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Trace element analysis of selected springs in the Virgin River Basin

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TRACE ELEMENT ANALYSIS
OF SELECTED SPRINGS
IN THE VIRGIN RIVER BASIN

by

Mary A. Yelken

A thesis submitted in partial fulfillment
of the requirements for the degree of

Master of Science

in

Water Resources Management

Department of Geoscience
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The thesis of Mary A. Yelken for the degree of Master of Science in Water Resources Management is approved.

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ABSTRACT

Spring water from 23 springs in and near the Virgin River Basin (southwestern Utah, northwestern Arizona, and southeastern Nevada) was collected and analyzed for field parameters and chemical concentrations. Trace element concentrations and major ion chemistry were used to determine the potential for using water chemistry, specifically trace element concentrations, to provide information on spring water source and flow pathways. Principal Component Analysis (PCA), rare earth element (REE) normalization patterns, and mineral equilibrium modeling (PHREEQE) techniques were used to analyze the data set. The PCA analysis grouped spring water with similar chemistries. Four major spring water groups were displayed from the analysis of the chemical data set. Pah Tempe Hot Springs grouped away from other springs except when the PCA analysis included only REE data. Petrified, Blue Point, and Roger's springs formed a consistent group throughout the PCA. Clover-UNK, Creeper, and Putting Green springs formed an isolated group only when REE data was a part of the PCA. The remainder of the springs clustered together with few subgroups emerging when different combinations of the data set were entered into the PCA. The analyses suggest that spring water chemical concentrations are a result of interactions with the rocks through which the waters flow. The small number of sampling locations relative to the large areal extent of the Virgin River Basin limited the usefulness of the water chemistry to suggest actual spring source and flow pathways. Although the PCA displayed four major spring water groupings, additional research is warranted in the study area to gain a better understanding of the groundwater flow system.

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LIST OF ABBREVIATIONS

cfs	cubic feet per second
gpm	gallon per minute
EC	Electrical Conductivity
HREE	Heavy Rare Earth Elements
HRC	Harry Reid Center for Environmental Studies at the University of Nevada, Las Vegas
ICP-MS	Inductively-Coupled Plasma Mass Spectrometry
L/s	Liters per second
LREE	Light Rare Earth Elements
MREE	Middle Rare Earth Elements
PC	Principal Component
PCA	Principal Component Analysis
ppb	parts per billion
ppm	parts per million
ppt	parts per trillion
REE	Rare Earth Elements
RSD	Relative Standard Deviation
UNLV	University of Nevada, Las Vegas

Spring Name Abbreviations

Petrified	Pet	Government	Gov
Lime Kiln	Lim	Pahcoon	Pcn
Welcome	Wel	Roger's	Rog
Blue Point	Blu	Big Muddy	Mud
Dodge	Dod	Creeper	Crp
Putting Green	Put	Clover-UNK	Clv
Juanita	Jua	Oak-Low Mtn.	Oak
Pah Tempe	Pah	Grapevine	Grp
Stout Canyon	Sto	Cascade Falls	Cas
Stave	Sta	Menu Falls	Men
Toquerville	Toq	Oak Grove Camp	Grv
Boilers	Boi		

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CHAPTER 1

INTRODUCTION

The Virgin River Basin is located in southwestern Utah, northwestern Arizona, and southeastern Nevada (Figure 1). The Virgin River is a river of rare status as compared to other rivers of the western United States due to relatively little development (MacAllister, 1993). For the most part the Virgin River is free-flowing. It provides the lifeblood for the basin, both environmentally and economically. Over the past 9,000 years the water resources in the Virgin River Basin have helped sustain several civilizations. Even though diversions have been made throughout these years, primarily for agricultural purposes, the human impact to the river basin has been relatively small. However, impacts to the Virgin River Basin resulting from human activity have increased in recent years and are likely to continue to increase in the future. The main reason for these impacts is the significant increases in population throughout and near the Virgin River Basin. As cities such as St. George, Utah and Las Vegas, Nevada continue to grow, new sources of water resources must be secured. The Virgin River Basin is a potential target for the additional development of groundwater and surface water resources to support these expanding urban centers. It is critical that areas targeted for future water withdrawals are hydrologically investigated to determine specific areas for development and to assess the

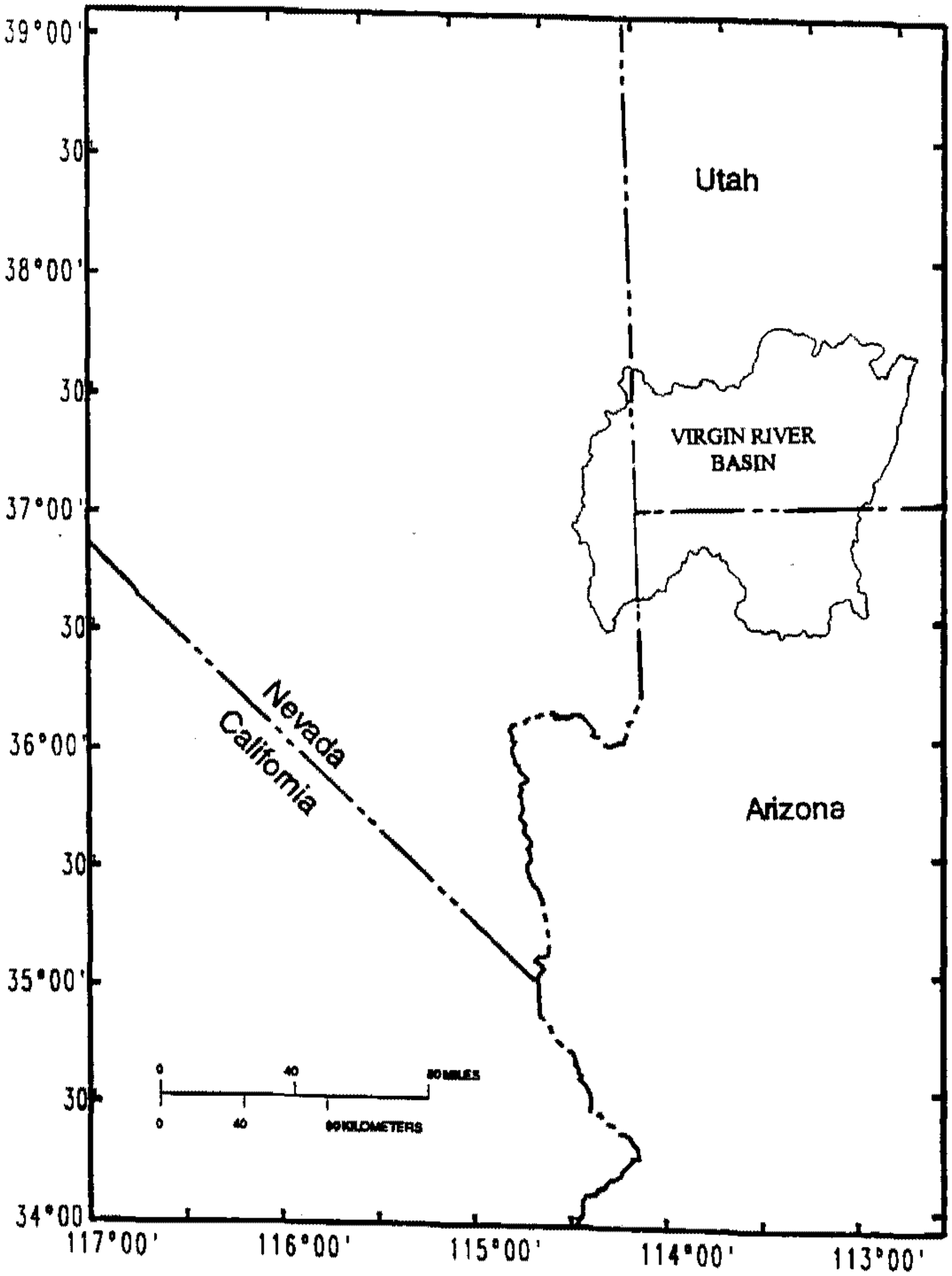


Figure 1: General Location of Study Area
(adapted from Metcalf, 1995)

potential for environmental impacts from the further development of water resources in the Virgin River Basin. Understanding the groundwater chemistry in the Virgin River Basin may help to define groundwater source and flow pathways which would then facilitate water resource management decisions concerning future development in the Virgin River Basin.

The central purpose of this research was to determine the usefulness of water chemistry to provide information on the sources and flow pathways of spring waters in the Virgin River Basin. Principal Component Analysis (PCA) was the primary technique used to assess the potential for using water chemistry, specifically trace elements, to define groundwater movement and origin. The PCA was used to separate spring waters with different chemistry and to group spring waters with similar chemical content. Rare Earth Element (REE) normalization patterns, mineral equilibrium modeling (PHREEQE), and Piper and Stiff Diagrams were other techniques used to analyze the chemical data set. Also, oxygen-18 and deuterium results are presented for additional comparison with the chemical concentrations of the spring waters in the Virgin River Basin and surrounding study area.

Several benefits were expected from this research. First, available information on groundwater in the Virgin River Basin was compiled and several data bases were searched. This information was useful in targeting which springs were to be sampled. The current research provided baseline water quality data on spring water throughout the Virgin River Basin and in areas of close proximity. Not only were major ion concentrations measured, but also approximately 57 trace element concentrations. Few previous studies have determined trace element concentrations for spring waters in the study area or for other groundwaters. The current research suggested some insight to help distinguish the movement and sources of the groundwater discharging from springs in and near the Virgin River Basin. Additionally, the analysis and comparison of spring water chemistry and the establishment of baseline water chemistry parameters of discharging groundwater will contribute to future hydrological modeling efforts, and provides information needed to assist in making water-related decisions concerning the Virgin River Basin. This research has provided some broad generalizations about spring waters in the study area and has targeted possibilities for future research to increase the understanding of groundwater resources in the Virgin River Basin and surrounding areas.

This research was accomplished by collecting and analyzing spring water samples from 23 spring sites in and near the Virgin River Basin in Utah, Arizona, and Nevada. Field chemistry parameters, major cation and anion chemistry, trace element concentrations, and stable isotopes (oxygen-18 and deuterium) were measured for each spring water sample. The data set, with the exception of stable isotopes, temperature, electrical conductivity, and pH, was examined by the multivariate statistical technique, Principal Component Analysis (PCA), to help identify waters of like chemistries. Rare earth element (REE) normalization patterns were also evaluated in order to distinguish similarities and differences in spring water chemistry. Relationships displayed by these hydrologic techniques were used to increase the understanding of the groundwater system in the Virgin River Basin.

The organization of this thesis is described below. Chapter 1 gives a generalized description of the study area including a location map of the study area, spring locations, major geologic features, urban areas and political boundaries. In addition, this section provides an overview of the basin's history, climate, and a discussion of the current demands on the water resources of the Virgin River Basin. Chapter 2 discusses the general geologic and topographic regions of the Virgin River Basin. Chapter 3 presents details on some of the major springs and an overview of what is known about groundwater in the Virgin River Basin. Chapter 4 provides the methodologies used to complete this research and includes a review of the field reconnaissance, spring selection, spring sampling criteria, and analytical procedures. The chemical concentrations of the spring waters resulting from the analysis are presented in Chapter 5 along with a brief summary of the water chemistry results. Chapter 6 provides information on the data analysis tools used in this research and a discussion of their results. Conclusions and suggestions for future research are discussed in Chapter 7.

Review of Literature

Several hydrologic studies have been completed on the Virgin River Basin, however, most of the previous research covers only portions of the basin and not the entire basin from the headwaters in Utah to the confluence of the Virgin River and the Colorado River at Lake Mead in southeastern Nevada as does this current study. The portions of the basin investigated were commonly determined by political boundaries, although some are designated on the basis of geologic boundaries or both. Hydrologic investigations have addressed surface water and groundwater in the Virgin River Basin.

Similar to the research presented here, many of the previous studies were conducted to provide hydrologic information required to manage the water resources in the Virgin River Basin. A list of previous studies is presented below. Specific information from many of these reports will be presented in the groundwater section as well as in the discussion sections.

Previous studies and management plans concerning groundwater and surface water in the Upper and Central Virgin River Basin have been developed mostly by governmental agencies. Cordova et al. (1972), Cordova (1978), and Cordova (1981) are Utah Department of Natural Resources publications that provide information on the groundwater system and on the determination of hydrologic effects on the basin resulting from increases in water withdrawals. Numerous other reports describe water resources in the Upper and Central Virgin River Basin (Bagley et al., 1955; Wilson and Thomas, 1964; United States Bureau of Reclamation, 1979; Utah Division of Water Resources, 1983; Utah Natural Resources and Energy, 1983; Sandberg and Sultz, 1985; United States Department of Agriculture, 1990; Clyde, 1990; Quail Creek Master Plan Committee and Washington County Water Conservancy District, 1992; Freethey, 1993; Utah Department of Natural Resources, 1993; Utah Board of Water Resources, 1993; Washington County Water Conservancy District, 1994). These reports provide both water quality and water quantity information for the Virgin River Basin.

In addition, many hydrologic research and management plans for the Lower Virgin River Basin have been completed. Computer modeling of surface and groundwater systems in the Lower Virgin River Basin are presented in Las Vegas Valley Water District and MARK Group (1992), Brothers et al. (1992), and Brothers et al. (1993). Research concerning the development and management of water resources, the potential for environmental impacts, and the granting of additional water rights in the Virgin River Basin is described in Las Vegas Valley Water District/ Southern Nevada Water Authority (1993), Woodward-Clyde Consultants, Dames and Moore, and the Las Vegas Valley Water District (1992, 1993). Other studies have also been completed in the Lower Virgin River Basin and include investigations on water quality, specifically salinity (Woessner et al.,1981; Soil Conservation Service, 1981; United States Department of the Interior and Bureau of Reclamation, 1982; United States Department of the Interior, Bureau of Reclamation Lower Colorado Region, and Las Vegas Valley Water District; 1993). Several additional reports present a variety of water reconnaissance, hyrdrologic, and management studies for the Lower Virgin River Basin (Glancy, and Van Denburgh, 1969; URS Company and Clark County Sanitation District, 1977; Trudeau, 1979; United States Department of Agriculture, 1979; Robinson and Pugsly, 1981; Panian et al., 1987; Clyde, 1990; Leslie and Associates, 1990; Black and Rascona, 1991; United States Bureau of Reclamation, 1992; Metcalf, 1995). Also, research on a more regional scale that has included portions of the Lower Virgin River Basin have been conducted (Hardman and Miller, 1934; Mifflin, 1968; Thomas and Mason, 1986; Harrill et al., 1988; Dettinger, 1989; Thomas et al., 1991; Dettinger, 1992; Burbey, and Prudic, 1993, Dettinger et al., 1995). Many of these studies focus on groundwater flow pathways in the carbonate rock province in southeastern Nevada which is thought to extend into the Lower Virgin River Basin.

