HYDROGEOCHEMICAL INTERPRETATION OF GROUND WATER IN THE OGALLALA AQUIFER, OKLAHOMA PANHANDLE

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INTRODUCTION

Purpose and Scope

The purpose of this thesis was to examine the hydrogeochemistry of the Ogallala aquifer, in the Oklahoma Panhandle, and relate water chemistry to the hydrogeologic setting of the region, rock-water interactions and chemical processes occurring within the system. Physical factors of the system such as the mineralogy of the Ogallala and underlying formations, and cross-formational flow from Pre-Tertiary bedrock into the Ogallala Formation are theorized as being primary factors which influence water chemistry. This project will also attribute water chemistry to chemical processes in the system such as dissolution or precipitation of minerals, cation exchange, and dedolomitization.

The major assumption and hypothesis during this project is that the chemical composition of ground water within the Ogallala aquifer is influenced by the dissolution of soluble minerals which exist in underlying bedrock. There exists substantial documented geologic situations which show that the evaporites and carbonates, which underlie the Ogallala, (especially in Permian formations) have undergone dissolution in the past and continue to do so presently.

Background information on the geology and hydrogeology was obtained by conducting a thorough literature review including : U.S.G.S., Oklahoma, Texas and Kansas Geological Survey documents, theses, dissertations, journals and periodicals.

Chemical analyses were obtained predominantly from the U.S.G.S. file HYDRODATA on CD-ROM, and also from U.S.G.S., Oklahoma Geological Survey, and Oklahoma Water Resources Board publications and documents.

The analyses were checked via the computer program WATEVAL (Hounslow and Goff) to ensure their integrity. WATEVAL calculates a cation-anion balance. If all ions in solution are accounted for, every analysis should have a balance of zero percent difference. Analyses with a cation-anion balance of greater than plus or minus 5 % were viewed as invalid and discarded. After duplicates and poor analyses were discarded the data base contained 375 analyses. The author believes the data base collected for this project to be more complete and more reliable than the any data base used previously within the study area.

Location

The area of study lies within the High Plains Aquifer. The High Plains Aquifer underlies about 174,000 square miles in parts of Colorado, Kansas, Nebraska, New Mexico, Texas, South Dakota, Wyoming and Oklahoma (Figure 1). The study area includes Cimarron, Texas, and Beaver counties which together comprise the Oklahoma Panhandle. The study area is in extreme northwest Oklahoma and encompasses 5,680 square miles (Figure 2).

Figure 1. Location and areal extent of the High Plains Aquifer. (from Havens 1982) Study area is shaded.

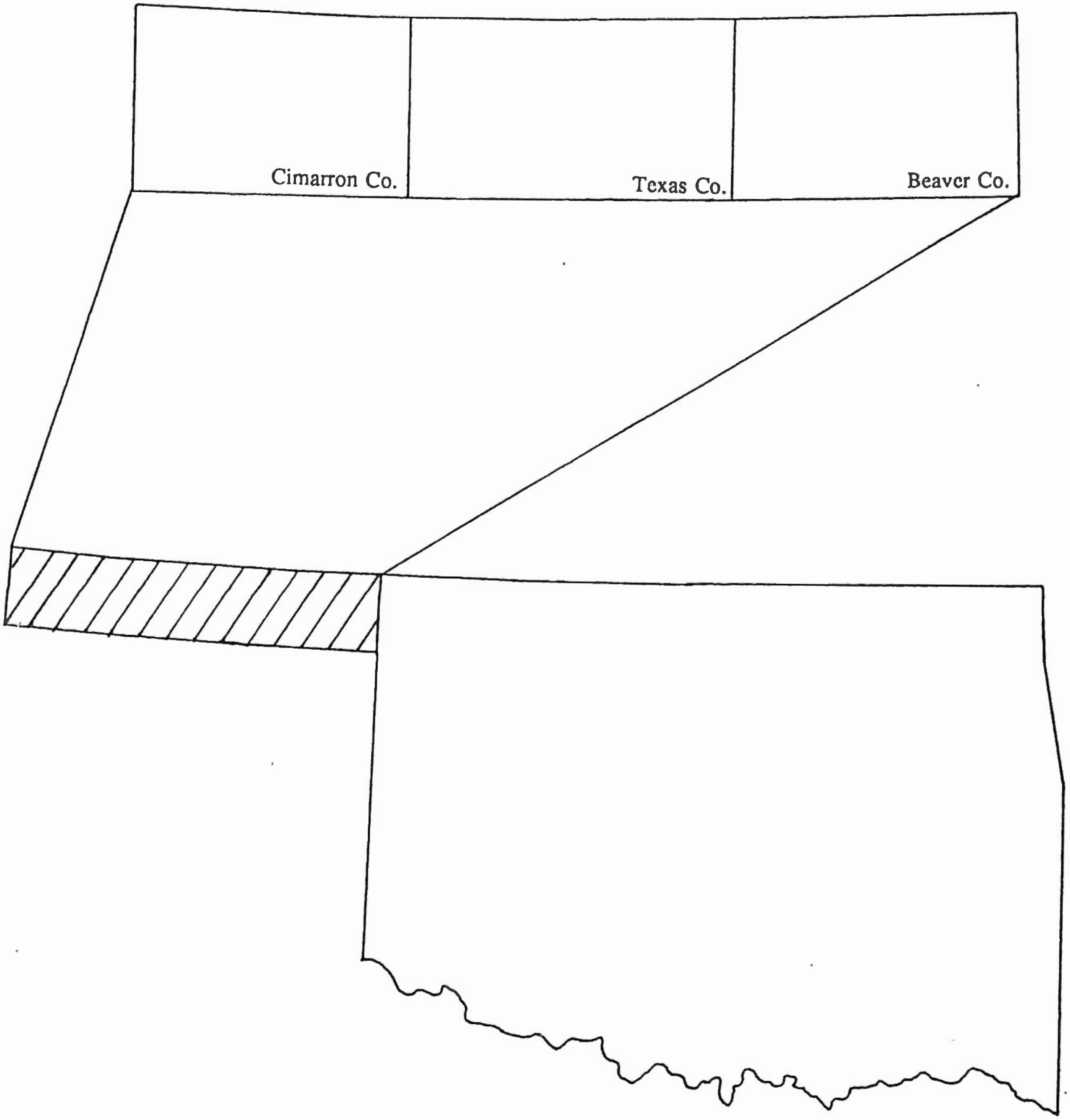


Figure 2. Study Area

Physiography

The High Plains occupies the southern part of the Great Plains physiographic province between the Rocky Mountains to the West and the Central Lowland to the East (Figure 3). The region extends from southern South Dakota to northwest Texas. The High Plains is characterized by flat to gently rolling terrain, which is a remnant of a vast alluvial fan, formed by sediments that were deposited by streams which flowed eastward from the Rocky Mountains. Erosion isolated most of the plain from the mountains and formed escarpments that typically mark the boundary of the High Plains. The Oklahoma Panhandle is an eastward-sloping plateau. The highest elevation of 4978 ft. is in northwest Cimarron County and lowest elevation of 1517 ft. is along the eastern margin of Beaver County. The average slope of the plateau is 14 feet per mile (U.S.G.S. WRI 25-75).

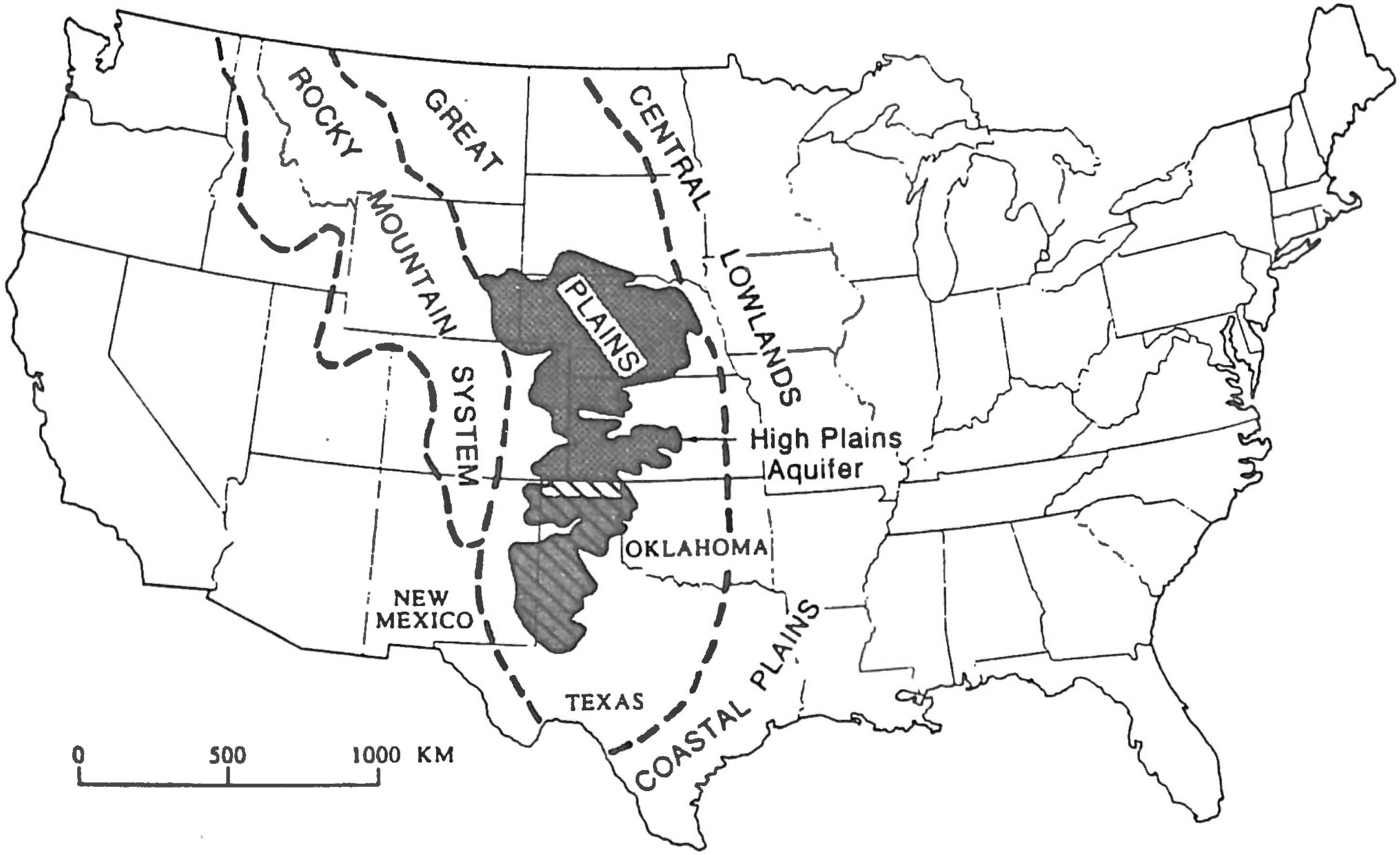


Figure 3. Location of the High Plains Aquifer and Physiographic Provinces. (from Johnson, 1991).

CHAPTER II

HYDROLOGIC SETTING

The Ogallala aquifer is the most productive, and reliable aquifer within the study area. The Miocene-Pliocene Ogallala Formation is the dominant formation in the aquifer. Mesozoic aquifers exist from central Texas County westward. These other aquifers are sandstones within the Triassic, Jurassic and Cretaceous systems. However, due to the limited yields of these aquifers and their questionable water quality they are not significant and are not a major topic of this research project.

The Miocene-Pliocene Ogallala aquifer is primarily unconsolidated clay, sand and gravel overlain by Quaternary alluvium and eolian deposits. The Tertiary deposits are hydraulically connected with overlying Quaternary alluvium and eolian deposits and the both are in effect one unconfined to semi-confined hydrogeologic system. The Tertiary and Quaternary deposits lie disconformably upon Permian through Cretaceous strata. The bedrock surface slopes generally east-southeast at 6-12 ft/mile or 0.1-0.2 degrees (Johnson 1991). Topography of the bedrock surface, is presented as Figure 5 (from Havens, 1981). The relief of the bedrock surface is a result of paleodrainage systems and dissolution of subsurface evaporites and resultant collapse of overlying strata. The bedrock in most areas is relatively impermeable and therefore prevents downward migration of ground water from the overlying aquifer.

The Ogallala aquifer is an unconsolidated to semi-consolidated unconfined to semiconfined system. The thickness of Ogallala deposits is related to Tertiary depositional systems such as alluvial fan lobes but the surface of the Ogallala is relatively flat. Therefore, the thickness of Tertiary and Quaternary deposits is predominantly a function of the bedrock topography, which is a function of paleodrainage patterns and the location of collapse and subsidence features.

The configuration and elevation of the water table is directly related to the slope of the underlying bedrock, which slopes to the east-southeast. The water table elevation also decreases to the east-southeast, implying that is also the general direction of ground-water movement. The configuration and elevation of the water table is shown in Figure 4 (from Havens, 1982).

The average hydraulic conductivity of the Ogallala aquifer in Oklahoma, Texas and New Mexico is about 62 ft/d, with values as high as 197 ft/d in areas. Higher hydraulic conductivity values mainly being along the paleovalleys (Johnson, 1989).

The average the specific yield of the Ogallala aquifer in the three-state region is from 5-25% with most areas being 10-20% (Johnson, 1989).

Recharge of the Ogallala aquifer is predominantly due to direct precipitation on its surface. The unconsolidated eolian mantle is an important aid in the recharge process. The eolian mantle allows quick and deep infiltration thus preventing evaporation or runoff. Other sources of recharge include playa-lake seepage, stream seepage, and upward flow from underlying strata. Most estimates of recharge range from .2 to .5 inches/yr (Johnson, 1989).

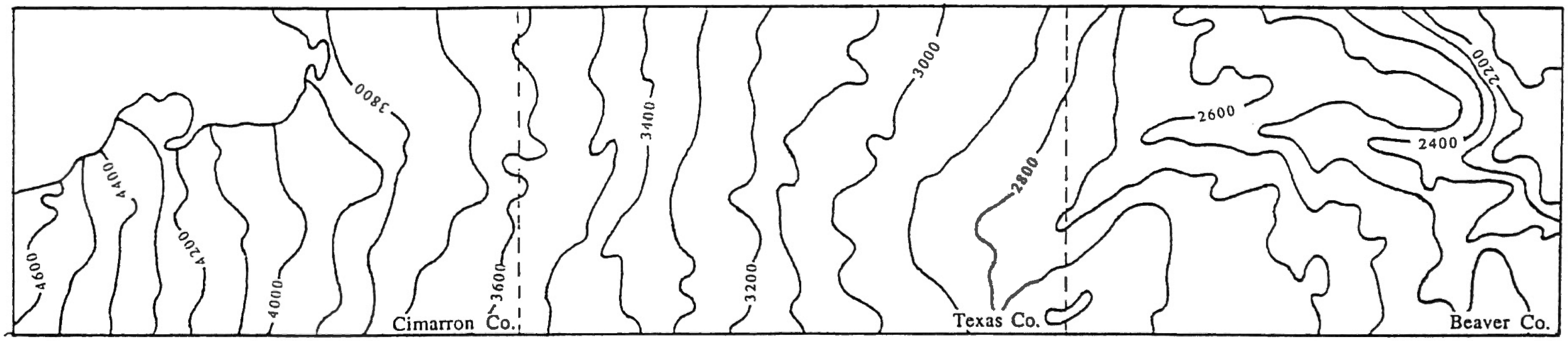


Figure 4. Altitude and Configuration of the Water Table in the High Plains Aquifer, Oklahoma Panhandle (modified from Havens, 1982).

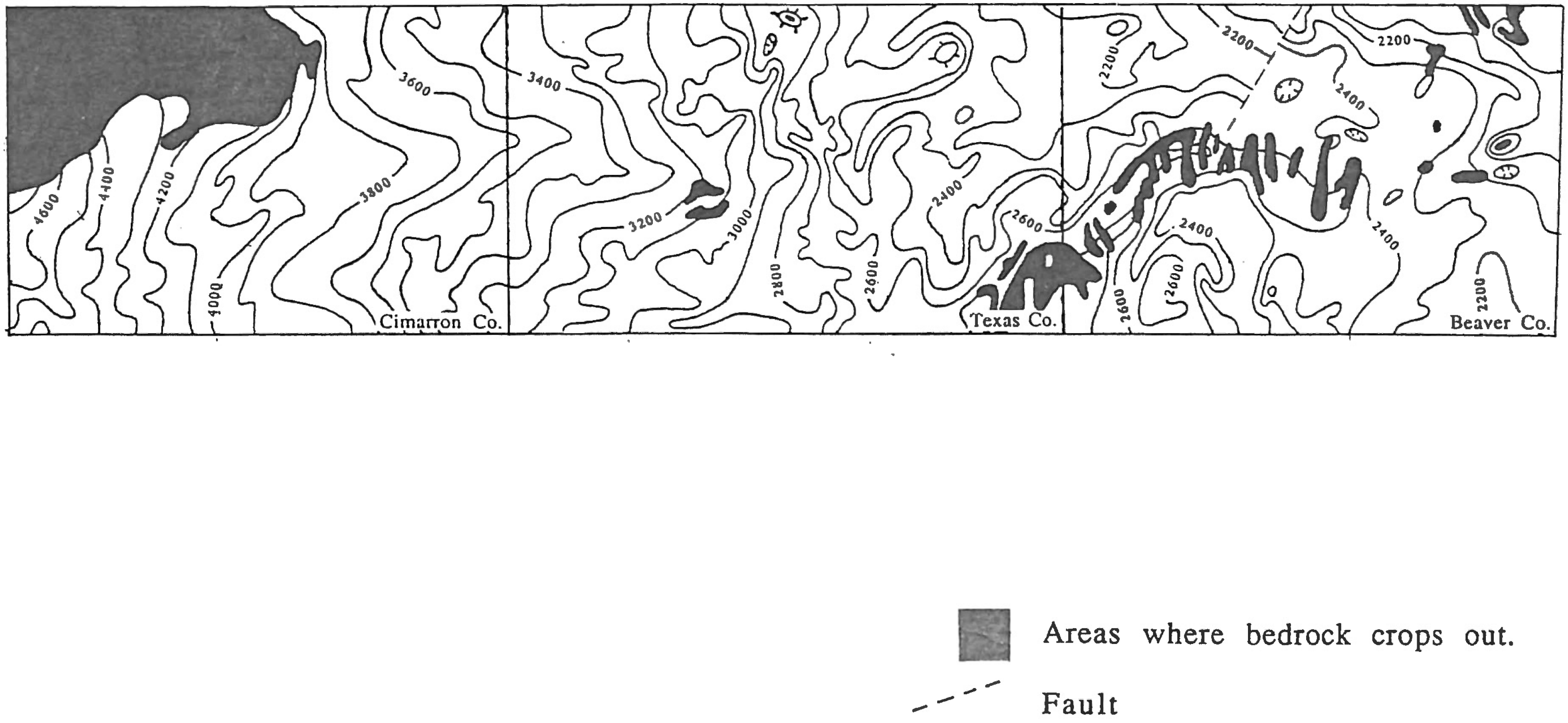


Figure 5. Altitude and Configuration of the Base of the High Plains Regional Aquifer, Oklahoma Panhandle (modified from Havens, 1981).

CHAPTER III

PREVIOUS INVESTIGATIONS

Because this is not a field-oriented project, previous investigations have proved vital for the author's becoming familiar with the regional and local geology.

Previous investigations are referenced throughout this report. In order to substantiate the hypothesis, this chapter discusses investigations which document the hydrogeologic interactions between underlying bedrock and the Ogallala aquifer.

Geologic studies performed within the study area and surrounding areas of Oklahoma, Texas and Kansas have documented situations that led to the principal working hypothesis of this project; bedrock effects the chemistry of ground water within the overlying Ogallala aquifer.

Previous work by Johnson, 1989; Nativ, 1988; Gustavson, 1986; Hart et al., 1975; Irwin and Morton, 1973; and Krothe and Oliver, 1982; has shown evidence that highly soluble carbonates and evaporites, which exist in the Permian System, have influenced the chemistry of water within the Ogallala aquifer and of surface waters, outside the study area. These works imply that this process is active in the Oklahoma Panhandle but do not directly provide evidence proving it. In the authors opinion, this evidence is formidable, but does not require the rejection of alternate hypotheses. The purpose of this endeavor is to acquire and evaluate evidence in a manner such that the principal working hypothesis or the set of alternate hypotheses is rejected.

It is commonly acknowledged that dissolution of carbonates and evaporites (predominantly Permian) occurred before, during and after deposition of the Miocene-Pliocene deposits. The location and thickness of these soluble beds along with paleotopography dictated the locality of the thickest Ogallala deposits.

Krothe and Oliver (1982) studied the ground-water chemistry of the Ogallala Formation in the Oklahoma Panhandle and southwest Kansas. They noticed that the concentration of dissolved solids increased in the direction of flow, which is from west to east. This could possibly be due to residence time, but knowing that the aquifer contains no highly soluble minerals they dismissed this possibility. Krothe and Oliver decided that the underlying bedrock appears to control ground-water chemistry within the Ogallala aquifer. The Ogallala is underlain by Triassic-Cretaceous rocks in the western half of the study area and Permian rocks in the eastern half of the study area. The mean total dissolved solids value in ground water from Triassic-Cretaceous rocks is 552 mg/L and Permian rocks is 4720 mg/L. The mean TDS value for water in the Ogallala Formation is 396 mg/L where it directly overlies Triassic-Cretaceous rocks and 569 mg/L where it overlies Permian rocks. Krothe and Oliver concluded that the Permian bedrock has a profound influence on the ground-water chemistry within the Ogallala aquifer.

Gustavson (1986) showed that the dissolution of Permian salt within 1300 feet of the surface resulted in as much as 600 feet of non-tectonic vertical displacement of strata in parts of the Texas and Oklahoma Panhandles and in New Mexico. Gustavson showed that dissolution and subsidence have occurred since the Cretaceous, and are active today along the western, northern and eastern escarpments of the Ogallala aquifer.

Plates 1 and 2 show and numerous authors explain that the regions with the thickest deposits of Tertiary and Quaternary deposits are associated with locations of salt dissolution and collapse of bedrock. Thus, dissolution and removal of evaporites and carbonates within the bedrock influenced bedrock configuration and elevation, paleodrainage patterns, sites of thick Ogallala deposits, and present saturated thickness.

Thick accumulations of Ogallala deposits in the eastern half of Texas County occupy a depression on the Permian surface believed to have been caused by solution and removal of the Flowerpot Salt. The Flowerpot Salt has not been removed beneath Beaver County and as a result the Permian bedrock surface is higher (U.S.G.S. Circular 630).

Dissolution of evaporites and carbonates, due to ground-water circulation, also continued after deposition of the Ogallala causing the Permian and Ogallala deposits to collapse into the voids. Thus, the Ogallala-Permian contact has collapse features which formed before, during and after deposition of the Ogallala.

Many formations within the Permian System originally contained soluble minerals that have since been dissolved. The Flowerpot Salt is documented as being the primary formation which underwent substantial dissolution in areas causing the overlying formations to collapse into the voids (Johnson, 1981). Thus, many of the areas of relatively thick Tertiary deposits are considered to be a result of either paleotopography or dissolution of the Flowerpot Salt or both. Situations such as described above are documented by Nativ, 1988; Weeks and Gutentag, 1984; Gustavson et al.,1981; Gustavson, 1986; Kastner, 1984; Reeves, 1984; Johnson, 1981; Hart et al., 1975; and Oklahoma Geological Survey Bulletins 59, 64, and 97.

The Flowerpot Salt is documented as undergoing "interstratal karst" in northern Texas Panhandle, just south of Texas County, Oklahoma by Johnson, 1989. That is, dissolution and removal by ground water occurring in a formation that is in the subsurface. Johnson showed that the Flowerpot ranges in thickness from 0-352 ft., and stated that this is predominantly due to dissolution of the Flowerpot and resultant subsidence and collapse of overlying formations.

The above mentioned hydrogeologic interactions between the Ogallala and underlying formations provide evidence that substantiates the hypothesis that lithologies of underlying formations do influence the ground-water quality of the Ogallala aquifer.

In order for the dissolution of surface or subsurface minerals to occur there are four basic requirements. The mineral deposit must be in contact with water and the water must be unsaturated with respect to the ions of the mineral with which it is in contact. The newly formed solution must be able to escape the system. Enough energy must exist (such as hydrostatic head) to cause the flow of water through the system. If the water cannot circulate through the system it will become saturated and the dissolution process will be stopped, Johnson (1981).

In western Oklahoma, ground water which dissolves the evaporites is typically recharged from the Ogallala Formation Johnson (1981). The water migrates downward and laterally to salt deposits which are 30-800 ft. beneath the surface, and dissolves the salt. The resultant brine is then forced laterally and upward by hydrostatic pressure through aquifers or fractures in aquitards until it is discharged at the surface.

The dissolution of salt is a self-perpetuating cycle. Salt dissolution results in subsidence, collapse and fracturing of overlying strata. The resulting disrupted bedrock has a greater vertical permeability that allows increased water percolation and additional salt dissolution Johnson (1981).

Lines of evidence which support the hypothesis that evaporite and carbonate dissolution is ongoing underneath parts of the Southern High Plains include: (1) The major streams draining the region carry high solute loads. (2) Brine springs, salt springs and salt pans appear along major stream valleys and throughout the Permian Basin, especially where the Ogallala is absent. (3) Abrupt loss of salt sequences between closely spaced oil and gas wells indicate salt dissolution. Structural collapse of overlying sediment is evident in wells where salt is missing. (4) Numerous sinkholes and closed depressions (dolines) have formed recently at the Ogallala surface as a result of dissolution of Permian strata Gustavson (1986).

Johnson's 1981 report covers three areas, none of which is in this project's study area. Also, none of these sites are in locations where the Ogallala exists. The study by Johnson is pertinent because the study areas are currently undergoing salt dissolution from the same geologic formations which exist beneath the Ogallala within this project's study area.

By calculating the ratios of ions Johnson (1981) presents several lines of evidence not presented by Gustavson (1986) which indicate salt is being, or has been dissolved. (1) The Na^+/Cl^- (mg/L) ratio of brines suspected of being from salt dissolution is very close to .64. If pure halite is dissolved its Na^+/Cl^- ratio is .65. Brines from oil-field formations commonly have a Na/Cl ratio of .55 or less. (2) Cavities, caverns or other openings in salt beds are evidence of past or present dissolution. (3) The occurrence of low-salinity to saturated brines in aquifers that do not contain salt interbeds may indicate salt dissolution where there is an appropriate Na/Cl ratio.

Johnson (1989) presented surficial structural evidence that dissolution and land subsidence is a very young geologic process. The caliche caprock, which is a common lithified surficial feature of the Ogallala is typically flat with relatively no dip. This indicates that most dissolution and disturbance occurred more than several million years ago, prior to the development of the caprock. However, at two places in Johnson's study area the caprock is sharply folded into troughs or basins. This provides further evidence that subsidence has occurred since the development of the caprock which is believed to have formed 3.5-2.4 mya (Johnson, 1989).

Kastner (1984), Weeks and Gutentag (1984), Krothe and Oliver (1982), Nativ (1988), and Hart et al. (1975) documented that either highly mineralized ground water within underlying formations is moving into the Ogallala or recent dissolution of soluble lithologies is affecting the chemistry of the groundwater within the Ogallala. Kastner (1984) stated that "Within areas of the Texas and Oklahoma Panhandles highly mineralized water from lower formations moves into the Ogallala aquifer." Kastner explained that artificial lowering of the water table in the Ogallala can cause the hydraulic head of water in the underlying formations to be greater than the hydraulic head of water in the Ogallala thus inducing highly mineralized ground water to move into the Ogallala. Nativ (1988) showed that, within the Texas Panhandle, geochemical similarities between ground water in the Ogallala and that of underlying aquifers implies cross-formational flow. Weeks and Gutentag (1984) stated that where the water contains more than 500 mg/L of dissolved solids, the water quality is probably affected by the bedrock.

Nativ (1988) showed that water chemistry along paleovalleys is relatively consistent because of a higher percentage of coarse sediments, increased thickness, and increased saturated thickness. Nativ believed that within the paleovalleys the thick saturated section helps to mask other recharge sources which may affect the chemical and isotopic composition of the groundwater. Nativ showed that in paleodivide areas the groundwater chemistry is highly variable. Nativ explained that the thin saturated section cannot mask local sources of ions. He also explains that in paleodivide areas the sediments are commonly finer grained; thus, residence times of ground water is longer and chemical composition more closely reflects local lithologies. Nativ (1988) also showed that "hydrochemical facies" are aligned from northwest to southeast within the Texas Panhandle. This alignment follows paleodrainage systems and groundwater flow paths. The work by Nativ shows that the chemical composition of groundwater within the Ogallala can be a function of thickness of saturated section and porosity and not entirely a function of underlying lithologies.

Krothe and Oliver (1982) suggested that high total dissolved solid (TDS) values and contamination could be due to ground water flow up through fractures associated with faults in the underlying bedrock. Krothe and Oliver used isotopic studies to suggest that not all sulfate is from the dissolution of gypsum but possibly from sulfate reduction in Permian brine formations. They proposed that movement of hydrogen sulfide through fractures and the oxidation to sulfate within the Ogallala Formation resulted in the sulfate having a lighter sulfur isotope than sulfate from gypsum.

Stratigraphic studies indicate that dissolution occurred before or during deposition of the Ogallala. Surface water chemistry and features imply that dissolution is still active. It has been implied by previous investigations that the ground-water chemistry in the Ogallala aquifer is influenced by this dissolution or "cross-formational flow." It is the goal of this thesis to show whether dissolution of Permian evaporites and carbonates and subsequent cross-formational flow are influencing the chemistry of ground water in the Ogallala aquifer in the Oklahoma Panhandle. Also, to define other physical and chemical factors which influence ground water chemistry.

CHAPTER IV

GEOLOGIC SETTING

It is the assumption of this report that the oldest strata which have any effect on the ground-water chemistry of the Ogallala aquifer are Permian in age. Therefore, bedrock older than Permian will be ignored in this report.

The Oklahoma Panhandle lies within the Permian Basin. The Permian Basin is not a single structural basin but is a large region of the southwest United States in which Permian salts and other evaporites were deposited with red beds and carbonates.

During the Early Permian the Oklahoma Panhandle was part of an epicontinental sea. Permian red beds and evaporites were deposited in an extensive shallow, brackish to saline sea subject to periodic influxes of marine water. The epicontinental seas were bounded to the West by the Sierra Grande Arch of northeastern New Mexico and to the South by the Wichita-Amarillo uplift. Also influencing depositional patterns is the Cimarron uplift, which is a series of elongate anticlines, extending from northeast Cimarron County southward. The major basins of the Permian influencing the study area include the Dalhart Basin and Anadarko Basin.

During Permian deposition, the sea entered this region from the South. Most of the detritus deposited in the basins was derived from the ancestral Rocky Mountains to the West and from the Amarillo-Wichita uplift to the south-southeast (McKee, 1967).

During intervals of the Permian the Oklahoma Panhandle underwent deposition of evaporites and carbonates, such as halite, gypsum, anhydrite, limestone and dolomite.

During the Triassic through Cretaceous Periods the study area underwent predominantly terrigenous clastic deposition with very little carbonates or evaporites being deposited. The clastic sediments consist of interbedded shale, siltstone, sandstone, and conglomerates.

Extensive post-Cretaceous erosion continued through the Miocene. Erosion left Permian through Cretaceous strata exposed in different areas of the study area (Plate 2). It is upon this erosional surface that the Miocene-Pliocene Ogallala Formation was deposited.

During the Mid-Late Tertiary the southern part of the Great Plains underwent terrigenous clastic deposition from numerous coalescent alluvial fans. The detritus was shed from the Rocky Mountains.

Ogallala sediments are entirely clastic except for caliche, which is a result of soil-forming processes. During the Quaternary, the Ogallala began to be dissected by erosion. At places, the erosion entirely removed the Ogallala. Also during the Quaternary, a mantle of eolian deposits, derived from recent floodplains draped much of the Ogallala. Lacustrine sediments are interbedded with the eolian deposits.

Permian System

Permian red beds underlie all of the study area and are consistently greater than 1000 feet thick (U.S.G.S. WRI 25-75). The red beds consist of dark reddish-brown terrigenous clastic deposits with grain size ranging from shale to coarse sand. Within most of the Permian red bed formations evaporites and/or carbonates are interbedded with the clastics, and occasionally the evaporites/carbonates dominate a formation.

Wellington Formation

In the study area the lowest formation of the Permian System is the Wellington Formation. The Wellington Formation typically is made up of a lower halite/anhydrite unit, and a middle shale unit and an upper anhydrite unit Morton (1973).

Hennessey Shale

Overlying the Wellington is the Hennessey Shale, with local lenses of anhydrite, gypsum and dolomite Morton (1973).

Cimarron Anhydrite

Above the Hennessey Shale is the Cimarron Anhydrite, which is commonly 40 feet thick, and consists of an upper and lower halite members and a middle unit of anhydrite. This unit is continuous throughout the study area and is commonly used for stratigraphic correlations Morton (1973).

Flowerpot-Hennessey Shales

Shales and sandy shales that exist between the Cimarron Anhydrite and, (where present) the Glorieta Sandstone or the Flowerpot Salt (where present) are referred to as the Flowerpot-Hennessey Shales (Jordan-Vosburg, 1963). The low permeability of the Flowerpot-Hennessey Shales has probably helped minimize the amount of dissolution of underlying salts (Johnson, 1989).

Glorieta Sandstone

Overlying the Flowerpot-Hennessey Shale is the Glorieta Sandstone, which is a slightly gypsiferous medium-grained sandstone. The Glorieta is the thickest sandstone member of the Permian System within the study area. The Glorieta Sandstone is absent locally leaving the Flowerpot-Hennessey shales in contact with Flowerpot Salts (Morton, 1973). The sand facies of the Glorieta pinches out just to the east of the Texas-Beaver County border. Rocks between the Glorieta and the Ogallala are relatively impermeable, but they have been subjected to solution and removal, resulting in collapse of overlying rocks. Where fracturing resulted from dissolution and collapse, passages for upward movement of the dissolution brine or from the Glorieta may exist (U.S.G.S. Circular 630).

Flowerpot Shale

The Flowerpot Shale is a gypsiferous unit that occupies the interval between the Glorieta Sandstone and the Blaine Gypsum/Anhydrite. The Flowerpot Shale pinches out to the east along with the Glorieta Sandstone. However, the interval just beneath the Blaine is occupied by the Flowerpot Salt where the Flowerpot Shale is absent (Plate 1).

Salt Zone of the Flowerpot Shale

The salt zone of the Flowerpot Shale is discontinuous in Texas and Cimarron Counties but is continuous in the subsurface of Beaver County (Figure 6). The zone grades from salt-bearing shale at the base into nearly pure halite at the top. The salt zone is completely absent in much of the study area west of Beaver County but is up to 500 ft. thick in Beaver County (Morton, 1973). The salt zone of the Flowerpot has been documented as being the major Permian formation that has undergone dissolution. Dissolution resulted in collapse, subsidence, fracturing, and faulting of overlying Permian and Tertiary strata. The brine created by the solution of the Flowerpot Salt undoubtedly migrated upward and laterally and discharged at rivers, springs or into overlying aquifers (U.S.G.S. HA-648).

Structural contour maps on the base of marker units, which underlie the Flowerpot Salt, such as the Cimarron Anhydrite, do not indicate that the units beneath the Flowerpot Salt have experienced vertical displacement. This evidence shows that evaporites beneath the Flowerpot Shale have not undergone substantial dissolution. If dissolution had occurred, the Cimarron Anhydrite structure map should show vertical

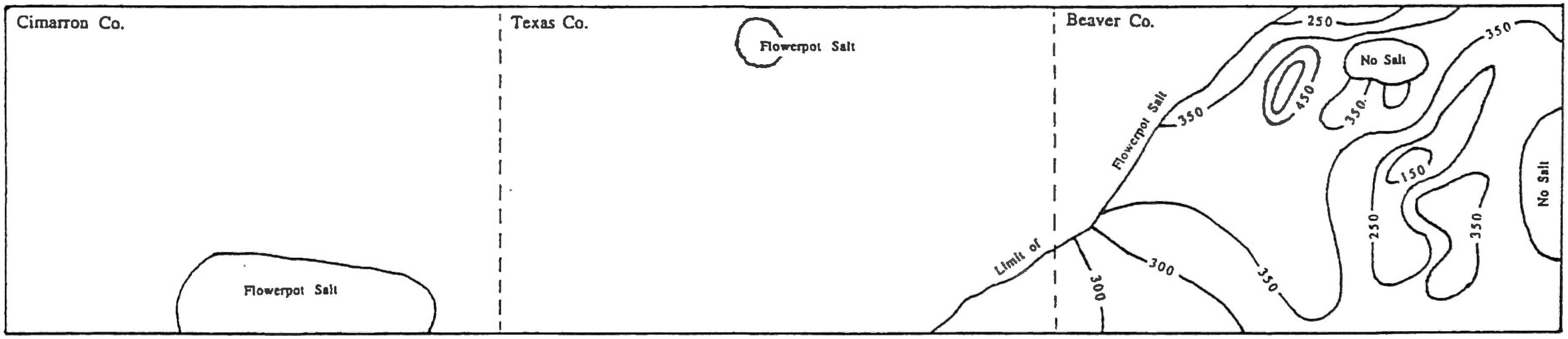


Figure 6. Limit and Extent of the Flowerpot Salt. (modified from Jordan and Vosburg, 1963 and Morton, 1973).

displacement and folding due to dissolution and collapse. Structural contour maps on laterally continuous marker units above the Flowerpot Salt, such as the Blaine Gypsum and the Permian bedrock surface, are chaotic, fractured, folded and appear to drape salt zones. This evidence shows that the Flowerpot Salt has undergone dissolution, in the past, and probably continues presently.

