HYDROGEOCHEMISTRY OF THE SUNDRE AQUIFER,
MINOT, NORTH DAKOTA

By

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HYDROGEOCHEMISTRY OF THE SUNDRE AQUIFER, MINOT, NORTH DAKOTA

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PREFACE

The hydrogeochemistry of the Sundre aquifer was studied to determine the types and extent of formation-water interactions occurring in the system, and to define the geochemical mechanisms responsible for the presence of sulfate in the ground water. It was determined that cation exchange and dedolomitization are occurring within the aquifer. Gypsum, present as an isolated occurrence within the aquifer, is responsible for elevated sulfate concentrations measured, and also acts as the catalyst species in the dedolomitization reactions.

I am deeply indebted to Dr. Arthur Hounslow, my advisor, for his guidance and support throughout the course of my work. I would like to thank Dr. Wayne Pettyjohn for providing the data for this thesis, and for serving as a committee member. Finally, I extend my thanks and appreciation to Dr. William Inskeep, for providing the much needed opinion of a non-geological scientist.

I would like to thank my friends in the Geology and Forestry Departments for making my time at Oklahoma State enjoyable. Appreciation is extended to the Soccer Club members for many good times and great soccer games.

Most of all, I wish to thank my parents and my husband, Andy, for their love and support.

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CHAPTER I

INTRODUCTION

Statement of Purpose

The purpose of this study was to examine the hydrogeochemistry of the Sundre Aquifer, and to relate the water quality to possible rock-water interactions.

Location

The study area is located in north-central North Dakota, six miles southeast of the city of Minot. The aquifer follows the trend of an ancient buried river channel (Figure 1). The water-quality data used in this study, representing the well field shown in Figure 1, were supplied by the North Dakota State Water Commission.

Figure 2 shows the well-numbering system used. Numbers denoting the township and range are listed first, followed by the section number. The lower case letters that follow indicate the position of the well within the section. The letter a refers to the northeast quarter, b the northwest quarter, c the southwest quarter, and d the southeast quarter. The quarter-quarter section and the quarter-quarter-quarter are then referred to with the correct lower case letter. If a quarter-quarter-quarter

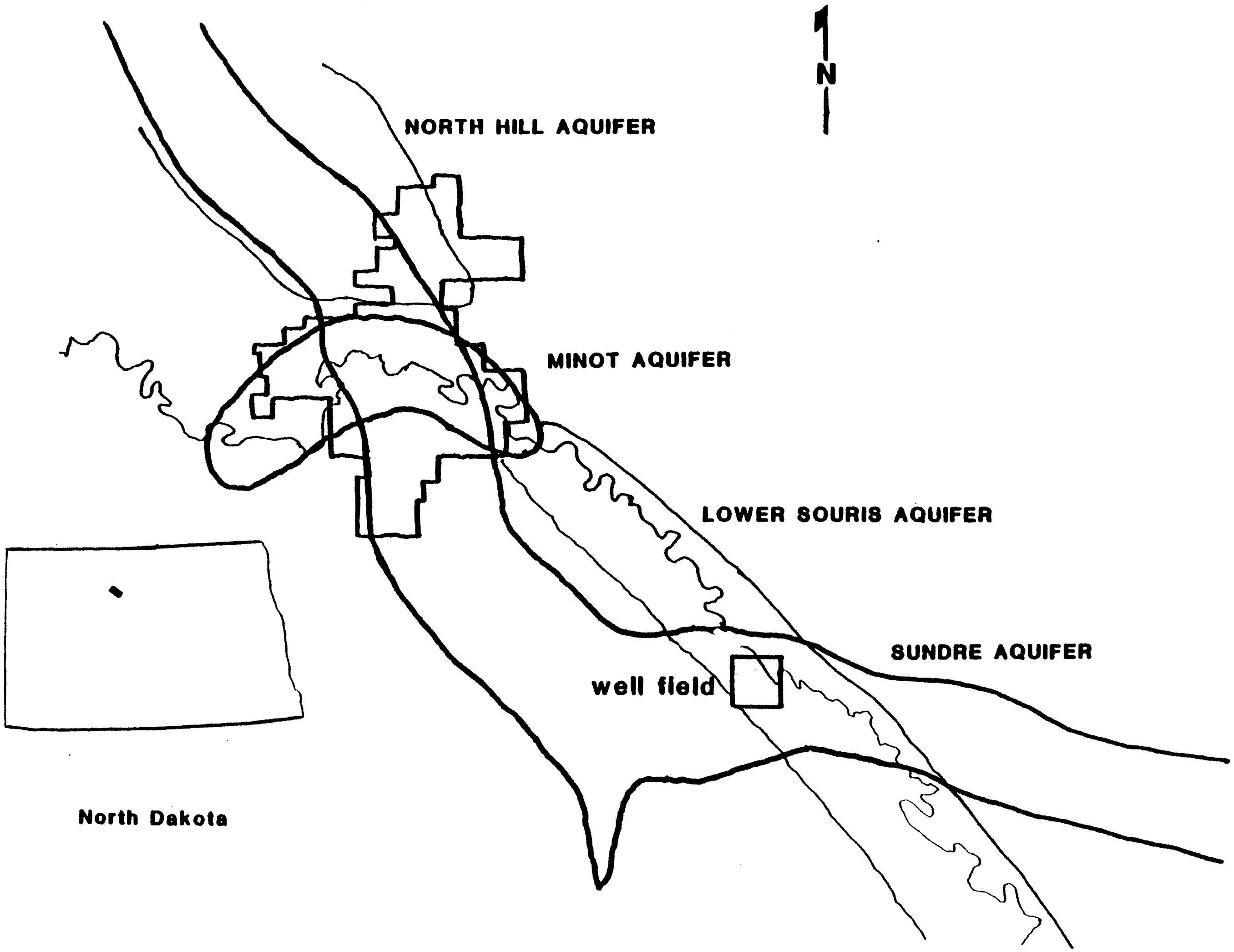


Figure 1. Location of study area with respect to local aquifers.

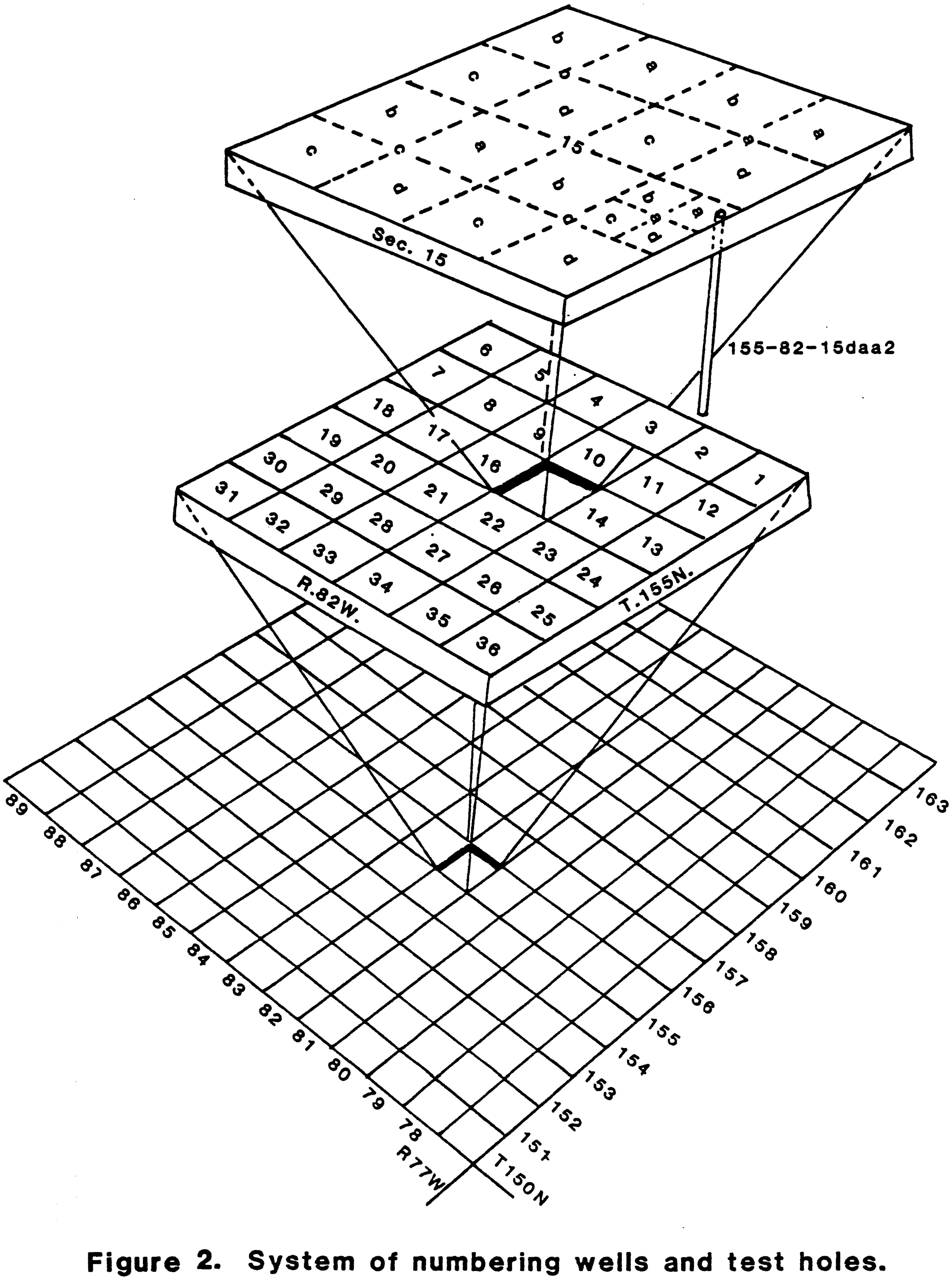


Figure 2. System of numbering wells and test holes.

section (a ten acre area) has more than one well on it, consecutive numbers begining with two, are added to the letters. This system is based on the public land classification of the United States Bureau of Land Management.

Scope

Background information on the geology and hydrogeology of the area was obtained from the literature, and water data was acquired from the North Dakota State Water Commission and the city of Minot. The latter included water-quality analyses, water production data, water-level measurments, well inventories, and records of logs of test holes and wells. The chemical equilibria of the system was examined by utilization of WATEQF, a hydrogeochemical modelling program developed by the United States Geological Survey. Correlation, factor analysis and simple statistics were produced using the Statistical Analysis System (SAS). BALANCE, a FORTRAN computer program that describes and quantifies ground water and mineral interactions (a mass balance approach), also developed by the USGS (Parkhurst et al, 1982) was used. Random Walk, a solute transport model, was utilized to enable determinations of ground-water movement rates and directions.

CHAPTER II

PREVIOUS INVESTIGATIONS

One of the first studies of the geology and hydrogeology of North Dakota was undertaken by Simpson (1929). His work included geologic logs and chemical analyses from wells in glacial and bedrock formations. A United States Geological Survey paper by Lemke (1960) describes the geology of the Souris River area, including the portion of Ward County which comprises this study. Akin (1947) wrote on the geology and ground-water conditions of the Minot area, and Pettyjohn (1967) expanded on his work. Numerous other North Dakota State Water Commission reports have been completed for the adjacent counties describing both the geology and the occurrence and nature of the groundwater.

The most up-to-date and thorough study on the geology and geotechnical conditions of the Minot area was completed by Kehew (1983). Kehew's report covers the geology and ground-water resources in detail, and contains numerous references to all pertinent works preceeding it.

One of the geochemical reactions determined to be occurring in the Sundre aquifer is the dissolution of dolomite. The dedolomitization processes, and the

the time, both of which are in Russian. Experimental parameters for dedolomitization were defined by deGroot in a 1967 publication. A Folk and Land (1975) work on the role the magnesium to calcium ratio and solution salinity play in dedolomitization is a good synopsis of the literature on dolomite and was useful in defining the conditions of dedolomitization. The most recent and in-depth work on dedolomitization was done by Back et al (1983). They studied the process and rate of dedolomitization in a regional carbonate aquifer using mass transfer and Carbon 14 dating processes.

CHAPTER III

PHYSIOGRAPHY

Description

Minot, North Dakota is located in the north-central portion of the state, in the physiographic province known as the Central Lowlands (Figure 3). Pettyjohn and Hutchison (1971) divided Ward County into three physiographic regions: the ground moraine plain, the valleys of the Souris and the Des Lacs Rivers, and the Coteau du Missouri. The physiography of the northeast-sloping ground morain plain is one of gently rolling hills and overall low relief. Pot holes, and streams, both of an intermittent nature, are present.

The valleys of the Souris and the Des Lacs are characterized by wide, flat flood plains. Dams and reservoirs have been built on both rivers. Except in periods of extreme drought, these rivers are flowing.

The southern and western portion of Ward County is characterized by three moraine types: stagnation moraine, ground moraine and end moraine. These moraine types are expressed as hummocky, corrugated landscapes that are also commonly pitted.

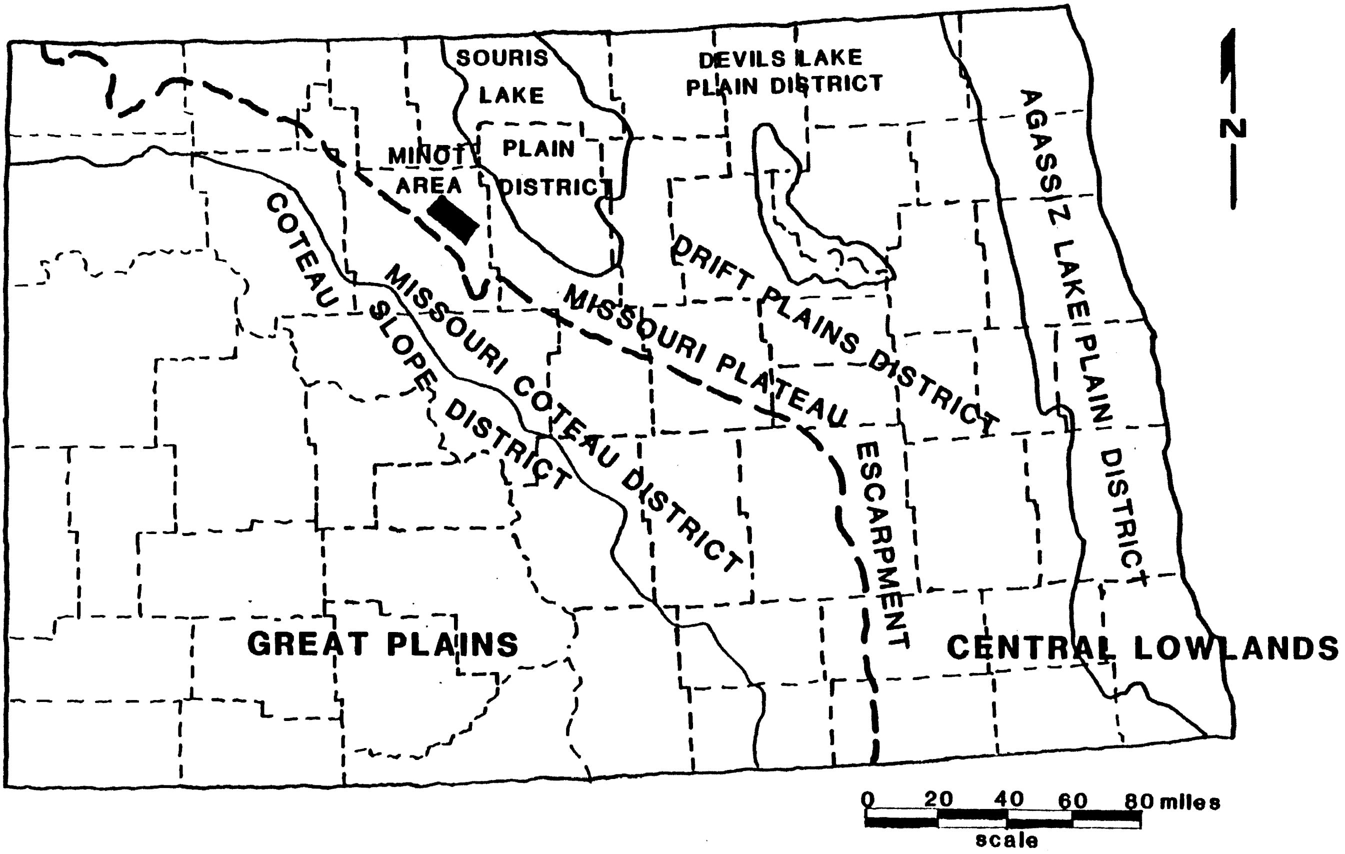


Figure 3. Physiographic regions of North Dakota (after Jakob, 1974).

Except for the river valleys, the area is poorly drained, with lake chains that represent partially buried valleys. Outwash sand and gravel deposits are also present. The northeastern margin of the Coteau du Missouri is made up of the Missouri Escarpment, a gentle slope from the higher Coteau du Missouri to the lower Drift Prairie. This Escarpment forms a band several miles wide that is dissected several feet by the Souris and Des Lacs Rivers and their tributaries. The location of the well field within the Souris River valley is shown in Figure 4.

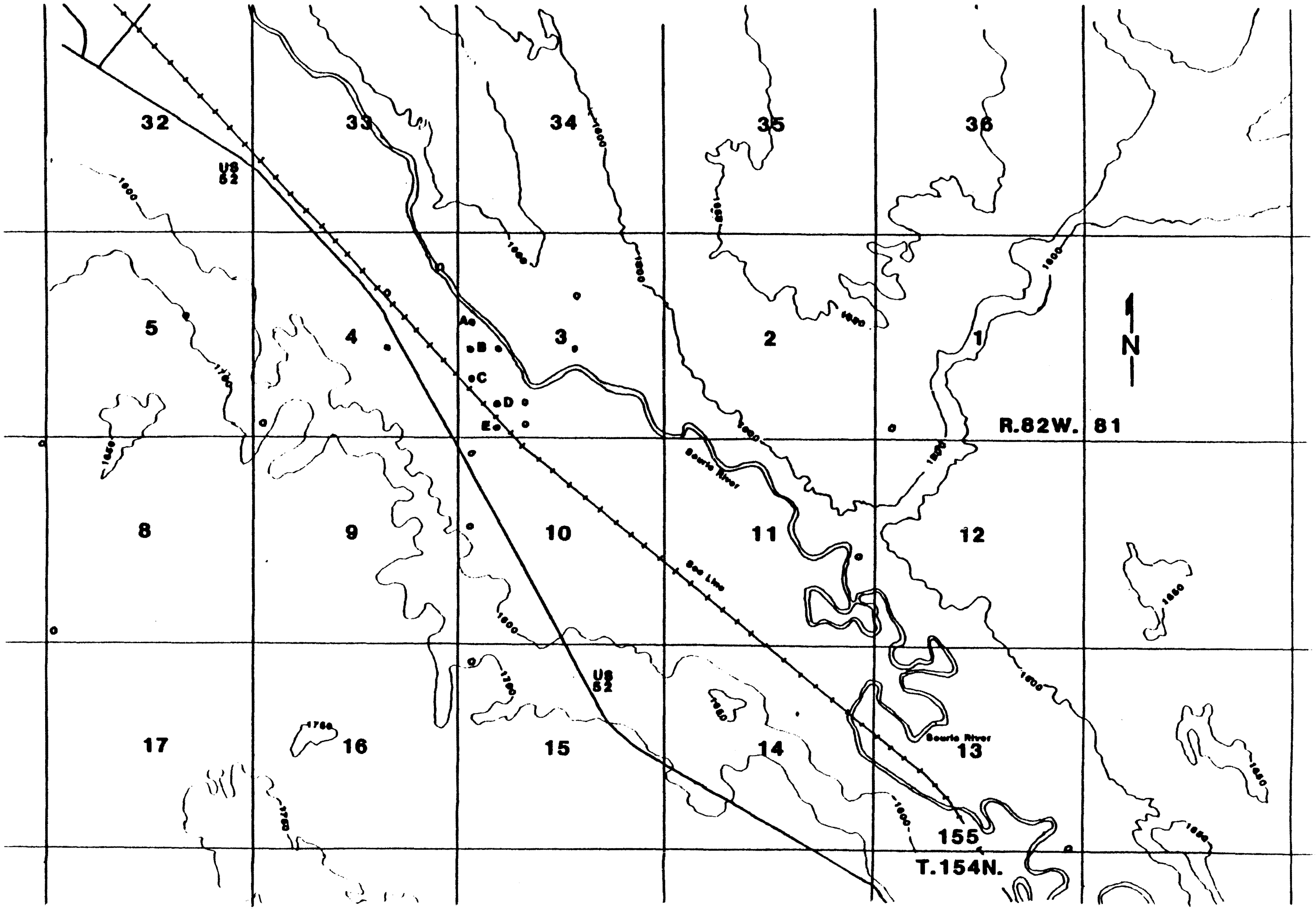


Figure 4. Location of city wells(A-E) and test holes

CHAPTER IV

LITHOLOGY

Bedrock Geology

The early Tertiary Fort Union Group consists of four formations, in ascending order, the Ludlow, the Cannonball, the Tongue River, and the Sentinel Butte (Figure 5). This group, considered the bedrock for the purposes of this study, subcrops beneath the glacial drift in the central part of the state. Locally, the continental Ludlow and the marine Cannonball are contemporaneous deposits whose interfingering makes it hard to differentiate the two in the subsurface. The Ludlow Formation consists of a series of interbedded sandstone, siltstone, shale, bentonitic claystone and lesser amounts of lignite. The Cannonball is a deposit of dark gray sand, clay and a few strata of thin, nodular, fossiliferous limestone beds. The Cannonball Formation commonly contains brackish to saline water. The continental Tongue River Formation is made up of clay, silt and sandstone, with numerous lignite beds. The Sentinel Butte is the youngest formation in the Fort Union Group, and is lithologically similar to the Tongue River to such an extent that the two are undifferentiated. Lemke (1960) reported a 615 foot thickness for the Fort Union, locally.

- Cenozoic Era
  - Quaternary Period
    - Pleistocene Epoch
      - Tejas Sequence
          - Oahe Formation
        - Coleharbor Group

  - Tretiary Period
    - Paleocene Epoch
      - Zuni Sequence
        - Fort Union Group
          - Sentinel Butte Formation
          - Tongue River Formation
          - Cannonball Formation
          - Ludlow Formation

Figure 5. Stratigraphic Sequence

In the logged well, the Tongue River was penetrated at 95 feet, indicating a thickness of 255 feet. The total thickness of the Ludlow and Cannonball was reported as 360 feet. The Ludlow strata are underlain by about 200 feet of Hell Creek Cretaceous strata.

In practice it is nearly impossible to distinguish the formations of the Fort Union as they appear locally, therefore, all rocks from the base of the glacial drift to the top of the Pierre Formation are grouped together (Pettyjohn and Hutchinson, 1971). Generally, the eroded surface of the Fort Union slopes more steeply to the northeast than the present land surface. From the study area westward, the strata thicken to several hundred feet.

Locally the Ludlow is not exposed. The Cannonball Formation crops out along the walls of the Souris River valley, where it consists of sandy shale. It is likely that it interfingers with both the Ludlow and the overlying Tongue River. Along the bank of the Souris River a maximum thickness for the Cannonball was recorded as 40 feet, most likely representing the total thickness for the area. The Tongue River commonly crops out in river and stream valleys. It underlies most of the Souris River area. It is near the base of the Tongue River that is found the only consolidated sandstone, a bed cemented with calcite.

Glacial Geology

Two or more glacial stages are evident in the glacial deposits of North Dakota. There are indications of a pre-

Wisconsin glaciation incident which covered all of the state except the southwest tip. Glacial landforms indicate the direction of glacial advance to be from the northwest toward the southeast (Jakob, 1973).

A criteria has been established for the local correlation of glacial sediment grain size and type, to origin. It has been determined that the very coarse sand is from both local and distant sources. Igneous and metamorphic grains arrived from the Canadian Shield Precambrian sources, and the Fort Union Bedrock. Distant Paleozoic limestones and dolomites supplied the carbonate grains. The shale, most likely, is from Cretaceous marine shales east and north of central North Dakota, and may also include some Fort Union Bedrock. The lignite also likely comes from the Fort Union.

Kehew (1983) attempts to differentiate till units by lithology, and relate them to specific ice marginal positions and thus specific glacial advances. Clayton et al (1980) compiled a correlation of 13 ice marginal positions, most of which represent advances and retreats of the Late Wisconsinan Laurentide ice sheet.

During the Pleistocene, glaciers advanced and retreated across North Dakota, leaving up to 600 feet of deposits; ground moraine, dead-ice moraine, end moraine, outwash, ice contact deposits, and glacial lake deposits (Pettyjohn and Hutchinson, 1971). Glacial deposits are usually composed of till - a heterogeneous mixture of mostly clay and silt, with some sand, gravel and boulders.

Throughout the till are scattered thin, discontinuous strata of sand and gravel. One-hundred feet is the local average thickness of the till, but it can vary from absent to 600 feet.

End or lateral moraines occur as 15 to 50 foot hills, aligned in linear ridges that typically parallel the Missouri Plateau Escarpment. The till plain topography, between moraines, is a gently rolling surface, with irregular, small winding streams. The moraines are commonly more porous that the materials of the till plain, due to the presence of sand and gravel lenses. Dead-ice moraine is expressed as hummocky spots on the Missouri Coteau. It is composed of till and small deposits of sand and gravel.