The investigations referred to above were reviewed to gain an understanding of the water resources in the Virgin River Basin. Information in previous works assisted in the field reconnaissance and spring selection portions of this study. The results and conclusions of the current research were compared with that of previous studies to provide insight into understanding the source and flow pathways of groundwater in the study area.

Overview of the Virgin River Basin

The Virgin River

The Virgin River, which is a major tributary of the Colorado River, flows approximately 200 miles (322 km) through the states of Utah, Arizona, and Nevada, with its drainage basin encompassing approximately 5900 square miles (15,280 square kilometers) (Figure 2). The Virgin River's headwaters are in the Dixie National Forest, north and east of Zion National Park within southwestern Utah's high plateaus. The two forks, the North Fork and the East Fork of the Virgin River, join just south of Springdale, Utah, near Zion National Park. The Virgin River flows southwesterly through Utah, passing near St. George, Utah, and continues into the Scenic Strip area of northwestern Arizona. The Virgin River flows through the Littlefield, Arizona area and continues into southeastern Nevada, passing near the towns of Mesquite and Bunkerville, Nevada before emptying into Lake Mead. Lake Mead is a reservoir on the Colorado River that was formed by the construction of Hoover Dam (United States Dept. of the Interior et al., 1982). As the Virgin River passes through Utah, Arizona, and Nevada, it receives

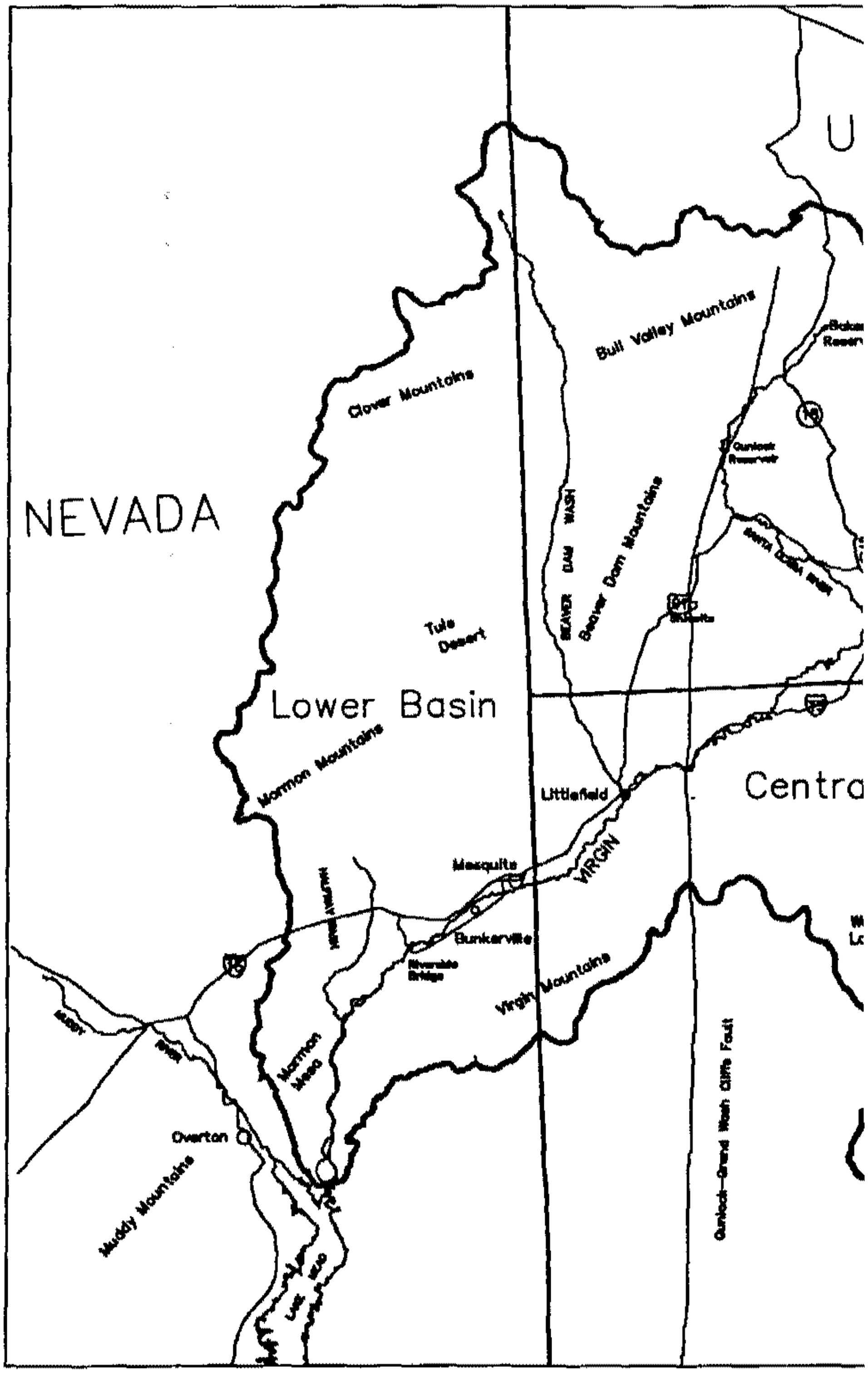
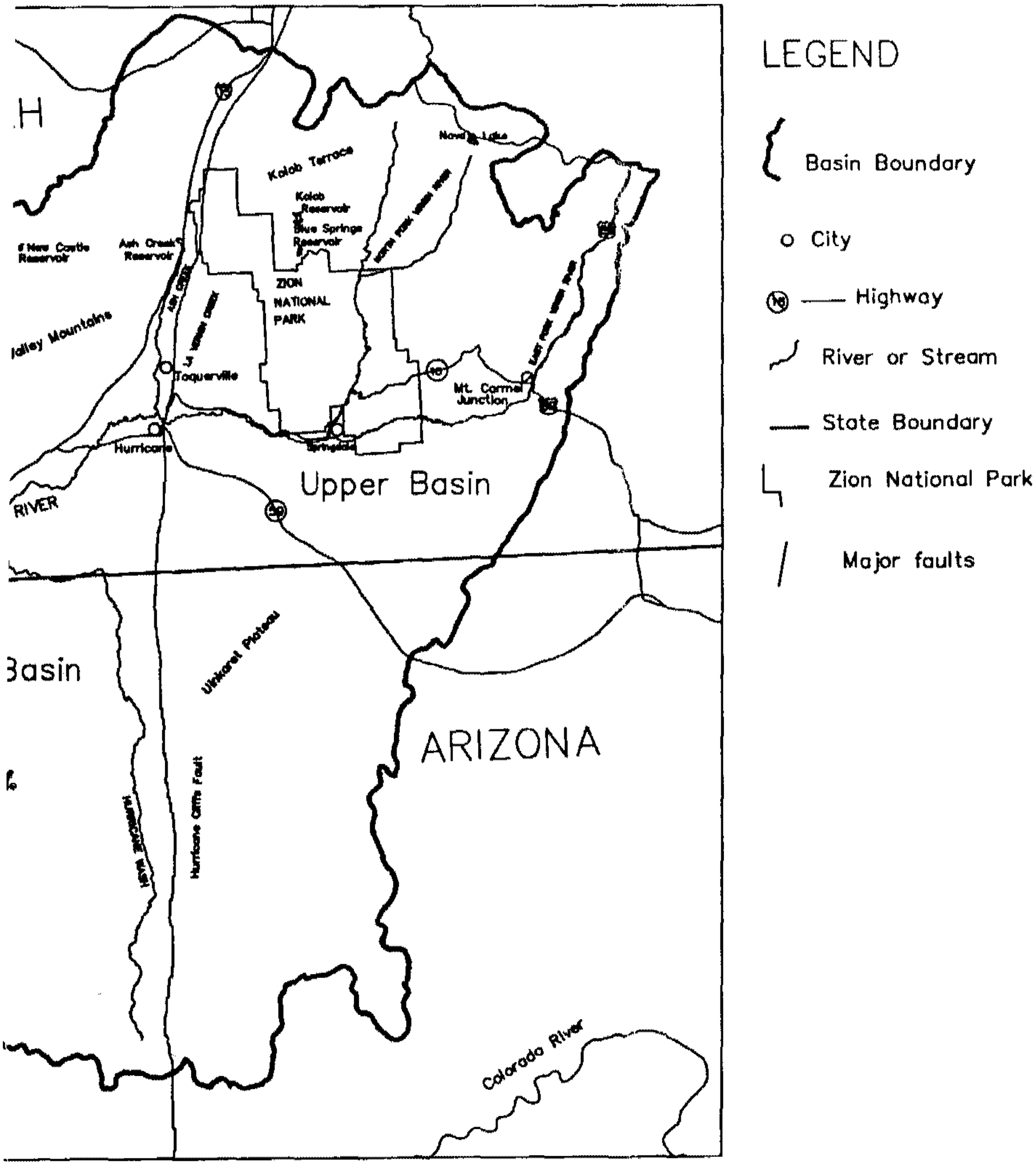


Figure 2: Map of Study Area (Virgin River Basin and Surrc
Division of study area is based on major faults



ding Area)
wer, Central, and Upper Virgin River Basin)

additional flow from several tributaries and streams including North Creek, Ash Creek, La Verkin Creek, Fort Pierce Wash, the Santa Clara River, and Beaver Dam Wash. Tributaries of the Virgin River can be perennial, intermittent, and ephemeral (Cordova et al., 1972). The majority of tributaries entering the basin from the south are intermittent or ephemeral and provide minor flow to the river system as a whole (Clyde, 1987).

The Virgin River flow varies greatly between wet and dry years, and also, between months of higher precipitation (October to May) and the dry summer months. At Littlefield, Arizona, the gaged flow as measured by the United States Geological Survey, averages about 174,000 acre-feet per year (Brothers et al., 1992). Approximately 128,000 acre-feet per year of groundwater and surface water is expected to reach Lake Mead (Woodward-Clyde Consultants et al., 1992).

The water quality of the Virgin River above Pah Tempe Hot Springs near La Verkin, Utah, is considerably higher in quality than below Pah Tempe Hot Springs. Concentrations of dissolved solids above the hot springs are 560 mg/l and 2,760 mg/l below Pah Tempe Hot Springs as measured by Sandberg and Sultz (1985). The discharge from Pah Tempe Hot Springs is the primary reason for the poor water quality downstream from La Verkin, Utah. Large salt loads are released into the river from the springs (Washington County Conservancy District, 1994). In order for water to be used for municipal purposes below Pah Tempe Hot Springs, the water would have to go through a desalination plant or be mixed with higher quality water before consumption. Also, much of the soil in the region is high in salinity and is easily eroded which, along with the combination of high evaporation rates from irrigated lands, causes extremely high dissolved solid concentrations in the Virgin River waters. Agriculture has also caused a decrease in water quality because of fertilizer, pesticide, and animal waste runoff (MacAllister, 1993). Even with these water quality problems in the Central and Lower Virgin River Basins, the river is still being considered as a potential source for municipal water supplies (Woodward-Clyde Consultants, Dames and Moore, and the Las Vegas Valley Water District, 1992, 1993; Turnipseed, 1994; Friends of the Virgin River, 1994)

Climate

The Virgin River Basin is an area of diverse climatic zones that range from subalpine conditions to desert environments. Many different plants and animals live in the diverse climatic zones of the basin (MacAllister, 1993). Moreover, the transition zones between climatic regions have a unique, delicate ecosystems. These climatic differences provide a home for very diverse groups of plant and animal life. Over 130 special status and endangered species live in the Virgin River Basin and include species such as the Bald Eagle, Desert Tortoise, and Gypsum Cactus (Woodward-Clyde Consultants, Dames and Moore, and the Las Vegas Valley Water District, 1992; MacAllister, 1993).

The Virgin River has a wide range of elevations that vary from less than 2000 feet (610 meters) near Lake Mead to almost 11,000 feet (3350 meters) in the mountainous areas in Utah (Woodward-Clyde Consultants et al., 1992). Although it is obvious that the higher elevation areas are typically cooler compared to lower elevation valley areas, the mean air temperatures also increases from the cooler northeastern part of the basin to the warmer southwestern part of the basin near the confluence of the Virgin River and Lake

Mead (Table 1). Figure 3 provides a map of the weather data site locations that are presented in Table 1. Overall, the winters are mild and the summers are hot and dry in the study area.

Like the temperature trends in the basin, the distribution of precipitation in the study area is variable from the northeast to the southwest and from mountainous areas to the valley floors. Generally, the greatest precipitation occurs at higher elevation in the northeastern portion of the Virgin River Basin. During the winter months these mountainous regions receive considerable snowfall. The lowest precipitation amounts occur on the valley floors of southeastern Nevada. Precipitation is generally highest in the winter months during longer precipitation events as compared to more localized thunderstorms in the summer months (Cordova, 1978). However, precipitation may be locally heavy. The headwaters area of the North Fork of the Virgin River near Navajo Lake, for example, receives approximately 40 inches of precipitation (Owenby, J. R., and Ezell, D. S., 1992b; Cordova, 1981), whereas the desert valley near Lake Mead in the Valley of Fire just outside the Virgin River Basin boundary receives around 5.8 inches of rain per year (Owenby and Ezell, 1992b). The runoff from melting winter snow at higher elevations is more important than intense summer storms in recharging the groundwater system (Clyde, 1987). Slower rates of overland flow allows for greater infiltration of snow melt compared to summer rainstorms with rapid runoff. Precipitation data from climatological stations in the proximity of the Virgin River Basin are presented in Table 1. Figure 3 provides a locational display of the precipitation data sites presented in Table 1. Evaporation rates are high throughout the basin and vary with elevation. Lower evaporation rates are reported for higher elevations and relatively higher rates occur at lower elevations. In the St. George, Utah area in the Central Virgin River Basin the evaporation rate is approximately 62 inches per year (Cordova, 1978).

