

**ENVIRONMENTAL EFFECTS OF OILFIELD  
OPERATIONS AND SECONDARY  
RECOVERY IN THE CEMENT  
FIELD, CADDO COUNTY,  
OKLAHOMA**

**By**

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The study of geology is not an exact science, although many geologists employ mathematics to describe natural geologic processes. Of necessity, mathematical solutions require assumptions about conditions below the surface of the earth of which the geologist may have little or no knowledge. The good geologist has the ability to visualize and understand the rocks beneath his feet and to use this ability to qualify the mathematical model of the natural processes. Dr. Wayne Pettyjohn has often said that anyone can analyze data that fits the model, but a skilled geologist is able to explain the data that deviates from the model.

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## NOMENCLATURE

bgs	below ground surface
Ca	calcium
Cl	chloride
CO <sub>3</sub>	carbonate
EPA	Environmental Protection Agency
gpd	gallons per day
gpd/ft	gallons per day per foot
gpd/ft <sup>2</sup>	gallons per day per square foot
gpm	gallons per minute
HCO <sub>3</sub>	bicarbonate
K	hydraulic conductivity
Mg	magnesium
m	saturated thickness
meq/l	milliequivalent per liter
mg/l	milligram per liter
Na	sodium
NO <sub>3</sub>	nitrate
OSDH	Oklahoma State Department of Health

OWRB	Oklahoma Water Resources Board
ppb	parts per billion
ppm	parts per million
S	storativity
s	drawdown
SiO <sub>2</sub>	silica
SO <sub>4</sub>	sulfate
T	transmissivity
U.S.G.S.	United States Geological Survey

## CHAPTER I

### INTRODUCTION

The mid-continent region of the United States is well known for petroleum hydrocarbon production. Until development of vast oil and natural gas fields in Alaska and the offshore areas of California and Texas, the mid-continent region produced the majority of domestic petroleum consumed in the United States. Early exploration efforts and field development were associated with surface topographic features which provided early geologists an indication that shallow structural traps may be present beneath the surface features. One of these surface features was the Cement Anticline located in Caddo County, Oklahoma. Exploratory drilling on the Cement Anticline led to the discovery of the Cement field in 1917 and exploration and development drilling have been extensive since its discovery. In the early 1970s, portions of the Cement field were unitized for secondary recovery operations consisting of waterfloods.

Oilfield operations use large and varied amounts of chemicals during drilling, completion, and workover activities. These chemicals are beneficial to the oil operators in performing their tasks, but when improperly stored, handled, or disposed of, can be sources of contamination to ground-water resources. Additionally, by-products of oil production, specifically produced formation water, can provide sources

of contamination to the environment. The produced oil itself can contaminate ground-water supplies through spillage during production, storage, or transportation activities.

The oil industry, especially in the early to mid 1900s, was not highly regulated and many operational practices had a severe impact on ground-water contamination. Chief among these practices were the surface disposal of produced formation water, the lack of protection of potable ground-water aquifers through the deficient use of surface casing, and the techniques used to abandoned wells. Even today the exploration and development activities of the oil industry are exempt from many environmental laws, and in fact are exempt from the definition of hazardous waste in the Resource Conservation and Recovery Act (RCRA).

The town of Cyril, Oklahoma is located in the southeastern portion of Caddo County approximately four miles south of the Cement field. Historically, the town has used ground water from the Rush Springs Sandstone as its domestic water supply. In 1947, chloride contamination was detected in the town's water supply well and the next year the well was abandoned. From 1948 through 1985, twelve additional wells were drilled; the wells were drilled successively further from the Cement field and deeper, to avoid the chloride contamination in the Rush Springs aquifer. By 1991, all of the Cyril water supply wells had been abandoned and the town had been connected to a Rural Water District line.

The purpose of this investigation was threefold: to characterize the geology, hydrogeology, and ground-water geochemistry of the Rush Springs Sandstone aquifer and deeper aquifers; to determine the types of chemicals attributable to oilfield operations and the migration pathways which may impact the environment; and to

determine which source and migration pathway of chloride contamination was responsible for abandonment of the Cyril well field.

The study area for the investigation is in Section 1, Township 5 North, Range 10 West and Section 6, Township 5 North, Range 9 West (Figure 1). Approximately 260 completion cards and 140 borehole geophysical logs were reviewed and evaluated to determine well construction details and subsurface stratigraphy of the exploration and development wells located in the study area. A total of 115 published ground-water chemical analyses were evaluated to determine the geochemistry of the subsurface aquifers.

Computer models used in this investigation include WATEVAL and the USGS Solute Transport Model. WATEVAL, developed by Hounslow and Goff (1991), performs a sequence of analytical checks and comparisons to indicate the overall quality of the entered analysis. Various ion ratios are calculated to suggest possible source rocks through which ground water may infiltrate or flow. WATEVAL also presents information in two graphical formats, the Piper plot and the Stiff diagram. Possible source rocks are suggested on the Piper plot and Stiff diagrams. The Piper plot can be used to indicate various geochemical reactions such as mixing, ion exchange, precipitation, and dissolution. The USGS Solute Transport Model, developed by Konikow and Bredehoeft (1978) was used to calculate the concentrations of chloride in the Rush Springs/Marlow aquifers at specific places and times. The model is a two-dimensional Fortran code which solves flow equations using a finite-difference method and uses the method of characteristics to solve solute-transport equations.

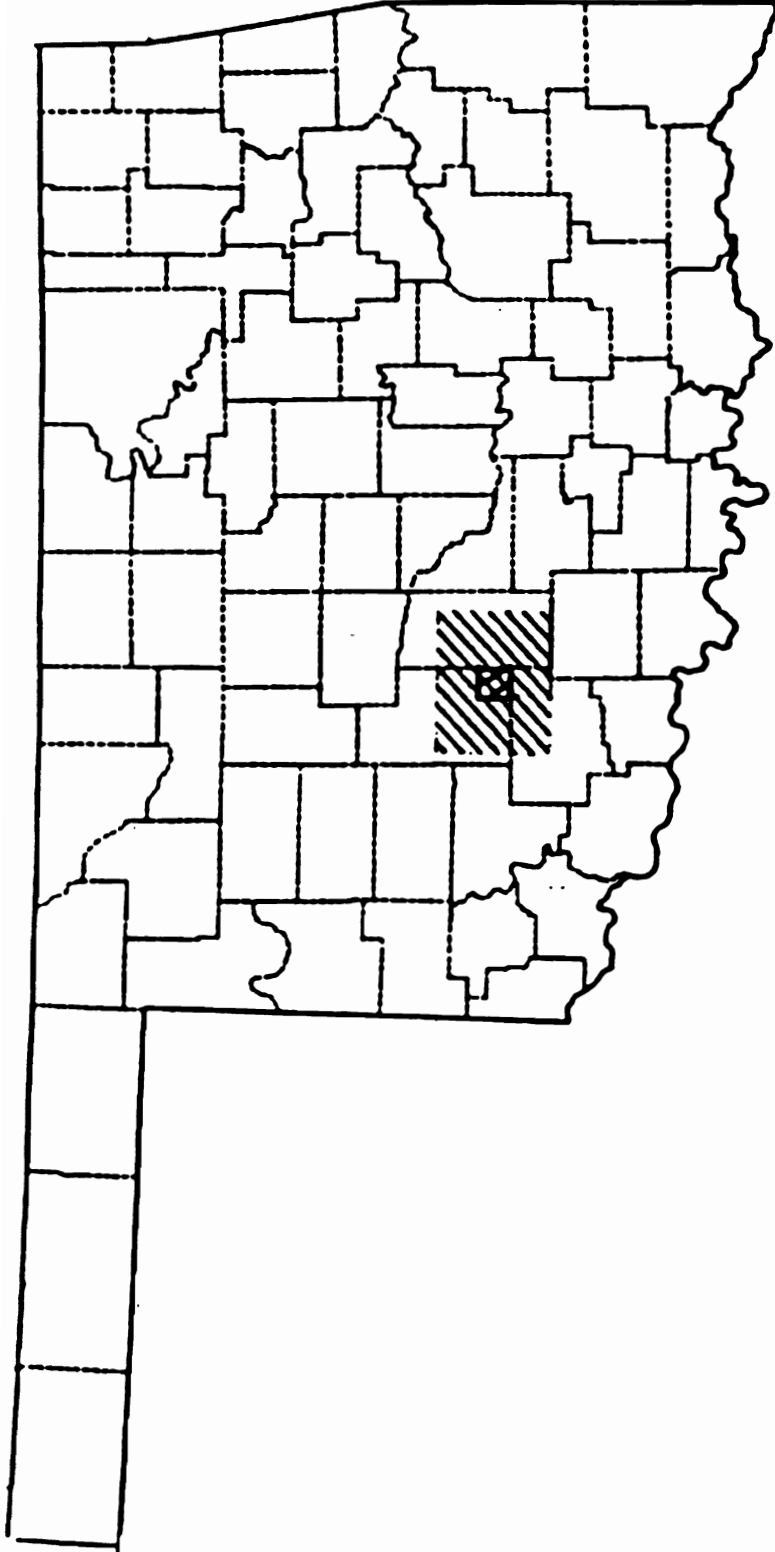


Figure 1. Study Area in Caddo County, Oklahoma

## CHAPTER II

### GEOLOGY

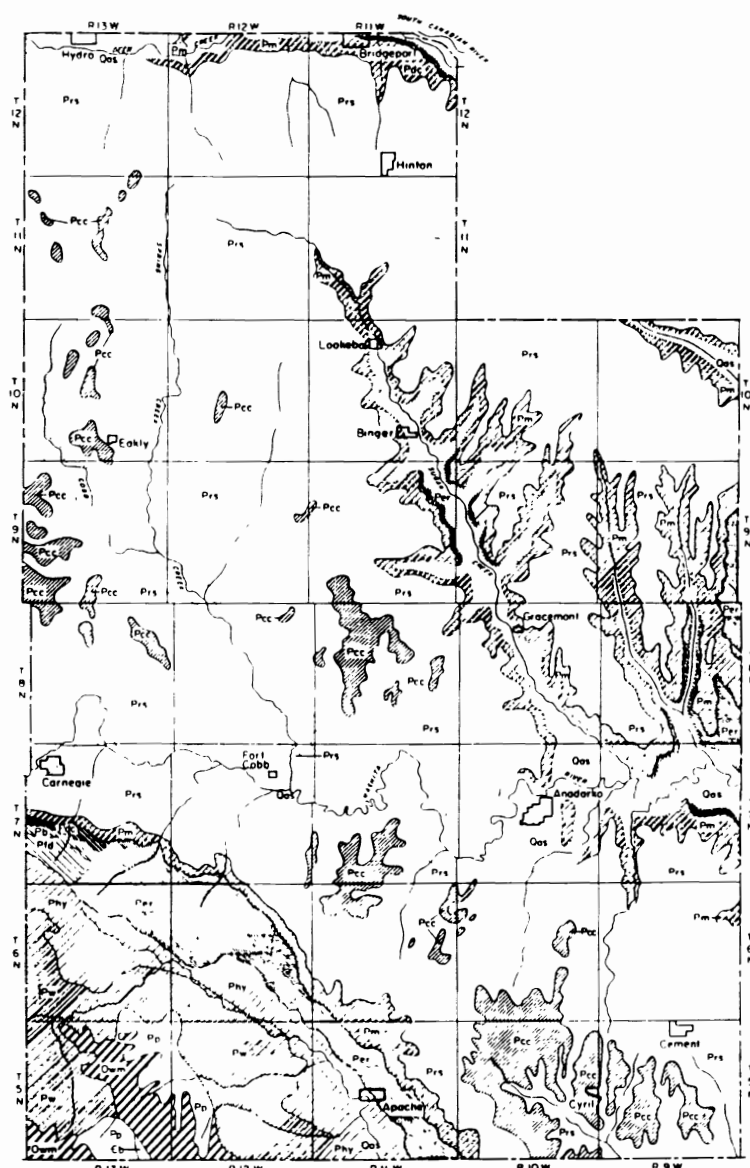
#### Surface Geology

Permian rocks outcropping in the study area consist primarily of the Rush Springs Sandstone of the Whitehorse Group and the Cloud Chief Formation (Figure 2). Tanaka and Davis (1963) note that the Whitehorse Group crops out in about eighty percent of Caddo County with the remainder covered by outliers of the overlying Cloud Chief Formation.

#### Rush Springs Sandstone

In the Cement area, the Rush Springs Sandstone outcrops typically consist of friable, reddish brown, cross-bedded to tabular, subangular to subrounded, fine- to very-fine silty sandstone. Lilburn (1981) described the Rush Springs Sandstone as normally red and friable but on outcrop over the Cement Anticline, it is buff to white and highly cemented. The cement is mostly calcium carbonate but some pyrite is present as small nodules. The thickness of the Rush Springs Sandstone outcrops in the Cement-Chickasha area range from 130 to 300 feet (Al-Shaieb, 1988).





#### Quaternary

Qas Alluvium on first and second bottoms and low terraces

#### Permian

Pcc Cloud Chief formation  
Prs Rush Springs Sandstone (Whitehorse group)  
Pm Marlow formation (Whitehorse group)  
Per El Reno group  
Pde Dog Creek Shale  
Pb Blaine Gypsum

#### Permian—Continued

Pfd Flowerpot Shale and Duncan Sandstone  
Phv Hennessey Shale  
Pw Wichita formation  
Pp Post Oak Conglomerate member of Wichita formation

#### Ordovician

Owm Upper part of Arbuckle group

#### Cambrian

Cb Lower part of Arbuckle group

Figure 2. Surface geology of Caddo County, Oklahoma (after USDA, 1973)

## Cloud Chief Formation

The Cloud Chief Formation outcrops in the study area are interbedded layers of gypsum and red shale approximately 30 feet thick; typically they are outliers overlying the Rush Springs Sandstone. Harlton (1960) reported that only the basal member of the Cloud Chief was exposed at Cement and consisted of ten feet of white and pink gypsum. This gypsum bed is known locally as the "Cyril Gypsum."

## Soils

The soils in the study area are predominantly the Cobb and Grant soils, and the Reinach soils. The soils south of the study area (Section 7, Township 5 North, Range 10 West and Section 12, Township 5 North, Range 9 West) are predominantly the Norge, Acme-Gypsum Outcrop, and Woodward-Quinlan Complex soils. The areal distribution of the soils is shown on Figure 3. The following soil descriptions are taken from the Soil Survey of Caddo County, Oklahoma (USDA, 1993).

### Acme-Gypsum Outcrop Complex

The Acme-Gypsum Outcrop Complex consists chiefly of Acme silt loam, on side slopes below the crests of hills, and of gypsum outcrops on hilltops and sides of hills. The Acme makes up 50 to 70 percent of the complex and the gypsum, from 15 to 35 percent. The remaining 5 to 20 percent consists of a soil similar to the Acme but with gypsum at depths between 20 and 36 inches. In a representative profile, the surface layer is dark brown, mildly alkaline, silt loam to a depth of 8 inches, and

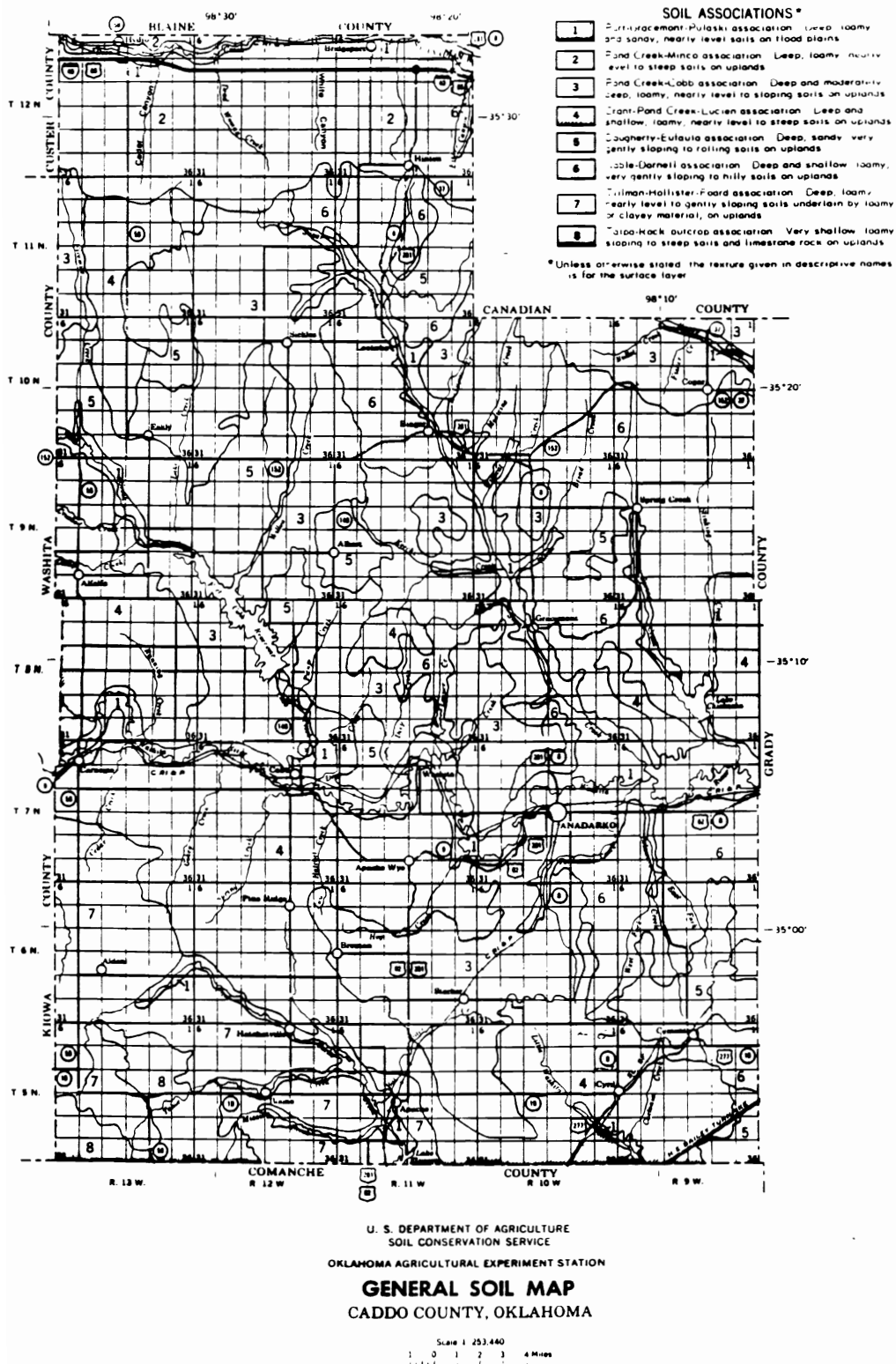


Figure 3. Soils map of Caddo County, Oklahoma (after USDA, 1973)

brown, calcareous, silt loam that is moderately alkaline to a depth of 15 inches with white crystalline gypsum below. The Acme soils are the only soils mapped in Caddo County that formed in material weathered from gypsum. The Acme soils have a rated permeability of 0.63 to 2.0 inches per hour.

### Cobb Series

The Cobb Series consists of moderately deep, very gently sloping to sloping soils on uplands. In a representative profile, the surface layer is reddish brown, fine sandy loam about 8 inches thick. Below this is a sandy clay loam, about 33 inches thick that is reddish brown in the upper part and red in the lower part. The underlying material is reddish sandstone. These soils are well drained and moderately permeable with rated permeabilities of 0.63 to 2.0 inches per hour.

### Grant Series

The Grant Series consists of deep, very gently sloping to sloping soils on uplands. These soils formed in loamy material from red beds under a cover of mid and tall grasses. The depth to sandstone or siltstone below this series is more than 40 inches. In a representative profile, the surface layer is brown, mildly alkaline, loam approximately 9 inches thick. The next layer, at a depth of between 9 and 19 inches, is reddish brown, mildly alkaline loam. Between a depth of 19 and 44 inches is a yellowish red, moderately alkaline, silt loam that grades to loam. Yellowish red, calcareous loam that contains a few hard concretions of calcium carbonate is between depths of 44 and 66 inches. The Grant soils are well-drained and moderately

permeable.

### Norge Series

The Norge Series consists of deep, very gently sloping to gently sloping soils on uplands. These soils formed in material weathered from alkaline loamy red beds. In a representative profile, the surface layer consists of reddish brown silt loam about 8 inches thick. The next layer, between 8 and 36 inches, is reddish brown silty clay loam that has prismatic and subangular blocky structure. Below, from 36 to 46 inches is neutral, red silty clay loam that has subangular blocky structure. These layers are underlain, at depths of between 46 and 74 inches, by red silty clay loam that has subangular blocky structure and contains few soft spots and hard concretions of calcium carbonate. The Norge soils are well-drained with moderately slow permeability.

### Reinach Series

The Reinach Series consists of deep, nearly level or very gently sloping soils on terraces or uplands. These soils formed in alkaline, loamy sediment laid down by wind and water. In a representative profile, the surface layer is reddish brown silt loam about 32 inches thick. At depths between 32 and 62 inches is reddish brown, calcareous loam. Next is yellowish red, very fine sandy loam that is calcareous and extends to a depth of 72 inches. The Reinach soils are well-drained and moderately permeable.

### Quinlan-Woodward Complex

The Quinlan-Woodward complex consists of shallow and moderately deep, sloping to strongly sloping soils on uplands. Quinlan series soils formed in material weathered from calcareous sandstone or siltstone. Quinlan soils are well-drained and permeability is moderately rapid.

### Woodward-Quinlan Complex

The Woodward-Quinlan complex consists of gently sloping soils on uplands. The Woodward series soils formed in materials weathered from calcareous sandstone and siltstone. Woodward soils are well-drained and moderately permeable.

### Subsurface Stratigraphy

The subsurface geologic formations of interest in the study area are Permian; in ascending order they are the El Reno Group, Whitehorse Group, and Cloud Chief Formation. A generalized geologic column of the rocks discussed in this section is provided on Figure 4.

### El Reno Group

The El Reno Group, named by Schweer, in Brown (1937), is defined by Davis (1955) as including Permian strata from the top of the Hennessey Shale to the base of the Marlow Formation; in ascending order, the group includes the Duncan Sandstone, Chickasha Formation, Blaine Formation, and Dog Creek Shale.

Southwest Okla (Cement-Chickasha Field)				Okla. Geol. Survey Terminology			
System	Series	Group	Formation	Group	Series	System	
PERMIAN	Guadalupian	Cloud Chief	Cloud Chief Formation	Cloud Chief	Custerian	PERMIAN	
		White-horse	Rush Springs Formation	White-horse			
			Marlow Formation				
	Leonardian	El Reno	Chickasha Formation	Dog Creek Shale Blaine Formation Flowerpot Shale	El Reno		Cimarronian
			Duncan Sandstone				
		Hennessey	Hennessey Formation	Bison Shale Purcell Sandstone Fairmont Shale	Hennessey		
			Sumner	Garber Sandstone			
		Wichita Group (Fortuna) Wellington Formation (Noble-Olson)		Granite Post Oak Wash Conglomerate (Subsurface) (Surface)			
		Wolfcampian	Pontotoc Formation		(Oscar) Undivided (Vanoss)		
	PENNSYLVANIAN	Virgilian	Cisco		Ada		Virgilian

Generalized geologic column (after Lilburn, 1981)

Duncan Sandstone. The first reference to the Duncan Sandstone was made by Wegeman (1915), who described a series of scarp-forming sandstones and interbedded shale about 40 feet thick in his study of the Duncan gas field. Gould (1924) quoted Wegemen's description of the scarp-forming sandstones, and noted that the formation ranged up to 250 feet thick and consisted in most places of two ledges of white or buff sandstone separated by shale. Gould assigned the Duncan Sandstone to a position between the Lower Enid Formation (Hennessey Shale) and the Chickasha Formation. Davis (1955) indicated that the base of the Duncan is considered to be unconformable with the underlying Hennessey Shale. The contact of the Duncan with the overlying Chickasha in Grady County is considered to be conformable, and probably is gradational. Self (1966) found no evidence of a major unconformity at the base or the top of the Duncan, but there is evidence (stream channeling) of minor disconformities in the unit.

Self (1966) reported that the Duncan Sandstone varies significantly both laterally and vertically. Laterally, the Duncan changes color from gray-green near Duncan, Oklahoma to buff around the nose of the Anadarko Basin to reddish orange further north. Bedding planes are uneven, and there is some lenticular cross-bedding. The Duncan is typically a fine- to very fine-grained sandstone, moderately well to moderately sorted, orthoquartzitic with dolomite cement. The sandstone becomes finer to the north or west from the nose of the Anadarko Basin. The channel-form and lenticular sandstones are the coarser materials in the Duncan, and the Duncan Sandstone typically becomes coarser higher in the section, eventually becoming conglomeratic, cherty, and containing clay galls near the top of the unit.



Davis (1955) described the Duncan Sandstone in Grady and northern Stephens Counties, Oklahoma as mostly sandstone, with minor amounts of interbedded shales and intraformational siltstone conglomerates. The sandstones at the southeastern end of the Anadarko Basin, in northeastern Stephens County, range from nearly white to light buff and are coarse-grained. Northward across Grady County the sandstones become red and progressively finer. The proportion of sandstone differs greatly from place to place and generally decreases northward.

Harlton (1960) found the Duncan to range in thickness from 300 to 375 feet at the Cement Field in Caddo County, Oklahoma. Harlton characterized the Duncan as very fine- to fine- to medium fine-grained, dolomitic sandstone grading into sandy dolomite. Intercalated thin streaks of pale green shale are in the lower 100 to 130 feet. The varying amounts of the dolomitic bonding material in the Duncan Sandstone are characteristically manifested by alternating sharp resistivity peaks of electric logs; therefore the dolomitic material easily differentiates this formation in its entirety over a wide area. Lilburn (1981) reported a thickness of the Duncan Sandstone at the Cement Field of 250 feet and noted that disseminated pyrite and calcareous cement were common. Based on the author's electric log correlations in the study area, the Duncan Sandstone is believed to be approximately 200 feet thick.

Chickasha Formation. The first reference to the Chickasha Formation was by Gould (1924). Gould described the Chickasha Formation as a series of sandstones and shales. Near the southern end of the Anadarko Basin, the Chickasha Formation is composed of about 175 feet of variegated sandstones and shales. On account of the predominating color of the rocks, the local name, "purple sandstone", has been used

for this formation by geologists of the region. Gould quoted Becker (1927) for the description of the Chickasha in which three divisions were recognized: 1) An upper purple sandstone member 70 to 80 feet thick, the upper 30 feet of which consist chiefly of loose pink sand in which occur numerous thin lenses of purple "mudstone conglomerate;" the lower portion consists of 40 to 50 feet of "heavy purple mudstone conglomerate" beds separated by thin strata of pink sand; 2) A middle pink sand member consisting of 50 feet of uncemented pink sand. Occasionally this sand shows cementation on both upper and lower contacts, but the lithologic characteristics are the same as of the pink sand, and not similar in texture or color to the "mudstone conglomerates."; and, 3) A lower purple sandstone member chiefly composed of "mudstone conglomerate," 50 feet thick, more distinctly stratified than any other portion of the "Purple Series." Gould's Chickasha Formation includes beds above the Duncan Sandstone and below the Blaine Formation. However, on the south side of the Anadarko Basin, on account of the absence in this region of the identifying rock gypsum in the next higher formation, the Blaine, it is not everywhere possible to separate these two formations. Sawyer (1929; 1930) recognized that the Blaine Formation and the Dog Creek Shale are absent at the type locality of the Chickasha Formation, and that the upper limit of the Chickasha, therefore, is the Marlow Formation.

Based on a study of electric logs, Davis (1955) found the thickness of the Chickasha to range from 395 to 580 feet. Davis described the Chickasha as being composed of a heterogeneous mixture of sandstones, shales, siltstones, and siltstone conglomerates cemented primarily by iron oxide, although in places the cement is

calcium carbonate or gypsum. Sand grains range from coarse to fine, decreasing in size northwestward from Stephens County. Many of the siltstone conglomerates are highly cross-bedded. Approximately the lower third of the Chickasha Formation contains many layers of fine-grained soft sandstone interbedded with shale.

At the Cement Field, Harlton (1960) found the Chickasha Formation to range in thickness from 200 to 300 feet and to be characterized by maroon gypsiferous mudstone containing coarse to very coarse sandstone grains and intercalated maroon shale. Interlayers of fine to medium fine sandstone occur at intervals. Lilburn (1981) reported that the sandstones and shales in the Cement Field area commonly contain carbonate cements and pyrite and are variegated. Where the Chickasha Formation grades into the Dog Creek Shale and the Blaine Formation north of the Cement Field, the section consists of red, blocky, silty shales, interbedded with fine-grained gypsiferous sandstones and locally pure gypsum.

Olmstead (1975) noted that the Chickasha Formation is distinguished from the Duncan Sandstone by its purple color and shaly characteristics. Northward and westward along the flanks of the Anadarko Basin, the Chickasha Formation is laterally gradational into brick red gypsiferous shales and siltstones.

The thickness of the Chickasha Formation in the study area is approximately 200 feet based on the author's electric log interpretation.

Blaine Formation - Dog Creek Shale Undifferentiated. There is some question as to whether the Blaine Formation and/or the Dog Creek Shale is present in the study area. Lilburn (1981) and Harlton (1960), in their studies at the Cement Field, did not recognize the presence of the Dog Creek Shale or Blaine Formation and indicated that

the Chickasha Formation was overlain by the Marlow Formation of the Whitehorse Group. Davis (1955) was unable to differentiate between the Dog Creek Shale and Blaine Formation in Grady and Stephens Counties and so described the interval as Blaine Formation - Dog Creek Shale Undifferentiated. This interpretation was followed by Allen (1980) and Olmstead (1975). Tanaka and Davis (1963) described the section as consisting of the Duncan Sandstone, Flowerpot Shale, Blaine Formation and Dog Creek Shale although their study was directed somewhat more to the west than this study. Nelson (1983) described the Chickasha Formation as grading laterally into the Flowerpot Shale, Blaine Formation, and Dog Creek. Based on electric log evaluations in the study area, the author believes that the Dog Creek Shale is present at the Cement Field and unconformably overlies the Chickasha Formation. The thickness of the Dog Creek shale in the study area is approximately 95 feet.

### Whitehorse Group

The Red Bluff Sandstone (Whitehorse Group) was first proposed by Cragin (1896) in Comanche County, western Kansas. Because the name "Red Bluff" was preoccupied, Gould (1905) established the name Whitehorse Sandstone for beds between the Dog Creek Shale and Day Creek Dolomite. The Whitehorse Sandstone was described in the Cement-Cyril area by both Clapp (1920) and Reeves (1921). The Whitehorse Sandstone was established as a formation by Gould (1924), who defined the lower boundary at the top of the Dog Creek Shale. The Marlow Formation was described by Sawyer (1924) as a lithologic unit between the Whitehorse Sandstone and the Dog Creek Shale. The Marlow Formation was given member status by Sawyer

(1929) who also changed the name Whitehorse Sandstone to the Rush Springs Sandstone Member and placed them both in the Whitehorse Formation. The Whitehorse Formation was elevated to group rank by Green (1936) and the Rush Springs Sandstone and Marlow Formation were raised to formation rank. The Cloud Chief Formation was considered by Green to be the uppermost formation of the Whitehorse Group. The Whitehorse Group was defined by Davis (1955) as all Permian beds above the El Reno Group and below the Cloud Chief Formation. Davis divided the Whitehorse Group into the Marlow Formation below and the Rush Springs Sandstone above.

Marlow Formation. The initial reference to the Marlow Formation was by Sawyer (1924). Sawyer noted that the Marlow Formation is located above the Duncan Sandstone and consists of brick-red shales and even-bedded brick-red sandstones with bands of fine white gypsum. The entire formation was described as gypsiferous by Sawyer, with a 1-foot layer of almost pure gypsum at the top of the formation.

Evans (1931) described two persistent dolomite beds at the top of the Marlow Formation which were designated the Upper Relay Creek and Lower Relay Creek dolomites. The two dolomites are separated by 25 feet of red sandstone and shale. Evans suggested that the top of the Marlow Formation should be the top of his Upper Relay Creek dolomite and that the base should be the top of the Dog Creek Shale. Fay (1962) revised the Upper and Lower Relay Creek dolomites and classified the Upper Relay Creek dolomite as the Emanuel Dolomite Bed, and the Lower Relay Creek dolomite as the Relay Creek Dolomite Bed.

Green (1936) described the base of the Marlow as definitely an overlapping

contact with the evidence of the unconformity more easily recognized along the south side of the (Anadarko) basin than on the north side. Brown (1937) also provided evidence for the unconformity by noting that structural contours on beds of the Marlow strike west-northwest which is in contrast to the strike of the Blaine-Chickasha contact, which is north-south.

Davis (1955) described the Marlow Formation in Grady and northern Stephens Counties as even-bedded fine-grained silty sandstones and shales that are predominantly reddish brown. Davis also described the entire formation as gypsiferous with satin spar occurring at random. Tanaka and Davis (1963) described the Marlow Formation in Caddo County as consisting mostly of even-bedded brick-red sandy shale, generally gypsiferous, with some very fine sand and silt loosely cemented with iron oxide and calcite.

O'Brien (1963) reported that the Marlow Formation was generally moderate reddish brown varying to reddish tan and composed of approximately equal amounts of even-bedded sandstones, shales, and siltstones. The sandstone members consist of fine-grained sands with varying amounts of silt and clay. Each grain is coated with iron oxide, a condition which gives the formation its gross color. Cementing agents in the Marlow Formation vary from gypsum, calcite, and iron oxide to smaller amounts of clay in conjunction with the former three. The degree of cementation varies from weakly (clay and iron oxide) to well indurated (calcite and gypsum). Calcite is the predominant cementing agent in the upper half of the formation with gypsum predominant in the lower half.

Thickness of the Marlow Formation has been reported to range from 105 feet

(Brown, 1937) to 130 feet (Davis, 1955). Based on the author's review of electric logs, the thickness of the Marlow Formation in the study area is approximately 145 feet.

Rush Springs Sandstone. The first reference to the Rush Springs Sandstone was by Sawyer (1929; 1930) who described a red cross-bedded sandstone with little or no shale or gypsum. What was to eventually be named the Rush Springs Sandstone was described initially by Reeves (1921) as the Whitehorse. Reeves described a friable reddish brown, cross-bedded to regular-bedded sandstone which weathers rapidly.

Davis (1955) reported that in Grady and northern Stephens Counties, the Rush Springs Sandstone is an even to highly cross-bedded, light-brown, soft, silty sandstone. The grains were described as subangular to subround, ranging in size from silt to coarse sand (average fine sand). Very coarse, frosted, almost perfectly spherical grains are common, most abundant in the lower part of the formation. The remainder of the grains are smooth and covered with stain of iron oxide. The entire Rush Springs Sandstone is remarkable in its homogeneity.

Tanaka and Davis (1963) described the Rush Springs Sandstone in Caddo County as an even-bedded to highly cross-bedded, reddish brown, very fine silty sandstone with a few calcareous beds in the upper part, but more common in the lower part of the formation. The calcareous beds range in thickness from 0.5 to 1.0 feet. Sand grains are subangular to subround and are loosely cemented with iron oxide and calcite. Loose sand may represent sandy beds from which calcium has been leached by movement of ground water. Harlton (1960) noted that the Rush Springs Sandstone

is white on top of the Cement anticline, but elsewhere it is deep red. Lilburn (1981) reported that normally the Rush Springs is red friable sandstone, but on outcrop over the Cement anticline, it is buff to white, highly cemented sandstone. The cement is mostly calcium carbonate but some pyrite is in nodules 1-inch across.

Johnson, et al. (1990) described the Rush Springs Sandstone as poorly cemented, reddish brown, fine-grained sandstone that is locally silty or argillaceous, containing some layers of red-brown shale. The formation is evenly bedded to highly cross-bedded, with large-scale trough cross-bedding. The Rush Springs Sandstone contains several thin but persistent beds of gypsum/anhydrite and dolomite. Johnson, et al. reported that the gypsum beds are typically 4 inches to 10 feet thick, and dolomite beds are 1 inch to 1 foot thick. The sand is loosely cemented with dolomite or calcite in places, but the predominant cement in the subsurface is gypsum. The majority of the formation has little or no cement.

Donovan (1974), in discussing the Rush Springs Sandstone in the Cement region, described the Rush Springs Sandstone as predominantly reddish brown, friable, very fine-grained, clayey, quartz sandstone. The sand grains are subangular to subrounded and loosely bonded by hematite. The dominant detrital materials are quartz, chert, orthoclase, plagioclase, microcline, and composite rock fragments. As much as 80% of the sandstone consists of clear and frosted subrounded to subangular quartz grains. Feldspar content of the rock ranges from 4 to 13% and both fresh and highly altered types are present. Orthoclase is the most common feldspar (as much as 10%). Fresh plagioclase is estimated to have a composition near oligoclase. The clay content is as much as 17% and is mostly illite, although some chlorite may be present.



Hematite rims quartz grains as a cement and also forms mottled stain on quartz grains. The hematite content appears highly variable and the rocks lightest in color have the least amount of hematite. In crestal areas, the Rush Springs Sandstone is cemented by secondary intergranular, fine to coarse sparry calcite and small amounts of euhedral to anhedral dolomite.

Lilburn (1981) described massive pink gypsum in the upper part of the Rush Springs Sandstone, called the "Weatherford Gypsum." This gypsum bed is reported by Lilburn to range in thickness from 1 to 40 feet. The Weatherford Gypsum is separated from the overlying Cloud Chief Gypsum by 10 to 15 feet of dolomitic sandstone and siltstone.

Thickness of the Rush Springs Sandstone has been reported to range from 136 feet (Davis 1955) to 300 feet (Green 1936). Based on the author's review of electric logs, the thickness of the Rush Springs Sandstone in the study area is approximately 220 feet.

### Cloud Chief Formation

The Cloud Chief Formation unconformably overlies the Rush Springs Sandstone. The first reference to the Cloud Chief Formation was by Gould (1924) who described the Cloud Chief as chiefly a red clay shale, interstratified at several horizons with red sandstone and gypsums. Davis (1955) described the Cloud Chief of Grady County as irregular, impure gypsum beds interbedded with gypsiferous shales. Tanaka and Davis (1963) reported that in Caddo County, the Cloud Chief is largely gypsum and includes the Weatherford Member at its base. The Weatherford Member

is a dolomite in most places but may be dolomitic shale, anhydrite, or gypsum.

O'Brien (1963) described the Cloud Chief in east-central Caddo County as composed of the Weatherford Dolomite phasing southward into a massive gypsum, overlain by undifferentiated sandstones, shales, and siltstones. O'Brien noted a massive bed of laminated microcrystalline gypsum, 25 feet thick, in Township 7 North, Range 11 West which appeared to overlie directly the Rush Springs Sandstone. The massive gypsum could be traced south to Cyril, where it is called the Cyril Gypsum. O'Brien found no evidence to suggest an unconformity with the Rush Springs Sandstone in the area of his report.

Harlton (1960) noted that at the Cement field, only the basal member (Weatherford Member) of the Cloud Chief Formation is exposed and is represented by exposures of about 10 feet of white and pink gypsum. Toward the crest of the Cement Anticline, the gypsum grades into closely intermixed gypsum and dolomite and at the crest it is dolomite. Harlton refers to this gypsum as the Cyril Gypsum. Donovan (1974) called the basal gypsum the Cyril Gypsum Member and described a thickness of about 40 feet on the southwest flank of the Cement structure in the area of Cyril. Allen (1980) described the basal portion of the Cloud Chief Formation as the Moccasin Creek Gypsum Member and gives a thickness of 85 feet. Allen reported that the Moccasin Creek Gypsum Member is the only representative of the Cloud Chief Formation present within the Cement area. Lilburn (1981), in discussing the Cloud Chief Formation at the Cement field, reported that only a small portion of the gypsum has been preserved. Lilburn also refers to this gypsum as the Moccasin Creek Gypsum Member, characterized by massive pink to white layers which contain a few

sandstone layers. Toward the crest of the Cement Anticline, the gypsum grades into mixed gypsum and carbonate and at the top of the "Keechie Hills", the  $\text{CaSO}_4$  of the gypsum has been completely replaced by  $\text{CaCO}_3$ . The result of the substitution is a resistive limestone with perfectly preserved gypsum crystal outlines.

### Depositional Environments

The Permian red beds of southern Oklahoma were deposited in a variety of marine, marginal marine, and fluvio-deltaic environments (Davis 1955) as indicated on Figure 5. The Permian Period was one of quiescence with the basin gradually filled with clastic sediments brought in from many directions (O'Brien 1963). Olmstead (1975) reported that the detrital materials in the Permian formations were derived primarily from the Ouachita Mountains in northern Texas and southern Oklahoma (Figure 6).

During the Early Permian, the Tussey delta was forming north of the Arbuckle Mountains (Green, 1937). Detrital materials from the Arbuckle and Ouachita Mountains were transported by northwestward-flowing streams into the Anadarko Basin. Deposition of the Duncan Sandstone and Chickasha Formation are believed by Fay (1964) to have occurred at the mouth of a large northwestward-flowing river. Self (1966) concluded that the Duncan Sandstone was formed in a delta consisting of a supratidal flat that was flooded by both streams during flood stage and by the sea during storms, followed by arid or semi-arid conditions. The wedge shape of the entire Duncan Sandstone/Chickasha Formation indicates a rapid outbuilding of sand.

