# THE GEOCHEMISTRY OF THE "N" AQUIFER SYSTEM, NAVAJO AND HOPI INDIAN RESERVATIONS, NORTHEASTERN ARIZONA

by

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## ABSTRACT

### THE GEOCHEMISTRY OF THE "N" AQUIFER SYSTEM, NAVAJO AND HOPI INDIAN RESERVATIONS, NORTHEASTERN ARIZONA

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The "N" aquifer system extends across much of northeastern Arizona, and is extensively utilized on the Navajo and Hopi Indian Reservations. The aqueous geochemistry of this aquifer has never been investigated, although several studies have been devoted to modeling groundwater supply. The "N" system is comprised of the Glen Canyon Group, dominated by the Navajo Sandstone, and including the Kayenta Formation, the Wingate Sandstone (Lukachukai Member), and the Moenave Formation. Following a strict sampling protocol, 44 wells and springs were sampled during one field season, with some analyses performed in the field. Laboratory analyses via flame atomic absorption spectrophotometer showed that calcium was the chief cation for most of the extent of the "N" system to the north and west, but that sodium was important along the eastern and southeastern portions of the thesis area. Bicarbonate was found to be the primary anion to the north and west, but sulfate and chloride also exhibited high concentrations to the east and southeast. Ratios of various cations and anions and a Piper diagram revealed two chemically distinct bodies of groundwater, with little gradation between their chemistries.

X-ray diffraction and petrographic analysis showed the dominant lithology of the "N" system to be quartz to feldspathic arenite with minimal illite and smectite as matrix. Calcite and silica were the major cements observed petrographically, although calcite cement was more unevenly distributed across the study area. Calcite cement was most noticeably absent near the surface and northwest and north of Black Mesa. Geochemical modeling was attempted with various computer programs, with varying results. The results of running WATEQF revealed that carbonate system geochemistry dominates most of the "N" aquifer to the north and west of Black Mesa, where the groundwater is close to equilibrium with respect to calcite. Other processes, probably mixing with groundwater leaking from both underlying and overlying aquifer systems, control water chemistry along the eastern and southeastern margins of the study area.

## ACKNOWLEDGEMENTS

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Laboratory analysis could not have been done without the advice and instruction of Tom Huntsberger of the Bilby Research Center Analytical Chemistry Laboratory, to whom I am very grateful. I want to thank Dorothy Bergman and Dave Zuber, fellow graduate students, who provided invaluable insights into the interpretation of the X-ray diffractograms and identification of clay minerals, as well as advice on other aspects of laboratory work and on water chemistry in general.

I profited from discussions with several individuals, to whom I am grateful. These included Don Bills, U.S. Geological Survey, Gary Small and Jack Edmonds, Salt River Project, Ted Smith and John Cochrane, Peabody Coal Company, Al Johnson, Tom Perry, and Michelle Kennard, Arizona Department of Water Resources, and many others. I am grateful to Wes Pierce of the Arizona Bureau of Mines, for allowing me access to archived well cuttings, to Gary McIntosh of the Office of Surface Mining for providing a copy of his program HC-Gram, and to Ken Jackson of Lawrence Livermore National Laboratories for providing a copy of the EQ3/6 package, although I did not use it. I also want to thank all the people of the various agencies which provided me with information on well construction and water chemistry, including the Navajo Tribal Utility Authority (particularly Hap Mayberry and Don Owen), Navajo Nation Surface Mining Office (particularly Mike Foley), Division of Water Resources, and Operations and Maintenance Department, National Park Service, Peabody Coal Company, U.S. Geological Survey, U.S. Environmental Protection Agency, Indian Health Service, Bureau of Indian Affairs Chinle and Tuba City Agencies, and many others.

It should be noted that some of the maps in this thesis were substantially modified to suit the editorial tastes of the Graduate Office of Northern Arizona University; readers desiring technically correct maps should contact the author directly.

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# CHAPTER 1

# INTRODUCTION TO THE STUDY

One of the least plentiful resources on the Navajo and Hopi Indian Reservations of northeastern Arizona is water, both surface water and ground water, of sufficient quantity and quality for human use. Ground water is the most utilized form of this critical but scarce resource. Any study which aims to clarify either aspect of ground water thus assumes major importance, particularly to those managers responsible for effective utilization of the resource. This investigation focuses on the quality of ground water found in one of the more developed aquifer systems in northeastern Arizona. The study area is defined as those areas of the Navajo and Hopi Indian Reservations of northeastern Arizona, and the area around Navajo Mountain in southernmost Utah, in which the "N" aquifer occurs. This introduction distinguishes that aquifer system from others in the area, provides a geographic setting for the study area, and defines four major objectives of this investigation.

## Objectives of the Study

Groundwater pumped from the "N" aquifer system is currently considered to be of adequate supply for all proposed uses on the Navajo and Hopi Indian Reservations (see Figure 1). Many Hopis and Navajos, however, remain very concerned about the large amounts of water pumped by Peabody Coal Company on Black Mesa and the effects of such water removals on their future supplies. Hence most work on the Reservations has been focused on questions of quantity.

Processes of aqueous geochemistry leading to different water chemistries in different areas have never been investigated. If water chemistry is noted at all in most studies, various classifications are given (sodium sulfate vs. calcium bicarbonate, for example). Occasionally the presence and amounts of other ions, as well as lithological characteristics which might give rise to varying concentrations, are discussed in a general manner (Cooley, Harshbarger, Akers, and Hardt 1969). The classification of groundwaters into various types, however, and brief discussions of major ionic concentrations, yield few insights into how the varying water chemistries may have arisen, or how the water has changed since it first entered the aquifer system.

Yet water quality is equivalent in importance to water quantity, and perhaps even more critical in many uses. It is important to understand the water-rock reactions which create the water chemistry seen at any given point within the aquifer system. The chemical composition of water cannot be predicted in the absence of basic knowledge of how it changes from the recharge area where it enters the

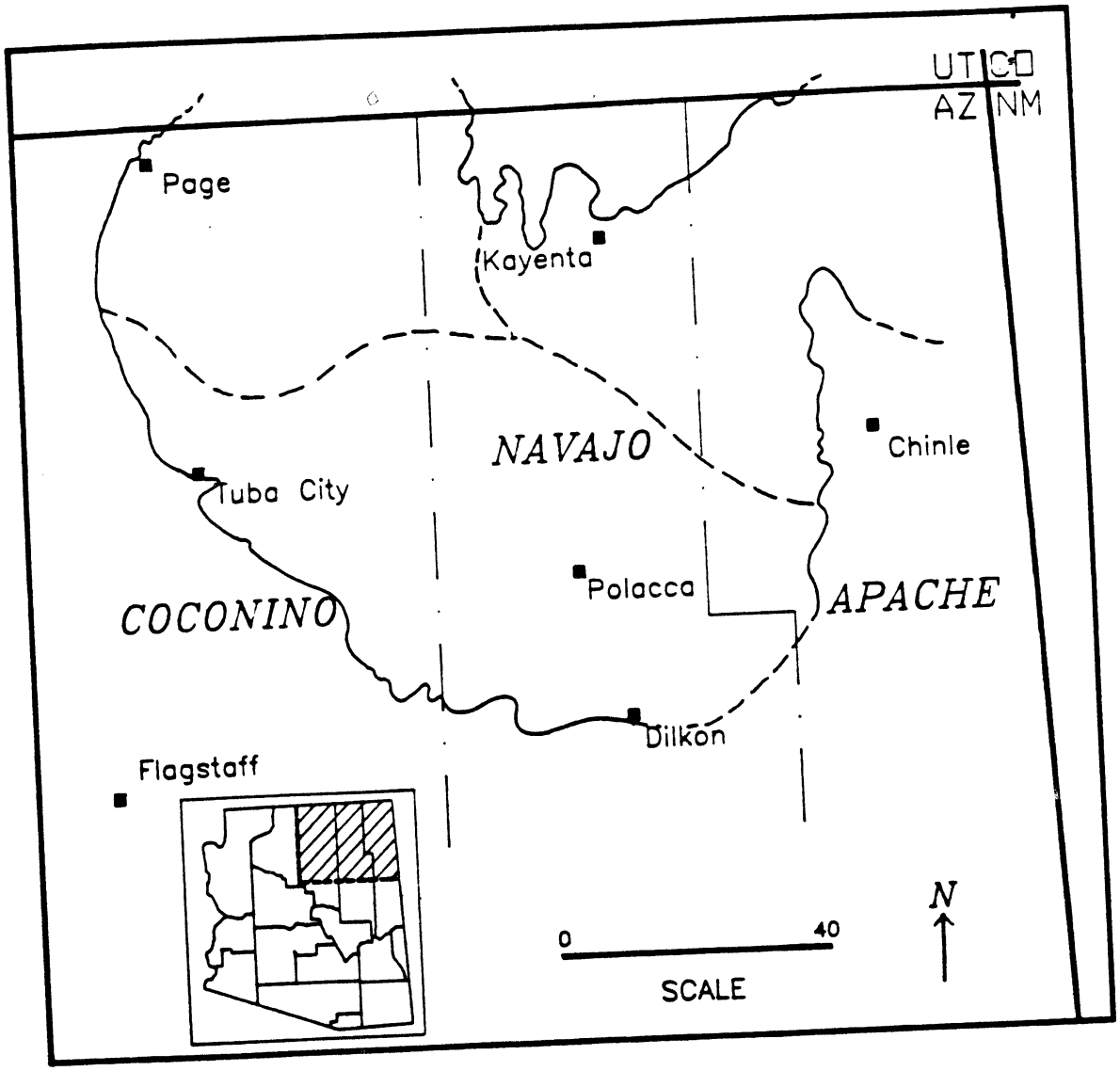


**Figure 1: Map showing limits of the "N" aquifer system within Coconino, Navajo, and Apache Counties, northeastern Arizona, with three sub-basins denoted by dashed lines.**

knowledge of how it changes from the recharge area where it enters the system to the discharge point where its water chemistry is of some concern, and where it is usually measured.

Currently no compilation of basic water chemistry data exists for the "N" aquifer system. The lack of this necessary first step precludes any subsequent development of theoretical models of water-rock reactions which would lead to understanding the geochemical processes at work in the system.

At least five sub-basins have been defined for the study area by the Arizona Department of Water Resources (Daniel 1981), although on the basis of groundwater flow an earlier major research effort defined only three (Cooley et.al. 1969). A recent and on-going research project by the Arizona Department of Water Resources (ADWR) also defines three groundwater sub-basins for the Navajo and Hopi Indian Reservations (T. Perry, personal communication), which closely approximate those postulated by Cooley et.al. (1969). These three sub-basins will be used in this thesis, and are shown on Figure 1. The nature of the boundaries between these sub-basins remains poorly understood. Differences in geochemical processes within each sub-basin have never been studied at all.

Thus there is a great need for a comprehensive investigation of the aqueous geochemistry of the "N" aquifer system, a major source of groundwater on the Navajo and Hopi Indian Reservations. This should include a compilation of basic water chemistry data, the definition of geochemically distinct sub-basins within the "N" system, and the

explanation of differing geochemical processes which lead to differing water chemistries. The following three major objectives for this thesis meet these needs.

Objective 1

The first objective of this thesis is to adequately describe the spatial variability of groundwater chemistry within the "N" aquifer system. No baseline study of the "N" aquifer system has been attempted for at least thirty years. Compiling various chemical analyses of water samples from different wells will provide a starting point. Chemical analyses from 44 wells sampled as part of this thesis, collected with one methodology during one season of one year and analyzed at one laboratory, will greatly expand this database.

Several chemical parameters will be assimilated. Field measurements include pH, temperature, conductivity, alkalinity, and concentrations of dissolved gases. Laboratory analyses provide concentrations of anions and cations such as bicarbonate, sulfate, chloride, nitrate, fluoride, calcium, magnesium, sodium, potassium, and other metals.

Data organized into tabular form provide the starting point for subsequent objectives. Several graphical methods exist which aid in describing the range of spatial variability of groundwater chemistry across the study area. Accompanying maps of the distribution of chemical parameters across the study area, and trilinear diagrams placing water analyses into specific chemical fields also organize

baseline information. Log activity diagrams and ratios of related ionic concentrations display important information.

Objective 2

The second objective involves the attempt to define distinct geochemical processes acting within each of the three sub-basins which were previously defined on the basis of flow patterns. It should be possible to define different water compositions which characterize each sub-basin. Here the necessity of the compilation of baseline information on water chemistry will be immediately apparent. It is hypothesized that water analyses from each sub-basin should group together. Graphical illustrations of water chemistry data would also reveal distinctions. This is because the chemical processes governing the final composition of groundwater within each sub-basin are hypothesized to be different for each. Differences between the water chemistry of each sub-basin may be sharp or gradational, but they should emerge from the baseline data.

Objective 3

The third objective is explanatory in nature. If distinct water compositions representing three distinct sub-basins can be statistically demonstrated, then each different water chemistry must be produced by a distinct set of water-rock reactions along the flow path for that sub-basin. Geological factors determine the set of water-rock reactions which will occur. This objective demands an

adequate understanding of the mineralogy of the Glen Canyon Group as a whole, along with knowledge of facies shifts found within its formations, and of structural features that act to control groundwater flow.

Modeling is the best tool to achieve an integrated understanding of the aqueous geochemistry operating within each sub-basin, and thus within the "N" aquifer system as a whole. Geochemical reaction path modeling is a theoretical process in which, given initial solution compositions and mineralogies encountered along the flow path, thermodynamically plausible sets of reactions are followed to a final water composition. The reactions path of a packet of water moving through a group of rocks can be followed in terms of its progress through the chemical stability fields of the minerals involved. Reaction path models can provide a basis for understanding the geochemical evolution of groundwater within the "N" aquifer system.

Geological factors such as differences in structure or facies shifts are hypothesized to explain the differences between each sub-basin. It is these geological factors which should produce a distinct set of aqueous geochemical reactions which change the groundwater composition from the area of recharge to the various discharge points within each sub-basin. The explanation of the geochemical evolution of "N" system groundwater in terms of these factors is perhaps the most important aspect of this thesis. These geological factors may shed light on the nature of flow boundaries between each sub-basin.

## The Final Result

Realization of all of the above objectives will result in a case study of the aqueous geochemistry of the "N" aquifer system, a major source of scarce groundwater on the Navajo and Hopi Reservations of northeastern Arizona. The geochemical evolution of groundwater as it moves from recharge areas, reacting with rocks of specific mineralogies, to discharge points will be modeled and explained in terms of the geology of the southwestern Colorado Plateau. This case study will be useful to all those concerned with effective management of this critical resource, including the U.S. Geological Survey, U.S. Environmental Protection Agency, Navajo Tribal Utility Authority, Indian Health Service, Navajo Nation Water Resources Division, Hopi Tribal Council, Peabody Coal Company, and Office of Surface Mining.

## The "N" Aquifer System

At least five major aquifers are recognized (Cooley et.al. 1969) within the Navajo and Hopi Indian Reservations of northeastern Arizona and southernmost Utah. The geologically uppermost aquifer is the Bidahochi Formation of early Tertiary age, important in that area southeast of Black Mesa. The late Cretaceous formations of Black Mesa itself--the Toreva and Wepo Formations--form another aquifer, but one of limited extent. An aquifer system formed by the hydraulically connected Dakota and Cow Springs Sandstones, the "D" aquifer system, is also utilized on Black Mesa. However, "D" system water is brackish, so poor in quality that it is used almost exclusively for

livestock. The "N" aquifer system is composed of the hydraulically connected formations of the Glen Canyon Group. The "C" aquifer system is dominated by the Coconino and De Chelly Sandstones, the Kaibab Limestone, all of Permian age, and the Shinarump Member of the Triassic Chinle Formation. This most extensive aquifer is utilized in the southern and eastern portions of the Navajo Reservation. Its quality varies from excellent in the eastern portion of the Reservation to poor in the southwestern corner.

The "N" aquifer system is the most utilized source of ground water on the Hopi Reservation and on the northern portion of the Navajo Reservation in northeastern Arizona and southernmost Utah. Several hundred wells have been drilled into this system since the last century, and numerous springs have also been developed. Most wells are equipped with windmills and pump water for use by livestock, although several isolated families also derive domestic water from these low capacity wells. Wells which are the source of water for domestic systems, municipal supplies, and industrial uses demand larger volumes, and generally are equipped with electric submersible pumps. It is because the "N" aquifer system is so heavily utilized for these purposes that it was selected as the focus of this investigation.

Several formations of Jurassic age compose the "N" aquifer system. The uppermost of these, the Navajo Sandstone, generally dominates the aquifer system. The Kayenta Formation is geographically widespread, in contrast to the Moenave Formation, which is present in

the western portion of the study area. The Lukachukai Member of the Wingate Sandstone is more prominent in the eastern portion of the study area.

Although most of these formations continue on into New Mexico to the east and Utah to the north, the study area was limited to provide better cohesion to the investigation and better comprehension of the processes involved. Boundaries were drawn somewhat arbitrarily to the northeast in the vicinity of Red Mesa. Elsewhere, erosional boundaries provided natural limits, beyond which "N" waters cannot flow. To the northwest, the Colorado River, a major discharge zone, provided another natural restriction to the study area.

## Physiography and Climate

The study area falls entirely within the southwestern portion of the Colorado Plateau, which is both a geologic and a physiographic province (Fenneman 1931). This region is dominated by Paleozoic and Mesozoic sedimentary strata, which are relatively horizontal save near major folds, which are mostly of Laramide date. The central physiographic feature in the study area is Black Mesa, a large highland area occupying the center of the Black Mesa structural basin (Stokes 1973). Several major washes drain this feature to the southwest, including Moenkopi, Dennebito, Oraibi, and Polacca Washes. To the west, north, and northeast of Black Mesa extend the Navajo Uplands, a broad but discontinuous area of sand dunes and wind-stripped rock surfaces,

principally the Navajo Sandstone (Cooley et.al. 1969). To the northwest this physiographic subdivision is drained by Navajo Creek, and to the northeast by Laguna Creek; Monument Valley intervenes to separate the two major areas of this discontinuous subdivision. East of Black Mesa lie the broad lowlands of the Chinle Valley, drained by Chinle Creek. South of Black Mesa, dropping off to the valley of the Little Colorado River, is the Painted Desert physiographic subdivision, characterized by broad and rolling tablelands in which the Hopi Buttes volcanic field forms a prominent intrusion. Figure 2 illustrates the relationships between these physiographic regions. Distinctive topographic features of the semi-arid to arid landscape of the study area include mesas, buttes, hoodoos, yardangs, rock terraces, escarpments, and canyons, both vertical-walled and V-shaped.

The highest elevations within the study area are found on Navajo Mountain (10,344 ft), and the lowest along the Little Colorado River to the southwest of the study area (approximately 4,500 ft). The northern and eastern portions of Black Mesa are also high (8,120 ft at its northernmost point), descending to approximately the 6,000 ft level at the Hopi villages on its southwestern extensions. The northwestern Navajo Uplands also range between 5,500 to 6,500 ft in elevation. The Chinle Valley is generally lower, in the 4,500 to 5,500 ft range.

Average annual precipitation on the southwestern portion of the Colorado Plateau ranges from 6 to 22 inches (Cooley et.al. 1969). Elevation is a major factor influencing precipitation amounts,

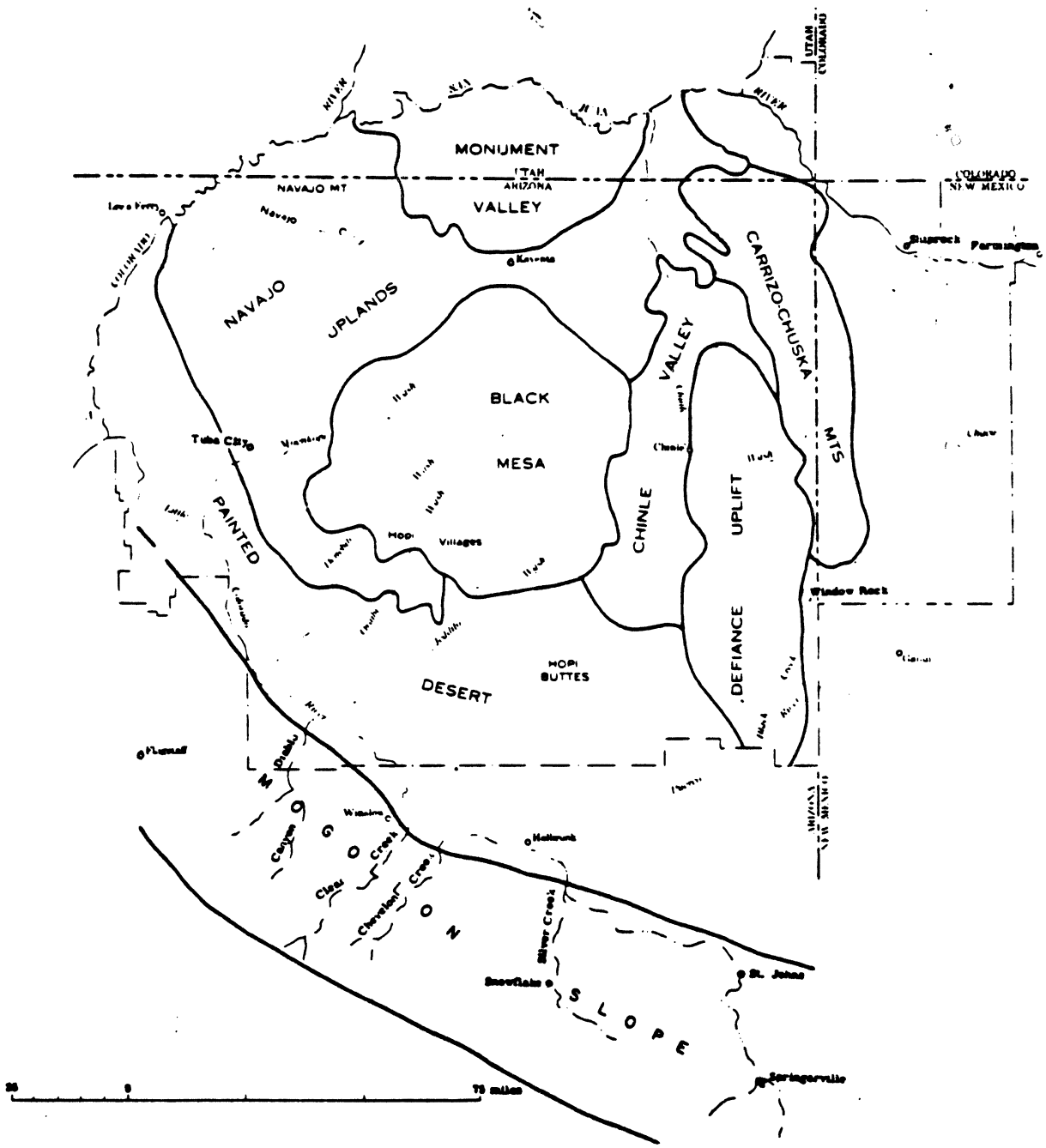


Figure 2: Map showing major physiographic subdivisions of the study area, taken from Akers and Harshbarger (1958).

particularly in the summer. Winter storms arise from Pacific air masses and frontal activity, while summer storms draw moist air from the distant Gulf of Mexico. The result is two distinct wet periods during the year, the first from December through February and the second from July through September; May and June are the driest months of the year (Sellers 1960). Summer precipitation occurs in the form of intense thunderstorms, often very localized, concentrated on highlands above 7,000 ft. Because rainfall is intense and short-lived, runoff is high with little infiltration. It is likely that greater recharge to the "N" and other aquifer systems occurs as a result of snowmelt than from summer thunderstorms (Cooley et.al. 1969), even though total amounts of precipitation are greater during the summer.

Six major vegetative zones are represented within the Colorado Plateau: the Lower and Upper Sonoran Zones, the Transition Zone, the Canadian Zone, the Hudsonian Zone, and the Alpine Zone (Hunt 1967). Only the first three actually occur within the study area, although the Transition Zone is represented in nearby mountainous areas. Distribution of these zones is correlated with differences in elevation, topography, soils, and climatic conditions.

# CHAPTER 2

# SUMMARY OF GEOLOGICAL AND HYDROLOGICAL CONDITIONS

## Introduction

Most previous geological studies on the southern Colorado Plateau have focused on problems of stratigraphy and sedimentology. Previous hydrological studies have concentrated on questions of water supply. Excellent regional studies have been performed under the auspices of the U.S. Geological Survey (Cooley et.al. 1969), in which both geology and hydrology were investigated. Several other studies of limited extent have been carried out by private sponsors and other governmental agencies. These have focused on specific wells or well fields, and the geological conditions to be expected. Several theses have concentrated on either geological or hydrological features of the southwestern Colorado Plateau (Luttrell 1987, Sargent 1984, Scott 1975, Francyzk 1987).

A basic understanding of the geological conditions inherent in the aquifer system must be attained before any understanding of hydrological conditions can be achieved (Freeze and Cherry 1979). The geological environment affects patterns of recharge and discharge areas, as well as the quantity of groundwater flowing through the system. Geological conditions determine which areas are under closed conditions, and which are open to the atmosphere. Flow directions are

influenced by underlying formations. Structural features can facilitate recharge along joints and faults, as well as discharge from springs. Facies shifts influence mineralogy, a major determinant of water chemistry, as proportions of grains, matrix, and cements vary between facies.

This chapter sets the background for the thesis. First, previous investigations within the study area are reviewed in order to summarize relevant information. Second, major sources of water chemistry data are discussed as to their utility and limitations. Third, the regional geology of the study area is summarized. Finally, hydrological characteristics of the "N" aquifer system are discussed in order to provide a framework for understanding the geochemical evolution of groundwater within this system.

## Major Regional Studies of Geology and Hydrogeology

In 1946 the U.S. Geological Survey initiated a field inventory of wells and springs on the Navajo and Hopi Indian Reservations of northeastern Arizona. Wells drilled up to 1961 were included in a compilation of wells and springs published by the Arizona State Land Department (Davis, Hardt, Thompson, and Cooley 1963). Some of this Navajo Project information has been incorporated into Appendix I of this thesis, which describes wells completed into the "N" aquifer system.

The second volume consisted of the results of chemical analyses of samples taken from various wells and springs over the course of the

Navajo Project (Kister and Hatchett 1963). These analyses included major cations and anions, field parameters such as pH and conductivity, and measurements such as sodium absorption ratio which are no longer routinely included in chemical analyses. The water samples were taken over several years time, and during different seasons, and thus do not accurately represent aquifer conditions at any one point in time. Analytical methods and field techniques are not discussed (Kister and Hatchett 1963). Most methods have undergone substantial changes over the last thirty years. Only some of these analyses have been incorporated into Appendix I of this thesis.

However, no serious attempt has been made to update this study in the intervening quarter-century. Many wells described in this report no longer exist, and many more have since been drilled. In particular, the information on water chemistry should be brought up to date using modern methods of sample collection and chemical analysis.

In order to check on the possible effects of heavy pumping by Peabody Coal Company on its Black Mesa leasehold, the U.S. Geological Survey during the late 1970's developed a mathematical model of groundwater flow within the "N" aquifer system (Eychaner 1983). The model was a standard U.S. Geological Survey two-dimensional finite difference model for non-steady state flow (Trescott, Pinder, and Larson 1976).

Initial estimates of saturated thicknesses, hydraulic conductivities, storativities, and water levels were made from data compiled by the U.S. Geological Survey, principally from the Navajo

Project (Cooley et.al. 1969). These data were considered representative of aquifer conditions prior to 1965 (Eychaner 1983). Since mining began after 1965, pre-1965 conditions represent the aquifer system in its natural equilibrium state. Conditions are monitored annually for several observation wells, and updates are issued by the U.S. Geological (Hill 1983, 1985, Hill and Whetten 1986).

The model was limited in its extent. No-flow boundaries were assumed to the southwest, south, and east, where rocks of the "N" system are truncated. The groundwater divide between the Kaibeto and Black Mesa sub-basins to the northwest was assumed to be another no-flow boundary (Eychaner 1983). An arbitrary boundary approximating that of this investigation was drawn to the northeast. But the model did not cover the total region encompassed by this thesis.

Calibration consists of adjusting input to the model until computed values, usually head values, are acceptably close to values observed in the field (Wang and Anderson 1982). In most modeling situations, this means adjusting the model until it agrees with the initial head values or water levels used to construct the model. In essence, this is using the original estimates of hydraulic conditions to match the original estimates of hydraulic conditions, a somewhat circular procedure. Only occasionally are models run to ascertain areas of uncertainty, and then new field values gathered where the model needs them the most.

Some limitations have been noted for this model. Estimates of evapotranspiration rates were off, although this apparently made little difference in model predictions (Brown and Eychaner 1988). The extent of the model was sufficient for its original purposes of monitoring Peabody Coal Company withdrawals, but does not cover the full extent of the study area encompassed by this thesis. A three-dimensional model might be considered more appropriate for an aquifer system composed of several hydraulically connected formations, particularly since the "N" system has a wealth of field data compared to other systems in northeastern Arizona (Wang and Anderson 1984).

This model received a significant update in 1988 (Brown and Eychaner 1988). Several refinements were made in the model grid, and in the manner in which leakance from the overlying "D" aquifer system was simulated. A more accurate representation of the aquifer was achieved. Close agreement between the revised and original 1983 models suggest that limitations discussed above did not affect model performance. This model is important in that it is accepted in this study as indicative of flow patterns and steady-state aquifer conditions, and thus of the beginning and ending points for reaction paths. Figure 3 illustrates equilibrium water levels and flow directions as modeled by the U.S. Geological Survey for 1984 (Brown and Eychaner 1988).

Several other studies have been done on the "N" aquifer system, but most have been focused one only one locality. Peabody Coal Company has for several years monitored conditions on and near its

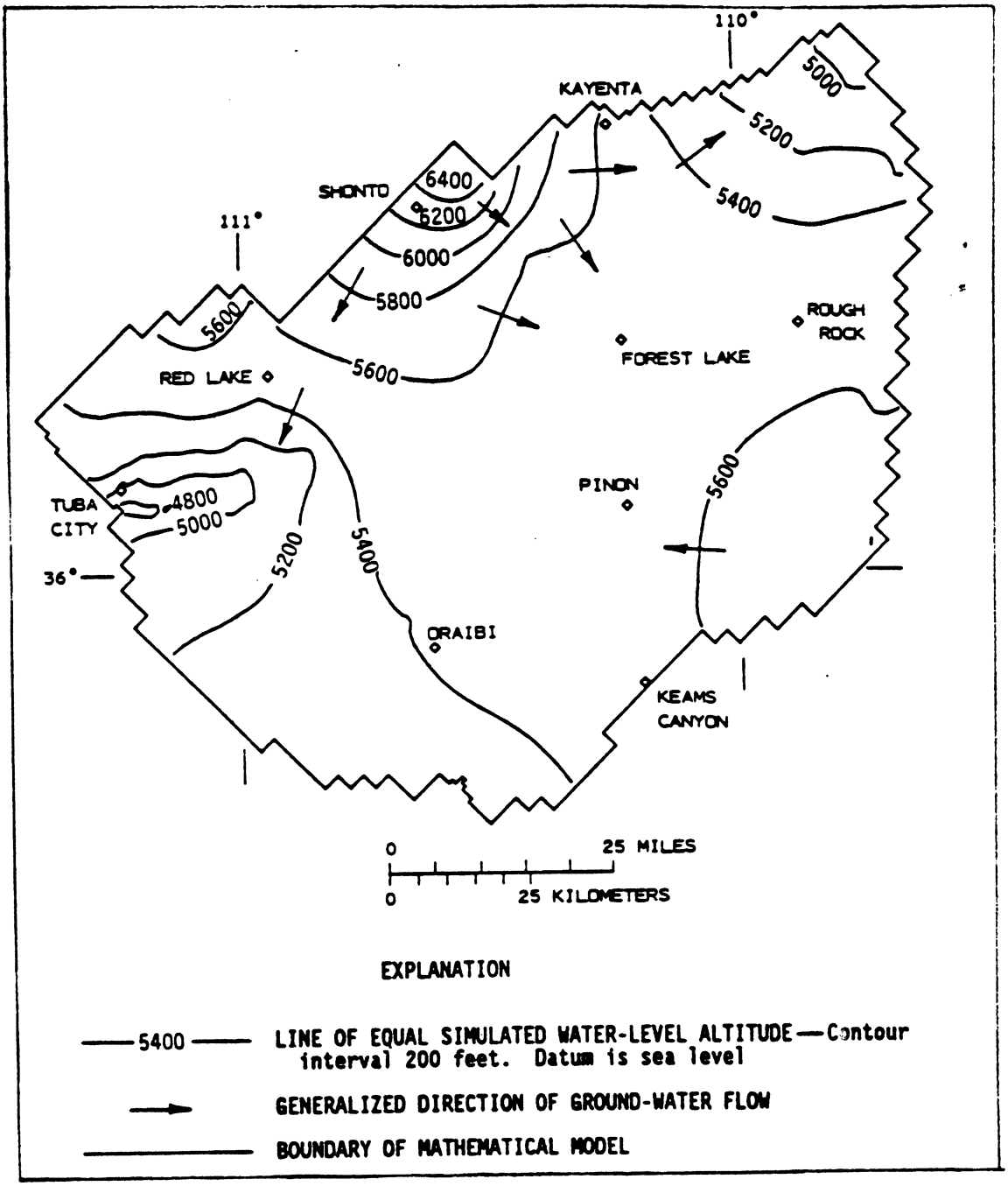


**Figure 3: Map Showing Groundwater Levels and Flow Directions for part of the "N" Aquifer System, taken from Brown and Eychaner (1988).**

Black Mesa leasehold, with particular attention paid to the "N" and "D" aquifer systems. Water levels in several wells are monitored on a continuous basis, and water samples are periodically taken for chemical analysis. Much of this data has been reported to the Office of Surface Mining, and has been examined as part of this thesis. Although Peabody Coal Company has prepared several reports on hydraulic and chemical conditions on their leasehold, these are not generally available for public distribution. Nonetheless, their leasehold is perhaps the most actively monitored locality within the area covered by this thesis.

Another intensively studied but extremely localized area is located six miles east of Tuba City in the northwestern Navajo Uplands, and consists of an abandoned mine with associated disposal ponds and tailings piles. This area is being investigated and cleaned up as a Uranium Mill Tailings Remedial Action project site by the U.S. Department of Energy (1986). Twenty-four wells and one spring were sampled in 1985 as part of the groundwater study, and the resulting chemical analyses were utilized to show movement of the contaminant plume under the mill site. Slug tests were also performed on eight of these wells, and aquifer characteristics such as hydraulic conductivity were measured. Transmissivity, storage coefficients, and hydraulic conductivities were also obtained from aquifer tests run at wells north of the former plant site.

Other localized studies have been performed by other governmental agencies. Levings and Farrar (1977a,b,c,d) prepared a

series of water-level maps for the "N" system under the auspices of the U.S. Geological Survey. The National Park Service (NPS) has performed a series of chemical analyses of water samples and pump tests to measure aquifer characteristics for their old well at Navajo National Monument north of Black Mesa. The Bureau of Indian Affairs (BIA) has also conducted water sampling for chemical analyses. The results, however, are not compiled into any one report or stored in any single repository; rather they are scattered across both Reservations in various Agency offices. The Indian Health Service (IHS) has also conducted geohydrological investigations at several localities, usually in advance of well construction. Once completed, wells are sampled and aquifer tests performed. The resulting chemical analyses and aquifer measurements are compiled into a project file for the specific wells built, which are then turned over to Navajo and Hopi authorities. One such authority is the Navajo Tribal Utility Authority (NTUA), which maintains and operates municipal water systems on the Navajo Reservation, and which keeps records on well construction at its main office. The Navajo Tribe has also compiled records for several water wells on the Navajo Reservation, although few chemical analyses for these wells are available.

The Arizona Department of Water Resources is currently investigating groundwater conditions in the Little Colorado River Basin as part of the adjudication of water rights within this basin (T. Perry, personal communication). Aquifer systems have been renamed for geological formations, with the "N" called the Navajo/Lukachukai

aquifer and the "D" called the Dakota/Cow Springs aquifer. However, most results of this ongoing study are as yet unpublished.

Several master's theses have been focused on geological processes in rocks related to the Glen Canyon Group located on or near the Navajo and Hopi Reservations. Sargent (1984) investigated intertonguing relationships between the Navajo Sandstone and the Kayenta Formation in northeastern Arizona; she found nine cyclically occurring sedimentary facies resulting from a variety of depositional environments. Three depositional episodes resulting in three major stratigraphic components in which the facies were found represent a shift from fluvial sedimentation to mixed fluvial and aeolian sedimentation to predominantly aeolian sedimentation (Sargent 1984). Luttrell (1987) performed a basin analysis of the Kayenta Formation in which petrology played a major role. She found the Kayenta Formation to be a continental redbed assemblage which could be divided into north and south regions based on differences in paleoclimatic indicators, depositional environments, and sandstone compositions. In the northern half of the basin, rivers flowing south and west deposited grains derived from uplifted crystalline rocks, sedimentary rocks, and localized metamorphic rocks (Luttrell 1987); this corresponds to the sandy facies of the Kayenta defined by Harshbarger, Repenning, and Irwin (1957). To the south, more intermittent streams flowed northwest, depositing grains derived from volcanic, plutonic, and sedimentary source rocks; the resulting sediments correspond to the silty facies of the Kayenta Formation (Harshbarger et.al. 1957).

Only a few theses have been written with the object of investigating groundwater in the study area. Ott (1981) constructed a model of the "N" system for the Black Mesa sub-basin which was independent of the better known U.S. Geological Survey model, but based on a similar finite difference computer code. Predictions based on the two models appear to be similar.

Several of these studies have provided useful information to this investigation; excellent mineralogical and hydrological data were taken from Luttrell (1987) and Ott (1981) in particular. None of these works have been oriented towards aqueous geochemistry, and certainly none have addressed the geochemical evolution of groundwater within the "N" system. The lack of information on aqueous geochemistry underlines the importance of this investigation.

## Historical Water Chemistry Data

Although processes of aqueous geochemistry acting to create differing water compositions within the project area have never been studied, water samples have been chemically analyzed by several agencies for years. The object of such water sampling is monitoring water quality. Appendix I of this thesis contains several historical water analyses. Table 1 lists several of the agencies from which well construction details and water quality data were obtained. In Table 1 the quality of information found at these agencies is subjectively assessed and assigned a ranked score from zero (non-existant) to five (excellent), based on completeness, accuracy, and relative age.

Table 1: List of Archival Sources of Well Construction and Water Quality Information.

| Agency | Data Source: Location | Office Type | Quality of Information: Chemical | Construction |
|---|---|---|---|---|
| U.S. Geological Survey | Flagstaff | sub-district | 4 | 4 |
| Bureau of Indian Affairs | Tuba City | agency | 1 | 3 |
| Bureau of Indian Affairs | Chinle | agency | 4 | 3 |
| Bureau of Indian Affairs | Ft. Defiance | agency | 2 | 3 |
| Bureau of Indian Affairs | Keams Canyon | agency | 2 | 5 |
| Navajo Water Resources Div. | Ft. Defiance | tribal | 0 | 5 |
| Navajo Water & Sanitation | various | tribal | 0 | 3 |
| Navajo Tribal Utility Authority | Ft. Defiance | water company | 4 | 3 |
| Indian Health Service | Keams Canyon | district | 4 | 5 |
| Indian Health Service | Tuba City | district | 4 | 5 |
| Office of Surface Mining | Denver | regional | 5 | 5 |
| Environmental Protection Agency | San Francisco | regional | 5 | 0 |
| Arizona Dept. Water Resources | Phoenix | state | 0 | 0 |
| Arizona Geological Survey | Tucson | state | 0 | 4 |
| Oil & Gas Commission | Phoenix | state | 0 | 4 |
| National Park Service | Ft. Collins | regional | 5 | 5 |

The Navajo Tribal Utility Authority operates its own chemistry laboratory, which has certification from the Environmental Protection Agency. Water samples are collected at regular intervals from various water systems operated by NTUA, and analyzed for major cations and anions, bacteriological counts, and radionuclide levels.

Several factors lower the accuracy of these analyses. A check of records at the Navajo Tribal Utility Authority showed that field parameters such as pH, temperature, and conductivity were not actually measured in the field. Water samples were usually collected from faucets along the water system rather than from the wellhead. While this method may result in samples representative of the water system,

it does not yield samples which represent water composition within the aquifer, since lengthy contact with pipes and the atmosphere permits changes in water chemistry. Delays of up to several months occurred between the collection of a water sample and its chemical analysis in the laboratory. Such delays permit chemical changes within the sample, and deterioration of the analytical results.

A computer listing of available water chemical analyses for the "N" system was obtained from the U.S. Geological Survey. These analyses covered a forty year span extending from 1947 to 1987. For each sample, date and time and analytical concentrations were listed. Little background information, such as field techniques, types of sampling points, preservation techniques, transportation and storage times, and analytical methods, was available. Often even the laboratory utilized for the analysis could not be determined. Such variables have changed considerably since 1947.

Of far greater value are the chemical analyses reported by the U.S. Geological Survey in the series of open file reports covering the monitoring of water levels in the "N" system around Black Mesa (Hill 1983, 1985; Hill and Whetten 1986). These samples are primarily from the wells on the Peabody Coal Company leasehold, although, since 1986, other wells from surrounding areas have also been sampled. Because field techniques, sample collection and preservation, and laboratory analysis are all to modern standards, this data can be considered highly reliable. By coincidence, some of the wells sampled by U.S. Geological Survey in 1988 were also sampled as part of this thesis.

The Bureau of Indian Affairs operates several wells at various BIA schools on both the Hopi and Navajo Reservations. These wells are sampled at regular intervals, and the waters analyzed at laboratories certified by the U.S. Environmental Protection Agency. The Bureau of Indian Affairs also operates a chemical laboratory in Gallup, New Mexico. Copies of water analyses of recent date were obtained from various offices across the Reservations, primarily the Chinle Agency office. Again, no indication of field techniques, sample and preservation methods, or storage time was provided, reducing the reliability of these reports. No water chemistry information at all could be obtained from the Bureau of Indian Affairs laboratory in Gallup.

Indian Health Service constructs wells which are then turned over to the Navajo Tribal Utility Authority on the Navajo Reservation, or to community water committees on the Hopi Reservation. Upon completion of the project, the wells are sampled and chemical analyses run. Again, field, collection, and preservation techniques, transportation and storage times, and analytical methods are not always clear, nor are records for all wells drilled in the last forty years available in the various field offices scattered across the Reservations. No records could be obtained from the Navajo area headquarters office in Window Rock. Many records are several years old, and may involve methods no longer considered acceptable.

Some chemical information incorporated into Appendix I was obtained from literature sources. The Uranium Mining Tailings Reclamation Act project near Tuba City collected water samples from 22 wells

for chemical analysis and published the results (Department of Energy 1986). No information was provided concerning field or preservation methods, storage time, or laboratories utilized.

The National Park Service provided considerable information on their well into the "N" system located at Navajo National Monument, near Shonto, Arizona. The Navajo Nation Division of Water Resources maintains records on various wells on the Navajo Reservation, but as yet has no water chemistry data. The Navajo Water and Sanitation Department operates mostly livestock wells, and does not collect or analyze water samples. The Hopi Tribal Water Resources Department is in the process of developing data base for the Hopi Reservation, has few records not available elsewhere, and does not yet collect or analyze water samples itself. The U.S. Office of Surface Mining provided chemical analyses for wells on and near the Peabody Coal Company leasehold, provided to them in turn by Peabody Coal Company. Virtually no other private well operator on either Reservation collects water samples or runs water analyses or even maintains records concerning their wells.

Unfortunately a number of problems restrict the utility of these historical analyses for evaluating water chemistry within the "N" system, as noted in a recent audit of the U.S. Environmental Protection Agency's implementation of the 1974 Safe Drinking Water Act (General Accounting Office, 1980). This report noted that no complete inventory exists of all water systems or of all water wells utilized for drinking water. The General Accounting Office also noted serious

deficiencies in sampling and analysis. These included lack of standardized sampling procedures (taking samples prior to flushing system or from contaminated sampling points thus obtaining an unrepresentative sample, not checking field parameters such as pH and temperature, inconsistent or non-existent preservation of samples), lack of training for field technicians, lack of record-keeping, transportation difficulties and consequent lengthy storage times. Due to often wide differences in analyst competency, analytical methodology, analytical equipment, and effectiveness of quality control procedures, the General Accounting Office (1980) found that most laboratories analyzing water samples from the Navajo Reservation exhibited wide ranges in accuracy and precision, often on multiple submissions of the same water sample. Water samples were collected and analyzed as part of this compliance review, yet even the General Accounting Office (1980) failed to completely report the methodolgy and results of chemical analyses of water samples which they collected, thus succumbing to the same errors which they pointed out in other agencies. Their report calls into question the validity of almost all water chemistry information historically available from the project area, and emphasizes the need for a database consisting of information gathered under one sampling methodology during one period of one year and analyzed by one analyst on the same equipment.

## Geological Description of the Study Area

The "N" aquifer system is made up of formations of the Glen Canyon Group of Jurassic age. The well-studied Glen Canyon Group can thus be considered the primary geological unit of analysis of this thesis. Its stratigraphy, lithology, and structural characteristics must be briefly described.

### Stratigraphy of the Glen Canyon Group

The uppermost formation in the Glen Canyon Group is the Navajo Sandstone of early Jurassic age (Blakey, Peterson, and Kocurek 1988). The Navajo Sandstone is described as a medium to fine-grained quartz arenite, weakly cemented with calcium carbonate (Harshbarger et.al. 1957); this lithology is remarkably consistent throughout its extent. Outcrops of this formation are extensive across much of the study area, particularly in the Navajo Uplands, and display conspicuous high-angle trough cross-stratification which identifies the Navajo Sandstone as a classic aeolian formation. Thickest to the northwest in the study area, it pinches out along the eastern and southeastern margins of Black Mesa. At Kaibito the Navajo Sandstone is 1150 ft thick, at Shonto 950 ft thick, at Kayenta 740 ft thick, at Dennehotso 478 ft thick, but only 15 ft thick west of Chinle (Harshbarger et.al. 1957). It is not found in New Mexico or on the Defiance Plateau (O'Sullivan and Green 1973).

In the northwestern portion of the study area, the Navajo Sandstone intertongues with the underlying Kayenta Formation in a

complex fashion described and analyzed by Sargent (1984). The Kayenta Formation of early Jurassic age is not divided into members, but, as thoroughly described by Luttrell (1987), distinct petrofacies are present due to lateral variations in deposition and source terranes within a single continental basin. Near Kayenta this formation is a fine-grained sandstone with some mudstone, the "sandy facies" recognized by Harshbarger and others (1957). Luttrell (1987) recognizes a subfeldspathic and a plutonic feldspathic petrofacies within this northern and northeastern division. To the southwest the Kayenta Formation grades into a series of intercalated siltstones, mudstone, and sandstone, and increases in thickness. Within this "silty facies" Luttrell (1987) recognizes a feldspathic volcaniclastic petrofacies, a mixing zone between the two. The "silty facies" of the Kayenta is not included in the definition of the "N" aquifer system, due to lower hydraulic conductivities. The "sandy facies" is 144 ft thick near Kayenta, 121 ft thick near Tsegi, and 153 ft thick near Navajo Creek; the formation thickens to the southwest as it grades into its "silty facies," becoming 495 ft thick at Moenave and 678 ft thick along Ward Terrace (Harshbarger et.al. 1957). The shift from one zone to the other is not well delineated, as it is largely buried under Black Mesa, but it does occur across much of the thesis area. Only the northeastern portion of Black Mesa and the northeastern Navajo Uplands clearly fall within the "sandy facies" of the Kayenta Formation. It is in this northeastern area that the formations of the Glen Canyon Group can most accurately be termed a multiple aquifer

system, for the "sandy facies" of the Kayenta Formation is water-bearing. This formation pinches out to the east and southeast, and is entirely absent at Steamboat Canyon.

Conformably underlying the Kayenta Formation are the two members of the Moenave Formation. The Dinosaur Canyon Member is a fine-grained to silty fluvial sandstones with some aeolian lenses, and the Springdale Sandstone Member is an aeolian sandstone. Both are spatially restricted to the western and northwestern portions of the study area. The Moenave Formation is not defined as part of the "N" aquifer system due mainly to its separation from the Navajo Sandstone but also due to its silty lithology and resulting low hydraulic conductivities. Along with the silty facies of the Kayenta Formation in the southern portion of the study area, the Moenave Formation separates the underlying Lukachukai Member of the Wingate Sandstone from the Navajo Sandstone.

The Wingate Sandstone is the lowest unit of the Glen Canyon Group, and consists of two members in northeastern Arizona. The lower Rock Point Member conformably overlies the Triassic Chinle Formation across much of the central portion of the Navajo and Hopi Reservations, but is not present to the west, north, and southeast. Here the Wingate Sandstone is not divided into members. The Lukachukai Member unconformably overlies the Chinle Formation. The Rock Point and Lukachukai Members are reported as intertongueing to the east and southeast of Black Mesa (Harshbarger et.al. 1957), but O'Sullivan and Green (1973) report unconformable contacts between the

two members. Of the two members of this formation, the Rock Point Member is now seen as late Triassic, while the Lukachukai Member is considered early Jurassic (Blakey et.al. 1988). Where the formation is undivided, north and west of Kayenta, the entire Wingate Sandstone is defined as early Jurassic (Blakey et.al. 1988). The Rock Point Member consists of a series of silty sandstone, siltstone, mudstone beds, and it is thus not defined as part of the "N" aquifer system. In contrast, the Lukachukai Member is described as a fine-grained quartz arenite with large-scale cross-stratification, an aeolian sandstone. It is a major unit the of the "N" multiple aquifer system where hydrologically connected to the Navajo Sandstone. It is approximately 300 ft thick across much of the study area (Harshbarger et.al. 1957), thinning to the west and south of Black Mesa. It is 127 ft thick at Piute Canyon north of Shonto, 17 ft thick at Navajo Creek, 74 ft thick at Dinosaur Canyon, 133 ft thick at Montezuma's Chair, and 113 ft thick at Steamboat Canyon.

The "N" multiple aquifer system is thus thickest in the northern and northeastern portions of the study area, where the Navajo Sandstone, the sandy facies of the Kayenta Formation, and the Lukachukai Member of the Wingate Sandstone are directly hydrologically connected. Figure 4 illustrates the stratigraphic relationships found along the northern portion of the study area. These rocks of the Glen Canyon Group are particularly well-exposed in the northern portion of the study area. To the south and southwest of the study area, the Moenave Formation and the silty facies of the Kayenta Formation separate the

two main water-bearing units, the Navajo Sandstone and the Lukachukai Member of the Wingate Sandstone, both of which are thinner in this direction. Here the Navajo Sandstone is the only significant formation of the "N" system.

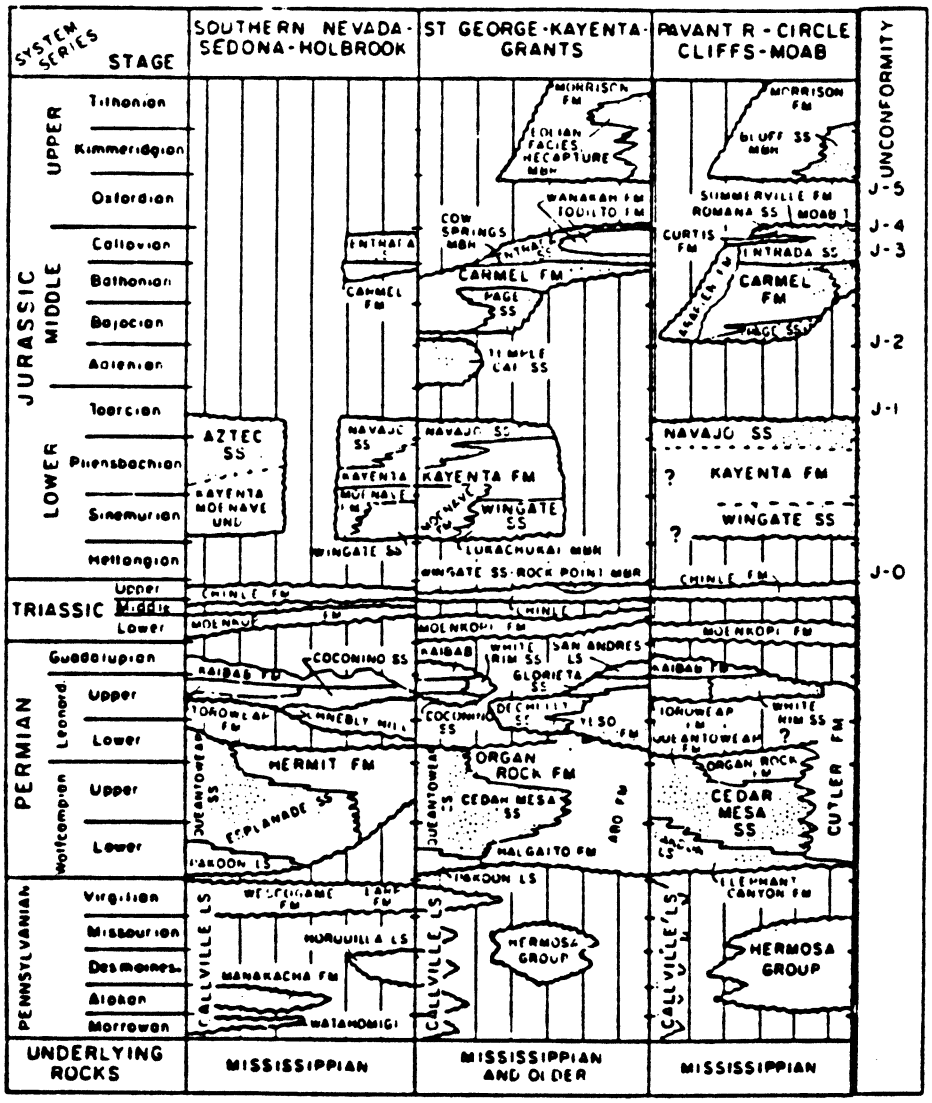


Figure 4: Stratigraphic column showing relationships and ages of late Paleozoic and early Mesozoic formations, from Blakey, Peterson, and Kocurek (1988).

Confining Layers

The silty member of the middle Jurassic Carmel Formation acts as the upper confining lay to the "N" aquifer system, wherever it is present. Where it is not present the "N" system is under unconfined or water-table conditions. The lithology of the Carmel Formation becomes progressively sandier to the south and southwest, where rocks of the "N" system thin out due to erosion or limits of deposition (O'Sullivan and Craig 1973). Above the Carmel Formation is the water-bearing Entrada Sandstone; the division between the two becomes arbitrary where the Carmel is predominantly sandstone.

The Triassic Chinle Formation, 800-1500 ft thick across most of the thesis area, acts as the lower confining layer for the "N" multiple aquifer system. Its uppermost member is the Owl Rock member, composed of limestone and calcareous siltstone (Akers, Cooley, and Repenning 1958). This unit is approximately 300 ft thick between Round Rock and Castle Butte southeast of Black Mesa, thinning to 270 ft thick near Cameron and 130 ft thick at Lees Ferry on the Colorado River (O'Sullivan and Green 1973). It has been eroded away in the Chinle Valley, but thins to the southeast of the Hopi Buttes area (Akers et.al. 1958). Below this unit lies a thick sequence of siltstones and mudstones, in which halite and gypsum beds are known to occur.