History of the Virgin River Basin

As far back as 8000 to 9000 years before present in the Paleoindian era, humans attempted to settle the Virgin River Basin. A group of Archaic people, nomadic basket makers, lived in the southwestern part of the present United States for approximately 6000 years (Dalley and McFadden, 1985; 1988). Little is known of these early inhabitants because much of the archeological record has been destroyed by erosional processes (MacAllister, 1993; U.S. Dept. of Agriculture et al., 1990). Archaeological studies at the Red Cliffs Site near St. George, Utah, and the Little Man site near Hurricane, Utah have provided some information of these early settlements in the Virgin River Basin (Dalley and McFadden, 1985; 1988). It is thought that the original Archaic people developed into the Anasazi (the "ancient ones") and are believed to have been horticulturists (MacAllister, 1993). Anasazi people diverted the Virgin River and used water controlling devices to irrigate their fields of squash, beans, and corn. The Anasazi people left the area about 800 years ago. When the Americans of European decent first explored the area, the Southern Piaute Indians lived in the basin. Irrigated agriculture was very important in sustaining the early settlements (MacAllister, 1993).

Mormons established settlements in the mid 1800's. St. George, Utah was one of the larger of these settlements. The majority of their water need was for agricultural purposes, as is still true today for much of the region. Other Mormon settlements were located in the lower Virgin River Basin including one near Bunkerville. Like previous settlements in the basin, irrigated agriculture was of major importance to the prosperity of these settlements (Glancy and Van Denburgh 1969). Since the time of the first European settlers, water has continued to be an increasingly important resource, not only for agriculture, but also for domestic and industrial uses.

Demands on the Virgin River Basin

Currently, the river flows through an area that is one of the most rapidly growing regions in the country (i.e., the Las Vegas Metropolitan area as well as the area surrounding St. George, Utah). This population growth is placing many additional demands on the water resources of the Virgin River Basin. Agriculture has been the primary user of water resources in the Virgin River Basin, but recently, domestic and industrial uses are needing additional water supplies to sustain current growth. Land ownership/control in the basin includes federal, Indian, state and private lands (Woodward-Clyde Consultants et al., 1992), but with this diversity in land ownership there is associated diversity in the type of water uses in the basin (agricultural, municipal, industrial, and recreational uses).

The growing population has become more aware of the river basin's natural values and various groups have been organized to protect the fragile Virgin River Basin ecosystems from further human development (MacAllister, 1993; Friends of the Virgin River Basin, 1994). Maintaining instream flows levels and ensuring the survival of endangered species are increasingly important issues for the Virgin River Basin. Moreover, tourism and recreational activities are placing additional demands on the water resources in the basin. As populations increase in the southwestern United States, contention over unappropriated waters will likely cause political disputes. Urban development in southern Nevada (Turnipseed, 1994) and southwestern Utah has caused water planners to look toward the Virgin River Basin as an additional water supply with potential future plans of diverting the river water and possibly utilizing the groundwater.

Since the Virgin River is not governed by an interstate compact, the basin is vulnerable to the exploitation of its resources. As the population in the area soars, the demands for water will continue to increase as will the competition between the three states (Utah, Arizona, and Nevada) for rights to water in the Virgin River Basin. Las Vegas and other urban areas like St. George, Utah, are expected to continue to have significant increases in population. St. George, Utah is expected to more than double in population by the year 2020. Clark County, Nevada already supports over a million people and continues to have large increases in populations. Many of the Virgin River Basin cities are exceeding a six percent annual population growth rate. With the additional urban demands on the basin for water, the possibility for the diversions and/or dam building on the river could arise (i.e., application by the Las Vegas Valley Water District for diversion of Virgin River Water at Halfway Wash in southeastern Nevada) (Las Vegas Valley Water District/ Southern Nevada Water Authority, 1993; MacAllister, 1993). The tradition of dam building in the west has for the most part not been realized on the Virgin River, but may become important in the future with the increased urbanization and the desire to maintain current agricultural projects (MacAllister, 1993).

Agriculture has been of major importance throughout the history of the basin. With increased urbanization, agricultures economic utility is declining in importance as compared with industry. Agriculture uses a large majority of the water in the basin, but only generates approximately 1/60 of the revenue of other businesses in the Virgin River Basin. Even with these economic shortfalls, water planners continue to maintain the large amounts of water reserved for the agricultural sector (MacAllister, 1993). The agricultural sector holds the majority of the initial water rights in the basin, and without the implementation of water transfers through an established water marketing system these rights are likely to remain in the agricultural industry.

CHAPTER 2

GEOLOGY OF THE VIRGIN RIVER BASIN

The Virgin River Basin is geologically complex due to several marine deposition and tectonic events (Stokes, 1986), and its location in the transition zone between the Basin Range Province and the Colorado Plateau (Figure 4). Several workers have described the geologic features in the study area (Anderson and Barnhard, 1993; Anderson, 1973; Axen, 1993; Bohannon, 1983; Carpenter and Carpenter, 1994; Hintze, 1986; Larsen et al., 1986; Schramm, 1994; Stewart 1980; Stokes, 1986). Presently, the basin is arid and semi-arid even though it owes much of its diverse geology to the paleo-oceans that once covered the area. Stratigraphic columns displaying a representation the geologic time periods present in the Virgin River Basin are presented in Figure 5 and Figure 6.

Lower Cambrian sandstones and shales overlie the lower Precambrian noncarbonates (gneiss, schist, pegmatite) (Hintze, 1986). These rocks are exposed in the Mormon Mountains and Virgin Mountains. Marine sediments were deposited by paleo-seas beginning in the Paleozoic Era and continuing through the Mesozoic Era. Sedimentary deposits composed of mostly sandstone were deposited during the Paleozoic Era (Hintze, 1986). During the Permian and Triassic Period (200 to 280 million years

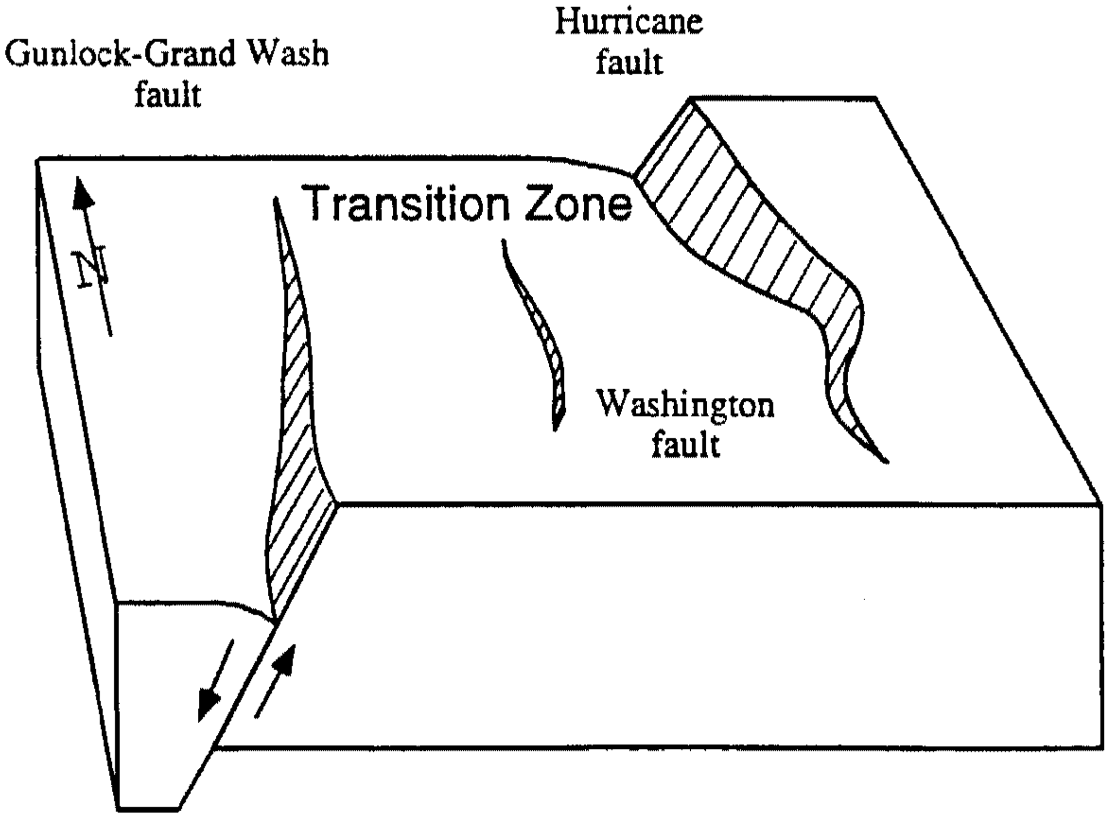


Figure 4: Geologic Diagram of Colorado Plateau and Basin and Range Province (from Schramm, 1994).

Schematic block diagram describing the displacement transfer zone relationship between the Gunlock-Grand Wash fault system, the Washington fault, and the Hurricane Fault. Displacement dies out at the tip line of the Gunlock fault as displacement increases on the Hurricane fault, 50 km east. This relationship could be generating the relatively wide width of the Transition Zone in this region. The Basin and Range province is to the west of the Gunlock-Grand Wash fault and the Colorado Plateau is to the east of the Hurricane fault. Diagram not to scale.

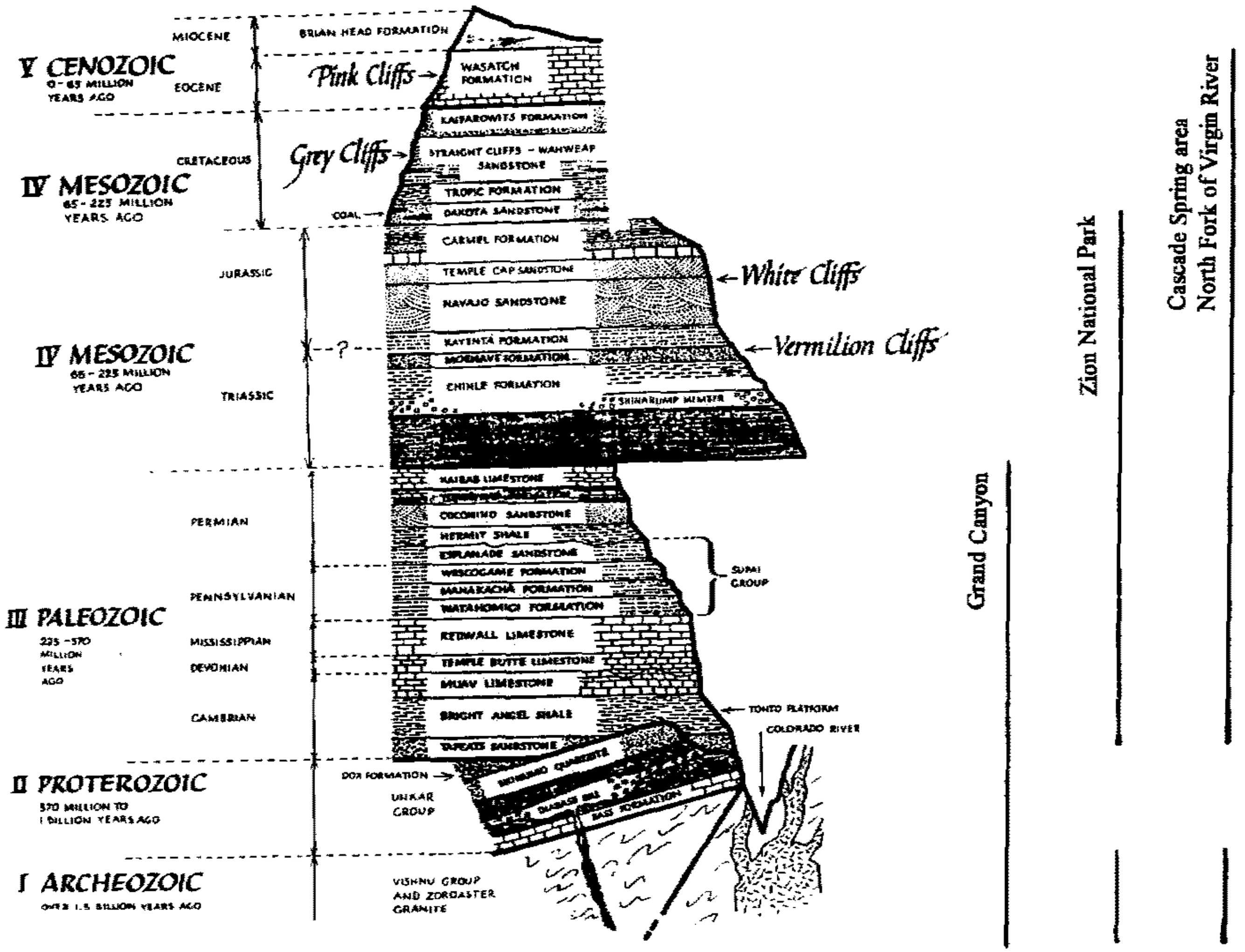
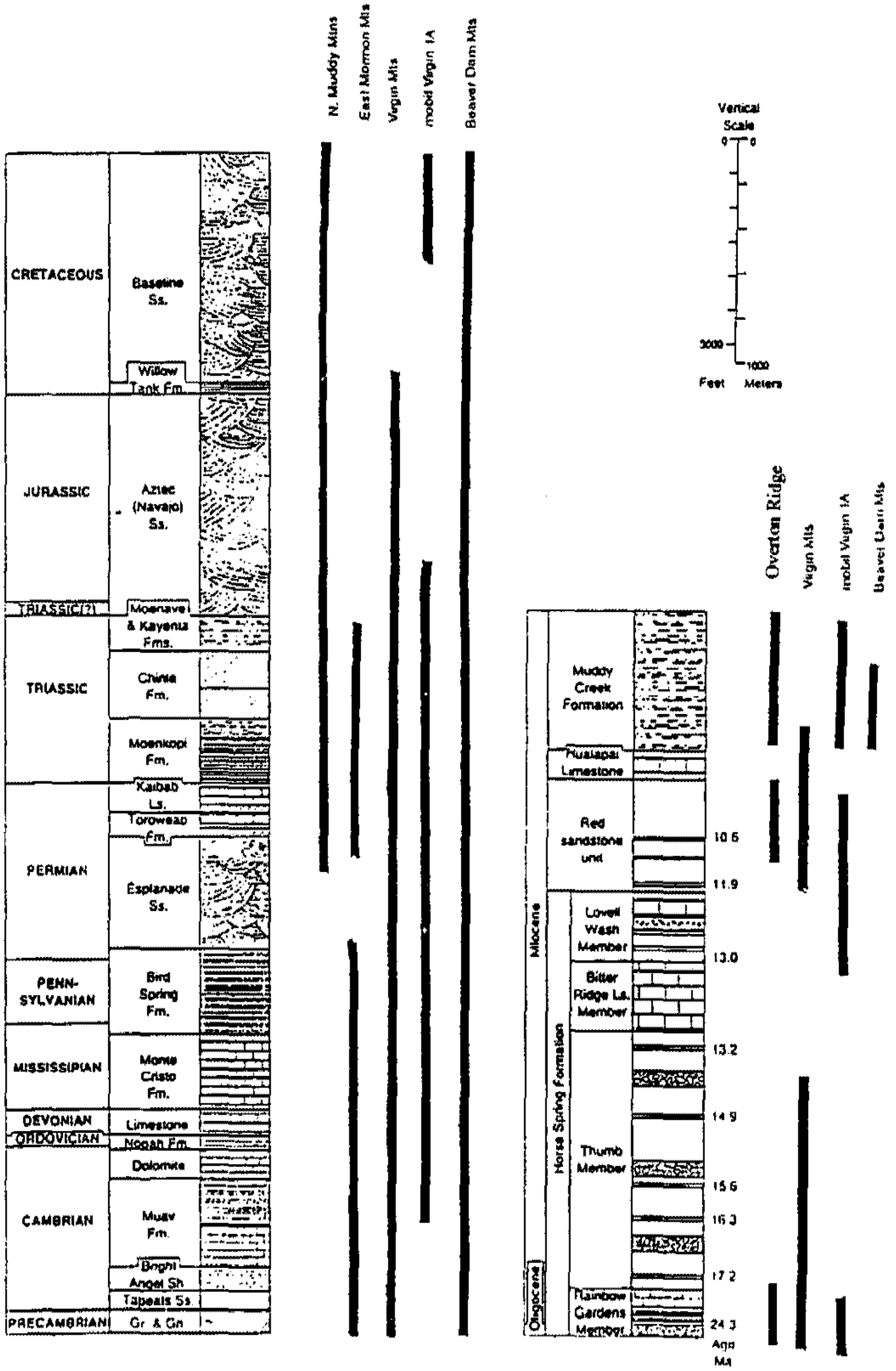