Figure 6 (modified from Morton, 1973 and Jordan and Vosburg, 1963) shows the areal extent of the salt zone of the Flowerpot Shale within the study area. The map shows that the 200-350 foot section of halite is suddenly absent. This has been interpreted to be a result of removal by dissolution and not facies change. The abrupt thinning and lateral discontinuity of the Flowerpot Salt and salt zones in the Blaine Formation and Dog Creek Shale is not consistent with the normal pattern of nearly uniform thickness for these salt-bearing strata that occur beneath thousands of square miles farther west, in the deeper subsurface of the Texas and Oklahoma Panhandles.

Thick accumulations of Ogallala deposits in the eastern half of Texas County occupy a depression on the Permian surface believed to have been caused by solution and removal of salt from the Flowerpot by migrating ground water prior to or during deposition of the Ogallala.

Blaine Gypsum

Above the Flowerpot is the Blaine Gypsum, which consists of seven distinct beds of gypsum or anhydrite that are separated by thinner beds of shale, dolomite, or halite (Morton, 1973).

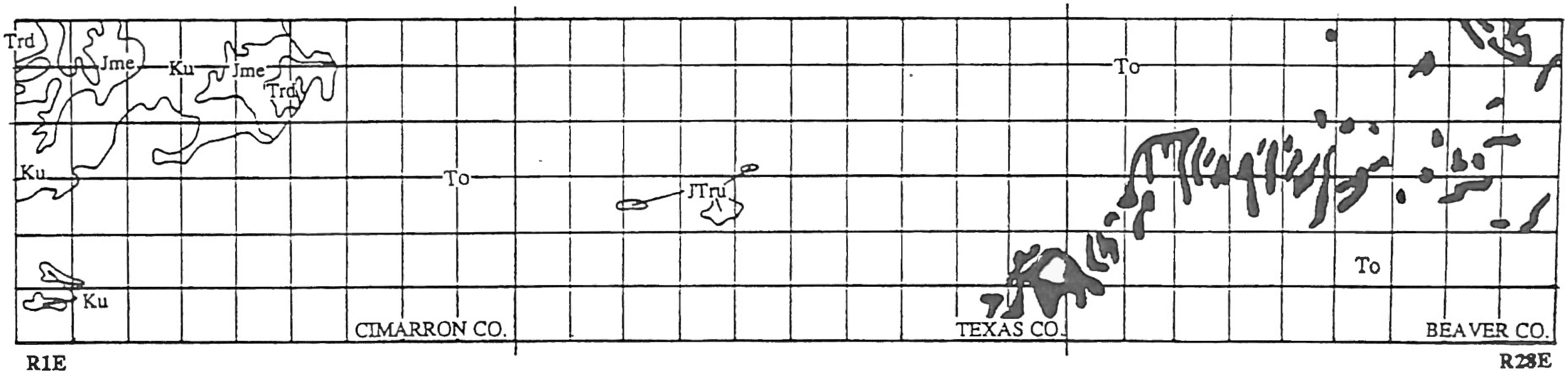
Structure contour maps on the base of the Blaine are chaotic as a result of partial or total dissolution of the Flowerpot Salt and subsequent collapse of overlying strata Johnson (1989). Jordan and Vosburg (1963) attribute a 300 foot decrease in elevation of the base of the Blaine, in Beaver County Oklahoma, to removal of underlying salt of the Flowerpot Formation.

Whitehorse Group, Cloud Chief Formation Quatermaster Formation, and Dog Creek Shale

Between the Blaine Gypsum and the Ogallala aquifer are the uppermost 200-600 feet of Permian strata. The Dog Creek Shale is the lowermost unit of this interval, which is overlain by the Marlow Formation and Rush Springs Sandstone; they make up the Whitehorse Group. Above the Whitehorse Group is the Cloud Chief Formation. The uppermost unit of this interval are the Alibates Dolomite Lentil, Doxy Member, and the Elk City Member, which make up the Quartermaster Formation (Plate 1).

These units are exposed at the surface, in the study area, as a consequence of removal of overlying Tertiary deposits along Quaternary drainage paths (Figure 7).

Gould and Lonsdale (1926) document that it is the Cloud Chief Formation that crops out in southeastern Texas County and along the Beaver River and its tributaries in Beaver County. However, due to the undulating bedrock surface probably all of these units are exposed at the Permian-Ogallala contact elsewhere in the study area. These units contain evaporites and carbonates, and most probably influence ground-water chemistry within the Ogallala.



To	Ogallala Formation	Trd	Dockum Group
JTru	Jurassic and Triassic rocks undifferentiated	Ku	Cretaceous rocks undifferentiated
JMe	Morrison Formation and Exter (Entrada) Sandstone	■	Permian rocks undifferentiated

EXPLANATION

TERTIARY
- Ogallala Formation

CRETACEOUS
- Colorado Group
- Dakota Sandstone
- Purgatoire Formation
- Kiowa Shale Member
- Cheyenne Sandstone

JURASSIC
- Morrison Formation
- Exeter (Entrada) S.S.

TRIASSIC
- Dockum Group

PERMIAN
- Undifferentiated-may include Dog Creek Shale, Whitehorse Group, Cloud Chief Formation, and Quartermaster Fm.
- Blaine Gypsum
- Flowerpot Shale
- Glorieta Sandstone
- Hennessey Shale-includes Cimarron Anhydrite
- Undifferentiated older Permian mostly units of the Wellington Fm

Figure 7. Surficial Geologic Map Showing Generalized Geology Exclusive of Quaternary Deposits (modified from Morton, 1973)

The Dog Creek Shale directly overlies the Blaine Gypsum and is predominantly shale and gypsum. Within the study area it is apparently very difficult to differentiate between the Dog Creek and the Blaine in the subsurface.

The Whitehorse Group consists of predominantly sandstone and shaly sandstone and thin discontinuous lenses of gypsum. The two members are impossible to separate in the study area (Evans 1930). Eastward both formations contain thin gypsum and dolomite beds.

To the east the Cloud Chief Formation consists almost entirely of gypsum but within the study area it consists of gypsum beds interbedded with shales and sandy shales.

The Quartermaster Formation includes all Permian strata above the Day Creek Dolomite and because the Day Creek Dolomite does not exist within the study area it is impossible to differentiate the Quartermaster from the Cloud Chief.

Many of the above formations contain lithologies which are lenticular and have lateral as well as vertical gradations of lithologies and are therefore impossible to trace accurately and correlate from one area to another (Evans, 1930).

Due to the similarity of lithologies between these units and the lack of adequate marker units these groups are nearly impossible to differentiate by electric log and are therefore typically left undifferentiated.

These units are predominantly red shale to fine grained sandstone and also contain anhydrite, gypsum, limestone, and dolomite.

Water-Bearing Properties

The shales and sandstones of the Permian System are relatively impermeable and yield little water to wells. These beds are used only where no other sources are available. The Permian rocks generally yield less than 10 gpm to wells (U.S.G.S. WRI 25-75) The few wells from which water is obtained from these rocks are in Beaver County and southeast Texas County where the Ogallala has been removed by erosion.

Ground water from Permian strata commonly contains more than 1000 mg/L of dissolved solids and is generally unsatisfactory for most uses without treatment or dilution. Halite and gypsum are believed to be the cause of poor quality of water within Permian rocks because of the elevated sulfate and chloride levels (U.S.G.S. WRI 25-75). Permian strata also are known to increase the solute load of surface waters. In southeast Beaver County, Permian strata either crop out or are near the surface and leaching of evaporites contaminates streams in the area (Morton, 1973).

In three areas along the eastern margin of the Permian basin where Permian strata are exposed, subsurface dissolution is manifested by salt plains, salt springs, and degradation of the water quality of major rivers (Johnson, 1981).

Triassic System

The Triassic Dockum Group, underlies part of Texas County and almost all of Cimarron County (Plates 1 and 2). For the purpose of this report the Dockum Group has been divided into lower and upper units. The lower unit is mostly fine- to medium-grained, micaceous, shaly, sandstone. Above the lower sand unit are a sequence of interbedded shales with sandstone. The upper unit of the Dockum consists of red and green shale with minor amounts of thin shaly sandstone. The Dockum ranges from 0-650 feet thick Morton (1973).

The Dockum commonly yields 10-50 gpm of water to wells and in a few localities yields as much as 500 gpm are obtainable (U.S.G.S. WRI 25-75). Water from this group is of relatively good quality. The eight available analyses of water from the Dockum have an average TDS of 585 mg/L. Several analyses show elevated sulfate values but they do not exceed drinking water standards.

Jurassic System

Jurassic rocks consist of the Exeter Sandstone (Entrada) and the Morrison Formation (Plates 1 and 2). The Exeter Sandstone is a fine- to medium-grained sandstone with a few local lenses of gravel and clay. The Exeter is as much as 50 feet thick; it is thickest in western Cimarron County. This unit is generally is too thin to provide more than minimal supplies. Wells tapping the aquifer yield 20 gpm or less (U.S.G.S. WRI 25-75).

The Morrison Formation is composed primarily of shales, marl, sandstone, conglomerate, limestone, and dolomite. The majority of the formation is shale but abrupt changes of lithology occur both laterally and vertically. The Morrison is present in the western half of Cimarron County and its maximum thickness is about 470 feet (Plates 1 and 2). Because of it's low permeability, the Morrison formation can be expected to produce less than 20 gpm. Locally, sandstones will produce significant amounts of water but due to their lenticular nature they have a limited volume (U.S.G.S. WRI 25-75).

The quality of the water from both Jurassic formations limits its usefulness. Analyses from Jurassic bedrock have average TDS values of 2000 mg/L and hardness of 531 mg/L as $CaCO_3$. These analyses show elevated sodium, bicarbonate, and sulfate values probably due to gypsum, halite, and carbonate dissolution and ion exchange.

Cretaceous System

Purgatoire Formation

The Purgatoire Formation is the basal unit of the Cretaceous System. The formation is present in the subsurface in the western third of Cimarron County where it has not been removed by erosion (Plates 1 and 2). Two members make up the Purgatoire Formation. The Cheyenne Sandstone Member, the lowest unit is fine- to medium-grained poorly cemented sandstone. The upper Member of the Purgatoire Formation is the Kiowa Shale. The Kiowa Shale is a black shale that grades upward into a sandy shale and sandstone. Also in the upper part of the Kiowa Shale are some thin limestone units (U.S.G.S. WRI 25-75).

Only the Cheyenne member of the Purgatoire Formation is known to yield water to wells. Yields as great as 500 gpm have been reported. Water in the Cheyenne is of good enough quality for human consumption (U.S.G.S. WRI 25-75). The Kiowa member is not known to yield water to wells and acts as an aquitard.

Dakota Sandstone

Overlying the Purgatoire Formation is the Dakota Sandstone, which is a fine- to medium-grained sandstone. The Dakota, present in most of the western third of Cimarron County, has a maximum thickness of about 200 feet. The Dakota yields up to 150 gpm where its saturated thickness is great but yields diminish to less than 20 gpm eastward. The quality of water from the Dakota is generally good enough for irrigation or human consumption. Analyses collected from the Dakota average 415 mg/L of dissolved solids and 200 mg/L of hardness. These analyses show no elevated chloride or sulfate.

Colorado Group.

Above the Dakota lies the Colorado Group. The Colorado Group consists of the Graneros Shale and the Greenhorn Limestone. Lithologies within the Colorado Group consist of alternating beds of shale, marl, limestone, and bentonite (U.S.G.S. WRI 25-75). The Colorado Group exists in a small area of west-central Cimarron County and has a maximum thickness of 200 feet. No wells are known to obtain water from the Colorado Group (U.S.G.S. WRI 25-75).

Regional Geologic History: Tertiary-Quaternary

A period of extensive erosion followed the Cretaceous. This erosional period left Permian strata exposed in much of the panhandle and drastically eroded, and in places completely removing the Triassic-Cretaceous formations. Formations exposed at the Pre-Ogallala bedrock surface are shown in Plate 2, and Figure 5 shows the altitude and configuration of the bedrock surface.

The area began to aggrade in the Middle to Late Miocene or early Pliocene as a result of the orogenic episode that created the Rocky Mountains. Sedimentation is believed to have occurred continuously throughout the Pliocene. As the topographic lows filled with sediment the sediment lobes began to coalesce with deposits from other drainage systems until topographic irregularities were obscured by a continuous alluvial plain. The alluvial plain contains predominantly alluvial material with local areas of lacustrine deposits. The lower part of the this Ogallala Formation consists mainly of fluvial sediments laid down within paleovalleys. The fluvial deposits are laterally extensive, vertically stacked sands and gravels deposited by intermittent or perennial high-energy braided streams. There are no significant fluvial deposits in the upper part of the Ogallala paleovalley fills or above paleodivides. Quaternary aeolian deposits of sand and silt overlie the fluvial fill and uplands deposits in much of the study area.

Numerous authors document that dissolution of Permian evaporites and carbonates before, during, and after the Miocene-Pliocene deposition had an effect on the thickness and type of Tertiary deposits (alluvium, lacustrine, or collapse-fill material). Structural highs and lows at the base of the Ogallala coincide closely with structural contour maps on Permian units above the Flowerpot Salt. Therefore, the elevation and configuration of the bedrock surface on which the Ogallala lies appears to be related to interstratal-karst development primarily in the Flowerpot Salt and to some extent other upper Permian formations.

Aggradation was completed in the late Pliocene and the major rivers began to erode valleys into the alluvial plain. Recent alluvium along major rivers, dune sand and lacustrine deposits have been deposited above the Miocene-Pliocene deposits.

In this report, the Miocene, Pliocene, and Pleistocene deposits will be referred to as the Ogallala Formation. The "Ogallala" includes rocks equivalent to the Laverne Formation, Ogallala Group, Rexroad Formation, Odee Formation, Meade Formation, Ballard Formation, Crooked Creek Formation, Sanborn Group, and equivalent formations used by other authors.

These formations will all be referred to as the Ogallala because of their similarity in lithologies and they form, in effect, one hydrogeologic unit.

Tertiary System

Ogallala Deposits. The Ogallala consists of a heterogeneous mixture of sand, gravel, silt, clay, and caliche. Locally beds are cemented with calcite but the clastics are generally unconsolidated. The clastic debris was derived from sedimentary formations exposed at the base of the Rocky Mountains and from bedrock within the study area.

The Ogallala Formation was deposited over the entire study area but has been thinned by erosion along major drainage valleys and in some areas removed completely.

The Ogallala has a maximum thickness of 650 feet within the study area (U.S.G.S. WRI 25- 75). Its thickness is a function of paleotopography, and recent thinning due to erosion along major rivers. Paleotopography is a function of paleodrainage patterns and the location of collapse features. It is believed that many of the thickest areas of the Ogallala are a result of dissolution of Permian salts, which occurred before or during deposition of the Ogallala (Chapter 3). Dissolution and removal, which occurred before deposition of the Ogallala, created huge subsurface voids into which the overlying strata collapsed. These collapse zones created topographic lows into which thicker than normal Ogallala deposits accumulated. Collapse which occurred after deposition of the Ogallala is manifest at the surface as dolines and sinkholes.

Sand and gravel of the Ogallala Formation are the principal source of ground water in the study area. Yields range from a few gallons per minute to more than 2000 gpm (U.S.G.S. WRI 25-75). Water from the Ogallala is moderately hard but is generally suitable for most uses. Locally water in the Ogallala has very elevated concentrations of certain ions. The ions which exhibit elevated concentrations include: sodium, calcium, magnesium, bicarbonate, chloride, and sulfate. Elevated concentrations of ions is believed to be natural and predominantly caused by dissolution of evaporites and carbonates in the underlying Permian bedrock.

Pliocene basalt, in extreme northwest Cimarron County, is the only igneous rock in the study area. Thickness of the basalt ranges from 50-85 feet. The basalt in not known to yield water to wells (U.S.G.S. WRI 25-75).

Quaternary alluvium and terrace deposits overlie the Ogallala Formation along present streams and rivers. Quaternary alluvial deposits differ from the Ogallala deposits only in morphology and age. Most of the Ogallala is composed of fluvial material and the recent alluvium is simply reworked Ogallala deposits. In this report Holocene alluvium is also referred to as Ogallala deposits because, in effect, it is also one hydrogeologic unit. Alluvium consists of clay, silt, sand, and gravel. Alluvium seldom exceeds 100 feet in thickness. Wherever alluvium is saturated it yields at least 20 gpm and commonly produces enough for water for irrigation (U.S.G.S. WRI 25-75).

The chemical quality of ground water in the alluvium is principally dependant of the water quality of the stream. At some places where Permian red beds are in contact with alluvium the ground water may be of unusable quality, such is the case in southeast Texas County and many areas along Beaver River in Beaver County, otherwise the chemical quality of water in the alluvium is generally suitable for most purposes (U.S.G.S. WRI 25-75).

Pleistocene and Holocene eolian deposits of the Blackwater Draw Formation (Carter, 1991) blanket a substantial percent of the area under study. Dune sand is fine- to medium-grained, well rounded quartz grains. The thickness of this eolian blanket ranges from zero feet to 50 feet (Holiday, 1989). Most Quaternary eolian deposits are above the water table and are unsaturated, therefore they are not a source of ground water. The eolian sands are very important because of their capacity to absorb precipitation and transmit the water to underlying aquifers.

"Caliche" is a very common term used to refer to layers rich in calcium carbonate which commonly exist at or near the surface of the Ogallala Formation. These layers of caliche range from being unconsolidated calcareous sands or clays to dense, massive, pure limestone. The hardest and densest beds of calcium carbonate are generally found nearest the surface (OGS Bulletin 59). Ten analyses performed by the Oklahoma Geological Survey (OGS) analyzed the composition of caliche show that caliche is not always entirely calcium (Ca^{++}) and carbonate

($CO3^{=}$). The analyses shows that the major constituents of caliche are calcium, carbonate, silica and magnesium. Minor elements include aluminum, iron, and manganese. The percent of calcium ranged from 18.9 to 49.3. The percent of magnesium ranged from .8 to 13.4 percent. Silica content ranged from 7.8 to 50.5 percent. No sulfur was found in the caliche (OGS Bulletin 59).

Caliche is not well understood but is commonly believed to be a diagenetic pedogenic feature. That is caliche forms postdepositionally due to soil forming processes.

There are numerous theories which attempt to explain the occurrence of caliche, and interpret its significance. It is acknowledged that none of the theories fit the occurrence of caliche in every circumstance however, each theory provides insight to explain the broad existence of caliche. Four theories will be presented in this report in order to explain the occurrence of caliche.

(1) Calcic soils form by upward capillary flow of calcareous ground water, induced by constant and rapid evaporation (Weide, 1985).

The water table is well below land surface, and soils within the study area develop in relatively coarse textured sediments. Therefore ground water could not possibly be drawn up from the present water table, especially by the coarse grained materials. Barring an extremely elevated water table, in the past, this theory has been dismissed.

(2) Caliche layers commonly form in soils which form above Ca-rich bedrock. Carbonate accumulates by in situ weathering of Ca^{++} into soil water and subsequent precipitation of $CaCO_3$ in the soil (Weide, 1985).

This theory does not explain caliche in the study area because of the absence of Ca-rich bedrock at the surface.

(3) Caliche in areas appears to be a result of leaching of ions from the upper soil zone and resultant concentration of $CaCO_3$ in the zone of accumulation at a slightly lower zone (OGS Bulletin 59).

This theory postulates that the soil itself is the lone source of calcium. This is unlikely to be entirely true in the study area because the soil's parent material is non-calcareous, but this process may be acting simultaneously with the next theory.

(4) The last theory presented postulates that an airborne supply of calcareous material is responsible for the formulation of caliche. Calcium carbonate is leached from the surface and is subsequently precipitated in lower soil horizons. This theory explains that the carbonate comes in from external sources such as; carbonate dust, silt and eolian sand as well as Ca^{++} dissolved in rain water (Weide, 1985).

This theory appears to best explain the caliche of the southwestern United States and within the study area of this project.

Some caliche is believed to have precipitated syndepositionally with the Ogallala. Caliche could form at the surface during periods of nondeposition (soil forming periods). This explains caliche layers which exist at lower levels and are buried by sands and gravels of the Ogallala.

No wells obtain water from caliche layers because it is relatively impermeable and most commonly above the water table (OGS Bulletin 59).

In areas where caliche is dense and impermeable it retards the ability of precipitation to recharge the aquifer.

CHAPTER V

BEDROCK AS A SOURCE OF CONTAMINATION

The hypothesis of this project is that the chemical composition of ground water within the Ogallala aquifer is influenced by the mineralogic properties of the underlying bedrock. The lithologies of the bedrock have previously been discussed in Chapter 4.

Also previously discussed are documented situations showing that soluble minerals within the bedrock are capable of contaminating overlying aquifers and surface water, such as springs, streams and rivers.

The emphasis in this chapter will be the discussion of each underlying formation as a source of natural contamination to the ground water in the Ogallala aquifer.

Permian System

The Permian system is assumed to be the oldest system which influences ground water chemistry of the Ogallala aquifer due to the abundance of evaporites and carbonates.

Wellington Formation, Hennessey Shale, and Cimarron Anhydrite

Minerals within the Wellington Formation, Hennessey Shale, and Cimarron Anhydrite that are susceptible to dissolution include limestone, dolomite, gypsum, anhydrite and halite. These rocks are possible sources of contamination to overlying aquifers. However, evidence shows that these formations have not experienced dissolution and have no influence on the chemistry of ground water within the Ogallala aquifer.

Structural contour maps on the base of laterally continuous marker units within and above these formations, such as the Cimarron Anhydrite and Glorieta Sandstone, suggests that the soluble minerals of these units have not been removed due to dissolution. The base of these units shows relatively flat surfaces not faulting or collapse features which would be expect if underlying units had been removed.

The low permeability of the overlying Flowerpot-Hennessey Shales (Plate 1) has probably helped minimize the amount of dissolution of underlying lithologies Johnson (1989).

Glorieta Sandstone

The Glorieta Sandstone is the thickest and most pure sandstone unit within the Permian section of the Oklahoma Panhandle. The Glorieta pinches out to the East and does not exist in the eastern third of the study area (USGS Circular 630). The Glorieta does not contain water-soluble evaporites or carbonates but does present reason for concern because it is the principal formation used for injection of oil-field brines. The Glorieta is confined and, due to injection of oil-field brines, is overpressurized. McMillion and Maxwell (1970) show that in southeast Texas County the natural potentiometric surface of the Glorieta Formation is higher than the water table in the Ogallala. Thus, if there exists adequate hydraulic connection, such as faulting or poorly plugged oil-field wells, the potential exists for the brines to migrate upward and into the Ogallala aquifer.

The mechanism which causes fracturing and faulting of the strata between the Glorieta and the Ogallala is as follows. Soluble evaporites and carbonates in the interval above the Glorieta are removed by dissolution, causing collapse, fracturing, and faulting which could provide conduits connecting the Glorieta and the Ogallala.

Salt Zone of the Flowerpot

The Flowerpot Salt is potentially a major contributor of natural contamination to the Ogallala aquifer, and evidence presented in this project suggests that it is.

The Flowerpot Salt occupies the interval immediately below the Blaine Gypsum, and immediately above the Flowerpot Shale, the Glorieta Sandstone or the Flowerpot-Hennessey Shale whichever exists at the given locality (Plate 1). However, the Flowerpot Salt is laterally discontinuous. It exists in the subsurface throughout most of Beaver County and localized remnants in Texas and Cimarron Counties (Figure 6).

The discontinuity, along with very abrupt boundaries of the unit, suggest that where the unit is absent it has been removed by dissolution. Johnson (1989) and Jordan and Vosburg (1963) created structural contour maps on the base of the Blaine. The base of the Blaine is not as level as one would expect if it were strictly depositional. The Blaine appears to drape the Flowerpot Salt. Where the salt is absent the base of the Blaine is 200-500 feet lower. This leads to the interpretation that the Blaine Gypsum subsided or collapsed into the void as a result of removal of the underlying Flowerpot Salt.

Structural contour maps created on units beneath the Flowerpot, such as the Glorieta and Cimarron Anhydrite, suggest that the lower units have not experienced substantial dissolution.

Structural contour maps on the Permian bedrock surface show that the entire Permian section above the Flowerpot Shale has subsided where the salt zone is absent. The majority of the subsidence apparently occurred before or during deposition of the Tertiary Ogallala because Ogallala deposits are much thicker above areas where the Flowerpot Salt is absent, because the bedrock surface was low in those areas. Topographic lows acted as localized basins which accumulated thicker than normal sections of Ogallala deposits.

It is probable that the Flowerpot Salt continues to undergo dissolution and evidence presented later suggests that this is the case.

Quartermaster Group, Cloud Chief Group, Whitehorse Group and Dog Creek Shale

Since these units are the uppermost units of the Permian section their potential for being the source of contamination to the Ogallala is very probable. These units do contain a substantial volume of evaporites and carbonate minerals which are susceptible to dissolution.

However, the soluble minerals in the rocks within these units are thin and laterally discontinuous. Therefore, these units have not been differentiated and without further stratigraphic study it is impossible to determine exactly where the evaporites and carbonates of these units exist.

Halite is a commonly occurring lighology throughout the Permian section except within the upper several hundred feet of strata. The upper

Permian units still contain evaporites such as gypsum, but no halite. Reasons for the absence of halite in the upper Permian may be: (1) Halite was never deposited in the Late Permian. This is unlikely because during the late Permian the study area was undergoing deposition during the late stages of an epicontinental sea. It is during the late stages that halite would be most likely to precipitate because it is the most soluble of the commonly occurring evaporites. The presence of gypsum and anhydrite indicates that evaporitic conditions did exist in the Late Permian and therefore, halite should be interbedded with the shales and gypsum. (2) The second and most likely explanation for the absence of halite is that halite was deposited and later removed by dissolution. The presence of the overlying Ogallala aquifer provides a source of fresh water with substantial gravitational head. Permeable rocks, fractures, or other hydraulic connections make the upper Permian formations vulnerable to dissolution. Thus, it is probable that halite was deposited in the Late Permian only to be removed by subsequent dissolution. Therefore, the absence of halite in these formations leads to the interpretation that the upper Permian formations are, to some degree, in hydraulic connection with the Ogallala aquifer.

Triassic, Jurassic and Cretaceous

The lithologies of the Triassic, Jurassic and Cretaceous systems have previously been discussed in Chapter 4. Except for a few thin carbonate units these systems do not contain rocks which are highly susceptible to dissolution. Therefore, these systems are believed to have little affect on the groundwater chemistry of the Ogallala aquifer. The ground water in these units is more mineralized than the ground water of the Ogallala but is less mineralized than that of the Permian formations.

These systems are thickest in western Cimarron County and thin to a feather edge in central Texas County. These systems have been eroded and removed from central Texas County eastward (Plate 2).

As will be discussed later, the ground-water chemistry within the Ogallala, above Triassic through Cretaceous bedrock suggests that these systems are not influencing Ogallala ground water and are in fact acting as a buffer protecting Ogallala ground water from highly mineralized ground water of the Permian System.

CHAPTER VI

METHODS OF ANALYSIS

Mass Balance

A mass balance approach has been used to help define and quantify chemical reactions between ground water and the aquifer. The Fortran computer program BALANCE (Parkhurst, Plummer, and Thorstenson) was used to calculate the amount of ions entering or leaving the aqueous phase (mass transfer) necessary to account for the observed chemical composition of the water samples.

BALANCE requires the user to input phases. The purpose of the phases is to provide a source or sink for the ions in solution. The phases can be minerals, gases or ion exchangers. The phases are selected on the basis of geology, hydrology, and mineralogy of the system. BALANCE also requires as input a set of ions and concentrations of each ion. The user assumes the majority of each ion in solution is contributed by one or more of the phases. BALANCE assumes that 100 percent of the concentration of each ion is due to any combination of the phases entered. BALANCE results are not dictated by thermodynamics therefore, care must be taken because BALANCE may imply reactions which are thermodynamically impossible.

All analyses which were complete were run through BALANCE. Sodium, calcium, magnesium, chloride, sulfate and carbon (HCO_3-) are the ions whose concentrations were entered. The phases assumed to be sources or sinks for these elements include: calcite, dolomite, gypsum, halite, ion exchange and carbon dioxide. BALANCE output is a positive or negative concentration value. The value is in moles per liter or millimoles per liter, depending on the units used for input. Positive values indicate that the phase is entering solution and negative values indicate precipitation of the respective phase, or removal by ion exchange (See Appendix E for sample output).

In order to determine if there was an relationship between two or more phases dissolving or precipitating the phases used were plotted against each other on X-Y graphs. The data points used were determined according to the amount of each respective phase which dissolved or precipitated as determined by BALANCE. The computer program GRAPHER was used to make the X-Y plots and to plot best fit lines (Results are shown in figures 9, 12-14).

The phases which indicate that their respective precipitation or dissolution are related include; Calcite-Gypsum (Figure 12), Calcite-Dolomite (Figure 13), and Gypsum-Dolomite (Figure 14). Figures 12, 13 and 14 provide strong evidence which support that dedolomitization is occurring within the system (Chapter 7).

The X-Y graphs presented as figures 9, 12-14 show less than perfect theoretical trends. This is due to all complete analyses being included in each plot.

The mass balance data was contoured with the computer software SURFER. The contour maps delineate where within the study area each phase is contributing or consuming it's respective ions and where these reactions are most pronounced.

Factor Analysis

Factor analysis has also been used to analyze ground-water chemical analyses and make hydrogeologic interpretations. Factor analysis has several advantages over graphical methods. (1) An unlimited number of variables can be analyzed not just the usual six major ions. (2) Neutral chemical species and nonchemical data may be entered such as temperature or TDS. (3) Variations of ions in small concentrations are not masked by other ions. (4) Actual concentrations can be used without converting the data to a percentage. (5) Secondary relationships not easily detectable on graphs are detected.

Factor analysis is useful for interpreting commonly collected ground-water quality data and relating them to specific hydrogeologic process.

The goal of factor analysis is to reduce a large set of variables to a smaller set of variables called factors. If there exists a relationship between two or more variables (species in solution) then they will be grouped as a factor. For example: If the concentration of sodium (Na) increased in proportion to an increase in chloride (Cl) concentration, sodium and chloride would be grouped within "factor 1." If the geologic setting included halite deposits then halite dissolution would be inferred. Other relationships between the variables will create more factors leading to other interpretations of the geological and chemical processes within the system.

The output from BALANCE, which consisted of five phases (now variables) calcite, dolomite, gypsum, halite and ion exchange and TDS were run through the factor analysis program FACTOR (Hounslow). The factor analysis approach was used in order to facilitate the consideration of 6 variables from each of 127 samples in an attempt to point out and quantify patterns of variable interrelation. The values assigned each variable correspond to the BALANCE output which is millimoles per liter of the respective phase (variable), that dissolved (+) into or precipitated (-) from the aqueous phase.

FACTOR output includes, (1) a correlation coefficient matrix, (2) an unrotated factor matrix and (3) a rotated factor matrix.

The correlation coefficient matrix shows how closely each variable is dependent on each other variable. Values of +1 or -1 indicate perfect correlation, whereas zero indicates no correlation.

Each factor is assigned values called "factor loadings," for each variable. Factor loadings are a measure of the extent to which each factor is associated with a particular variable. The factor loadings can be thought of as correlation coefficients. The closer the factor loading is to 1.0 the more influence the variable has on the factor.

Factor rotation has the effect of producing a set of uncorrelated factors in which each variable has high loadings on some factors and near-zero loadings on the other factors (Ruiz, Gomis and Blasco, 1990). The rotated factor matrix acts to de-emphasize loadings which are less important thus the factor is more clearly defined and more easily interpreted.

The correlation coefficient matrix indicates that four of the six variables are interrelated. A correlation coefficient of .9139 indicates that the variable halite is related to the variable total dissolved solids (TDS). Halite is known to exist within the Permian system of the Oklahoma Panhandle and has been documented as undergoing dissolution in the past and also presently. The correlation coefficient leads to the interpretation that dissolution of Permian halite is presently occurring beneath the Ogallala and the subsequent waters are migrating into the overlying Ogallala aquifer.

The correlation coefficient matrix also shows that calcite and dolomite exhibit an inverse relationship. This means that the dissolution or precipitation of one mineral induces the opposite reaction of the other mineral. This opens four scenarios for the user to interpret. In this case it has been interpreted that the precipitation of calcite induces dissolution of dolomite. This scenario was interpreted because, if in fact this is the case, this data supports one of the original hypothesis that dedolomitization is occurring. Discussion in Chapter 7 explains dedolomitization and explains why this data supports the theory of dedolomitization.

The rotated factor matrix also indicates a strong correlation between halite dissolution and elevated TDS values. The factor analysis data supports the X-Y graph of halite vs. TDS (Figure 9). This data also suggests that contemporary dissolution of Permain halite is the dominant geochemical process dictating the TDS of ground water in the Ogallala aquifer.

The correlation coefficient matrix and the rotated factor matrix as well as the X-Y graph (Figure 13) show an inverse relationship between the variables calcite and dolomite. The above mentioned data has been interpreted to be indicating that as calcite precipitates from the aqueous phase dolomite dissociates. This leads to the interpretation that the geochemical reaction known as dedolomitization is occurring. Dedolomitization will be discussed at length in the following chapter.

Ratios of Ions

Ratios of major ions were calculated in order to identify source rock lithologies and chemical reactions that occur between ground water and the aquifer matrix.

Ratios are important in the interpretation of the chemistry of water. Concentration of species in solution varies because of to physical processes within the aquifer. However, ratios are unaffected by dilution or concentration; therefore the chemical signature of the system is retained.

Ratios of ions indicate the presence and identity of soluble rocks that influence ground-water chemistry (for example, halite, dolomite, and gypsum), as well as pointing out active geochemical reactions (such as cation exchange and dedolomitization). For example: if halite dissolves it yields one mole of sodium and one mole of chloride; therefore the Na^+/Cl^- molar ratio is equal to 1. If the Na^+/Cl^- molar ratio is much greater than 1 it is interpreted that ion exchange in contributing excess sodium to solution. Dissolution of dolomite yields one mole each of calcium and magnesium ions and two moles of carbonate ion. The Ca^{++}/Mg^{++} molar ratio of a dolomite solution will be 1

Saturation Indices

The computer program WATEQF (U. S. Geological Survey) was used to calculate the saturation indices with respect to calcite, dolomite, gypsum and halite. Saturation index is defined by equation 1.

$$(1)\ \text{Saturation Index (SI)} = \frac{\text{Ion Activity Product (IAP)}}{\text{Equilibrium Constant } (K_{sp})}$$

First WATEQF calculates the ionic strength (I) of the solution.

Ionic strength of a solution is a function of the concentration of dissolved ions in the solution. The ionic strength is calculated because it has a direct effect on the solubility of a mineral. The solubility of a mineral increases as the solution becomes more highly mineralized, that is increases its ionic strength. In highly mineralized solutions, ions tend to interfere for example: with Ca^{++} and $CO3^{=}$ ions from joining in order to precipitate. Therefore, as ionic strength increases higher concentrations of ions will go into and remain in solution instead of reaching equilibrium or precipitating. Highly mineralized solutions act to decrease the effective concentration of ions in solution. The concentration of ions is therefore influenced by ionic strength. The resultant "effective concentration" is referred to as the activity.

Secondly, WATEQF determines the activity of each ion in question. For example: To determine the SI of calcite the activity must be calculated for Ca^{++} and $CO3^{=}$.

$$(2)\quad \text{activity} = \text{activity coefficient} \bullet \text{concentration}$$

Activity coefficients are multiplication coefficients less than 1.0. They decrease as the ionic strength increases.

Next WATEQF attains the Ion Activity Product (IAP) by multiplying the activity of Ca^{++} by the activity of $CO3^{=}$. Finally WATEQF presents the SI of calcite by dividing the IAP by the solubility product of calcite.

If the IAP/K_{sp} ratio is greater than 1 the solution is supersaturated and the mineral thermodynamically should precipitate. If the ratio is less than 1 the solution is undersaturated and the solution will dissolve the mineral if they come into contact. If the ratio is 1.0 the solution is at equilibrium with respect to that particular mineral.

Piper Plots

All complete analyses were plotted on a trilinear diagram called Piper Plots using WATEVAL (Hounslow). The data was divided into three groups going from west to east according to counties.

The Piper Plots are useful to show regional variations in the major cations and anions. The regional variations along with knowledge of the geologic system has led to interpretations and has corroborated interpretations arrived at via other methods.

The most important aspect of Piper Plots are the "cation triangle" and the "anion triangle." Each analysis has a point plotted in each triangle. The cation triangle has end points of calcium, magnesium and sodium plus potassium. The anion triangle has end points of sulfate, chloride and bicarbonate.

In order to plot points from a given analysis the concentration of ions must first be converted into moles/L or mmoles/L. Secondly, the cations and anions are separated into two groups. Then the relative percentages of each cation and each anion is determined with each group totaling 100 percent. Finally, the plots are made in the triangles according to the percentage of each ion.

Piper Plots are good for graphically showing major ions for one analysis or a group of analyses. They are also very useful for showing mixtures of two waters.

Piper Plots also have several shortfalls. The user is limited to three cations and three anions. Trends of the major ions will be expressed however, secondary trends or trends of ions not used will be masked or entirely overlooked. Within the cation and anion triangles it is impossible to differentiate concentrated from dilute solutions.

Cimarron County

The results of plotting all complete analyses from Cimarron County on a Piper plot are shown in Figure 8A. Figure 8A shows a definite grouping within both the cation and anion triangles with very little variation. Analyses from Cimarron County show a mixed cation signature of calcium and magnesium and very little sodium. The anion triangle shows that the dominant anion is bicarbonate and the analyses have very little chloride or sulfate.

This Piper plot of leads to the interpretation that the Ogallala aquifer in Cimarron County is not influenced by gypsum/anhydrite or halite dissolution or by oil-field brines.

Texas County

The Piper plot of analyses in Texas County (Figure 8B) shows an anion triangle that is identical to that of Cimarron County with calcium and magnesium being the dominant cations. However, three analyses, which show sodium as the dominant cation, strongly deviate from the otherwise pronounced group.