Other Aquifer Systems

The aquifer system located above the "N" system is the "D" aquifer system, comprised primarily of the Dakota and Cow Springs Sandstones, and Westwater Canyon Member of the Morrison Formation. This system is limited to Black Mesa and its immediate environs; elsewhere erosion has removed it. Figure 5 illustrates the relative positions of the "D" aquifer, the "N" system, and the underlying "C" system by means of a simplified cross-section across Black Mesa. The "D" system is currently developed almost solely for livestock use on both Reservations, due to the brackish nature of the groundwater. The "D" system contains levels of fluoride which can exceed six ppm (Cooley et.al. 1969). On Black Mesa the zone of the greatest

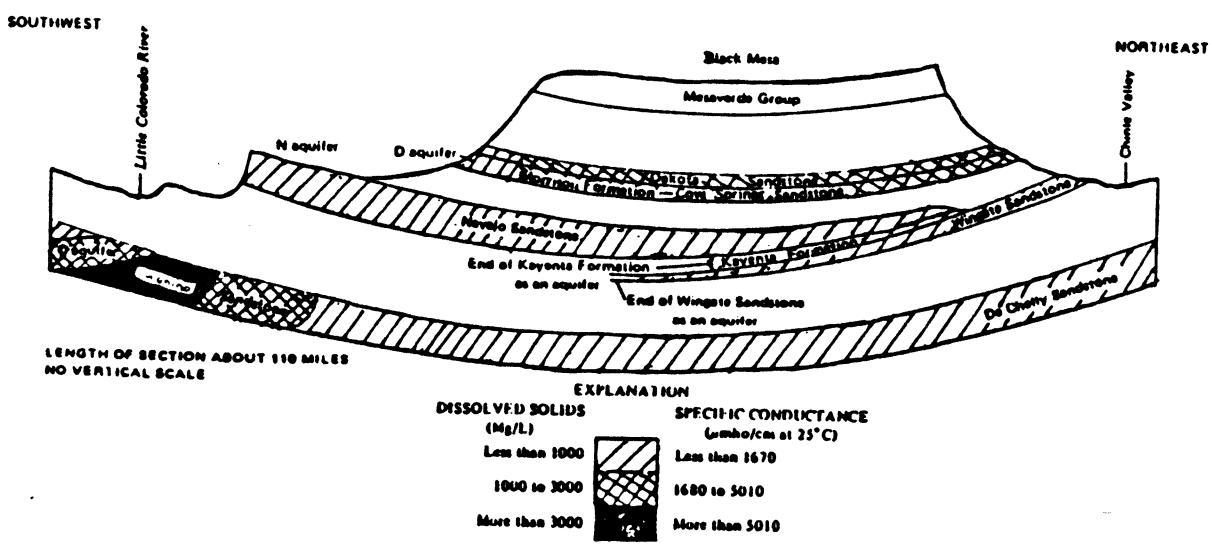


Figure 5: Simplified cross-section across Black Mesa illustrating relative positions of multiple aquifer systems.

saturated thickness of the "D" and its highest hydraulic head values overlie a major groundwater divide in the "N" system (Levings and Farrar 1977a, 1977c) from which "N" groundwaters flow both northeast and south. Eychaner (1983) has noted that concentrations of sulfate and chloride are much higher in the "D" than the "N" system, and that hydraulic heads in the "D" system are about 300 ft higher than in the "N" aquifer. Although significant leakance from the "D" to the "N" has been discounted (Eychaner 1983) for purposes of modeling water supply, it is not clear that leakance does not to a large extent determine water chemistry by means of mixing; the evidence is lacking to clearly establish its role. The possibilities of interformational leakage across the Carmel Formation and the Entrada Sandstone must be considered relatively high, particularly in the southern portion of the study area where the Carmel and Entrada become virtually indistinguishable sandstones.

The underlying aquifer system is the "C," composed primarily of the Coconino and de Chelly Sandstones, as well as the Shinarump Member of the Chinle Formation, and the Kaibab Formation. This system is by far the most widespread in northeastern Arizona, and also one of the least well-known. Few wells are drilled into this system in the Black Mesa area due to its depth. Recharge occurs along the Defiance Uplift and the Mogollon Slope (Cooley et.al. 1969), and groundwater moves east and north. Near the recharge areas the quality of "C" system groundwater is good, but dissolved solids concentrations rise as the waters flow down gradient (Daniels 1981). Dissolution of extensive

evaporite beds within the underlying Supai Group or the overlying Chinle Formation could contribute to increasing ionic concentrations (Cooley et.al. 1969); Edmonds (1967) reports sodium, bicarbonate, and sulfate as having elevated concentrations in the Sonsela Sandstone Bed of the overlying Chinle Formation. In the Chinle Valley the "C" groundwaters become confined under exposures of the Glen Canyon Group, where the "N" system groundwater is unconfined.

The possibilities of interformational leakage across the thick sequence of relatively impermeable Chinle beds from the "C" to the overlying "N" multiple aquifer system might seem remote at first glance until possible differences in hydraulic head in the Chinle Valley are considered. Potentiometric maps of the "C" and "N" aquifer systems prepared as part of an ongoing ADWR project (M. Kennard, personal communication) show the potentiometric surface of the "C" ranging from slightly greater than to nearly equal to that of the "N" in the northeastern portion of the study area, from the vicinity of Many Farms north to Dennehotso. Upward leakance is quite possible in this area, but is less likely under the eastern margins of Black Mesa, where the "C" potentiometric surface is several hundred feet lower than the "N" surface. There is also a possible source of elevated sodium, chloride, and bicarbonate concentrations in the "C" aquifer south of the study area. Flow lines suggest that even along the southern margins of the study area, flow in the "C" aquifer is east to west, with virtually no possibility of northward movement of groundwater from the saline Holbrook Basin area.

Structural Elements of the Southwestern Colorado Plateau

Geological structures on the southwestern Colorado Plateau affect groundwater flow, and thus are important in the geochemical evolution of groundwater within the "N" system. The main structural elements include monoclinal folds, normal faults, and extensive jointing. Figure 6 illustrates many of the major structural features of northeastern Arizona. Scattered volcanic features of Tertiary age are also related to these structural elements.

Folds occur across the study area, and while many are not well expressed in topography, the large monoclinal folds are striking prominent. Davis (1977) has recognized two major orientations in fold patterns on the Colorado Plateau, trending N20$^{0}$W and N55$^{0}$E, resulting from reactivated fault orientations in the underlying Pre-Cambrian basement rocks over which younger rocks have draped. Within the study area large monoclinal folds, the Cow Springs and Red Lake Monoclines, form the boundaries of the Black Mesa sub-basin on the northwest and west. The Echo Cliffs and Organ Rock Monoclines form the western and eastern edges of the northern half of the study area itself. The Cow Springs and Red Lake Monoclines also mark the division between confined and unconfined conditions within the "N" aquifer system west and northwest of Black Mesa. The total hydrological effect of these large drape folds, however, is not totally clear.

Numerous anticlines and synclines also exist within the study area, and while less prominent, may exert considerable influence on hydrological characteristics. The large Black Mesa syncline runs

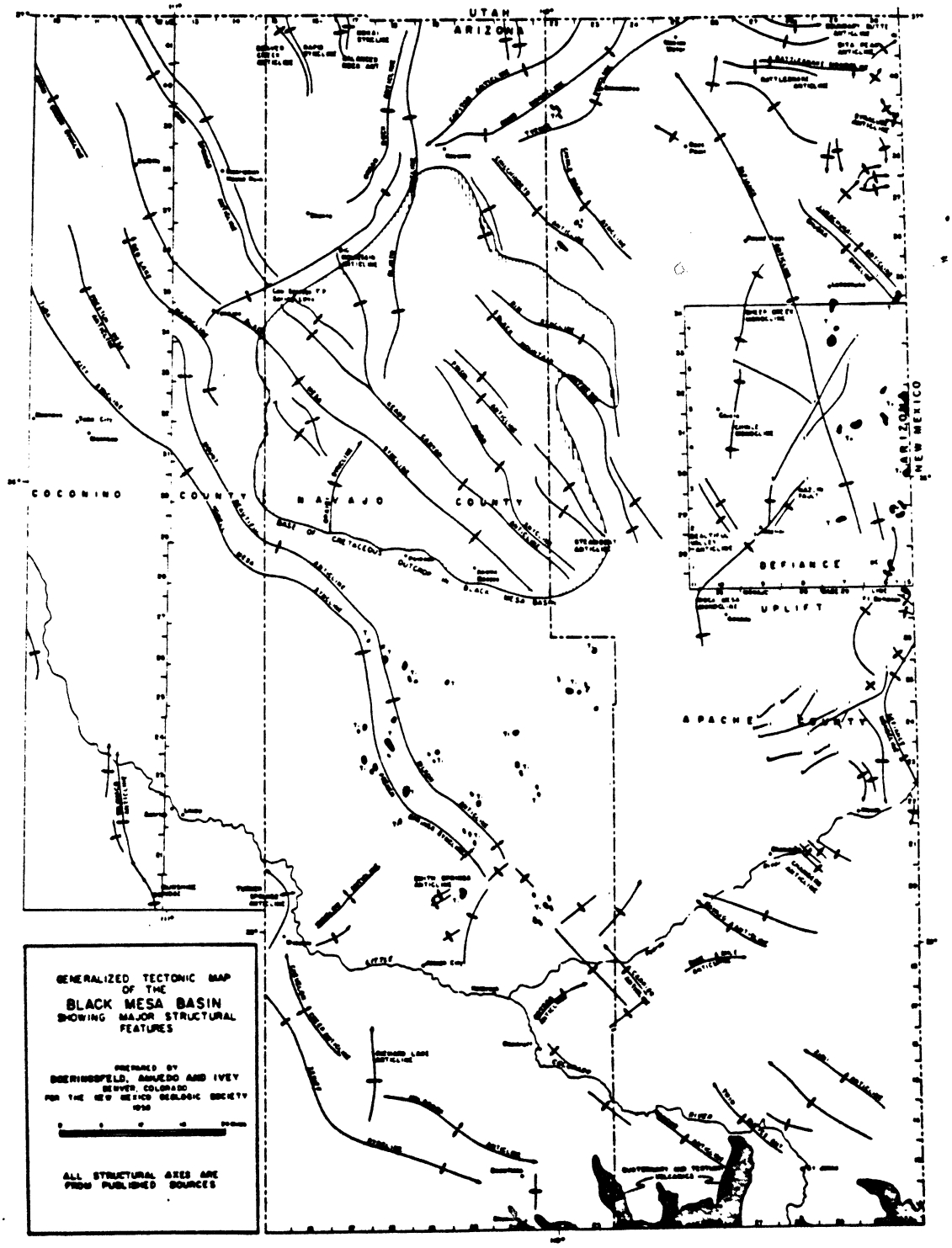


Figure 6: Map showing locations of major structural elements of northeastern Arizona, note numerous folds under southeastern Black Mesa; from Doeringsfeld, Amuedo, and Ivey (1958).

north-northwest to south-southeast through the Kaibeto Saddle under Black Mesa. A large syncline running northeast through the Tyende Saddle may determine a groundwater flow divide in that area.

Several folds underlie the southeastern and eastern margins of Black Mesa. These include the Rim Syncline, Black Mountain Anticline, Pinon Anticline and Syncline, and the Keams Canyon Anticline. Although they may not be surficially expressed, faults often accompany such folds, providing conduits for vertical groundwater movement. Interestingly, this area underlies the area of "D" system recharge, as well as one of the major groundwater divides for the "N" system from which groundwaters flow both south towards the Little Colorado River and northeast towards Laguna Creek and Chinle Creek (Levings and Farrar 1977a).

Faults in the study area tend to be normal, high-angle, and with the exception of reactivated high-angle Pre-Cambrian basement faults, exhibit small displacements. Few truly major fault systems, such as occur in the Grand Canyon area (Huntoon 1969), have been mapped. A few faults have been mapped in the area of Navajo Mountain, but these probably have little effect on groundwater flow. By far the majority of faults have been mapped in the northwestern portion of the thesis area, between Kaibeto, Copper Mine, and Page. Orientations of these faults are both parallel and transverse to the trends of the numerous synclines and anticlines also running through the area. The groundwater divide mapped by Levings and Farrar (1977b) occurs in this area, and may be related to these numerous faults.

Jointing is prominent across the Colorado Plateau, occurring in all kinds and ages of rocks (Kelley 1966). Unlike the folds, joints are probably the result of several tectonic forces and thus of several diverse ages (Kelley 1966). In the Black Mesa basin fractures are poorly exposed due to aeolian sand, vegetative cover, and mud derived from the Mancos Shale. Three trends have been noted, to the northwest, to the northeast, and a minor westerly trend. Towards the northwestern portion of the study area, in the Kaibeto Saddle, fracture trends are northeasterly, northerly, easterly, and less prominently northwesterly, and are much better exposed at the surface. There seems to be little relationship to the northwesterly folds crossing the area (Kelley 1960). West of Black Mesa most joints trend northerly, and several small faults occur parallel to the crest of the Preston Mesa anticline. Northeast of Black Mesa on the Tyende Saddle jointing tends to be northerly, although some northwesterly and westerly trends have also been mapped, despite extensive sand cover. North of Black Mesa jointing trends are irregular and diverse, with no consistent relationship to the numerous steep folds which run across the area (Kelley 1960). It seems likely that joints are vital to recharge of the "N" aquifer system, given their ubiquity and prominence across outcrops of the Glen Canyon Group. They also contribute significantly to the development of secondary permeability.

Occasional volcanic features are scattered across the thesis area. The Hopi Buttes volcanic field is the most prominent zone along the southern reaches of the "N" aquifer system, and volcanics appear

to overlie the Lukachukai Member of the Wingate Sandstone near its pinchout near Dilkon. Plugs and dikes occur between Kayenta and Rough Rock, generally following jointing trends. Dikes north of Tuba City also follow fracture patterns. These volcanic features are important in that they introduce differing mineralogies along the groundwater flow path; they extent to which they contribute to controlling water-rock reactions is limited by their restricted geographic extent.

## Description of Hydrological Characteristics

The "N" aquifer system is both confined (its full thickness is saturated and the water is under pressure) and unconfined. The limits of the confined portion of the aquifer generally coincide with the limits of the overlying confining layer, the Carmel Formation, and thus with the limits of Black Mesa. Figure 7 illustrates areas in the vicinity of Black Mesa which are confined versus unconfined areas, and shows flow directions as formerly interpreted. Elsewhere within the thesis area the aquifer system is under water table conditions; the aquifer is only partially saturated. Water-table conditions prevail in the Navajo Uplands west, northwest, north and northeast of Black Mesa, and in the eastern portion of the aquifer in the Chinle Valley. White Mesa, composed of later Mesozoic formations, overlies "N" rocks north of Black Mesa, but water in the "N" system is apparently still unconfined under this smaller physiographic feature.

Direct recharge to outcrops of the Navajo Sandstone takes place in the Navajo Uplands portion of the thesis area, mostly between the

Echo Cliffs and Monument Valley (Cooley et.al. 1969). Direct recharge to the Lukachukai Member of the Wingate Sandstone occurs in the southern portion of the Chinle Valley (Eychaner 1983). McGavock and Levings (1973) report that all recharge to that portion of the aquifer under confined conditions occurs as direct recharge to "N" rocks exposed between Shonto and Black Mesa. Ott (1981) notes that

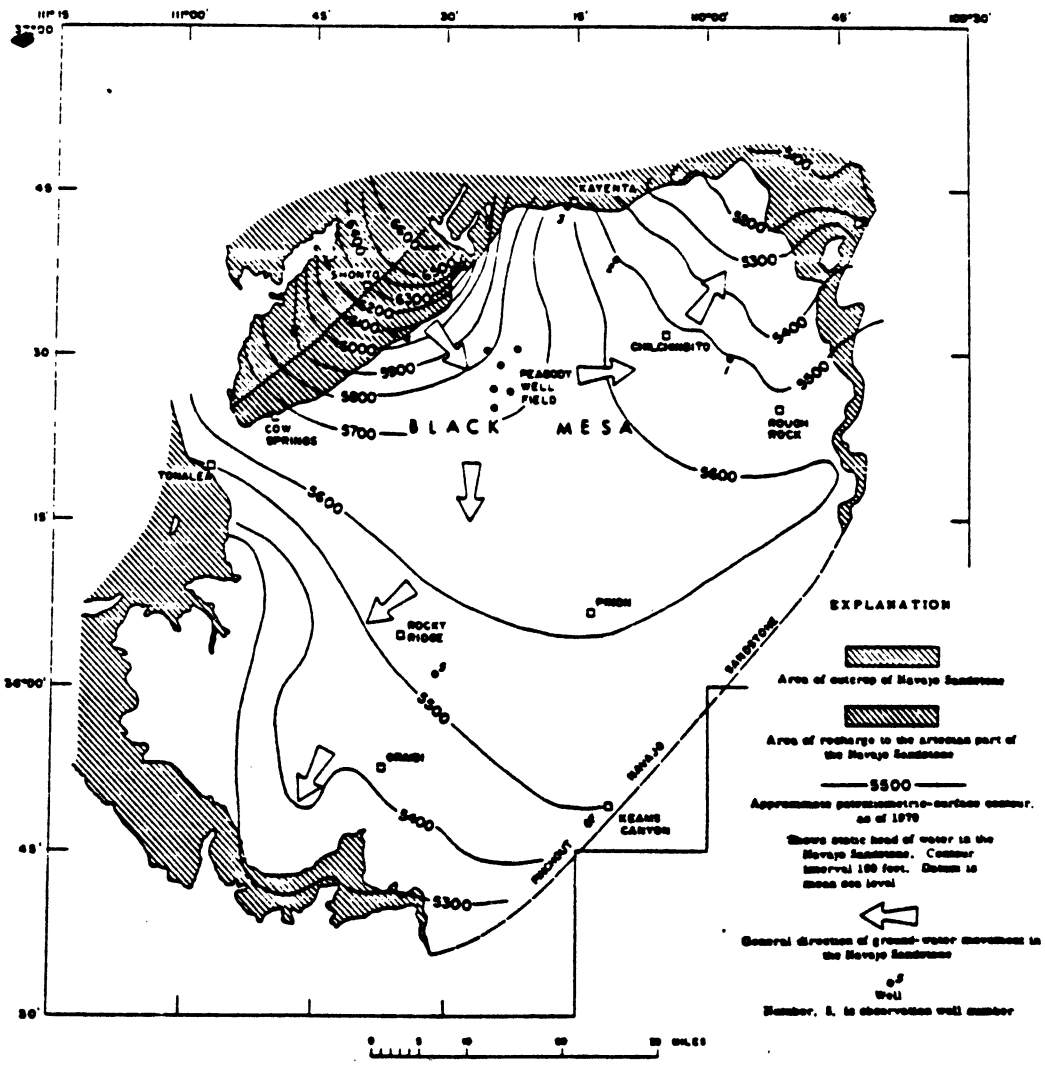


Figure 7: Map showing confined versus unconfined (shaded) areas near Black Mesa, from McGavock and Levings (1973).

considerable recharge occurs along the interior drainages of Shonto and Begashibito Washes, which empty into a small ephemeral lake near Cow Springs formed by dune sands separating it from Moenkopi Wash. Recharge results from winter precipitation; flashy summer storms contribute little to groundwater recharge (Ott 1981).

The actual mechanisms of recharge are unclear, but may involve several of the hypothesized scenarios below. a) Dune fields are common in the Navajo Uplands, and dunes may contribute to recharge in that they store precipitation which otherwise would be lost to evaporation, and allow it to percolate into the underlying outcrop. b) Severe structural deformation north of Black Mesa also likely contributes to recharge by providing joints which greatly increase secondary permeability, and allow precipitation to percolate directly into the rock. c) Rock pools found on the surface of the Navajo Sandstone can hold preciptation for several days, allowing it to percolate into the rock, and form a point of entry into the system. This postulated mechanism, however, is limited by the small size of these pools, and by clays which accumulate along the bottom and reduce porosity. d) Alluvium in direct contact with "N" system rocks can store runoff, allowing that portion which does not re-enter the wash system to percolate down and into the underlying sandstone.

Natural discharge occurs along several streams. To the northwest Navajo Creek, which is perennial in some reaches and flows directly into the Colorado River, would appear to receive considerable discharge from the "N" aquifer. To the northeast Laguna Creek is also

perennial in stretches between Navajo National Monument and Kayenta (Cooley and others 1969), and probably receives considerable input from the "N" aquifer system, across which it flows to eventually join Chinle Creek. To the east Chinle Creek is the major stream, tributary to the San Juan River, but it is totally unclear how much of a contribution to its flow is made by the "N" aquifer system. Many of its tributaries draining Black Mesa to the west probably receive inflow from springs discharging the "N" system. Many springs contribute significant amounts of water to Moenkopi Wash and the other washes draining Black Mesa to the southwest, all of which are tributary to the Little Colorado River. Moenkopi Wash would appear to receive the greatest inflow, as it has been reported as perennial near Tuba City in the past (Cooley et.al. 1969). Discharge varies seasonally, with the greatest amounts in the winter and spring (Ott 1981), and is likely to be hidden in the alluvium of dissected washes, where it is mixed with discharge from other aquifer systems such as the "D" system.

Groundwater flow has been reported by most authors as moving from recharge areas around Shonto and Navajo National Monument south under Black Mesa, hence either southwest or east and northeast (Cooley et.al. 1969, Ott 1981, McGavock and Levings 1973). Brown and Eychaner (1988) also show groundwater moving north and west from the southeastern and eastern margins of the "N" system near the Chinle Valley. Maps have shown a groundwater divide running southwest and northeast from the vicinity of Kaibeto to the Copper Mine area

(Levings and Farrar 1977b). Another groundwater divide has been proposed from Shonto south and southeast through Black Mesa, dividing the Black Mesa and Monument Valley sub-basins. These boundaries are based on potentiometric highs, and can change location with changing piezometric surfaces (Ott 1981). Geological factors governing the location of these flow divides remain unexplained, and indeed, it is not clear how large a role geological factors play in the determination of hydrological characteristics such as flow divides. Water can be in transit for several thousands of years, judging from the single reported radiocarbon date of 15,500 years for an area less than eight miles distant from the edge of the recharge zone (McGavock and Levings 1973).

# CHAPTER 3

# FIELD AND LABORATORY METHODS

## Introduction

This chapter covers the methods used to collect snow and water samples from the study area, field analytical and preservation techniques, and analytical methods utilized in the laboratory to ascertain concentrations of cations and anions. Possible sources of sampling and analytical error are also reviewed. Such a methods review is necessary in order to establish the quality of water chemistry data.

Information retrieval and field sampling proceeded in several phases. These phases included retrieval of archival information, inspection tours of various wells, collection and analysis of snow samples, collection of water samples from pumping wells, measurements of field parameters, transportation and analysis of the various samples in the laboratory. These phases often overlapped, with archival searches done, for example, whenever the need for additional information arose. Samples were analyzed as quickly as possibly upon returning from the field, prior to the next field trip, so that sample collection and analysis proceed concurrently.

## Archival Searches and Field Inspections

Archival information was gathered from a variety of sources. The information sought included details of well construction such as total depth, casing depth, perforated intervals, types of pumps, construction dates, as well as hydrological information such as static water levels, pump test results, and the dates various measurements were taken. Historical chemical analyses were particularly sought out. Naturally water resource offices of both the Navajo and Hopi Tribes were first approached. Personnel in these offices were quite helpful in providing full access to whatever limited information was available on specific wells. Agency offices of the Bureau of Indian Affairs (BIA) in Tuba City, Chinle, Ft. Defiance, and Keams Canyon also provided considerable amounts of information, although, as discussed in the previous chapter, this data was often limited in scope and reliability. Offices of the Navajo Tribal Utility Authority (NTUA), particularly the main office in Ft. Defiance, provided free access to laboratory analyses and well records. Field offices of the Indian Health Service (IHS) across both Reservations proved important sources of data. The various Operations and Maintenance offices of the Navajo Tribal Water and Sanitation Department were also visited for information, particularly for those windmills falling under their jurisdiction. The U.S. Geological Survey provided computer printouts of historical chemical analyses and well construction details for wells developed into the "N" system, and allowed free access to well folders.

After archival information had been gathered for specific wells of interest, field inspection tours were made prior to sampling to determine the condition of these wells and their suitability as sampling points. Often wells were found to be abandoned and capped. Very often well pumps were broken and the wells consequently no longer used, although they still existed; this was particularly true of windmills. Points near the wellhead to which the sampling apparatus could be attached were not available on several wells. For those wells which were obviously unsuitable for sampling, alternates were found during these field inspection tours, and then archival sources were revisited to obtain information on these alternative wells.

## Snow Sampling

Because snowmelt constitutes the major source of direct recharge to outcrops of "N" system rocks (Cooley et.al. 1969, Ott 1981), the snow pack of northeastern Arizona was sampled to determine the chemical composition of snowmelt prior to its entry as recharge into the "N" system. Precipitation is not pure and free of inorganic chemicals as it falls (Taylor 1987, Colbeck 1981). One must know the initial composition of recharge waters, particularly for the "N" aquifer system, since the recharge waters are little affected by processes in the largely absent soil zone. Knowledge of actual chemical constituents is vital in modeling the first stages of the geochemical evolution of the groundwater; the water chemistry of the snowmelt becomes a true inital solution.

Eight snow sampling locations were selected across the northern portion of the study area where the Navajo Sandstone is best exposed. They ranged from Navajo National Monument in the east to Kaibeto in the west, but are clustered within 30 miles of Shonto, the location most often named as the prinicipal recharge area (Cooley and others 1969, Ott 1981, Eychaner 1983). Table 2 lists the sample locations, along with pH values, conductivity values, and the final temperatures after each sample had been measured for pH and conductivity. Locations are given in terms of Universal Transverse Mercator coordinates, both in Table 2 and most subsequent tables, since this system is world-wide, measured in meters, and can be used in computer mapping; other locational systems in northeastern Arizona are confusing, duplicative, unfamiliar to most people, and cannot be used in computer mapping. A concentrated effort was made to gather all the snow samples in one field trip, in order to minimize any differences due to differential melting over time. Samples were taken from the thickest portions of the snowpack at each sampling location. Samples at most locations probably do not represent snowfalls throughout the winter season, but only drifts of the latest heavy snowfall which occured about a week prior to sample collection. However, samples taken at Navajo National Monument and at Navajo Mountain may represent several preserved snowfalls; at these points small trenches were cut with a trowel rinsed in distilled water, and some evidence of layering within the snowpack was observed.

Table 2: Snow Sample Locations, pH Values, Final Temperatures, and Conductivites

| Sample Number | Sample Location | UTM Northing | UTM Easting | Melting Temperature (degrees C) | pH | Specific Conductiv (mV) |
|---|---|---|---|---|---|---|
| 1 | Navajo Nat'l Mon | 4059150 | 541000 | 13.9 | 8.48 | 7 |
| 2 | Navajo Nat'l Mon | 4059150 | 541000 | 12.6 | 8.52 | 8 |
| 3 | Shonto TP | 4050650 | 534400 | 13.8 | 8.15 | 7 |
| 4 | Navajo Creek | 4051200 | 515050 | 12.5 | 6.48 | 7 |
| 5 | Navajo Mtn. | 4110000 | 520000 | 13.2 | 6.84 | 9 |
| 6 | Navajo Mtn. | 4110000 | 520000 | 12.9 | 6.05 | 9 |
| 7 | Piute Canyon | 4078450 | 526450 | 10.2 | 8.33 | 10 |
| 8 | Kaibeto | 4043700 | 492600 | 10.5 | 6.81 | 12 |
| 9 | Wildcat Peak | 4025700 | 497850 | 10.9 | 6.84 | 12 |
| Mean= | | | Mean: | 12.28 | 7.39 | 9.00 |
| Std. Dev.= | | | Standard Deviation: | 1.32 | 0.91 | 1.89 |

In order to sample the full anticipated depth of the snow pack, a snow sampling tube was constructed of two inch diameter Schedule 40 PVC pipe. One end of the five foot long pipe was closed with a removable plug, while a sharpened coupling was attached to the other end to act as a bit. The device was built on the model of a Bureau of Reclamation snow depth measuring tube, with chemically inert PVC substituted for stainless steel. This device was acid-washed prior to the snow sampling field trip, and was rinsed with distilled water between each sample. The bit was detached and stored in a sealable plastic bag, and the tube closed during travel between collection sites in order to minimize contamination with dust or dirt.

The snow sample was taken by ramming the tube into the snow pack, and emptying the contents into sealable plastic freezer bags. Amounts taken averaged about a quart. Samples were doubled-bagged in freezer bags to minimize contamination or leakage. Samples were transported back to Bilby Research Center in a frozen state; no other preservation method was attempted.

A few samples were taken in a slightly different manner, by digging a small hole into the snowpack with a stainless steel trowel, also acid-washed prior to the field trip, and then scooping up snow from the excavation wall into plastic freezer bags. The trowel was rinsed with distilled water prior to sampling, and was stored itself in a freezer bag. This additional method was carried out with the goal of examining differences between the two methods; it was felt that digging out snow from below the snow pack surface might eliminate any contamination from surface dust, which would be picked up in the sampling tube with the sample column.

Several sources of sample contamination which could skew the analytical results can be found in the sampling process. Falling plant debris such as pine needles or bark could introduce organic components with which snowmelt could react. Changes in concentrations result from alternate melting and freezing over time, particularly within the first portions of meltwater to undergo such cycles (Johannessen and Henriksen 1978). Dust is a major source of contamination (Legrand, Aristarain, and Delmas 1982), particularly if several snowfalls have left a multi-layered snowpack with each level

exposed for some time to the surface. Handling samples with plastic gloves, rinsing equipment with deionized water, and double bagging can minimize chances of contamination during the sampling process (Taylor 1987); only the first technique was not utilized in this study.

The freshest snows collected had been on the ground over a week, and no further snowfall was recorded due to the end of the winter. No rain was collected during the summer for analysis since summer precipitation is described as a minor source of recharge (Cooley et.al. 1969, Eychaner 1983, Ott 1981).

Once transported back to Bilby Research Center, the double-bagged snow samples were stored in a freezer a few days until analysis. The snow samples were placed in a refrigerator to slowly melt, which required two days; slow melting allowed sample temperatures to remain at about $4^0$ C to preclude any bacteriological activity that would affect the dilute concentrations in the meltwater. The samples were not melted in an inert gas atmosphere container, and remained in contact with the room air. The meltwater was then filtered through a 0.2 micron Millipore filter and collected in acid-washed polypropylene bottles, with each bag yielding about 200 ml of water. These procedures are similar to those recommended by Taylor (1987), again with the exception that plastic gloves were not worn.

The first parameter measured was pH. An Orion 701 meter with a Corning combination electrode was used, after calibration with standard buffer solutions. Sample water, still at $4^0$ C, was placed in a beaker and the electrode inserted and readings taken. The resulting

values, along with the temperatures recorded at the end of the initial measurements (room temperatures), were presented in Table 2.

A problem was quickly noted. Measurements did not stabilize, and shifted over time from about 8.5 to 7.0 as the sample water remained in contact with the room atmosphere and quickly heated to room temperature. The problem might have been avoided had the samples been melted in an atmosphere of inert gas such as nitrogen. It seems likely that contact with carbon dioxide in the atmosphere caused the pH shift observed. It also seems likely that such a shift would also occur in meltwater entering the "N" aquifer system as direct recharge, since the snowpack has sufficient pore spaces to allow atmospheric contact with the meltwater prior to its infiltration; indeed, near the ground surface cavities occasionally develop on the bottomside of the snow pack.

Specific conductivity was also measured, but found to be uniformly low. Alkalinity titrations were done for each sample, and the results, reported in meq/l and in mg/l, also were uniformly low. Given the pH range, alkalinity may be considered to be dominated by the bicarbonate anion, which the titration measured. Fluoride was measured with the selective ion electrode, but in each sample levels were below detection limits. Cation concentrations were measured on the flame atomic absorbtion spectrophotometer, as described in a following section. Anion concentrations were run on the ion chromatograph, as described in a following section. Results are listed in Table 3 for each sample, along with statistical means and

standard deviations from that mean. Any concentration falling beyond one standard deviation from the mean attracted particular attention.

Table 3: Chemical Constituents of Snow Samples

| Sample Number | Alkalinity (meq/l) | Alkalinity (mg/l) | Calcium (mg/l) | Magnesium (mg/l) | Sodium (mg/l) | Potassium (mg/l) | Chloride (mg/l) | Nitrate (mg/l) | Sulfate (mg/l) | Phosphate (mg/l) | Ammonia (mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | unknown | unknown | 0.31 | 0.03 | 0.10 | 0.10 | 0.08 | 0.16 | 0.14 | 0.00 | 0.02 |
| 2 | 35.20 | 0.70 | 0.26 | 0.03 | 0.10 | 0.10 | 0.14 | 0.30 | 0.41 | 0.00 | 0.02 |
| 3 | 70.40 | 1.41 | 0.45 | 0.07 | 0.80 | 0.50 | 0.69 | 0.75 | 0.91 | 0.03 | 0.43 |
| 4 | 158.40 | 3.17 | 2.72 | 0.05 | 0.10 | 0.00 | 0.25 | 0.37 | 0.42 | 0.00 | 0.00 |
| 5 | 52.80 | 1.06 | 0.62 | 0.07 | 0.20 | 0.10 | 0.22 | 0.89 | 0.56 | 0.00 | 0.00 |
| 6 | 26.40 | 0.53 | 0.25 | 0.04 | 0.20 | 0.00 | 0.12 | 1.23 | 0.66 | 0.00 | 0.04 |
| 7 | 88.00 | 1.76 | 0.84 | 0.11 | 0.30 | 0.50 | 0.52 | 0.09 | 0.50 | 0.04 | 0.00 |
| 8 | 83.60 | 1.67 | 1.21 | 0.13 | 0.20 | 0.30 | 0.26 | 0.41 | 0.63 | 0.00 | 0.00 |
| 9 | 123.20 | 2.46 | 1.18 | 0.12 | 0.60 | 0.30 | 0.31 | 0.42 | 1.07 | 0.00 | 0.31 |
| Mean= | 70.89 | 1.42 | 0.87 | 0.07 | 0.29 | 0.21 | 0.29 | 0.51 | 0.59 | 0.01 | 0.09 |
| Std. Dev.= | 46.49 | 0.93 | 0.74 | 0.04 | 0.23 | 0.19 | 0.19 | 0.35 | 0.26 | 0.01 | 0.15 |

As can be seen in Table 3, the greatest variability in any single constituent occurred in calcium, which exhibited the lowest concentrations in samples taken from the deepest snowpacks and the highest concentrations in samples removed from shallow beds of snow representing only the latest snowfall. Reasons for this calcium enrichment are unclear. It would be expected that deeper snowpacks, have had a longer period of time to equilibrate with the atmosphere and take in more carbon dioxide, would have lower pH values, and thus contain larger concentrations of calcium. Yet it is the more shallow,

fresher snowpacks that have the higher concentrations. Similar patterns occur in alkalinity values, but not in magnesium concentrations.

Other constituents displaying considerable variability included sodium, chloride, nitrate, sulfate and ammonia. Sodium and chloride were equally high in Sample 3, which might be taken as evidence of contamination from handling the sample without gloves. Sodium was also higher than expected in Sample 9, and the reason is unclear. Chloride was also slightly higher than expected in Sample 7, for unknown reasons. Nitrate levels were quite high in the two samples from Navajo Mountain, and again the reason is unclear, since nitrate levels were appreciably lower in the other samples taken from a deeper snowpack. Sulfate levels were elevated beyond one standard deviation from the mean in Samples 3 and 9. Ammonia levels were elevated in the same two samples. Sulfatte and ammonia might be taken as evidence of airborne pollution, such as might be expected downwind from the coal-fired Navajo Generating Station at Page, Arizona, but Sample 3 is from Shonto, much farther downwind than Samples 8 and 9, and Sample 8 did not exhibit unusually high levels of sulfate and ammonia. It should be noted that all concentrations are relatively low, and all variability could be explained solely as statistical sampling error during analysis.

When viewed as sampling locations, Samples 3 and 9, from Shonto and Wildcat Peak respectively, displayed the highest concentrations in most categories. Sample 3 was taken with the stainless steel trowel,

due to the shallowness of the snowpack at that location. Sample 9 was taken with the PVC snow sampling tube, so differences in sampling techniques do not explain their elevated concentrations. For the two locations sampled in pairs with the two techniques, the stainless steel trowel seemed to deliver higher concentrations for most ions except calcium. The reason is not clear.

## Water Sampling and Field Analyses

Water sample collection from the finalized sampling points consumed several months of field effort. This phase of the thesis project was carried out in conjunction with a large sampling program undertaken by Hydro Geo Chem, Inc., on behalf of the Bureau of Indian Affairs, Branch of Rights Protection. As a consequence and a benefit, much of the sampling plan was dictated by the needs of the Hydro Geo Chem program. The goal of their program was to obtain well-controlled isotopic and water samples from that portion of the aquifer system falling within the Little Colorado River Basin in order to calibrate a regional groundwater flow model with water chemistry, so the widest possible areal extent is reflected in their selection of sampling points, which are shown in Figure 8.

As part of the Hydro Geo Chem sampling program, 20 wells were selected from wells known to be developed solely into the "N" aquifer system. These wells formed the core of the thesis sampling plan. But the thesis area extends beyond the area covered by the Hydro Geo Chem model, so additional sampling points were required, particularly to

the northwest. Wells were selected for additional sampling points on the basis of geographic position, suitability for sampling, and the

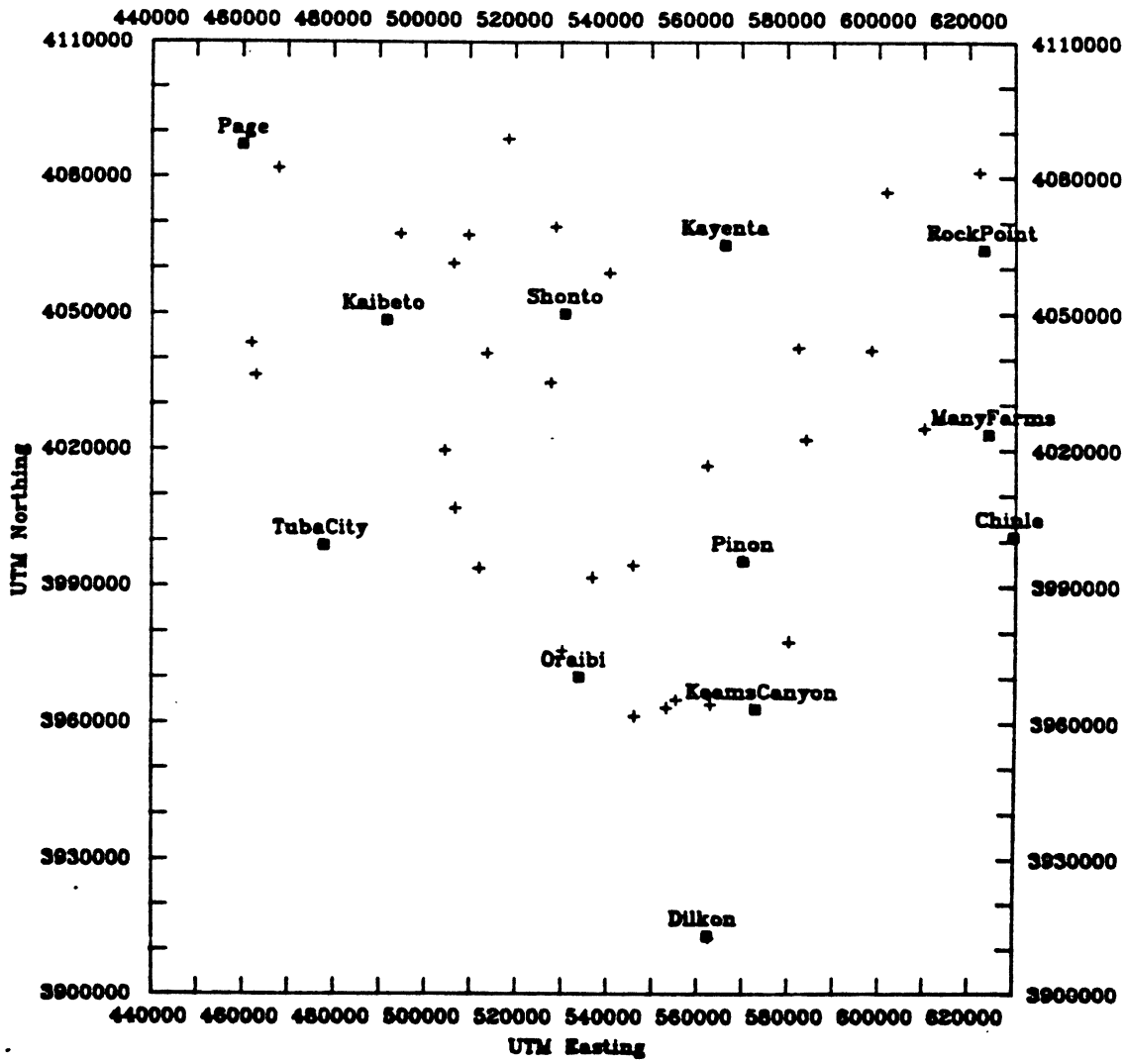


Figure 8: Map showing locations of sampling points within the "N" aquifer system, as well as "D" wells sampled.

amount of well construction information that could be found for that well. Wells were also selected to provide sampling points along flow paths so that changes in water chemistry from one point to the next could be observed. A total of 43 wells and one spring were sampled for the thesis. Of the three sub-basins, Black Mesa was the best sampled and Monument Valley the least sampled, due to the lack of wells available in that area. All wells sampled were pumping wells.

Wells equipped with electric submersible pumps had sampling bibs attached near the wellhead. Windmills chosen for sampling as part of the Hydro Geo Chem project were fitted with one inch couplings about one foot above the flat plate by tribal personnel; another coupling was placed over a hole cut through the flat plate to allow water level measurements. This allowed connection with the sampling apparatus near the wellhead. However, no such fittings were installed on additional windmills selected for thesis sampling. These windmills were sampled at the discharge pipe where it emptied into the storage tank or near the top of the standpipe where the discharge pipe was connected by a union. Windmills were only intended to be sampled when a steady wind was available for pumping, and although field realities often dictated sampling during light and unsteady winds, this intention was generally achieved.

## Serial Sampling

Accurate characterization and analysis of groundwater depends heavily on the appropriate sampling procedure. The goal of an

appropriate sampling procedure is to obtain water samples and selected field parameter measurements which adequately represent that region of the aquifer system around the sampling point. The water samples must have minimal contamination from anthropogenic influences and surface conditions.

Serial sampling was the method used to determine when pumped waters were free from human contamination, contamination from the well casing, and representative of groundwater within the "N" aquifer system. Serial sampling consisted of in-line flow cell measurements of pH, temperature, and specific conductance for two to six hours until these parameters exhibited stability. An easily measured field parameter, pH is sensitive to species in the water. A Hach pH meter and combination electrode was employed, sensitive to 0.01 pH units. The electrode seemed to more quickly stabilize than other electrodes. Water temperature fluctuates with changes in surface temperature, especially at low flow rates, and its stability reflected aquifer conditions. Temperature was measured with a glass bulb mercury thermometer marked in increments of $0.01^{0}$ C, until all thermometers broke; then temperatures were read from the conductivity probe. Specific conductance depends upon temperature and the total dissolved salts in solution, which might result from casing contamination, and is also easily measured in the field. A Hach conductivity meter, calibrated daily, was utilized for this parameter. It also measured total dissolved solids and temperature.

The flow cell itself consisted of PVC pipe designed to be immersed in a water bath to maintain constant sample temperatures. The flow cell is attached to the sampling bib or coupling near the wellhead via chemically inert plastic tubing; outside air never enters the system. Four outlets allow insertion of pH and conductivity probes and the thermometer through a diaphragm or rubber grommet such that pumped well water flows continuously over the instrumentation while remaining free of atmospheric contamination. The water bath also allows temperature equilibration of standard buffer solutions used in pH meter calibration, since a critical concern is that standards be of the same or similar temperature as waters to be measured. The same applies to conductivity standards. Flow rates through the cell were never high enough at windmills to provide any flow potential effects on pH readings; at electrically pumped wells the rate was kept low by turning down the sampling faucet.

Serial measurements were taken at 10 to 15 minute intervals over a two to six hour period. Measurements were documented on forms and in field notebooks, and the pH, temperature, and specific conductance numbers for each well in Appendix II are the final serial measurements recorded. Rates of change were followed. Temperature was found to be consistently the most stable measurement; specific conductance usually exhibited the greatest variability. Stability was deemed to have been achieved when measurements of pH and specific conductance varied less than 3% over three consecutive measurement periods. Regardless of apparent stability, at least three well volumes were pumped from the

well over the course of the serial sampling period to insure that the well bore was flushed and free of casing contamination. The practice of purging three well volumes has assumed the status of a custom in water sampling techniques.

Field Analyses

In addition to parameters measured as part of the serial sampling procedure, concentrations of several inorganic species were measured in the field. These were mostly anions and dissolved gases, which might be affected by the lengthy storage and transportation times involved in any sampling program on the Reservations. Alkalinity was another important parameter measured in the field.

Most field concentrations were analyzed with a portable Hach 2000 spectrophotometer; two were purchased new for the project by Hydro Geo Chem, Inc. Only waters collected from the flow cell after chemical stability had been achieved were utilized for analysis; however, the pH electrode and conductivity probe often remained in the flow cell as this water was collected, which may have introduced some sampling error. Over 250 species can be analyzed with this programmable instrument, but only about ten were measured as part of the Hydro Geo Chem sampling protocol, and thus as part of this thesis.

Sulfate, chloride, nitrate, and fluoride were all measured in the field, and were also analyzed later in the laboratory. Analyses were run for nitrite, ferrous iron, total iron, silica as $SiO_2$, and sulfide when dissolved oxygen was less than 0.5 mg/l. Dissolved

oxygen was the only dissolved gas measured in the field. No comparisons of Hach results with oxygen concentrations measured via Winkler titrations or dissolved oxygen meters were done. Ferrous and total iron, and to some extent nitrate and nitrite, were measured as redox couples, since Eh is considered such an unreliable parameter when measured with an Eh reference probe.

The analytical procedure was prescribed by Hach Corporation, and was closely adhered to. Two optically pure and matched glass cuvettes were used, one filled with 25 ml of sample and one with a blank (either sample water or deionized water). Reagents were added to the sample, and reactions allowed to proceed for a specified time period. The wavelength (in Angstroms) was set for the method specified. The blank was then inserted into the light path of the spectrophotometer, the instrument zeroed, the blank inserted, and concentrations directly read. Results were recorded in field notes and on the same forms used in the serial sampling.

Total alkalinity is a conservative parameter, and thus is often measured in the laboratory. However, in order to preclude any precipitation of calcium carbonate in unacidified samples over lengthy transport and storage times, with resultant shifts in alkalinity, titrations were done in the field. The titrant was 0.01639 N. $H_2SO_4$ of reagent grade, and sample aliquots normally were 100 ml. A Class A buret was used, and the sample water was stirred with a magnetic stir bar and a portable Hach table. The amount of titrant delivered (in increasingly smaller steps as the inflection point was approached) and

the resulting pH (read from the already calibrated Hach pH meter) were recorded on alkalinity titration forms, along with notes on termperature shifts. Graphs were usually prepared to detect the inflection point, but this was found almost invariably slightly below a pH of 4.5. Titrations were continued to a pH of 3.0, since this is such a vital field parameter. Although in truth other species contribute to total alkalinity, in a carbonate system with a pH greater than 8.0 the dominant anions determining total alkalinity are $HCO_3$ and $CO_3$. Because the carbonate anion is only present in negligble concentrations below a pH of 10.3, the alkalinity measurement is taken as the bicarbonate concentration as well, specifically for modeling inputs.

Some field analytical problems arose. During alkalinity titrations some amount of pH drift occurred due to equilibration of the sample aliquot with surface temperatures. Changes in temperature were noted, and did not always move up; during the coldest field sessions sample aliquots often cooled down below the aquifer temperatures by several degrees. One pH probe failed during a field session at the BIA Cottonwood 3 well, and may have been inaccurate for an unknown number of samples prior to its failure, although calibrations gave no indication of such failure. Sulfate and chloride levels at some wells were so high that dilutions were required to measure them, and although Class A glassware was used to secure accurate volumetric deliveries, field dilutions are always more suspect than those done in a laboratory setting. This is because field dilutions were done in a

25 ml graduated cylinder, without Eppendorf pipettes and without thorough mixing. Fortunately laboratory analyses could always be substituted for field Hach analyses for these anions, and other species virtually never exceeded detection limits. Problems keeping the Hach glass cuvettes clean also arose, although they were cleaned in the field with deionized water and acetone. Over the many months of field work, scratches also developed on these cuvettes. This decreasing optical purity may have affected analytical accuracy to some unpredictable degree, different for each cuvette used.

Each Hach kit was calibrated in the laboratory by running known amounts of standard solutions. The standards analyses were run both at Hydro Geo Chem offices in Tucson and at Bilby Research Center at Northern Arizona University. Fluoride was consistently accurate. Sulfate and chloride were not as accurate, and nitrate was not as accurate at lower levels, but all of these species later were measured on the ion chromatograph in the laboratory. Although analysts at Hydro Geo Chem developed correction factors for these anions, the field results noted in Appendix II have not had any correction factors applied to them.

Flow rates at the well where measured whenever possible. At most wells equipped with electrical submersible pumps, flow meters were installed, and timed readings were taken from them. Flow rates ranged from 30 to over 100 gpm at such wells. Because these flow meters are periodically checked for accuracy by the U.S. Geological Survey, and several of the wells utilized as sampling points had had

their flow meters checked within a few months of the field season, the readings were taken as accurate within 10%. At those windmills where the discharge pipe could be accessed from the outside of the storage tank, a five gallon bucket was filled over a timed interval. Rarely did flow rates at windmills exceed three to four gallons per minute.

## Sample Collection and Preservation

After chemical stability of the pumped well water had been ascertained via serial sampling, and after (or occasionally concurrent with) field analyses, water samples were drawn for laboratory analysis. Samples were collected in 250 ml polypropylene bottles which were thoroughly acid-washed prior to field work (soaked in 10% hydrochloric acid solution and rinsed three times with distilled deionized water). Most of these bottles were new, but some were acquired from a previous study of mine drainages with extremely low pH values; all were washed in the same manner. At the well site, water was forced through an in-line Millipore filter (0.2 micron pore diameter) by the pressure of the discharging well. At windmills where such pressure was usually insufficient to force sample waters through the filtration system, a hand pump was used. Each sample bottle was rinsed with filtered sample water three times before being completely filled. Three labeled bottles were filled per well, one for cations, one for anions, and one for archival purposes.

Filtration must be done prior to sample collection to remove bacteria, suspended clays, and a large proportion of iron and

manganese oxyhydroxides from the sample waters. These colloidal particles are often more representative of materials brought up from near the well screen or perforated interval than they are of the ground water in the aquifer system itself. They also react to change the chemistry of the water samples prior to analysis. Bacteria consume nitrates, for example, and clay particles exchange cations.

All samples were refrigerated after collection, in a cooler filled with crushed ice. Cation samples were further preserved with analytical grade nitric acid (triple distilled), added to drop the sample pH below 2.0. Nitric acid of this grade is generally preferred as a preservative over other strong acids because of its higher purity. Anion samples were further preserved by the addition of phenyl mercuric acetate, a technique often used at Bilby Research Center; its drawback lies in the fact that the acetate anion completely masks the fluoride peak during ion chromtography. However, as discussed in the following section, another difficulty with this preservative was found during laboratory analysis. The filtered and refrigerated third sample was dependent solely upon refrigeration for its preservation.

Additonal hydrological information was gathered wherever possible, in order to update or supplement information obtained from archival sources. This consisted primarily of water levels, which were measured with a Stevens electrical sonde with a 300 meter graduated tape. While the original intent was to measure water levels at every well, difficulties were encountered which made attainment of

this goal impossible. First, only windmills fitted with couplings and holes in the flat plate to allow insertion of the probe down the hole between the drop pipe and well casing could be measured. There was no way to gain access to those windmills not fitted with such couplings, and only windmills on the Hydro Geo Chem sampling list were so fitted. Even when a coupling was installed, the crookedness of the drop pipe in the hole often meant that the probe did not have an unimpeded descent; it often got caught long before it dropped to water level, and several times nearly did not come back up.

Second, wells equipped with electrical submersible pumps were also equipped with centralizers ("spiders") to maintain spacing of the drop pipe from the well casing down the hole, and these rubber or steel devices totally blocked the descent of the probe. It was later learned from various field technicians that water levels in these wells are only measured when the pump is pulled from the hole, allowing a clean and unimpeded descent of a water level measuring device. The water levels listed in Appendix II represent the most recent measurements available, either from governmental sources or from field measurements.

Originally it had been planned to run pump tests at most wells sampled by Hydro Geo Chem, but this proved impractical due largely to the water level measurement difficulties noted above, and due to time limitations. No observation wells were used, only the pumping well. One pump test was run at windmill 9Y-92, which at the time was outfitted with a pump jack driven by a gasoline motor. Only one

pumping rate could be used, which itself was very low and did not produce sufficient drawdown for a good test. Archival searches yielded good pump test results from several sources, particularly Indian Health Service and National Park Service.

## Possible Sources of Sampling Error

Although every effort was made to obtain representative samples and to preserve them against chemical degradation prior to laboratory analysis, it is recognized that several kinds of field sampling errors could have occurred. This may have affected the validity of the results, and must be discussed.

Possibly the greatest single source of error lay in the lengthy storage times often involved between sample collection, transportation back to Northern Arizona University, and analysis at Bilby Research Center. It was not usually posssible to return to Bilby Research Center the day after a sample was gathered, nor was it always possible to perform analyses within a day of returning from the field. Filtration, refrigeration, and preservation techniques applied in the field were designed to minimize reactions within the sample bottle that might affect concentrations of analytes. Samples were also refrigerated in the laboratory prior to analysis. However, some effect of lengthy storage times must be expected, particularly on anion concentrations. But the amount of error from this source could not be measured.

Wells equipped with electrical submersible pumps usually discharged steadily between 25 and 225 gallons per minute. But wells pumped by windmills never discharged at such high rates, nor was the rate constant. Slow and uneven pumping rates at windmills, which formed a considerable proportion of the sample universe, may have allowed some sample contamination through lengthy contact with pipe materials and the well casing. Some pH, temperature, and alkalinity shifts may have occurred as contact with the atmosphere occurred during the long lift times from the aquifer. Again, the extent of such error could not be measured.

Serial sampling was an attempt to minimize such drift in samples. It is not certain that continued measurements of pH, temperature and conductivity insured a totally representative sample, but it seems likely that minimal shifts in such measurements indicated minimal shifts in sample parameters as well. It is clear in the field notes maintained for each well that drift in pH, temperature, and conductivity for wells pumped by electric pumps and for wells pumped by windmills where winds were steady and strong was at an equally low level.

The worst sampling situations occurred when the winds were erratic and light. Occasionally winds would die down altogether for some time, and serial sampling measurements exhibit considerable variability for those instances. Due to time constraints, some samples had to be taken on days with light and variable winds, when serial sampling never indicated good chemical stability. These

samples are the worst gathered during the field phase. It is unusual that good weather can cause bad sampling.

In order to have some indication of the presence or extent of sampling error in the field, duplicate, and in one case triplicate, samples were taken at selected wells. The greatest percentage of error in laboratory analyses of the triplicate samples was less than one percent; wells for which duplicate samples were gathered had higher percentage differences for the same parameter, probably because the duplicate sample was collected at a later date than the original.

## Laboratory Analyses

The goal of laboratory analysis of water samples collected from the Navajo and Hopi Indian Reservations during one field season with one field methodology was to provide a consistent set of accurate chemical compositions for "N" aquifer system groundwaters at several points across the study area. This provides an accurate description of the water chemistry of the aquifer system for a relatively brief period of time during one season of the year.

Performance of all analyses by one analyst using a standardized methodology on one set of instrumentation with one set of reagents mitigates against the introduction of various biases inherent in using several workers at several laboratories with differing methods. The report by the General Accounting Office (1980) notes wide disparities in analytical results for both real-world samples and spiked samples from differing analytical laboratories, despite utilization of similar

EPA-certified laboratory methods. In order to obtain the greatest possible analytical precision for this thesis, the author alone performed all chemical analyses using equipment, reagents, and distilled water at Bilby Research Center.

Major anion concentrations were determined on the ion chromatograph, a Wescan Ion Analyzer equipped with a Spektra-Physiks solvent delivery system. Preparation of eluant (5 mM PHBA, pH 8.5) and anion standards has been standardized at Bilby Research Center, and this procedure was strictly followed. The basic analytical procedure is to inject the sample through an injection port into the stream of eluant flowing through the system and into the separator column. In the separator column the passage of sample anions is selectively retarded and thus various anions separated out; the resulting changes in electrical conductivity are monitored by a conductivity cell, and the results passed to either a chart recorder or a computer for recording. Comparison of these curve areas with those of known concentrations of standards yields sample concentrations. Analyses of thesis samples were recorded as data files by a program called "Chromatograph-Chart" which later allowed quick analysis of those data files.