The discharge of the streams varied widely, perhaps seasonally, and the stream

Stratigraphic Unit	Depositional Environment	
Cloud Chief Formation	Restricted Marine (Ham, 1960)	
Rush Springs Formation	Near Shore (O'Brien, 1963)	
Marlow Formation	Tidal Flat (MacLachlan, 1967)	
Chickasha Formation	(south) Fluvial Deltaic (Fay, 1964)	(north) DOG CREEK SH.-BLAINE FM. Tidal Flat (Fay, 1964)
Duncan Sandstone	Fluvial Deltaic (Self, 1966)	
Hennessey Shale	Tidal Flat (Stith, 1968)	(east) BISON SH. Tidal Flat
	(southwest) surface POST OAK CONG. Piedmont	(east) PURCELL SS. Fluvial Deltaic
		(northeast) FAIRMONT SH. Tidal Flat
Garber Sandstone	(southwest) subsurface	(southwest)
Wellington Formation	POST OAK CONG.	Tidal Flat and Supratidal
Oscar Group	Piedmont	(Flood, 1969)
		(east and southeast) Fluvial Deltaic (Flood, 1969)

Figure 5. Depositional environments in south-central Oklahoma  
(after Olmstead, 1975)

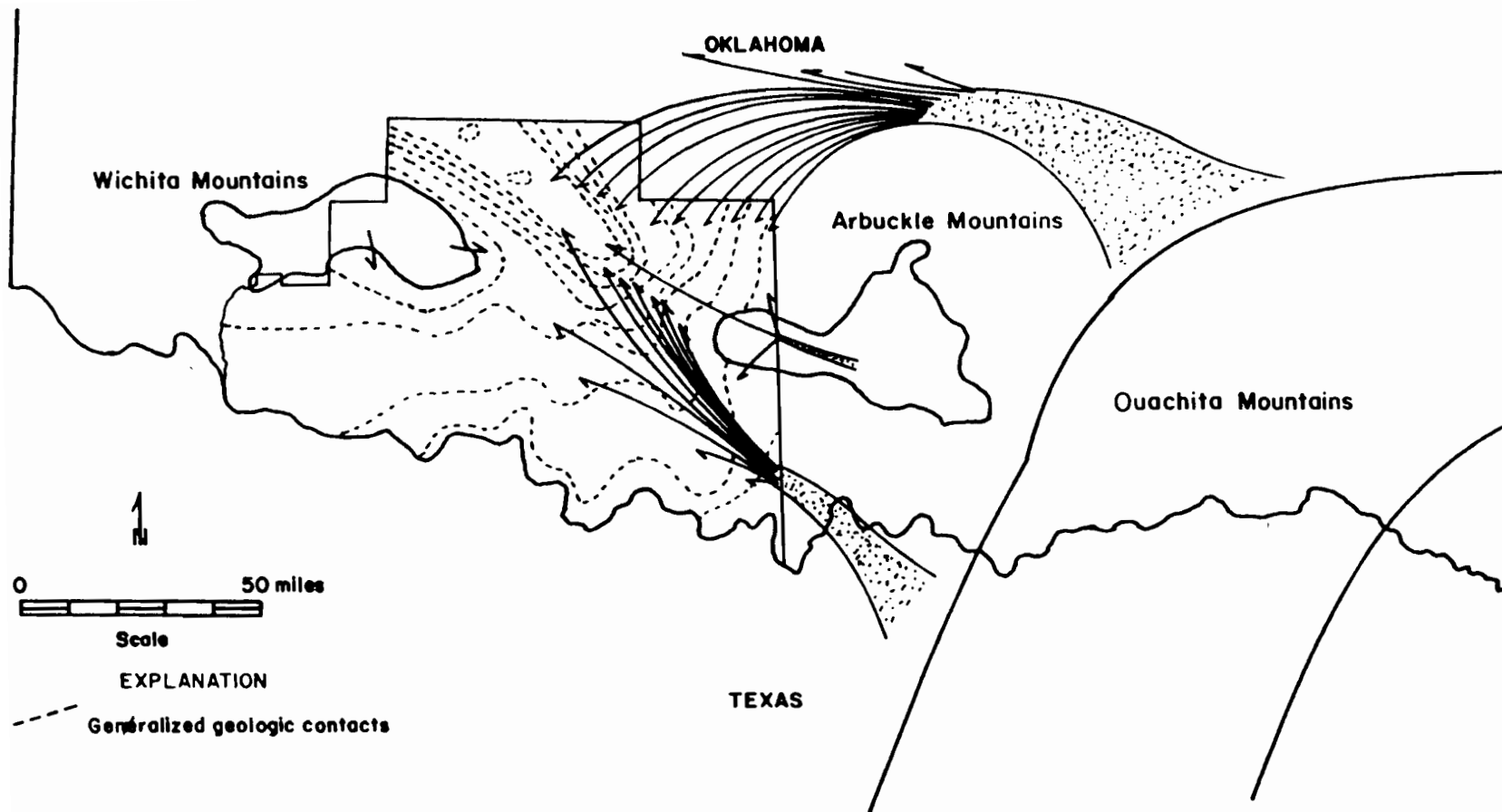


Figure 6. Source areas during late Pennsylvanian and Permian time (after Olmstead, 1975)

channels suggest distributaries in a delta system. MacLachlan (1967) concluded that basinward equivalents of the Duncan Sandstone and Chickasha Formation contain evaporitic and some dolomitic deposits indicative of a restricted, shallow-marine environment.

Towards the end of Chickasha time, a transgressing sea inundated the slowly subsiding Tussey delta and a period of shallow-water, brackish-marine deposition ensued (Fay, 1964). The Dog Creek Shale was deposited during this period of shallow and extensive Permian seas. O'Brien (1963) reported that by early Marlow time, the Permian seas began a long period of advance and retreat. During periods of regression, a super-saline condition would be formed by the restriction of shallow marine seas, causing evaporites and minor amounts of carbonates to be deposited. Coarser clastics began to be brought into the area, possibly by minor uplifting and consequential increase in stream competence to the east. From these cyclical conditions and increase in sand-sized materials, the upper part of the Dog Creek Shale and the Marlow Formation were deposited.

As Marlow time progressed, the continued transportation of coarse material and shallow unrestricted seas caused the deposition of increased amounts of sand (O'Brien, 1963). Shallow, warm, marine seas encouraged flocculation of calcium carbonate which became deposited with the sands. During middle Marlow time, an offshore bar (Verden Lentil) was deposited by longshore currents indicating high energy deposition in a shallow sea. By Relay Creek time, sand was the major constituent being deposited in the Marlow Formation. The rapid deposition resulted in the basin becoming shallow and restricted causing deposition of carbonates with local deposition

of evaporites (Relay Creek and Emanuel Dolomite). By the end of Marlow time, encroaching seas brought in quantities of sand that became interbedded with sands of continental origin (O'Brien, 1963).

Davis (1955) described the Rush Springs Sandstone as probably having been deposited in a shallow-marine bay, with sediment apparently having been supplied by the newly uplifted Ouachita Mountains. Sands probably were deposited along the eastern side of a shallow embayment that was at times cut off, or severely restricted, from the main Permian sea. Tanaka and Davis (1963) noted that westward from Caddo County, the sandstones grade laterally into anhydrite and gypsum and gypsiferous silty clay in what must have been a dessication basin in western Oklahoma during the time of Rush Springs Sandstone deposition. Lilburn (1981) reported that the Rush Springs Sandstones were exposed periodically by sea-level fluctuations and were reworked into eolian dunes. MacLachlan (1967) concluded that the dunes were probably coastal in origin and O'Brien (1963) believed that some of the sands may have formed strandline deposits. Allen (1980) concluded that coastal plain playa lakes or brackish backshore lagoons were represented by the siltstones and shales within the formation, while gypsum and dolomite beds may be coastal sabkha deposits. By the end of Rush Springs time, the quantity of coarse clastics decreased, possibly due to a gradual decrease in competence of the source streams (O'Brien, 1963).

In late Rush Springs and early Cloud Chief time, the seas again became shallow, warm, and partially restricted leading to the deposition of carbonates along the flank of the basin and the deposition of massive gypsum beds as seas became more restricted (O'Brien, 1963). Olmstead (1975) concluded that Cloud Chief deposition

took place in a semi-enclosed arm of the sea which had periodic influxes of sulfate-rich waters. Deposition of the Weatherford Member occurred during this period. Following deposition of the gypsum, a relatively short period of deeper water and unrestricted sea occurred leading to the deposition of sands, silts, and shales. The basin again became partially filled causing local restrictions and thereby creating favorable conditions for additional gypsum deposition (O'Brien, 1963).

### Structure

The Cement area is located near the southwestern end of the Anadarko basin, a large asymmetrical syncline approximately 40,000 feet thick. The Anadarko basin was named by Gould (1924); its axis passes to the east of the Cement area in a southeast-to-northwest direction. Ham, Denison, and Merritt (1964) included the Anadarko basin in the Southern Oklahoma geosyncline which received sediments derived from the Paleozoic rocks that were folded during Pennsylvanian time. Two episodes of Pennsylvanian deformation, the Wichita and Arbuckle orogenies, were responsible for the tectonic setting in the Cement area (Olmstead, 1975). By early Permian, most tectonic activity in the area had ceased except for the minor folding of Permian units over older Pennsylvanian structures (Lilburn, 1981).

The dominant structural feature in the study area is the Cement Anticline, approximately 11 miles in length and 2 miles in width. The axis of the Cement anticline trends approximately west by northwest (N70°W), subparallel to the axis of the Anadarko basin. The crest of the anticline is expressed at the surface as a series of topographic highs, referred to in the past as the Keeche Hills (Reeves, 1921) and more



recently as the West and East Cement Domes (Lilburn, 1981). The Permian section unconformably overlies faulted and tightly folded structures ranging in age from Pennsylvanian to Mississippian. Herrman (1961) concluded that the deformation at the Cement structure commenced in Early Pennsylvanian, because Pennsylvanian rocks show evidence of thinning over the crest of the structure, indicating continued structural growth. The faulting appears to be pre-Permian as the faults are truncated by the unconformity at the top of the Pennsylvanian (Lilburn, 1981). The Permian beds are gently folded into a slightly asymmetrical anticline that has increasing asymmetry with depth. Minor structural deformation in post-Cloud Chief Formation time produced a gentle, near-symmetric upfold in the Permian units (Allen, 1980).

## CHAPTER III

### GROUND-WATER RESOURCES

#### Hydrologic Characteristics

The hydrologic properties of geologic formations are those properties which determine the volume of ground water stored in the formation, the volume of ground water the formation can yield, and the rate at which ground water can flow through the subsurface.

The volume of ground water that saturated rocks can store is determined by the rocks porosity. Porosity is defined as the ratio of void space in the rock to the total volume of the rock and is expressed as a percentage or decimal fraction. Primary porosity is developed at the time of deposition of the rock material and consists of the open spaces between the grains of the rock. The extent of primary porosity is generally determined by the degree of sorting (i.e. the range of grain size in the rock) and the shape and arrangement of the individual grains. Secondary porosity occurs subsequent to deposition and typically consists of fractures and void spaces caused by the dissolution of the rock by ground-water movement.

Although the total volume of water stored in the rock is determined by its porosity, the amount of water available for withdrawal is determined by its specific yield. Specific yield is defined as the volume of water in a unit volume of saturated

rock that will drain from the rock by gravity. The volume of water retained in the rock is called specific retention and is caused by the capillary attraction between the water in the void spaces and the rock grains. Specific retention generally increases as grain size and sorting decrease. The volume of water that saturated rock materials will release from or take into storage per unit surface area of the aquifer per unit change in head is referred to as storativity. In water table (unconfined) aquifers, the storativity is approximately equal to specific yield and the water is released from the aquifer due to gravity drainage and dewatering of the aquifer. The storativity in confined aquifers is significantly smaller than in unconfined aquifers as the water released from storage is due to the expansion of the water and the compaction of the aquifer, both of which are minimal when compared to gravity drainage and aquifer dewatering.

The ability of ground water to flow through an aquifer is determined by the product of the hydraulic conductivity of the aquifer materials and the saturated thickness of the aquifer. This product is known as the aquifer transmissivity.

Hydraulic conductivity is defined as the volume of water that will flow through a unit area of the aquifer under a unit change in the hydraulic gradient perpendicular to the direction of flow. Hydraulic conductivity is related to grain size, sorting, cementation, secondary openings, and the viscosity of the aquifer fluid. Transmissivity is the rate at which water will flow through a unit width of the aquifer under a unit hydraulic gradient. The hydraulic gradient is the slope of the water table or potentiometric surface and is the driving force that causes ground water to flow along lines of decreasing total hydraulic head. Hydraulic head is represented by the water level in water wells, ground-water monitoring wells, or piezometers and is usually measured in

feet above mean sea level.

### Recharge

Recharge is the addition of water to the ground-water system. Recharge may consist of infiltration from precipitation events, infiltration due to irrigation, inter-aquifer leakage, seepage from surface water bodies, or underflow from adjacent areas.

Tanaka and Davis (1963) determined annual recharge in the Cobb Creek basin in Caddo County during a four year period from 1953 through 1956. Annual recharge during this period ranged from a high of 3.5 inches per year during 1953 to a low of 1.5 inches per year during 1956 with an average over the four year period of 2.4 inches per year. Tanaka and Davis noted however, that 1954 and 1956 were unusually dry years and that a recharge rate of 2.8 inches would be a more likely average over a protracted period of time. Tanaka and Davis reported that the recharge rate is approximately equal to 10% of annual precipitation which averages about 28.1 inches per year in the Caddo County area. Davis (1950) reported an annual recharge rate of 0.93 inches per year in the Pond Creek basin in Caddo County, which Davis determined to be approximately 3% of average annual precipitation.

Powell (1992) calculated recharge rates to the Rush Springs aquifer in the Cyril area using the computer program RECHARGE (Pettyjohn and Henning, 1978). Stream flow data from the Little Washita River were used representing the period from 1952 through 1985. Regional ground-water recharge rates were reported to range from a low of 0.23 inches per year in 1971 to a high of 2.5 inches per year in 1960. The mean regional recharge rate for the period from 1952 through 1985 was reported to be

1.1 inches per year.

Powell also calculated local recharge rates for the Cyril area using the Darcy equation  $Q = KIA$ . Powell assumed that if the water table remains nearly constant with the area, then the volume of water that flows through a cross-section of the aquifer should equal the volume of water infiltrating to the saturated zone. The calculated recharge rates ranged from 1.9 inches per year to 3.6 inches per year which Powell reported to fall within the same order of magnitude as the recharge rates determined using the RECHARGE computer program.

Johnson, et al (1990) reported recharge rates to the Rush Springs-Marlow aquifer to be 10% of annual precipitation. Based on reported average annual precipitation values in their report, recharge rates ranged from 2.36 inches per year to 3.15 inches per year.

## Discharge

Discharge is the removal of water from the aquifer system and can generally be attributed to natural discharge and artificial discharge.

### Natural Discharge

Natural discharge occurs through flow of ground water to streams and springs, transpiration by plants, evaporation, underflow into adjacent areas, and through inter-aquifer leakage. Natural discharge by transpiration and evaporation are generally quite small, except in areas where the water table surface is close to the ground surface. However, transpiration and evaporation are significant processes in reducing the

amount of precipitation that infiltrates into the aquifer, regardless of the depth to the water table. Tanaka and Davis (1963) estimated evaporation and transpiration to account for 80% of the total water which entered the Cobb Creek basin and projected this value over their entire project area. Underflow into adjacent areas and inter-aquifer leakage may be significant sources of natural discharge, but are hard to quantify.

Ground-water discharge to streams can be calculated by relating stream base flow to the average water level in wells constructed in the aquifer which discharges into the stream. Tanaka and Davis (1963) calculated the ground-water discharge from the Rush Springs aquifer into Cobb Creek for the period from 1953 through 1957 to average 15,000 acre-feet per year.

#### Artificial Discharge

Artificial discharge occurs primarily through ground-water withdrawals by irrigation wells. Additional sources of artificial discharge are public water supply systems, industrial use, and private water well use. Tanaka and Davis (1963) summarized the pumpage in the Caddo County area by use of the water and calculated a total average use during the period from 1956 through 1960 of 30,600 acre-feet per year.

#### Aquifer Coefficients

The determination of an aquifers transmissivity and storativity can be estimated through the performance of controlled aquifer pumping tests. If saturated thickness

(m) values can be determined for the aquifer, then using transmissivity (T) values obtained from aquifer tests, hydraulic conductivity (K) values may be estimated using the relationship  $K = T \div m$ . Combined with effective porosity (n) values for the aquifer and the hydraulic gradient (I) of the aquifer's water table or potentiometric surface, interstitial ground-water flow velocity (v) values can be calculated using the formula  $v = K I \div 7.48 n$ . These aquifer coefficients can be used to estimate yield to wells constructed in the aquifer and for contaminant transport modeling. Aquifer coefficients for the Duncan Sandstone, Chickasha Formation, Marlow Formation, and Rush Springs Sandstone are summarized on Table 1.

### Duncan Sandstone

Davis (1955) described two aquifer tests in the Duncan Sandstone in Grady County, Oklahoma. The first test was performed at the Oklahoma Natural Gas Company booster station in Section 14, Township 5 North, Range 8 West on March 28 and 29, 1946. The Duncan Sandstone at this location was described as consisting of 34 feet of sandstone and 18 feet of interbedded shale. The aquifer was reported to be confined. Drawdown and recovery curves were analyzed using the Theis non-equilibrium equation. Average values for transmissivity and storativity were reported to be 500 gallons per day per foot (gpd/ft) and  $4.6 \times 10^{-4}$ , respectively.

The second test was performed at the Consolidated Gas Utilities Company booster station in Section 22, Township 5 North, Range 8 West (approximately one mile southwest of the first test). The aquifer was reported to be 34 feet thick consisting of 8 feet of gypsiferous sandstone and 26 feet of fine-grained sandstone.

TABLE 1

**AQUIFER COEFFICIENTS**  
Caddo and Grady Counties, Oklahoma

Aquifer	Range of Transmissivity (gpd/ft.sq.)	Range of Storativity	Range of Hydraulic Conductivity (gpd/ft)	Source
Duncan Sandstone	500 to 1,300	4.6E-04 to 1.0E-04	9.6 to 38	a
Chickasha Formation (1)	200 to 20,000	1.0E-04	1 to 100	b
Marlow Formation (2)	6 to 600	0.20	0.3 to 30	b,c
Rush Springs Sandstone (3)	11,000 to 14,000	0.01 to 0.1		c
Rush Springs Sandstone (4)	353 to 1,664	1.5E-04 to 3.8E-03	6.4 to 23	d

(1) Storativity and hydraulic conductivity based on lithology. Transmissivity based on saturated thickness of 200 feet.

(2) Storativity based on lithology. Transmissivity based on saturated thickness of 20 feet.

(3) Hydraulic conductivity not calculated due to lack of information on saturated thickness.

(4) Calculated from aquifer tests in the study area evaluated by the author.

Source:

a = Davis (1955)

b = Fetter (1988)

c = Tanaka and Davis (1963)

d = Pettyjohn (1992)



The aquifer was reported to be confined at this location. Drawdown and recovery curves were analyzed in a recovery well using the Theis non-equilibrium equation. Values for transmissivity and storativity were reported to be 1,300 gpd/ft and  $1.0 \times 10^{-4}$ , respectively.

#### Chickasha Formation

No aquifer tests were reported in the Chickasha Formation in the literature. Values of hydraulic conductivity are estimated range from 1 to 100 gallons per day per foot squared (gpd/ft<sup>2</sup>) based on a lithology consisting of silty sands to clean sand (Fetter, 1988). Assuming a saturated thickness of 200 feet, transmissivity could be expected to range from 200 to 20,000 gpd/ft. The Chickasha Formation is a confined aquifer and storativity can be expected to be approximately  $1.0 \times 10^{-4}$ .

#### Marlow Formation

No aquifer tests were reported in the Marlow Formation in the literature. Tanaka and Davis (1963) reported hydraulic conductivity values ranging from 0.3 to 30 gpd/ft<sup>2</sup> with an average of 12 gpd/ft<sup>2</sup> according to analyses performed at the United States Geological Survey (USGS) Hydrologic Laboratory. Based on an aggregate thickness of permeable beds of 20 feet in a borehole geophysical log of a well in the northwest quarter of Section 23, Township 10 North, Range 12 West, a value for transmissivity in the Marlow Formation was calculated at 240 gpd/ft.

### Rush Springs Sandstone

Davis (1955) reported on the results of an aquifer test in the Rush Springs Sandstone in Grady County, Oklahoma. The test was performed on a water well owned by the Magnolia Petroleum Company located in Section 3, Township 4 North, Range 7 West. The water well penetrated the entire thickness of the Rush Springs Sandstone which was reported to be 122 feet of homogeneous, fine-grained sandstone. Static water level prior to testing was measured at 50 feet below ground surface. The saturated thickness of the Rush Springs aquifer was determined to be 72 feet (122 feet less 50 feet). Recovery data was analyzed using the Theis equation and transmissivity was calculated to be 13,000 gpd/ft. Storativity was not determined as the Rush Springs was reported to exist under unconfined conditions at the location. Davis estimated the storativity to be 0.10

Tanaka and Davis (1963) reported porosity ranges of 0.24 to 0.43 (average 0.32), specific yield ranges of 0.13 to 0.38 (average 0.25), and permeability ranges of 0.3 gpd/ft<sup>2</sup> to 100 gpd/ft<sup>2</sup> (average 30 gpd/ft<sup>2</sup>). The reported values were based on laboratory analyses of 27 samples from the Rush Springs Sandstone and the upper part of the Marlow Formation in Caddo County. Four samples of the Rush Springs Sandstone were analyzed for particle size. The particle size analyses indicated that generally, the Rush Springs Sandstone is composed of very fine to fine sand, with silt and clay size particles averaging a little more than 20 percent of the total. Two samples of the Marlow Formation were analyzed and found to contain a higher percentage of silt and clay materials than the Rush Springs Sandstone.

Tanaka and Davis (1963) described two aquifer tests in the Rush Springs Sandstone in Caddo County, Oklahoma. The first aquifer test was conducted on a well located in Section 23, Township 10 North, Range 12 West, on the C.E. Smith farm near Sickles in Caddo County. The test was performed during April 1956. Transmissivity and storativity values were calculated by the Theis non-equilibrium formula, the Thiem formula, and the Jacob modified non-equilibrium formula. Transmissivity was reported to range from 11,000 gpd/ft to 14,000 gpd/ft and storativity ranged from 0.01 to 0.03 and averaged 0.02. The second test was conducted on a well in Section 2, Township 10 North, Range 13 West, four miles north of Eakley in Caddo County. The test was performed during March 1959. Transmissivity was calculated from recovery data using the Jacob modified non-equilibrium formula. Transmissivity was determined to be 13,000 gpd/ft.

Two aquifer test were performed in the study area in the Spring of 1991. One test was performed in the northwest quarter of Section 6, Township 5 North, Range 9 West. The pumped well, W-PW, was constructed to a depth of 119 feet below ground surface with 2-inch casing and a manufactured well screen 20-feet in length installed at the boring termination depth. The Rush Springs Sandstone was described on the boring log from W-PW as a red to brown to tan sandstone with a thickness of approximately 110 feet. Static water level prior to the test was measured at 49 feet below ground surface. Saturated thickness was determined to be 61 feet (110 feet less 49 feet). One observation well, W-6, located 67.4 feet from the pumped well, was constructed to a depth of 119 feet below ground surface with 2-inch casing and a manufactured well screen 20-feet in length installed at the boring termination depth.

The Rush Springs Sandstone was described on the boring log from W-6 as 115 feet of red to gray to tan sandstone with some interbedded shales. Static water level prior to the test was measured at 36 feet below ground surface. The saturated thickness was determined to be 79 feet (115 feet less 36 feet). Well W-PW was pumped for 240 minutes at a discharge rate of 13.5 gallons per minute. Drawdown was measured in both the pumped well and the observation well. The drawdown data was corrected for unconfined aquifer conditions and plotted on 3 x 5 cycle logarithmic graph paper. The resultant drawdown curves were analyzed using the Theis non-equilibrium equation. Transmissivity was calculated to be 573 gpd/ft in the pumped well (W-PW) and 1,664 gpd/ft in the observation well (W-6). Using the calculated saturated thickness values for W-PW and W-6, hydraulic conductivity values were determined to be 9.4 gpd/ft<sup>2</sup> and 21 gpd/ft<sup>2</sup>, respectively. Storativity in observation well W-6 was calculated to be  $1.5 \times 10^{-4}$ . However the test was not run for a sufficient period of time to allow the cone of depression to reach equilibrium, so the calculated storativity will not reflect the storativity of the aquifer at equilibrium. Boring logs/well construction diagrams, test data, drawdown curves, and calculations are included in Appendix A.

The second test was performed in the southeast quarter of Section 1, Township 5 North, Range 10 West approximately 1/2 mile southwest of the first test. The pumped well, D-5PW, was constructed to a depth of 106 feet below ground surface with 2-inch casing and a manufactured well screen 30-feet in length installed at the boring termination depth. The Rush Springs Sandstone was described on the boring log from D-5PW as a 101 feet of soft weathered sandstone with some clay in the lower part. Static water level prior to the test was measured at 46 feet below ground

surface. Saturated thickness was determined to be 55 feet (101 feet less 46 feet). One observation well, D-2, located 60.5 feet from the pumped well, was constructed to a depth of 99 feet below ground surface with 2-inch casing and a manufactured well screen 20-feet in length installed at the boring termination depth. The Rush Springs Sandstone was described on the boring log from D-2 as 96 feet of light to dark brown to gray sandstone. Static water level prior to the test was measured at 48 feet below ground surface. The saturated thickness was determined to be 48 feet (96 feet less 48 feet). Well D-5PW was pumped for 240 minutes at a discharge rate of 12 gallons per minute. Drawdown was measured in both the pumped well and the observation well. The drawdown data was corrected for unconfined aquifer conditions and plotted on 3 x 5 cycle logarithmic graph paper. The resultant drawdown curves were analyzed using the Theis non-equilibrium equation. Transmissivity was calculated to be 353 gpd/ft in the pumped well (D-5PW) and 1,100 gpd/ft in the observation well (D-2). Using the calculated saturated thickness values for W-PW and W-6, hydraulic conductivity values were determined to be 6.4 gpd/ft<sup>2</sup> and 23 gpd/ft<sup>2</sup>, respectively. Storativity in observation well D-2 was calculated to be  $3.8 \times 10^{-3}$ . However the test was not run for a sufficient period of time to allow the cone of depression to reach equilibrium, so the calculated storativity will not reflect the storativity of the aquifer at equilibrium. Boring logs/well construction diagrams, test data, drawdown curves, and calculations are included in Appendix A.

## CHAPTER IV

### GEOCHEMISTRY

Ground-water contains minerals dissolved from subsurface soils and rocks through which infiltration occurs and ground water flows. The concentrations of dissolved minerals in the ground water are a function of the mineral composition of the soil and the rock materials through which the water has passed, the physiochemical environment of the unsaturated and saturated zones, and the residence time of the ground water in the aquifer system.

The natural occurrence of minerals in the ground water may be exacerbated by the activities of man such as disposal of sewage and industrial waste, either directly through injection or through leachate, industrial activities, and the effect of agricultural operations. In the study area, ground water chemistry has been affected by oil field operations and secondary recovery at the Cement field.

A total of 115 ground-water chemical analyses were evaluated using the computer program WATEVAL (Hounslow and Goff, 1991). The chemical analyses were comprised of 19 analyses from the Duncan Sandstone, 13 analyses from the Chickasha Formation, 1 analyses from the Marlow Formation, and 82 analyses from the Rush Springs Sandstone.

WATEVAL performs a sequence of analytical checks and comparisons to

indicate the overall quality of the entered analysis. Various ion ratios are calculated to suggest possible source rocks through which the ground water may infiltrate or flow. Figure 7 illustrates the logic of water quality interpretation using simplified mass balance.

WATEVAL also presents information in two graphical formats, the Piper plot and the Stiff diagram. The Piper plots consist of two triangular diagrams and one diamond shaped diagram. The percentages of cations (sodium plus potassium, calcium, and magnesium) and the percentages of anions (chloride, bicarbonate, and sulfate) are plotted on the left triangle and right triangle, respectively. The percentages of the cations and anions are cross-plotted on the diamond diagram which can be used to determine water types. Possible source rocks and various geochemical reactions such as mixing, ion exchange, precipitation, and dissolution can be indicated on the triangular diagrams. Figure 8 indicates typical Piper plots for source rocks on the triangular diagrams and Figure 9 indicates the water type regions on the diamond diagram.

In the Stiff diagrams, milliequivalents per liter (meq/l) concentrations of anions and cations are plotted on the left and right sides, respectively, of a zero concentration index line. The shape of the resultant diagram can suggest possible source rock types and the overall size of the pattern is approximately equivalent to the total ionic content (dissolved solids). Figure 10 shows a Stiff diagram with typical source rock plots.

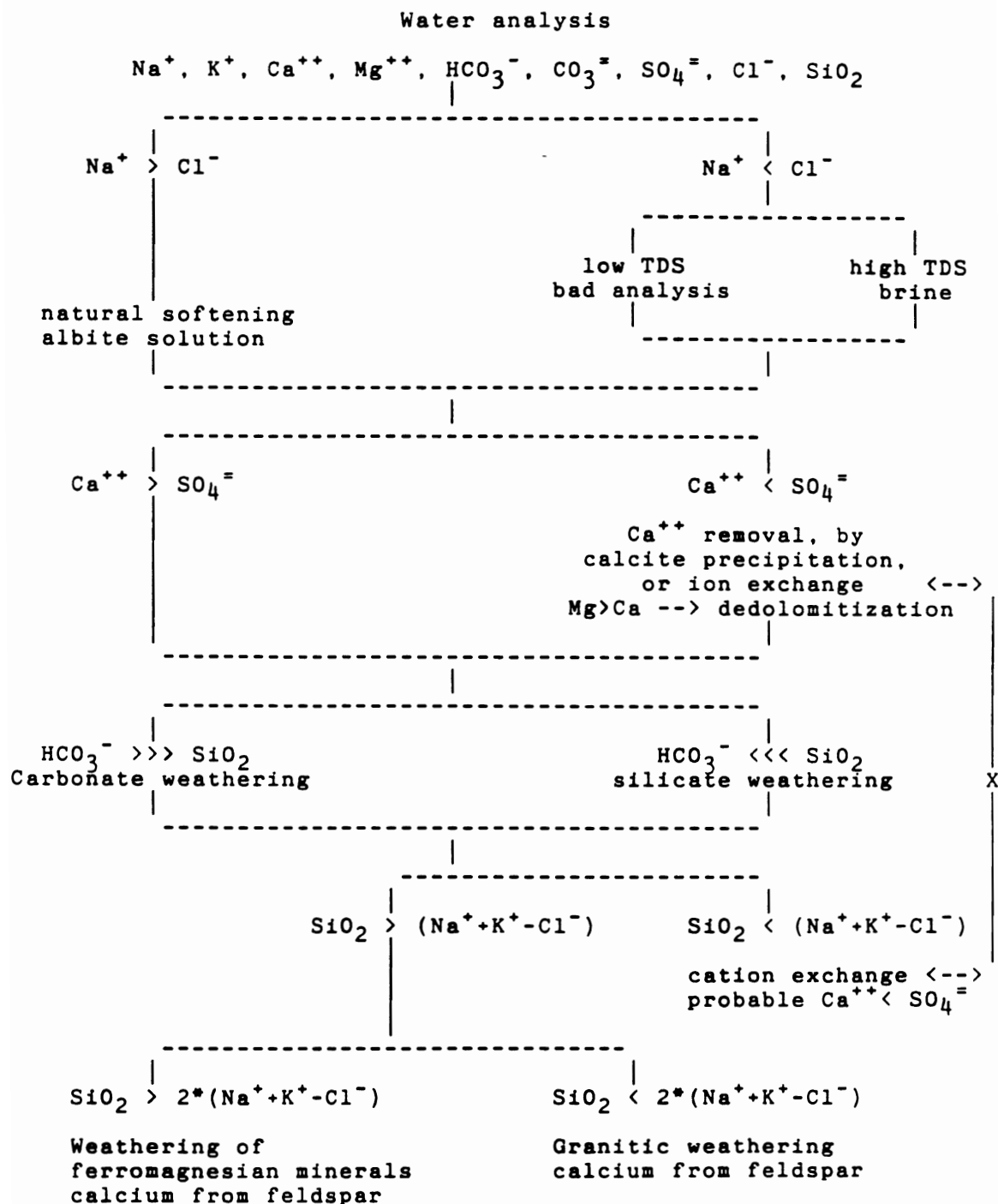


Figure 7. Weathering flowchart (after Hounslow, 1991)



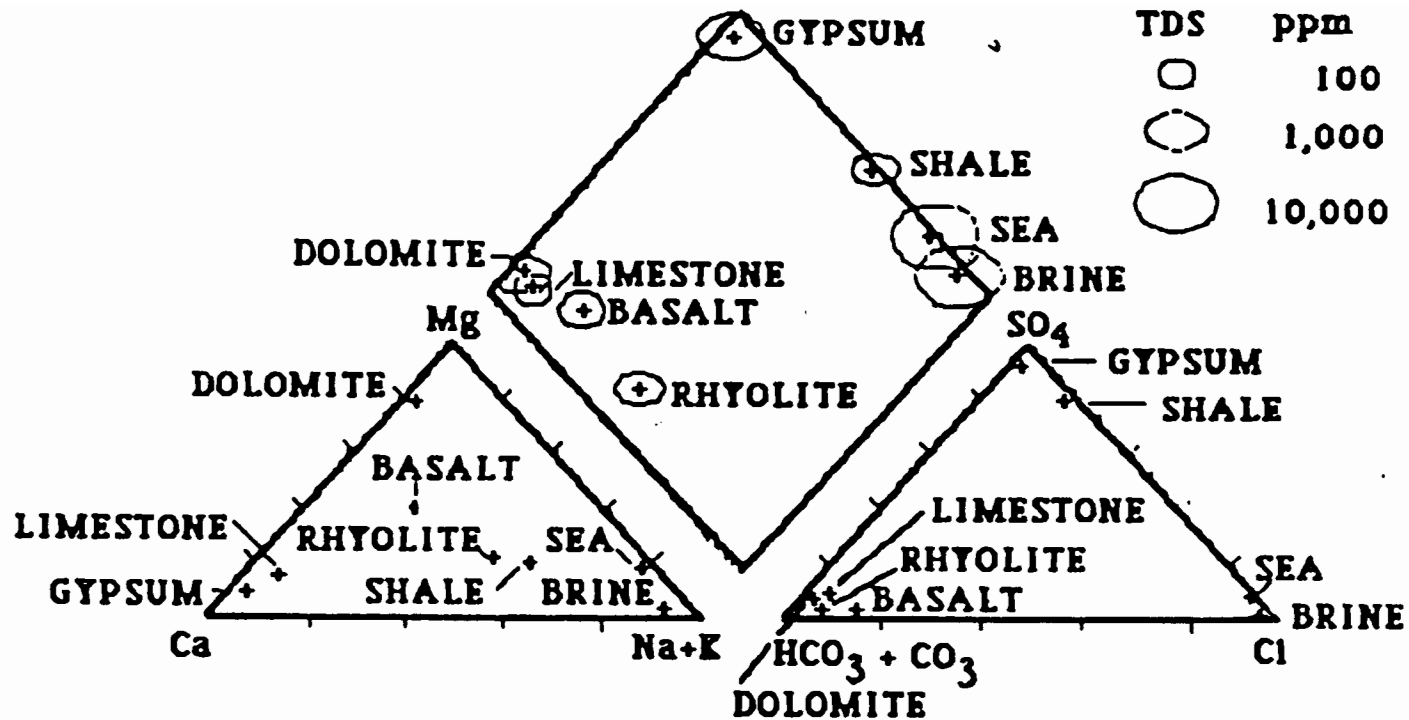
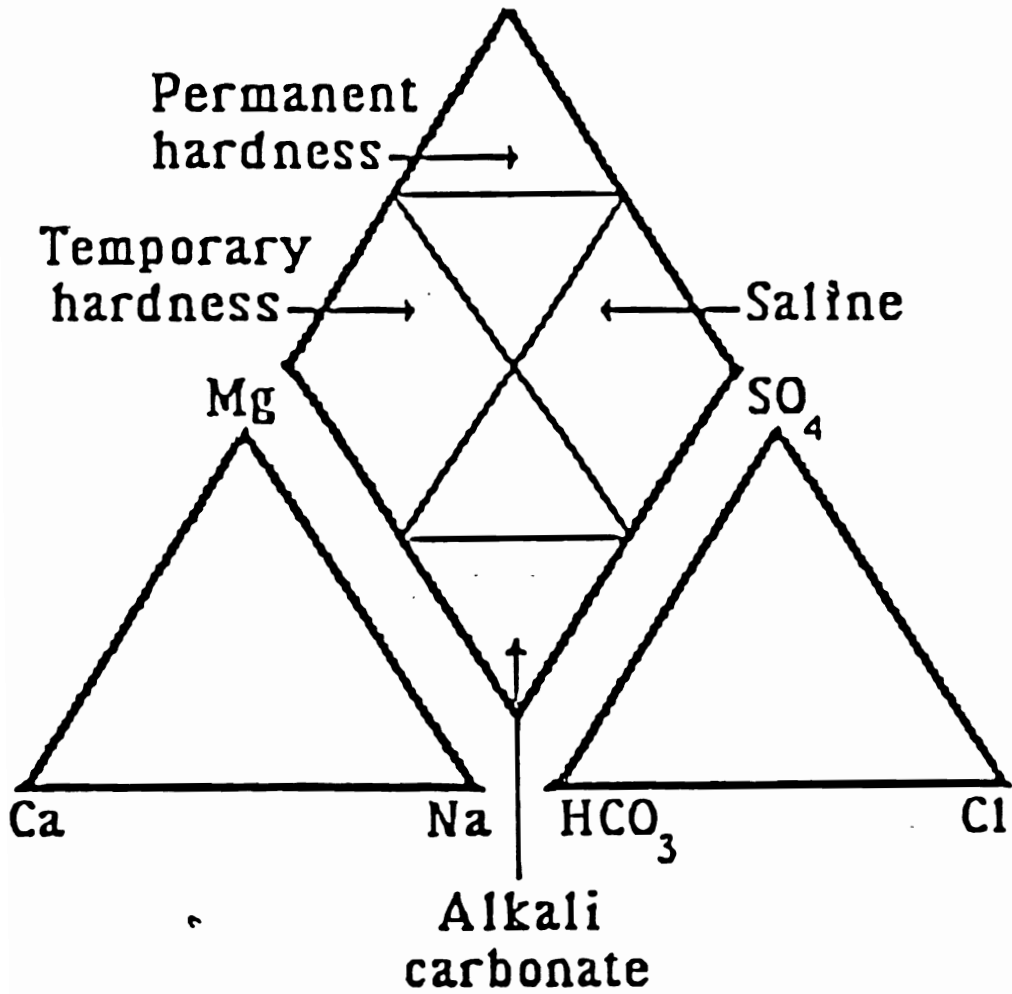
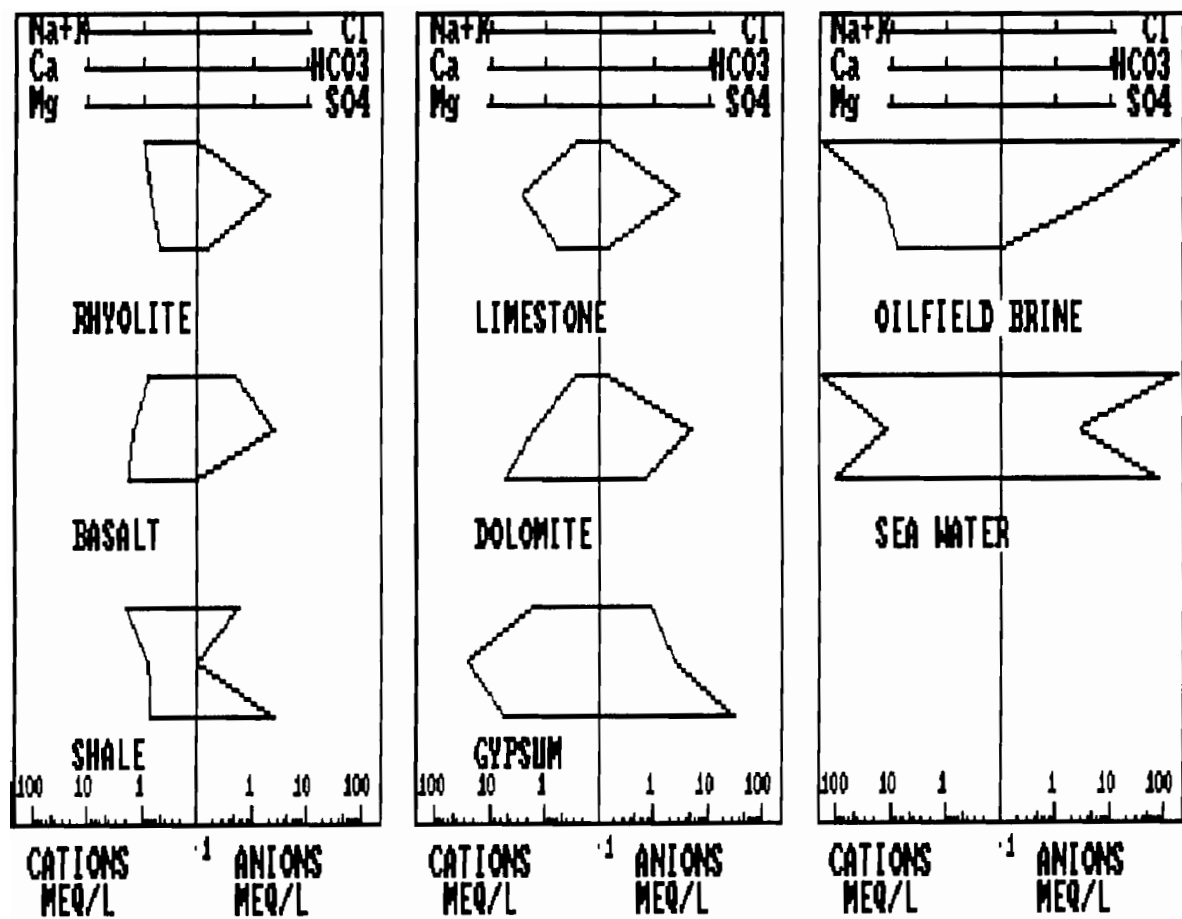


Figure 8. Piper plot illustrating common source rock relationships (after Hounslow, 1991)



Piper plot illustrating typical water types (after Hounslow, 1991)



Stiff diagram illustrating typical source rock shapes (after Hounslow, 1991)

## Duncan Sandstone

Davis (1955) reported that water quality in the Duncan Sandstone is variable in Grady and northern Stephens counties. Ground water was described as potable in some areas, but too highly mineralized, even for stock use, in other areas. Tanaka and Davis (1963) described the ground water in the Duncan Sandstone in Caddo county as being high in dissolved solids and relatively high in sulfate. In a report prepared by Bechtel Environmental (1991) at the Oklahoma Refining Company Site at Cyril, the Duncan Sandstone was described as having potential for use as a drinking water supply, but is not in the Cyril area because sulfate concentrations are relatively high.

Nineteen chemical analyses from the Duncan Sandstone were evaluated using WATEVAL. The analyses were taken from Davis (1955), Tanaka and Davis (1963), Stanley Engineering (1986), and the Oklahoma State Department of Health. The analyses are shown on Table 2. One analyses, D8, was incomplete and not used in the assessment of the Duncan Sandstone.