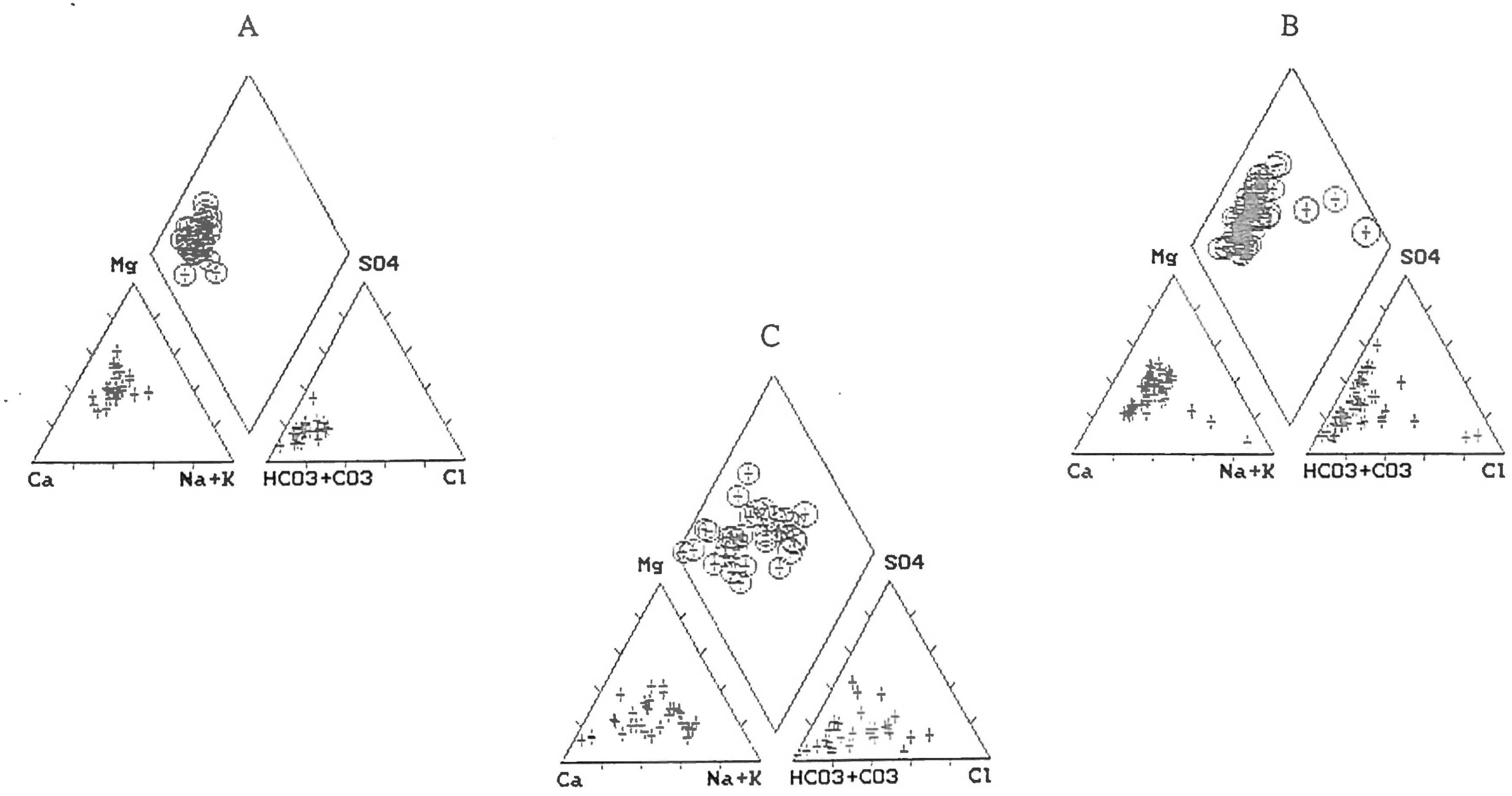


Figure 8. Piper Diagrams of Analyses in (A) Cimarron County, (B) Texas County, (C) Beaver County.

The anion triangle of Texas County is very different than that of Cimarron County. The same three analyses which show elevated sodium also show elevated chloride. Many analyses show sulfate is the dominant anion.

The Piper plot in Texas County leads to the interpretation that gypsum/anhydrite dissolution is contributing sulfate ions to ground water of the Ogallala aquifer and halite dissolution is responsible for the elevated sodium and chloride in the three anomalous analyses.

Beaver County

Pronounced grouping in the cation and anion triangles in Cimarron and Texas Counties is not seen in the Piper plot of analyses from Beaver County (Figure 8C). The major cation and anion varies regionally in this county.

The cation triangle shows less magnesium than analyses from the west. The major cation has shifted to slightly more calcium and considerably more sodium.

The anion triangle shows less sulfate and a pronounced increase in chloride.

The shift of major ions toward sodium and chloride leads to the interpretation that the dissolution of halite is influencing the ground water chemistry of the Ogallala aquifer in Beaver County.

Discussion of Piper plots strengths and weaknesses. The use of Piper plots in interpreting the regional geochemistry of groundwater in the Ogallala aquifer has limited usefulness.

By dividing the data into three groups according to county it is possible to show how the major ions vary regionally. The Piper plots initiate the interpretation that gypsum dissolution in Texas County and halite dissolution in Beaver County are influencing the ground water chemistry in the Ogallala aquifer. However, Piper plots do not effectively show the regional variation of TDS. Piper plots do not easily show exactly where in the county gypsum or halite dissolution is most pronounced. Piper plots are unable to point out the geochemical reactions of ion exchange, reverse ion exchange and dedolomitization.

Therefore, Piper plots, in this case, fail to provide information which has been obtained via: the mass balance method, factor analysis, and by calculating ratios of ions, but the Piper plots do corroborate their conclusions.

CHAPTER VII

HYDROGEOCHEMICAL DISCUSSION

Total Dissolved Solids

Total dissolved solids (TDS) contour maps were produced for each county in the study area. These show regional variation of the dissolved solid content of groundwater within the Ogallala Aquifer.

The data collected has been contoured in Plate 3 using the computer software SURFER (Golden Software, Inc.). These SURFER contour maps were used only as an aid to the final product. The SURFER maps do not include geologic interpretation and SURFER extents contour lines through areas where the Ogallala does not exist. Therefore, SURFER maps were used as an aid along with surface geologic maps, saturated thickness maps and Ogallala thickness maps.

The Ogallala aquifer consists entirely of clastic material except for thin diagenetic caliche layers which are believed to be a result of soil forming processes. Except for caliche, the Ogallala contains no known carbonates or evaporites either as beds or cements. If the groundwater quality of the Ogallala aquifer were unaffected by underlying formations the chemical quality should be relatively consistent and exhibit relatively low dissolved solid content. However, the data collected shows TDS values ranging from 179 mg/L to 4145 mg/L.

There are two anomalous points in Texas and Beaver counties which report TDS values of groundwater in the Ogallala to be 24,300 and 11,700 mg/L respectively. It is assumed that these samples are in error and the respective wells actually partly tap the Permian bedrock.

Almost all analyses collected reported the TDS value as TDS(180). This indicates that the sample was heated to 180° C in order to dry off the water. The sample was then weighed to determine the TDS content. TDS values determined by this procedure do not represent the true TDS because during evaporation half of the bicarbonate ($HCO3^{-}$) is lost from the sample as carbon dioxide gas and water vapor.

$$(3)\quad 2HCO3^{-} \quad \text{<---->} \quad CO3^{--} \quad + \quad CO2_{(g)} \quad + \quad H2O_{(g)}$$

Two moles of bicarbonate has a mass of 122 grams per mole, and one mole of carbonate has a mass of 60 grams per mole. Therefore, approximately half of the original mass of bicarbonate is represented in the final sample. TDS(180) is actually the sum of ions plus silica minus half of the reported bicarbonate.

It should be noted that the U.S.G.S. includes a TDS contour map of Beaver County in HA-450. According to the U.S.G.S. map the Ogallala groundwater in Beaver County is always less than 600 mg/L of dissolved solids while data accumulated for this project show TDS values commonly above 400 mg/L up to 2109 mg/L (Plate 3). The U.S.G.S. lists 26 incomplete analyses which were used in the construction of their map. Data accumulated during the literature search phase of this project revealed the complete analyses used by the U.S.G.S. and it is obvious that TDS(180) values were used instead of the true TDS values.

The TDS of Ogallala groundwater in Cimarron county ranges from 323 to 523 mg/L (Plate 3). Cimarron County has relatively low TDS values as compared to Texas and Beaver counties. The TDS data in Cimarron County does not indicated any areas are experiencing contamination due to evaporite dissolution or cross-formational flow. The TDS data is low and very consistent and contains no anomalous data points or zones unlike Texas and Beaver counties.

The low TDS values in Cimarron county can be attributed to two factors. (1) The Ogallala aquifer in Cimarron county is up-gradient relative to Texas and Beaver counties. Groundwater flow is from west to east (Havens, 1982). Therefore, groundwater in Cimarron County has not been in the aquifer for the length of time as the groundwater in Texas and Beaver counties. The longer groundwater is in an aquifer the more opportunity it has to dissolve constituents of the aquifer matrix. (2) The second reason the TDS values of Cimarron County are relatively low and consistent is probably due to the fact that in Cimarron county the Ogallala aquifer does not directly overly Permian bedrock, except in the extreme northeast and southeast corners (Plates 2 and 3). As discussed in the Previous Investigations chapter, evaporites and carbonates within the Permian system have been shown to be experiencing dissolution. Superimposing the TDS map (Plate 3) on the bedrock subcrop map (Plate 2) indicates a substantial increase in TDS values within the Ogallala wherever the Ogallala directly overlies Permian bedrock. This dissolution has been documented as being the source of natural contamination of rivers and overlying freshwater aquifers (Chapter 3).

The fact that groundwater in the Ogallala has relatively low and consistent dissolved solid content in areas where the Ogallala is not directly overlying Permian bedrock, and the fact that groundwater in areas where the Ogallala directly overlies the Permian system is much more highly mineralized supports the assumption that soluble minerals of the Permian system do influence groundwater quality of the Ogallala aquifer.

Groundwater from the Ogallala in Texas county is much more variable and highly mineralized than in Cimarron County. TDS values range from 362 to 4145 mg/L (Plate 3). The highly mineralized areas do overlie Permian bedrock. The most noticeable area of concern is in the southeast corner of Texas County. The increased TDS values are probably related to a thin Ogallala section (Wood and Hart, 1967, sheet 2) and numerous outcrops of the Permian Cloud Chief Formation (Plate 2). The region in the northeast corner of Texas County with relatively low TDS values corresponds to a zone of thick saturated section defined by Wood and Hart (1967, sheet 2) this is probably due to dilution.

The TDS of groundwater in the Ogallala of Beaver County range from 179 to 2109 mg/L. (Plate 3). Beaver County has the highest average TDS content of the three counties.

Plate 3 indicates a large zone with very little data which dissects the county from west to east. This data gap is due to the Beaver River which flows from west to east through the same area. In this region the Ogallala has been thinned and in many areas completely removed due to Holocene erosion. Plate 2 shows the numerous Permian outcrops along this drainage path. The lack of data is due to small saturated thickness therefore small yield. Highly mineralized groundwater due to the Permian bedrock, and highly irregular topographic relief is not conducive to retaining groundwater or using groundwater in this area. Morton and Goemaat (1973, sheet 1) indicate this area as widely ranging in groundwater quality and state that the groundwater from the Ogallala is frequently degraded by water from Permian bedrock.

Elevated TDS values in Beaver County can be related to four factors. (1) Beaver county is down gradient relative to the other counties. Therefore residence time of the groundwater will be greater increasing the opportunity to dissolve minerals. (2) The Ogallala in all of Beaver County directly overlies Permian aged deposits which are known to contain carbonates and evaporites (Plates 1 and 2). (3) The Permian bedrock commonly outcrops in Beaver County (Plate 2). This shows that the suspected contaminant source is near to the surface. (4) The Ogallala deposits in Beaver county are relatively thin in most areas except in the northwest corner (Morton and Goemaat, 1973, sheet 2). Where the Ogallala is thin the saturated thickness is small and the volume of good quality water is not sufficient to dilute and mask contributions due to dissolution of *soluble lithologies or cross-formational flow.*

By comparing TDS data with bedrock age and outcrop locations it is evident that in areas where the Ogallala directly overlies Permian bedrock the groundwater is much more likely to have elevated TDS values. In areas where the Permian bedrock is close to the surface (thin section of Ogallala) or where there are outcrops of Permian bedrock nearby the groundwater in the Ogallala is even more likely to have elevated TDS values.

The TDS data and maps indicate the evaporites and carbonates within the Permian are influencing the chemistry of ground water in the Ogallala aquifer. If the Ogallala were simply a sand and gravel system not influenced by dissolution of minerals within the bedrock the TDS values of the Ogallala would be expected to be relatively consistent and much lower.

The TDS maps are a useful indicator to show how the dissolved solid content varies on a regional basis. The subsequent segments of this project will further determine the sources of the highly mineralized groundwater.

Ion Exchange

Ion exchange is a geochemical reaction between the ionic constituents in groundwater and aquifer materials (primarily clays). The reaction involves the adsorption of Ca^{++} and Mg^{++} and the release of Na^{+}. When relatively fresh groundwater comes in contact with sodium rich clay each calcium or magnesium ion within the groundwater replaces two sodium ions on the clay surface.

$$\text{(4)} \quad 2\text{Na-Clay} \quad + \quad Ca^{++} \longleftrightarrow \quad \text{Ca-Clay} \quad + \quad 2Na^{+}$$

The factors which dictate which ions will be held more tightly to a surface and which ions will be released include; size, charge and ability to form covalent bonds (Krauskopf, 1979). The smaller of the two ions will be held more firmly. Multivalent ions will be held more firmly than univalent ions. Ions whose bonds have strong covalent character would be more readily adsorbed than one whose bonds are dominantly ionic (Krauskopf, 1979). Therefore, the divalent calcium ion, which is basically the same size as the sodium ion will replace two sodium ions and will be held more tightly to the clay surface.

Two methods were used to delineate regions where ion exchange is an important factor controlling the chemistry of groundwater in the Ogallala aquifer.

A mass balance approach was first used to predict areas of high ion exchange. The Fortran computer program BALANCE (Parkhurst et al., 1982) was used. The reaction assumed in BALANCE was:

$$(5)\quad Ca^{++} + \text{Na-Clay} \longleftrightarrow 2Na^{+} + \text{Ca-Clay}$$

This equation shows that calcium ions are removed from groundwater and adsorbed onto sodium rich clay. One mole of Ca^{++} that is adsorbed releases two moles of Na^{+}, due to the divalent nature of Ca^{++} and univalent nature of Na^{+}. To assign a value of ion exchange, BALANCE discounts the Na^{+} contributed by halite dissolution and divides the remaining Na^{+} by 2 (Na-Cl/2). Only the complete analyses were run through BALANCE. In order to add more data points to the ion exchange mass balance map ion exchange values were calculated for all analyses including incomplete analyses which had sodium and chloride concentrations reported. The results were plotted on a base map and contoured by the computer software SURFER and the result is shown as Plate 4. Plate 4 indicates that to some degree ion exchange is occurring throughout the study area but is much more pronounced from eastern Cimarron County through central Beaver County.

A Na^{+}/Cl^{-} ratio map was created from all analyses (Plate 5). This data corroborates the ion exchange mass balance map because areas predicted to be influenced by ion exchange by BALANCE showed elevated Na^{+}/Cl^{-} ratios.

Milliequivalents were used instead of milligrams so that the ions concentrations could be compared directly. A Na^{+}/Cl^{-} ratio equal to 1 implies that the groundwater is influenced by halite dissolution because halite dissociates to yield one mole of Na^{+} and one mole of Cl^{-}. Ion exchange increases the Na^+ concentration while having no effect on the Cl^- concentration, thus increasing the Na^+/Cl^- ratio

The Effect of Saturated Thickness on Ion Exchange

By comparing the ion exchange mass balance map and the Na^+/Cl^- ratio map with the saturated thickness maps of Havens (1981) it appears that areas of greater than average ion exchange corresponds with areas of small saturated thickness. It is probable that these zones of thin saturated thickness are due to paleotopography and are in fact above paleodivide regions. It has been shown by stratigraphic studies that Ogallala deposits directly above paleodivide areas are made up of finer-grained clastics and contain much more clay than do the major channel systems. This fact would lead to the prediction that the Na^+/Cl^- ratio would be higher above paleodivide areas as opposed to paleochannels due to ion exchange occurring on the clays. The data supports this theory because high ion exchange and elevated Na^+/Cl^- ratios correlate with thin saturated areas; and low ion exchange and low Na^+/Cl^- ratios in thick saturated areas. Regions along the southern and eastern margin of Cimarron County which have thin saturated thickness and northeast Beaver County with thick saturated sections and high ion exchange support this theory.

Reverse Cation Exchange

The ion exchange mass balance map defines several zones where reverse cation exchange is believed to be influencing the ground water chemistry. Reverse exchange refers to the cation exchange reaction

$$(6)\ Ca^{++} + 2(Na\text{-}Clay) <\text{----}> Ca\text{-}Clay + 2Na^{+}$$

going from right to left or the reverse of what is normal. This means the clay adsorbs sodium from solution and releases calcium and/or magnesium. Reverse ion exchange is induced when sodium rich waters such as brines or halite solutions come into contact with cation exchangers.

Negative values of ion exchange were calculated during the mass balance approach using BALANCE. Negative values indicate that there is more chloride than sodium in solution. Two scenarios could explain this. (1) Oil-field brines would exhibit these ratios. (2) Highly concentrated halite solutions could induce reverse exchange.

Reverse exchange zones defined by the mass balance method were checked by looking at the Na^{+}/Cl^{-} ratio in meq/L. It was expected that the analyses predicted by BALANCE to be influenced by reverse exchange should also show a Na^{+}/Cl^{-} ratio of less than one due to the removal of Na^{+} from solution. The Na^{+}/Cl^{-} ratios were plotted and contoured by SURFER and the zones of negative ion exchange (reverse exchange) correlate perfectly with zones which exhibit a Na^{+}/Cl^{-} ratio less than 1.0.

The largest zone of reverse exchange occurs in northeast and southeast Texas County and in areas of Beaver County (Plate 4). The Na^{+}/Cl^{-} ratio map was used to predict whether halite dissolution or brines induced this reverse exchange. In most of these reverse exchange zones the Na^{+}/Cl^{-} ratio is approximately 1.0 therefore, if in fact reverse exchange is occurring it was induced by halite dissolution. However, in northeast Beaver County and northeast Texas County the Na^{+}/Cl^{-} ratio is commonly less than 0.5. Two scenarios could explain this. (1) The analyses with Na^{+}/Cl^{-} ratios less than 0.5 are most likely brine contaminated waters. (2)

Halite solutions migrating into the Ogallala aquifer induce the clays to adsorb sodium thus decreasing the Na^+/Cl^- ratio.

Brines and Ion Exchange

A possible driving force of reverse exchange is brines. Brine waters can enter the aquifer in several ways. (1) Brines can naturally migrate upward through faults, and fractures because brine formations are typically highly pressurized. (2) Brines can also migrate up through poorly plugged oil-field wells. Brines can be induced to migrate upward by artificially lowering the hydrostatic head of the fresh water system. (3) Brines have probably been introduced into the Ogallala in the past due to the negligent use of "evaporation/infiltration" pits used by the oil and gas industry.(4) Brines can be forced to migrate upward by the practice of salt-water injection. In Cimarron and Texas counties the Glorieta Sandstone is the principal formation which receives injected oil-field brines. The sand facies of the Glorieta pinches out near the Texas-Beaver county border (U.S.G.S. Circular 630). The Glorieta Sandstone is therefore overpressurized and if conduits exist the brine undoubtedly migrates upward. If the Hydraulic head in the Glorieta is great enough the brines could migrate into the Ogallala aquifer. McMillion and Maxwell, 1970 show that throughout Cimarron and most of Texas Counties there is no potential for contamination due to upward migration from the Glorieta because the hydraulic head of the Glorieta is much lower than the base of the Ogallala. However, in the southeast corner of Texas County the hydraulic head in the Glorieta is greater than that of the Ogallala. Therefore, in southeast Texas

County, the potential for brines migrating into the Ogallala from the Glorieta does exist.

The southeast corner of Texas County does have the highest TDS in the study area and exhibits reverse ion exchange. However, the Na:Cl ratios are very near 1.0 or slightly above. Therefore, the conclusion is that the reverse exchange in the southeast corner of Texas County is driven by halite dissolution brines, and no conduits exist which allow brines from the Glorieta to migrate into the Ogallala.

A region in northern Texas County and in northeast Beaver County is experiencing reverse exchange. By examining the Na^+/Cl^- ratio of these areas the reverse exchange is believed to be induced by brines. The Na^+/Cl^- ratio is well below 1.0 and commonly below .05.

Halite Dissolution

It is theorized that halite within the Permian bedrock is being dissolved by the circulation of fresh groundwater and the resultant water is having an effect on ground water chemistry within the Ogallala aquifer. This theory has been substantiated and discussed within the Previous Investigations chapter of this report. The following discussion explains how the data available suggests that in fact this process is occurring and is influencing the chemistry of ground water within the Ogallala aquifer.

Two methods were used to delineate the areal extent of Ogallala ground water which is influenced by halite dissolution.

A mass balance approach was taken using the computer program BALANCE. BALANCE assumes that all chloride is contributed by the dissolution of halite (NaCl). All complete analyses were run through

BALANCE. BALANCE essentially assigns the halite dissolution value according to the chloride concentration in millimoles per liter. In order to make a better map with more definition the chloride concentration from all analyses was plotted on a base map and was contoured by SURFER (Plate 6).

The halite mass balance map is basically a plot of chloride concentration since BALANCE assigns the halite dissolution value based on the chloride concentration. The validity of this method could be questioned because it is conceivable that the concentration of ions is influenced by the saturated thickness. If this were the case it would be expected that areas of thick saturated section would show little halite dissolution due to dilution of Cl^- concentration, and areas of thin saturated section would show much halite dissolution due to more concentrated waters. This does not appear to be a factor. Areas predicted to be experiencing much halite dissolution cross thick as well as thin saturated sections of Ogallala deposits.

An X-Y plot of predicted halite dissolution (by BALANCE) vs. TDS values (Figure 9) shows that many of the elevated TDS values are related to halite dissolution (Discussed in chapter 6). Figure 9 graphically corroborates the conclusion arrived at via the factor analysis method that the TDS values are strongly influenced by halite dissolution.

The second method used to delineate zones of halite dissolution is the Na^+/Cl^- (meq/L) ratio map (Plate 5). Regions which show a Na^+/Cl^- ratio of approximately 1.0 correlate with areas predicted by BALANCE to be influenced by halite dissolution (Plate 6).

These methods predict that halite dissolution is influencing the Ogallala aquifer water chemistry in the southeast corner of Texas County

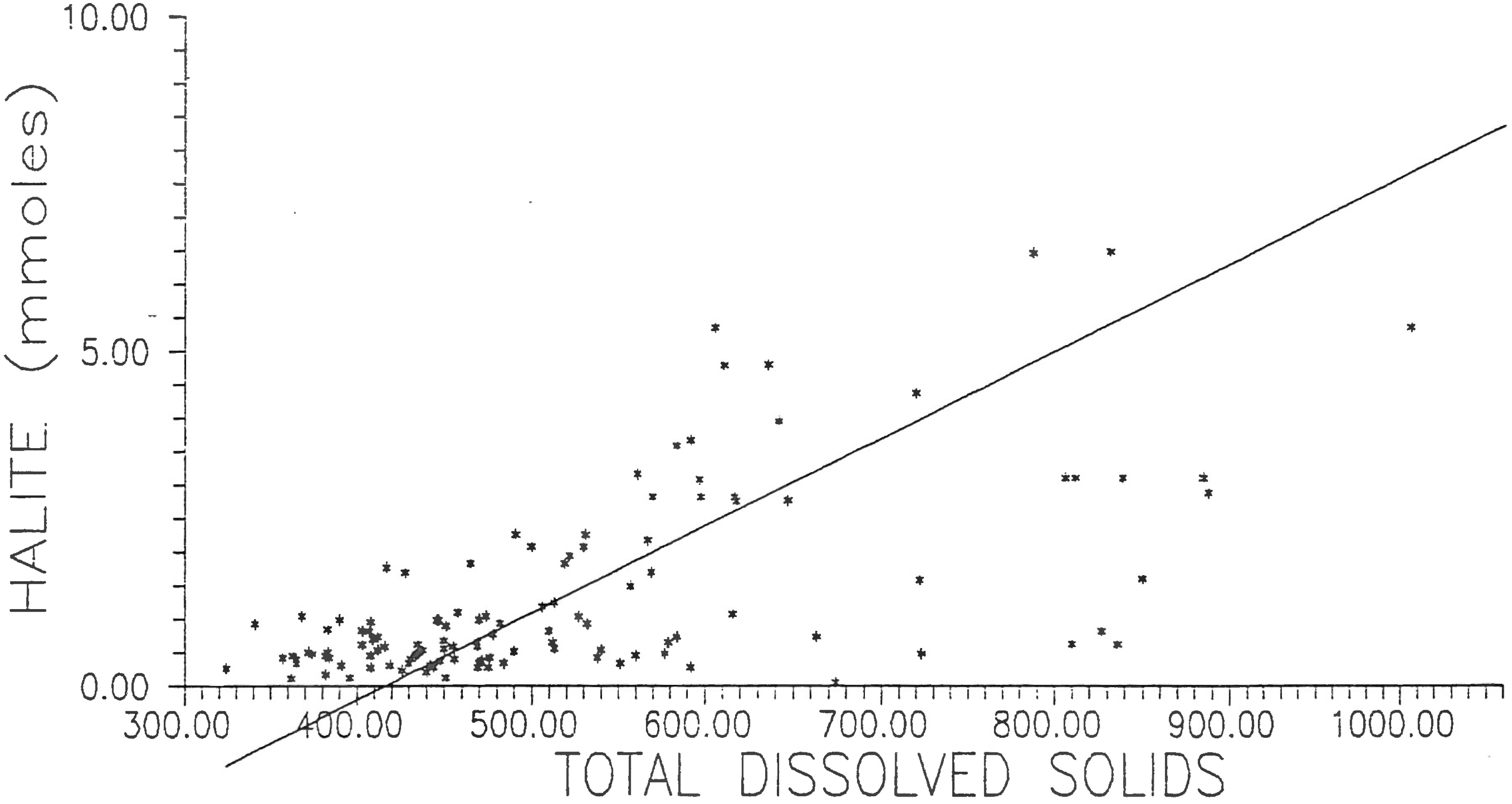


Figure 9. Halite vs. Total Dissolved Solids. Mass Balance Prediction From BALANCE.

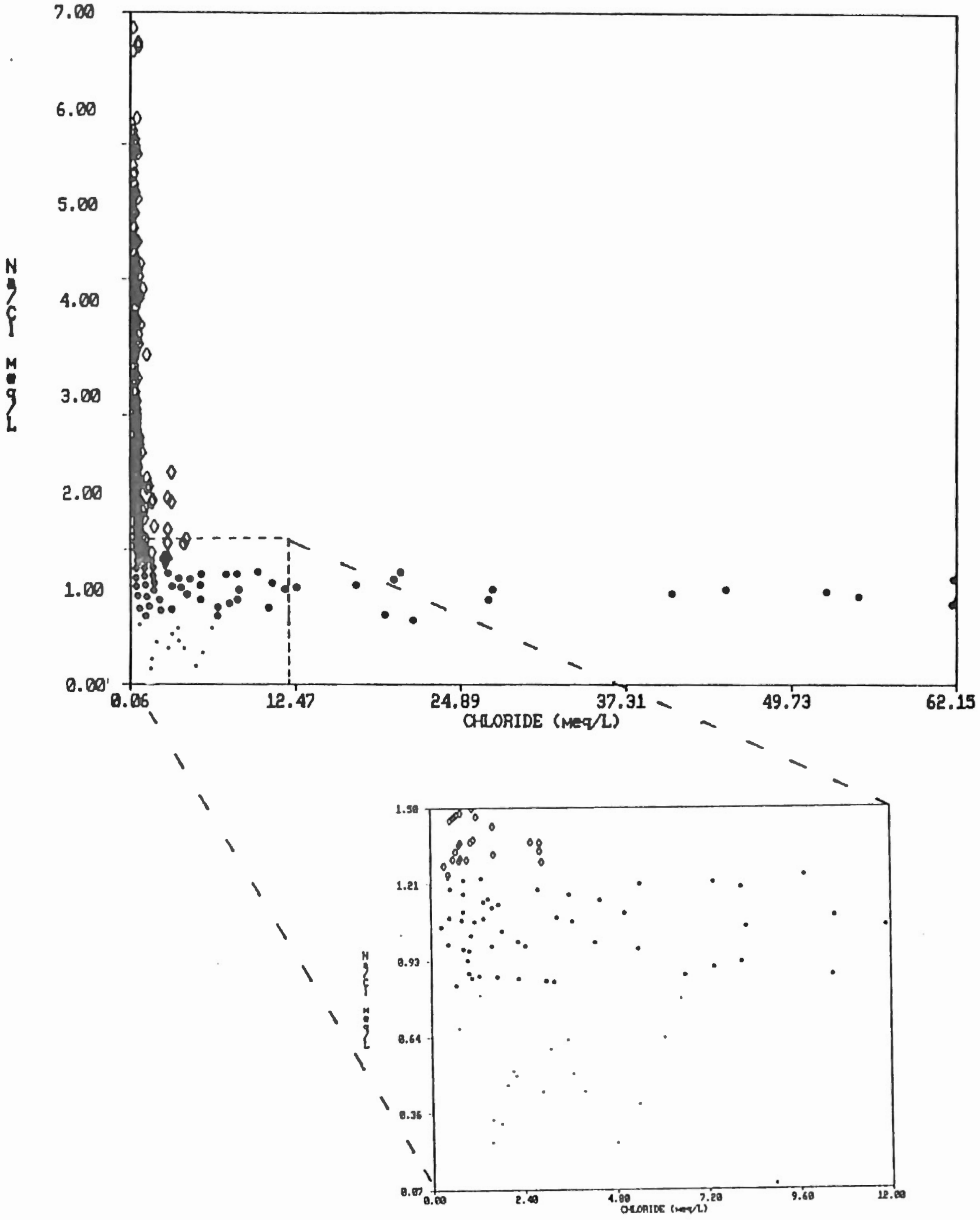
and in most of Beaver County. Coincidentally, Permian bedrock outcrops are common in southeast Texas and Throughout Beaver Counties (Plate 2).

The fact that this area is influenced by halite dissolution is supported by the TDS maps which show that elevated TDS values mimic the area influenced by halite dissolution. This implies that the dissolution of halite is the cause of elevated TDS of the groundwater. This was previously shown by the factor analysis program FACTOR which showed a strong relationship between halite dissolution and elevated TDS (Figure 10).

Figure 10 is an X-Y plot of Na^+/Cl^- vs. Cl^-. This plot effectively differentiates analyses influenced by halite dissolution, ion exchange and brines. The graph shows that in all analyses which have elevated Cl^- concentrations the Na^+/Cl^- ratio is approximately equal to 1. This graphically illustrates that elevated Cl^- values are due to halite dissolution. Analyses with Na^+/Cl^- much greater than 1 are influenced by ion exchange. Analyses with Na^+/Cl^- ratio much less than 1 are possibly influenced by oil-field brines.

Figure 11 shows that elevated TDS values are associated to elevated Cl^- values. Elevated Cl^- values have previously been related to halite dissolution. Thus, this graphically illustrates the conclusion arrived at via the mass balance method that halite dissolution is strongly influencing TDS values. Figure 11 illustrates that some analyses with TDS values up to 1160 mg/L appear to not be influenced by halite dissolution. These elevated TDS values are probably due to gypsum dissolution.

Calculation of the saturation index of halite showed that every water sample from the Ogallala was substantially undersaturated with respect to halite. This is to be expected because halite is very soluble.



◊ - analyses influenced by ion exchange

● - analyses influenced by halite dissolution

· - analyses influenced by brines

Figure 10. Na:Cl Ratio Versus Chloride

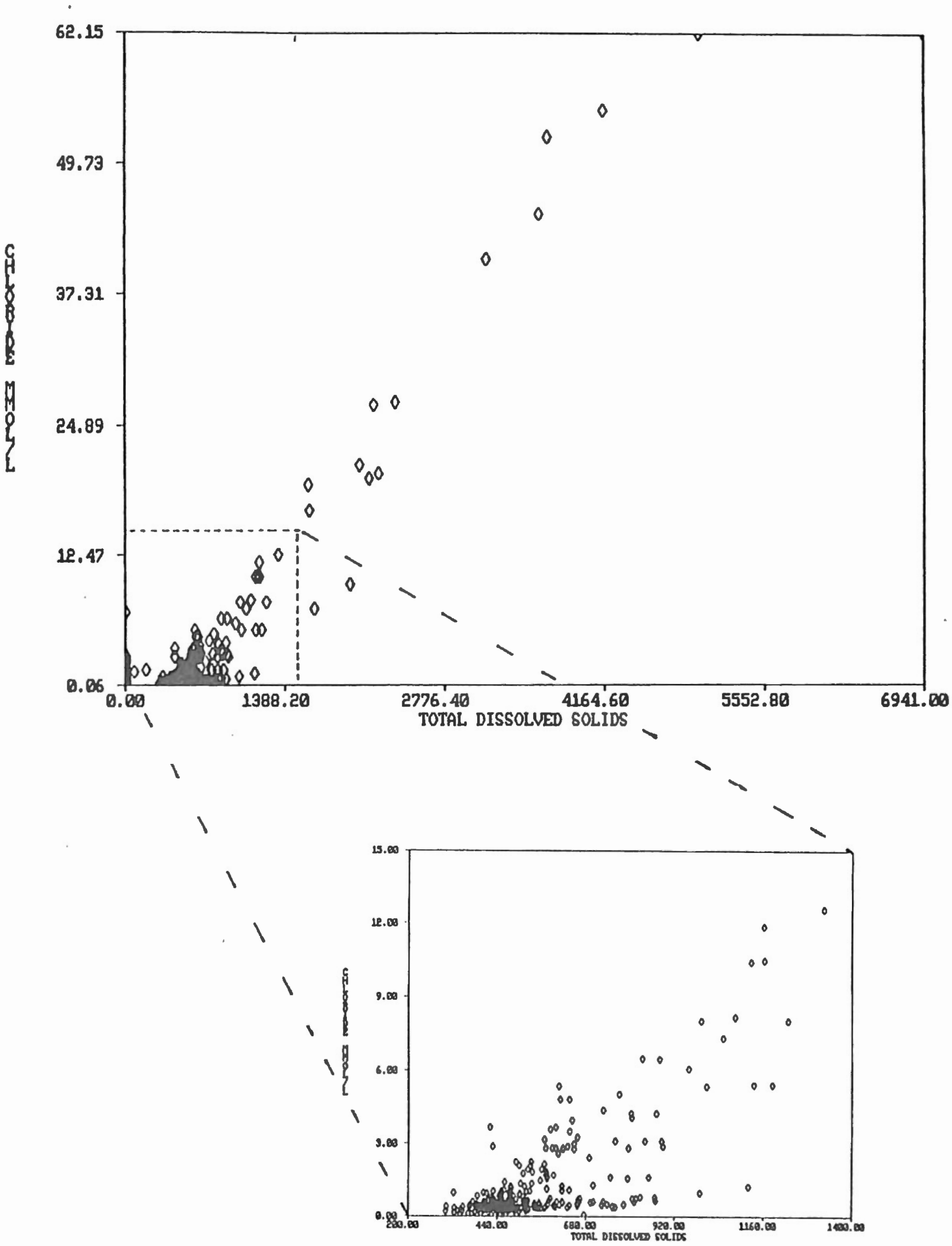


Figure 11. Chloride Versus Total Dissolved Solids

The salt zone of the Flowerpot is a possible source as well as halite beds of the Cloud Chief, Dog Creek Shale, Quartermaster Group,Whitehorse Group (Plate 1 and Chapter 7).

Gypsum/Anhydrite Dissolution

The dissolution of gypsum within Permian bedrock is believed to be an ongoing process due to the circulation of fresh groundwater from the overlying Ogallala aquifer. The dissolution of gypsum is suspected as being the source of elevated sulfate levels within Ogallala groundwater, and the driving force for the geochemical reaction of dedolomitization.

Another possible source of sulfate in the Ogallala ground water would be the oxidation pyrite (FeS_2). Pyrite is commonly associated with sediments which are deposited under reducing conditions. Reducing conditions occur in deep seas with little or no water circulation. Reducing sedimentary environments also occur as peat bogs or coal swamps where there is an abundance of organic matter and little water circulation.

If pyrite did exist within the system it would be exposed to an oxygenated environment. Pyrite (FeS_2) is unstable in an oxygenated environment, and it will dissociate releasing sulfur as sulfate ($SO4^{--}$).

The Permian and Ogallala deposits do not exhibit any sediments which were deposited under reducing sedimentary conditions. The fact that all shales are red instead of black imply oxygen rich environments. The Permian epicontinental seas were very shallow brackish to saline and oxygen rich. The Permian system and Ogallala Formation also have no coal or peat deposits. These two factors support the conclusion that sulfate within the Permian and Ogallala is not a result of the oxidation of pyrite, but from the dissolution of gypsum or anhydrite.

The mass balance program BALANCE was used to predict the amount of gypsum/anhydrite necessary to dissolve in order to account for the observed sulfate in the groundwater. Only complete analyses could be used with BALANCE. This limited the number of data points. However, in order to produce a more detailed map of gypsum dissolution the sulfate value from all analyses were used and contoured with SURFER (Plate 7).

Comparing the gypsum mass balance map (Plate 7) with the bedrock subcrop map (Plate 2) shows that only areas of the Ogallala which are directly underlain by Permian strata are influenced by the dissolution of gypsum/anhydrite. The region of gypsum dissolution includes a trend from northwest to southeast Texas County and the northwest and southwest corners of Beaver County.

Calculation of the saturation index of gypsum yielded little information because no analyses were saturated with respect to gypsum. This is to be expected because although gypsum is less soluble than halite it is more soluble than calcite and dolomite.