Stagnation moraine deposits cap the Missouri Coteau, a bedrock high. The topography seen here is an expression of the extensive stagnation that occurred. Hummocky moraine, perched lake plains, eskers, kames, kettles and outwash forms are seen, as well as large clusters of lakes that are characteristic of the non-integrated drainage patterns of the area.

Buried Valley Deposits

Proir to glaciation, rivers in North Dakota flowed toward Hudson Bay. The slope of the land surface was to the northeast. Many river valleys cut into the bedrock run in a southeastward direction, and are narrow with steep sides. Bluemle (1972) describes these as glacial diversion trenches, once located at the edge of glaciers and cut rapidly by great amounts of swiftly flowing water.

Outwash streams from glacial episodes carved valleys into the Fort Union bedrock, and were subsequently buried by glacial drift from later advances. Interbedded layers of sand, gravel, and clay commonly fill these valleys. The Sundre channel deposits freach thicknesses of up to 300 feet, and have been traced over a hundred miles acress north central North Dakota (North Dakota State Water Commission, 1982).

Lacustrine Deposits

As debris-containing meltwater flowed from the ice fronts it deposited thick accumulations of fine sand and silt. These enclosed basins filled with as much as 100 feet of silt, until the glaciers retreated enough to allow for the return of the northward flowing drainage. These deposits are thickest at their center, and thin outward to feather thin strata at their edges. The Agassiz Lake Plain contains the thickest deposits, and is the most extensive in size. The Souris and Devil's Lake Plains are similar structures but not as thick.

Outwash Deposits

Outwash consists of gravel, sand, silt and clay that was deposited by the meltwater flowing away from the glacier. It occurs along the south and west side of morainal belts, and is expressed topographically by a smooth surface. It is common for these deposits to form terraces in modern stream valleys. In the Souris River valley, outwash deposits reach thicknesses of up to 150 feet (Pettyjohn and Hutchison, 1971). Within the valley they are overlain by alluvial material. It is from such a deposit that the Minot well field derives its' water.

CHAPTER V

HYDROGEOLOGY

Introduction

The Tertiary Formations in the Minot area are treated as a single, bedrock aquifer for the purposes of this study, whereas the hydrogeology of the glacial deposits is considered in detail.

Bedrock Aquifer System

The Fort Union Group, Hell Creek and Fox Hills Formations are treated as a single aquifer system, with some variations within it. In the Fort Union the fine sandstone and lignite strata are a source of water. Often the lignite is underlain by clay, restricting the downward movement of water but allowing for its lateral movement to a point of discharge. This accounts for the formation of many springs in the Souris River Valley. Also, due to the presence of methane in the lignite seams, many water wells that tap the Fort Union flow.

In wells that tap the Tertiary strata the water level may be more than 100 feet below the surface, but locally there is enough artesian or gas pressure to cause the wells to flow. Most of these flowing wells are located south and east of Burlington, which is six miles northwest of Minot.

Recharge to the Fort Union occurs in three ways; infiltration through the overlying glacial deposits, infiltration of precipitation where the formation crops out, and underflow from the southwest. Discharge occurs where the units crop out, by evapotranspiration where the overlying strata is thin or absent, by leakage to adjacent strata, or by pumping wells.

Generally, the water from the Fort Union is high in dissolved solids and very soft (Kehew, 1983). There are two strata within the Fort Union that control the water chemistry, the Cannonball and the Tongue River. Water from the Cannonball Formation is typically high in sodium chloride, often containing several hundred parts per million (Pettyjohn, 1970). The older Tongue River and Sentinel Butte Formations produce water that is usually high in sodium and bicarbonate.

Glacial Aquifer System

The Souris River enters the United States from the north, near the northwest corner of Renville County, and flows southeasterly across that county and Ward County. The large flat-floored river valley is 150 ft. below the regional land surface in some places. Through the Minot area the width of the valley is 3/4 of a mile. North of Burlington the river valley is characterized by a number of oxbow lakes. Below the confluence of the Des Lacs River at Burlington there are few lakes. Upstream from Burlington the streams into the Souris are short and few. The average gradient of the valley is one foot/mile. Downstream from Burlington the river valley is cut into the bedrock, and is deepest near Minot, where there is as much as 200 feet. of relief. Generally, due to the northeast slope of the upland, the north valley wall is lower than the south wall. To the south the tributaries are deep and long; whereas the ones to the north are few and short due to the upland slope away from the valley.

Following the last glaciation (Pleistocene), sands and gravels of the Oahe Formation were deposited in the Souris and Des Lacs Valleys. Fine-grained sediments were deposited in glacial lake Souris (Kehew, 1983). Previous reports subdivided this aquifer into local aquifers, named after the area which they served. The Souris Valley Aquifer consists of the Burlington, Minot and Lower Souris Aquifers, these being the most important local sources of ground water. The till itself yields little or no water as it is mostly clay and silt, but rather it is the stratified sand and gravel that contains appreciable amounts of water. Most aquifers are either valley fill or outwash deposits.

The Minot aquifer has been a source of water for the city since 1916. Presently, 70 percent of Minot's water supply is from ground-water sources, half of which is pumped from the Minot aquifer, the other half is obtained from the Sundre aquifer.

The Lower Souris aquifer extends downstream from

Minot. The aquifer deposits are generally confined to the Souris fiver floodplain and the presence of clay-rich sediments causes them to be locally discontinuous. This aquifer eupplies the baseflow to the Souris River.

The Oahe Formation is complex in this region. It is made up of sediments from the Souris and Des Lacs Rivers which flowed during several episodes of discharge from Glacial Lake Regina. During this erosion, patches of the reworked Coleharbor Group gravels were deposited as point bars along the sides of the valleys. In the valleys the aquifer consists of fluvial channel sediments, and finer lacustrine sediments. In many places it is possible that the Coleharbor Group sediments are in hydraulic connection with the shallow, unconfined Souris Valley Aquifer.

The Burlington portion of the Souris Valley Aquifer averages 10 feet deep, 88 feet thick and .75 miles wide. The Lower Souris portion is 12 to 87 feet deep and 10 to 58 feet thick. The Minot portion is 80 feet deep and 30 to 50 feet thick.

Glacial river valley deposits, eroded into the Fort Union bedrock and buried by glacial sediments, make up the Sundre Aquifer. The high-yielding aquifer consists of fine to coarse sand, fine to medium gravel, and interbeds of clay. It is similar in size to the Souris Valley. The buried valley represents drainage during an interglacial episode long enough to allow complete filling of the valley with fluvial sediments (Kehew, 1983). Within the Minot area the aquifer passes under the Souris Valley Aquifer and receives recharge from it at those points.

The sand and gravel, ranging from 9 to 275 ft. thick, is interbedded with silt and clay (Pettyjohn, 1970). Figure 6 consists of a fence diagram drawn from the well logs of city wells A - E (Appendix A).

Natural recharge to the Sundre Aquifer probably occurs from direct infiltration of precipitation, the Souris River, the glacial drift, and the underlying Fort Union Group. The aquifer stores approximately 3000 acre feet of ground-water per linear mile.

After a comprehensive aquifer test in 1969, five high-volume municipal wells were completed in the Sundre aquifer in 1975. The wells are located in the Souris River floodplain, southeast of Minot. The average withdrawal rate of the five wells combined is approximately 3.4 million gallons a day.

Pumping at Minot and the Sundre Aquifer Well Field has caused flow reversals and created ground-water divides. Appendix B contains a predevelopment potentiometric map for the Sundre Aquifer, and a potentiometric map drawn from the 1985 water level data. The ground-water gradient northwest of the divide is in the northwest direction, at 7 ft. per mile, and to the southeast the gradient is 1 ft per mile. Pumping also causes water-level fluctuations in the aquifer. The ground water occurs under both water table and artesian conditions, depending on the type and presence of overlying beds.

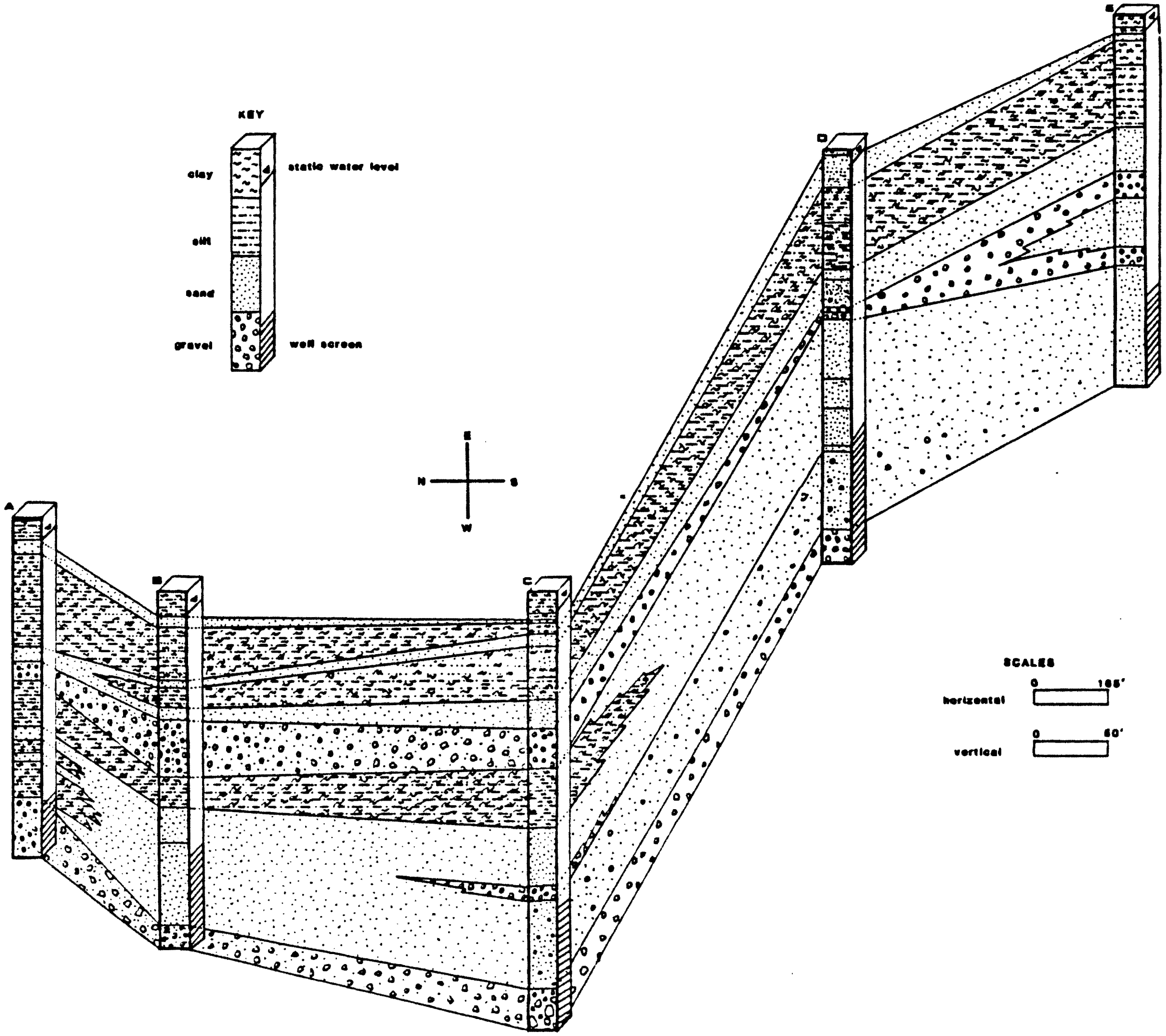


Figure 6. Cross-section at Minot Well Field

CHAPTER VI

METHODS AND MATERIALS

Data Sources

Data on the water quality of the Sundre aquifer were obtained from the city of Minot and the North Dakota State Water Commission. Chemical analyses of water from seven wells were utilized and a total of 177 analyses were available for interpretation. Two of the seven wells (CDC1 and CDC3) are on Northern States Power Company property near the Bison Plant, the other five (A, B, C, D, and E) make up the city well field (Figure 4). The two Bison Plant wells were drilled for the purpose of aquifer testing, in 1968. The other five water supply wells were drilled in 1974. Appendix C is a listing of the water quality data. The parameters analyzed for were: dissolved oxygen, alkalinity, pH, conductivity, calcium, potassium, magnesium, sodium, silica, sulfate, iron, chloride, bicarbonate, carbonate, fluoride, nitrate, boron, dissolved solids, conductance, and temperature.

Methods of Data Evaluation

Primary components of the water sampled were analyzed graphically by means of a Piper Diagram (Piper, 1944). The

FORTRAN IV version of WATEQ (Truesdell and Jones, 1974), WATEQF (Plummer et al., 1976), was used to calculate the equilibrium distribution of inorganic aqueous species of the major elements. The data were also statistically analyzed using the Statistical Analysis Systems Institute (SAS) program available on the Oklahoma State University VAX 11-780 computer system. Statistical methods utilized were of two types - a basic statistics procedure, producing a mean, standard deviation, minimum, maximun, sum, and other simple statistics, and the factor analysis capability of SAS. BALANCE (Parkhurst, Plummer and Thorstenson, 1982), a Fortran computer program designed to define and quantify chemical reactions between ground water and minerals, was also used, as well as the solute transport model Random Walk.

Graphical Expression of Analyses

A Piper plot of complete analyses of water from the Sundre aquifer is presented in Figure 7. The two lower triangles represent relative percentages of cations and anions (meq/L), respectively. Points plotted in the central diamond represent the total water analysis, and are a result of the intersection of lines drawn from the corresponding cation and anion point.

In the central diamond the data point cluster is indicative of water dominated slightly by bicarbonate + carbonate and sodium + potassium. The presence of the bicarbonate ions is indicative of the dissolution of a

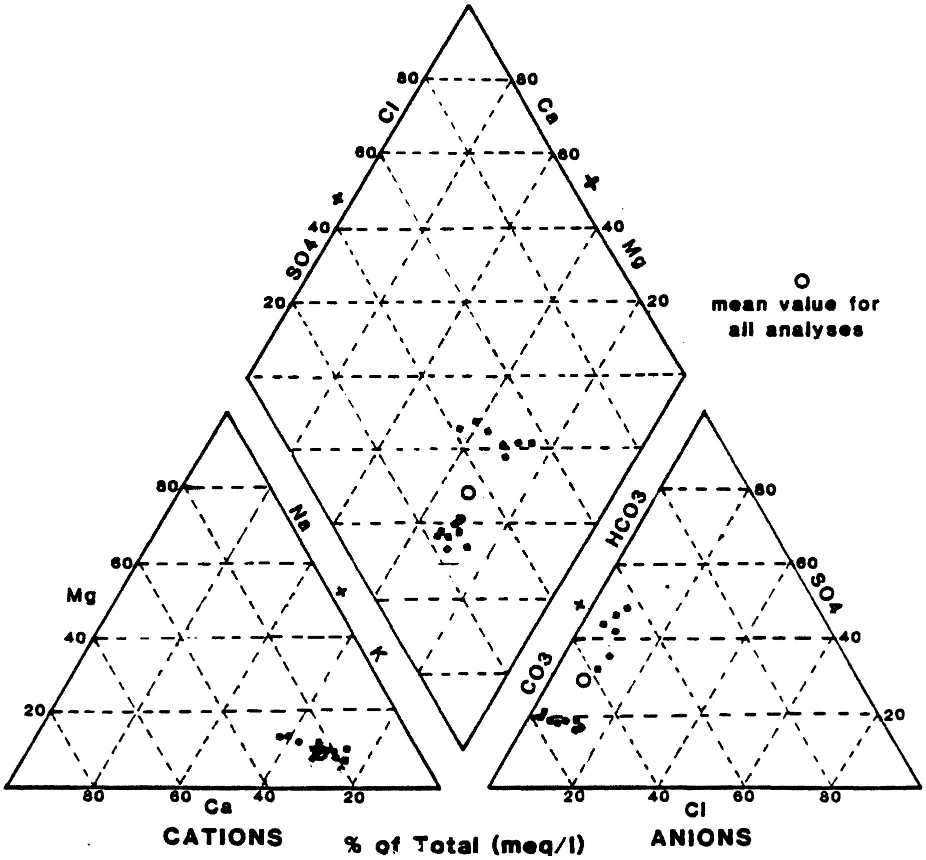


Figure 7. Piper Plot of Selected Analyses

carbonate solid phase, while the excess of sodium over chloride in the water tends to show that the calcium in solution is exchanging for the sodium in a solid mineral phase such as a sodic-rich clay. The samples high in sulfate and calcium indicate that major amounts of gypsum have been dissolved.

The statistical compilation produced by SAS provides an average of all the water samples analyzed from the Sundre Aquifer. If these averages are plotted on a Piper Diagram the nature of the water is seen to be that of a sodium bicarbonate water with a signifigant percentage of calcium and sulfate present. Figure 7 depicts just such a plot.

Statistical Summary

To summarize the data the SAS statement PROC MEANS was used to compile basic statistics for the water analyses, including; mean value, standard deviation, minimum value, maximum value, standard error of mean, sum, variance and coefficient of variation for the variables calcium, magnesium, sodium, chloride, sulfate, bicarbonate, ionic strength, and total dissolved solids. Appendix D contains this statistical data, as well as the SAS program used to compile it.

Multivariate Analyses

The factor analysis capabilities of SAS were utilized to facilitate the simultaneous consideration of large numbers of variables in attempting to explain patterns of data correlation. The factor analysis output depicts how much each variable contributed to the whole data set. "A common factor is an unobservable, hypothetical variable that contributes to the variance of at least two of the observed variables" (Rummel, 1967). Once factor analysis shows which variables are acting together to form a common factor it is up to the interpretor to determine why.

The basic theory and terminology of factor analysis is that of matrix algebra. In any set of observations, the patterns seen can be attributed to one or more factors. Factor analysis enables the user to separately identify these factors. The interpretation of the meaning of the factors must be based on knowledge of the nature of the data set. Algebraically, the theory can be stated: $x_1 = f(g) + f(u_1)$, where x_1 is a variable which is a function of one common factor g, and a second factor that is specific to x_1, known as u_1. Simply put, the value of any variable is dependent on two influences, one that acts on every variable in the data set and one that acts on that variable alone.

The factor analysis procedure is best thought of as a series of five matrices. The initial matrix of k cases and n variables ($k > n$) is the required input data for the SAS program. In this case is consisted of each sampling episode represented as a case and the primary ions (Ca, Mg, Na, Cl, SO4, and HCO3) the variables. The factoring was done for all wells with no differentiation as to the source of the samples.

The SAS procedure PROC CORR is then enacted to convert the k * n matrix into a n * n correlation matrix between variables (Pearson correlation coefficients). To perform principal component analysis of these correlations the SAS procedure PROC FACTOR was used.

The factoring procedure produces an n * n original factor matrix of loadings (degree of closeness of the relationship between two variables or a variable and a factor). Then an n * m rotated factor matrix with new loadings for variables on m rotated factors. Since m is typically much smaller than n rotating acts to de-emphasize loadings that are less important, thus the factor is more clearly defined and more easily interpreted. The type of rotation depends on the feature or features of the data set being sought.

Finally, FACTOR SCORE is utilized, a SAS procedure which computes a k * m matrix that gives the values for the factor (m) on the original observations, the cases (k). These score vaules are a product of the formula that defines factors as a function of the original variables, weighted by their respective loadings from the preceeding matrix. If a factor has high loadings with a variable, that variable should be instrumental in the interpretation of the meaning of the factor. Loadings near zero represent variables the factor does not represent, also important information. Negative loadings indicate a potential bipolar factor, a factor which loads high positively on one type of variable and high negatively on other variables.

In this study, factor analysis was used to help in the understanding of the interrelationships between chemical consitiuents and properties of the ground water and was an important aid in the interpretation and identification of geochemical processes occurring in this system.

Appendix E contains a listing of the SAS factor analysis statements.

Equilibrium Considerations

The computer program, WATEQ (Truesdell and Jones, 1974), and WATEQF (Plummer et al, 1976), the Fortran Version, require the chemical analysis and in situ measurments of temperature, pH, and redox potential, in order to model the states of reaction of the water with solid and gaseous phases. In order to determine the mineral phases with which the water is saturated, calculated activities of the dissolved ions are combined to produce an ion activity product (IAP) which is compared to the solubility equilibrium constant (K). If the activity product is greater than the equilibrium solubility product precipitation of the oversaturated minerals is thermodynamically predicted to occur.

The WATEQF printout includes the total concentration of input species, the distribution of species (including the activity and activity coefficients and the logarithms), the ion activity products and the solubility product constants of all solid phases, and the ratio of IAP to Ksp (or saturation index).

All available water quality data was initially run on WATEQF to provide a comprehensive data base that contained both the primary information on the water chemistry as well as some interpretations of this information. WATEQF was instrumental in providing a general descriptive picture of the chemistry of the Sundre aquifer. Appendix F contains a sample WATEQF printout.

Mass Balance Approach

The final method of data analysis employed was a Fortran computer program, BALANCE, designed to define and quantify chemical reactions between water and minerals (Parkhurst, Plummer and Thorstenson, 1982). Input required of this program consists of the chemical composition of one or two water samples. BALANCE, using a set of common phases (minerals, organic substances and/or gases), calculates the mass transfer (amounts of phases entering or leaving the aqueous phases) necessary to account for an observed change, or simplistically describe the isotopic composition of the sample. In utilizing BALANCE it must be understood that it is assumed that only the phases selected participate in the chemical reactions that determine the composition of the water.

BALANCE can be run for one of three output options. The simplest option calculates the ionic composition of a ground water sample. This option was utilized for three samples from each of the seven wells. Another component of the BALANCE program requires the chemical compositions of water samples from two points along a flow path, and calculates the difference in the ionic composition of the two samples. The output can be interpreted as what changes occured to input sample one to result in input sample two. In utilizing this option, two samples from each of the seven wells were entered; sample one, an early analysis and sample two, a recent analysis. The third program option with BALANCE requires a "final" water composition and two "end member" waters. It then calculates the relative percentage of each "end member" that comprises the "final" water. This option was utilized for each well in an efford to determine temporal changes in the water chemistry. Appendix F contains an example of the printout from a run requiring two end members and a final mixing product in order to calculate the mixing that occurred. Also in Appendix G is a run from each of the seven wells in which an early and a recent analysis was entered and the difference between the two calculated.

CHAPTER VII

RESULTS AND DISCUSSION

Introduction

The methods outlined in the preceeding chapter were utilized for the purpose of describing the water chemistry of the Sundre aquifer to provide for the subsequent analytical determination of the geochemical processes occurring.

As Plummer and Back (1980) observed, there are two principle types of predictive models for determining the chemistry of water in hydrologic systems: (1) the theoretical and experimental study of the kinetics of all possible reactions for the system, and (2) application of mass balance calculations to observed chemical and ionic data from natural water systems. The first approach is fundamental, and theoretically will yield the most correct results, but is years from being directly applicable to field situations. For the purpose of modeling chemical reactions in aquifers, the mass balance application is the most practical method to choose.

The USGS computer program BALANCE, uses mass balance calculations on a specific data set to balance equations of reactions that may occur in the system. The validity of some of the reactions may be checked by a program based on thermodynamicss, such as WATEQF, which is used to determine which reactions could occur in a given type of system. For example if BALANCE suggests that a certain phase was precipitated then WATEQF could be used to determine the IAP/solubility product to determine if such a reaction is likely.

In the case of the Sundre aquifer, it seems that the two approaches both point to two reaction types that are occurring. First, cation exchange is taking place in these waters, and secondly, dedolomitization is the principle rock-water interaction controlling the chemistry of this ground water system. Not all samples, in all instances of evaluation, point to these conclusions, but support for both the cation exchange and the dedolomitization arguments can be shown by most of the WATEQF data as well as that of BALANCE.

Water Description

BALANCE, a mass transfer calculation program, calculates the amounts of given phases, entering or leaving the aqueous phase, necessary to account for the observed changes. This program was utilized to produce several sets of results.

One feature of BALANCE is its descriptive ability. A single water analysis is entered and BALANCE calculates, in millimoles per liter (mmol/L), the amount of calcite, dolomite, gypsum, halite, carbon dioxide gas, ion exchange, and potash feldspar that is either precipitated (-), or dissolved (+). This program option was used for 3 samples from each of the seven Sundre wells. Twenty-one total samples were averaged and it was seen that the following amounts of materials are dissolving into the Sundre aquifer: 2.6 mmol/L of calcite, 1.3 mmol/L of dolomite, 3.1 mmol/L of gypsum, 1.3 mmol/L of halite, 4.1 mmol/L of carbon dioxide gas, .2 mmol/L of k-spar, and 4.2 mmol/L of ion exchange is occurring.

Another BALANCE feature utilized was the calculation of the difference between two analyses. In this instance an early and a recent sample were used so that the changes occurring represent aquifer changes with respect to time. Again, the results were for the following species; calcite, dolomite, gypsum, halite, CO2 gas, k-spar, and ion exchange. If the results from all seven wells are averaged the following values are calculated; .15mmol/L calcite precipitated, .63mmol/L dolomite dissolved, 2.26mmol/L gypsum dissolved, .32mmol/L halite precipitated, .36mmol/L CO2 gas leaves the solution, .06mmol/L k-spar dissolved and 1.44 mmol/L calcium in solution was exchanged for sodium.