The anions analyzed by this procedcure in the laboratory were also analyzed in the field on the Hach 2000 portable spectrophotometer. Differences between the field results and the laboratory results were often substantial, as can be seen in Table 4. Reasons for the high percentage differences between the two analyses were not always clear, although it should be noted that actual

Table 4: Differences between Field and Laboratory Anion Analyses

| Well Number | Well Name | Chloride Field | Chloride Lab | Chloride % Diffe | Sulfate Field | Sulfate Lab | Sulfate % Diffe | Nitrate Field | Nitrate Lab | Nitrate % Diffe |
|---|---|---|---|---|---|---|---|---|---|---|
| 1K-203 | 01-060-09.15X01.85 | 6.9 | 8.03 | 16.4 | 12.0 | 9.68 | 19.4 | 68.4 | 12.86 | 81.2 |
| 1K-509 | none known | 5.8 | 6.42 | 10.6 | 12.0 | 10.99 | 8.4 | 11.0 | 9.10 | 17.6 |
| 1T-239 | unknown | 2.1 | 3.08 | 46.5 | 210.0 | 169.83 | 19.1 | 10.2 | 6.64 | 34.7 |
| 1K-214 | 01 058-10.73X06.78 | 3.2 | 3.81 | 19.1 | 12.0 | 11.17 | 7.0 | 12.8 | 10.27 | 19.9 |
| 1K-215 | 01-043-09.82X14.66 | 8.6 | 7.50 | 12.8 | 13.0 | 10.70 | 17.7 | 19.4 | 11.55 | 40.6 |
| 1T-227 | 01-041-09.85X03.75 | 5.0 | 3.85 | 23.0 | 8.0 | 6.15 | 23.1 | 5.3 | 4.40 | 19.0 |
| 1T-229 | 01-027-03.42X16.92 | 2.6 | 2.05 | 21.2 | 2.0 | 6.25 | 212.5 | 8.0 | 4.80 | 39.7 |
| 1T-504 | 01 026-07.83X17.10 | 12.1 | 6.20 | 48.8 | 11.0 | 10.45 | 5.0 | 11.0 | 7.86 | 28.9 |
| 2A-93 | 02-026-02.25x03.86 | 2.7 | 3.30 | 22.2 | 3.0 | 5.50 | 83.3 | 5.3 | 0.66 | 87.5 |
| 2K-319 | 02 041-05.32X16.02 | 3.9 | 4.44 | 13.8 | 7.0 | 5.94 | 15.1 | 11.0 | 9.37 | 15.2 |
| 2K-322 | Hilltop Well | 2.4 | 2.95 | 22.9 | 1.0 | 3.30 | 230.0 | 6.2 | 4.17 | 32.6 |
| 3M-156 | 03 076-06.53X11.01 | 52.0 | 29.50 | 43.3 | 100.0 | 70.40 | 29.6 | 1.3 | 0.00 | 100.0 |
| 8T-510 | Long Valley Windmill | 1.2 | 1.01 | 16.3 | 3.5 | 29.76 | 750.1 | 27.0 | 26.09 | 3.2 |
| 8T-518 | 08 037-08.51X15.87 | 14.5 | 25.52 | 76.0 | 18.0 | 19.42 | 7.9 | 5.7 | 4.31 | 25.1 |
| 8T-522 | 08 039-08.31X05.09 | 7.7 | 13.19 | 71.4 | 90.0 | 102.49 | 13.9 | 6.2 | 3.60 | 41.9 |
| 9K-215 | 09 036-10.89X12.14 | 16.2 | 229.41 | 1316.1 | 280.0 | 376.97 | 34.6 | 47.7 | 54.84 | 14.9 |
| 9K-218 | 09 021-07.22X08.93 | 6.3 | 7.50 | 19.0 | 22.0 | 20.05 | 8.9 | 8.0 | 4.78 | 39.9 |
| 9Y-92 | 09 037-01.81X14.35 | 4.5 | 228.98 | 4988.4 | 510.0 | 378.21 | 25.8 | 18.1 | 15.73 | 13.2 |
| 10R-111 | 10 054-01.47X09.39 | 5.9 | 88.05 | 1392.4 | 140.0 | 1952.75 | 1294.8 | 0.0 | 3.41 | 100.0 |
| 10R-111 | 10 054-01.47X09.39 | 5.9 | 101.46 | 1619.6 | 140.0 | 1990.09 | 1321.5 | 0.0 | 0.00 | 0.0 |
| Polacca 6 | INS Polacca 6 | 1332.5 | 447.40 | 66.4 | 350.0 | 407.65 | 16.5 | 1.3 | 0.00 | 100.0 |
| Notevilla 2 | BIA Notevilla PM2 | 0.9 | 1.42 | 57.8 | 2.0 | 5.44 | 171.7 | 7.1 | 5.35 | 24.3 |
| SecondMsSch2 | BIA Second Mesa Schl PM2 | 5.2 | 7.26 | 39.5 | 19.0 | 14.43 | 24.0 | 5.7 | 0.00 | 100.0 |
| PolaccaPD&C2 | Polacca Day School PM2 | 21.0 | 28.68 | 36.6 | 31.0 | 27.24 | 12.1 | 2.7 | 30.89 | 1064.9 |
| Hopi HS3 | Hopi High School PM3 | 214.0 | 218.55 | 2.1 | 90.0 | 79.50 | 11.7 | 2.7 | 7.59 | 186.1 |
| KeamsCyn2 | Keams Canyon PDC2 | 74.0 | 93.38 | 26.2 | 41.0 | 43.26 | 5.5 | 2.2 | 0.00 | 100.0 |
| 4T-521 | NTUA Kitsillie 1 | 3.3 | 3.25 | 1.5 | 0.0 | 4.90 | 100.0 | 7.5 | 4.90 | 34.7 |
| Navajo N Mon | A-38-17 17-1,Old Well | 2.2 | 0.00 | 100.0 | 0.0 | 2.90 | 100.0 | 5.3 | 2.93 | 44.8 |
| BIA Tuba C 5 | 03 077-13.83X07.79 | 2.7 | 5.14 | 90.2 | 10.0 | 9.56 | 4.5 | 12.4 | 6.54 | 47.2 |
| BIA RedLake1 | BIA Red Lake PM1 | 1.0 | 1.41 | 40.9 | 1.0 | 1.91 | 91.0 | 8.8 | 5.02 | 43.2 |
| BIA RedLake1 | BIA Red Lake PM1 | 1.0 | 1.33 | 32.5 | 1.0 | 1.72 | 72.5 | 8.8 | 4.66 | 47.3 |
| BIA RedLake1 | BIA Red Lake PM1 | 1.0 | 1.31 | 31.0 | 1.0 | 1.83 | 83.0 | 8.8 | 4.74 | 46.4 |
| BIA Dennehe2 | BIA Dennehotso PM2 | 0.1 | 6.55 | 6450.0 | 15.0 | 13.80 | 8.0 | 10.6 | 5.49 | 48.3 |
| BIA Kaynta 2 | BIA Kayenta PM2 | 3.2 | 3.66 | 14.2 | 84.0 | 68.66 | 18.3 | 6.2 | 3.70 | 40.1 |
| BIA LowMtn 2 | BIA Low Mountain 2 (New) | 180.0 | 180.25 | 0.1 | 80.0 | 60.90 | 23.9 | 2.7 | 1.74 | 34.3 |
| BIA Chilchn3 | BIA Chilchinbeto PM3 | 1.2 | 2.32 | 93.7 | 2.0 | 3.69 | 84.5 | 10.2 | 5.01 | 50.7 |
| BIA Dilkon 2 | BIA Dilkon 2 | 42.0 | 82.20 | 95.7 | 230.0 | 192.95 | 16.1 | 10.2 | 0.00 | 100.0 |
| BIA Dilkon 2 | BIA Dilkon 2 | 42.0 | 80.31 | 91.2 | 230.0 | 173.54 | 24.5 | 10.2 | 9.46 | 7.0 |
| BIA Cttnwd 3 | BIA Cottonwood PM3 | 15.9 | 21.75 | 36.8 | 5.3 | 43.82 | 726.9 | 7.5 | 3.58 | 52.4 |
| BIA Pinon 6 | 04 073-12.26X10.09 | 3.7 | 3.05 | 17.6 | 0.0 | 4.59 | 100.0 | 9.7 | 7.49 | 23.0 |
| BIA Rocky 2 | 04 075-05.09X12.30 | 0.2 | 1.35 | 575.0 | 8.0 | 5.69 | 28.9 | 8.0 | 9.80 | 23.2 |
| BIA Kaibeto2 | none | 2.5 | 2.50 | 0.0 | 9.0 | 7.05 | 21.7 | 16.8 | 7.59 | 54.8 |
| INS HardRk N | INS Hard Rocks "N" | 6.8 | 3.84 | 43.5 | 0.0 | 5.38 | 100.0 | 0.0 | 5.52 | 100.0 |
| | Average Difference: | | | 412.6 | | | 138.9 | | | 72.7 |
| | Standard Deviation: | | | 1237.7 | | | 301.0 | | | 157.3 |
| | Maximum Difference: | | | 6450.0 | | | 1321.5 | | | 1064.9 |
| | Minimum Difference: | | | 0.0 | | | 4.5 | | | 0.0 |

concentration unit differences were often much smaller than the percentage difference would suggest. In some samples laboratory analysis was delayed due to lengthy transportation times back to Bilby Research Center; this may have played a major role in sample deterioration. Samples analyzed in the field were usually not filtered, whereas samples taken back to the laboratory were invariably filtered through a 0.2 micron Millipore filter; this too may have been a major factor in the analytical differences that were seen. Dilutions in the field were more hastily done with less satisfactory equipment than those done in the laboratory where good glassware and Eppendorf pipettes were available, and this is certainly a causative factor in differences between analyses for anions with higher concentrations. Field analyses were often performed under less than ideal conditions of blowing dust and extreme temperatures, whereas careful control of reagents, waters, and methods was rigorously maintained in the laboratory. This too may represent a source of divergence between values derived from field analyses and those determined in the laboratory. In all cases, the laboratory results are taken as superior to those concentrations resulting from field analyses, and are used in the geochemical modeling portion of this thesis.

Some parameters, however, were better measured in the field. Nitrite was measured in the field, but no appreciable nitrite concentrations could be found in laboratory analyses. Nitrite degrades so rapidly upon contact with oxygen in the atmosphere that

even minimal transportation times allow drastic reductions in concentrations; hence field measurement of this parameter is the best method available. In almost all ion chromatograph runs at Bilby Research Center the fluoride peak was masked by a broad peak which may represent some unknown organic compound, which could never be identified. Hence the fluoride concentrations obtained from field analyses are preferable because they are the only concentrations available. Silicon dioxide was measured in the field quickly and easily, whereas laboratory colorimetric analysis would have involved time-consuming and difficult preparations without any promise of substantially more accurate results, so field determinations were used. However, later measurements of accuracy at Hydro Geo Chem revealed an error factor of up to 28% (Cheng, personal communication), showing in hindsight that laboratory determinations of silica concentrations should have been performed.

No cations were analyzed in the field, so only those results obtained at Bilby Research Center are available. Cations were analyzed on a Perkins-Elmer 500 flame atomic absorbtion spectrophotometer. Chemical interference was overcome by adding a lanthanum-cesium solution to the sample to free up all cations.

The only cations measured were calcium, magnesium, potassium, and sodium, the most commonly analyzed metals. Iron was analyzed in the field, and sensitivity on the Perkins-Elmer atomic absorption spectrophotometer did not allow a more accurate determination of this cation. Field figures were used for iron concentrations, although in

retrospect, the lack of consistency in using filtered versus unfiltered sample waters may have detracted from the utility of such measurements. Manganese also requires greater sensitivity than allowed by the instrument at Bilby Research Center, and the same is true for aluminum. Barium, boron, arsenic, cadmium, silver, copper, chromium, and lead are other metals which are often measured in water quality analyses but which were not analyzed for this thesis. Some of these, particularly aluminum, could have been measured by utilizing the graphite furnace atomic absorption spectrophotometer at Bilby Research Center, but the time and funding required to use this high-resolution instrument were not available.

Stock solutions at known strengths of ultra high-purity calcium, magnesium, potassium, and sodium have been made up at Bilby Research Center, and several dilutions were prepared from these standard solutions for use in calibrations. Dilutions were also prepared for each sample to be run in order to match the working range of the instrument for the specific element being analyzed. To each dilution, both sample and calibration standards, the appropriate amount of lanthanum-cesium solution was added to minimize matrix interferences. During analysis the concentrations reported by the instrument were recorded on paper, and later multiplied by the correct factor to account for the dilution. Care was taken to check the linearity of the calibration curve at frequent intervals to eliminate a source of electronic error.

## Accuracy and Precision

Accuracy is defined as how closely a measured value agrees with the correct value; precision is defined as how closely individual measurements agree with one another (Whitten and Gailey 1981). The success of any laboratory analysis can be judged from how accurate and precise the measurements of various parameters are. Yet it is not an easy matter to assess accuracy and precision in most laboratory analyses, even though it is important to try.

Accuracy was measured at Bilby Research Center by spiking samples after they had been initially run and re-analyzing them. "Spiking" refers to the addition of a known amount of a standard solution to a sample solution to see how much of that standard is recovered during the analysis. It is similar to the use of standard additions (Klein and Hach 1977), but uses only one added amount of standards rather than several stepwise increments, and is intended to check accuracy rather than provide a working calibration curve simultaneously with analysis of the sample.

Two separate spikes were added to the three Red Lake PM1 samples. The first contained 2 ppm of fluoride, chloride,and sulfate standards (each), while the second was composed of four ppm of fluoride, chloride, and sulfate standards. Both contained 44.3 ppm nitrate, due solely to forgetting to add the second 500 microliter injection of that standard solution to the second spike. Then all were run on the ion chromatograph in one day. The results are presented in Table 5. It can be seen that the amounts recovered were

Table 5: Accuracy of Spiked Anion Analyses

| | | Analytical Concentrations | | | Amounts Recovered | | | Per Cent Recovered | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sample | Spike | Chloride | Nitrate | Sulfate | Chloride | Nitrate | Sulfate | % Cl | % NO3 | % SO4 |
| Red Lake 1-1 | none | 1.385 | 4.378 | 1.599 | | | | | | |
| Red Lake 1-1 | one | 3.303 | 26.441 | 5.516 | 1.918 | 22.063 | 3.917 | 4.275 | -0.286 | 2.119 |
| Red Lake 1-1 | two | 5.206 | 25.832 | 9.769 | 3.821 | 21.454 | 8.170 | 4.685 | 2.545 | -2.081 |
| Red Lake 1-2 | none | 1.390 | 4.514 | 1.831 | | | | | | |
| Red Lake 1-2 | one | 3.240 | 26.661 | 5.926 | 1.850 | 22.147 | 4.095 | 8.108 | -0.664 | -2.320 |
| Red Lake 1-2 | two | 5.111 | 26.066 | 9.409 | 3.721 | 21.552 | 7.578 | 7.498 | 2.079 | 5.569 |
| Red Lake 1-3 | none | 1.382 | 4.338 | 1.815 | | | | | | |
| Red Lake 1-3 | one | 3.428 | 26.865 | 6.010 | 2.046 | 22.529 | 4.195 | -2.248 | -2.348 | -4.649 |
| | | | | | | | Average: | 4.464 | 0.265 | -0.272 |

remarkably consistent, and quite close to the actual amounts added, thus establishing a high degree of accuracy for the chloride, sulfate, and nitrate analyses. As with all previous runs, the fluoride peak was masked by an unknown substance, and the accuracy of measurements of this anion cannot be established. However, field measurements of fluoride were used throughout the thesis project.

Five samples were also rerun with calcium and magnesium spikes to test the accuracy of cation analysis. The original intention was to run spikes of calcium, magnesium, sodium, and potassium with unspiked samples, in the amounts of 12.5 mg/l, 2.5 mg/l, 25 mg/l, and 12.5 mg/l respectively. However, an unfortunate dilution error resulted in a ten-fold increase in each spike concentration, which left only the first two cations still within the detection limits of the instrument. Thus a spike of 125 mg/l of calcium and 25 mg/l of

Table 6: Accuracy of Spiked Cation Analyses

| Sample | Calcium | w/Spike | Difference | Magnesium | w/Spike | Difference |
|---|---|---|---|---|---|---|
| Red Lake 1-1 | 14.1 | 143.5 | 129.4 | 4.4 | 30.2 | 25.8 |
| Red Lake 1-2 | 13.9 | 142.8 | 128.9 | 4.3 | 30.1 | 25.8 |
| Red Lake 1-3 | 14.0 | 143.8 | 129.8 | 4.3 | 30.0 | 25.7 |
| Dennehotso 2 | 7.7 | 133.5 | 125.8 | 1.9 | 27.5 | 25.6 |
| Polacca 6 | 4.6 | 128.2 | 123.6 | 1.1 | 27.2 | 26.1 |
| Mean Recovered: | | | 127.5 | | | 25.8 |
| Std.Deviation: | | | 2.4 | | | 0.2 |

magnesium was added to each of five water samples. The results are presented in Table 6 above.

Both Tables 5 and 6 demonstrate that considerable accuracy was achieved in analyzing anions on the ion chromatograph and cations on the flame atomic absorbtion spectrophotometer. Precision was measured by comparing analyses of the same sample water performed on different days with the same equipment and procedures. Here the three samples from Red Lake PM1 proved very useful, as they were independently analyzed on at least three different days for cations. Table 7 presents the results of these runs for cations, and shows that a lower level of precision was achieved than of accuracy.

Table 7 contains comparisons of different runs from wells other than Red Lake PM1, and like that well, these different analyses of the same water exhibit differing degrees of precision for differing cations. Magnesium displayed the greatest degree of precision, possibly as a result of the inherent low variability of low

Table 7: Precision of Cation Measurements

| Sample | Analysis | Calcium | Magnesium | Sodium | Potassium |
|---|---|---|---|---|---|
| Red Lake 1-1 | 1 | 15.8 | 4.6 | 3.9 | 1.9 |
| Red Lake 1-2 | 1 | 15.9 | 4.6 | 7.9 | 1.8 |
| Red Lake 1-3 | 1 | 15.8 | 4.6 | 4.4 | 1.8 |
| Red Lake 1-1 | 2 | 14.1 | 4.4 | 3.7 | 1.4 |
| Red Lake 1-2 | 2 | 13.9 | 4.3 | 3.7 | 1.3 |
| Red Lake 1-3 | 2 | 14.0 | 4.3 | 3.7 | 1.4 |
| | Mean: | 14.9 | 4.5 | 4.6 | 1.6 |
| | Maximum: | 15.9 | 4.6 | 7.9 | 1.9 |
| | Minimum: | 13.9 | 4.3 | 3.7 | 1.3 |
| | Percent Difference: | 12.6 | 6.5 | 53.2 | 30.1 |
| 1T-227 | 1 | 27.5 | 3.4 | 4.1 | 1.2 |
| 1T-227 | 2 | 27.7 | 3.5 | 2.8 | 1.2 |
| | Mean: | 19.5 | 4.5 | 14.3 | 7.1 |
| | Percent Difference: | 0.7 | 2.9 | 31.7 | 4.0 |
| 3M-156-1 | 1 | 0.7 | 0.1 | 132.0 | 0.5 |
| 3M-156-2 | 1 | 0.8 | 0.1 | 132.0 | 0.5 |
| 3M-156-1 | 2 | 0.4 | 0.1 | n/a | 0.1 |
| 3M-156-2 | 2 | 0.6 | 0.1 | n/a | n/a |
| | Mean: | 0.6 | 0.1 | | |
| | Maximum: | 0.8 | 0.1 | | |
| | Minimum: | 0.4 | 0.1 | | |
| | Percent Difference: | 50.0 | 0.0 | | |

concentrations. Some of the difference between concentrations measured for the same sample waters may be due to the difference in analytical dates. The second run of each sample water was performed over two months after the initial analysis on the flame atomic absorption spectrophotometer. Despite their preservation with nitric acid and storage in a refrigerator, some chemical deterioration may have occured, thus reducing cation concentrations. However, the degree to which the declines in cation concentrations can be

attributed to sample degradation versus differences in equipment, methods, standard preparation, and dilution on two different occasions cannot be determined.

Table 8 summarizes the results of several anion analyses of the same sample waters on different dates. Here three different runs of waters from Red Lake PM1, plus different analyses of waters from other wells, show that ion chromatography is less precise than atomic absorbtion spectrophotometry. While an interval of two months passed between the second and third analyses of the Red Lake PM1 samples, only a week separated the first two runs, so deterioration of samples is less a factor in the analyses of the Red Lake PM1 samples. The same is not true for the other sample waters, where some chemical deterioration may have occured despite storage in a refrigerator, thus causing some decline in anionic concentrations.

In both Tables 7 and 8 differences between separate analyses of the same sample waters yielded ionic concentrations which often differed only one or two mg/l, usually less. In Table 4, which includes all wells sampled, not just duplicate samples, the field and laboratory analyses of the same ion often differed only by one or two mg/l, sometimes less. It seems likely that some of the differences between field and laboratory analyses of duplicate waters from the same well can be explained best by differences in equipment, dilution, methods, and standards. Some of the large differences in concentrations for the same sample, of course, do betray errors in analysis, and field analyses are usually more suspect than laboratory

Table 8: Precision of Anion Analyses on the Ion Chromatograph

| Sample | Dilution | Analysis | Chloride | Nitrate | Sulfate |
|---|---|---|---|---|---|
| Red Lake 1-1 | full | 1 | 1.41 | 5.02 | 1.91 |
| Red Lake 1-2 | full | 1 | 1.33 | 5.66 | 1.73 |
| Red Lake 1-3 | full | 1 | 1.31 | 4.74 | 1.83 |
| Red Lake 1-1 | full | 2 | 1.13 | 4.73 | 1.96 |
| Red Lake 1-2 | full | 2 | 1.12 | 4.84 | 1.98 |
| Red Lake 1-3 | full | 2 | 1.25 | 5.00 | 1.86 |
| Red Lake 1-1 | full | 3 | 1.39 | 4.38 | 1.55 |
| Red Lake 1-2 | full | 3 | 1.39 | 4.51 | 1.83 |
| Red Lake 1-3 | full | 3 | 1.38 | 4.34 | 1.82 |
| | | Mean: | 1.30 | 4.80 | 1.83 |
| | | Maximum: | 1.41 | 5.66 | 1.98 |
| | | Minimum: | 1.12 | 4.34 | 1.55 |
| | | Percent Difference: | 20.64 | 23.37 | 21.77 |
| BIA Dilkon 2-1 | 1:25 | 1 | 82.20 | none | 192.95 |
| BIA Dilkon 2-1 | 1:10 | 2 | 78.43 | none | 172.22 |
| BIA Dilkon 2-2 | 1:10 | 1 | 80.31 | none | 173.94 |
| BIA Dilkon 2-2 | 1:25 | 1 | 77.53 | none | 170.83 |
| | | Mean: | 79.62 | | 177.49 |
| | | Maximum: | 82.20 | | 192.95 |
| | | Minimum: | 77.53 | | 170.83 |
| | | Percent Difference: | 5.69 | | 11.46 |

analyses. That anion analyses proved slightly less accurate than cation analyses was expected, given the differing methods; in that flame atomic absorption spectroscopy is a well-proven technique, without as many possible sources of error as liquid chromatography.

## Charge Balance Error

Perhaps the most commonly used measure of laboratory accuracy is the ion balance figure. In all waters the total equivalent charges of cations must equal the total equivalent charges of anions, because the waters are electrochemically neutral. In modern analyses which are reasonably complete, the percentage difference between the two should always be less than 10% and prefereably less than 5% (Hem 1980), although larger percentage differences can occur when the total of anions and cations falls under five milliequivalents per liter.

Table 9 presents ion balance figures for most of the wells analyzed. Besides the well number and name, total anions and cations in milliequivalents per liter are presented. Of the final two columns, one is the percentage difference calculated between the total anions and cations, with the minus sign indicating a preponderance of anions. The last column is the charge balance percentage error as calculated by WATEQ, a computer program discussed at length in a subsequent chapter which yields equilibrium speciation information, among other things.

Most of the numbers cluster around 5%, because those analyses which exceed 20% were not included in this table. These glaring exceptions are listed in Appendix II, and consist only of a few wells. These exceptions, usually with percentage differences of above 50%, mostly represent wells from the eastern and southeastern margins of the thesis area. These wells include 1K-214, where the wind died during sampling, 8T-510, 8T-522, 9K-215, 9Y-92, BIA Kayenta 2, all

Table 9: Charge Balance Percentage Error

| Well Number | Well Name | Total Anions (meq/l) | Total Cations (meq/l) | Ionic Balance Percentage Error | WATEQ Charge Balance Error |
|---|---|---|---|---|---|
| 1K-203 | 01-060-09.15X01.85 | 2.159 | 1.983 | -4.249 | 2.800 |
| 1K-509 | none known | 2.327 | 2.082 | -5.557 | 4.630 |
| 1T-239 | unknown | 5.402 | 5.155 | -2.340 | 2.270 |
| 1K-215 | 01-043-09.82X14.66 | 2.047 | 1.858 | -4.840 | 3.970 |
| 1T-227 | 01-041-09.85X03.75 | 1.996 | 1.860 | -3.527 | 1.560 |
| 1T-229 | 01-027-03.42X16.92 | 2.379 | 2.140 | -5.289 | 4.600 |
| 1T-504 | 01 026-07.83X17.10 | 2.323 | 2.127 | -4.404 | 3.740 |
| 2A-93 | 02-026-02.25x03.86 | 4.136 | 3.563 | -7.443 | 6.740 |
| 2K-319 | 02 041-05.32X16.02 | 2.482 | 2.033 | -9.945 | 7.630 |
| 2K-322 | Hilltop Well | 2.268 | 1.971 | -7.006 | 5.820 |
| 3M-156 | 03 076-06.53X11.01 | 6.625 | 5.798 | -6.657 | 6.830 |
| 3M-156 | 03 076-06.53X11.01 | 6.622 | 5.802 | -6.600 | 6.790 |
| 8T-518 | 08 037-08.51X15.87 | 6.929 | 5.793 | -8.929 | 8.510 |
| 9K-218 | 09 021-07.22X08.93 | 2.263 | 2.076 | -4.310 | 3.590 |
| 10R-111 | 10 054-01.47X09.39 | 44.539 | 46.973 | 2.660 | 2.550 |
| 10R-111 | 10 054-01.47X09.39 | 45.640 | 44.236 | -1.562 | 1.620 |
| Polacca 6 | IHS Polacca 6 | 24.681 | 24.339 | -0.698 | 0.870 |
| Hotevilla 2 | BIA Hotevilla PM2 | 3.140 | 2.420 | -12.950 | 10.960 |
| SecondMsSch2 | BIA Second Mesa Schl PM2 | 6.570 | 5.239 | -11.271 | 10.450 |
| PolaccaPD&C2 | Polacca Day School PM2 | 8.594 | 7.143 | -9.220 | 8.810 |
| Hopi HS3 | Hopi High School PM3 | 14.695 | 14.861 | 0.562 | 0.180 |
| Keams Cyn2 | Keams Canyon PDC2 | 10.910 | 9.644 | -6.159 | 6.170 |
| 4T-521 | NTUA Kitsillie 1 | 4.207 | 3.781 | -5.333 | 4.810 |
| 4T-523 | NTUA Forest Lakes | 3.519 | 3.127 | -5.898 | 5.320 |
| 2T-516 | NTUA Shonto Junction 1 | 3.863 | 3.439 | -5.807 | 5.250 |
| Navajo N Mon | A-38-17 17-1,Old Well | 2.205 | 2.011 | -4.602 | 3.860 |
| BIA Tuba C 5 | 03 077-13.83X07.79 | 2.006 | 1.714 | -7.849 | 6.210 |
| BIA RedLake1 | BIA Red Lake PM1 | 1.636 | 1.385 | -8.309 | 6.870 |
| BIA RedLake1 | BIA Red Lake PM1 | 1.623 | 1.561 | -1.947 | 2.120 |
| BIA RedLake1 | BIA Red Lake PM1 | 1.626 | 1.404 | -7.327 | 4.960 |
| BIA Denneho2 | BIA Dennehotso PM2 | 2.905 | 2.661 | -4.384 | 3.730 |
| BIA LowMtn 2 | BIA Low Mountain 2 (New) | 13.429 | 12.960 | -1.777 | 2.150 |
| BIA Chilchn3 | BIA Chilchinbeto PM3 | 4.076 | 3.830 | -3.112 | 2.980 |
| BIA Dilkon 2 | BIA Dilkon 2 | 8.188 | 7.571 | -3.915 | 3.730 |
| BIA Dilkon 2 | BIA Dilkon 2 | 7.883 | 7.477 | -2.643 | 2.540 |
| BIA Shonto 2 | BIA Shonto PM2 | 3.040 | 2.524 | -9.274 | 7.730 |
| BIA Pinon 6 | 04 073-12.26X10.09 | 4.663 | 4.041 | -7.146 | 6.500 |
| BIA Kaibeto2 | none | 1.700 | 1.588 | -3.406 | 2.940 |
| IHS HardRk N | IHS Hard Rocks "N" | 3.128 | 2.342 | -14.369 | 12.060 |
| IHS HardRk D | IHS Hard Rocks 'D' | 22.788 | 21.259 | -3.471 | 3.640 |
| 6M-64 | none | 20.111 | 17.882 | -5.867 | 6.020 |
| | Maximum Value: | 45.64 | 46.97 | 2.66 | 12.06 |
| | Minimum Value: | 1.62 | 1.38 | -14.37 | 0.18 |
| | Mean Value: | 7.84 | 7.36 | -5.52 | 4.99 |
| | Standard Deviation: | 10.13 | 10.20 | 3.39 | 2.71 |

five of which are grouped to the northeastern portion of the thesis area, and BIA Cottonwood 3. BIA Rocky Ridge 2 also had an unexpectedly high percentage error, as can be seen in Appendix II, though lower than the others.

WATEQ computes the percentage charge balance error as part of its calculations. Its figures are consistently less than those computed on the basis of total anions and cations, due to the fact that WATEQF speciates analytical results, which lends greater accuracy to the calculations.

There are two possible causes for the extraordinarily high percentage error figures in these seven wells. First, since the anion concentrations are far more elevated in these samples than cation concentrations, an unknown systematic error may have been introduced inadvertantly during analysis. Four of these samples were analyzed on the ion chromatograph on the same day, which certainly points to analytical error. Yet other samples analyzed during that run do not exhibit gross percentage errors. All cations were analyzed in two days, yet if cations were missed to cause the gross imbalance, other analyses should also exhibit depleted levels of cations. None do.

The second possiblity lies in the sample bottles themselves, some of which had previously been utilized for an acid mine drainage study. It is very possible that the acid-washing process was insufficient to thoroughly clean these previously used bottles, and that some ions remained attached to the bottle walls. There is no way to judge the extent of this source of sampling error.

It is also possible that both of these sources of error were operative to some extent. The massive imbalance in the charge balance was not seen in samples from some of the same wells analyzed at Hydro Geo Chem, so clearly sampling error did occur.

When the charge balance error percentage figures were recalculated without the seven wells which grossly exceeded 10%, the average error percentage was 5.52%, and only 4.99% as computed by WATEQ. The standard deviation was 3.39%, and 2.71% in the WATEQ column. These are the figures shown in Table 9. This demonstrates the overall accuracy of most of the laboratory analyses.

## Notes on Anion Preservation

Three samples were collected for each well, one for cations and preserved with nitric acid, one for anions and unpreserved, and one for anions which was preserved with phenyl mercuric acetate. All were refrigerated. It was not clear at the beginning of the field phase that preservation with ice alone would be sufficient to prevent deterioration of the anion samples. Because other researchers have used it before in an attempt to prevent changes in anion concentrations, dilute phenyl mercuric acetate was added to the third archival sample. Phenyl mercuric acetate is also commonly used as a preservative for commercial products such as nasal sprays. Several of these archival samples were later run on the ion chromatograph, and the results compared with samples run simultaneously, but which had only been refrigerated. The results are presented in Table 10.

Table 10: Comparisons of Anion Concentrations in Samples With and Without Phenyl Mercuric Acetate (PMA)

| Sample | Nitrate | | | Sulfate | | | Chloride | | |
|---|---|---|---|---|---|---|---|---|---|
| Number | w/PMA | wo/PMA | % Diff | w/PMA | wo/PMA | % Diff | w/PMA | wo/PMA | % Diff |
| 1K-239 | 0.54 | 0.64 | -19.78 | 13.73 | 16.11 | -17.32 | 4.14 | 2.57 | 38.06 |
| 1K-203 | 12.88 | 12.59 | 2.26 | 9.36 | 9.69 | -3.46 | 5.90 | 8.03 | -35.99 |
| 1T-509 | 9.11 | 8.93 | 1.88 | 10.76 | 10.99 | -2.15 | 2.56 | 6.42 | -150.43 |
| 2K-319 | 8.53 | 7.83 | 8.24 | 5.54 | 5.64 | -1.88 | 4.08 | 4.44 | -8.90 |
| 10R-111#1 | 0.00 | 0.00 | 0.00 | 1966.30 | 1980.83 | -0.74 | 96.91 | 101.98 | -5.23 |
| Polacca 6 | 0.00 | 0.00 | 0.00 | 342.55 | 345.01 | -0.72 | 420.67 | 423.44 | -0.66 |
| BIA Dilkon 2-1 | 2.35 | 7.15 | -203.91 | 130.23 | 172.22 | -32.24 | 66.47 | 78.43 | -17.99 |
| BIA Dilkon 2-2 | 9.46 | 7.63 | 19.33 | 173.03 | 173.54 | -0.30 | 80.04 | 80.31 | -0.33 |
| BIA Low Mtn 2 | 0.00 | 0.00 | 0.00 | 66.55 | 60.63 | 8.90 | 199.50 | 180.25 | 9.65 |
| BIA Cottonwd 3 | 0.00 | 0.00 | 0.00 | 48.20 | 42.21 | 12.44 | 23.50 | 21.75 | 7.45 |
| Red Lake 1-2 | 4.59 | 4.51 | 1.63 | 1.84 | 1.83 | 0.70 | 1.04 | 1.39 | -34.04 |
| Mean: | | | 17.30 | | | 3.34 | | | 18.04 |
| Standard Deviation: | | | 59.64 | | | 11.57 | | | 46.25 |

With a few glaring exceptions which are more likely due to some unknown analytical or sample contamination error rather than real differences between samples with and without the phenyl mercuric acetate, the percentage difference columns for both nitrate and sulfate show no discernable trends. However, the percentage difference column for chloride is dominated by minus signs, which indicate a drop in chloride concentrations between samples without the preservative and those with phenyl mercuric acetate. Although the numbers are not overwhelming, they suggest a trend in which chloride concentrations decline in those samples preserved with phenyl mercuric acetate. The reason may lie in the valence state of the mercury; with a valence of one, the mercury cation attracts the chloride anion in

preference to the higher valence sulfate or nitrate anions, forming a salt which precipitates out of solution.

Because phenyl mercuric acetate appears to cause some degree of chemical deterioration in chloride concentrations, it probably should not be used as a preservative where laboratory measurements of chloride are anticipated. Constant refrigeration appears to be the preferable preservative technique.

## Discussion

During the field phase, great pains were taken to collect water samples which were as representative as possible of the groundwater within the "N" aquifer system. Considerable time was spent at each sampling point in serial sampling to determine chemical stability, as well as in determination of important parameters such as pH, conductivity, temperature, alkalinity, and concentrations of several of the less preservable constituents of the water. Although it took longer than anticipated, the field sampling program was successful in achieving broad coverage of the thesis area and in obtaining the highest quality samples possible.

The laboratory analyses of these representative water samples was also successful. Standardized methods were strictly followed on high-grade analytical equipment to obtain the measurements reported in Appendix II. The concentrations that were measured for the major cations and anions are replicable, precise, and accurate within acceptable limits. Spiking samples with known concentrations of standards

as well as the charge balance percentage differences all indicate a high degree of accuracy and precision. Only a few samples yielded suspect data, either as a result of contaminated sample bottles or as a reflection of one day of poor analytical technique in the laboratory. These samples are not included in subsequent discussions of analytical results.

The field and analytical methods having been demonstrated to be rigorous and relevant to the problem, a major source of error in many projects can be eliminated. The water chemistry data can be trusted, and is acceptable for use in geochemical modeling.

# CHAPTER 4

## RESULTS OF CHEMICAL ANALYSES

Because this thesis is a regional study, presentation of analytical results in terms of ionic concentrations in tabular form alone is insufficient. Tables do not clearly illustrate patterns of regional variation, although presentation of exact results, as in Appendix II, is essential to any hydrogeochemical study. In this chapter the results of analyses are discussed on an ion-by-ion basis, to better isolate those parameters most important to understanding the "N" aquifer.

Lloyd and Heathcote (1985) suggest graphical representation of groundwater chemistry as the best initial approach to understanding processes involved, including X-Y plots to spot specific relationships, distribution maps for pertinent parameters, and Piper (1944) plots of several analyses to discern related groups or types within the waters. For each of the parameters discussed below a distribution map has been prepared, with concentrations contoured as isochems across the study area, so that regional trends can be discerned.

## Anions

Figure 9 is a map illustrating the distribution of sulfate across the study area, with concentrations expressed in milligrams per liter. In this map, as in most maps that follow, the tick marks to the sides are Universal Transverse Mercator (UTM) coordinates, in 10,000 meter increments; the metric coordinates are more easily mapped than latitudes and longitudes. Also on this and all suceeding maps,

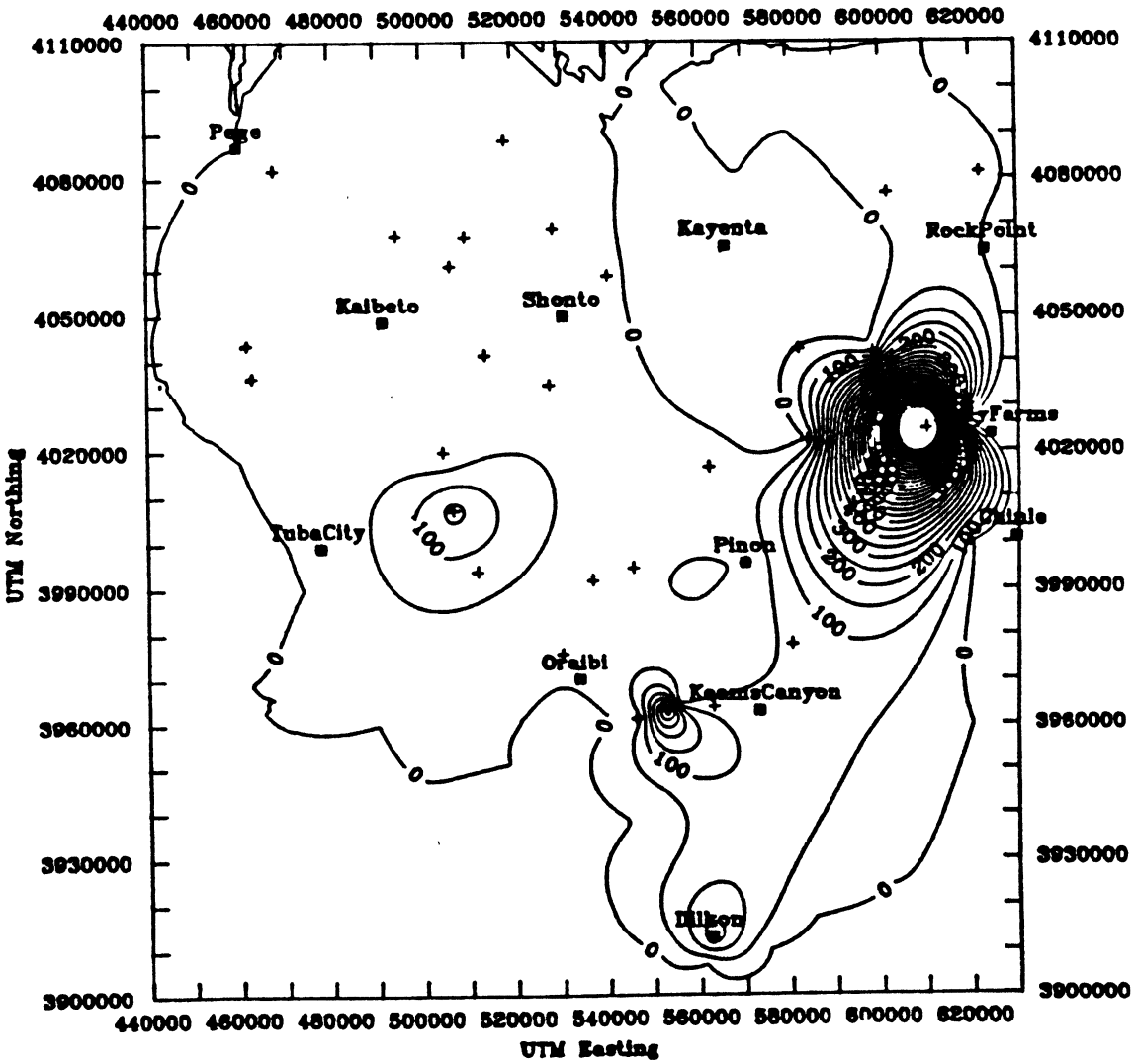


Figure 9: Distributions of Sulfate Concentrations (CI=50 mg/l)

prominent Reservation towns are plotted for better comprehension, as are well locations (crosses), and the top of the map is north. All of the distribution or isochem maps in this and following chapters were plotted with a geostatistical algorithm called kriging to determine gradients between data points. It can quickly be seen that the major accumulations of sulfate occur along the southeast edge of the study area, and that one well, 10R-111, accounts for the one major high for this anion. It is not clear why this one well such have such high sulfate concentrations. One of the more likely explanations for the high levels of sulfate in this well is leakage from the overlying "D" aquifer system, probably along the corroded well casing. This well was originally drilled in 1935, and is one of the oldest wells sampled.

Sulfate levels are also elevated in the vicinity of Polacca and south of Red Lake, again for unknown reasons. Corroded well casings and vertical leakance are unlikely explanations for every high occurence of sulfates. The primary source for sulfate in groundwater is the dissolution of gypsum (Freeze and Cherry 1979, Faust and Aly 1981). Yet none of the formations or members of the "N" aquifer system are noted for large amounts of gypsum or any other evaporite.

Wherever sulfate concentrations are high, if gypsum dissolution is the source, then calcium concentrations should also be elevated. In Figure 10 calcium concentrations for each sample in which the charge balance error was less than 20% are plotted on one axis against sulfate concentrations, both expressed in milliequivalents per liter.

Two groups are apparent, one with higher ratios of calcium to sulfate and the other with higher ratios of sulfate to calcium. The linear relationship which would be expected if gypsum dissolution were controlling the concentrations of these ions does not appear. The group with the higher ratio of calcium to sulfate may be the result of the dissolution/precipitation of calcium carbonate, which is a system which must always be considered. The group with the higher concentrations of sulfate relative to a steady value of calcium is

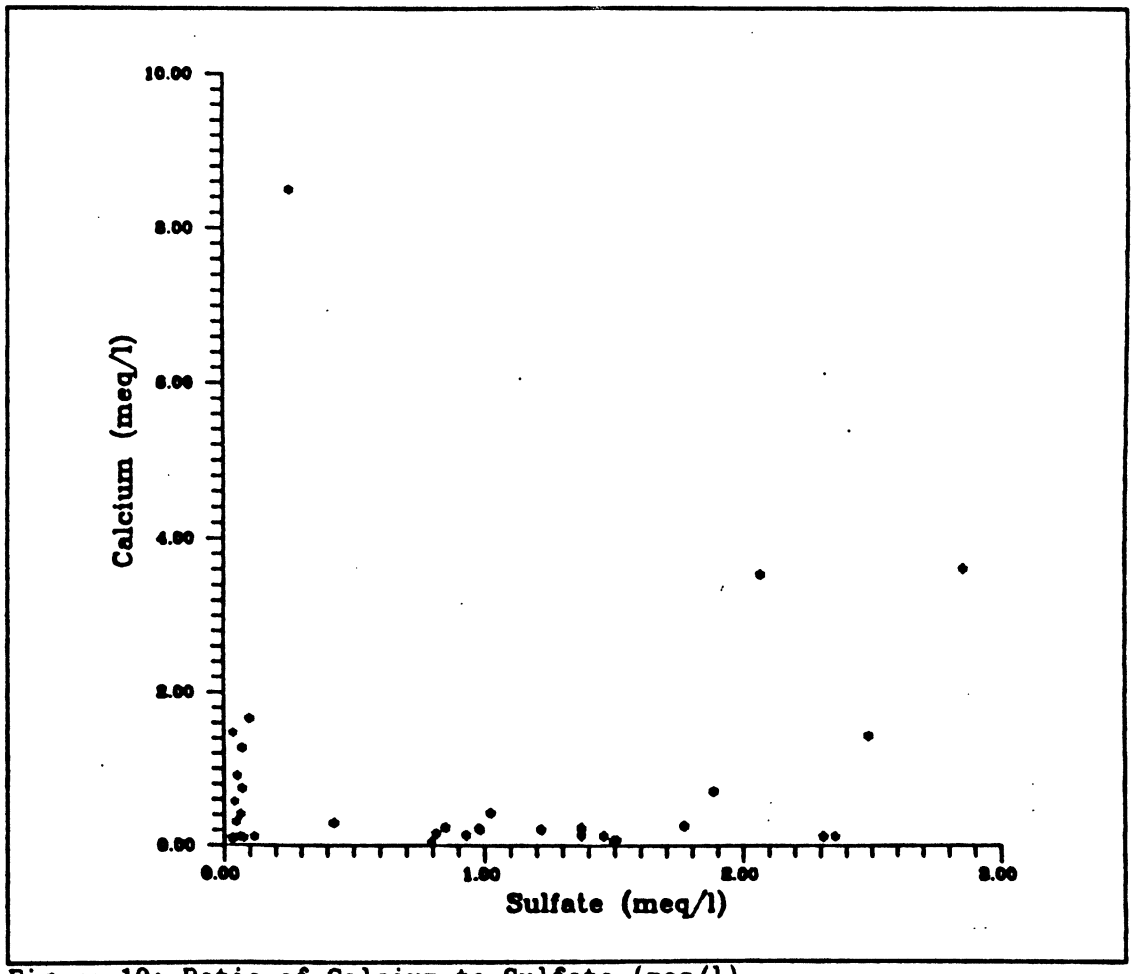


Figure 10: Ratio of Calcium to Sulfate (meq/l)

more difficult to explain without the presence of pyrite or other common sources of this anion.

Figure 11 is a map illustrating the distribution of chloride, expressed in milligrams per liter, across the study area. Again higher chloride concentrations are noticeably skewed to the southeastern edge, with the wells associated with Hopi towns exhibiting consistently high concentrations of this anion. Another

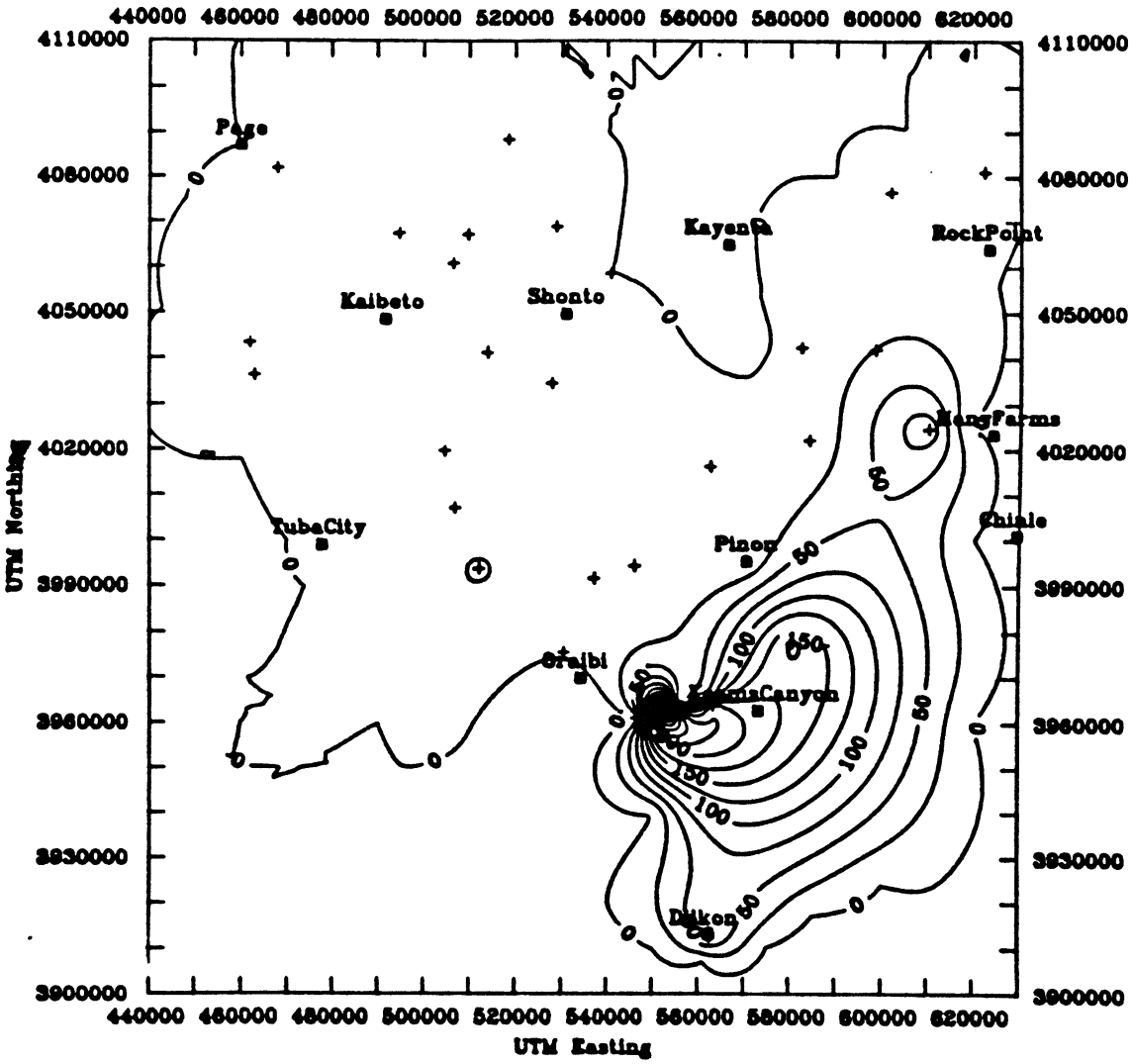


Figure 11: Distributions of Chloride Concentrations (CI=25 mg/l)

area of elevated concentrations occurs near Many Farms along the eastern edge of Black Mesa. Chloride too is usually derived from the dissolution of evaporites (Freeze and Cherry 1979), and again halite is a mineral noticeably absent from descriptions of "N" system mineralogy.

Figure 12 is an X-Y plot of sodium versus chloride concentrations, in milliequivalents per liter, for each well. In this

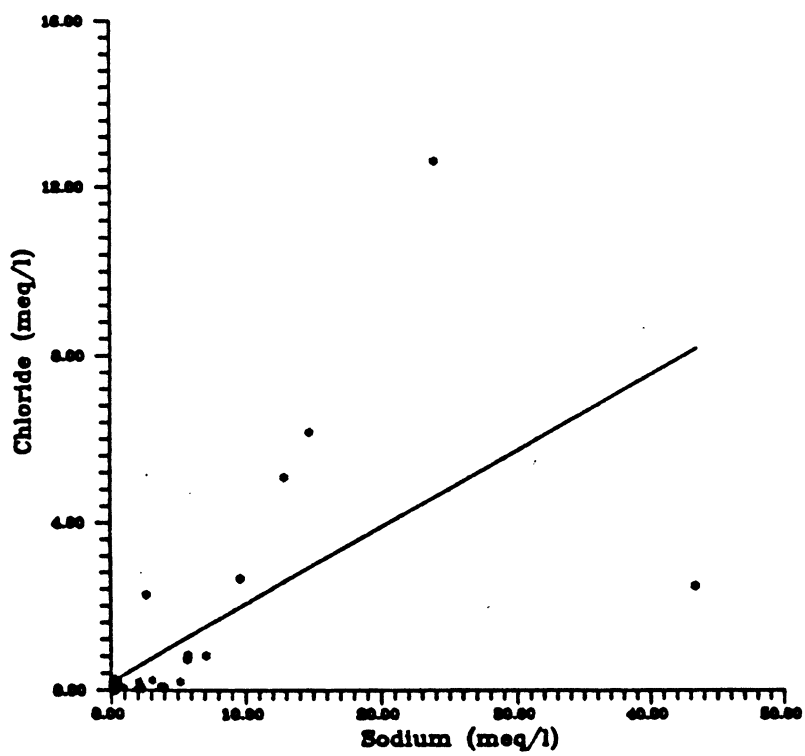


Figure 12: Ratio of Sodium to Chloride (meq/l)

figure a linear relationship does seem to emerge, suggesting dissolution of halite as a major mechanism for the introduction of chloride (and sodium) into the "N" system. The $r^2$ value for this relationship was calculated at 0.334, which is not a regression value confirming a linear relationship. The best fit line is slightly skewed due to one sample with an abnormally high sodium concentration. Because the Glen Canyon Group contains few evaporites, with no known concentrations of halite or gypsum beds along the southeastern margin of Black Mesa, the reasons for elevated levels of chloride in this area are not at all clear. However, halite and gypsum beds are known to occur within the underlying formations, particularly the Moenkopi and Chinle Formations, as well as in overlying Cretaceous beds.

Figure 13 is a map illustrating the distribution of fluoride across the thesis area, using fluoride concentrations determined in the field. Notable highs occur along the eastern and southeastern flanks of the thesis area. Another mound is found between Tuba City and Oraibi, but this may be an anomolous well or the result of a poor field analysis. Fluoride concentrations tend to run under three mg/l, but occasional higher amounts have been reported for the southern Colorado Plateau. However, none of the field analyses yielded concentrations beyond the expected range.

Source minerals for fluoride include fluorite and apatite, as well as some amphiboles, and more rarely, cryolite, sellaite, and ralstonite (Faust and Aly 1981, Hem 1985). Most of these usually occur in igneous rocks, but there are no heavy concentrations of

igneous rocks in the vicinity of the elevated concentrations of fluoride seen in the southern and eastern portions of the study area. Volcanic ash is considered a material which could contribute significant amounts of fluoride. However, within the study area the only volcanic features intruded into the Glen Canyon Group are dikes and sills scattered primarily northwest and east of Black Mesa. Navajo Mountain is a major laccolithic feature affecting "N" system

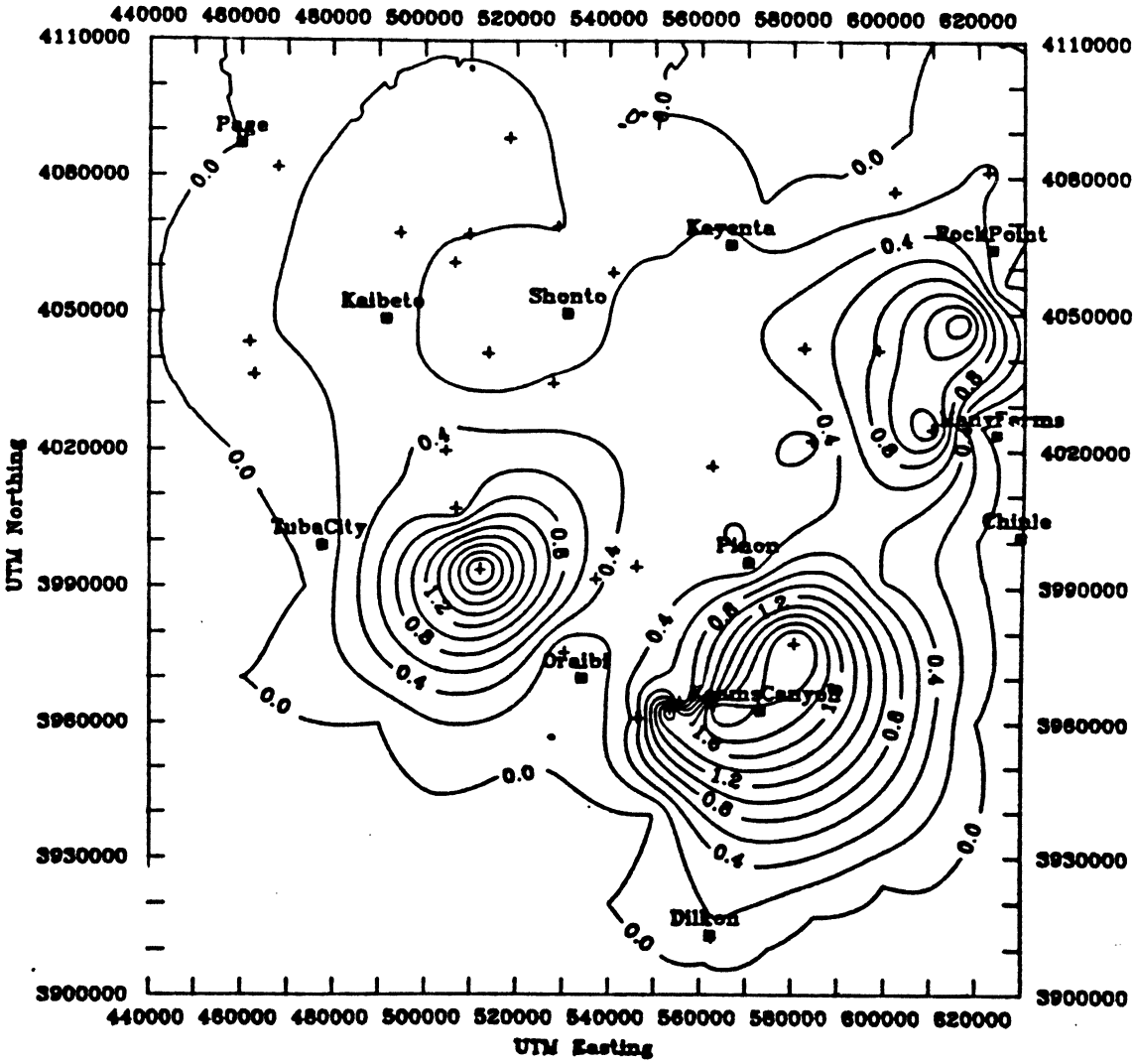


Figure 13: Distributions of Fluoride Concentrations (CI=0.2 mg/l)

rocks, but no elevated fluoride levels were seen near it. Hem (1985) notes that higher fluoride concentrations can be expected in waters with lower calcium concentrations, since higher calcium concentrations can lead to equilibrium with respect to fluorite. Certainly calcium levels are not elevated in those areas along the southeastern and eastern margins of Black Mesa with higher fluoride concentrations. Again the direct cause of the slightly elevated levels of fluoride noted to the south and east cannot be easily ascertained, but this ion does not appear to be of critical importance in the geochemical evolution of "N" system groundwaters.