Figure 5: Generalized Stratigraphy of the Upper Virgin River Basin (from Coney and Beasley, 1985)



After Bohannon and others (1993), with Beaver Dam Mountains data from Hintze, 1986

Figure 6: Generalized Stratigraphy of the Lower Virgin River Basin (from Metcalf, 1995).

ago) depositional period a shallow sea was evaporated in the basin area producing saline ponds, lagoons, and bays that eventually resulted in deposits of gypsum, limestone, and dolomite. After the complete disappearance of the sea, a dry period followed in which sedimentation, erosion, geologic uplift, and canyon incisions occurred in progression. Again during the Mesozoic (i.e., the Triassic Period) the sea transgressed the area before receding during the Jurassic Period. It was during the Jurassic and Triassic (?) that the Navajo Sandstone layer (dominant formations in Zion National Park) was deposited (Stokes, 1986).

The following Cenozoic Era was dominated by igneous activity and rapid erosion. The transgression and regression of seas in and out of the area resulted in the deposition of formations of gypsum, sandstone and other sedimentary rocks that are common in much of the basin (Stokes, 1986).

Older alluvium ("old river deposits") (Tertiary and Quaternary Periods) are moderately cemented gravel, sand, and silt. The active river channel and dry wash tributaries are younger alluvium composed of gravels, sands, and silts, with clays and silts being deposited at the delta of the river as it enters Lake Mead (Glancy and Van Denburgh, 1969).

Major Geologic Structures

The Virgin River Basin is traditionally divided in the literature into two or three major sections (Glancy and Van Denburgh, 1969; Axen, 1993; Bohannon, 1983). These divisions are typically related to political boundaries. For this research the Virgin River

Basin is divided into three areas: the Upper, Central (middle), and Lower Virgin River Basins (Figure 2). Major geologic structures in the Virgin River Basin, the Hurricane Fault and the Gunlock-Grand Wash Cliffs Fault, are the basis for these divisions. A more detailed description of basin geology is summarized below according to these regional designations.

The Hurricane fault is a major normal fault with high-angle west-dipping structure marked by the Hurricane Cliffs, that extends south to north within the Virgin River Basin. The fault continues for approximately 250 km (156 miles) from northwestern Arizona into southwestern Utah (Figure 2). The northern portion of the fault borders the eastern edge of the Basin and Range Province and lies in the transition zone between the Colorado Plateau and the Basin and Range Province to the south. The Virgin River crosses the Hurricane fault near the town of La Verkin, Utah. The intersection of the Virgin River and the Hurricane fault is approximately three miles south of Toquerville, Utah (Figure 2). The age of the Hurricane Fault is controversial, but it is known to be currently active (Schramm, 1994).

The Gunlock-Grand Wash fault is located approximately 50 km (31 miles) west of the Hurricane fault and marks the western boundary of the Colorado Plateau (Hintze, 1985b). The Gunlock-Grand Wash fault divides the Central from the Lower Virgin River Basin in the western region of the study area. It is similar to the Hurricane fault as both are normal faults and down-drop on the west side (Hintze, 1985). The Gunlock-Grand Wash fault extends from the northwestern part of Arizona in a northerly direction into southwestern Utah (Figure 2). Near the Arizona-Utah state line the displacement of the

Gunlock portion of the fault is approximately 460 meters (1500 feet) (Hintze, 1986). The displacement is maximized near Gunlock, Utah (914 meters, 3000 feet) and minimized to near zero at Shivwits, Utah (Hintze, 1986).

Geologic Subdivisions of the Virgin River Basin

Upper Virgin River Basin

The Upper Virgin River Basin includes the headwaters of the Virgin River north and east of Zion National Park westward to the Hurricane fault and Hurricane Cliffs (Figure 2). This portion of the basin is consists of spacious plateaus and mesas. The regional terrain has been substantially altered by erosion due to the North and East Forks of the Virgin River. The East Fork begins northeast of Glendale, Utah at a lower altitude in comparison to where the North Fork (8900 feet, 2700 meters) originates at Cascade (Falls) Spring near Navajo Lake (Sandberg and Sultz, 1985). Zion National Park is located in the middle of this region. The East and North forks of the Virgin River join just south of Zion National Park.

Central Virgin River Basin

The Central part of the Virgin River Basin extends downstream along the Virgin River from the Hurricane fault area in Utah to the eastern Beaver Dam Mountains in western Utah and Arizona near the entry of the Virgin River Gorge area (Figure 2). The western boundary for the central basin is the Gunlock-Grand Wash fault. The Bull Valley and the Pine Valley Mountains provide the northern boundary of this section. The

Pine Valley Mountains display features characteristics of the Basin and Range Province to the west, and are composed of intrusive igneous rock (Clyde, 1987). This area is within the transition zone between the Colorado Plateau on the east and the Basin and Range Province on the west. The transition zone is complex with tectonic features characteristic of both the Colorado Plateau and the Basin and Range Province (Hintze, 1986). The southern boundary of the Central Virgin River Basin cuts through northwestern Arizona. The majority of the Central Virgin River Basin consists of sedimentary rocks that are younger than the Paleozoic Era and have low angle dip, rapidly eroding escarpments, and youthful drainage patterns (Cordova, 1978). In the western area of the Central basin the sedimentary rocks are more steeply dipping. Navajo Sandstone outcrops in 23 percent of the Utah portion of the Central Virgin River Basin (Clyde, 1987).

Lower Virgin River Basin

The Lower Virgin River Basin extends west from the Gunlock-Grand Wash fault into southeastern Nevada to where the Virgin River empties into Lake Mead. The Lower Virgin River Basin lies in the Basin and Range Province and is marked by major elevational decreases in the Virgin River Depression with major uplifts of the Virgin Mountains and the Beaver Dam Mountains (Anderson and Barnhard, 1993). The Lower Virgin River Basin lies in an area of Cenozoic normal faulting and Mesozoic folding and thrusting. This area is part of a transition between thinner Cambrian through Permian strata to the east compared to thicker Precambrian and Paleozoic strata to the west (Carpenter and Carpenter, 1994). Primary topographic features in the Lower Virgin River

Basin include the Beaver Dam Mountains, Virgin Mountains, Mormon Mountains, Mormon Mesa, and large alluvial valleys characteristic of the Basin and Range Province.

The Beaver Dam Mountains lie along the eastern region of the Basin and Range Province. The stratigraph exposed in the Beaver Dam Mountains is a six mile thick sequence of Paleozoic, Mesozoic, and Cenozoic sedimentary and volcanic rocks that overlie Precambrian rocks (i.e., gneiss, schist, and pegmatite) (Hintze, 1986; Anderson and Barnhard, 1993). Extensive folding and compressional faults are thought to be the result of Sevier orogenic forces (Hintze, 1986).

The Virgin Mountains are located in southeastern Nevada and northwestern Arizona. Significant exposures of the Precambrian core are present in these mountains. Paleozoic and Mesozoic sedimentary rocks, and some Tertiary basin-fill sedimentary and volcanic rocks comprise the remainder of the Virgin Mountains (Anderson and Barnhard, 1993). The Virgin River flows through the alluvial-filled valley (Muddy Creek Formation) (Anderson and Barnhard, 1993) and discharges into Lake Mead at the confluence of the Colorado River at the southern border of the basin (Figure 2).

CHAPTER 3

GROUNDWATER

Groundwater varies in both quality and quantity in the Virgin River Basin. It is estimated that over 800 springs discharge in the Utah portion of the Central and Upper Virgin River Basin (Clyde, 1987) with several additional springs discharging in the Lower Basin. Distinct aquifers occur throughout the region in both consolidated and unconsolidated rocks. Groundwater in the basin generally flows from higher to lower elevations in a direction toward streams and the Virgin River (Glancy and Van Denburgh, 1969; Clyde, 1978). This chapter provides an overview of groundwater in the Virgin River Basin and is followed by a discussion of some of the major springs discharging in the region.

Previous Investigations: Groundwater

As mentioned previously, several workers have studied the groundwater in the Virgin River Basin. Clyde (1987) incorporated information from several of these studies into a report on the feasibility of further development of groundwater resources in the Utah portion of the Virgin River Basin. Cordova et al. (1972) investigated the groundwater resources in the Central Virgin River Basin and Cordova (1978) described the Navajo sandstone aquifer in the Central Virgin River Basin. In addition, Cordova

(1981) studied the groundwater hydrology of the Upper Virgin River Basin. Clyde (1987) used these reports and gathered new information on water quality and quantity to provide a perspective for the best management of the groundwater in the basin.

According to Cordova (1978) the Navajo Sandstone is a very important aquifer in the Central and Upper Basin and provides large amounts of high quality groundwater. It consists of red and white sandstone and is 670 meters (2200 feet) thick in some areas (Cordova, 1978). Other consolidated rocks capable of transmitting lesser amounts of groundwater include the Wasatch Formation, Straight Cliffs Sandstone, Wahweap Sandstone, Kaibab Limestone, and the Kayenta, Moenave, Chinle, and Moenkopi Formations (Cordova, 1978, 1981). Unconsolidated alluvial deposits in valley portions of the Upper and Central Basin are the most extensive producing aquifers, but have less storage than the Navajo Sandstone (Cordova, 1978). The Virgin River and other streams in the basin can be gaining or losing streams depending on local geologic features (Cordova, 1981). Alluvial aquifers are commonly hydrologically connected to the streams and can be affected by groundwater pumping (Cordova, 1981).

The groundwater conditions in the Lower Virgin River Basin have been described in several reports (Glancy and Van Denburgh, 1969; Woessner et al., 1981; Black and Rascona, 1991; Brothers et al., 1992; and Metcalf, 1995). Groundwater, discharging in the mountainous areas of the Lower Virgin River Basin, occurs where carbonate rocks outcrop as well as in fractures in Precambrian rocks such as those that outcrop in the Virgin Mountains. Carbonate rock aquifers allow for the transmission of groundwater where solution cavities commonly form as a result of initial fracturing or other structural weakness (Glancy and Van Denburgh, 1969). Regional carbonate aquifers are present in some portions of the Lower Virgin River Basin and have been the subject of several studies (Dettinger, 1989; Burbey and Prudic, 1991; Prudic et al., 1993). These areas of thick sequences of Paleozoic carbonate rocks transmit large amounts of groundwater and are responsible for the discharge at many large regional springs (e.g., Muddy River Springs and Pahranagat Valley Springs) (Eakin, 1966; Winograd and Thordarson, 1975). The regional carbonate groundwater system of eastern Nevada may also be important in the Lower Virgin River Basin (Burbey and Prudic, 1991). The large abundance of fractured carbonate rocks in the area may provide an inflow access for groundwater from outside the basin (Brothers et al., 1993). Groundwater flow is believed to originate from recharge areas in the Virgin River Basin and then thought to move toward the Virgin River and then in a direction parallel to the river flow. The total groundwater recharge to the Lower Virgin River Basin is estimated to be 11,600 acre-feet per year (Glancy and Van Denburgh, 1969). Geochemical data from two separate studies, indicate that the groundwater is not being recharged from the Virgin River, but possibly from sources outside the basin (Las Vegas Valley Water District et al., 1992). Metcalf (1995) conducted a study on the Lower Virgin River Basin and concluded that there was no significant evidence for groundwater increasing the flow of the Virgin River downstream from Littlefield, Arizona.

