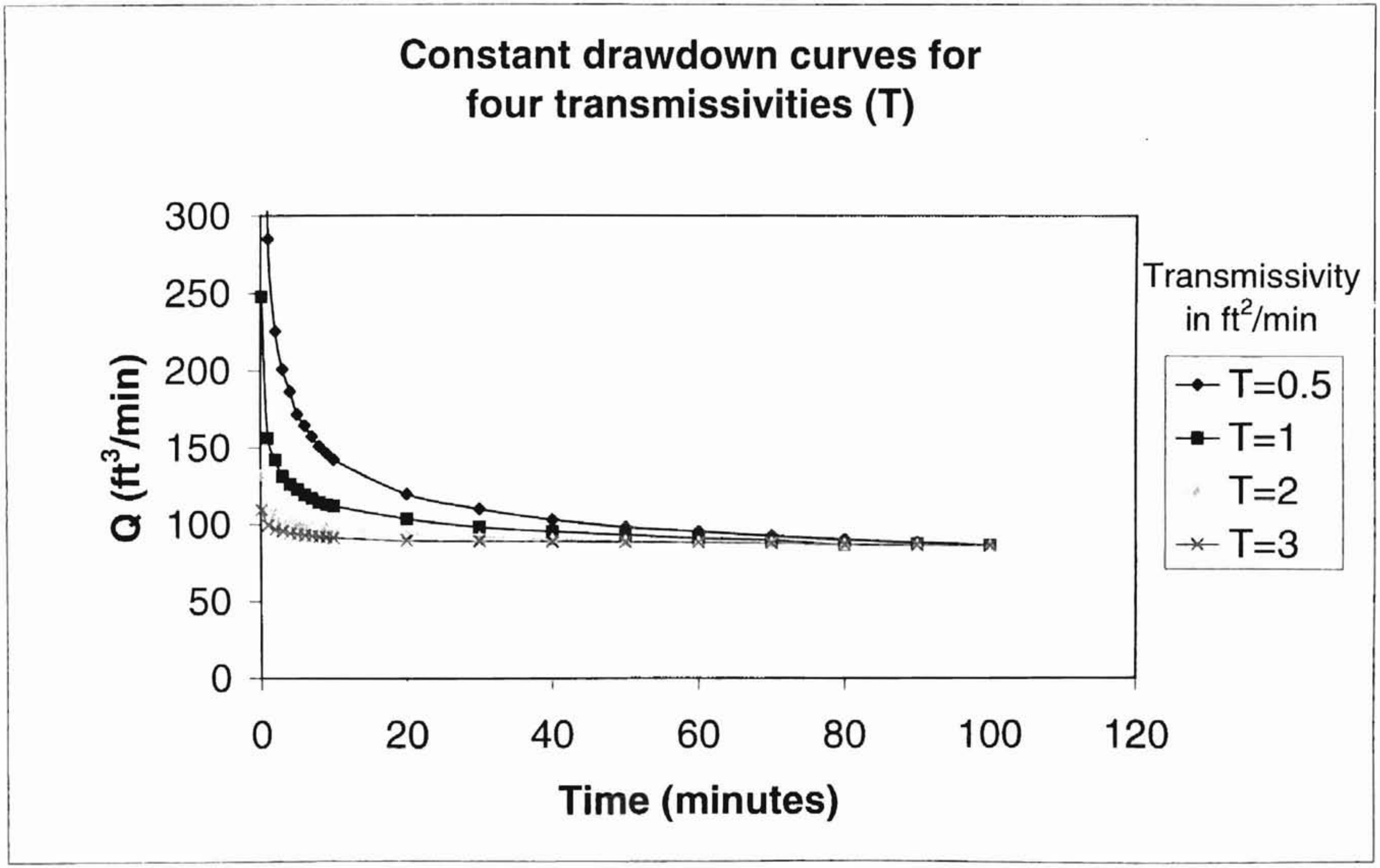

Constant drawdown curves for four transmissivities (T)
Q (ft³/min)
300
250
200
150
100
50
0
0
20
40
60
80
100
120
Time (minutes)
Transmissivity in ft²/min
T=0.5
T=1
T=2
T=3

Figure 38

important to realize that this curve represents the most permeable consolidated sandstone aquifer expected.

When flow versus time data is plotted for $T = 2\ ft^2/min$, the line flattens out more rapidly. This recovery, however, still does not occur as quickly as witnessed in the test, although a much more reasonable S of 1.884×10^{-5} was found under this scenario. Because recovery was occurring faster and S values were becoming more acceptable, it was obvious that increasing transmissivity was starting to produce the desired results. At $T = 3\ ft^2/min$, predicted recovery occurred even quicker than in the previous condition of $T = 2\ ft^2/min$. The well, however, still does not appear to fully recover (flattening of the line) until around 10 minutes, which is later than the 3-4 minute recovery time in the test at Vendome. The trend seems to indicate that as the T is increased, a scenario arises that more closely resembles Vendome. Recovery occurs at a time that is more similar to that of Vendome, while a value for S (8.475×10^{-10}) is within a range associated with a fractured aquifer.

It would have been highly desirable to plot the flow data for a transmissivity of $4\ ft^2/min$ to see the continuation of the trend. Unfortunately, this requires $G(\alpha)$ and α values outside the range of published values. Yet, plots of the four different T scenarios (see Figure 38) display a pronounced trend. As the T is increased (and S subsequently decreased) the line shifts to the left and suggests more rapid recovery.

Although an exact value was not assigned for T and S to the aquifer at Vendome, several important conclusions were reached. Based on inductive reasoning, it was estimated that $T > 3\ ft^2/min$ and $S < 8.475 \times 10^{-10}$. This is significant because it tells us that the transmissivity in the local aquifer is *at least* three times greater than what would be expected in the most permeable consolidated sandstone aquifer, given the previously stipulated conditions at Vendome. Because the rock mass is composed of low permeability carbonate rocks, the best explanation for the observed response is that flow is occurring through secondary porosity, such as fractures. Fractures are known to exist extensively throughout the carbonate Arbuckle Group in the subsurface beneath Vendome. Therefore, it is logical to assume that this is the primary conduit through which flow is delivered to Vendome.

One should be aware of a few relationships that may affect the above results. First of all, as transmissivity is increased, a large change occurs when solving for $G(\alpha)$ in equation 1. In the range of values considered, small changes in T lead to large changes in S. Also, the estimate of Sw is directly dependent on estimated roughness of the open hole portion of the well. Although Sw has a smaller effect than T on flow as a function of time, uncertainty in Sw leads to uncertainty in our estimates of T and S. If Sw is greater than the estimate, then T would go down and S would go up. Conversely, decreased Sw would increase T and lead to a yet smaller S.

CHAPTER XI

CONCLUSIONS AND RECOMMENDATIONS

This thesis led to the following conclusions regarding the hydrologic system at Vendome Well:

1) Data taken from the well cuttings suggests that the Arbuckle Group is lying uncomformably beneath the Vanoss Formation at this locale. The Simpson Group is located stratigraphically between these two units, but this approximately 2000 foot thick group appears to have been removed from the localized subsurface and lithologic examination. X-ray diffraction tests indicate that the carbonate is a uniform and massive dolomitic unit resembling the Arbuckle Group, as opposed to a limestone with sequences of sandstone, which would be more characteristic of the Simpson Group.

2) Chemical analysis of water from Vendome Well indicates that it is derived from a carbonate source. Source rock deduction of the springs and wells in the area suggests that the water at Vendome passes through a mixture of the Arbuckle and Simpson Groups. Although it has been suggested that only the dolomitic Arbuckle Group is lying beneath the Vanoss Formation at Vendome, a mixture could occur if rocks of the Simpson Group lie in the flow path between the recharge area and Vendome.

3) Evaluation of data from a constant drawdown test performed at Vendome indicate that transmissivity is high (> 3 ft^2/min) and storativity is low (< 8.475×10^{-10}). Limitations on data collected during the test and published tables for parameters needed to predict T and S preclude a more accurate estimation of these parameters. The combination of a high transmissivity and low storativity suggests that flow at Vendome is being derived from fractures.

4) Rates of flow from the new well should not be directly compared to those of the original well, as the two wells tap different portions of the aquifer. The original well was drilled to a depth of only 365 feet, whereas the new well was drilled to 775 feet. Therefore, barring a fault zone (the rocks should not change much in 35 feet), one would expect transmissivity of the new well to be much higher, on the basis of increased open hole.

5) Through a combination of hydrologic and geologic information presented within this thesis, evidence suggests that water at Vendome Well is being delivered through fractures located within the Arbuckle Group.

RECOMMENDATIONS

1) Cates (1989) suggested that Vendome lies on a horst, a conclusion that is consistent with data obtained in this thesis. Faults may act as barriers or conduits to flow. We may never fully understand the hydrology of the area as long as the location of major faults and their hydrologic significance remain unknown. Therefore, further investigation of structural and stratigraphic relationships would greatly help our understanding.

2) Due to institutional constraints, formation head was estimated in this study. Head was narrowed to a range between the average height of the potentiometric surface at a topographic high area believed to be the recharge area (upper bound), and the lower bound, which is the elevation at the well outlet. If possible a test that directly measures head would lead to a better understanding of the local aquifer.

3) Numerous springs and wells are located in the area surrounding Vendome. Understanding the influence that these wells and springs have on one another would increase our comprehension of the hydrologic system. In such a test, one would select a group of springs and wells and then monitor flow rates as wells are shut down. The delay time and amount of effect would provide information on the aquifer. One possibility would be to shut in the Sulphur City wells, which are located within a mile of Vendome Well.

4) While data in this thesis suggest fracture flow, confirmation is needed by borehole geophysics. In particular, a video log could be useful in identifying and measuring the producing zones. This log could also be helpful in checking for karstic structures in the subsurface.

REFERENCES

Axtmann, T. C., 1983, Structural mechanisms and oil accumulation along the Mountain View-Wayne Fault, south-central Oklahoma, Shale Shaker, v. 34, p. 1-12.

Barker, B. M., and Jameson, C., 1975, Platt National Park: Environment and Ecology, 1st edition, Norman, Oklahoma, University of Oklahoma Press, 127 p.

Barthel, C. J., 1985, Hydrologic investigation of artesian spring flow, Sulphur, Oklahoma area, unpublished M. S. thesis, University of Oklahoma, 104 p.

Bates, R. L., and Jackson, J. A., 1984, Dictionary of geological terms, 3rd edition, New York, New York, Doubleday Publishers, 571 p.

Bauer, J. A., 1990, Stratigraphy and Conodant Biostratigraphy of the Upper Simpson Group, Arbuckle Mountains, Oklahoma, Oklahoma Geological Survey Guidebook 27, p. 39-53.

Boeger, P. H., 1987, Oklahoma Oasis: from Platt National Park to Chickasaw National Recreation Area, Muskogee, Oklahoma, Western Heritage Books, 211 p.

Booth, S. L., 1981, Structural analysis of portions of the Washita Valley fault zone, Arbuckles Mountains, Oklahoma, Shale Shaker, v. 31, p. 107-120.

Brown, O. H., 1977, Murray County, Oklahoma: In the heart of Eden, Edition 1, Wichita Falls, TX, Nortex Press.

Brown, O. H., 1999, Vendome Well and Sulphur area historian, Personal communication.

Brown, T. L., 1998, Chickasaw National Recreation Area: Societal preferences and rationale for traditional and current collection and consumption of spring waters, unpublished M.S. thesis, Oklahoma State University, 94 p

Brown, R.H., Ferris, J. G., Knowles, D. B., and Stallman, R. W., 1962, Theory of aquifer tests, Geological Survey water-supply paper 1536-E, Washington, D.C., United States government printing office, 95 p.

Burke, K., and Dewey, J. F., 1973, Plume generated triple junctions: key indicators in applying plate tectonics to old rocks, Journal of Geology, v. 81, p. 406-433.

Burke, K., 1977, Aulacogens and continental breakup, Ann. Rev. Earth Planet, Science 5, p. 371-396.

Cates, S. W., 1989, Fault distribution in the Sulphur, Oklahoma area based on gravity, magnetic, and structural data, unpublished M. S. thesis, University of Oklahoma, 101 p.