Figure 14 is a map which illustrates the regional distribution of nitrate concentrations across the thesis area. Faust and Aly (1981) note that there are few geochemical sources for nitrate or even nitrite. Nitrogen in organic form is converted into nitrate and nitrite by bacteria in the process called nitrification (Hem 1985). The presence of nitrate is usually considered indicative of pollution of the groundwater by human and agricultural sources of nitrogen, particularly wastes and fertilizers. On Figure 14 only a few areas with elevated concentrations of nitrate can be seen. The major zone of high nitrates is to the south, near the Hopi towns and centered around Polacca School 2, a shallower well in a long settled community with numerous older septic tanks, leach fields, and livestock; it is very possible that organic wastes may have reached the "N" system at this point given the lengthy amount of time they have had to do so. The amount of nitrates found in the groundwater in this area of the

Hopi Reservation could pose a health risk to infants and young children. Another zone of elevated nitrates can be seen near Shonto and Navajo National Monument, and may be explained by the close proximity of sewage treatment lagoons to the wells sampled. Wells north of Tuba City and south of Copper Mine, and the well near Dilkon also showed anomolous highs. Several wells exhibited no detectable nitrate (or nitrite) whatsoever, either in the field or in the

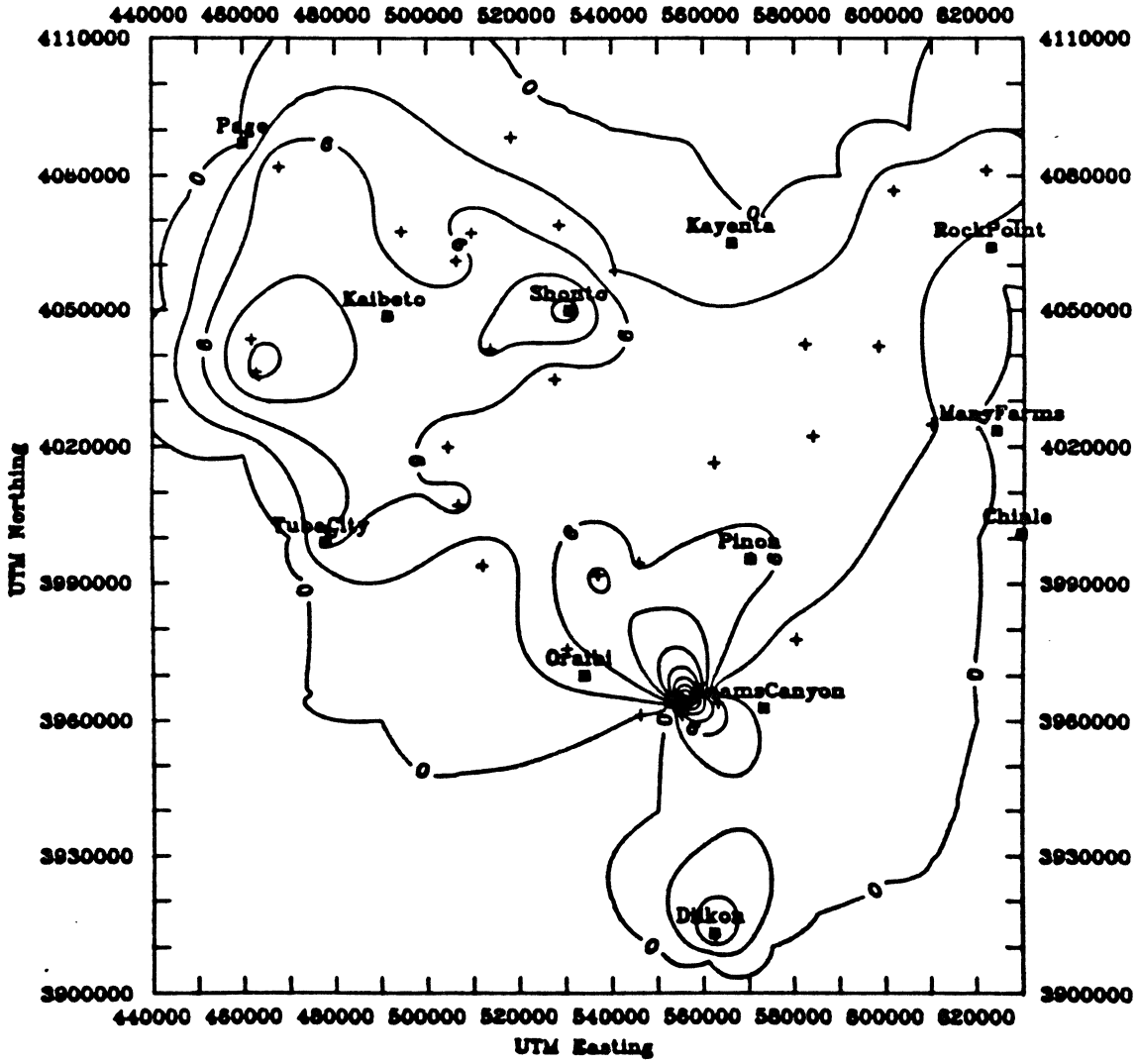


Figure 14: Distributions of Nitrate Concentrations, CI=3 mg/l

laboratory. Most displayed minor concentrations. The scattered nature of nitrate highs reveals no consistent pattern which can be related to "N" system geology.

Figure 15 is a map which illustrates the distribution of bicarbonate anions across the thesis area. Even with a contour interval of 30 mg/l, the number of highs and lows outlined by the contour lines reveals a complex pattern. This is only to be expected,

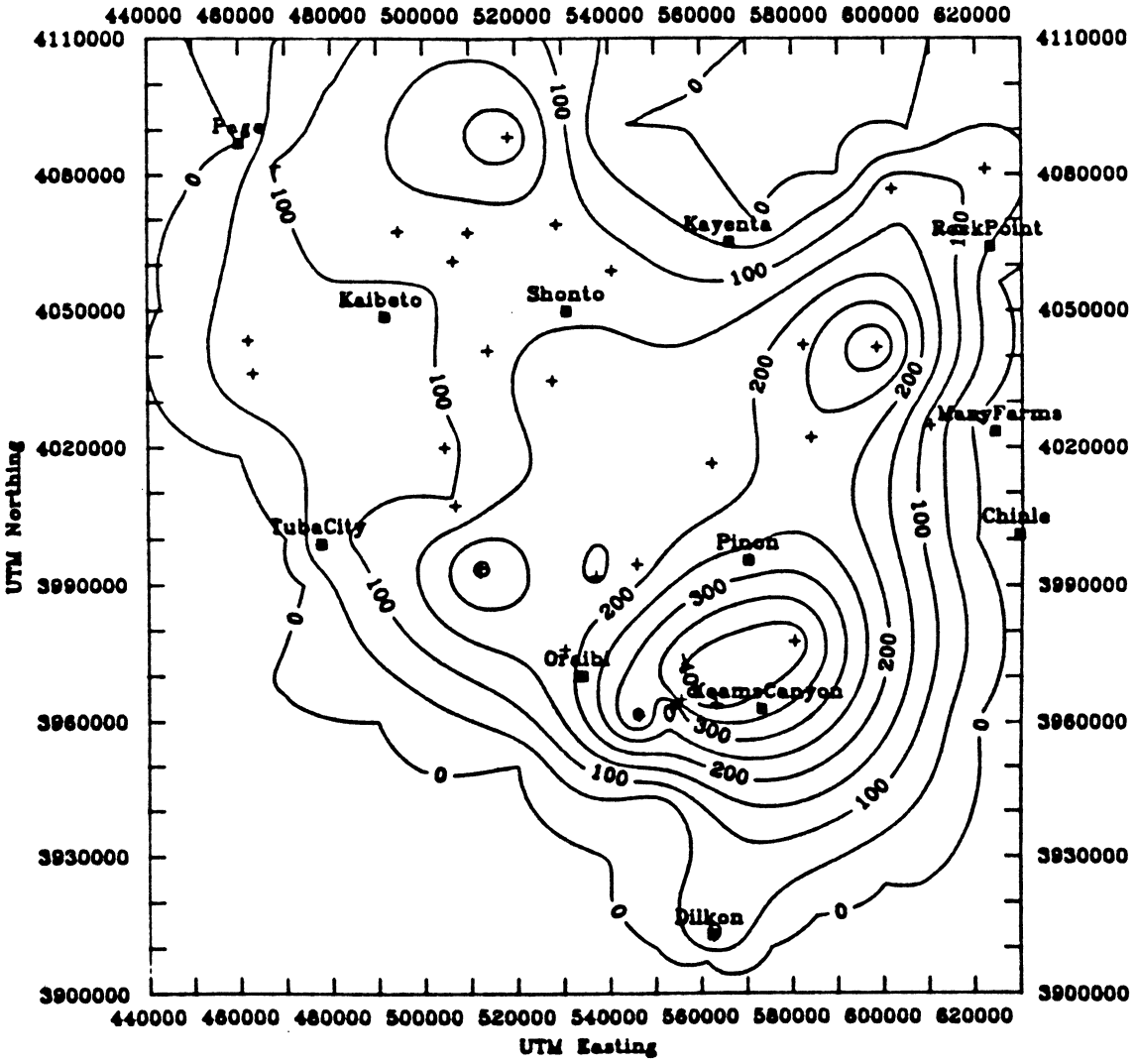


Figure 15: Distributions of Bicarbonate (CI=50 mg/l)

since the bicarbonate anion is a major part of the carbonate system, which clearly dominates the "N" aquifer's geochemistry. Bicarbonate levels are controlled by pH, which in turn is controlled by the partial pressure of carbon dioxide, and across most of the thesis area the bicarbonate concentrations are synonymous with alkalinity. The highest levels of this anion are seen along the eastern and southeastern edges of Black Mesa. Under Black Mesa, where the aquifer is confined and closed to the atmosphere, bicarbonate concentrations are also elevated. The pH levels begin to rise in this area, since carbon dioxide can no longer exchange with the atmosphere. The lowest concentrations occur in those areas identified as recharge zones, which are also largely open to the atmosphere, and thus permit carbon dioxide to enter the system and keep pH values more acidic.

Figure 16 illustrates the ratio of calcium to bicarbonate, with bicarbonate values derived from alkalinity measurements. In a geochemical situation dominated by simple dissolution/precipitation within the carbonate system, bicarbonate should be directly related to calcium concentrations according to the stoichiometry of the basic equation (Freeze and Cherry 1979). Since the carbonate system was envisioned as the primary determinant of "N" system aqueous geochemistry, this plot was expected to reveal such a relationship. However, with a regression $r^2$ of 0.346, no linear one-to-one relationship emerges on this X-Y plot. Instead, two linear relationships seem apparent, one in which the amount of calcium increases relative to bicarbonate and another in which bicarbonate

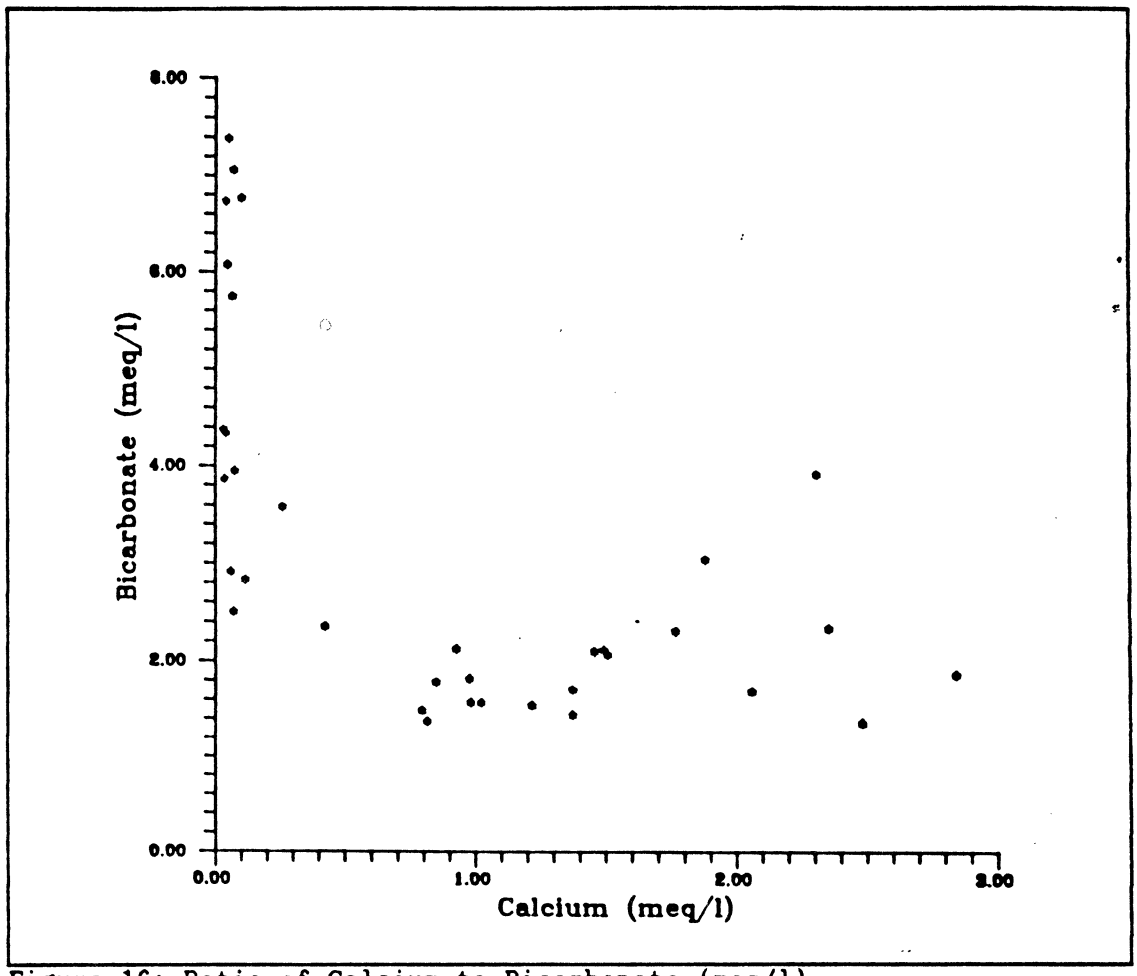


Figure 16: Ratio of Calcium to Bicarbonate (meq/l)

concentrations increase while calcium concentrations remain stable. This suggests that even the carbonate system within the "N" aquifer is not as simple as might be expected, and that simple precipitation/dissolution is not the only reaction controlling calcium and bicarbonate concentrations.

Of the common anions, then, bicarbonate, chloride, and sulfate exhibit the most significant variability. The association of chloride with sodium seems clear-cut and causal. The grouping of both bicarbonate and sulfate into two groups when plotted against calcium,

the major expected cation, does not yield quickly discernable explanations.

## Cations

Figure 17 is a map which illustrates the distribution of calcium concentrations (in milligrams per liter) across the thesis area. Again this map is gridded in terms of UTM coordinates, and sampled

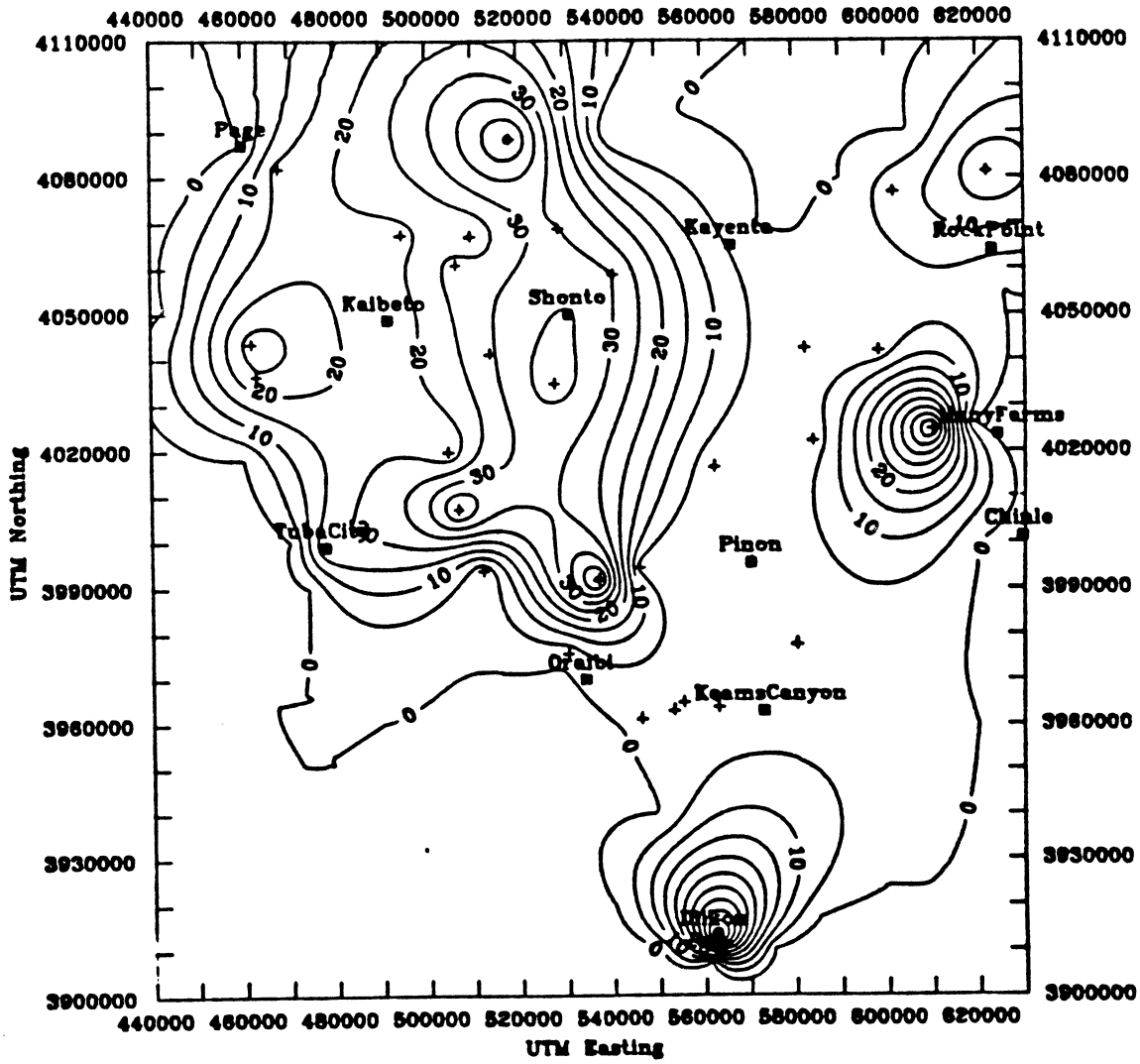


Figure 17: Distribution of Calcium Concentrations (CI=5 mg/l)

wells and Reservation towns are plotted for easy reference. This map is clearly different than most the preceding figures. Several areas of elevated concentrations are revealed, most to the northwest of that region of the study area where anions have higher concentration levels. Indeed, this map seems almost a mirror image of Figure 15 which showed bicarbonate highs and lows. The largest set of mounds forms a continuous high across the thesis area extending south from Navajo Mountain across Black Mesa to the vicinity of Pinon, and reaching west to the Tuba City area. Large portions of this area correspond to the recharge zones for the "N" aquifer system.

At Dilkon, south of Black Mesa, one well is associated with a major calcium high. The Dilkon well is relatively shallow and may represent recharge waters more similar to those in the northwestern portion of the study area, thus displaying similar calcium concentrations for similar reasons. The elevated calcium levels may also be related to the extensive volcanics, containing calcic plagioclases, which overlie the Wingate Sandstone at that point. At 10R-111, west of Many Farms, another calcium mound can be seen. This well has produced anomolous concentrations of other species, and may be an example of leakance along a corroded well casing from the overlying "D" aquifer system.

In contrast to the elevated calcium levels to the west, the depressed concentrations along the eastern and southeastern portions of Black Mesa are less easily explained. It is not immediately clear why geochemical processes acting to the west should not be equally

active to the east, but clearly this eastern area exhibits minimal levels of calcium. Off to the northeast of Black Mesa in the northeastern portion of the Chinle Valley calcium levels again rise, and this area too has exposures of the Glen Canyon Group that act as a recharge zone.

Figure 18 further illustrates that two distinct bodies of groundwater are represented in the "N" system chemistry. The ratio of

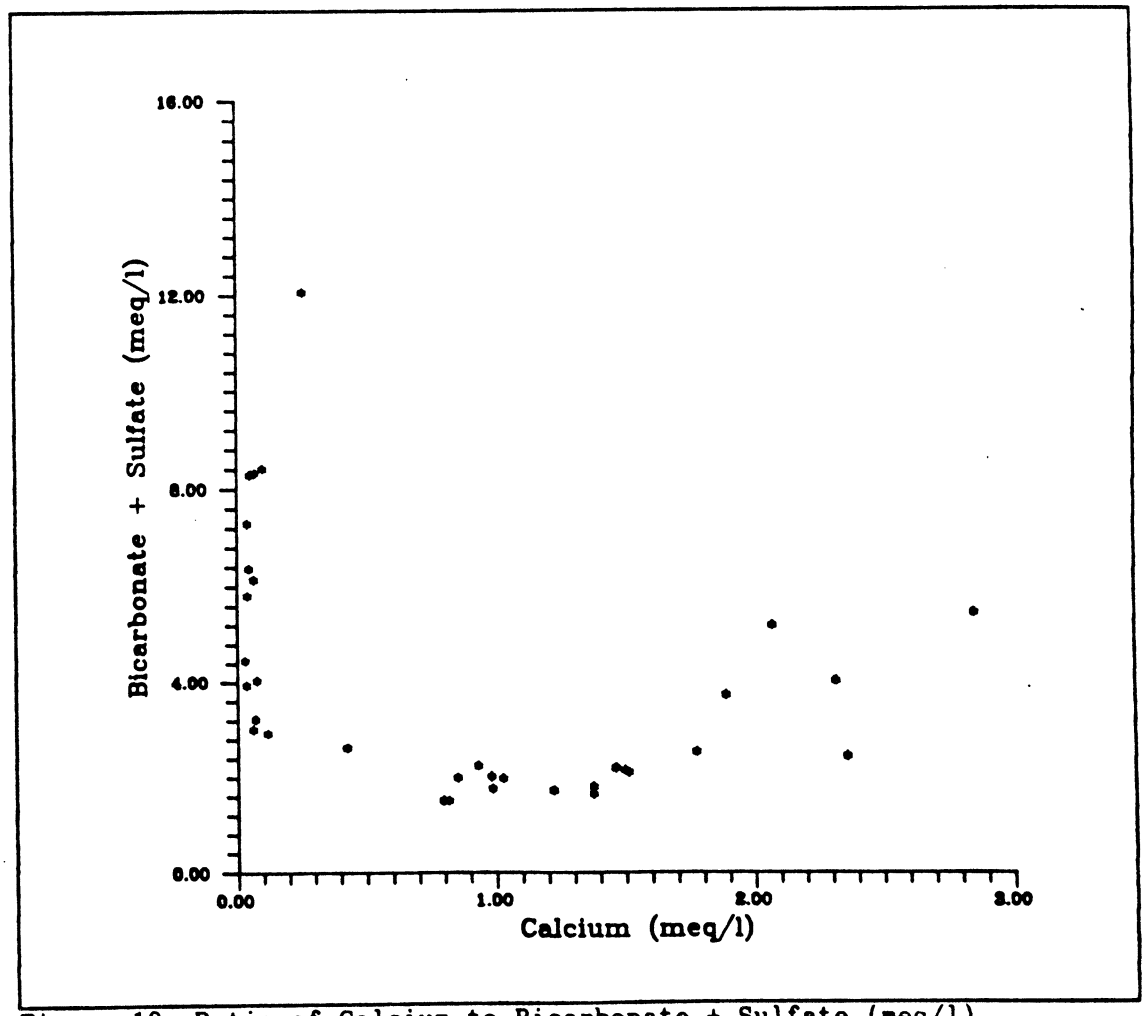


Figure 18: Ratio of Calcium to Bicarbonate + Sulfate (meq/l)

bicarbonate plus sulfate to calcium, in milliequivalents per liter, is essentially the ratio of the major anions to the major cation. Two straight line relationships can be discerned, with no intermediate zone between the two. In one grouping, anion concentrations tend to rise while calcium concentrations remain stable; in the other calcium concentrations tend to rise against more slowing rising values of bicarbonate and sulfate. In these two groups of waters, two different processes are occurring. The lack of intermediate points suggests that one group is not evolving into the other.

Calcium is one of the most common cations found in groundwater, and has a variety of geological sources. Dissolution of calcite and aragonite is the chief source, but dissolution of gypsum is also important where that mineral is found (Hem 1985). However, Figure 10 eliminated that process as controlling the "N" system. Other minerals which can contribute calcium include dolomite, anhydrite, fluorite, fluorapatite, and apatite, as well as calcium-rich plagioclases, amphiboles, and pyroxenes. In some instances cation exchange with sodium can contribute calcium to groundwater (Hem 1985).

Figure 19 is a map which illustrates regional trends in the distribution of magnesium. No significant differences from trends noted on the calcium distribution map can be discerned. Magnesium is not as easily precipitated as calcium, and once dissolved, tends to stay in solution until a high magnesium to calcium ratio is attained (Hem 1985). Magnesium can be precipitated as dolomite or magnesian calcite, if sufficiently high magnesium to calcium ratios are attained

in the initial solution (Folk and Land, 1979). However, soil waters and groundwater found in sandstone aquifers rarely reaches the ratios high enough to precipitate anything but calcite, which does contain low amounts of magnesium. Samples farther along the flow path of the "N" system should be enriched with magnesium relative to those samples closer to recharge areas, but such a trend is not readily apparent. Sources of magnesium include dolomite, magnesium-rich calcium

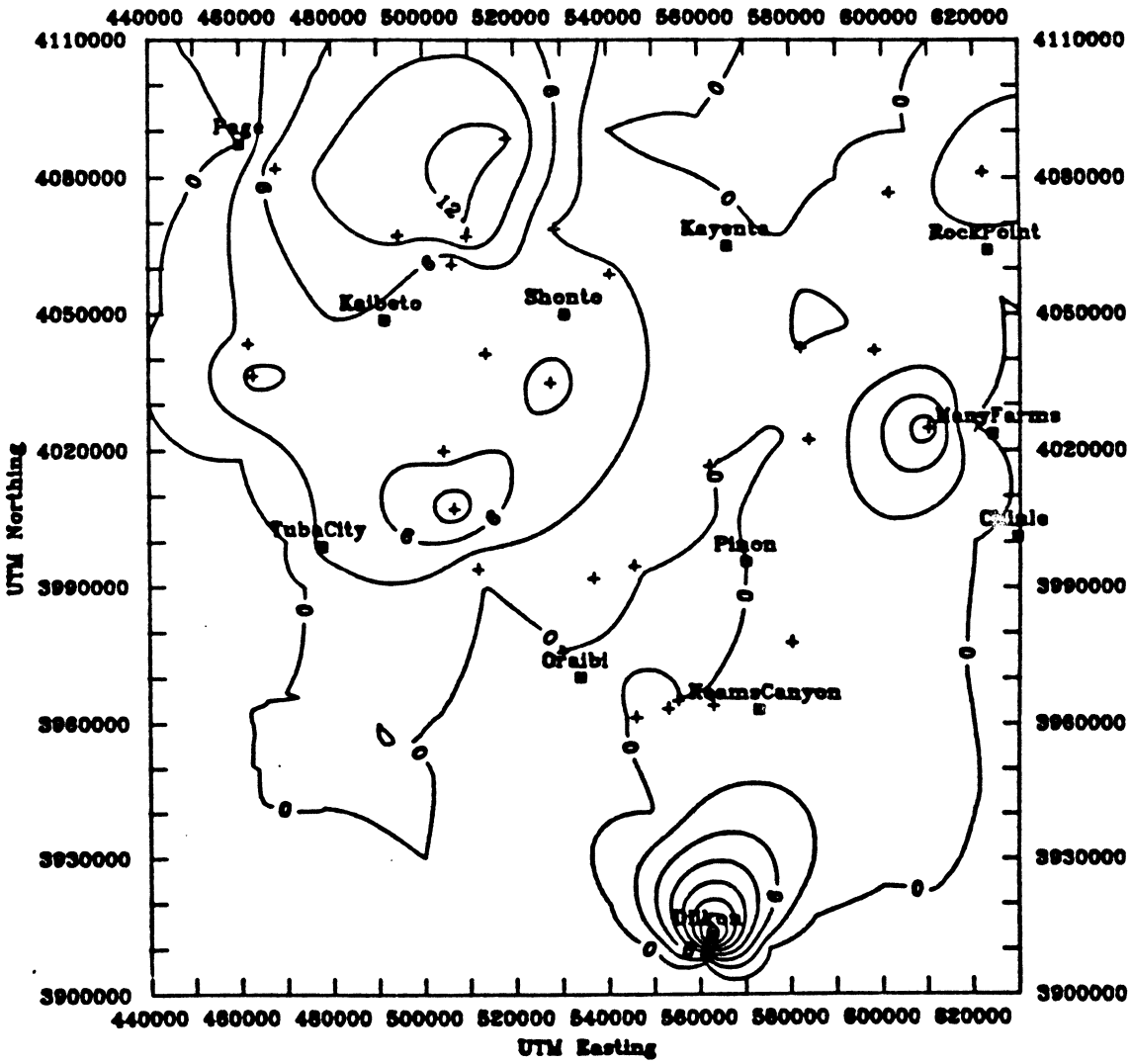


Figure 19: Distributions of Magnesium Concentrations (CI=3 mg/l)

carbonate, and ferro-magnesian minerals such as olivine, pyroxenes, amphiboles, biotite and others. Concentrations of magnesium in most samples were quite small, often below the detection limits of the flame atomic absorbtion spectrophotometer.

Figure 20 is an X-Y plot of the ratio of calcium to magnesium. It reveals no significant trends, only the nearly linear relationship that might be expected for these closely related cations, with a $r^2$ of 0.612, a higher regression value than other such plots. Most calcite

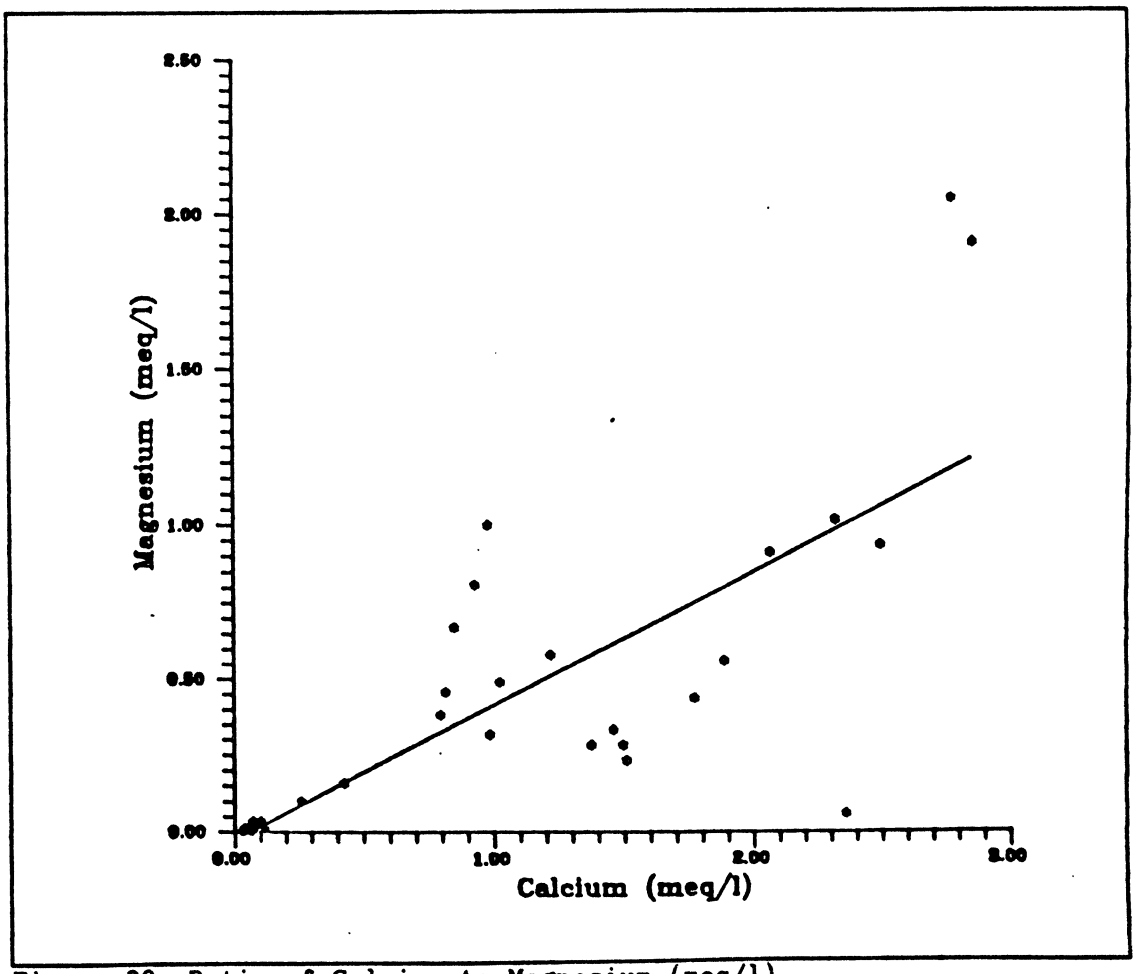


Figure 20: Ratio of Calcium to Magnesium (meq/l)

contains some magnesium substituting for calcium within the crystal structure. It seems likely that the dissolution of calcite containing low amounts of magnesium is the source for this cation. The ratio of calcium to magnesium within calcite varies somewhat, but given the low magnesium to calcium ratios in most soil waters and the rapid crystallization rate, calcite with minimal magnesium substitution is the expected form of any calcium carbonate precipitated (Folk and Land, 1975). Dolomite involves very slow crystallization rates and much higher ratios of magnesium to calcium, such as might be expected in hypersaline waters, and these higher ratios were not observed. Nor was any dolomite observed petrographically.

Figure 21 is a map which illustrates distributions of sodium concentrations across the thesis area. Sodium is an important cation in the consideration of which geochemical processes are controlling water chemistry in that it is such a common cation, and tends to exchange readily with calcium in clays. Cation exchange can often be assessed by examining the relationship of sodium to calcium and various other species. The regional trend seen on this map is similar to those of sulfate and chloride in that concentrations along the eastern edge of Black Mesa, the southeastern and eastern portions of the thesis area, are elevated, while sodium seems almost absent to the north and west. The correspondence of elevated sodium and chloride levels is clearly related, since Figure 12 demonstrated almost a linear relationship.

Figure 22 is an X-Y plot of the ratio of sodium to calcium plus magnesium, again expressed in milliequivalents per liter. If cation exchange were a major process controlling concentrations of these cations, then a mixed scatter of points across the field might be expected, since clays are thinly but evenly scattered through the Glen Canyon Group, which might be expected to lead to continous cation exchange. But this scatter of points was not seen. Two distinct

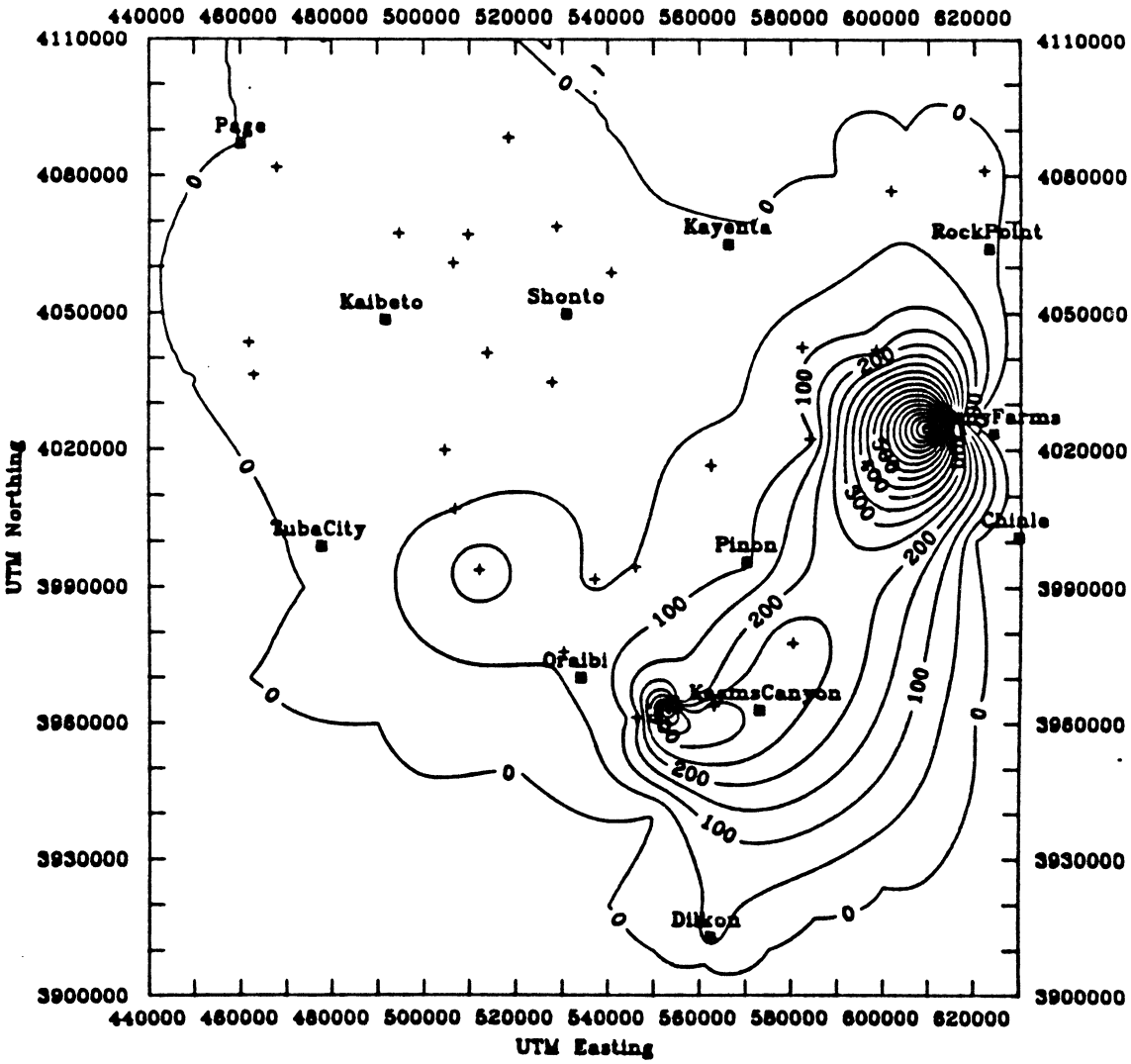


Figure 21: Distributions of Sodium Concentrations (50 mg/l)

linear relationships emerged, again suggesting two distinct bodies of water. The near total lack of any points falling in the intermediate zone between the two linear groups probably indicates that little cation exchange is occuring, and does not support the idea that one water may have evolved into the other.

Potassium levels were low across most of the study area, and this parameter accordingly was not mapped. Such trends as are apparent in Appendix II tend to closely approximate trends observed

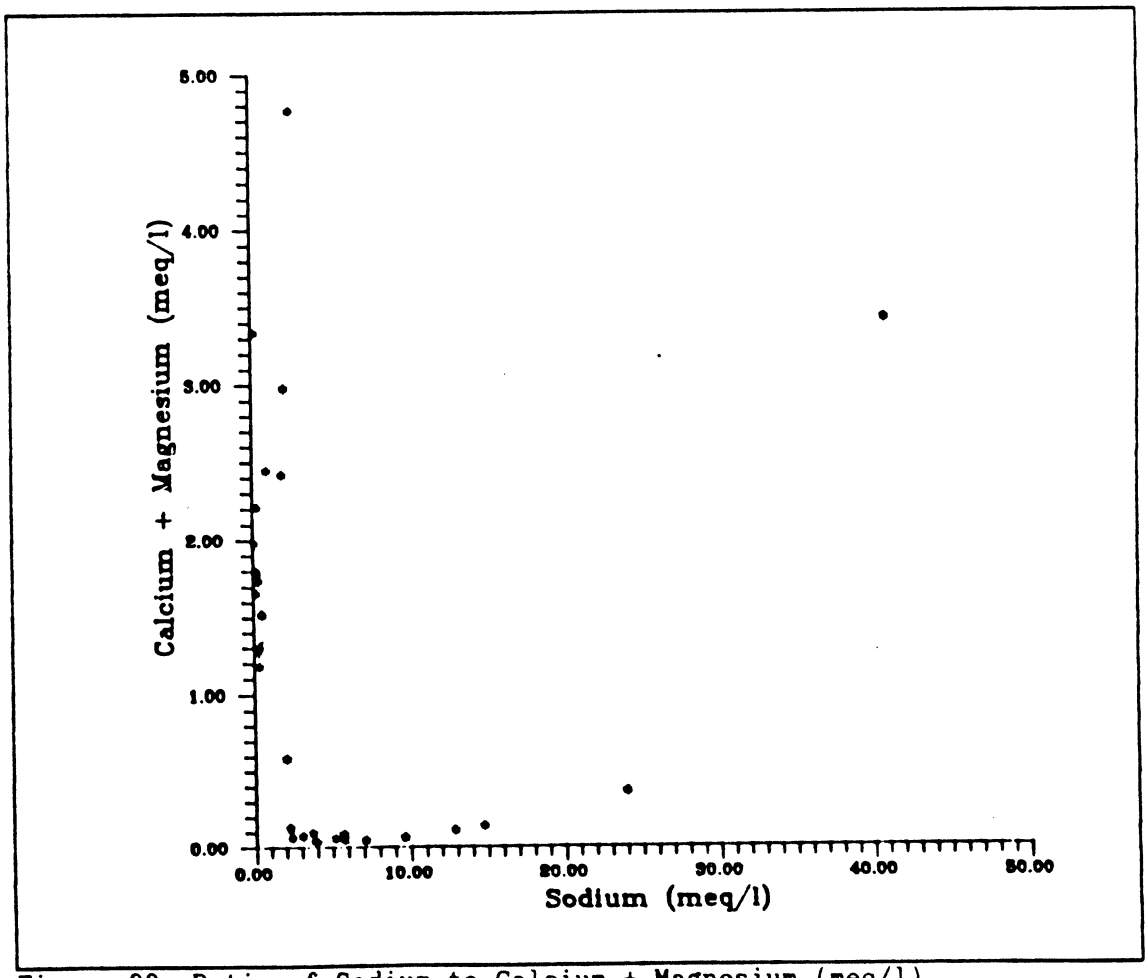


Figure 22: Ratio of Sodium to Calcium + Magnesium (meq/l)

for sodium concentrations; potassium levels were minimal to the north and west and elevated along the eastern and southeastern portions of the study area. Potassium is another cation usually derived from feldspar weathering or the breakdown of volcanic rocks.

As seen in Figure 23, concentrations of total iron tended to be quite low across most of the thesis area. The solubility of iron is controlled largely by pH and reduction-oxidation potential, and given

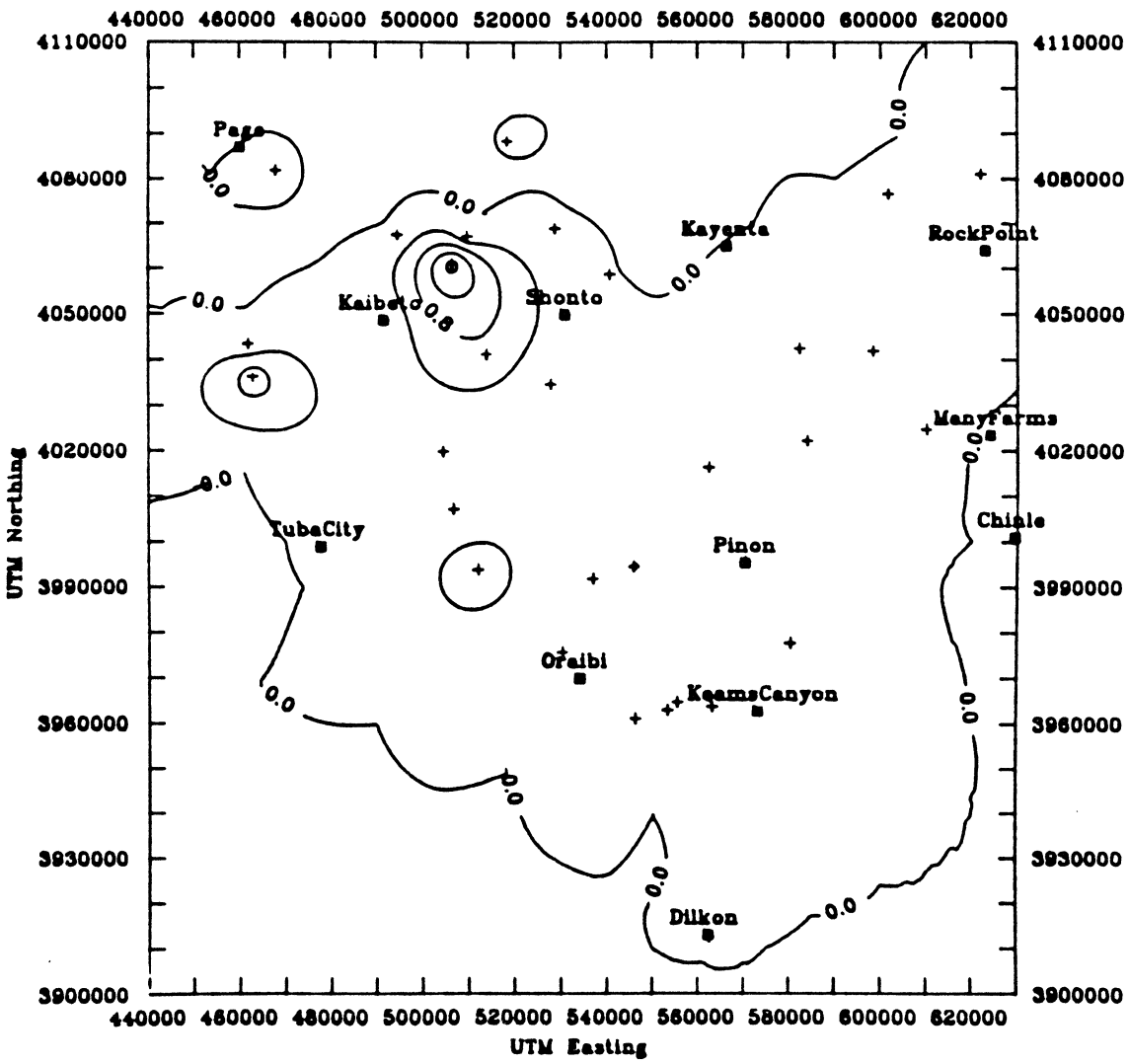


Figure 23: Distributions of Total Iron Concentrations (0.4 mg/l)

the right conditions, iron can be dissolved by oxidation, commonly of pyrite (Hem 1985). Iron-bearing minerals are prolific, and include pyroxenes, amphiboles, biotite, and olivine. Several minerals, such as hematite, goethite, siderite, pyrite, and marcasite, are formed as iron precipitates under varying conditions of pH and Eh.

The various mounds of elevated total iron concentrations are scattered and isolated across the thesis area, and few occur towards the eastern portion. High levels of dissolved oxygen to the north and west and generally low or non-existant levels of iron sulfides within the Glen Canyon Group suggest sources for these highs other than water-rock reactions with the "N" aquifer system. Metal particles from well casings often contaminate samples, and many samples analyzed in the field were unfiltered. Windmills had low flow rates, and even several hours of purging may have been insufficient to flush the well casing of metal particles. This is probably the best explanation of the scattered highs, most of which seem to be associated with windmills. There is also some possibility in the confined areas of the "N" system of vertical leakance from the overlying "D" aquifer, which does contain considerable amounts of ferrous sulfides.

Figure 24 is a map of two parameters super-imposed to demonstrate the degree to which they are interrelated. The solid lines represent concentrations of silicon dioxide in milligrams per liter, as determined in field analyses. The dashed lines indicate temperature in degrees Celsius. Temperature of groundwater within the "N" aquifer system is controlled by the geothermal gradient, as can be

seen by the fact that temperatures are highest under the structural basin of Black Mesa, where Glen Canyon Group rocks are most deeply buried. The primary control on silica solubility is temperature, when a single source of silica is involved. Feldspar dissolution also plays a complex role (Hem 1985; Holdren and Berner 1979), and other sources of silica also exist, such as quartz, chalcedony, and amorphous silica. The widespread nature of weathered feldspars in

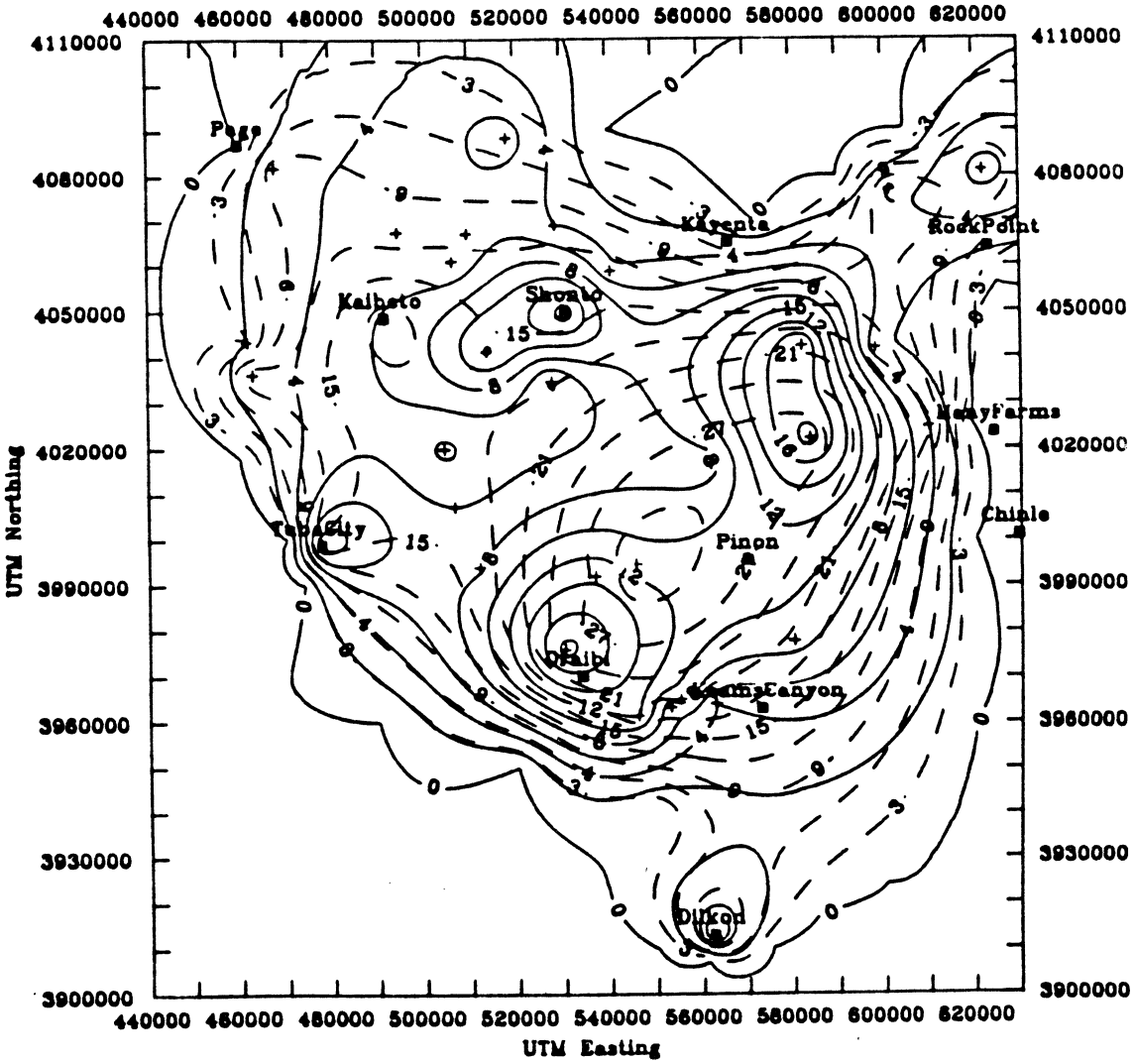


Figure 24: Distributions of Silica (solid lines, CI=3 mg/l) and Temperature (dashed lines, CI=4$^0$ C), superimposed.

Glen Canyon Group rocks, which is discussed in the following chapter, makes their distribution almost a constant, and while quartz is also ubiquitous, other forms of silica were less common. Feldspars seem the most likely source mineral for silica. The pattern seen in Figure 24 for silica concentrations, then, may well reflect the overriding control of temperature on silica solubility. In general, the higher the temperature, the greater the concentration of dissolved silica. However, some of the contours towards the center portion of Black Mesa represent unusually high levels of silica, and other processes may also be contributing to silica concentrations at depth.

## Piper Diagram

In order to facilitate interpretation of evolutionary trends and hydrochemical processes, Lloyd and Heathcote (1985) note that some form of graphical representation of water chemistry data should be used in conjunction with distribution maps. One of the most widely used means of representing large numbers of analyses for comparative purposes is the Piper (1944) diagram, a variation of a trilinear diagram in which two base trilinear diagrams plot anion and cation equivalent percentages. These are then respectively extended into a diamond field where the intersection point represents the sample. This diagram also has the advantage of programmability, and several computer programs exist that can plot Piper diagrams from water chemistry data (Cheng 1988).

Figure 25 is a Piper diagram which plots major cation and anion equivalent percentages for all "N" system samples analyzed for this thesis, with a charge balance error of less than 20%. It is quickly apparent that two major groupings exist within the data. One cluster is dominated by sodium and a variety of anions such as bicarbonate,

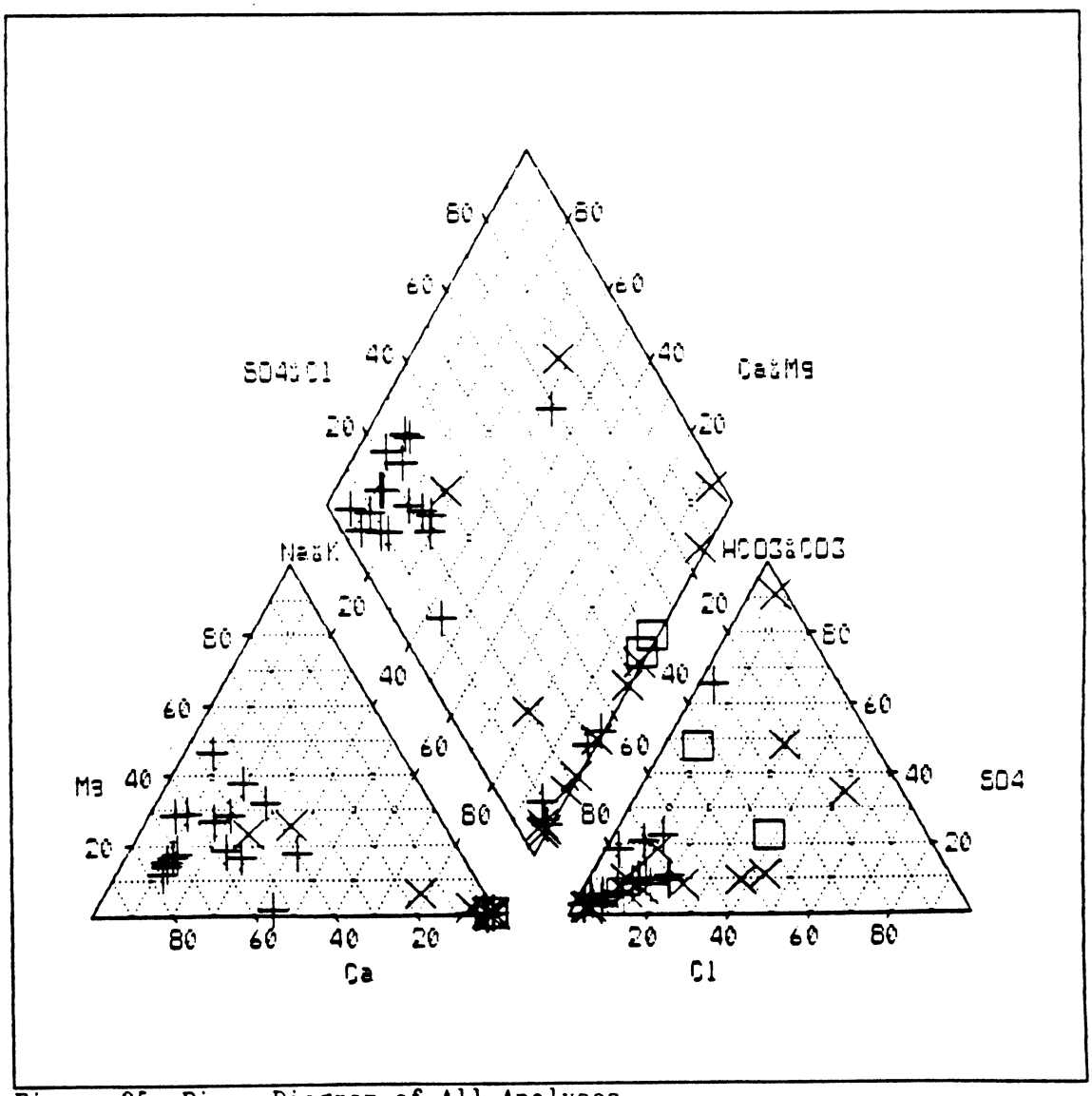


Figure 25: Piper Diagram of All Analyses

sulfate, and chloride; these analyses are mostly from the eastern and southeastern portions of the study area. Another more tightly clustered grouping is dominated by calcium as the chief cation and bicarbonate as the principal anion, and these samples are mostly from the northern and western portions of the thesis area. There are virtually no analyses which fall in the intermediate zone between these two distinct groups. Often analyses which plot between tight clusters suggest some degree of mixing between the two groups.