Krothe and Oliver, (1982) showed using sulfur isotopes that elevated concentrations of sulfate in Ogallala ground water in northeast Beaver County is due partly to influx of hydrogen sulfide (H_2S). The H_2S is thought to be entering the Ogallala through faulting in the Permian bedrock. The sulfur in the H_2S originates from gypsum in the Permian system and the sulfate released due to dissolution is reduced to H_2S gas. The H_2S is subsequently oxidized to $SO4^{=}$ within the oxidizing conditions of the Ogallala.

The scenario proposed, by Krothe and Oliver, to explain elevated sulfate concentrations seems unlikely. In order for $H_2S_{(g)}$ to form strongly reducing conditions must exist. Reducing conditions could not exist, except in very localized areas, within the Permian redbed aquifers because of the abundance of ferric iron (Fe^{+++}). Therefore, influxes of organic material (such as a petroleum seep) could induce a reducing environment but only locally. If H_2S were introduced into the Permian system from below it would be oxidized to sulfate in that system. Therefore, it is the assumption of the author that all sulfate in the Ogallala aquifer is due to the dissolution of gypsum and not the influx of hydrogen sulfide gas.

The primary Permian formation which consists of gypsum or anhydrite that could be undergoing dissolution and resultant contamination of the Ogallala is the Blaine Gypsum. But it has been documented that the undifferentiated upper Permian which consists of the Dog Creek Shale, Whitehorse Group, Cloud Chief Group and the Quartermaster Group commonly contain gypsum as a cementing agent, thin flakes, veins which intersect beds at any angle and as beds.

Dedolomitization

Within a aquifer which contains gypsum and/or anhydrite, calcite and dolomite; and where a continued circulation of water occurs, the geochemical process of dedolomitization will proceed. The continued influx of fresh water is important in any dissolution reaction because if the solution were to reach equilibrium with respect to the mineral being dissolved the process would stop.

The geochemical process of dedolomitization simply put is the dissolution of gypsum induces the precipitation of calcite which induces the dissolution of dolomite (Back et. al. 1983).

Gypsum is the most soluble of the three minerals therefore it will dissociate first and most completely.

$$(1) \quad CaSO_4 \bullet 2H_2O \text{ ---> } Ca^{++} + SO_4^{--} + 2H_2O$$

Gypsum dissociates according to equation 1 releasing calcium and sulfate ions to solution. The increase in Ca^{++} in solution results in oversaturation of the solution with respect to calcite.

$$(2) \quad CaCO_3 \text{ <---- } Ca^{++} + CO_3^{=}$$

Oversaturation with respect to calcite results in the precipitation of calcite. Equation 2 shows that the addition of Ca^{++} from gypsum forces equation 2 to the left. The precipitation of calcite removes $CO_3^{=}$ from solution thus decreasing the pH. The Ca^{++} combines with HCO_3^- releasing the hydrogen ion.

$$(3) \quad Ca^{++} + HCO_3^- \text{ ---> } CaCO_{3(s)} + H^+$$

Another perspective explains that HCO_3^- is a weak acid because it slightly dissociates in water to release the hydrogen ion and carbonate ion (equation 4).

$$(4) \quad HCO_3^- \text{ ---> } CO_3^{--} + H^+$$

If carbonate is removed from solution due to calcite precipitation more HCO_3^- will dissociate releasing more H^+. Removal of $CO_3^{=}$ in equation 4 will result in the reaction going to the right and the pH of the solution will decrease, or become more acidic.

Dolomite will be induced to dissolve in order to buffer the more acidic conditions and restore carbonate equilibrium.

$$(5)\quad CaMg(CO_3)2 \longrightarrow Ca^{++} + Mg^{++} + 2CO_3^{=}$$

Dolomite dissociates according to equation 5. The $CO3^{=}$ released combines with the excess H^+ according to equation 6.

$$(6)\quad H^+ + CO_3^{=} \longrightarrow HCO_3^-$$

This reaction neutralizes the acidity.

X-Y graphs of mass balance output provide strong evidence to support that dedolomitization is an ongoing reaction within the ground water system.

The calcite vs. gypsum graph (Figure 12) shows that as more and more gypsum dissolves more calcite precipitates. This fits the theory of dedolomitization because gypsum dissolution oversaturates the solution with respect to calcite by adding Ca^{++}.

The dolomite vs. calcite graph (Figure 13) shows that as calcite precipitates dolomite dissolves. This is predicted to occur because the precipitation of calcite removes $CO_3^{=}$ from solution and increases the acidity. Dolomite dissolves in order to buffer the acidity and restore carbonate equilibrium.

The gypsum vs. dolomite graph (Figure 14) directly shows the relationship between the two phases. Figure 14 graphically illustrates that the dissolution of gypsum induces the dissolution of dolomite.

Dissolution of dolomite releases one mole of calcium and one mole of magnesium ions. Plate 10 is a map showing the Ca^{++}/Mg^{++} ratio in milliequivalents. A ratio of one indicates dissolution of dolomite.

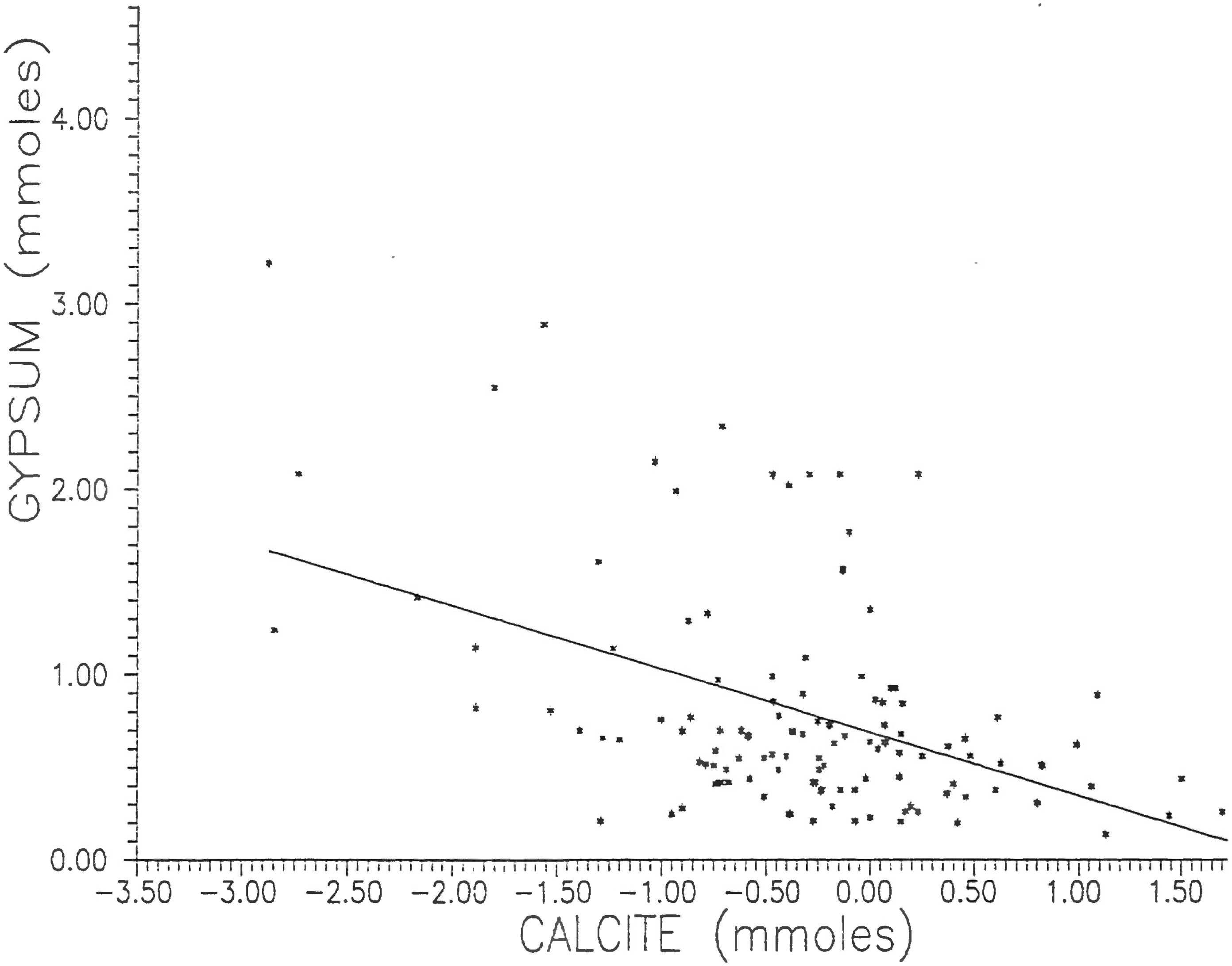


Figure 12. Gypsum vs. Calcite. Mass Balance Prediction From BALANCE.

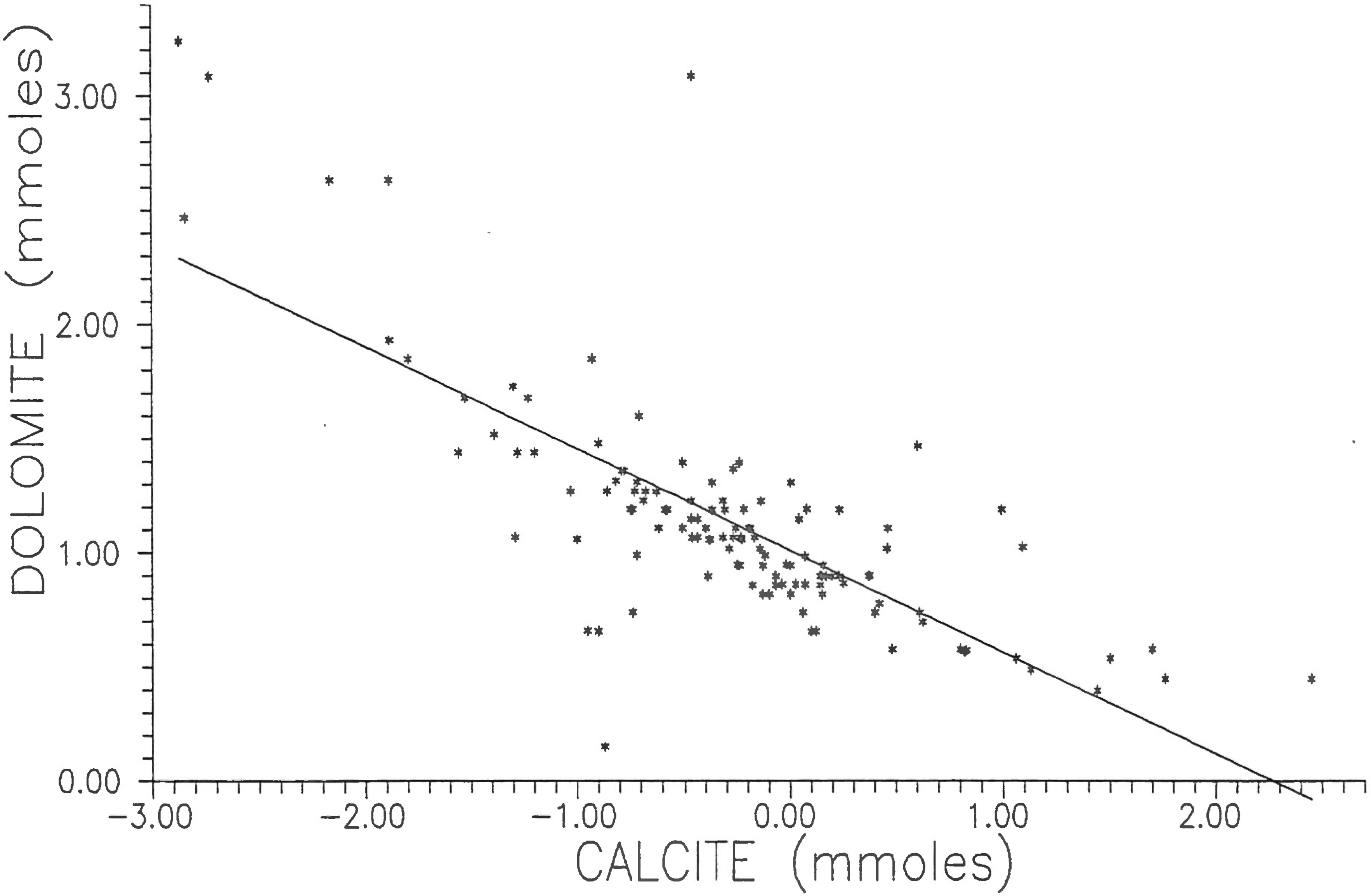


Figure 13. Dolomite vs. Calcite. Mass Balance Prediction From BALANCE.

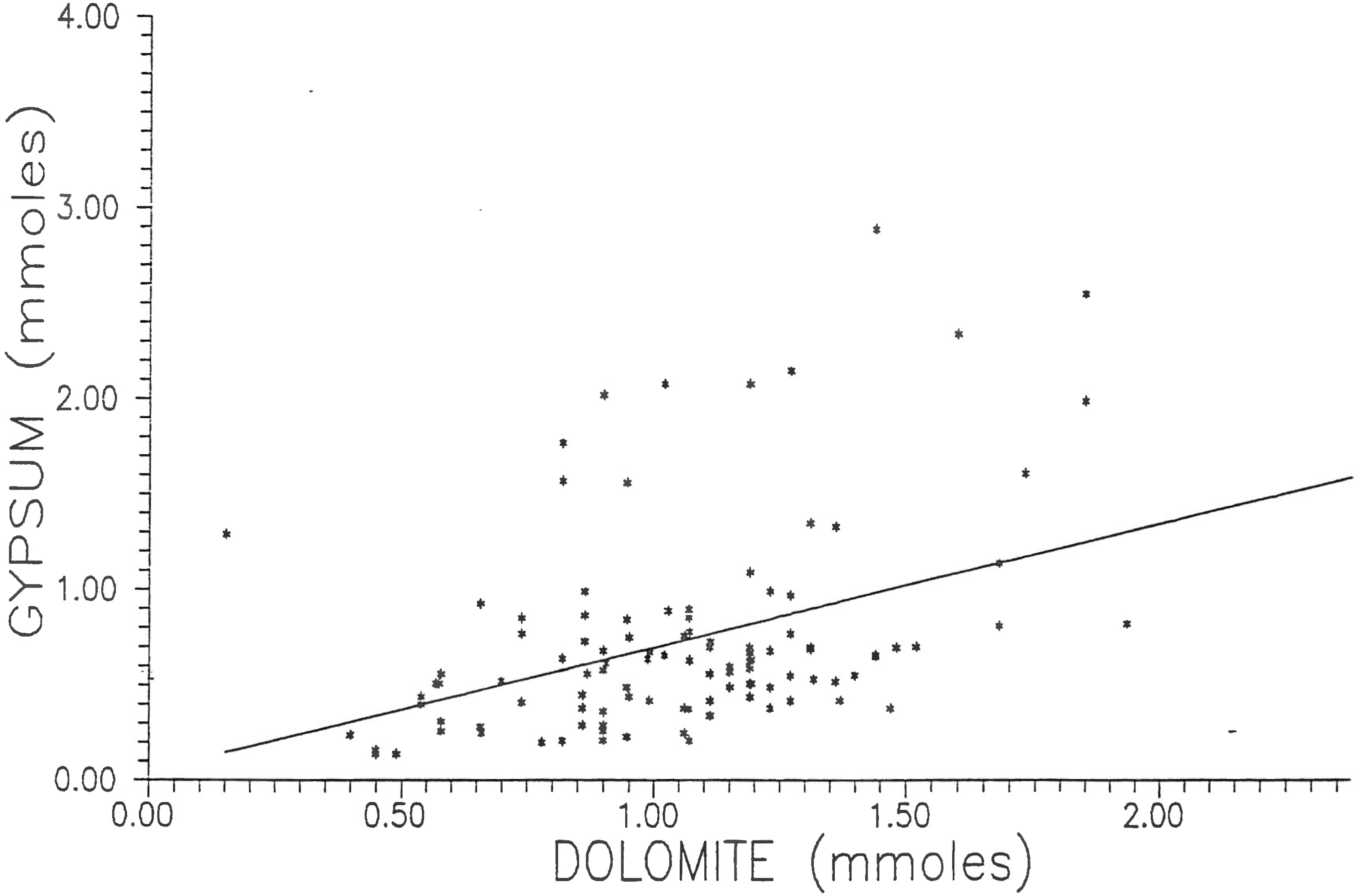


Figure 14. Gypsum vs. Dolomite. Mass Balance Prediction From BALANCE.

The dissolution of dolomite is believed to be the primary source of magnesium in the groundwater of the Ogallala. Slightly elevated Mg^{++} levels occur in several regions within the study area. Again the mass balance approach was used to predict areas experiencing dolomite dissolution. BALANCE assigns the value for dolomite dissolution directly from the magnesium concentration. The results have been mapped by SURFER Plate 8.

Discussion of Calcite

The mass balance prediction for calcite has been contoured by SURFER (Plate 9). Plate 9 shows calcite should have precipitated in most of the study area except for the western one-third of Cimarron County and central Beaver County. A zone of elevated calcite precipitation trends from northwest to southeast Texas County. This trend of elevated calcite precipitation correlates with the zone of gypsum and dolomite dissolution (Figures 7 and 8). This supports the theory that dedolomitization is occurring in this zone

Calculation of the saturation index (SI) of calcite shows that 58 of the 82 analyses were either at equilibrium or oversaturated. Analyses with a SI down to -.1 were included in this group because this is in the range of experimental error. If the pH determination is incorrect this will affect the SI value. The SI data supports the mass balance prediction that calcite precipitation is expected to have occurred within the system.

The fact that 58 of 82 analyses are oversaturated with respect to calcite raises the question, why is the ground water of a predominantly sand, gravel and clay aquifer saturated with respect to calcite?

Atmospheric CO_2 is the source of carbonate ions due to dissociation of carbonic acid (H_2CO_3) and (HCO_3^-), but what is the source of calcium ions?

Presented are three scenarios which provide a source of calcium ions which could cause supersaturation and result in calcite precipitation.

(1) The calcium enters the Ogallala during cross-formational flow. Dissolution of gypsum, limestone and dolomite within the bedrock contributes calcium ions to the Ogallala ground water.

(2) If in fact caliche layers formed throughout deposition of the Ogallala aquifer and not only recently at the surface, caliche layers in the saturated zone would maintain near equilibrium conditions in the system. Thus, rather than being the manifestation of oversaturated ground water conditions caliche could be the source which provides the Ca^{++} to make the system oversaturated.

(3) Weide, 1985 believes that most caliche layers have as a source of calcium, windblown particles which are calcareous, and calcium rich rain water. In areas with a water table near land surface this calcium could become incorporated into the groundwater instead of precipitating.

(4) Some calcium is undoubtedly in solution due to the dissolution of silicate minerals (silicate hydrolysis). However, the aquifer matrix is predominantly quartz and feldspars. Very little calcium could be contributed by these silicate minerals. The clays within the aquifer matrix are also silicate minerals which commonly have adsorbed calcium ions. However, calcium being divalent is generally strongly adsorbed and the clays act as a sink for calcium removing it from solution.

CHAPTER VIII

GEOCHEMISTRY CORRELATED TO BEDROCK

Total Dissolved Solids

As previously discussed, the Permian System has a pronounced influence on the TDS values of ground water within the Ogallala aquifer. Superimposing plate 2 and plate 3 shows that ground water in the Ogallala, above Triassic-Cretaceous bedrock, has relatively low and consistent TDS values. TDS values increase significantly in areas where the Ogallala directly overlies Permian bedrock. The mass balance and factor analysis methods show that halite dissolution has the most influence on TDS however, gypsum/anhydrite, calcite and dolomite dissolution are also contributing to the dissolved solid content.

In many cases the TDS is also apparently related to the thickness of the saturated section. Where the Permian bedrock is near to the surface (thin saturated section of Ogallala) elevated TDS values generally occur. Thick saturated sections generally exhibit lower TDS values. The increased volume of water within thick saturated sections lower TDS values by dilution whereas contributions of ions within thin saturated sections are not diluted because of the limited volume of water.

Halite Dissolution

Triassic through Cretaceous bedrock contain no halite and therefore present no reason for concern as far as contributing sodium and chloride ions to the Ogallala aquifer. As previously discussed halite was either not deposited in the Permian units above the Blaine Gypsum or has been removed by dissolution. However halite is common within the Blaine and lower Permian formations.

The most significant halite unit is the salt zone of the Flowerpot Formation, commonly called the Flowerpot Salt. As previously discussed (Chapter 3, 4, and 5) the Flowerpot Salt has experienced dissolution and this process probably continues presently. Jordan and Vosburg, 1963 as well as Morton, 1973, show the areal extent of the Flowerpot Salt (Figure 7). It exists continuously from southeast Texas County throughout most of Beaver County. The lateral extent of the Flowerpot Salt correlates exactly with the area defined in this project to be influenced by halite dissolution (Plates 5 and 6).

The halite mass balance map (Plate 6) and the Na^+/Cl^- ratio map (Plate 5) both predict that the Ogallala groundwater in southeastern Texas County and Beaver County is influenced by halite dissolution.

Three lines of evidence support the conclusion that the Flowerpot Salt is the source of halite contamination within the Ogallala aquifer. (1) The lack of halite in any formation above the Blaine Gypsum. This fact implies that the sodium and chloride come from the Flowerpot Salt, because it is the closest unit to the surface which contains halite. (2) Documented geologic situations which show that the Flowerpot Salt has experienced dissolution in the past and substantiates that this process continues presently. (3) The perfect correlation between the halite influenced zone (Plates 5 and 6) with the lateral extent of the Flowerpot Salt (Figure 7).

Ion Exchange

As previously discussed (Chapter 7) the geochemical reaction of ion exchange does influence the chemistry of groundwater in the Ogallala aquifer. Ion exchange, to some degree, influences the ground water in all of the study area but the reaction is most pronounced from south and east Cimarron County to the northwest and southwest corners of Beaver County (Plate 4).

Unlike halite dissolution and gypsum dissolution, ion exchange is not limited to either the Ogallala or the Permian system. Ion exchange could be occurring in both systems and it almost undoubtedly is. The only situation which would prevent ion exchange from occurring would be when the sodium rich clays reach equilibrium with respect to the aquifer water. This occurs over time as clays release all available sodium or when the aquifer matrix is subjected to a sodium rich water such as a brine or a halite solution. Given a water of constant chemistry moving through a clay (or any material capable of cation exchange) the clay adsorbs calcium and magnesium and releases sodium. The clay can reach a point of equilibrium and loose the capacity to exchange cations.

Because it is impossible to differentiate ion exchange which occurred in the Permian system from that which occurred in the Ogallala the detection of ion exchange does not provide any insight into the interaction of the Ogallala and the underlying system. However, reverse ion exchange does lead to interpretations of how the systems interact.

In several areas the analyses exhibit reverse ion exchange. Reverse exchange refers to the cation exchange reaction

$$(1)\ Ca^{++} + 2(Na\text{-}Clay) \longleftrightarrow Ca\text{-}Clay + 2Na^{+}$$

going from right to left (or the reverse of what is normal). This means the clay adsorbs sodium from solution and releases calcium and/or magnesium. This type of situation occurs when a solution highly concentrated with sodium such as an brine or halite solution comes into contact with a clay.

These analyses which show reverse exchange possibly represent areas of brine contamination or strong halite dissolution influence.

Reverse exchange is occurring as several small zones in Cimarron and Texas counties as well as in southeast Texas County and within a large region in Beaver county (Plate 4).

From the data previously discussed such as; Na^{+}/Cl^{-} map, halite mass balance map, and the ion exchange mass balance map it appears that it is the influence of halite dissolution waters which induces reverse ion exchange.

Gypsum/Anhydrite Dissolution

Triassic-Cretaceous bedrock contain no gypsum and/or and therefore they present no reason for concern as far as contributing sulfate to ground water of the Ogallala aquifer. Gypsum is a common constituent of almost every unit within the Permian section of the study area. Evidence previously discussed in Chapter 4 suggests that dissolution is not occurring beneath the Flowerpot-Hennessey Shale. However, evidence previously discussed indicate the units above the Flowerpot-Hennessey Shale (Flowerpot Salt, Blaine Gypsum, Dog Creek Shale, Rush Springs, Cloud Chief, and Quartermaster) are subject to dissolution. All of these units contain gypsum to varying degrees. Gypsum in these units exists as massive beds, thin lenses, cementing agents or veins filling fractures.

The location of gypsum beds within these upper Permian units is discontinuous and has not been mapped.

It has previously been shown that units as deep as the Flowerpot Salt are to some degree in hydraulic connection with the fresh water system.

The perfect correlation of the halite zone with known existence of the Flowerpot Salt substantiates the conclusion that an undefined gypsum source in fact exists and correlates with the gypsum zone defined by the mass balance method of this project (Plate 7).

Dedolomitization

As previously discussed in Chapter 7 dedolomitization is driven by the dissolution of gypsum. Therefore, the zone determined to be influenced by dolomite dissolution would be expected to correlate with the zone of gypsum dissolution. A comparison of Plates 7 and 8 show this to be the case.

The "dolomite zone" within the Ogallala extends from northwest to southeast Texas County and in the northwest and southwest corners of Beaver County. This correlates perfectly with the "gypsum zone" defined by this project.

Plates 7 and 9 along with Plate 8 provide strong evidence to support the conclusion that dedolomitization is occurring in this region because the precipitation of calcite is most pronounced in this region.

Discussion of Calcite

The Ogallala aquifer exhibits elevated values of bicarbonate ($HCO3^-$). This is partly due to the dissolution of carbonates and partly due to the system's connection to atmospheric carbon dioxide.

Calcite ($CaCO_3$) is less soluble than the evaporites. The addition of calcium ions from any source (calcite, dolomite, gypsum or anhydrite) can easily cause the system to become saturated or oversaturated with respect to calcite.

The theory of dedolomitization explains that gypsum, being more soluble than calcite, adds calcium to solution beyond the point that the solution is saturated with respect to calcite. Thus, the dissolution of gypsum induces calcite precipitation. Therefore, one would expect calcite to precipitate in the zone influenced by gypsum dissolution.

As previously discussed a mass balance approach was taken to predict areas where calcite would dissolve or precipitate. The results are presented as Plate 9. Comparison of Plate 9 with Plate 7 and Plate 8 shows that the zone of elevated calcite precipitation correlates with the zone of gypsum dissolution and with the zone of dolomite dissolution. The calcite mass balance results provides further support for the conclusion that dedolomitization is occurring in this region.

CHAPTER IX

SUMMARY AND CONCLUSIONS

The purpose of this project was to examine the hydrogeochemistry of the Ogallala aquifer, in the Oklahoma panhandle, and relate the ground water chemistry to: the mineralogy of the Ogallala and underlying formations, chemical reactions occurring in the system such as dissolution or precipitation of evaporites and carbonates, cation exchange, reverse exchange and dedolomitization.

The hypothesis and major assumption of this thesis is that the chemical composition of ground water within the Ogallala aquifer is influenced by the mineralogy of underlying bedrock. Three hundred and seventy-five ground water analyses from the Ogallala aquifer were used in order to interpret physical and chemical processes which occur in this system.

Chemical analyses were obtained predominantly from the U.S.G.S. file HYDRODATA on CD-ROM. The analyses were checked for validity via the computer program WATEVAL (Hounslow & Goff) by calculating the cation-anion balance.

The formations which make up the Miocene-Pliocene Ogallala aquifer are a remnant of a vast alluvial fan which was shed eastward from the Rocky Mountains. The Ogallala aquifer is predominantly an unconsolidated, unconfined to semiconfined system of clay, sand and gravel. In areas these deposits are overlain by consolidated caliche layers at the surface.

Previous investigations by numerous authors show that the dissolution and removal of evaporites and carbonates from within the Permian section has occurred in the past and continues to do so currently. It has been shown that this dissolution has resulted in collapse of overlying strata. Collapse, which occurred before deposition of the Ogallala, resulted in abnormally thick Tertiary deposits in these areas. Thus, dissolution influenced bedrock configuration and elevation, paleodrainage patterns, locations of abnormally thick accumulations of Tertiary deposits and present day saturated thicknesses.

The Flowerpot Salt is believed to be the principle formation, which was removed, inducing collapse. Stratigraphic evidence shows dissolution occurred before or during deposition of the Ogallala. Numerous authors also present evidence to substantiate the hypothesis that dissolution continues presently. (1) Major streams draining the region such as the Arkansas, Cimarron and Beaver Rivers carry high solute loads. (2) Brine springs, salt springs and salt pans appear along major stream valleys and throughout the Permian basin, especially in areas where no Ogallala deposits exist.

Stratigraphic studies such as structural contour maps on laterally continuous marker units show that Permian formations below the Flowerpot-Hennessey Shales have not undergone dissolution and removal because of the apparent lack of faulting and collapse.

The Glorieta Sandstone is the deepest Permian formation of concern. The Glorieta undoubtedly contains highly mineralized water naturally. Within much of the study area the Glorieta is used as an oil-field brine disposal reservoir. If hydraulic connections exist such as fracturing or poorly plugged wells the potential does exist for the water from the Glorieta to migrate upward and into the Ogallala aquifer.

The Flowerpot Salt is up to 500 feet of nearly pure halite. Stratigraphic studies show that it exists throughout most of Beaver County but only localized remnants exist in Texas and Cimarron Counties. The discontinuity appears not to be stratigraphic because structural contour maps on the base of the Blaine shows that the it appears to drape the Flowerpot Salt. These two factors suggest that the Flowerpot Salt has undergone substantial dissolution and removal. Where the salt is absent the base of the Blaine is abruptly 200-500 feet lower. Structural contour maps on the surface of the bedrock show that the entire Permian section above the Flowerpot Shale has subsided where the salt zone is absent. This leads to the interpretation that all units above the Flowerpot Salt subsided into the void created by dissolution and removal of the Flowerpot Salt. Most dissolution must have occurred after Late Permian and no later than during the deposition of the Miocene-Pliocene Ogallala Formation. It is very probable that the Flowerpot Salt continues to undergo dissolution.

The formations above the Flowerpot Salt include the Quatermaster Group, Cloud Chief Group, Dog Creek Shale and the Whitehorse Group. These upper Permian units do contain substantial amounts of gypsum, anhydrite, limestone and dolomite, but very little or no halite. It is most likely that halite, being the most soluble, was initially deposited and has since been removed by dissolution. These units are viewed as the most likely source of elevated sulfate values in the Ogallala aquifer.

Triassic, Jurassic and Cretaceous strata exist in the subsurface above Permian strata and beneath the Ogallala aquifer from central Texas

County westward. These units thin to a feather edge in Texas County and thicken westward. These units apparently act as a aquiclude protecting the ground water within the Ogallala from highly mineralized ground water in the Permian formations.

A mass balance approach was used to help define and quantify chemical reactions between ground water and the aquifer. The Fortran computer program BALANCE (Parkhurst et al., 1982) was used to calculate the amount of ions entering or leaving the aqueous phase necessary to account for the observed chemical composition of the water samples. The phases used include: calcite, dolomite, halite, gypsum, ion exchange and carbon dioxide. Output from BALANCE is quantitative values of each phase.

In order to exhibit correlations between phases, the phases were plotted against each other on X-Y graphs, according to the amount of each respective phase as determined by BALANCE. The X-Y graphs indicate that: halite-TDS, calcite-gypsum, calcite-dolomite and gypsum-dolomite show significant correlations. These X-Y graphs lead to the interpretation that TDS of ground water in the study area is strongly related to the dissolution of halite. The X-Y graphs also provide support for the hypothesis that dedolomitization is occurring within the system.

Output from BALANCE was also used to create a contour map of halite, calcite, dolomite, gypsum and ion exchange. The value assigned to each of these phases was plotted on base maps and the data was contoured by the computer program SURFER (Golden Software, Inc.). These maps proved to be very valuable because they effectively delineate where within the study area each phases is contributing or consuming their respective ions.

Factor analysis was also used to analyze ground water quality data and make hydrogeologic interpretations. The output from BALANCE was run through the factor analysis program FACTOR (Hounslow). This approach was used to point out and quantify patterns of phase interrelation. Factor analysis indicates that the TDS is related to the phase halite. This leads to the interpretation that dissolution of Permian halite is presently occurring and the resultant waters are migrating into the Ogallala aquifer.

Factor analysis also indicates that calcite and dolomite have a inverse relationship. The interpretation is that the precipitation of calcite induces dissolution of dolomite. Therefore, factor analysis corroborates the interpretations made via the X-Y graphs of mass balance output.

Ratios of ions were used extensively during this project in order to help identify source rock lithologies and chemical reactions which occur between ground water and the aquifer matrix. The most useful ratio proved to be Na^+/Cl^-. This ratio, of each analyses, was plotted on a base map and the data was contoured. This map helped delineate where ground water was influenced by cation exchange, halite dissolution and brines.

The computer program WATEQF (U.S. Geological Survey) was used to calculate the saturation indices with respect to calcite, dolomite, gypsum and halite for each complete analysis. No analyses were found to be saturated with respect to gypsum and halite. Seventy-two percent of the analyses were saturated with respect to calcite, and 35% were saturated with respect to dolomite.

The computer program WATEVAL (Hounslow & Goff) was used to plot all analyses on Piper plots. The data was divided into three groups according to county in order to show regional variations of the major cations and anions. The regional variations along with knowledge of the geologic system did not provide enough information to arrive at any conclusions. Results of the Piper plots led to the hypotheses that gypsum dissolution in Texas County and halite dissolution in Beaver County influences ground-water chemistry within the Ogallala aquifer. This data corroborates conclusions arrived at via other methods.

A TDS contour map was produced for the study area. This map shows regional variation of the dissolved solid content of ground water within the Ogallala aquifer. Superimposing the TDS map on bedrock subcrop map shows areas of the Ogallala, which directly overlie Permian bedrock, have much higher TDS values than does the Ogallala which directly overlies Mesozoic strata. This suggests that soluble evaporites and carbonates within the Permian system are being dissolved and that this process is influencing ground water chemistry within the Ogallala aquifer, and that Mesozoic strata acts as a aquitard protecting the Ogallala from highly mineralized Permian ground water. The TDS map proves that the Ogallala is not simply a sand and gravel aquifer overlying an irrelevant impermeable aquitard.

Ion exchange is a geochemical reaction between clays and the ground water. During the ion exchange reaction, clays exchange the univalent sodium ion for divalent calcium and/or magnesium ions releasing sodium into solution. Two methods were used to delineate regions where ion exchange is an important factor controlling the chemistry of the ground water. A mass balance approach was taken using the computer program BALANCE. The ion exchange reaction was quantified by BALANCE. The results were plotted on a base map and contoured to show regional trends.The Na^+/Cl^- ratio map also delineated zones of ion exchange. This method is effective because the ion exchange reaction contributes only sodium to solution thus increasing the ratio. Both of these methods show that ion exchange is most pronounced in extreme eastern Cimarron County, throughout most of Texas County and in the northwest and southwest corners of Beaver County.

The ion exchange mass balance map delineates several zones where reverse cation exchange is predicted to be influencing the ground water chemistry. Reverse exchange refers to clays adsorbing sodium from solution and releasing calcium and/or magnesium ions. Reverse exchange is induced when sodium rich waters such as brines or halite solution come into contact with cation exchangers. The Na^+/Cl^- ratio map was used to predict whether halite waters or brines induced this reverse exchange. In most of these zones the Na^+/Cl^- ratio is approximately 1.0 therefore, if in fact reverse exchange is occurring it was induced by halite solutions. However, in northeast Beaver County and northeast Texas County the Na^+/Cl^- ratio was less than 0.5. This implies that brines may be inducing reverse exchange.

It has been documented by previous investigations that halite in the Permian system is being dissolved by circulating fresh ground water. It has also been documented that this process contributes substantial amounts of sodium and chloride to surface waters draining the region. Two methods were used to show the areal extent of Ogallala ground water which is influenced by halite dissolution. A mass balance calculation using BALANCE was made assuming that all chloride in solution was contributed by halite.The output was plotted on a base map and contoured. The second method used to delineate areas influenced by halite dissolution is the Na^+/Cl^- ratio map. When halite dissolved it yields one mole of sodium and one mole of chloride therefore areas with a Na^+/Cl^- ratio of approximately 1.0 are assumed to be influenced by halite dissolution. Both methods predict that this process is influencing ground water in southeast Texas County and in much of Beaver County.

Just as Permain halite dissolution influences Ogallala ground-water chemistry Permian gypsum and/or anhydrite dissolution does also. It is believed that gypsum dissolution contributes calcium and sulfate ions to the Ogallala aquifer and that this process is the driving force for the geochemical reaction of dedolomitization. The mass balance program BALANCE was used to predict the amount of gypsum and/or anhydrite necessary to dissolve in order to account for the observed sulfate in the analyses. Again, a contour map was created using BALANCE output to show where gypsum dissolution influences the Ogallala aquifer. The map shows a trend of pronounced gypsum dissolution from northwest to southeast Texas County and in northwest Beaver County.

Within a aquifer which contains gypsum, calcite and dolomite and where a continued circulation of water occurs the geochemical reaction of dedolomitization will proceed. Dedolomitization simply put is the dissolution of gypsum inducing the precipitation of calcite which in turn induces the dissolution of dolomite. X-Y graphs, of mass balance output, provide strong evidence suggesting that dedolomitization is an ongoing process within this system. The graphs infer dedolomitization because of the relationships between the minerals. Figure 13 shows that as gypsum dissolves calcite precipitates. Figure 14 shows that as calcite precipitates dolomite dissolves. Figure 15 shows that as gypsum dissolves dolomite dissolves. These relationships are consistent with the process of dedolomitization. A contour map was made of the mass balance output of dolomite. The map delineated a zone from northwest to southeast Texas

County and in the southwest corner of Beaver County. This region correlates strongly with the region defined as experiencing anomalously high gypsum dissolution and calcite precipitation. This supports the hypothesis that dedolomitization is occurring because these reactions occur in the same region.

The following conclusions have been made as a result of this study:

1) Evidence from structural contour maps, stratigraphic studies and water chemistry of the Ogallala formation led to the conclusion; evaporites and carbonates within the upper Permian System overlying the Flowerpot Salt are susceptible to dissolution and removal. This process does influence the ground-water chemistry of the Ogallala aquifer. Units above the Flowerpot-Hennessey Shale are, to some degree, in hydraulic connection to the Ogallala and are therefore susceptible to dissolution.