Cation Exchange

In cation exchange reactions, the concentrations of adsorbable solutes will approximately obey the law of mass action, when the solution is in contact with the exchange medium. Ions can be adsorbed onto colloidal particles, into crystals, or in particles of any dimension (Krauskopt, 1979). Some assumptions can be made regarding ion exchange, but the exceptions to these generalities are numerous. Usually it can be assumed that the smaller of the two ions will be held tighter, that a multivalent ion will be held more tightly than a univalent one and ions forming covalent bonds are more readily adsorbed than ones forming ionic bonds. It has been experimentally shown that the partition coefficient (the ratio of free to adsorbed ions) is a straight line function of the log of the concentration of a competing ion where the latter was in excess (Krauskopt, 1979).

The evidence for cation exchange in the Sundre is in the relationships between the calcium, sodium and chloride. In the Piper Diagram the calcium values in the water seem to be decreasing as the sodium increases, indicating that there is an exchange reaction occurring. Since calcium ions are removed from solution much easier than sodium ions, equilibrium is established when the ratio of sodium to calcium ions is much greater than one. In systems where cation exchange is not occurring the chloride ion acts as an indicator of the amount of sodium to be expected in solution. The low chloride values suggest that the sodium values should also be in that range, but instead they are larger, due to cation exchange.

Cations plot in one distinct cluster on the Piper Diagram, characterized by a dominance of sodium + potassium. A linear trend appears to exist between calcium + magnesuim and sodium + potassium; as the calcium +

magnesium value decreases the sodium + potassium value increases. This trend indicates possible cation exchange occurring; the replacement of adsorbed sodium ions by calcium ions in solution.

The SAS factor correlation data, in calculating relationships between ions, showed a positive correlation between sodium and calcium and no correlation between sodium and chloride. In most aquifer systems the majority of the sodium and chloride in solution is from halite, so some relationship should exist unless sodium has a separate source such as from cation exchange.

The BALANCE calculations also support the cation exchange hypothesis. The ion exchange reaction used by BALANCE, is: $Na_2X + Ca^{++} = 2Na^+ + CaX$. Thus, a positive value indicates the reaction is going to the right, therefore the calcium ions in solution are being taken up and sodium ions are freed into solution.

Factor analysis was another SAS procedure used. The factor analysis program isolates variables that show similarity in actions and groups them into factors. It also determines the influence each variable has on the formation of a particular factor. The usefulness of factor analysis comes in the interpretors ability to explain why variables group the way they do.

When factor analysis was employed on all the wells, for the variables Ca, Mg, Na, Cl, SO4, and HCO3, two factors were present. Figure 8 is the rotated factor pattern with the loading for each variable. For the first

	FACTOR ONE	FACTOR TWO
CA	0.96638	0.07143
MG	0.95076	0.06964
NA	0.89248	0.08256
CL	0.07082	0.99745
SO4	0.98132	0.04974
HCO3	0.95524	0.06260

Figure 8. Rotated Factor Pattern

factor calcium, magnesium, sodium, sulfate, and bicarbonate loaded high, while only chloride was influencial in factor two. Since the amount of sodium in a system is usually related to chloride something must be interfering with the placing of sodium and chloride together in a factor. Ion exchange, calcium for sodium, is the most probable process accounting for the disassociation of sodium from chloride.

Both Kehew (1983) and sources from the Soil Conservation Service (1970) confirm the presence of sodium-rich clay sediments and soils in the Minot area. These montmorillonite clays are found both at the surface and in all glacial deposits. The river valley fill deposits making up the Sundre Aquifer also are known to contain montmorillonite clays. It is through contact with these clays that the ground water experiences cation exchange.

Dedolomitization

The literature on dedolomitization is in general agreement as to how this phenomena occurs. As ground water moves through a carbonate or carbonate rich aquifer, it dissolves the calcite, dolomite and gypsum present at varying rates. The system typically becomes saturated with respect to calcite first. Calcite precipitation is followed by dolomite saturation and precipitation. The dissolution of gypsum causes additional dissolution of dolomite. The calcium from the gypsum, and the dolomite and the carbonate from the dolomite combine to precipitate calcium carbonate.

The process may be viewed mechanistically as follows:

A) dissolution of calcite

$H_2O + CO_{2s} + CaCO_3 \rightarrow$

$Ca_c^{+2} + 2HCO_{3s,c}^-$

B) dissolution of dolomite

$2H_2O + 2CO_{2s} + CaMg(CO_3)_2 \rightarrow$

$Ca_d^{+2} + Mg_d^{+2} + 4HCO_{3s,d}^-$

C) dissolution of gypsum

$CaSO_4 + 2H_2O \rightarrow$

$Ca_g^{+2} + SO_{4g}^{-2} + 2H_2O$

where c, d, and g represent ions from calcite, dolomite and gypsum; and s represents CO_2 from soil gas. When occurring simultaneously, $CaCO_3$ will precipitate as follows:

$Ca_c^{+2} + Ca_d^{+2} + Ca_g^{+2} +$

$6HCO_{3c,d,s}^- \rightarrow 3Ca_{c,d,g}CO_{3c,d,s} +$

$3HCO_3^- + 3H^+$

The results found support the conclusion that dedolomitization is occurring. Using the Piper Diagram as a simplistic model of the water, the excess carbonate and bicarbonate and the inverse relationship between these carbonates and sulfate indicates the potential for calcite precipitation occurring concurrently with gypsum dissolution. Again, if calcite is precipitated, taking calcium and carbonate ions out of solution, and gypsum dissolution contributes calcium and sulfate ions to the solution, then dolomite will be dissolved, to add carbonates to the solution to join with the calcium ions to form calcite. Thus calcite precipitation and gypsum solution lead to dolomite dissolution. The majority of points in the anionic triangle of the Piper Diagram plot in the region where bicarbonate + carbonate comprises > 50% of the total. The chloride values are all at less than 20% and sulfate accounts for 25 - 65%, with a distinct cluster at 25 - 35%.

Back et al. (1983) reported on dedolomitization, relating its process and rate to mass transfer. Their findings suggested that ground water, in the presence of gypsum, will be saturated or supersaturated with respect to calcite. This can be attributed to the common ion effect - the dissolution of gypsum contributed calcium ions to the solution resulting in the precipitation of calcite. As the calcite continues to precipitate the pH of the solution drops, causing the removal of carbonate from the solution, and thus resulting in the dissolution of dolomite - as an attempt to restore carbonate to the solution.

Dolomite is near equilibrium at 25 C in a ground water that is also in equilibrium with calcite and has a Mg/Ca = 1 (Hanshaw et al, 1971). The BALANCE program calculated a calcite value of 2.6 mmol/L, twice that of dolomite

(1.3mmol/L). Since it has also been shown that the dissolution of gypsum is a driving force in the dedolomitization reaction, it is important to note that the amount of gypsum dissolving into solution is higher than that of either calcite or dolomite. Thus, the most important catalyst in this reaction is the gypsum, by providing an abundant supply of calcium in order to maintain a low Mg/Ca ratio. The other critical aspect in maintaining dolomite subsaturation (Back et al, 1983) is calcite precipitation. The precipitation of calcite removes the carbonate ion. For every mole of dolomite dissolved, two moles of carbonate are released into the water. If this carbonate was not removed by calcite precipitation the water would attain equilibrium with dolomite and the reaction would cease. If the dissolution of gypsum stops then the precipitation of calcite would cease, thus halting the dedolomitization process.

The mineralogy of the aquifer, and the geochemistry of the solution waters within the aquifer contribute to the saturation indices, which provide the basis for identification of the controlling chemical reactions within the aquifer. Interpretation of the values of saturation indices for the important minerals in the system - calcite, aragonite, dolomite, anhydrite and gypsum - shows that the significant reactions can be estimated by the following mass balance relations:

/_\ Ca = /_\ calcite + /_\dolomite + /_\gypsum

/_\ Mg = /_\dolomite + /_\ SO_4 = /_\gypsum

CO_2 = /_\calcite + 2/_\dolomite + /_\$CO_2$gas

This mass balance approach assumes that (1) the moles of calcium from dolomite are equal to the moles of magnesium from dolomite due to congruent dissolution and that (2) the moles of calcium from gypsum equal the moles of total sulfate in the system. The second assumption, common for carbonate systems, requires little or no reduction to sulfide species.

In calculating the thermodynamic speciation of inorganic ions and complex species in solution for the given ground water analyses, WATEQF provided information as to the state of saturation of minerals in the Sundre aquifer. Figure 9 is a plot of the saturation indices for calcite, dolomite, gypsum, anhydrite and aragonite, plotted against the dissolved sulfate concentration. As the sulfate concentration increases the gypsum and anhydrite does also - but remains unsaturated. Dolomite is either saturated of unsaturated in the solution, and does not appear to change with respect to sulfate. An exception to this is seen when sulfate values are extremely high (1000 mg/l or above), then dolomite supersaturates the solution. Calcite is also at or below saturation as sulfate increases, but, when the sulfate concentrations are high (1000 or above) the calcite drops below equilibrium in the solution. Aragonite remains below equilibrium at all times plotted.

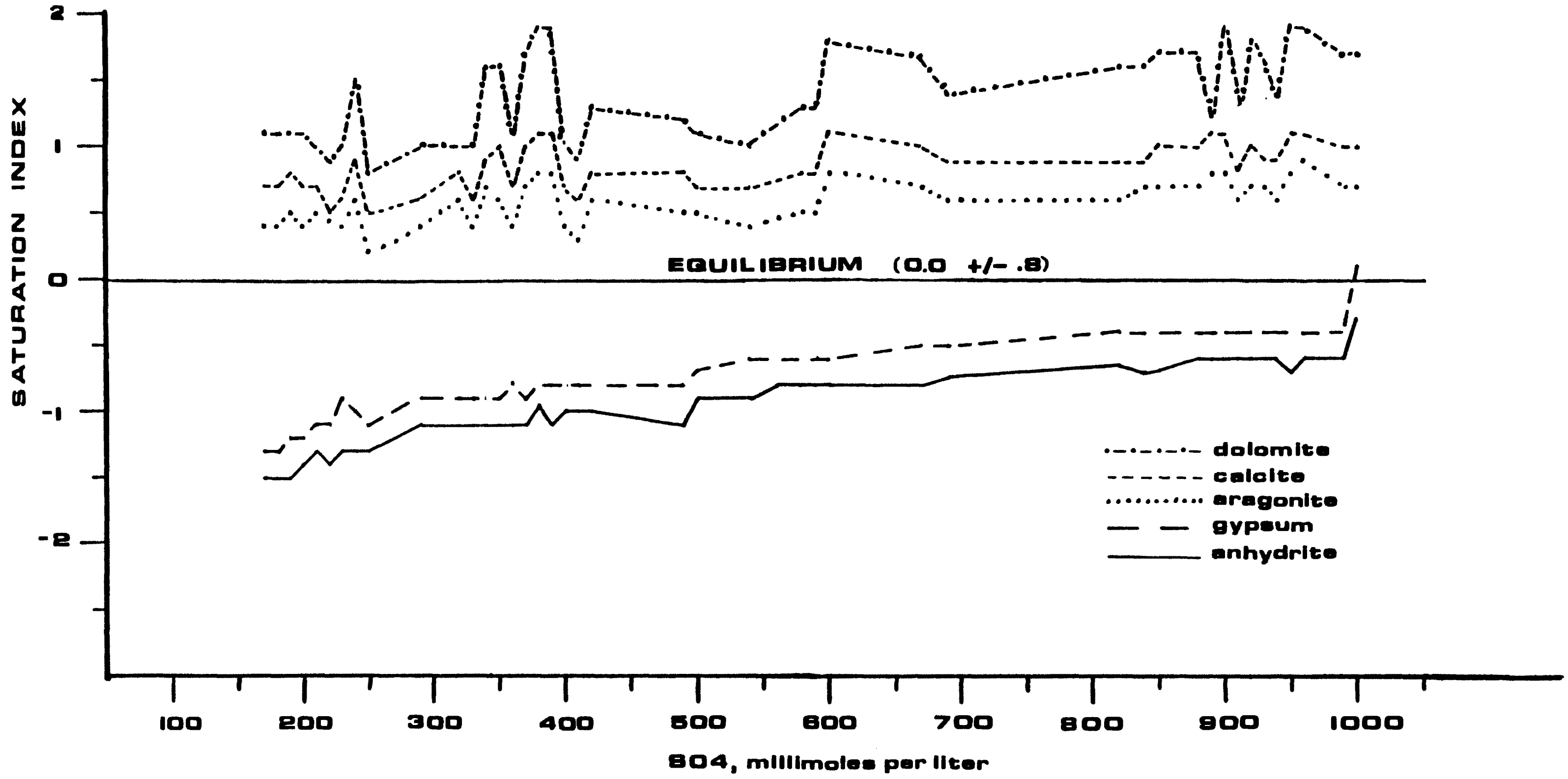


Figure 9. Sulfate Concentrations as an Indication of Saturation Index Variations

In a carbonate aquifer containing no gypsum or anhydrite, calcite would dissolve until equilibrium was reached, the same with dolomite, although the process would most likely be slower. Once dolomite saturation is reached, it would be expected that some of the calcite would precipitate. This scenario changes in the presence of gypsum. In looking at the indices of saturation for calcite, dolomite, gypsum and anhydrite it is shown that they are acting concurrently. The dissolution of gypsum, contributing calcium ions to the solution, would cause the ground water to remain at saturation or slightly above with respect to calcite. The calcite is near equilibrium but the gypsum remains below saturation, thus causing the precipitation of calcite and the dissolution of gypsum. As calcite continued to be added from gypsum the precipitation of calcite would follow, due to the common ion effect. The removal of calcium ions from the solution decreases the pH and removes carbonate from the solution, thereby causing further dissolution of dolomite.

In the factor analysis of the data the ions fell into groups of related or similarly influenced ions. Consistently, the calcium, sulfate, and carbonates clustered together as a factor. These are the ions that would be moving into and out of solution in a water where dedolomitization was occurring. Calcium, an ion from many sources ($CaCO_3$, $CaMg[CO_3]_2$, $CaSO_4*2H_2O$), acting within this system as a critical component, showed high correlations with magnesium, sulfate, bicarbonate, and sodium. This is an important indication of the dependency of the dedolomitization reaction on the presence of calcium in solution.

The factor analysis program output provides a matrix of variable correlations. Within this matrix high correlations were present between the following pairs of ions: Ca & Mg, Ca & SO_4, Ca & HCO_3, Mg & SO_4, Mg & HCO_3, and SO_4 & HCO_3. Slightly lower correlations were present between Ca & Na, Na & SO_4, and Na & HCO_3. Correlations between chloride and the other ions was quite low. Here again it is shown that the sodium and chloride are acting separately in this system. Another important feature that is brought out in the correlation matrix is the secondary nature of the sodium in its reactions with the other ions. This is likely due to the fact that the dedolomitization occurring in the system is controlled by the amount of calcium in solution, which is in turn slightly influenced by the ion exchange with sodium. Otherwise sodium does not influence this system to any extent.

For dedolomitization to occur there has to be a dolomite source to dissolve. The carbonate grains within the glacial sediments of the Minot area are from distant exposures of Paleozoic limestones and dolomites (Kehew, 1983). Studies show the tills are comprised of 20-30% carbonates. The fluvial sediments of the Sundre Aquifer are chiefly reworked glacial material, thus there is a proven supply of dolomite ions to the system.

CHAPTER VIII

SOLUTE TRANSPORT MODELING

Solute transport, in one dimension, can be simply stated as: DISPERSION - CONVECTION +/- PRODUCTION = QUALITY ACCUMULATION (Prickett at al, 1981). The Random Walk solute transport model by Prickett (1981) is a computer simulation of solute transport in groundwater. The model name is derived from the technique utilized to calculate dispersion. Random Walk is based on the concept that dispersion in porous media is a random process. A 'particle', a mass of a specific chemical constituent contained in a defined volume of water, moves through an aquifer with two types of motion, in the direction of flow, as determined by the physical qualities of the aquifer, and in a random motion, governed by probability curves related to flow length and the dispersion coefficients.

Convection, dispersion and chemical reactions can be accounted for with this model, which simulates one- or two-dimensional nonsteady or steady flow in heterogeneous water table, artesian or leaky artesian conditions.

The advantages of Random Walk over other numerical models include: 1. There is no dispersion equation to solve. 2. Particle movement takes place in continuous space. (Thus there is only one finite difference grid involved in solving for the influence of convection.) 3. Concentrations are calculated only when of interest instead of at every time step in the simulation. 4. Computer processing time - both for data entry and simulation, is reduced. 5. Particles can be selectively introduced by location, number and relative time. 6. Solutions are additive, thus the results from a subsequent run can be added to an initial run.

The disadvantages of this program include: 1. Concentrations greater than the initial concentration may be generated. 2. Concentration and particle print-outs may not be easy to read due to the spacing of the grid area. 3. A large number of particles may be necessary to provide an acceptable solution, but the program limits the maximum number of particles to 1000. 4. Success in applying this code to field situations comes only with experience.

A thorough mathematical discussion of the computer code can be found in Prickett et al (1981). The code consists of two basic parts; the flow model and the solute transport model.

"The basis for the transport calculations of dissolved constituents in this computer code is that the distribution of the concentration of chemical constituents of the water in an aquifer can be represented by the distribution of a finite number of discrete particles." The two primary mechanisms for changing contaminant concentrations in ground water are 1. dispersion, and 2. dilution and mixing.

The effects of mechanical dispersion through the porous medium are described by dispersion and convection, while the effects of dilution and mixing are expressed by convection and production. These are related to the following equation: DISPERSION - CONVECTION +/- PRODUCTION = QUALITY ACCUMULATION.

The program can utilize time-varying pumpage or injection from or into as many as 20 wells, and allows for specification of the water quality concentrations of any part of the model to a total of 1000 particles. Additional features include variable finite difference grid sizes, printouts of input data, concentration and particle maps.

The version of Random Walk used for this study has been altered so that it is a menu driven program which utilizes user defined regional velocities instead of a flow model to define the gradient.

Based on the USGS system of well numbering and locating, each well could be located to a precision of 330 feet square which was therefore the cell size utilized.

The purpose of using Random Walk in this study was to define the physical environment in which this hydrogeochemical scenario was evolving as well as to determine the possible extent of the area of influence of the pumped wells.

Aquifer Coefficients

The hydrogeologic parameters required by Random Walk are discussed below. Most of the actual values used in the simulations were obtained from Pettyjohn (1971), although some were obtained from other sources.

The transmissivity for a confined aquifer of thickness b, and hydraulic conductivity K, is defined as equal to Kb. The value K represents the hydraulic conductivity. Hydraulic conductivity is a property of the media through which the water is flowing. Conductivity can be defined as the control on ground water velocity if the gradient is held constant.

Dispersivity is defined as the tendency for a solute to spread out from the path it would be expected to follow due to the linear velocity of the flow system. Solute spreading in the direction of flow is longitudinal dispersivity, while spreading in directions normal to the flow is transverse dispersivity. Longitudinal dispersivity is normally much stronger than lateral dispersion. For this reason values of 100 and 20 for longitudinal and transverse dispersivity, respectively, were chosen.

The regional flow velocity (.06 ft. per day) is a function of the gradient (the slope of the water surface) and the conductivity.

Porosity is considered the volume of the voids within a material divided by the total volume of the material. Effective porosity, which in this case equals .35, is the volume of pore space that allows flow, and thus is less than the actual porosity.

The volume of water that a confined aquifer releases from storage per unit surface area of the aquifer, per unit decline in the component of hydraulic head normal to that surface is known as the storage coefficient. This value varies from 0.005 to 0.00005. The value chosen for this simulation is .0003.

The retardation coefficient represents the change in solute concentration in the fluid caused by chemical reactions with the aquifer. Reactions such as adsorption and organic fixation tend to retard the movement of the consitiuent relative to the ground water velocity. A coefficient of one was used, thus assuming a substance is not affected (retarded) by the aquifer materials..

Other information required by the program includes the location of well(s) and the contaminant source(s), the pumping rate of any wells and the number of particles of contaminant.

The pumping rate of the wells can be set so that the well or wells were operating prior to the introduction of the contaminant, and they can be turned off or on at any time.

Particle location can be viewed at any time requested. A particle or a concentration map (based on the number of particles per pound) can be viewed.

For the purposes of this study the modeled concentration of the solution was not considered. First, there was no way of determining particle mass accurately, and second, particles were moved towards and subsequently pumped out of the system by the pumping wells.

The maximum number of particles allowed in a simulation is 1000, and using nearly this many allowed for easy locating of the central portion of the plume and its most concentrated spots.

Formulation of the Problem

Examination of the chemical data available from the well field showed that high concentrations (that varied with time) of SO_4 existed in wells D and E. By comparing the SO_4 concentration fluctuations with the monthly pumping rates for wells D and E some relationships became apparent. It was also noted that test wells CDC1 and CDC3 were monitored in 1968 and 1969, prior to development of the well field, and showed no elevated sulfate concentrations. Subsequent analyses, done on well CDC1 in 1980 and 1981, showed sulfate concentrations of 1000 mg/l, matching the highest values seen in the analyses of the well field samples.

It must be emphasized that the pumping rate of well D is, on the average, almost an order of magnitude greater than any other well in the field. Occassionally (approximately four times since 1976), the pumping rate of well D is decreased significantly or turned off. When this occurred, the pumping of well E was increased to compensate for the decrease in what is the major producing well in the field. Appendix H contains graphs of the pumpage of each of the 5 Sundre wells.

When well D is being pumped the SO_4 values for E are high or peak, but when D is not pumping the SO_4 values for

E are lower. When well D is turned down or off the SO_4 in E decreases, and it is at this time that the SO_4 peaks in the D well occur. The sulfate contamination of CDC1 suggests that the source is located such that the pumping of the well field caused the movement of sulfate towards the test well.

Observation of these trends indicates that the flow of the solute, in this situation, SO_4, is controlled by the flow variations which occur depending on well utilization.

It was thought that flow line analysis of a potentiometric surface map of the Sundre Aquifer would give an indication of source location. Copies of pre- and post-development potentiometric surface maps of the area were obtained from Clark Poore (1987), who is currently modeling the regional ground water flow within this area. By utilizing these maps, a source location was tentatively determined and contaminant movement was then modeled using Random Walk.

Simulation and Results

The grid location of the wells, and their pumping rates is shown in Figure 10. The object of the Random Walk simulation was to determine a source area which would cause each of several reactions: 1- it must"contaminate" well E when all wells in the well field are operating, 2- it must be a source that reaches both well D and well E when all wells except well D are pumping, and 3- it is important that high concentrations not reach wells A, B and C, as no

```
          AQUIFER COEFFICIENTS

 1. TRANSMISSIVITY                   350000  GPD/FT
 2. HYDRAULIC CONDUCTIVITY           3500  GPD/FT2
 3. LONGITUDINAL DISPERSIVITY        100  FT
 4. TRANSVERSE DISPERSIVITY          20  FT
 5. REGIONAL X FLOW                 -.06  FT/DAY
 6. REGIONAL Y FLOW                  0  FT/DAY
 7. EFFECTIVE POROSITY               .35
 8. STORAGE COEFFICIENT              .0003
 9. RETARDATION COEFFICIENT          1

 WELL            RATE           DAYS
 (X,Y)           (GPD)          ACTIVE
------          ------          ------
A495 , 2805      213556          365
B330 , 2475      183463          365
C330 , 1650      258510          365
E1650 , 330      129432          365
D1320 , 990      1507311         365
      PARTICLES AFTER  0  DAYS
      NUMBER OF PARTICLES  999                NUMBER OF WELLS  5
```

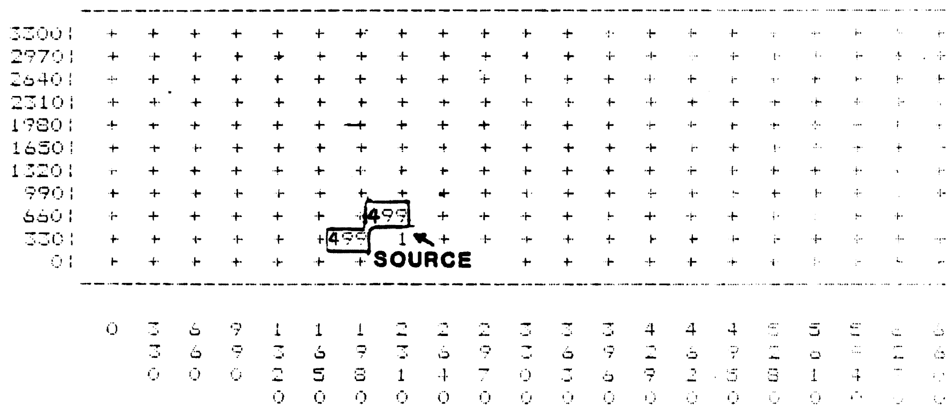


Figure 10. Location of Wells and their Pumping Rates

sulfate contamination of them has yet been detected. By locating the source as shown in Figure 10, these three criteria are satisfied. Figure 11 illustrates the situation within the aquifer when well D is not pumping but all others are, and Figure 12 shows the solute movement that occurrs when all wells are pumped.