Carter, D. W., 1979, A study of strike-slip movement along the Washita Valley fault, Arbuckle Mountains, Oklahoma, Shale Shaker, v. 30, p. 80-108.

Cumiford, H. F., Benefield, B. G., Harkins, R. D., Redman, T. N., and Shauntona, B. B., 1968, A study of the bacterial contamination of Hillside Spring at Platt National Park, Ada, Oklahoma, Federal Water Pollution Control Administration, Robert S. Kerr Water Research Center, 34 p.

Cunningham, R., 1941, A study of the bacterial contamination of Hillside Spring at Platt National Park, unpublished M. A. thesis, Oklahoma Agriculture and Mechanical College, 65 p.

Daugherty, R. L., and Franzini, J. B., 1977, Fluid mechanics with engineering applications, New York, NY, McGraw-Hill Book Company, 564 p.

Davis, G. H., 1984, Structural geology of rocks and regions, New York, NY, John Wiley and Sons, Inc., 492 p.

Decker, C. E., 1939, Progress report on the classification of the Timbered Hills and Arbuckle Groups of Rocks, Arbuckle and Wichita Mountains, Oklahoma, Oklahoma Geological Survey Circular no. 22, 62 p.

Decker, C. E., and Merritt, C. A., 1931, The stratigraphy and physical characteristics of the Simpson Group, Oklahoma Geological Survey Bulletin 55, 112 p.

Department of Interior, 1995, Arbuckle project: Appraisal report for the city of Sulphur and the Arbuckle Master Conservancy District, Washington, D.C., United States government printing office, 55 p.

Driscoll, F. G., 1986, Groundwater and wells, 2nd edition, St. Paul, MN, Johnson Division, 1089 p.

Dunham, R. J., 1955, Pennsylvanian conglomerates, structure, and orogenic history of Lake Classen Area, Arbuckle Mountains, Oklahoma, American Association of Petroleum Geologists Bulletin, v. 39, no. 1, p. 1-30.

Fairchild, R. W., Hanson, R. L., and Davis, R. E., 1981, Geohydrology of the Arbuckle-Simpson Aquifer, south-central Oklahoma, Oklahoma Geological Survey, Open-File Report 81-4100, Oklahoma City, OK, 127 p.

Fairchild, R. W., Hanson, R. L., and Davis, R. E., 1990, Hydrology of the Arbuckle Mountains area, south-central Oklahoma, Oklahoma Geological Survey, Circular 91, 112 p.

Fay, R. O., 1989, Geology of the Arbuckle Mountains along Interstate 35, Carter and Murray Counties, Oklahoma, Oklahoma Geological Survey Guidebook 26, 83 p.

Feinstein, S., 1981, Subsidence and thermal history of the southern Oklahoma aulacogen: Implications for petroleum exploration, American Association of Petroleum Geologists Bulletin, v. 65, p. 2521-2533.

Fetter, C. W., 1994, Applied Hydrogeology, 3rd edition, Englewood Cliffs, NJ, Prentice Hall, 691 p.

Gould, C. N., 1906, Platt National Park: Letter of Aug. 13, 1906, to honorable B. A. Hitchcock, Secretary of the Interior, Washington, D.C., 11 p.

Gould, C. N., 1925, Index to the stratigraphy of Oklahoma, Oklahoma Geological Survey Bulletin 35, 115 p.

Gould, C. N., and Schoff, S. L., 1939, Geological report on water conditions at Platt National Park, Oklahoma, National Park Service Report 249, 38 p.

Haas, E. A., 1981, Structural analysis of a portion of the Reagan fault zone Murray County, Oklahoma, Shale Shaker, v. 31, p. 93-105.

Ham, W. E., 1954, Collins Ranch Conglomerate, Late Pennsylvanian in Arbuckle Mountains, Oklahoma, American Association of Petroleum Geologists Bulletin, v. 38, p. 2035-2045.

Ham, W. E., 1955, Geology of the Arbuckle Mountain region, Part I: Geology of the Arbuckle and Timbered Hills group, Part II: Regional stratigraphy and structure of the Arbuckle Mountain region, Oklahoma Geological Survey Guidebook 3, 61 p.

Ham, W. E., Denison, R. E., and Merritt, C. A., 1964, Basement rocks and structural evolution of southern Oklahoma, Oklahoma Geological Survey Bulletin 95, 302 p.

Ham, W. E., 1969, Regional geology of the Arbuckle Mountains, Oklahoma, Oklahoma Geological Survey Special Publication 73-3, 52 p.

Ham, W. E., 1973, Regional geology of the Arbuckle Mountains, Oklahoma, Oklahoma Geological Survey Special Publication 73-3, 61 p.

Ham, W. E., 1978, Regional geology of the Arbuckle Mountains, Oklahoma, Reprinted for the American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, annual convention, Oklahoma City, Oklahoma, Oklahoma Geological Survey Special Publication 73-3, 61 p.

Hanson, R. L., and Cates, S. W., 1992, Appraisal of the hydrology of the Chickasaw National Recreation Area, Murray County, Oklahoma, United States Geological Survey, Water-Resources Investigations Report 92-xxxx, 82 p.

Hanson, R. L., and Cates, S. W., 1994, Hydrogeology of the Chickasaw National Recreation Area, Murray County, Oklahoma, United States Geological Survey, Water-Resources Investigations Report 94-4102, 86 p.

Hoffman, P., Burke, K., and Dewey, J. F., 1974, Aulacogens and their genetic relation to geosynclines, with a Proterozoic example from the Great Slave Lake, Canada *in* Dott, R. H., Jr., and Shaver, R. H. (eds.), Modern and Ancient Geosyncline Sedimentation, Society of Economic Paleontologists and Mineralogists Special Publication 19, p. 38-55.

Hounslow, A. W., 1995, Water Quality Data, New York, NY, Lewis Publishers, 220 p.

Jacob, C. E., and Lohman, S. W., 1952, Nonsteady flow to a well of constant drawdown in an extensive aquifer, American Geophysical Union Transactions, v. 33, p. 559-569.

Jennings, J. N., 1971, An introduction to systematic geomorphology Volume 7: Karst, Canberra, Australia, Australian National University Press.

Johnson, K. S., 1991, Geologic setting of the Arbuckle Group in Oklahoma, Oklahoma Geological Survey Special Publication 91-3, p. 3-7.

Johnson, K. S., Burchfield, M. R., and Harrison, W. E., 1984, Guidebook for Arbuckle field trip, southern Oklahoma, Oklahoma Geological Survey Special Publication 84-1, 21 p.

Johnson, K. S., and McCasland, W., 1971, Highway geology in the Arbuckle Mountains and Ardmore area, southern Oklahoma, 22nd Annual Highway Geology Symposium, April 22, 1971. 73 p.

Kazmann, R. G., 1972, Modern geology, second edition, New York, NY, Harper and Row Publishers.

Kearey, P., and Vine, F. J., 1990, Global tectonics, Boston, MA, Blackwell Scientific Publications, 301 p.

Klein, C., and Hurlbut, C. S., 1993, Manual of mineralogy, 21st edition, New York, NY, John Wiley and Sons, 681 p.

LeMay, H. E., Brown, T. L., and Bursten, B. E., 1990, Chemistry-the central science, 6th edition, Englewood, NJ, Prentice Hall, 348 p.

Lohman, S. W., 1972, Ground-water hydraulics, Geological Survey professional paper 708, Washington, D.C., United States government printing office, 70 p.

Manning, J. C., 1997, Applied principles of hydrology, 3rd edition, Upper Saddle River, NJ, Prentice Hall.

McConnell, D. A., Goydas, M. J., and Chitwood, J. P., 1990, Morphology of the frontal fault zone, southwest Oklahoma: implications for deformation and deposition in the Wichita Uplift and Anadarko Basin, Geology, v. 18, p. 634-637.

Merritt, M. L., 1997, Computation of the time-varying flow rate from an artesian well in central Dade County, Florida, by analytical and numerical simulation methods, United States Geological Survey water-supply paper 2491, Washington, D.C., United States government printing office, 44 p.

Meinzer, O. E., 1923, The occurrence of groundwater in the United States, with Discussion of principles, U.S. Geological Survey water-supply paper 489, Washington, D.C., United States government printing office, 321 p.

Moore, D. M. and Reynolds, R. C. Jr., 1997, X-ray diffraction and the Identification of clay minerals, 2nd edition, New York, NY, Oxford University Press, 330 p.

Munson, B. R., Young, D. F., and Okiishi, T. H., 1990, Fundamentals of fluid Dynamics, New York, NY, John Wiley and Sons, 843 p.

National Park Service, 1985, The Civilian Conservation Corps and the National Park Service, 1933-1942 an administrative history, Washington, D.C., 105 p.

National Park Service, 1996, Planning your visit, Chickasaw National Recreation Area, Southwest Parks and Monuments Association.

National Parks and Conservation Association, 1993, "Chickasaw National Recreation Area" Park Waters in Peril, Washington, D.C., 77 p.

Nicholl, M., Wikle, T., Brown, T., Nord, J., and Parker, R., 1999, Water quality issues at Chickasaw National Recreation Area, Park Science, v. 19, No. 2, p. 30-32.

Perry, W. J., 1989, Tectonic evolution of the Anadarko Basin region, Oklahoma, United States Geological Society Bulletin 1886-A, 19 p.

Prautt, M. A., 1975, The southern Oklahoma aulacogen: A geophysical and geological investigation, unpublished M. S. thesis, University of Oklahoma.

Price, C. L., 1997, Frontal fault zone of the Wichita Mountains: Identification and Characterization of a Fault-Associated Lateral Seal, unpublished M. S. thesis, Oklahoma State University.

Ragland, D. A., and Donovan, R. N., 1991, Sedimentology and diagenesis of the Arbuckle Group in outcrops of southern Oklahoma, Oklahoma Geological Survey Special Publication 91-3, p. 9-29.

Sallee K., and Schoneweis, P. J., 1997, A cultural landscape inventory of the Platt District, Sulphur, Oklahoma, Natrional Park Service.

Sanders, L. L., 1998, A manual of field hydrogeology, Upper Saddle River, NJ, Prentice Hall, 381 p.

Shatski, N. S., 1946, The Great Donets Basin and Wichita system, Comparative tectonics of old landforms, SSSR Izvestia Seriya Geologichaskaya, no. 1, p. 5-62.

Silver, B. A., 1978, Techniques of using geological data, Tulsa, Oklahoma, IED Exploration, Institute, 195 p.

Smith, C.L, and Wilson, B., 1983, Hydrogeology and geochemistry of the Arbuckle-Simpson aquifer in Murray, Carter, Johnston, and Ponotoc Counties, Oklahoma, 38 p.

Streebin, L. E., and Harp, J.F., 1977, Water quality management study for the Chickasaw National Recreation Area, Norman, Oklahoma, University of Oklahoma, 116 p.

Tapp, B., 1997, "Tectonic provinces of Oklahoma", [http://arbuckle.utulsa.edu/oklahoma/arbuckle/arbuckle.html].

Tearpock D. J. and Bischke, R. E., 1991, Applied subsurface geological mapping, Englewood, NJ, Prentice Hall, 648 p.

Thompson, T. L., 1976, Plate tectonics in oil and gas exploration of continental margins, American Association of Petroleum Geologists Bulletin, v. 60, p. 1463-1501.

Thompson, T. L., 1978, Southern Oklahoma oil country in context of plate tectonics (abs.), American Association of Petroleum Geologists, v. 62, p. 567.

Webster, R. E., 1980, Evolution of the southern Oklahoma aulacogen, Oil and Gas Journal, v. 1, p. 150-172.

Webring, M. S., 1985, Saki: A Fortran program for generalized linear inversion of gravity and magnetic profiles, U. S. Geological Survey, Open File Report 85-112.

Wickham, J. W., Roeder, R., and Briggs, G., 1976, Plate tectonic models for the Ouachita Foldbelt, Geology, v. 4, p. 173-176.