Cheng (1988) has noted the inherent difficulties of defining hydrochemical changes and geochemical evolutionary trends based solely on the positions of water chemistry groupings within the diagram. In particular, the inference of mixing as a major chemical mechanism is difficult to draw based only on trends seen in a Piper diagram, because of the variety of post-mixing reactions that are possible (Cheng 1988). It is thus a mistake to define a set of geochemical reactions on the positions or trends seen in a Piper diagram, but the diagram remains an extremely useful tool for presenting large amounts of hydrochemical information in a comprehensible format. Often its greatest use lies in the definition of hydrochemical facies (Freeze and Cherry 1979), by which means water chemistries are succintly described, though not explained.

## Discussion

At least two chemically distinct groundwaters are present within the "N" aquifer system. One is a calcium-dominated water to the north

and west, while the other, located along the eastern and southeastern margins of the thesis area, is a sodium bicarbonate to sodium sulfate water. The set of reactions which create the chemically distinct water to the north and west are clearly dominated by dissolution-precipitation reactions within the carbonate system. But to the south and southeast a different set of processes controls the evolution of the water. Silica represents one parameter which appears to be controlled primarily by temperature across the entire study area. Having examined the groundwater chemistry, it is now important to examine the mineralogy of these areas to understand the other half of the water-rock reactions which are occurring.

# CHAPTER 5

# MINERALOGY OF THE GLEN CANYON GROUP

## Introduction

This chapter discusses the mineralogy of the various formations and members of the Glen Canyon Group, the main rock body comprising the "N" aquifer system. Methods of study are explained, analytical results are presented, sources of uncertainty discussed, and general trends observed across the thesis area are evaluated.

Of the various formations of the Glen Canyon Group that make up the "N" aquifer system, only the Kayenta Formation has been thoroughly investigated in terms of mineralogy, mostly in the form of recent master's theses (Sargent 1984, Luttrell 1987). No detailed analyses of the mineralogy of the Lukachukai Member of the Wingate Sandstone could be located in the literature, and the Navajo Sandstone has also received only perfunctory mineralogical treatment. Probably because both are interpreted as classic aeolian sandstones, they are almost uniformly described as clean quartz arenites (Harshbarger et.al. 1957). Such descriptions are insufficient to explain the geochemical changes in water chemistry noted in the previous chapter.

Mineralogical analyses were therefore performed on samples of the Glen Canyon Group, particularly the Wingate Sandstone and the

Navajo Sandstone, in order to clarify what materials in what abundances are available within the "N" aquifer system for water-rock reactions. Such mineralogical knowledge is necessary for a variety of reasons.

Plummer (1984) has noted that virtually all attempts to model geochemical reactions within groundwater systems have paid far too little attention to mineralogy. Since modeling is a process of inferring the most plausible set of water-rock reactions that would produce a specific water chemistry, good information on the mineralogy of the rocks involved in those reactions is just as necessary as accurate water analyses.

Perhaps as important as knowing which minerals are available for water-rock reactions is knowing which minerals are absent and could not possibly be involved in the geochemical evolution of the groundwater. In the previous chapter the elevated levels of sodium and chloride were noted for the eastern and southeastern portions of the thesis area. The single most likely geochemical mechanism that would produce such elevated concentrations is the dissolution of halite. Yet evaporite beds have never been reported for the Glen Canyon Group. If halite cannot be found within "N" system rocks, or textures suggesting its former presence, then the reactions which produce sodium and chloride cannot be occurring within the aquifer, and another source must be sought.

The goals of the mineralogical analysis, then, were to clarify the compositions of the rocks with which the groundwaters react as the

flow from recharge to discharge areas, and to obtain some idea of the relative abundance of the important minerals across the thesis area, so that regional trends, if any, could be traced. The two analytical methods used to realize these goals were X-ray diffraction and petrographic analysis. These two methods complement one another in delineating grains, cements, and matrix within the rock.

X-ray diffraction was judged to be the best method of approaching clay mineralogy. The clays are probably the most important minerals involved in any ion exchange reactions which might be occurring within the system, and detailed knowledge of their mineralogy and relative abundance is necessary to understand ion exchange reactions.

Petrographic analysis of thin-sections enables a determination of the grains present within the rock, their relative abundances, and textures which provide clues concerning geochemical processes. Under the petrographic microscope it is also possible to see the kinds and amounts of cement present, and postulate a sequence of development for those cements. Matrix is less easily approached via petrographic techniques.

## Provenance of Analytical Samples

All materials used for X-ray diffraction analysis were obtained from archived drilling cuttings. Several thin-sections were obtained from these cuttings as well. Additionally, surface rock samples were collected in the field, and several selected for thin-sectioning and

petrographic analysis. Table 11 presents sample locations and descriptions.

The Arizona Bureau of Mines in Tucson, Arizona, maintains an archive of drilling samples, mostly rock cuttings, from most of the recorded oil and gas wells within the State of Arizona. A map showing well locations accompanied by some construction details, available from the Arizona Oil and Gas Commission (Conley 1975), was used to select wells within or near the thesis area completed through the Glen Canyon Group. More detailed lithologic logs were examined in Tucson and a shorter list developed. Cuttings for each well were examined, and the largest culled out for analysis from 13 wells.

These cuttings have the advantage of representing the aquifer materials at depth, not solely at the surface where water-rock reactions may be different, and where weathering may have seriously affected mineralogy. But their disadvantages are many. First, oil wells are not evenly distributed across the state or the thesis area; most are located in the far northeastern corner of Arizona. So there is little representation of the western and southwestern portions of the thesis area. Cuttings were taken from the complete Glen Canyon Group interval as logged, not from single formations or limited depth intervals which would not have yielded sufficient material for analysis. So they represent the Glen Canyon Group as a whole, and not any single formation, a disadvantage when trying to ascertain which specific geochemical reactions occurred within which specific formation within a thick sequence. These samples are thus not truly

Table 11: Sample Locations and Analytical Methods

| Arizona BureauMines Number | Well Name | General Location | UTM East | UTM North | Ground Level Elevation | Lithological Interval | X-Ray Diff? | Thin-Sectioned? |
|---|---|---|---|---|---|---|---|---|
| 2506 | Champlin #1 Nav 335 | 6 mi.NNE Red Mesa | 657400 | 4094500 | 5203 | all | yes | no |
| 2089 | Amer.Mining #1 Navajo | 10 mi.WSW of Rock Point | 610700 | 4059300 | 5423 | Wingate SS | yes | no |
| 2051 | Amerada #1 Hopi | 7 mi. NNE Polacca | 561950 | 3976600 | 6171 | all | yes | no |
| 2041 | Atlantic Refng #9-1 Hopi | 7 mi.SSW Kykotsmovi | 523600 | 3966100 | 5808 | all | yes | yes |
| 2033 | Tenneco #1 Nav 8939 | 6 mi. NW Rough Rock | 594700 | 4036900 | 6097 | all | yes | no |
| 2030 | Cactus #1 Navajo 8515 | 11 mi. NNW Rough Rock | 594000 | 4042300 | 5910 | all | yes | no |
| 2027 | Amerada #1 Navajo 91 | 5 mi.SE Dennehotso | 608200 | 4072800 | 5185 | Wingate SS | yes | yes |
| 2013 | Tenneco #1 Navajo | 3 mi.S of Kayenta, 1.5 mi.S HolidayInn | 567500 | 4059600 | 5857 | all | yes | yes |
| 1678 | Gulf #1 Garnet Ridge-Navajo | 2 mi.NW TesNesIah | 612500 | 4091500 | 5165 | all | yes | no |
| 1186 | Texas Pacific #2 Monsanto Nav-138 | 3 mi. E Red Mesa | 651400 | 4093200 | 5966 | all | yes | no |
| 1005 | Gulf #1 Walker Creek-Navajo | 2 mi.E MexWater TP | 628200 | 4087300 | 5192 | all | yes | yes |
| 287 | Sinclair #1 Navajo | 3 mi.W Inscription House Clinic | 514300 | 4048900 | 6609 | Kayenta-Navajo | yes | yes |
| 68 | Amerada-Stanolind #1-Nav-Black Mtn | 4 mi. NNE Cottonwood | 603000 | 3998000 | 6320 | all | yes | no |
| | Surface 1 | Comb Ridge N.Kynta | 571700 | 4069100 | | Wingate SS | no | yes |
| | Surface 2 | 3.5 mi.W ManyFarms | 618900 | 4025700 | | Wingate SS | no | yes |
| | Surface 3 | 4.5 mi.W ManyFarms | 615800 | 4026900 | | Wingate SS | no | yes |
| | Surface 4 | Navajo Nat'l Mon | 544700 | 4047250 | | Navajo SS | no | yes |
| | Surface 5 | 5 mi.W Many Farms | 615000 | 4027100 | | Navajo SS | no | yes |
| | Surface 6 | 4 mi.N Kayenta | 568700 | 4066700 | | Navajo SS | no | yes |
| | Surface 7 | Blue Canyon | 509600 | 4000900 | | Navajo SS | no | yes |

representative of either the horizontal or vertical variability within the Glen Canyon Group, but they were the only subsurface samples available.

In order to obtain a clear picture of mineralogy within specific formations, particularly the Wingate and Navajo Sandstones, several surface samples were collected during the course of fieldwork. Using detailed geological maps (Cooley et.al. 1969), locations were verified as within the formation desired. Samples were collected from the vicinity of Blue Canyon, Navajo National Monument, Kayenta, and Many Farms. These samples have the advantage of being evenly distributed across the thesis area, and definitely identified as to formation. They have the disadvantage of being surface rock samples, thus more highly weathered than subsurface samples. They are also few in number, and cannot be considered truly representative of the spatial variability of the mineralogy of the Glen Canyon Group.

Despite the scattered nature of these samples, both vertically and horizontally, they are important in that the mineralogical information derived from them cannot be found elsewhere. Interpretation of these few samples suggests trends for the lithology of the "N" aquifer system as a whole. No claim is made that these few samples constitute a definitive study of the Glen Canyon Group.

## X-Ray Diffraction Analysis

X-ray diffraction was performed at Bilby Research Center by a qualified geological technician. Prior to analytical runs, the

samples were treated in two different manners. One portion of each sample was simply ground to the appropriate size and run as an unoriented whole rock mount. The other portion was mixed with distilled water, sonified, and size segregated by centrifugation to retrieve the clay fraction of the rock, and this portion of each sample, the less than two micron fraction, received further attention. Diffractograms were produced for each analytical run, and interpretations appear in Table 12.

Three distinct steps were involved in the preparation of each clay fraction sample. The first step was the preparation of a slide using a water/clay mixture. This has the effect of orienting the C-axes of the clay minerals perpendicular to the slide in order to obtain clear peaks on the diffractogram for better interpretation. Glycolation was the second step, involving treatment of the sample with ethylene glycol. This produces an expansion of the clays, and is particularly useful in aiding identification of swelling clays such as dioctrahedral smectite (Srodon 1980). The final step consisted of heating the previously treated slide to over $500^0$ C in order to collapse the peaks which had been accentuated by glycolation. By comparing diffractograms of all three slides, clay minerals and their rough proportions can be identified.

The whole rock mounts were prepared from unoriented powder which were site packed in a random powder mount, placed in the goniometer, and analyzed. Schulz (1964) pioneered a rough technique for estimating amounts of various minerals present in the rock based on

Table 12: Relative Amounts of Major Minerals as Determined by X-Ray Diffraction.

| ABM Number | Clay Fraction Smectite % | Illite % | Other/Comments | Whole Rock Fraction Quartz | Feldspars | Calcite |
|---|---|---|---|---|---|---|
| 2506 | 82 | 18 | mixed-layer? | dominant | minor | major amt. |
| 2089 | 76 | 24 | Wingate only | dominant | plag?,others | minor |
| 2051 | 90 | 10 | good sample | dominant | minor | minor |
| 2041 | 90 | 10 | minor kaolinite? | major amt. | minor | major amt. |
| 2033 | 80 | 20 | poor run | major amt. | minor | major amt. |
| 2030 | 70 | 30 | mixed-layer? | major amt. | minor | major amt. |
| 2027 | impossible | | to interpret | dominant | minor | minor |
| 2013 | 80 | | 20% mixed-layer | dominant | minor | minor |
| 1678 | 75 | | 25% mixed-layer | dominant | albite?other | minor |
| 1186 | 90 | 10 | minor kaolinite? | dominant | minor | major amt. |
| 1005 | 11 | 89 | mixed-layer? | dominant | plag?,others | minor |
| 287 | 44 | 56 | mixed-layer? | dominant | minor | minor |
| 68 | 95 | 5 | | dominant | minor | minor |

relative strengths of characteristic peaks seen on the diffractogram, but no attempt was made here to estimate percentages. Mineral components could be seen as major, minor, or dominant, and are so noted in Table 12. The aggregate nature of the samples, representing all of the Glen Canyon Group rather than one formation, would render precise estimates less meaningful. Also, the whole rock mounts did not receive sufficient rotation to permit identification of smaller

secondary peaks of some minerals; over $60^0$ of two-theta rotation may be necessary to see all relevant peaks for some minerals on the diffractogram.

Results of running the three slides (oriented, glycolated, and heat-treated) for each clay fraction sample were more successful. Smectite and illite peaks consistently stood out on most of the resulting diffractograms, and it was possible to determine their ratio following Srodon (1980). Rough estimates of smectite and illite percentages appear in Table 12. Noise made identification of mixed-layer smectite/illite clays more difficult, and very few indications of kaolinite were seen. In almost all samples, smectite is the dominant clay type, with some illite present. No regional variability could be seen; however, it should be remembered that these samples represent the entire Glen Canyon Group, not any one unit such as either facies of the Kayenta Formation.

Quartz, as expected, was the dominant mineral seen in the whole rock mounts. Minor amounts of feldspars accompanied the quartz. Exact feldspar identifications were rendered impossible by the foreshortened two-theta rotation, as well as the overlapping nature of primary feldspar peaks, which tended to mask one another. The calcite peak was almost always present, often in surprising strength. Although no regional trends could be discerned, it is clear that at depth calcite is a major component of the Glen Canyon Group. Since calcite is not considered a major grain type in the Glen Canyon Group, the calcite peaks seen in X-ray diffraction probably represent cement.

## Petrographic Analysis of Thin-Sections

The largest cuttings from five of the wells represented at the Arizona Bureau of Mines were sent to National Petrographic, Inc., for thin-sectioning. Potassium feldspars were stained yellow in each slide for easier and more complete identification. Epoxy was colored blue in order to permit better porosity estimates. A sixth sample of volcanic material from a location near Chilchinbito on the east side of Black Mesa was also submitted, in order to assess ions contributed by igneous source rocks. Because only five samples were thin-sectioned, they cannot be considered an adequate representation of the Glen Canyon Group, but their analysis does provide a basis for suggestions concerning lithological trends within the "N" aquifer system.

Slides were analyzed at Northern Arizona University by the author. No point counts were done, since five to nine large chunks of Glen Canyon Group were mounted on each slide. It was felt that no one chunk was large enough to permit 300 points to be counted, and which chunk came from which formation was not randomized enough to provide a valid representative sample. Instead proportions were estimated utilizing percentage charts.

Several trends were noted for these five subsurface samples. First, most of the grain-supported sandstone chunks (probably Navajo Sandstone and Wingate Sandstone) contained virtually no matrix. Some chunks were identified as siltstones (wackes) on the basis of much larger amounts of clays; these may represent the Kayenta and Moenave

Formations. Secondly, calcite was the latest and usually dominant cement, although quartz overgrowths were consistently present. This agrees with peaks seen in X-ray diffraction. Calcite occurred as large blocky crystals, and some evidence of recrystallization was seen in a few slides. Thirdly, although quartz was the dominant grain type, far more feldspars were present than had been expected. Most of these showed some signs of alteration. Several of the sandstone chunks might more properly be termed sub-feldspathic arenites rather than quartz arenites, as feldspar percentages were routinely estimated to be greater than 20%. Porosity was often choked off by calcite cement, and where noticeable, often was greater outside layers of larger grains which were often totally cemented with large calcite crystals. These layers of larger grains between fields of smaller grains may represent micro-strata resulting from regular perturbations in sand flow, such as create the phenomenon of climbing translatent strata.

Two slides were obtained for analysis that represent the Navajo Sandstone near Gap, Arizona, at the western edge of the thesis area. Both were very similar. Both exhibited low porosity, and were well-cemented with silica in the form of kaolinite. No trace of calcite could be found. Some feldspars were present, and were very badly altered to sericite. Occasional pockets of authigenic matrix were noted.

The seven surface rock samples collected during the field phase were also thin-sectioned. They were not stained for potassium

feldspars, and no blue dye was added to the epoxy. Three were from the Lukachukai Member of the Wingate Sandstone, and four from exposures of the Navajo Sandstone. The quality of these slides was rather uneven, and all had too many grains ripped out during the grinding process to permit good point-counts, or even good estimates of porosity. However, several trends could be observed. Petrographic observations for all of the slides thin-sectioned are summarized in Table 13, although the observations for the Arizona Bureau of Mines samples represent only the sandstone chunks present on each slide.

One of the most striking trends noted in the four surface Navajo Sandstone samples was the lack of calcite cement in these slides. Only one slide, from west of Many Farms, displayed traces of large calcite crystals. All had silica cement, in the form of quartz overgrowths. Matrix seemed somewhat more plentiful, and feldspars were far more thoroughly altered than in the subsurface samples. Berner and Holdren (1979) have pointed out that initial water-rock reactions quickly alter feldspars, and such weathering processes would tend to occur near the surface. Weathering of feldspars can release cations such as sodium, potassium, and calcium, depending on the composition of the solid solution. But it is not clear that this process is the chief source of these ions.

Calcite cement is far more common in the three samples of the Lukachukai Member of the Wingate Sandstone. Kaolinite and quartz overgrowths also serve as cement, but calcite appears to be the most recent. In several spots calcite was observed to be replacing

Table 13: Summary of Petrographic Observations

| Sample | Formation | General Location | Sample Type | Matrix % | Matrix Types | Porosity Percent | Cement % | Cement Types | Comments on Cements | Total Grain Percent | Qtz % | Spar % | Feldspar Types | Other Grains: % | Other Grains: Types |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1:?rel | Lukachukai M, Wingate SS | Comb Ridge, N of Kayenta | surface | 5 | sericite | 5 | 15 | calcite, silica | some recrallization within large blocky calcite xtals | 75 | 75 | 20 | orthoclase? | 20 | muscovite, ferromags |
| 2:?rel | Lukachukai M, Wingate SS | 3.5 mi.N of Many Farms | surface | 5 | sericite | 5 | 10 | silica, calcite | qtz.overgrowths/chert with patchy calcite xtals | 80 | 70 | 20 | plagioclase, orthoclase | 10 | amphiboles, micas,calcite |
| 3:?rel | Lukachukai M, Wingate SS | 4.5 mi.N of Many Farms | surface | 3 | sericite | 5 | 12 | silica, calcite | qtz.overgrowths/chert with calcite replacing chert | 80 | 75 | 20 | plagioclase, orthoclase | 5 | muscovite, amphiboles |
| 4:Jn | Navajo SS | Navajo MM/ Hwy 160 junc | surface | 3 | sericite, illite? | 10 | 12 | silica | no calcite seen, silica is chert | 75 | 80 | 20 | orthoclase, plag,microcline | | |
| 5:Jn | Navajo SS | 5 mi.N of Many Farms | surface | 5 | sericite | 15 | 20 | calcite, silica | large calcite xtals replacing qtz.overgrowths | 60 | 80 | 20 | orthoclase, plagioclase | | |
| 6:Jn | Navajo SS | 4 mi.N of Kayenta | surface | 5 | sericite | 15 | 5 | silica | minor qtz.overgrowths; very little cement | 75 | 90 | 10 | plagioclase, orthoclase | | |
| 7:Jn | Navajo SS | Blue Canyon at Moenkopi Wash | surface | 10 | sericite | 10 | 5 | silica | minor qtz.overgrowths; no calcite seen | 75 | 85 | 15 | plagioclase, orthoclase | | |
| J?rag-1 | Navajo SS | Echo Cliffs near Gap | surface | 5 | sericite | 0 | 25 | silica | mostly kaolinite cement, some qtz.overgrowths | 70 | 90 | 10 | orthoclase, plagioclase | | |
| J?rag-2 | Navajo SS | Echo Cliffs near Gap | surface | 10 | sericite, illite? | 0 | 30 | silica | kaolinite cement, no calcite,qtz | 60 | 95 | 5 | orthoclase | | |
| ABM 287,1 | Glen Canyon Group SS | N of Inscrp. House ?? | subsurf | 2 | sericite | 30 | 5 | calcite, silica | large calcite xtals, some recrtalis,minor qtz | 63 | 80 | 18 | orthoclase, plagioclase | 2 | VRFs? |
| ABM 2041,2 | Glen Canyon Group SS | 10 mi.SW of Oraibi | subsurf | 2 | sericite | 5 | 33 | calcite, silica | large calcite xtals, replacing qtz.overgrowths | 60 | 80 | 15 | orthoclase | 5 | muscovite |
| ABM 2013,3 | Glen Canyon Group SS | 3 mi.S of Kayenta | subsurf | 2 | sericite | 20 | 3 | silica, calcite | qtz.overgrowths,kaolinite, one area of calcite xtals | 75 | 65 | 32 | orthoclase, plagioclase | 3 | VRFs, SRFs |
| ABM 2027,4 | Glen Canyon Group SS | 5 mi.SE of Beanehotso | subsurf | 5 | sericite | 20 | 15 | calcite, silica | large calcite xtals in layers of large grains | 60 | 57 | 40 | orthoclase, plagioclase | 3 | micas, pyroxenes |
| ABM 1005,5 | Glen Canyon Group SS | At junction of Hwys 160, 191 | subsurf | 2 | sericite | 15 | 40 | calcite | all calcite cement, large crystals | 43 | 75 | 25 | orthoclase, plagioclase | | |

kaolinite. Feldspars were mostly altering to sericite, and matrix appeared to be somewhat more abundant than in either the subsurface sandstones or the Navajo Sandstone samples. It should be noted that these samples were collected from the northeast and eastern margins of the thesis area, where the Lukachukai Member of the Wingate Sandstone is directly hydrologically connected with the Navajo Sandstone and the Kayenta Formation.

## Kayenta Formation Mineralogy

No surface samples of the Kayenta Formation were collected for thin-sectioning. Luttrell (1987) has done the most detailed petrographic work within the thesis area. Luttrell (1987) recognizes a subfeldspathic and a plutonic feldspathic petrofacies within the northern and northeastern portions of the extent of the Canyon Group. To the southwest of Black Mesa the Kayenta Formation grades into a series of intercalated siltstones, mudstone, and sandstone, and increases in thickness. Within this "silty facies" Luttrell (1987) recognizes a feldspathic volcaniclastic petrofacies, a mixing zone between the two. The "silty facies" of the Kayenta is not included in the definition of the "N" aquifer system, due to lower hydraulic conductivities.

Luttrell's (1987) plutonic feldspathic petrofacies is characterized by sandstone petrology which is rich in feldspars and lithic fragments, although quartz grains still dominate. Feldspars are mostly orthoclase and microcline, which release potassium upon

weathering. Lithic fragments reflect a plutonic source terrane (Luttrell 1987), are mostly quartzose. This varied petrological nature is found in the northern portion of Black Mesa and the northeastern Navajo Uplands, where the Kayenta Formation is directly connected to the Navajo and Wingate Sandstones.

In the far northeastern portion of the thesis area, Luttrell (1987) describes a subfeldspathic petrofacies which is closer in composition to the Wingate and Navajo Sandstones. Quartz comprises about two-thirds of the grains, with reduced percentages of feldspars and lithic fragments. Rock fragments are both plutonic and metamorphic clasts (Luttrell 1987). However, this petrofacies is too limited in extent within the thesis area to have substantial impact on the chemistry of the groundwater.

The "silty" facies of the Kayenta Formation as first defined by Harshbarger and others (1957) extends across most of the southern and southwestern portions of the thesis area. The fine-grained sandstones, siltstones, and mudstones in this region contain considerable amounts of illite and smectite, as well as quartz, feldspars, and volcanic lithic fragments (Luttrell 1987). Although the flow of groundwater through these rocks is slight due to lowered hydraulic conductivities, processes such as cation exchange make some contribution to the water chemistry at the lower boundaries of the Navajo Sandstone.

## Discussion

X-ray diffraction and petrographic analysis of the limited number of samples described in this chapter is not a definitive study of the lithology and mineralogy of the Glen Canyon Group. However, several major trends were noted for "N" aquifer system mineralogy, both between subsurface and surface samples, and regionally across the entire thesis area:

1) Calcite cement dominated subsurface sandstone samples, often choking off porosity, and usually associated with larger grains around which porosity had originally been greater. Crystals were large and blocky, indicating continuous crystal growth.

2) Calcite cement was almost totally lacking in most surface samples, although scattered traces of blocky calcite suggested that it had once been pervasive. Silica cement, primarily quartz overgrowths, was more common in most surface samples.

3) The lack of calcite cement in surface samples was most notable for Navajo Sandstone slides from the west and northwest of the thesis area. The one Navajo Sandstone slide from the southeastern portion of the thesis area displayed more signs of formerly pervasive calcite cement than the others. All three samples of the Lukachukai Member of the Wingate Sandstone showed considerable calcite cement; all are from the eastern and northeastern edges of the thesis area.

4) Feldspars were far more common than expected in sandstones, particularly in subsurface samples. They were also far less altered in subsurface slides than in surface samples. No regional differences

could be observed across the thesis area.

5) Matrix was common only in the subsurface chunks that were clearly siltstones, probably from the Kayenta or Moenave Formations. Matrix was almost entirely lacking in subsurface sandstone samples, and was only slightly more prevalent in surface samples. Navajo Sandstone samples from the western and northwestern portions of the study area exhibited the greatest amounts of matrix for sandstones, probably derived from the intensive alteration of feldspars in these rocks. Its composition, as revealed by X-ray diffraction, was mostly smectite with some illite, and very probably some undeterminable amount of mixed-layer smectite-illite clays.

From these trends several water-rock reactions can be predicted. By far the major activity appears to be with the calcite cement, particularly near the surface, and particularly in exposed Navajo Sandstone to the north and west. These dissolution-precipitation reactions dominate the "N" system water chemistry across much of its extent. The amount of matrix is too small to contribute significantly to water chemistry via ion exchange reactions. Feldspar weathering contributes sodium, calcium, and potassium ions. No trace of evaporite minerals was found, particularly to the east and south. These then are the factors that must be taken into account in describing geochemical evolution of "N" system groundwater.

# CHAPTER 6

# GEOCHEMICAL MODELING

## Introduction

Geochemical modeling is an attempt to derive the most thermodynamically plausible hypothetical set of water-rock reactions that yield specific water chemistries. Because of the excessively large number of computations required, geochemical modeling is usually performed on a computer (Plummer 1984), and a wide variety of programs exist that do the necessary calculations. No geochemical modeling has ever been done on the "N" aquifer system of northeastern Arizona, an omission which may be part of the reason for the overall lack of knowledge concerning the aqueous geochemistry of this system.

This chapter takes the results of the laboratory and field water analyses, and the results of mineralogical studies, and attempts to model the hydrogeochemical reactions which create the two distinct water chemistries observed. A brief overview of modeling in aqueous geochemistry is provided, as well as discussions of the more relevant programs.

## An Overview of Geochemical Modeling

### Goals

Geochemical modeling revolves around the attempt to better understand processes occurring within the aquifer which cannot be directly observed. It is because the water-rock reactions of interest cannot be directly observed as they proceed within the aquifer materials that modeling is required. Several diverse goals have been noted (Plummer, Parkhurst, and Thorstenson 1983) for all efforts at geochemical modeling:

1) Determination of the type of reaction controlling the evolution of the groundwater, under what conditions, and to what extent. It is a major goal to reasonably infer that dissolution, precipitation, cation exchange, or oxidation-reduction reactions are occuring, reversibly or irreversibly. The kinetic rates at which these reactions are occurring are also desired information, but are not always computed by most models.

2) Identification of the minerals which are involved in the postulated reactions. It is a major goal to determine which minerals are dissolving, precipitating, oxidizing, or reducing along the flow path, and to trace changes in mineralogy. This goal is often most important to petroleum geologists following the evolution of a diagenetic front.

3) Description of the spatial variation in the dominant reactions across the study area. A set of water-rock reactions which proceeds along one flow path may be different than a set of reactions

controlling the evolution of nearby groundwaters. If spatial variability exists across an aquifer, modeling is often the best way to study it.

4) Prediction of water quality at points beyond the flow path analyzed. The set of reactions seen between two points (two water chemistry analyses) can be extrapolated into areas where no water chemistry data is available. This is an important goal for resource managers in predicting water quality in unknown areas.

Required Input

Three types of information are required for effective geochemical modeling (Plummer 1984). First, accurate knowlege of water compositions at several points within the study area is essential. Water chemistry data must include ionic concentrations in water samples which are representative of groundwaters within the aquifer. Conditions within the aquifer itself must also be known, including parameters such as pH, reduction-oxidation potential, temperature, alkalinity, and concentrations of dissolved gases, particularly oxygen. For this thesis, considerable attention was devoted to obtaining information on aquifer conditions and water samples which were truly representative of the groundwater within the aquifer through the use of serial sampling and field analyses. Laboratory analyses were carefully performed in order to retrieve the most accurate and precise water chemistry data possible. This data requirement, then, is fully met.

Second, thorough knowledge of the mineralogy of aquifer materials is required for effective geochemical modeling. It is necessary to know what minerals are present, in what amounts those minerals are present, and how they vary spatially across the study area. The presence of any regional trends in composition or textures that can be related to the direction of groundwater flow is also needed. Evidence of changes in textures, such as secondary versus primary minerals, replacement textures, coatings, zoned crystals, sequence of cements and other observations, aids in interpretations of the geochemical evolution of groundwater. The X-ray diffraction and petrographic analyses done for this thesis had the aim of obtaining much of this information.

Third, thorough understanding of the hydrological flow system of the aquifer is required for effective geochemical modeling. Recharge and discharge areas must be identified, so that beginning and end points are known. Areas where the aquifer is under confined conditions, and areas where it is under water table conditions, must also be identified. Flow lines must be known, since modeling is an attempt to understand water-rock reactions along those flow lines. While no new hydrological studies were performed for this thesis, ongoing work by the U.S. Geological Survey (Eychaner 1983, Brown and Eychaner 1988, Hill and Whetten 1986) and the Arizona Department of Water Resources (T. Perry, personal communication) provides a rather complete picture of groundwater flow within the "N" system for most of the thesis area; only the far northwestern portion is not covered. So

flow lines, transmissivities, confined areas, and other hydrological factors are known.

Equilibrium Speciation Calculations

Equilibrium speciation calculations of solutes are the first step along the modeling process. From these speciations, the saturation state of the groundwater with respect to several minerals and even gases assumed to be present in the aquifer system (Plummer, Parkhurst, and Thorstenson 1983) can be determined. Although such calculations point to which minerals could be dissolving or precipitating within the system, they cannot alone provide the answer as to whether or not the mineral is actually reacting as predicted.

Speciation calculations depend both on the accuracy of the water chemistry data which is available for the system and on the accuracy of the thermodynamic database which is utilized for the calculations. The thermodynamic databases used for major minerals function quite well (Plummer 1984), but thermodynamic data for trace minerals is less satisfactory and speciations of these minerals are less accurate as a result. Thermodynamic data is largely derived from published and replicable chemical experiments, but the accuracy of water analyses depends on the analyst.

Saturation indices for specific minerals are the result of equlibrium speciation calculations. The saturation index is the log of the ion activity product divided by the equilibrium constant, and thus is a measure of the degree to which that mineral is dissolving or

precipitating. Because saturation and true equilibrium are present only at a value of zero, this measure is often called the disequilibrium index. Saturation indices computed for simple solids such as calcite or gypsum avoid the uncertainties inherent in complex stoichiometries such as smectite or apatite, and are thus more reliable indicators (Plummer 1984).

Mass Balance Calculations

Mass balance calculations define the net masses of minerals entering or leaving, in a physical sense, the aqueous system as a result of water-rock reactions (Plummer et.al. 1983). Used with speciation models to eliminate unlikely reactions, mass balance calculations can identify the more likely reaction paths from initial to final points along a flow path.

Those minerals which enter or leave the water along the flow path are chosen from a set of plausible phases, chemical constituents which could reasonably be expected to participate in reactions. This set of mineral phases is derived from mineralogical, petrographic, geological, or chemical evidence. The difficulties of mass balance calculations lie in the multiplicity of plausible phases that can be identified for many aquifer systems.

Two other theoretical constraints are vital in mass balance calculations, conservation of mass and conservation of electrons (Plummer et.al. 1983). The total amounts for each element must be balanced between reactants and products, so that nothing is lost.

Also, the total amounts of electrons transferred between reactants and products must be maintained, through the technique of equating any change in redox state between initial and final solutions to the change in electrons. For both of these conditions to be met, the ion balance difference in the water analyses used must be as low as possible.

Reaction Path Simulation Calculations

Reaction path simulations trace the progress of water-rock reactions from a starting composition to a final water chemistry, based on assumptions of equilibrium and specific irreversible reactions. Such simulations predict what the composition of the water should be at any given point, as well as the amount of minerals transferred among the aqueous and solid phases, given specific irreversible reactions and thermodynamic conditions (Plummer 1984).

The number of reactions paths thermodynamically possible for an aquifer system depends on the number of irreversible reactions defined for that system. If only one irreversible reaction can be defined, then the reaction path is simple. But if several can be defined, then choosing among the more likely reaction path candidates becomes more difficult. Definition of the most probable reaction path depends heavily on knowledge of kinetic rates of irreversible reactions (Plummer 1984), which is often not available. Such information was not available for this study. Following the progress of a reaction path variable, such as temperature or the number of moles of reactant

leaving a system, is the usual means of selecting the thermodynamically most likely reaction path.

Results of reaction path simulation calculations include the masses of minerals dissolved and precipitated as a result of the reaction, as well as the water composition. It seems possible to compare the final predicted water composition with observed analytical values along a flow path to determine the predictive validity of any reaction path simulated.

Interpretation depends heavily on the definition of the problem and the plausible set of mineral phases postulated for the aquifer. In turn, independent evidence from petrography, geology, and other sources, including X-ray diffraction, facilitates the selection of plausible phases and the definition of the problem. Accurate water analyses are obviously a major requirement.

## Computer Modeling Programs

Because all geochemical modeling essentially involves huge numbers of mathematical calculations, a wide variety of computer programs has been developed over the years to perform the modeling calculations discussed above. Some of these codes are rather obscure and used only by their authors, but several are widely known and used, including such codes as WATEQF, PHREEQE, and EQ3/6. These programs are briefly summarized below. It proved possible to use only WATEQF in this study, due primarily to time constraints and the difficulties of developing acceptable input files for the other two programs.

WATEQF

WATEQF was originally written by Truesdell and Jones (1974) for mainframe computers, but has been widely modified since for a wide variety of machines, including personal computers, and has been made far easier to use. Its ease of use has made it widely used, and many researchers employ WATEQF as an essential first step in interpretation, deriving ion balances, molal concentrations, activities, and saturation indices as guides for further modeling efforts. The input to this program includes the thermodynamic database, which again has been modified over the years and can be further modified by any researcher investigating a problem for which mineral solubilities are not yet in that database. Water analyses are also specified for the program, including variables such as dissolved oxygen, pH, temperature, concentrations of major cations and anions, and concentrations of optional ions such as nitrate.

WATEQF computes ion activities for each reported constituent based on either the Debye-Huckel or Davies ion activity coefficient equation. Having computed ion activity coefficients, WATEQF then computes activities for both ion pairs and free ions in the solution, as well as ion activity ratios, ion activity products, and solubility products.

Finally saturation indices for several minerals of interest are computed. This is probably the major feature of the program for most researchers. If the saturation index for a mineral is zero, the water is at equilibrium with that mineral. If the saturation index is less

than zero, the solution is undersaturated with respect to that mineral and thus likely to dissolve; if greater than zero the solution is supersaturated, and that mineral is likely to precipitate out. The last two situations do not represent equilibrium conditions, hence the term disequilibrium index. WATEQF does not predict whether or not dissolution/precipitation is actually occurring within the system, only whether it is thermodynamically probable or not.

PHREEQE

PHREEQE is a U.S. Geological Survey computer program which simulates reaction paths from an initial water composition. PHREEQE follows the evolution of the solution along one or more phase boundaries by calculating pH and pe as dependent variables (Parkhurst, Thorstenson, and Plummer 1980). PHREEQE can simulate reactions such as addition of reactants to a system, mixing of two waters, and titration of one water with another. Provided by the user with approriate mineral equilibria, PHREEQE can compute reaction paths to the requested points at phase boundaries (Plummer 1984). Various input codes (Fleming and Plummer 1983) should make PHREEQE easier to use than many reaction path programs, but these programs themselves do not always work.

Input consists of an initial water composition and a set of plausible reactants. Exact mineral equilibria and compositions should be specified. Alternatively, the user can provide two initial solutions for the situation in which it is desired to assess the

effects of mixing of two waters or titration of one water with another. PHREEQE expects that the initial solution will be electrically neutral, but this can be overridden, since in many actual water analyses the charge balance does not quite equal zero (Plummer 1984). The program can also accept a water composition from a previous run as an initial solution, allowing a series of runs to simulate the progress of water-rock reactions. The user must also make assumptions as to which irreversible reactions are involved in the system.

Output consists of a description of the final solution, distribution of aqueous species including molality and log activity for each, total molalities for all elements, and saturation indices. The program also calculates several other quantities, including pH, pe, and the amounts of minerals or other phases transferred into or out of the aqueous phase (Parkhurst et.al. 1980). The user must then interpret these results, and there is no guarantee that the final water composition will match any observed water chemistry along a flow path (Plummer et.al. 1983). If however such a match is attained, the analyst can infer that the net transfer involved is thermodynamically valid.

EQ3NR/EQ6

An entire package of computer programs was developed at Lawrence Livermore National Laboratory for performing equilibrium speciation, mass balance, and reaction path modelling (Wolery 1983). Commonly

called EQ3/6, these programs are too big for a personal computer, and must run on mainframes or minicomputers. A copy of the package was obtained and modified to run on the Digital Equipment Corporation VAX minicomputer at Northern Arizona University.

Like WATEQF, the EQ3NR portion of the package computes speciation-solubility information for a set of water analyses. Input consists of water analyses in a variety of concentration units, which are converted to molalities. Temperature and pH are also normally supplied. Various constraints are specified with a series of flags. But setting up an input file for EQ3NR is not as easy as in WATEQF.

Output from EQ3NR is similar to that of WATEQF, in that it provides the distribution of aqueous species in terms of concentrations (molalities) and thermodynamic activities (Wolery 1983). The program provides saturation indices for minerals in its large thermodynamic database. By specifying the thermodynamic state of each redox couple in the water, the program also defines the degree of disequilibrium among these redox couples. Finally it writes a pickup file for use by the EQ6 portion of the package.

Using the results of EQ3NR, EQ6 calculates the reaction path taken by the solution changing in response to one or more irreversible water-rock reactions. EQ6 differs from PHREEQE in that the computer code itself selects the reaction path (Plummer 1984); in PHREEQE the analyst must choose among different plausible reaction paths. EQ6 allows fewer selections of critical variables, and thus fewer manipulations of the system. Also, EQ6 computes the reaction path

incrementally throughout the entire progress of the reaction variable followed; PHREEQE only computes changes at specified intervals, usually phase boundaries (Plummer 1984). The output of EQ6 is similar to that of PHREEQE.

## Results of Running WATEQF

WATEQF was run utilizing the water analyses of the various wells sampled during the field phase. The goal of running WATEQF with these analyses was to obtain saturation indices for the most important minerals thought to be dissolving and/or precipitating. In addition to these indices, which were added to Appendix II, detailed descriptions of each solution were generated.

Two important constraints were set for WATEQF. First, Eh was calculated from the dissolved oxygen concentrations determined in the field, rather than being set to a constant value. Figure 26 is a map of the distribution of dissolved oxygen across the study area, and illustrates the shifts in Eh. Of the variety of means of calculating this variable, the dissolved oxygen concentration was felt to represent the best field measurement available. A previous attempt to calculate Eh using total iron and ferrous iron concentrations with the Nernst equation failed to provide reasonable numbers.

Second, the Debye-Huckel equation was used to calculate activity coefficients, rather than the Davies equation. Given the dilute nature of most of the water analyses, this was felt to be the better means of approaching ion activities.

WATEQF also computed ion balances, and for several samples derived a large error percentage that prevented further computations. Saturation indices for these wells are listed in Appendix II as 9.999, which is an arbitrary value marking the program's inability to continue calculations. These wells occurred mostly in the eastern and southeastern portions of the thesis area, and their large ion balance error was discussed in Chapter 4.

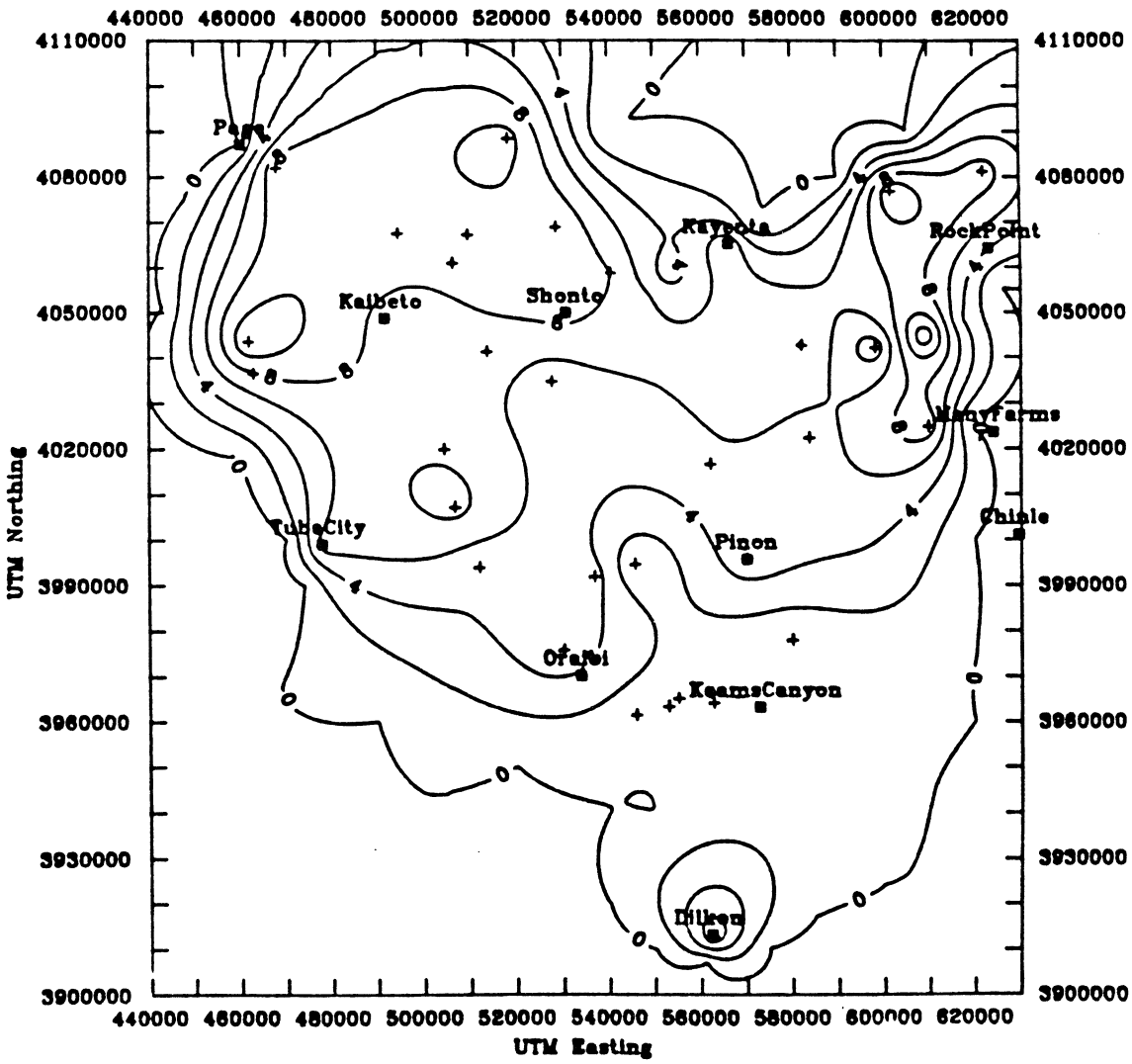


Figure 26: Distributions of Dissolved Oxygen Concentrations, CI=2.0 mg/l

Figure 27 below represents a contour map of the saturation indices with respect to calcite, the most important mineral for which saturation indices were calculated. A saturation index of zero indicates equilibrium the water with calcite, while a value less than zero indicates undersaturation. A value greater than zero indicates a supersaturated solution. The contour interval on the map is 0.2 (dimensionless) units. Contours below -0.5 units have been blanked

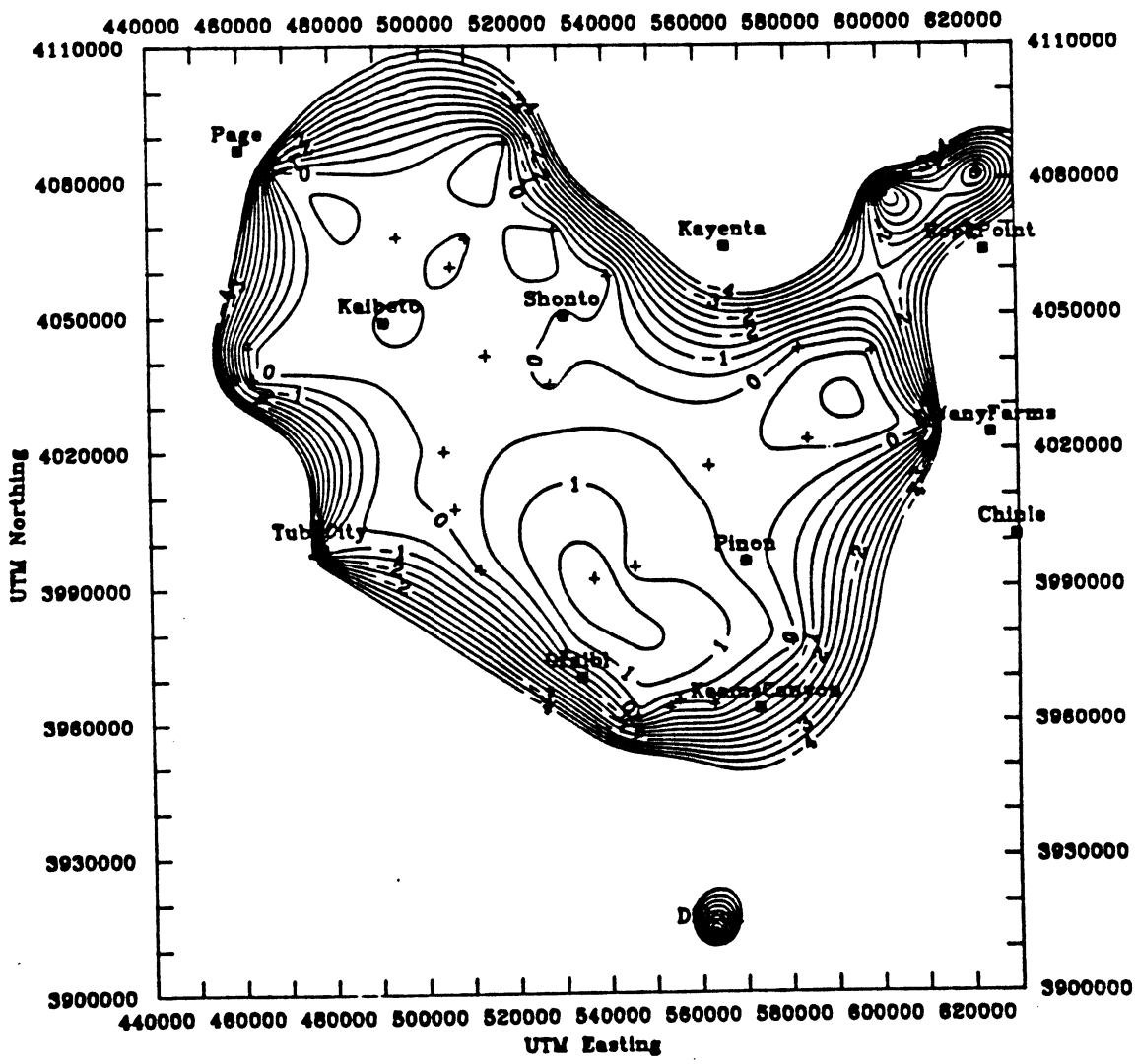


Figure 27: Calcite Saturation Indices, CI=0.4, blanked below -4.0

out, since no lower figures were calculated and since -9.999 was used at several points as an arbitrary base level.

From the map it can be seen that equilibrium of "N" system groundwaters with respect to calcite is attained under Black Mesa. Indeed, along the eastern edges of Black Mesa, as well as the south-western flanks, the waters are slightly super-saturated with repsect to calcite, and it is thermodynamically likely that calcite is precipitating out in these areas, probably as cement. In most of the areas which have been described either as recharge zones or areas under water-table (open) conditions, the groundwater is undersaturated with respect to calcite, which should be dissolving.

Petrographic data seem to support these thermodynamic indicators. As discussed in the previous chapter, calcite cement was noticeably lacking in surface samples from the northern and western portions of the thesis area, although traces of formerly widespread calcite crystals were often seen. Yet calcite cement dominated sub-surface samples taken at depth from oil wells on or near Black Mesa. It would be expected that surface samples in recharge zones would exhibit the greatest effects of calcite dissolution, having been the more thoroughly flushed with waters undersaturated with respect to calcite.

Figure 28 is a contour map of the saturation indices for gypsum, a major source of both calcium and sulfate ions when dissolved. Values below -6.0 had no contours plotted, again because -9.999 was used as an arbitrary base level. It can quickly be seen that all

groundwater within the thesis area is significantly under-saturated with respect to gypsum. There are no areas where this mineral is likely to precipitate out, and it is thermodynamically likely to dissolve wherever encountered. Petrographic analysis revealed no trace of gypsum anywhere in the Glen Canyon Group, and this absence explains why "N" system groundwaters are under-saturated with respect to this mineral. Both thermodynamic calculations and petrographic

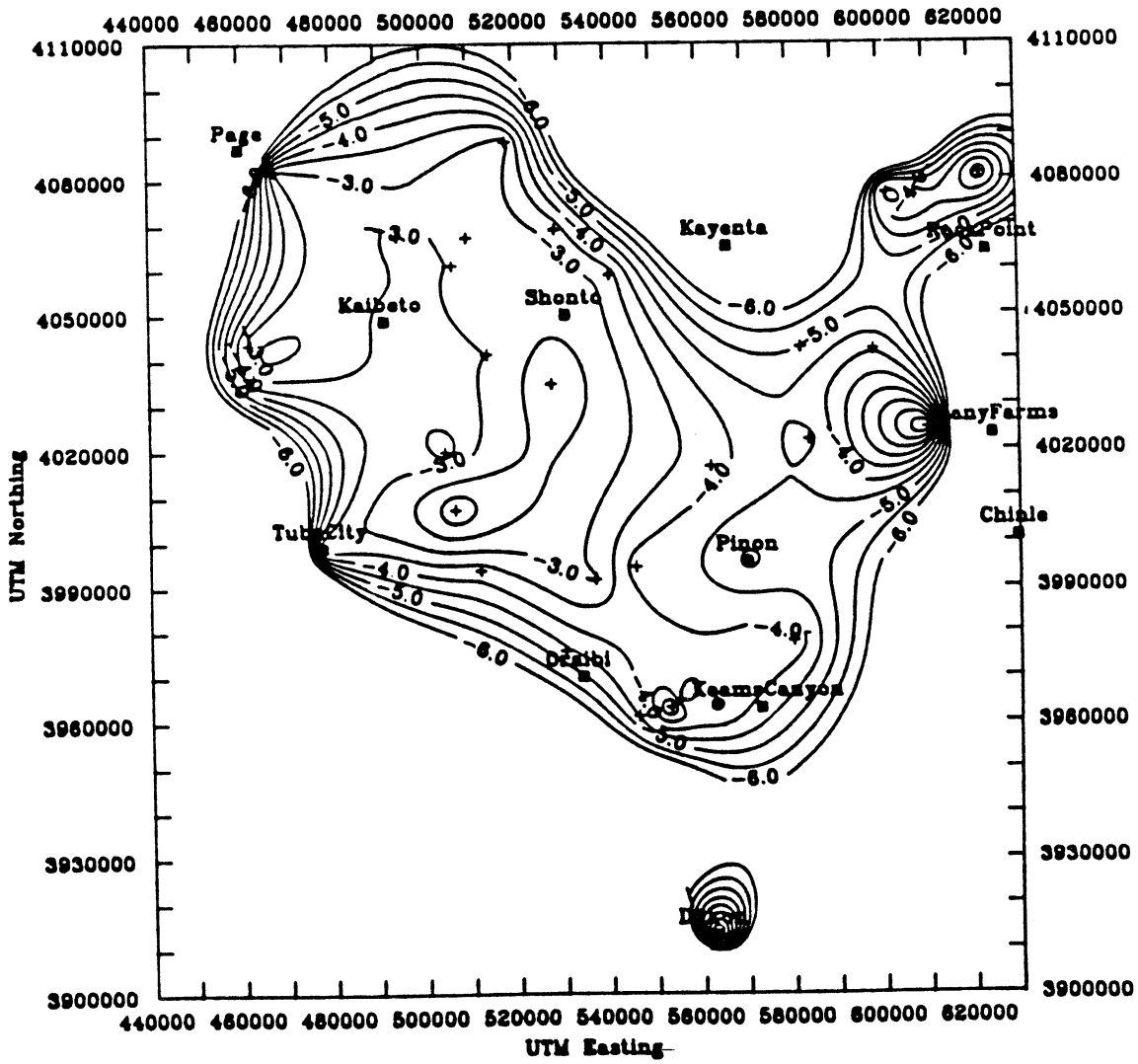


Figure 28: Gypsum Saturation Indices, CI=2.0, blanked below -8.0

observations, then, point away from "N" system rocks as a source of the high sulfate concentrations most apparent along the eastern and southeastern margins of Black Mesa.

Figure 29 is a contour map of the saturation indices computed by WATEQF for fluorite. Again, no contours were plotted for values less than -5.0. Again, "N" system groundwaters are undersaturated with respect to this mineral, only approaching equilibrium in a few isolated areas around the margins of Black Mesa. These "highs" approximate those areas of elevated fluoride concentrations seen in Figure 13. Fluorite is not the only source of fluoride ions, and when concentrations are low, other mineral sources may be more important. This demonstrates the limits on the utility of WATEQF, in that the saturation indices calculated by the program cannot adequately describe all dissolution/precipitation processes which control ionic concentrations. However, WATEQF is often the only model which can be run.

The modeling effort involving WATEQF to compute ionic activities and saturation indices was an important first step in understanding geochemical processes within the "N" aquifer system. Mapping the calculated saturation indices for calcite demonstrated how close "N" system groundwater is to being in thermodynamic equilibrium with this important mineral, only slightly undersaturated in recharge zones or areas of open conditions, and slightly oversaturated under Black Mesa (confined conditions). This suggests that the dissolution and precipitation of calcite is a major ongoing geochemical process, which

agrees with petrographic observations.