Apparently, wells A, B and C are not affected by the SO_4 source due to the high rate of pumping of well D. When D is being pumped, any sulfate that reaches D is diluted because of the large amount of water being drawn into D. The wells A, B and C are not contaminated because D acts to "intercept" any SO4 moving in their direction.

In the simulation of the SO_4 movement with Random Walk one aspect of the system could not be accmomdated for by the model. Vertical movement of a solute within an aquifer cannot be considered. In the case of the Sundre Aquifer, the depth of the gypsum occurrence could affect its movement in solution.

Recommendations for Remediation

At the present time the city of Minot mixes the waters from the well field, in order to dilute any water high in sulfate that is coming from wells D or E. This is an effective solution but does not address the problem at its source.

Based on the nature of the aquifer material and the occurrences of SO_4 concentrations, it is believed that gypsum lenses or beds are located interspersed throughout

```
                AQUIFER COEFFICIENTS

  1. TRANSMISSIVITY                350000  GPD/FT
  2. HYDRAULIC CONDUCTIVITY        3500  GPD/FT2
  3. LONGITUDINAL DISPERSIVITY     100  FT
  4. TRANSVERSE DISPERSIVITY       20  FT
  5. REGIONAL X FLOW              -.06  FT/DAY
  6. REGIONAL Y FLOW               0  FT/DAY
  7. EFFECTIVE POROSITY            .35
  8. STORAGE COEFFICIENT           .0003
  9. RETARDATION COEFFICIENT       1

  WELL            RATE           DAYS
  (X,Y)           (GPD)          ACTIVE
 ------          ------          ------
A495 , 2805      213556           2555
B330 , 2475      183463           2555
C330 , 1650      258510           2555
E1650 , 330      129432           2555

      PARTICLES AFTER  2555  DAYS
      NUMBER OF PARTICLES  589             NUMBER OF WELLS  4
     --------------------------------------------------------------
3300!  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +
2970!  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +
2640!  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +
2310!  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +
1980!  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +
1650!  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +
1320!  +  +  1  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +  +
 990!  +  +  +  5 13 19 12  +  +  +  +  +  +  +  +  +  +  +  +  +  +
 660!  +  +  + 1135158 76 14  3  +  +  +  +  +  +  +  +  +  +  +  +
 330!  +  +  +  + 72 44 17  6  +  +  +  +  +  +  +  +  +  +  +  +  +
   0!  +  +  +  1  4  1  5  +  +  +  +  +  +  +  +  +  +  +  +  +  +
     --------------------------------------------------------------

       0  3  6  9  1  1  1  2  2  2  3  3  3  4  4  4  5  5  5  6  6
          3  6  9  3  6  9  3  6  9  3  6  9  2  6  9  2  6  9  2  6
          0  0  0  2  5  8  1  4  7  0  3  6  9  2  5  8  1  4  7  0
                   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
```

Figure 11. Location of Source and Plume Created from the Pumping of Wells A, B, C, and E

```
           AQUIFER COEFFICIENTS

    1. TRANSMISSIVITY                350000  GPD/FT
    2. HYDRAULIC CONDUCTIVITY        3500  GPD/FT2
    3. LONGITUDINAL DISPERSIVITY     100  FT
    4. TRANSVERSE DISPERSIVITY       20  FT
    5. REGIONAL X FLOW              -.06  FT/DAY
    6. REGIONAL Y FLOW               0  FT/DAY
    7. EFFECTIVE POROSITY            .35
    8. STORAGE COEFFICIENT           .0003
    9. RETARDATION COEFFICIENT       1

    WELL            RATE          DAYS
    (X,Y)          (GPD)         ACTIVE
    ------        ------         ------
  A495 , 2805     213556          365
  B330 , 2475     183463          365
  C330 , 1650     258510          365
  E1650 , 330     129432          365
  D1320 , 990     1507811         365

         PARTICLES AFTER  365  DAYS
         NUMBER OF PARTICLES  890               NUMBER OF WELLS  5
         ---------------------------------------------------------------------------------
    3300!   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +
    2970!   +   +   +   +   +   +   + _ +   +   +   +   +   +   +   +   +   +   +   +   +
    2640!   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +
    2310!   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +
    1980!   +   +   +   1   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +
    1650!   +   +   1   +   1   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +
    1320!   +   +   +  17   5   1   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +
     990!   +   +   +   9  68  81  31   2   +   +   +   +   +   +   +   +   +   +   +   +   +
     660!   +   +   +   2  29283186  36   3   +   +   +   +   +   +   +   +   +   +   +   +
     330!   +   +   +   +   +  15  79  28   6   +   +   +   +   +   +   +   +   +   +   +   +
       0!   +   +   +   +   +   +   +   4   2   +   +   +   +   +   +   +   +   +   +   +   +
         ---------------------------------------------------------------------------------

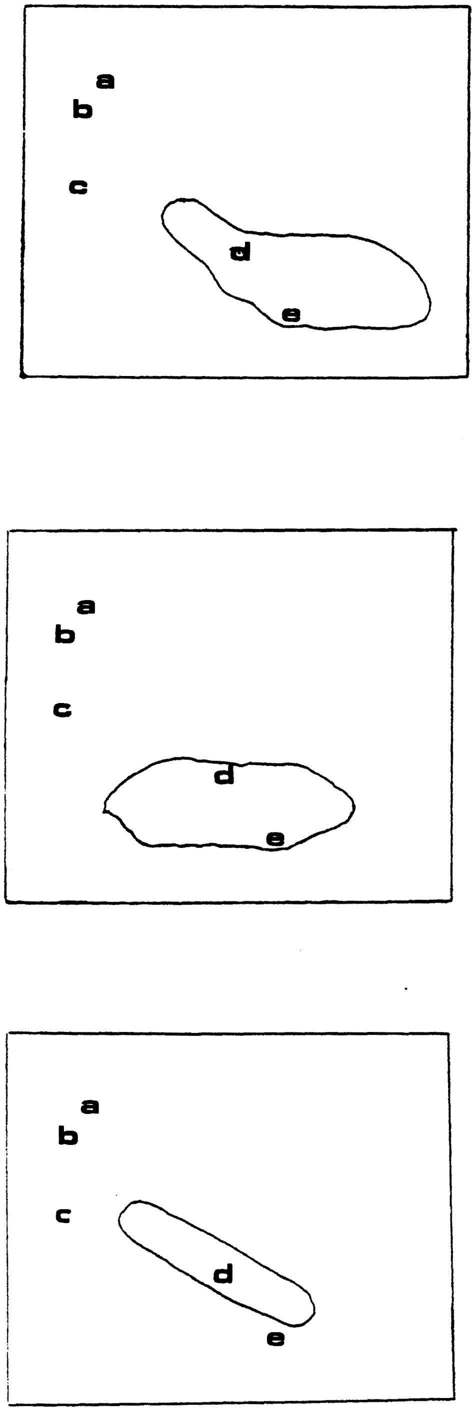
            0   3   6   9   1   1   1   2   2   2   3   3   3   4   4   4   5   5   5   6   6
                3   6   9   3   6   9   3   6   9   3   6   9   2   6   9   2   6   9   2   6
                0   0   0   2   5   8   1   4   7   0   3   6   9   2   5   8   1   4   7   0
                                0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
```

Figure 12. Location of Source and Plume Created from the Pumping of Wells A - E

the aquifer. Glacio-fluvial sediments, such as those found in the Sundre Aquifer, are often unstratified conglomerations of any and all local material moved by the glacier or carried by the river. This type of geological phenomena could result in occurrences of gypsum from the glacially eroded Fort Union. The occurrence of high SO_4 concentrations in waters from a few of the test wells supports the conclusion that the incidences of gypsum in the aquifer are isolated and discontinuous.

In order to discuss remediation solutions it is necessary to summarize the situation as it now exists. Figure 13 illustrates the solute movement under various pumping conditions, as determined through Random Walk. At all times, wells A, B and C are kept pumping. Pumping conditions that exist concerning wells D and E include: 1- all wells pumping, 2- all wells except well D pumping, and 3- all wells pumping except well E. Both wells D and E are affected by the sulfate under all of the above conditions, but to varying degrees.

With this in mind, the initial solution attempted was the elimination of well E as a pumping well. To compenaste for the decrease in the total volume of water pumped from the aquifer, wells A, B and C were pumped to a greater extent. Figure 14, the Random Walk simulation of such a scenario provides the new pumping rates for wells A, B and C, as well as an illustration of the type of plume that would develop under such conditions. With well E remaining off for five years, the source moves past well E but is



all wells pumping

all wells except D pumping

all wells except E pumping

Figure 13. Solute Movement Under Various Pumping Conditions

```
          AQUIFER COEFFICIENTS

   1. TRANSMISSIVITY               250000  GPD/FT
   2. HYDRAULIC CONDUCTIVITY       3500  GPD/FT2
   3. LONGITUDINAL DISPERSIVITY    100  FT
   4. TRANSVERSE DISPERSIVITY      20  FT
   5. REGIONAL X FLOW             -.06  FT/DAY
   6  REGIONAL Y FLOW              0  FT/DAY
   7  EFFECTIVE POROSITY           .35
   8. STORAGE COEFFICIENT           0003
   9  RETARDATION COEFF.CIENT      1

   WELL            RATE          DAYS
   (X,Y)           (GPD)         ACTIVE
  ------          ------         ------
A 495 , 2805       253556         1825
B 330 , 2475       223463         1825
C 330 , 1650       298510         1825
D 1320 , 990       1507911        1825

        PARTICLES AFTER  1825  DAYS
        NUMBER OF PARTICLES  135                  NUMBER OF WELLS  4
        ----------------------------------------------------------------------------------
  3300:   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +
  2970:   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +
  2640:   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +
  2310:   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +       +   +
  1980:   +   +   1   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +   +
  1650:   +   +   9   +   +   1   +   +   +   +   +   +   +   +   +   +   +   +   +   +
  1320:   +   1   5  32   4   4   1   +   +   +   +   +   +   +   +   +   +   +       +   +
   990:   +   +   +   4  25   3   1   +   +   +   +   +   +   +   +   +   +   +   +   +   +
   660:   +   +   +   1   5  22   3   +   +   +   +   +   +   +   +   +   +   +   +   +   +
   330:   +   +   2   +   +   +   4   2   +   +   +   +   +   +   +   +   +   +   +   +   +
     0:   +   +   +   +   +   +   1   3   +   +   +   +   +   +   +   +   +   +   +   +   +
        ----------------------------------------------------------------------------------

          0   3   6   9   1   1   1   2   2   2   3   3   3   4   4   4   5   5   5   6   6
              3   6   9   3   6   9   3   6   9   3   6   9   2   6   9   2   6   9   2   6
              0   0   0   2   5   8   1   4   7   0   3   6   9   2   5   8   1   4   7   0
                          0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
```

Figure 14. Remediation by Pumping all Wells Except E

seen at well D. If this is the solution attempted it is important to consider the assumptions made regarding this situation. Well D, being the primary producer of the field, is pumped six times more that well A, B or C. This large amount of water moving toward D acts in two ways important in maintaining this solution: 1- dilution at well D prevents high SO_4 from becoming a problem at the well, and 2- the cone of influence around D prevents most of the SO_4 from travelling to well C or on to wells B and A. Simply stated, not pumping well E would increase the sulfate concentrations at D but they would still be diluted to the point that the water is safe for drinking.

A second solution to consider is the pumping of well E, and the disposal of the water by some means. The pumping of well E acts to draw the SO_4 away from well D. This is desirable considering the importance of well D to the Minot water supply. A potential means of disposing of the high sulfate water from well E is through injection into the aquifer, or into a non-producing interval such as the Fort Union. If the water were injected upgradient from the source it would act to push the in situ source water towards well E faster, provided it was injected into the Sundre Aquifer. Injection into the Fort Union or other deep, non-water bearing strata would eliminate the water from the system. If reinjected into the aquifer, the rate at which this is done should not exceed the pumping rate, in order to keep the flow toward E and away from well D.

Another strategy for remediation requires the installation of a pumping well to act as a purging or diversion well, and an injection well for recirculation of the sulfate-rich water. The location of the pumping well should be such that it is near enough to the source to couunter-act the influence that well D has on the flow, while the injection should occur slightly upgradient from the source. This system, if operated correctly, will contain the source in an area as long as it is kept operating. The injection rate should not exceed the pumping rate or it well act to push the sulfate toward the well field. One of the drawbacks of this soultion is that with any injection system the success of the action cannot be predicted with complete accuracy. In any instance when installation of a well is recommended, the system should be thoroughly studied to determine the cost effectiveness of such a project.

The techniques for remediation discussed above are only preliminary and their potential for success has not been fully considered.

CHAPTER IX

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been made from this study:

1. Cation exchange, where sodium ions go into solution and calcium are removed from solution, is occurring between the water of the Sundre Aquifer and the montmorillonite clays within the river valley fill deposits which make up the aquifer.

2. Dedolomitization is the principle rock-water interaction controlling the chemistry of this ground water system. The catalyst for the dedolomitization process is gypsum dissolution into the ground water. Gypsum contributes calcium ions to the ground water, which in turn combine with carbonate ions present and precipitate as calcium carbonate once saturation is exceeded. Once calcite precipitation occurs dolomite saturation and precipitation follows. The subsequent dissolution of gypsum contributes calcite ions to the solution, thus perpetuating dolomite dissolution, which occurs in order to contribute carbonate ions to the solution. These ions join with the calcite ions to precipitate calcite, begining the cycle once again.

3. The source for excessive gypsum found in water from wells D and E may be within the aquifer, and to the south and east of the well field area. This determination was made with the aid of Random Walk, a solute transport model.

The following are the author's suggestions for further research:

1. The drilling of boreholes, particularly in the source area as predicted through Random Walk, will provide actual physical evidence as to the composition of the aquifer, specifically, the presence of gypsum.

2. All information derived from the physical modeling of this aquifer (which is being done concurrently with this study) should be utilized as aquifer coefficient input into the Random Walk solute transport model.

3. Other physical and chemical tests and models are available that could be used to confirm the conclusions drawn by the author concerning the geochemical processes taking place within the Sundre Aquifer.

4. Water level measurments, done under specific conditions with respect to the pumping of the well field, would provide information on the affect of the well field on the regional ground water flow direction.

5. The mass balance program, BALANCE, has an option which chemically describes a mixing product if the two end points are known. This option could be utilized to delineate the timing and location of the reactions.

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APPENDIXES

APPENDIX A

WELL DRILLERS REPORTS

BOARD OF WATER WELL CONTRACTORS 47
900 E. BOULEVARD, BISMARCK, NORTH DAKOTA 58501

WELL DRILLER'S REPORT

State law requires that this report be filed with the State Board of Water Well Contractors within 30 days after completion or abandonment of the well.

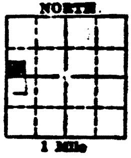
LL OWNER

me CITY OF MINOT

dress

ELL LOCATION

etch map location must agree with written location



FROM

unty WARD

¼ ¼ NW ¼ Sec 3 Twp 154 N. Rg 82 W.

OPOSED USE

Domestic ☐ Irrigation ☐ Industrial
Stock ☒ Municipal ☐ Test Hole

THOD DRILLED

Cable ☐ Reverse Rotary ☐ Bored
Forward Rotary ☐ Jetted ☐ Other
other, specify

ATER QUALITY

s a water sample collected for chemical analysis?
Yes ☐ No
o, to what laboratory was it sent

LL CONSTRUCTION

ameter of hole 12 5 inches. Depth 195 234 feet.
sing: ☐ Steel ☐ Plastic ☐ Concrete
☐ Threaded ☒ Welded ☐ Other
other, specify

e Weight:	Diameter:	From:	To:
lb/ft.	inches	0 feet	195 feet
lb/ft.	inches	feet	feet
lb/ft.	inches	feet	feet
lb/ft.	inches	feet	0 feet

s perforated pipe used? ☐ Yes ☒ No
ngth of pipe perforated feet
s casing left open end? ☐ Yes ☒ No
s a well screened installed? ☒ Yes ☐ No
terial STEEL Diameter 16" NOM inches
(stainless steel, bronze, etc.)
t size 40 set from 195 feet to 200 feet
t size set from 200 feet to 215 feet
t size 50 set from 215 feet to 230 feet
t size set from feet to feet
s a packer or seal used? ☒ Yes ☐ No
o, what material
e of well: Straight screen ☒ Gravel packed ☐
s the well grouted? Yes ☒ No ☐
what depth? 195 feet
terial used in grouting Cement
l head completion: Pitless adapter will have
above grade Other
other, specify
infected upon completion? ☒ Yes ☐ No

7. WATER LEVEL 1/26/75

Static water level 14.72 feet below land surface
If flowing: closed-in pressure psi
GPM flow through inch pipe
Controlled by: ☐ Valve ☐ Reducers ☐ Other
If other, specify

8. WELL TEST DATA

☒ Pump ☐ Bailer ☐ Other

Pumping level below land surface:

26.94 ft. after 2 hrs. pumping 1000 gpm
33.36 ft. after 1 hrs. pumping 1400 gpm
39.92 ft. after 1 hrs. pumping 1809 gpm
45.72 1 2200

9. WELL LOG

Formation	Depth (ft.) From	Depth (ft.) To
TOP SOIL	0	1
CLAY, SILTY, YELLOWISH BROWN	1	15
SAND, FINE TO MEDIUM	15	24
CLAY, SILTY, OLIVE GRAY	24	88
SAND, MEDIUM TO COARSE	88	97
GRAVEL, FINE TO COARSE, SANDY	97	110
CLAY, SILTY	110	142
SAND, MEDIUM TO COARSE	142	151
SILT, CLAYEY	151	158
SAND, FINE TO COARSE	158	165
SILT, CLAYEY	165	189
GRAVEL, FINE TO COARSE,	189	
SANDY, BECOMES MUCH		
COARSER AFTER 222',		
TAKING SOME DRILLING FLUID		242

(Use separate sheet if necessary.)

Final completion with pitless expected July 1975

10. DATE COMPLETED

11. WAS WELL PLUGGED OR ABANDONED?

☐ Yes ☒ No

If so, how

12. REMARKS: MINOT SUNDRE WELL 'A'

13. DRILLER'S CERTIFICATION

This well was drilled under my jurisdiction and this report is true to the best of my knowledge.

C. A. SIMPSON & SON — Driller's or Firm's Name
2 — Certificate No.
BISBEE, NORTH DAKOTA — Address
Simpson — Signed by
7/3/75 — Date

BOARD OF WATER WELL CONTRACTORS 468
[illegible] E. BOULEVARD BISMARCK, NORTH DAKOTA 58501

WELL DRILLER'S REPORT

State law requires that this report be filed with the State Board of Water Well Contractors within 30 days after completion or abandonment of the well.

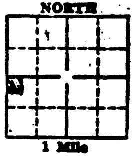
LL OWNER

me CITY OF MINOT

dress MINOT, NORTH DAKOTA

LL LOCATION

etch map location must agree with written location.



EST. ELEV. 1872
FROM 7.5 MIN QUAD

unty [illegible]

[illegible] ¼ [illegible] ¼ [illegible] ¼ Sec. 3 Twp. 154 N. Rg. 82 W.

OPOSED USE

Domestic ☐ Irrigation ☐ Industrial
Stock ☒ Municipal ☐ Test Hole

ETHOD DRILLED

Cable ☐ Reverse Rotary ☐ Bored
Forward Rotary ☐ Jetted ☐ Other
other, specify

TER QUALITY

s a water sample collected for chemical analysis?
Yes ☐ No
so, to what laboratory was it sent SWC

ELL CONSTRUCTION

ameter of hole ~~22~~ 15 inches. Depth ~~180~~ 243 feet.
sing: ☐ Steel ☐ Plastic ☐ Concrete
☐ Threaded ☒ Welded ☐ Other
other, specify

e Weight:	Diameter:	From:	To:
lb/ft.	inches	0 feet	180 feet
lb/ft.	inches	feet	feet
lb/ft.	inches	feet	feet
lb/ft.	inches	feet	feet

s perforated pipe used? ☐ Yes ☒ No
gth of pipe perforated feet
s casing left open end? ☐ Yes ☒ No
s a well screened installed? ☒ Yes ☐ No
aterial [illegible] STEEL Diameter 16 INCH inches
(stainless steel, bronze, etc.)
ot size 75 set from 180 feet to 190 feet
ot size 25 set from 190 feet to 230 feet
ot size [illegible] set from 230 feet to 243 feet
ot size set from feet to feet
s a packer or seal used? ☒ Yes ☐ No
so, what material [illegible]
e of well: Straight screen ☒ Gravel packed ☐
s the well grouted? Yes ☒ No ☐
what depth? 180 feet
terial used in grouting CEMENT
head completion: Pitless adapter will have
above grade [illegible] Other
other, specify
[illegible] completion? ☒ Yes ☐ No

COPY

7. WATER LEVEL 12/21/74

Static water level 15.38 feet below land surface
If flowing: closed-in pressure psi
GPM flow through inch pipe
Controlled by: ☐ Valve ☐ Reducers ☐ Other
If other, specify

8. WELL TEST DATA

☒ Pump ☐ Bailer ☐ Other
Pumping level below land surface

30.40 ft. after	2 hrs. pumping	1000 gpm
37.61 ft. after	1 hrs. pumping	1400 gpm
46.06 ft. after	1 hrs. pumping	1810 gpm
54.19	1	2200

9. WELL LOG

Formation	Depth (ft.) From	To
CLAY, SILTY, YELLOWISH GRAY	0	17
SAND, MEDIUM TO COARSE	17	24
SILT, CLAYEY INTERBEDDED		
LAYERS OF FINE SAND	24	60
SAND, FINE	60	65
CLAY, VERY SILTY	65	78
SAND, FINE TO MEDIUM	78	87
GRAVEL, MEDIUM TO COARSE,	87	
SANDY [illegible]	[illegible]	125
SILT, CLAYEY	125	146
SAND, ABUNDANT LIGNITE	146	170
SAND, FINE TO COARSE	170	227
GRAVEL, FINE TO COARSE,	227	
SANDY, VERY COARSE		
AFTER 233'		243

(Use separate sheet if necessary.)

Final Completion with pitless expected July 1975

10. DATE COMPLETED ~~OCTOBER 30, 1974~~

11. WAS WELL PLUGGED OR ABANDONED?

☐ Yes ☒ No
If so, how

12. REMARKS: MINOT SUNDRE WELL B

Well will have pitless unit

13. DRILLER'S CERTIFICATION

This well was drilled under my jurisdiction and this report is true to the best of my knowledge.

C. A. SIMPSON & SON 2
Driller's or Firm's Name Certificate No.

~~BI[illegible], [illegible]~~
Address

F. J. Simpson 7/3/75
Signed by Date

BOARD OF WATER WELL CONTRACTORS 489
900 E. BOULEVARD • BISMARCK, NORTH DAKOTA 58501

WELL DRILLER'S REPORT

State law requires that this report be filed with the State Board of Water Well Contractors within 30 days after completion or abandonment of the well.

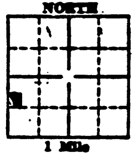
LL OWNER

ne [illegible]

ress [illegible], NORTH DAKOTA

LL LOCATION

etch map location must agree with written location.



ELEV. [illegible]
EST. FROM [illegible]
7.5 MIN. QUAD.

nty [illegible]

_¼ [illegible] ¼ [illegible] ¼ Sec. 3 Twp. 154 N. Rg. 82 W.

)POSED USE

Domestic	☐ Irrigation	☐ Industrial
Stock	☒ Municipal	☐ Test Hole

:THOD DRILLED

Cable	☐ Reverse Rotary	☐ Bored
Forward Rotary	☐ Jetted	☐ Other

ther, specify

.TER QUALITY

:s a water sample collected for chemical analysis?
Yes ☐ No
so, to what laboratory was it sent

:LL CONSTRUCTION

ameter of hole ~~22~~ 15 inches. Depth ~~215~~ 297 feet.

ising:	☐ Steel	☐ Plastic	☐ Concrete
	☐ Threaded	☒ Welded	☐ Other

ther, specify

e Weight:	Diameter:	From:	To:
lb/ft.	[illegible] inches	0 feet	215 feet
lb/ft.	inches	feet	feet
lb/ft.	inches	feet	feet
lb/ft.	inches	feet	feet

:s perforated pipe used? ☐ Yes ☒ No
igth of pipe perforated feet
is casing left open end? ☐ Yes ☒ No
s a well screened installed? ☒ Yes ☐ No
terial [illegible] STEEL Diameter 16 NOM. inches
(stainless steel, bronze, etc.)

t s ze [illegible] set from 215 feet to 267 feet
t size [illegible] set from 267 feet to 277 feet
t size [illegible] set from 277 feet to 297 feet
t size set from feet to feet

s a packer or seal used? ☒ Yes ☐ No
so, what material LEAD
e of well: Straight screen ☒ Gravel packed ☐
s the well grouted? Yes ☒ No ☐
what depth? 215 feet
terial used in grouting NEAT CEMENT
l head completion: Pitless adapter X will have
above grade Other
ther, specify
[illegible] disinfected upon completion? ☐ Yes ☐ No

7. WATER LEVEL 3/11/75

Static water level 13.62 feet below land surface
If flowing: closed-in pressure psi
GPM flow through inch pipe
Controlled by: ☐ Valve ☐ Reducers ☐ Other
If other, specify

8. WELL TEST DATA

☒ Pump ☐ Bailer ☐ Other

Pumping level below land surface: STEP TEST

21.43 ft. after 2 hrs. pumping 1800 gpm
24.34 ft. after 1 hrs. pumping 2300 gpm
27.36 ft. after 1 hrs. pumping 2800 gpm
30.90 1 3300
34.78 1 3800

9. WELL LOG

Formation	Depth (ft.)	
	From	To
SILT, CLAYEY, OXIDIZED	0	14
SILT, AS ABOVE EXCEPT OLIVE GRAY	14	18
SAND, FINE TO COARSE	18	21
CLAY, SILTY, OLIVE GRAY	21	28
SAND, MEDIUM TO COARSE	28	37
SAND WITH CLAY LAYERS	37	58
CLAY, SILTY	58	73
SAND, MEDIUM, SOME FINE	73	93
GRAVEL, FINE TO COARSE	93	119
CLAY & SILT	119	160
SAND, MEDIUM	160	200
GRAVEL, FINE TO MEDIUM	200	210
SAND, COARSE TO VERY COARSE		
SOME FINE GRAVEL	210	271
GRAVEL, COARSE TO VERY COARSE,		
PEBBLES, & COBBLES	271	297

(Use separate sheet if necessary.)