Wickham, J. W., 1978, The Southern Oklahoma aulacogen, *in* Field guide to the structure and stratigraphy of the Ouachita Mountains and the Arkoma Basin, Annual meeting of the American Association of Petroleum Geologists, Oklahoma City, 111 p.

Wikle, T., Nicholl, M., Brown, T., Nord, J., and Parker, R., 1998, Water resources management plan for Chickasaw National Recreation Area, National Park Service, 121 p.

Wilson, J. L., Fritz, R. D., and Medlock, P. L., 1991, The Arbuckle Group-relationship of core and outcrop analyses to cyclic stratigraphy and correlation, Oklahoma Geological Survey Special Publication 91-3, p.133-143.

Wyrick, G. G., and Floyd, E. O., 1961, Microtime measurements in aquifer tests on open-hole artesian wells, United States Geological Survey water-supply paper 1545-A, Washington, D.C., United States government printing office, 11 p.

APPENDICES

APPENDIX A

PAUL CHRISTENSEN'S NOTES

DRILLING AND CONSTRUCTION OF VENDOME WELL NO. 2
NOTES TAKEN BY PAUL CHRISTENSEN
14 AUG 1998

(Notes intended for preparing geologic log and describing well cuttings. The well cuttings need to be described in a report of some type.)

October 28, 1997
Interval, ft (depths below land surface)

0-4	Fill (overburden)
2-24	Shale, brown, sandy in part, soft
24-55	Limestone, light gray to light brown, hard, sandy at top

Set and grouted 10-in dia. stainless steel casing to 54 feet bls

October 29, 1997

55-65	Limestone, light gray to light brown, hard
65-70	Arkose, gray
70-75	Shale, light gray, silty, soft
75-85	Shale, gray, hard
85-95	Limestone, light gray to light brown, w/ pyrite
95-100	Arkose, gray
100-115	Shale gray, silty
115-125	Limestone, gray, sandy, oil show
125-136	Shale, brown, gray, black
136-150	Limestone, gray, sandy
150-170	Shale, red, silty to sandy
170-175	Sandstone, gray, fine-grained, w/gray siltstone
175-199	Limestone, light brown, pyrite, greenish color in cuttings at base
199-202	Shale, gray, greenish in part

October 30, 1997. Blew hole dry, no water.

205-230	Sandstone, siltstone, and shale, gray, grading to shale with depth
230-235	Limestone, soft , sandy
235-260	Limestone, gray , hard, some granitic clasts (conglomerate?)
260-273	Shale, gray ,grading to siltstone and fine-grained sandstone
273-287	Sandstone, gray, water, flowing 25 gpm, oil show
277-283	Limestone, gray, flowing 50 gpm
283-302	Shale and limestone, gray, interbedded

October 31, 1997. 6-in stainless steel casing set and grouted to 302 feet

November 3, 1997. Contractor cleaned out hole

302-305	Shale, reddish-brown
305-315	Limestone, gray
315-329	Shale, gray

329-340	Limestone, gray, pyrite, w/ black shale, making water
340-377	Limestone, light gray, making water, rate increasing depth, flowing 60 gpm, water has sulfurous smell
377-402	Limestone, no gain in production

November 12-13, 1997. Measured rate of water flowing from well --120 gpm. Contractor cleaned out hole. Compressor malfunction on November 12.

402-427	Limestone, light gray to gray, fine-grained, w/ black chert, drilling hard
427-430	Limestone, brown, more water
430-435	Shale, grayish brown, silty
435-440	Limestone, light brown, very –fine grained
440-447	Limestone, light brown and light gray, more water, flowing 180 gpm

November 14, 1997

447-450	Limestone, light brown and light gray, w/ dark brown siltstone
450-465	Limestone, light grayish brown, light brown
465-498	Limestone, light brown, w/white calcite fracture fill, flowing 200+ gpm
498-505	Limestone, light gray, hard
505-545	Limestone, light brown, light gray in part, fractures, white calcite fracture fill
545-555	Limestone, gray, not fractured
555-565	Limestone, light brown
565-567	Solution cavity
567-572	Limestone, light brown, fractured
572-577	Limestone, light brown, hard, not fractured

November 15, 1997

577-580	Limestone, light brown
580-600	Limestone, light gray, fractures from 588 down
600-615	Limestone, light brown
615-630	Limestone, light gray and light brown
630-635	Limestone, light brown, more water
635-645	Limestone, light gray
645-662	Limestone, light brown, fractures 645-653
662-664	Solution cavity
664-666	Limestone, light brown
666-668	Solution cavity, flowing 300+ gpm
668-710	Limestone, light brown, fractures at 692 and 695, w/ white calcite fracture fill
710-727	Limestone, gray, fracture at 725

See Drillers log and notes of Tim Jarrell (NPS) for remainder of drilling history, and the completion data regarding the well. Well drilled to a depth of 750 or 775 feet. Cones on drilling bit lost in hole and were not retrievable. Further drilling ceased. Water encountered below 302 feet has sulfurous smell (rotten eggs).

APPENDIX B

PETROLOG OF VENDOME WELL

Petrologic Log

Legend

Company________________________
Well Location________________________
Formation(s) ________________________

Lithology

- Clay/Claystone
- Silty Claystone/ Mudstone
- Silt/Siltstone
- Sand/Sandstone
- Interbedded Sandstone/Mudstone
- Muddy Sandstone
- Conglomerate
- Limestone
- Marl
- Dolomite
- Dolomitic Rocks
- Gypsum/ Anhydrite
- Gypsiferous Rocks
- Halite
- Chert
- Cherty Rocks
- Coal/Lignite
- Volcanic Rocks
- Intrusive Rocks
- Metamorphic

Bedding (B) Laminae (L)

- Massive
- Horizontal
- Initial Slope/Dip
- Graded
- Cross Bedding (Dunes-Waves) T-Trough, P-Planar

Surface Features

- Ripple Laminae C-Current, D-Ripple Drift W-Wave, F-Flaser
- Current Solemarks F-Flute, T-Tool, Fa-Flame

Deformation

- Flowage (F) Faulted (Ft), Load (L)
- Water Escape D-Dish, P-Pipe
- Disrupted M-Mud Crack, D-Dikes S-Syneresis Crack

Organic

- Burrow Trace Fossil
- Bioturbated
- Root Traces

Chemical

- Concretions
- Stylolites

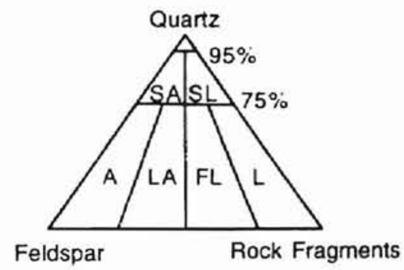
Contacts of Strata

- Abrupt
- Transitional
- Erosional
- Bored
- Deformed

Constituents

Quartz
M-Monocrystalline
P-Polyocrystalline
C-Chert
O-Other
Feldspar
K-K-Feldspar
P-Plagioclase
O-Other
Rock Fragments
M-Metamorphic
I-Intrusive
V-Volcanic
Clay & Carbonate
C-Clay
CA-Carbonate
Fossils
Plant
C-Carbonaceous material
W-Wood
Invertebrates & Algae
A-Algae
Ar-Arthropod
B-Brachiopod
C-Cephalopod
E-Echinoderm
F-Forams
G-Gastropod
P-Pelesopod
S-Sponge
Clay Minerals
C-Chlorite
I-Illite
K-Kaolinite
S-Smectite
ML-Mixed Layer
Carbonate
C-Calcite
FC-Ferrean Calcite
D-Dolomite
Fe-Ferrean Dolomite
S-Siderite
Silica
O-Quartz Overgrowth
M-Micro Quartz
Cd-Chalcedony
Sulfides
P-Pyrite
Sufates
G-Gypsum
A-Anhydrite
B-Berile
Mica
M-Muscovite
B-Biotite