Major Springs

Twenty-three springs were sampled for this research in and near the Virgin River Basin (Figure 7). Some of the springs sampled for this research are located just outside the Virgin River Basin. These springs, Big Muddy in the Moapa Valley and Roger's and Blue Point, south and west of the confluence of the Virgin River and the Colorado River at Lake Mead, were sampled to provide additional geochemical information. Many of the springs sampled in this study have limited water quality information available in the literature. The springs receiving the most attention in the literature are generally those with the highest flows and those that are important to the local economies. Some of the largest springs in the Virgin River Basin that are economically and environmentally important to the area include Toquerville Springs, Littlefield Springs, and Pah Tempe Hot Springs (La Verkin Springs). These springs are discussed in detail below. Geologic descriptions, location descriptions, and comments pertaining to these springs and the other springs sampled for this research are described in the appendix. A brief discussion of the geology in the vicinity of each spring site is in Appendix A. Information on spring site access and individual spring site descriptions is in Appendix B.

Pah Tempe Hot Springs

Pah Tempe Hot Springs (La Verkin Springs or Dixie Hot Springs) discharges directly out of Kaibab Limestone from the side walls and the bed of the Virgin River. The springs lie east of the Hurricane fault in Utah between La Verkin and Hurricane, Utah (Figure 7). The temperature of the Pah Tempe Hot Springs exceeds 100 °F (38 °C) and

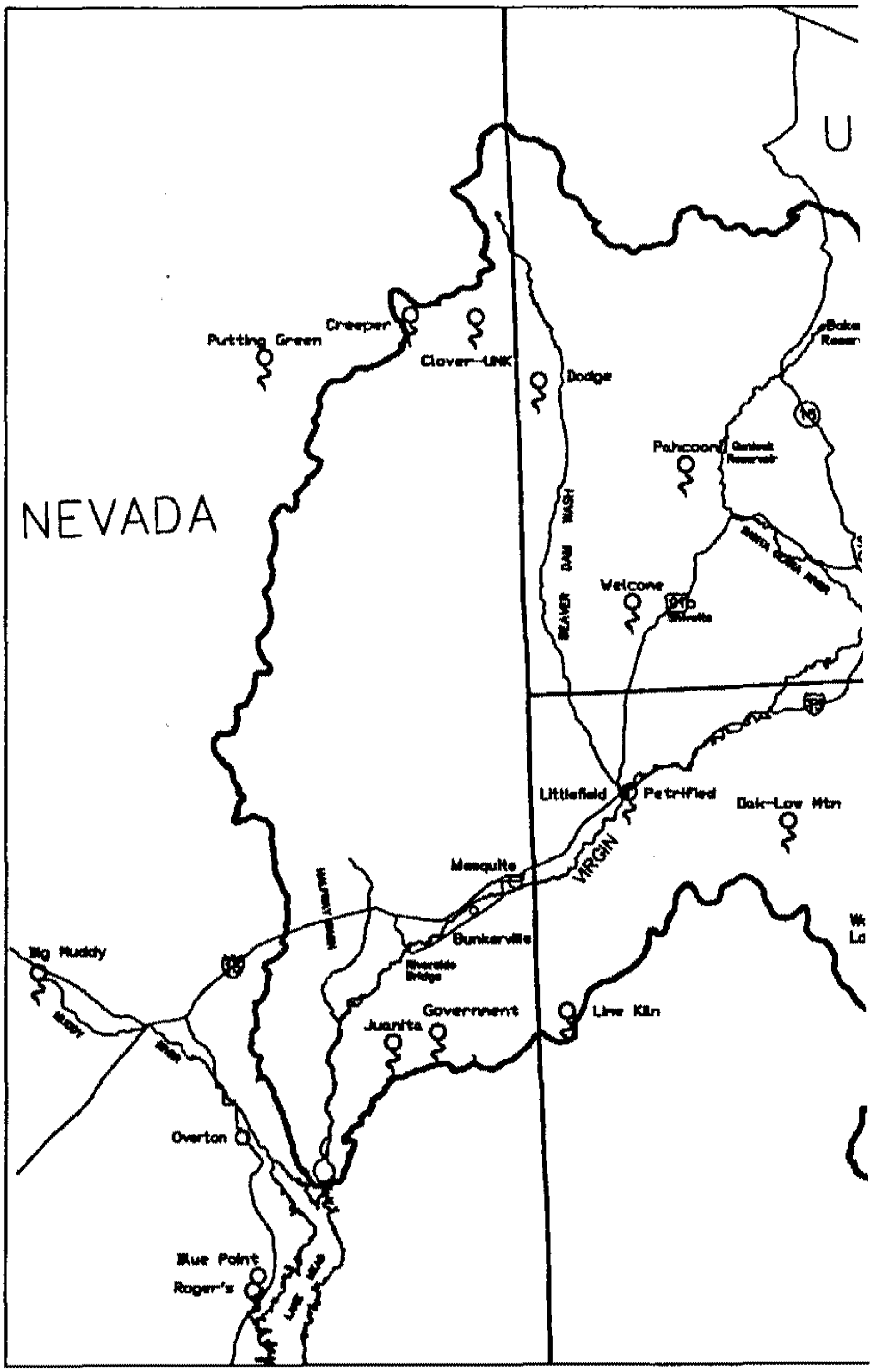
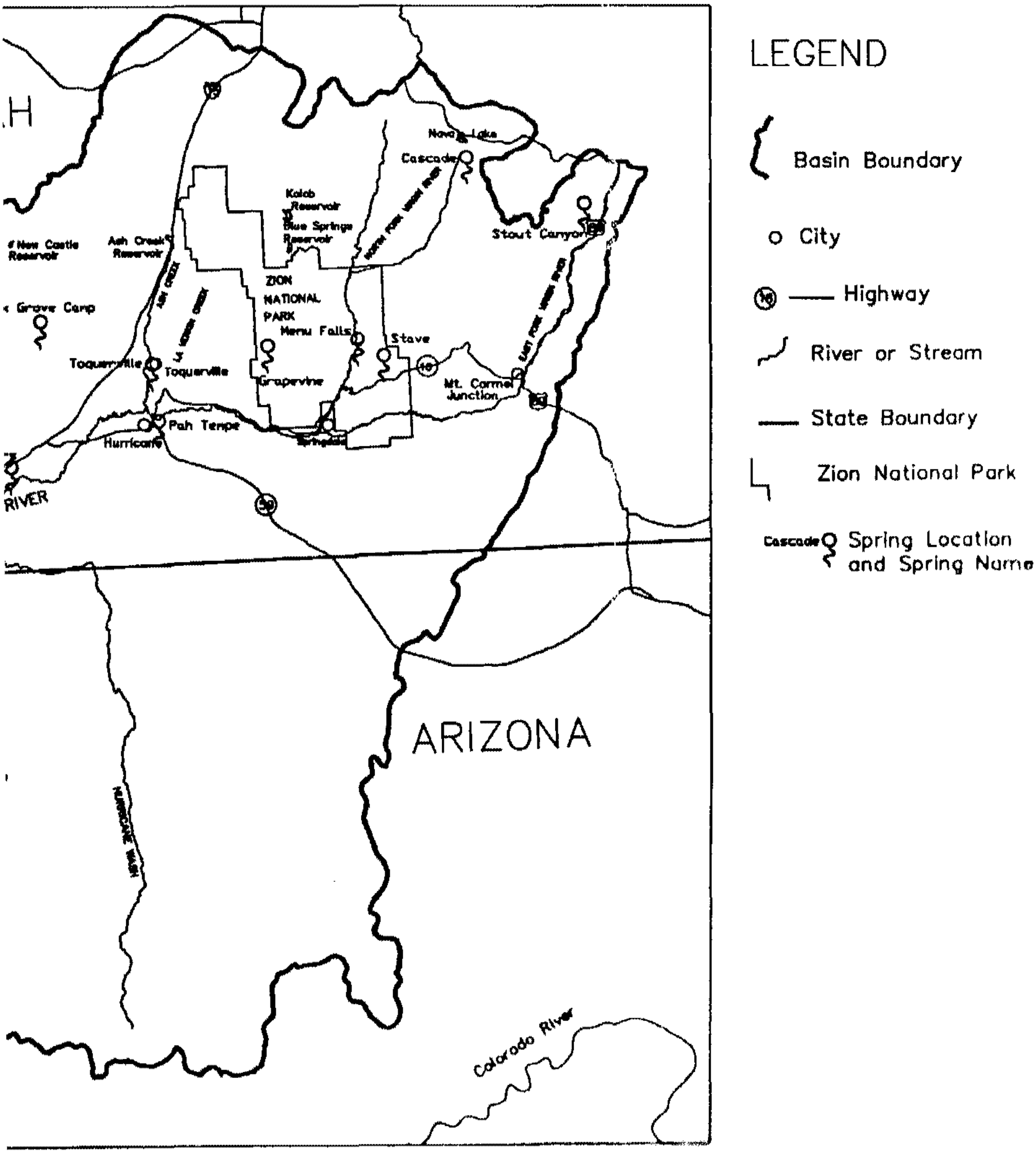


Figure 7: Spring Location Map


.H
Navajo Lake
Cascade
Kolob Reservoir
Blue Springs Reservoir
North Fork Virgin River
Stout Canyon
New Castle Reservoir
Ash Creek Reservoir
Ash Creek
La Verkin Creek
ZION NATIONAL PARK
Grove Camp
Menu Falls
Stave
Toquerville
Toquerville
Grapevine
Mt. Carmel Junction
East Fork Virgin River
Pah Tempe
Hurricane
Springdale
RIVER
59
15
9
89
ARIZONA
Hurricane Wash
Colorado River
LEGEND
Basin Boundary
City
Highway
River or Stream
State Boundary
Zion National Park
Cascade
Spring Location and Spring Name

adds approximately 11 to 12 cfs (cubic feet per second) (.31 to .34 m^3/s) to the flow of the river (Mundorff, 1970). The water quality of these springs' is very poor. The high concentration of total dissolved solids negatively affects the general water quality of the Virgin River downstream from the point of discharge at these hot springs. For example, boron levels in the river as a result of the springs' discharge are above plant tolerance levels (Sandberg and Sultz 1985).

Extensive hydrologic studies have been conducted by the United States Bureau of Reclamation to develop potential options for removing the high total dissolved solid content of the springs' waters. There has been discussion about removing the water discharging from Pah Tempe Hot Springs so that it will not flow into the Virgin River and negatively impact the water quality (Washington County Water Conservancy District, 1994). One proposal involves pumping the spring water to desaltation or evaporation facilities (Sandberg and Sultz, 1985). Currently, the Pah Tempe spring area is privately owned and used as a recreational resort. It has been proposed that the removal of the spring water would allow for the "implementation of improved irrigation practices, eliminate the requirement for winter irrigation practices to remove excess salts, permit the selection of higher value crops and make the agricultural water of suitable quality to be converted to municipal uses as agricultural ground is put to other uses" (Washington County Water Conservancy District, 1994).

The Hurricane fault is likely providing an impermeable boundary which allows groundwater to surface at Pah Tempe Hot Springs. It is likely that the spring water is genetically related to the Hurricane Fault and is influenced by concealed igneous masses adds approximately 11 to 12 cfs (cubic feet per second) (.31 to .34 m^3/s) to the flow of the river (Mundorff, 1970). The water quality of these springs' is very poor. The high concentration of total dissolved solids negatively affects the general water quality of the Virgin River downstream from the point of discharge at these hot springs. For example, boron levels in the river as a result of the springs' discharge are above plant tolerance levels (Sandberg and Sultz 1985).

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Toquerville Springs

Toquerville Springs represent the largest spring discharge in the Central and Upper Virgin River Basin. The springs emerge from the banks and stream bed of Ash Creek near the Hurricane Fault just north of Toquerville, Utah (Figure 7). The total flow from both the upper and lower Toquerville Springs has been estimated to be 30 cfs (.85 m^3/s) (Utah Board of Water Resources, 1993). The origin of Toquerville springs has not been established although Sandberg and Sultz (1985) suggest that spring flow is sustained by underflow from Ash Creek and /or La Verkin Creek. Moreover, Cordova et al. (1972) noted an increase in the discharge from Toquerville springs after the completion of the Ash Creek Reservoir in 1961. The bottom and sides of the reservoir are composed of highly jointed basalts that extend to the Toquerville Springs area. These rocks likely provide a pathway for reservoir water to discharge from Toquerville Springs. Mower (1982) indicated that seepage from Ash Creek Reservoir likely contributes up to 5 cfs (0.14 m^3/s) to the spring flow at the Toquerville Springs. Additionally, Cordova et al. (1972) suggested that fluctuations in local precipitation likely cause variation in spring discharges. Toquerville Springs are believed to originate from Navajo sandstone along the

Hurricane fault (Utah Board of Water Resources Department Report, 1993).

Littlefield Springs

The Littlefield Springs have several orifices that occur along a six mile stretch of the Virgin River located in northwestern Arizona. Previous studies by Trudeau (1979) and Metcalf (1995) indicate very similar water chemistry for the different orifices of the Littlefield Springs. For this specific study, Petrified Spring, which is a spring in the group of Littlefield Springs was sampled as a representative of the Littlefield Springs (Figure 7). These springs occur along the region from the Virgin River Gorge in Arizona to the area of Littlefield, Arizona. The springs are very important to the agricultural economy of the region. During summer months, for example, there are times when the Virgin River would have no flow if it were not for the contributions of groundwater from these springs (Trudeau, 1979). The discharge of Littlefield Springs is estimated to be a relatively constant flow of 65 cfs (1.8 m^3/s) (Glancy and Van Denburgh 1969). These investigators argue that the Littlefield Springs originate upstream in an influent area of the Virgin River and flow through carbonate rocks (karst terrain) until they discharge downstream (Trudeau, 1979). In addition, this same source of the Littlefield Springs was also suggested by Bagley et al. (1955). Total dissolved solids of the Littlefield Springs was reported to be approximately 3000 ppm by Glancy and Van Denburgh (1969). Based on water quality and quantity information, Trudeau (1979) suggests that the source of the Littlefield Springs is a combination of influent river water and a smaller portion of infiltration and percolation of local meteoric water (i.e., precipitation).