Final Completion with pitless expected July 1975

10. DATE COMPLETED MARCH, 1975

11. WAS WELL PLUGGED OR ABANDONED?

☐ Yes ☒ No

If so, how

12. REMARKS: SUNDRE WELL 'C'
DRILLED 43' [illegible] OF TEST HOLE 4

13. DRILLER'S CERTIFICATION

This well was drilled under my jurisdiction and this report is true to the best of my knowledge.

[illegible] 2
Driller's or Firm's Name Certificate No.

[illegible], NORTH DAKOTA
Address

7/5/75
Signed by Date

COPY

BOARD OF WATER WELL CONTRACTORS 490
900 E. BOULEVARD, BISMARCK, NORTH DAKOTA 58501

WELL DRILLER'S REPORT

State law requires that this report be filed with the State Board of Water Well Contractors within 30 days after completion or abandonment of the well.

LL OWNER

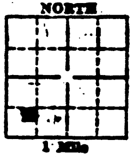
me ~it. of Minot

dress Minot, North Dakota

ELL LOCATION

etch map location must agree with written location.

NORTH



ELEV - 1541
EST. FROM
7.5 MIN. QUAD

ounty Ward

__ ¼ __ ¼ __ ¼ Sec. 3 Twp. 154 N. Rg. 82 W.

OPOSED USE

Domestic ☐ Irrigation ☐ Industrial
Stock ☒ Municipal ☐ Test Hole

ETHOD DRILLED

Cable ☐ Reverse Rotary ☐ Bored
Forward Rotary ☐ Jetted ☐ Other
other, specify

ATER QUALITY

as a water sample collected for chemical analysis?
Yes ☐ No
so, to what laboratory was it sent

ELL CONSTRUCTION

meter of hole 22.5 inches. Depth 195 284 feet.
sing: ☐ Steel ☐ Plastic ☐ Concrete
☐ Threaded ☒ Welded ☐ Other
other, specify

e Weight:	Diameter:	From:	To:
lb/ft.	inches	0 feet	195 feet
lb/ft.	inches	feet	feet
lb/ft.	inches	feet	feet
lb/ft.	inches	feet	feet

s perforated pipe used? ☐ Yes ☒ No
ngth of pipe perforated ______ feet
as casing left open end? ☐ Yes ☒ No
s a well screened installed? ☐ Yes ☐ No
terial [illegible] steel Diameter 16 NOM inches
(stainless steel, bronze, etc.)
t size 35 set from 195 feet to 230 feet
t size 35 set from 230 feet to 260 feet
t size ___ set from 260 feet to 270 feet
t size ___ set from 270 feet to 280 feet
s a packer or seal used? ☒ Yes ☐ No
so, what material Lead
e of well: Straight screen ☒ Gravel packed ☐
s the well grouted? Yes ☒ No ☐
what depth? 195' feet
terial used in grouting Neat Cement
l head completion: Pitless adapter X will have
above grade ______ Other ______
other, specify
s well disinfected upon completion? ☐ Yes ☐ No

7. WATER LEVEL 4/27/75

Static water level 10.70 feet below ~~land surface~~ M.P.
If flowing: closed-in pressure ______ psi
GPM flow - through ______ inch pipe
Controlled by: ☐ Valve ☐ Reducers ☐ Other
If other, specify

8. WELL TEST DATA

☒ Pump ☐ Bailer ☐ Other
Pumping level below land surface: Step-test

23.55	ft. after	2	hrs. pumping	1800	gpm
27.97	ft. after	2	hrs. pumping	2300	gpm
32.39	ft. after	1	hrs. pumping	3800	gpm
37.39		1		3300	
42.60		1		3800	

9. WELL LOG

Formation	Depth (ft.) From	To
	0	4
Sand, Fine Silty	4	27
Silt, Clayey	27	35
Clay, Silty , Olive Gray	50	82
Sand, Very Fine To Fine	82	88
Sand, Medium To Coarse	88	107
Gravel, With Cobbles	107	110
Gravel, Medium to Coarse	110	115
Sand, Medium	115	155
Sand, Medium toCoarse	155	175
Sand, Coarse to Very Coarse	175	201
Sand, Fine To Medium	201	204
Sand, Coarse, Gravelly	204	257
Gravel, Fine to Coarse	257	280

(Use separate sheet if necessary.)

Final Completion with pitless expected July 1975

10. DATE COMPLETED June 1975

11. WAS WELL PLUGGED OR ABANDONED?

☐ Yes ☒ No
If so, how

12. REMARKS: Sunire Well 'D'
Drilled at Test Hole 5. Drilled in October, 1970

13. DRILLER'S CERTIFICATION

This well was drilled under my jurisdiction and this report is true to the best of my knowledge.

J. A. Simpson & Son 34
Driller's or Firm's Name Certificate No.
Minot, North Dakota
Address
J. Simpson 7/5/75
Signed by Date

BOARD OF WATER WELL CONTRACTORS

900 E. BOULEVARD, BISMARCK, NORTH DAKOTA 58505

WELL DRILLER'S REPORT

State law requires that this report be filed with the State Board of Water Well Contractors within 30 days after completion or abandonment of the well.

LL OWNER

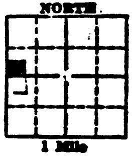
me CITY OF MINOT

dress MINOT, [illegible]

ELL LOCATION

etch map location must agree with written location

NORTH



1 Mile

EST FOR —

FROM 55.MW GOOD

unty WARD

¼ SW ¼ NW ¼ Sec. 3 Twp. 154 N. Rg. 82 W.

OPOSED USE

Domestic ☐ Irrigation ☐ Industrial

Stock ☒ Municipal ☐ Test Hole

THOD DRILLED

Cable ☐ Reverse Rotary ☐ Bored

Forward Rotary ☐ Jetted ☐ Other

other, specify

TER QUALITY

as a water sample collected for chemical analysis?

Yes ☐ No

o, to what laboratory was it sent

LL CONSTRUCTION

ameter of hole 12 5 inches. Depth 195 230 feet.

sing: ☐ Steel ☐ Plastic ☐ Concrete

☐ Threaded ☒ Welded ☐ Other

other, specify

e Weight:	Diameter:	From:	To:
lb/ft.	inches	0 feet	195 feet
lb/ft.	inches	feet	feet
lb/ft.	inches	feet	feet
lb/ft.	inches	feet	0 feet

s perforated pipe used? ☐ Yes ☒ No

ngth of pipe perforated feet

s casing left open end? ☐ Yes ☒ No

s a well screened installed? ☒ Yes ☐ No

terial [illegible] STEEL Diameter 16" NOM inches
(stainless steel, bronze, etc.)

t size 40 set from 195 feet to 200 feet

t size [illegible] set from 200 feet to 215 feet

t size 90 set from 215 feet to 230 feet

t size set from feet to feet

s a packer or seal used? ☒ Yes ☐ No

o, what material [illegible]

e of well: Straight screen ☒ Gravel packed ☐

s the well grouted? Yes ☒ No ☐

what depth? 195 feet

terial used in grouting Cement

l head completion: Pitless adapter will have

above grade Other

other, specify

[illegible] infected upon completion? ☒ Yes ☐ No

7. WATER LEVEL 1/26/75

Static water level 14.72 feet below land surface

If flowing: closed-in pressure psi

GPM flow through inch pipe

Controlled by: ☐ Valve ☐ Reducers ☐ Other

If other, specify

8. WELL TEST DATA

☒ Pump ☐ Bailer ☐ Other

Pumping level below land surface:

26.94 ft. after 2 hrs. pumping 1000 gpm

33.36 ft. after 1 hrs. pumping 1400 gpm

39.92 ft. after 1 hrs. pumping 1809 gpm

45.72 1 2200

9. WELL LOG

Formation	Depth (ft.)	
	From	To
TOP SOIL	0	1
CLAY, SILTY, YELLOWISH BROWN	1	15
SAND, FINE TO MEDIUM	15	24
CLAY, SILTY, OLIVE GRAY	24	88
SAND, MEDIUM TO COARSE	88	97
GRAVEL, FINE TO COARSE, SANDY	97	110
CLAY, SILTY	110	142
SAND, MEDIUM TO COARSE	142	151
SILT, CLAYEY	151	158
SAND, FINE TO COARSE	158	165
SILT, CLAYEY	165	189
GRAVEL, FINE TO COARSE,	189	
SANDY, BECOMES MUCH		
COARSER AFTER 222',		
TAKING SOME DRILLING FLUID		242

(Use separate sheet if necessary.)

Final completion with pitless expected July 1975

10. DATE COMPLETED

11. WAS WELL PLUGGED OR ABANDONED?

☐ Yes ☒ No

If so, how

12. REMARKS: MINOT SUNDRE WELL 'A'

13. DRILLER'S CERTIFICATION

This well was drilled under my jurisdiction and this report is true to the best of my knowledge.

C. A. SIMPSON & SON — 2

Driller's or Firm's Name — Certificate No.

BISBEE, NORTH DAKOTA

Address

F. J. Simpson — 7/5/75

Signed by — Date

Minot Sundre Well "E"

:T ELEV- 1574 FROM 7.5 MIN. QUAD.

STATE OF NORTH DAKOTA

BOARD OF WATER WELL CONTRACTORS 491

900 E. BOULEVARD • BISMARCK, NORTH DAKOTA 58501

WELL DRILLER'S REPORT

State law requires that this report be filed with the State Board of Water Well Contractors within 30 days after completion or abandonment of the well.

LL OWNER

me City of Minot

dress Minot, North Dakota

LL LOCATION E

etch map location must agree with written location.

NORTH

1 Mile

unty Ward

__¼ __¼ SE ¼ Sec. 3 Twp. 154 N. Rg. 82 W.

OPOSED USE

Domestic ☐ Irrigation ☐ Industrial

Stock ☒ Municipal ☐ Test Hole

ETHOD DRILLED

Cable ☐ Reverse Rotary ☐ Bored

Forward Rotary ☐ Jetted ☐ Other

other, specify

ATER QUALITY

as a water sample collected for chemical analysis?

Yes ☐ No

so, to what laboratory was it sent [illegible]

ELL CONSTRUCTION

ameter of hole 22.5 inches. Depth ~~200 260~~ 200 feet.

sing: ☒ Steel ☐ Plastic ☐ Concrete

☐ Threaded ☒ Welded ☐ Other

other, specify

e Weight: Diameter: From: To:

[illegible] lb/ft. 16 inches 0 feet 200 feet

lb/ft. inches feet feet

lb/ft. inches feet feet

lb/ft. inches feet feet

s perforated pipe used? ☐ Yes ☒ No

gth of pipe perforated feet

s casing left open end? ☐ Yes ☒ No

s a well screened installed? ☒ Yes ☐ No

terial [illegible] Steel Diameter 16 nom inches
(stainless steel, bronze, etc.)

t size [illegible] set from 200 feet to 226 feet

t size set from 226 feet to 256 feet

t size set from feet to feet

t size set from feet to feet

s a packer or seal used? ☒ Yes ☐ No

so, what material Lead

e of well: Straight screen ☒ Gravel packed ☐

the well grouted? Yes ☒ No ☐

what depth? 40' feet

erial used in grouting Neat cement

l head completion: Pitless adapter will have

above grade Other

other, specify

fected upon completion? ☐ Yes ☐ No

7. WATER LEVEL

Static water level 12.90 feet below ~~land surface~~ M.P.

If flowing: closed-in pressure psi

GPM flow through inch pipe

Controlled by: ☐ Valve ☐ Reducers ☐ Other

If other, specify

8. WELL TEST DATA

☒ Pump ☐ Bailer ☐ Other

Pumping level below ~~land surface~~ M.P. = +1:

25.90 ft. after 2 hrs. pumping 1016 gpm

30.54 ft. after 1 hrs. pumping 1405 gpm

36.02 ft. after 1 hrs. pumping 1809 gpm

9. WELL LOG

Formation	Depth (ft.) From	Depth (ft.) To
Top Soil	0	1
Silt	1	8
Clay, Yellowish Gray	8	16
Clay, Olive Gray	16	20
Sand, Coarse	20	25
Clay, Olive Gray	25	42
Silt, Clay Layers	42	84
Sand, Fine to Coarse	84	114
Gravel, Fine	114	132
Sand, Medium to Coarse	132	165
Gravel, Fine	165	178
Sand, Medium to Coarse	[illegible]	260

(Use separate sheet if necessary.)

Final completion with pitless expected July 197[illegible]

10. DATE COMPLETED September [illegible], 1974

11. WAS WELL PLUGGED OR ABANDONED?

☐ Yes ☒ No

If so, how

12. REMARKS:

Minot Sundre Well 'E'

MP is approximately 1' above Land Surface.

13. DRILLER'S CERTIFICATION

This well was drilled under my jurisdiction and this report is true to the best of my knowledge.

[illegible] Simpson & Son 2

Driller's or Firm's Name Certificate No.

Bisbee, North Dakota

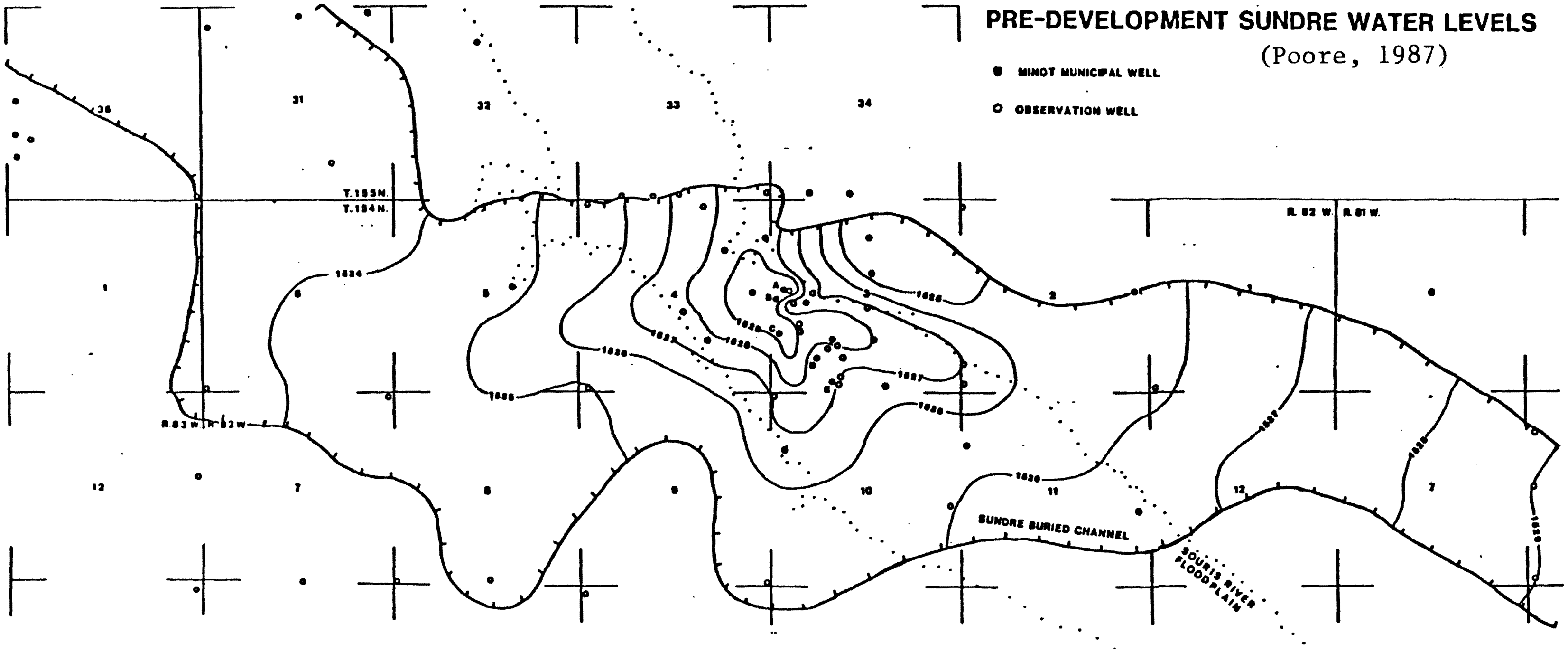
Address

7/5/75

Signed by Date

APPENDIX B

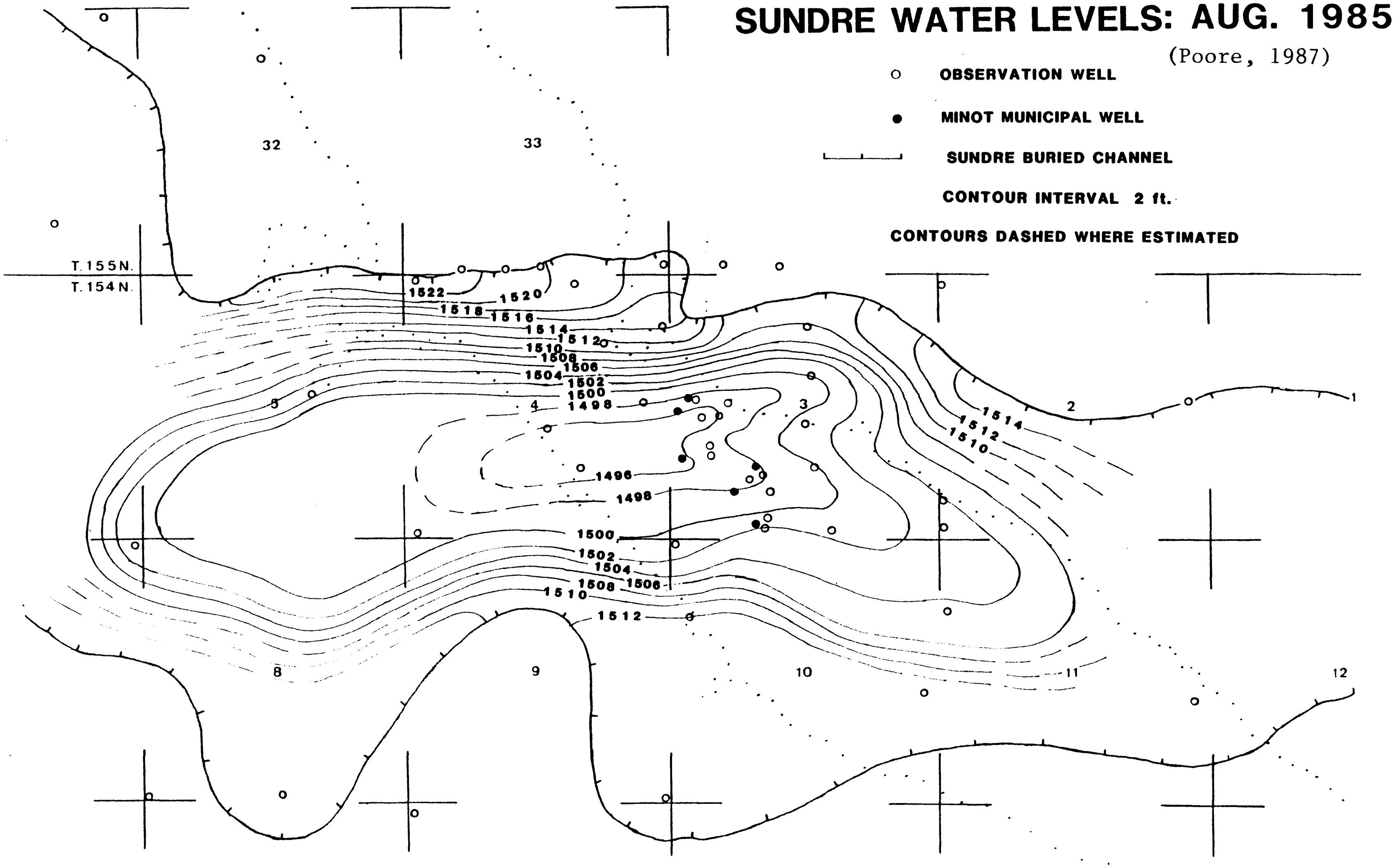
PRE- AND POST-DEVELOPMENT SUNDRE WATER LEVELS



PRE-DEVELOPMENT SUNDRE WATER LEVELS
(Poore, 1987)

SUNDRE WATER LEVELS: AUG. 1985

(Poore, 1987)



APPENDIX C

WATER QUALITY DATA

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                                                             SAS                             10:59 THURSDAY, JULY 31, 1986  1

OBS   WELL     DATE       CA   MG   NA    CL    SO4   HCO3     ION         TDS     ANHD      ARAG      CALC       DOLO      GYP

  1   3CBB   10/05/74     88   22   140   11    200   490   0.0160869    986.1   -1.3869   0.35709   0.61857    0.9208   -1.1623
  2   3CBB   10/06/74     85   24   140   11    210   490   0.0161848    988.8   -1.3835   0.33910   0.60058    0.9380   -1.1589
  3   3CBB   09/27/78     85   19   150   18    190   498   0.0159201    991.9   -1.4376   0.50937   0.77501    1.1627   -1.1878
  4   3CBB   08/03/79     90   18   150   20    180   513   0.0160638   1009.4   -1.4259   0.37424   0.63733    0.8510   -1.1902
  5   3CBB   05/01/80     85   21   160   24    190   536   0.0166606   1049.5   -1.4414   0.44756   0.71204    1.0854   -1.1976
  6   3CBB   08/12/80     82   21   160   26    190   524   0.0164396   1042.8   -1.4488   0.73281   0.99513    1.6806   -1.2174
  7   3CBB   08/21/81     83   23   170   26    180   546   0.0169327   1066.6   -1.4742   0.35094   0.61506    0.9424   -1.2325
  8   3CBB   12/29/81     80   24   170   39    180   510   0.0167737   1042.1   -1.4749   0.43251   0.69387    1.1510   -1.2513
  9   3CBB   05/27/82     84   22   160   22    180   515   0.0163208   1014.5   -1.4533   0.45418   0.71607    1.1330   -1.2257
 10   3CBB   08/26/82     77   22   160   23    180   503   0.0160187   1002.7   -1.4932   0.39035   0.65412    1.0362   -1.2535
 11   3CBB   02/17/83     78   21   170   25    180   510   0.0162930   1024.4   -1.4817   0.41829   0.68018    1.0732   -1.2541
 12   3CBB   08/18/83     80   21   160   30    190   519   0.0165701   1059.7   -1.4557   0.52545   0.78777    1.2756   -1.2250
 13   3CBB   10/03/84     81   21   160   23    180   520   0.0162397   1016.1   -1.4813   0.21189   0.47773    0.6300   -1.2304
 14   3CBB   10/11/84     80   21   160   24    180   513   0.0161313   1010.8   -1.4784   0.31530   0.57924    0.8483   -1.2377
 15   3CBB   10/24/84     82   22   160   23    190   518   0.0164831   1030.9   -1.4576   0.21192   0.47776    0.6454   -1.2068
 16   3CBB   11/08/84     84   22   160   25    190   525   0.0165942   1042.0   -1.4364   0.45406   0.71638    1.1314   -1.2058
 17   3CBB   11/20/84     84   23   160   24    190   519   0.0166457   1038.9   -1.4358   0.25305   0.51538    0.7481   -1.2052
 18   3CBB   01/09/85     83   22   170   28    210   531   0.0171376   1079.1   -1.4195   0.81553   1.07947    1.8566   -1.1788
 19   3CBB   02/12/85     79   22   160   23    200   516   0.0164086   1035.0   -1.4425   0.70849   0.97081    1.6689   -1.2118
 20   3CBB   03/06/85     77   22   160   23    190   519   0.0162970   1025.7   -1.4732   0.10331   0.36725    0.4611   -1.2325
 21   3CBB   03/21/85     80   21   170   24    190   531   0.0166204   1049.5   -1.4652   0.61633   0.88027    1.4519   -1.2245
 22   3CBB   04/18/85     78   21   160   24    200   527   0.0165027   1039.2   -1.4496   0.21050   0.47444    0.6503   -1.2089
 23   3CBB   05/15/85     83   22   170   22    190   512   0.0166607   1034.7   -1.4559   0.40763   0.67347   -2.2430   -1.2051
 24   3CBB   06/26/85     85   23   170   24    200   522   0.0170264   1059.9   -1.4080   0.36932   0.63031    0.9819   -1.1874
 25   3CBB   07/30/85     81   22   160   17    200   511   0.0164503   1025.6   -1.4345   0.21433   0.47827    0.6619   -1.1938
 26   3CBB   08/28/85     82   22   160   14    230   511   0.0169186   1052.0   -1.3866   0.29316   0.55900    0.8100   -1.1358
 27   3CDC1  09/26/68     87   17   287  120    239   618   0.0207803   1404.7   -1.0323   0.67050   0.93853    1.4345   -0.7714
 28   3CDC1  12/03/68     75   20   288  120    234   585   0.0202970   1358.0   -1.0940   0.29598   0.56401    0.8223   -0.8331
 29   3CDC1  12/05/69    100   28   260  122    302   550   0.0212420   1395.2   -0.9016   0.46047   0.72850    1.1768   -0.6407
 30   3CDC1  05/01/80    210   57   440   53   1000   731   0.0352775   2528.8   -0.3327   0.69471   0.95919    1.6600   -0.0895
 31   3CDC1  08/12/80    200   22   440   56   1000   580   0.0326550   2338.5   -0.3298   0.59197   0.85430    1.0675   -0.0998
 32   3CDC1  08/21/81    230   57   460   53   1100   782   0.0375277   2728.4   -0.2791   0.64550   0.90962    1.5245   -0.0381
 33   3CDC1  05/26/83    230   68    40   67   1000   730   0.0354646   2538.7   -0.2897   1.04248   1.30451    2.3933   -0.0617
 34   3CDC1  08/18/83    220   68   380   68   1000   630   0.0341831   2409.1   -0.3146   0.64260   0.90865    1.6108   -0.0633
 35   3CBC   03/23/75     78   23   210   61     23   537   0.0187768   1156.3   -1.4014   0.13144   0.39243    0.5440   -1.1808