Figure 11 is a Piper plot of the analyses. The Piper plot indicates three distinctive water types; temporary hardness (bicarbonate), permanent hardness, and saline. The analyses plotting as bicarbonate generally have lower concentrations of sulfate and occur in wells with depths of 300 feet or less. The permanent hardness and saline water types have sulfate concentrations an order of magnitude greater than the bicarbonate waters and generally occur in wells with depths greater than 300 feet. The permanent hardness waters are differentiated from the saline waters primarily by significantly higher concentrations of calcium. Several analyses plot in an

TABLE 2

## DUNCAN SANDSTONE WATER QUALITY ANALYSES

I.D.	Location	Depth	Temp.	SiO <sub>2</sub>	Ca	Mg	Na+K	HCO <sub>3</sub>	CO <sub>3</sub>	SO <sub>4</sub>	Cl	F	NO <sub>3</sub>	TDS	Hard	Cond.	pH	Source
D1	4-3N-5W	91	63	NR	33	54	48	238	7	27	108	0.1	28	570	304	979	NR	a
D2	8-3N-5W	250	68	NR	12	36	37	236	9	11	26	NR	1.7	264	178	462	NR	a
D3	18-5N-5W	300+	64	NR	29	40	29	286	8	35	8.8	NR	2.2	310	237	510	NR	a
D4	20-5N-5W	72	64	NR	38	67	56	207	14	15	64	NR	240	664	370	110	NR	a
D5	12-9N-5W	49	NR	NR	19	41	52	151	20	26	34	0	120	338	216	710	NR	a
D6	14-5N-8W	379	65	NR	52	11	181	202	10	322	36	NR	NR	717	175	NR	NR	a
D7	14-5N-8W	392	63	18	62	14	171	250	0	307	36	0.2	NR	758	212	1100	NR	a
D8	22-5N-8W	420	NR	NR	NR	NR	NR	274	NR	NR	40	NR	NR	NR	193	NR	NR	a
D9	18-5N-9W	1010	NR	18	87	41	183	236	0	504	44	0.4	0.7	1000	384	1420	7.9	b
D10	18-5N-9W	944	NR	NR	1650	NR	NR	109.7	NR	1363	10	NR	NR	3145	2740	2420	7.3	c
D11	18-5N-9W	923	NR	NR	1536	NR	NR	158.5	NR	576	50	NR	NR	2322	620	1650	7.5	c
D12	18-5N-9W	1025	NR	NR	98.8	34.3	82.4	253.6	NR	373	30	NR	NR	875	388	1250	7.7	c
D13	18-5N-9W	979	NR	NR	64.2	29.1	63.5	282.9	NR	249	30	NR	NR	720	280	1000	7.7	c
D14	18-5N-9W	NR	NR	NR	60.8	26.3	99.3	256	NR	300	40	NR	NR	783	260	2300	7.3	c
D15	13-5N-10W	1000	NR	NR	190	29	141	263.4	NR	396	193	NR	NR	965	437	1304	7.5	d
D16	24-5N-10W	962	NR	NR	60	20.7	142	284.1	NR	246	39	NR	NR	714	235	NR	8	d
D17	24-5N-10W	854	NR	NR	64.2	45.6	41.3	280.4	NR	191	40	NR	NR	665	348	1000	7.6	c
D18	33-6N-7W	300	72	NR	98	36	279	180	0	640	130	NR	22	1330	392	1800	NR	a
D19	36-9N-11W	67	NR	NR	182	72	28	168	0	547	50	0.7	40	1220	750	1600	NR	b

Source:

a - Davis (1955)

b - Tanaka &amp; Davis (1963)

c - Stevens Engineering (xxxx)

d - Oklahoma ???

Note:

Temperatures (Temp.) measured in degrees Fahrenheit

Specific conductance (Cond.) measured in micro-mhos at 25 degrees Celsius

Dissolved solids (TDS) reported as residue on evaporation at 180 degrees Celsius

Concentrations are reported in parts per million

NR = Not Reported

Concentrations calculated by WATEVAL from other analysis parameters

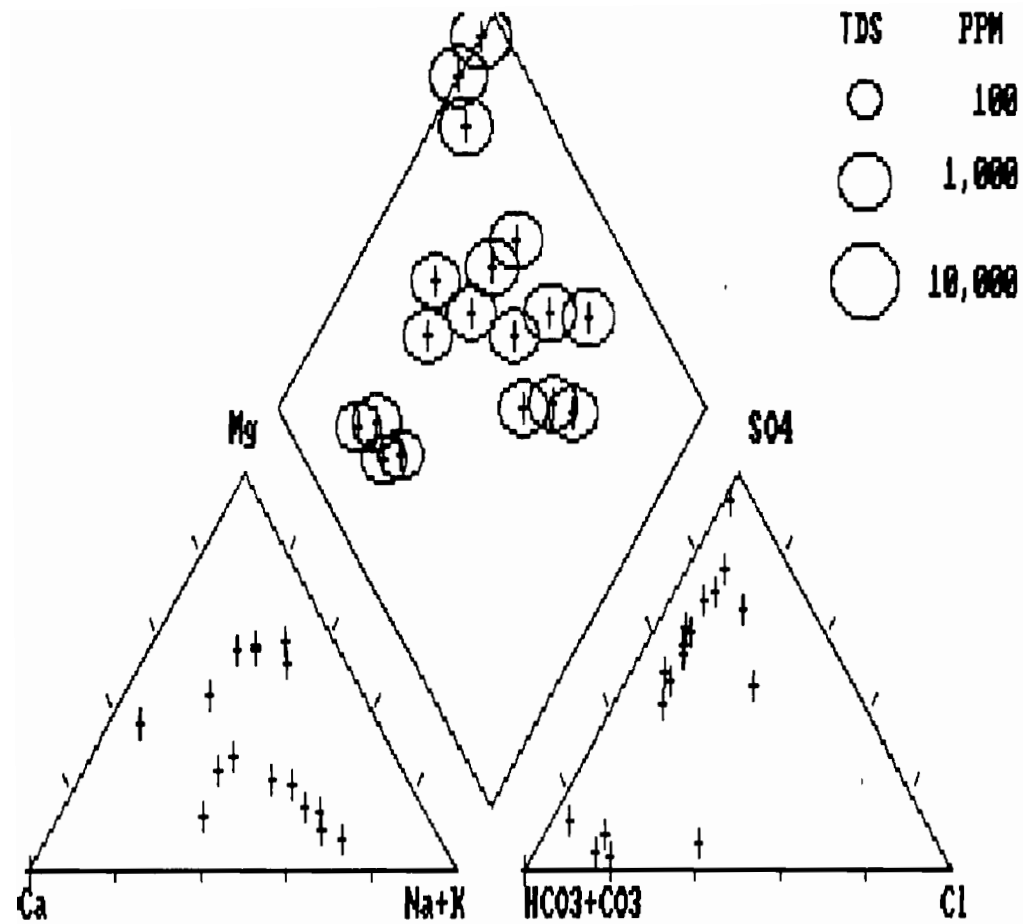


Figure 11. Piper plot of Duncan Sandstone analyses

intermediate position between the three main water types. Three of these analyses, D12 through D14, may not represent the actual chemical composition of the ground water as magnesium was calculated from calcium and total hardness, sodium plus potassium was calculated by difference, and bicarbonate was calculated from alkalinity.

The bicarbonate waters typically had Na/Cl ratios greater than 1 indicating a Na source other than halite. The Na/Cl ratio could be indicative of natural softening. Ca/SO<sub>4</sub> ratios were greater than 1 indicating a Ca source other than gypsum. The Ca/SO<sub>4</sub> ratios indicate silicate weathering or possible calcite or dolomite dissolution. Ca/Mg ratios ranged from 0.69 to 0.83 indicating a Mg source other than dolomite. The Mg source may be due to the weathering of shale. The plot of the analyses on a Piper diagram fell in the area typical for dolomitic rock types and the shape of the plots on a Stiff diagram (Figure 12) were similar to that of a dolomitic source rock. The saline waters had Na/Cl ratios significantly greater than 1 and Ca/SO<sub>4</sub> ratios of less than 1. These ratios and the SiO<sub>2</sub>/non-halite Na ratio suggest that the saline waters may be undergoing natural softening (ion exchange). Two of the analyses reported SiO<sub>2</sub> and both evaluations indicated carbonate weathering. The SiO<sub>2</sub> concentration was significantly less than the non-halite Na in both analyses, also indicating carbonate weathering. Ca/Mg ratios ranged from 0.26 to 0.44 indicating dissolution of limestone to dolomitic limestone. The high Ca/Mg ratios may be indicating the dissolution of calcite cement and dolomitic sandstones. The plot of the analyses on a Piper diagram are typical of ground waters with a shale source rock. The shapes of the analyses on the Stiff diagram (Figure 12) were more typical of a

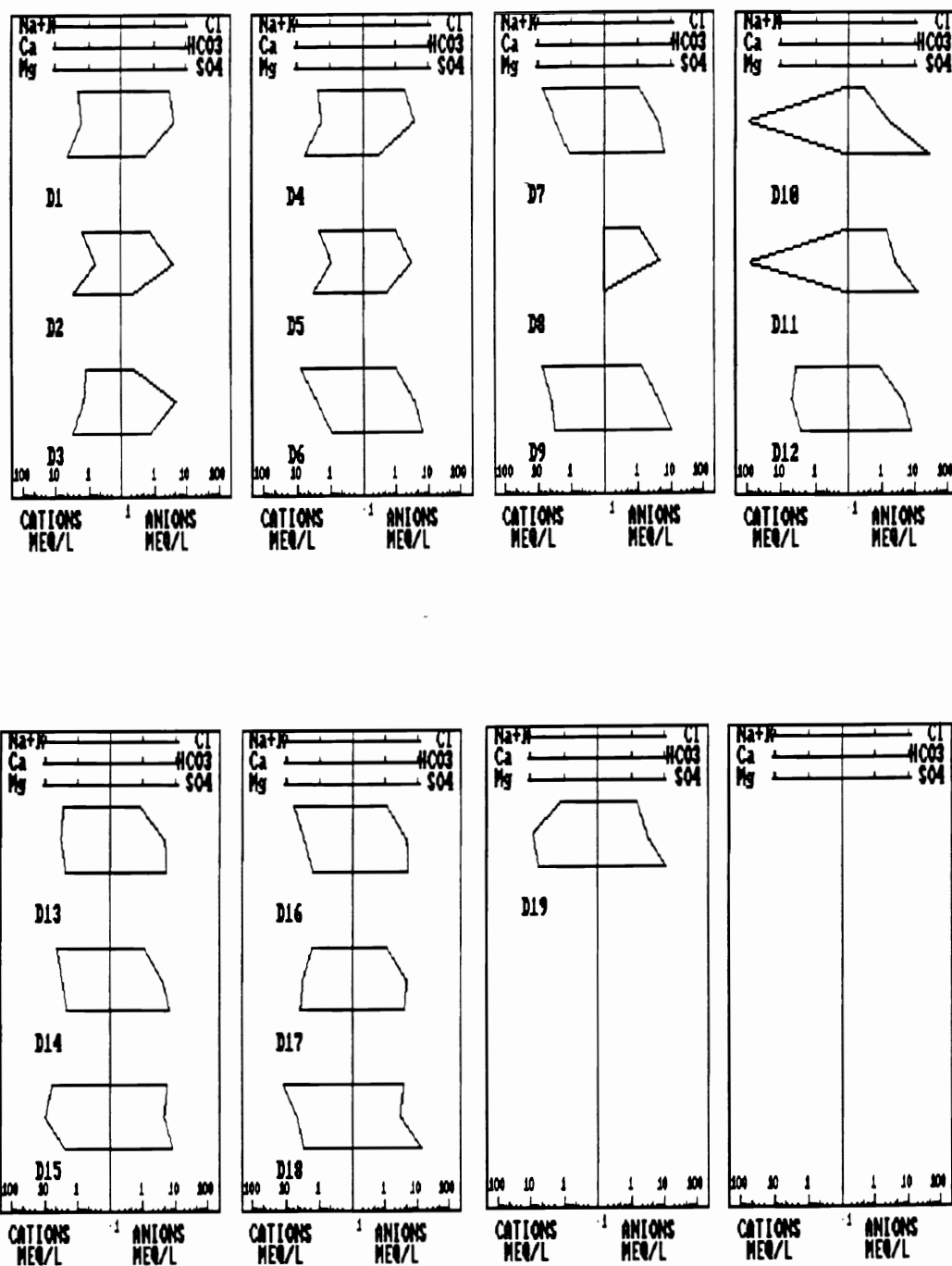


Figure 12. Stiff diagram of Duncan Sandstone analyses



gypsum source rock, although the sodium concentrations were higher than would normally be expected. It is likely that the source rock for the aquifer is probably gypsiferous in nature and that cation exchange has increased the sodium and decreased the calcium concentrations in the water as evidenced on the Piper and Stiff diagrams.

### Chickasha Formation

Davis (1955) described the water from the Chickasha Formation in Grady and northern Stephens Counties to be generally suitable for human and stock use, but in some areas it is too highly mineralized even for stock. Thirteen analyses reported by Davis (1955) were entered into WATEVAL . The analyses are shown on Table 3. One sample was partially reported and two samples were suspected of being in error due to Na/Cl ratios of less than 1 and TDS concentrations of less than 500 mg/l.

Figure 13 shows the analyses from the Chickasha Formation plotted on a Piper diagram. The analyses generally plot in the area of temporary hardness (bicarbonate) on the diamond diagram. The plot of the analyses on the triangular diagrams fell into the areas of dolomite and shale. The shapes of the analyses on plotted on Stiff diagrams are shown on Figure 14 and appear similar to the shape of typical dolomites.

Overall, the analyses exhibited Na/Cl ratios of greater than 1 indicating a source of Na other than halite and suggesting that natural softening may be occurring. Ten of the analyses had Ca/SO<sub>4</sub> ratios greater than 1 indicating a source of Ca other than gypsum, possibly the dissolution of calcite or dolomite. Two samples had Ca/SO<sub>4</sub> ratios less than 1 indicating natural softening or the precipitation of calcite or

TABLE 3

## CHICKASHA FORMATION WATER QUALITY ANALYSES

I.D.	Location	Depth	Temp.	SiO <sub>2</sub>	Ca	Mg	Na+K	HCO <sub>3</sub>	CO <sub>3</sub>	SO <sub>4</sub>	Cl	F	NO <sub>3</sub>	TDS	Hard.	Cond.	Source
C1	16-6N-5W	80	68	NR	50	45	8.7	240	12	29	38	NR	36	386	310	625	a
C2	34-6N-7W	80	68	NR	84	104	40	303	0	55	103	NR	340	1060	637	1370	a
C3	4-7N-5W	32	NR	NR	20	40	68	321	11	20	41	0.3	2	524	214	785	a
C4	16-7N-6W	105	NR	NR	26	61	7.4	292	17	14	17	NR	32	407	316	789	a
C5	27-7N-6W	185	NR	NR	93	61	51	480	63	60	22	0	1.5	648	403	965	a
C6	32-7N-6W	200	70	NR	46	54	79	306	15	161	40	NR	11	598	337	904	a
C7	9-8N-5W	38	NR	NR	NR	NR	NR	154	0	16	9	NR	60	NR	291	NR	a
C8	25-8N-5W	70	60	NR	99	59	49	456	0	69	50	0	100	618	490	1010	a
C9	31-8N-5W	Spring	NR	NR	58	54	31	474	0	19	17	0	1.5	396	366	724	a
C10	22-8N-6W	60	NR	NR	10	21	88	219	42	19	21	0.3	3	284	111	545	a
C11	23-8N-7W	40	NR	NR	21	22	56	217	14	39	13	0.2	6	252	143	616	a
C12	16-9N-6W	27	NR	NR	34	14	25	159	9	15	17	0.2	15	317	142	534	a
C13	22-9N-7W	42	NR	NR	469	116	779	72	0	2030	825	0.5	5	4440	1650	5450	a

Source:

a - Davis (1955)

Note:

Temperatures (Temp.) measured in degrees Fahrenheit

Specific conductance (Cond.) measured in micro-mhos at 25 degrees Celsius

Dissolved solids (TDS) reported as residue on evaporation at 180 degrees Celsius

Concentrations are reported in parts per million

NR = Not Reported

Concentration calculated by WATEVAL from other analysis parameters

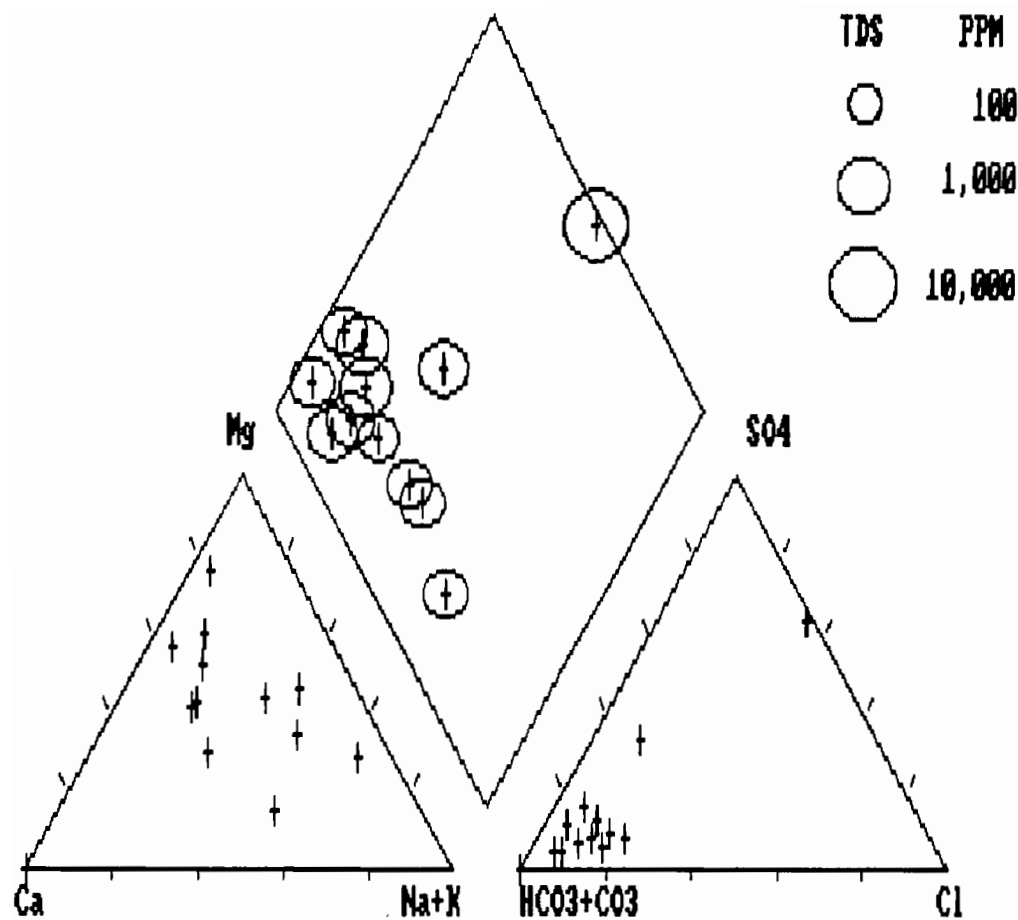


Figure 13. Piper plot of Chickasha Formation analyses

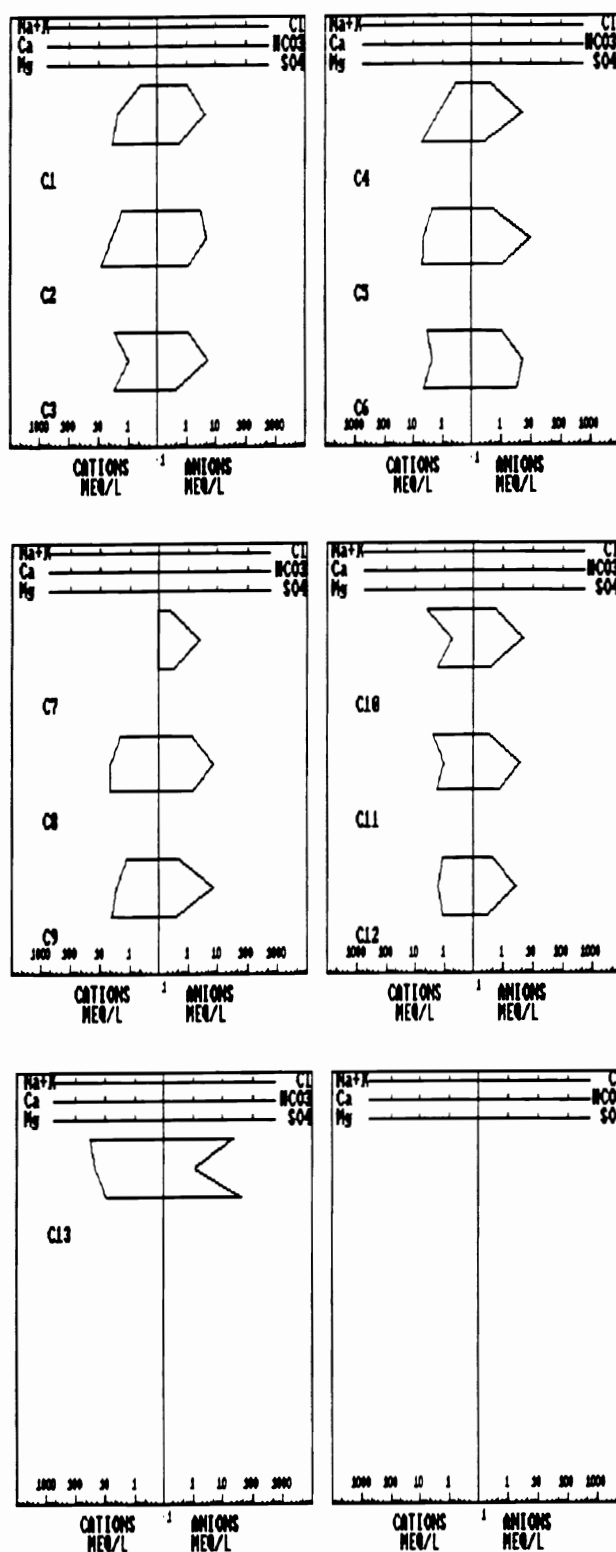


Figure 14. Stiff diagram of Chickasha Formation analyses

gypsum. No silica was reported in any of the samples. Ca/Mg ratios ranged from 0.29 to 0.78. Four samples had ratios of less than 0.61, one sample had a ratio of 0.61, and the remaining samples had ratios greater than 0.61. A ratio of 0.61 would indicate the dissolution of dolomite with the lower ratios indicating the dissolution of limestone. The higher ratios indicate a source of Mg other than dolomite.

The red color of the sediments in the Chickasha Formation and the presence of iron oxide as a cementing agent may indicate that ferromagnesian minerals were deposited in significant amounts in the sediments (Hounslow, 1992). This could be supported by the Ca/Mg ratios which indicate a source of Mg other than dolomite.

### Marlow Formation

In its report on ground water in Oklahoma, the Oklahoma Water Resources Board (1965) described ground water in the Marlow Formation as being hard and high in total solids and sulfates due to disseminated gypsum. Davis (1950) described ground water from the Marlow Formation in the Pond Creek basin in Caddo County as generally hard and high in calcium, magnesium, and sodium sulfates, but free from magnesium bicarbonate. The Marlow Formation in northern Stephens and Grady Counties was described by Davis (1955) as yielding ground water that is extremely hard and high in sulfate. Tanaka and Davis (1963) reported that the ground water in the Marlow Formation in Caddo County contains much disseminated gypsum and as a result the water is harder and has a higher sulfate and dissolved solids concentration than does water from the Rush Springs Sandstone.

One chemical analysis from the Marlow Formation in Caddo County was

reported by Tanaka and Davis (1963). The analysis, M1, is shown on Table 4. Figure 15 shows a Piper diagram and a Stiff diagram for the analysis. On the Piper plot, the analysis plots in the area of temporary hardness (bicarbonate waters) on the diamond diagram and in the area typical of limestone to dolomite source rocks on the triangular diagrams. The shape of the analysis on the Stiff diagram suggests a dolomitic limestone source rock.

The analysis had a Na/Cl ratio of greater than 1 indicating a source of Na other than halite. The  $\text{Ca}/\text{SO}_4$  ratio was also greater than 1 indicating a Ca source other than gypsum. The Ca/Mg ratio was calculated at 0.25, suggesting the dissolution of limestone. The evaluation of the WATEVAL output indicate that ion exchange (natural softening) is probably taking place in the aquifer as evidenced by the excess Na concentrations. Typically, when natural softening occurs, the  $\text{Ca}/\text{SO}_4$  ratio is less than 1, however, the dissolution of limestone or dolomite may be providing sufficient Ca to create a  $\text{Ca}/\text{SO}_4$  ratio of greater than 1. Tanaka and Davis (1963) reported that this analysis shows a close similarity to water from the Rush Springs Sandstone and is probably not typical of most of the water in the Marlow.

### Rush Springs Sandstone

Tanaka and Davis (1963) described the ground water from the Rush Springs Sandstone as hard but low in dissolved solids and generally suitable for municipal and irrigation uses. Depending on the degree of hardness, the water may require treatment for removal of hardness-causing cations for some industrial uses. Chemical analyses of 42 samples collected from wells and springs in the Rush Springs

TABLE 4

## RUSH SPRINGS SANDSTONE AND MARLOW FORMATION WATER QUALITY ANALYSES

I.D.	Location	Depth	Temp.	SiO2	Ca	Mg	Na+K	HCO3	CO3	SO4	Cl	F	NO3	TDS	Hard	Cond	pH	Source
R1	16-3N-7W	60	61.5		66	24	24	360	0	3	9		5	335	263			a
R2	17-3N-7W	70	61		55	19	57	344	0	13	17		25	378	216			a
R3	26-3N-7W	200	61		62	27	40	155	0	14	109	0.2	70	429	266	706		a
R4	26-3N-7W	200	61					148		15	114	0.6	70		263	674		a
R5	2-3N-8W	100	60.5		68	44	44	192	0	21	43		255	704	350			a
R6	3-3N-8W	53	60		78	78	28	326	0	68	61		189	748	515			a
R7	4-3N-8W	40			68	37	49	163	0	13	64		236	694	322			a
R8	9-3N-8W	95	60.5		83	15	17	160	0	60	32		84	487	268			a
R9	15-3N-8W	45						114	0	68	102		352		596			a
R10	3-4N-7W	122	60		87	14	12	257	0	53	23		4	365	274	560		a
R11	5-4N-7W	21	59		90	10	6.2	278	0	24	12		11	344	266			a
R12	9-4N-7W	97	59		61	7.5	34	250	0	15	8		30	329	183			a
R13	16-4N-7W	41	60		29	14	21	74	0	14	53		33	305	130			a
R14	29-4N-7W	20			100	46	3.2	207	0	176	54		21	603	438			a
R15	29-4N-7W	25			88	19	17	229	0	95	26		14	463	298	625		a
R16	10-4N-8W	100	62		48	12	70	196	0	14	12		223	476	170			a
R17	14-4N-8W	105			68	16	20	276	0	12	18		19	342	236			a
R18	15-4N-8W	18	60.5		57	29	29	248	0	95	10		9	420	262			a
R19	17-4N-8W	50	62		299	57	78	192	0	449	183		330	1490	980			a
R20	20-4N-8W	80	61		279	13	110	118	0	591	183		24	1260	750			a
R21	23-4N-8W	40	60		364	33	22	198	0	876	9		5.5	1400	1040			a
R22	23-4N-8W	60	59.5		100	17	1.6	199	0	140	5		9.6	436	320			a
R23	23-4N-8W	60	60		37	22	59	312	0	31	7		17	327	183			a
R24	23-4N-8W	31	60.5		144	20	163	137	0	532	43		86	1060	442			a
R25	25-4N-8W	14	60.5		10	8.1	18	96	0	10	4		2	115	58			a
R26	26-4N-8W	60	59		68	28	94	288	0	221	8		1	558	274			a
R27	27-4N-8W	40	61		64	17	15	203	0	46	9		43	367	230			a
R28	28-4N-8W	Spring	61.5		274	20	9.7	238	0	536	8		28	993	766			a

TABLE 4 (Continued)

I.D.	Location	Depth	Temp.	SiO2	Ca	Mg	Na+K	HCO3	CO3	SO4	Cl	F	NO3	TDS	Hard	Cond	pH	Source
R29	28-4N-8W	33	61		63	30	62	150	0	60	36		211	638	280			a
R30	29-4N-8W	46	61.5		215	22	9.2	254	0	385	10		30	874	627			a
R31	33-4N-8W	53			82	20	23	224	0	224	34	0.1	5	456	286	584		a
R32	33-4N-8W	148			304	20	46	90	0	777	40	0.4	1	1640	840	1660		a
R33	33-4N-8W	252			541	31	144	99	0	1570	52	0.4	0.2		1480	2200		a
R34	36-4N-8W	72	60		58	22	19	278	0	12	6		33	306	235			a
R35	33-5N-7W	92	61		77	6.6	6.2	220	0	14	8		33	332	219			a
R36	18-6N-8W	80			36	15	17	113	0	64	13		14	264	152	375		a
R37	9-9N-8W	36			122	37	16	49	9	393	18	0.4	2	796	456	1060		a
R38	34-10N-8W	34			34	13	11	105	8	26	14	0.2	20	215	138	422		a
R39	3-5N-9W	200		22	62	6.2	4	122	0	28	28	0	20	236	180	388	7.7	b
R40	3-5N-9W			22	385	80	396	264	0	201	1160	0	65	3160	1290	4290	7.1	b
R41	35-5N-9W	300			54	12	39	212	0	41	20		30	310	184	490		b
R42	1-5N-10W	140		22	92	17	15	272	0	78	11	0.3	16	407	300	610	8.1	b
R43	1-5N-10W	170		24	100	12	16	274	0	7	37	0	60	399	298	640	7.3	b
R44	2-5N-10W	175		16	141	33	12	258	0	261	15	0	7.2	646	488	890	7.3	b
R45	10-7N-10W	80			605	83	28	159	0	1690	14	0.4	2	2700	1850	2630		b
R46	30-7N-11W				246	6.6	39	216	0	476	8	0.3	50	986	64	1200		b
R47	2-7N-12W				37	7.7	16	132		10	3		50	186	124	310	7.7	b
R48	2-7N-12W			24	74	8.5	14	189	0	79	7	0.3	7	318	220	477	7.5	b
R49	5-7N-12W	32			12	4.4	38	107	0	16	6		20	174	48	237		b
R50	34-7N-12W	57			21	0.3	49	158	0	12	10	0	4	154	54	222		b
R51	4-8N-10W				57	51	17	218	0	190	7	0.6	0.5	555	352	849		b
R52	5-8N-12W	250			24	12	2	99	0	10	14	0	4	192	109	296		b
R53	5-8N-12W	348	63		24	12	2.4	99	0	9.9	14		4	192	109	192		c
R54	11-8N-12W	200			66	9.2	8	236	0	7	16				203		7.7	b
R55	12-8N-12W				35	15		216	0	15	11						7.1	b
R56	13-8N-12W	120			36	15		216	0	12	11						7.2	b
R57	14-8N-12W	200			86	12		418	0	32	11		0				7.5	b
R58	1-8N-13W	40	62		27	13	29	110	0	16	11	0	75	273	121	393		b,c



TABLE 4 (Continued)

I.D.	Location	Depth	Temp.	SiO <sub>2</sub>	Ca	Mg	Na+K	HCO <sub>3</sub>	CO <sub>3</sub>	SO <sub>4</sub>	Cl	F	NO <sub>3</sub>	TDS	Hard	Cond	pH	Source
R59	1-8N-13W	250			448	45	29		0	1270	36		0	2020	1310	2110		b
R60	4-9N-10W	57			40	19	25	196	10	23	10	0.2	20	287	170	515		b
R61	16-9N-10W	85			66	27	32	280	13	9	8	0.2	90	343	276	626		b
R62	1-9N-12W	80	61		17	7.6	16	72	0	12	12	0.2	25	144	74	204		b,c
R63	12-9N-12W	90			47	18	16	206	12	9	10	0.4	15	202	191	389		b
R64	16-9N-12W	90	59.5		47	18	16	206	12	8.7	10	0.4	15	202	191	389		c
R65	19-9N-12W	62	60		20	10	13	99	0	10	14	0	10	145	91	217		b,c
R66	24-9N-12W	120	61		36	16	108	316	0	21	49	0	50	448	157	742		b,c
R67	3-9N-13W		59.5		47	8.7	47	239	0	12	9	0.4	40	296	153	455		b,c
R68	28-9N-13W	335	60		54	13	15	188	0	20	9		40	282	188	407		b,c
R69	5-10N-11W				12	7.3	8	75		10	3	0.4	0	79	60	149		b
R70	32-10N-11W	225			47	9.4	14	210	0	4	8		1.3	220	156	356	7.0	b
R71	33-10N-11W				53	2.9	21	170	0	38	6		8.5	270	144	414	8.0	b
R72	23-10N-12W	288		30	48	7.3	11	185	0	13	5	0	1.2	204	150	325	7.4	b
R73	31-10N-12W	67	60		57	19	21	260	0	16	25	0.1	1	280	221	477		b,c
R74	4-10N-13W		59.5		37	5.2	16	145	0	7.8	14	0	3	156	114	268		b,c
R75	3-11N-11W				59	13	31	249	11	8	14	0.2	3	262	200	455		b
R76	22-11N-11W				48	13	20	172	10	11	16		30	244	173	383		b
R77	22-11N-11W	280			64	18	16	304	0	6	7		4.5	286	234	489		b
R78	3-11N-12W	110	61		73	9.2	22	210	18	5.7	14		50	290	220	465		b,c
R79	31-12N-11W	155			45	9	50	289	0	4	12	0	0	252	149	447		b
R80	34-12N-11W	225						240		17	35		20			580		b
R81	4-12N-13W	150		24	54	13	26	266	0	9	8	0	1.9	259	188	476	7.6	b
R82	33-12N-13W	80	60.5		70	8	39	326	0	5.8	11		5	339	208	554		b,c

TABLE 4 (Continued)

I.D.	Location	Depth	Temp.	SiO <sub>2</sub>	Ca	Mg	Na+K	HCO <sub>3</sub>	CO <sub>3</sub>	SO <sub>4</sub>	Cl	F	NO <sub>3</sub>	TDS	Hard	Cond	pH	Source
R59	1-8N-13W	250			448	45	29		0	1270	36		0	2020	1310	2110		b
R60	4-9N-10W	57			40	19	25	196	10	23	10	0.2	20	287	170	515		b
R61	16-9N-10W	85			66	27	32	280	13	9	8	0.2	90	343	276	626		b
R62	1-9N-12W	80	61		17	7.6	16	72	0	12	12	0.2	25	144	74	204		b,c
R63	12-9N-12W	90			47	18	16	206	12	9	10	0.4	15	202	191	389		b
R64	16-9N-12W	90	59.5		47	18	16	206	12	8.7	10	0.4	15	202	191	389		c
R65	19-9N-12W	62	60		20	10	13	99	0	10	14	0	10	145	91	217		b,c
R66	24-9N-12W	120	61		36	16	108	316	0	21	49	0	50	448	157	742		b,c
R67	3-9N-13W		59.5		47	8.7	47	239	0	12	9	0.4	40	296	153	455		b,c
R68	28-9N-13W	335	60		54	13	15	188	0	20	9		40	282	188	407		b,c
R69	5-10N-11W				12	7.3	8	75		10	3	0.4	0	79	60	149		b
R70	32-10N-11W	225			47	9.4	14	210	0	4	8		1.3	220	156	356	7.0	b
R71	33-10N-11W				53	2.9	21	170	0	38	6		8.5	270	144	414	8.0	b
R72	23-10N-12W	288		30	48	7.3	11	185	0	13	5	0	1.2	204	150	325	7.4	b
R73	31-10N-12W	67	60		57	19	21	260	0	16	25	0.1	1	280	221	477		b,c
R74	4-10N-13W		59.5		37	5.2	16	145	0	7.8	14	0	3	156	114	268		b,c
R75	3-11N-11W				59	13	31	249	11	8	14	0.2	3	262	200	455		b
R76	22-11N-11W				48	13	20	172	10	11	16		30	244	173	383		b
R77	22-11N-11W	280			64	18	16	304	0	6	7		4.5	286	234	489		b
R78	3-11N-12W	110	61		73	9.2	22	210	18	5.7	14		50	290	220	465		b,c
R79	31-12N-11W	155			45	9	50	289	0	4	12	0	0	252	149	447		b
R80	34-12N-11W	225						240		17	35		20			580		b
R81	4-12N-13W	150		24	54	13	26	266	0	9	8	0	1.9	259	188	476	7.6	b
R82	33-12N-13W	80	60.5		70	8	39	326	0	5.8	11		5	339	208	554		b,c

TABLE 4 (Continued)

I.D.	Location	Depth	Temp.	SiO <sub>2</sub>	Ca	Mg	Na+K	HCO <sub>3</sub>	CO <sub>3</sub>	SO <sub>4</sub>	Cl	F	NO <sub>3</sub>	TDS	Hard	Cond	pH	Source
M1	24-9N-12W	29			92	19	14	370		4	21	0.4	0	423	308	724		b

## Source:

a - Davis (1955)

b - Tanaka &amp; Davis (1963)

c - Davis (1950)

## Note:

Temperatures measured in degrees Fahrenheit

Specific conductance measured in micro-mhos at 24 degrees Celsius

Dissolved solids reported as residue on evaporation at 180 degrees Celsius

Concentrations are reported in parts per million

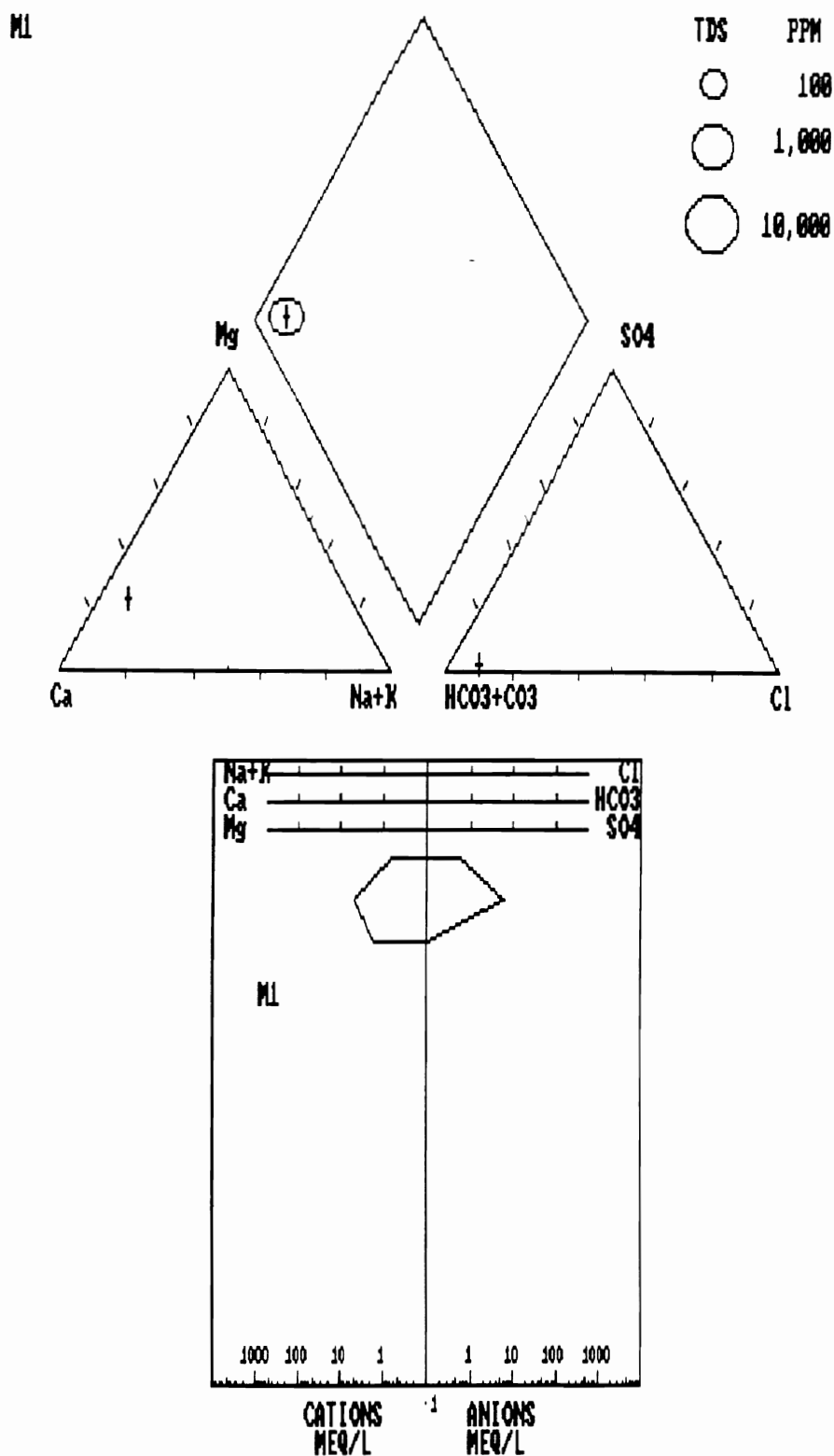


Figure 15. Piper plot and Stiff diagram of Marlow Formation analyses

Sandstone in Caddo County indicate the quality of water is suitable for irrigation and domestic use.

Eighty-two chemical analyses from the Rush Springs Sandstone were evaluated using WATEVAL. The analyses were taken from Davis (1950), Davis (1955), and Tanaka and Davis (1963). The analyses are shown on Table 4. Three analyses were incomplete as cation concentrations were not reported. Three additional analyses were incomplete as to a lack of reported Na + K concentrations. In these three analyses, concentrations for Na + K were calculated as the difference in meq/l between the reported cation and anion concentrations. One sample did not report bicarbonate, and when an attempt was made to calculate bicarbonate from hardness, the anion/cation balance indicated that the analyses was probably in error.

Figures 16 and 17 are Piper plots of analyses R1 through R50 and R51 through R82, respectively, from the Rush Springs Sandstone. On the diamond portion of the diagram, the analyses generally plot in the area of bicarbonate waters (temporary hardness) with a lesser number of analyses plotting in the area of sulfate waters (permanent hardness). The plot of the analyses on the triangular diagrams fell primarily into the areas of limestones and gypsum. Stiff diagrams of all analyses are included in Appendix B. The shapes of the analyses on the Stiff diagrams range from brines to gypsum to limestone. The vast majority of the Rush Springs Sandstone analyses, when plotted on a Stiff diagram, have shapes indicating a limestone source rock.