2) The absence of halite in the upper Permian strata leads to the interpretation that halite, being the most soluble evaporite, has been dissolved and removed from this strata. This corroborates the previous conclusion that the upper Permian bedrock is, to some degree, hydraulically connected to the Ogallala Formation and is susceptible to dissolution.

3) Superimposing the TDS and the subcrop map shows that the concentration of dissolved solids where the Ogallala directly overlies Mesozoic strata is relatively low and TDS values are substantially elevated where the Ogallala directly overlies Permian bedrock. Therefore, Triassic through Cretaceous strata act as a buffer protecting the Ogallala from the highly mineralized ground water in Permian formations.

4) Ion exchange, a geochemical reaction which contributes sodium to solution while removing calcium and magnesium, occurs between ground

water and clays within the aquifer matrix. The mass balance and the Na^+/Cl^- ratio maps both quantify and show the aerial extent where ion exchange is influencing the ground water chemistry. Ion exchange increases the Na^+/Cl^- ratio in most of Cimarron and Texas Counties.

5) Ion exchange, which occurs between the ground water and the aquifer matrix, halite dissolution waters, which migrate upward into the Ogallala aquifer from Permian formations, and possible brine waters all dictate the Na^+/Cl^- ratio of ground water in the Ogallala aquifer.

6) Elevated levels of sulfate, in the Ogallala aquifer, led to the interpretation that dissolution of Permian gypsum and/or anhydrite influences Ogallala ground water in a northwest-southeast trend through Texas County. The Piper plot implies this and the gypsum mass balance contour map delineates the area of influence.

7) Results of: the TDS map, the halite mass balance map, the Na^+/Cl^- ratio map, and Piper diagrams led to the conclusion that elevated TDS values and elevated chloride concentrations, in the eastern third of the study area, are the result of the dissolution of Permian halite and the migration of resultant waters into the Ogallala aquifer. Factor analysis shows a strong correlation between chloride and TDS indicating that the dissolution of halite is strongly influential in determining the TDS of ground water in the Ogallala aquifer.

8) The dolomite mass balance contour map shows that a northwest-southeast trend through Texas County is influenced by Permian dolomite dissolution.

9) The calcite mass balance map delineates a region, which extends from northwest to southeast Texas County, where an relatively large

amount of calcite is expected to precipitate. WATEQF determined that 72% analyses were at equilibrium or over saturated with respect to calcite.

10) The mass balance maps show that gypsum and dolomite dissolution occurs in the same region that excess calcite precipitates. This provides strong support for the theory that dedolomitization occurs in a zone from northwest to southeast Texas County.

11) The areal extent of the Flowerpot Salt correlates perfectly with the region defined, by this project, to be influenced by halite dissolution waters. This leads to the conclusion that the Flowerpot Salt continues to undergo dissolution and that it is the Flowerpot Salt which contributes sodium and chloride ions to the Ogallala aquifer in the eastern third of the study area.

SELECTED BIBLIOGRAPHY

Ashley, R. P., and Lloyd, J. W., 1978, An Example of the Use of Factor Analysis and Cluster Analysis in Groundwater Chemistry Interpretation: Journal of Hydrology, 39(1978) p. 355-364.

Back, W., Hanshaw, Plummer, Rahn, 1983, Process and Rate of Dedolomitization: Mass Transfer and ^{14}C Dating in a Regional Carbonate Aquifer: Geological Society of America Bulletin, V. 94, p. 1415-1429, December 1983.

Carter, Brian J., 1991, Soils and Soil Parent Materials in Northwest Oklahoma: Guidebook 9th Annual Meeting., South-Central Friends of the Pleistocene, May 1991.

Chapelle, Francis H., 1983, Groundwater Geochemistry and Calcite Cementation of the Aquia Aquifer in Southern Maryland: Water Resources Research, Vol. 19, No. 2, p. 545-558.

Dalton, Matthew G., and Upchurch, Sam B., 1978, Interpretation of Hydrochemical Facies by Factor Analysis: Ground Water, Vol, 16, No. 4, p. 228-233, July-August 1978.

Dixon, George H., Paleotectonic Investigations of the Permian System in the United States

Gomis, Ruiz., and Blasco, P., 1990, Application of Factor Analysis to the Hydrogeochemical Study of a Coastal Aquifer: Journal of Hydrology, 119 (1990) 169-177.

Gould, Chas. N., 1925, Index to the Stratigraphy of Oklahoma: Oklahoma Geological Survey Bulletin No. 35.

Gould, Chas. N., and Lonsdale, John T., 1926, Geology of Texas County Oklahoma: Oklahoma Geological Survey Bulletin No. 37.

Gould, Chas. N., and Lonsdale, John T., 1926, Geology of Beaver County Oklahoma: Oklahoma Geological Survey Bulletin No. 38.

Gustavson, Thomas C., 1986, Geomorphic Development of the Canadian River Valley, Texas Panhandle: An Example of Regional Salt Dissolution and Subsidence: Geological Society of America Bulletin, v.97, p.459-472.

Gustavson, Thomas C., 1986, Geomorphology and Quaternary Stratigraphy of the Rolling Plains, Texas Panhandle: Bureau of Economic Geology, Guidebook 22.

Gustavson, Thomas C., and Winkler, Dale A., 1988, Depositional facies of the Miocene-Pliocene Ogallala Formation, Northwestern Texas and Eastern New Mexico: Geology v. 16, p. 203-206, Mardch 1988.

Hart, D. L., Hoffman, G. L., and Goemaat R. L., 1975, Geohydrology of the Oklahoma Panhandle, Beaver, Cimarron, and Texas Counties: U.S.G.S. Water Resources Investigation 25-75.

Havens, John S., 1981, Generalized Altitude and Configuration of the Base of the High Plains Regional Aquifer, Northwestern Oklahoma: U.S.G.S. Water-Resources Investigations Open-File Report 81-1117.

Havens, John S.,1982, Saturated Thickness of the High Plains Regional Aquifer in 1980, Northwestern Oklahoma: U.S.G.S. Water-Resources Investigations Open-File Report 82-760.

Havens, John S., 1982, Altitude and Configuration of the Predevelopment Water Table in the High Plains Regional Aquifer, Northwestern Oklahoma: U.S.G.S. Water-Resources Investigations Open-File Report 82-275.

Hem, John D., 1989, Study and Interpretation of the Chemical Characteristics of Natural Water: U.S.G.S. Water-Supply Paper 2254.

Irwin, James., and Morton, Robert B., 1969, Hydrogeologic Information on the Glorieta Sandstone and the Ogallala Formation in the Oklahoma Panhandle and Adjoining Areas as Related to Underground Waste Disposal: U.S.G.S. Circular 630.

Johnson, Kenneth S., 1989, Salt Dissolution, Interstratal Karst, and Ground Subsidence in the Northern Part of the Texas on Sinkholes and the Engineering and Environmental Impacts of Karst St. Pertersburg Beach/Florida, 1989.

Johnson, Kenneth S., 1981, Dissolution of Salt on the East Flank of the Permian Basin in the Southwestern U.S.A.: Journal of Hydrology, 54(1981) p. 75-93.

Johnson, Kenneth S., 1991, Exploitation of the Tertiary-Quaternary Ogallala Aquifer in the High Plains of Texas, Oklahoma, and New Mexico, Southwestern U.S.A.:

Jordan, L., and Vosburg, D. L., 1963, Permian Salt and Associated Evaporites in the Anadarko Basin of the Western Oklahoma-Texas Panhandle Region, Oklahoma Geological Survey Bulletin 102.

Kastner, William., 1984, Ogallala Aquifer Study, Ogallala Aquifer Symposium (2nd: 1984 : Texas Tech Univ.) Proceedings of the Ogallala Aquifer SymposiumII.

Kreitler, Charles W., Dutton, Alan R., 1984, Hydrogeology of the Palo Duro Basin: Interactions with the Ogallala Aquifer. Proceedings of the Ogallala Aquifer Symposium II (2nd :1984: Texas Tech University)

Krothe, Noel C., and Oliver, Joseph W., 1982, Sulfur Isotopic composition and Water Chemistry in Water From the High Plains Aquifer, Oklahoma Panhandle and Southwestern Kansas: U.S.G.S. Water-Resources Investigations 82-12.

Krothe, Noel C., Oliver, Joseph W., and Weeks, John B., 1982, Dissolved Solids and Sodium in Water From the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S.G.S. Hydrologic Investigations Atlas HA-658.

Dutton, Alan R., Richter, Bernd C., and Kreitler, Charles W., 1989, Brine Discharge and Salinization, Concho River Watershed, West Texas: Ground Water, May-June 1989, Vol. 27, No.3, p.375-383.

McKee, Edwin D., and Oriel, Stephen., 1967, Paleotectonic Maps of the Permain System: U.S.G.S. Miscellaneous Geologic Investigations Map I-450.

McMillion, Leslie G., and Maxwell, Bruce W., 1970, Determination of Pollutional Potential of the Ogallala Aquifer by Salt-Water Injection: Robert S. Kerr Water Research Center.

Marine, Wendell I., and Schoff, Stuart L., 1962, Ground-Water Resources of Beaver County, Oklahoma: Oklahoma Geological Survey Bulletin No. 97.

Morton, R. B., and Goemaat, 1973, Reconnaissance of the Water Resources of Beaver County, Oklahoma: U.S.G.S. Hydrologic I nvestigations Atlas HA-450.

Morton, Robert B., 1973, Preliminary Investigations of the Hydrogeology of the Permian to Tertiary Rocks of the Oklahoma Panhandle: U.S.G.S. Miscellaneous Geologic Investigations Map I-738.

Nativ, Ronit., 1988, Hydrogeology and Hydrochemistry of the Ogalala Aquifer, Southern High Plains, Texas Panhandle and Eastern New Mexico: Texas Bureau of Economic Geology Report of Investigations No. 177.

Parkhurst, David L., Plummer, Niel L., and Thorstenson, Donald C., 1982, BALANCE- A Computer Program for Calculating Mass Transfer for Geochemical Reactions in Ground Water: U.S.G.S. Water-Resources Investigations 82-14.

Plummer, Niel L., and Back, William., 1980, The Mass Balance Approach: Application to Interpreting the Chemical Evolution of Hydrologic Systems: American Journal of Science, Vol. 280, February, 1980, p. 130-142.

Reeves, C. C. Jr., 1976, Caliche:

Reeves, C. C., Jr., 1984, The Ogallala Depositional Mystery, Proceedings of the Ogallala Aquifer Symposium II (2nd : 1984: Texas Tech University).

Richter, Bernd C., and Kreitler, Charles W., 1987, Sources of Ground Water Salinization in Parts of West Texas: Ground Water Monitoring Review, Fall 1987, p. 75-84.

Richter, Bernd C., and Kreitler, Charles W., 1986, Geochemistry of Salt Water Beneath the Rolling Plains, North-Central Texas: Ground Water, Vol. 24, No. 6, November-December 1986, p. 735.

Sapik, D. B., and Goemaat, R. L., 1973, Reconnaissance of the Ground-Water Resources of Cimarron County, Oklahoma: U.S.G.S. Hydrologic Investigations Atlas HA-373.

Schoff, Stuart L., 1943, Geology and Ground Water Resources of Cimarron County, Oklahoma: Oklahoma Geological Survey Bulletin No. 64.

Schoff, Stuart L., 1939, Geology and Ground Water Resources of Texas County Oklahoma: Oklahoma Geological Survey Bulletin No. 59.

Weeks, John B., and Gutentag, Edwin D., 1981, Bedrock Geology, Altitude of Base, and 1980 Saturated Thickness of the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S.G.S. Hydrologic Investigations Atlas HA-648.

Weeks, John B., and Gutentag, Edwin B., 1984, The High Plains Regional Aquifer--Geohydrology, Proceedings of the Ogallala Aquifer Symposium II (2nd : 1984: Texas Tech University).

Wood, P. R., and Hart, D. L., 1967, Availability of Ground Water in Texas County, Oklahoma: U.S.G.S. Hydrologic Investigations Atlas HA-250.

APPENDIXES

APPENDIX A

WATER QUALITY DATA

WELL NUMBER	LOCATION	SPECIFIC CONDUCTANCE	pH	HCO3- mg/L	HCO3- meq/L	CA++ mg/L
1	T1N-R4E-25	554	7.9	236	3.87	
2	T1N-R2E-19	353	7.9	180	2.95	
3	T1N-R1E-28	386	8.1	196	3.21	
4	T1N-R5E-20	515	8.2	234	3.84	
5	T1N-R5E-20	499	8.1	236	3.87	
6	T1N-R7E-18	566	7.6	272	4.46	
7	T1N-R2E-10	442	7.5	234	3.84	48
8	T2N-R7E-26	490	7.8	222	3.64	
9	T2N-R7E-26	505	8.2	232	3.80	
10	T2N-R8E-21	514	8.1	228	3.74	
11	T2N-R8E-21	530	8	230	3.77	
12	T2N-R8E-19	507	8.2	226	3.70	
13	T2N-R7E-15	508	8.2	214	3.51	
14	T2N-R8E-16	553	8.1	238	3.90	
15	T2N-R8E-16	541	8.2	232	3.80	
16	T2N-R7E-10	458	8.2	212	3.48	
17	T2N-R7E-9	488	8.3	216	3.54	
18	T2N-R6E-12	514	7.7	228	3.74	
19	T2N-T7E-9	473	7.8	232	3.80	
20	T2N-R5E-2	516	8	234	3.84	
21	T2N-R7E-6	508	8	244	4.00	
22	T2N-R7E-6	482	8.1	204	3.34	
23	T3N-R6E-33	470	8.1	208	3.41	
24	T3N-R6E-33	496	8	200	3.28	
25	T3N-R6E-33	493	7.9	204	3.34	
26	T3N-R6E-33	495	8.1	204	3.34	
27	T3N-R7E-32	472	7.8	220	3.61	27
28	T3N-R4E-28	531	8.1	218	3.57	
29	T3N-R4E-23	539	8.2	216	3.54	
30	T3N-R7E-20	528	8.2	286	4.69	
31	T3N-R5E-13	474	8.1	204	3.34	
32	T3N-R5E-16	385	8.1	196	3.21	
33	T3N-R6E-15	433	8.5	182	2.98	
34	T3N-R5E-10	516	8.1	218	3.57	
35	T3N-R3E-11	497	7.9	218	3.57	
36	T3N-R4E-2	555	7.4	230	3.77	49
37	T3N-R4E-30	566	8.2	262	4.30	
38	T4N-R5E-34	465	7.6	220	3.61	34
39	T4N-R5E-36	452	7.7	204	3.34	
40	T4N-R7E-16	570	7.5	220	3.61	35
41	T4N-R7E-16	460	8	212	3.48	33
42	T4N-R7E-8	456	8	208	3.41	25
43	T4N-R3E-12			276	4.52	30
44	T4N-R7E-1	482	7.6	210	3.44	34
45	T4N-R7E-5	449	8	194	3.18	

WELL NUMBER	LOCATION	SPECIFIC CONDUCTANCE	pH	HCO3- mg/L	HCO3- meq/L	CA++ mg/L
46	T5N-R8E-24	525	7.4	210	3.44	40
47	T5N-R9E-14	408	7.5	240	3.93	25
48	T1N-R4E-28	450	7.5	217	3.56	47
49	T1N-R1E-24	280	7.4	184	3.02	39
50	T2N-R7E-13	400	7.7	232	3.80	42
51	T3N-R3E-11	500	7.8	292	4.79	37
52	T3N-R5E-11	600	7.3	274	4.49	61
53	T3N-R9E-23	352	7.9	260	4.26	26
54	T4N-R4E-34	450	7.5	247	4.05	41
55	T4N-R7E-15	370	7.7	220	3.61	34
56	T3N-R7E-32	472	7.8	220	3.61	27
57	T5N-R9E-19	525	7.4	210	3.44	40
58	T5N-R9E-13	408	7.5	240	3.93	25
59	T4N-R7E-21	570	7.4	220	3.61	35
60	T4N-R8E-8	482	7.6	210	3.44	34
61	T3N-R4E-3	555	7.4	230	3.77	49
62	T3N-R5E-2	465	7.6	220	3.61	34
63	T1N-R1E-28	386		196	3.21	
64	T1N-R2E-10	442		234	3.84	48
65	T1N-R4E-25	554		236	3.87	
66	T1N-R5E-20	500		236	3.87	
67	T1N-R7E-18	523		272	4.46	
68	T1N-R9E-15			207	3.39	39
69	T2N-R3E-1			259	4.25	
70	T2N-R5E-2	516		234	3.84	
71	T2N-R7E-10	458		212	3.48	
72	T2N-R8E-19	508		226	3.70	
73	T3N-R3E-11	498		218	3.57	
74	T3N-R4E-23	539		216	3.54	
75	T3N-R5E-10	517		218	3.57	
76	T3N-R6E-33	496		200	3.28	
77	T3N-R7E-20	528		286	4.69	
78	T4N-R5E-36			204	3.34	
79	T4N-R7E-5	449		194	3.18	
80	T1N-R18E-14	3099	7.5	252	4.13	
81	T1N-R16E-31	515	8.2	226	3.70	
82	T1N-R17E-30	660	7.5	230	3.77	
83	T2N-R11E-31	459	8	212	3.48	
84	T2N-R18E-32	662	8.1	252	4.13	
85	T2N-R18E-27	518	7.9	230	3.77	
86	T2N-R18E-28	689	7.9	244	4.00	
87	T2N-R18E-28	752	8.1	232	3.80	
88	T2N-R17E-22	892	7.9	258	4.23	
89	T2N-R14E-23	534	8	240	3.93	
90	T2N-R18E-22	703	7.9	246	4.03	
91	T2N-R18E-24	5949	7.9	268	4.39	
92	T2N-R18E-24	6259	5.6	6	0.10	
93	T2N-R15E-15	571	8.1	226	3.70	
94	T2N-R15E-15	543	8.1	224	3.67	

WELL NUMBER	LOCATION	SPECIFIC CONDUCTANCE	pH	HCO3- mg/L	HCO3- meq/L	CA++ mg/L
95	T2N-R15E-16	526	8.1	224	3.67	
96	T2N-R15E-15	603	8.8	252	4.13	
97	T2N-R17E-7	1150	8	248	4.07	
98	T2N-R18E-16	6659	7.9	232	3.80	
99	T2N-R18E-32	885	8.1	238	3.90	
100	T2N-R14E-12	510	8.3	186	3.05	
101	T2N-R16E-10	619	8.1	256	4.20	
102	T2N-R15E-6	475	7.9	206	3.38	
103	T2N-R15E-4	615	8.1	216	3.54	
104	T2N-R15E-6	506	7.9	220	3.61	
105	T2N-R15E-6	504	7.8	216	3.54	
106	T2N-R18E-8	490	7.9	228	3.74	46
107	T2N-R18E-23	5159	8.1	240	3.93	90
108	T2N-R18E-8	2690	7.9	226	3.70	112
109	T2N-R15E-6	505	7.9	220	3.61	
110	T2N-R16E-5	604	8.1	246	4.03	
111	T2N-R15E-3	566	7	244	4.00	
112	T4N-R19E-27	8109	8	222	3.64	
113	T4N-R17E-22	613	8	192	3.15	
114	T4N-R17E-22	681	7.9	167	2.74	
115	T4N-R16E-24	581	8	228	3.74	
116	T4N-R16E-19	764	8.1	238	3.90	
117	T4N-R16E-24	716	8.6	218	3.57	
118	T4N-R17E-21	650	7.8	186	3.05	
119	T4N-R18E-15	3340	8	224	3.67	
120	T4N-R17E-15	614	8.1	190	3.11	
121	T4N-R17E-15	657	8	210	3.44	
122	T4N-R16E-17	718	8	216	3.54	
123	T4N-R17E-12	545	8.2	232	3.80	
124	T4N-R16E-5	704	7.8	194	3.18	
125	T4N-R10E-34	948	8	244	4.00	
126	T4N-R18E-32	581	8.2	216	3.54	
127	T4N-R17E-35	687	8.2	220	3.61	
128	T4N-R10E-31	614	8	236	3.87	
129	T4N-R17E-36	594	8.1	220	3.61	
130	T4N-R18E-29	549	8.2	228	3.74	
131	T4N-R17E-27	749	8.4	200	3.28	
132	T4N-R19E-27	609	7.8	292	4.79	
133	T5N-R16E-32	713	7	196	3.21	
134	T5N-R14E-31	391	7.8	222	3.64	38
135	T5N-R14E-31	398	8.4	204	3.34	
136	T5N-R19E-19	505	8.2	224	3.67	
137	T5N-R15E-22	951	7.7	316	5.18	
138	T5N-R15E-20	752	8	244	4.00	
139	T5N-R15E-20	560	8	226	3.70	
140	T5N-R13E-14	494	8.2	216	3.54	
141	T5N-R13E-14	465				
142	T5N-R13E-14	485				
143	T5N-R15E-17	1140	7.8	322	5.28	

WELL NUMBER	LOCATION	SPECIFIC CONDUCTANCE	pH	HCO3- mg/L	HCO3- meq/L	CA++ mg/L
144	T5N-R17E-17	577	8.1	192	3.15	
145	T5N-R15E-18	857	8.4	256	4.20	
146	T5N-R15E-34	814	8	258	4.23	
147	T5N-R15E-34	958	7.7	324	5.31	
148	T5N-R19E-28	530	8.1	242	3.97	
149	T5N-R16E-26	644	8.1	200	3.28	
150	T5N-R15E-29	594	7.9	232	3.80	
151	T5N-R17E-23	486	7.9	210	3.44	
152	T5N-R13E-7	530	7.4	240	3.93	38
153	T4N-R13E-7	651	8.1	240	3.93	
154	T5N-R13E-8	571	8.2	224	3.67	
155	T5N-R11E-10	502	7.5	240	3.93	31
156	T5N-R10E-11	472	7.5	230	3.77	30
157	T5N-R16E-5	620	7.4	200	3.28	82
158	T5N-R17E-1	580	8.2	208	3.41	
159	T5N-R15E-15	874	8	256	4.20	
160	T5N-R11E-16	448	8.1	236	3.87	
161	T5N-R13E-5	1060	7.6	372	6.10	
162	T6N-R15E-29	784	8.2			
163	T6N-R14E-31	1000	7.9	342	5.61	
164	T6N-R17E-17	770	7.2	200	3.28	91
165	T6N-R10E-26	530	7.5	250	4.10	30
166	T6N-R15E-29	772	8.2			
167	T6N-R12E-26	470	7.2	240	3.93	57
168	T6N-R19E-27	1140	7	350	5.74	100
169	T6N-R12E-20	861	8.1	342	5.61	
170	T6N-R15E-23	662	7.2	190	3.11	85
171	T6N-R14E-28	855	7.8	308	5.05	
172	T6N-R13E-22	905	7.3	190	3.11	79
173	T6N-R12E-19	680	7.3	300	4.92	58
174	T6N-R14E-24	767	7.9	252	4.13	
175	T6N-R12E-19	850	8.2	316	5.18	
176	T6N-R14E-22	585	7.4	180	2.95	70
177	T6N-R18E-24	552	7.4	220	3.61	55
178	T6N-R17E-14	620	7.3	220	3.61	72
179	T6N-R18E-16	540	7.4	210	3.44	60
180	T6N-R17E-13	588	7.4	220	3.61	63
181	T6N-R14E-15	467	8	180	2.95	
182	T6N-R18E-15	632	7.4	230	3.77	60
183	T5N-R10E-11	472	7.5	230	3.77	30
184	T6N-R10E-25	530	7.5	250	4.10	30
185	T5N-R10E-11	502	7.5	240	3.93	31

WELL NUMBER	LOCATION	SPECIFIC CONDUCTANCE	pH	HCO3- mg/L	HCO3- meq/L	Ca++ mg/L
186	T6N-R17E-18D	770	7.2	200	3.28	91
187	T6N-R18E-25B	525	7.4	212	3.48	51
188	T6N-R17E-14D	425	7.2	197	3.23	64
189	T6N-R15E-29B	600	7.3	219	3.59	79
190	T6N-R13E-29D	925	7.1	379	6.21	75
191	T5N-R19E-28D	800	7.4	236	3.87	37
192	T5N-R18E-27C	545	7.5	239	3.92	37
193	T5N-R14E-34D	350	7	231	3.79	35
194	T5N-R14E-1A	750	7.2	365	5.98	84
195	T5N-R17E-28D	575	7.6	185	3.03	47
196	T5N-R16E-8C	700	7.3	180	2.95	80
197	T2N-R17E-26A	625	7.5	235	3.85	53
198	T2N-R18E-29C	700	7.3	239	3.92	55
199	T3N-R10E-24B	450	7.7	219	3.59	33
200	T3N-R15E-30D	1000	7.5	268	4.39	53
201	T3N-R18E-1B	525	7.5	254	4.16	40
202	T4N-R17E-17A	700	7.8	197	3.23	84
203	T4N-R18E-6D	475	7.5	212	3.48	52
204	T4N-R19E-34B	900	7.2	206	3.38	57
205	T5N-R10E-1D	430	7.5	229	3.75	30
206	T5N-R11E-2B	510	7.3	229	3.75	33
207	T1N-R12E-32D	550	7.3	237	3.89	48
208	T2N-R16E-5B	700	7.3	285	4.67	53
209	T3N-R18E-4A	787		240	3.93	
210	T4N-R15E-21A	769		264	4.33	62
211	T4N-R16E-19D	764		238	3.90	
212	T4N-R17E-22C	681		204	3.34	
213	T4N-R18E-29C	549		228	3.74	
214	T4N-R19E-27A	610		292	4.79	
215	T5N-R11E-16A	448		236	3.87	
216	T5N-R12E-5B	658		266	4.36	
217	T5N-R13E-14D	494				
218	T5N-R14E-31A	399		204	3.34	
219	T5N-R15E-34A	958		324	5.31	
220	T5N-R16E-32B	714		196	3.21	
221	T5N-R17E-17C	577		192	3.15	
222	T5N-R19E-19C	506		224	3.67	
223	T6N-R10E-23A	785		298	4.89	
224	T6N-R12E-19D	850		316	5.18	
225	T6N-R13E-35B	869		246	4.03	
226	T6N-R14E-28B	856		308	5.05	
227	T6N-R15E-29B	784				
228	T6N-R17E-14D	491		148	2.43	50
229	T6N-R18E-25C	592		219	3.59	54
230	T1N-R15E-6B	520				51
231	T1N-R16E-6B	539		239	3.92	44
232	T1N-R16E-31C	516		226	3.70	
233	T1N-R17E-30A	660		230	3.77	
234	T2N-R11E-31D	459		212	3.48	
235	T2N-R12E-25D	511		226	3.70	39
236	T2N-R13E-28B	484		224	3.67	32
237	T2N-R14E-12D	510		194	3.18	

WELL NUMBER	LOCATION	SPECIFIC CONDUCTANCE	pH	HCO3- mg/L	HCO3- meq/L	Ca++ mg/L
238	T2N-R14E-23C	534		240	3.93	
239	T2N-R15E-15B	604		252	4.13	
240	T2N-R15E-34A	958		324	5.31	
241	T2N-R16E-10B	620		256	4.20	
242	T2N-R17E-7C	1150		248	4.07	
243	T2N-R18E-8B	491		228	3.74	46
244	T2N-R18E-24B	5950		268	4.39	
245	T3N-R15E-30A	722		252	4.13	61
246	T3N-R16E-35C	658		256	4.20	
247	T5N-R25E-18B	825	7.4	214	3.51	113
248	T5N-R27E-12D	800	7.3	397	6.51	117
249	T5N-R22E-29C	600	7.3	237	3.89	53
250	T5N-R23E-25A	500	7.4	265	4.34	69
251	T1N-R21E-4C	700	7.6	247	4.05	38
252	T2N-R22E-2D	600	7.6	206	3.38	48
253	T1N-R27E-6	1100	7.6	247	4.05	85
254	T4N-R24E-6	750	7.3	326	5.34	58
255	T5N-R20E-28	750	6.4	240	3.93	43
256	T2N-R24E-25	600	6.2	213	3.49	71
257	T3N-R26E-33	700	7.2	225	3.69	52
258	T1N-R20E-15			182	2.98	
259	T1N-R21E-21			232	3.80	
260	T1N-R22N-21			300	4.92	
261	T1N-R23E-12			213	3.49	
262	T1N-R23E-19	706		228	3.74	54
263	T1N-R23E-26	530		236	3.87	31
264	T1N-R23E-26	909		226	3.70	46
265	T1N-R23E-29	1100		232	3.80	56
266	T1N-R23E-33			220	3.61	48
267	T1N-R24E-15			253	4.15	
268	T1N-R25E-2			264	4.33	
269	T1N-R26E-22			297	4.87	
270	T1N-R27E-9			244	4.00	
271	T1N-R28E-22			217	3.56	
272	T2N-R23E-14			228	3.74	
273	T2N-R24E-9			238	3.90	
274	T2N-R25E-9			225	3.69	
275	T2N-R26E-21			214	3.51	
276	T2N-R27E-27			337	5.52	
277	T2N-R28E-10			240	3.93	
278	T3N-R20E-23			296	4.85	
279	T3N-R22E-5	394		187	3.07	42
280	T3N-R22E-14			206	3.38	
281	T3N-R26E-29			222	3.64	
282	T3N-R27E-25			229	3.75	
283	T4N-R20E-22			250	4.10	
284	T4N-R24E-7			243	3.98	
285	T4N-R25E-29			301	4.93	
286	T4N-R27E-2	323		252	4.13	88
287	T4N-R27E-10	0		198	3.25	
288	T5N-R20E-22	759		252	4.13	46
289	T5N-R20E-27	0		258	4.23	
290	T5N-R20E-34	2570		260	4.26	68

WELL NUMBER	LOCATION	SPECIFIC CONDUCTANCE	pH	HCO3- mg/L	HCO3- meq/L	Ca++ mg/L
291	T5N-R21E-28			248	4.07	
292	T5N-R22E-14			255	4.18	
293	T5N-R23E-13			308	5.05	
294	T5N-R23E-13	562		302	4.95	77
295	T5N-R24E-10			229	3.75	
296	T5N-R24E-30	547		254	4.16	54
297	T5N-R25E-17			247	4.05	
298	T5N-R26E-25			220	3.61	
299	T5N-R27E-9			237	3.89	
300	T5N-R28E-15			229	3.75	
301	T5N-R28E-32	539		291	4.77	91
302	T6N-R20E-20			235	3.85	
30	T6N-R21E-29			238	3.90	
304	T6N-R22E-29			233	3.82	
305	T6N-R23E-34			313	5.13	
306	T6N-R24E-20			259	4.25	
307	T6N-R25E-33			244	4.00	
308	T6N-R27E-30			282	4.62	
309	T6N-R20E-15	515	7.4	250	4.10	36
310	T6N-R21E-32	840	7.4	250	4.10	55
311	T5N-R25E-8	945	7.4	220	3.61	110
312	T3N-R26E-32	855	7.7	250	4.10	46
313	T5N-R27E-30	785	7.5	220	3.61	96
314	T1N-R20E-32	602		224	3.67	
315	T1N-R21E-3	1560		186	3.05	
316	T1N-R22E-26	1380		232	3.80	
317	T1N-R23E-8	1020		282	4.62	
318	T1N-R23E-26	909		226	3.70	46
319	T1N-R27E-6	1100		256	4.20	
320	T2N-R22E-26	318		68	1.11	
321	T2N-R23E-21	574		238	3.90	
322	T2N-R25E-33	629		272	4.46	
323	T2N-R26E-34	693		360	5.90	
324	T2N-R28E-31	2090		246	4.03	
325	T4N-R27E-2	323		252	4.13	88
326	T5N-R20E-34			244	4.00	
327	T5N-R22E-29	596		236	3.87	
328	T5N-R24E-30	547		254	4.16	54
329	T5N-R25E-17			247	4.05	
330	T5N-R26E-25			200	3.28	
331	T5N-R28E-32	539		291	4.77	91
332	T6N-R20E-35	1090		260	4.26	
333	T1N-R21E-32	3200	7.9	218	3.57	
334	T1N-R21E-32	602	7.9	224	3.67	
335	T1N-R21E-3	1560	7.6	186	3.05	
336	T1N-R22E-26	1380	8	232	3.80	
337	T1N-R23E-20	579	7.7	232	3.80	
338	T1N-R23E-20	515	8.3	236	3.87	
339	T1N-R23E-8	1020	7.8	282	4.62	
340	T1N-R21E-4	1380	8	228	3.74	
341	T1N-R21E-5	570	7.8	256	4.20	
342	T1N-R27E-6	1100	8	256	4.20	

WELL NUMBER	LOCATION	SPECIFIC CONDUCTANCE	pH	HCO3- mg/L	HCO3- meq/L	Ca++ mg/L
343	T2N-R26E-34	693	7.4	360	5.90	
344	T2N-R26E-34	3499	7.6	234	3.84	
345	T2N-R25E-33	629	7.8	272	4.46	
346	T2N-R22E-26	318	7.6	68	1.11	
347	T2N-R24E-23	800	8	216	3.54	
348	T2N-R23E-21	574	8.1	236	3.87	
349	T2N-R27E-15	865	7.8	230	3.77	
350	T2N-R23E-4	643	8	232	3.80	
351	T2N-R27E-2	821	7.9	262	4.30	
352	T2N-R28E-31	827	8.1	280	4.59	
353	T3N-21E-33	855	7.7	250	4.10	46
354	T3N-R22E-23	520	7.5	240	3.93	45
355	T4N-R25E-21	1980	7.8	174	2.85	
356	T4N-R20E-22	1260	8.2	256	4.20	
357	T4N-R20E-22	879	8.3	256	4.20	
358	T4N-R22E-13	2590	8.2	250	4.10	
359	T4N-R20E-5	2090	7.7	246	4.03	
360	T4N-R23E-29	8939	7.4	44	0.72	
361	T4N-R20E-5	153	8.2	246	4.03	
362	T5N-R26E-25	785	7.5	220	3.61	96
363	T5N-R28E-28	692	7.4	310	5.08	75
364	T5N-R22E-20	1280	7.7	250	4.10	64
365	T5N-R28E-21	1305	7.4	340	5.57	110
366	T5N-R27E-7	608	6.9	400	6.56	120
367	T5N-R25E-4	945	7.4	220	3.61	110
368	T5N-R21E-4	590	7.4	240	3.93	52
369	T5N-R28E-6	1050	7.4	320	5.25	110
370	T5N-R20E-34	1810	8	244	4.00	
371	T5N-R22E-29	595	8	236	3.87	
372	T5N-R28E-27	1020	7.8	372	6.10	
373	T5N-R21E-20	3759	8.1	268	4.39	
374	T5N-R21E-11	1980	8.1		0.00	
375	T5N-R21E-7	573	7.8	232	3.80	

WELL NUMBER	CA++ mmol/L	Ca++ meq/L	Mg++ mg/L	Mg++ mmol/L	Mg++ meq/L	Na+ mg/L	Na+ mmol/L	Na+ meq/L
1						34	1.48	1.48
2						6.2	0.27	0.27
3						7.6	0.33	0.33
4						86	3.74	3.74
5						43	1.87	1.87
6						32	1.39	1.39
7	1.20	2.40	18	0.74	1.48	25	1.09	1.09
8						21	0.91	0.91
9						33	1.43	1.44
10						32	1.39	1.39
11						32	1.39	1.39
12						31	1.35	1.35
13						26	1.13	1.13
14						33	1.43	1.44
15						31	1.35	1.35
16						21	0.91	0.91
17						23	1.00	1.00
18						26	1.13	1.13
19						22	0.96	0.96
20						22	0.96	0.96
21						29	1.26	1.26
22						23	1.00	1.00
23						23	1.00	1.00
24						24	1.04	1.04
25						22	0.96	0.96
26						23	1.00	1.00
27	0.67	1.35	30	1.23	2.47	16	0.70	0.70
28						19	0.83	0.83
29						24	1.04	1.04
30						20	0.87	0.87
31						23	1.00	1.00
32						7.6	0.33	0.33
33						21	0.91	0.91
34						23	1.00	1.00
35						17	0.74	0.74
36	1.22	2.45	29	1.19	2.39	20	0.87	0.87
37						50	2.17	2.17
38	0.85	1.70	26	1.07	2.14	24	1.04	1.04
39						21	0.91	0.91
40	0.88	1.75	35	1.44	2.88	21	0.91	0.91
41	0.82	1.65				14	0.61	0.61
42	0.63	1.25				12	0.52	0.52
43	0.75	1.50				57	2.48	2.48
44	0.85	1.70	34	1.40	2.80	19	0.83	0.83
45						12	0.52	0.52

WELL NUMBER	CA++ mmol/L	Ca++ meq/L	Mg++ mg/L	Mg++ mmol/L	Mg++ meq/L	Na+ mg/L	Na+ mmol/L	Na+ meq/L
46	1.00	2.00	27	1.11	2.22	22	0.96	0.96
47	0.63	1.25	26	1.07	2.14	20	0.87	0.87
48	1.17	2.35	24	0.99	1.98	21	0.91	0.91
49	0.97	1.95	17	0.70	1.40	10	0.43	0.43
50	1.05	2.10	23	0.95	1.89	28	1.22	1.22
51	0.92	1.85	29	1.19	2.39	44	1.91	1.91
52	1.52	3.04	36	1.48	2.96	34	1.48	1.48
53	0.65	1.30	28	1.15	2.30	51	2.22	2.22
54	1.02	2.05	21	0.86	1.73	22	0.96	0.96
55	0.85	1.70	28	1.15	2.30	19	0.83	0.83
56	0.67	1.35	30	1.23	2.47	16	0.70	0.70
57	1.00	2.00	27	1.11	2.22	22	0.96	0.96
58	0.63	1.25	26	1.07	2.14	20	0.87	0.87
59	0.88	1.75	35	1.44	2.88	21	0.91	0.91
60	0.85	1.70	34	1.40	2.80	19	0.83	0.83
61	1.22	2.45	29	1.19	2.39	20	0.87	0.87
62	0.85	1.70	26	1.07	2.14	24	1.04	1.04
63						8	0.35	0.35
64	1.20	2.40	18	0.74	1.48	25	1.09	1.09
65						34	1.48	1.48
66						45	1.96	1.96
67						32	1.39	1.39
68	0.97	1.95	25	1.03	2.06	27	1.17	1.17
69								
70						22	0.96	0.96
71						23	1.00	1.00
72						33	1.43	1.44
73						17	0.74	0.74
74						26	1.13	1.13
75						28	1.22	1.22
76						27	1.17	1.17
77						27	1.17	1.17
78						21	0.91	0.91
79						12	0.52	0.52
80						354	15.39	15.40
81						26	1.13	1.13
82						32	1.39	1.39
83						22	0.96	0.96
84						34	1.48	1.48
85						24	1.04	1.04
86						28	1.22	1.22
87						25	1.09	1.09
88						53	2.30	2.31
89						24	1.04	1.04
90						46	2.00	2.00
91						1090	47.39	47.41
92						1230	53.48	53.50
93						26	1.13	1.13
94						24	1.04	1.04