 36   3CBC   03/27/75     79   25   210   66    230   536   0.0189977   1165.5   -1.3978   0.13806   0.39881    0.5890   -1.1792
 37   3CBC   09/27/78     87   20   180   44    210   517   0.0175635   1088.3   -1.40 7   0.42431   0.68994    1.0051   -1.1538
 38   3CBC   08/03/79     90   30   170   53    210   523   0.0183054   1112.8   -1.3914   0.36331   0.62641    1.0522   -1.1558
 39   3CBC   05/01/80     85   21   160   35    190   512   0.0166214   1036.6   -1.4402   0.42885   0.69333    1.0482   -1.1964
 40   3CBC   08/12/80     83   25   160   42    200   511   0.0169885   1057.1   -1.4295   0.72234   0.98466    1.7305   -1.1968
 41   3CBC   08/21/81     89   24   200   62    220   555   0.0190994   1189.4   -1.3853   0.26995   0.53407    0.7700   -1.1436
 42   3CBC   12/29/81     82   30   180   54    210   499   0.0180125   1090.9   -1.4189   0.51788   0.77923    1.4094   -1.1953
 43   3CBC   05/27/82     87   24   160   32    190   499   0.0166821   1023.2   -1.4256   0.74123   1.00312    1.7315   -1.1980
 44   3CBC   08/26/82     81   26   180   51    220   518   0.0179755   1113.4   -1.4172   0.69472   0.95849    1.6985   -1.1776
 45   3CBC   11/16/82     82   26   190   57    210   523   0.0182038   1125.8   -1.4279   0.61673   0.87966    1.5391   -1.1933
 46   3CBC   02/17/83     78   25   200   64    220   520   0.0184698   1143.7   -1.4231   0.20841   0.47044    0.7296   -1.1945
 47   3CBC   05/26/83     83   26   160  420    220   504   0.0173384   1070.6   -1.4026   0.79344   1.05704    1.8867   -1.1639
 48   3CBC   08/18/83     84   24   150   30    210   492   0.0165744   1026.2   -1.4024   0.80666   1.06898    1.8774   -1.1718
 49   3CBC   11/23/83     82   25   160   31    180   490   0.0163999   1003.2   -1.4737   0.40324   0.66718    1.0896   -1.2330
 50   3CBC   02/28/84     92   28   140   38    200   506   0.0170103   1039.6   -1.3990   0.84258   1.10652    1.9703   -1.1583
 51   3CBC   04/12/84    110   32   150   45    240   522   0.0190844   1132.5   -1.2721   0.62684   0.89078    1.5188   -1.0314
 52   3CBC   05/22/84     87   25   160   45    200   468   0.0168861   1021.3   -1.4152   0.69258   0.95652    1.6449    1.1745
 53   3CBC   08/16/84     91   26   150   39    212   501   0.0173244   1053.5   -1.3819   0.23376   0.49961    0.7174   -1.1311
 54   3CBC   08/31/84     89   27   180   54    220   514   0.0184254   1120.4   -1.3866   0.22750   0.49334    0.7312   -1.1357
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OBS   WELL     DATE      CA    MG      NA     CL   SO4   HCO3      ION        TDS      ANHD      ARAG       CALC     DOLO      GYP

 55   3CBC   09/12/84    85   25.0   190.0   64   220   524   0.0185496   1143.5   -1.3984   0.32880        1   0.92634   -1.1577
 56   3CBC   09/20/84    87   26.0   190.0   58   220   523   0.0184821   1138.4   -1.3981   0.91407        1   2.10701   -1.1574
 57   3CBC   09/27/84    86   26.0   190.0   59   220   521   0.0185514   1133.3   -1.4022   0.41390        1   1.10306   -1.1514
 58   3CBC   10/03/84    95   28.0   150.0   40   210   500   0.0175839   1053.8   -1.3721   0.25067        1   0.76462   -1.1213
 59   3CBC   10/11/84    92   27.0   160.0   43   220   497   0.0177876   1070.8   -1.3675   0.23103        0   0.72397   -1.1167
 60   3CBC   10/24/84    89   27.0   160.0   43   200   504   0.0174316   1058.1   -1.4150   0.13005        0   0.53532   -1.1642
 61   3CBC   11/08/84    89   26.0   160.0   44   210   506   0.0174791   1070.2   -1.3831   0.45463        1   1.18080   -1.1525
 62   3CBC   11/20/84    90   28.0   130.0   31   170   488   0.0161151    973.0   -1.4501   0.26483        1   0.82640   -1.2195
 63   3CBC   01/09/85    97   29.0   150.0   41   230   511   0.0181299   1093.9   -1.3257   0.17857        0   0.63289   -1.0850
 64   3CBC   02/12/85   140   42.0   150.0   75   290   554   0.0223394   1287.8   -1.1241   0.35552        1   0.99540   -0.8935
 65   3CBC   03/06/85   140   41.0   170.0   66   330   561   0.0232263   1344.3   -1.0866   0.33462        1   0.93875   -0.8460
 66   3CBC   04/18/85   100   30.0   160.0   53   220   534   0.0187328   1126.8   -1.3385   0.40607        1   1.08925   -1.0978
 67   3CBC   05/15/85    89   27.0   170.0   47   190   515   0.0175368   1071.9   -1.4442   0.82019        1   1.91780   -1.1933
 68   3CBC   07/02/85    82   25.0   180.0   54   230   506   0.0180883   1108.1   -1.3997   0.47867        1   1.23712   -1.1489
 69   3CBC   07/29/85    92   28.0   150.0   41   200   505   0.0173278   1050.7   -1.4055   0.63457        1   1.54718   -1.1546
 70   3CBC   08/27/85    92   29.0   150.0   40   220   497   0.0176570   1062.4   -1.3680   0.32994        1   0.95308   -1.1171
 71   3CDC3  12/19/68   106   24.0    17.9   51   220   544   0.0179691   1214.4   -0.9578   0.43359        1   1.02530   -0.6969
 72   3CDC3  12/20/68   112   21.0   179.0   56   213   548   0.0173631   1164.5   -0.9409   0.54409        1   1.16367   -0.6799
 73   3CDC3  07/17/69   107   25.0   173.0   64   209   537   0.0173710   1150.1   -0.9670   0.53719        1   1.24505   -0.7060
 74   3CDC3  10/20/69   146    1.9   173.0   75   209   543   0.0175834   1184.3   -0.8373   0.77425        1   0.46428   -0.5763
 75   3CDC3  10/21/69    60   24.0   181.0   74   218   384   0.0148777    976.8   -1.1678   0.34076        1   1.08912   -0.9067
 76   3CDC3  10/22/69    68   23.0   182.0   75   224   399   0.0152944   1006.1   -1.1106   0.40671        1   1.14827   -0.8496
 77   3CDC3  10/23/69   116   26.0   173.0   78   226   542   0.0181820   1197.4   -0.9154   0.66165        1   1.47659   -0.6544
 78   3CDC3  12/19/69   106   24.0   179.0   51   220   544   0.0191273   1158.8   -1.3610   0.43836        1   0.99641   -1.0584
 79   3CDC3  12/19/69   109   22.0   179.0   53   222   546   0.0192075   1166.2   -1.3538   0.43409        1   0.93199   -1.0407
 80   3CDC3  12/20/69   112   21.0   179.0   56   213   548   0.0191796   1163.9   -1.3591   0.44944        1   0.93014   -1.0459
 81   3CDC3  12/20/69   112   20.0   179.0   59   216   546   0.0191836   1167.1   -1.3530   0.44734        1   0.90502   -1.0398
 82   3CCA   06/08/75    98   28.0   160.0   53   230   507   0.0184130   1104.9   -1.3055   0.31592        1   0.90278   -1.0909
 83   3CCA   06/09/75   100   32.0   170.0   60   250   521   0.0194878   1161.8   -1.2757   0.22807        0   0.77662   -1.0610
 84   3CCA   09/27/78    12   27.0   190.0   47   320   552   0.0215001   1287.6   -1.1481   0.55037        1   1.25160   -0.8786
 85   3CCA   08/03/79   120   32.0   190.0   53   330   560   0.0221252   1321.8   -1.1314   0.37872        1   0.99006   -0.8968
 86   3CCA   05/01/80   140   36.0   210.0   55   410   588   0.0250068   1477.2   -1.0159   0.32864        1   0.87108   -0.7723
 87   3CCA   08/12/80   120   36.0   200.0   56   350   568   0.0228888   1367.4   -1.1186   0.86807        1   2.02446   -0.8881
 88   3CCA   08/21/81   120   34.0    21.0   54   350   589   0.0232701   1397.3   -1.1240   0.47899        1   1.21380   -0.8824
 89   3CCA   12/28/81   130   40.0   210.0   68   370   554   0.0241448   1409.3   -1.0684   0.70271        1   1.70812   -0.8449


 90   3CCA   05/27/82   170   47.0   240.0   54   560   581   0.0292801   1687.9   -0.8475   0.97613        1   2.21120   -0.6201
 91   3CCA   08/26/82   120   34.0   190.0   49   350   550   0.0224621   1330.7   -1.1154   0.35855  1362232   0.97392   -0.8758
 92   3CCA   11/16/82   120   34.0   200.0   51   340   549   0.0224921   1333.7   -1.1257   0.65998        1   1.58012   -0.8911
 93   3CCA   02/17/83   120   34.0   200.0   51   350   545   0.0225337   1339.2   -1.1126   0.85687        2   1.97902   -0.8851
 94   3CCA   05/26/83   130   37.0   200.0   52   390   558   0.0238218   1405.3   -1.0496   0.79228        1   1.85165   -0.8210
 95   3CCA   08/18/83   130   37.0   190.0   52   380   558   0.0234839   1386.1   -1.0573   0.69617        1   1.65762   -0.8267
 96   3CCA   11/23/83   130   37.0   200.0   56   390   556   0.0236602   1396.1   -1.0695   0.96552        1   2.19243   -0.8289
 97   3CCA   02/28/84   180   50.0   230.0   57   600   567   0.0301258   1724.4   -0.8150   1.05810        1   2.37183   -0.5744
 98   3CCA   04/12/84   180   48.0   230.0   53   560   603   0.0297775   1710.3   -0.8342   0.70810        1   1.65134   -0.5936
 99   3CCA   05/22/84   150   40.0   210.0   57   420   587   0.0257558   1503.1   -0.9853   0.55490        1   1.34149   -0.7447
100   3CCA   08/16/84   130   36.0   190.0   57   360   565   0.0232733   1371.8   -1.0878   0.38280        1   1.00659   -0.8370
101   3CCA   09/12/84   130   36.0   190.0   53   350   564   0.0230939   1359.4   -1.0904   0.39995        1   1.04606   -0.8497
102   3CCA   09/20/84   130   36.0   200.0   51   360   565   0.0234277   1378.6   -1.0826   0.49570        1   1.23809   -0.8420
103   3CCA   09/27/84   130   36.0   190.0   51   350   562   0.0230342   1352.1   -1.0982   0.57924        1   1.39969   -0.8474
104   3CCA   10/03/84   140   39.0   210.0   54   400   573   0.0249214   1449.5   -1.0311   0.40774        1   1.06013   -0.7803
105   3CCA   10/11/84   160   43.0   210.0   54   500   588   0.0274485   1589.2   -0.9122   0.45165        1   1.13496   -0.6615
106   3CCA   10/24/84   180   47.0   230.0   55   540   607   0.0295761   1697.9   -0.8514   0.40526        1   1.03016   -0.6007
107   3CCA   11/20/84   180   48.0   240.0   56   580   613   0.0304088   1759.9   -0.8168   0.52952        1   1.29919   -0.5864
108   3CCA   01/09/85   180   48.0   240.0   57   600   621   0.0308155   1785.4   -0.8133   0.51589        1   1.26724   -0.5728
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                                                                    SAS                                  10:59 THURSDAY, JULY 31, 1986  3

OBS   WELL     DATE      CA    MG    NA    CL    SO4   HCO3     ION         TDS      ANHD      ARAG       CALC        DOLO       GYP

109   3CCA   02/12/85   180    50   230    57    590   607   0.0303513   1752.2   -0.8119   0.71948    0.98181    1.69762    -0.5815
110   3CCA   03/06/85   170    48   240    57    550   614   0.0297077   1716.5   -0.8612   0.39837    0.66231    1.05581    -0.6206
111   3CCA   03/21/85   170    45   220    56    520   621   0.0286936   1667.5   -0.8838   0.68957    0.95541    1.60483    -0.6331
112   3CCA   04/18/85   150    40   210    57    440   588   0.0260781   1517.2   -0.9686   0.35462    0.61856    0.94110    -0.7280
113   3CCA   05/15/85   140    40   200    55    400   566   0.0246855   1438.0   -1.0310   0.59932    0.86516    1.45484    -0.7802
114   3CCA   06/26/85   140    33   200    52    380   565   0.0238026   1406.1   -1.0213   0.65011    0.91109    1.48863    -0.8007
115   3CCA   07/29/85   140    38   200    51    370   572   0.0240884   1407.5   -1.0583   0.80463    0.07047    1.84292    -0.8075
116   3CCA   08/27/85   130    40   200    52    400   568   0.0243130   1426.8   -1.0576   0.56985    0.83569    1.42814    -0.8069
117   3CCD   09/11/68   111    30   282    18    489   583   0.0260129   1541.6   -1.0979   0.49097    0.77434    1.18493    -0.7848
118   3CCD   09/07/74    89    19   220    96    200   570   0.0194578   1220.8   -1.4016   0.23014    0.49016    0.60524    -1.1900
119   3CCD   09/08/74    90    23   210    78    200   560   0.0192534   1191.0   -1.4152   0.29133    0.55443    0.79199    -1.1796
120   3CCD   08/03/79   220    61   340    71    850   693   0.0393509   2278.0   -0.6519   0.70216    0.96510    1.66389    -0.4176
121   3CCD   05/01/80   210    45   310    83    690   671   0.0352218   2046.7   -0.7273   0.68489    0.94936    1.51034    -0.4838
122   3CCD   08/12/80   220    63   350    61    910   664   0.0401346   2311.1   -0.6287   0.68136    0.94368    1.63929    -0.3984
123   3CCD   80/21/81   230    55   450    55   1000   766   0.0444311   2602.7   -0.6019   0.52924    0.79335    1.25202    -0.3606
124   3CCD   12/29/81   210    62   440    68   1000   720   0.0436579   2543.3   -0.6256   0.78487    1.04622    1.86424    -0.4024
125   3CCD   05/27/82   220    61   340    70    890   697   0.0397601   2316.0   -0.6368   1.09358    1.35547    2.45226    -0.4095
126   3CCD   08/26/82   210    61   320    71    840   684   0.0386391   2234.8   -0.6736   0.67226    0.93586    1.61697    -0.4352
127   3CCD   09/27/82   190    52   280    74    670   633   0.0335967   1934.5   -0.7744   0.71355    0.97899    1.67158    -0.5258
128   3CCD   11/16/82   200    59   390    49    960   710   0.0412424   2412.4   -0.6554   0.75076    1.01369    1.79015    -0.4211
129   3CCD   02/17/83   190    57   390    49    950   696   0.0405317   2397.1   -0.6731   0.82343    1.08560    1.94556    -0.4439
130   3CCD   05/26/83   220    62   380    50    990   713   0.0421369   2456.5   -0.6110   0.88882    1.15144    2.04795    -0.3787
131   3CCD   08/18/83   210    62   350    62    920   702   0.0404049   2350.1   -0.6598   0.84557    1.11162    1.97162    -0.4082
132   3CCD   02/17/83   190    57   390    49    950   696   0.0405371   2372.7   -0.6738   0.82537    1.08769    1.94894    -0.4435
133   3CCD   05/26/83   220    62   380    50    990   713   0.0421448   2454.9   -0.6095   0.89195    1.15428    2.05514    -0.3792
134   3CCD   08/18/83   210    62   350    62    920   702   0.0404126   2348.5   -0.6589   0.84730    1.11314    1.97552    -0.4084
135   3CCD   11/23/83   210    60   370    52    950   704   0.0410018   2387.7   -0.6433   0.85860    1.12254    1.98917    -0.4030
136   3CCD   02/28/84   240    64   320    66    890   706   0.0401833   2329.0   -0.6153   1.21135    1.47529   -0.02361    -0.3749
137   3CCD   04/12/84   230    62   310    67    820   704   0.0387086   2232.6   -0.6495   0.82205    1.08599    1.88804    -0.4091
138   3CCD   05/22/84   260    67   350    50   1000   705   0.0431196   2476.5   -0.5506   0.74921    1.01314    1.72525    -0.3102
139   3CCD   05/22/84   260    67   350    50   1000   725   0.0432799   2496.5   -0.5515   0.76053    1.02447    1.74779    -0.3111
140   3CCD   08/16/84   230    60   330    63    890   721   0.0401892   2336.1   -0.6247   0.52673    0.79067    1.28373    -0.3844
141   3CCD   08/31/84   250    68   360    48   1000   716   0.0432297   2484.9   -0.5733   0.72322    0.98906    1.69199    -0.3228
142   3CCD   09/20/84   240    63   370    48    990   720   0.0427520   2471.8   -0.5922   0.52824    0.79218    1.29099    -0.3419
143   3CCD   09/27/84   250    65   370    47   1000   720   0.0433402   2490.9   -0.5722   0.52900    0.79484    1.28362    -0.3217


144   3CCD   10/03/84   240    63   330    60    900   717   0.0407112   2349.5   -0.6154   0.81960    1.08544    1.86796    -0.3649
145   3CCD   10/11/84   240    63   330    61    890   711   0.0405956   2334.3   -0.6172   0.52381    0.78965    1.27562    -0.3667
146   3CCD   10/24/84   210    58   310    51    820   678   0.0375095   2166.7   -0.6833   0.46016    0.72600    1.16974    -0.4327
147   3CCD   11/08/84   230    65   360    50    930   702   0.0413271   2378.6   -0.6153   0.50867    0.77261    1.28308    -0.3749
148   3CCD   11/20/84   180    49   290    44    690   651   0.0332923   1941.8   -0.7697   0.53095    0.79327    1.31305    -0.5394
149   3CCD   01/09/85   220    62   340    45    910   688   0.0399475   2304.0   -0.6335   0.48572    0.74966    1.23584    -0.3932
150   3CCD   02/12/85   230    65   320    58    920   707   0.0403723   2341.0   -0.6087   0.62773    0.89006    1.52599    -0.3784
151   3CCD   03/06/85   230    63   330    59    380   714   0.0334781   1816.5   -0.9169   0.70423    0.96817    1.64898    -0.6764
152   3CCD   03/21/85   240    63   330    59    880   717   0.0404336   2327.2   -0.6217   0.72511    0.99095    1.67832    -0.3711
153   3CCD   04/18/85   250    65   360    46    990   723   0.0429209   2471.0   -0.5675   0.54772    0.81166    1.32560    -0.3271
154   3CCD   05/15/85   250    68   360    46   1000   723   0.0432131   2489.1   -0.5740   0.82470    1.09054    1.89516    -0.3235
155   3CCD   07/02/85   230    61   330    53    930   625   0.0398348   2268.5   -0.6082   0.75688    1.02082    1.75305    -0.3678
156   3CCD   07/03/85   230    63   370    47    960   712   0.0419186   2423.6   -0.6152   0.88550    1.15134    2.01974    -0.3647
157   3CCD   08/28/85   230    60   350    47    940   707   0.0410350   2373.0   -0.6161   0.59419    0.86003    1.41497    -0.3656
158   3BCC   02/25/75    72    22   170    16    210   512   0.0163940   1031.1   -1.4442   0.49799    0.75801    1.29822    -1.2326
159   3BCC   20/26/75    71    22   170    16    210   509   0.0163444   1017.2   -1.4475   0.39416    0.65409    1.09678    -1.2368
160   3BCC   09/27/78    72    15   190    26    190   524   0.0163913   1053.0   -1.5050   0.36030    0.63574    0.83414    -1.2562
161   3BCC   08/03/79    72    19   190    30    190   542   0.0168243   1080.2   -1.5024   0.29225    0.55551    0.80717    -1.2658
162   3BCC   05/01/80    71    20   190    29    190   552   0.0168915   1076.6   -1.5173   0.47641    0.74108    1.19990    -1.2725
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APPENDIX D

SAS STATISTICAL STATEMENTS AND PRINTOUT

PROGRAM STATEMENTS FOR SAS STATISTICAL PROGRAM

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DATA GW;
INFILE SASDAT;
INPUT WELL$ 1-6 DATE$ 8-17 CA MG NA CL SO4 HCO3 ION TDS;
PROC PRINT;
PROC MEANS;
VAR CA MG NA CL SO4 HCO3 ION;
TITLE 'ALL WELLS BASIC STATS';
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                                                                           SAS                           10:59 THURSDAY, JULY 31, 1986

OBS   WELL     DATE      CA   MG    NA    CL   SO4   HCO3      ION         TDS      ANHD        ARAG      CALC      DOLO      GYP

163   3BCC   08/12/80    69   21   190    30   190   546    0.0168057   1085.0   -1.5238    0.76784   1.03016   1.82645   -1.2932
164   3BCC   08/21/81    73   17   230    55   180   611    0.0183810   1206.2   -1.5368    0.33449   0.59861   0.83375   -1.2952
165   3BCC   05/27/82    77   20   190    30   180   538    0.0168496   1067.4   -1.4935    0.52897   0.79086   1.27934   -1.2659
166   3BCC   08/26/82    69   20   190    34   190   541    0.0168494   1085.3   -1.5251    0.56169   0.82529   1.38690   -1.2864
167   3BCC   02/17/83    65   20   230    57   170   582    0.0178634   1160.4   -1.5959    0.48354   0.74557   1.26107   -1.3674
168   3BCC   05/26/83    68   21   190    44   190   531    0.0173102   1116.0   -1.5328    0.75084   1.01287   1.80011   -1.3042
169   3BCC   11/20/84    74   21   200    29   210   533    0.0177282   1106.2   -1.5727   -0.06218   0.25556   0.04335   -1.1835
170   3BCC   01/09/85    76   22   190    33   210   534    0.0177046   1101.0   -1.5624    0.04926   0.36700   0.27499   -1.1731
171   3BCC   02/12/85    77   23   190    29   220   533    0.0178815   1107.8   -1.5436    0.44347   0.76120   1.07882   -1.1543
172   3BCC   03/06/85    76   23   180    31   220   539    0.0177268   1103.8   -1.5440   -0.04884   0.26889   0.09861   -1.1548
173   3BCC   03/21/85    78   22   190    31   220   541    0.0179763   1116.0   -1.5360    0.06256   0.38030   0.29087   -1.1467
174   3BCC   04/18/85    78   22   200    41   210   568    0.0183993   1148.8   -1.5585    0.08308   0.40082   0.33065   -1.1692
175   3BCC   05/15/85    74   21   220    49   190   581    0.0184321   1170.1   -1.6245    0.56262   0.88035   1.29240   -1.2352
176   3BCC   07/02/85    71   21   200    51   180   568    0.0176537   1123.5   -1.6571    0.63728   0.95502   1.45981   -1.2678
177   3BCC   08/27/85    73   21   190    31   190   534    0.0171454   1073.8   -1.6042   -0.04028   0.27159   0.09795   -1.2261
```

APPENDIX E

SAS STATISTICAL STATEMENTS AND PRINTOUT

SAS STATEMENTS FOR THE FACTOR ANALYSIS PROCEDURE