Based on the results of the WATEVAL evaluation, six samples calculated as brines (Na/Cl ratios less than 1 and TDS greater than 500 mg/l), and ten samples

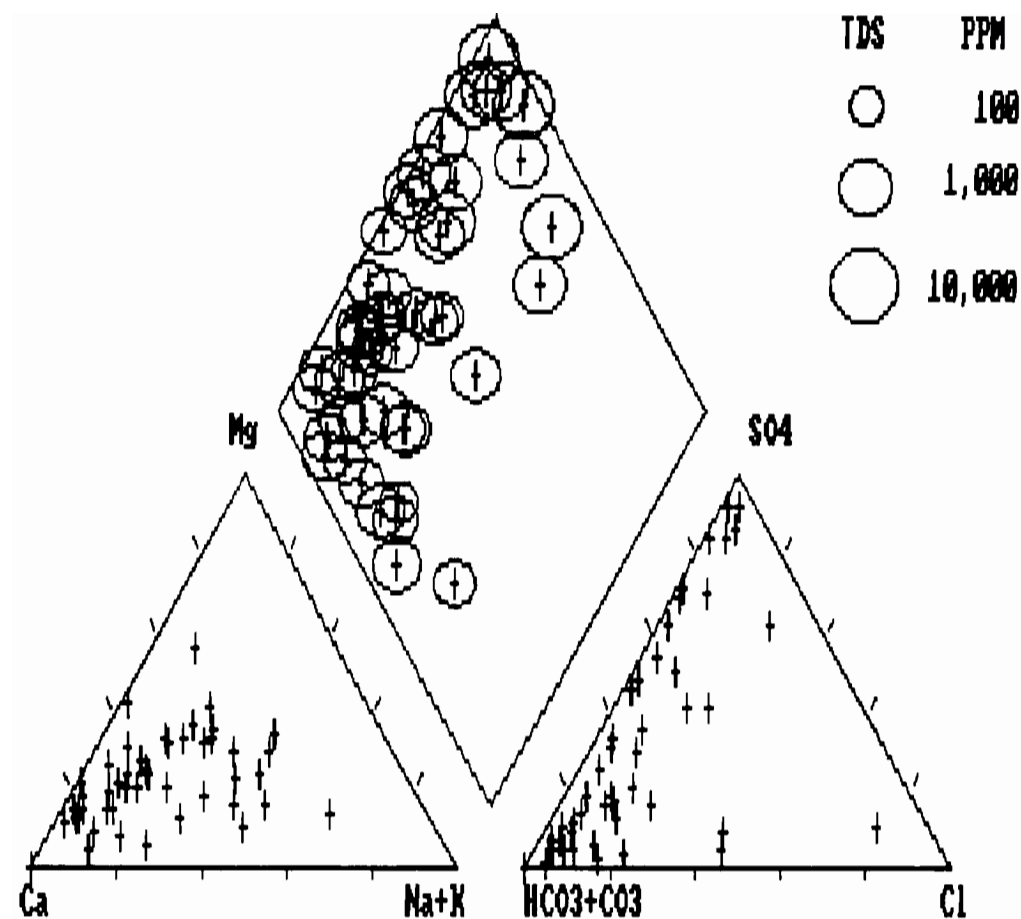


Figure 16. Piper plot of Rush Springs Sandstone analyses R1 through R50

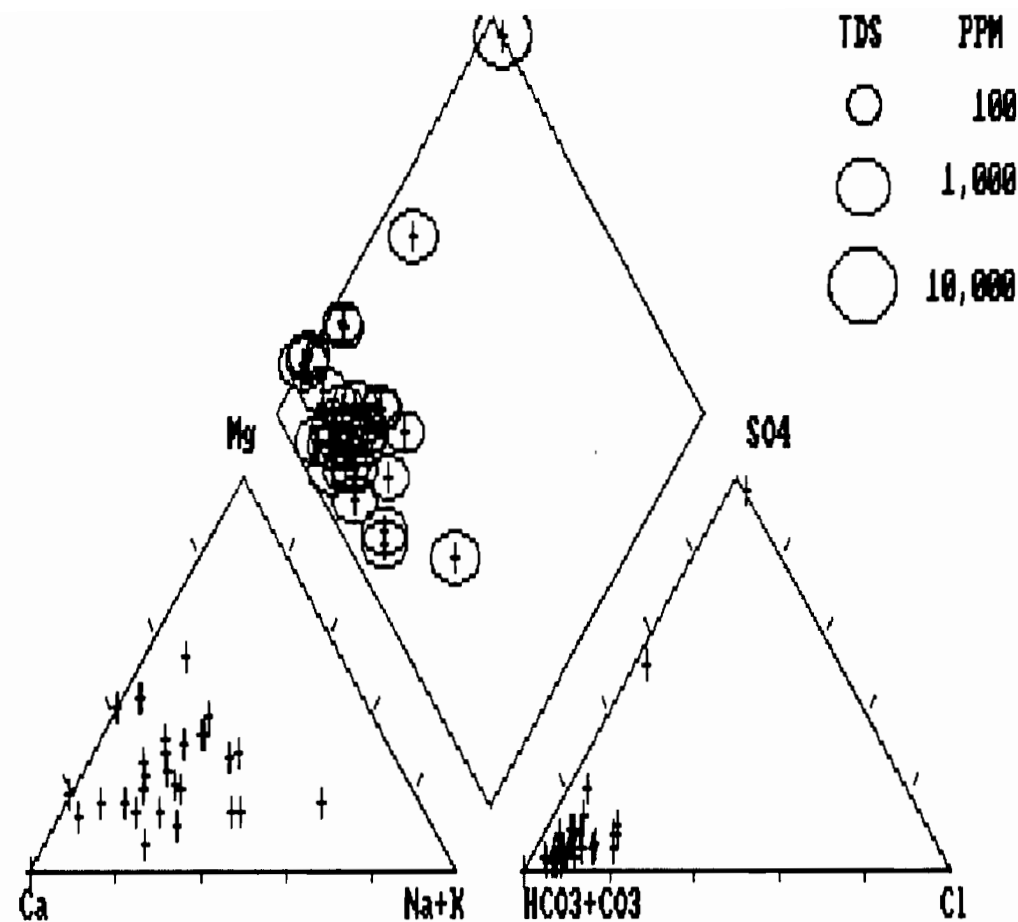


Figure 17. Piper plot of Rush Springs Sandstone analyses R51 through R82

calculated as probably in error (Na/Cl ratios less than 1 and TDS less than 500 mg/l). Five of the six brine samples and all of the samples reported as probably in error exhibited ion exchange (Na/Cl ratios greater than 1 and Ca/SO<sub>4</sub> ratios less than 1). Nine samples indicated reverse ion exchange (Na/Cl ratios less than 1 and Ca/SO<sub>4</sub> ratios greater than 1) and six of these samples had shapes indicating a gypsum source rock on the Stiff diagrams. The other three samples exhibiting reverse ion exchange had shapes typical of limestones on the Stiff diagrams. Seven of the analyses reported concentrations of SiO<sub>2</sub>, and of these analyses, five indicated carbonate weathering and two indicated silicate weathering. Of the five samples indicating carbonate weathering, three of the samples had had a negative value for non-halite due to the sodium versus halite concentrations described above. Of the other two samples, one sample had a silica concentration greater than the non-halite sodium, but less than two times the non-halite sodium, which indicated that weathering of sodium feldspars may be occurring. The other sample had a silica concentration greater than two times the non-halite concentration which indicated that the source rock may contain ferromagnesium minerals. The ratio of magnesium to calcium ranged from 0.02 to 0.62 which indicated that limestone dissolution was occurring. Fifty-four samples had Na/Cl ratios and Ca/SO<sub>4</sub> ratios greater than 1, indicating a Na source other than halite and a Ca source other than gypsum.

Based upon the results of the WATEVAL analyses, the water in the Rush Springs aquifer has undergone carbonate weathering, most likely due to the dissolution of gypsum and dolomite from infiltration of precipitation through the Moccasin Creek Gypsum Bed of the Cloud Chief Formation, as well as infiltration through the



Weatherford Gypsum Bed of the Rush Springs which may contain gypsum and dolomite. Dissolution of the overlying dolomite and the calcite cement in the sandstones of the Rush Springs would provide calcium concentrations greater than those expected just from the dissolution of gypsum. It is likely that there is sufficient calcium to participate in ion exchange (natural softening) with the sodium, thereby increasing the concentrations of sodium, while still maintaining a sufficient concentration of calcium which exceeds that of sulfate.

## CHAPTER V

### CEMENT FIELD

#### History

Oil and natural gas was discovered in 1916 in a well drilled approximately three miles east of the town of Cement (Clapp 1920). The Oklahoma Star Kunsemuller well, located in Section 22, Township 6 North, Range 9 West, is generally acknowledged as the discovery well for the Cement field. The Kunsemuller well, drilled in 1917, led to a period of active development in the field and by early 1920, twenty-six wells had been completed in the field with thirty-six wells actively drilling (Reeves, 1921).

Hermann (1961) reported that development of oil and gas production in the Cement field took place in approximately ten year cycles. These cycles are represented by drilling activities in 1912 to 1922, 1930, 1936 to 1945, and 1947 to 1950. Drilling for shallow Permian production continued into the early sixties.

In the 1970's and 1980's, activity in the Cement field included unitization and operations for secondary recovery and drilling for deeper, lower Pennsylvanian natural gas reservoirs (Al Shaieb, 1988). Al Shaieb also noted that by the late 1980's, approximately 1,900 wells had been drilled in the Cement field in twenty-six different reservoirs delineated in the Permian and Pennsylvanian. In 1991, the

Cement field produced approximately 1.2 million barrels of oil from an estimated 843 producing wells. Cumulative production through 1991 was approximately 134.8 million barrels of oil with estimated remaining reserves of 7.8 million barrels of oil (Beck, 1992).

In the study area, portions of the Cement field have been unitized to allow for the development of secondary recovery operations. The West Cement Unit, operated by Mobil Oil Corporation, is located primarily in Sections 35 and 36, Township 6 North, Range 10 West and consists of approximately 1,120 acres. Production is from the lower Permian (Fortuna Sandstone, Noble Olson Sandstone, and Basal Permian) and upper Pennsylvanian (Rowe Sandstone and Niles Sandstone). The dominant lithology is sandstone at an average depth of 2,400 feet. The reservoirs were created by anticlinal structures and initial production occurred via solution gas drive and water drive. Secondary recovery is presently accomplished using water injection.

The Cement I Unit, also operated by Mobil Oil Corporation, is located in Section 1, Township 5 North, Range 10 West, and Sections 5, 6, 7, and 8, Township 5 North, Range 9 West and consists of approximately 1,230 acres. Producing formations are the lower Permian Fortuna and Noble Olson Sandstones. The dominant lithology is sandstone at an average depth of 2,000 feet. The reservoirs were created by lateral pinchout of channel sandstones. Initial production occurred via solution gas drive. Secondary recovery is presently accomplished using water injection.

## Operations

Drilling and completion information was obtained on 248 wells in the West Cement and Cement I Units. The information was archived on completion cards and scout tickets located at the geological libraries in Oklahoma City and Tulsa, Oklahoma. The information reviewed consisted of: dates of drilling and completion; surface casing size, depth, and cement volumes; production casing size, depth, and cement volumes; completion procedures; and formation treatment data. Although not all well data in the West Cement and Cement I Units was available for the study, the 248 reviewed wells should be representative of the typical wells drilled in the Cement field.

### Drilling

Well depths fall into three depth categories: wells drilled to approximately 3,000 feet to explore for the lower Permian Fortuna and Noble Olson Sandstones; wells drilled to approximately 5,000 to 7,000 feet to tap the upper Pennsylvanian Rowe, Niles, Wade, Medrano, and Marchand Sands; and wells drilled below 10,000 feet exploring for lower Pennsylvanian natural gas reservoirs.

Typically, surface casing was set to control cavings and washouts of poorly consolidated near surface formations and to prevent contamination of fresh-water sands by drilling muds, oil, ash, or salt-water (Braunlich, 1975). Surface casing size ranged from 8 5/8-inch to 10 3/4-inch in diameter. The depth to which surface casing was set ranged from 0 feet (no surface casing) to 300 feet in the deeper wells. The surface

casing was typically cemented in place with anywhere from 50 to 350 sacks of cement. After the surface casing was set, the well was drilled to its total depth and electric logging was performed in the open borehole. If oil or gas was detected in the well cuttings, or indicated on the electric logs, then production casing was installed to the total well depth and cemented in place. Production casing separates the producing zone from undesirable fluids (saltwater) and acts as a workshaft to the producing zone (Braunlich, 1975). If the well had no indication of recoverable hydrocarbons, the well was plugged and abandoned.

### Completion

Production. After production casing was set, the well was perforated by shooting holes in the production casing with a wireline perforating tool. The perforating tool shoots holes through the casing and cement, out into the productive formation creating a channel through which hydrocarbons can migrate into the casing. The well may then produce oil or gas naturally, may produce oil and gas only after the formation is artificially stimulated by acidization or hydraulic fracturing, or in some cases, the perforated zone may not produce at all. If the zone is determined to be non-productive, then other zones of interest would be tested in a similar manner. When all potential zones had been tested, the well was either placed in production or plugged and abandoned.

Plugging. When a well was determined to be non-productive prior to running production casing, the well was plugged and abandoned. Plugging techniques were probably very primitive in the early years of the development of the field and plugging

operations may have been no more involved than filling the borehole with drilling mud and placing a wooden or cement plug at the surface. In later years, as oilfield operations became more regulated, plugging operations became more stringent.

Plugging operations subsequent to running production casing in the early years of the Cement field may have been similar to the plugging operations prior to setting casing. If possible, the production casing would be retrieved from the hole and the plugging would be completed. In later years, plugging requirements provided for sealing off all productive zones with cement plugs, filling the non-productive intervals in the borehole with mud of specific properties, and placing a cement plug across the base of the surface casing and at the ground surface. A welded plate would then be installed at the wellhead with a record of the well number and plugging date affixed to the welded plate.

Secondary Recovery. The first phase of production from an oil or gas field is typically referred to as primary recovery. During primary recovery, the natural forces which control the reservoir drive mechanisms are allowed to proceed until the rates of production have declined to some lower economic limit. The primary recovery phase generally recovers only a small percentage of the original oil in place. An Original Oil in Place (OOIP) study for the Cement I Unit, prepared by Mobil Oil Company, indicated cumulative primary recovery from the unit was 11% of the OOIP. At that point in time the oil or gas field is evaluated to determine the feasibility for secondary recovery operations. A unitization study prepared by Mobil in 1969 predicted secondary recovery of 11.6% of the OOIP. The Cement I area was unitized in September of 1970 and secondary recovery operations consisting of a waterflood were

commenced.

The waterflood activities consisted of converting existing wellbores into water injection wells (WIW) and pumping produced formation water and make-up water into the injection wells to "flood" the producing zones. The result of the recovery method is to drive oil in the reservoir towards production wells thereby maximizing the recovery of oil remaining in the reservoir after the primary recovery has been accomplished. Due to the age and condition of the wellbores converted to injection wells, the potential for failure of the injection system is significant. Problems associated with these failures can typically be attributed to casing failures. Casing failures can result in discharge of injection fluids outside of the intended receiving reservoir directly into fresh-water zones. Injection fluids may also migrate into fresh-water zones through the annular space between the borehole and the casing where cement has deteriorated or is non-existent or where fresh-water aquifers have not been adequately protected by surface casing.

## CHAPTER VI

### CYRIL MUNICIPAL WELL FIELD

The town of Cyril has historically used ground water withdrawn from the Rush Springs Sandstone aquifer for its public water supply. Table 5 summarizes water usage for the town of Cyril for the years from 1975 to 1992. Average daily water consumption during this period is calculated to be 170,000 gpd. The town of Cyril has a population of approximately 1,500 people, so the average daily consumption, per capita, is 113 gpd. The average continuous well production to provide this quantity of water is calculated to be 118 gpm. Tables 6 and 7 depict reported water well production in gallons per year and gallons per day, respectively.

The initial development of the Cyril water well field occurred in Section 1, Township 5 North, Range 10 West, where a total of eight wells were reportedly constructed. The earliest known public water supply wells were identified as AB, AB-1 and AB-2. Two drillers logs on water wells were found at the Oklahoma City geological library. One well was completed in 1929 to a total depth of 850 feet bgs and the other well was completed in 1937 to a total depth of 861 feet bgs. No well construction details were reported for the first well. The second well had surface casing (10-inch) set at 570 feet bgs and grouted with 40 sacks of cement. A liner (8 1/4-inch) was set at total depth and extended 17 feet up into the surface casing. The liner was perforated from 705-810 feet and 825 to 861 feet bgs with galvanized cave



TABLE 5

## WATER USE FOR THE TOWN OF CYRIL (X 1000 GALLONS)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1975	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	45,565
1976	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	52,337
1977	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	48,566
1978	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	61,812
1979	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	56,931
1980	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	59,303
1981	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	58,684
1982	4,528	5,234	5,110	5,151	5,931	6,788	8,707	7,757	6,109	5,484	5,028	5,508	71,335
1983	5,150	4,726	4,768	4,980	5,415	5,479	8,114	10,701	9,947	8,082	5,120	7,332	79,814
1984	8,037	5,377	5,918	6,336	7,771	7,985	9,225	8,914	6,221	4,508	4,308	4,426	79,026
1985	4,570	4,396	4,672	4,567	5,140	5,034	6,192	7,479	5,235	4,678	4,584	4,822	61,369
1986	4,824	4,441	5,788	5,170	5,224	5,050	7,559	6,226	4,394	4,612	4,444	4,569	62,301
1987	4,505	4,051	4,370	4,714	4,712	5,356	7,250	9,062	5,339	5,051	4,677	6,178	65,265
1988	5,011	5,198	5,375	5,197	5,993	6,943	7,996	7,786	6,546	5,165	4,579	5,672	71,461
1989	5,213	4,714	5,052	4,169	5,682	5,441	6,396	5,379	4,941	5,574	3,365	3,823	59,749
1990	4,595	4,562	5,197	4,692	5,087	5,976	5,592	5,417	5,699	5,554	5,410	4,844	62,625
1991	3,556	4,043	4,097	4,033	4,539	4,312	5,573	4,948	4,018	4,538	3,955	4,542	52,154
1992	5,034	4,163	4,333	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AVGa	5,002	4,628	4,971	4,901	5,549	5,836	7,260	7,367	5,845	5,325	4,547	5,172	61,665
AVGb	4,664	4,446	4,861	4,649	5,197	5,445	6,651	6,614	5,167	5,025	4,431	4,921	62,132

AVGa = average of all available data

AVGb = average of available data from 1985 through 1992

TABLE 6

## CYRIL WATER WELL PRODUCTION (GALLONS PER YEAR)

YEAR	74-0477 A-4 & A-5	76-0810 D-3	77-0544 D-2	81-0512 C-1	87-0529 C-3
1975	45,565,000				
1976	52,337,000				
1977	18,391,000	23,112,000	17,063,000		
1978	7,907,000	16,298,000	37,607,000		
1979	28,622,000	5,145,000	23,164,000		
1980	30,736,000	23,146,000	5,421,000		
1981	26,537,000	10,391,000	13,409,000	8,347,000	
1982	18,301,000	973,000	14,629,000	37,462,000	
1983	15,555,000	3,587,000	6,984,000	53,439,000	
1984	14,155,000	994,000	8,700,000	54,912,000	
1985	5,253,000	0	794,000	55,475,000	
1986	6,298,000	0	1,377,000	54,898,000	
1987	10,681,000	0	1,760,000	51,789,000	2,035,700
1988	13,234,000	0	646,000	55,581,000	2,000,000
1989	1,343,000	0	0	41,832,000	16,574,000

TABLE 7

## CYRIL WATER WELL PRODUCTION (AVERAGE GALLONS PER MINUTE)

YEAR	74-0477 A-4 & A-5	76-0810 D-3	77-0544 D-2	81-0512 C-1	87-0529 C-3
1975	87	NA	NA	NA	NA
1976	100	NA	NA	NA	NA
1977	35	44	32	NA	NA
1978	15	31	72	NA	NA
1979	54	10	44	NA	NA
1980	58	44	10	NA	NA
1981	50	20	26	16	NA
1982	35	2	28	71	NA
1983	30	7	13	102	NA
1984	27	2	17	104	NA
1985	10	NA	2	106	NA
1986	12	NA	3	104	NA
1987	20	NA	3	99	4
1988	25	NA	1	106	4
1989	3	NA	NA	80	32

catchers welded on the liner above each set of perforations. The identity of these two drillers logs cannot be determined, although it is suspected that they are for two of the three AB wells.

Two replacement water supply wells were drilled in 1948 to replace AB-1 and AB-2. These two water supply wells, identified as A-1 and A-2, were constructed in the Rush Springs Sandstone at depths of 110 feet bgs and 140 feet bgs, respectively. No additional construction details were reported on either well.

In 1954, water supply wells A-3 and A-4 were added to the well field in Section 1. Both wells were constructed in the Rush Springs Sandstone. Well A-3 was drilled to a total depth of 110 feet bgs. No other construction details were reported. Well A-4 (also identified as C-2 or #4 well in other reports) was drilled to a total depth of 170 feet bgs. Surface casing was grouted in place at an unspecified depth. Below the surface casing, the well was apparently constructed as an open borehole well. Wilson (1986) reported that a pump was set at 150 feet bgs and the well was pumped at a rate of 86 gpm (123,840 gpd). Water supply well A-5 was drilled in 1960 to a total depth of 180 feet bgs in the Rush Springs Sandstone. No additional construction details were reported.

From 1975 through 1977, three deeper water supply wells were drilled to the south of the existing well field. All three wells were constructed in the Duncan Sandstone aquifer. Well D-1 (Section 13, Township 5 North, Range 10 West) was drilled in 1975 to a total depth of 1,000 feet bgs. Casing was set and grouted in place from total depth to the ground surface. The casing was perforated over the following intervals (in feet bgs): 738-750, 790-800, 860-870, 878-888, 908-913, 920-925, and

960-965. Well D-1 was test pumped at a rate of 50 gpm (72,000 gpd) and temporarily capped (Wilson, 1986). Water supply well D-3 (also identified as #3 well) was drilled in 1976 at a location in Section 24, Township 5 North, Range 10 West. Well D-3 was drilled to a total depth of 962 feet bgs and surface casing was set and grouted in place from total depth to the ground surface. The casing was perforated over the following intervals (in feet bgs): 711-721, 748-758, 800-830, 850-860, 890-900, and 914-924.

Wilson (1986) reported that a pump was set at 750 feet bgs and the well pumped at a rate of 100 gpm (144,000 gpd). However, the ground water from the well reportedly had high  $\text{SO}_4$  concentrations and was therefore used only for emergency purposes.

Water supply well D-2 (also identified as #2 well) was drilled in 1977 in Section 24, Township 5 North, Range 10 West, to a total depth of 854 feet bgs. Casing was set and grouted in place from total depth to the ground surface. The casing was reportedly perforated over the same interval as well D-3 (Wilson, 1986). Wilson also reported that the pump was set at 734 feet bgs and pumped at a rate of 100 gpm (144,000 gpd). Well D-2 also reportedly has high  $\text{SO}_4$  concentrations leading to complaints of taste and odor. Apparently, the ground water is satisfactory if it is aerated.

Water supply well C-1 (also identified as #1 well) was drilled in 1980 at a location in Section 7, Township 5 North, Range 10 West to a total depth of 383 feet bgs. Surface casing was set at 150 feet and grouted to the surface. Well C-1 was apparently constructed as an open borehole well in the Rush Springs Sandstone and Marlow Formations. The well was reportedly perforated from 184-210 feet bgs and from 350-375 feet bgs, and was packed with pea gravel from total depth to the base of

the surface casing (383 to 150 feet). Wilson (1986) reported that a pump was set at 210 feet and pumped at a rate of 140 gpm (201,600 gpd).

Water supply well C-3 (Section 12, Township 5 North, Range 10 West) was drilled in 1985 to a total depth of 430 feet bgs. Surface casing was set at 200 feet and grouted to the ground surface. Well C-3 was apparently constructed as an open borehole well in the Rush Springs Sandstone and Marlow Formation. The well was packed with pea gravel from total depth to the base of the surface casing (430 to 200 feet). Wilson (1986) reported that well C-3 pumped at a rate of 115 gpm (165,600 gpd).

## CHAPTER VII

### GROUND-WATER CONTAMINATION

Analysis of ground-water samples collected from the Cyril water supply wells indicate elevated levels of chloride and in some instances, calcium. Natural concentrations of chloride in ground water are usually associated the presence of halite (NaCl) in the subsurface. Hem (1989) reports that chloride is present in all natural waters, but mostly the concentrations are low. Natural concentrations of calcium in ground water in the study area are primarily due to the presence of gypsum ( $\text{CaSO}_4 \cdot \text{H}_2\text{O}$ ) and anhydrite ( $\text{CaSO}_4$ ) and to a lesser extent limestone ( $\text{CaCO}_3$ ) or dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ). Assuming gypsum and/or anhydrite as a common source of calcium, the equivalent concentration of calcium should be equal to or slightly higher than the concentration of sulfate. Equivalent calcium concentrations significantly greater than sulfate concentrations have been observed in the water-quality analyses, indicating a source of calcium other than gypsum or anhydrite. Potential sources of chloride and calcium concentrations due to oilfield operations and other, non-oilfield operations, are summarized on Table 8

#### Contamination from Oilfield Operations

The potential for ground-water contamination due to oilfield operations begins

TABLE 8

## SOURCES OF CHLORIDE AND CALCIUM CONTAMINATION

Source	Constituent	Use
Drilling Fluid	calcium hydroxide calcium chloride calcium carbonate calcium sulfate calcium oxide calcium magnesium silicate	bactericide, corrosion inhibitor density control, shale control density control flocculating agent, shale control shale control viscosifier
Completion/Workover Fluids	calcium carbonate calcium chloride hydrochloric acid calcite potassium chloride	cement accelerator, workover fluid acidization treatment fluid weighting workover fluid
Produced Formation Water	sodium chloride calcium chloride	production by-product production by-product
Salt plains/springs	sodium chloride	natural occurrence of halite
Construction	calcium carbonate calcium chloride	cement accelerator
Highway construction	calcium chloride	dust palliative, frost action preventative skidding preventative, granular stabilization

when well is drilled, continues through completion activities and the productive life of the well, and may exist for long periods of time after a well is plugged and abandoned. The pathways for contamination during drilling, completion, and production processes is through the introduction of liquids in the subsurface environment through the borehole or well casing and through the use of unlined pits for salt water (formation water) disposal during production operations.

### Drilling Fluids

The primary purpose of drilling fluids are to transport drill cuttings to the surface, control subsurface formation pressures, maintain borehole stability, protect productive formations, protect against corrosion, and cool and lubricate the bit and drill string (Simpson, 1975). The major types of drilling fluids are air or gas, clear water or brine, water muds (clay-based or polymer), and oil muds.

Additives are often added to drilling fluids to control their rheological properties. Common additives which could provide a source for chloride or calcium contamination are: calcium hydroxides (bactericide, corrosion inhibitor), calcium chloride (density controller, shale control), calcium carbonate (density controller), calcium sulfate (flocculating agent, shale control), calcium oxide (shale control), and calcium magnesium silicate (viscosifier).

Drilling mud may contaminate ground water if conductor casing or surface casing strings have not been set deep enough to protect shallow ground-water aquifers or if the casing has been improperly cemented to competent subsurface zones (Figure 18). Drilling mud may also contaminate ground water when drilling fluids lost in



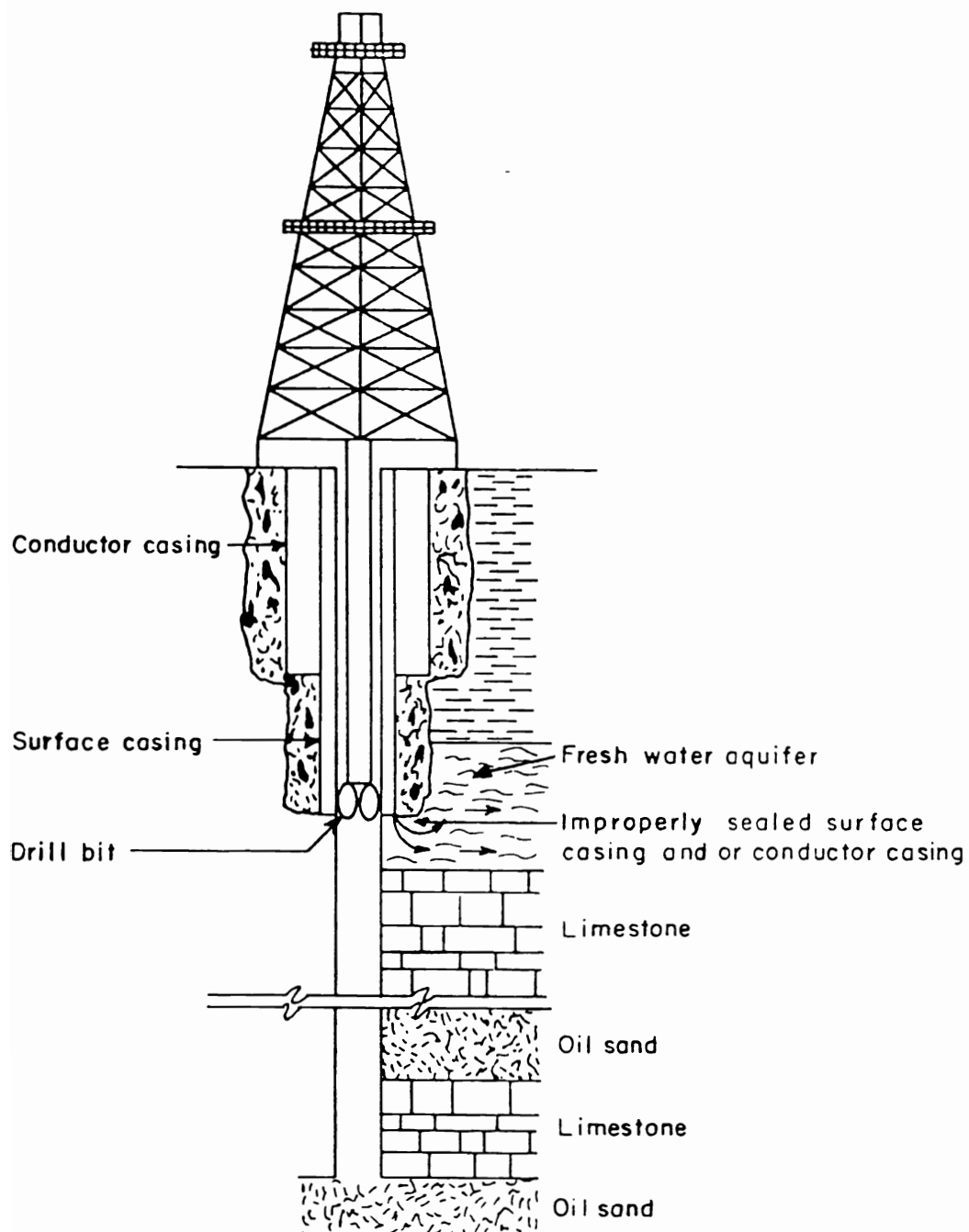


Figure 18. Contaminant pathways through improperly sealed casing  
(after Collins, 1975)

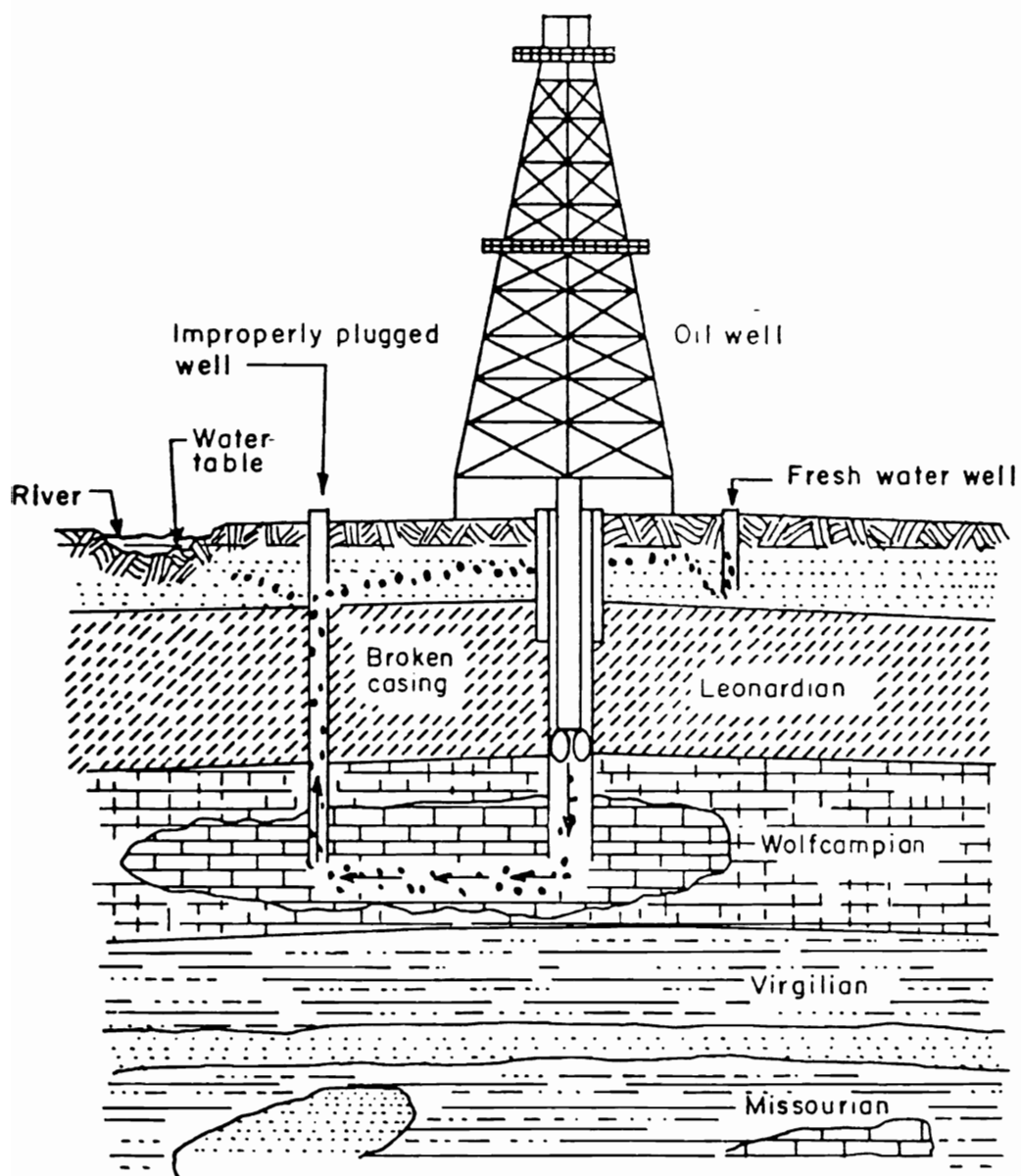


Figure 19. Contaminant pathways through improperly plugged wells  
(after Collins, 1975)

deeper formations with high porosity and permeability during the drilling process can come back up an improperly plugged and abandoned well as indicated on Figure 19 (Collins, 1975). Improper storage of drilling mud chemical additives at a drill site could result in spillage which could leach to the water table and contribute to ground-water contamination.

### Completion and Well Workover Fluids

When a decision is made to complete an exploratory or development borehole as a production well, generally the first step is to set production casing in the borehole. The casing is installed by cementing the annular space between the outside of the casing and the borehole. Typically, a "neat" cement consisting of Portland cement (grout) and water is used but quite often chemical additives are required to provide special properties to the cement slurry. Calcium chloride (2% - 4% weight percent) was widely used as an accelerator to reduce the setting time for the cement. Along with the calcium which is an intrinsic component of cement, the calcium chloride could provide a source of calcium and chloride contamination.

After production casing is set and the desired production interval is perforated, a well is quite often treated with acid to increase the permeability of the reservoir rocks. The increase in permeability improves fluid flow and increases the recovery of oil and gas. Acid also improves fluid injection in secondary oil recovery and disposal operations (Collins, 1975). Hydrochloric acid, nitric acid, sulfuric acid, hydrofluoric acid, formic acid, and acetic acid are most often used. By-products of acid treatments include soluble compounds such as calcium chloride.

When a producing well experiences production problems or a decision is made to abandon a producing zone to recomplete into another zone, well workover operations are performed. Workover or completion fluids are used in the producing well during the workover operations. Although in limited use today, calcite was often used for weighting drilling fluids and as late as 1974, three-thousand tons of calcite were sold for this purpose (Grantham and Sloan, 1975). The calcite weighted fluids were most often used in workover or completion fluids for normally pressured formations and depleted draw-down reservoirs. Today, most well workover fluids consist of potassium chloride waters (KCl), although in the past calcium chloride waters were used as well workover fluids.

#### Produced Formation Water

The production of formation water in conjunction with oil production has been a major cause of ground-water contamination in areas of intense petroleum exploration and development. Pettyjohn (1971) notes that the water-bearing strata contaminated by brines may remain unusable, depending on the degree of contamination and on hydrologic conditions, for years, decades, or even millenia. The amount of formation water produced from oil wells varies considerably with different wells and is dependent upon the producing formation and the location, construction, and age of the well (Collins, 1974). The majority of formation waters are sodium chloride and calcium chloride brine and these constituents would be expected to be the chief ground-water contaminants associated with produced formation water disposal. Potential pathways for calcium and chloride contamination to the ground water are

evaporation pits and injection wells (including salt water disposal wells and secondary recovery waterflood wells).

Evaporation Pits. Disposal of formation water by letting it run over the ground was a common practice in the early days of oil production. However, environmental damage to surface waters, soils and vegetation, and animals was eventually evident and this disposal method was abandoned. Unsealed surface pits, initially used to contain drilling fluids, were often used as evaporation pits for the disposal of produced formation water. The long-term practice of discharge to unlined pits stems from days when there was very little regulation of oil exploration and development (Atkinson, 1986). Initial contamination of the subsurface environment probably occurred by the direct infiltration of the disposal water to the unsaturated zone since the evaporation pit would tend to act as an infiltration gallery. As the evaporative process proceeded, large quantities of soluble salts were left at the bottom of the pits. The soluble salts were then leached into the soil and eventually the water table during subsequent precipitation and infiltration events. Collins (1974) reported that the Kansas State Department of Health studied the soils beneath and near an old unsealed brine disposal pond that had been abandoned for 10 years. Chemical analyses of core samples from the soils beneath and adjacent to the pond indicated that about 1.4% of the original soluble salt introduced into the disposal pond still remained to be leached out of the soil in the pond area. This amount of soluble or leachable salt remaining in the area indicates that the return of the subsurface water and soils to their pre-pollution level is a very slow process and may take several decades.

Injection Wells. Most oil field brines today are returned to oil producing

zones or deep saline aquifers through old production wells or water injection wells. This is done either for the purpose of water flooding or secondary recovery (reinjection of brine into the oil producing zone to increase reservoir yields), or just as a disposal method (Atkinson, 1986). The greatest potential for contamination occurs in the immediate vicinity of the wellbore, where the natural geologic structures relied upon to contain the waste have been breached by well construction. Fryberger (1984) notes that by far the greatest potential for pollution of potable ground water from underground injection is related to the injection of oil field brines. Although the resulting problem is not highly toxic, the potential problem is large. Miller (1980) indicates the major concern of subsurface injection through wells is the potential contamination of usable ground water by the following mechanisms;

- direct emplacement into potable zones;
- escape into a potable aquifer by wellbore failure;
- upward migration from receiving zone along outside of casing;
- leakage through inadequate confining beds;
- leakage through confining beds due to unplanned hydraulic fracturing;
- leakage through deep abandoned wells;
- displacement of saline water into a potable aquifer;
- injection into a saline aquifer eventually classified as a potable water source; and
- migration to potable water source in the same aquifer.

Atkinson (1986) reports that the acidic nature of the formation water corrodes well casing and coupled with excessive injection pressures may rupture casing joints, crack the cement seal, and move out into shallower potable water zones. Excessive injection pressure can cause leaks at the wellhead allowing formation water to flow across the surface. Injection may reverse the existing hydraulic gradient. Wells with corroded casing or leaky wells which have been transferring shallow fresh water

downward into the deeper saline formations, will now transfer saline water upward to the potable zones. Other wells in the vicinity of an injection well drilled to or through a receiving formation, such as unplugged, abandoned oil and gas wells, can act as conduits for the migration of fluid. Improper or incomplete cementing of casing or the use of easily corrodable casing serves as another conduit for disposal fluid migration where brine travels up the annular space between the casing and the borehole to contaminate shallower zones.

### Well Abandonment

Another significant pathway for calcium and chloride contamination to the ground water is improper well abandonment. Improperly abandoned wells can provide the conduit for the migration of injected fluids (or formation fluids) outside of the intended injection zone. Atkinson (1986) indicates that the major problem of ground-water contamination is the discharge of saline water from abandoned oil and gas wells rather than the disposal of waste brine through injection or secondary recovery wells at active petroleum recovery fields. Wells of all kinds near an injection well, either producing or abandoned that penetrate the injection zone, have the potential to become conduits for migration. Whether or not such wells will leak is a function of how the wells were constructed or plugged, as well as the operating pressure of the injection well and the pressure build-up of the receiving formation (Anzzolin and Graham, 1984).

Many older improperly plugged wells were just loaded with mud which through time will settle out and allow channeling of saltwater through the borehole.

The cement plugs in most older wells were determined to be inadequate. Top plugs were usually a thin cap of cement and it was not uncommon for bottom plugs to be absent. Although the plugging methods satisfied the then existing regulations, they nevertheless provide flow paths for upward migration of reservoir fluids to shallower freshwater zones (Fryberger, 1984). In a study of improperly abandoned wells in central Oklahoma, Fairchild (1984) reviewed abandonment records for 8,524 plugged and abandoned wells and found that 72% of the oil wells, 57% of the gas wells, and 77% of the dry holes were improperly plugged when evaluated against the plugging regulations in effect at the time of their abandonment. When the same wells were evaluated for plugging requirements against the 1980 regulations, 90% of the oil wells, gas wells, and dry holes were improperly plugged.

#### Potential Contamination From Other Sources

The intensity of petroleum exploration, development, and production activities in the study area has been significant over the years. This activity would logically appear to have the most impact on contaminating the environment. However, other sources of contamination may exist, although the likelihood of such sources having a significant widespread impact are not considered to be great.

Powell (1992) notes that several salt plains occur in western Oklahoma which are located several miles northwest of the study area. The distance from the study area and the hydrogeological setting would preclude chlorides leached from salt plains having local impact on ground-water quality. The location of a saltwater spring in Section 36, Township 6 North, Range 10 West was described by NUS (1989) and



suggests the possibility of halite (NaCl) occurrence in younger Permian rocks immediately north of the study area. However, the spring is hydrogeologically separated from the study area by the Cement Anticline (inferred ground-water divide).

As previously mentioned, calcium chloride is used as an accelerator to reduce the setting times for cement. The mixture of 2% calcium chloride with portland cement to make concrete results in a higher early strength and a safer, speedier curing (Sloane, et al, 1931). It has been discussed that cement used in oilfield operations could serve as a source for calcium and chloride contamination. Construction activities where concrete is used as either foundation materials, road materials, or building materials could also be considered a potential source for contamination. Although the concrete itself is not likely to create a source for ground-water contamination, the inadvertant or planned disposal of waste calcium chloride could provide such a source if it is exposed to precipitation and subsequent infiltration to the ground water.

Calcium chloride has also been widely used in the past for highway construction activities. Calcium chloride has variously been used as a dust palliative, as an aid in the prevention of freezing of subgrades, as an aid to decreasing the damage to gravel roads due to frost action, and in the treatment of sand and similar materials used as skidding preventatives on icy pavements (Cuthbert, 1945). Calcium chloride has also been used in the granular stabilization of roads wherein treatment with calcium chloride effects a volume change and an increase in the density and stability of graded road mixtures (Cuthbert, 1945).