WELL NUMBER	CA++ mmol/L	Ca++ meq/L	Mg++ mg/L	Mg++ mmol/L	Mg++ meq/L	Na+ mg/L	Na+ mmol/L	Na+ meq/L
95						24	1.04	1.04
96						26	1.13	1.13
97						97	4.22	4.22
98						1250	54.35	54.37
99						55	2.39	2.39
100						13	0.57	0.57
101						44	1.91	1.91
102						22	0.96	0.96
103						23	1.00	1.00
104						18	0.78	0.78
105						22	0.96	0.96
106	1.15	2.30	22	0.91	1.81	19	0.83	0.83
107	2.25	4.49	45	1.85	3.70	950	41.30	41.32
108	2.80	5.59	60	2.47	4.94	352	15.30	15.31
109						18	0.78	0.78
110						32	1.39	1.39
111						30	1.30	1.30
112						1660	72.17	72.21
113						25	1.09	1.09
114						34	1.48	1.48
115						36	1.57	1.57
116						42	1.83	1.83
117						35	1.52	1.52
118						26	1.13	1.13
119						582	25.30	25.32
120						27	1.17	1.17
121						34	1.48	1.48
122						29	1.26	1.26
123						28	1.22	1.22
124						31	1.35	1.35
125						69	3.00	3.00
126						29	1.26	1.26
127						35	1.52	1.52
128						34	1.48	1.48
129						29	1.26	1.26
130						28	1.22	1.22
131						35	1.52	1.52
132						24	1.04	1.04
133						28	1.22	1.22
134	0.95	1.90	23	0.95	1.89	13	0.57	0.57
135						11	0.48	0.48
136						17	0.74	0.74
137						69	3.00	3.00
138						58	2.52	2.52
139						35	1.52	1.52
140						30	1.30	1.30
141						30	1.30	1.30
142						30	1.30	1.30
143						94	4.09	4.09

WELL NUMBER	CA++ mmol/L	Ca++ meq/L	Mg++ mg/L	Mg++ mmol/L	Mg++ meq/L	Na+ mg/L	Na+ mmol/L	Na+ meq/L
144						30	1.30	1.30
145						69	3.00	3.00
146						58	2.52	2.52
147						68	2.96	2.96
148						40	1.74	1.74
149						38	1.65	1.65
150						34	1.48	1.48
151						23	1.00	1.00
152	0.95	1.90	29	1.19	2.39	33	1.43	1.44
153						42	1.83	1.83
154						40	1.74	1.74
155	0.77	1.55	27	1.11	2.22	32	1.39	1.39
156	0.75	1.50	29	1.19	2.39	26	1.13	1.13
157	2.05	4.09	23	0.95	1.89	23	1.00	1.00
158						21	0.91	0.91
159						66	2.87	2.87
160						29	1.26	1.26
161						100	4.35	4.35
162						49	2.13	2.13
163						80	3.48	3.48
164	2.27	4.54	21	0.86	1.73	21	0.91	0.91
165	0.75	1.50	29	1.19	2.39	31	1.35	1.35
166						46	2.00	2.00
167	1.42	2.84	14	0.58	1.15	17	0.74	0.74
168	2.50	4.99	64	2.63	5.27	43	1.87	1.87
169						51	2.22	2.22
170	2.13	4.24	20	0.82	1.65	28	1.22	1.22
171						47	2.04	2.04
172	1.97	3.94	47	1.93	3.87	40	1.74	1.74
173	1.45	2.89	29	1.19	2.39	36	1.57	1.57
174						53	2.30	2.31
175						50	2.17	2.17
176	1.75	3.49	16	0.66	1.32	20	0.87	0.87
177	1.38	2.74	21	0.86	1.73	27	1.17	1.17
178	1.80	3.59	21	0.86	1.73	23	1.00	1.00
179	1.50	2.99	23	0.95	1.89	29	1.26	1.26
180	1.57	3.14	21	0.86	1.73	26	1.13	1.13
181						25	1.09	1.09
182	1.50	2.99	26	1.07	2.14	28	1.22	1.22
183	0.75	1.50	29	1.19	2.39	26	1.13	1.13
184	0.75	1.50	29	1.19	2.39	31	1.35	1.35
185	0.77	1.55	27	1.11	2.22	32	1.39	1.39

WELL NUMBER	Ca++ mmol/L	Ca++ meq/L	Mg++ mg/L	Mg++ mmol/L	Mg++ meq/L	Na+ mg/L	Na+ mmol/L	Na+ meq/L
186	2.27	4.54	21	0.86	1.73	21	0.91	0.91
187	1.27	2.54	21	0.86	1.73	25	1.09	1.09
188	1.60	3.19	19	0.78	1.56	19	0.83	0.83
189	1.97	3.94	22	0.91	1.81	43	1.87	1.87
190	1.88	3.74	45	1.85	3.70	62	2.70	2.70
191	0.92	1.85	24	0.99	1.98	36	1.57	1.57
192	0.92	1.85	21	0.86	1.73	31	1.35	1.35
193	0.88	1.75	22	0.91	1.81	17	0.74	0.74
194	2.10	4.19	39	1.60	3.21	71	3.09	3.09
195	1.17	2.35	23	0.95	1.89	20	0.87	0.87
196	2.00	3.99	20	0.82	1.65	22	0.96	0.96
197	1.32	2.64	31	1.28	2.55	33	1.43	1.44
198	1.38	2.74	37	1.52	3.05	25	1.09	1.09
199	0.82	1.65	30	1.23	2.47	35	1.52	1.52
200	1.32	2.64	30	1.23	2.47	32	1.39	1.39
201	1.00	2.00	32	1.32	2.63	19	0.83	0.83
202	2.10	4.19	35	1.44	2.88	42	1.83	1.83
203	1.30	2.59	26	1.07	2.14	20	0.87	0.87
204	1.42	2.84	31	1.28	2.55	111	4.83	4.83
205	0.75	1.50	27	1.11	2.22	31	1.35	1.35
206	0.82	1.65	29	1.19	2.39	24	1.04	1.04
207	1.20	2.40	26	1.07	2.14	26	1.13	1.13
208	1.32	2.64	33	1.36	2.72	44	1.91	1.91
209	0.00	0.00	0	0.00	0.00	29	1.26	1.26
210	1.55	3.09	32	1.32	2.63	58	2.52	2.52
211						45	1.96	1.96
212						34	1.48	1.48
213						31	1.35	1.35
214						24	1.04	1.04
215						29	1.26	1.26
216						59	2.57	2.57
217						30	1.30	1.30
218						13	0.57	0.57
219						72	3.13	3.13
220						31	1.35	1.35
221						32	1.39	1.39
222						19	0.83	0.83
223						95	4.13	4.13
224						54	2.35	2.35
225						79	3.43	3.44
226						47	2.04	2.04
227						49	2.13	2.13
228						26	1.13	1.13
229						28	1.22	1.22
230	1.27	2.54						
231	1.10	2.20	30	1.23	2.47	30	1.30	1.30
232						26	1.13	1.13
233						32	1.39	1.39

WELL NUMBER	Ca++ mmol/L	Ca++ meq/L	Mg++ mg/L	Mg++ mmol/L	Mg++ meq/L	Na+ mg/L	Na+ mmol/L	Na+ meq/L
234						25	1.09	1.09
235	0.97	1.95	33	1.36	2.72	17	0.74	0.74
236	0.80	1.60	31	1.28	2.55	20	0.87	0.87
237						13	0.57	0.57
238						24	1.04	1.04
239						26	1.13	1.13
240						72	3.13	3.13
241						47	2.04	2.04
242						97	4.22	4.22
243	1.15	2.30	22	0.91	1.81	21	0.91	0.91
244						1090	47.39	47.41
245	1.52	3.04	42	1.73	3.46	34	1.48	1.48
246						42	1.83	1.83
247	2.82	5.64	20	0.82	1.65	48	2.09	2.09
248	2.92	5.84	25	1.03	2.06	41	1.78	1.78
249	1.32	2.64	23	0.95	1.89	44	1.91	1.91
250	1.72	3.44	13	0.53	1.07	33	1.43	1.44
251	0.95	1.90	20	0.82	1.65	89	3.87	3.87
252	1.20	2.40	27	1.11	2.22	52	2.26	2.26
253	2.13	4.24	26	1.07	2.14	118	5.13	5.13
254	1.45	2.89	17	0.70	1.40	82	3.57	3.57
255	1.07	2.15	26	1.07	2.14	72	3.13	3.13
256	1.77	3.54	21	0.86	1.73	13	0.57	0.57
257	1.30	2.59	14	0.58	1.15	97	4.22	4.22
258								
259								
260								
261								
262	1.35	2.69	31	1.28	2.55	45	1.96	1.96
263	0.77	1.55	19	0.78	1.56	48	2.09	2.09
264	1.15	2.30	32	1.32	2.63	91	3.96	3.96
265	1.40	2.79	37	1.52	3.05	116	5.04	5.05
266	1.20	2.40	41	1.69	3.37	62	2.70	2.70
267								
268								
269								
270								
271								
272								
273								
274								
275								
276								
277								
278								
279	1.05	2.10	19	0.78	1.56	9.7	0.42	0.42
280								
281								
282								
283								
284								
285								

WELL NUMBER	Ca++ mmol/L	Ca++ meq/L	Mg++ mg/L	Mg++ mmol/L	Mg++ meq/L	Na+ mg/L	Na+ mmol/L	Na+ meq/L
286	2.20	4.39	9.8	0.40	0.81	11	0.48	0.48
287								
288	1.15	2.30	29	1.19	2.39	77	3.35	3.35
289								
290	1.70	3.39	46	1.89	3.79	417	18.13	18.14
291								
292								
293								
294	1.92	3.84	14	0.58	1.15	30	1.30	1.30
295			0	0.00	0.00	0	0.00	0.00
296	1.35	2.69	12	0.49	0.99	41	1.78	1.78
297								
298								
299								
300								
301	2.27	4.54	11	0.45	0.91	10	0.43	0.43
302								
30								
304								
305								
306								
307								
308								
309	0.90	1.80	28	1.15	2.30	27	1.17	1.17
310	1.38	2.74	27	1.11	2.22	76	3.30	3.31
311	2.75	5.49	26	1.07	2.14	27	1.17	1.17
312	1.15	2.30	14	0.58	1.15	100	4.35	4.35
313	2.40	4.79	22	0.91	1.81	25	1.09	1.09
314						69	3.00	3.00
315						152	6.61	6.61
316						224	9.74	9.74
317						162	7.04	7.05
318	1.15	2.30	32	1.32	2.63	91	3.96	3.96
319						128	5.57	5.57
320						12	0.52	0.52
321						63	2.74	2.74
322						32	1.39	1.39
323						48	2.09	2.09
324						318	13.83	13.83
325	2.20	4.39	9.8	0.40	0.81	11	0.48	0.48
326						263	11.43	11.44
327						43	1.87	1.87
328	1.35	2.69	12	0.49	0.99	41	1.78	1.78
329								
330								
331	2.27	4.54	11	0.45	0.91	10	0.43	0.43
332						154	6.70	6.70
333						534	23.22	23.23
334						69	3.00	3.00
335						152	6.61	6.61
336						224	9.74	9.74
337						36	1.57	1.57

WELL NUMBER	Ca++ mmol/L	Ca++ meq/L	Mg++ mg/L	Mg++ mmol/L	Mg++ meq/L	Na+ mg/L	Na+ mmol/L	Na+ meq/L
338						43	1.87	1.87
339						162	7.04	7.05
340						205	8.91	8.92
341						41	1.78	1.78
342						128	5.57	5.57
343						48	2.09	2.09
344						599	26.04	26.06
345						320	13.91	13.92
346						9	0.39	0.39
347						87	3.78	3.78
348						60	2.61	2.61
349						51	2.22	2.22
350						50	2.17	2.17
351						37	1.61	1.61
352						81	3.52	3.52
353	1.15	2.30	14	0.58	1.15	100	4.35	4.35
354	1.13	2.25	22	0.91	1.81	28	1.22	1.22
355						154	6.70	6.70
356						89	3.87	3.87
357						59	2.57	2.57
358						277	12.04	12.05
359						318	13.83	13.83
360						1330	57.83	57.85
361						198	8.61	8.61
362	2.40	4.79	22	0.91	1.81	25	1.09	1.09
363	1.88	3.74	25	1.03	2.06	37	1.61	1.61
364	1.60	3.19	31	1.28	2.55	130	5.65	5.65
365	2.75	5.49	32	1.32	2.63	120	5.22	5.22
366	3.00	5.99	11	0.45	0.91	4.2	0.18	0.18
367	2.75	5.49	26	1.07	2.14	27	1.17	1.17
368	1.30	2.59	24	0.99	1.98	37	1.61	1.61
369	2.75	5.49	29	1.19	2.39	72	3.13	3.13
370						263	11.43	11.44
371						40	1.74	1.74
372						130	5.65	5.65
373						654	28.43	28.45
374						288	12.52	12.53
375						41	1.78	1.78

WELL NUMBER	K+ mg/L	K+ mmol/L	K+ meq/L	Cl- mg/L	Cl- mmol/L	Cl- meq/L	SO4-- mg/L	SO4-- mmol/L
1				19	0.54	0.54	58	0.56
2				9	0.25	0.25	17	0.16
3				5.8	0.16	0.16	19	0.18
4				102	2.88	2.88	43	0.41
5	4.1	0.11	0.11	130	3.67	3.67	50	0.48
6				23	0.65	0.65	42	0.40
7				9.5	0.27	0.27	39	0.38
8				16	0.45	0.45	48	0.46
9				17	0.48	0.48	46	0.44
10	3.6	0.09	0.09	20	0.56	0.56	46	0.44
11	3.6	0.09	0.09	20	0.56	0.56	47	0.45
12	3.4	0.09	0.09	19	0.54	0.54	45	0.43
13	4.4	0.11	0.11	20	0.56	0.56	50	0.48
14	3.7	0.09	0.09	22	0.62	0.62	54	0.52
15	4.3	0.11	0.11	19	0.54	0.54	52	0.50
16	4.4	0.11	0.11	17	0.48	0.48	37	0.36
17	4.5	0.12	0.12	18	0.51	0.51	42	0.40
18				18	0.51	0.51	50	0.48
19	5.4	0.14	0.14	18	0.51	0.51	36	0.35
20				18	0.51	0.51	38	0.37
21	4.9	0.13	0.13	20	0.56	0.56	43	0.41
22				24	0.68	0.68	47	0.45
23	4.6	0.12	0.12	16	0.45	0.45	36	0.35
24	4.6	0.12	0.12	24	0.68	0.68	36	0.35
25	4.6	0.12	0.12	26	0.73	0.73	43	0.41
26	4.6	0.12	0.12	27	0.76	0.76	45	0.43
27				11	0.31	0.31	37	0.36
28				30	0.85	0.85	51	0.49
29	4.3	0.11	0.11	27	0.76	0.76	55	0.53
30	7.9	0.20	0.20	12	0.34	0.34	33	0.32
31				22	0.62	0.62	47	0.45
32				5.8	0.16	0.16	19	0.18
33	4.8	0.12	0.12	14	0.40	0.39	43	0.41
34	4.5	0.12	0.12	26	0.73	0.73	39	0.38
35				20	0.56	0.56	45	0.43
36	4.4	0.11	0.11	33	0.93	0.93	49	0.47
37				21	0.59	0.59	54	0.52
38	5.1	0.13	0.13	12	0.34	0.34	36	0.35
39				19	0.54	0.54	29	0.28
40	5.6	0.14	0.14	37	1.05	1.04	63	0.61
41				18	0.51	0.51	40	0.38
42				17	0.48	0.48	36	0.35
43				6	0.17	0.17	24	0.23
44	5.1	0.13	0.13	15	0.42	0.42	53	0.51
45				22	0.62	0.62	34	0.33

WELL NUMBER	K+ mg/L	K+ mmol/L	K+ meq/L	Cl- mg/L	Cl- mmol/L	Cl- meq/L	SO4-- mg/L	SO4-- mmol/L
46	5.9	0.15	0.15	35	0.99	0.99	33	0.32
47	6.6	0.17	0.17	4.1	0.12	0.12	20	0.19
48				29	0.82	0.82	40	0.38
49				12	0.34	0.34	20	0.19
50				26	0.73	0.73	47	0.45
51				21	0.59	0.59	60	0.58
52				60	1.69	1.69	67	0.64
53				16	0.45	0.45	58	0.56
54				22	0.62	0.62	28	0.27
55				18	0.51	0.51	55	0.53
56				11	0.31	0.31	37	0.36
57				35	0.99	0.99	33	0.32
58				4.1	0.12	0.12	20	0.19
59				37	1.05	1.04	63	0.61
60				15	0.42	0.42	53	0.51
61				33	0.93	0.93	49	0.47
62				12	0.34	0.34	36	0.35
63				6	0.17	0.17	19	0.18
64				10	0.28	0.28	39	0.38
65				19	0.54	0.54	58	0.56
66				13	0.37	0.37	50	0.48
67				23	0.65	0.65	42	0.40
68				18	0.51	0.51	49	0.47
69				22	0.62	0.62	60	0.58
70				18	0.51	0.51	38	0.37
71				17	0.48	0.48	37	0.36
72				19	0.54	0.54	45	0.43
73				20	0.56	0.56	17	0.16
74				27	0.76	0.76	55	0.53
75				26	0.73	0.73	39	0.38
76				24	0.68	0.68	36	0.35
77				12	0.34	0.34	33	0.32
78				19	0.54	0.54	29	0.28
79				22	0.62	0.62	34	0.33
80				750	21.19	21.15	225	2.16
81				8	0.23	0.23	69	0.66
82				17	0.48	0.48	128	1.23
83	4.5	0.12	0.12	16	0.45	0.45	33	0.32
84	5.8	0.15	0.15	48	1.36	1.35	67	0.64
85				30	0.85	0.85	35	0.34
86				40	1.13	1.13	91	0.88
87				44	1.24	1.24	120	1.15
88				57	1.61	1.61	160	1.54
89				11	0.31	0.31	59	0.57
90				62	1.75	1.75	69	0.66
91				1590	44.92	44.85	338	3.25
92				1850	52.26	52.18	364	3.50
93	5.6	0.14	0.14	8.1	0.23	0.23	95	0.91
94	5.2	0.13	0.13	10	0.28	0.28	78	0.75

WELL NUMBER	K+ mg/L	K+ mmol/L	K+ meq/L	Cl- mg/L	Cl- mmol/L	Cl- meq/L	SO4-- mg/L	SO4-- mmol/L
95	5.4	0.14	0.14	12	0.34	0.34	65	0.63
96				7.4	0.21	0.21	97	0.93
97				150	4.24	4.23	170	1.63
98				1940	54.80	54.72	255	2.45
99	7.2	0.18	0.18	86	2.43	2.43	122	1.17
100				16	0.45	0.45	72	0.69
101	5.6	0.14	0.14	13	0.37	0.37	105	1.01
102				20	0.56	0.56	65	0.63
103	5.4	0.14	0.14	30	0.85	0.85	84	0.81
104				8	0.23	0.23	70	0.67
105	5	0.13	0.13	8	0.23	0.23	65	0.63
106	3.5	0.09	0.09	16	0.45	0.45	25	0.24
107				1440	40.68	40.62	245	2.36
108	6.9	0.18	0.18	680	19.21	19.18	120	1.15
109				8	0.23	0.23	69	0.66
110				10	0.28	0.28	105	1.01
111				8.7	0.25	0.25	1.3	0.01
112				2200	62.15	62.05	679	6.53
113				18	0.51	0.51	137	1.32
114				15	0.42	0.42	168	1.62
115				10	0.28	0.28	101	0.97
116	4.7	0.12	0.12	16	0.45	0.45	184	1.77
117	5	0.13	0.13	20	0.56	0.56	170	1.63
118				17	0.48	0.48	155	1.49
119				719	20.31	20.28	424	4.08
120	4.8	0.12	0.12	12	0.34	0.34	131	1.26
121				12	0.34	0.34	149	1.43
122	4.3	0.11	0.11	19	0.54	0.54	172	1.65
123	4.7	0.12	0.12	18	0.51	0.51	76	0.73
124				16	0.45	0.45	185	1.78
125				18	0.51	0.51	260	2.50
126	4.9	0.13	0.13	14	0.40	0.39	96	0.92
127	5.4	0.14	0.14	12	0.34	0.34	166	1.60
128	5.1	0.13	0.13	11	0.31	0.31	115	1.11
129	5	0.13	0.13	11	0.31	0.31	112	1.08
130	4.9	0.13	0.13	10	0.28	0.28	84	0.81
131	10	0.26	0.26	14	0.40	0.39	195	1.88
132				20	0.56	0.56	57	0.55
133	4.3	0.11	0.11	17	0.48	0.48	193	1.86
134	4.4	0.11	0.11	4	0.11	0.11	22	0.21
135	4.7	0.12	0.12	8	0.23	0.23	23	0.22
136	4	0.10	0.10	20	0.56	0.56	39	0.38
137	6.4	0.16	0.16	26	0.73	0.73	215	2.07
138				22	0.62	0.62	164	1.58
139				11	0.31	0.31	80	0.77
140	5.9	0.15	0.15	10	0.28	0.28	54	0.52
141				7	0.20	0.20	53	0.51
142				8	0.23	0.23	50	0.48
143				35	0.99	0.99	302	2.90

WELL NUMBER	K+ mg/L	K+ mmol/L	K+ meq/L	Cl- mg/L	Cl- mmol/L	Cl- meq/L	SO4-- mg/L	SO4-- mmol/L
144	4	0.10	0.10	12	0.34	0.34	116	1.12
145				21	0.59	0.59	218	2.10
146	6.3	0.16	0.16	25	0.71	0.71	185	1.78
147	6.5	0.17	0.17	26	0.73	0.73	220	2.12
148	4.5	0.12	0.12	9	0.25	0.25	67	0.64
149				13	0.37	0.37	143	1.38
150				14	0.40	0.39	99	0.95
151	4.6	0.12	0.12	13	0.37	0.37	58	0.56
152	5.8	0.15	0.15	10	0.28	0.28	67	0.64
153				14	0.40	0.39	118	1.13
154	6.1	0.16	0.16	14	0.40	0.39	82	0.79
155	6.3	0.16	0.16	14	0.40	0.39	54	0.52
156	6.3	0.16	0.16	19	0.54	0.54	42	0.40
157	3.8	0.10	0.10	12	0.34	0.34	50	0.48
158	4.4	0.11	0.11	22	0.62	0.62	101	0.97
159				22	0.62	0.62	215	2.07
160				5.5	0.16	0.16	28	0.27
161				23	0.65	0.65	245	2.36
162				18	0.51	0.51		
163				28	0.79	0.79	230	2.21
164	3.7	0.09	0.09	69	1.95	1.95	83	0.80
165	6.1	0.16	0.16	10	0.28	0.28	65	0.63
166				16	0.45	0.45		
167	5.3	0.14	0.14	7.2	0.20	0.20	30	0.29
168	0.9	0.02	0.02	110	3.11	3.10	110	1.06
169	5.7	0.15	0.15	14	0.40	0.39	180	1.73
170	3.5	0.09	0.09	17	0.48	0.48	170	1.63
171				18	0.51	0.51	195	1.88
172	8.4	0.22	0.22	140	3.95	3.95	79	0.76
173	5.1	0.13	0.13	23	0.65	0.65	61	0.59
174				16	0.45	0.45	180	1.73
175	5.6	0.14	0.14	15	0.42	0.42	180	1.73
176	3.4	0.09	0.09	35	0.99	0.99	89	0.86
177	4.1	0.11	0.11	21	0.59	0.59	70	0.67
178	4	0.10	0.10	44	1.24	1.24	54	0.52
179	4	0.10	0.10	13	0.37	0.37	81	0.78
180	4	0.10	0.10	23	0.65	0.65	95	0.91
181				12	0.34	0.34	71	0.68
182				33	0.93	0.93	86	0.83
183				19	0.54	0.54	42	0.40
184				10	0.28	0.28	65	0.63
185				14	0.40	0.39	54	0.52

WELL NUMBER	K+ mg/L	K+ mmol/L	K+ meq/L	Cl- mg/L	Cl- mmol/L	Cl- meq/L	SO4-- mg/L	SO4-- mmol/L
186				69	1.95	1.95	83	0.80
187				13	0.37	0.37	56	0.54
188				19	0.54	0.54	26	0.25
189				26	0.73	0.73	194	1.87
190				22	0.62	0.62	191	1.84
191				12	0.34	0.34	64	0.62
192				10	0.28	0.28	43	0.41
193				14	0.40	0.39	20	0.19
194				29	0.82	0.82	225	2.16
195				12	0.34	0.34	72	0.69
196				15	0.42	0.42	151	1.45
197				37	1.05	1.04	93	0.89
198				77	2.18	2.17	67	0.64
199				39	1.10	1.10	47	0.45
200				19	0.54	0.54	95	0.91
201				27	0.76	0.76	51	0.49
202				17	0.48	0.48	278	2.67
203				23	0.65	0.65	75	0.72
204				102	2.88	2.88	207	1.99
205				11	0.31	0.31	40	0.38
206				21	0.59	0.59	57	0.55
207				17	0.48	0.48	60	0.58
208				26	0.73	0.73	128	1.23
209				102	2.88	2.88	35	0.34
210				22	0.62	0.62	152	1.46
211				16	0.45	0.45	184	1.77
212				15	0.42	0.42	168	1.62
213				10	0.28	0.28	84	0.81
214				20	0.56	0.56	58	0.56
215				6	0.17	0.17	28	0.27
216				16	0.45	0.45	103	0.99
217				8	0.23	0.23	50	0.48
218				8	0.23	0.23	23	0.22
219				26	0.73	0.73	220	2.12
220				17	0.48	0.48	193	1.86
221				12	0.34	0.34	116	1.12
222				20	0.56	0.56	39	0.38
223				22	0.62	0.62	157	1.51
224				15	0.42	0.42	180	1.73
225				22	0.62	0.62	232	2.23
226				18	0.51	0.51	195	1.88
227				18	0.51	0.51	0	0.00
228				16	0.45	0.45	92	0.88
229				25	0.71	0.71	73	0.70
230				8	0.23	0.23	76	0.73
231				11	0.31	0.31	65	0.63
232				8	0.23	0.23	69	0.66
233				17	0.48	0.48	128	1.23
234				16	0.45	0.45	33	0.32

WELL NUMBER	K+ mg/L	K+ mmol/L	K+ meq/L	Cl- mg/L	Cl- mmol/L	Cl- meq/L	SO4-- mg/L	SO4-- mmol/L
235				18	0.51	0.51	50	0.48
236				16	0.45	0.45	40	0.38
237				16	0.45	0.45	72	0.69
238				11	0.31	0.31	59	0.57
239				7	0.20	0.20	97	0.93
240				26	0.73	0.73	220	2.12
241				13	0.37	0.37	105	1.01
242				150	4.24	4.23	170	1.63
243				15	0.42	0.42	25	0.24
244				1590	44.92	44.85	338	3.25
245				16	0.45	0.45	155	1.49
246				18	0.51	0.51	112	1.08
247				190	5.37	5.36	20	0.19
248				56	1.58	1.58	86	0.83
249				65	1.84	1.83	42	0.40
250				32	0.90	0.90	38	0.37
251				100	2.82	2.82	62	0.60
252				80	2.26	2.26	68	0.65
253				229	6.47	6.46	82	0.79
254				92	2.60	2.59	21	0.20
255				65	1.84	1.83	73	0.70
256				63	1.78	1.78	36	0.35
257				127	3.59	3.58	54	0.52
258				20	0.56	0.56	28	0.27
259				88	2.49	2.48	200	1.92
260				2	0.06	0.06	7	0.07
261				3	0.08	0.08	3	0.03
262				80	2.26	2.26	53	0.51
263				30	0.85	0.85	19	0.18
264				130	3.67	3.67	67	0.64
265				155	4.38	4.37	124	1.19
266				112	3.16	3.16	78	0.75
267				50	1.41	1.41	70	0.67
268				10	0.28	0.28	8	0.08
269				49	1.38	1.38	72	0.69
270				15	0.42	0.42	12	0.12
271				18	0.51	0.51	32	0.31
272				6	0.17	0.17	7	0.07
273				19	0.54	0.54	23	0.22
274				105	2.97	2.96	38	0.37
275				10	0.28	0.28	22	0.21
276				22	0.62	0.62	12	0.12
277				22	0.62	0.62	26	0.25
278				248	7.01	7.00	1000	9.62
279				15	0.42	0.42	24	0.23
280				14	0.40	0.39	12	0.12
281				53	1.50	1.49	48	0.46
282				6	0.17	0.17	8	0.08
283				37	1.05	1.04	40	0.38
284				49	1.38	1.38	38	0.37
285				32	0.90	0.90	66	0.63
				25	0.71	0.71	23	0.22

WELL NUMBER	K+ mg/L	K+ mmol/L	K+ meq/L	Cl- mg/L	Cl- mmol/L	Cl- meq/L	SO4-- mg/L	SO4-- mmol/L
286				63	1.78	1.78	14	0.13
287				60	1.69	1.69	105	1.01
288				14	0.40	0.39	52	0.50
289				595	16.81	16.78	207	1.99
290				21	0.59	0.59	54	0.52
291				6	0.17	0.17	10	0.10
292				22	0.62	0.62	36	0.35
293				15	0.42	0.42	27	0.26
294				4	0.11	0.11	13	0.13
295				34	0.96	0.96	13	0.13
296				35	0.99	0.99	38	0.37
297				18	0.51	0.51	13	0.13
298				24	0.68	0.68	17	0.16
299				42	1.19	1.18	15	0.14
300				8	0.23	0.23	15	0.14
301				13	0.37	0.37	46	0.44
302				16	0.45	0.45	42	0.40
30				99	2.80	2.79	60	0.58
304				80	2.26	2.26	230	2.21
305				11	0.31	0.31	26	0.25
306				12	0.34	0.34	10	0.10
307				26	0.73	0.73	15	0.14
308				20	0.56	0.56	47	0.45
309				98	2.77	2.76	70	0.67
310				170	4.80	4.80	24	0.23
311				100	2.82	2.82	49	0.47
312				74	2.09	2.09	59	0.57
313				50	1.41	1.41	46	0.44
314				192	5.42	5.42	352	3.38
315				285	8.05	8.04	207	1.99
316				110	3.11	3.10	125	1.20
317				130	3.67	3.67	67	0.64
318				178	5.03	5.02	68	0.65
319				55	1.55	1.55	13	0.13
320				44	1.24	1.24	33	0.32
321				13	0.37	0.37	87	0.84
322				39	1.10	1.10	20	0.19
323				445	12.57	12.55	174	1.67
324				25	0.71	0.71	23	0.22
325				372	10.51	10.49	148	1.42
326				42	1.19	1.18	37	0.36
327				34	0.96	0.96	13	0.13
328				35	0.99	0.99	38	0.37
329				18	0.51	0.51	13	0.13
330				8	0.23	0.23	15	0.14
331				150	4.24	4.23	155	1.49
332				705	19.92	19.89	370	3.56
333				50	1.41	1.41	46	0.44
334				192	5.42	5.42	352	3.38

WELL NUMBER	K+ mg/L	K+ mmol/L	K+ meq/L	Cl- mg/L	Cl- mmol/L	Cl- meq/L	SO4-- mg/L	SO4-- mmol/L
335				285	8.05	8.04	207	1.99
336				48	1.36	1.35	31	0.30
337	5.5	0.14	0.14	37	1.05	1.04	26	0.25
338				110	3.11	3.10	125	1.20
339				260	7.34	7.33	137	1.32
340				24	0.68	0.68	46	0.44
341				178	5.03	5.02	68	0.65
342				39	1.10	1.10	20	0.19
343				949	26.81	26.77	150	1.44
344				13	0.37	0.37	87	0.84
345	5.3	0.14	0.14	55	1.55	1.55	13	0.13
346				100	2.82	2.82	64	0.62
347	5.1	0.13	0.13	44	1.24	1.24	33	0.32
348	2.8	0.07	0.07	124	3.50	3.50	33	0.32
349				58	1.64	1.64	61	0.59
350				46	1.30	1.30	139	1.34
351				115	3.25	3.24	33	0.32
352	3.6	0.09	0.09	100	2.82	2.82	49	0.47
353	5	0.13	0.13	24	0.68	0.68	28	0.27
354				260	7.34	7.33	534	5.13
355				215	6.07	6.06	40	0.38
356				106	2.99	2.99	47	0.45
357	5	0.13	0.13	345	9.75	9.73	654	6.29
358				445	12.57	12.55	172	1.65
359				2200	62.15	62.05	1860	17.88
360	5	0.13	0.13	290	8.19	8.18	126	1.21
361	4.1	0.11	0.11	74	2.09	2.09	59	0.57
362	3.3	0.08	0.08	38	1.07	1.07	63	0.61
363	5.8	0.15	0.15	230	6.50	6.49	74	0.71
364	6	0.15	0.15	190	5.37	5.36	130	1.25
365	2.1	0.05	0.05	2	0.06	0.06	14	0.13
366	4.3	0.11	0.11	170	4.80	4.80	24	0.23
367	3.7	0.09	0.09	29	0.82	0.82	61	0.59
368	5	0.13	0.13	57	1.61	1.61	200	1.92
369				372	10.51	10.49	148	1.42
370	4.3	0.11	0.11	42	1.19	1.18	37	0.36
371				100	2.82	2.82	95	0.91
372	6.6	0.17	0.17	960	27.12	27.08	213	2.05
373				420	11.86	11.85	135	1.30
374				16	0.45	0.45	81	0.78
375								

WELL NUMBER	SO4-- meq/L	SiO2 mg/L	TDS mg/L	Na/Cl meq/L	Ca/Mg meq/L	Cl/Na meq/L	Ca+Mg/SO4 meq/L
1	0.56		459	2.76		0.36	
2	0.16		330	1.06		0.94	
3	0.18		323	2.02		0.49	
4	0.41		428	1.30		0.77	
5	0.48		421	0.51		1.96	
6	0.40		523	2.15		0.47	
7	0.38		390	4.06	1.62	0.25	10.34
8	0.46		445	2.02		0.49	
9	0.44		445	2.99		0.33	
10	0.44		447	2.47		0.41	
11	0.45		449	2.47		0.41	
12	0.43		439	2.52		0.40	
13	0.48		438	2.00		0.50	
14	0.52		468	2.31		0.43	
15	0.50		453	2.52		0.40	
16	0.36		387	1.91		0.52	
17	0.40		412	1.97		0.51	
18	0.48		469	2.23		0.45	
19	0.35		423	1.88		0.53	
20	0.37		438	1.88		0.53	
21	0.41		455	2.24		0.45	
22	0.45		426	1.48		0.68	
23	0.35		400	2.22		0.45	
24	0.35		416	1.54		0.65	
25	0.41		417	1.30		0.77	
26	0.43		422	1.31		0.76	
27	0.36		414	2.24	0.55	0.45	10.73
28	0.49		446	0.98		1.02	
29	0.53		451	1.37		0.73	
30	0.32		472	2.57		0.39	
31	0.45		404	1.61		0.62	
32	0.18		323	2.02		0.49	
33	0.41		347	2.31		0.43	
34	0.38		428	1.36		0.73	
35	0.43		444	1.31		0.76	
36	0.47	33	476	0.93	1.02	1.07	10.26
37	0.52		478	3.67		0.27	
38	0.35	27	412	3.08	0.79	0.32	11.08
39	0.28		402	1.70		0.59	
40	0.61	34	474	0.88	0.61	1.14	7.64
41	0.38		382	1.20		0.83	4.28
42	0.35		368	1.09		0.92	3.60
43	0.23		416	14.65		0.07	6.49
44	0.51	38	428	1.95	0.61	0.51	8.82
45	0.33		373	0.84		1.19	

WELL NUMBER	SO4-- meq/L	SiO2 mg/L	TDS mg/L	Na/Cl meq/L	Ca/Mg meq/L	Cl/Na meq/L	Ca+Mg/SO4 meq/L
46	0.32	30	321	0.97	0.90	1.03	13.29
47	0.19	30	396	7.52	0.58	0.13	17.61
48	0.38			1.12	1.19	0.90	11.23
49	0.19		324	1.29	1.39	0.78	17.40
50	0.45		442	1.66	1.11	0.60	8.83
51	0.58		484	3.23	0.77	0.31	7.34
52	0.64		592	0.87	1.03	1.14	9.32
53	0.56		482	4.92	0.56	0.20	6.46
54	0.27		434	1.54	1.18	0.65	14.02
55	0.53		407	1.63	0.74	0.61	7.57
56	0.36		341	2.24	0.55	0.45	10.73
57	0.32		403	0.97	0.90	1.03	13.29
58	0.19		372	7.52	0.58	0.13	17.61
59	0.61		451	0.88	0.61	1.14	7.64
60	0.51		408	1.95	0.61	0.51	8.82
61	0.47		447	0.93	1.02	1.07	10.26
62	0.35		384	3.08	0.79	0.32	11.08
63	0.18		323	2.06		0.49	0.00
64	0.38		390	3.86	1.62	0.26	10.34
65	0.56		459	2.76		0.36	
66	0.48		421	5.34		0.19	
67	0.40		523	2.15		0.47	
68	0.47		410	2.31	0.95	0.43	8.50
69	0.58			0.00			
70	0.37		438	1.88		0.53	
71	0.36		387	2.09		0.48	
72	0.43		439	2.68		0.37	
73	0.16		553	1.31		0.76	
74	0.53		451	1.49		0.67	
75	0.38		428	1.66		0.60	
76	0.35		416	1.73		0.58	
77	0.32		472	3.47		0.29	
78	0.28		401	1.70		0.59	
79	0.33		373	0.84		1.19	
80	2.16		2026	0.73		1.37	
81	0.66		452	5.01		0.20	
82	1.23		552	2.90		0.34	
83	0.32		391	2.12		0.47	
84	0.64		534	1.09		0.92	
85	0.34		445	1.23		0.81	
86	0.88		574	1.08		0.93	
87	1.15		615	0.88		1.14	
88	1.54		747	1.43		0.70	
89	0.57		451	3.36		0.30	
90	0.66		572	1.14		0.87	
91	3.25		3583	1.06		0.95	
92	3.50		3652	1.03		0.98	
93	0.91		468	4.95		0.20	
94	0.75		447	3.70		0.27	