CHAPTER 4

METHODOLOGY

In this chapter the basic approach that was taken to collect the information needed to perform the Principal Component Analysis as well as other analysis tools is discussed. The focus of this research was to examine the water chemistry of selected springs within and in close proximity to the Virgin River Basin. The methods of sample collection and chemical analysis of the groundwaters are discussed below.

Field Reconnaissance and Spring Selection

In May and June of 1995 field reconnaissance was conducted to assist in determining which springs in the study area would be chosen for spring water sample collection and water chemistry analysis. Because of the large areal extent of the Virgin River Basin (5900 sq. miles, 15280 sq. kilometers) and the numerous springs (over 800 in the Upper and Central Basin alone), field reconnaissance was essential in order to determine which springs were to be sampled for chemical analysis. The field exploration of springs in the Virgin River Basin was completed to determine actual spring locations and to conduct basic field measurements. Some specific parameters measured included pH, temperature, alkalinity, and estimation of flow rates. The accessibility of the springs was also addressed during this field reconnaissance. Field data collected during the field reconnaissance pertaining to each spring are presented in the Appendix C.

In order to meet the goals of the research in a timely and cost efficient manner, the large number of possible spring sampling sites located in the Virgin River Basin had to be eliminated. The criteria used for selecting which springs would be sampled were based on information gathered from the literature as well as the field reconnaissance. Important criteria used in the spring selection process included accessibility to the spring site as well as whether the spring is representative of the geographic, geologic, and climatic diversity within the basin. Springs on which previous chemical analysis had been performed were preferred to enable a baseline chemical concentration comparison between sampling events. Also, springs of hydrological, environmental, or political importance were targeted for sampling. For example, Littlefield Springs (i.e., Petrified Spring) and Toquerville Springs are vital to the economies in the areas in which they discharge because of the need for water for irrigation and domestic purposes. Pah Tempe Hot Spring, on the other hand, was sampled because of its relatively large discharge in the proximity of a major geologic structure (i.e., Hurricane fault), and its significant impact on the overall water quality to the Virgin River.

Sample Collection

Sample collection methods for analyses of groundwater chemistry followed the standard operating procedures developed at the Harry Reid Center for Environmental Studies at the University of Nevada at Las Vegas (Stetzenbach et al., 1994; HRC Standard Operating Procedure, 1995). The procedures are based on the sample collection protocol that evolved from the research by Bruland et al. (1979). Consistent sampling techniques were utilized throughout the sample collection procedure to provide uniformity of results. Sample containers, pump tubing, and all equipment that could come in contact with the spring water during sampling were subject to the extensive acid pre-cleaning procedures outlined in Table 2.

Isotope samples for deuterium and oxygen-18 were collected in 50 ml glass bottles. Samples for these stable isotopes were not filtered or acidified. Isotopic samples were analyzed at the Desert Research Institute in Las Vegas, Nevada.

Sample containers used in the collection of major and trace element chemistry samples were made of low density polyethylene (Nalgene). The cleaning process consisted of initially washing the bottles with tap water and detergent, followed by rinsing three times with Nanopure water. The sample collection bottles were soaked in 10-20% (volume per volume) reagent-grade nitric acid solution for one week and then rinsed three times with Nanopure water. The bottles were soaked another week in 10-20% trace-metal grade nitric acid and rinsed twice with Nanopure water and once with distilled water. After air-drying in a covered environment the bottles were capped and placed in sealable plastic bags. During all cleaning and sampling procedures, clean polyethylene gloves were worn to prevent the contamination of sample containers.

Records of sample collection were kept in a field log book and then entered into the HRC sample tracking data base. Samples were tracked by a unique sample number, date and time, sample location name, and sample type. Sample numbers consisted of the date of collection and specific bottle number (i.e., 071995-01). The sample number and

Table 2: Sample Collection Parameters

Purpose	# of bottles	Amount (ml)	Filtered	Acidify	Acid Volume (ml)*
ICP-MS (trace elements)	4	1000	yes	yes	10
AA-Cations	1	125	yes	yes	1.25
Uranium**	1	1000	yes	yes	10
Anions	1	125	yes	no	--
Alkalinity	1	125	no	no	--
Isotopes*** (glass or non-acid cleaned bottles)	1	50	no	no	--

* Concentrated Seastar Acid (ultrapure nitric acid).

** Uranium isotope samples were collected, but have not been analyzed at this time.

*** Oxygen-18 and deuterium isotope samples were collected and analyzed at the Desert Research Institute in Las Vegas, Nevada.

spring name appeared together in all laboratory entries. Information concerning sample collection displayed in Table 2.

Measured field parameters included electrical conductivity, temperature, and pH which were all measured at the spring sampling site. Alkalinity samples were kept on ice after collection and analyzed at the end of the sampling day. Measurements for total alkalinity were based on titrations using a Hach Digital Titrator (Model 16900-01). Samples were titrated with sulfuric acid to a colorimetric end point corresponding to a specific pH and then alkalinity was caluclated according to the Hach Digital Titrator manual (1992). Electrical conductivity was measured by using a Corning Checkmate 90 or a Cole-Parmer meter (1481-61). Temperature and pH were measured by a Corning Checkmate 90 or a Beckman meter. Standard solutions pH and electrical conductivity were checked at the time of daily instrument calibrations and at each sampling site to ensure the stability and accuracy of the measurements. Instruments were recalibrated if standard check measurements were not reading properly. The field measurements and information gathered during spring sampling are presented in Table 3, Chapter 5.

Spring water samples for trace elements (ICP-MS analysis), cations, anions, and uranium analysis were collected in acid precleaned polyethylene bottles. Extreme care was taken to ensure a representative noncontaminated sample was collected at each spring site by using consistent sampling techniques. During the sampling process clean polyethylene gloves were worn when handling any equipment that came in contact with the spring water. This reduced the potential for contamination to the spring water samples. Sample teams utilized a "clean hands-dirty hands" process to further ensure clean techniques. The person that was responsible for actually collecting the filtered sample in the acid, pre-cleaned bottles, touched only the bottles and placed the bottle directly into a preassigned sealable plastic bag. Another person held the bag, sealed each bag, and then placed all of the bagged samples in a large plastic bag designated for the specific spring. At each spring site individuals were assigned specific tasks in order to maintain a clean environment throughout the sampling procedure. The consistency of the sampling procedure is important to maintain contamination-free equipment and spring water samples.

Samples were collected as close to the orifice of the spring as possible by using a peristaltic pump apparatus (Cole-Parmer Masterflex Variable Speed Sampling Pump, battery-charged power drills with peristaltic pump head, or peristaltic hand pumps). Acid washed teflon tubing was used in the collection process except for approximately 25 cm of pliable Tygon tubing (acid washed) used directly in the pump head. At spring locations where it was difficult to get directly at the orifice, teflon tubing was attached to a PVC rod and held in the main flow from the spring orifice.

As noted in Table 2, a 0.45 micron Gelman in-line filter was used in the sample collection such that all groundwater samples were filtered through this 0.45 micron filter. Care was taken to protect all collection equipment from contamination between each sampling site by covering the equipment with clean plastic.

At least one liter of the spring water was pumped through the sampling system prior to the actual collection of a sample to flush the sample tubing. Each sample container was rinsed three times with approximately 50 ml of the filtered spring water before collecting the sample. In the case of inclement conditions (e.g. wind) a clean polyethylene bag was used to cover the filter and bottle opening to reduce the potential contamination from dust particles.

As noted in Table 2, samples were acidified with ultrapure Seastar nitric acid as soon after sample collection as possible to bring the pH of the sample to below a pH of 2. All samples were stored on ice in insulated coolers while in the field. When samples were returned to the Harry Reid Center laboratory they were placed in the cold storage facilities at 4°C for preservation until analysis and verification of data could be completed.

Quality control procedures were maintained to ensure the quality of the sampling procedures. A lab blank consisting of unfiltered Nanopure water was collected for all sample types being collected during that sampling trip. The lab blanks remained in the cold storage facility at the HRC laboratory. Additional blanks labeled as field blanks were collected at the beginning of each sampling trip and were treated as if they were actual spring samples. These blanks, for example, consisted of Nanopure water that was pumped through the peristaltic pump apparatus and treated as spring water samples. All blanks were acidified according to Table 2.

Sample Analysis

Sample analysis was conducted at the Harry Reid Center for Environmental Studies (HRC) on the UNLV campus (unless otherwise noted). Analytical techniques for trace element analysis is detailed in Stetzenbach et al. (1994). Briefly, trace elements were determined by inductively coupled plasma mass spectrometry (ICP-MS) (Perkin-Elmer Elan 5000). The lanthanides (rare earth elements, REE) were preconcentrated by using cation exchange (HRC Standard Operating Procedures, 1995). Rare earth elements are commonly present in spring water at concentrations less than one part per trillion (ppt). These concentrations are at or below the direct measurement detection limits of the ICP-MS. The preconcentration procedure allows for the analysis of the rare earth elements (REE) by ICP-MS (HRC standard operating procedures, 1995). Laboratory procedures and quality control parameters used at HRC follow U.S. EPA methods (Stetzenbach et al., 1994). The measurement precision was typically less than +/- 10% of the standard deviation (RSD), but was exceeded (greater than 10% RSD) for measurements of some elements due to sample matrix problems. Recoveries for all trace elements were always within +/- 25% RSD. High total dissolved solids that are present in some samples caused difficulty in the measurements due to the complex nature of the concentrated matrix. However, internal standards were used to correct for this decrease in intensity.

Anions were analyzed within 48 hours of sample collection using a Dionex ion chromatograph. The anion analysis procedure follows the standard operating procedure established at HRC based on the EPA methods (HRC Standard Operating Procedures, 1995). Cations were analyzed on a Varian Atomic Absorption Spectrometer. EPA methods were used and are detailed in the HRC standard operating procedures (HRC Standard Operating Procedure, 1995).

CHAPTER 5

RESULTS OF CHEMICAL ANALYSIS

The results of the field measurements and the analytical chemistry analyses conducted on the 23 springs selected for sampling in the study area are presented in this chapter. Moreover, observations made from inspection of the raw data are summarized. Tables 3-7 display the chemical data for each of the 23 spring sites.

Field Parameters

Field parameters that were measured include temperature, pH, alkalinity, and electrical conductivity and are presented in Table 3. Field parameter values varied greatly throughout the Virgin River Basin. Temperatures, for example, ranged from 9°C (Stout Canyon Spring) to 40°C (Pah Tempe Hot Springs) and alkalinity values varied from 79 mg/l (Creeper) to 1032 mg/l (Pah Tempe Hot Springs). Creeper and Pah Tempe also had the extremes in electrical conductivity values with EC values of 230 µS and 10,670 µS respectively.

Discharge rates were visually estimated at most spring sites, however, spring discharges cited in the literature are were used if available. Several springs had relatively low discharges at the time of sample collection. The springs with lower discharges (1-2 gpm) included Government, Pahcoon, Stave, and Oak Spring at Low Mountain. The

Table 3: Field Parameters and Location of Spring Sites

SPRING NAME	GENERAL LOCATION	DATE SAMPLED	LATITUDE* (north)	LONGITUDE* (west)	ELEVATION (feet)	DISCHARGE (j)	WATER TYPE	pH	TEMP. oC	ALK. (i) mg/l	EC µS
Petrified	Littlefield, AZ	7/6/95	36 53.61 N	113 55.00 W		29000 gpm (a)	Ca,SO4	7.0	28.2	369	3507
Government	Virgin Mtns, NV	7/6/95	36 38.74 N	114 10.95 W		1-2 gpm	Mg, Na, Ca, HCO3	7.2	30.2	184	811
Lime Kiln	Virgin Mtns, NV	7/6/95	36 39.80 N^	114 00.63 W^	4700	2-3 gpm	Ca, HCO3	7.3	25.2	402	961
Pahcoon	Beaver Dam Mtns., UT	7/8/95	37 14.46N	113 49.60 W	3760	2 gpm (b)	Ca, Mg, HCO3	7.4	20.8	356	636
Welcome	Beaver Dam Mtns., UT	7/8/95	37 05.80 N	113 54.25 W		5-10 gpm	Ca, Mg, HCO3	7.3	20.6	173	949
Roger's	Lake Mead, NV	7/10/95	36 22.65 N	114 26.33 W		880 gpm (c)	Ca,SO4	7.0	31.8	141	3490
Blue Point	Lake Mead, NV	7/10/95	36 23.59 N	114 25.89 W		400 gpm (c)	Ca,SO4	7.0	29.2	145	3977
Big Muddy	Moapa Valley, NV	7/10/95	36 43.31 N	114 43.01 W	1760	3400 gpm (d)	Na, HCO3, SO4	7.1	30.8	215	968
Dodge	Beaver Dam Mtns., UT	7/17/95	37 20 09 N	114 01 32 W		5-10 gpm	Ca, Mg, Na, HCO3	7.6	28.6	292	701
Creeper	Clover Mtns., NV	7/17/95	37 24 54 N	114 11 40 W		0.50 cfs 220 gpm	Ca, HCO3	6.9	24.2	79	230
Putting Green	Clover Mtns., NV	7/17/95	37 22 14 N	114 23 35 W		10-20 gpm	Mg, Ca, HCO3	6.9	19.3	126	284
Clover-UNK	Clover Mtns., NV	7/17/95	37 24 29 N	114 06 22 W		110 gpm	Ca,SO4	6.6	20.3	317	1367

^ estimated from map
* Data from GPS readings unless otherwise noted

a - Glancy and Van Denburgh, 1969
b - Cordova et al., 1972
c - Mifflin, 1968
d - Dettinger et al., 1995
i - alkalinity, mg/l
j - flows were visually estimated unless otherwise noted

Table 3: Field Parameters and Location of Spring Sites (cont.)