## Contamination of the Cyril Municipal Well Field

The earliest known reports of contamination at the Cyril well field occurred in 1947 when the town of Cyril requested that the Oklahoma Planning and Resources Board, Division of Water Resources (OWRD), investigate the cause for the increasing chloride content in their municipal water wells. The OWRD reportedly concluded that the source of the chloride contamination in the Cyril water supply wells was from surface disposal pits used for saltwater evaporation in the West Cement Field. The area of concern was identified as south of the "Keechie Hills" in Section 36, Township 6 North, Range 10 West and Section 31, Township 6 North, Range 9 West, as well as Section 1, Township 5 North, Range 10 West, and Section 6, Township 5 North, Range 9 West. Operators in the area of concern were requested to use means other than surface evaporation to dispose of their saltwater. Additionally, the OWRD requested that all disposal pits in the area of concern be abandoned and filled to above surface.

In 1951, stock reportedly refused to drink water from a stream located downgradient from surface disposal pits. Testing of the stream waters reportedly yielded results ranging from "slightly salty" to "extremely salty". The surface disposal pits were reportedly not adequate to dispose of the produced saltwater entirely by evaporation. Considerable seepage was noted around the base of the pits and around one of the pits, a salt crust existed and approximately three acres of vegetation had been killed.

By 1948, the three initial Cyril water supply wells (AB, AB-1, and AB-2) had

been abandoned due to chloride contamination (Hamburg, 1952; Wilson, 1986). By 1966, elevated chloride concentrations were detected in ground-water samples collected from water supply wells A-1, A-2, A-3, A-4, and A-5. The drinking water standard for chloride (250 mg/l) was exceeded in well A-1 by 1970, in wells A-2 and A-5 by 1973, in well A-3 by 1975, and in well A-4 by 1985. Historical chloride concentrations for the Cyril water supply wells is summarized on Table 9. Water supply wells A-1 and A-2 were abandoned in 1978. Water supply wells A-3 and A-5 were abandoned in 1980 and 1985, respectively.

Water supply well C-1 had chloride levels of 124 mg/l within 5 years of its construction and in just over 10 years, had chloride levels exceeding the drinking water standards. Water supply wells C-1, A-4 (C-2), and C-3 were abandoned in late fall 1990 or early spring 1991 when Cyril tied into the Rural Water District system (Pettyjohn, 1991). The deeper water supply wells (D-1, D-2, and D-3) may also have been abandoned at this time, although chloride contamination has not been a problem in these wells.

As a result of the contamination of the Cyril water wells, hearings have been held at the Oklahoma Corporation Commission (OCC) to determine the cause and extent of the chloride contamination. As part of the ongoing contamination assessment, numerous ground-water quality samples have been collected from the Cyril water supply wells, private water wells, and monitoring wells installed as part of the contamination assessment.

TABLE 9

## HISTORICAL CHLORIDE CONCENTRATIONS TOWN OF CYRIL WATER SUPPLY WELLS

Sample Date	AB	AB-1	AB-2	A-1	A-2	A-3	A-4 (C-2)	A-5	C-1	C-3	D-1	D-2	D-3
8/23/51					11								
8/16/56							37						
2/24/64							44						
2/6/65							38						
2/18/66				178	132	72	46	164					
5/10/66				198									
7/21/66				210	150	38							
5/27/70				588	204	217	54	217					
6/19/70				592	202								
2/25/71				680	209	246	67	221					
3/7/72				768	276	273	70	210					
3/1/73				230	468	90		260					
8/9/73				890	369	304	76	191					
5/13/74				1018	406	550	80	336					
4/16/75				933	350	390	91	375					
3/3/78										15		23	39
10/6/78							105						
10/10/80									12				
2/20/85							454		124		103	14	20
6/12/89							560		220	20			
8/16/89				688	968		400		226	24			
12/14/89													
6/12/90									262	40			
2/6/91					3872		901						
2/13/91	233	2790	5483		1440		939		260				
3/12/91	158	115	371		833		986			58			
7/17/91	162	152	528		801		1019						

## CHAPTER VIII

### ASSESSMENT OF GROUND-WATER CONTAMINATION

Chloride contamination of the water supply wells for the town of Cyril as well as numerous domestic water wells is well documented. The source of the chloride contamination may have been the result of the surface disposal of produced formation water (brine), the subsurface disposal of produced formation water, the injection of produced formation water during secondary recovery operations, or a combination of any or all of the above.

#### Computer Modeling

Two computer simulations were performed using the USGS Solute Transport Model developed by Konikow and Bredehoeft (1978). The USGS Solute Transport Model is a two-dimensional Fortran code for contaminant transport. Flow equations are solved using a finite-difference method and the method of characteristics is used to solve solute-transport equations. The purpose of the simulation model was to compute the concentration of chloride in the Rush Springs/Marlow aquifers at specific places and time.

The first simulation assumed that the only source of chloride contamination was the surface disposal pits. The second simulation assumed that chloride

contamination was initially caused by surface disposal of brine, but was later compounded by the injection of brine during secondary recovery operations. Disposal of brine into the subsurface prior to secondary recovery may have occurred, but no salt water disposal wells were identified in the vicinity of the Cyril water wells, so this potential source was not simulated.

### Finite-Difference Grid

The simulated area was divided into a finite-difference grid of uniformly spaced squares (Figure 20). The grid contains 15 columns (x) and 20 rows (y). Each cell of the grid is 330 feet by 330 feet. By convention, nodes are located at the centers of the cells of the block-centered grid.

### Aquifer Properties

Based on the reported and calculated aquifer coefficients discussed in Chapter III, the following aquifer properties were used as input for the computer simulation: storativity (S) - 0.25; porosity (n) - 0.25; hydraulic conductivity (K) - 25 gpd/ft<sup>2</sup>; and saturated thickness (m) - 365 feet.

Constant head boundaries were used at the perimeter of the grid to represent underflow or recharge sufficient to maintain a nearly constant water table elevation. Water table elevation values were assigned to the grid nodes by overlaying the grid on a water table elevation contour map for the study area (Figure 21).

Initial chloride concentrations of 15 mg/l were input as normal background concentrations. This value was determined as a result of the evaluation of Rush

contamination was initially caused by surface disposal of brine, but was later compounded by the injection of brine during secondary recovery operations. Disposal of brine into the subsurface prior to secondary recovery may have occurred, but no salt water disposal wells were identified in the vicinity of the Cyril water wells, so this potential source was not simulated.

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Initial chloride concentrations of 15 mg/l were input as normal background concentrations. This value was determined as a result of the evaluation of Rush

Springs and Marlow water quality analyses described in Chapter IV. The chloride concentration of disposed formation water was estimated to be 70,000 ppm based on the average of 32 formation water samples in the Cement Field (Preston 1982).

### Recharge and Discharge

Recharge from precipitation was estimated to be 2.5 inches per year. The recharge from surface disposal of produced formation water was site specific and recharge (injection) values were assigned to specific nodes which approximately coincide with the location of the disposal pits. Recharge (injection) rates for the disposal pits are summarized on Table 10. Surface disposal was assumed to be in process at the initiation of the simulation (1940) and was discontinued in 1955. The recharge from subsurface injection of formation water was also site specific and injection values were assigned to specific nodes which approximately coincide with the location of the injection wells. Injection rates for the subsurface injection wells are summarized on Table 11. For the purpose of the simulation, subsurface injection was commenced in 1970 and discontinued in 1990.

Discharge from the aquifer occurred through pumping of the Cyril water wells. An average withdrawal rate of 120 gpm was used which was apportioned to the number of wells actively pumping during the period of simulation. Pumping rates are summarized on Table 12.



TABLE 10

## RECHARGE RATES FOR SURFACE DISPOSAL PITS

Grid Location		Surface Area	Seepage Rate	Seepage Rate	Concentration
x	y	(sq. ft.)	(cu. ft./day)	(cu. ft./sec.)	(ppm)
2	3	4,800	1.92	2.20E-05	70,000
2	6	24,000	9.60	1.00E-04	70,000
3	2	3,200	1.28	1.50E-04	70,000
3	11	6,400	2.56	3.00E-05	70,000
4	8	3,200	1.28	1.50E-05	70,000
4	9	12,800	5.12	6.00E-05	70,000
4	11	3,200	1.28	1.50E-05	70,000
5	8	2,400	0.96	1.00E-05	70,000
6	5	33,600	13.44	1.60E-04	70,000
6	7	20,000	8.00	9.30E-05	70,000
6	11	9,600	3.84	4.40E-05	70,000
8	8	9,600	3.84	4.40E-05	70,000
8	11	6,800	2.72	3.10E-05	70,000
8	14	3,600	1.44	1.70E-05	70,000
9	8	6,400	2.56	3.00E-05	70,000
9	10	3,600	1.44	1.70E-05	70,000
9	13	10,200	4.08	4.70E-05	70,000
10	5	9,600	3.84	4.40E-05	70,000
12	7	9,600	3.84	4.40E-05	70,000
14	7	13,200	5.28	6.00E-05	70,000

TABLE 11

## INJECTION RATES FOR SUBSURFACE INJECTION WELLS

WIW ID	Grid Location		Injection Rate (gpd)	Injection Rate (cu. ft./sec.)	Concentration (ppm)
	x	y			
#8-4	5	1	42,000	6.644E-02	70,000
#25-7	6	5	44,394	7.023E-02	70,000
#37-3	6	10	67,200	1.063E-01	70,000
#51-1	6	15	29,400	4.651E-02	70,000
#53-1	9	13	37,800	5.980E-02	70,000
#58-3	14	7	46,200	7.309E-02	70,000

WIW ID	Grid Location		Injection Rate at 5% of Actual (gpd)	Injection Rate at 5% of Actual (cu. ft./sec.)	Concentration (ppm)
	x	y			
#8-4	5	1	2,100	3.322E-03	70,000
#25-7	6	5	2,220	3.511E-03	70,000
#37-3	6	10	3,360	5.315E-03	70,000
#51-1	6	15	1,470	2.325E-03	70,000
#53-1	9	13	1,890	2.990E-03	70,000
#58-3	14	7	2,310	3.654E-03	70,000

TABLE 12

## SIMULATED PUMPING RATES FOR CYRIL WATER SUPPLY WELLS

Well ID	Grid Location		Pumping Rate (gallons per minute)					
	x	y	1940-1950	1950-1955	1955-1960	1960-1980	1980-1985	1985-1990
AB-1	4	7	60					
AB-2	6	8	60					
A-1	9	11		60	30	24		
A-2	9	12		60	30	24		
A-3	10	13			30	24		
A-4 (C-2)	11	14			30	24	40	40
A-5	8	17				24	40	
C-3	11	19					40	40
C-1	12	14						40

## Calibration

Insufficient field data was available to accurately calibrate the hydraulic head distribution calculated by the model over the period of simulation. The initial hydraulic head distribution for the model was based on water table elevations measured in selected monitoring wells and Cyril water supply wells in July 1991 (Figure 21), therefore this data could not be used for calibration purposes.

Chloride contamination values calculated by the model were generally calibrated to reported chloride contamination values in the Cyril water supply wells. An exact calibration was not achieved for the following reasons; the location of the Cyril wells did not coincide with the nodes of the finite-difference grid and the dates of the water-quality analyses did not necessarily coincide with the end of the simulated pumping period.

Seven pumping periods were used in the first simulation: 1940 to 1950; 1950 to 1955; 1955 to 1960; 1960 to 1980; 1980 to 1985; 1985 to 1990; and 1990 to 1991. The pumping periods were selected to facilitate the calibration of actual chloride concentrations to modeled chloride concentrations and to allow variation in the discharge from the Cyril water wells to reflect well abandonment and well replacement. Surface disposal sources were turned off at the end of the second period (1950 to 1955).

Eight pumping periods were used in the second simulation: 1940 to 1950; 1950 to 1955; 1955 to 1960; 1960 to 1970; 1970 to 1980; 1980 to 1985; 1985 to 1990; and 1990 to 1991. The pumping periods were selected for the same reasons as

the first simulation, except that the period from 1970 to 1980 was added to allow for the commencement of subsurface injection.

### Contamination by Surface Disposal

In this simulation, the source of chloride contamination was restricted to the surface disposal of produced formation water. Simulated chloride contamination at the end of each pumping period is summarized on Table 13. A chloride isoconcentration contour map of the simulated chloride concentration at the end of the sixth pumping period (1990) is presented as Figure 22.

The most complete historical laboratory analytical data exists for Cyril water supply wells A-1, A-2, and A-4 (C-2), therefore these wells were used for comparison with the model results for the chloride contamination. Figures 23, 24,, and 25 are graphs of the actual chloride contamination versus the chloride contamination simulated by the model. A correlation of modeled chloride contamination to actual chloride contamination was not observed in wells A-1 and A-2. In well A-4 (C-2), the modeled chloride contaminations correlate reasonably well with the actual chloride contamination, although the modeled values are lower.

### Contamination by Subsurface Injection

In this simulation, the source of chloride contamination was the surface disposal of produced formation water from 1940 to 1955 and the subsurface disposal of formation water from 1970 to 1990. Six injection wells were selected as source areas due to reported casing collapses, surface casing leaks, production casing leaks,

TABLE 13

## SIMULATED CHLORIDE CONCENTRATIONS FROM SURFACE DISPOSAL

Year	AB	AB-1	AB-2	A-1	A-2	A-3	A-4	A-5	C-1	C-3
1945	14	145	316	22	21	16	15	15	15	15
1950	10	407	752	57	32	27	15	15	15	15
1955	9	411	827	1342	709	93	15	14	14	14
1960	8	431	840	1312	667	106	14	14	14	14
1965	7	451	1153	870	973	156	16	14	14	14
1970	6	425	1179	656	714	665	12	14	14	14
1975	5	487	1124	517	397	223	19	15	14	14
1980	4	492	1177	430	372	495	18	15	14	14
1985	5	329	1413	376	391	402	62	14	13	13
1990	6	222	1654	450	382	291	208	13	15	13
1991	6	223	1640	382	382	290	207	13	16	13

TABLE 14

SIMULATED CHLORIDE CONCENTRATIONS FROM SURFACE  
DISPOSAL AND SUBSURFACE INJECTION

Year	AB	AB-1	AB-2	A-1	A-2	A-3	A-4	A-5	C-1	C-3
1945	14	145	316	22	21	16	15	15	15	15
1950	10	407	752	57	32	27	15	15	15	15
1955	9	411	827	1342	709	93	15	14	14	14
1960	8	431	840	1312	667	106	14	14	14	14
1965	7	451	1153	870	973	156	16	14	14	14
1970	6	424	1181	660	716	665	12	14	14	14
1975	5	487	1045	517	334	227	19	15	14	14
1980	5	493	1181	460	1005	1414	15	15	14	14
1985	6	330	1418	462	1094	2100	106	15	13	13
1990	7	222	1664	527	1157	3280	781	27	18	13
1991	7	85	1652	484	1175	3239	936	28	20	13

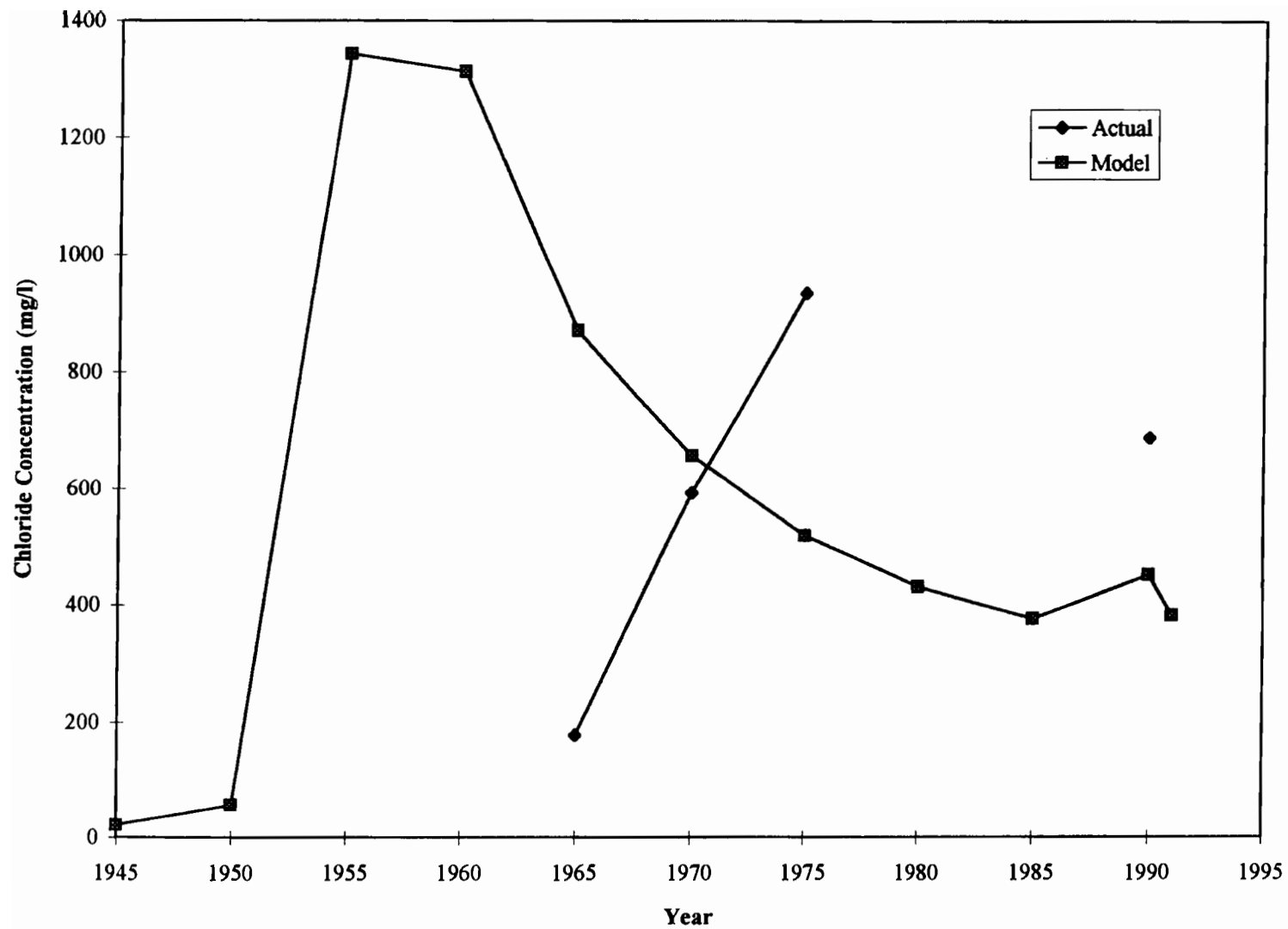


Figure 23. Comparison of actual to simulated chloride concentrations from surface disposal in Cyril well A-1

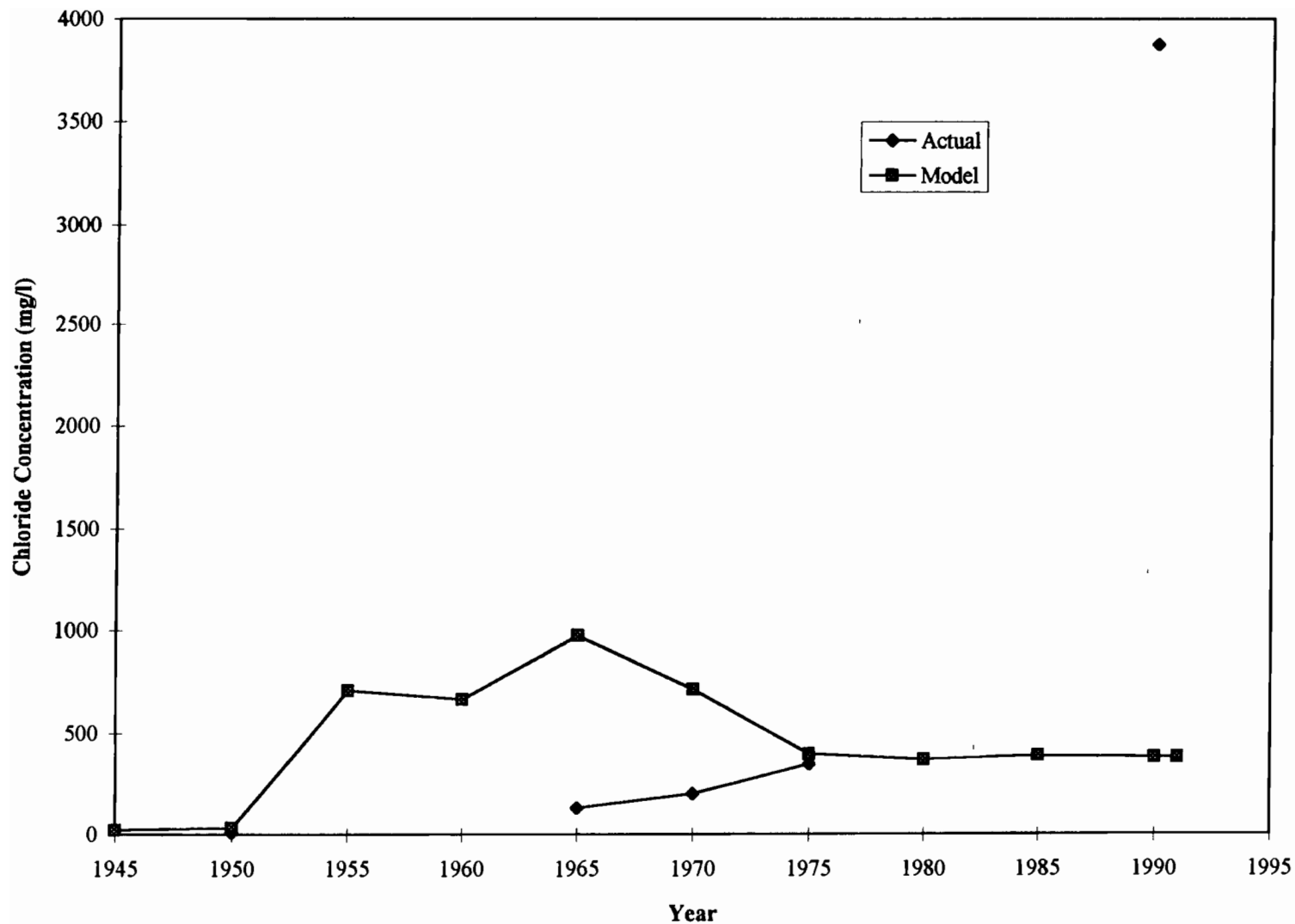


Figure 24. Comparison of actual to simulated chloride concentrations from surface disposal in Cyril well A-2



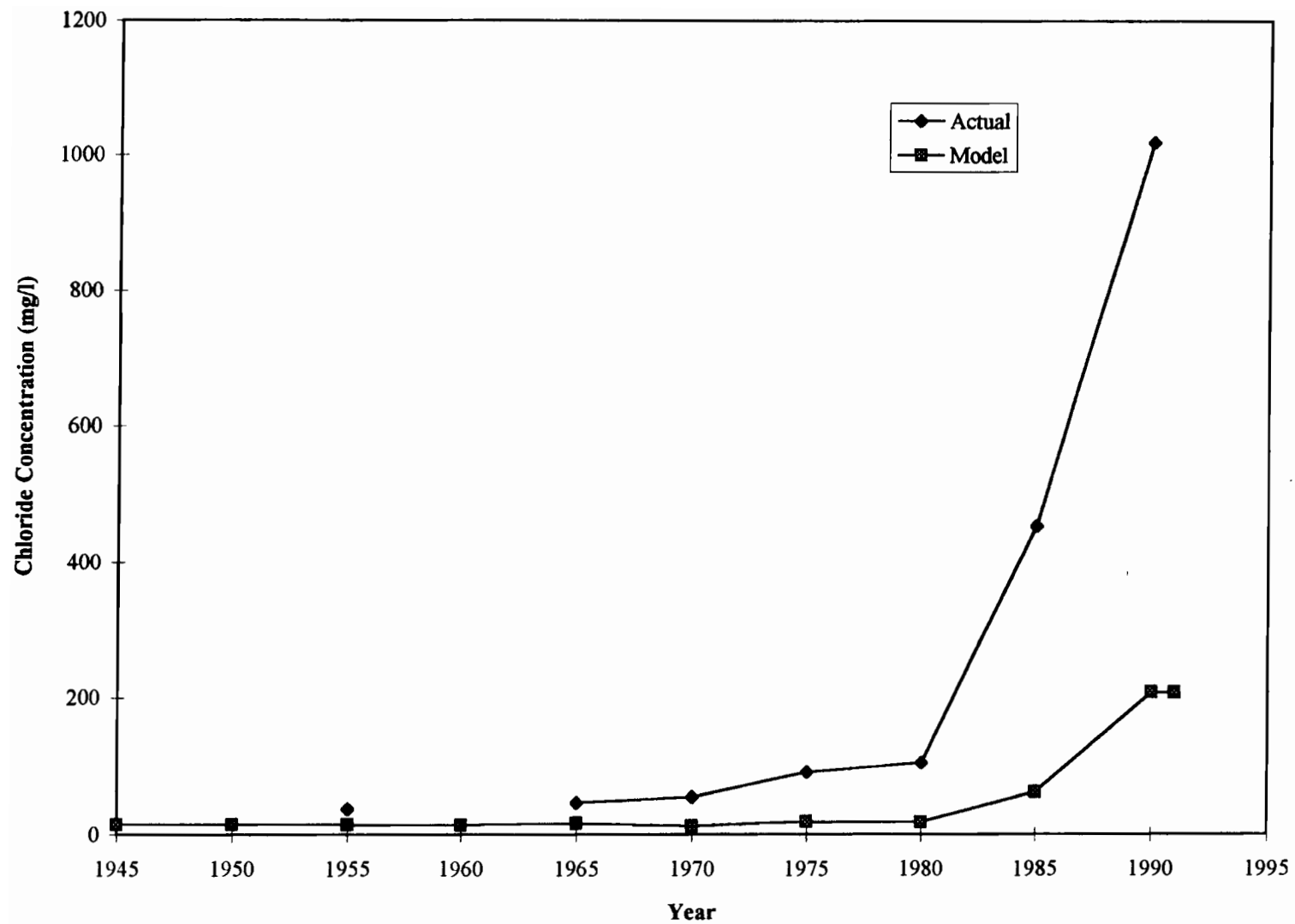


Figure 25. Comparison of actual to simulated chloride concentrations from surface disposal in Cyril well A-4

and flows of water to the surface. The injection rate used for each well was 5% of the injection rate reported in Oklahoma Corporation Commission Document MO 000962. The sensitivity of the injection rate was determined through several iterations of the simulation. It was found that execution of the model failed at injection rates of 10% and greater. This failure is believed to have occurred due to the limitation of the model to plot concentrations greater than five figures at individual nodes. The 5% injection rate allowed the model to execute and provided concentrations in general agreement with actual concentrations. Simulated chloride contamination at the end of each pumping period is summarized on Table 14. A chloride isoconcentration contour map of the simulated chloride concentration at the end of the seventh pumping period (1990) is presented as Figure 26.

Cyril water supply wells A-1, A-2, and A-4 (C-2) were again used for comparison with the model results for the chloride contamination. Figures 27, 28, and 29 are graphs of the actual chloride contamination versus the chloride contamination from both simulations of the model. A correlation of modeled chloride contamination to actual chloride contamination was not observed in wells A-1 and A-2. However, the chloride concentration in this simulation is closer to actual than the concentration calculated in the first simulation. In well A-4 (C-2), the modeled chloride contaminations again correlate reasonably well with the actual chloride contamination. The chloride concentration in the second simulation is closer to actual than the concentration calculated in the first simulation and the curve of the simulated concentration data points is similar to the curve of the actual concentration data points.



Figure 27. Comparison of actual to simulated chloride concentrations from surface and subsurface disposal in Cyril well A-1

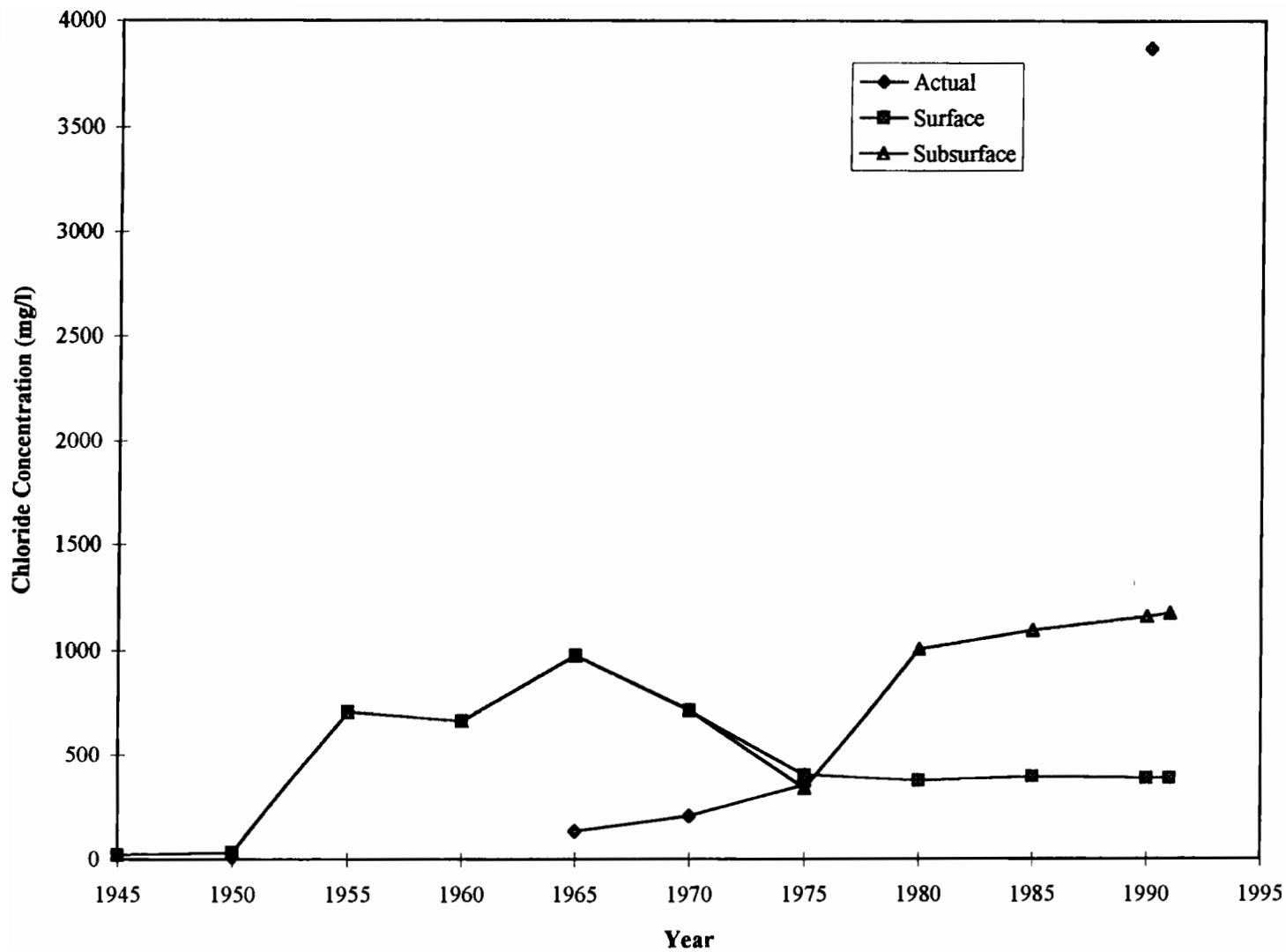


Figure 28. Comparison of actual to simulated chloride concentrations from surface and subsurface disposal in Cyril well A-2

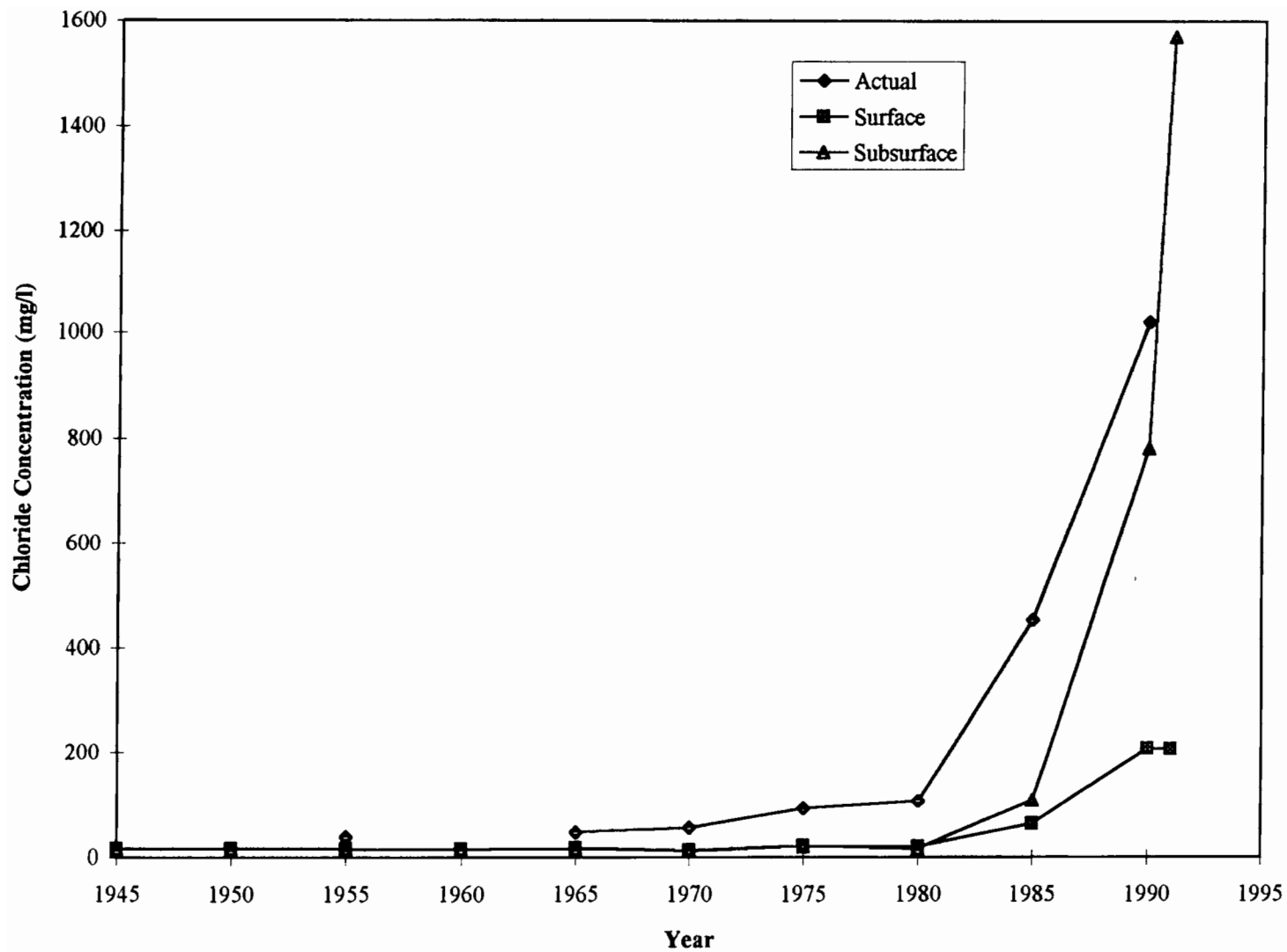


Figure 29. Comparison of actual to simulated chloride concentrations from surface and subsurface disposal in Cyril well A-4

## CHAPTER IX

### SUMMARY AND CONCLUSIONS

#### Summary

Four aquifer systems are present in the study area: the Duncan Sandstone, the Chickasha Formation, the Marlow Formation, and the Rush Springs Sandstone. Of the four identified aquifers, only the Chickasha Formation did not have water supply wells constructed in the aquifer at the study area. The majority of the ground-water supply in the study area was attributable to the Rush Springs Sandstone, an unconfined water table aquifer.

The transmissivity of the Duncan Sandstone, a confined aquifer, ranged from 500 to 1,300 gpd/ft and storativity ranged from  $1.0 \times 10^{-4}$  to  $4.6 \times 10^{-4}$ . The range of estimates of transmissivity for the Chickasha Formation, also a confined aquifer, were 200 to 2,000 gpd/ft and storativity was estimated to be  $1.0 \times 10^{-4}$ . In the Marlow Formation, transmissivity was calculated to be 240 gpd/ft. Storativity in the Marlow Formation, which may be semi-confined to confined would be expected to range from  $1.0 \times 10^{-3}$  to  $1.0 \times 10^{-4}$ . The transmissivity of the Rush Springs Sandstone ranged from approximately 350 to 13,000 gpd/ft, although in the study area a range of 350 to 1,600 gpd/ft would be more representative of the aquifer characteristics. Storativity values are expected to be approximately equal to specific yield which has been

reported to range from 0.13 to 0.38 with an average of 0.25.

Ground water in the Duncan Sandstone varies from potable to highly mineralized with the water quality in Caddo County reported to be high in total dissolved solids and sulfate. Three distinctive water types are present; temporary hardness (bicarbonate waters), permanent hardness (sulfate waters), and saline. The bicarbonate waters generally have lower sulfate concentrations and occur in wells shallower than 300 feet. Higher sulfate concentrations generally occur in the permanent hardness and saline water types in wells deeper than 300 feet. The source rocks for the ground water in the Duncan Sandstone are probably gypsiferous in nature and cation exchange is likely occurring increasing sodium concentrations and decreasing calcium concentrations.

Ground water in the Chickasha Formation may be suitable for human consumption, although in some areas it is highly mineralized. Water types are typically bicarbonate and source rock analyses indicate shales and dolomites. Natural softening may be occurring in the aquifer. In the Marlow Formation, ground water has been described as hard and high in total solids and sulfates due to disseminated gypsum. Insufficient water quality analyses were available to quantify the ground-water quality in the Marlow Formation.

Ground water in the Rush Springs Sandstone is suitable for both domestic and agricultural use and serves as the principal source of ground water in the study areas as well as in this area of southern Oklahoma. Water quality is generally low in dissolved solids with varying degrees of hardness. Water types are generally bicarbonate with some sulfate waters present. Source rock analyses are typical of

gypsum and dolomite. Several analyses indicated brine sources (Na/Cl ratios greater than 1 and TDS greater than 500) and may be indicative of contamination by oilfield brines. Salt springs could also indicate brines, although generally a sodium source other than halite was observed in the analyses. Ca/SO<sub>4</sub> ratios indicate a source of calcium other than gypsum. Dissolution of calcite or dolomite could be a source of additional calcium concentrations.

Chloride contamination of the Cyril water supply wells has been well-documented and has resulted in the abandonment of the Cyril well field. Additionally, anomalously elevated calcium concentrations were observed in several of the water supply wells. Both calcium and chloride are associated with oilfield operations. In the study area, operations in the Cement field commenced in 1916 and are ongoing at the present time. By the late 1980's, approximately 1,900 wells had been drilled. Secondary recovery via waterflooding was commenced in 1970. Calcium and/or chloride contamination can be introduced to the ground water through the use of drilling fluids during exploration or exploitation phases of reservoir development; the use of completion or well workover fluids after the wells have been drilled; the disposal or re-use of produced formation water (brines) either at the surface or through subsurface injection; and through the improper abandonment of wells at the end of their usefulness.

The earliest known reports of chloride contamination in the Cyril water supply wells occurred in 1947. The cause of the contamination was postulated to be from the use of surface evaporation pits for brine disposal. By 1948, three wells (AB, AB-1, and AB-2) had been abandoned and by 1966, elevated chloride concentrations were



detected in five new wells (A-1, A-2, A-3, A-4, and A-5). The drinking water standard for chloride (250 mg/l) was exceeded in one of these wells in 1970, in two more wells by 1973, in the fourth well by 1975, and in the last well (A-5) by 1985. Generally, chloride contamination and calcium concentrations increased markedly in the early 1970s and the Cyril well field was abandoned in the early 1990s.

Two contamination scenarios were simulated using the USGS Solute Transport Model. In the first simulation, the source of ground-water contamination was restricted to surface evaporation pits. The simulation was commenced in 1940, the sources for the surface disposal were turned off in 1955, and the simulation was terminated in 1991. The second simulation assumed that the source of ground-water contamination was caused by a combination of surface disposal and injection of brines. The second simulation was also commenced in 1940, the sources for the surface disposal were turned off in 1955, the sources for injection were turned on in 1970 and turned off in 1990, and the simulation was terminated in 1991. Generally, the results of the second simulation compared more favorably to actual chloride contamination in the Cyril water wells than did the first simulation, although neither simulation provided an exact match with the contaminated Cyril water supply wells.

## Conclusions

Based on the evaluation of published ground-water quality analyses using the computer program WATEVAL, the Duncan Sandstone, Chickasha Formation, Marlow Formation, and Rush Springs Sandstone are capable of providing sources of ground

water for agricultural use and, depending on the geochemistry of specific areas, for domestic use. In the study area, water supply wells have been constructed in the Duncan Sandstone, Marlow Formation, and Rush Springs Sandstone.

Chloride contamination at the Cyril well field was caused primarily through the disposal of produced formation water. Possible secondary sources of chloride contamination are the use of chloride-based well workover/completion fluids ( $\text{CaCl}_2$  and  $\text{KCl}$ ) and the use of chloride-based stimulation fluids ( $\text{HCl}$ ). Computer modeling results suggest that the abandonment of the Cyril well field was likely due to ground-water contamination resulting from the combined sources of disposal of brines in surface evaporation pits and injection of brines associated with secondary recovery operations. However, the computer simulations did not provide results that correlated directly with the observed contamination in the Cyril water supply wells.

Based on calcium/sulfate ratios greater than 1, sources of calcium other than the dissolution of gypsum are common in the Rush Springs Sandstone. Of the analyses reporting calcium and sulfate, 69 had calcium/sulfate ratios greater than 1 and of these, 58 had ratios greater than 2. Only three of the analyses with ratios greater than 2 were attributable to brines samples. Although these ratios would indicate that the elevated calcium concentrations observed in the Cyril water wells could be a result of natural processes, they do not explain the marked increase in calcium concentrations observed in the early 1970s. These increases in calcium concentrations are likely to have been caused by the use of calcium chloride completion/well workover fluids and/or the use of hydrochloric acid as a well stimulation fluid (calcium chloride is a common soluble by-product of acid

treatments).

The USGS Solute Transport Model can be used to model the flow and transport of ground-water contaminants. Aquifer coefficients, fate and transport parameters, and contaminant sources are easily handled by the program. Matrix entry of recharge, saturated thickness, background chemical concentrations, permeability (hydraulic conductivity), and potentiometric head distribution facilitate the configuration of the aquifer and geochemical system to be modeled.