WELL NUMBER	SO4-- meq/L	SiO2 mg/L	TDS mg/L	Na/Cl meq/L	Ca/Mg meq/L	Cl/Na meq/L	Ca+Mg/SO4 meq/L
95	0.63		434	3.08		0.32	
96	0.93		500	5.42		0.18	
97	1.63		869	1.00		1.00	
98	2.45		4145	0.99		1.01	
99	1.17		689	0.99		1.01	
100	0.69		449	1.25		0.80	
101	1.01		524	5.22		0.19	
102	0.63		407	1.70		0.59	
103	0.81		483	1.18		0.85	
104	0.67		429	3.47		0.29	
105	0.63		444	4.24		0.24	
106	0.24	16	382	1.83	1.27	0.55	17.08
107	2.36	0	3130	1.02	1.21	0.98	3.48
108	1.15	16	1580	0.80	1.13	1.25	9.12
109	0.66		429	3.47		0.29	
110	1.01		524	4.93		0.20	
111	0.01		517	5.32		0.19	
112	6.53		4970	1.16		0.86	
113	1.32		512	2.14		0.47	
114	1.62		571	3.50		0.29	
115	0.97		494	5.55		0.18	
116	1.77		635	4.05		0.25	
117	1.63		618	2.70		0.37	
118	1.49		541	2.36		0.42	
119	4.08		2192	1.25		0.80	
120	1.26		502	3.47		0.29	
121	1.43		559	4.37		0.23	
122	1.65		657	2.35		0.42	
123	0.73		477	2.40		0.42	
124	1.78		596	2.99		0.33	
125	2.50		782	5.91		0.17	
126	0.92		495	3.19		0.31	
127	1.60		567	4.50		0.22	
128	1.11		505	4.77		0.21	
129	1.08		486	4.07		0.25	
130	0.81		450	4.32		0.23	
131	1.88		629	3.86		0.26	
132	0.55		514	1.85		0.54	
133	1.86		608	2.54		0.39	
134	0.21	27	362	5.01	1.00	0.20	17.91
135	0.22		345	2.12		0.47	
136	0.38		438	1.31		0.76	
137	2.07		806	4.09		0.24	
138	1.58		602	4.07		0.25	
139	0.77		471	4.91		0.20	
140	0.52		421	4.63		0.22	
141	0.51			6.61		0.15	
142	0.48			5.78		0.17	
143	2.90		988	4.14		0.24	

WELL NUMBER	SO4-- meq/L	Si02 mg/L	TDS mg/L	Na/Cl meq/L	Ca/Mg meq/L	Cl/Na meq/L	Ca+Mg/SO4 meq/L
144	1.12		517	3.86		0.26	
145	2.10		693	5.07		0.20	
146	1.78		659	3.58		0.28	
147	2.12		815	4.03		0.25	
148	0.64		449	6.85		0.15	
149	1.38		496	4.51		0.22	
150	0.95		486	3.75		0.27	
151	0.56		438	2.73		0.37	
152	0.64	25	475	5.09	0.79	0.20	6.65
153	1.13		538	4.63		0.22	
154	0.79		467	4.41		0.23	
155	0.52	27	456	3.52	0.70	0.28	7.26
156	0.40	30	438	2.11	0.63	0.47	9.62
157	0.48	34	551	2.96	2.16	0.34	12.45
158	0.97		518	1.47		0.68	
159	2.07		726	4.63		0.22	
160	0.27		379	8.13		0.12	
161	2.36		868	6.71		0.15	
162				4.20		0.24	
163	2.21		866	4.41		0.23	
164	0.80	35	560	0.47	2.63	2.13	7.86
165	0.63	24	469	4.78	0.63	0.21	6.21
166				4.43		0.23	
167	0.29	29	440	3.64	2.47	0.27	13.85
168	1.06	28	885	0.60	0.95	1.66	9.70
169	1.73		758	5.62		0.18	
170	1.63	34	577	2.54	2.58	0.39	3.60
171	1.88		737	4.03		0.25	0.00
172	0.76	27	642	0.44	1.02	2.27	10.28
173	0.59	29	579	2.41	1.21	0.41	9.00
174	1.73		657	5.11		0.20	
175	1.73		752	5.14		0.19	
176	0.86	33	470	0.88	2.65	1.13	5.62
177	0.67	33	469	1.98	1.59	0.50	6.65
178	0.52	34	513	0.81	2.08	1.24	10.25
179	0.78	36	471	3.44	1.58	0.29	6.27
180	0.91	34	512	1.74	1.82	0.57	5.33
181	0.68		410	3.21		0.31	
182	0.83		501	1.31	1.40	0.76	6.21
183	0.40		412	2.11	0.63	0.47	9.62
184	0.63		445	4.78	0.63	0.21	6.21
185	0.52		431	3.52	0.70	0.28	7.26

WELL NUMBER	SO4-- meq/L	SiO2 mg/L	TDS mg/L	Na/Cl meq/L	Ca/Mg meq/L	Cl/Na meq/L	Ca+Mg/SO4 meq/L
186	0.80		522	0.47	2.63	2.13	7.86
187	0.54		448	2.97	1.47	0.34	7.94
188	0.25		403	1.54	2.04	0.65	19.03
189	1.87		663	2.55	2.18	0.39	3.08
190	1.84		810	4.35	1.01	0.23	4.05
191	0.62		470	4.63	0.93	0.22	6.21
192	0.41		406	4.78	1.07	0.21	8.65
193	0.19		365	1.87	0.96	0.53	18.50
194	2.16		827	3.78	1.31	0.26	3.42
195	0.69		430	2.57	1.24	0.39	6.12
196	1.45		538	2.26	2.43	0.44	3.88
197	0.89		527	1.38	1.04	0.73	5.81
198	0.64		567	0.50	0.90	2.00	8.99
199	0.45		458	1.38	0.67	0.72	9.11
200	0.91		540	2.60	1.07	0.39	5.60
201	0.49		478	1.09	0.76	0.92	9.44
202	2.67		723	3.81	1.46	0.26	2.65
203	0.72		469	1.34	1.21	0.75	6.57
204	1.99		888	1.68	1.11	0.60	2.71
205	0.38		391	4.35	0.67	0.23	9.67
206	0.55		455	1.76	0.69	0.57	7.36
207	0.58		436	2.36	1.12	0.42	7.86
208	1.23		584	2.61	0.97	0.38	4.36
209	0.34		629	0.44		2.28	
210	1.46		615	4.07	1.17	0.25	3.92
211	1.77		635	4.34		0.23	
212	1.62		571	3.50		0.29	
213	0.81		450	4.78		0.21	
214	0.56		514	1.85		0.54	
215	0.27		379	7.45		0.13	
216	0.99		542	5.69		0.18	
217	0.48		300	5.78		0.17	
218	0.22		345	2.51		0.40	
219	2.12		816	4.27		0.23	
220	1.86		608	2.81		0.36	
221	1.12		517	4.11		0.24	
222	0.38		438	1.47		0.68	
223	1.51		662	6.66		0.15	
224	1.73		752	5.55		0.18	
225	2.23		700	5.54		0.18	
226	1.88		737	4.03		0.25	
227	0.00			4.20		0.24	
228	0.88		364	2.51	1.78	0.40	4.40
229	0.70		490	1.73	1.09	0.58	7.36
230	0.73		335				3.48

WELL NUMBER	SO4-- meq/L	SiO2 mg/L	TDS mg/L	Na/Cl meq/L	Ca/Mg meq/L	Cl/Na meq/L	Ca+Mg/SO4 meq/L
231	0.63		447	4.21	.89	0.24	7.46
232	0.66		452	5.01		0.20	
233	1.23		552	2.90		0.34	
234	0.32		391	2.41		0.41	
235	0.48		429	1.46	.72	0.69	9.70
236	0.38		380	1.93	.63	0.52	10.79
237	0.69		453	1.25		0.80	
238	0.57		451	3.36		0.30	
239	0.93		500	5.73		0.17	
240	2.12		816	4.27		0.23	
241	1.01		524	5.58		0.18	
242	1.63		869	1.00		1.00	
243	0.24		415	2.16	.27	0.46	17.08
244	3.25		3584	1.06		0.95	0.00
245	1.49		593	3.28	.88	0.31	4.36
246	1.08		554	3.60		0.28	
247	0.19		606	0.39	3.43	2.57	37.88
248	0.83		793	1.13	2.84	0.89	9.55
249	0.40		535	1.04	1.40	0.96	11.24
250	0.37		501	1.59	3.22	0.63	12.35
251	0.60		570	1.37	1.15	0.73	5.94
252	0.65		531	1.00	1.08	1.00	7.06
253	0.79		878	0.79	1.98	1.26	8.09
254	0.20		604	1.37	2.07	0.73	21.26
255	0.70		572	1.71	1.00	0.59	6.11
256	0.35		509	0.32	2.05	3.14	15.23
257	0.52		584	1.18	2.25	0.85	7.22
258	0.27						
259	1.92						
260	0.07						
261	0.03						
262	0.51		491	0.87	1.06	1.15	10.29
263	0.18		386	2.47	0.99	0.41	17.03
264	0.64		597	1.08	0.87	0.93	7.65
265	1.19		726	1.15	0.92	0.87	4.90
266	0.75		567	0.85	0.71	1.17	7.69
267	0.67						
268	0.08						
269	0.69						
270	0.12						
271	0.31						
272	0.07						
273	0.22						
274	0.37						
275	0.21						
276	0.12						
277	0.25						
278	9.62						
279	0.23		302	1.00	1.34	1.00	15.86

WELL NUMBER	SO4-- meq/L	SiO2 mg/L	TDS mg/L	Na/Cl meq/L	Ca/Mg meq/L	Cl/Na meq/L	Ca+Mg/SO4 meq/L
280	0.12						
281	0.46						
282	0.08						
283	0.38						
284	0.37		70				
285	0.63						
286	0.22		431	0.68	5.44	1.47	23.50
287	0.13			0.00	ERR		
288	1.01		571	1.98	0.96	0.51	4.64
289	0.50			0.00	ERR		
290	1.99		1593	1.08	0.90	0.93	3.61
291	0.52						
292	0.10						
293	0.35						
294	0.26		597	3.08	3.33	0.32	19.24
295	0.13			0.00	ERR		
296	0.13		411	1.86	2.73	0.54	29.46
297	0.37						
298	0.13						
299	0.16						
300	0.14						
301	0.14		458	1.93	5.02	0.52	37.76
302	0.44						
303	0.40						
304	0.58						
305	2.21						
306	0.25						
307	0.10						
308	0.14						
309	0.45		450	2.08	0.78	0.48	9.07
310	0.67		618	1.20	1.24	0.84	7.38
311	0.23		611	0.24	2.57	4.08	33.06
312	0.47		598	1.54	1.99	0.65	7.32
313	0.57		500	0.52	2.65	1.92	11.64
314	0.44		459	2.13		0.47	
315	3.38		1133	1.22		0.82	
316	1.99		1226	1.21		0.83	
317	1.20		759	2.27		0.44	
318	0.64		597	1.08	0.87	0.93	7.65
319	0.65		770	1.11		0.90	
320	0.13		174	0.34		2.97	
321	0.32		476	2.21		0.45	
322	0.84		543	3.80		0.26	
323	0.19		635	1.90		0.53	
324	1.67		1323	1.10		0.91	
325	0.22		431	0.68	5.44	1.47	23.50
326	1.42		1162	1.09		0.92	
327	0.36		478	1.58		0.63	
328	0.13		453	1.86	2.73	0.54	29.46

WELL NUMBER	SO4-- meq/L	SiO2 mg/L	TDS mg/L	Na/Cl meq/L	Ca/Mg meq/L	Cl/Na meq/L	Ca+Mg/SO4 meq/L
329	0.37						
330	0.13						
331	0.14		487	1.93	5.02	0.52	37.76
332	1.49		801	1.58		0.63	
333	3.56		2109	1.17		0.86	
334	0.44		459	2.13		0.47	
335	3.38		1183	1.22		0.82	
336	1.99		1226	1.21		0.83	
337	0.30		503	1.16		0.86	
338	0.25		429	1.79		0.56	
339	1.20		759	2.27		0.44	
340	1.32		1050	1.22		0.82	
341	0.44		476	2.63		0.38	
342	0.65		770	1.11		0.90	
343	0.19		0	1.90		0.53	
344	1.44		2157	0.97		1.03	
345	0.84		543	37.96		0.03	
346	0.13		179	0.25		3.96	
347	0.62		588	1.34		0.75	
348	0.32		475	2.10		0.48	
349	0.32		636	0.63		1.58	
350	0.59		577	1.33		0.75	
351	1.34		699	1.24		0.81	
352	0.32		657	1.09		0.92	
353	0.47	35	617	1.54	1.99	0.65	7.32
354	0.27	37	450	1.80	1.24	0.56	15.07
355	5.13		1637	0.91		1.09	
356	0.38		958	0.64		1.57	
357	0.45		647	0.86		1.16	
358	6.29		1945	1.24		0.81	
359	1.65		1323	1.10		0.91	
360	17.88		6941	0.93		1.07	
361	1.21		1083	1.05		0.95	0.00
362	0.57		530	0.52	2.65	1.92	11.64
363	0.61	34	616	1.50	1.82	0.67	9.57
364	0.71	31	832	0.87	1.25	1.15	8.07
365	1.25	51	1006	0.97	2.08	1.03	6.50
366	0.13	31	674	3.24	6.61	0.31	51.21
367	0.23	30	636	0.24	2.57	4.08	33.06
368	0.59	38	510	1.97	1.31	0.51	7.79
369	1.92	31	850	1.95	2.30	0.51	4.10
370	1.42		1162	1.09		0.92	
371	0.36		478	1.47		0.68	
372	0.91		794	2.00		0.50	
373	2.05		2344	1.05		0.95	
374	1.30		1160	1.06		0.95	
375	0.78		480	3.95		0.25	

APPENDIX B

MASS BALANCE OUTPUT DATA

WELL NUMBER	CALCITE	DOLOMITE	GYPSUM	HALITE	ION EXCHANGE
7	0.4615	0.74	0.406	0.268	0.4095
36	-0.5105	1.193	0.51	0.931	-0.0305
38	-0.243	1.069	0.375	0.338	0.353
40	-1.2885	1.44	0.656	1.044	-0.0655
41	-0.9565	1.365	0.416	0.508	0.0505
42	-1.2	1.474	0.375	0.48	0.021
43	0.993	0.66	0.25	0.17	1.155
44	-0.9005	1.398	0.552	0.423	0.2015
46	-0.471	1.111	0.343	0.987	-0.015
47	-0.276	1.069	0.208	0.116	0.377
48	-0.1825	0.987	0.416	0.818	0.0475
49	0.1145	0.699	0.208	0.338	0.0485
50	-0.1445	0.946	0.489	0.733	0.2425
51	-0.234	1.193	0.625	0.592	0.661
52	-0.74	1.481	0.697	1.692	-0.085
53	-0.2235	1.152	0.604	0.451	0.8835
54	0.035	0.864	0.292	0.621	0.168
55	-0.718	1.152	0.573	0.508	0.159
56	-0.752	1.234	0.385	0.31	0.193
57	-0.471	1.11	0.343	0.987	-0.015
58	-0.27	1.069	0.208	0.116	0.377
59	-1.2885	1.44	0.656	1.044	-0.0655
61	-0.5105	1.193	0.51	0.93	-0.036
62	-0.243	1.069	0.375	0.338	0.353
64	0.5955	0.74	0.406	0.282	0.5435
68	-0.232	1.028	0.51	0.508	0.333
106	0.1705	0.905	0.26	0.451	0.187
107	-1.8035	1.851	2.55	40.6	0.3515
108	-2.844	2.468	1.249	19.15	-1.921
134	0	0.946	0.229	0.113	0.226
152	-0.3655	1.193	0.697	0.282	0.576
155	-0.4008	1.11	0.562	0.395	0.498
156	-0.5845	1.193	0.473	0.536	0.297
157	-0.13	0.946	1.56	0.338	0.331
165	-0.589	1.19	0.677	0.282	0.533
167	0.802	0.576	0.312	0.203	0.268
168	-1.898	2.632	1.145	3.105	-0.6165
170	-0.103	0.823	1.77	0.48	0.396
172	-1.88	1.93	0.822	3.945	-1.1045
173	0.0775	1.193	0.635	0.649	0.4585
176	0.1215	0.658	0.927	0.987	-0.0585
177	0.07	0.864	0.729	0.592	0.291
178	0.249	0.864	0.562	1.241	-0.1205
179	0.155	0.946	0.843	0.367	0.447
180	-0.04	0.864	0.989	0.649	0.241
182	-0.3235	1.069	0.895	0.931	0.143

WELL NUMBER	CALCITE	DOLOMITE	GYPSUM	HALITE	ION EXCHANGE
183	-0.5845	1.193	0.437	0.536	0.297
184	-0.589	1.193	0.677	0.282	0.533
185	-0.4005	1.11	0.562	0.395	0.498
186	0.0255	0.864	0.864	1.946	-0.5165
187	0.145	0.905	0.583	0.367	0.36
188	0.0605	0.78	0.802	0.733	0.0465
189	-0.3855	0.905	2.02	0.733	0.5685
190	-0.93	1.85	1.988	0.621	1.038
191	-0.116	0.987	0.666	0.338	0.614
192	0.144	0.864	0.448	0.282	0.533
193	-0.068	0.905	0.208	0.395	0.172
194	-0.715	1.604	2.342	0.818	1.135
195	-0.256	0.946	0.749	0.338	0.266
196	-0.132	0.823	1.572	0.423	0.267
197	-0.7255	1.275	0.968	1.044	0.1955
198	-1.389	1.522	0.697	2.172	-0.5425
199	-0.689	1.234	0.489	1.1	0.211
200	-0.47	1.234	0.989	0.536	0.428
201	-0.817	1.316	0.531	0.762	0.032
202	-1.5645	1.44	2.89	0.48	0.6735
203	-0.44	1.069	0.781	0.649	0.1105
204	-1.0325	1.275	2.155	2.877	0.9755
205	-0.26	1.11	0.416	0.31	0.519
206	-0.737	1.193	0.593	0.226	2.108
207	-0.17	1.06	0.625	0.48	0.3255
208	-0.7765	1.357	1.332	0.733	0.5905
210	-0.4	1.316	1.582	0.621	0.95
227	-0.06	0.699	0.958	0.451	0.34
229	0.0205	0.823	0.76	0.705	0.2565
231	-0.31	1.234	0.677	0.31	0.4975
235	-0.789	1.357	0.521	0.508	0.1155
236	-0.6835	1.275	0.416	0.451	0.2095
243	0.228	0.905	0.26	0.423	0.245
245	-1.3	1.727	1.614	0.451	0.514
247	0.152	0.823	0.208	5.359	-1.635
248	1.0975	1.028	0.895	1.58	0.0115
249	-0.0205	0.946	0.437	1.833	0.0405
250	1.057	0.535	0.396	0.903	0.266
251	0.005	0.823	0.645	2.821	0.525
252	-0.6185	1.11	0.7	2.257	0.0025
253	-0.678	1.11	0.635	2.087	-0.13
254	-15.85	0.699	0.219	2.595	-16.38
255	-0.1	1.06	0.76	1.833	0.6495
256	-0.074	0.864	0.375	1.777	-0.606
257	0.4775	0.576	0.562	3.582	0.318
262	-0.63	1.275	0.55	2.25	-0.15
263	0.416	0.781	0.198	0.846	0.621
264	-0.7195	1.316	0.697	3.667	0.1455
265	-0.8745	1.522	1.291	4.372	0.5415

WELL NUMBER	CALCITE	DOLOMITE	GYPSUM	HALITE	ION EXCHANGE
266	-1.531	1.686	0.812	3.159	-0.231
286	1.44	0.403	0.239	0.705	-0.11
288	-0.3095	1.193	1.09	1.69	0.8285
309	-0.43	1.15	0.489	0.564	0.305
310	-0.197	1.11	0.729	2.76	0.271
311	-0.3855	1.069	0.25	4.795	-1.8105
312	0.8265	0.576	0.51	2.82	0.7645
313	0.376	0.905	0.614	2.087	-0.5
318	-0.7195	1.316	0.697	3.667	0.1455
330	1.13	0.494	0.135	0.959	0.412
331	1.7665	0.452	0.153	0.26	0.104
353	0.8265	0.576	0.51	2.82	0.76
355	0.1965	0.905	0.292	0.677	0.2705
362	0.376	0.905	0.614	2.087	-0.5
363	0.455	1.028	0.656	1.07	0.2685
364	-0.865	1.275	0.77	6.48	-0.417
365	0.007	1.31	1.35	5.35	-0.07
366	2.45	0.452	0.146	0.056	0.0635
367	-0.3855	1.069	0.25	4.795	-1.8105
368	0.0705	0.98	0.635	0.818	0.395
369	0.231	1.19	2.08	1.6	0.76
378	0.6245	0.699	0.521	1.49	0.1225
379	-0.197	1.11	0.729	2.764	0.27
380	0.889	0.74	0.26	1.58	0
381	-2.87	3.24	3.22	1.24	1.53
382	-0.15	1.028	2.082	3.103	1.493
383	-1.236	1.686	1.145	10.43	-0.651
384	0.1535	0.905	0.687	0.564	0.522

APPENDIX C

SAMPLE WATEQF PRINTOUT

```
415

                TEMP      =        17.500000
                PH        =         7.400000
                EHM       =         9.900000
                DOC       =          .000000
                DOX       =         7.400000
                CORALK    =         0
                FLG       =       MG/L
                DENS      =         1.000000
                PRNT      =         0
                PUNCH     =         1
                EHOPT     =         0
                EMPOX     =         0
                ITDS      =       513.000000
                COND      =       582.000000
                SIGMDO    =          .000000
                SIGMEH    =          .000000
                SIGMPH    =          .000000

    Species    Index No      Input Concentration
    ---------------------------------------------
    Ca         :     0   :       49.00000000
    Mg         :     1   :       22.00000000
    Na         :     2   :       37.00000000
    K          :     3   :        3.90000000
    Cl         :     4   :       20.00000000
    SO4        :     5   :       66.00000000
    HCO3       :     6   :      250.00000000
    Fe total   :    16   :         .02000000
    H2S aq     :    13   :         .00000000
    CO3        :    17   :         .00000000
    SiO2 tot   :    34   :       33.00000000
    NH4        :    38   :         .00000000
    B tot      :    86   :         .12000000
    PO4        :    44   :         .00000000
    Al         :    50   :         .00000000
    F          :    61   :        1.30000000
    NO3        :    84   :       12.00000000
    Fe         :     7   :         .00002000
    Br         :    97   :         .20000000
    Mn         :   109   :         .00010000
    NO2        :   202   :         .03000000
```

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 415                                                                              Date =  1/04/80   2:22

     DOX =       7.4000          DOC =        .0      INPUT TDS =    513.0
Anal Cond =    582.0     Calc Cond =    599.9

***** Eh and pE calculated from iron 2/3 activity ratio have been substituted for input Eh data *****

Anal EPMCAT =    5.9681   Anal EPMAN =    6.3038   Percent difference in input cation/anion balance =   -5.4708
Calc EPMCAT =    5.6068   Calc EPMAN =    6.0231   Percent difference in calc  cation/anion balance =   -5.7448
Total  Ionic  Strength   (T.I.S.) from input data =     .00895
Effective Ionic Strength (E.I.S.) from speciation =     .00840

                                   Sato                                                Calc
  Input  Sigma   Fe3/Fe2 Sigma   H2O2/O2 Sigma   NO3/NO2 Sigma   NO3/NH4 Sigma   H2O2/O2 Sigma   SO4/S=  Sigma   As5/A
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - Eh - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  9.900   .000     .410   .000     .177   .000     .492   .000    9.900   .000     .797   .000    9.900   .000    9.9

 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - pE - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
100.000   .000    7.106   .000    3.076   .000    8.535   .000  100.000   .000   13.819   .000  100.000   .000  100.0

                          Effective
    T      pH     TDS ppm  Ionic Str   pO2 Atm   pCO2 Atm   pCH4 Atm   CO2 Tot   Uncom CO2  ppm Uncom CO2   Ncr
  17.50   7.400    494.6     .00840   2.08E-28   8.66E-03   8.85E-95    .00445   4.02E-03     1.77E+02      1.5

   I  Species          Anal ppm         Calc ppm     Anal Molal  Calc Molal  Activity       Act Coeff    -Log Act
   0  Ca          2      49.000          45.012      1.223E-03   1.124E-03   7.791E-04        .6934       3.108
  28  CaOH        1                        .000163               2.852E-09   2.595E-09        .9100       8.586
  31  CaSO4 aq    0                       8.165                  6.001E-05   6.012E-05       1.0019       4.221
  81  CaHSO4      1                        .000002               1.308E-11   1.190E-11        .9100      10.924
  29  CaHCO3      1                       3.531                  3.495E-05   3.180E-05        .9100       4.498
  30  CaCO3 aq    0                        .418                  4.182E-06   4.190E-06       1.0019       5.378
 100  CaF         1                        .022                  3.796E-07   3.454E-07        .9100       6.462
   1  Mg          2      22.000          20.315      9.054E-04   8.360E-04   5.829E-04        .6972       3.234
  18  MgOH        1                        .000542               1.312E-08   1.194E-08        .9100       7.923
  22  MgSO4 aq    0                       4.729                  3.931E-05   3.938E-05       1.0019       4.405
  21  MgHCO3      1                       2.228                  2.613E-05   2.377E-05        .9100       4.624
  20  MgCO3 aq    0                        .152                  1.807E-06   1.810E-06       1.0019       5.742
  19  MgF         1                        .030                  2.073E-06   1.887E-06        .9100       5.724
   2  Na          1      37.000          36.856      1.610E-03   1.604E-03   1.461E-03        .9109       2.835
  43  NaSO4      -1                        .368                  3.095E-06   2.816E-06        .9100       5.550
  42  NaHCO3aq    0                        .252                  3.002E-06   3.008E-06       1.0019       5.522
  41  NaCO3      -1                        .006115               7.372E-08   6.708E-08        .9100       7.173
 297  NaF aq      0                        .000430               1.024E-08   1.026E-08       1.0019       7.989
   3  K           1       3.900           3.890      9.979E-05   9.954E-05   9.045E-05        .9086       4.044
  45  KSO4       -1                        .033                  2.467E-07   2.245E-07        .9100       6.649
  63  H           1                        .000044               4.328E-08   3.981E-08        .9198       7.400
  26  OH         -1                        .002608               1.535E-07   1.396E-07        .9100       6.855
  17  CO3        -2                        .316                  5.263E-06   3.651E-06        .6938       5.438
   6  HCO3       -1     250.000         244.608      4.099E-03   4.011E-03   3.661E-03        .9127       2.436
  85  H2CO3 aq    0                      22.611                  3.647E-04   3.655E-04       1.0021       3.437
   5  SO4        -2      66.000          56.141      6.874E-04   5.847E-04   4.039E-04        .6906       3.394
  62  HSO4       -1                        .000135               1.396E-09   1.270E-09        .9100       8.896
  61  F          -1       1.300           1.253      6.846E-05   6.599E-05   6.005E-05        .9100       4.221
 125  HF aq       0                        .000061               3.029E-09   3.035E-09       1.0019       8.518
 126  HF2        -1                        .000000               7.261E-13   6.607E-13        .9100      12.180
 296  H2F2 aq     0                        .000000               3.344E-17   3.350E-17       1.0019      16.475
   4  Cl         -1      20.000          19.999      5.644E-04   5.644E-04   5.128E-04        .9086       3.290
  97  Br         -1        .200            .200      2.504E-06   2.504E-06   2.279E-06        .9100       5.642
  34  SiO2 tot    0      33.000                      5.495E-04
  23  H4SiO4aq    0                      52.671                  5.483E-04   5.494E-04       1.0019       3.260
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  I Species          Anal ppm        Calc ppm      Anal Molal  Calc Molal  Activity      Act Coeff    -Log Act
 24 H3SiO4   -1                       .114                     1.202E-06   1.094E-06      .9100        5.961
 25 H2SiO4   -2                       .000003                  3.254E-11   2.231E-11      .6857       10.652
124 SiF6     -2                       .000000                  2.902E-28   1.990E-28      .6857       27.701
 86 B tot     0        .120                        1.111E-05
 35 H3BO3 aq  0                       .677                     1.095E-05   1.098E-05     1.0019        4.960
 36 H2BO3    -1                       .009154                  1.506E-07   1.370E-07      .9100        6.863
101 BF(OH)3  -1                       .000021                  2.660E-10   2.421E-10      .9100        9.616
102 BF2(OH)2 -1                       .000000                  6.921E-14   6.298E-14      .9100       13.201
103 BF3OH    -1                       .000000                  2.099E-19   1.910E-19      .9100       18.719
104 BF4      -1                       .000000                  2.076E-24   1.889E-24      .9100       23.724
202 NO2      -1        .030           .030         6.524E-07   6.524E-07   5.937E-07      .9100        6.226
 84 NO3      -1      12.000         11.999         1.936E-04   1.936E-04   1.762E-04      .9100        3.754
  7 Fe        2        .000020        .000019      3.583E-10   3.425E-10   2.349E-10      .6857        9.629
 10 FeOH      1                       .000000                  1.154E-12   1.050E-12      .9100       11.979
 79 Fe(OH)2   0                       .000000                  1.147E-16   1.149E-16     1.0019       15.940
 11 Fe(OH)3  -1                       .000000                  1.093E-19   9.942E-20      .9100       19.003
 33 FeSO4 aq  0                       .000002                  1.462E-11   1.465E-11     1.0019       10.834
122 FeHSO4    1                       .000000                  3.942E-18   3.587E-18      .9100       17.445
  8 Fe        3        .019980        .000000      3.579E-07   4.207E-16   1.800E-16      .4278       15.745
  9 FeOH      2                       .000002                  2.706E-11   1.855E-11      .6857       10.732
 76 Fe(OH)2   1                       .024                     2.667E-07   2.427E-07      .9100        6.615
 77 Fe(OH)3   0                       .007634                  7.147E-08   7.161E-08     1.0019        7.145
 78 Fe(OH)4  -1                       .002447                  1.976E-08   1.798E-08      .9100        7.745
179 Fe2(OH)2  4                       .000000                  5.755E-20   1.272E-20      .2210       19.896
180 Fe3(OH)4  5                       .000000                  6.582E-24   6.223E-25      .0945       24.206
 14 FeSO4     1                       .000000                  5.603E-16   5.099E-16      .9100       15.293
108 Fe(SO4)2 -1                       .000000                  6.943E-18   6.318E-18      .9100       17.199
123 FeHSO4    2                       .000000                  1.007E-22   6.904E-23      .6857       22.161
 15 FeCl      2                       .000000                  3.185E-18   2.184E-18      .6857       17.661
 27 FeCl2     1                       .000000                  7.016E-21   6.385E-21      .9100       20.195
 32 FeCl3 aq  0                       .000000                  3.268E-25   3.274E-25     1.0019       24.485
105 FeF       2                       .000000                  2.221E-14   1.523E-14      .6857       13.817
106 FeF2      1                       .000000                  3.651E-14   3.322E-14      .9100       13.479
107 FeF3 aq   0                       .000000                  3.075E-15   3.081E-15     1.0019       14.511
109 Mn        2        .000100        .000091      1.821E-09   1.657E-09   1.136E-09      .6857        8.945
119 MnHCO3    1                       .000010                  8.509E-11   7.743E-11      .9100       10.111
111 MnCl      1                       .000000                  2.590E-12   2.357E-12      .9100       11.628
112 MnCl2 aq  0                       .000000                  3.277E-16   3.283E-16     1.0019       15.484
113 MnCl3    -1                       .000000                  8.342E-20   7.591E-20      .9100       19.120
116 MnF       1                       .000000                  5.307E-13   4.829E-13      .9100       12.316
114 MnOH      1                       .000000                  4.304E-13   3.917E-13      .9100       12.407
115 Mn(OH)3  -1                       .000000                  3.134E-22   2.852E-22      .9100       21.545
118 Mn(NO3)2  0                       .000000                  1.426E-16   1.428E-16     1.0019       15.845
117 MnSO4 aq  0                       .000011                  7.580E-11   7.595E-11     1.0019       10.119
110 Mn        3                       .000000                  3.431E-28   1.468E-28      .4278       27.833
121 MnO4     -2                       .000000                  3.661E-43   2.510E-43      .6857       42.600
120 MnO4     -1                       .000000                  4.561E-46   4.151E-46      .9100       45.382
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	Phase	Log AP/KT	Sigma(A)	Sigma(T)	Log AP/MinKT	Log AP/MaxKT	Log AP	Log KT	Log MinKT	Log MaxKT
17	Anhydrite	-1.936					-6.502	-4.566		
21	Aragonite	-.254		.020			-8.546	-8.292		
150	Artinite	-6.998					3.145	10.144		
19	Brucite	-5.724					-16.944	-11.220		
12	Calcite	-.105		.020	-.035		-8.546	-8.441	-8.511	
97	Chalcedony	.350					-3.260	-3.610		
20	Chrysotile	-5.032					-57.353	-52.322		
29	Clinoenstite	-3.420			-3.054	-3.714	-20.204	-16.784	-17.150	-16.490
99	Cristobalite	.431					-3.260	-3.691		
28	Diopside	-3.778					-40.283	-36.505		
11	Dolomite	-.375					-17.218	-16.843		
340	Epsomite	-4.435					-6.629	-2.193		
112	Ferrihydrite	1.564			4.898	1.459	6.455	4.891	1.557	4.996
419	Fe3(OH)8	-2.141			.969	-6.024	18.081	20.222	17.112	24.105
181	FeOH)2.7Cl.3	6.288					3.248	-3.040		
401	Fe2(SO4)3	-46.369			-42.139		-41.671	4.698	.468	
62	Fluorite	-.509					-11.551	-11.042		
27	Forsterite	-9.363					-37.149	-27.786		
110	Goethite	5.681		.800			6.455	.774		
111	Greenalite	-11.818					8.992	20.810		
18	Gypsum	-1.897					-6.502	-4.605		
64	Halite	-7.690					-6.125	1.565		
108	Hematite	16.335					12.910	-3.425		
117	Huntite	-5.081					-34.562	-29.481		
38	Hydrmagnesit	-15.353					-51.633	-36.279		
204	Jarosite Na	-1.942		1.000			-12.458	-10.516		
205	Jarosite K	.542		1.100		-1.758	-13.666	-14.208		-11.908
337	Jarosite H	-5.966					-17.023	-11.057		
98	Magadiite	-5.164					-19.464	-14.300		
109	Maghemite	6.524					12.910	6.386		
10	Magnesite	-.760			-.510	-1.010	-8.672	-7.912	-8.162	-7.662
107	Magnetite	13.389			13.759	10.531	18.081	4.691	4.321	7.549
339	Melanterite	-10.499					-13.024	-2.524		
66	Mirabilite	-7.592					-9.065	-1.473		
58	Nahcolite	-4.653					-5.272	-.618		
60	Natron	-9.500					-11.109	-1.609		
143	Nesquehonite	-3.161			-3.649	-4.236	-8.672	-5.512	-5.024	-4.437
101	Quartz	.864					-3.260	-4.124		
36	Sepiolite(c)	-2.521					13.351	15.872		
153	Sepiolite(a)	-5.309					13.351	18.660		
9	Siderite	-4.618			-3.064		-15.067	-10.449	-12.003	
100	SiO2 (a,L)	-.158					-3.260	-3.102		
395	SiO2 (a,M)	-.476					-3.260	-2.784		
37	Talc	-.619		2.000	1.549	-2.367	21.656	22.276	20.108	24.024
65	Thenardite	-8.896					-9.064	-.168		
61	Thermonatr	-11.286					-11.108	.178		
31	Tremolite	-3.306					-144.439	-141.132		
59	Trona	-15.926					-16.380	-.455		
183	Pyrolusite	-7.541				-7.718	8.872	16.413		16.590
184	Birnessite	-9.219					8.872	18.091		
185	Nsutite	-8.632					8.872	17.504		
186	Bixbyite	-10.944			-9.329	-11.125	-11.267	-.323	-1.938	-.142
187	Hausmannite	-16.479					46.577	63.056		
188	Pyrocroite	-9.660				-9.953	5.855	15.515		15.808
189	Manganite	-5.396					-5.634	-.238		
190	Rhodochrosit	-4.012			-3.403	-4.429	-14.382	-10.371	-10.980	-9.954
191	MnCl2, 4H2O	-17.906					-15.525	2.381		
182	MnSO4	-15.300					-12.338	2.962		
134	Mn2(SO4)3	-60.876					-65.848	-4.972		
195	a-Cryptomeln						-130.779			
198	Todorokite						-68.906			
200	Rancieite						-60.066			

```
Mole ratios from analytical molality   -   Log activity ratios

        Cl/Ca       =   4.6143E-01       Log Ca      /H2  =     11.6316
        Cl/Mg       =   6.2341E-01       Log Mg      /H2  =     11.5656
        Cl/Na       =   3.5052E-01       Log Na      /H1  =      4.5647
        Cl/K        =   5.6560E+00       Log K       /H1  =      3.3564
        Cl/Al       =   0.0000E+00       Log Al      /H3  =       .0000
        Cl/Fe       =   1.5752E+06       Log Fe      /H2  =      5.1708
        Cl/SO4      =   8.2108E-01       Log Ca/Mg        =       .1260
        CL/HCO3     =   1.3769E-01       LOG NA/K         =      1.2083
        Ca/Mg       =   1.3510E+00       Log Ca/K2        =      4.9788
        Na/K        =   1.6136E+01       Log Diss Fe/H2   =     14.8000
```