Rock Classification



Cores

45 / 5 / 55 — Core Interval and Core Number

- Recovery
- No Recovery

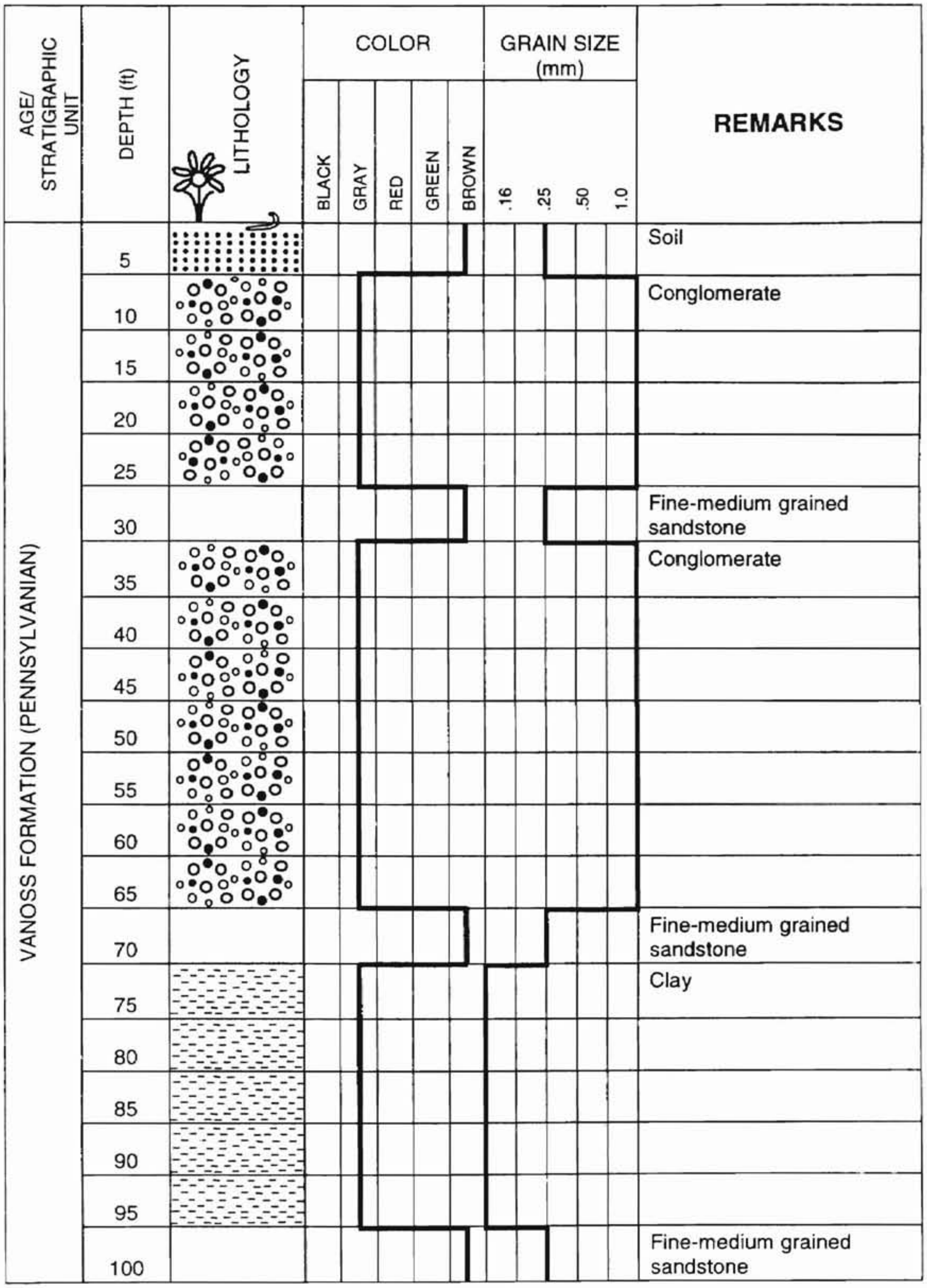
Miscellaneous

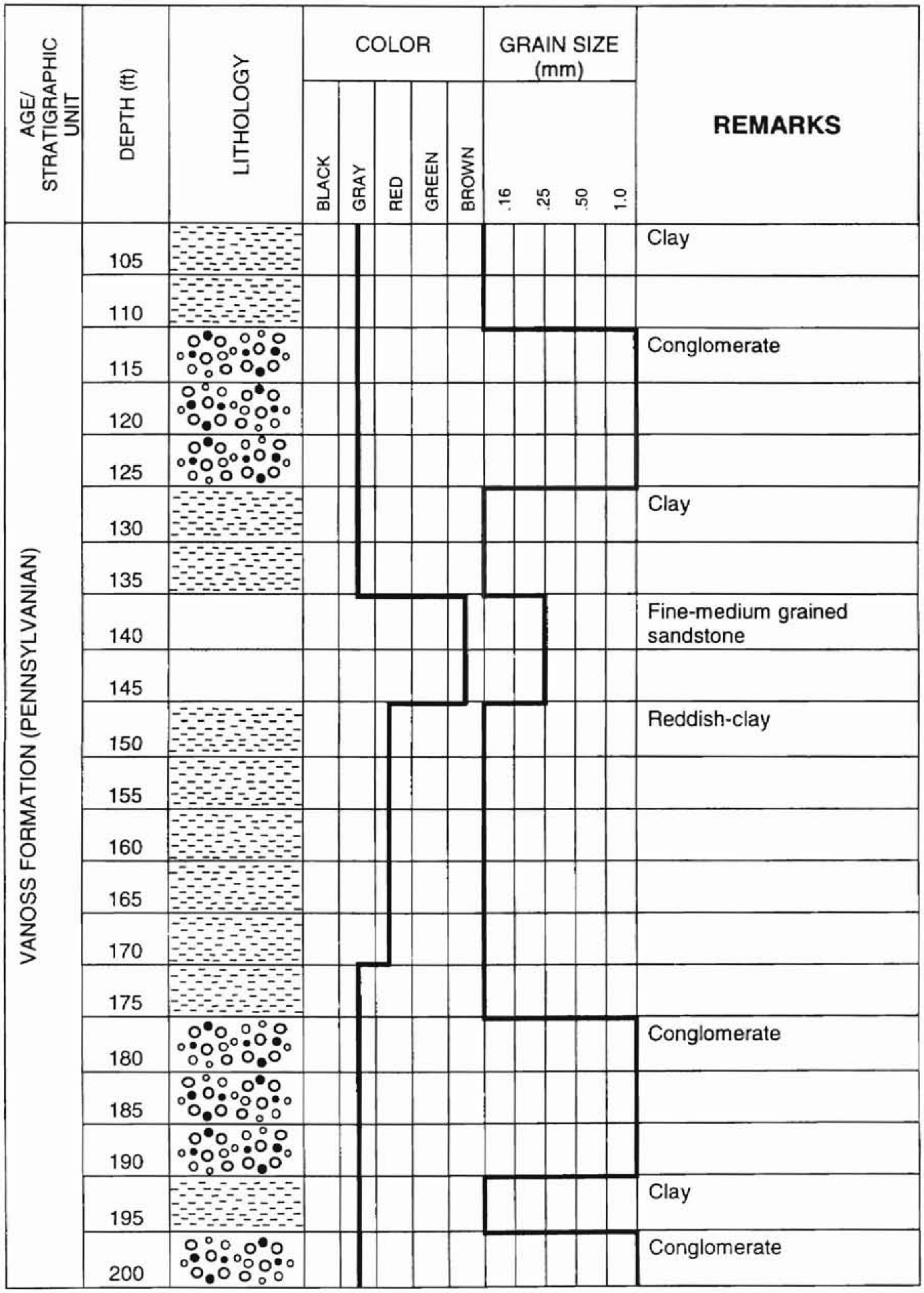
- Thin Section
- P & P Analysis
- SEM

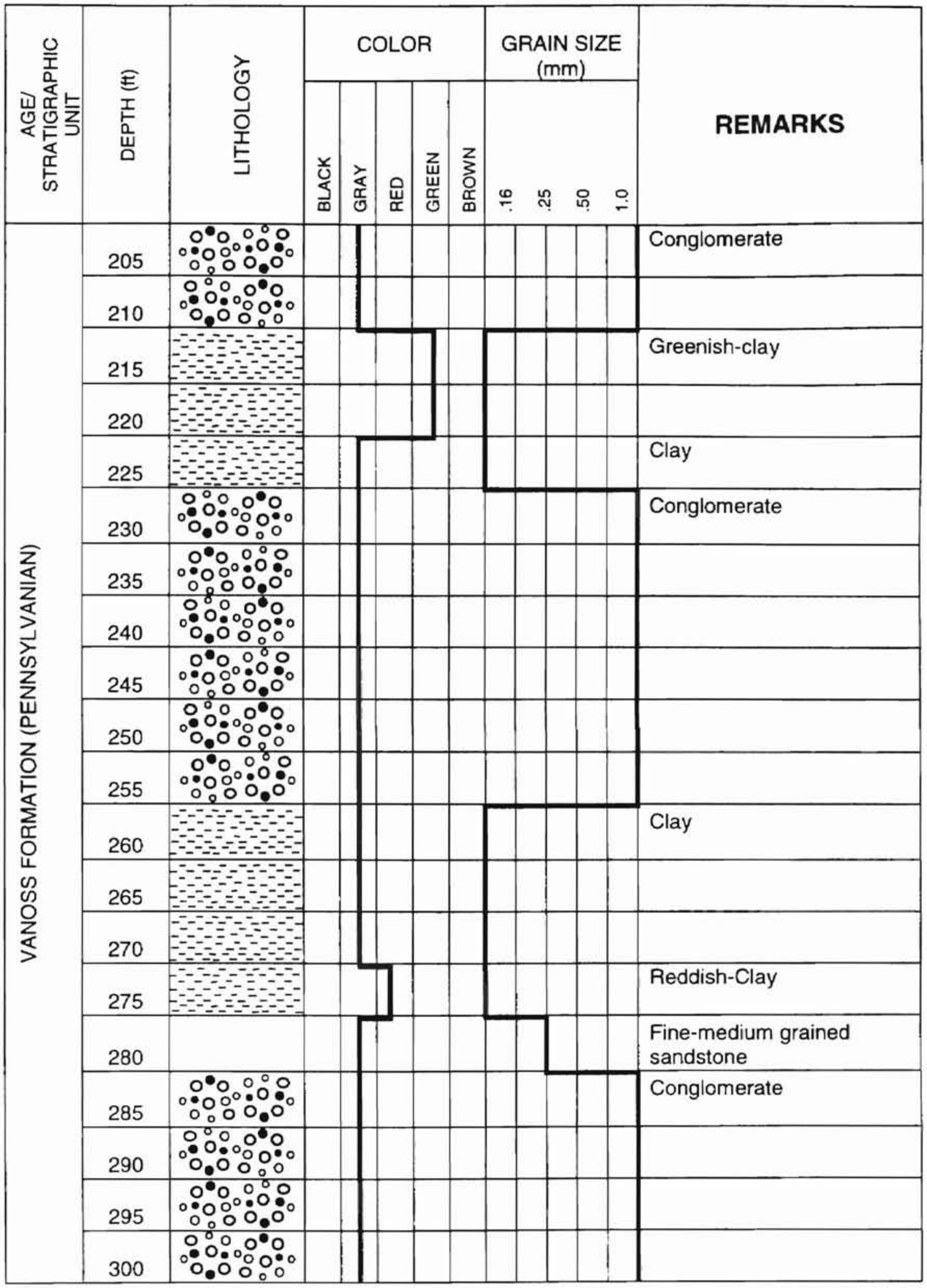
Porosity

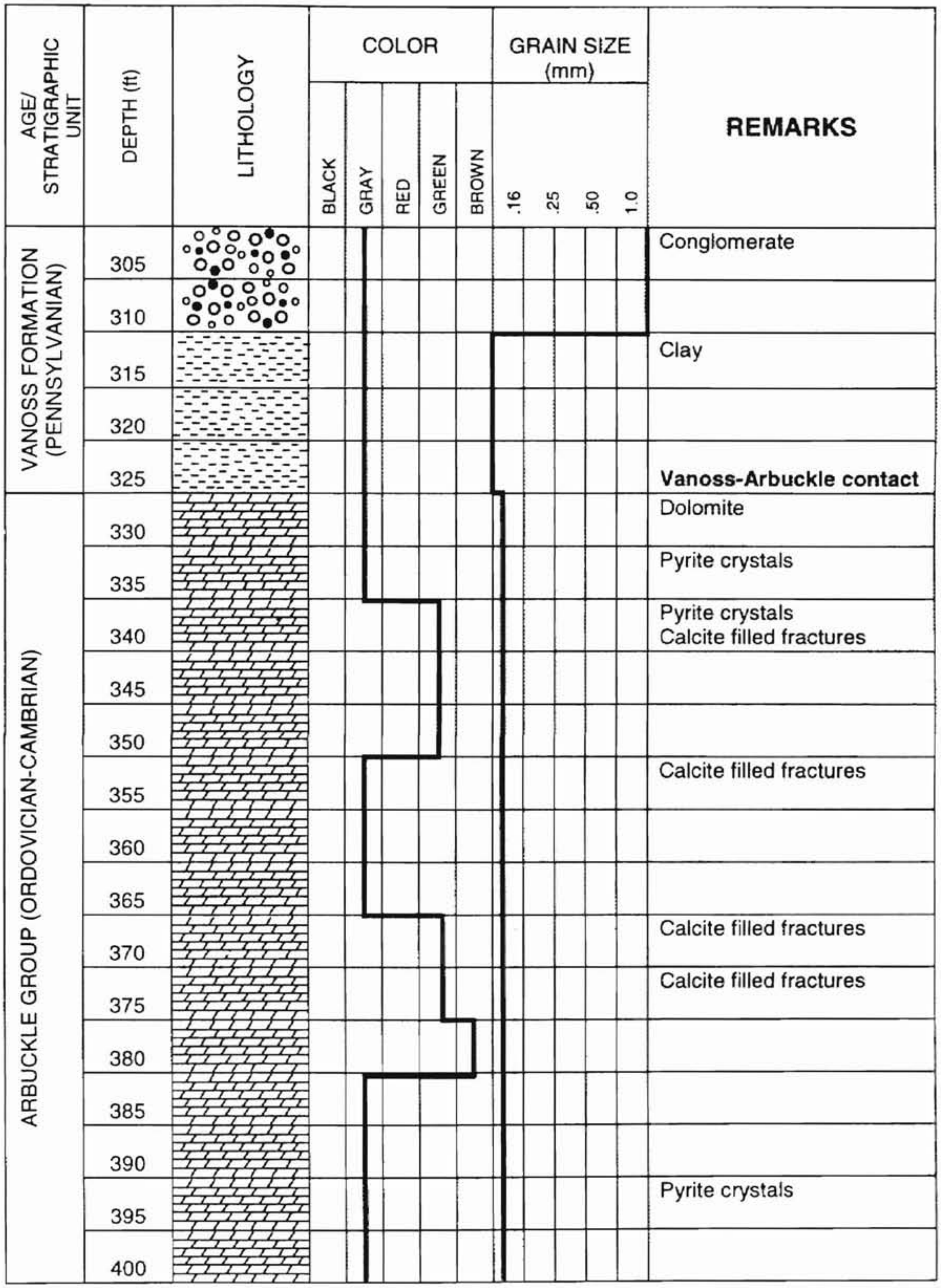
P-Primary
S-Secondary
M-Microporosity

Vendome Well
Location: Sec. 8, T.9N, R.22W. Murray County, OK



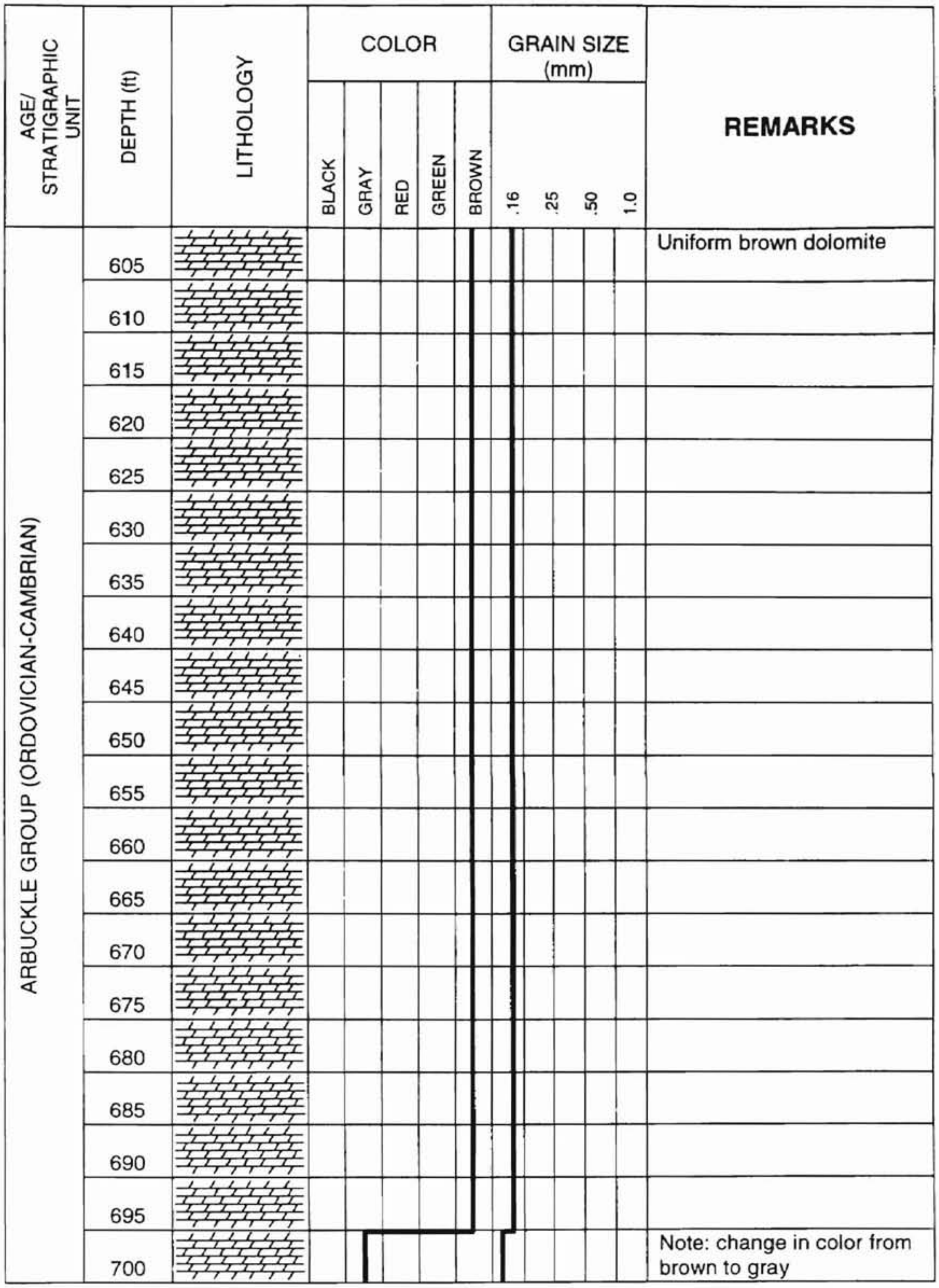

AGE/ STRATIGRAPHIC UNIT
DEPTH (ft)
LITHOLOGY
COLOR
BLACK
GRAY
RED
GREEN
BROWN
GRAIN SIZE (mm)
.16
.25
.50
1.0
REMARKS
VANOSS FORMATION (PENNSYLVANIAN)
105
110
115
120
125
130
135
140
145
150
155
160
165
170
175
180
185
190
195
200
Clay
Conglomerate
Clay
Fine-medium grained sandstone
Reddish-clay
Conglomerate
Clay
Conglomerate


AGE/ STRATIGRAPHIC UNIT
DEPTH (ft)
LITHOLOGY
COLOR
BLACK
GRAY
RED
GREEN
BROWN
GRAIN SIZE (mm)
.16
.25
.50
1.0
REMARKS
VANOSS FORMATION (PENNSYLVANIAN)
205
210
215
220
225
230
235
240
245
250
255
260
265
270
275
280
285
290
295
300
Conglomerate
Greenish-clay
Clay
Conglomerate
Clay
Reddish-Clay
Fine-medium grained sandstone
Conglomerate


AGE/ STRATIGRAPHIC UNIT
DEPTH (ft)
LITHOLOGY
COLOR
BLACK
GRAY
RED
GREEN
BROWN
GRAIN SIZE (mm)
.16
.25
.50
1.0
REMARKS
VANOSS FORMATION (PENNSYLVANIAN)
ARBUCKLE GROUP (ORDOVICIAN-CAMBRIAN)
305
310
315
320
325
330
335
340
345
350
355
360
365
370
375
380