```
DATA GW;
INFILE SASDAT;
INPUT WELL$ 1-6 DATE$ 8-17 CA MG NA CL SO4 HCO3
ION TDS ANHD ARAG CALC DOLO GYP;
PROC PRINT;
PROC FACTOR SCREE MINEIGEN=.9 SCORE ROTATE=
VARIMAX OUTSTAT=FCOEF CORR EIGENVECTORS PLOT;
VAR CA MG NA CL SO4 HCO3;
PROC SCORE DATA=GW SCORE=FCOEF TYPE=SCORE
OUT=FSCORE;
PROC PRINT DATA=FSCORE;
TITLE 'ALL WELLS FACTOR ANALYSIS WITH MINEIGEN=.9';
```

APPENDIX F

SAMPLE WATEQF PRINOUT

```
    3CCD 9-8-74


      .90000E+02
       23000E+02
      .21000E+03
      .59000E+01
      .78000E+02
      .20000E+03
      .56000E+03
      .19000E+02
      .16000E+01
       00000E+00
      .00000E+00
      .40000E+00
ONC  85  .25000E+01 87  .35000E+00101  .28000E+00  0  .00000E+00  0  .00000E+00



                                                     ----------------
                                                     INITIAL SOLUTION
                                                     ----------------



TEMPERATURE =  22.50 DEGREES C   PH = ,  7.500ANALYTICAL EPMCAT =   15.755ANALYTICAL EPMAN =   15.622


   ***** OXIDATION - REDUCTION *****


DISSOLVED OXYGEN =  1.000 MG/L
EH MEASURED WITH CALOMEL =  9.9000 VOLTS
MEASURED EH OF ZOBELL SOLUTION =  9.9000 VOLTS
CORRECTED EH =  9.9000 VOLTS
PE COMPUTED FROM CORRECTED EH = 100.000




  *** TOTAL CONCENTRATIONS OF INPUT SPECIES ***

   TOTAL            LOG TOTAL           TOTAL
  SPECIES         MOLALITY            MOLALITY            MG/LITRE
  -------         --------            --------            --------


  CA        2     .224819E-02          -2.6482            .900000E+02
  MG        2     .947163E-03          -3.0236            .230000E+02
  NA        1     .914538E-02          -2.0388            .210000E+03
  K         1     .151067E-03          -3.8208            .590000E+01
  CL       -1     .220272E-02          -2.6570            .780000E+02
  SO4      -2     .208448E-02          -2.6310            .200000E+03
  HCO3     -1     .918857E-02          -2.0367            .560000E+03
  SIO2 TOT  0     .316597E-03          -3.4995            .190000E+02
  FE        2     .286839E-04          -4.5424            .160000E+01
  F        -1     .210795E-04          -4.6761            .400000E+00
  NO3      -1     .403675E-04          -4.3940            .250000E+01
  B TOT     0     .324160E-04          -4.4892            .350000E+00
  MN        2     .510255E-05          -5.2922            .280000E+00
```

```
*** CONVERGENCE ITERATIONS ***

ITERATION    S1-ANALCO3       S2-SO4TOT        S3-FTOT          S4-PTOT          S5-CLTOT

  1        2.451828E-04    6.591943E-04    8.537663E-07     .000000E+00    2.002344E-08
  2        2.175104E-05    3.651413E-05    8.272218E-08     .000000E+00    4.656613E-10
  3       -7.832423E-07   -1.531327E-06   -2.699380E-09     .000000E+00     .000000E+00
  4        7.264316E-08    1.098961E-07    2.783054E-10     .000000E+00     .000000E+00
  5       -1.862645E-09   -3.026798E-09     .000000E+00     .000000E+00     .000000E+00
```

```
                              ****DESCRIPTION OF SOLUTION ****

              ANALYTICAL   COMPUTED             PH                ACTIVITY H2O =    .9996
      EPMCAT    15.755       14.825            7.500              PCO2 =  1.569133E-02
      EPMAN     15.622       14.732                               LOG PCO2 =  -1.8043
                                            TEMPERATURE           PO2 =    .000000E+00
      EH = 9.9000  PE =  13.076             22.50 DEG C           PCH4 =    .000000E+00
      PE CALC S =  1.000000E+02                                   CO2 TOT =  9.716906E-03
      PE CALC DOX= 1.307617E+01            IONIC STRENGTH         DENSITY =   1.0000
      PE SATO DOX= 2.758810E+00             1.924697E-02          TDS =     1191.0MG/L

IN COMPUTING THE DISTRIBUTION OF SPECIES, PE =  13.076     EQUIVALENT EH =   .767VOLTS
```

```
                                    -----------------------
                                    DISTRIBUTION OF SPECIES
                                    -----------------------

 I  SPECIES          PPM          MOLALITY       LOG MOL      ACTIVITY       LOG ACT     ACT. COEFF.     LOG A COF

  1 CA        2   7.63267E+01   1.90663E-03    -2.7197    1.13108E-03    -2.9465    5.93237E-01       -.2268
  2 MG        2   1.97112E+01   8.11728E-04    -3.0906    4.86967E-04    -3.3125    5.99914E-01       -.2219
  3 NA        1   2.08077E+02   9.06165E-03    -2.0428    7.92409E-03    -2.1011    8.74464E-01       -.0583
  4 K         1   5.86032E+00   1.50051E-04    -3.8238    1.30513E-04    -3.8843    8.69791E-01       -.0606
 64 H         1   3.57275E-05   3.54862E-08    -7.4499    3.16228E-08    -7.5000    8.91129E-01       -.0501
  5 CL       -1   7.79993E+01   2.20270E-03    -2.6570    1.91589E-03    -2.7176    8.69791E-01       -.0606
  6 SO4      -2   1.65806E+02   1.72809E-03    -2.7624    1.01590E-03    -2.9932    5.87871E-01       -.2307
  7 HCO3     -1   5.43661E+02   8.92057E-03    -2.0496    7.82972E-03    -2.1063    8.77715E-01       -.0566
 18 CO3      -2   1.11080E+00   1.85325E-05    -4.7321    1.09989E-05    -4.9587    5.93491E-01       -.2266
 36 H2CO3     0   3.54300E+01   5.71899E-04    -3.2427    5.74620E-04    -3.2406    1.00476E+00        .0021
 27 OH       -1   5.12956E-03   3.01973E-07    -6.5200    2.62479E-07    -6.5809    8.69213E-01       -.0609
 62 F        -1   3.84922E-01   2.02849E-05    -4.6928    1.76319E-05    -4.7537    8.69213E-01       -.0609
 19 MGOH      1   9.49019E-04   2.29953E-08    -7.6384    2.02853E-08    -7.6928    8.82151E-01       -.0545
 23 MGSO4 AQ  0   9.59241E+00   7.97837E-05    -4.0981    8.01330E-05    -4.0962    1.00444E+00        .0019
 22 MGHCO3    1   4.27177E+00   5.01219E-05    -4.3000    4.36844E-05    -4.3597    8.71562E-01       -.0597
 21 MGCO3 AQ  0   4.12472E-01   4.89750E-06    -5.3100    4.91925E-06    -5.3081    1.00444E+00        .0019
 20 MGF       1   2.62711E-02   6.07299E-07    -6.2166    5.30676E-07    -6.2752    8.73829E-01       -.0586
 29 CAOH      1   4.74971E-04   3.32999E-09    -8.0794    7.33185E-09    -8.1348    8.80175E-01       -.0554
 32 CASO4 AQ  0   3.10567E+01   2.28099E-04    -3.6419    2.29112E-04    -3.6400    1.00444E+00        .0019
 30 CAHCO3    1   9.75374E+00   9.65938E-05    -4.0151    8.50195E-05    -4.0705    8.80175E-01       -.0554
```

```
 49 CAF+       1  1.10321E-02    1.86959E-07    -6.7283    1.63779E-07    -6.7857    8.76018E-01      -.0575
 44 NASO4     -1  5.63276E+00    4.73701E-05    -4.3245    4.15774E-05    -4.3811    8.77715E-01      -.0566
 43 NAHCO3     0  2.91397E+00    3.47353E-05    -4.4592    3.48896E-05    -4.4573    1.00444E+00       .0019
 42 NACO3     -1  1.34360E-01    1.62074E-06    -5.7903    1.42255E-06    -5.8459    8.77715E-01      -.0566
 34 NACL       0  8.82283E-31    1.51145E-35   -34.8206    1.51817E-35   -34.8187    1.00444E+00       .0019
 46 KSO4      -1  1.37152E-01    1.01592E-06    -5.9931    8.91686E-07    -6.0498    8.77715E-01      -.0566
 95 KCL        0  1.85378E-32    2.48943E-37   -36.6039    2.50049E-37   -36.6020    1.00444E+00       .0019
 63 HSO4      -1  3.22850E-04    3.32993E-09    -8.4776    2.90979E-09    -8.5361    8.73829E-01      -.0586
 24 H4SIO4AQ   0  3.02793E+01    3.15406E-04    -3.5011    3.16806E-04    -3.4992    1.00444E+00       .0019
 25 H3SIO4    -1  1.13158E-01    1.19421E-06    -5.9240    1.03821E-06    -5.9837    8.71562E-01      -.0597
 26 H2SIO4    -2  7.91175E-06    8.41788E-11   -10.0748    4.99594E-11   -10.3014    5.93491E-01      -.2266
  8 FE         2  6.95741E-10    1.24728E-14   -13.9040    7.48586E-15   -14.1258    6.00173E-01      -.2217
  9 FE         3  1.12024E-09    2.00830E-14   -13.6972    7.11696E-15   -14.1477    3.54377E-01      -.4505
 10 FEOH       2  1.54680E-04    2.12567E-09    -8.6725    1.25184E-09    -8.9025    5.88914E-01      -.2299
 11 FEOH       1  5.14697E-12    7.07311E-17   -16.1504    6.19617E-17   -16.2079    8.76018E-01      -.0575
 12 FE(OH)3   -1  1.86932E-18    1.75125E-23   -22.7567    1.53413E-23   -22.8141    8.76018E-01      -.0575
 77 FE(OH)2    1  1.78537E+00    1.98916E-05    -4.7013    1.74592E-05    -4.7580    8.77715E-01      -.0566
 78 FE(OH)3    0  6.89031E-01    6.45513E-06    -5.1901    6.48380E-06    -5.1882    1.00444E+00       .0019
 79 FE(OH)4   -1  2.88903E-01    2.33497E-06    -5.6317    2.04944E-06    -5.6884    8.77715E-01      -.0566
 80 FE(OH)2    0  1.19658E-15    1.33317E-20   -19.8751    1.33909E-20   -19.8732    1.00444E+00       .0019
 15 FESO4      1  9.85059E-09    6.49228E-14   -13.1876    5.68736E-14   -13.2451    8.76018E-01      -.0575
 16 FECL       2  5.13075E-11    5.62636E-16   -15.2498    3.31345E-16   -15.4797    5.88914E-01      -.2299
 28 FECL2      1  5.70275E-13    4.50447E-18   -17.3464    3.94600E-18   -17.4038    8.76018E-01      -.0575
 33 FECL3      0  1.20269E-16    7.42343E-22   -21.1294    7.45640E-22   -21.1275    1.00444E+00       .0019
 34 FESO4      0  1.95080E-10    1.28572E-15   -14.8909    1.29144E-15   -14.8889    1.00444E+00       .0019
101 MN         2  2.13051E-01    3.88251E-06    -5.4109    2.33018E-06    -5.6326    6.00173E-01      -.2217
102 MN         3  9.26424E-14    1.68826E-18   -17.7726    5.98280E-19   -18.2231    3.54377E-01      -.4505
106 MNOH       1  1.40885E-04    1.96322E-09    -8.7070    1.71981E-09    -8.7645    8.76018E-01      -.0575
107 MN(OH)3   -1  3.08171E-13    2.91173E-18   -17.5358    2.55073E-18   -17.5933    8.76018E-01      -.0575
111 MNHCO3     1  1.25432E-01    1.08299E-06    -5.9654    9.48715E-07    -6.0229    8.76018E-01      -.0575
109 MNSO4      0  1.72131E-02    1.14125E-07    -6.9426    1.14632E-07    -6.9407    1.00444E+00       .0019
110 MN(NO3)2   0  5.84823E-10    3.27187E-15   -14.4852    3.28640E-15   -14.4833    1.00444E+00       .0019
103 MNCL       1  1.86159E-03    2.06180E-08    -7.6858    1.80617E-08    -7.7432    8.76018E-01      -.0575
104 MNCL2      0  1.17641E-06    9.35853E-12   -11.0288    9.40010E-12   -11.0269    1.00444E+00       .0019
105 MNCL3     -1  1.49327E-09    9.26813E-15   -14.0330    8.11905E-15   -14.0905    8.76018E-01      -.0575
108 MNF        1  2.45210E-05    3.32029E-10    -9.4788    2.90863E-10    -9.5363    8.76018E-01      -.0575
115 HMNO2     -1  2.68037E-13    3.05132E-18   -17.5155    2.67301E-18   -17.5730    8.76018E-01      -.0575
 36 H3BO3 AQ   0  1.96245E+00    3.17758E-05    -4.4979    3.19169E-05    -4.4960    1.00444E+00       .0019
 37 H2BO3     -1  3.88976E-02    6.40262E-07    -6.1936    5.53344E-07    -6.2570    8.64246E-01      -.0634
 35 NO3       -1  2.50000E+00    4.03675E-05    -4.3940    3.49895E-05    -4.4561    8.66775E-01      -.0621



 MOL RATIOS FROM ANALYT MOLALITY      MOL RATIOS FROM COMP MOLALITY     LOG ACT RATIOS
 -------------------------------      -----------------------------     --------------
         CL/CA    =  9.7978E-01                CL/CA    =  1.1553E+00       LOG CA/H2 =   12.0535
         CL/MG    =  2.3256E+00                CL/MG    =  2.7136E+00       LOG MG/H2 =   11.6875
         CL/NA    =  2.4086E-01                CL/NA    =  2.4308E-01       LOG NA/H1 =    5.3989
         CL/K     =  1.4581E+01                CL/K     =  1.4680E+01       LOG K/H1  =    3.6157
         CL/AL    =  2.2027E+27                CL/AL    =  2.2027E+27       LOG AL/H3 =   22.5000
         CL/FE    =  7.6793E+01                CL/FE    =  1.7660E+11       LOG FE/H2 =     .8742
         CL/SO4   =  1.0567E+00                CL/SO4   =  1.2746E+00       LOG CA/MG =     .3660
         CL/HCO3  =  2.3972E-01                CL/HCO3  =  2.4692E-01       LOG NA/K  =    1.7833
         CA/MG    =  2.3736E+00                CA/MG    = 2.3489E+00
         NA/K     =  6.0538E+01                NA/K     =  6.0390E+01



     PHASE          IAP         KT        LOG IAP    LOG KT      IAP/KT      LOG IAP/KT    DELGR

 18 ANHYDRIT   1.1491E-06   2.9879E-05    -5.9397    -4.5246   3.8458E-02    -1.41502    -1.91430
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151 ARTIN     9.6815E-25   4.0871E-19   -24.0141  -18.3886   2.3688E-06   -5.62548    -7.61039
 20 BRUCITE   3.3550E-17   3.8435E-12   -16.4743  -11.4153   8.7288E-06   -5.05904    -6.84410
 13 CALCITE   1.2441E-08   3.4693E-09    -7.9052   -8.4598   3.5859E+00     .55460      .75029
 98 CHALC     3.1709E-04   2.8080E-04    -3.4988   -3.5516   1.1292E+00     .05279      .07141
 21 CHRYSOTL                            -56.4204  -51.9710                -4.44940    -6.01935
 30 CLENSTIT  1.0643E-20   1.2264E-17   -19.9729  -16.9114   8.6784E-04   -3.06156    -4.14182
100 SILGEL    3.1709E-04   1.8446E-03    -3.4988   -2.7341   1.7190E-01    -.76473    -1.03456
 29 DIOPSIDE                            -39.5799  -36.3508                -3.22910    -4.36846
 12 DOLOMITE  6.6633E-17   1.0749E-17   -16.1763  -16.9686   6.1988E+00     .79231     1.07187
113 FEOH3A    2.2476E+08   7.6736E+04     8.3517    4.8850   2.9289E+03    3.46671     4.68992
 63 FLUOR     3.5164E-13   1.0252E-11   -12.4539  -10.9892   3.4299E-02   -1.46472    -1.98153
 28 FORSTRIT  3.5723E-37   7.2413E-29   -36.4471  -28.1402   4.9332E-09   -8.30687   -11.23790
111 GOETH                               -33.8902  -44.3554                10.46516    14.15773
112 GREENA                              -88.8601  -63.1900               -25.67015   -34.72770
 19 GYPSUM    1.1480E-06   1.7353E-05    -5.9400   -4.7606   6.6156E-02   -1.17943    -1.59558
 65 HALITE    1.5182E-05   3.7697E+01    -4.8187    1.5763   4.0273E-07   -6.39499    -8.65142
109 HEMATI    5.0583E+16   1.5282E-04    16.7040   -3.8158   3.3100E+20   20.51983    27.76013
118 HUNTITE   1.9115E-33   4.4633E-31   -32.7186  -30.3503   4.2828E-03   -2.36827    -3.20390
 39 HYDMAG                              -41.2884  -37.6618                -3.62653    -4.90612
 99 MAGADI    1.3273E-21   5.0119E-15   -20.8770  -14.3000   2.6483E-07   -6.57703    -8.89770
110 MAGHEM    5.0583E+16   2.3442E+06    16.7040    6.3700   2.1578E+10   10.33401    13.98030
 11 MAGNESIT  5.3561E-09   6.2840E-09    -8.2712   -8.2018   8.5234E-01    -.06939     -.09387
108 MAGNET    2.5337E-09   4.8641E-10    -8.5962   -9.3130   5.2090E+00     .71676      .96966
 67 MIRABI    6.3504E-08   5.8792E-02    -7.1972   -1.2307   1.0801E-06   -5.96652    -8.07177
 59 NAHCOL    6.2043E-05   2.6850E-01    -4.2073    -.5711   2.3107E-04   -3.63625    -4.91928
 61 NATRON    6.8754E-10   3.9031E-02    -9.1627   -1.4086   1.7615E-08   -7.75412   -10.49011
150 NESQUE    5.3489E-09   6.6816E-06    -8.2717   -5.1751   8.0054E-04   -3.09662    -4.18924
102 QUARTZ    3.1709E-04   9.0458E-05    -3.4988   -4.0436   3.5054E+00     .54473      .73694
 37 SEPIOLIT                            -43.4454  -40.2644                -3.18092    -4.30329
 10 SIDERITE  8.2336E-20   3.0410E-11   -19.0844  -10.5170   2.7075E-09   -8.56743   -11.59040
101 SILGLAS   3.1709E-04   9.0257E-04    -3.4988   -3.0445   3.5132E-01    -.45430     -.61459
 38 TALC                                -63.4178  -62.5693                 -.84851    -1.14789
 66 THENAR    6.3789E-08   6.6764E-01    -7.1953    -.1755   9.5544E-08   -7.01980    -9.49669
 62 THRNAT    6.9032E-10   1.3879E+00    -9.1609     .1424   4.9738E-10   -9.30331   -12.58593
 32 TREMOLIT                           -142.5776 -140.8591                -1.71842    -2.32475
 60 TRONA     4.2811E-14   2.0728E-01   -13.3684    -.6834   2.0653E-13  -12.68501   -17.16084
154 SEP PT                              -43.4454  -37.2120                -6.23337    -8.43277
172 MANGANO   2.3291E+09   1.2215E+18     9.3672   18.0869   1.9067E-09   -8.71971   -11.79640
173 PYROLUST  7.1234E+24   1.1012E+16    24.8527   16.0419   6.4689E+08    8.81083    11.91968
174 BIRNSITE  7.1234E+24   1.2331E+18    24.8527   18.0910   5.7768E+06    6.76169     9.14751
175 NUSTITE   7.1234E+24   3.1915E+17    24.8527   17.5040   2.2320E+07    7.34869     9.94163
176 BIXBYITE  3.5746E+08   3.0443E-01     8.5532    -.5165   1.1742E+09    9.06974    12.26994
177 HAUSMITE                             69.2537   62.0367                 7.21703     9.76352
178 MNOH2     1.6054E-19   1.1550E-13   -18.7944  -12.9374   1.3899E-05   -5.85701    -7.92362
179 MNOH3     1.0819E-38   1.7041E-36   -37.9658  -35.7685   6.3490E-03   -2.19730    -2.97260
180 MANGANIT  1.8902E+04   5.7810E-01     4.2765    -.2380   3.2698E+04    4.51452     6.10743
181 RHODOCHR  2.5629E-11   2.9777E-11   -10.5913  -10.5261   8.6070E-01    -.06515     -.08814
183 MNCL2     8.5532E-12   7.3998E+08   -11.0679    8.8692   1.1559E-20  -19.93709   -26.97177
184 MNCL2,1W  8.5494E-12   3.6853E+05   -11.0681    5.5665   2.3199E-17  -16.63453   -22.50393
185 MNCL2,2W  8.5455E-12   9.1918E+03   -11.0683    3.9634   9.2969E-16  -15.03166   -20.33549
186 MNCL2,4W  8.5379E-12   4.0020E+02   -11.0687    2.6023   2.1334E-14  -13.67093   -18.49463
187 TEPHRITE  1.7202E+15   2.3458E+23    15.2356   23.3703   7.3331E-09   -8.13471   -11.00500
188 RHODONIT  1.7209E+00   4.5461E+09      .2358    9.6576   3.7855E-10   -9.42187   -12.74632
190 MNSO4     2.3672E-09   5.8203E+02    -8.6258    2.7649   4.0672E-12  -11.39070   -15.40984
191 MN2SO4,3                            -45.4256   -5.4689               -39.95673   -54.05521
```

APPENDIX G

BALANCE PRINTOUTS