Mapping saturation indices for gypsum and fluorite was useful in revealing processes which are not occurring. These two minerals exhibited signficant disequilibrium, with "N" system groundwaters consistently very under-saturated with respect to both. The fact that groundwaters could not dissolve enough sulfate to approach equilibrium with respect to gypsum suggests that gypsum was not present in

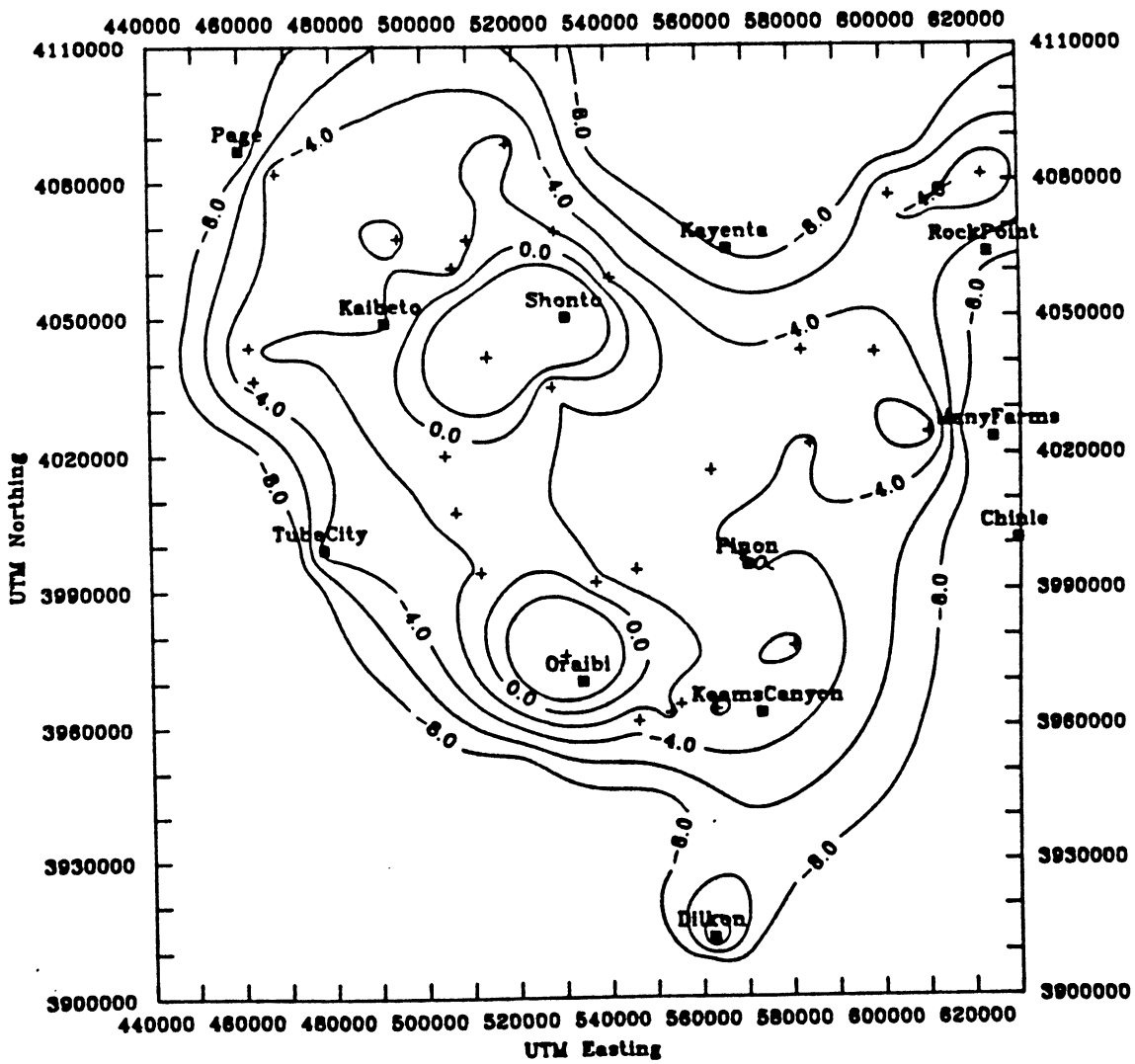


Figure 29: Fluorite Saturation Indices, CI=0.5, blanked below -5.0

sufficient quantities (if at all) to shift equilibrium calculations, and again this agrees with petrographic observations. So elevated levels of anions such as sulfate cannot be adequately explained via dissolution of common minerals within the "N" system rocks; other processes are operative. The fact that groundwaters did not approach equilibrium with respect to fluorite might suggest that insufficient amounts of that mineral are present to act as the sole source of the fluoride anions, but other minerals also yield fluoride, and this situation is more ambiguous.

# CHAPTER 7

# INTEGRATION AND INTERPRETATION

This chapter assesses the efforts described in previous chapters, integrates the results, and provides an interpretation of the aqueous geochemistry of the "N" aquifer system of northeastern Arizona. Some final observations concerning future research and management of this critical water resource are also provided.

## Assessments and Summaries

Assessing the success of each stage of this regional investigation lends more credence to the results of each stage. Each phase of the project built on the results of the preceding phase, and incorporates the strengths and weaknesses of all previous stages of research.

### Archival Information

The prerequisite background literature search revealed few studies of the water chemistry of the "N" aquifer system, but several excellent studies of hydrological flow within the aquifer. Many of these consisted of models which require accurate spatial information from one point in time concerning water levels. The model most

recently modified by the U.S. Geological Survey (Brown and Eychaner 1988) provided a picture of water levels and directions of groundwater flow that were directly adopted for this thesis. In this model, groundwater is depicted as moving south from recharge areas in the vicinity of Navajo Mountain and Shonto, where the aquifer is unconfined, under Black Mesa, where conditions are confined, and hence southwesterly towards discharge points along major washes such as Moenkopi Wash and Polacca Wash. There is also, once the water moves under Black Mesa, an northeasterly flow towards the northern portion of the Chinle Valley. Most notably different from other models is the picture along the eastern and southeastern portions of the "N" system, where groundwater moves northwesterly from sources in the southern Chinle Valley.

Water chemistry information was difficult to gather and assess, since most of it is unpublished and stored in offices scattered among several agencies across both Reservations. That information which was gathered was often suspect, due to a variety of sampling and analytical difficulties discussed by the General Accounting Office (1980). What this archival search clearly established was the need for recent and reliable information from a wide selection of sampling points with a uniform and rigorous field sampling protocol and equally rigorous and consistent laboratory procedures. This became the goal of the field and laboratory phases, and considerable effort was devoted to the realization of this goal.

Field Sampling

During the field phase, great pains were taken to collect water samples which were as representative as possible of the groundwater within the "N" aquifer system. Considerable time was spent at each sampling point in serial sampling to determine chemical stability, as well as in determination of important parameters such as pH, conductivity, temperature, alkalinity, and concentrations of several of the less preservable constituents of the water. Although it took longer than anticipated, the field sampling program was successful in achieving broad coverage of the thesis area and in obtaining the highest quality samples possible. This was perhaps the most successful stage of the entire project.

It is important to note that the 49 samples obtained (some duplicates) represent essentially one point in time, so that seasonal or annual variations were minimized. No attempt was made to sample temporal variability, only spatial variability. The sampling protocol was very rigorous and consistently applied. No better water samples have been gathered for the entire extent of the "N" system.

Laboratory Analyses

The laboratory analyses of these representative water samples was also successful. Standardized methods were strictly followed on high-grade analytical equipment to obtain the measurements reported in Appendix II. The concentrations that were measured for the major cations and anions are replicable, precise, and accurate within

acceptable limits. Spiking samples with known concentrations of standards as well as the charge balance percentage differences all indicate a high degree of accuracy. However, the laboratory stage of the project was not entirely without flaws, as the source of the large charge balance errors in certain samples could not be ascertained.

Laboratory analyses of representative water samples did clearly demonstrate certain trends in water chemistry. At least two chemically distinct groundwaters are present within the "N" aquifer system. One is a relatively dilute and very fresh water to the north and west, while the other, located along the eastern and southeastern margins of the thesis area, is a more brackish water dominated by excessive concentrations of bicarbonate, sodium, and sulfate.

Mineralogical Analyses

X-ray diffraction and petrography were the two methods of mineralogical analysis applied to several surface and subsurface samples of "N" system rocks gathered during the project. X-ray diffraction was the preferred method of clay analysis, but served mostly to point out how little clay is contained in most of the formations of the Glen Canyon Group, with the exception of the Kayenta Formation. Petrographic analysis provided useful but not exhaustive information on grain types, cements, and textures present in the sandstones which are the major water-bearing rocks of the system.

Several trends were noted. Calcite cement was common in most of the subsurface sandstones, but was absent in those samples taken from

surface exposures. This lack of calcite cement was most evident in samples from the northwestern portion of the thesis area. Feldspars were more common than suggested by literature sources, and most displayed considerable evidence of dissolution. Matrix was rare, and where present was mostly smectite with some illite.

From these trends several water-rock reactions can be predicted. By far the major activity appears to be with the calcite cement, particularly near the surface, and particularly in exposed Navajo Sandstone to the north and west. Carbonate system geochemical reactions dominate the "N" system water chemistry across much of its extent. The amount of matrix is too small to contribute significantly to water chemistry via ion exchange reactions. Feldspar weathering, seen petrographically in both surface and sub-surface samples, probably contributes sodium, calcium, and potassium ions. No trace of evaporite minerals was found, particularly to the east and south. These then are the factors that must be taken into account in modeling geochemical evolution of "N" system groundwater.

## Geochemical Modeling

Computer codes that embodied principles of equilibrium speciation and reaction path simulation were employed for geochemical modeling of the "N" aquifer system. WATEQF is a widely used equilibrium speciation program which provides information on water solutions and saturation indices, with those indices indicating whether dissolution or precipitation is thermodynamically likely for

specific minerals. PHREEQE is a reaction path model which provides estimates on pH and Eh at phase boundaries when given initial water compositions and a set of plausible minerals with which the water is assumed to react. EQ3/6 is a combined package which computes equilibrium data and a reaction path.

The results of running these programs with the data derived from earlier stages of the project were not as clear as had been anticipated. WATEQF proved most useful in describing dissolution and precipitation in the carbonate system which dominates the northern and western portions of the thesis area. This is probably because this area is so close to equilibrium conditions with respect to the carbonate system, a situation ideal for description with saturation indices alone. Clear reaction paths did not emerge.

The geochemical modeling portion of the project was its least successful aspect. This is unfortunate, because the development of water chemistry within the "N" system can now be described in only the most general terms.

## Interpretations

The waters of the "N" aquifer system of northeastern Arizona can be divided into two groups, one major body to the north and west of the thesis area, and one smaller body located along the eastern and southeastern portions of the thesis area. The chemistry of each is controlled by different processes.

For most of the thesis area, particularly to the north and west, the dominant reaction is that of dissolution-precipitation of the calcite cement that is ubiquitious in the sandstones of the Glen Canyon Group. This reaction is not irreversible in those areas under water-table conditions, and thus is difficult to model. Under Black Mesa where the "N" system is confined, temperature rises and gases, particularly carbon dioxide, cannot enter or leave the system, and thus thermodynamic conditions change; this produces a definite direction for the carbonate reaction. Other more minor reactions in this major portion of the thesis area include the dissolution of feldspars, particularly orthoclase and microcline, with a subsequent enrichment of the waters with potassium and sodium. Cation exchange occuring within the smectites and minor illites of sandstone matrix and especially within the Kayenta Formation provide another source of sodium for the water.

To the east and southeast ionic concentrations are excessive, and dominated by bicarbonate, sulfate, and sodium. The most likely mineral sources of such ions are beds of evaporites such as gypsum and halite, but no trace of these minerals was found during mineralogical analysis. The best explanation, then, for these brackish waters is that they are mixed with waters from another aquifer system. This is further supported by the hydrological flow model, which notes a water mound to the east and southeast. It seems likely that this area of higher head is created by both recharge to exposed Glen Canyon Rocks and by flow into the "N" system from another aquifer. The most likely

candidate appears to be the overlying "D" aquifer system, which has both very brackish waters and much higher hydraulic head than the "N" system. The area of maximum recharge and highest piezometric surfaces in the "D" is found on the eastern and southeastern portions of Black Mesa, jwhere a series of underlying folds may have produced faulting to provide easy conduits for vertical downward leakance to the "N" in that area where a flow divide occurs and where "N" groundwaters are most brackish. However, the underlying "C" system is also a probable source of mixing water for the northeastern portion of the study area, in that hydraulic heads in the "C" in this area match those of the "N" aquifer system.

## Recommendations

It is clear that resource managers on both Reservations who wish to further develop the "N" system as a primary source of high quality water should develop that area to the north and west of Black Mesa. The area to the south and east of Black Mesa yields water which is too brackish for most human or industrial uses. Only livestock wells should be developed in this area. It is also clear that intensive development of the "N" system in the area between the fresh waters and the brackish area will produce a greater hydraulic gradient which will increase the extent of the brackish water over time; this should be avoided. While the effects of large groundwater withdrawals connected with the Peabody Coal Company lease on Black Mesa are not clear, it is likely that, if pumped too heavily, the quality of the water will

deteriorate over time as the brackish water moves west with increased hydraulic gradients. No time frame is possible for such postulated effects. The actual mechanism of mixing remains unknown, and while it is postulated that faulting near prominent folds plays a major role, detailed hydrologic and isotopic studies are needed to identify the means by which "N" groundwater is mixed with that of other systems.

The "N" aquifer system is not as chemically simple as most researchers describe it. The major portion of its extent can be described in terms of a few chemical reactions, but the mixing which is apparently occuring along its eastern and southeastern margins is more complex. More study is needed in this area before the precise degree of mixing can be ascertained. More information is required on the mineralogy of this area, as well as water chemistry information on surrounding aquifer systems. More hydrological information from pump tests, flow models and other sources is needed for the "C", the "D", and "N" systems in this area, so that mixing mechanisms can be assessed and future effects on "N" aquifer groundwaters can be evaluated.

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# APPENDIX I

# EXISTING WELL INFORMATION

| Well Number | UTM East | UTM North | Latitude | Longitude | Data Source | Elevation | Well Depth | Diameter |
|---|---|---|---|---|---|---|---|---|
| 1T-240 C | 452767 | 4054434 | 363810 | 1113142 | | 0.0 | 0.0 | 0.00 |
| 1K-231 | 454828 | 4049708 | 363537 | 1113018 | | 0.0 | 0.0 | 0.00 |
| TUBA C PM5 | 477706 | 3998935 | 360812 | 1111452 | | 0.0 | 0.0 | 0.00 |
| TUB CT PM6 | 477856 | 3998626 | 360802 | 1111446 | | 0.0 | 0.0 | 0.00 |
| PM 2 | 477983 | 3999427 | 360828 | 1111441 | | 0.0 | 0.0 | 0.00 |
| PM 1 | 477983 | 3999488 | 360830 | 1111441 | | 0.0 | 0.0 | 0.00 |
| TUBA C PM4 | 478281 | 3998779 | 360807 | 1111429 | | 0.0 | 0.0 | 0.00 |
| 3T-54 | 478416 | 4002815 | 361018 | 1111424 | | 0.0 | 0.0 | 0.00 |
| NTUA 5 TC | 478416 | 4002815 | 361018 | 1111424 | | 0.0 | 0.0 | 0.00 |
| NTUA 3 | 478462 | 4001151 | 360924 | 1111422 | | 0.0 | 0.0 | 0.00 |
| NTUA 1 | 478960 | 4000534 | 360904 | 1111402 | | 0.0 | 0.0 | 0.00 |
| RARE MET 1 | 487681 | 4000671 | 360909 | 1110813 | | 0.0 | 0.0 | 0.00 |
| RARE MET 2 | 487831 | 4000948 | 360918 | 1110807 | | 0.0 | 0.0 | 0.00 |
| KAI SCH 4 | 491451 | 4048115 | 363449 | 1110544 | | 0.0 | 0.0 | 0.00 |
| KAIBIT PM3 | 493838 | 4050023 | 363551 | 1110408 | | 0.0 | 0.0 | 0.00 |
| SHONTO PM2 | 530684 | 4050292 | 363558 | 1103925 | | 0.0 | 0.0 | 0.00 |
| SHONTO PM2 | 530684 | 4050292 | 363558 | 1103925 | | 0.0 | 0.0 | 0.00 |
| SHNT PM3 | 531006 | 4050015 | 363549 | 1103912 | | 0.0 | 0.0 | 0.00 |
| SHONTO PM4 | 531106 | 4050478 | 363604 | 1103908 | | 0.0 | 0.0 | 0.00 |
| USPHS ORAI | 534654 | 3969952 | 355230 | 1103658 | | 0.0 | 0.0 | 0.00 |
| ORAIBI PM4 | 534980 | 3970138 | 355236 | 1103645 | | 0.0 | 0.0 | 0.00 |
| ORAIBI PM4 | 534980 | 3970138 | 355236 | 1103645 | | 0.0 | 0.0 | 0.00 |
| ORAIBI PM4 | 534980 | 3970138 | 355236 | 1103645 | | 0.0 | 0.0 | 0.00 |
| ORAIBI PM4 | 534980 | 3970138 | 355236 | 1103645 | | 0.0 | 0.0 | 0.00 |
| 2T-514 | 536059 | 4042455 | 363143 | 1103550 | | 0.0 | 0.0 | 0.00 |
| BM 4 | 536059 | 4042455 | 363143 | 1103550 | | 0.0 | 0.0 | 0.00 |
| ROCKY PM1 | 536569 | 3991865 | 360421 | 1103538 | | 0.0 | 0.0 | 0.00 |
| ROCKY | 536644 | 3991897 | 360422 | 1103535 | | 0.0 | 0.0 | 0.00 |
| ROCKY | 536644 | 3991897 | 360422 | 1103535 | | 0.0 | 0.0 | 0.00 |
| ROCKY PM2 | 536845 | 3991774 | 360418 | 1103527 | | 0.0 | 0.0 | 0.00 |
| BETKN N M | 540681 | 4058776 | 364032 | 1103241 | | 0.0 | 0.0 | 0.00 |
| HOPI A & C | 542720 | 3966629 | 355041 | 1103137 | | 0.0 | 0.0 | 0.00 |
| BM OBS 5 | 544055 | 3985553 | 360055 | 1103040 | | 0.0 | 0.0 | 0.00 |
| PEABODY 2 | 552017 | 4039517 | 363005 | 1102509 | | 0.0 | 0.0 | 0.00 |
| PEABODY 2 | 552017 | 4039517 | 363005 | 1102509 | | 0.0 | 0.0 | 0.00 |
| PEABODY 2 | 552017 | 4039517 | 363005 | 1102509 | | 0.0 | 0.0 | 0.00 |
| PEABODY 2 | 552017 | 4039517 | 363005 | 1102509 | | 0.0 | 0.0 | 0.00 |
| PEABODY 2 | 552017 | 4039517 | 363005 | 1102509 | | 0.0 | 0.0 | 0.00 |
| PEABODY 2 | 552017 | 4039517 | 363005 | 1102509 | | 0.0 | 0.0 | 0.00 |
| PEABODY 4 | 552900 | 4033422 | 362647 | 1102435 | | 0.0 | 0.0 | 0.00 |
| PEABODY 4 | 552900 | 4033422 | 362647 | 1102435 | | 0.0 | 0.0 | 0.00 |
| PEABODY 4 | 552900 | 4033422 | 362647 | 1102435 | | 0.0 | 0.0 | 0.00 |

| Well Number | UTM East | UTM North | Latitude | Longitude | Data Source | Elevation | Well Depth | Diameter |
|---|---|---|---|---|---|---|---|---|
| PEABODY 4 | 552900 | 4033422 | 362647 | 1102435 | | 0.0 | 0.0 | 0.00 |
| PEABODY 4 | 552900 | 4033422 | 362647 | 1102435 | | 0.0 | 0.0 | 0.00 |
| | 553220 | 4030003 | 362456 | 1102423 | | 0.0 | 0.0 | 0.00 |
| BN 6 | 553762 | 4006867 | 361225 | 1102407 | | 0.0 | 0.0 | 0.00 |
| BN 6 | 553762 | 4006867 | 361225 | 1102407 | | 0.0 | 0.0 | 0.00 |
| PEABODY 5 | 554219 | 4037559 | 362901 | 1102341 | | 0.0 | 0.0 | 0.00 |
| PEABODY 5 | 554219 | 4037559 | 362901 | 1102341 | | 0.0 | 0.0 | 0.00 |
| PEABODY 5 | 554219 | 4037559 | 362901 | 1102341 | | 0.0 | 0.0 | 0.00 |
| PEABODY 5 | 554219 | 4037559 | 362901 | 1102341 | | 0.0 | 0.0 | 0.00 |
| PEABODY 5 | 554219 | 4037559 | 362901 | 1102341 | | 0.0 | 0.0 | 0.00 |
| PEABODY 5 | 554219 | 4037559 | 362901 | 1102341 | | 0.0 | 0.0 | 0.00 |
| PEABODY 5 | 554219 | 4037559 | 362901 | 1102341 | | 0.0 | 0.0 | 0.00 |
| PEABODY 5 | 554219 | 4037559 | 362901 | 1102341 | | 0.0 | 0.0 | 0.00 |
| PEABODY 3 | 555842 | 4032762 | 362625 | 1102237 | | 0.0 | 0.0 | 0.00 |
| PEABODY 3 | 555842 | 4032762 | 362625 | 1102237 | | 0.0 | 0.0 | 0.00 |
| PEABODY 3 | 555842 | 4032762 | 362625 | 1102237 | | 0.0 | 0.0 | 0.00 |
| PEABODY 3 | 555842 | 4032762 | 362625 | 1102237 | | 0.0 | 0.0 | 0.00 |
| PEABODY 3 | 555842 | 4032762 | 362625 | 1102237 | | 0.0 | 0.0 | 0.00 |
| PEABODY 3 | 555842 | 4032762 | 362625 | 1102237 | | 0.0 | 0.0 | 0.00 |
| PEABODY 3 | 555842 | 4032762 | 362625 | 1102237 | | 0.0 | 0.0 | 0.00 |
| PEABODY 3 | 555842 | 4032762 | 362625 | 1102237 | | 0.0 | 0.0 | 0.00 |
| PEABODY 6 | 556420 | 4039606 | 363007 | 1102212 | | 0.0 | 0.0 | 0.00 |
| PEABODY 6 | 556420 | 4039606 | 363007 | 1102212 | | 0.0 | 0.0 | 0.00 |
| PEABODY 6 | 556420 | 4039606 | 363007 | 1102212 | | 0.0 | 0.0 | 0.00 |
| PEABODY 6 | 556420 | 4039606 | 363007 | 1102212 | | 0.0 | 0.0 | 0.00 |
| PEABODY 6 | 556420 | 4039606 | 363007 | 1102212 | | 0.0 | 0.0 | 0.00 |
| PEABODY 6 | 556420 | 4039606 | 363007 | 1102212 | | 0.0 | 0.0 | 0.00 |
| KEANS CYN3 | 562464 | 3966531 | 355034 | 1101830 | | 0.0 | 0.0 | 0.00 |
| KEANS CYN2 | 562541 | 3966193 | 355023 | 1101827 | | 0.0 | 0.0 | 0.00 |
| KEANS CYN2 | 562541 | 3966193 | 355023 | 1101827 | | 0.0 | 0.0 | 0.00 |
| KEANS CYN2 | 562541 | 3966193 | 355023 | 1101827 | | 0.0 | 0.0 | 0.00 |
| KEANS CYN2 | 562541 | 3966193 | 355023 | 1101827 | | 0.0 | 0.0 | 0.00 |
| KEANS CYN2 | 562541 | 3966193 | 355023 | 1101827 | | 0.0 | 0.0 | 0.00 |
| ST-500 | 565831 | 4064664 | 364338 | 1101546 | | 0.0 | 0.0 | 0.00 |
| BN 3 | 565831 | 4064664 | 364338 | 1101546 | | 0.0 | 0.0 | 0.00 |
| PINON PN 6 | 570310 | 3995553 | 360614 | 1101308 | | 0.0 | 0.0 | 0.00 |
| PINON PN 6 | 570310 | 3995553 | 360614 | 1101308 | | 0.0 | 0.0 | 0.00 |
| PINON PN 6 | 570310 | 3995553 | 360614 | 1101308 | | 0.0 | 0.0 | 0.00 |
| PINON PN 6 | 570310 | 3995553 | 360614 | 1101308 | | 0.0 | 0.0 | 0.00 |
| | 574292 | 4055858 | 363850 | 1101008 | | 0.0 | 0.0 | 0.00 |
| ST-538 | 574292 | 4055858 | 363850 | 1101008 | | 0.0 | 0.0 | 0.00 |
| L MTN PN2 | 580173 | 3977890 | 355638 | 1100640 | | 0.0 | 0.0 | 0.00 |

| Well Number | UTM East | UTM North | Latitude | Longitude | Data Source | Elevation | Well Depth | Diameter | |
|---|---|---|---|---|---|---|---|---|---|
| CHLCHN PM3 | 582390 | 4042589 | 363137 | 1100447 | | 0.0 | 0.0 | 0.00 | |
| 8K-431 | 593834 | 4065079 | 364343 | 1095657 | | 0.0 | 0.0 | 0.00 | |
| 8T-537 | 594518 | 4038984 | 362936 | 1095641 | | 0.0 | 0.0 | 0.00 | |
| BM 1 | 594518 | 4038984 | 362936 | 1095641 | | 0.0 | 0.0 | 0.00 | |
| ROUGH PM3 | 601147 | 4029568 | 362428 | 1095219 | | 0.0 | 0.0 | 0.00 | |
| 10T-251 | 601368 | 4029817 | 362436 | 1095210 | USGS TUCSON WRD | 6210.0 | 1401.0 | 8.75 | 1 |
| 10T-251 | 601368 | 4029817 | 362436 | 1095210 | USGS TUCSON WRD | 6210.0 | 1401.0 | 8.75 | 1 |
| 8K-434 | 602436 | 4069801 | 364613 | 1095108 | | 0.0 | 0.0 | 0.00 | |
| 8K-403 | 602906 | 4078035 | 365040 | 1095045 | | 0.0 | 0.0 | 0.00 | |
| 8K-521 | 603028 | 4078191 | 365045 | 1095040 | | 0.0 | 0.0 | 0.00 | |
| 8T-519 | 608371 | 4086609 | 365516 | 1094700 | | 0.0 | 0.0 | 0.00 | |
| 9Y-92 | 609004 | 4044579 | 363232 | 1094656 | | 0.0 | 0.0 | 0.00 | |
| 10E-235 | 614113 | 4030561 | 362455 | 1094338 | USGS TUCSON WRD | 5687.0 | 703.0 | 10.00 | 6 |
| 10K-235 | 614113 | 4030561 | 362455 | 1094338 | USGS TUCSON WRD | 5687.0 | 703.0 | 10.00 | 6 |
| 10K-235 | 614113 | 4030561 | 362455 | 1094338 | USGS TUCSON WRD | 5687.0 | 703.0 | 10.00 | 6 |
| 9Y-12 | 631046 | 4094296 | 365915 | 1093139 | | 0.0 | 0.0 | 0.00 | |
| 763 | 0 | 0 | 0 | 0 | UWTRA | 0.0 | 0.0 | 0.00 | |
| 901 | 0 | 0 | 0 | 0 | UWTRA | 0.0 | 0.0 | 6.60 | |
| 902 | 0 | 0 | 0 | 0 | UWTRA | 0.0 | 0.0 | 6.50 | |
| 903 | 0 | 0 | 0 | 0 | UWTRA | 0.0 | 0.0 | 6.50 | |
| 904 | | | | | UWTRA | | 0.0 | 6.60 | |
| 910 | | | | | UWTRA | | 197.0 | 8.50 | |
| 911 | | | | | UWTRA | | 351.0 | 8.50 | |
| 913 | | | | | UWTRA | | 371.0 | 8.50 | |
| 914 | | | | | UWTRA | | 156.0 | 8.50 | |
| 917 | | | | | UWTRA | | 150.0 | 8.50 | |
| 920 | | | | | UWTRA | | 156.0 | 8.50 | |
| 921 | | | | | UWTRA | | 355.0 | 8.50 | |
| 970 | | | | | UWTRA | | | | |
| 971 | | | | | UWTRA | | | | |
| 972 | | | | | UWTRA | | | | |

| Well Number | BIA Quadrangle Number | Other Number | Aquifer Code | Top Open Interval | Bottom Open Interval | Water Level | Water Altitude |
|---|---|---|---|---|---|---|---|
| 1T-240 C | 01-044-01.53X07.84 | 1T-240 C | 220NVJO | 1200.00 | 1400.00 | 0.00 | 6120.00 |
| 1K-231 | 01-044-00.30X10.80 | 1K-231 | 220NVJO | 212.00 | 1200.00 | 0.00 | 6340.00 |
| TUBA C PM5 | 03 077-13.83X07.79 | TUBA C PM5 | 220NVJO | 0.00 | 0.00 | 0.00 | 5030.00 |
| TUB CT PM6 | 03 077-13.75X07.98 | TUB CT PM6 | 220NVJO | 65.00 | 145.00 | 0.00 | 4970.00 |
| PM 2 | 03 077-13.65X07.50 | PM 2 | 220NVJO | 0.00 | 0.00 | 0.00 | 5050.00 |
| PM 1 | 03 077-13.65X07.45 | PM 1 | 220NVJO | 0.00 | 0.00 | 0.00 | 5060.00 |
| TUBA C PM4 | 03 077-13.50X07.89 | TUBA C PM4 | 220NVJO | 0.00 | 0.00 | 0.00 | 4970.00 |
| 3T-54 | 03 077-13.40X05.38 | 3T-54 | 220NVJO | 470.00 | 510.00 | 0.00 | 5230.00 |
| NTUA 5 TC | 03 077-13.40X05.38 | NTUA 5 TC | 220NVJO | 150.00 | 430.00 | 0.00 | 5230.00 |
| NTUA 3 | 03 077-13.36X06.44 | NTUA 3 | 220NVJO | 142.00 | 0.00 | 34.20 | 5180.00 |
| NTUA 1 | 03 077-13.05X06.81 | NTUA 1 | 220NVJO | 0.00 | 0.00 | 29.00 | 5120.00 |
| BABE MET 1 | 03 077-07.65X06.70 | BABE MET 1 | 220NVJO | 106.00 | 707.00 | 0.00 | 5110.00 |
| BABE MET 2 | 03 077-07.55X06.55 | BABE MET 2 | 220NVJO | 100.00 | 705.00 | 57.00 | 5108.00 |
| KAI SCH 4 | 01-042-05.30X11.65 | KAI SCH 4 | 220NVJO | 850.00 | 870.00 | 0.00 | 6100.00 |
| KAIBIT PM3 | 01-042-03.82X10.54 | KAIBIT PM3 | 220NVJO | 668.00 | 948.00 | 0.00 | 5800.00 |
| SHONTO PM2 | 02 040-08.73X10.37 | SHONTO PM2 | 220NVJO | 485.00 | 510.00 | 0.00 | 6470.00 |
| SHONTO PM2 | 02 040-08.73X10.37 | SHONTO PM2 | 220NVJO | 485.00 | 510.00 | 0.00 | 6470.00 |
| SHNT PM3 | 02 040-08.52X10.57 | SHNT PM3 | 220NVJO | 0.00 | 0.00 | 0.00 | 6470.00 |
| SHONTO PM4 | 02 040-08.47X10.29 | SHONTO PM4 | 220NVJO | 300.00 | 550.00 | 0.00 | 6470.00 |
| USPHS ORAI | 06 095-06.55X08.65 | USPHS ORAI | 220NVJO | 655.00 | 675.00 | 0.00 | 5650.00 |
| ORAIBI PM4 | 06 095-06.34X08.54 | ORAIBI PM4 | 220NVJO | 850.00 | 1220.00 | 0.00 | 5630.00 |
| ORAIBI PM4 | 06 095-06.34X08.54 | ORAIBI PM4 | 220NVJO | 850.00 | 1220.00 | 0.00 | 5630.00 |
| ORAIBI PM4 | 06 095-06.34X08.54 | ORAIBI PM4 | 220NVJO | 850.00 | 1220.00 | 0.00 | 5630.00 |
| ORAIBI PM4 | 06 095-06.34X08.54 | ORAIBI PM4 | 220NVJO | 850.00 | 1220.00 | 0.00 | 5630.00 |
| 2T-514 | 02 040-05.38X15.27 | 2T-514 | 220NVJO | 250.00 | 400.00 | 218.41 | 6350.00 |
| BM 4 | 02 040-05.38X15.27 | BM 4 | 220NVJO | 0.00 | 0.00 | 219.72 | 6350.00 |
| ROCKY PM1 | 04 075-05.25X12.25 | ROCKY PM1 | 220NVJO | 1400.00 | 1500.00 | 0.00 | 6000.00 |
| ROCKY | 04 075-05.21X12.23 | ROCKY | 220NVJO | 1640.00 | 1810.00 | 0.00 | 6000.00 |
| ROCKY | 04 075-05.21X12.23 | ROCKY | 220NVJO | 1640.00 | 1810.00 | 0.00 | 6000.00 |
| ROCKY PM2 | 04 075-05.09X12.30 | ROCKY PM2 | 220NVJO | 1480.00 | 1780.00 | 0.00 | 5990.00 |
| BETKN N M | 02 040-02.48X05.16 | BETKN N M | 220NVJO | 10.00 | 753.00 | 0.00 | 7240.00 |
| HOPI A & C | 06 095-01.53X10.75 | HOPI A & C | 220NVJO | 1430.00 | 1600.00 | 0.00 | 6290.00 |
| BM OBS 5 | 04 075-00.61X16.21 | BM OBS 5 | 220NVJO | 1520.00 | 1680.00 | 326.84 | 5860.00 |
| PEABODY 2 | 08-039-09.44X17.18 | PEABODY 2 | 220NVJO | 1820.00 | 3600.00 | 0.00 | 6540.00 |
| PEABODY 2 | 08-039-09.44X17.18 | PEABODY 2 | 220NVJO | 1820.00 | 3600.00 | 0.00 | 6540.00 |
| PEABODY 2 | 08-039-09.44X17.18 | PEABODY 2 | 220NVJO | 1820.00 | 3600.00 | 0.00 | 6540.00 |
| PEABODY 2 | 08-039-09.44X17.18 | PEABODY 2 | 220NVJO | 1820.00 | 3600.00 | 0.00 | 6540.00 |
| PEABODY 2 | 08-039-09.44X17.18 | PEABODY 2 | 220NVJO | 1820.00 | 3600.00 | 0.00 | 6540.00 |
| PEABODY 2 | 08-039-09.44X17.18 | PEABODY 2 | 220NVJO | 1820.00 | 3600.00 | 0.00 | 6540.00 |
| PEABODY 4 | 04 056-09.00X03.73 | PEABODY 4 | 220NVJO | 2030.00 | 3460.00 | 0.00 | 6230.00 |
| PEABODY 4 | 04 056-09.00X03.73 | PEABODY 4 | 220NVJO | 2030.00 | 3460.00 | 0.00 | 6230.00 |
| PEABODY 4 | 04 056-09.00X03.73 | PEABODY 4 | 220NVJO | 2030.00 | 3460.00 | 0.00 | 6230.00 |

| Well Number | BIA Quadrangle Number | Other Number | Aquifer Code | Top Open Interval | Bottom Open Interval | Water Level | Water Altitude |
|---|---|---|---|---|---|---|---|
| PEABODY 4 | 04 056-09.00X03.73 | PEABODY 4 | 220NVJO | 2030.00 | 3460.00 | 0.00 | 6230.00 |
| PEABODY 4 | 04 056-09.00X03.73 | PEABODY 4 | 220NVJO | 2030.00 | 3460.00 | 0.00 | 6230.00 |
| | 04 056-08.80X05.85 | | 220NVJO | 0.00 | 0.00 | 0.00 | 6390.00 |
| BM 6 | 04 074-08.95X02.95 | BM 6 | 220NVJO | 1950.00 | 2510.00 | 736.00 | 6340.00 |
| BM 6 | 04 074-08.95X02.95 | BM 6 | 220NVJO | 1950.00 | 2510.00 | 736.00 | 6340.00 |
| PEABODY 5 | 04 056-08.11X01.15 | PEABODY 5 | 220NVJO | 2090.00 | 3740.00 | 0.00 | 6590.00 |
| PEABODY 5 | 04 056-08.11X01.15 | PEABODY 5 | 220NVJO | 2090.00 | 3740.00 | 0.00 | 6590.00 |
| PEABODY 5 | 04 056-08.11X01.15 | PEABODY 5 | 220NVJO | 2090.00 | 3740.00 | 0.00 | 6590.00 |
| PEABODY 5 | 04 056-08.11X01.15 | PEABODY 5 | 220NVJO | 2090.00 | 3740.00 | 0.00 | 6590.00 |
| PEABODY 5 | 04 056-08.11X01.15 | PEABODY 5 | 220NVJO | 2090.00 | 3740.00 | 0.00 | 6590.00 |
| PEABODY 5 | 04 056-08.11X01.15 | PEABODY 5 | 220NVJO | 2090.00 | 3740.00 | 0.00 | 6590.00 |
| PEABODY 5 | 04 056-08.11X01.15 | PEABODY 5 | 220NVJO | 2090.00 | 3740.00 | 0.00 | 6590.00 |
| PEABODY 5 | 04 056-08.11X01.15 | PEABODY 5 | 220NVJO | 2090.00 | 3740.00 | 0.00 | 6590.00 |
| PEABODY 3 | 04 056-07.11X04.13 | PEABODY 3 | 220NVJO | 1950.00 | 3590.00 | 0.00 | 6450.00 |
| PEABODY 3 | 04 056-07.11X04.13 | PEABODY 3 | 220NVJO | 1950.00 | 3590.00 | 0.00 | 6450.00 |
| PEABODY 3 | 04 056-07.11X04.13 | PEABODY 3 | 220NVJO | 1950.00 | 3590.00 | 0.00 | 6450.00 |
| PEABODY 3 | 04 056-07.11X04.13 | PEABODY 3 | 220NVJO | 1950.00 | 3590.00 | 0.00 | 6450.00 |
| PEABODY 3 | 04 056-07.11X04.13 | PEABODY 3 | 220NVJO | 1950.00 | 3590.00 | 0.00 | 6450.00 |
| PEABODY 3 | 04 056-07.11X04.13 | PEABODY 3 | 220NVJO | 1950.00 | 3590.00 | 0.00 | 6450.00 |
| PEABODY 3 | 04 056-07.11X04.13 | PEABODY 3 | 220NVJO | 1950.00 | 3590.00 | 0.00 | 6450.00 |
| PEABODY 3 | 04 056-07.11X04.13 | PEABODY 3 | 220NVJO | 1950.00 | 3590.00 | 0.00 | 6450.00 |
| PEABODY 6 | 08 039-06.68X17.11 | PEABODY 6 | 220NVJO | 2050.00 | 3490.00 | 0.00 | 6640.00 |
| PEABODY 6 | 08 039-06.68X17.11 | PEABODY 6 | 220NVJO | 2050.00 | 3490.00 | 0.00 | 6640.00 |
| PEABODY 6 | 08 039-06.68X17.11 | PEABODY 6 | 220NVJO | 2050.00 | 3490.00 | 0.00 | 6640.00 |
| PEABODY 6 | 08 039-06.68X17.11 | PEABODY 6 | 220NVJO | 2050.00 | 3490.00 | 0.00 | 6640.00 |
| PEABODY 6 | 08 039-06.68X17.11 | PEABODY 6 | 220NVJO | 2050.00 | 3490.00 | 0.00 | 6640.00 |
| PEABODY 6 | 08 039-06.68X17.11 | PEABODY 6 | 220NVJO | 2050.00 | 3490.00 | 0.00 | 6640.00 |
| KEAMS CYN3 | 06 094-03.27X10.80 | KEAMS CYN3 | 220NVJO | 931.00 | 1090.00 | 0.00 | 5800.00 |
| KEAMS CYN2 | 06 094-03.23X11.05 | KEAMS CYN2 | 220NVJO | 906.00 | 1110.00 | 0.00 | 5809.00 |
| KEAMS CYN2 | 06 094-03.23X11.05 | KEAMS CYN2 | 220NVJO | 906.00 | 1110.00 | 0.00 | 5809.00 |
| KEAMS CYN2 | 06 094-03.23X11.05 | KEAMS CYN2 | 220NVJO | 906.00 | 1110.00 | 0.00 | 5809.00 |
| KEAMS CYN2 | 06 094-03.23X11.05 | KEAMS CYN2 | 220NVJO | 906.00 | 1110.00 | 0.00 | 5809.00 |
| KEAMS CYN2 | 06 094-03.23X11.05 | KEAMS CYN2 | 220NVJO | 906.00 | 1110.00 | 0.00 | 5809.00 |
| ST-500 | 08 039-00.70X01.57 | ST-500 | 220NVJO | 712.00 | 868.00 | 54.50 | 5740.00 |
| BM 3 | 08 039-00.70X01.57 | BM 3 | 220NVJO | 0.00 | 0.00 | 55.00 | 5740.00 |
| PINON PM 6 | 04 073-12.26X10.09 | PINON PM 6 | 220NVJO | 1900.00 | 2240.00 | 0.00 | 6400.00 |
| PINON PM 6 | 04 073-12.26X10.09 | PINON PM 6 | 220NVJO | 1900.00 | 2240.00 | 0.00 | 6400.00 |
| PINON PM 6 | 04 073-12.26X10.09 | PINON PM 6 | 220NVJO | 1900.00 | 2240.00 | 0.00 | 6400.00 |
| PINON PM 6 | 04 073-12.26X10.09 | PINON PM 6 | 220NVJO | 1900.00 | 2240.00 | 0.00 | 6400.00 |
| | 08 038-09.40X07.08 | | 220NVJO | 0.00 | 0.00 | 160.72 | 5650.00 |
| ST-538 | 08 038-09.40X07.08 | ST-538 | 220NVJO | 470.00 | 1340.00 | 127.10 | 5650.00 |
| L MTN PM2 | 07 093-06.25X03.85 | L MTN PM2 | 220NVJO | 1180.00 | 1260.00 | 0.00 | 6140.00 |

| Well Number | BIA Quadrangle Number | Other Number | Aquifer Code | Top Open Interval | Bottom Open Interval | Water Level | Water Altitude | |
|---|---|---|---|---|---|---|---|---|
| CHLCHN PM3 | 08 038-04.43X15.39 | CHLCHN PM3 | 220NVJO | 1140.00 | 1570.00 | 0.00 | 5950.00 | |
| 8K-431 | 08 037-11.05X01.48 | 8K-431 | 220NVJO | 476.00 | 528.00 | 0.00 | 5570.00 | |
| 8T-537 | 08 054-10.96X00.63 | 8T-537 | 220NVJO | 300.00 | 360.00 | 376.65 | 5860.00 | |
| BM 1 | 08 054-10.96X00.63 | BM 1 | 220NVJO | 730.00 | 780.00 | 378.95 | 5860.00 | |
| ROUGH PM3 | 10 054-06.80X06.35 | ROUGH PM3 | 220NVJO | 1150.00 | 1520.00 | 0.00 | 6230.00 | |
| 10T-251 | 10 054-06.66X06.18 | | 220NVJO | 1390.00 | 1400.00 | 0.00 | 6210.00 | |
| 10T-251 | 10 054-06.66X06.18 | 10T-251 | 220NVJO | 1250.00 | 1390.00 | 0.00 | 6210.00 | |
| 8K-434 | 08 022-05.65X15.80 | 8K-434 | 220NVJO | 9.00 | 202.00 | 0.00 | 5240.00 | |
| 8K-403 | 08 022-05.28X10.68 | 8K-403 | 220NVJO | 170.00 | 210.00 | 0.00 | 5040.00 | |
| 8K-521 | 08 022-05.23X10.58 | 8K-521 | 220NVJO | 475.00 | 675.00 | 0.00 | 5020.00 | |
| 8T-519 | 08 022-01.80X05.45 | 8T-519 | 220NVJO | 18.00 | 420.00 | 0.00 | 5200.00 | |
| 9Y-92 | 09 037-01.81X14.35 | 9Y-92 | 220NVJO | 154.00 | 300.00 | 0.00 | 5620.00 | |
| 10K-235 | 10 053-12.67X05.84 | | 220NVJO | 496.00 | 703.00 | 0.00 | 5687.00 | |
| 10K-235 | 10 053-12.67X05.84 | | 220NVJO | 474.00 | 496.00 | 0.00 | 5687.00 | |
| 10K-235 | 10 053-12.67X05.84 | 10K-235 | 220NVJO | 180.00 | 203.00 | 0.00 | 5687.00 | |
| 9Y-12 | 09 021-01.53X00.87 | 9Y-12 | 220NVJO | 489.00 | 592.00 | 0.00 | 5165.00 | |
| 763 | | | 220NVJO | 0.00 | 0.00 | 0.00 | 0.00 | |
| 901 | | | 220NVJO | 58.00 | 78.00 | 5049.00 | 0.00 | M |
| 902 | | | 220NVJO | 63.00 | 73.00 | 4704.00 | 0.00 | M |
| 903 | | 903 | 220NVJO | 28.00 | 48.00 | 0.00 | 4704.00 | M |
| 904 | | 904 | 220NVJO | 32.00 | 42.00 | | 4879.00 | M |
| 910 | | 910 | | 97.00 | 197.00 | | 5048.00 | M |
| 911 | | 911 | 220NVJO | 311.00 | 351.00 | | 5054.00 | M |
| 913 | | 913 | 220NVJO | 331.00 | 371.00 | | 4987.00 | M |
| 914 | | 914 | 220NVJO | 139.00 | 156.00 | | 4969.00 | M |
| 917 | | 917 | 220NVJO | 130.00 | 150.00 | | 4977.00 | M |
| 920 | | 920 | 220NVJO | 116.00 | 156.00 | | 4954.00 | M |
| 921 | | 921 | 220NVJO | 315.00 | 355.00 | | 4940.00 | M |
| 970 | | 970 | 220NVJO | | | | 5047.00 | |
| 971 | | 971 | | | | | 5073.00 | |
| 972 | | | | | | | 5082.00 | |

| Well Number | Construction Date | Sample Date | Specific Conductance | pH | Temperature | Calcium mg/l | Magnesium mg/l | Sodium mg/l | Potassium mg/l |
|---|---|---|---|---|---|---|---|---|---|
| 1T-240 C | 19650404 | 04-04-65 | 1370 | 7.30 | -1.0 | 49.00 | 5.20 | -1.00 | -1.00 |
| 1K-231 | 19560614 | 07-00-56 | 316 | 6.90 | 18.5 | 32.00 | 16.00 | -1.00 | -1.00 |
| TUBA C PM5 | 19520122 | 09-16-65 | 220 | 8.10 | -1.0 | 24.00 | 4.90 | 10.00 | 1.20 |
| TUB CT PM6 | 19630208 | 03-00-63 | 116 | 8.80 | -1.0 | -1.00 | -1.00 | -1.00 | -1.00 |
| PM 2 | 0 | 09-16-65 | 230 | 8.00 | -1.0 | 26.00 | 4.90 | 8.30 | 1.20 |
| PM 1 | 0 | 09-16-65 | 220 | 8.00 | -1.0 | 26.00 | 4.90 | 8.00 | 1.20 |
| TUBA C PM4 | 19511101 | 09-16-65 | 210 | 8.20 | -1.0 | 24.00 | 3.60 | 8.30 | 1.20 |
| 3T-54 | 19711001 | 10-19-71 | 190 | 7.80 | 15.5 | 24.00 | 4.10 | 7.10 | 1.00 |
| NTUA 5 TC | 19711001 | 10-19-71 | 190 | 7.80 | 15.5 | 24.00 | 4.10 | 7.10 | 1.00 |
| NTUA 3 | 19711001 | 11-09-71 | 193 | 7.60 | 16.0 | 23.00 | 4.20 | 7.80 | 1.00 |
| NTUA 1 | 19590825 | 09-16-65 | 230 | 8.00 | -1.0 | 28.00 | 4.90 | 9.40 | 1.20 |
| RABE MET 1 | 19550201 | 04-11-55 | 246 | 7.80 | 16.0 | 25.00 | 6.40 | -1.00 | -1.00 |
| RABE MET 2 | 19550901 | 09-20-55 | 268 | 7.30 | 15.5 | 29.00 | 9.00 | -1.00 | -1.00 |
| KAI SCH 4 | 19630209 | 03-00-63 | 181 | 8.10 | -1.0 | -1.00 | -1.00 | -1.00 | -1.00 |
| KAIBIT PM3 | 19580625 | 06-26-59 | 290 | 7.90 | -1.0 | 30.00 | 12.00 | 9.70 | 0.80 |
| SHONTO PM2 | 19610505 | 05-05-61 | 290 | 7.50 | -1.0 | 41.00 | 6.20 | -1.00 | -1.00 |
| SHONTO PM2 | 19610505 | 05-20-86 | 302 | 7.10 | 14.0 | 41.00 | 5.40 | 5.70 | 1.60 |
| SHNT PM3 | 19621227 | 08-07-73 | 290 | 8.30 | -1.0 | 44.00 | 4.90 | 5.00 | 1.60 |
| SHONTO PM4 | 19640715 | 08-07-73 | 280 | 8.30 | -1.0 | 42.00 | 4.90 | 5.00 | 1.60 |
| USPHS ORAI | 19670220 | 02-20-67 | -1 | 9.30 | -1.0 | -1.00 | -1.00 | -1.00 | -1.00 |
| ORAIBI PM4 | 19680807 | 07-29-82 | 385 | 9.50 | 22.0 | 0.43 | 0.04 | 85.00 | 0.40 |
| ORAIBI PM4 | 19680807 | 08-14-84 | 385 | 9.90 | 21.0 | 0.43 | 0.02 | 86.00 | 0.40 |
| ORAIBI PM4 | 19680807 | 08-15-83 | 400 | 9.60 | 22.0 | 0.50 | 0.16 | 87.00 | 0.50 |
| ORAIBI PM4 | 19680807 | 10-11-68 | 400 | 9.80 | -1.0 | 2.00 | -4.00 | 88.00 | 0.40 |
| 2T-514 | 19720215 | 06-16-72 | 236 | 7.90 | 14.0 | 36.00 | 3.70 | 3.50 | 1.30 |
| BM 4 | 19720215 | 06-16-72 | 236 | 7.90 | 14.0 | 36.00 | 3.70 | 3.50 | 1.30 |
| ROCKY PM1 | 19590819 | 11-30-67 | 280 | 9.40 | -1.0 | 2.00 | 0.00 | 59.00 | 0.60 |
| ROCKY | 19760309 | 03-09-76 | 270 | 9.60 | -1.0 | 4.00 | -4.00 | 57.00 | 1.20 |
| ROCKY | 19760309 | 09-02-82 | 255 | 9.20 | 26.0 | 0.52 | -2.00 | 56.00 | 0.50 |
| ROCKY PM2 | 19630626 | 07-00-63 | 364 | 8.40 | 24.0 | 5.40 | 0.10 | -1.00 | -1.00 |
| BETKN N M | 19620701 | 07-25-62 | 220 | 7.40 | 14.0 | 34.00 | 4.40 | -1.00 | -1.00 |
| HOPI A & C | 19690101 | 11-23-72 | -1 | -1.00 | 9.5 | -1.00 | 0.40 | -2.00 | -1.00 |
| BM OBS 5 | 19720225 | 11-23-72 | 386 | 9.00 | -1.0 | 1.30 | 0.30 | 77.00 | 1.50 |
| PEABODY 2 | 19670601 | 02-21-86 | 172 | 8.70 | 31.0 | 9.40 | 0.21 | 26.00 | 0.90 |
| PEABODY 2 | 19670601 | 08-09-79 | 220 | 8.50 | 31.0 | 8.20 | 0.20 | 43.00 | 0.80 |
| PEABODY 2 | 19670601 | 08-17-67 | 221 | 8.80 | 29.0 | 7.00 | 1.00 | 42.00 | 1.20 |
| PEABODY 2 | 19670601 | 08-19-80 | 225 | 7.70 | 30.5 | 8.50 | 0.50 | 39.00 | 0.70 |
| PEABODY 2 | 19670601 | 09-10-75 | 230 | 8.20 | 31.0 | 7.80 | 0.20 | 41.00 | 0.80 |
| PEABODY 2 | 19670601 | 11-17-76 | 260 | 8.60 | 30.0 | 4.90 | -2.00 | 41.00 | 0.70 |
| PEABODY 4 | 19680501 | 03-25-86 | 205 | 9.30 | 32.0 | 4.90 | 0.04 | 41.00 | 0.70 |
| PEABODY 4 | 19680501 | 08-09-79 | 220 | 8.80 | 32.0 | 5.10 | 0.10 | 45.00 | 0.70 |
| PEABODY 4 | 19680501 | 08-19-80 | 230 | 9.10 | 32.0 | 4.60 | 0.10 | 44.00 | 0.70 |

| Well Number | Construction Date | Sample Date | Specific Conductance | pH | Temperature | Calcium mg/l | Magnesium mg/l | Sodium mg/l | Potassium mg/l |
|---|---|---|---|---|---|---|---|---|---|
| PEABODY 4 | 19680501 | 09-10-75 | 220 | 8.40 | 34.0 | 4.90 | 0.20 | 41.00 | 0.70 |
| PEABODY 4 | 19680501 | 11-17-76 | 240 | 9.10 | 32.0 | 7.00 | 0.10 | 40.00 | 0.80 |
| | 19720614 | 01-18-77 | 220 | 9.20 | 32.0 | 3.50 | 0.40 | 45.00 | 0.60 |
| BM 6 | 19770131 | 08-30-77 | 200 | 9.40 | 30.0 | -1.00 | -1.00 | -1.00 | -1.00 |
| BM 6 | 19770131 | 08-30-77 | 205 | 9.40 | 30.0 | 14.00 | 0.10 | 45.00 | 0.60 |
| PEABODY 5 | 19680101 | 01-18-77 | 220 | 9.20 | 32.0 | 3.50 | 0.40 | 45.00 | 0.60 |
| PEABODY 5 | 19680101 | 01-23-86 | 398 | 9.60 | 31.0 | -1.00 | -1.00 | -1.00 | -1.00 |
| PEABODY 5 | 19680101 | 01-23-86 | 398 | 9.60 | 31.0 | 0.94 | 0.01 | 89.00 | 0.70 |
| PEABODY 5 | 19680101 | 06-12-68 | 224 | 9.20 | 31.5 | 2.80 | 1.00 | 51.00 | 0.90 |
| PEABODY 5 | 19680101 | 08-09-79 | 220 | 8.70 | 31.0 | 4.30 | 0.10 | 43.00 | 0.70 |
| PEABODY 5 | 19680101 | 08-19-80 | 210 | 9.10 | 32.0 | 4.50 | 0.10 | 42.00 | 0.80 |
| PEABODY 5 | 19680101 | 08-23-77 | 220 | 9.30 | 33.0 | 3.80 | -2.00 | 47.00 | 0.70 |
| PEABODY 5 | 19680101 | 09-10-75 | 240 | 8.50 | 34.0 | 3.50 | 0.10 | 52.00 | 0.70 |
| PEABODY 3 | 19680401 | 01-23-86 | 175 | 9.20 | 32.0 | 4.00 | 0.03 | 36.00 | 0.70 |
| PEABODY 3 | 19680401 | 01-23-86 | 175 | 9.20 | 32.0 | -1.00 | -1.00 | -1.00 | -1.00 |
| PEABODY 3 | 19680401 | 04-29-68 | 236 | 8.20 | 31.0 | 2.40 | 1.20 | 55.00 | 0.90 |
| PEABODY 3 | 19680401 | 08-09-79 | 240 | 8.50 | 32.0 | 3.10 | 0.10 | 53.00 | 0.70 |
| PEABODY 3 | 19680401 | 08-19-80 | 230 | 9.10 | 32.0 | 3.40 | 0.10 | 50.00 | 0.70 |
| PEABODY 3 | 19680401 | 08-23-77 | 230 | 9.30 | 32.0 | 3.90 | -2.00 | 49.00 | 0.70 |
| PEABODY 3 | 19680401 | 09-10-75 | 240 | 8.50 | 31.0 | 3.30 | 0.20 | 52.00 | 0.70 |
| PEABODY 3 | 19680401 | 11-18-76 | 250 | 9.20 | 32.0 | 3.50 | -2.00 | 50.00 | 0.70 |
| PEABODY 6 | 0 | 01-23-86 | 182 | 9.10 | 33.5 | 4.70 | 0.04 | 38.00 | 0.80 |
| PEABODY 6 | 0 | 01-23-86 | 182 | 9.10 | 33.5 | -1.00 | -1.00 | -1.00 | -1.00 |
| PEABODY 6 | 0 | 06-29-68 | 201 | 9.00 | 34.0 | 2.80 | 0.50 | 52.00 | 0.90 |
| PEABODY 6 | 0 | 08-09-79 | 260 | 8.50 | 33.5 | 3.10 | 0.10 | 52.00 | 0.70 |
| PEABODY 6 | 0 | 08-19-80 | 260 | 8.90 | 32.0 | 4.00 | 0.00 | 50.00 | 0.80 |
| PEABODY 6 | 0 | 08-23-77 | 240 | 9.30 | 34.0 | 4.00 | 0.10 | 51.00 | 0.80 |
| KEAMS CYN3 | 19760201 | 01-22-76 | -1 | -1.00 | 9.3 | -1.00 | 6.00 | 7.30 | -1.00 |
| KEAMS CYN2 | 19700501 | 05-14-70 | -1 | -1.00 | 8.5 | -1.00 | 8.00 | 4.90 | -1.00 |
| KEAMS CYN2 | 19700501 | 08-13-84 | 0 | 0.00 | 9.3 | 19.00 | 0.90 | 0.20 | -1.00 |
| KEAMS CYN2 | 19700501 | 08-23-83 | 0 | 0.00 | 9.1 | 19.00 | 0.99 | 0.14 | -1.00 |
| KEAMS CYN2 | 19700501 | 09-01-82 | 0 | 0.00 | 9.0 | 19.00 | 0.82 | 0.25 | -1.00 |
| KEAMS CYN2 | 19700501 | 11-23-72 | -1 | -1.00 | 8.8 | -1.00 | 0.80 | 0.10 | -1.00 |
| ST-500 | 19590729 | 06-07-62 | 592 | 7.40 | 15.0 | 26.00 | 8.00 | -1.00 | -1.00 |
| BM 3 | 19590729 | 06-07-62 | 592 | 7.40 | 15.0 | 26.00 | 8.00 | -1.00 | -1.00 |
| PINON PM 6 | 19700201 | 05-29-70 | 490 | 9.80 | -1.0 | 1.00 | 0.61 | 110.00 | -4.00 |
| PINON PM 6 | 19700201 | 08-14-84 | 490 | 10.00 | 27.0 | 0.50 | 0.01 | 110.00 | 0.40 |
| PINON PM 6 | 19700201 | 08-16-83 | 505 | 9.70 | 24.5 | 0.56 | 0.07 | 110.00 | 0.50 |
| PINON PM 6 | 19700201 | 09-16-82 | 485 | 9.60 | 25.5 | 0.58 | -2.00 | 110.00 | 0.50 |
| | 19720129 | 01-18-77 | 220 | 9.20 | 32.0 | 3.50 | 0.40 | 45.00 | 0.60 |
| ST-538 | 19720129 | 11-23-72 | 302 | 8.70 | -1.0 | 1.30 | 0.20 | -1.00 | 1.40 |
| L MTN PM2 | 19720401 | 04-27-72 | 1470 | 9.00 | -1.0 | 2.00 | 1.20 | 320.00 | -4.00 |