385
390
395
400
Conglomerate
Clay
Vanoss-Arbuckle contact
Dolomite
Pyrite crystals
Pyrite crystals
Calcite filled fractures
Calcite filled fractures
Calcite filled fractures
Calcite filled fractures
Pyrite crystals

AGE/ STRATIGRAPHIC UNIT	DEPTH (ft)	LITHOLOGY	COLOR: BLACK	GRAY	RED	GREEN	BROWN	GRAIN SIZE (mm): .16	.25	.50	1.0	REMARKS
ARBUCKLE GROUP (ORDOVICIAN-CAMBRIAN)	405											
	410											
	415											
	420											
	425											Calcite filled fractures
	430											
	435											
	440											
	445											
	450											
	455											
	460											
	465											
	470											
	475											Note: abrupt change in color from gray to brown
	480											Note: slightly larger grain size in brown dolomite
	485											
	490											
	495											
	500											

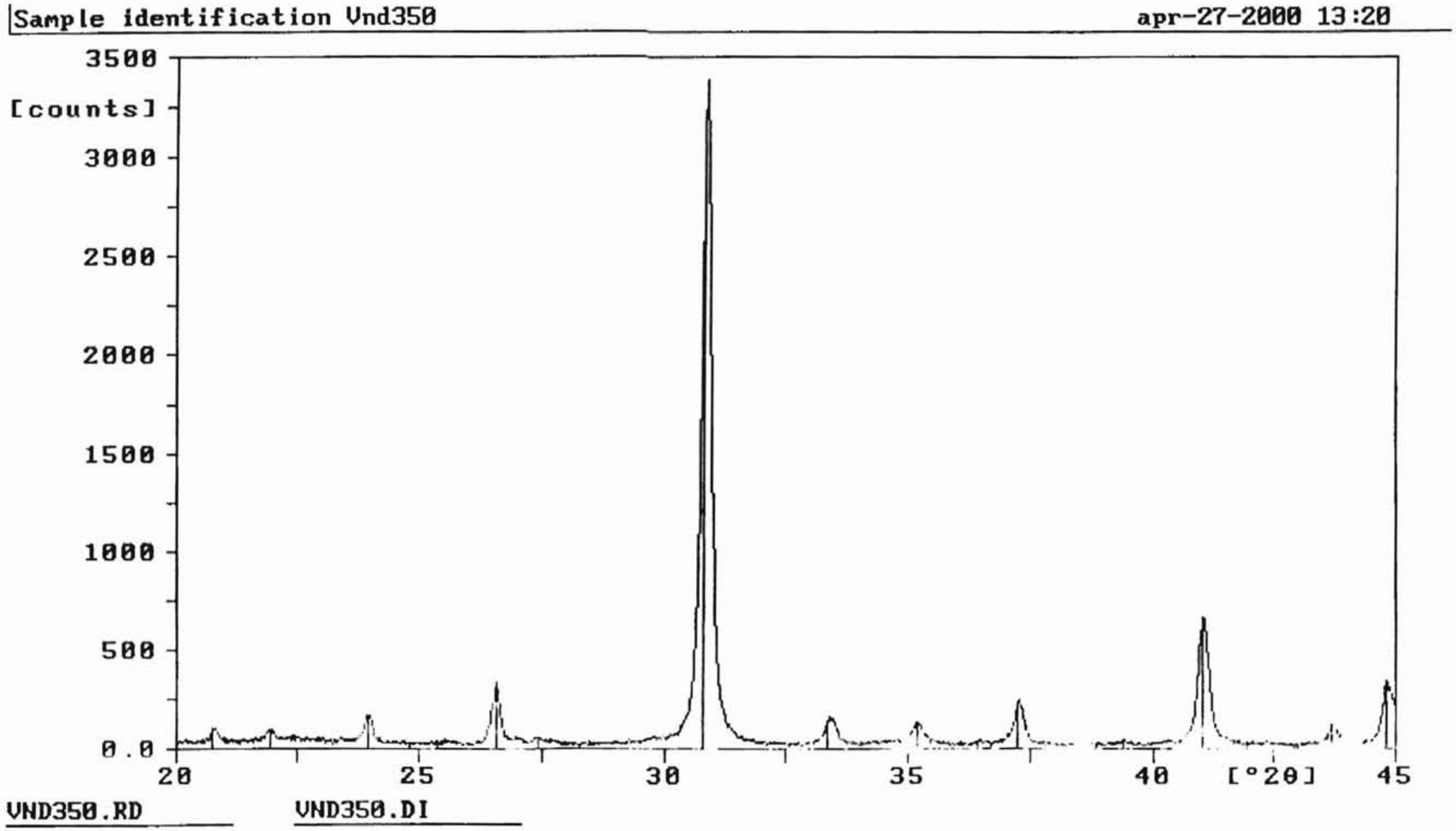
AGE/ STRATIGRAPHIC UNIT	DEPTH (ft)	LITHOLOGY	COLOR					GRAIN SIZE (mm)				REMARKS
			BLACK	GRAY	RED	GREEN	BROWN	.16	.25	.50	1.0	
ARBUCKLE GROUP (ORDOVICIAN-CAMBRIAN)	505											Calcite filled fractures
	510											
	515											
	520											
	525											
	530											Greenish-dolomite
	535											
	540											
	545											
	550											
	555											
	560											
	565											
	570											
	575											
	580											
	585											
	590											
	595											Greenish-dolomite
	600											