Problems were encountered in using the USGS Solute Transport Model. In addition to the lack of calibration, the version of the model available to the author was restricted to 25 rows and columns. The finite-difference grid needed to be large enough to cover the study area which precluded a grid spacing small enough to allow the cell nodes to coincide with the observation points (Cyril water supply wells). The location of the nodes did not coincide with the location of the Cyril wells which may partially explain the poor correlation between actual and simulated concentrations. Additional columns and rows would allow a smaller grid to be embedded in a larger grid and allow the cell nodes to be located in closer proximity to the observation points.

The USGS Solute Transport Model is a two-dimensional model which did not allow the sources attributable to the injection wells to be entered at a depth below surface. The model treated the injections wells in the same manner as the surface evaporation pits which undoubtedly had an effect on the results of the second simulation and may have resulted in simulated concentrations less than actual. The use of a three-dimensional model could more accurately simulate the injection wells.

Contaminant loading assumed that the source areas for the surface evaporation pits were active throughout the specified pumping period and that the volume of produced formation water placed in the pits was distributed equally. There was no way to quantify which pits were actually being used or how much formation water was actually placed in the pits. Variations to the assumed loading could have a significant affect on the simulated chloride concentrations.

Ground-water withdrawal rates for the Cyril water supply wells were estimated based on anticipated water requirements for the current population of Cyril. The pumping rates required to provide the water supply were apportioned over the potentially active wells during each pumping period in the simulation. Variations in pumping rates could have an affect on the capture zones for the individual water supply wells and the resulting simulated chloride concentrations.

Oilfield operations and secondary recovery have significant potential to impact ground water. From a volumetric standpoint, the disposal or re-use of produced formation water has the greatest potential for adverse impacts on ground-water quality. Other oilfield operations, as well as non-oilfield sources, may have local impacts, but are not expected to create widespread contamination. Major contaminant pathways are through infiltration from surface sources, direct injection into the ground water via absence of protective casing or the impairment of casing and/or annular cement, and indirect migration of contamination through improperly abandoned boreholes.

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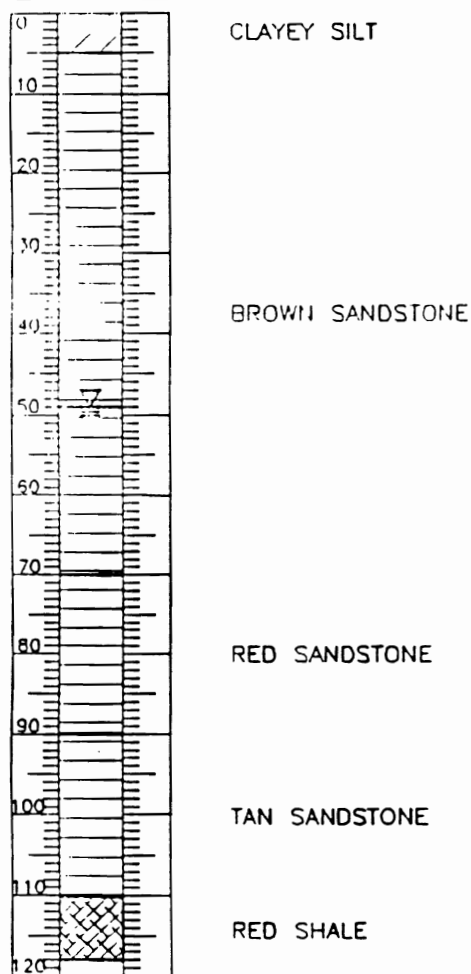
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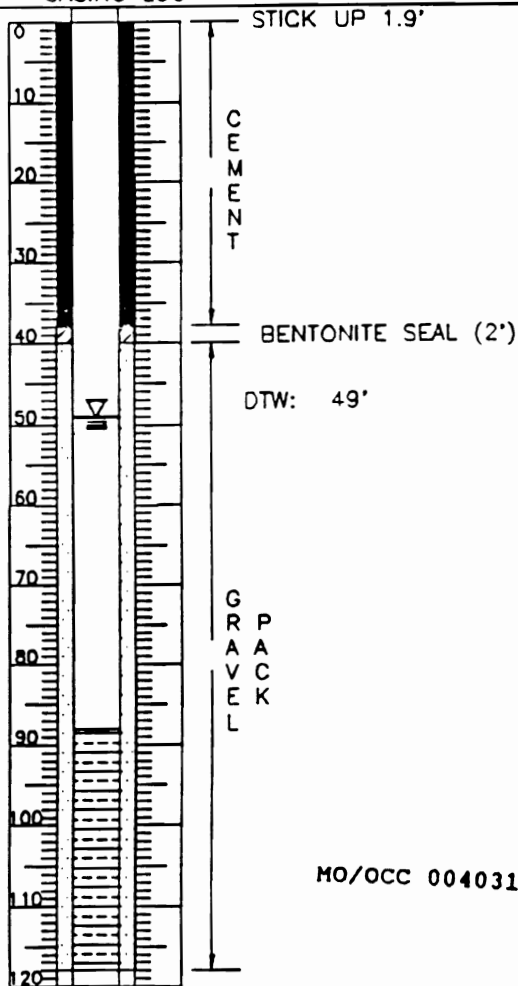
**APPENDIX A****AQUIFER TEST DATA**

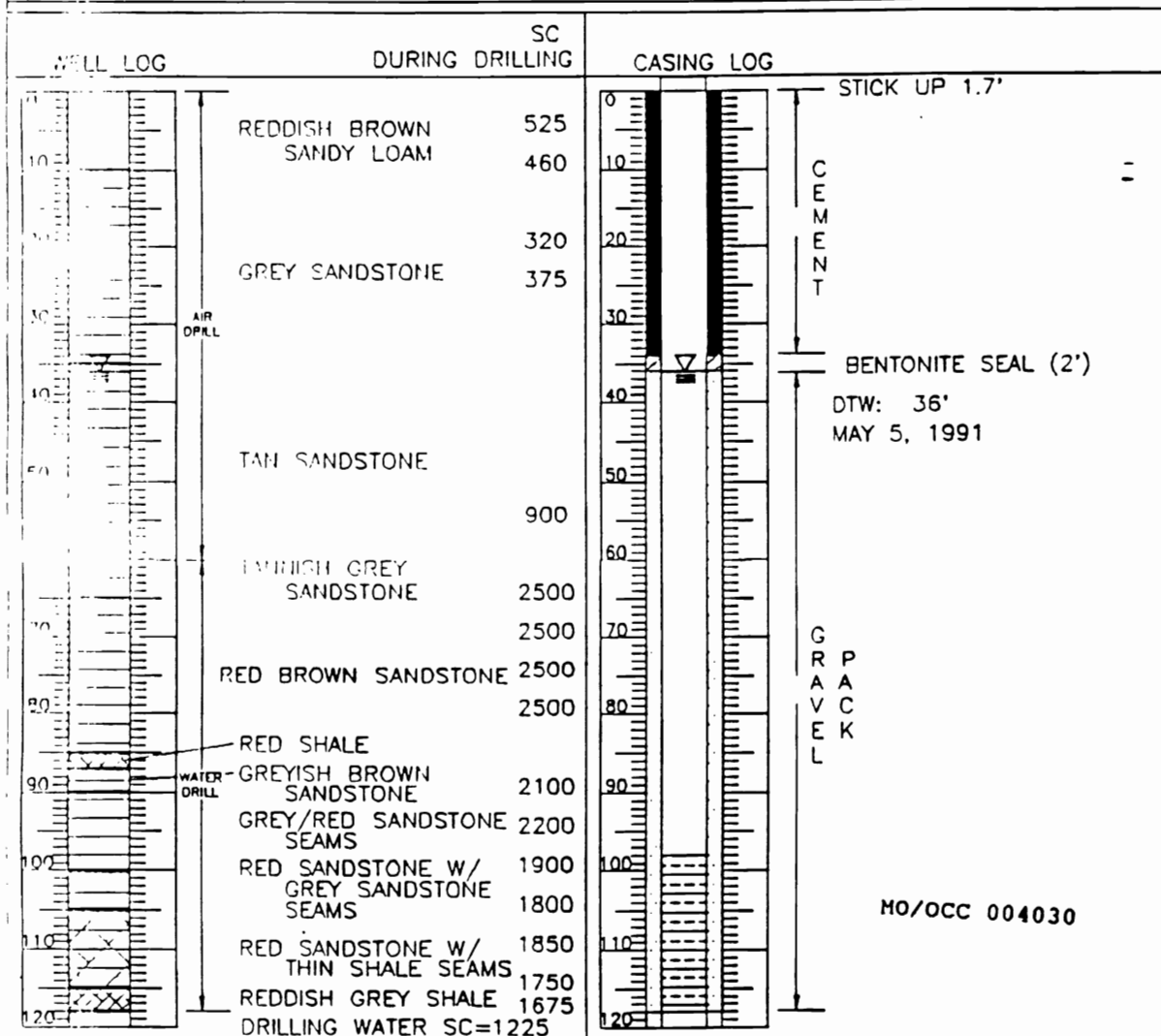
WELL W-PWPROJECT MOBIL - CYRILTOP OF CASING ELEVATION 1479.93- COORDINATES: NORTH 6842.05BOTTOM OF CASING ELEVATION 1360.3EAST 9486.32TOTAL DEPTH 119.6CASING DIAMETER 6"GROUND ELEVATION 1477.9DATE DRILLED APRIL 4, 1991TOP OF SCREEN ELEVATION 1390.3DRILLED BY EUBANK DRILLING CO.TOTAL LENGTH OF SCREEN 30'FAIRVIEW, OK.LOGGED BY: STREIT

## WELL LOG



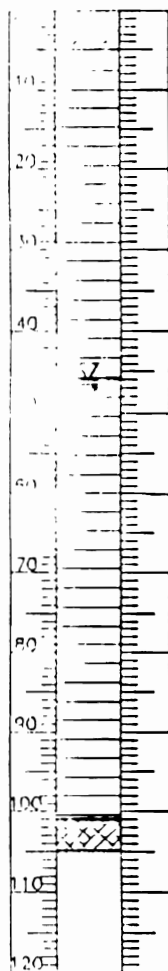
## CASING LOG



WELL W-6PROJECT MOBIL - CYRILTOP OF CASING ELEVATION 1479.41COORDINATES: NORTH 6845.33BOTTOM OF CASING ELEVATION 1360.3EAST 9425.75TOTAL DEPTH 119.1CASING DIAMETER 2"GROUND ELEVATION 1477.7DATE DRILLED MAY 5, 1991TOP OF SCREEN ELEVATION 1380.3DRILLED BY EUBANK DRILLING CO.TOTAL LENGTH OF SCREEN 20'FAIRVIEW, OK.LOGGED BY: MAST

WELL D-5PWPROJECT MOBIL - CYRILTOP OF CASING ELEVATION 1495.99COORDINATES: NORTH 8170.40BOTTOM OF CASING ELEVATION 1389.9EAST 10.603.74TOTAL DEPTH 106.1CASING DIAMETER 5"GROUND ELEVATION 1494.3DATE DRILLED APRIL 4, 1991TOP OF SCREEN ELEVATION 1419.9DRILLED BY EUBANK DRILLING CO.TOTAL LENGTH OF SCREEN 30'FAIRVIEW, OK.LOGGED BY: STREIT

## MUD LOG



SANDY CLAY

SOFT WEATHERED SANDSTONE

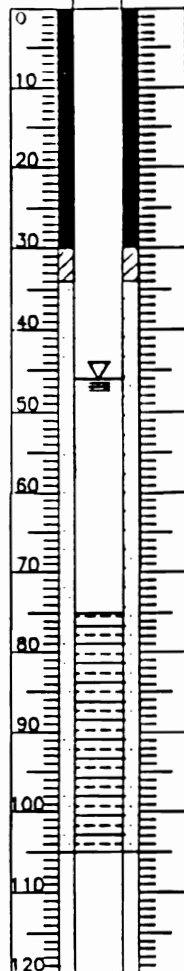
DRILLING WATER THICKENED  
AT 40'-LARGE AMOUNT OF  
FINES IN SANDSTONE

CALLED FOX VACUUM TRUCK-  
PIT LIQUID IS TOO THICK  
SC=1600  
SC DISTILLED WATER = 45

SOME CLAY AT 96'

BLUE GREY SHALE

## CASING LOG



STICK UP 1.7'

C  
E  
M  
E  
N  
T

BENTONITE SEAL (4.8')

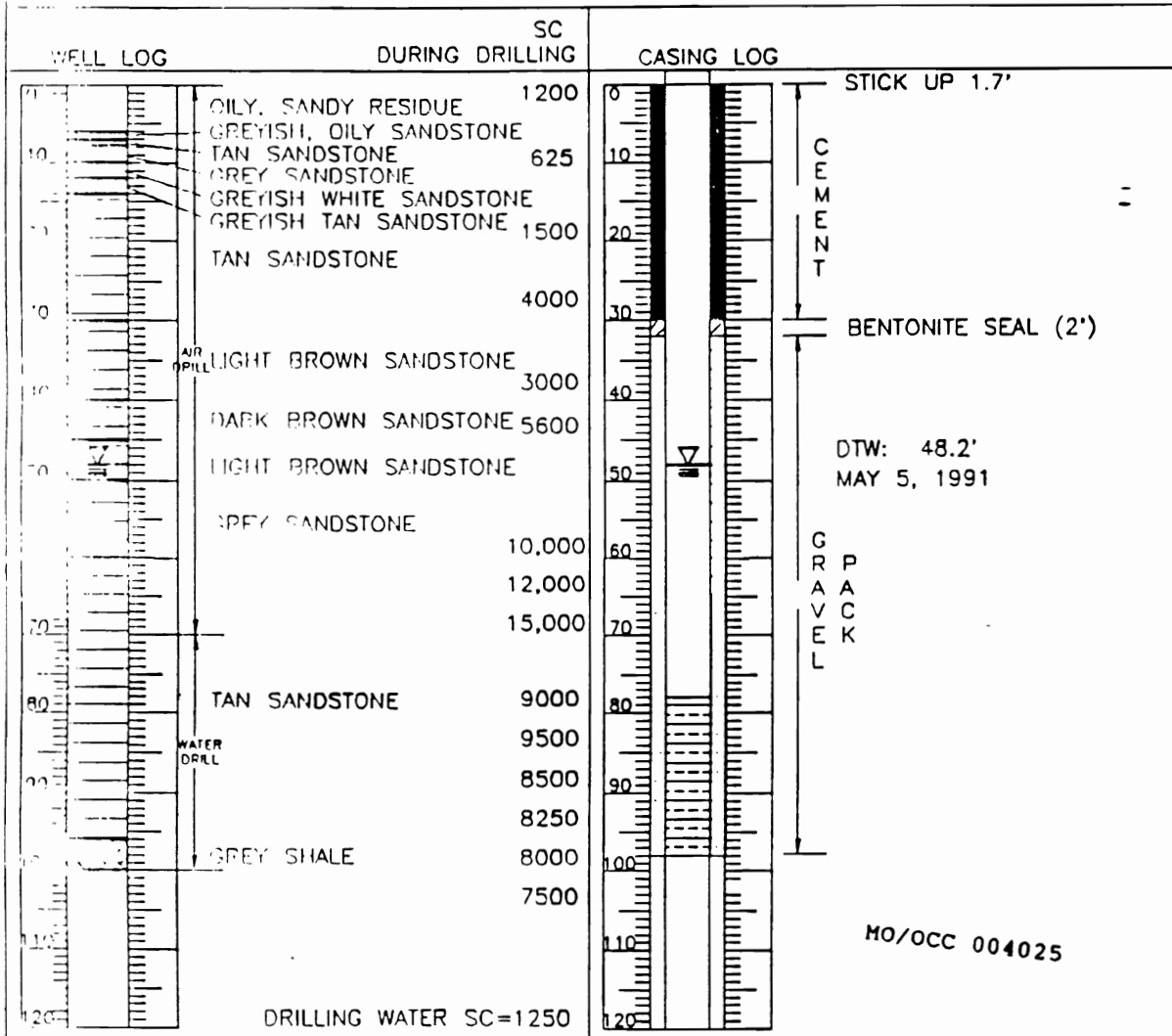
DTW: 46'  
APRIL 15, 1991

G  
R  
A  
V  
E  
L

MO/OCC 004028

WELL D-2PROJECT MOBIL - CYRILTOP OF CASING ELEVATION 1497.78COORDINATES: NORTH 8824.08BOTTOM OF CASING ELEVATION 1398.0EAST 10.632.13TOTAL DEPTH 99.8CASING DIAMETER 2"GROUND ELEVATION 1496.1DATE DRILLED APRIL 4, 1991TOP OF SCREEN ELEVATION 1418.0DRILLED BY EUBANK DRILLING CO.TOTAL LENGTH OF SCREEN 20'

FAIRVIEW, OK.

LOGGED BY: MAST

# AQUIFER TEST AT CYRIL, OK

Pumped Well WPW, Observation Well W-6

Distance from Wpw to W-6 = 67.4 ft

Discharge Rate = 13.5 gpm; Saturated thickness = 60 ft

Time (min)	Drawdown, ft	Time, min	Drawdown, ft
0	0	0	0
1	.27?	1	.05
2	9.10	2	.40
3	9.96	3	.70
4	10.29	4	.90
5	11.46	5	1.10
6	11.31	6	1.25
7	11.23	7	1.35
8	11.13	8	1.43
9	11.10	9	1.50
10	10.94	10	1.55
15	10.98	15	1.75
20	10.98	20	1.80
30	11.25	30	1.85
40	11.31	40	1.90
50	11.31	50	1.95
60	11.19	60	2.00
70	11.06	70	2.00
80	11.06	80	2.00
90	11.06	90	2.03
100	11.08	100	2.05
120	11.13	120	2.05
150	11.17	150	2.05
180	11.19	180	2.10
210	11.19	210	2.10
240	11.23	240	2.10



## AQUIFER TEST AT CYRIL, OK

Pumped Well D-5pw, Observation Well D-2

Distance from D-5pw to D-2 = 60.5 ft

Discharge Rate = 12 gpm; Saturated thickness = 61 ft

Time (min)	Drawdown, ft	Time, min	Drawdown, ft
0	0	0	0
1	10.98	1	0
2	15.33	2	.01
3	18.08	3	.02
4	19.92	4	.05
5	21.25	5	.05
6	22.21	6	.10
7	23.17	7	.10
8	23.71	8	.15
9	24.31	9	.15
10	24.81	10	.17
15	27.63	15	.20
20	30.38	20	.25
30	34.50	30	.35
40	36.46	40	.40
50	39.44	50	.55
60	40.96	60	.65
70	42.33	70	.70
80	43.67	80	.80
90	44.42	90	.95
100	45.23	100	1.00
120	46.75	120	1.20
150	50.04	150	1.40
180	52.90	180	1.65
210	54.29	210	1.80
240	54.46	240	1.95

AQUIFER TEST AT CYRIL, OKLAHOMA  
Water-Table Conditions Drawdown Correction

Time (min)	WELL WPW		WELL W-6		WELL D-5PW		WELL D-2	
	Measured Drawdown (ft)	Corr Drawdown (ft)	Measured Drawdown (ft)	Corr Drawdown (ft)	Measured Drawdown (ft)	Corr Drawdown (ft)	Measured Drawdown (ft)	Corr Drawdown (ft)
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.27	0.27	0.05	0.05	10.98	9.88	0.00	0.00
2	9.10	8.42	0.40	0.40	15.33	13.19	0.01	0.01
3	9.96	9.15	0.70	0.70	18.08	15.11	0.02	0.02
4	10.29	9.42	0.90	0.89	19.92	16.31	0.05	0.05
5	11.46	10.38	1.10	1.09	21.25	17.14	0.05	0.05
6	11.31	10.26	1.25	1.24	22.21	17.73	0.10	0.10
7	11.23	10.20	1.35	1.34	23.17	18.29	0.10	0.10
8	11.13	10.11	1.43	1.42	23.71	18.60	0.15	0.15
9	11.10	10.09	1.50	1.49	24.31	18.94	0.15	0.15
10	10.94	9.96	1.55	1.53	24.81	19.21	0.17	0.17
15	10.98	9.99	1.75	1.73	27.63	20.69	0.20	0.20
20	10.98	9.99	1.80	1.78	30.38	21.99	0.25	0.25
30	11.25	10.21	1.85	1.83	34.50	23.68	0.35	0.35
40	11.31	10.26	1.90	1.88	36.46	24.38	0.40	0.40
50	11.31	10.26	1.95	1.93	39.44	25.30	0.55	0.55
60	11.19	10.16	2.00	1.97	40.96	25.71	0.65	0.65
70	11.06	10.06	2.00	1.97	42.33	26.04	0.70	0.69
80	11.06	10.06	2.00	1.97	43.67	26.33	0.80	0.79
90	11.06	10.06	2.03	2.00	44.42	26.48	0.95	0.94
100	11.08	10.07	2.05	2.02	45.23	26.63	1.00	0.99
120	11.13	10.11	2.05	2.02	46.75	26.88	1.20	1.19
150	11.17	10.15	2.05	2.02	50.04	27.28	1.40	1.38
180	11.19	10.16	2.10	2.07	52.90	27.46	1.65	1.62
210	11.19	10.16	2.10	2.07	54.29	27.50	1.80	1.77
240	11.23	10.20	2.10	2.07	54.46	27.50	1.95	1.91

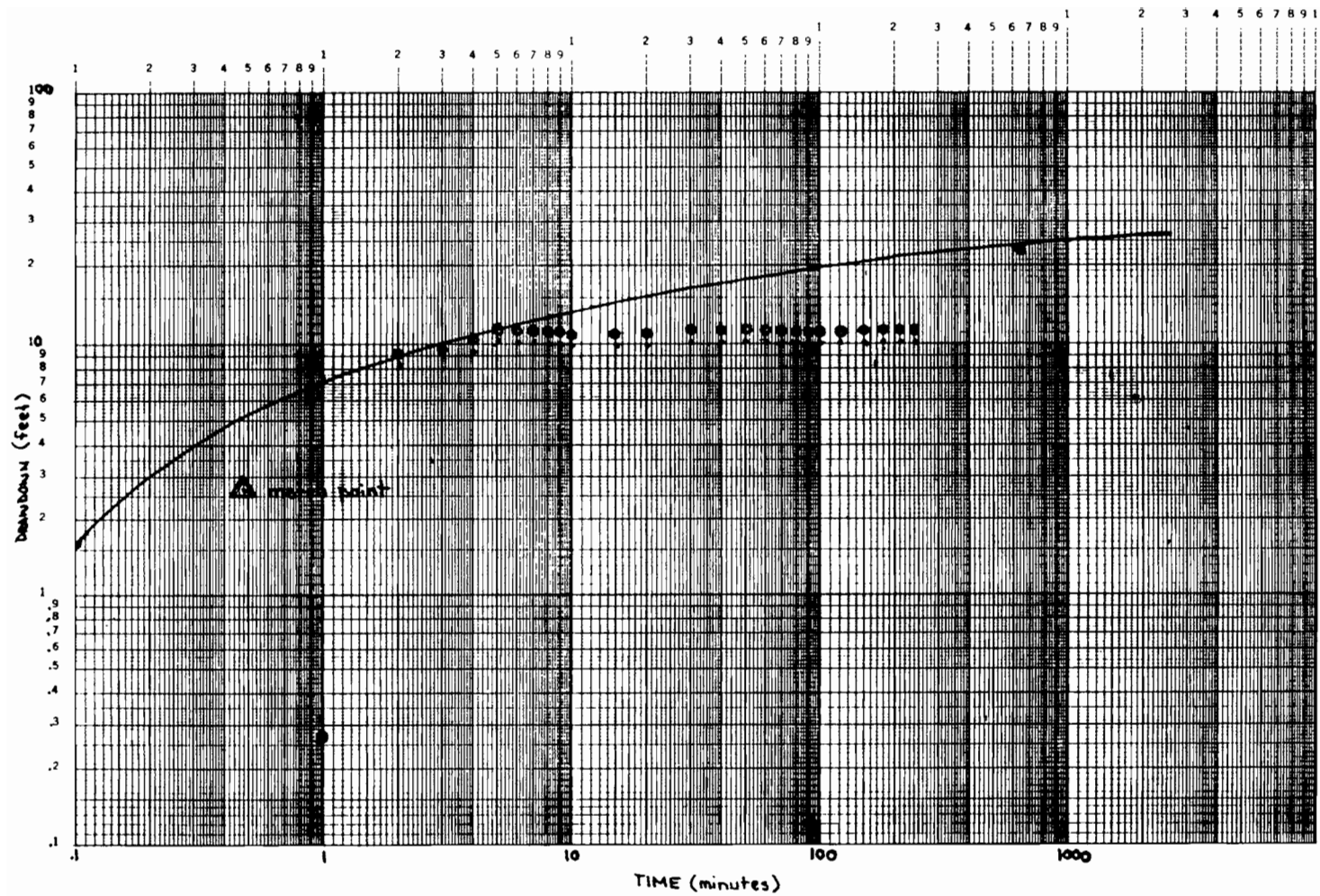
m = 61 ft.

m = 79 ft.

m = 55 ft.

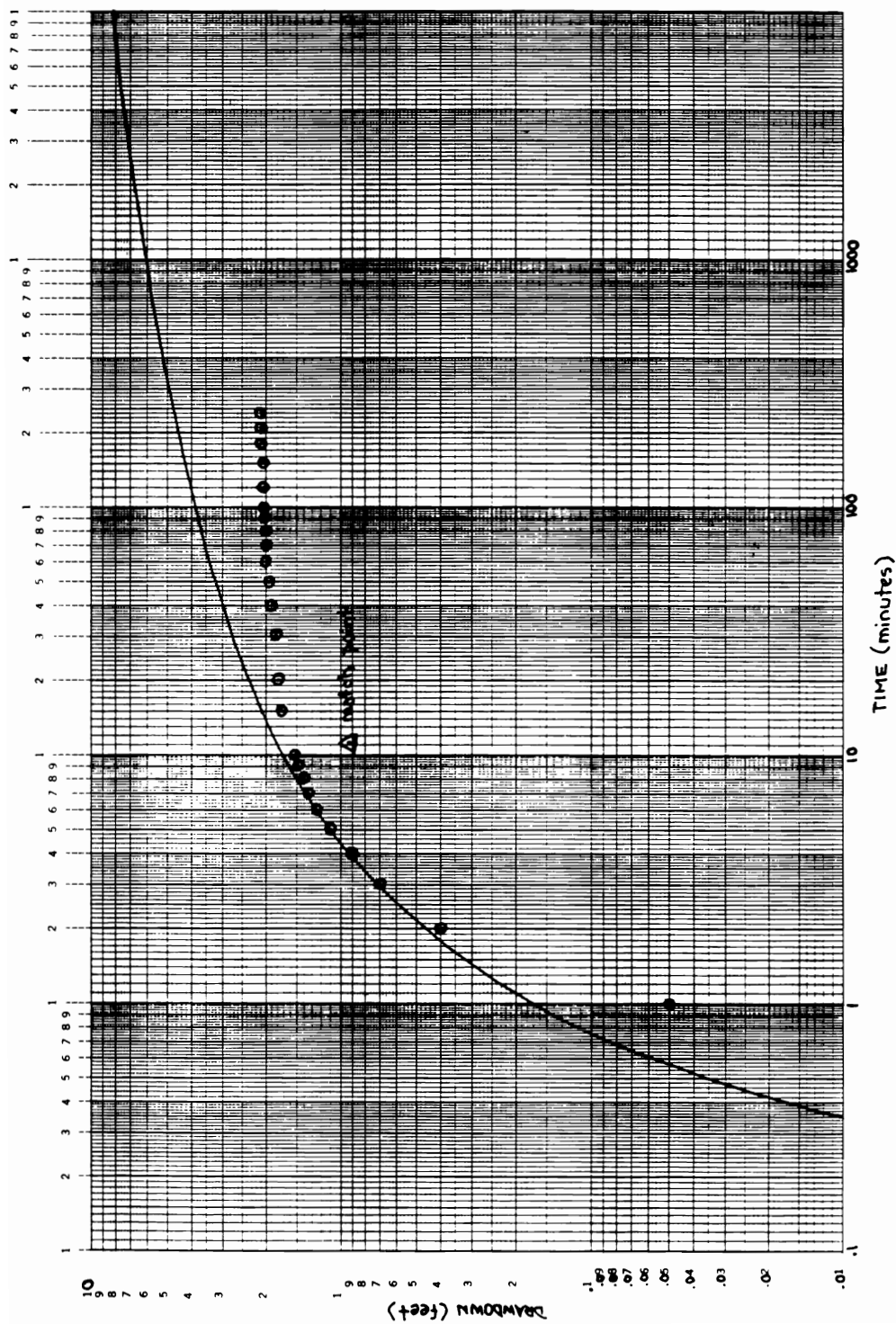
m = 48 ft.

Correction Formula:  $s[\text{corr}] = s[\text{meas}] - ((s[\text{meas}] * s[\text{meas}]) / 2m)$



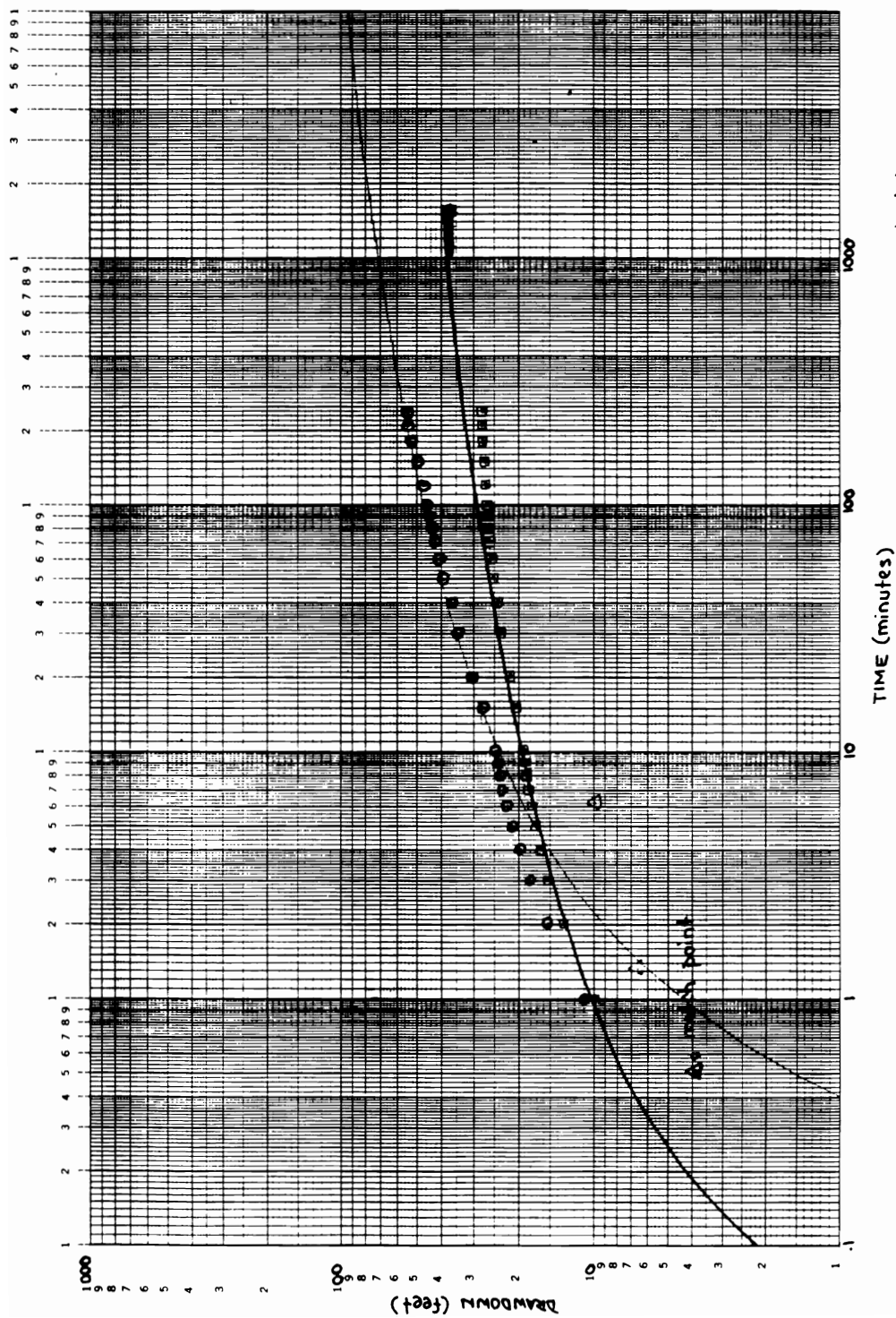
PUMPED WELL WPW  
 $Q = 13.5 \text{ gpm}$

⊙ original drawdown  
 • corrected drawdown



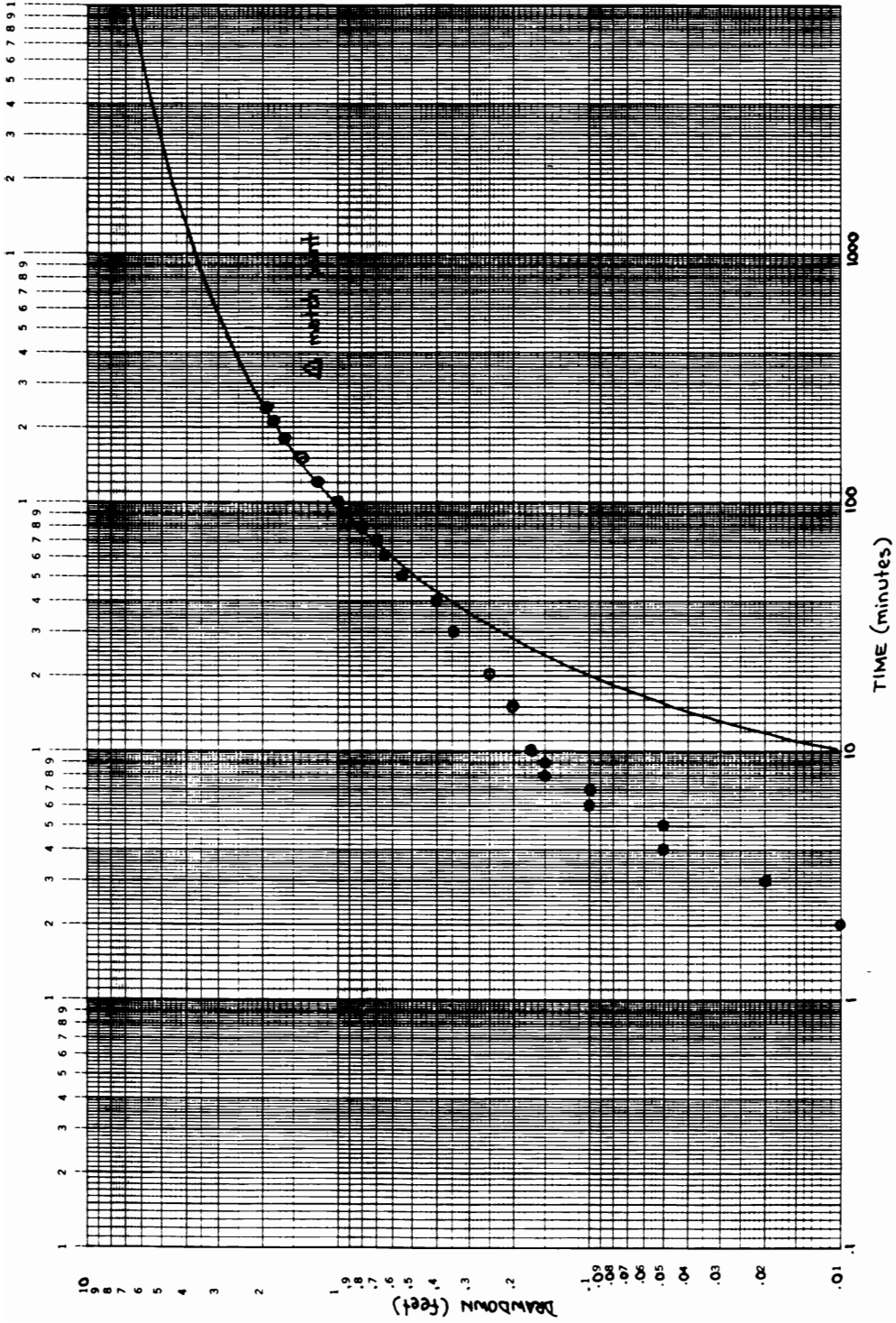
OBSERVATION WELL W-6

 $Q = 13.5 \text{ gpm}$  $r = 67.4 \text{ ft.}$



● original drawdown  
• corrected drawdown

PUMPED WELL D-5pw  
Q = 12 gpm



OBSERVATION WELL D-2  
 $Q = 12 \text{ gpm}$   
 $r = 60.5 \text{ ft.}$

**EVALUATION OF AQUIFER TEST**  
**at Cyril, Oklahoma**  
**March 24, 1992**

**Well WPW (pumped well)**

$$Q = 13.5 \text{ gpm} \quad m = 61 \text{ feet} \quad W(u) = 1 \quad (u) = 0.1$$

$$s = 2.7 \text{ feet} \quad t = 0.48 \text{ minutes}$$

$$T = [114.6 * Q * W(u)] / s = [114.6 * 13.5 \text{ gpm} * 1] / 2.7 \text{ feet} = 573 \text{ gpd/ft}$$

$$K = T / m = 573 \text{ gpd/ft} / 61 \text{ feet} = 9.4 \text{ gpd/ft}^2$$

**Well W-6 (observation well)**

$$Q = 13.5 \text{ gpm} \quad m = 79 \text{ feet} \quad W(u) = 1 \quad (u) = 0.1$$

$$s = 0.93 \text{ feet} \quad t = 11 \text{ minutes} \quad r = 67.4 \text{ feet}$$

$$T = [114.6 * Q * W(u)] / s = [114.6 * 13.5 \text{ gpm} * 1] / 0.93 \text{ feet} = 1,664 \text{ gpd/ft}$$

$$S = [T * (u) * t] / [2693 * r^2]$$

$$S = [1,664 \text{ gpd/ft} * 0.1 * 11 \text{ minutes}] / [2693 * 67.4^2 \text{ feet}] = 0.00015 = 1.5E-4$$

$$K = T / m = 1,664 \text{ gpd/ft} / 79 \text{ feet} = 21 \text{ gpd/ft}^2$$

**EVALUATION OF AQUIFER TEST**  
**at Cyril, Oklahoma**  
**March 24, 1992**

**Well D-5PW (pumped well)**

$$Q = 12 \text{ gpm} \quad m = 55 \text{ feet} \quad W(u) = 1 \quad (u) = 0.1$$

$$s = 9.9 \text{ feet} \quad t = 1.62 \text{ minutes}$$

$$s \text{ (corr)} = 3.9 \text{ feet} \quad t \text{ (corr)} = 0.5 \text{ minutes}$$

$$T = [114.6 * Q * W(u)] / s = [114.6 * 12 \text{ gpm} * 1] / 3.9 \text{ feet} = 353 \text{ gpd/ft}$$

$$K = T / m = 353 \text{ gpd/ft} / 55 \text{ feet} = 6.4 \text{ gpd/ft}^2$$

**Well D-2 (observation well)**

$$Q = 12 \text{ gpm} \quad m = 48 \text{ feet} \quad W(u) = 1 \quad (u) = 0.1$$

$$s = 1.25 \text{ feet} \quad t = 340 \text{ minutes} \quad r = 60.5 \text{ feet}$$

$$T = [114.6 * Q * W(u)] / s = [114.6 * 12 \text{ gpm} * 1] / 1.25 \text{ feet} = 1,100 \text{ gpd/ft}$$

$$S = [T * (u) * t] / [2693 * r^2]$$

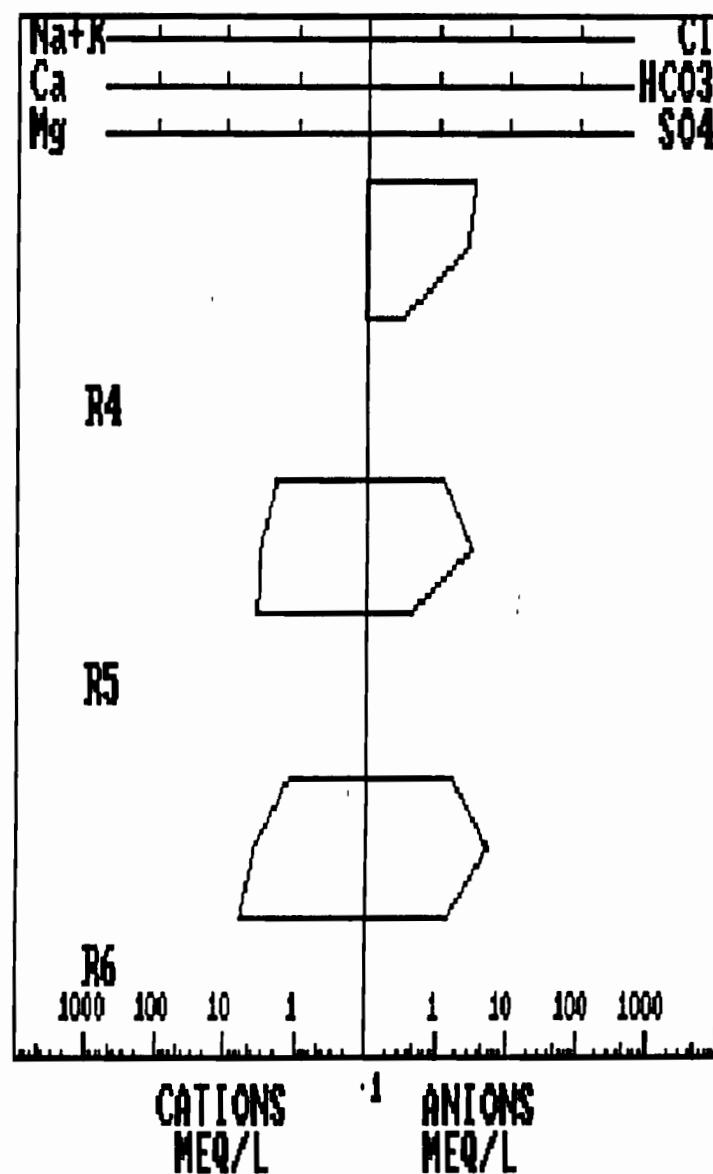
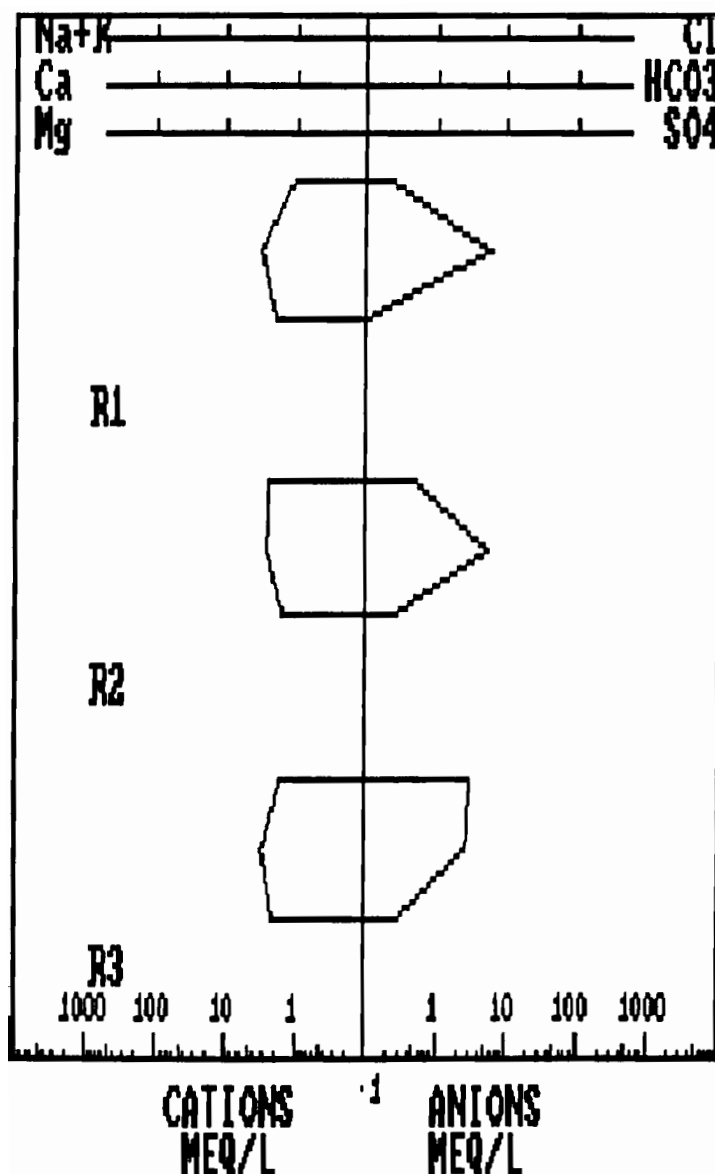
$$S = [1,100 \text{ gpd/ft} * 0.1 * 340 \text{ minutes}] / [2693 * 60.5^2 \text{ feet}] = 0.0038 = 3.8\text{E-}3$$