SPRING NAME	GENERAL LOCATION	DATE SAMPLED	LATITUDE* (north)	LONGITUDE* (west)	ELEVATION (feet)	DISCHARGE (j)	WATER TYPE	pH	TEMP. oC	ALK. (i) mg/l	EC µS
Juanita	Virgin Mtns., NV	7/17/95	36 38 15 N	114 14 50 W		500 gpm	Ca,SO4	6.8	28.3	169	1042
Oak-Low Mtn.	Virgin Mtns., AZ	7/17/95	36 51 40 N	113 42 22 W		1-2 gpm	Ca, Mg, HCO3, SO4	6.8	16.6	278	987
Pah Tempe	La Verkin, UT	7/18/95	37 11 21 N	113 16 06 W	3100	4700 gpm (e)	Na, Cl	6.1	40.2	1032	10670
Grapevine	Zion Natl. Park, UT	7/18/95	37 16 52 N	113 05 39 W	4500	360 gpm	Ca, Mg, HCO3	8.3	19.5	140	360
Stout Canyon	Stout Canyon, UT	7/19/95	37 26 13 N	112 34 21 W	7000	225 gpm	Mg, Ca, HCO3	8.0	9.0	261	480
Cascade	Navajo Lake, UT	7/19/95	37 30 09 N	112 45 28 W	8900	450-2700 gpm (f)	Ca, Mg, HCO3	8.0	10.3	152	293
Stave	Zion Natl. Park, UT	7/19/95	37 15 39 N	112 54 16 W		1-2 gpm	Ca, HCO3	7.4	11.2	408	800
Menu Falls	Zion Natl. Park, UT	7/19/95	37 16 70 N	112 56 59 W		3-5 gpm	Na, Cl, SO4	8.4	21.1	185	1540
Toquerville	Toquerville, UT	7/20/95	37 15 54 N	113 16 48 W	3200	13500gpm (g)	Ca, Mg, SO4, HCO3	7.8	17.7	172	700
Oak Grove Camp	Pine Valley Mtns., UT	7/20/95	37 19 10 N	113 27 12 W		2-5 gpm (h)	Ca, HCO3	7.4	11.2	213	407
Boilers	St. George, UT	7/20/95	37 08 15 N	113 30 46 W	2760	700 gpm	Ca, HCO3, SO4	7.7	25.7	161	511

* uncorrected values
** GPS value not available
estimated from topographic maps

e - Cordova, 1981
f - Sandberg and Sultz, 1985
g - Utah Board of Water Resources, 199

h - flow at one orifice
i - alkalinity, mg/l, HCO3+CO3
j - flows were visually estimated unless otherwise noted

greatest discharge in the study area issues from the Muddy Springs (37,000 acre-feet per year). The Muddy Springs, of which Big Muddy Spring is a part, are thought to belong to the regional carbonate aquifer system of eastern Nevada (Eakin, 1966; Winograd and Thordarson, 1975; Dettinger, 1989) and, therefore, do not represent groundwaters characteristic of the Virgin River Basin. Instead, the Littlefield Springs, which are located within the Virgin River Basin exhibit the largest collective discharge values of all of the springs within the drainage basin (60 to 65 cfs) (1.7 to 1.8 m^3/s) (Glancy and Van Denburgh, 1969; Trudeau, 1979). The extreme variations in field parameters is also reflected in the overall analysis of these spring waters.

Chemical Concentrations

The results of the chemical analysis of the spring waters are presented in Tables 4-7. Detection limits for the concentration of each element or ion are listed in each table along with the associated standard deviation of each measurement. In some cases, concentrations below the detection limits were reported and used in the principal component analysis based on the reasonableness of the standard deviation of the measurement. These concentrations have been marked with a star (*).

There is generally substantial diversity between the chemistry of spring waters throughout the study area. Major cation and anion data are listed in Table 4. The concentrations for HCO_3 and CO_3 were generated from PHREEQE (geochemical model) and were based on field alkalinity measurements. Tables 5 and 6 present the trace element concentration (without REE) for the spring waters sampled in the study area. The REE concentrations are presented in Table 7.

The differences in chemical concentrations is likely a result of many factors. Some of these factors may include the geologic and/or topographic setting, the length of flow path, and the source of the groundwater. Observations made concerning major ion concentration, trace elements, and rare earth elements are detailed in later sections.

Table 4: Major Ion Data for Spring Waters (Virgin River Basin and Surrounding Study Area)

1st # concentration
2nd # standard deviation

all values in ppm

Element	Detection Limit	Petrified	Government	Lime Kiln	Pahcoon	Welcome	Roger's	Blue Point	Big Muddy	Dodge	Creeper	Putting Green	Clover-UNK
Ca	0.3	404.2	55	96.8	61.9	82.5	430.3	484.2	61.2	56.8	23.0	30	215.7
		0.2	2	0.6	0.4	0.3	0.7	0.2	0.2	0.7	0.8	1	0.3
K	0.1, 0.001	27.72	5.54	2.84	1.54	1.19	20.46	21.75	9.43	1.56	1.9	1.214	1.43
		0.02	0.05	0.04	0.04	0.02	0.02	0.06	0.02	0.05	0.02	0.006	0.02
Mg	0.1	122.2	36.53	8.55	29.85	48.96	146.5	162.95	27.88	30.19	5.7	21.11	46.22
		0.1	0.09	0.07	0.06	0.06	0.1	0.09	0.08	0.06	0.04	0.07	0.07
Na	0.7	284.8	61.7	55.7	26.6	67.8	301	384	101.3	52.9	11.32	27.3	40.6
		0.6	0.4	0.4	0.2	0.7	4	0.4	0.3	0.7	0.03	0.5	0.5
F	0.006	2.14	0.81	0.97	0.50	0.58	2.35	2.6	1.74	0.26	0.230	2.04	0.23
		0.07	0.01	0.01	0.01	0.02	0.08	0.3	0.02	0.01	0.005	0.03	0.01
Cl	0.002	408	76.8	38.6	43.1	49.4	328	376	63.7	33.5	17.3	7.1	16.4
		2	0.3	0.200	0.400	0.2	5	2	0.3	0.20	0.20	0.2	0.2
Br	0.01	0.69	0.517	0.38	0.32	0.379	0.172	0.217	0.219	0.29	0.180	0.080	0.199
		0.01	0.009	0.01	0.01	0.006	0.003	0.002	0.002	0.02	0.001	0.003	0.002
NO3	0.01	2.68	34.6	ND	10.7	1.48	1.450	0.93	1.91	0.098	1.62	0.43	0.48
		0.01	0.3		0.2	0.02	0.009	0.01	0.01	0.006	0.01	0.01	0.01
PO4	0.02	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
SO4	0.02	1186	75.2	77.2	83.1	97.9	1608	1837	162.2	43.90	8.6	7.73	471
		2	0.4	0.3	0.3	0.4	3	8	0.1	0.07	0.3	0.02	4
HCO3*	NM	337.6	175.8	384.6	341.1	164.2	128.5	131.7	206.2	277.2	77.0	122.0	299.6
CO3*	NM	0.3	0.2	0.5	0.5	0.2	0.1	0.1	0.2	0.8	0.0	0.1	0.1

* concentration generated from the use of PHREEQE, based of field alkalinity, standard deviation not calculated
ND - Not Detected
NM - Not Measured

Table 4: Major Ion Data for Spring Waters (Virgin River Basin and Surrounding Study Area) (cont.)

all values in ppm

1st # concentration
2nd # standard deviation

Element	Detection Limit	Juanita	Oak-Low Mtn.	Pah Tempe	Grapevine	Stout Canyon	Cascade	Stave	Menu Falls	Toquerville	Oak Grove Camp	Boilers
Ca	0.3	137.5	104.6	775	28.7	51.6	41.0	112.0	79.5	75.1	69.1	68
		0.3	0.5	2	0.2	0.3	0.4	0.4	0.1	0.4	0.1	2
K	0.1, 0.001	5.05	2.40	153.98	3.66	0.761	0.419	1.16	7.79	2.29	0.312	2.42
		0.06	0.04	0.02	0.05	0.002	0.002	0.02	0.05	0.04	0.008	0.05
Mg	0.1	44	57.75	145.6	15.98	36.36	9.23	43.09	37.19	31.96	8.19	15.34
		0.08	0.04	0.1	0.02	0.07	0.09	0.02	0.04	0.03	0.06	0.08
Na	0.7	24.73	24.9	2270	13.93	1.59	0.97	6.5	212.8	20.31	4.9	9.01
		0.02	0.1	20	0.1	0.01	0.01	0.02	0.3	0.01	0.01	0.01
F	0.006	0.54	0.17	ND	0.103	0.133	0.037	0.35	ND	ND	0.08	0.178
		0.04	0.01		0.004	0.001	0.003	0.01			0.01	0.002
Cl	0.002	16.80	56.6	3250	7.82	2.99	2.1	6.6	259	15.2	2.95	6.510
		0.09	0.3	10	0.09	0.1	0.2	0.2	2	0.1	0.03	0.008
Br	0.01	0.126	0.347	2.4	0.063	0.026	ND	0.044	0.073	0.065	ND	0.033**
		0.003	0.005	0.1	0.001	0.002		0.002	0.002	0.002		
NO3	0.01	3.67	1.4	5.1	17.3	0.11	0.597	ND	0.28	2.79	0.089	1.31
		0.05	0.01	0.1	0.01	0.01	0.008		0.01	0.02	0.004	0.01
PO4	0.02	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
SO4	0.02	371.4	187	1891	12.10	5.24	3.05	55.3	244.9	158.6	5.110	88.10
		0.2	2	3	0.01	0.02	0.04	0.4	0.6	0.7	0.005	0.06
HCO3*	NM	160.5	264.8	906.7	130.9	247.2	145.7	387.8	165.1	162.9	205.5	153.0
CO3*	NM	0.1	0.1	0.2	1.4	1.0	0.6	0.5	2.7	0.6	0.2	0.5

* concentration generated from the use of PHREEQE, based of field alkalinity, standard deviation not calculated
** only one measurement taken
ND - Not Detected
NM - Not Measured

Table 5: Trace Element Concentrations # 1 (without REE) for Spring Waters

all values in ppt

1st # concentration
2nd # standard deviation

Element	Detection Limit	Petrified	Government	Lime Kiln	Pahcoon	Welcome	Roger's	Blue Point	Big Muddy
Y	0.02	5.3	20.09	25.9	8.5	27.7	4.57	6.1	5.98
		0.4	0.08	0.4	0.2	0.5	0.04	0.2	0.06
Ru	4.0	3.5*	ND	ND	ND	ND	3.7*	4	ND
		0.9					0.5	1	
Rh	2.3	36	7.2	4.7	12	3.9	40	48	10.7
		2	0.7	0.5	1	0.2	4	3	0.3
Pd	5.3	8.3	9	8.5	4.5*	3.8*	8	8	5*
		0.8	1	0.8	0.9	0.8	1	2	1
Sn	15.0	80	32	16	14*	17	31	32	20
		20	6	2	2	2	6	6	2
Sb	4.4	42	23	72	53	84	15	21	464
		2	2	3	2	2	3	4	6
Te	20.6	110	ND	ND	ND	ND	100	150	ND
		20					30	30	
Hf	5.7	11	17	6	20	12	5*	4.7*	17
		3	6	1	7	4	2	0.6	4
Ir	4.6	ND	ND	ND	ND	ND	ND	ND	ND
Pt	7.0	10	18	70	43	47	ND	ND	8
		5	2	4	2	4			2
Au	21.7	92	36	10*	490	55	37	30	ND
		7	9	2	60	8	7	5	
Ge	13.9	1080	50	23	87	22	33	380	750
		30	40	2	4	1	7	30	20
Zr	3.8	15	14	40	18	13	9.5	8	49
		2	5	2	6	1	0.4	2	2
Nb	9.2	30	ND	5.4*	7.4*	6.9*	23	18	6.9*
		10		0.5	0.7	0.1	5	3	0.6
Mo	30.3	3900	15300	16700	4600	3800	11600	13600	6200
		100	600	200	100	20	400	600	100
Ta	13.7	500	16	21	49	54	330	260	59
		300	1	2	4	4	90	40	4
W	10.4	96	40	25	13.9	22.3	44	6.7	1300
		2	1	1	0.8	0.8	5	0.9	20
Re	3.3	54.9	48	36	35.1	27.2	48	49	19
		0.7	3	1	0.7	0.5	5	4	1
Th	0.05	0.10	0.05	0.12	0.08	0.06	ND	0.10	0.06
		0.03	0.03	0.04	0.02	0.04		0.04	0.02

ND - Not Detected

* concentration below detection limit, based on RSD and was used in PCA

Table 5: Trace Element Concentrations # 1 (without REE) for Spring Waters (cont.)

all values in ppt

1st # concentration
2nd # standard deviation

Element	Detection Limit	Dodge	Creeper	Putting Green	Clover-UNK	Juanita	Oak-Low Mtn.	Pah Tempe	Grapevine
Y	0.02	9.1	84	122	107	3.1	10.8	34.1	3.66
		0.2	1	2	2	0.3	0.2	0.4	0.4
Ru	4.0	ND	ND	ND	ND	3*	ND	31	ND
						1		4	
Rh	2.3	80	12.2	11	390	105	99	100	21
		4	0.3	2	20	5	5	10	2
Pd	5.3	3*	ND	3*	ND	5*	ND	9	5*
		1		1		1		8	1
Sn	15.0	ND	ND	ND	ND	ND	ND	140	ND
								50	
Sb	4.4	192	121	277	1430	280	34	35	26
		7	6	4	70	40	2	8	4
Te	20.6	ND	ND	ND	ND	ND	ND	2000	ND
								30	
Hf	5.7	11	6	30	4*	5*	3.6	7	10
		3	1	10	1	2	0.5	4	3
Ir	4.6	4*	5.3	4.1*	3.1*	ND	ND	ND	8
		1	0.6	0.8	0.7				2
Pt	7.0	5.1*	6*	ND	4*	ND	5*	ND	ND
		0.6	3		1		1		
Au	21.7	60	23	ND	ND	ND	ND	40	42
		20	4					10	9
Ge	13.9	28	39	211	61	183	45	6300	34
		6	2	4	7	2	8	700	1
Zr	3.8	9	8	14	4.9	4	11	330	6.8
		2	1	4	0.2	2	1	20	0.7
Nb	9.2	9	7*	8.0*	10	6.2*	9*	28	11
		1	1	0.9	3	0.6	1	6	1
Mo	30.3	490	200	990	533	4620	1310	330	1200
		10	10	30	8	80	20	30	50
Ta	13.7	18	15	15	130	47	13*	160	15
		1	3	3	50	5	4	50	4
W	10.4	34	11	220	ND	81	18.7	700	86
		3	2	10		7	0.9	70	5
Re	3.3	13.9	4.9	6	30	27	17	6	12
		0.1	0.9	2	2	1	2	3	3
Th	0.05	0.06	0.11	0.10	0.12	0.06	0.08	0.1	ND
		0.03	0.03	0.03	0.02	0.02	0.04	0.02	