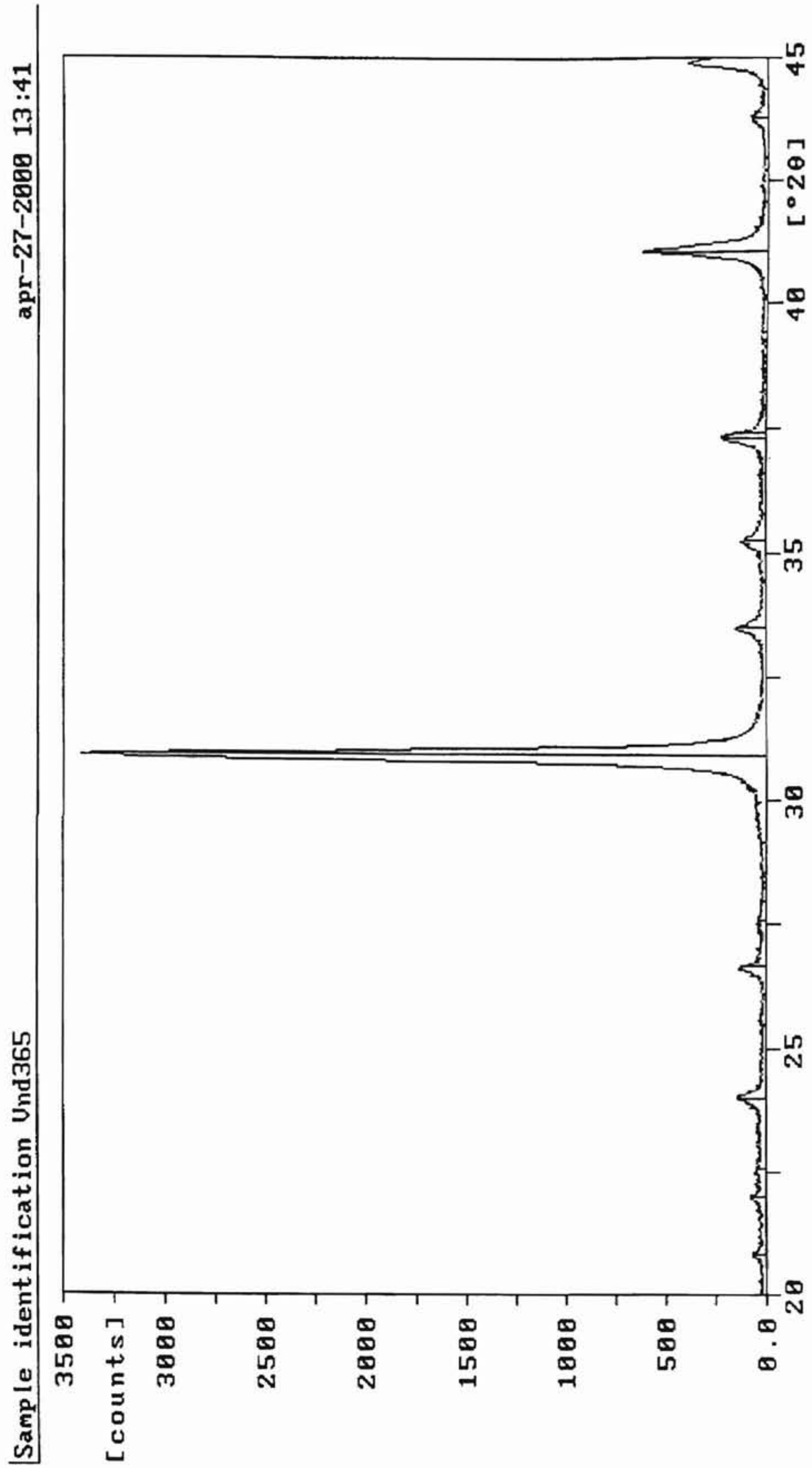

AGE/ STRATIGRAPHIC UNIT
DEPTH (ft)
LITHOLOGY
COLOR
BLACK
GRAY
RED
GREEN
BROWN
GRAIN SIZE (mm)
.16
.25
.50
1.0
REMARKS
ARBUCKLE GROUP (ORDOVICIAN-CAMBRIAN)
605
610
615
620
625
630
635
640
645
650
655
660
665
670
675
680
685
690
695
700
Uniform brown dolomite
Note: change in color from brown to gray

AGE/ STRATIGRAPHIC UNIT	DEPTH (ft)	LITHOLOGY	COLOR					GRAIN SIZE (mm)				REMARKS
			BLACK	GRAY	RED	GREEN	BROWN	.16	.25	.50	1.0	
ARBUCKLE GROUP (ORDOVICIAN-CAMBRIAN)	705											Uniform gray dolomite
	710											
	715											
	720											
	725											
	730											
	735											
	740											
	745											
	750											
	755											
	760											
	765											
	770											
	775											

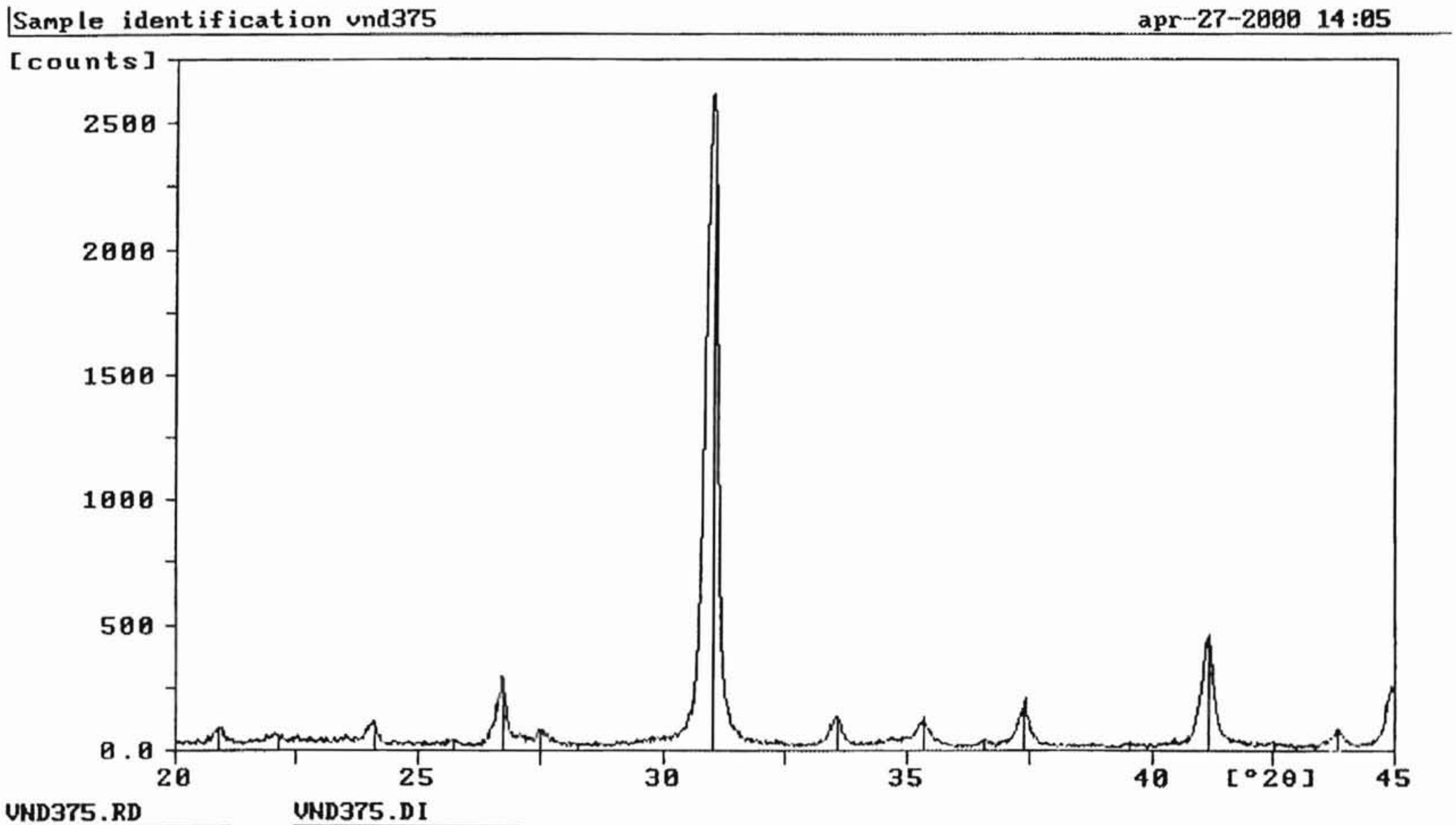
APPENDIX C

X-RAY DIFFRACTION

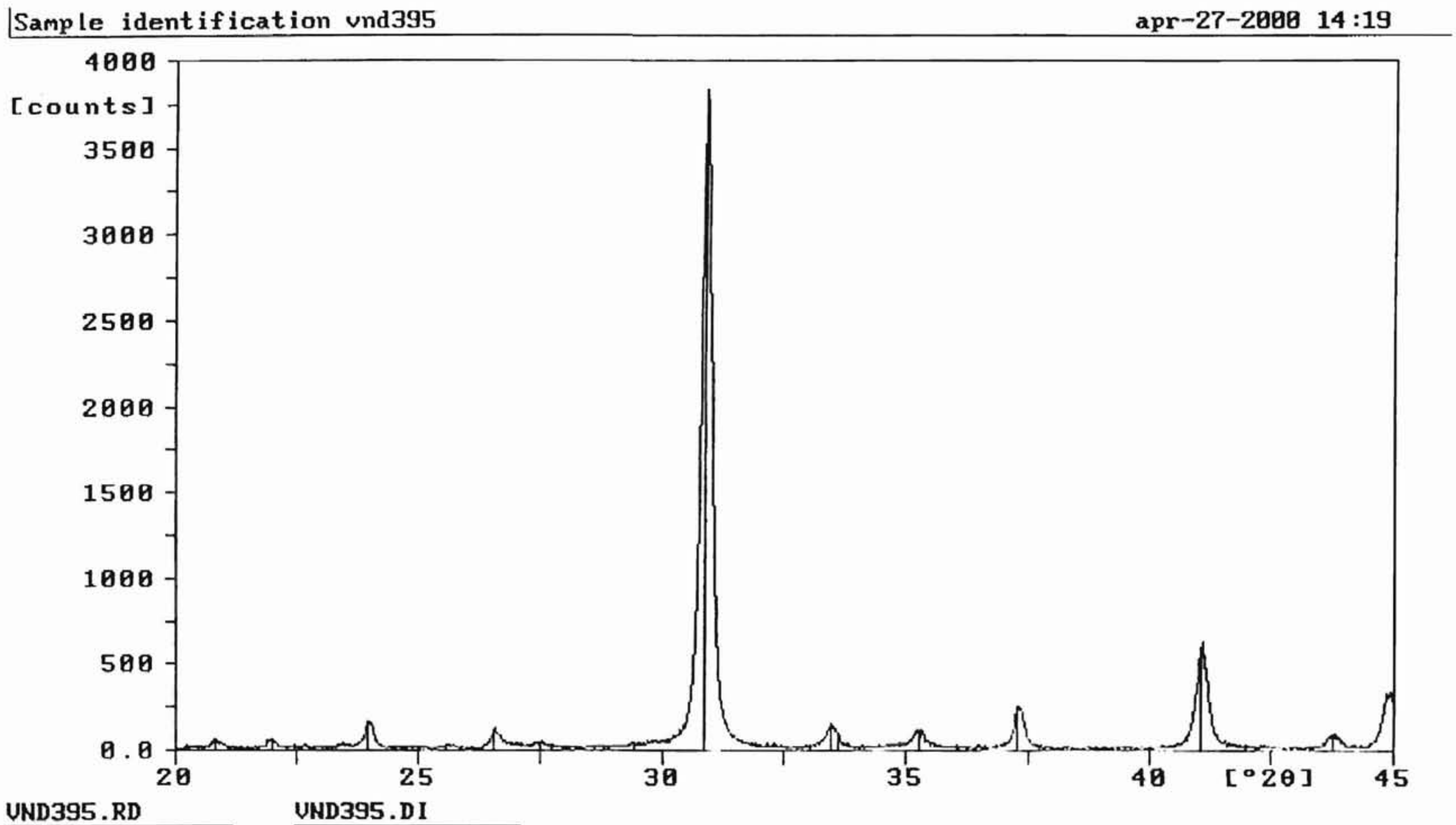

Sample identification Vnd350
apr-27-2000 13:20
3500
[counts]
3000
2500
2000
1500
1000
500
0.0
20
25
30
35
40
[°2θ]
45
VND350.RD
VND350.DI