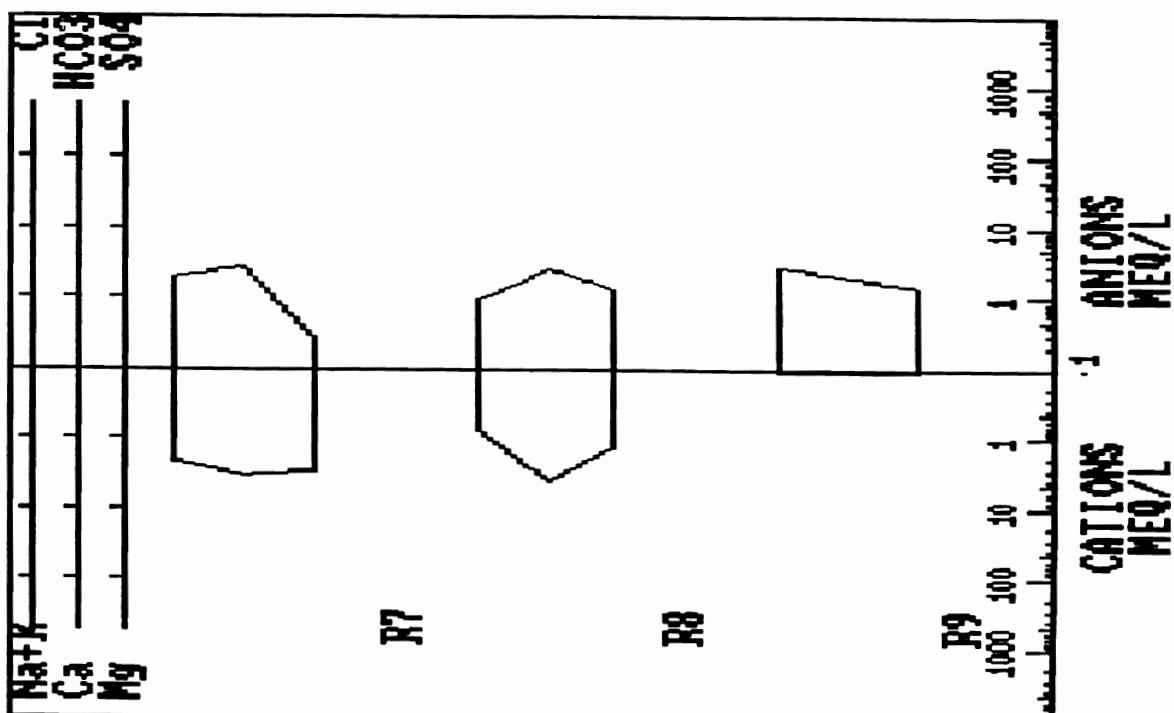
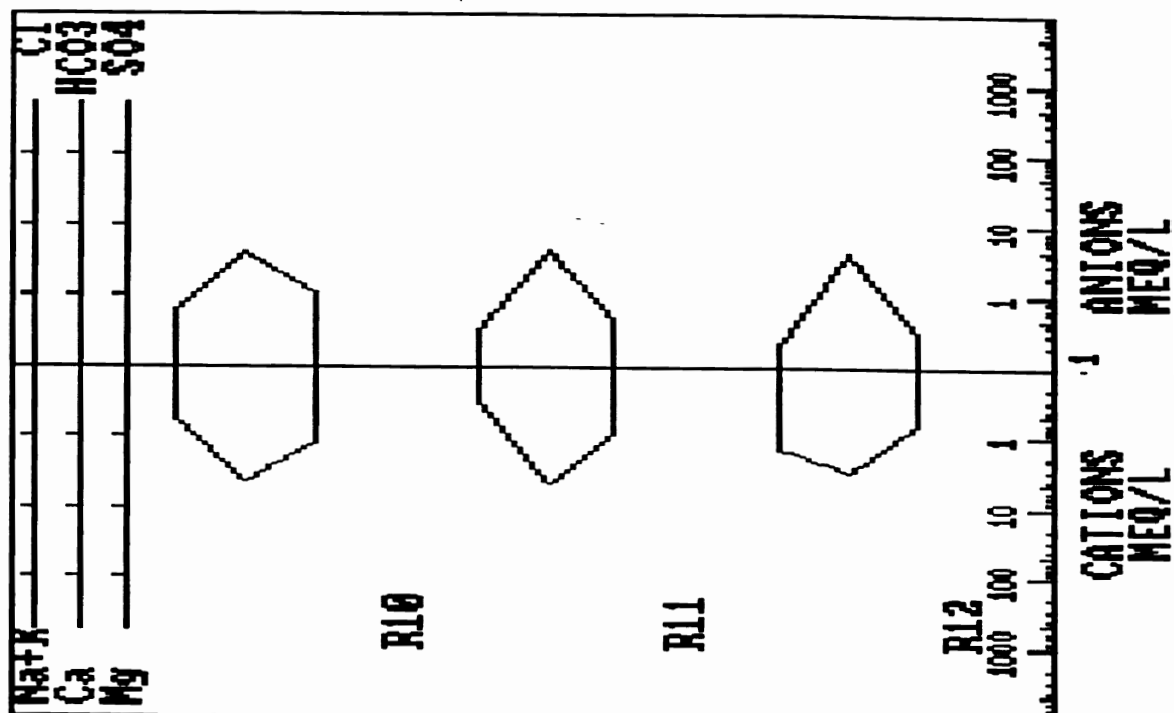
$$K = T / m = 1,100 \text{ gpd/ft} / 48 \text{ feet} = 23 \text{ gpd/ft}^2$$

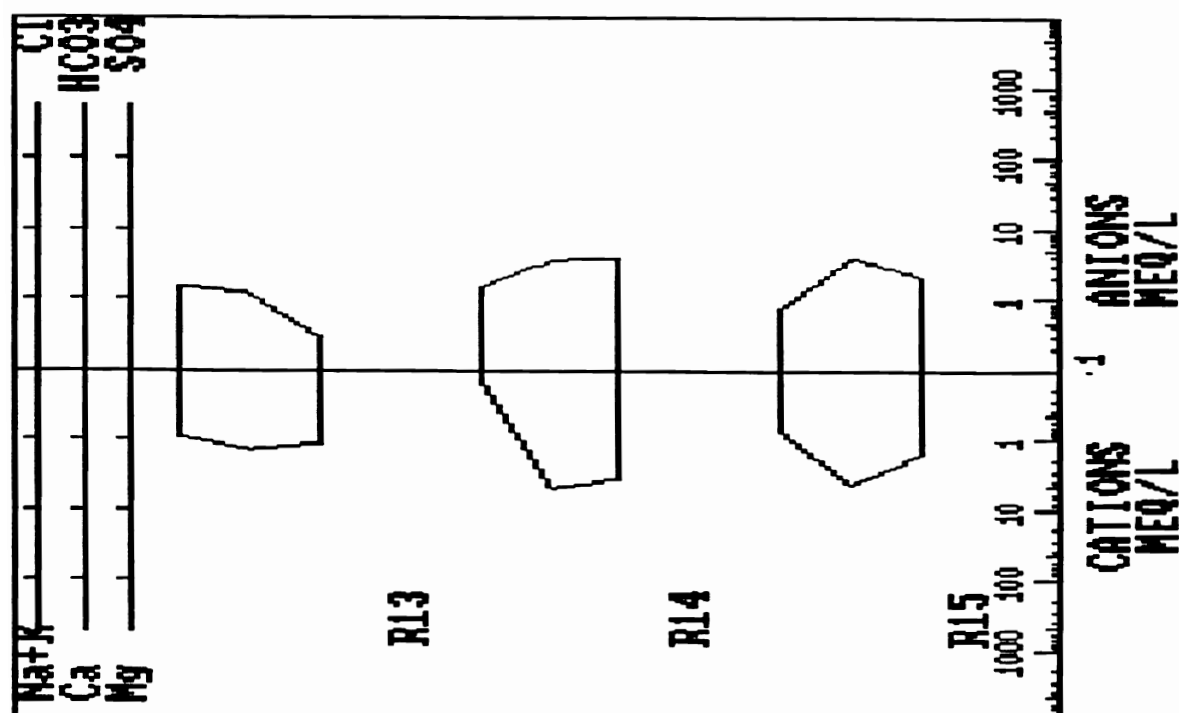
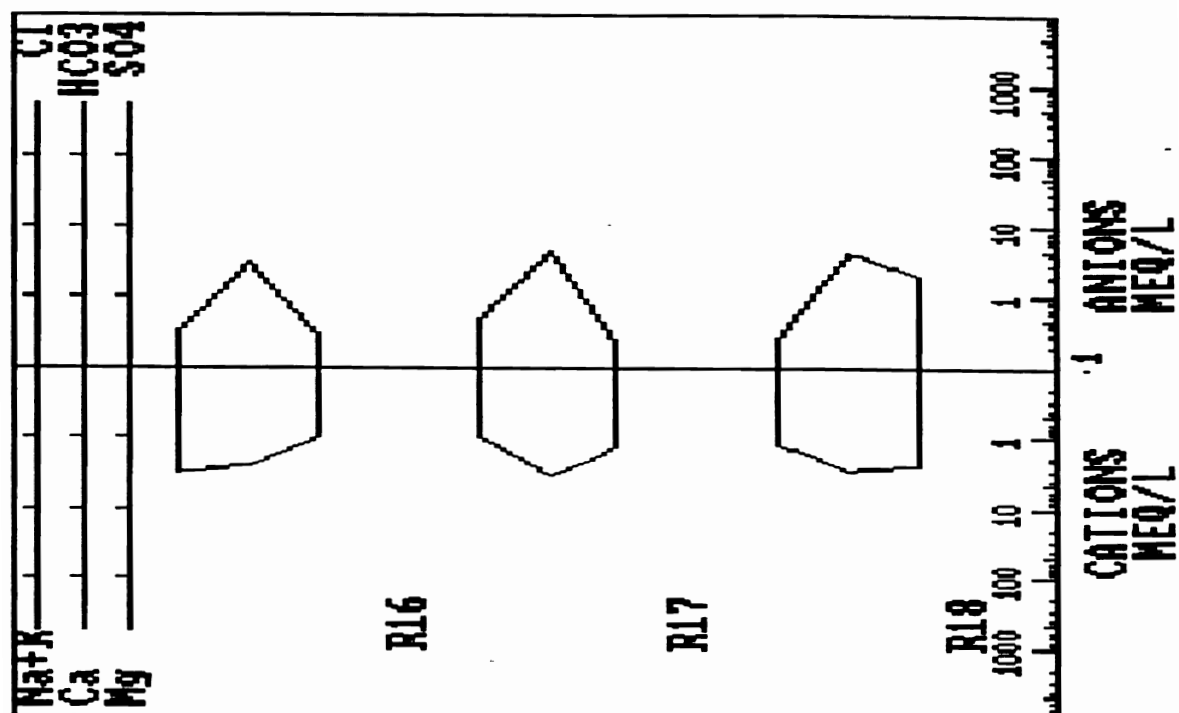


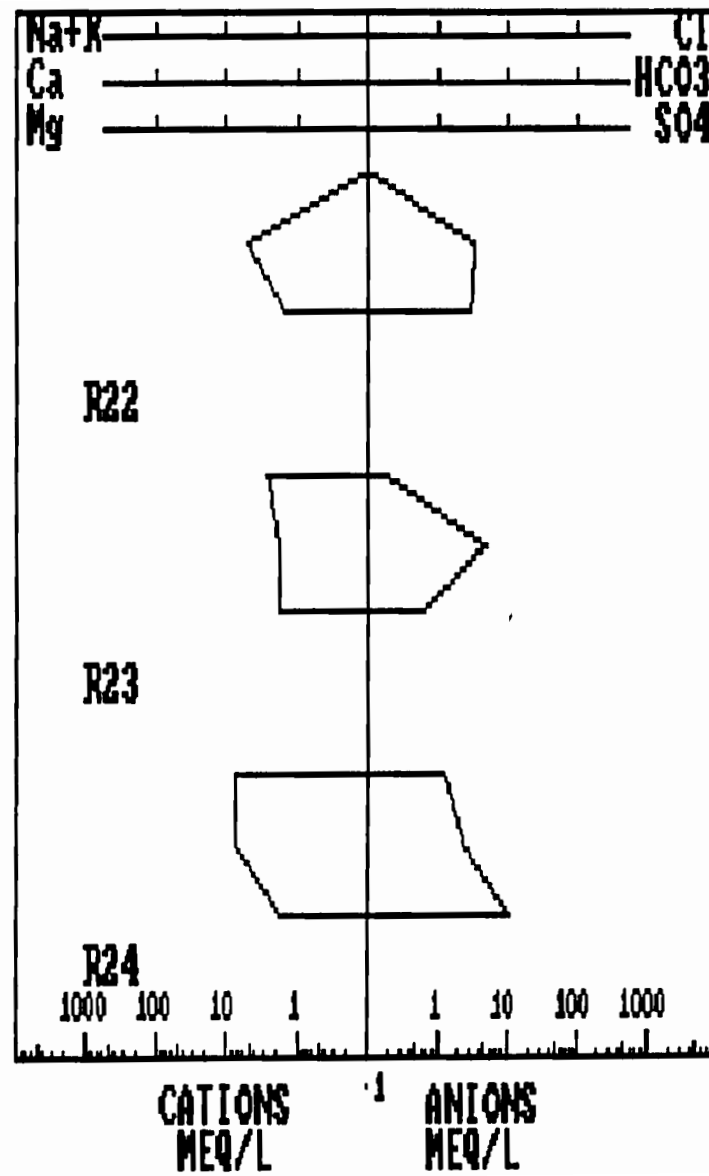
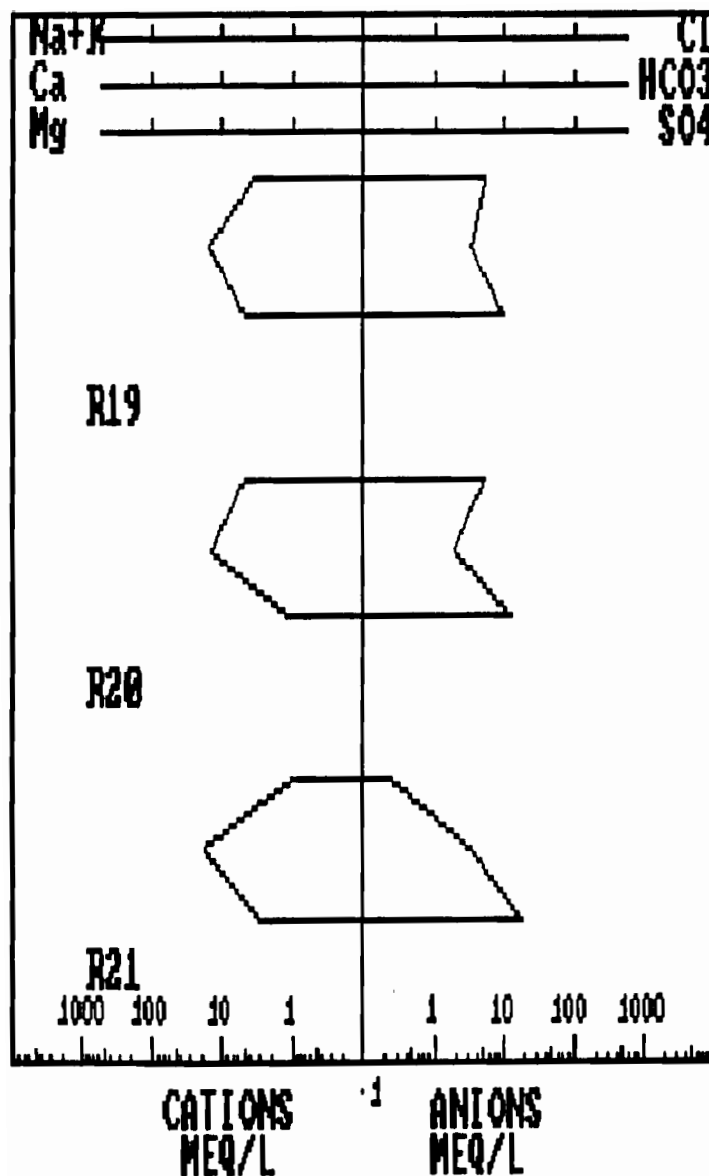
## APPENDIX B

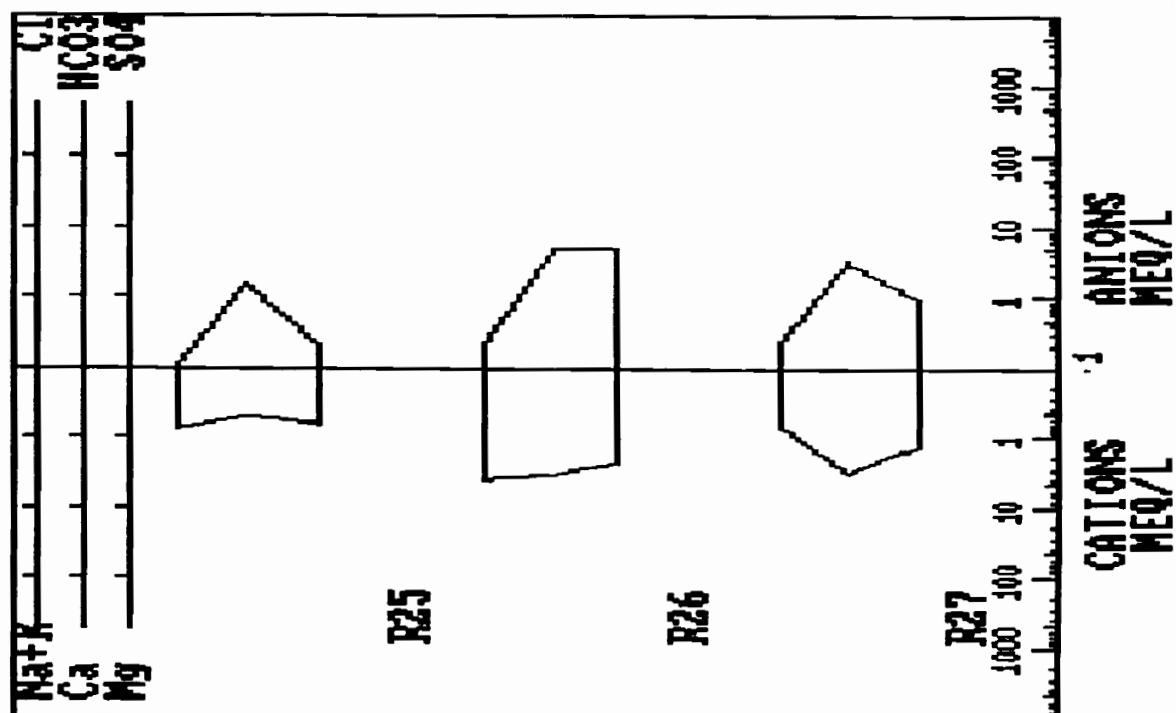
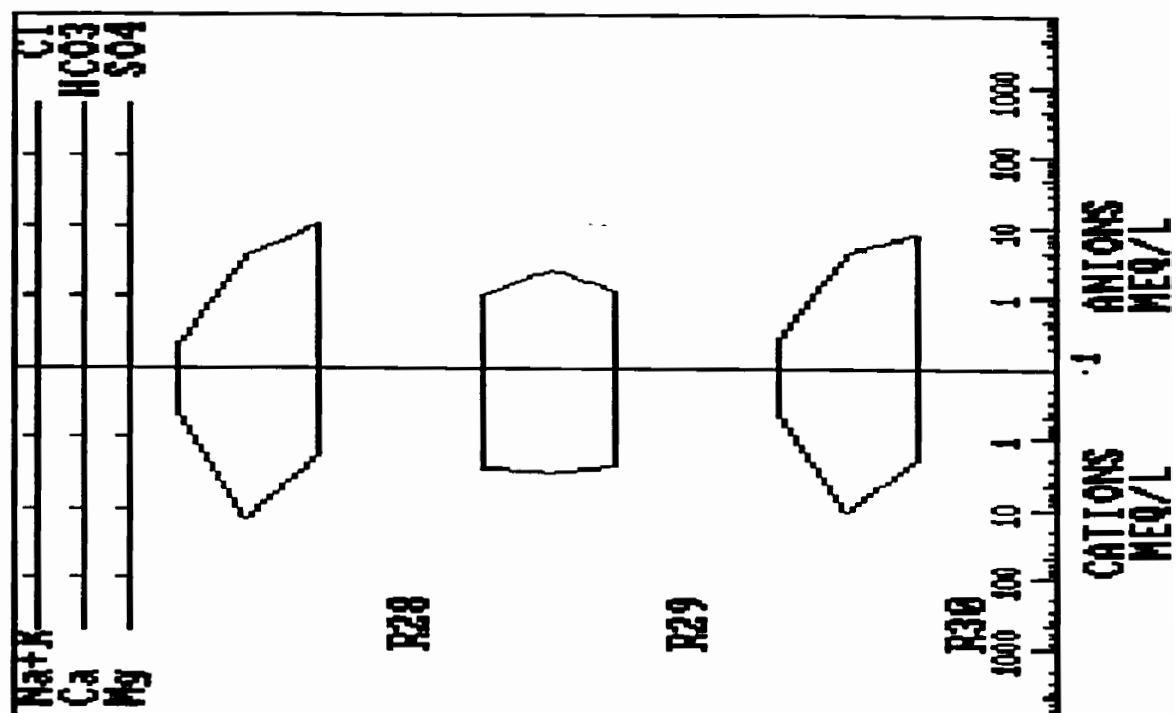
### STIFF DIAGRAMS OF RUSH SPRINGS SANDSTONE ANALYSES

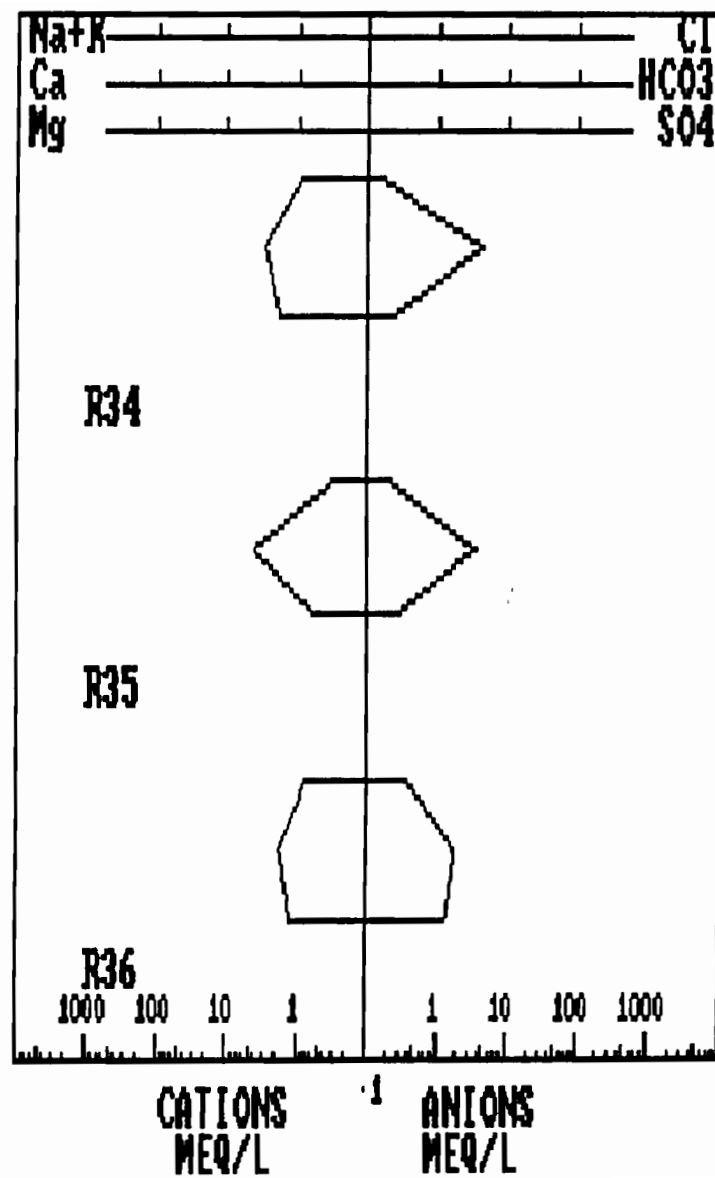
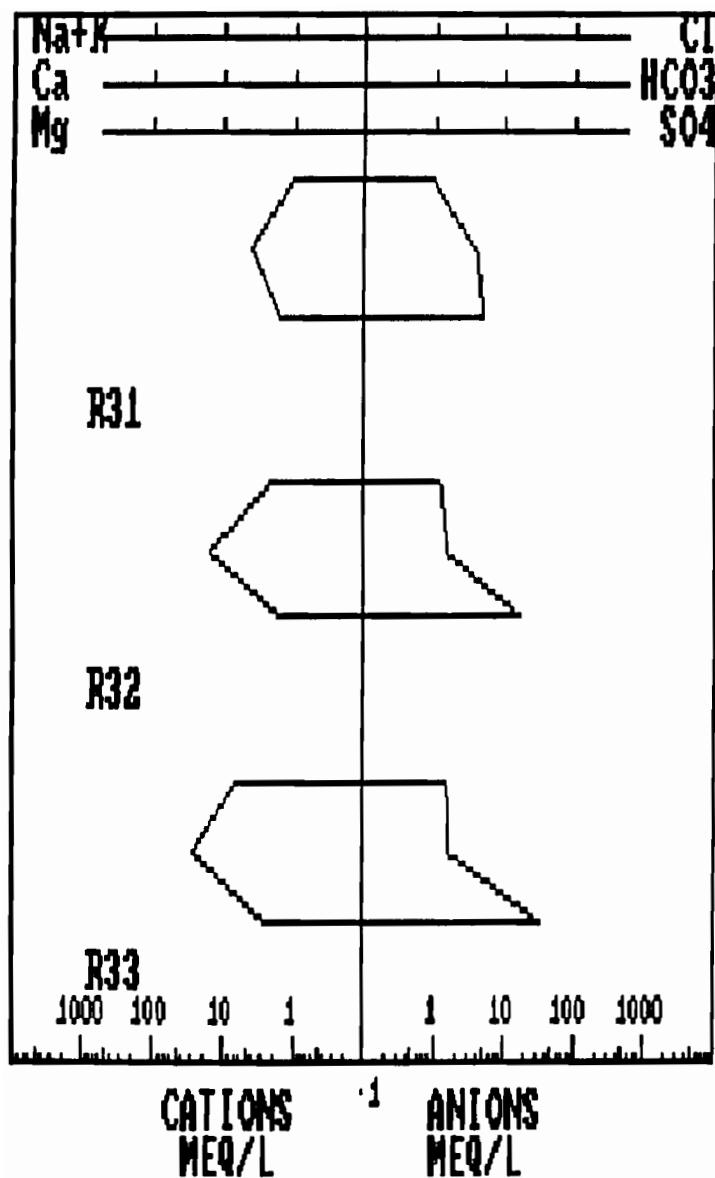


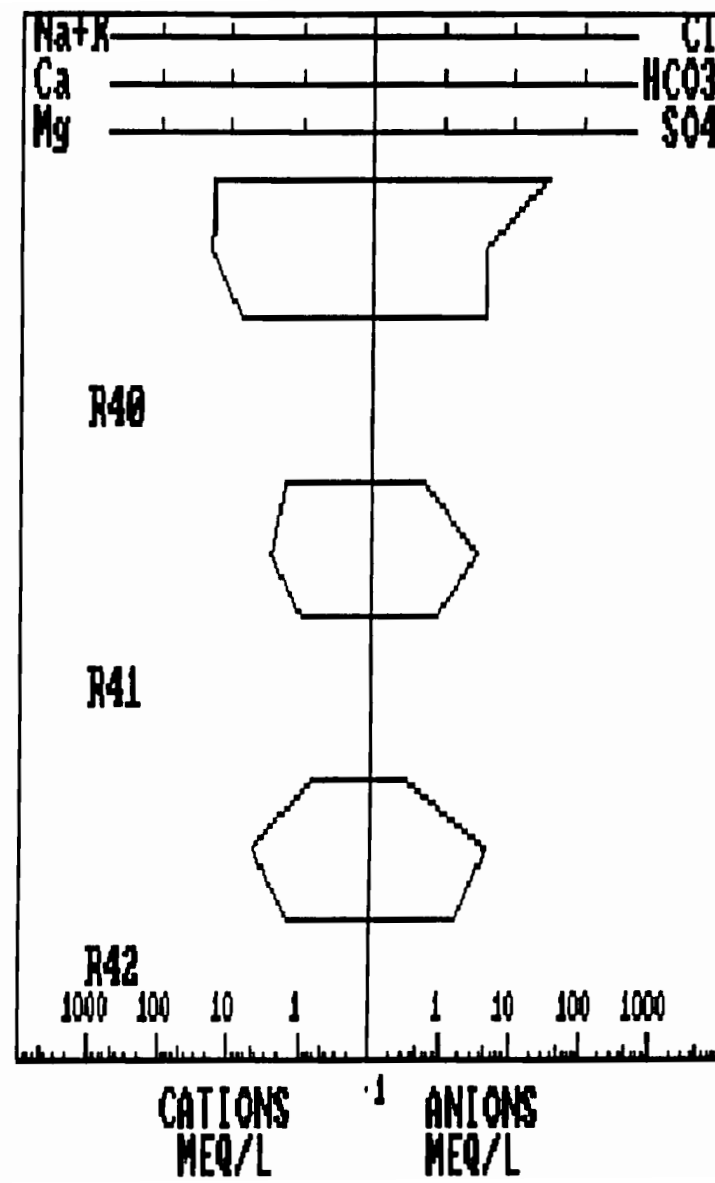
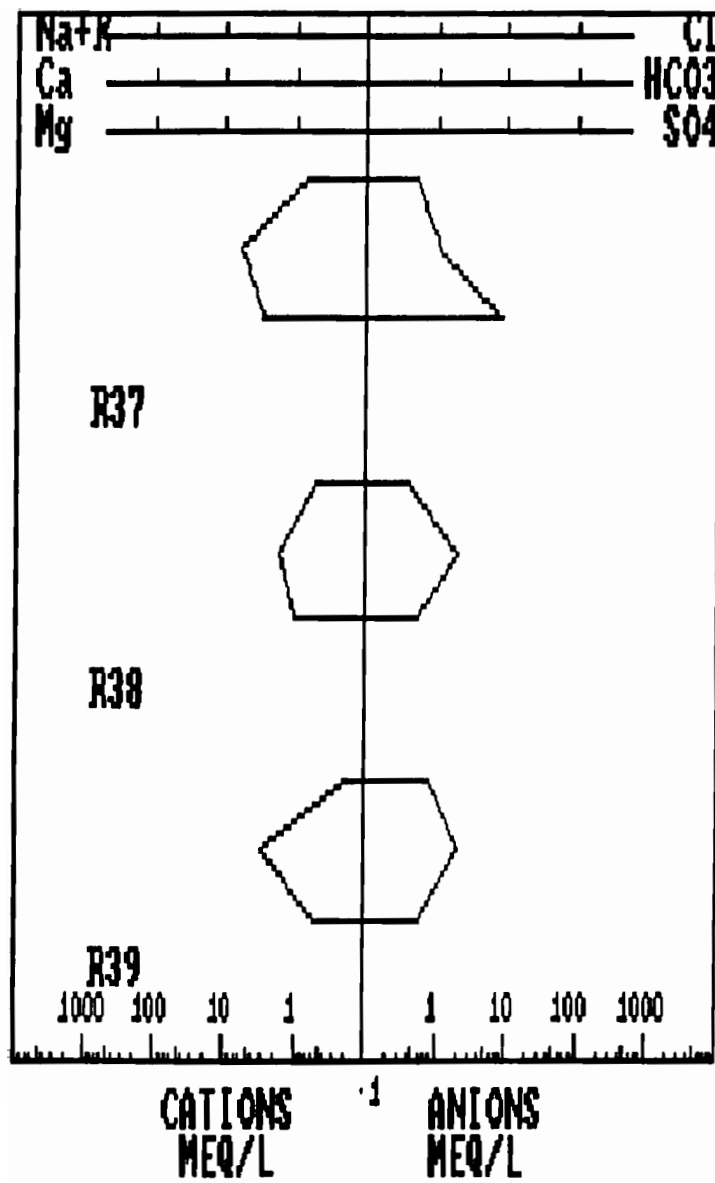




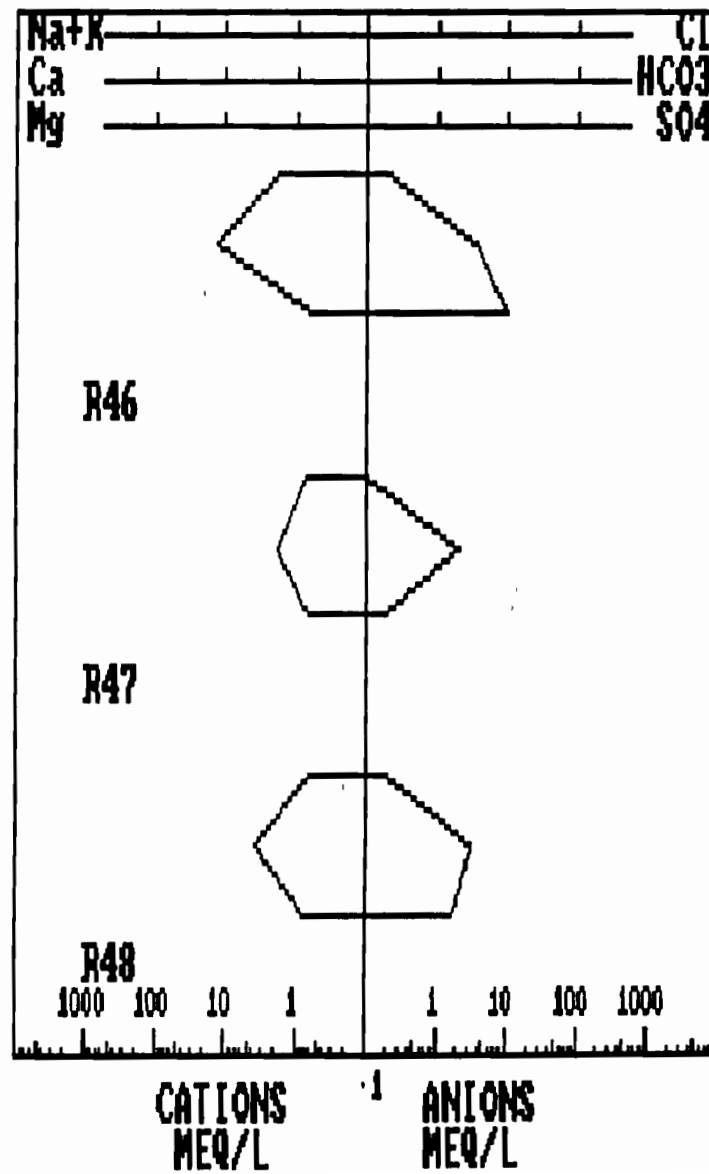
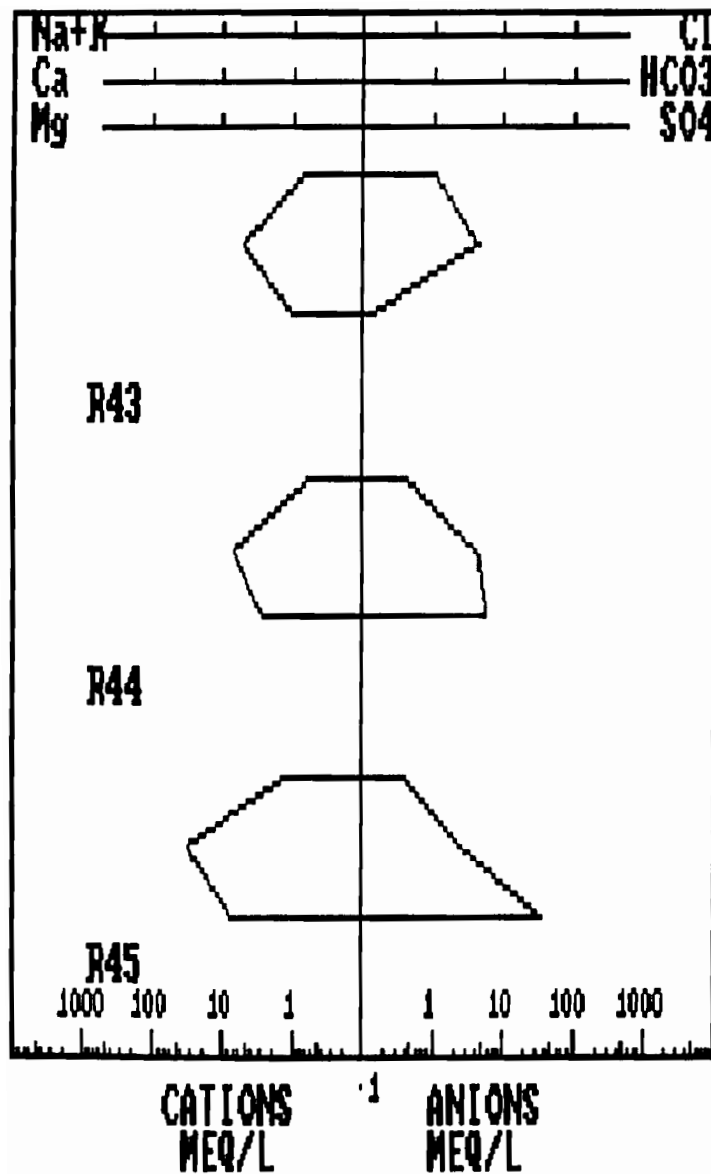


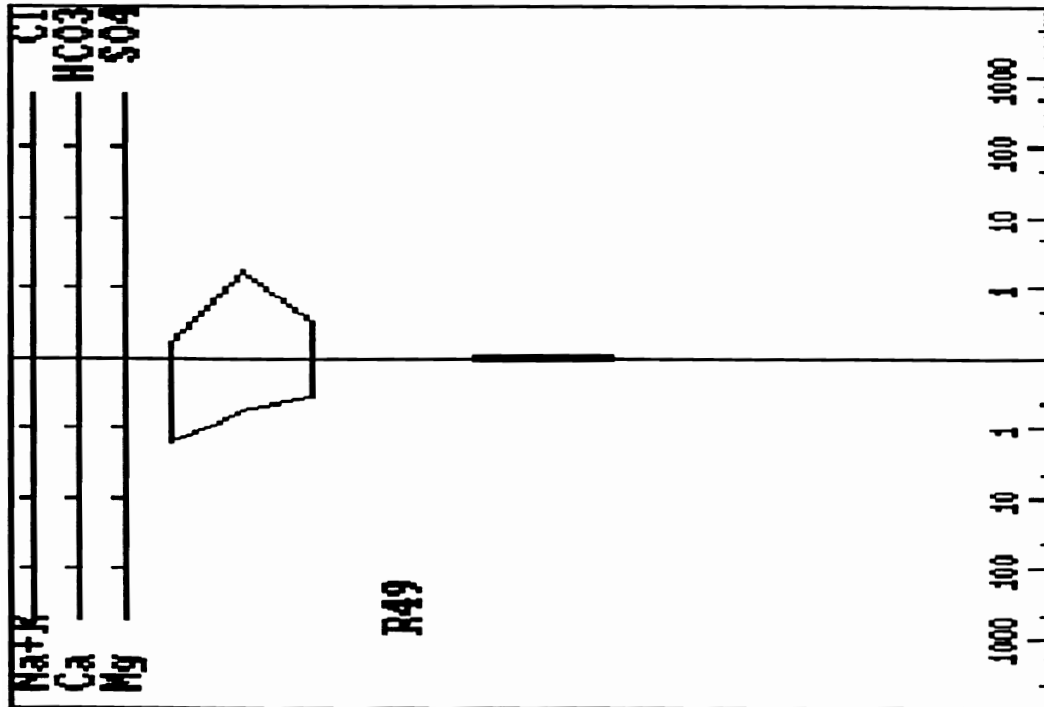
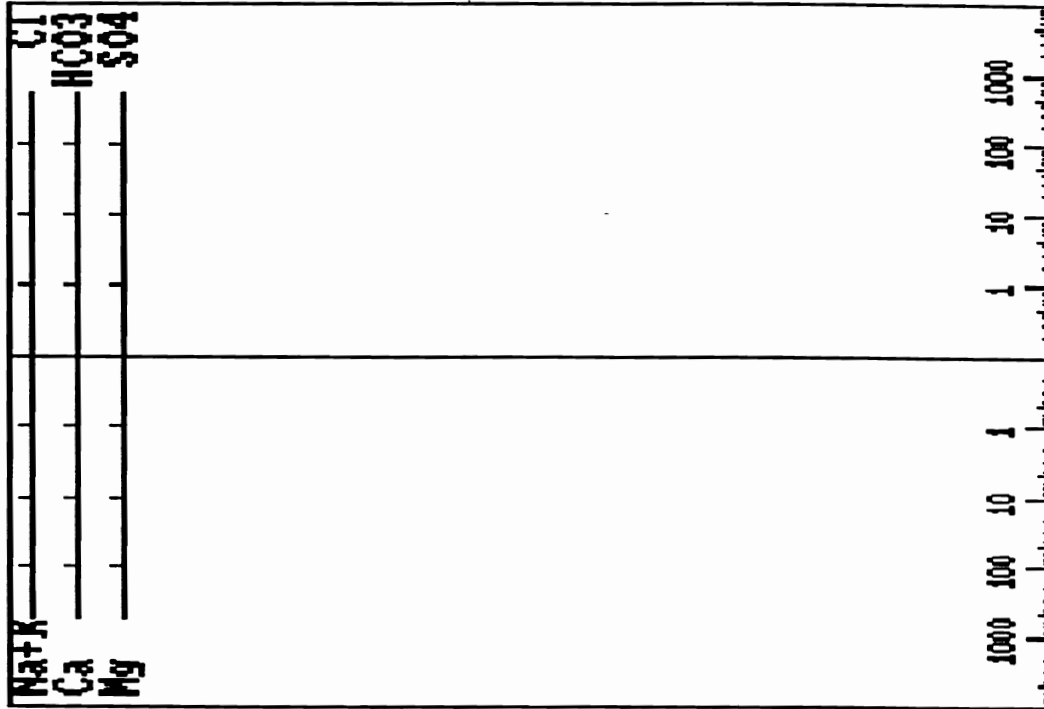