APPENDIX D

SAMPLE BALANCE PRINTOUT

```
DELTA                  CALCITE    DOLOMITE   GYPSUM     HALITE     ION EXCH   CO2

1.566   NA              .000       .000       .000      1.000      2.000       .000
1.896   CA             1.000      1.000      1.000       .000     -1.000       .000
 .740   MG              .000      1.000       .000       .000       .000       .000
1.580   CL              .000       .000       .000      1.000       .000       .000
 .260   S               .000       .000      1.000       .000       .000       .000
4.261   C              1.000      2.000       .000       .000       .000      1.000

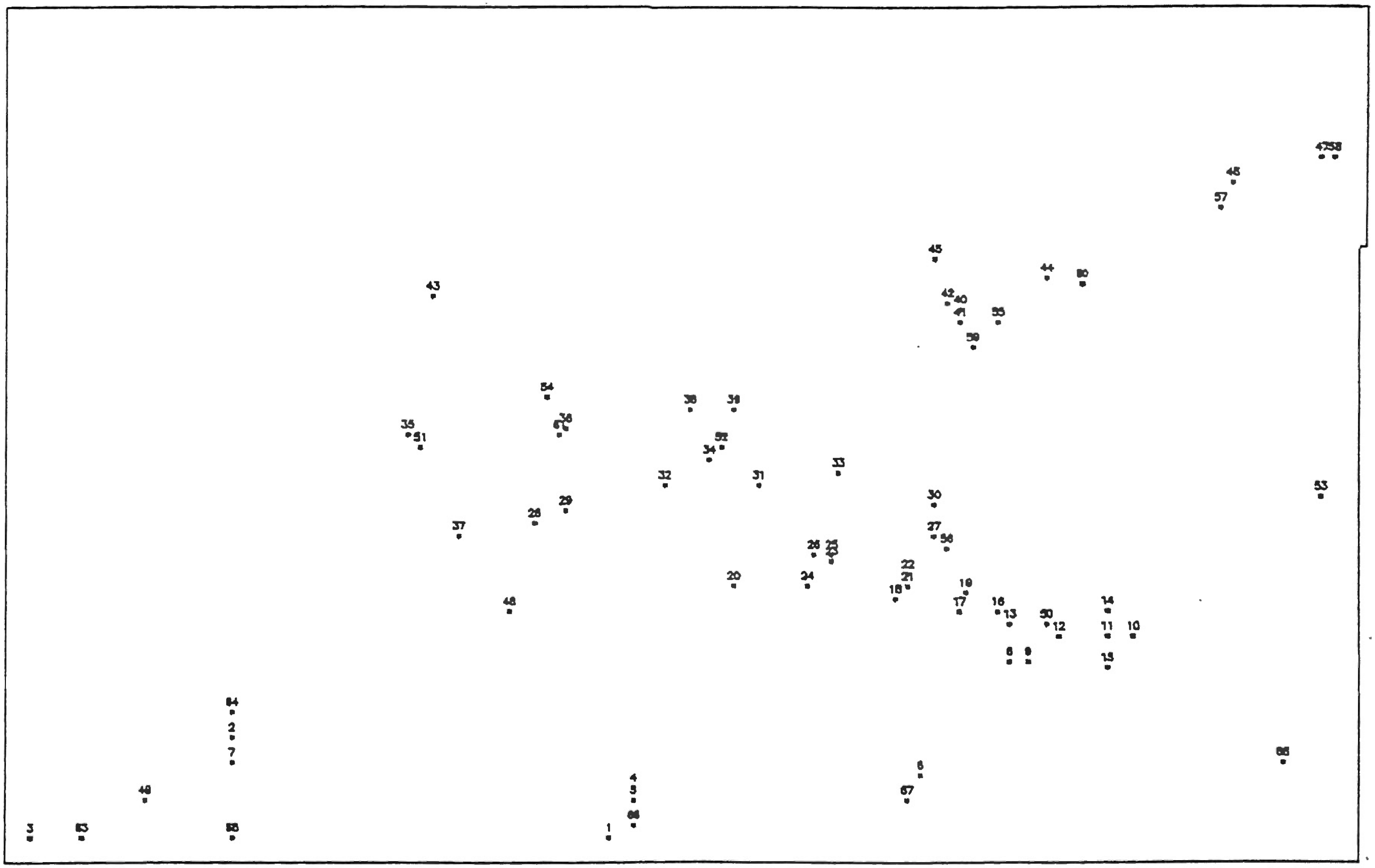
                           DELTA PHASES

                       CALCITE          .8890
                       DOLOMITE         .7400
                       GYPSUM           .2600
                       HALITE          1.5800
                       ION EXCH        -.0070
                       CO2             1.8920
```

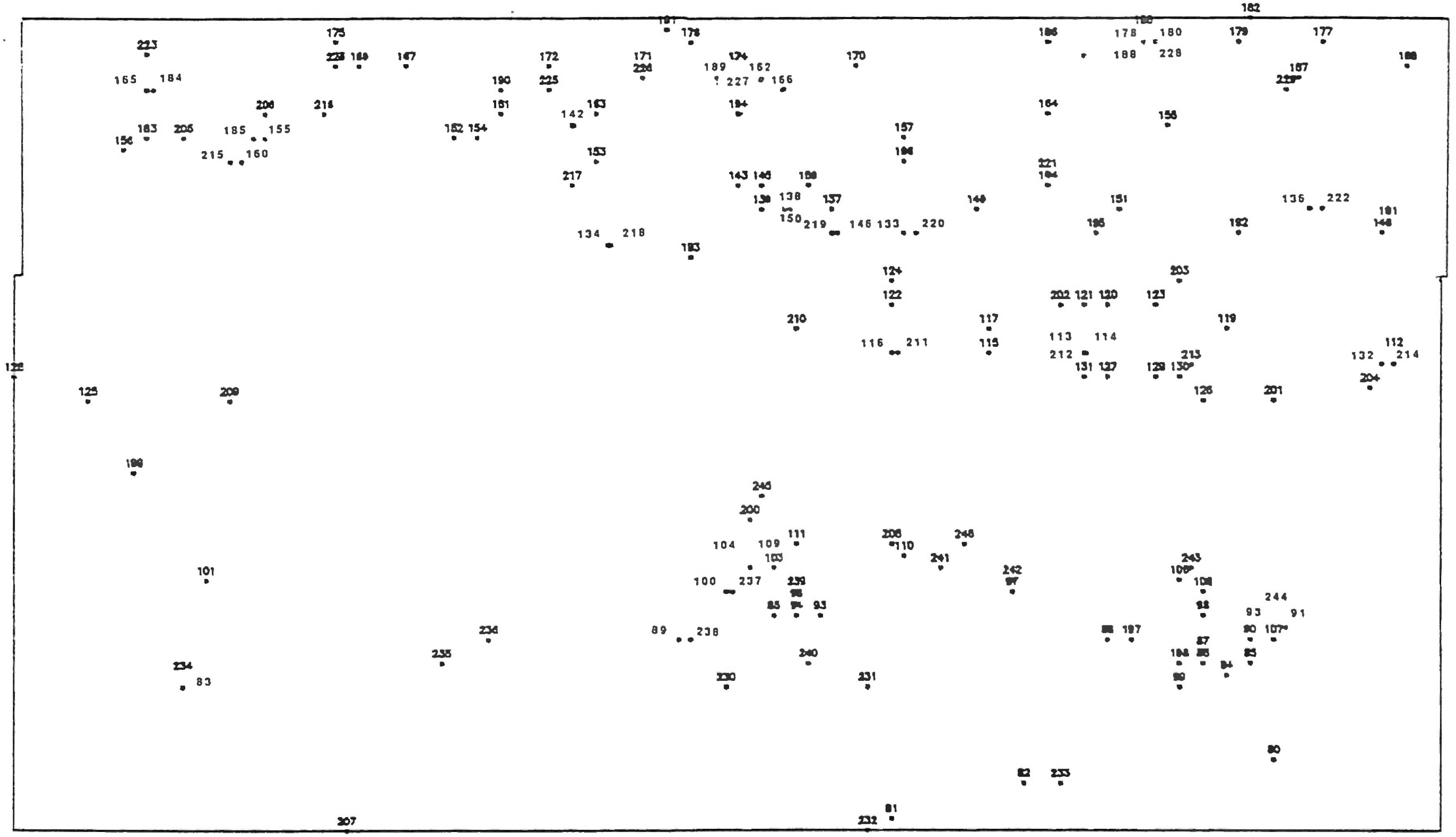
APPENDIX E

SAMPLE LOCATIONS

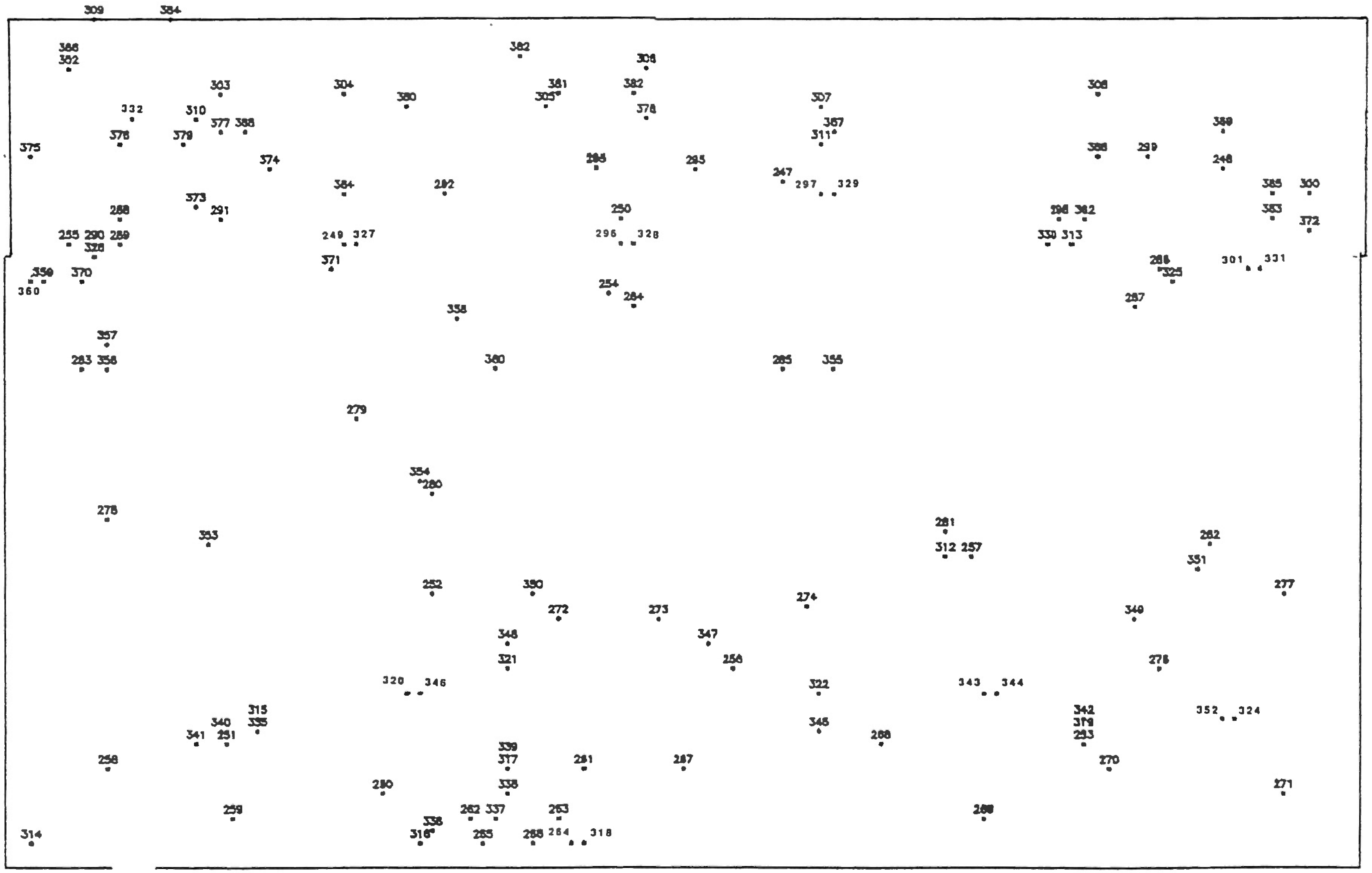
DATA POINTS IN CIMARRON COUNTY, OKLAHOMA



DATA POINTS IN TEXAS COUNTY, OKLAHOMA



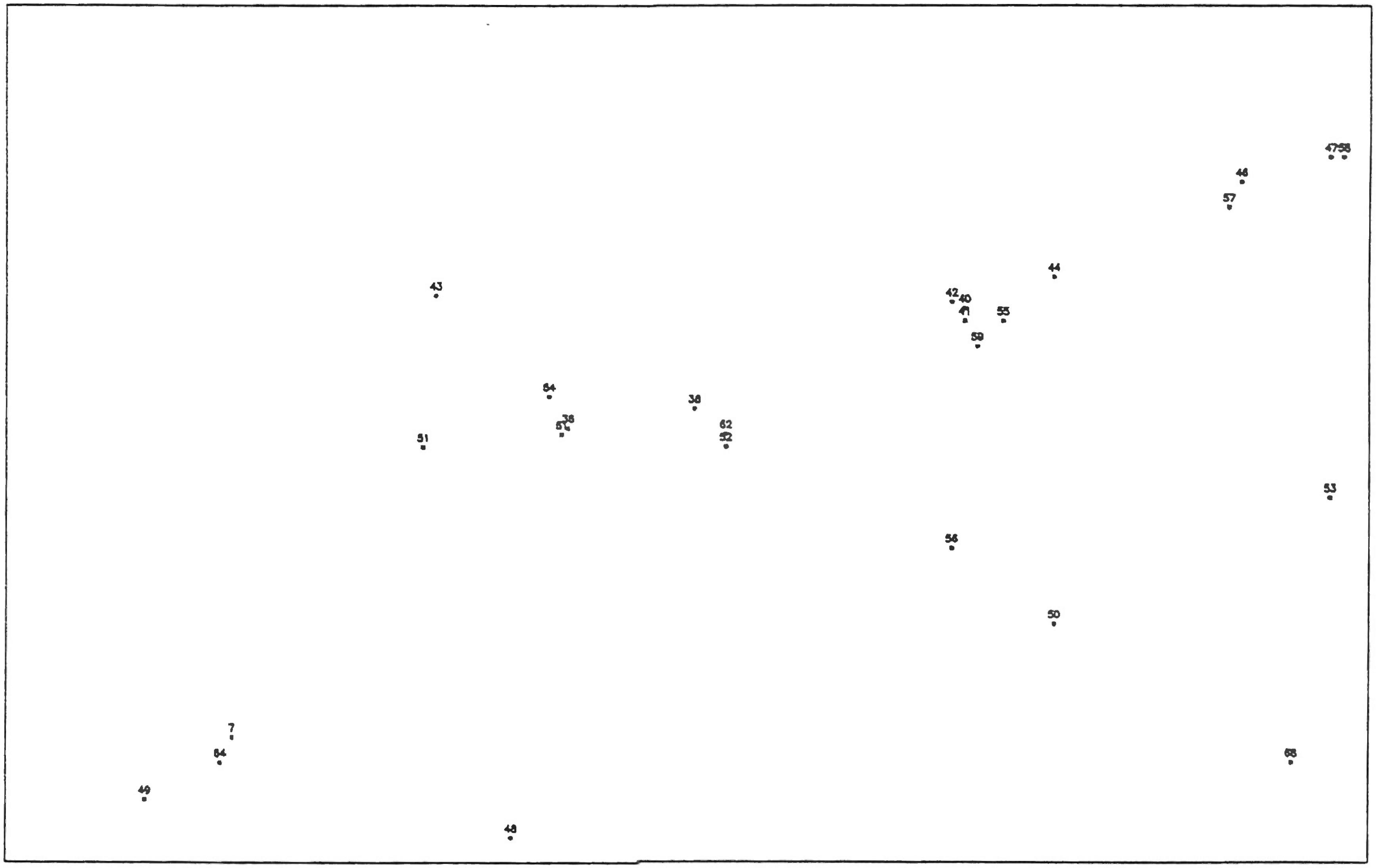
DATA POINTS IN BEAVER COUNTY, OKLAHOMA

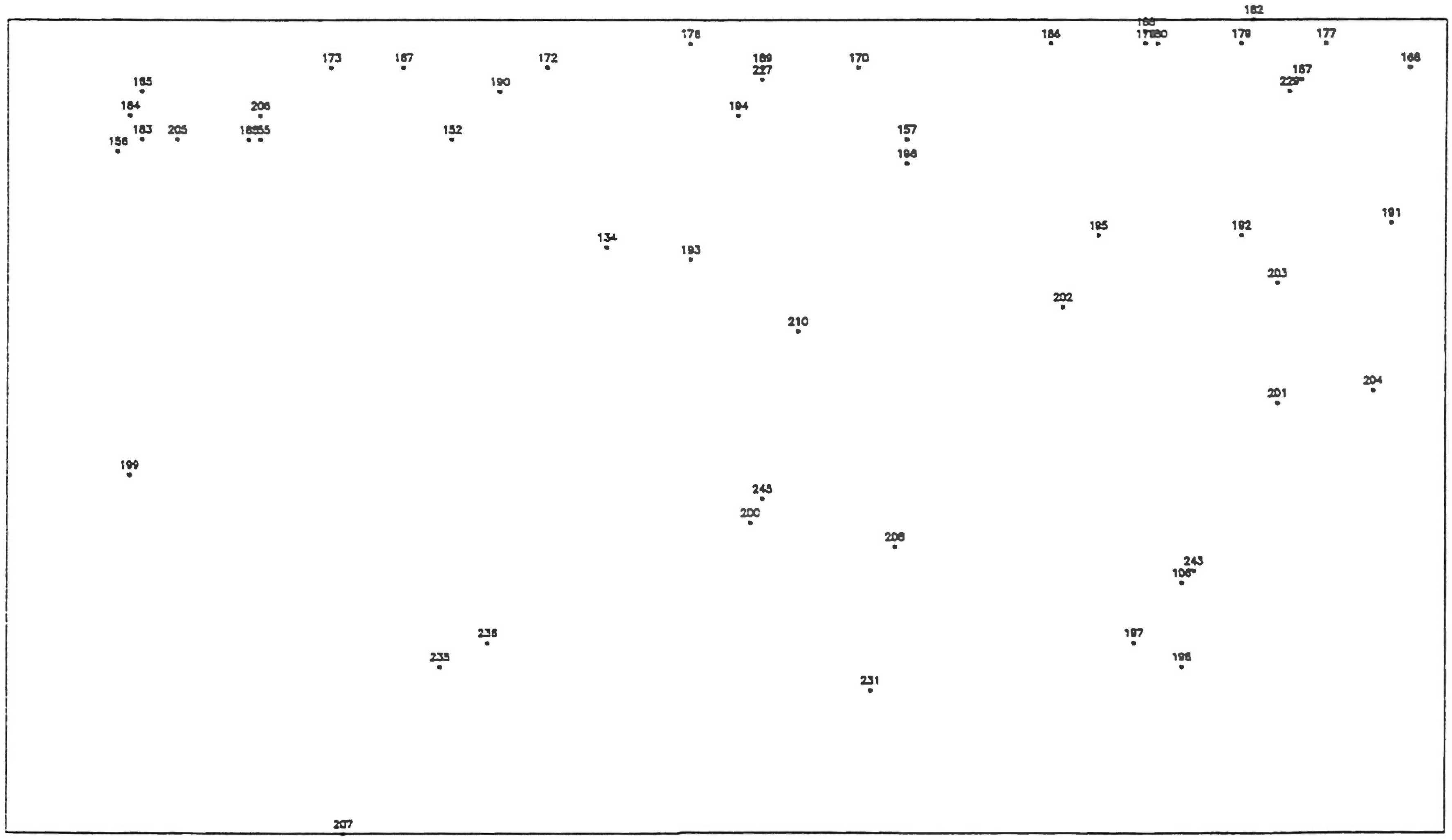


APPENDIX F

LOCATIONS OF ANALYSES USED IN "BALANCE"

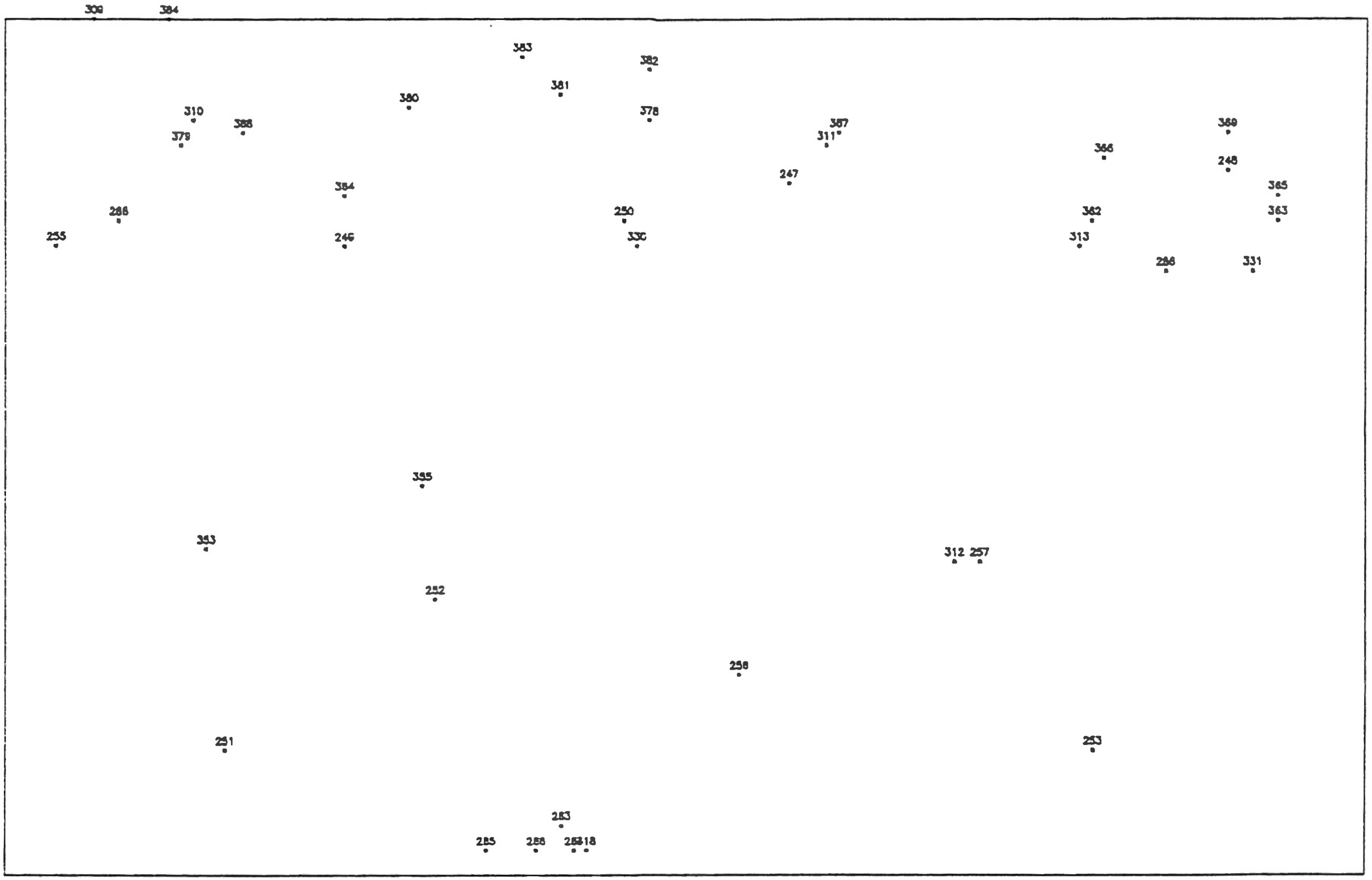
DATA POINTS IN CIMARRON COUNTY, OKLAHOMA





DATA POINTS IN TEXAS COUNTY, OKLAHOMA

DATA POINTS IN BEAVER COUNTY, OKLAHOMA



APPENDIX G

FACTOR ANALYSIS OUTPUT

```
PARAMETERS
COL  1 - 5 =      6
COL 6 - 10 =  127
COL 11 - 15 = 11100
COL 16 - 20 =  4111
COL 21 - 25 = 11100
F14          357.0000    0.2300    0.9000    0.2600    0.4200    0.2500
F7           363.0000   -0.6800    1.2700    0.4200    0.4500    0.2100
F16          560.0000   -1.3000    1.7300    1.6100    0.4500    0.5100
F6           383.0000   -0.7900    1.3600    0.5200    0.5100    0.1200
F2           419.0000   -0.3200    1.2300    0.6800    0.3100    0.5000
13           390.0000    0.4600    1.1100    0.3400    0.9900   -0.0100
45           476.0000   -0.5100    1.4300    0.5500    0.4200    0.2000
47           412.0000   -0.2400    0.9500    0.4900    0.7300    0.2400
50           474.0000   -1.2800    1.4400    0.6800    1.0400   -0.0700
51           382.0000   -0.9500    0.6600    0.2500    0.1700    1.1500
52           368.0000   -1.2000    1.4400    0.6500    1.0400   -0.0700
53           416.0000    0.9900    1.1900    0.6300    0.5900    0.6600
55           428.0000   -0.9000    1.4800    0.7000    1.6900   -0.0900
57           436.0000   -0.4700    1.1500    0.5700    0.5100    0.1600
58           396.0000   -0.2700    1.0700    0.2100    0.1200    0.3800
60           836.0000   -2.7300    3.0900    2.0800    0.6200    0.5200
61           435.0000   -0.1800    0.8600    0.2900    0.6200    0.1700
63           324.0000    0.4000    0.7400    0.4100    0.2700    0.4100
64           442.0000   -0.1400    1.2300    0.3800    0.3100    0.1900
66           484.0000   -0.2300    1.0700    0.3800    0.3400    0.3500
67           592.0000   -0.7400    0.7400    0.4100    0.2800    0.5400
68           482.0000   -0.2200    1.1900    0.5100    0.9300   -0.0300
69           434.0000    0.0400    1.1500    0.6000    0.4500    0.8800
70           407.0000   -0.7200    0.9900    0.4200    0.8200    0.0500
71           341.0000   -0.7500    1.1900    0.5100    0.9300   -0.0300
72           403.0000   -0.4700    3.0900    2.0800    0.6200    0.5200
73           372.0000   -0.2700    1.3700    0.4200    0.5100    0.0500
74           451.0000   -1.2900    1.0700    0.2100    0.1200    0.3800
75           408.0000   -0.9000    0.6600    0.2800    0.4500    0.1700
75.1         447.0000   -0.5100    1.1100    0.3400    0.9900   -0.0100
75.2         384.0000   -0.2400    1.4000    0.5500    0.4200    0.2000
77           374.0000    0.6000    1.4700    0.3800    0.4800    0.0200
81           365.0000   -0.2300    1.0600    0.3800    0.3400    0.3500
121          382.0000    0.1700    0.9000    0.2600    0.4500    0.1900
122         3103.0000   -1.8000    1.8500    2.5500   40.6000    0.3500
123         1580.0000   -2.8400    2.4700    1.2400   19.1500   -1.9200
149          362.0000    0.0000    0.9500    0.2300    0.1100    0.2300
163          475.0000   -0.3700    1.1900    0.7000    0.2800    0.5800
166          456.0000   -0.4000    1.1100    0.5600    0.4000    0.5000
167          438.0000   -0.5800    1.1900    0.4400    0.5400    0.3000
168          551.0000   -0.1300    0.9500    1.5600    0.3400    0.3300
176          469.0000   -0.5900    1.1900    0.6700    0.2800    0.5300
178          440.0000    0.8000    0.5800    0.3100    0.2000    0.2700
179          885.0000   -1.8900    2.6300    1.1400    3.1000   -0.6200
181          577.0000   -0.1000    0.8200    1.7700    0.4800    0.3700
183          642.0000   -1.8900    1.9300    0.8200    3.9500   -1.1000
184          579.0000    0.0800    1.1900    0.6300    0.6500    0.4600
187          470.0000    0.1200    0.6600    0.9300    0.9900   -0.0600
188          469.0000    0.0700    0.8600    0.7300    0.5900    0.2900
189          513.0000    0.2500    0.8700    0.5600    1.2400   -0.1200
190          471.0000    0.1600    0.9500    0.8400    0.3800    0.4500
191          512.0000   -0.0400    0.8600    0.9900    0.6500    0.2400
193          532.0000   -0.3200    1.0700    0.8900    0.9300    0.1400
194          412.0000   -0.5800    1.1900    0.4400    0.5400    0.3000
195          444.0000   -0.5800    1.1900    0.6700    0.2800    0.5300
196          431.0000   -0.4000    1.1100    0.5600    0.4000    0.5000
201          446.0000    0.1000    0.6600    0.9300    0.9900   -0.0500
204          522.0000    0.0300    0.8600    0.8600    1.9500   -0.5200
210          806.0000   -2.1700    2.6300    1.4100    3.1000   -0.6200
211          448.0000    0.1400    0.9000    0.5800    0.3700    0.3600
212          403.0000    0.0600    0.7400    0.8500    0.8200    0.0700
213          663.0000   -0.3900    0.9000    2.0200    0.7300    0.5700
214          810.0000   -0.9300    1.8500    1.9900    0.6200    1.0400
215          470.0000   -0.1200    0.9900    0.6700    0.3400    0.6100
216          408.0000    0.1400    0.8600    0.4500    0.2800    0.5300
217          365.0000   -0.0700    0.9000    0.2100    0.4000    0.1700
218          827.0000   -0.7100    1.6000    2.3400    0.8200    1.1300
219          430.0000   -0.2500    0.9500    0.7500    0.3400    0.2700
220          538.0000   -0.1300    0.8200    1.5700    0.4200    0.2700
221          527.0000   -0.7300    1.2700    0.9700    1.0400    0.2000
222          567.0000   -1.3900    1.5200    0.7000    2.1700   -0.5400
223          458.0000   -0.6900    1.2300    0.4900    1.1000    0.2100
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224	540.0000	-0.4700	1.2300	0.9900	0.5400	0.4300
225	478.0000	-0.8200	1.3200	0.5300	0.7600	0.0300
226	723.0000	-1.5600	1.4400	2.8900	0.4800	0.6700
227	469.0000	-0.4400	1.0700	0.7800	0.6500	0.1100
228	888.0000	-1.0300	1.2700	2.1500	2.8800	0.3800
229	391.0000	-0.2600	1.1100	0.4200	0.3100	0.5200
230	455.0000	-0.7400	1.1900	0.5900	0.5900	0.2300
231	435.0000	-0.1700	1.0700	0.6300	0.4800	0.3300
232	584.0000	-0.7800	1.3600	1.3300	0.7300	0.5900
255	606.0000	0.1500	0.8200	0.2100	5.3500	-1.6300
256	722.0000	1.0900	1.0300	0.8900	1.5800	0.1000
257	465.0000	-0.0200	0.9500	0.4400	1.8300	0.0400
258	451.0000	1.0600	0.5400	0.4000	0.9000	0.2700
259	570.0000	0.0000	0.8200	0.6400	2.8200	0.5200
260	531.0000	-0.6200	1.1100	0.7000	2.2600	0.0000
261	788.0000	-0.4700	1.0700	0.8500	6.4600	-0.6600
262	597.0000	0.6100	0.7400	0.7700	3.0800	0.5500
263	519.0000	-1.0000	1.0600	0.7600	1.8300	0.6500
264	417.0000	-0.0700	0.8600	0.3800	1.7700	-0.6000
265	584.0000	0.4800	0.5800	0.5600	3.5800	0.3200
270	491.0000	-0.6300	1.2700	0.5500	2.2600	-0.1500
271	383.0000	0.4200	0.7800	0.2000	0.8500	0.6200
272	592.0000	-0.7200	1.3100	0.7000	3.6700	0.1500
273	720.0000	-0.8700	0.1500	1.2900	4.3700	0.5400
274	561.0000	-1.5300	1.6800	0.8100	3.1600	-0.2300
301	409.0000	1.4400	0.4000	0.2400	0.7000	-0.1100
303	569.0000	-0.3100	1.1900	1.0900	1.6900	0.8300
309	506.0000	1.5000	0.5400	0.4400	1.1800	0.7800
310	490.0000	1.7000	0.5800	0.2600	0.5100	0.5100
325	450.0000	-0.4400	1.1500	0.4900	0.5600	0.3100
327	618.0000	-0.1900	1.1100	0.7300	2.7600	0.2700
332	1100.0000	-1.2300	1.6800	1.1400	10.4300	-0.6500
333	812.0000	-0.2900	1.0200	208.0000	3.1000	1.4900
335	611.0000	-0.3900	1.0600	0.2500	4.7900	-1.8100
336	598.0000	0.8300	0.5800	0.5100	2.8200	0.7600
337	500.0000	0.3700	0.9000	0.3600	2.0800	-0.5000
346	592.0000	-0.3700	1.3100	0.6900	3.6600	0.1400
357	408.0000	1.1300	0.4900	0.1400	0.9600	0.4100
360	426.0000	1.7600	0.4500	0.1600	0.2300	0.1000
382	617.0000	0.8200	0.5700	0.5100	2.8200	0.7600
383	450.0000	0.1900	0.9000	0.2900	0.6800	0.2700
392	530.0000	0.3800	0.9000	0.6100	2.0800	-0.5000
393	616.0000	0.4600	1.0200	0.6600	1.0700	0.2700
394	832.0000	-0.8600	1.2700	0.7700	6.4800	-0.4100
395	1006.0000	0.0000	1.3100	1.3500	5.3500	0.0000
396	674.0000	2.4500	0.4500	0.1400	0.0500	0.0600
397	636.0000	-0.3800	1.0600	0.2500	4.8000	-1.8500
398	510.0000	0.0700	0.9900	0.6300	0.8200	0.4000
399	850.0000	0.2300	1.1900	2.0800	1.6000	0.7600
409	557.0000	0.6200	0.7000	0.5200	1.4900	0.1200
410	647.0000	-0.2000	1.1100	0.7300	2.7600	0.2700
412	1118.0000	-2.8700	3.2400	3.2200	1.2400	1.5300
413	839.0000	-0.1400	1.0200	2.0800	3.1000	1.4800
414	1126.0000	-1.2300	1.6800	1.1400	10.4000	-0.6500
415	513.0000	0.1500	0.9000	0.6800	0.5600	0.5200

```
INTERCORRELATION ANALYSIS.

 MEAN            1          2          3          4          5          6
             564.5040    -.2911     1.1408     2.4102     1.9285      .1988

 SIGM            1          2          3          4          5          6
             293.7833     .8399      .4977    18.3247     4.1740      .5592

 R MA            1          2          3          4          5          6

   1          1.0000    -.3909      .3920      .0934      .9139    -.0915

   2          -.3909    1.0000     -.7518     -.0155     -.3152     .1450

   3           .3920    -.7518     1.0000     -.0038      .2499    -.1038

   4           .0934    -.0155     -.0038     1.0000      .0346     .2149

   5           .9139    -.3152      .2499      .0346     1.0000    -.2936

   6          -.0915     .1450     -.1038      .2149     -.2936    1.0000

PRINCIPAL AXIS ANALYSIS.

TRACE =     6.0000

 95.02 PCT. OF TRACE WAS EXTRACTED BY  4 ROOTS.

 EROO            1          2          3          4
              2.5786     1.2073     1.1784      .7369

 PCT             1          2          3          4
             42.9764    20.1209    19.6396    12.2813

 P LO            1          2          3          4

   1           .8573      .2520      .3626      .2092

   2          -.7471      .0827      .5509      .0578

   3           .7188     -.0779     -.6003      .0048

   4           .0316      .8187     -.0581     -.5702

   5           .8183      .1052      .5366      .0806

   6          -.3135      .6704     -.3029      .5985

 P WT            1          2          3          4

   1           .3325      .2087      .3077      .2840

   2          -.2897      .0685      .4675      .0785

   3           .2787     -.0645     -.5094      .0065

   4           .0122      .6782     -.0493     -.7738

   5           .3173      .0872      .4554      .1094

   6          -.1216      .5553     -.2570      .8121
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VARIMAX ROTATION ANALYSIS.

 PCT           1          2          3          4
            31.5154    16.8034    29.6794    17.0191

 PCT           1          2          3          4          5          6
            97.3658    87.1850    88.3077    99.9776    97.5119    99.7560

 V LO          1          2          3          4

   1          .9495      .0475    -.2627      .0290

   2        -.1784     -.0331      .9115      .0902

   3          .1440    -.0012    -.9283     -.0229

   4          .0491      .9942      .0136      .0940

   5          .9605      .0075    -.1245     -.1925

   6        -.1090       .1283      .0588      .9827

 V WT          1          2          3          4

   1          .5410    -.0445      .0358      .1768

   2          .1038    -.0434      .5468      .0247

   3        -.1160     -.0060    -.5692      .0529

   4        -.0444     1.0209      .0108     -.1340

   5          .5490    -.0341      .1414     -.0611

   6          .0783    -.0947     -.0454     1.0181
```

VITA

John Robert Field

Candidate for the Degree of

Master of Science

Thesis: HYDROGEOCHEMICAL INTERPRETATION OF GROUND WATER IN THE OGALLALA AQUIFER, OKLAHOMA PANHANDLE

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Biographical:

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