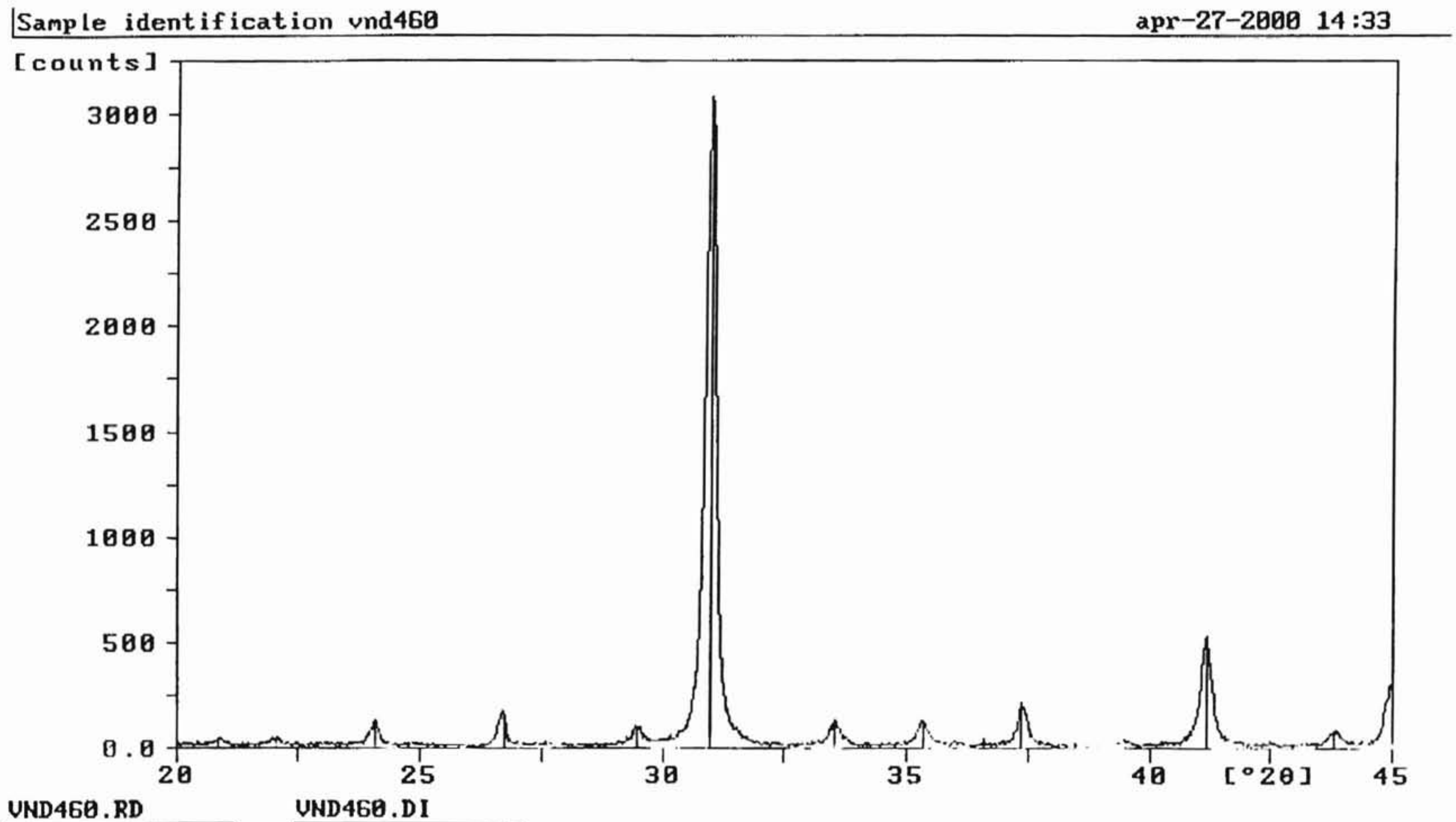


Sample identification Und365
apr-27-2000 13:41
3500
[counts]
3000
2500
2000
1500
1000
500
0.0
20
25
30
35
40
45
[°2θ]
UND365.DI
UND365.RD

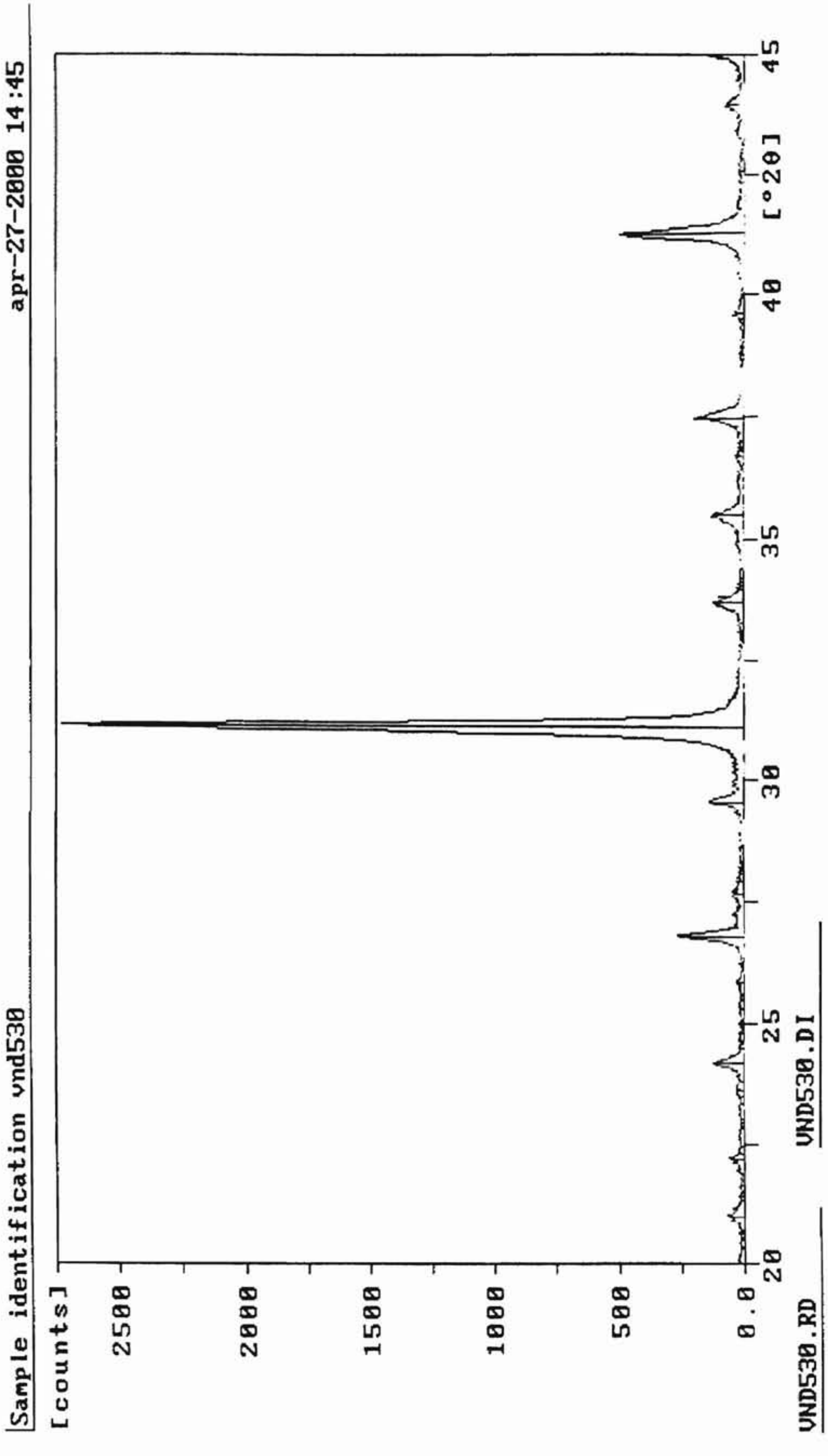


Sample identification vnd375
apr-27-2000 14:05
[counts]
2500
2000
1500
1000
500
0.0
20
25
30
35
40
[°2θ]
45
VND375.RD
VND375.DI

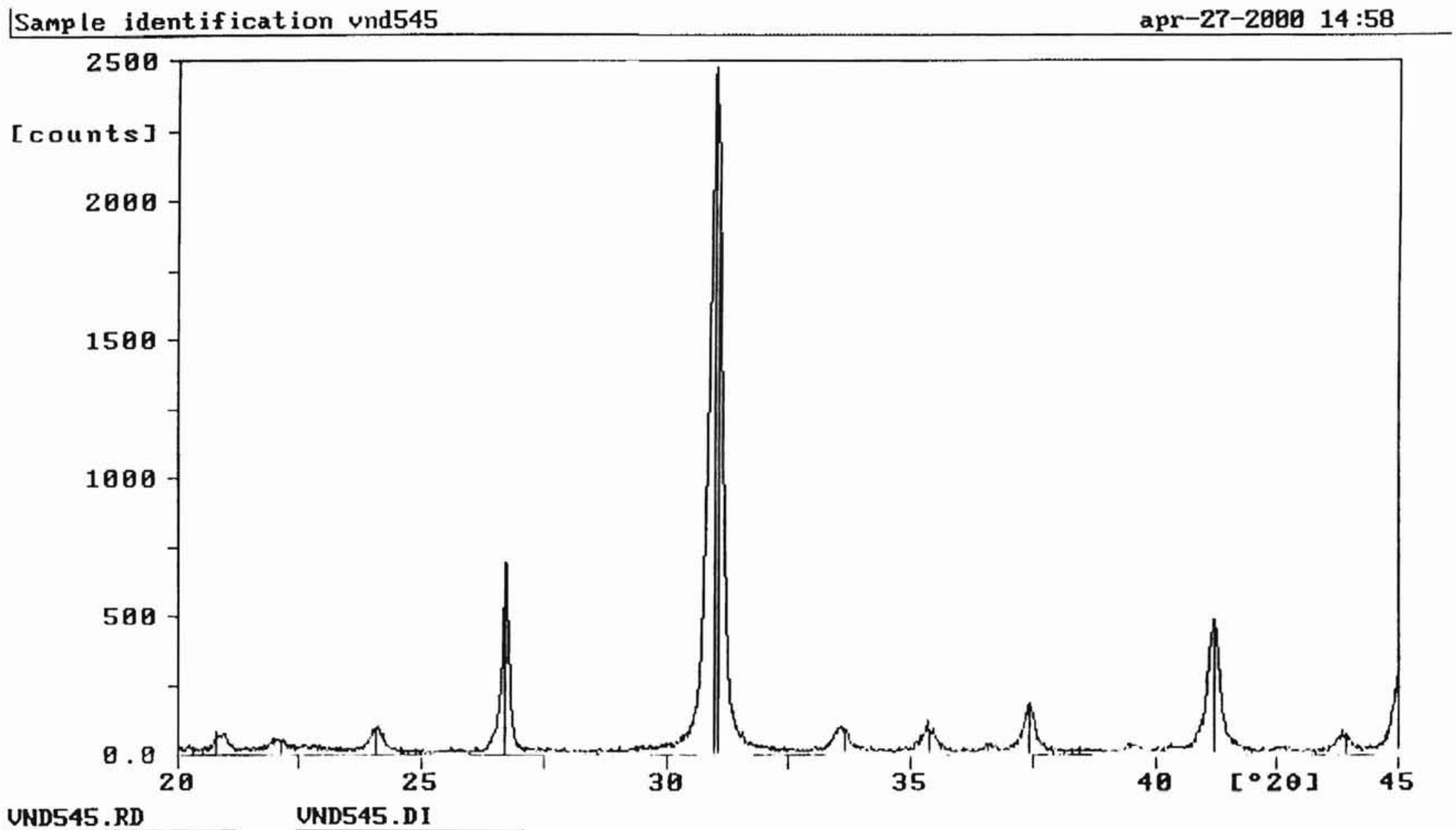

Sample identification vnd395
apr-27-2000 14:19
4000
[counts]
3500
3000
2500
2000
1500
1000
500
0.0
20
25
30
35
40
[°2θ]
45
VND395.RD
VND395.DI