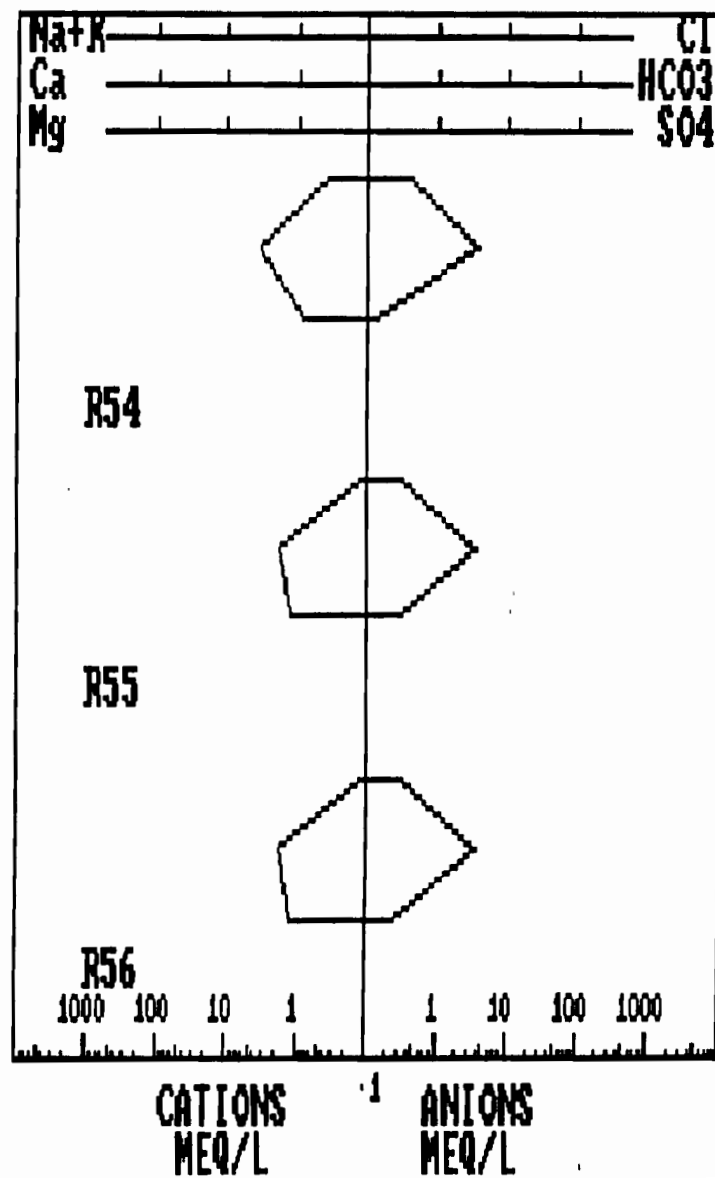
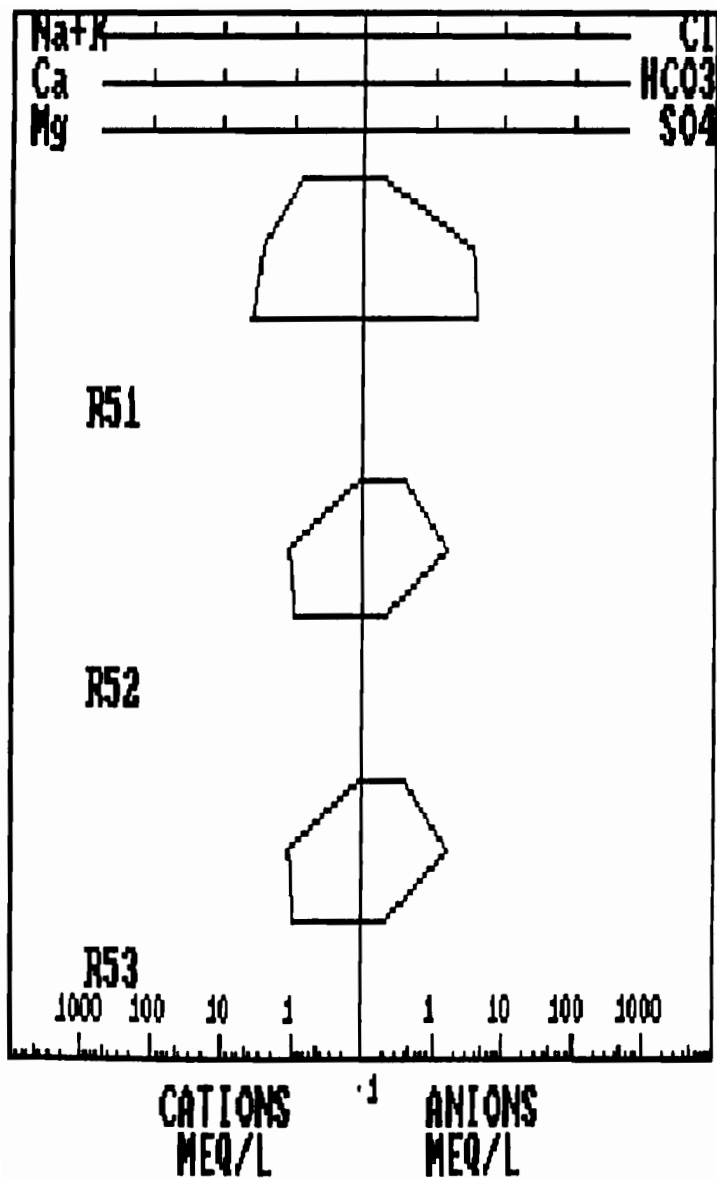


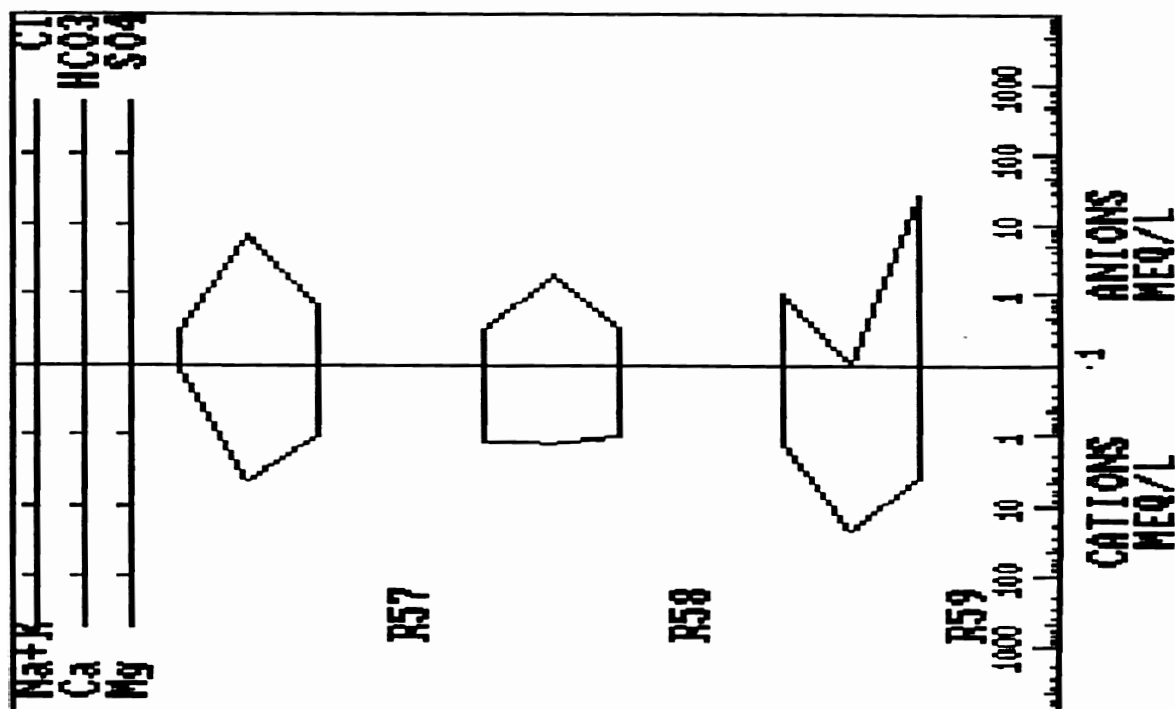
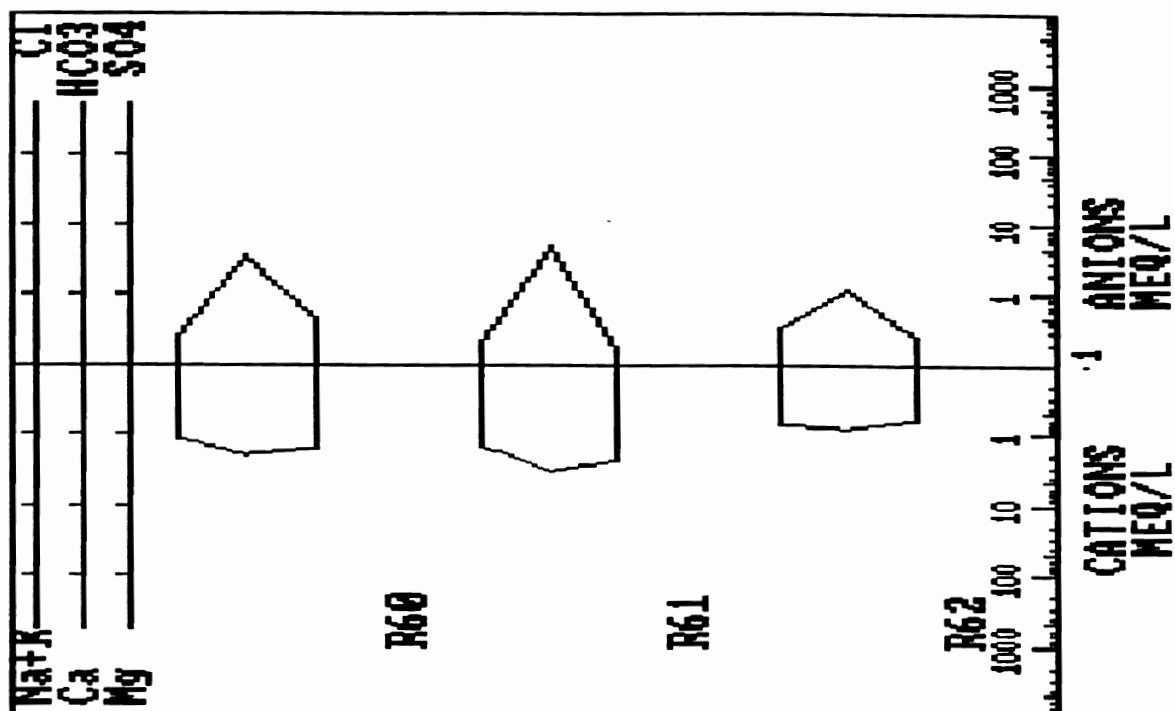


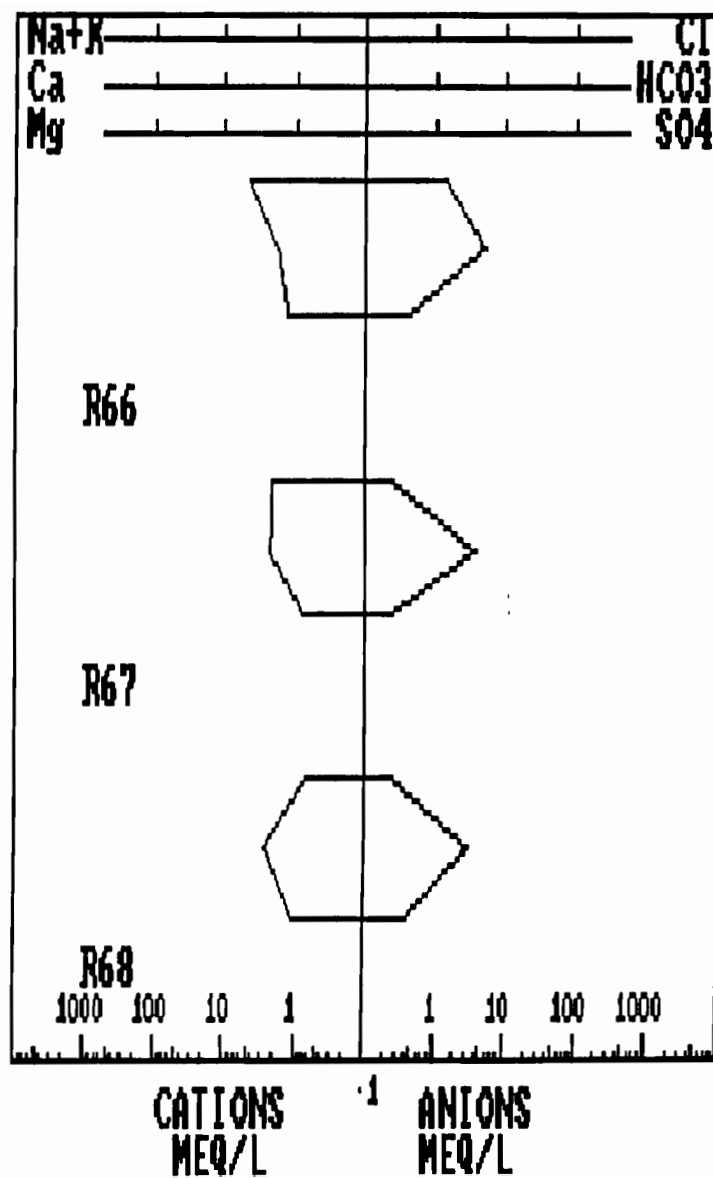
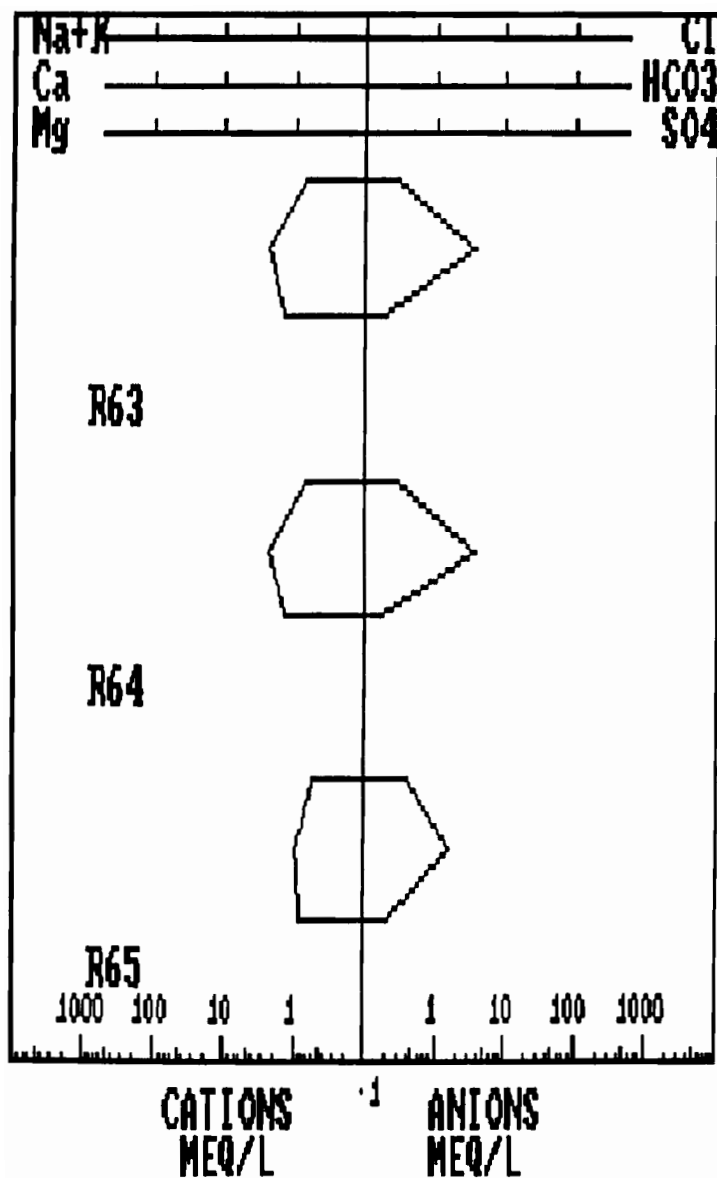


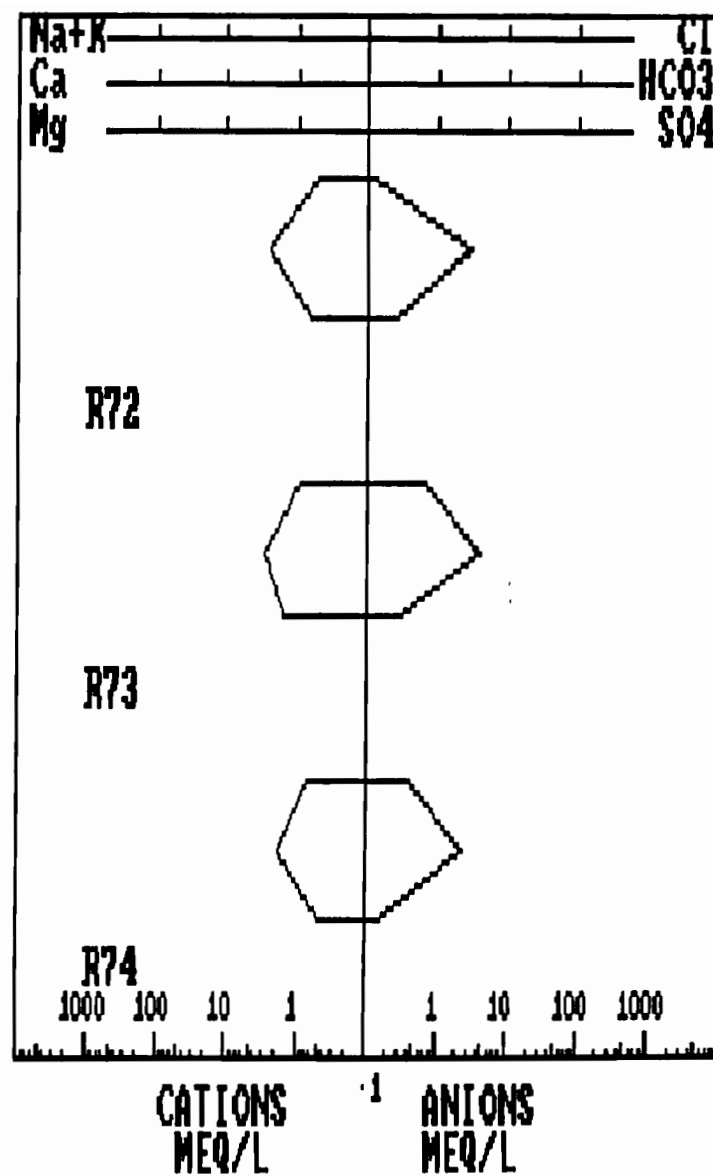
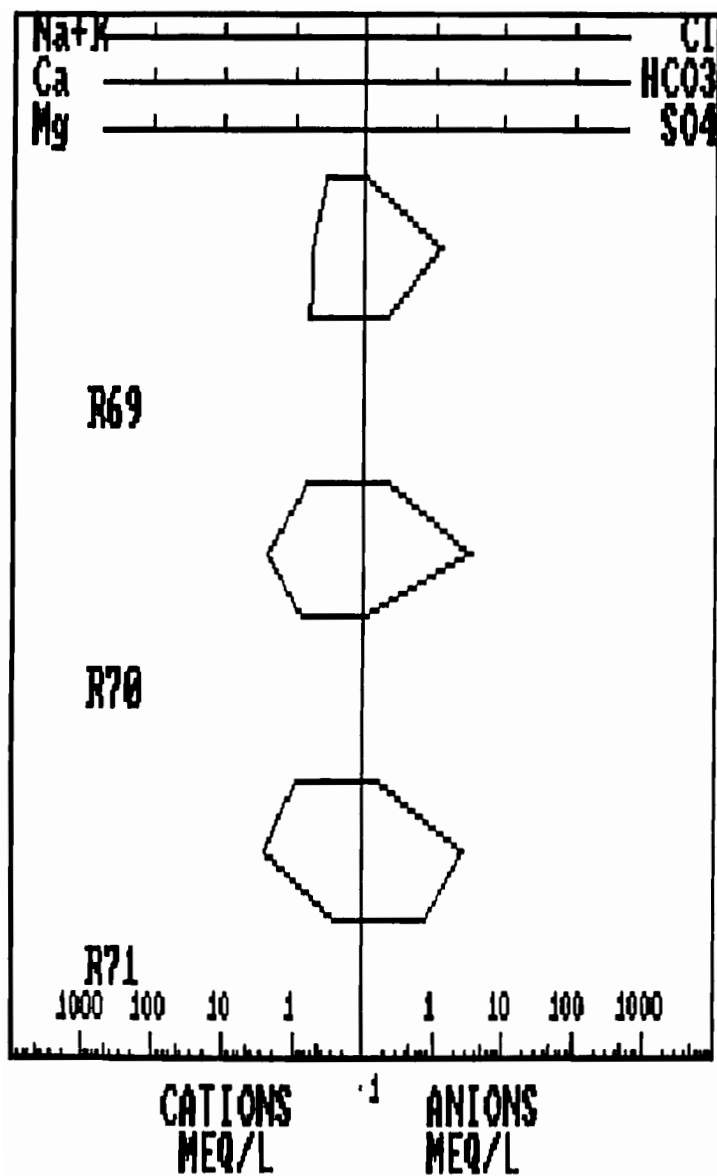


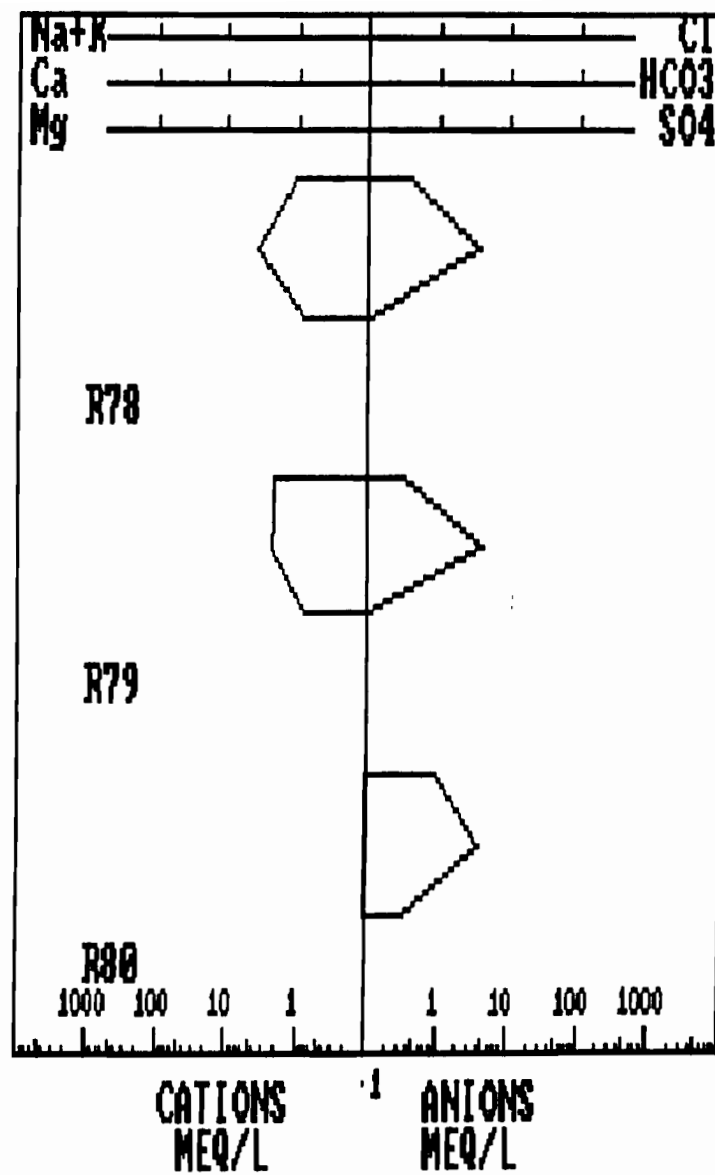
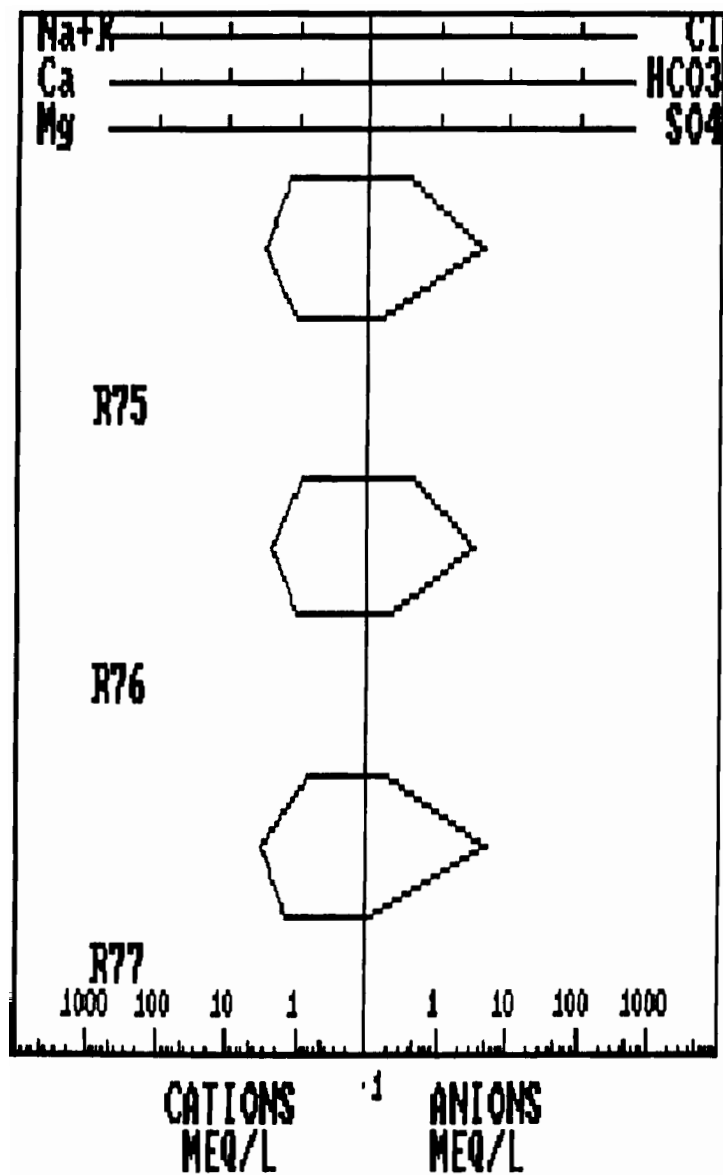


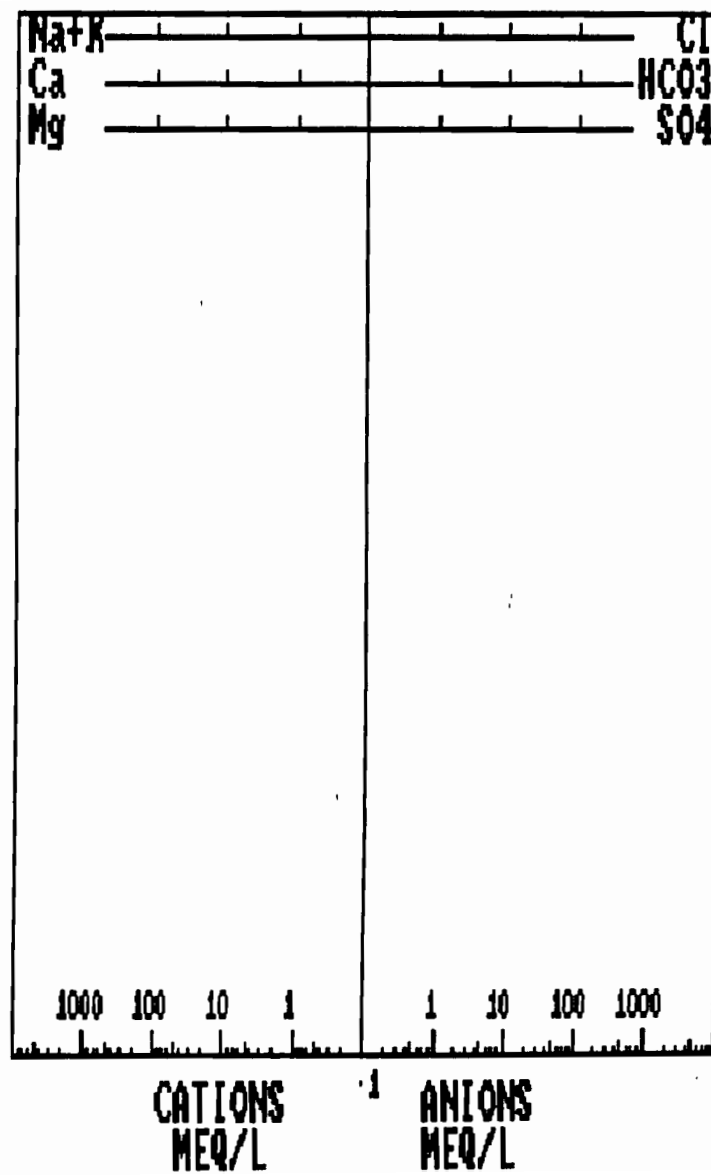
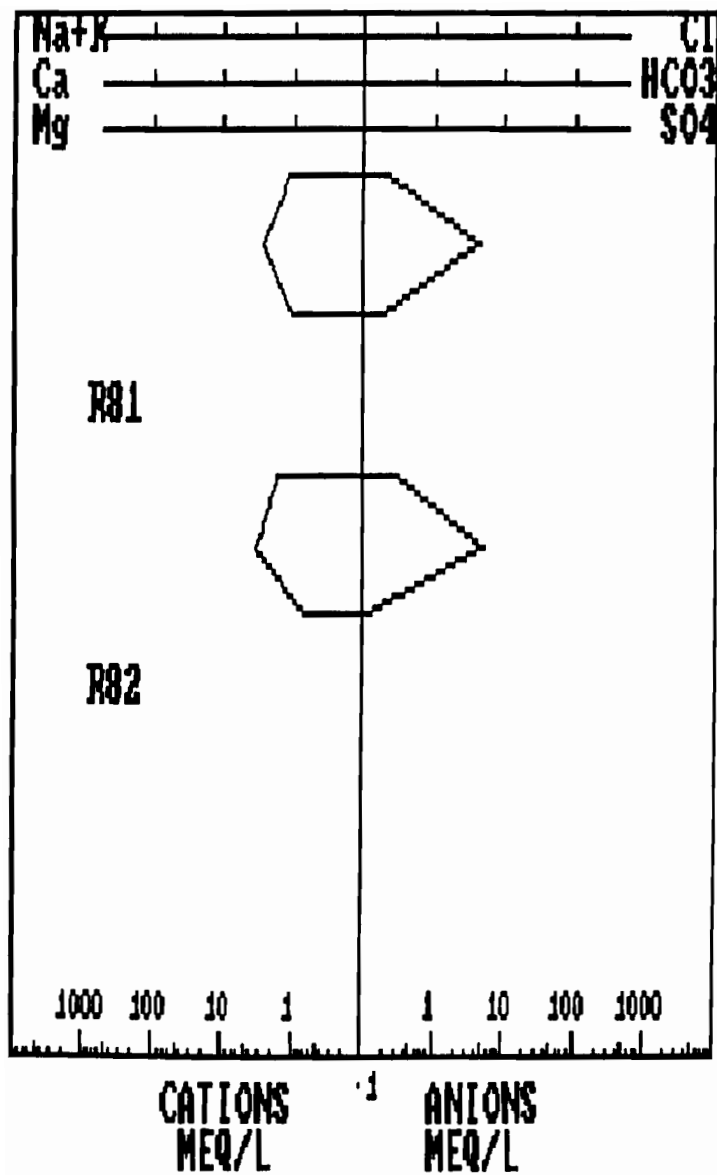














# VITA 2

Paul S. Johnstone

Candidate for the Degree of

Master of Science

**Thesis:** ENVIRONMENTAL EFFECTS OF OILFIELD OPERATIONS  
AND SECONDARY RECOVERY IN THE CEMENT FIELD,  
CADDO COUNTY, OKLAHOMA

**Major Field:** Geology

**Biographical:**

**Personal Data:**

Born in Burbank, California, June 13, 1950, the son of Paul M. and Joan C. Johnstone.

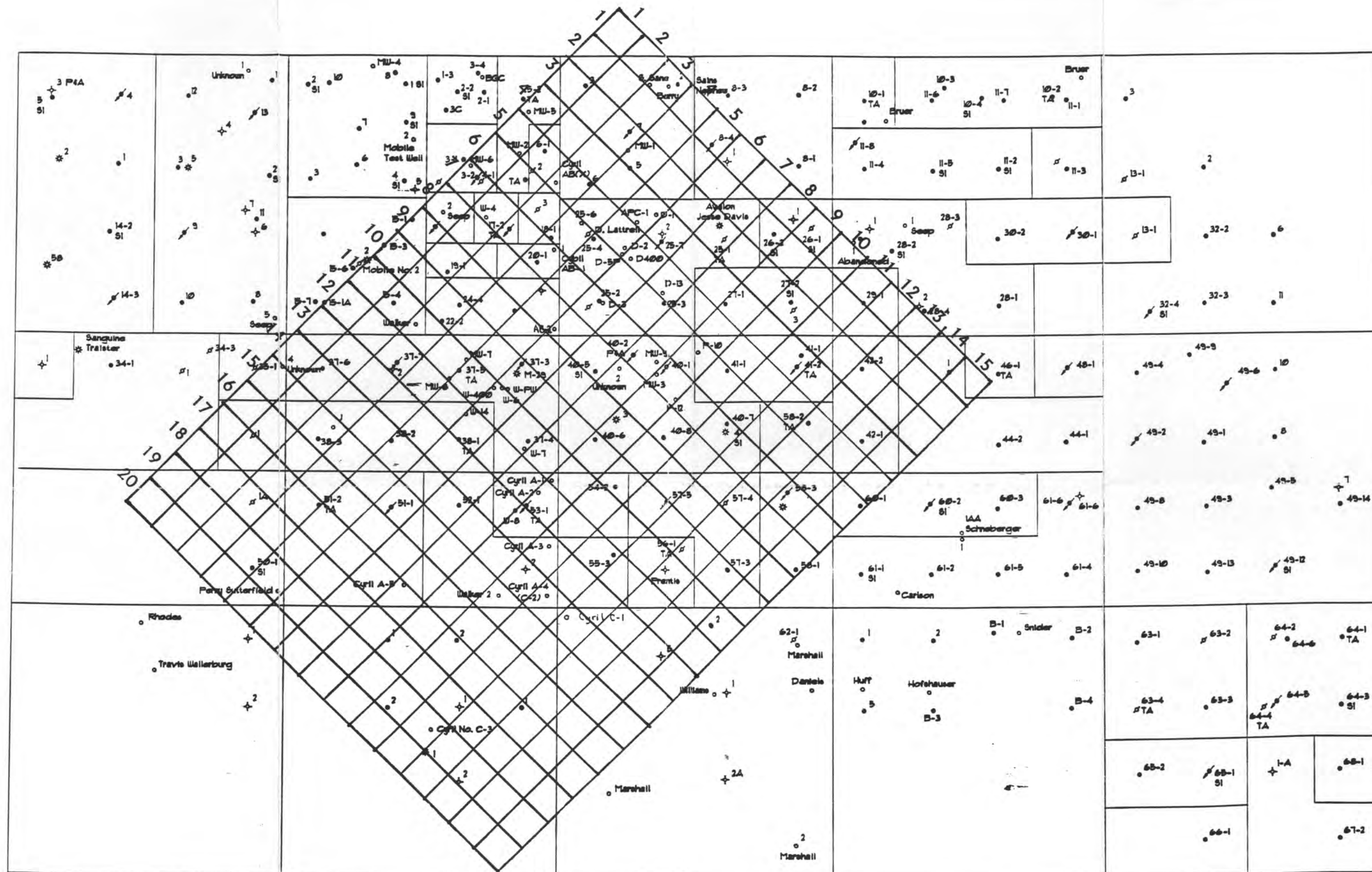
**Education:**

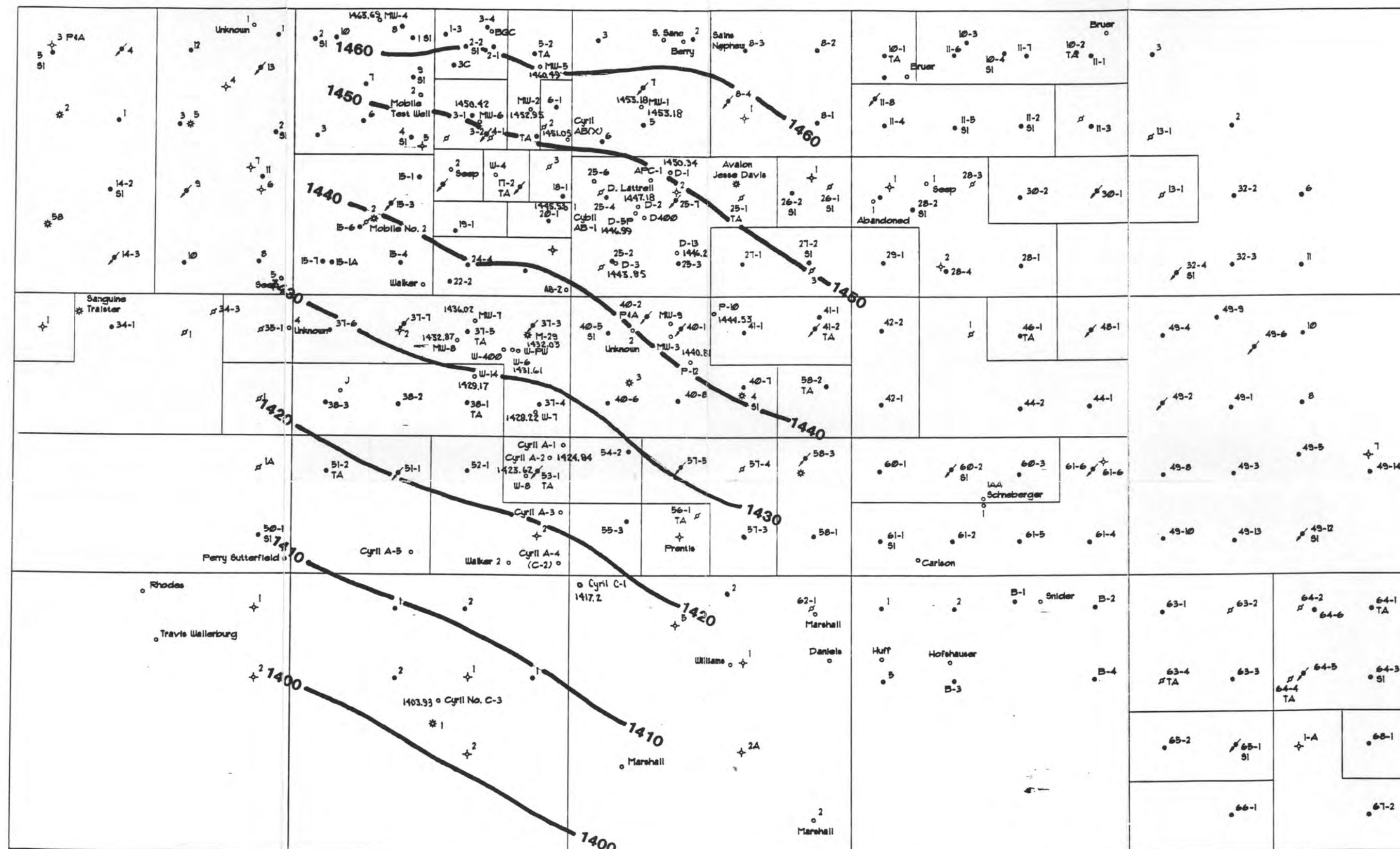
Graduated from Coral Gables Senior High School, Coral Gables, Florida, in June 1968; received Bachelor of Science Degree in Geology from Duke University in May 1972; attended University of New Mexico in Albuquerque, New Mexico from September 1973 to June 1974, no degree received; completed requirements for the Master of Science degree at Oklahoma State University in December, 1995.

**Professional:**

Senior Hydrogeologist, Law Engineering, Inc., Greenville, South Carolina, September 1992 to present; Teaching Assistant, Department of Geology, Oklahoma State University, January, 1992, to August, 1992; President, Oak Cliff Operating Company, November, 1986, to September, 1991; Vice President, Shanley Oil Company, November, 1985, to November, 1986; Consulting Geologist, July, 1984 to November, 1985; Vice President Exploration, Trans-Western Exploration, Inc., September, 1978, to July, 1984; Geologist, Trans-Western Exploration, Inc., December, 1977, to September, 1978; Geologist, Cities Service Oil Company, June, 1974, to December, 1977.

Figures 20, 21,  
22, and 26.





DRAWN	DATE	REVISIONS		
		No.	DESCRIPTION	BY
JOHNSTONE	11/2/95			

WATER TABLE ELEVATION CONTOUR MAP  
STUDY AREA  
CADDO COUNTY, OKLAHOMA