```
CDC3


DELTA              CALCITE   DOLOMITE  GYPSUM    HALITE    CO2 GAS   K SPAR    ION EXCH

 .249  CA          1.000     1.000     1.000      .000      .000      .000    -1.000

 .082  MG           .000     1.000      .000      .000      .000      .000      .000

-.261  NA           .000      .000      .000     1.000      .000      .000     2.000

 .003  K            .000      .000      .000      .000      .000     1.000      .000

 .063  S            .000      .000     1.000      .000      .000      .000      .000

 .761  CL           .000      .000      .000     1.000      .000      .000      .000

-.033  C           1.000     2.000      .000      .000     1.000      .000      .000


                 DELTA PHASES

               CALCITE      -.4070

               DOLOMITE      .0820

               GYPSUM        .0630

               HALITE        .7610

               CO2 GAS       .2100

               K SPAR        .0030

               ION EXCH     -.5110
```

```
300


DELTA           CALCITE   DOLOMITE  GYPSUM    HALITE    CO2 GAS   K SPAR    ION EXCH


 .025  CA       1.000     1.000     1.000      .000      .000      .000    -1.000

-.041  MG        .000     1.000      .000      .000      .000      .000      .000

7.525  NA        .000      .000      .000     1.000      .000      .000     2.000

 .051  K         .000      .000      .000      .000      .000     1.000      .000

-.208  S         .000      .000     1.000      .000      .000      .000      .000

 .423  CL        .000      .000      .000     1.000      .000      .000      .000

 .361  C        1.000     2.000      .000      .000     1.000      .000      .000


                  DELTA PHASES


                CALCITE      3.8250

                DOLOMITE     -.0410

                GYPSUM       -.2080

                HALITE        .4230

                CO2 GAS     -3.3820

                K SPAR        .0510

                ION EXCH     3.5510
```

```
CDC1


DELTA           CALCITE  DOLOMITE GYPSUM   HALITE   CO2 GAS  K SPAR   ION EXCH


 3.817  CA       1.000    1.000    1.000     .000     .000     .000   -1.000

 1.892  MG        .000    1.000     .000     .000     .000     .000     .000

 4.915  NA        .000     .000     .000    1.000     .000     .000    2.000

  .089  K         .000     .000     .000     .000     .000    1.000     .000

 5.736  S         .000     .000    1.000     .000     .000     .000     .000

-1.467  CL        .000     .000     .000    1.000     .000     .000     .000

 2.082  C        1.000    2.000     .000     .000    1.000     .000     .000


                   DELTA PHASES


                CALCITE      -.6200

                DOLOMITE     1.8920

                GYPSUM       5.7360

                HALITE      -1.4670

                CO2 GAS     -1.0820

                K SPAR        .0890

                ION EXCH     3.1910
```

```
C9B


DELTA           CALCITE  DOLOMITE  GYPSUM   HALITE   CO2 GAS  K SPAR   ION EXCH

-.150  CA       1.000    1.000     1.000     .000     .000     .000    -1.000

 .000  MG        .000    1.000      .000     .000     .000     .000      .000

 .870  NA        .000     .000      .000    1.000     .000     .000     2.000

 .014  K         .000     .000      .000     .000     .000    1.000      .000

 .312  S         .000     .000     1.000     .000     .000     .000      .000

 .085  CL        .000     .000      .000    1.000     .000     .000      .000

 .344  C        1.000    2.000      .000     .000    1.000     .000      .000


                     DELTA PHASES

                CALCITE       -.0695

                DOLOMITE       .0000

                GYPSUM         .3120

                HALITE         .0850

                CO2 GAS        .4135

                K SPAR         .0140

                ION EXCH       .3925
```

```
CBC


 DELTA          CALCITE  DOLOMITE GYPSUM   HALITE   CO2 GAS  K SPAR   ION EXCH

  .349  CA      1.000    1.000    1.000     .000     .000     .000   -1.000

  .247  MG       .000    1.000     .000     .000     .000     .000     .000

-2.610  NA       .000     .000     .000    1.000     .000     .000    2.000

  .033  K        .000     .000     .000     .000     .000    1.000     .000

 -.104  S        .000     .000    1.000     .000     .000     .000     .000

 -.593  CL       .000     .000     .000    1.000     .000     .000     .000

 -.656  C       1.000    2.000     .000     .000    1.000     .000     .000


                   DELTA PHASES

                CALCITE      -.8025

                DOLOMITE      .2470

                GYPSUM       -.1040

                HALITE       -.5930

                CO2 GAS      -.3475

                K SPAR        .0330

                ION EXCH    -1.0085
```

```
CCA


DELTA              CALCITE   DOLOMITE  GYPSUM    HALITE    CO2 GAS   K SPAR    ION EXCH

 .799  CA          1.000     1.000     1.000      .000      .000      .000    -1.000

 .493  MG           .000     1.000      .000      .000      .000      .000      .000

1.740  NA           .000      .000      .000     1.000      .000      .000     2.000

 .074  K            .000      .000      .000      .000      .000     1.000      .000

1.770  S            .000      .000     1.000      .000      .000      .000      .000

-.028  CL           .000      .000      .000     1.000      .000      .000      .000

1.000  C           1.000     2.000      .000      .000     1.000      .000      .000


                      DELTA PHASES

                   CALCITE       -.5800

                   DOLOMITE       .4930

                   GYPSUM        1.7700

                   HALITE        -.0280

                   CO2 GAS        .5940

                   K SPAR         .0740

                   ION EXCH       .8840
```

```
JCOB



DELTA           CALCITE  DOLOMITE GYPSUM   HALITE   CO2 GAS  K SPAR   ION EXCH


3.518  CA        1.000    1.000    1.000     .000     .000     .000   -1.000

1.686  MG         .000    1.000     .000     .000     .000     .000     .000

5.654  NA         .000     .000     .000    1.000     .000     .000    2.000

 .133  K          .000     .000     .000     .000     .000    1.000     .000

7.704  S          .000     .000    1.000     .000     .000     .000     .000

-1.382 CL         .000     .000     .000    1.000     .000     .000     .000

2.245  C         1.000    2.000     .000     .000    1.000     .000     .000



                   DELTA PHASES


                CALCITE     -2.3540

                DOLOMITE     1.6860

                GYPSUM       7.7040

                HALITE      -1.3820

                CO2 GAS      1.2270

                K SPAR        .1330

                ION EXCH     3.5180
```

```
CAS-BCC


FINAL          INIT1     INIT2     CALCITE   DOLOMITE  GYPSUM    HALITE    CO2 GAS   ION EXCH


1.821  CA      1.921     2.046     1.000     1.000     1.000      .000      .000    -1.000

 .864  MG       .823     1.152      .000     1.000      .000      .000      .000      .000

8.264  NA      6.655     5.393      .000      .000      .000     1.000      .000     2.000

 .171  K        .128      .240      .000      .000      .000      .000      .000      .000

1.978  S       2.207     1.822      .000      .000     1.000      .000      .000      .000

 .874  CL       .197     1.128      .000      .000      .000     1.000      .000      .000

8.752  C       7.850     7.015     1.000     2.000      .000      .000     1.000      .000

1.000  MIX     1.000     1.000      .000      .000      .000      .000      .000      .000


            DELTA PHASES


         INIT1          .6161

         INIT2          .3839

         CALCITE        .9055

         DOLOMITE     -.0853

         GYPSUM       -.0812

         HALITE         .3196

         CO2 GAS        .4877

         ION EXCH       .8870
```

```
CCD-CDC1


 FINAL            INIT1     INIT2    CALCITE   DOLOMITE  GYPSUM    HALITE    CO2 GAS   ION EXCH


 5.988  CA        1.871     2.769     1.000     1.000     1.000      .000      .000    -1.000

 2.591  MG         .823     1.234      .000     1.000      .000      .000      .000      .000

17.398  NA       12.527    12.266      .000      .000      .000     1.000      .000     2.000

  .281  K          .166      .164      .000      .000      .000      .000      .000      .000

 8.224  S         2.436     5.091      .000      .000     1.000      .000      .000      .000

 1.918  CL        3.385      .508      .000      .000      .000     1.000      .000      .000

12.210  C         9.588     9.555     1.000     2.000      .000      .000     1.000      .000

 1.000  MIX       1.000     1.000      .000      .000      .000      .000      .000      .000


                     DELTA PHASES


                 INIT1         58.5002

                 INIT2        -57.5002

                 CALCITE      -49.7202

                 DOLOMITE      25.4006

                 GYPSUM       158.4510

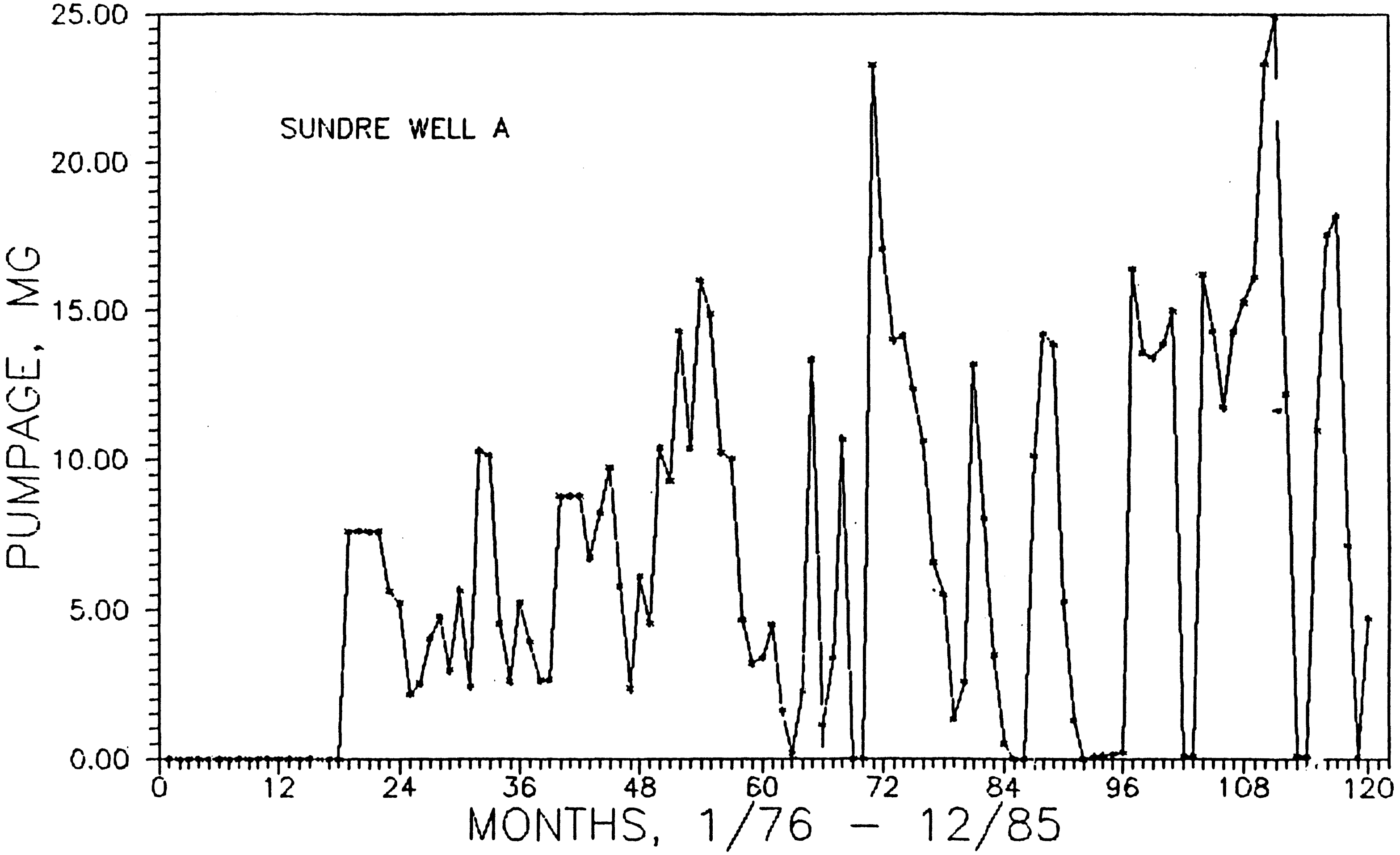
                 HALITE      -166.9951

                 CO2 GAS        -.3565

                 ION EXCH      78.3792
```

APPENDIX H

WELL PUMPAGE GRAPHS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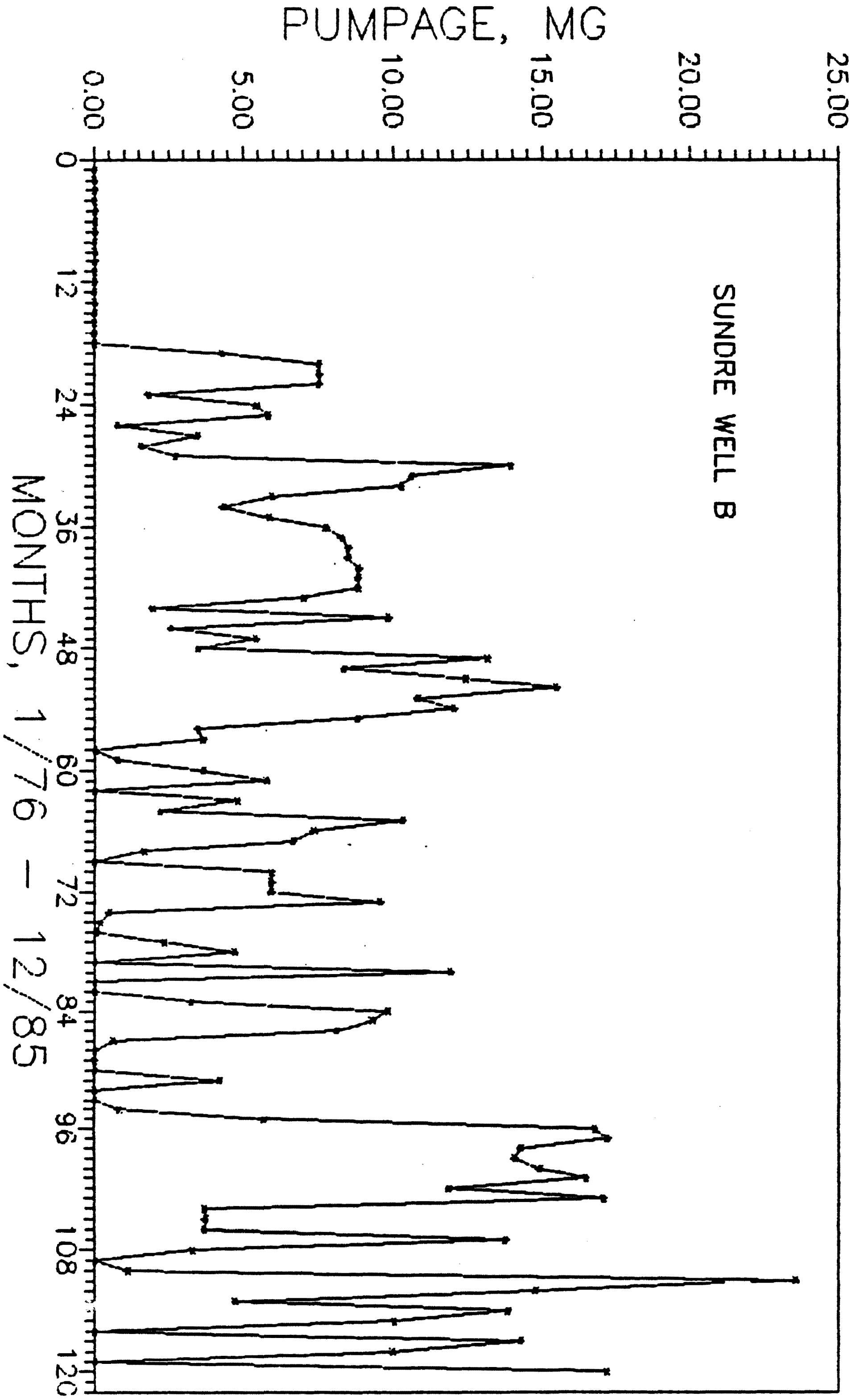
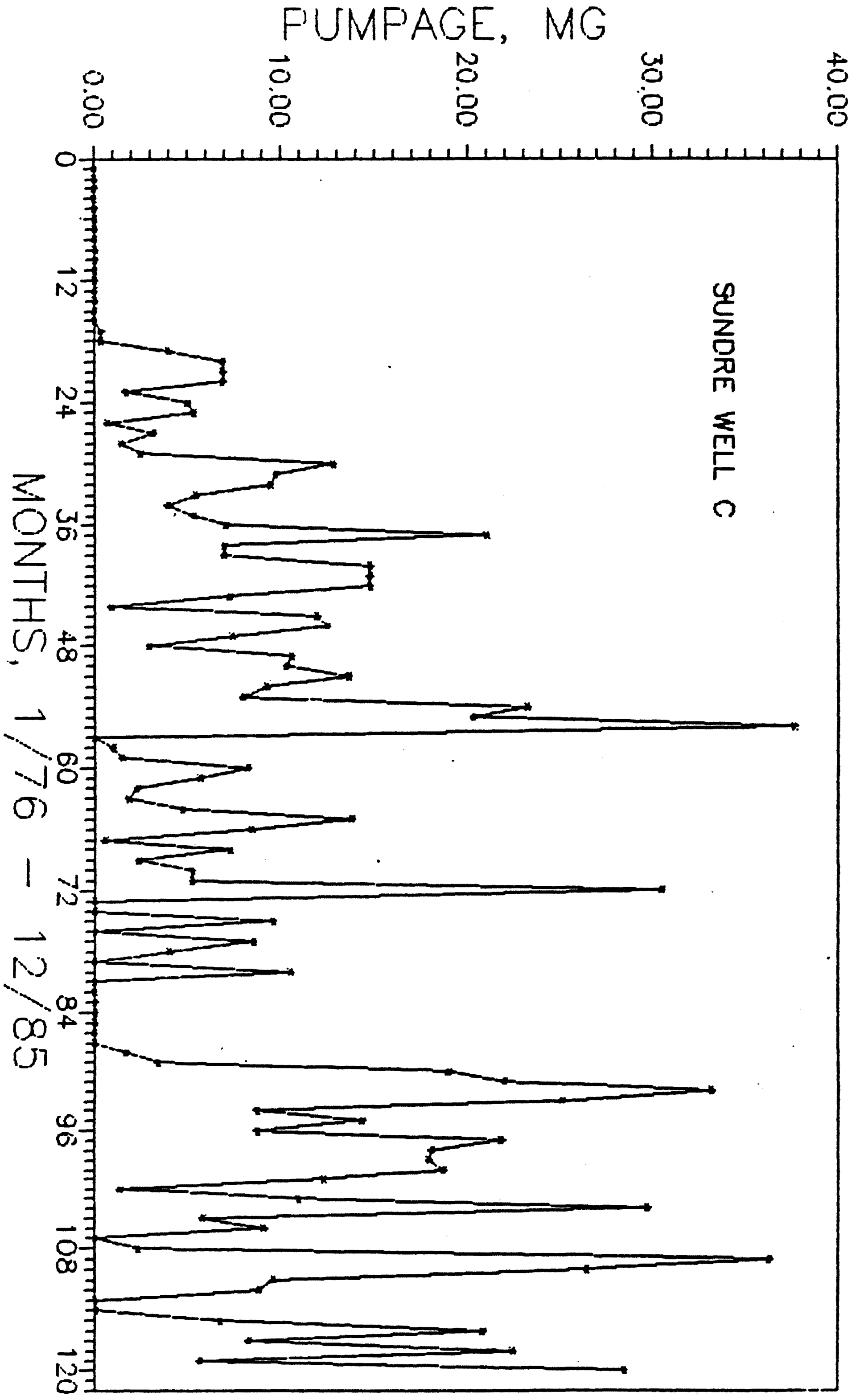
15.00
20.00
25.00
0
12
24
36
48
60
72
84
96
108
120


SUNDRE WELL B
PUMPAGE, MG
0.00
5.00
10.00
15.00
20.00
25.00
MONTHS, 1/76 – 12/85
0
12
24
36
48
60
72
84
96
108
120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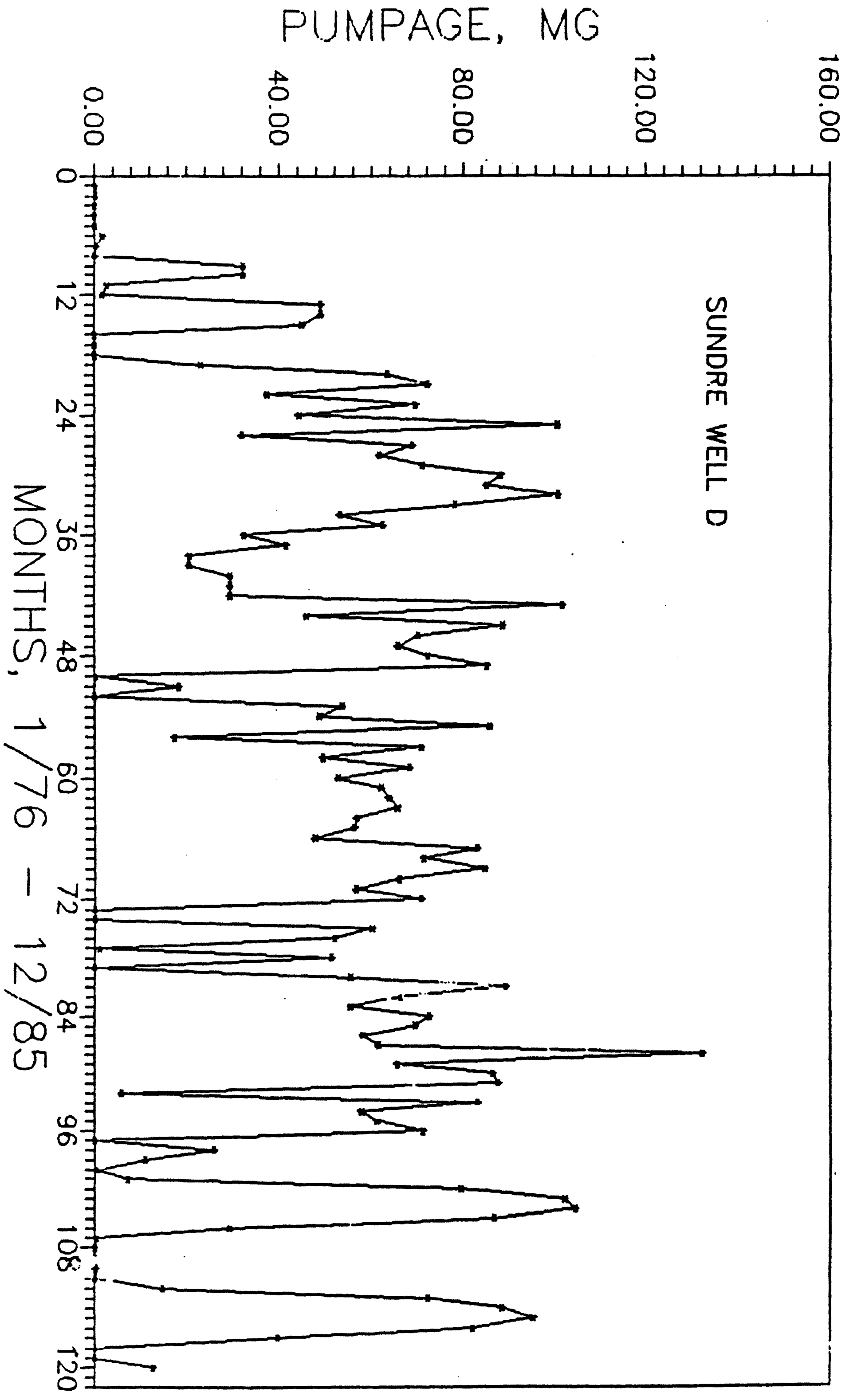
PUMPAGE, MG
0.00
10.00
20.00
30.00
40.00
MONTHS, 1/76 – 12/85
0
12
24
36
48
60
72
84
96
108
120


PUMPAGE, MG
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160.00
SUNDRE WELL D
0
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24
36
48
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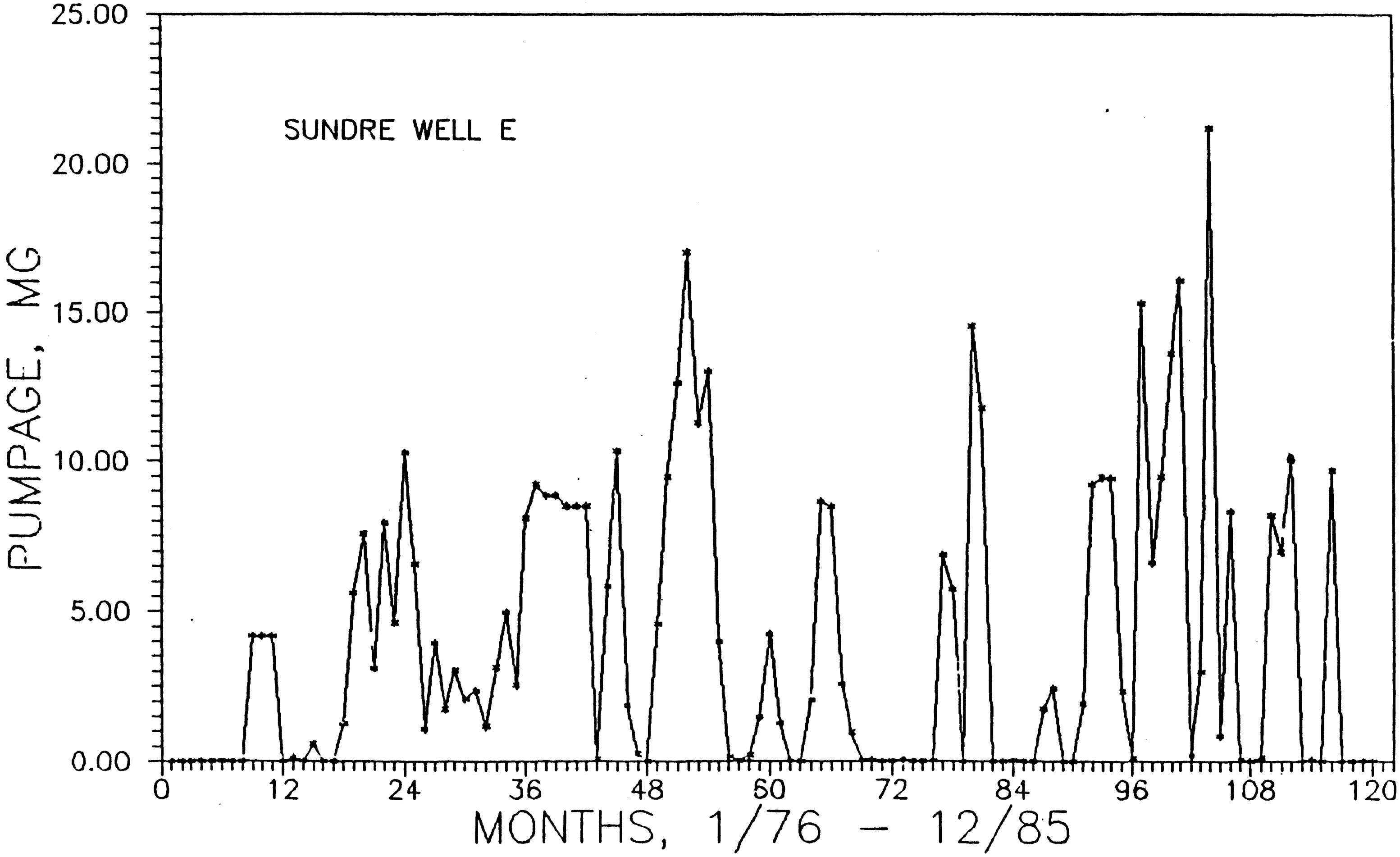
72
84
96
108
120
MONTHS, 1/76 – 12/85


SUNDRE WELL E
PUMPAGE, MG
25.00
20.00
15.00
10.00
5.00
0.00
0
12
24
36
48
60
72
84
96
108
120
MONTHS, 1/76 - 12/85

VITA

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