| Well Number | Construction Date | Sample Date | Specific Conductance | pH | Temperature | Calcium mg/l | Magnesium mg/l | Sodium mg/l | Potassium mg/l |
|---|---|---|---|---|---|---|---|---|---|
| CHLCHN PM3 | 19650925 | 08-13-73 | 320 | 8.80 | -1.0 | 16.00 | 2.40 | 53.00 | 0.78 |
| 8K-431 | 19550404 | 04-05-55 | 600 | 7.20 | -1.0 | -1.00 | -1.00 | -1.00 | -1.00 |
| 8T-537 | 19720201 | 05-24-72 | 538 | 9.20 | 21.0 | 3.70 | 0.30 | 120.00 | 1.10 |
| BM 1 | 19720201 | 05-24-72 | 538 | 9.20 | 21.0 | 3.70 | 0.30 | 120.00 | 1.10 |
| ROUGH PM3 | 19590301 | 03-26-59 | 1530 | 9.00 | -1.0 | 20.00 | 4.80 | -1.00 | -1.00 |
| 10T-251 | 19581002 | 10-19-70 | 1010 | 8.90 | -1.0 | 3.00 | -4.00 | 220.00 | 34.00 |
| 10T-251 | 19581002 | 10-19-70 | 1010 | 8.90 | -1.0 | 3.00 | -4.00 | 220.00 | 34.00 |
| 8K-434 | 19550617 | 06-17-55 | 410 | 7.30 | 14.5 | 54.00 | 8.30 | -1.00 | -1.00 |
| 8K-403 | 19480801 | 07-25-69 | 370 | 8.80 | -1.0 | 10.00 | 3.00 | 72.00 | 4.00 |
| 8K-521 | 19640605 | 07-30-64 | 350 | 8.70 | -1.0 | 8.00 | 3.70 | 67.00 | 0.80 |
| 8T-519 | 19641228 | 12-28-64 | 594 | 9.80 | -1.0 | 8.20 | 0.10 | -1.00 | -1.00 |
| 9Y-92 | 19390102 | 08-23-71 | 1270 | 8.00 | -1.0 | 120.00 | 57.00 | 62.00 | 0.80 |
| 10K-235 | 19520818 | 05-10-55 | 339 | 7.20 | 14.0 | 24.00 | 7.20 | -1.00 | 2.00 |
| 10K-235 | 19520818 | 05-10-55 | 339 | 7.20 | 14.0 | 24.00 | 7.20 | -1.00 | 2.00 |
| 10K-235 | 19520818 | 05-10-55 | 339 | 7.20 | 14.0 | 24.00 | 7.20 | -1.00 | 2.00 |
| 9Y-12 | 19350212 | 03-11-55 | 9 | 14.50 | 0.8 | 0.90 | 140.00 | 0.80 | 220.00 |
| 763 | 0 | 7-22-85 | 270 | 7.44 | 16.0 | 29.00 | 8.70 | 77.00 | 2.00 |
| 901 | 1985 | 3-20-86 | 210 | 7.30 | 15.0 | 31.40 | 5.90 | 16.40 | 1.20 |
| 902 | 1985 | 7-23-85 | 250 | 9.15 | 19.0 | 0.70 | 0.15 | 71.00 | 1.10 |
| 903 | 1985 | 7-24-85 | 160 | 7.86 | 19.0 | 37.00 | 8.20 | 9.00 | 1.50 |
| 904 | 1985 | 7-24-85 | 240 | 7.62 | 17.0 | 38.00 | 12.00 | 64.00 | 1.20 |
| 910 | 1985 | 1-8-86 | 140 | 7.62 | 16.0 | 31.00 | 5.04 | 16.60 | 1.20 |
| 911 | 1985 | 1-8-86 | 150 | 9.46 | 16.0 | 16.90 | 2.55 | 30.00 | 7.57 |
| 913 | 1985 | 4-10-86 | 140 | 9.69 | 17.0 | 8.52 | 1.54 | 20.40 | 10.70 |
| 914 | 1985 | 4-9-86 | 215 | 8.22 | 17.0 | 31.90 | 6.83 | 14.40 | 2.18 |
| 917 | 1985 | 4-10-86 | 190 | 8.08 | 17.0 | 31.20 | 6.12 | 9.31 | 1.86 |
| 920 | 1985 | 4-9-86 | 185 | 8.08 | 17.0 | 30.70 | 6.74 | 7.30 | 2.36 |
| 921 | 1985 | 4-10-86 | 140 | 8.66 | 17.0 | 20.30 | 3.12 | 12.70 | 6.87 |
| 970 | | 7-22-85 | 180 | 8.00 | 16.0 | 23.00 | 6.00 | 14.00 | 1.20 |
| 971 | | 7-23-85 | 800 | 8.79 | 15.0 | 2.20 | 0.84 | 230.00 | 0.80 |
| 972 | | 7-23-85 | 205 | 7.49 | 16.0 | 30.00 | 5.70 | 12.00 | 1.10 |

| Well Number | Bicarbonate mg/l | Carbonate mg/l | Alkalinity mg/l | Sulfate mg/l | Chloride mg/l | Fluoride mg/l | Silica mg/l | Nitrate mg/l | Phosphate mg/l |
|---|---|---|---|---|---|---|---|---|---|
| 1T-240 C | 110 | 0 | 90 | 260.00 | 160.00 | 0.40 | 16.0 | 2.40 | -1.00 |
| 1K-231 | 130 | 0 | 107 | 15.00 | 16.00 | 0.60 | 12.0 | 17.00 | -1.00 |
| TUBA C PM5 | 78 | 6 | 74 | 8.20 | 9.90 | 0.10 | -1.0 | 6.20 | -1.00 |
| TUB CT PM6 | 26 | 6 | 31 | -1.00 | 6.50 | 0.20 | -1.0 | -1.00 | -1.00 |
| PM 2 | 87 | 3 | 76 | 10.00 | 12.00 | 0.10 | -1.0 | 5.00 | -1.00 |
| PM 1 | 91 | -4 | 75 | 12.00 | 8.00 | 0.20 | -1.0 | 6.20 | -1.00 |
| TUBA C PM4 | 75 | 8 | 75 | 6.20 | 8.20 | 0.10 | -1.0 | 6.10 | -1.00 |
| 3T-54 | 95 | 0 | 78 | 8.00 | 4.80 | 0.20 | 12.0 | 1.50 | 0.03 |
| NTUA 5 TC | 95 | 0 | 78 | 8.00 | 4.80 | 0.20 | 12.0 | 1.50 | 0.03 |
| NTUA 3 | 97 | 0 | 80 | 9.20 | 4.60 | 0.20 | 11.0 | 1.30 | 0.03 |
| NTUA 1 | 82 | 8 | 81 | 14.00 | 9.90 | 0.10 | -1.0 | 5.60 | -1.00 |
| RARE MET 1 | 120 | 0 | 98 | -1.00 | 6.00 | -1.00 | -1.0 | 11.00 | -1.00 |
| RARE MET 2 | 160 | 0 | 131 | 13.00 | 12.00 | 0.30 | 13.0 | 12.00 | -1.00 |
| KAI SCH 4 | 88 | 0 | 72 | -1.00 | 5.00 | 0.30 | -1.0 | -1.00 | -1.00 |
| KAIBIT PM3 | 98 | -4 | 80 | 39.00 | 14.00 | 0.20 | -1.0 | 6.20 | -1.00 |
| SHONTO PM2 | 130 | 0 | 105 | 16.00 | 10.00 | 0.10 | 15.0 | 12.00 | -1.00 |
| SHONTO PM2 | -1 | -1 | 101 | 14.00 | 10.00 | -2.00 | 14.0 | 3.30 | 0.03 |
| SHNT PM3 | 120 | 8 | 108 | 24.00 | 7.10 | -4.00 | 6.8 | 12.00 | -1.00 |
| SHONTO PM4 | 120 | 6 | 105 | 23.00 | 3.60 | -4.00 | 6.4 | 12.00 | -1.00 |
| USPHS ORAI | 130 | 100 | 273 | -1.00 | 50.00 | 1.00 | -1.0 | -1.00 | -1.00 |
| ORAIBI PM4 | -1 | -1 | 167 | 10.00 | 4.00 | 0.20 | 23.0 | 0.55 | -1.00 |
| ORAIBI PM4 | -1 | -1 | 174 | 9.90 | 4.00 | 0.20 | 22.0 | 1.20 | 0.09 |
| ORAIBI PM4 | -1 | -1 | 180 | 9.80 | 4.10 | 0.20 | 23.0 | 1.20 | 0.06 |
| ORAIBI PM4 | 140 | 26 | 158 | 39.00 | 3.60 | 0.10 | -1.0 | 4.30 | -1.00 |
| 2T-514 | 120 | 0 | 95 | 12.00 | 7.60 | 0.00 | 14.0 | 2.90 | -1.00 |
| BM 4 | 120 | 0 | 95 | 12.00 | 7.60 | 0.00 | 14.0 | 2.90 | -1.00 |
| ROCKY PM1 | 99 | 17 | 110 | 23.00 | 1.10 | -4.00 | -1.0 | 5.20 | -1.00 |
| ROCKY | 61 | 38 | 113 | 3.80 | 5.30 | 0.30 | -1.0 | 1.50 | -1.00 |
| ROCKY | -1 | -1 | 114 | 6.00 | 1.40 | 0.10 | 20.0 | 1.20 | 0.06 |
| ROCKY PM2 | 180 | 4 | 154 | 18.00 | 14.00 | 0.60 | 31.0 | 2.70 | -1.00 |
| BETKN N M | 130 | 0 | 105 | 3.60 | 3.40 | 0.10 | -1.0 | -1.00 | -1.00 |
| HOPI A & C | 120 | 0 | 140 | 67.00 | 226.00 | 20.00 | 4.3 | 300.00 | 0.20 |
| BM OBS 5 | 140 | 26 | 158 | 6.60 | 1.80 | 0.20 | 25.0 | 4.10 | -1.00 |
| PEABODY 2 | -1 | -1 | -1 | 8.10 | 2.60 | 0.10 | 22.0 | 0.97 | -1.00 |
| PEABODY 2 | 100 | 0 | 82 | 24.00 | 3.40 | 0.10 | 22.0 | 0.93 | -1.00 |
| PEABODY 2 | 76 | 22 | 99 | 21.00 | 5.00 | 0.10 | 18.0 | 1.00 | -1.00 |
| PEABODY 2 | -1 | -1 | 67 | 20.00 | 11.00 | 0.20 | 21.0 | 0.90 | 0.28 |
| PEABODY 2 | 100 | 0 | 84 | 20.00 | 5.00 | 0.20 | 20.0 | 0.86 | 0.00 |
| PEABODY 2 | 78 | 9 | 79 | 16.00 | 3.60 | 0.20 | 22.0 | 1.20 | 0.03 |
| PEABODY 4 | -1 | -1 | 80 | 12.00 | 4.20 | 0.20 | 20.0 | 1.00 | 0.06 |
| PEABODY 4 | 96 | 4 | 85 | 19.00 | 3.90 | 0.20 | 23.0 | 0.94 | -1.00 |
| PEABODY 4 | -1 | -1 | 84 | 13.00 | 4.30 | 0.20 | 21.0 | 0.95 | 0.00 |

| Well Number | Bicarbonate mg/l | Carbonate mg/l | Alkalinity mg/l | Sulfate mg/l | Chloride mg/l | Fluoride mg/l | Silica mg/l | Nitrate mg/l | Phosphate mg/l |
|---|---|---|---|---|---|---|---|---|---|
| PEABODY 4 | 70 | 16 | 84 | 13.00 | 3.40 | 0.20 | 21.0 | 0.95 | 0.00 |
| PEABODY 4 | 78 | 7 | 76 | 19.00 | 2.90 | 0.20 | 21.0 | 1.20 | 0.03 |
| | 87 | 14 | 95 | 13.00 | 3.00 | 0.20 | 21.0 | 3.20 | 0.09 |
| BM 6 | -1 | -1 | -1 | -1.00 | -1.00 | -1.00 | -1.0 | -1.00 | -1.00 |
| BM 6 | 89 | 29 | 120 | 5.50 | 1.20 | 0.10 | 19.0 | 0.81 | 0.28 |
| PEABODY 5 | 87 | 14 | 95 | 13.00 | 3.00 | 0.20 | 21.0 | 3.20 | 0.09 |
| PEABODY 5 | -1 | -1 | 134 | -1.00 | -1.00 | -1.00 | -1.0 | -1.00 | -1.00 |
| PEABODY 5 | -1 | -1 | 134 | 28.00 | 8.00 | 0.20 | 20.0 | -2.00 | -1.00 |
| PEABODY 5 | 81 | 22 | 103 | 16.00 | 3.50 | -1.00 | -1.0 | -1.00 | -1.00 |
| PEABODY 5 | 100 | 2 | 85 | 15.00 | 2.90 | 0.20 | 21.0 | 0.82 | -1.00 |
| PEABODY 5 | -1 | -1 | 84 | 9.50 | 2.90 | 0.20 | 21.0 | 0.80 | 0.00 |
| PEABODY 5 | 98 | 15 | 110 | 12.00 | 3.00 | 0.20 | 21.0 | 0.90 | 0.06 |
| PEABODY 5 | 100 | 10 | 99 | 18.00 | 4.00 | 0.20 | 20.0 | 0.88 | 0.00 |
| PEABODY 3 | -1 | -1 | -1 | 9.70 | 2.40 | 0.20 | 20.0 | -2.00 | -1.00 |
| PEABODY 3 | -1 | -1 | 64 | -1.00 | -1.00 | -1.00 | -1.0 | -1.00 | -1.00 |
| PEABODY 3 | 130 | 0 | 104 | 17.00 | 4.00 | 0.61 | 30.0 | 4.00 | -1.00 |
| PEABODY 3 | 110 | 14 | 110 | 17.00 | 3.30 | 0.40 | 21.0 | 0.83 | -1.00 |
| PEABODY 3 | -1 | -1 | 90 | 14.00 | 3.50 | 0.40 | 20.0 | 0.77 | 0.00 |
| PEABODY 3 | 100 | 16 | 110 | 12.00 | 3.20 | 0.50 | 20.0 | 0.88 | 0.06 |
| PEABODY 3 | 88 | 16 | 99 | 14.00 | 2.80 | 0.50 | 19.0 | 0.74 | 0.00 |
| PEABODY 3 | 38 | 42 | 101 | 11.00 | 3.00 | 0.40 | 17.0 | 1.60 | 0.03 |
| PEABODY 6 | -1 | -1 | 76 | 9.60 | 2.30 | 0.20 | 22.0 | 0.72 | -1.00 |
| PEABODY 6 | -1 | -1 | 76 | -1.00 | -1.00 | -1.00 | -1.0 | -1.00 | -1.00 |
| PEABODY 6 | 81 | 25 | 108 | 13.00 | 3.00 | 0.40 | 34.0 | 2.60 | -1.00 |
| PEABODY 6 | 120 | 13 | 120 | 19.00 | 3.20 | 0.30 | 22.0 | 0.75 | -1.00 |
| PEABODY 6 | -1 | -1 | 100 | 15.00 | 3.50 | 0.30 | 20.0 | 0.72 | 0.12 |
| PEABODY 6 | 120 | 0 | 98 | 13.00 | 3.20 | 0.20 | 22.0 | 0.85 | 0.06 |
| KEAMS CYN3 | 200 | 2 | 280 | 74.00 | 353.00 | 36.00 | 71.0 | 500.00 | -1.00 |
| KEAMS CYN2 | 470 | -4 | 420 | 31.00 | 396.00 | 490.00 | 83.0 | 5.00 | 2.50 |
| KEAMS CYN2 | 240 | 1 | -1 | -1.00 | 336.00 | 36.00 | 96.0 | 578.00 | -1.00 |
| KEAMS CYN2 | 250 | 1 | -1 | -1.00 | 330.00 | 42.00 | 120.0 | 630.00 | -1.00 |
| KEAMS CYN2 | 240 | 1 | -1 | -1.00 | 348.00 | 35.00 | 94.0 | 590.00 | -1.00 |
| KEAMS CYN2 | 240 | 1 | 370 | 24.00 | 343.00 | 46.00 | 91.0 | 620.00 | 0.10 |
| ST-500 | 230 | 0 | 189 | 95.00 | 14.00 | 0.20 | 17.0 | 0.00 | -1.00 |
| BM 3 | 230 | 0 | 189 | 95.00 | 14.00 | 0.20 | 17.0 | 0.00 | -1.00 |
| PINON PM 6 | 120 | 70 | 216 | 22.00 | 1.80 | 0.30 | -1.0 | 5.60 | -1.00 |
| PINON PM 6 | -1 | -1 | 220 | 5.40 | 3.70 | 0.20 | 26.0 | 1.40 | -1.00 |
| PINON PM 6 | -1 | -1 | 210 | 5.30 | 3.60 | 0.20 | 27.0 | 1.40 | -1.00 |
| PINON PM 6 | -1 | -1 | 228 | 5.00 | 3.70 | 0.20 | 27.0 | 1.40 | 0.09 |
| | 87 | 14 | 95 | 13.00 | 3.00 | 0.20 | 21.0 | 3.20 | 0.09 |
| ST-538 | 140 | 10 | 135 | 6.00 | 2.10 | 0.20 | 14.0 | 1.90 | -1.00 |
| L MTN PM2 | 350 | 48 | 367 | 59.00 | 200.00 | 3.20 | -1.0 | -4.00 | -1.00 |

| Well Number | Bicarbonate mg/l | Carbonate mg/l | Alkalinity mg/l | Sulfate mg/l | Chloride mg/l | Fluoride mg/l | Silica mg/l | Nitrate mg/l | Phosphate mg/l |
|---|---|---|---|---|---|---|---|---|---|
| CHLCHN PM3 | 120 | 12 | 117 | 33.00 | 7.00 | 0.15 | -1.0 | 6.20 | -1.00 |
| 8K-431 | 330 | 0 | 268 | 45.00 | 10.00 | 0.80 | 12.0 | 0.70 | -1.00 |
| 8T-537 | 210 | 44 | 247 | 15.00 | 11.00 | 0.40 | 12.0 | 0.96 | 0.06 |
| BM 1 | 210 | 44 | 247 | 15.00 | 11.00 | 0.40 | 12.0 | 0.96 | 0.06 |
| ROUGH PM3 | -1 | 81 | 11 | 66.00 | 570.00 | 51.00 | 1.3 | 1000.00 | -1.00 |
| 10T-251 | -4 | 290 | 21 | 274.00 | 45.00 | 110.00 | 3.2 | 610.00 | -1.00 |
| 10T-251 | -4 | 290 | 21 | 274.00 | 45.00 | 110.00 | 3.2 | 610.00 | -1.00 |
| 8K-434 | 150 | 0 | 123 | 36.00 | 25.00 | -1.00 | 19.0 | 10.00 | -1.00 |
| 8K-403 | 140 | 13 | 136 | 29.00 | 11.00 | 0.20 | -1.0 | 9.00 | -1.00 |
| 8K-521 | 120 | 13 | 120 | 31.00 | 12.00 | 0.20 | -1.0 | 4.40 | -1.00 |
| 8T-519 | 9 | 26 | 51 | 170.00 | 22.00 | 0.50 | 1.8 | 2.80 | -1.00 |
| 9Y-92 | 100 | -4 | 82 | 540.00 | 13.00 | 1.20 | -1.0 | 9.30 | -1.00 |
| 10K-235 | -1 | 120 | 0 | 98.00 | 44.00 | 13.00 | 0.8 | 210.00 | -1.00 |
| 10K-235 | -1 | 120 | 0 | 98.00 | 44.00 | 13.00 | 0.8 | 210.00 | -1.00 |
| 10K-235 | -1 | 120 | 0 | 98.00 | 44.00 | 13.00 | 0.8 | 210.00 | -1.00 |
| 9Y-12 | 30 | 230 | 64 | 16.00 | 0.30 | 11.00 | -1.0 | -1.00 | -1.00 |
| 763 | 135 | 0 | 135 | 81.00 | 30.00 | 0.70 | 0.0 | 21.00 | 0.10 |
| 901 | 0 | 0 | 104 | 17.00 | 11.00 | 0.20 | 0.0 | 3.00 | 0.00 |
| 902 | 0 | 0 | 132 | 6.00 | 8.00 | 8.00 | 0.0 | 11.00 | 0.00 |
| 903 | 0 | 0 | 88 | 18.00 | 16.00 | 0.20 | 12.0 | 24.00 | 0.10 |
| 904 | | | 115 | 48.00 | 84.00 | 0.40 | 23.0 | 12.00 | 0.01 |
| 910 | | | 93 | 17.10 | 11.00 | | 10.0 | 3.00 | |
| 911 | | | 74 | 84.90 | 9.00 | | | 3.00 | |
| 913 | | | 65 | 10.20 | 6.00 | | | 3.00 | |
| 914 | | | 93 | 19.00 | 14.00 | | | 3.00 | |
| 917 | | | 88 | 15.10 | 10.00 | | | 5.00 | |
| 920 | | | 93 | 13.10 | 10.00 | | | 3.00 | |
| 921 | | | 73 | 8.10 | 7.00 | | | 2.00 | |
| 970 | | | 86 | 8.00 | 7.00 | 0.20 | 0.0 | 17.00 | |
| 971 | | | 292 | | 49.00 | 4.60 | | 35.00 | |
| 972 | | | 100 | 19.00 | 11.00 | 0.20 | | 1.00 | |

| Well Number | Boron mg/l | Arsenic mg/l | Iron mg/l | Manganese mg/l | Selenium mg/l | TDS mg/l |
|---|---|---|---|---|---|---|
| 1T-240 C | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | 750.00 |
| 1K-231 | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | -1.00 |
| TUBA C PM5 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | 140.00 |
| TUB CT PM6 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |
| PM 2 | -1.00 | 130.00 | -1.00 | -1.00 | -1.00 | 130.00 |
| PM 1 | -1.00 | 130.00 | -1.00 | -1.00 | -1.00 | 130.00 |
| TUBA C PM4 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | 130.00 |
| 3T-54 | -1.00 | -1.00 | 10.00 | 50.00 | -1.00 | 110.00 |
| NTUA 5 TC | -1.00 | -1.00 | 10.00 | 50.00 | -1.00 | 110.00 |
| NTUA 3 | -1.00 | -1.00 | 10.00 | 40.00 | -1.00 | 110.00 |
| NTUA 1 | -1.00 | 200.00 | 34.00 | -1.00 | -1.00 | 140.00 |
| RARE MET 1 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |
| RARE MET 2 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | 170.00 |
| KAI SCH 4 | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | -1.00 |
| KAIBIT PM3 | 150.00 | -1.00 | 70.00 | -1.00 | 0.00 | 170.00 |
| SHONTO PM2 | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | 170.00 |
| SHONTO PM2 | 20.00 | -1.00 | 71.00 | -1.00 | 0.00 | 160.00 |
| SHNT PM3 | 320.00 | -1.00 | -4.00 | -1.00 | 0.00 | 170.00 |
| SHONTO PM4 | -1.00 | -4.00 | -1.00 | -1.00 | 0.00 | 160.00 |
| USPHS ORAI | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | 460.00 |
| ORAIBI PM4 | -1.00 | 40.00 | 16.00 | 1.00 | -1.00 | 220.00 |
| ORAIBI PM4 | -1.00 | 50.00 | 11.00 | -1.00 | -1.00 | 230.00 |
| ORAIBI PM4 | -1.00 | 40.00 | 46.00 | 2.00 | -1.00 | 230.00 |
| ORAIBI PM4 | -1.00 | 50.00 | 70.00 | -1.00 | -1.00 | 240.00 |
| 2T-514 | -1.00 | -1.00 | 10.00 | -1.00 | 0.00 | 140.00 |
| BM 4 | -1.00 | -1.00 | 10.00 | -1.00 | 0.00 | 140.00 |
| ROCKY PM1 | -1.00 | -4.00 | 70.00 | -1.00 | -1.00 | 170.00 |
| ROCKY | -1.00 | 120.00 | 150.00 | -1.00 | -1.00 | 170.00 |
| ROCKY | -1.00 | 150.00 | 28.00 | 3.00 | -1.00 | -1.00 |
| ROCKY PM2 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | 250.00 |
| BETKN N M | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | 130.00 |
| HOPI A & C | -1.00 | -1.00 | -1.00 | -1.00 | -2.00 | 24.00 |
| BM OBS 5 | -1.00 | -1.00 | 150.00 | -1.00 | -1.00 | 240.00 |
| PEABODY 2 | -1.00 | 20.00 | 4.00 | -2.00 | -1.00 | 110.00 |
| PEABODY 2 | -1.00 | 30.00 | -2.00 | -2.00 | -1.00 | 150.00 |
| PEABODY 2 | -1.00 | -1.00 | 50.00 | 40.00 | -1.00 | 180.00 |
| PEABODY 2 | -1.00 | 30.00 | 250.00 | -1.00 | -1.00 | 140.00 |
| PEABODY 2 | -1.00 | 30.00 | -2.00 | -1.00 | -1.00 | 150.00 |
| PEABODY 2 | 3.00 | 30.00 | 60.00 | -1.00 | 1.00 | 140.00 |
| PEABODY 4 | -1.00 | 20.00 | 27.00 | 3.00 | -1.00 | 130.00 |
| PEABODY 4 | -1.00 | -2.00 | -2.00 | -2.00 | -1.00 | 150.00 |
| PEABODY 4 | -1.00 | 50.00 | -2.00 | -1.00 | -1.00 | 140.00 |

| Well Number | Boron mg/l | Arsenic mg/l | Iron mg/l | Manganese mg/l | Selenium mg/l | TDS mg/l |
|---|---|---|---|---|---|---|
| PEABODY 4 | -1.00 | 30.00 | 30.00 | -1.00 | -1.00 | 150.00 |
| PEABODY 4 | 3.00 | 30.00 | 30.00 | -1.00 | 1.00 | 140.00 |
| | -1.00 | 30.00 | 20.00 | -2.00 | -1.00 | 160.00 |
| BM 6 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |
| BM 6 | 3.00 | -2.00 | 220.00 | -1.00 | 1.00 | 190.00 |
| PEABODY 5 | -1.00 | 30.00 | 20.00 | -2.00 | -1.00 | 160.00 |
| PEABODY 5 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |
| PEABODY 5 | -1.00 | 50.00 | 10.00 | -2.00 | -1.00 | 260.00 |
| PEABODY 5 | -1.00 | -1.00 | 20.00 | -4.00 | -1.00 | 170.00 |
| PEABODY 5 | -1.00 | 40.00 | -2.00 | -2.00 | -1.00 | 140.00 |
| PEABODY 5 | -1.00 | 60.00 | -2.00 | -1.00 | -1.00 | 130.00 |
| PEABODY 5 | -1.00 | 40.00 | -2.00 | -2.00 | -1.00 | 150.00 |
| PEABODY 5 | -1.00 | 30.00 | 30.00 | -1.00 | -1.00 | 170.00 |
| PEABODY 3 | -1.00 | 20.00 | 14.00 | 1.00 | -1.00 | 130.00 |
| PEABODY 3 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |
| PEABODY 3 | -1.00 | -1.00 | 20.00 | -4.00 | -1.00 | 170.00 |
| PEABODY 3 | -1.00 | 60.00 | -2.00 | -2.00 | -1.00 | 180.00 |
| PEABODY 3 | -1.00 | 70.00 | -2.00 | -1.00 | -1.00 | 150.00 |
| PEABODY 3 | -1.00 | 50.00 | -2.00 | -2.00 | -1.00 | 160.00 |
| PEABODY 3 | -1.00 | 50.00 | -2.00 | -1.00 | -1.00 | 170.00 |
| PEABODY 3 | -1.00 | 50.00 | 30.00 | -1.00 | -1.00 | 150.00 |
| PEABODY 6 | -1.00 | 20.00 | 10.00 | -2.00 | -1.00 | 150.00 |
| PEABODY 6 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |
| PEABODY 6 | -1.00 | 300.00 | 70.00 | -2.00 | -1.00 | 200.00 |
| PEABODY 6 | -1.00 | 40.00 | -2.00 | -2.00 | -1.00 | 190.00 |
| PEABODY 6 | -1.00 | 70.00 | 80.00 | -1.00 | -1.00 | 150.00 |
| PEABODY 6 | -1.00 | 40.00 | 20.00 | 20.00 | -1.00 | 150.00 |
| KEAMS CYN3 | -1.00 | -1.00 | 280.00 | -4.00 | -1.00 | 1.00 |
| KEAMS CYN2 | -1.00 | -1.00 | ******* | 1200.00 | -1.00 | 5.00 |
| KEAMS CYN2 | -2.00 | -1.00 | 680.00 | 8.00 | -1.00 | 12.00 |
| KEAMS CYN2 | -2.00 | 0.00 | 730.00 | 37.00 | -1.00 | 12.00 |
| KEAMS CYN2 | -2.00 | -1.00 | 850.00 | -2.00 | -1.00 | 13.00 |
| KEAMS CYN2 | -1.00 | -1.00 | -1.00 | -1.00 | -2.00 | 12.00 |
| ST-500 | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | 370.00 |
| BM 3 | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | 370.00 |
| PINON PM 6 | -1.00 | -1.00 | 70.00 | -1.00 | -1.00 | 300.00 |
| PINON PM 6 | -1.00 | 60.00 | 6.00 | -1.00 | -1.00 | 280.00 |
| PINON PM 6 | -1.00 | 50.00 | 32.00 | 1.00 | -1.00 | 270.00 |
| PINON PM 6 | -1.00 | 100.00 | 5.00 | -2.00 | -1.00 | -1.00 |
| | -1.00 | 30.00 | 20.00 | -2.00 | -1.00 | 160.00 |
| ST-538 | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | 170.00 |
| L MTN PM2 | -1.00 | ******* | -1.00 | -1.00 | -1.00 | 830.00 |

| Well Number | Boron mg/l | Arsenic mg/l | Iron mg/l | Manganese mg/l | Selenium mg/l | TDS mg/l |
|---|---|---|---|---|---|---|
| CHLCHN PM3 | 180.00 | -1.00 | -4.00 | -1.00 | 0.00 | 190.00 |
| 8K-431 | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | -1.00 |
| 8T-537 | -1.00 | -1.00 | 80.00 | 0.00 | -1.00 | 360.00 |
| BM 1 | -1.00 | -1.00 | 80.00 | 0.00 | -1.00 | 360.00 |
| ROUGH PM3 | -1.00 | -1.00 | 70.00 | -1.00 | -1.00 | 11.00 |
| 10T-251 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |
| 10T-251 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |
| 8K-434 | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | 240.00 |
| 8K-403 | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | 210.00 |
| 8K-521 | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | -1.00 |
| 8T-519 | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | 350.00 |
| 9Y-92 | -4.00 | -1.00 | -4.00 | -1.00 | 0.00 | 980.00 |
| 10K-235 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | 17.00 |
| 10K-235 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | 17.00 |
| 10K-235 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | 17.00 |
| 9Y-12 | -1.00 | -1.00 | -1.00 | -1.00 | 0.00 | 0.00 |
| 763 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 370.00 |
| 901 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 160.00 |
| 902 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 200.00 |
| 903 | 0.20 | 0.01 | 0.03 | 0.01 | 0.00 | 120.00 |
| 904 | 0.20 | 0.01 | 0.03 | 0.01 | 0.02 | 370.00 |
| 910 | | | | 0.01 | | 158.00 |
| 911 | | | | | | 161.00 |
| 913 | | | | | | 142.00 |
| 914 | | | | | | 174.00 |
| 917 | | | | | | 182.00 |
| 920 | | | 0.05 | | | 163.00 |
| 921 | | | | | | 126.00 |
| 970 | 0.01 | | 0.03 | | | 210.00 |
| 971 | 0.10 | 0.01 | 0.03 | 0.01 | | 600.00 |
| 972 | 0.10 | | | | | 140.00 |

# APPENDIX II

# THESIS WELL AND ANALYTICAL DATA

| Well Number | Well Name | Other Identifier | BIA Quadrangle Number | UTM East | UTM North | Latitude |
|---|---|---|---|---|---|---|
| 1K-203 | 01-060-09.15X01.85 | 1K-203 | 01-060-09.15X01.85 | 462846 | 4036328 | 362824 |
| 1K-509 | none known | 1T-509 | none available | 509600 | 4067100 | 365307 |
| 1T-239 | unknown | Hopi no. | 01 076-09.74X02.71 | 506817 | 4007104 | 361238 |
| 1K-214 | 01 058-10.73X06.78 | 1K-214 | 01 058-10.73X06.78 | 505180 | 4028300 | 362406 |
| 1K-215 | 01-043-09.82X14.66 | 1K-215 | 01-043-09.82X14.66 | 461807 | 4043450 | 363215 |
| 1T-227 | 01-041-09.85X03.75 | 1T-227 | 01-041-09.85X03.75 | 506476 | 4060900 | 364144 |
| 1T-229 | 01-027-03.42X16.92 | 1T-229 | 01-027-03.42X16.92 | 494544 | 4067401 | 364515 |
| 1T-504 | 01 026-07.83X17.10 | 1T-504 | 01 026-07.83X17.10 | 509720 | 4067128 | 364506 |
| 2A-93 | 02-026-02.25x03.86 | Spring | 02 026-02.25X03.86 | 518400 | 4088375 | 365638 |
| 2K-319 | 02 041-05.32X16.02 | 2K-319 | 02 041-05.32X16.02 | 513778 | 4041158 | 363103 |
| 2K-322 | Hilltop Well | HILLTOP WL | 02 025-09.86X16.06 | 528758 | 4068896 | 364602 |
| 3M-156 | 03 076-06.53X11.01 | 3M-156 | 03 076-06.53X11.01 | 512003 | 3993799 | 360526 |
| 3M-156 | 03 076-06.53X11.01 | 3M-156 | 03 076-06.53X11.01 | 512003 | 3993799 | 360526 |
| 8T-510 | Long Valley Windmill | 8T-510 | 08 039-11.83X08.69 | 548060 | 4053114 | 363727 |
| 8T-518 | 08 037-08.51X15.87 | 8T-518 | 08 037-08.51X15.87 | 598191 | 4041983 | 363112 |
| 8T-522 | 08 039-08.31X05.09 | 2-X TSEGI | 08 039-08.31X05.09 | 553613 | 4058909 | 364034 |
| 9K-215 | 09 036-10.89X12.14 | 9K-215 | 09 036-10.89X12.14 | 616665 | 4048193 | 363426 |
| 9K-218 | 09 021-07.22X08.93 | 9K-218 | 09 021-07.22X08.93 | 622085 | 4081155 | 365213 |
| 9Y-92 | 09 037-01.81X14.35 | 9Y-92 | 09 037-01.81X14.35 | 609004 | 4044579 | 363232 |
| 10R-111 | 10 054-01.47X09.39 | 10R-111 | 10 054-01.47X09.39 | 609827 | 4024773 | 362149 |
| 10R-111 | 10 054-01.47X09.39 | 10R-111 | 10 054-01.47X09.39 | 609827 | 4024773 | 362149 |
| Polacca 6 | IHS Polacca 6 | PH 81-428 | none available | 553175 | 3963210 | 354840 |
| Hotevilla 2 | BIA Hotevilla PM2 | Hotevilla 2 | none available | 530150 | 3975750 | 355522 |
| SecondMsSch2 | BIA Second Mesa Schl PM2 | Secnd Mesa 2 | none available | 546150 | 3961325 | 354730 |
| PolaccaPD&C2 | Polacca Day School PM2 | Polacca PM2 | 094 7.75X11.70 | 555385 | 3965000 | 354747 |
| Hopi HS3 | Hopi High School PM3 | BIA Hopi HS3 | none available | 563000 | 3964000 | 354930 |
| Keams Cyn2 | Keams Canyon PDC2 | IHS#3,LowMt306 | 094-03.23X11.05 | 562541 | 3966193 | 355023 |
| 4T-521 | NTUA Kitsillie 1 | 4T-521 | none available | 583990 | 4022290 | 362130 |
| 4T-523 | NTUA Forest Lakes | 4T-523 | none available | 562300 | 4016450 | 361730 |
| 2T-516 | NTUA Shonto Junction 1 | IHS NA83-739 | none available | 527625 | 4034675 | 362730 |
| Navajo N MonA-38-17 | 17-1,Old Well | BETKN N M | 02 040-02.48X05.16 | 540681 | 4058776 | 364032 |
| BIA Tuba C 503 | 077-13.83X07.79 | TUBA C PM5 | 03 077-13.83X07.79 | 477706 | 3998935 | 360812 |
| BIA RedLake1 | BIA Red Lake PM1 | RED LK PM1 | 01 058-11.03X11.97 | 504585 | 4019810 | 361933 |
| BIA RedLake1 | BIA Red Lake PM1 | RED LK PM1 | 01 058-11.03X11.97 | 504585 | 4019810 | 361933 |
| BIA RedLake1 | BIA Red Lake PM1 | RED LK PM1 | 01 058-11.03X11.97 | 504585 | 4019810 | 361933 |
| BIA Denneho2 | BIA Dennehotso PM2 | Dennehotso 2 | none available | 601600 | 4076700 | 365000 |
| BIA Kaynta 2 | BIA Kayenta PM2 | Kayenta 2 | none available | 566315 | 4065000 | 364400 |
| BIA LowMtn 2 | BIA Low Mountain 2 (New) | L MTN PM2 | none available | 580150 | 3977800 | 355638 |
| BIA Chilchn3 | BIA Chilchinbeto PM3 | AZ0033002 | none available | 582280 | 4042515 | 363137 |
| BIA Dilkon 2 | BIA Dilkon 2 | Horseshoe Ms | 07 129-02.91X09.89 | 562420 | 3912610 | 352124 |
| BIA Dilkon 2 | BIA Dilkon 2 | Horseshoe Ms | 07 129-02.91X09.89 | 562420 | 3912610 | 352124 |
| BIA Cttnwd 3 | BIA Cottonwood PM3 | none | none available | 599620 | 3991800 | 360600 |
| BIA Shonto 2 | BIA Shonto PM2 | SHONTO PM2 | 02 040-08.73X10.37 | 530825 | 4049800 | 363558 |
| BIA Pinon 6 | 04 073-12.26X10.09 | PINON PM 6 | 04 073-12.26X10.09 | 570310 | 3995553 | 360614 |
| BIA Rocky 2 | 04 075-05.09X12.30 | ROCKY PM2 | 04 075-05.09X12.30 | 536845 | 3991774 | 360418 |
| BIA Kaibeto2 | none | Kaibeto PM2 | none available | 491710 | 4048475 | 363430 |
| IHS HardRk N | IHS Hard Rocks "N" | NA86-972 | none available | 545900 | 3994500 | 360500 |
| IHS HardRk D | IHS Hard Rocks 'D' | NA86-972 | none available | 545900 | 3994500 | 360500 |
| 6M-64 | none | none | none available | 562850 | 3970510 | 355300 |

| Well Number | Longitude | Sub-Basin | Approximate Location | Elevation | Aquifer Code Primary | Secondary | System |
|---|---|---|---|---|---|---|---|
| 1K-203 | 1112453 | KAIB | About 20 mi NNW of Tuba City | 5690.0 | 220NVJO | 220NVJO | N |
| 1K-509 | 1112123 | KAIB | Approx.7 mi.NW of Inscription House | 4620.0 | 220NVJO | | N |
| 1T-239 | 1105527 | BLMSA | West edge of Black Mesa,SE Tuba Cty | 5505.0 | 220NVJO | | N |
| 1K-214 | 1105632 | KAIB | About 6 mi N of Red Lake,E of rails | 5771.0 | 220NVJO | 220NVJO | N |
| 1K-215 | 1112536 | KAIB | About 5 mi S of Copper Mine | 5850.0 | 220NVJO | 220NVJO | N |
| 1T-227 | 1105539 | KAIB | About 5 mi N of Inscription House | 5920.0 | 220NVJO | 220NVJO | N |
| 1T-229 | 1110340 | KAIB | About 11 mi N of Kaibeto | 5640.0 | 220NVJO | 220NVJO | N |
| 1T-504 | 1105328 | KAIB | North of Kaibeto;W of Navajo Creek | 5740.0 | 220NVJO | | N |
| 2A-93 | 1104724 | KAIB | Apprx.5 mi.SE Navajo Mtn on main rd | 6040.0 | 231WNGT | 220NVJO | N |
| 2K-319 | 1105046 | KAIB | About 12 mi SSW of Inscrip.House TP | 6080.0 | 220NVJO | 220NVJO | N |
| 2K-322 | 1104040 | KAIB | About 7 mi N of Inscription HouseTP | 7180.0 | 220NVJO | | N |
| 3M-156 | 1105200 | BLMSA | About 4 mi S of Blue Canyon,NW Hotv | 5598.0 | 220NVJO | 220NVJO | N |
| 3M-156 | 1105200 | BLMSA | About 4 mi S of Blue Canyon,NW Hotv | 5598.0 | 220NVJO | 220NVJO | N |
| 8T-510 | 1102745 | BLMSA | NE end Long Valley,12 mi.SW Kayenta | 6260.0 | 220NVJO | | N |
| 8T-518 | 1095412 | BLMSA | About 10 mi.E of Chilchinbito | 5630.0 | 220NVJO | 220NVJO | N |
| 8T-522 | 1102400 | BLMSA | Aprx 11 mi WSW Kayenta at Laguna Cr | 6040.0 | 220NVJO | 231WNGT | N |
| 9K-215 | 1094146 | CHNLE | About 15 mi.NE of Rough Rock | 5485.0 | 231LKCK | 231LKCK | N |
| 9K-218 | 1093749 | CHNLE | About 10 mi.N of Rock Point off hwy | 5300.0 | 220NVJO | 231LKCK | N |
| 9Y-92 | 1094656 | BLMSA | About 14 mi.NE of Chilchinbito | 5620.0 | 220NVJO | 220NVJO | N |
| 10E-111 | 1094633 | BLMSA | About 5 mi.SE of Rough Rock | 5757.0 | 220NVJO | 220NVJO | N |
| 10R-111 | 1094633 | BLMSA | About 5 mi.SE of Rough Rock | 5757.0 | 220NVJO | 220NVJO | N |
| Polacca 6 | 1102430 | BLMSA | About 2 mi.SW of Polacca N of Hy264 | 5617.0 | 220NVJO | | N |
| Hotevilla 2 | 1104002 | BLMSA | Just S of Hotevilla School main bld | 6350.0 | 220NVJO | | N |
| SecondMsSch2 | 1103050 | BLMSA | Apprx.0.5 mi.NNE of school on hill | 5765.0 | 220NVJO | | N |
| PolaccaPD&C2 | 1103000 | BLMSA | At BIA Polacca School,S edge ground | 5765.0 | 220NVJO | | N |
| Hopi HS3 | 1101530 | BLMSA | N.of Hopi HS, 1.3 mi.S of Hwy 264 | 5820.0 | 220NVJO | ? | N |
| Keams Cyn2 | 1101827 | BLMSA | 7.1 mi.E Keams Cnyn at Low Mtn junc | 5809.0 | 220NVJO | | N |
| 4T-521 | 1100400 | BLMSA | Just E of Kitsillie School at HUD | 6784.0 | 220NVJO | | N |
| 4T-523 | 1101830 | BLMSA | Just SE of Forest Lakes HUD housing | 6655.0 | 220NVJO | | N |
| 2T-516 | 1104130 | BLMSA | About 1 mi.S of Hwy 160/Hwy 98 jnct | 6164.0 | 220NVJO | 221KYNT | N |
| Navajo N Mon | 1103241 | BLMSA | About 1/2 mi.SW of Park HQ | 7240.0 | 220NVJO | 221KYNT | N |
| BIA Tuba C 5 | 1111452 | TUBA | West edge of Tuba Cty at graveyard | 5030.0 | 220NVJO | 220NVJO | N |
| BIA RedLake1 | 1105650 | TUBA | Bldg 875,center BIA Red Lake campus | 5595.0 | 220NVJO | | N |
| BIA RedLake1 | 1105650 | TUBA | Bldg 875,center BIA Red Lake campus | 5595.0 | 220NVJO | | N |
| BIA RedLake1 | 1105650 | TUBA | Bldg 875,center BIA Red Lake campus | 5595.0 | 220NVJO | | N |
| BIA Denneho2 | 1095200 | CHNLE | BIA school campus, north edge | 5180.0 | | | N |
| BIA Kaynta 2 | 1101500 | BLMSA | BIA Kayenta school,N edge of campus | 5710.0 | 220NVJO | 231KYNT | N |
| BIA LowMtn 2 | 1100640 | HOPI | LowMtn school,across road,Bldg825 | 6135.0 | 220NVJO | | N |
| BIA Chilchn3 | 1100447 | BLMSA | SE Fac.Mgmnt at NE edge campus,pit | 5950.0 | 220NVJO | 231KYNT | N |
| BIA Dilkon 2 | 1101805 | HOPI | About 2 mi.E of BIA school | 6145.0 | 231LKCK | | N |
| BIA Dilkon 2 | 1101805 | HOPI | About 2 mi.E of BIA school | 6145.0 | 231LKCK | | N |
| BIA Cttnwd 3 | 1095430 | CHNLE | West edge of campus | 6085.0 | 220NVJO | 231LKCK | N |
| BIA Shonto 2 | 1103925 | BLMSA | Just S of main scl entry,Bldg 629 | 6470.0 | 220NVJO | | N |
| BIA Pinon 6 | 1101308 | BLMSA | North of campus in Pinon | 6397.0 | 220NVJO | 220NVJO | N |
| BIA Rocky 2 | 1103527 | BLMSA | North edge of campus at water tank | 5985.0 | 220NVJO | 220NVJO | N |
| BIA Kaibeto2 | 1110500 | KAIB | North edge of campus,Bldg 417 | 6290.0 | 220NVJO | | N |
| IHS HardRk N | 1103000 | BLMSA | N Hard Rocks 4.5 mi,ManyBobcatsHill | 6165.0 | 220NVJO | | N |
| IHS HardRk D | 1103000 | BLMSA | Approx.4.5 mi.N of Hard Rocks | 6165.0 | 221CSPG | | D |
| 6M-64 | 1101730 | HOPI | Approx.3 mi.N of Hwy 264 on Low Mtn | 5770.0 | 221DKOT | | D |

| Well Number | Water Level | SWL Elevation | SWL Measured Year | Month | Day | Owner/ Operator | Sampling Comments | Original Data Source |
|---|---|---|---|---|---|---|---|---|
| 1K-203 | 274.00 | 5416.0 | 1971 | 0 | 0 | Tribal O&M | Good sample;pumping | USGS |
| 1K-509 | 1009.00 | 3611.0 | 1961 | 4 | 26 | Tribal O&M | Tank sample | USGS |
| 1T-239 | 282.00 | 5223.0 | 1957 | 5 | 10 | Hopi RngeM | Tank Sample;no wind | USGS |
| 1K-214 | 188.00 | 5583.0 | 1953 | 6 | 4 | Navajo O&M | Confined;light winds | USGS TUCSON WRD 2/26/85 |
| 1K-215 | 460.60 | 5389.4 | 1953 | 1 | 12 | Navajo O&M | Bad sample;no winds | USGS |
| 1T-227 | 554.00 | 5366.0 | 1955 | 5 | 10 | Navajo O&M | Good sample from pip | USGS TUCSON WRD 2/26/85 |
| 1T-229 | 1113.00 | 4527.0 | 1955 | 5 | 13 | Navajo O&M | No wind;tank sample | USGS TUCSON WRD 2/26/85 |
| 1T-504 | 545.00 | 5195.0 | 1955 | 5 | 13 | Navajo O&M | Tank Sample;no winds | USGS |
| 2A-93 | 623.50 | 5416.5 | 1953 | 2 | 17 | Navajo O&M | Probably a spring | USGS |
| 2K-319 | 385.00 | 5696.0 | 1954 | 9 | 3 | Navajo O&M | Good sample;strong w | USGS TUCSON WRD 2/26/85 |
| 2K-322 | 640.00 | 6540.0 | 1956 | 6 | 5 | Navajo O&M | Tank sample;no winds | USGS |
| 3M-156 | 316.00 | 5282.0 | 1953 | 11 | 3 | Hopi Range | Good sample/winds | USGS TUCSON WRD 2/26/85 |
| 3M-156 | 316.00 | 5282.0 | 1953 | 11 | 3 | Hopi Range | Good sample/winds | USGS TUCSON WRD 2/26/85 |
| 8T-510 | 99.00 | 6161.0 | 0 | 0 | 0 | Navajo O&M | Good winds & sample | USGS |
| 8T-518 | 210.67 | 5419.3 | 1988 | 9 | 24 | Navajo O&M | Strong wind,good sam | USGS TUCSON WRD 2/26/85 |
| 8T-522 | 122.00 | 5918.0 | 1963 | 7 | 7 | Navajo O&M | Steady winds,gd samp | USGS |
| 9K-215 | 18.66 | 5466.3 | 1988 | 9 | 24 | Navajo O&M | Light,unsteady winds | USGS, Navajo O&M |
| 9K-218 | 0.00 | 5300.0 | 0 | 0 | 0 | Navajo O&M | Light winds;tank sam | USGS, TecNos Pos O&M |
| 9Y-92 | 167.85 | 5452.1 | 1988 | 9 | 22 | Navajo O&M | Pump-jack sample | USGS, ChInle O&M |
| 10R-111 | 199.45 | 5557.6 | 1988 | 10 | 8 | Navajo O&M | Unsteady winds | USGS TUCSON WRD 2/26/85 |
| 10R-111 | 199.45 | 5557.6 | 1988 | 10 | 8 | Navajo O&M | Unsteady winds | USGS TUCSON WRD 2/26/85 |
| Polacca 6 | 162.00 | 5455.0 | 1986 | 6 | 16 | IHS Keams | New well,good sample | IHS Keams Canyon |
| Hotevilla 2 | 951.00 | 5399.0 | 1988 | 7 | 0 | BIA Keams | Both PM1&2 are alike | BIA and IHS,Keams Canyon |
| SecondMsSch2 | 376.00 | 5389.0 | 1968 | 11 | 0 | IHS Keams | Good sampling point | BIA Keams Canyon |
| PolaccaPD&C2 | 376.00 | 5389.0 | 1968 | 10 | 10 | Polacca WC | Confused well ID | IHS Keams Canyon,wellsite |
| Hopi HS3 | 0.00 | 5820.0 | 0 | 0 | 0 | BIA Keams | Newer well | BIA Keams Canyon |
| Keams Cyn2 | 168.00 | 5641.0 | 1975 | 2 | 13 | BIA Keams | Good sampling point | IHS Keams Canyon |
| 4T-521 | 1254.00 | 5530.0 | 0 | 0 | 0 | NTUA Chinl | Little const.data | NTUA Chinle,Ft.Defiance |
| 4T-523 | 1096.00 | 5559.0 | 1982 | 5 | 2 | NTUA Kyent | Newer well,good samp | NTUA Kayenta, Ft.Defiance |
| 2T-516 | 273.00 | 5891.0 | 1985 | 10 | 21 | NTUA Kynta | Uncertain tribal ID | IHS Kayenta, Tuba City |
| Navajo N Mon | 543.25 | 6696.8 | 1988 | 7 | 25 | Nat'l Park | Great archival data | USGS, NPS Ft. Collins |
| BIA Tuba C 5 | 0.00 | 5030.0 | 0 | 0 | 0 | BIA Tuba C | Little const. data | USGS, BIA Tuba City |
| BIA RedLake1 | 136.50 | 5458.5 | 1984 | 6 | 24 | BIA Tuba C | Triplicate field sam | BIA Tuba City |
| BIA RedLake1 | 136.50 | 5458.5 | 1984 | 6 | 24 | BIA Tuba C | Triplicate field sam | BIA Tuba City |
| BIA RedLake1 | 117.00 | 5478.0 | 0 | 0 | 0 | BIA Tuba C | Sampled in triplicat | USGS |
| BIA Denneho2 | 16.00 | 5164.0 | 1982 | 0 | 0 | BIA Tuba C | Little const.data | BIA Tuba City |
| BIA Kaynta 2 | 48.00 | 5662.0 | 0 | 0 | 0 | BIA Tuba C | Little const.data | BIA Tuba City |
| BIA LowWtn 2 | 551.00 | 5584.0 | 1986 | 12 | 29 | BIA Chinle | Little constr.data | BIA Chinle Agency |
| BIA Chilchn3 | 603.00 | 5347.0 | 1988 | 0 | 0 | BIA Tuba C | Good data for 8T-540 | BIA Tuba City |
| BIA Dilkon 2 | 138.70 | 6006.3 | 1972 | 1 | 24 | BIA Ft.Def | Uncertain aquifer ID | BIA Ft.Defiance |
| BIA Dilkon 2 | 138.70 | 6006.3 | 1972 | 1 | 24 | BIA Ft.Def | Uncertain aquifer ID | BIA Ft.Defiance |
| BIA Cttnwd 3 | 980.00 | 5105.0 | 0 | 0 | 0 | BIA Chinle | Bad const.data;aq ID | BIA Chinle Agency FM |
| BIA Shonto 2 | 243.00 | 6227.0 | 1975 | 9 | 9 | BIA Tuba C | Uncertain const.data | BIA Tuba City |
| BIA Pinon 6 | 783.25 | 5613.8 | 1988 | 9 | 9 | BIA Tuba C | USGS sampling point | USGS,BIA Tuba City Agency |
| BIA Rocky 2 | 458.00 | 5527.0 | 1980 | 1 | 30 | BIA Tuba C | Good records | USGS;BIA Tuba City Agency |
| BIA Kaibeto2 | 853.00 | 5437.0 | 0 | 0 | 0 | BIA Tuba C | Few constr.details | BIA Tuba City FM |
| IHS HardRk N | 0.00 | 6165.0 | 1989 | 4 | 8 | IHS Tuba C | Few constr.details | IHS Tuba City OEH |
| IHS HardRk D | 780.00 | 5385.0 | 1988 | 10 | 18 | IHS Tuba C | Few constr.details | IHS Tuba City |
| 6N-64 | 0.00 | 5770.0 | 1988 | 0 | 0 | Hopi Tribe | Artesian well, | Hopi Tribe |