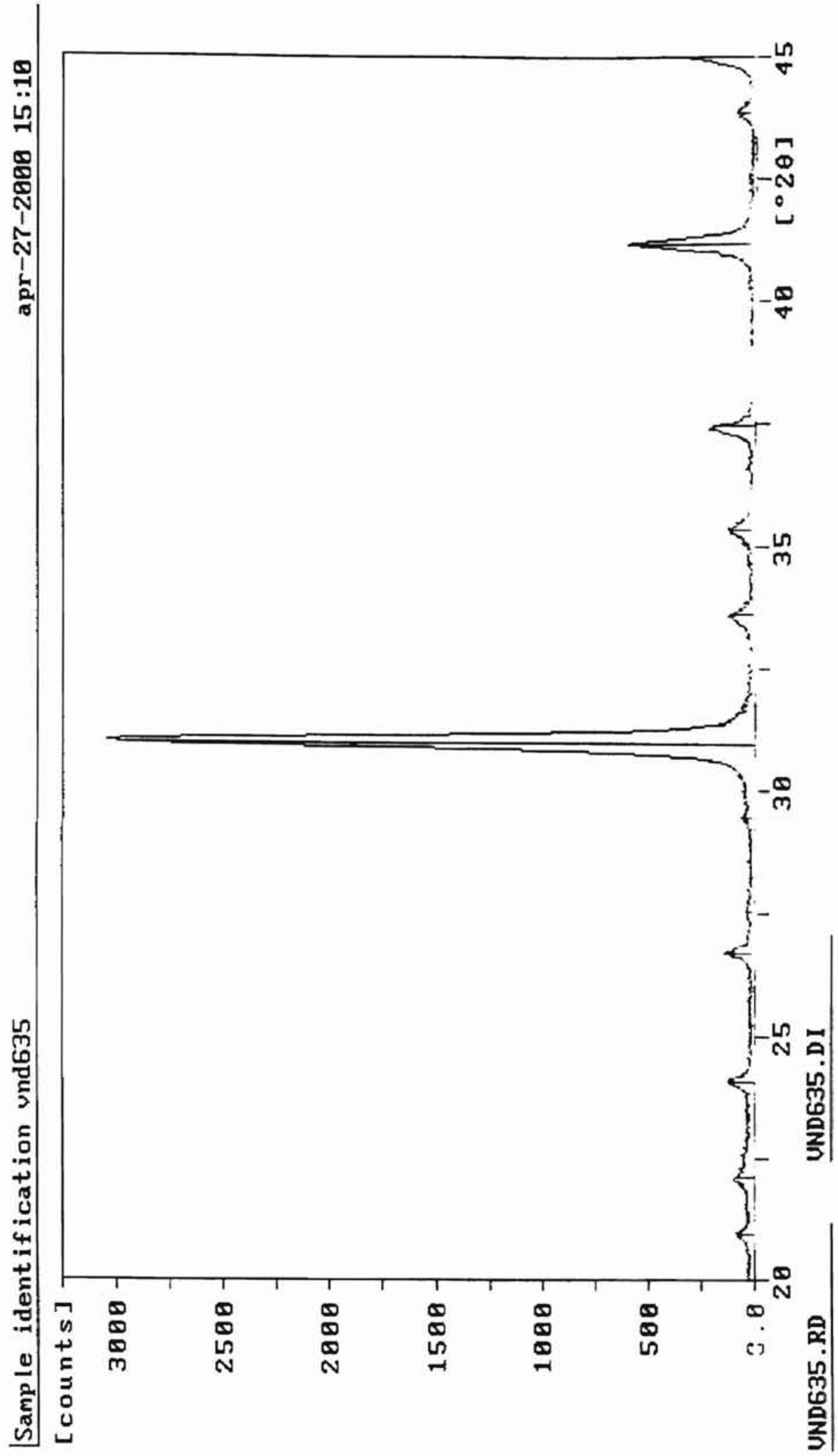


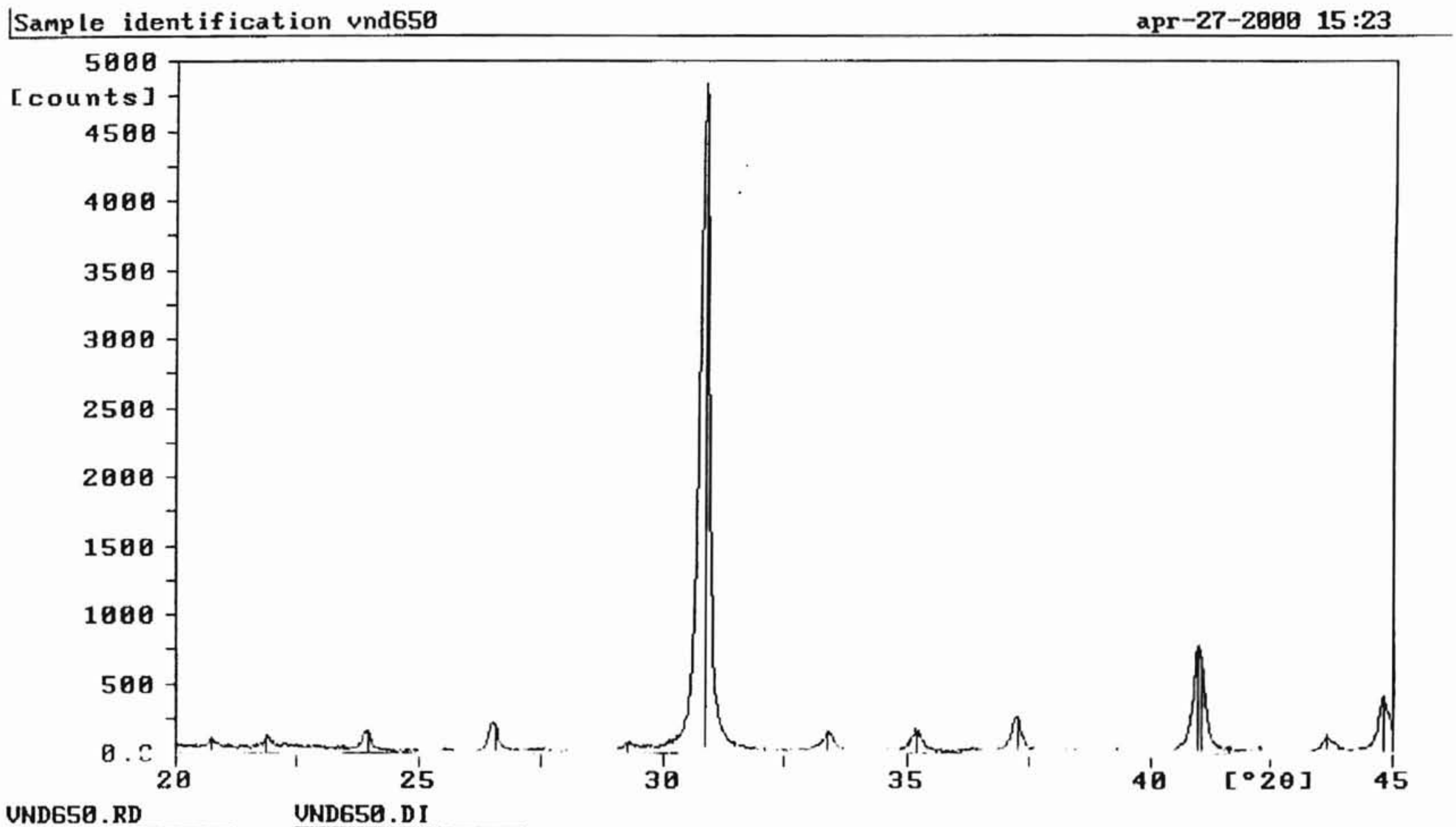
Sample identification vnd460
apr-27-2000 14:33
[counts]
3000
2500
2000
1500
1000
500
0.0
20
25
30
35
40
[°2θ]
45
VND460.RD
VND460.DI

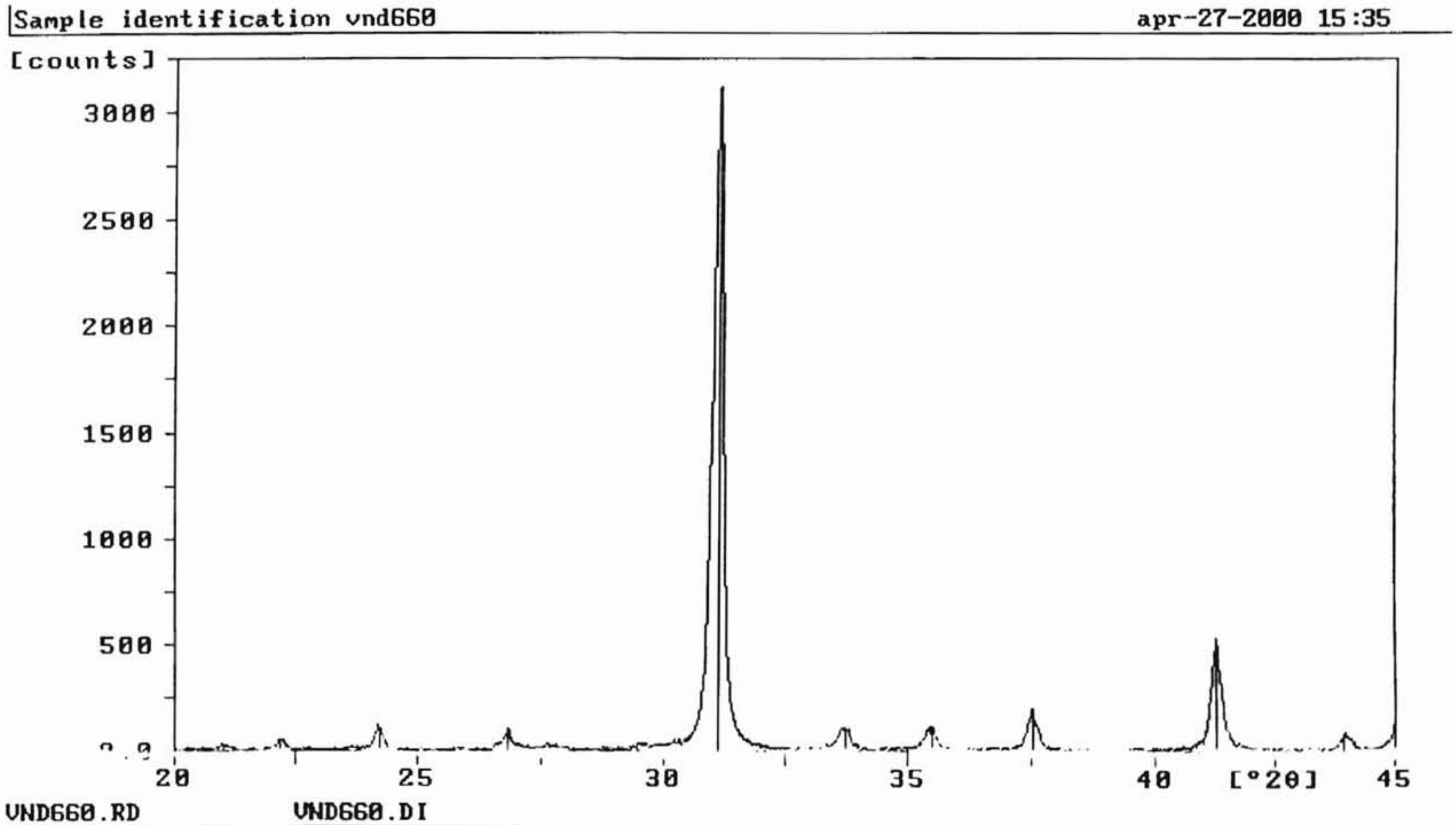


Sample identification vnd530
apr-27-2000 14:45
[counts]
2500
2000
1500
1000
500
0.0
20
25
30
35
40
45
[°2θ]
VND530.RD
VND530.DI


Sample identification vnd545
apr-27-2000 14:58
2500
[counts]
2000
1500
1000
500
0.0
20
25
30
35
40
[°2θ]
45
VND545.RD
VND545.DI


Sample identification vnd635
apr-27-2000 15:10
[counts]
3000
2500
2000
1500
1000
500
0.0
20
25
30
35
40
45
[°2θ]
VND635.RD
VND635.DI


Sample identification vnd650
apr-27-2000 15:23
5000
[counts]
4500
4000
3500
3000
2500
2000
1500
1000
500
0.0
20
25
30
35
40
[°2θ]
45
VND650.RD
VND650.DI


Sample identification vnd660
apr-27-2000 15:35
[counts]
3000
2500
2000
1500
1000
500
20
25
30
35
40
[°2θ]
45
VND660.RD
VND660.DI

VITA

Jason Daryl Nord

Candidate for the degree

of Master of Science

Thesis: GEOLOGIC AND HYDROLOGIC CONTROLS ON FLOW AT VENDOME WELL, SULPHUR, OK

Major Field: Geology

Biographical:

Personal Data: Born in Bottineau, North Dakota, on April 25, 1973, the son of Daryl and Barbara Nord.

Education: Graduated from Stillwater High School, Stillwater, Oklahoma in May 1991; received Bachelor of Science degree in Geology from Oklahoma State University, Stillwater, Oklahoma in May 1996. Completed the requirements for the Master of Science degree with a major in Geology at Oklahoma State University in July 2000.

Experience: Research assistant for the School of Geology.

Professional Memberships and Awards: President's Honor Roll, Dean's Honor Roll, 1994 Oklahoma State University Outstanding Male Residence Hall Athlete.