| Well Number | Well Use | Well Construction Start | Well Construction End | Depth | Open Interval Top | Open Interval Bottom | Hole Diameter | Casing Diameter | Upper Casing From | Upper Casing To | Material |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1K-203 | Stock | | June1941 | 356.0 | 298.00 | 356.00 | 0.00 | 6.62 | 0.0 | 0.0 | |
| 1K-509 | Stock | | 4-22-61 | 1540.0 | 1480.00 | 1540.00 | 0.00 | 9.62 | 0.0 | 1540.0 | steel |
| 1T-239 | Stock | | 5-10-57 | 408.0 | 40.00 | 408.00 | 10.00 | 10.00 | 0.0 | 408.0 | steel |
| 1K-214 | Stock | 1950052619500526 | | 356.0 | 168.00 | 356.00 | 0.00 | 8.00 | 0.0 | 168.0 | steel |
| 1K-215 | Stock | | August51 | 585.0 | 0.00 | 585.00 | 0.00 | 8.00 | 0.0 | 585.0 | open |
| 1T-227 | Stock | 1955051019550510 | | 851.0 | 22.00 | 851.00 | 0.00 | 8.62 | 1.0 | 22.0 | STL |
| 1T-229 | Stock | 1955051319550513 | | 1248.0 | 94.00 | 1250.00 | 0.00 | 8.62 | 0.0 | 94.0 | steel |
| 1T-504 | Stock | | 5-13-55 | 688.0 | 60.00 | 688.00 | 0.00 | 12.00 | 0.0 | 688.0 | open? |
| 2A-93 | Stock | | 7-26-35 | 733.0 | 0.00 | 0.00 | 0.00 | 6.62 | 0.0 | 733.0 | |
| 2K-319 | Stock | 1954090319540903 | | 626.0 | 28.00 | 626.00 | 0.00 | 8.00 | 0.0 | 28.0 | STL |
| 2K-322 | Stock | | 6-5-1956 | 742.0 | 18.00 | 742.00 | 0.00 | 8.00 | 0.0 | 742.0 | open |
| 3M-156 | Stock | 1935022319350223 | | 529.0 | 360.00 | 529.00 | 0.00 | 8.00 | 0.0 | 529.0 | STL |
| 3M-156 | Stock | 1935022319350223 | | 529.0 | 360.00 | 529.00 | 0.00 | 8.00 | 0.0 | 529.0 | STL |
| 8T-510 | Stock | | | 314.0 | 0.00 | 0.00 | 12.00 | 12.00 | 0.0 | 0.0 | open |
| 8T-518 | Stock | 1964122619641226 | | 1160.0 | 813.00 | 1160.00 | 8.38 | 6.62 | 0.0 | 813.0 | STL |
| 8T-522 | Stock | | | 933.0 | 180.00 | 933.00 | 0.00 | 6.75 | 0.0 | 180.0 | steel |
| 9K-215 | Stock | | 9-18-52 | 641.0 | 500.00 | 641.00 | 0.00 | 6.62 | 0.0 | 567.0 | steel |
| 9K-218 | Stock | | 6-23-53 | 517.0 | 0.00 | 517.00 | 8.00 | 8.00 | 0.0 | 517.0 | |
| 9Y-92 | Stock | | | 300.0 | 154.00 | 300.00 | 6.62 | 6.62 | 0.0 | 300.0 | steel |
| 10R-111 | Stock | 1935041119350411 | | 360.0 | 267.00 | 360.00 | 6.62 | 6.62 | 0.0 | 267.0 | STL |
| 10R-111 | Stock | 1935041119350411 | | 360.0 | 267.00 | 360.00 | 6.62 | 6.62 | 0.0 | 267.0 | STL |
| Polacca 6 | PWS | 1985 | 04141986 | 915.0 | 760.00 | 900.00 | 0.00 | 18.00 | 0.0 | 22.0 | stl |
| Hotevilla 2 | PWS | | | 1800.0 | 1050.00 | 1500.00 | 0.00 | 8.00 | 0.0 | 1450.0 | steel |
| SecondMsSch2 | PWS | | | 1090.0 | 740.00 | 1090.00 | 0.00 | 8.00 | 0.0 | 922.0 | steel |
| PolaccaPD&C2 | PWS | | | 1090.0 | 740.00 | 1090.00 | 0.00 | 8.00 | 0.0 | 922.0 | steel |
| Hopi HS3 | PWS | | | 0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.0 | 0.0 | |
| Keams Cyn2 | PWS | | May 1970 | 1106.0 | 906.00 | 1106.00 | 0.00 | 8.00 | 0.0 | 906.0 | steel |
| 4T-521 | PWS | | | 2540.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.0 | 0.0 | |
| 4T-523 | PWS | | | 2674.0 | 1108.00 | 2674.00 | 8.00 | 8.00 | 0.0 | 2674.0 | steel |
| 2T-516 | PWS | 01041984 | | 1197.0 | 472.00 | 592.00 | 0.00 | 8.62 | 0.0 | 614.0 | steel |
| Navajo N MonPWS | | | 1962 | 780.0 | 10.00 | 753.00 | 8.00 | 8.00 | 0.0 | 10.0 | steel |
| BIA Tuba C 5PWS | | | 1952 | 300.0 | 220.00 | 300.00 | 8.00 | 8.00 | 0.0 | 220.0 | steel |
| BIA RedLake1PWS | | | | 545.0 | 150.00 | 0.00 | 0.00 | 8.00 | 0.0 | 545.0 | steel |
| BIA RedLake1PWS | | | | 545.0 | 150.00 | 0.00 | 0.00 | 8.00 | 0.0 | 545.0 | steel |
| BIA RedLake1PWS | | | | 545.0 | 150.00 | 0.00 | 0.00 | 8.00 | 0.0 | 545.0 | steel |
| BIA Denneho2PWS | | 1934 | | 675.0 | 0.00 | 0.00 | 0.00 | 8.00 | 0.0 | 675.0 | steel |
| BIA Kaynta 2PWS | | 1934 | 1934 | 840.0 | 268.00 | 816.00 | 0.00 | 10.00 | 0.0 | 840.0 | steel |
| BIA LowMtn 2PWS | | | 1986 | 1340.0 | 1180.00 | 1260.00 | 8.00 | 8.00 | 0.0 | 1150.0 | steel |
| BIA Chilchn3PWS | | | 1965? | 1593.0 | 1142.00 | 1572.00 | 0.00 | 8.00 | 0.0 | 1140.0 | steel |
| BIA Dilkon 2PWS | | | 9-1964 | 202.0 | 125.00 | 202.00 | 8.00 | 8.00 | 0.0 | 202.0 | steel |
| BIA Dilkon 2PWS | | | 9-1964 | 202.0 | 125.00 | 202.00 | 8.00 | 8.00 | 0.0 | 202.0 | steel |
| BIA Cttnwd 3PWS | | | unknown | 1202.0 | 0.00 | 0.00 | 0.00 | 8.00 | 0.0 | 0.0 | steel |
| BIA Shonto 2PWS | | 4-1961 | 1961 | 554.0 | 485.00 | 554.00 | 0.00 | 8.00 | 0.0 | 554.0 | steel |
| BIA Pinon 6 PWS | | | 2-1970 | 2248.0 | 1900.00 | 2240.00 | 0.00 | 0.00 | 0.0 | 0.0 | |
| BIA Rocky 2 PWS | | | 6-26-63 | 1780.0 | 1480.00 | 1780.00 | 0.00 | 8.62 | 0.0 | 1450.0 | steel |
| BIA Kaibeto2PWS | | | | 1204.0 | 0.00 | 0.00 | 10.00 | 10.00 | 0.0 | 1204.0 | steel |
| IHS HardRk HPWS | | 1988 | 1989 | 2677.0 | 0.00 | 0.00 | 10.00 | 0.00 | 0.0 | 0.0 | |
| IHS HardRk DPWS | | 1988 | 1989 | 0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.0 | 0.0 | |
| 6M-64 | Stock | 1930 | 1930 | 0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.0 | 0.0 | |

| Well Number | Perforations From | Perforations To | Casing Diameter | Lower Casing From | Lower Casing To | Material | Perforations From | Perforations To | Casing Diameter | Lowest Casing From | Lowest Casing To | Perforat From |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1K-203 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 1K-509 | 1480.0 | 1540.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 1T-239 | 0.0 | 408.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 1K-214 | 168.0 | 356.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 1K-215 | 0.0 | 585.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 1T-227 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 1T-229 | 94.0 | 1248.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 1T-504 | 0.0 | 0.0 | 8.00 | 0.0 | 0.0 | open? | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 2A-93 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 2K-319 | 28.0 | 626.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 2K-322 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 3M-156 | 360.0 | 529.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 3M-156 | 360.0 | 529.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 8T-510 | 0.0 | 0.0 | 7.62 | 0.0 | 0.0 | open | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 8T-518 | 81.0 | 3.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 8T-522 | 180.0 | 933.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 9K-215 | 567.0 | 641.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 9K-218 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 9Y-92 | 154.0 | 300.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 10R-111 | 267.0 | 360.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 10R-111 | 267.0 | 360.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| Polacca 6 | 0.0 | 0.0 | 10.00 | 0.0 | 647.0 | steel | 0.0 | 0.0 | 8.00 | 635.0 | 915.0 | 775.0 |
| Hotevilla 2 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| SecondMsSch2 | 740.0 | 860.0 | 6.00 | 922.0 | 1090.0 | steel | 922.0 | 1090.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| PolaccaPD&C2 | 740.0 | 860.0 | 6.00 | 922.0 | 1090.0 | steel | 922.0 | 1090.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| Hopi HS3 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| Keams Cyn2 | 906.0 | 1106.0 | 6.00 | 895.0 | 1106.0 | steel | 906.0 | 1106.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 4T-521 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 4T-523 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 2T-516 | 472.0 | 592.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| Navajo N Mon | 0.0 | 0.0 | 6.00 | 10.0 | 780.0 | steel | 660.0 | 780.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA Tuba C 5 | 220.0 | 300.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA RedLake1 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA RedLake1 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA RedLake1 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA Denneho2 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA Kaynta 2 | 268.0 | 280.0 | 0.00 | 0.0 | 0.0 | | 691.0 | 816.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA LowMtn 2 | 0.0 | 0.0 | 6.00 | 1150.0 | 1340.0 | steel | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA Chilchn3 | 0.0 | 0.0 | 6.62 | 1120.0 | 1594.0 | steel | 1142.0 | 1572.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA Dilkon 2 | 125.0 | 202.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA Dilkon 2 | 125.0 | 202.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA Cttnwd 3 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA Shonto 2 | 485.0 | 554.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA Pinon 6 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA Rocky 2 | 0.0 | 0.0 | 6.62 | 1440.0 | 1780.0 | steel | 1480.0 | 1780.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| BIA Kaibeto2 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| IHS HardRk N | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| IHS HardRk D | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| 6M-64 | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |

| Well Number | ions To | Sample Date | Hach Kit | WATEQ Eh | Specific Conductance (mS/cm) | pH | Temperature (Celsius) | Alkalinity (mg/l) | Dissolved Oxygen (mg/l) |
|---|---|---|---|---|---|---|---|---|---|
| 1K-203 | 0.0 | February 3,1989 | 1 | 0.772 | 0.018 | 7.98 | 13.9 | 93.000 | 7.700 |
| 1K-509 | 0.0 | 3 February 1989 | 1 | 0.753 | 0.230 | 8.48 | 10.7 | 108.000 | 9.800 |
| 1T-239 | 0.0 | 4 February 1989 | 1 | 0.761 | 0.610 | 8.12 | 15.4 | 102.000 | 8.700 |
| 1K-214 | 0.0 | Sept. 9, 1988 | 1 | 0.000 | 0.250 | 8.02 | 15.6 | 135.000 | 6.600 |
| 1K-215 | 0.0 | 18 Decembr 1988 | 2 | 0.801 | 0.252 | 0.00 | 2.8 | 87.000 | 12.000 |
| 1T-227 | 0.0 | 30 Novembr 1988 | 1 | 0.771 | 0.210 | 8.05 | 13.1 | 103.000 | 8.400 |
| 1T-229 | 0.0 | 30 Novembr 1988 | 1 | 0.765 | 0.240 | 8.28 | 10.3 | 129.000 | 8.600 |
| 1T-504 | 0.0 | 30 Novembr 1988 | 1 | 0.767 | 0.240 | 8.21 | 10.8 | 110.000 | 8.600 |
| 2A-93 | 0.0 | 3 December 1988 | 1 | 0.783 | 0.390 | 8.22 | 4.8 | 239.000 | 10.800 |
| 2K-319 | 0.0 | 20 Sept. 1988 | 1 | 0.769 | 0.228 | 7.97 | 15.4 | 127.000 | 7.200 |
| 2K-322 | 0.0 | 3 December 1988 | 1 | 0.755 | 0.220 | 8.42 | 11.2 | 125.000 | 9.800 |
| 3M-156 | 0.0 | 8 November 1988 | 1 | 0.669 | 0.905 | 9.61 | 16.5 | 264.000 | 4.400 |
| 3M-156 | 0.0 | 23 November 1988 | 1 | 0.669 | 0.905 | 9.61 | 16.5 | 264.000 | 4.400 |
| 8T-510 | 0.0 | Sept.25, 1988 | 1 | 0.000 | 0.370 | 7.65 | 12.5 | 180.000 | 6.500 |
| 8T-518 | 0.0 | | 1 | 0.674 | 0.616 | 9.47 | 16.4 | 350.000 | 2.500 |
| 8T-522 | 0.0 | Sept. 21,1988 | 2 | 0.000 | 0.770 | 7.37 | 13.2 | 370.000 | 2.800 |
| 9K-215 | 0.0 | Sept.24,1988 | 1 | 0.000 | 2.070 | 8.51 | 15.3 | 250.000 | 4.300 |
| 9K-218 | 0.0 | Novembr 29,1988 | 1 | 0.758 | 0.420 | 8.32 | 12.1 | 95.000 | 9.000 |
| 9Y-92 | 0.0 | Sept.22,1988 | 1 | 0.000 | 1.040 | 8.11 | 14.6 | 110.000 | 13.800 |
| 10R-111 | 0.0 | October 13,1988 | 2 | 0.740 | 5.140 | 8.46 | 16.3 | 82.000 | 9.500 |
| 10R-111 | 0.0 | October 13,1988 | 2 | 0.740 | 5.140 | 8.46 | 16.3 | 82.000 | 9.500 |
| Polacca 6 | 915.0 | Sept.5, 1988 | 2 | 0.710 | 2.830 | 8.56 | 19.3 | 218.000 | 0.600 |
| Hotevilla 2 | 0.0 | | 2 | 0.633 | 0.304 | 9.81 | 26.0 | 177.000 | 5.600 |
| SecondMsSch2 | 0.0 | Septembr 2,1988 | 1 | 0.641 | 0.549 | 9.73 | 20.0 | 370.000 | 0.700 |
| PolaccaPD&C2 | 0.0 | Septembr 5,1988 | 2 | 0.648 | 0.743 | 9.61 | 21.8 | 410.000 | 1.600 |
| Hopi HS3 | 0.0 | Septembr 6,1988 | 1 | 0.682 | 1.550 | 8.81 | 20.2 | 412.000 | 0.100 |
| Keams Cyn2 | 0.0 | Septembr 2,1988 | 2 | 0.660 | 1.043 | 9.27 | 19.8 | 450.000 | 0.200 |
| 4T-521 | 0.0 | Novembr 17,1988 | 2 | 0.625 | 0.450 | 9.81 | 28.7 | 240.000 | 5.300 |
| 4T-523 | 0.0 | Novembr 17,1988 | 1 | 0.636 | 0.389 | 9.63 | 28.9 | 152.000 | 5.700 |
| 2T-516 | 0.0 | December 1,1988 | 1 | 0.779 | 0.390 | 7.65 | 17.7 | 185.000 | 4.700 |
| Navajo N Mon | 0.0 | Decembr 31,1988 | 1 | 0.767 | 0.220 | 8.10 | 13.4 | 128.000 | 8.000 |
| BIA Tuba C 5 | 0.0 | Sept. 26, 1988 | 2 | 0.765 | 0.208 | 7.99 | 16.6 | 95.000 | 6.800 |
| BIA RedLake1 | 0.0 | September 26, 1988 | 1 | 0.744 | 0.149 | 8.36 | 16.8 | 90.000 | 7.700 |
| BIA RedLake1 | 0.0 | September 26, 1988 | 1 | 0.744 | 0.149 | 8.36 | 16.8 | 90.000 | 7.700 |
| BIA RedLake1 | 0.0 | September 26, 1988 | 1 | 0.744 | 0.149 | 8.36 | 16.8 | 90.000 | 7.700 |
| BIA Denneho2 | 0.0 | Novembr 29,1988 | 1 | 0.702 | 0.358 | 9.16 | 16.1 | 143.000 | 11.800 |
| BIA Kaynta 2 | 0.0 | Sept. 23, 1988 | 2 | 0.000 | 0.381 | 8.17 | 16.2 | 123.000 | 7.800 |
| BIA LowMtn 2 | 0.0 | November 16, 1988 | 2 | 0.665 | 1.540 | 9.16 | 20.3 | 430.000 | 0.200 |
| BIA Chilchn3 | 0.0 | September 22, 1988 | 2 | 0.660 | 0.388 | 9.66 | 20.2 | 235.000 | 8.100 |
| BIA Dilkon 2 | 0.0 | November 18, 1988 | 1 | 0.764 | 0.985 | 8.06 | 15.3 | 113.000 | 7.700 |
| BIA Dilkon 2 | 0.0 | November 18, 1988 | 1 | 0.764 | 0.985 | 8.06 | 15.3 | 113.000 | 7.700 |
| BIA Cttnwd 3 | 0.0 | October 14,1988 | 1 | 0.701 | 0.490 | 8.44 | 30.0 | 445.000 | 3.200 |
| BIA Shonto 2 | 0.0 | Sept. 20, 1988 | 2 | 0.785 | 0.291 | 7.78 | 13.8 | 140.000 | 8.600 |
| BIA Pinon 6 | 0.0 | Novmber 16,1988 | 1 | 0.619 | 0.468 | 10.00 | 27.0 | 266.000 | 5.300 |
| BIA Rocky 2 | 0.0 | Septembr 7,1988 | 1 | 0.644 | 0.224 | 9.55 | 27.4 | 142.000 | 4.900 |
| BIA Kaibeto2 | 0.0 | November 30, 1988 | 1 | 0.746 | 0.177 | 8.20 | 19.4 | 83.000 | 7.400 |
| IHS HardRk N | 0.0 | April 8, 1989 | 1 | 0.627 | 0.251 | 9.64 | 32.5 | 172.000 | 0.000 |
| IHS HardRk D | 0.0 | October 18,1988 | 2 | 0.707 | 2.470 | 8.30 | 27.4 | 542.300 | 0.800 |
| 6M-64 | 0.0 | | 1 | 0.705 | 1.168 | 8.65 | 16.6 | 540.000 | 0.200 |

| Well Number | Field Chloride (mg/l) | Field Sulfate (mg/l) | Field Nitrate (mg/l) | Field Nitrite (mg/l) | Ferrous Iron (mg/l) | Total Iron (mg/l) | Field Silica (mg/l) | Field Fluoride (mg/l) | Field Sulfide (mg/l) |
|---|---|---|---|---|---|---|---|---|---|
| 1K-203 | 6.900 | 12.000 | 68.377 | 0.072 | 0.010 | 1.060 | 3.200 | 0.110 | 0.000 |
| 1K-509 | 5.800 | 12.000 | 11.050 | 0.016 | 0.000 | 0.040 | 3.300 | 0.140 | 0.000 |
| 1T-239 | 2.100 | 210.000 | 10.166 | 0.007 | 0.000 | 0.120 | 6.000 | 0.400 | 0.000 |
| 1K-214 | 3.200 | 12.000 | 12.818 | 0.013 | 0.000 | 0.250 | 5.900 | 0.300 | 0.000 |
| 1K-215 | 8.600 | 13.000 | 19.448 | 0.079 | 0.000 | 0.060 | 2.000 | 0.180 | 0.000 |
| 1T-227 | 5.000 | 8.000 | 5.304 | 0.000 | 0.010 | 1.780 | 4.100 | 0.110 | 0.000 |
| 1T-229 | 2.600 | 2.000 | 7.956 | 0.013 | 0.000 | 0.070 | 4.700 | 0.340 | 0.000 |
| 1T-504 | 12.100 | 11.000 | 11.050 | 0.016 | 0.010 | 0.070 | 4.900 | 0.210 | 0.000 |
| 2A-93 | 2.700 | 3.000 | 5.304 | 0.174 | 0.000 | 0.020 | 7.000 | 0.320 | 0.000 |
| 2K-319 | 3.900 | 7.000 | 11.050 | 0.102 | 0.020 | 0.710 | 12.300 | 0.000 | 0.000 |
| 2K-322 | 2.400 | 1.000 | 6.188 | 0.013 | 0.010 | 0.040 | 4.000 | 0.210 | 0.000 |
| 3M-156 | 52.000 | 100.000 | 1.326 | 0.007 | 0.000 | 0.620 | 7.700 | 2.330 | 0.004 |
| 3M-156 | 52.000 | 100.000 | 0.300 | 0.002 | 0.000 | 0.620 | 7.700 | 2.330 | 0.004 |
| 8T-510 | 1.200 | 3.500 | 26.962 | 0.092 | 0.000 | 0.090 | 9.000 | 0.390 | 0.000 |
| 8T-518 | 14.500 | 18.000 | 5.746 | 0.059 | 0.000 | 0.200 | 2.500 | 0.820 | 0.000 |
| 8T-522 | 7.700 | 90.000 | 6.188 | 0.098 | 0.120 | 0.870 | 9.100 | 0.220 | 0.000 |
| 9K-215 | 16.200 | 280.000 | 47.736 | 0.023 | 0.000 | 0.800 | 4.200 | 1.590 | 0.000 |
| 9K-218 | 6.300 | 22.000 | 7.956 | 0.016 | 0.001 | 0.200 | 7.000 | 0.230 | 0.000 |
| 9Y-92 | 4.500 | 510.000 | 18.122 | 0.131 | 0.050 | 0.290 | 8.400 | 1.220 | 0.000 |
| 10R-111 | 5.900 | 140.000 | 0.000 | 0.000 | 0.030 | 0.040 | 4.100 | 1.380 | 0.000 |
| 10R-111 | 5.900 | 140.000 | 0.000 | 0.000 | 0.030 | 0.040 | 4.100 | 1.380 | 0.000 |
| Polacca 6 | 1332.500 | 350.000 | 1.326 | 0.134 | 0.090 | 0.180 | 6.600 | 1.860 | 0.000 |
| Hotevilla 2 | 0.900 | 2.000 | 7.072 | 0.118 | 0.000 | 0.050 | 18.800 | 0.000 | 0.000 |
| SecondMsSch2 | 5.200 | 19.000 | 5.746 | 0.272 | 0.000 | 0.320 | 12.200 | 0.470 | 0.000 |
| PolaccaPD&C2 | 21.000 | 31.000 | 2.652 | 0.121 | 0.000 | 0.030 | 9.200 | 0.530 | 0.000 |
| Hopi HS3 | 214.000 | 90.000 | 2.652 | 0.010 | 0.000 | 0.130 | 4.000 | 2.170 | 0.003 |
| Keams Cyn2 | 74.000 | 41.000 | 2.210 | 0.020 | 0.000 | 0.050 | 5.900 | 1.330 | 0.000 |
| 4T-521 | 3.300 | 0.000 | 7.514 | 0.010 | 0.000 | 0.020 | 18.900 | 0.150 | 0.000 |
| 4T-523 | 0.000 | 40.000 | 4.420 | 0.010 | 0.000 | 0.050 | 7.100 | 0.330 | 0.000 |
| 2T-516 | 0.000 | 40.000 | 7.956 | 0.013 | 0.000 | 0.030 | 3.700 | 0.240 | 0.000 |
| Navajo N Mon | 2.200 | 0.000 | 5.304 | 0.007 | 0.000 | 0.010 | 4.400 | 0.140 | 0.000 |
| BIA Tuba C 5 | 2.700 | 10.000 | 12.376 | 0.285 | 0.000 | 0.080 | 11.800 | 0.080 | 0.000 |
| BIA RedLake1 | 1.000 | 1.000 | 8.840 | 0.016 | 0.000 | 0.060 | 3.500 | 0.550 | 0.000 |
| BIA RedLake1 | 1.000 | 1.000 | 8.840 | 0.016 | 0.000 | 0.060 | 3.500 | 0.550 | 0.000 |
| BIA RedLake1 | 1.000 | 1.000 | 8.840 | 0.016 | 0.000 | 0.060 | 3.500 | 0.550 | 0.000 |
| BIA Denneho2 | 0.100 | 15.000 | 10.608 | 0.016 | 0.000 | 0.030 | 3.800 | 0.070 | 0.000 |
| BIA Kaynta 2 | 3.200 | 84.000 | 6.188 | 0.020 | 0.000 | 0.130 | 13.700 | 0.320 | 0.000 |
| BIA LowMtn 2 | 180.000 | 80.000 | 2.652 | 0.010 | 0.000 | 0.040 | 8.900 | 2.360 | 0.007 |
| BIA Chilchn3 | 1.200 | 2.000 | 10.166 | 0.259 | 0.000 | 0.140 | 18.100 | 0.510 | 0.000 |
| BIA Dilkon 2 | 42.000 | 230.000 | 10.166 | 0.010 | 0.001 | 0.010 | 6.000 | 0.190 | 0.000 |
| BIA Dilkon 2 | 42.000 | 230.000 | 10.166 | 0.010 | 0.001 | 0.010 | 6.000 | 0.190 | 0.000 |
| BIA Cttnwd 3 | 15.900 | 5.300 | 7.514 | 0.010 | 0.000 | 0.060 | 5.300 | 0.370 | 0.000 |
| BIA Shonto 2 | 6.500 | 25.000 | 22.984 | 0.256 | 0.000 | 0.190 | 15.200 | 0.000 | 0.000 |
| BIA Pinon 6 | 3.700 | 0.000 | 9.724 | 0.016 | 0.000 | 0.020 | 11.400 | 0.220 | 0.000 |
| BIA Rocky 2 | 0.200 | 8.000 | 7.956 | 0.016 | 0.000 | 0.020 | 13.600 | 0.460 | 0.000 |
| BIA Kaibeto2 | 2.500 | 9.000 | 16.796 | 0.095 | 0.000 | 0.010 | 6.200 | 0.280 | 0.000 |
| IHS HardRk N | 6.800 | 0.000 | 0.000 | 0.049 | 0.000 | 0.420 | 11.000 | 0.230 | 0.000 |
| IHS HardRk D | 221.000 | 200.000 | 3.094 | 1.476 | 0.020 | 0.450 | 11.400 | 2.510 | 0.000 |
| 6M-64 | 9.300 | 420.000 | 2.210 | 0.112 | 0.010 | 0.090 | 4.200 | 244.000 | 0.002 |

| Well Number | Field TDS (mg/l) | WATEQ TDS (mg/l) | Analysis Number | Calcium (mg/l) | Magnesium (mg/l) | Sodium (mg/l) | Potassium (mg/l) | Sulfate (mg/l) | Chloride (mg/l) | Fluoride (mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1K-203 | 90.000 | 164.200 | 1 | 24.400 | 7.000 | 3.700 | 1.100 | 9.678 | 8.029 | 0.000 |
| 1K-509 | 120.000 | 176.800 | 1 | 17.000 | 8.100 | 12.100 | 1.600 | 10.989 | 6.416 | 0.000 |
| 1T-239 | 310.000 | 391.300 | 1 | 41.300 | 11.100 | 49.200 | 1.600 | 169.834 | 3.077 | 0.000 |
| 1K-214 | 124.900 | 0.000 | 1 | 11.300 | 3.200 | 3.500 | 0.900 | 11.165 | 3.810 | 0.000 |
| 1K-215 | 126.000 | 155.100 | 1 | 27.500 | 3.400 | 4.100 | 1.110 | 10.700 | 7.500 | 0.000 |
| 1T-227 | 100.000 | 159.600 | 1 | 27.500 | 3.400 | 4.100 | 1.190 | 6.150 | 3.850 | 0.000 |
| 1T-229 | 120.000 | 185.500 | 1 | 18.600 | 9.800 | 8.500 | 1.410 | 6.250 | 2.050 | 0.000 |
| 1T-504 | 120.000 | 175.600 | 1 | 19.600 | 12.100 | 2.500 | 1.720 | 10.450 | 6.200 | 0.000 |
| 2A-93 | 200.000 | 320.300 | 1 | 46.300 | 12.400 | 4.700 | 1.140 | 5.500 | 3.300 | 0.000 |
| 2K-319 | 0.000 | 199.300 | 1 | 29.200 | 4.000 | 4.700 | 1.670 | 5.940 | 4.440 | 0.000 |
| 2K-322 | 110.000 | 178.600 | 1 | 30.200 | 2.800 | 4.600 | 1.340 | 3.300 | 2.950 | 0.000 |
| 3M-156 | 0.000 | 507.900 | 1 | 0.700 | 0.100 | 132.000 | 0.500 | 70.400 | 29.500 | 0.000 |
| 3M-156 | 0.000 | 508.100 | 2 | 0.800 | 0.100 | 132.000 | 0.460 | 71.300 | 28.750 | 2.330 |
| 8T-510 | 186.300 | 0.000 | 1 | 9.000 | 0.900 | 1.000 | 0.110 | 29.755 | 1.005 | 0.000 |
| 8T-518 | 0.000 | 535.800 | 1 | 1.300 | 0.200 | 131.000 | 0.560 | 19.420 | 25.520 | 0.305 |
| 8T-522 | 0.000 | 0.000 | 1 | 4.100 | 1.300 | 2.800 | 0.140 | 102.485 | 13.195 | 0.000 |
| 9K-215 | 0.000 | 0.000 | 1 | 11.400 | 5.100 | 89.000 | 0.890 | 376.975 | 229.410 | 0.810 |
| 9K-218 | 210.000 | 174.700 | 1 | 20.500 | 5.900 | 12.400 | 1.100 | 20.050 | 7.500 | 0.000 |
| 9Y-92 | 0.000 | 0.000 | 1 | 22.700 | 11.300 | 14.900 | 0.860 | 378.205 | 228.976 | 0.300 |
| 10R-111 | 0.000 | 3196.400 | 1 | 53.250 | 10.800 | 995.000 | 5.680 | 1952.745 | 88.050 | 0.025 |
| 10R-111 | 0.000 | 3180.800 | 2 | 49.750 | 11.400 | 935.000 | 5.600 | 1990.086 | 101.458 | 0.000 |
| Polacca 6 | 0.000 | 1640.300 | 1 | 5.200 | 1.200 | 550.000 | 2.170 | 407.654 | 447.395 | 0.700 |
| Hotevilla 2 | 0.000 | 263.700 | 1 | 1.200 | 0.000 | 54.000 | 0.420 | 5.435 | 1.420 | 0.025 |
| SecondMsSch2 | 0.000 | 525.100 | 1 | 0.900 | 0.100 | 119.000 | 0.410 | 14.435 | 7.255 | 0.000 |
| PolaccaPD&C2 | 0.000 | 670.900 | 1 | 0.800 | 0.000 | 163.000 | 0.520 | 27.235 | 28.680 | 0.000 |
| Hopi HS3 | 0.000 | 1065.300 | 1 | 2.000 | 0.400 | 338.000 | 0.990 | 79.500 | 218.550 | 1.000 |
| Keams Cyn2 | 0.000 | 815.700 | 1 | 1.000 | 0.100 | 220.000 | 0.630 | 43.260 | 93.380 | 0.850 |
| 4T-521 | 0.000 | 358.900 | 1 | 1.500 | 0.200 | 84.500 | 0.540 | 4.895 | 3.250 | 0.840 |
| 4T-523 | 189.000 | 278.300 | 1 | 1.400 | 0.000 | 70.000 | 0.460 | 35.400 | 8.600 | 0.110 |
| 2T-516 | 190.000 | 297.300 | 1 | 37.700 | 6.800 | 21.600 | 2.280 | 33.950 | 2.250 | 0.000 |
| Navajo N Mon | 110.000 | 177.600 | 1 | 29.900 | 3.400 | 4.900 | 1.020 | 2.900 | 0.000 | 0.000 |
| BIA Tuba C 5 | 0.000 | 161.700 | 1 | 19.700 | 3.800 | 9.000 | 1.040 | 9.555 | 5.135 | 0.000 |
| BIA RedLake1 | 0.000 | 128.600 | 1 | 15.800 | 4.600 | 3.900 | 1.860 | 1.910 | 1.409 | 0.110 |
| BIA RedLake1 | 0.000 | 132.000 | 2 | 15.900 | 4.600 | 7.900 | 1.770 | 1.725 | 1.325 | 0.180 |
| BIA RedLake1 | 0.000 | 125.500 | 3 | 15.800 | 4.600 | 4.400 | 1.790 | 1.830 | 1.310 | 0.180 |
| BIA Denneho2 | 188.000 | 231.200 | 1 | 8.500 | 1.900 | 47.500 | 0.580 | 13.800 | 6.550 | 0.000 |
| BIA Kaynta 2 | 0.000 | 0.000 | 1 | 19.900 | 1.700 | 6.700 | 0.230 | 68.665 | 3.655 | 0.000 |
| BIA LowMtn 2 | 0.000 | 982.000 | 1 | 1.400 | 0.400 | 295.000 | 0.980 | 60.900 | 180.250 | 0.225 |
| BIA Chilchn3 | 0.000 | 352.900 | 1 | 0.700 | 0.000 | 87.000 | 0.420 | 3.690 | 2.325 | 0.130 |
| BIA Dilkon 2 | 432.000 | 539.600 | 1 | 55.400 | 25.000 | 61.000 | 3.800 | 192.950 | 82.200 | 0.000 |
| BIA Dilkon 2 | 432.000 | 526.500 | 2 | 57.000 | 23.250 | 60.750 | 3.000 | 173.539 | 80.308 | 0.000 |
| BIA Cttnwd 3 | 250.000 | 570.700 | 1 | 10.400 | 3.700 | 78.000 | 4.970 | 43.825 | 21.750 | 0.000 |
| BIA Shonto 2 | 0.000 | 239.500 | 1 | 35.400 | 5.300 | 6.600 | 1.380 | 12.145 | 9.675 | 0.000 |
| BIA Pinon 6 | 230.000 | 385.700 | 1 | 0.600 | 0.000 | 92.000 | 0.370 | 4.590 | 3.050 | 0.000 |
| BIA Rocky 2 | 0.000 | 265.100 | 1 | 47.200 | 0.700 | 44.000 | 0.300 | 5.690 | 1.350 | 0.000 |
| BIA Kaibeto2 | 88.000 | 136.200 | 1 | 16.300 | 5.500 | 6.900 | 0.860 | 7.050 | 2.500 | 0.000 |
| IHS HardRk N | 125.000 | 251.900 | 1 | 2.300 | 0.100 | 50.900 | 0.200 | 5.384 | 3.843 | 0.000 |
| IHS HardRk D | 0.000 | 1602.500 | 1 | 4.600 | 0.600 | 481.000 | 2.220 | 247.050 | 310.400 | 0.000 |
| 6M-64 | 0.000 | 1476.900 | 1 | 4.000 | 0.800 | 404.000 | 1.630 | 460.450 | 59.300 | 0.000 |

| Well Number | Nitrate (mg/l) | Calcium (meq/l) | Magnesium (meq/l) | Sodium (meq/l) | Potassium (meq/l) | Ferrous Iron (meq/l) | Total Iron (meq/l) | Sulfate (meq/l) | Nitrite (meq/l) | Nitrate (meq/l) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1K-203 | 12.884 | 1.218 | 0.576 | 0.161 | 0.028 | 0.000 | 0.056 | 0.201 | 0.002 | 0.208 |
| 1K-509 | 9.105 | 0.848 | 0.667 | 0.526 | 0.041 | 0.000 | 0.002 | 0.229 | 0.000 | 0.147 |
| 1T-239 | 6.635 | 2.061 | 0.913 | 2.140 | 0.041 | 0.000 | 0.006 | 3.536 | 0.000 | 0.107 |
| 1K-214 | 10.266 | 0.564 | 0.263 | 0.152 | 0.023 | 0.000 | 0.013 | 0.232 | 0.000 | 0.166 |
| 1K-215 | 11.554 | 1.372 | 0.280 | 0.178 | 0.028 | 0.000 | 0.003 | 0.223 | 0.002 | 0.186 |
| 1T-227 | 4.403 | 1.372 | 0.280 | 0.178 | 0.030 | 0.000 | 0.095 | 0.128 | 0.000 | 0.071 |
| 1T-229 | 4.801 | 0.928 | 0.806 | 0.370 | 0.036 | 0.000 | 0.004 | 0.130 | 0.000 | 0.077 |
| 1T-504 | 7.860 | 0.978 | 0.996 | 0.109 | 0.044 | 0.000 | 0.003 | 0.218 | 0.000 | 0.127 |
| 2A-93 | 0.664 | 2.310 | 1.020 | 0.204 | 0.029 | 0.000 | 0.001 | 0.115 | 0.004 | 0.011 |
| 2K-319 | 9.374 | 1.457 | 0.329 | 0.204 | 0.043 | 0.001 | 0.037 | 0.124 | 0.002 | 0.151 |
| 2K-322 | 4.168 | 1.507 | 0.230 | 0.200 | 0.034 | 0.000 | 0.002 | 0.069 | 0.000 | 0.067 |
| 3M-156 | 0.000 | 0.035 | 0.008 | 5.742 | 0.013 | 0.000 | 0.033 | 1.466 | 0.000 | 0.000 |
| 3M-156 | 0.000 | 0.040 | 0.008 | 5.742 | 0.012 | 0.000 | 0.033 | 1.484 | 0.000 | 0.000 |
| 8T-510 | 26.091 | 0.449 | 0.074 | 0.043 | 0.003 | 0.000 | 0.005 | 0.619 | 0.002 | 0.421 |
| 8T-518 | 4.306 | 0.065 | 0.016 | 5.698 | 0.014 | 0.000 | 0.011 | 0.404 | 0.001 | 0.069 |
| 8T-522 | 3.598 | 0.205 | 0.107 | 0.122 | 0.004 | 0.004 | 0.040 | 2.134 | 0.002 | 0.058 |
| 9K-215 | 54.836 | 0.569 | 0.420 | 3.871 | 0.023 | 0.000 | 0.043 | 7.849 | 0.001 | 0.885 |
| 9K-218 | 4.785 | 1.023 | 0.486 | 0.539 | 0.028 | 0.000 | 0.011 | 0.417 | 0.000 | 0.077 |
| 9Y-92 | 15.728 | 1.133 | 0.930 | 0.648 | 0.022 | 0.002 | 0.013 | 7.874 | 0.003 | 0.254 |
| 10R-111 | 3.413 | 2.657 | 0.889 | 43.282 | 0.145 | 0.001 | 0.001 | 40.656 | 0.000 | 0.055 |
| 10R-111 | 0.000 | 2.483 | 0.938 | 40.672 | 0.143 | 0.001 | 0.001 | 41.434 | 0.000 | 0.000 |
| Polacca 6 | 0.000 | 0.259 | 0.099 | 23.925 | 0.056 | 0.003 | 0.005 | 8.487 | 0.003 | 0.000 |
| Hotevilla 2 | 5.352 | 0.060 | 0.000 | 2.349 | 0.011 | 0.000 | 0.003 | 0.113 | 0.003 | 0.086 |
| SecondMsSch2 | 0.000 | 0.045 | 0.008 | 5.176 | 0.010 | 0.000 | 0.017 | 0.301 | 0.006 | 0.000 |
| PolaccaPD&C2 | 30.894 | 0.040 | 0.000 | 7.090 | 0.013 | 0.000 | 0.002 | 0.567 | 0.003 | 0.498 |
| Hopi HS3 | 7.588 | 0.100 | 0.033 | 14.703 | 0.025 | 0.000 | 0.007 | 1.655 | 0.000 | 0.122 |
| Keams Cyn2 | 0.000 | 0.050 | 0.008 | 9.570 | 0.016 | 0.000 | 0.003 | 0.901 | 0.000 | 0.000 |
| 4T-521 | 4.905 | 0.075 | 0.016 | 3.676 | 0.014 | 0.000 | 0.001 | 0.102 | 0.000 | 0.079 |
| 4T-523 | 2.970 | 0.070 | 0.000 | 3.045 | 0.012 | 0.000 | 0.003 | 0.737 | 0.000 | 0.048 |
| 2T-516 | 3.797 | 1.881 | 0.560 | 0.940 | 0.058 | 0.000 | 0.002 | 0.707 | 0.000 | 0.061 |
| Navajo N Mon | 2.927 | 1.492 | 0.280 | 0.213 | 0.026 | 0.000 | 0.001 | 0.060 | 0.000 | 0.047 |
| BIA Tuba C 5 | 6.539 | 0.983 | 0.313 | 0.391 | 0.027 | 0.000 | 0.004 | 0.199 | 0.006 | 0.105 |
| BIA RedLake1 | 5.020 | 0.788 | 0.379 | 0.170 | 0.048 | 0.000 | 0.003 | 0.040 | 0.000 | 0.081 |
| BIA RedLake1 | 4.658 | 0.793 | 0.379 | 0.344 | 0.045 | 0.000 | 0.003 | 0.036 | 0.000 | 0.075 |
| BIA RedLake1 | 4.742 | 0.788 | 0.379 | 0.191 | 0.046 | 0.000 | 0.003 | 0.038 | 0.000 | 0.076 |
| BIA Denneho2 | 5.487 | 0.424 | 0.156 | 2.066 | 0.015 | 0.000 | 0.002 | 0.287 | 0.000 | 0.089 |
| BIA Kaynta 2 | 3.705 | 0.993 | 0.140 | 0.291 | 0.006 | 0.000 | 0.007 | 1.430 | 0.000 | 0.060 |
| BIA LowMtn 2 | 1.742 | 0.070 | 0.033 | 12.832 | 0.025 | 0.000 | 0.002 | 1.268 | 0.000 | 0.028 |
| BIA Chilchn3 | 5.012 | 0.035 | 0.000 | 3.784 | 0.011 | 0.000 | 0.008 | 0.077 | 0.006 | 0.081 |
| BIA Dilkon 2 | 0.000 | 2.764 | 2.057 | 2.653 | 0.097 | 0.000 | 0.000 | 4.017 | 0.000 | 0.000 |
| BIA Dilkon 2 | 9.458 | 2.844 | 1.913 | 2.643 | 0.077 | 0.000 | 0.000 | 3.613 | 0.000 | 0.153 |
| BIA Cttnwd 3 | 3.576 | 0.519 | 0.304 | 3.393 | 0.127 | 0.000 | 0.003 | 0.912 | 0.000 | 0.058 |
| BIA Shonto 2 | 13.606 | 1.766 | 0.436 | 0.287 | 0.035 | 0.000 | 0.010 | 0.253 | 0.006 | 0.219 |
| BIA Pinon 6 | 7.487 | 0.030 | 0.000 | 4.002 | 0.009 | 0.000 | 0.001 | 0.096 | 0.000 | 0.121 |
| BIA Rocky 2 | 9.801 | 2.355 | 0.058 | 1.914 | 0.008 | 0.000 | 0.001 | 0.118 | 0.000 | 0.158 |
| BIA Kaibeto2 | 7.590 | 0.813 | 0.453 | 0.300 | 0.022 | 0.000 | 0.001 | 0.147 | 0.002 | 0.122 |
| IHS HardRk N | 5.524 | 0.115 | 0.008 | 2.214 | 0.005 | 0.000 | 0.023 | 0.112 | 0.001 | 0.089 |
| IHS HardRk D | 0.000 | 0.230 | 0.049 | 20.923 | 0.057 | 0.001 | 0.023 | 5.144 | 0.032 | 0.000 |
| 6M-64 | 0.000 | 0.200 | 0.066 | 17.574 | 0.042 | 0.000 | 0.004 | 9.587 | 0.002 | 0.000 |

| Well Number | Fluoride (meq/l) | Chloride (meq/l) | Bicarbonate (meq/l) | Carbonate (meq/l) | Total Anions (meq/l) | Total Cations (meq/l) | Ion Balance | WATEQ Charge Balance | Calcite Saturation Index |
|---|---|---|---|---|---|---|---|---|---|
| 1K-203 | 0.006 | 0.226 | 1.524 | 0.000 | 2.159 | 1.983 | -4.249 | 2.800 | -0.215 |
| 1K-509 | 0.007 | 0.181 | 1.770 | 0.000 | 2.327 | 2.082 | -5.557 | 4.630 | 0.128 |
| 1T-239 | 0.021 | 0.087 | 1.672 | 0.000 | 5.402 | 5.155 | -2.340 | 2.270 | 0.091 |
| 1K-214 | 0.016 | 0.107 | 2.213 | 0.000 | 2.718 | 1.002 | -46.129 | 36.300 | 9.999 |
| 1K-215 | 0.009 | 0.212 | 1.426 | 0.000 | 2.047 | 1.858 | -4.840 | 3.970 | -0.354 |
| 1T-227 | 0.006 | 0.109 | 1.688 | 0.000 | 1.996 | 1.860 | -3.527 | 1.560 | -0.056 |
| 1T-229 | 0.018 | 0.058 | 2.114 | 0.000 | 2.379 | 2.140 | -5.289 | 4.600 | 0.044 |
| 1T-504 | 0.011 | 0.175 | 1.803 | 0.000 | 2.323 | 2.127 | -4.404 | 3.740 | -0.066 |
| 2A-93 | 0.017 | 0.093 | 3.917 | 0.000 | 4.136 | 3.563 | -7.443 | 6.740 | 0.518 |
| 2K-319 | 0.000 | 0.125 | 2.082 | 0.000 | 2.482 | 2.033 | -9.945 | 7.630 | 0.007 |
| 2K-322 | 0.011 | 0.083 | 2.049 | 0.000 | 2.268 | 1.971 | -7.006 | 5.820 | 0.392 |
| 3M-156 | 0.123 | 0.832 | 4.327 | 0.000 | 6.625 | 5.798 | -6.657 | 6.830 | -0.026 |
| 3M-156 | 0.123 | 0.811 | 4.327 | 0.000 | 6.622 | 5.802 | -6.600 | 6.790 | 0.032 |
| 8T-510 | 0.021 | 0.028 | 2.950 | 0.000 | 4.018 | 0.569 | -75.191 | 61.770 | 9.999 |
| 8T-518 | 0.043 | 0.720 | 5.736 | 0.000 | 6.929 | 5.793 | -8.929 | 8.510 | 0.273 |
| 8T-522 | 0.012 | 0.372 | 6.064 | 0.000 | 8.628 | 0.438 | -90.338 | 80.840 | 9.999 |
| 9K-215 | 0.084 | 6.472 | 4.097 | 0.000 | 19.303 | 4.883 | -59.621 | 57.220 | 9.999 |
| 9K-218 | 0.012 | 0.212 | 1.557 | 0.000 | 2.263 | 2.076 | -4.310 | 3.590 | 0.018 |
| 9Y-92 | 0.064 | 6.459 | 1.803 | 0.000 | 16.390 | 2.733 | -71.417 | 67.890 | 9.999 |
| 10R-111 | 0.073 | 2.484 | 1.344 | 0.000 | 44.539 | 46.973 | 2.660 | 2.550 | 0.042 |
| 10R-111 | 0.073 | 2.862 | 1.344 | 0.000 | 45.640 | 44.236 | -1.562 | 1.620 | 0.009 |
| Polacca 6 | 0.098 | 12.621 | 3.573 | 0.000 | 24.681 | 24.339 | -0.698 | 0.870 | -0.172 |
| Hotevilla 2 | 0.000 | 0.040 | 2.901 | 0.000 | 3.140 | 2.420 | -12.950 | 10.960 | 0.286 |
| SecondMsSch2 | 0.025 | 0.205 | 6.064 | 0.000 | 6.570 | 5.239 | -11.271 | 10.450 | 0.263 |
| PolaccaPD&C2 | 0.028 | 0.809 | 6.720 | 0.000 | 8.594 | 7.143 | -9.220 | 8.810 | 0.184 |
| Hopi HS3 | 0.114 | 6.165 | 6.753 | 0.000 | 14.695 | 14.861 | 0.562 | 0.180 | 0.021 |
| Keams Cyn2 | 0.070 | 2.634 | 7.375 | 0.000 | 10.910 | 9.644 | -6.159 | 6.170 | 0.110 |
| 4T-521 | 0.008 | 0.092 | 3.934 | 0.000 | 4.207 | 3.781 | -5.333 | 4.810 | 0.457 |
| 4T-523 | 0.017 | 0.243 | 2.491 | 0.000 | 3.519 | 3.127 | -5.898 | 5.320 | 0.240 |
| 2T-516 | 0.013 | 0.063 | 3.032 | 0.000 | 3.863 | 3.439 | -5.807 | 5.250 | -0.045 |
| Navajo N Mon | 0.007 | 0.000 | 2.098 | 0.000 | 2.205 | 2.011 | -4.602 | 3.860 | 0.123 |
| BIA Tuba C 5 | 0.004 | 0.145 | 1.557 | 0.000 | 2.006 | 1.714 | -7.849 | 6.210 | -0.239 |
| BIA RedLake1 | 0.029 | 0.040 | 1.475 | 0.000 | 1.636 | 1.385 | -8.309 | 6.870 | 0.018 |
| BIA RedLake1 | 0.029 | 0.037 | 1.475 | 0.000 | 1.623 | 1.561 | -1.947 | 2.120 | 0.019 |
| BIA RedLake1 | 0.029 | 0.037 | 1.475 | 0.000 | 1.626 | 1.404 | -7.327 | 4.960 | 0.019 |
| BIA Denneho2 | 0.004 | 0.185 | 2.344 | 0.000 | 2.905 | 2.661 | -4.384 | 3.730 | 0.614 |
| BIA Kaynta 2 | 0.017 | 0.103 | 2.016 | 0.000 | 3.609 | 1.430 | -43.243 | 36.140 | 9.999 |
| BIA LowMtn 2 | 0.124 | 5.085 | 7.048 | 0.000 | 13.429 | 12.960 | -1.777 | 2.150 | 0.154 |
| BIA Chilchn3 | 0.027 | 0.066 | 3.852 | 0.000 | 4.076 | 3.830 | -3.112 | 2.980 | 0.034 |
| BIA Dilkon 2 | 0.010 | 2.319 | 1.852 | 0.000 | 8.188 | 7.571 | -3.915 | 3.730 | 0.168 |
| BIA Dilkon 2 | 0.010 | 2.265 | 1.852 | 0.000 | 7.883 | 7.477 | -2.643 | 2.540 | 0.189 |
| BIA Cttawd 3 | 0.019 | 0.614 | 7.294 | 0.000 | 8.878 | 4.343 | -34.301 | 32.360 | 0.657 |
| BIA Shonto 2 | 0.000 | 0.273 | 2.295 | 0.000 | 3.040 | 2.524 | -9.274 | 7.730 | -0.095 |
| BIA Pinon 6 | 0.012 | 0.086 | 4.360 | 0.000 | 4.663 | 4.041 | -7.146 | 6.500 | 0.121 |
| BIA Rocky 2 | 0.024 | 0.038 | 2.327 | 0.000 | 2.641 | 4.335 | 24.283 | 20.860 | 1.623 |
| BIA Kaibeto2 | 0.015 | 0.071 | 1.360 | 0.000 | 1.700 | 1.588 | -3.406 | 2.940 | -0.127 |
| IHS HardRk N | 0.012 | 0.108 | 2.819 | 0.000 | 3.128 | 2.342 | -14.369 | 12.060 | 0.535 |
| IHS HardRk D | 0.132 | 8.756 | 8.888 | 0.000 | 22.788 | 21.259 | -3.471 | 3.640 | 0.049 |
| 6M-64 | 12.844 | 1.673 | 8.851 | 0.000 | 20.111 | 17.882 | -5.867 | 6.020 | 0.133 |

| Well Number | Aragonite Saturation Index | Dolomite Saturation Index | Fluorite Saturation Index | Gypsum Saturation Index |
|---|---|---|---|---|
| 1K-203 | -0.367 | -0.781 | -2.773 | -2.853 |
| 1K-509 | -0.027 | 0.072 | -2.685 | -2.946 |
| 1T-239 | -0.060 | -0.158 | -1.582 | -1.554 |
| 1K-214 | 9.999 | 9.999 | 9.999 | 9.999 |
| 1K-215 | -0.515 | -1.640 | -2.134 | -2.713 |
| 1T-227 | -0.209 | -0.843 | -2.700 | -2.988 |
| 1T-229 | -0.111 | -0.062 | -1.872 | -3.155 |
| 1T-504 | -0.220 | -0.203 | -2.279 | -2.916 |
| 2A-93 | 0.358 | 0.483 | -1.504 | -2.877 |
| 2K-319 | -0.144 | -0.633 | 9.999 | -2.997 |
| 2K-322 | 0.238 | -0.103 | -2.081 | -3.224 |
| 3M-156 | -0.176 | -0.603 | -1.937 | -3.787 |
| 3M-156 | -0.118 | -0.546 | -1.879 | -3.724 |
| 8T-510 | 9.999 | 9.999 | 9.999 | 9.999 |
| 8T-518 | 0.122 | 0.026 | -2.566 | -4.068 |
| 8T-522 | 9.999 | 9.999 | 9.999 | 9.999 |
| 9K-215 | 9.999 | 9.999 | 9.999 | 9.999 |
| 9K-218 | -0.136 | -0.342 | -2.190 | -2.610 |
| 9Y-92 | 9.999 | 9.999 | 9.999 | 9.999 |
| 10R-111 | -0.109 | -0.323 | -0.862 | -0.942 |
| 10R-111 | -0.141 | -0.335 | -0.895 | -0.965 |
| Polacca 6 | -0.320 | -0.679 | -1.391 | -2.324 |
| Hotevilla 2 | 0.143 | 9.999 | 9.999 | -4.596 |
| SecondMsSch2 | 0.116 | -0.052 | -3.343 | -4.449 |
| PolaccaPD&C2 | 0.038 | 9.999 | -3.328 | -4.253 |
| Hopi HS3 | -0.126 | -0.341 | -1.585 | -3.317 |
| Keams Cyn2 | -0.037 | -0.439 | -2.346 | -3.903 |
| 4T-521 | 0.315 | 0.521 | -4.171 | -4.642 |
| 4T-523 | 0.099 | 9.999 | -3.413 | -3.703 |
| 2T-516 | -0.195 | -0.580 | -2.010 | -2.204 |
| Navajo N Mon | -0.030 | -0.516 | -2.464 | -3.288 |
| BIA Tuba C 5 | -0.389 | -0.958 | -3.163 | -2.936 |
| BIA RedLake1 | -0.132 | -0.261 | -1.574 | -3.712 |
| BIA RedLake1 | -0.131 | -0.262 | -1.574 | -3.756 |
| BIA RedLake1 | -0.131 | -0.260 | -1.574 | -3.729 |
| BIA Denneho2 | 0.464 | 0.824 | -3.697 | -3.194 |
| BIA Kaynta 2 | 9.999 | 9.999 | 9.999 | 9.999 |
| BIA LowMtn 2 | 0.007 | 0.101 | -1.707 | -3.620 |
| BIA Chilchn3 | -0.113 | 9.999 | -3.259 | -5.012 |
| BIA Dilkon 2 | 0.017 | 0.222 | -2.152 | -1.437 |
| BIA Dilkon 2 | 0.038 | 0.217 | -2.130 | -1.462 |
| BIA Cttnwd 3 | 0.516 | 1.291 | -2.410 | -3.631 |
| BIA Shonto 2 | -0.247 | -0.824 | 9.999 | -2.629 |
| BIA Pinon 6 | -0.021 | 9.999 | -4.277 | -5.131 |
| BIA Rocky 2 | 1.481 | 1.832 | -1.524 | -2.950 |
| BIA Kaibeto2 | -0.275 | -0.449 | -2.188 | -3.145 |
| IHS HardRk N | 0.396 | 0.209 | -3.564 | -4.309 |
| IHS HardRk D | -0.093 | -0.389 | -1.263 | -2.574 |
| 6M-64 | -0.017 | -0.159 | -1.255 | -2.384 |

## BIOGRAPHICAL STATEMENT

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DATE OF BIRTH: January 16, 1949

EDUCATIONAL INSTITUTIONS ATTENDED:

Northern Arizona University, M.S., 1989
Northern Arizona University, B.S., 1984
University of Texas at Austin, M.A., 1975
Austin College, B.A., 1971

PROFESSIONAL EXPERIENCE:

Arizona Department of Environmental Quality, 1989-present
Hydro Geo Chem, Inc., 1986-1989
Salt River Project, 1985
School of American Research, 1984
Northern Arizona University Archaeology Laboratory, 1983-1984
Museum of Northern Arizona, 1976-1983
Texas Archaeological Survey, 1975-1976

PROFESSIONAL SOCIETY MEMBERSHIPS:

Society for American Archaeology
Geological Society of America
American Association of Petroleum Geologists
Arizona Hydrological Society
National Water Well Association
Computer Oriented Geological Society

PUBLICATIONS AND REPORTS:

1986 Petrographic analysis of archaeological potsherds from the Tucson Aqueduct Project, Pinal County, Arizona. Paper presented at the Annual Meeting of the Geological Society of America. San Antonio, Texas.

1986 (with David S. Brumbaugh) Faulting along the Hunters Point segment of the East Defiance monoclinal complex, Apache County, Arizona. Paper presented at the 39th Annual Symposium on Southwestern Geology and Paleontology, Museum of Northern Arizona. Flagstaff, Arizona.

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