ND - Not Detected

* concentration below detection limit, based on RSD and was used in PCA

Table 5: Trace Element Concentrations # 1 (without REE) for Spring Waters

all values in ppt 1st # concentration
2nd # standard deviation

Element	Detection Limit	Stout Canyon	Cascade	Stave	Menu Falls	Toquerville	Oak Grove Camp	Boilers
Y	0.02	13.3	9.1	23.4	5.9	3.0	42.2	27.9
		0.1	0.3	0.8	0.1	0.1	0.7	0.2
Ru	4.0	ND	ND	ND	ND	ND	ND	ND
Rh	2.3	12	10	148	190	140	ND	6.4
		2	1	4	7	5		0.1
Pd	5.3	4*	ND	ND	6	ND	ND	ND
		2			1			
Sn	15.0	ND	ND	ND	23	ND	15	40
					5		2	2
Sb	4.4	90	80	31	12	30	39	276
		10	10	2	1	7	3	1
Te	20.6	ND	ND	ND	70	23	ND	ND
					10	4		
Hf	5.7	9	6	8	8.3	ND	3.8*	ND
		6	3	3	0.8		0.7	
Ir	4.6	8	5.1	4*	8	ND	ND	ND
		2	0.4	1	3			
Pt	7.0	ND	ND	5*	9	ND	7	ND
				2	4		3	
Au	21.7	16*	9*	8*	40	11	ND	ND
		4	3	2	10	3		
Ge	13.9	60	30	23	103	80	28	71
		10	9	3	4	10	2	1
Zr	3.8	17.6	4	18	ND	8	4.5	3.8
		0.9	1	4		3	0.2	0.9
Nb	9.2	7.6*	6.4*	6*	6*	7.2*	ND	ND
		0.6	0.9	2	1	0.9		
Mo	30.3	228	75	640	2230	1290	307	2320
		8	5	20	70	30	5	10
Ta	13.7	14	12*	11*	50	17	ND	15
		5	6	4	10	5		1
W	10.4	9*	9*	8*	7*	90	11	297
		2	2	4	1	20	2	7
Re	3.3	11.8	10	14.6	36	20.8	7.2	5
		0.8	3	0.8	3	0.7	0.6	0.3
Th	0.05	0.12	0.10	0.06**	0.33	ND*	0.13	0.07
		0.05	0.01	0.04	0.03		0.02	0.03

ND - Not Detected
* concentration below detection limit, based on RSD and was used in PCA

Table 6: Trace Element Concentrations # 2 (without REE) for Spring Waters

all values in ppt

1st # concentration
2nd # standard deviation

Element	Detection Limit	Petrified	Government	Lime Kiln	Pahcoon	Welcome	Roger's	Blue Point	Big Muddy
Li	49	550000	25900	13600	50000	7350	640000	710000	154000
		20000	200	100	1000	80	20000	20000	6000
Be	28	ND	8	ND	ND	ND	ND	ND	ND
			4						
Al	170	310	870	931	870	790	460	340	710
		40	30	9	20	10	40	30	60
V	14	1680	8500	2540	29800	3100	2860	6530	2730
		40	300	40	200	90	20	70	70
Cr	33	444	350	90	900	130	280	710	590
		7	30	20	30	60	20	20	20
Mn	6.2	540	800	20100	25	780	148	30	31
		20	40	400	8	30	5	4	3
Co	2.1	497	45	123	33	59.3	610	720	26
		8	2	2	1	0.9	10	20	1
Ni	29	11300	568	1270	750	1050	11900	13600	800
		400	5	40	30	40	100	300	30
Cu	27	2330	500	470	360	520	3080	3600	461
		90	30	20	20	20	70	100	4
Zn	27	15000	85300	2350	2330	18300	8600	6600	1520
		800	500	80	30	500	200	100	10
Ga	1.5	5	0.9	1.1	0.8	0.8	5	5.4	ND
		1	0.1	0.1	0.1	0.1	1	0.9	
As	45	17700	4050	1100	14800	983	43000	52000	15600
		100	40	20	200	5	1000	1000	600
Se	180	7500	5200	1180	5600	2180	5500	5600	1300
		300	200	90	200	70	100	400	200
Rb	11	93000	670	287	2060	229	52100	58900	28000
		1000	30	9	40	4	500	800	1000
Sr	280	4000000	670000	445000	1210000	367000	4620000	5010000	1040000
		100000	8000	5000	50000	7000	40000	90000	20000
Ag	5.6	10	12	3.1	3.1	2.5	ND	ND	7
		6	4	0.6	0.6	0.7			3
Cd	2.8	44	104	34	12	15.8	37	52	14
		5	5	2	1	0.8	5	6	1
In	0.8	144	17	4.9	5.3	6.8	94	122	9.5
		1	1	0.8	0.4	0.4	4	7	0.3
Cs	2.8	35100	18	9.5	35	3.8	5500	7000	4700
		700	6	0.6	0.6	0.3	200	200	100
Ba	8.1	14000	6200	83000	46800	64600	14700	10100	42300
		200	200	1500	500	800	600	300	400
Tl	8.6	500	69	54	55	59	590	400	290
		40	6	6	7	5	10	9	20
Pb	3.7	29	194	6	7	37	7	5	6
		4	6	2	2	4	3	3	3
Bi	2.5	670	69	19	23	35	420	529	40
		30	8	2	2	2	10	9	3
U	1.8	5100	9100	42900	2510	15700	3800	3800	4100
		400	300	500	70	200	200	200	200

ND - Not Detected

Table 6: Trace Element Concentrations # 2 (without REE) for Spring Waters

all values in ppt 1st # concentration
2nd # standard deviation

Element	Detection Limit	Dodge	Creeper	Putting Green	Clover-UNK	Juanita	Oak-Low Mtn.	Pah Tempe	Grapevine
Li	49	11800	7600	14500	2600	32000	14000	2600000	6000
		200	300	500	100	600	400	100000	200
Be	28	ND	24	86	ND	ND	ND	530	ND
			4	4				80	
Al	170	768	779	760	268	460	2040	6200	1973
		7	8	10	8	20	50	300	8
V	14	7800	559	2490	463	2800	9500	5300	11340
		200	4	40	8	100	400	200	40
Cr	33	80	50	165	25	280	250	700	1200
		10	2	6	2	10	10	30	8
Mn	6.2	1540	3140	62	8490	7	480	20500	ND
		20	50	2	70	1	20	300	
Co	2.1	76	29.4	23.9	110	57	64	950	21.4
		1	0.4	0.5	2	1	2	20	0.4
Ni	29	870	340	490	1830	1470	1740	10000	370
		20	10	20	80	30	20	1000	10
Cu	27	910	290	383	620	480	580	2590	256
		10	10	7	30	10	10	70	6
Zn	27	407	150	93	860	1790	5200	3500	239
		4	6	2	20	50	200	200	8
Ga	1.5	ND	1.6	1.08	ND	7	2.2	26	12.5
			0.1	0.08		1	0.2	3	0.8
As	45	2070	620	1680	317	14500	1740	40800	1820
		20	10	30	5	600	6	800	20
Se	180	660	800	320	580	1680	3980	5200	1140
		70	60	50	50	50	60	800	90
Rb	11	505	5260	1870	690	6600	1720	390000	4360
		9	70	40	10	300	50	10000	40
Sr	280	900000	107400	123000	4100000	1020000	800000	10500000	150000
		20000	700	3000	100000	30000	20000	200000	4000
Ag	5.6	4.3	3.2	ND	ND	ND	8	14	ND
		0.4	0.4				3	6	
Cd	2.8	7	4.5	3.3	6.9	8	21	51	3.2
		2	0.9	0.6	0.7	0.9	2	4	0.7
In	0.8	2.8	0.78	ND	0.8	ND	7.1	1900	ND
		0.3	0.08		0.1		0.4	100	
Cs	2.8	6.8	40.6	140	5.8	1130	4.4	95600	95.5
		0.7	0.8	2	0.5	80	0.3	500	0.7
Ba	8.1	116700	1390	2620	61500	18700	40000	35100	235000
		600	20	80	600	400	300	500	4000
Tl	8.6	42	37	27	42	480	60	1660	32
		7	6	6	7	30	8	20	6
Pb	3.7	ND	35	ND	ND	6	20	80	ND
			4			3	3	5	
Bi	2.5	10	2.1	ND	2.8	2.6	42	9000	ND
		1	0.4		0.4	0.3	5	1000	
U	1.8	3810	480	2360	1950	7000	2100	670	1310
		50	10	30	60	400	100	50	20

ND - Not Detected

Table 6: Trace Element Concentrations # 2 (without REE) for Spring Waters

all values in ppt 1st # concentration
2nd # standard deviation

Element	Detection Limit	Stout Canyon	Cascade	Stave	Menu Falls	Toquerville	Oak Grove Camp	Boilers
Li	49	8900	1430	25000	46000	10700	5600	13900
		100	50	1000	2000	400	100	400
Be	28	ND	ND	ND	ND	ND	ND	ND
Al	170	310	310	678	470	2050	322	550
		10	10	8	10	20	7	10
V	14	80	610	240	2220	7310	3450	3170
		20	20	3	30	20	50	90
Cr	33	174	104	41	246	1011	196	530
		2	5	5	7	3	3	20
Mn	6.2	670	780	118	420	362	2170	148
		20	10	3	10	2	40	5
Co	2.1	61.4	33	72	50	45.8	65.2	33
		0.6	1	2	1	0.9	0.4	2
Ni	29	858	620	1560	1050	1140	1110	820
		7	10	20	20	20	20	40
Cu	27	571	370	470	350	444	294	332
		9	20	10	5	6	4	9
Zn	27	440	89	1370	690	631	370	720
		20	6	40	20	5	20	20
Ga	1.5	ND	1.2	ND	4.5	4.2	1.1	18.5
			0.1		0.2	0.2	0.1	0.3
As	45	360	570	237	2920	2400	2790	5000
		20	30	2	10	20	40	100
Se	180	350	ND	1110	600	1510	200	560
		60		60	100	60	60	90
Rb	11	3200	560	2860	15900	3670	573	4600
		100	20	30	600	40	1	100
Sr	280	151000	56000	1060000	1450000	800000	106000	580000
		2000	1000	10000	20000	10000	2000	10000
Ag	5.6	ND	ND	ND	6	ND	ND	ND
					2			
Cd	2.8	ND	ND	5.7	20	ND	8	335
				0.8	2		1	2
In	0.8	ND	ND	ND	105	0.6	ND	ND
					2	0.1		
Cs	2.8	2110	139	400	1610	171	25.8	830
		80	2	10	70	5	0.3	30
Ba	8.1	494000	35600	66200	23100	44100	24400	41800
		8000	700	400	300	900	500	300
Tl	8.6	30	26	61	150	33	24700	61
		7	7	8	9	7	400	7
Pb	3.7	ND	ND	11	7	ND	ND	28
				4	4			4
Bi	2.5	ND	ND	ND	590	ND	ND	ND
					20			
U	1.8	1480	278	1660	1830	4200	4400	2030
		60	4	20	90	100	100	60

ND - Not Detected

Table 7: Rare Earth Element Concentrations for Spring Waters (Virgin River Basin and Surrounding Area)

all values in ppt

1st # concentration
2nd # standard deviation

Element	Detection Limit	Petrified	Government	Lime Kiln	Pahcoon	Welcome	Roger's	Blue Point	Big Muddy
La	0.06	3.07	5.9	10.6	5.2	16.25	3.16	3.9	4.7
		0.07	0.2	0.2	0.1	0.05	0.04	0.2	0.1
Ce	0.04	1.7	0.39	6.8	0.61	2.2	1.18	0.59	1.2
		0.1	0.05	0.3	0.04	0.1	0.05	0.05	0.1
Pr	0.01	0.20	0.81	1.57	0.55	2.03	0.14	0.15	0.35
		0.03	0.04	0.06	0.05	0.08	0.03	0.02	0.02
Nd	0.08	0.6	4.4	8	2.4	8.9	0.5	0.44	1.2
		0.2	0.8	1	0.2	0.5	0.2	0.08	0.1
Sm	0.04	1.4	1.4	2.9	1.0	2.37	0.38	0.5	1.7
		0.1	0.3	0.1	0.2	0.04	0.03	0.1	0.4
Eu ***	0.02	0.77	0.79	8.6	4.1	5.36	0.69	0.43	3.7
	-	0.04	0.05	0.2	0.3	0.09	0.07	0.04	0.2
Gd	0.03	0.25	1.55	2.6	0.46	2.6	0.15	0.21	0.13
		0.03	0.08	0.3	0.05	0.1	0.05	0.03	0.02
Tb	0.01	0.04	0.24	0.36	0.09	0.36	ND*	0.03	0.03
		0.02	0.02	0.04	0.02	0.06		0.01	0.01
Dy	0.04	0.19	1.51	2.30	0.57	2.6	0.12	0.16	0.14
		0.02	0.08	0.09	0.09	0.1	0.04	0.03	0.04
Ho	0.02	0.05	0.31	0.58	0.136	0.66	0.04	0.05	0.027
		0.01	0.09	0.04	0.004	0.05	0.01	0.01	0.002
Er	0.03	0.12	1.20	1.93	0.42	1.8	0.08	0.12	0.05
		0.02	0.06	0.05	0.07	0.1	0.03	0.05	0.02
Tm	0.01	0.02	0.13	0.29	0.06	0.24	ND	ND	0.019
		0.01	0.02	0.01	0.01	0.02			0.003
Yb	0.03	0.08	0.9	1.5	0.30	1.5	0.06	0.10	0.07
		0.04	0.1	0.2	0.01	0.1	0.02	0.02	0.03
Lu	0.02	ND	0.16	0.26	0.04	0.24	ND	0.015	0.02
			0.06	0.01	0.01	0.02		0.004	0.01

ND - Not Detected

In order to attain these detection limits, preconcentration procedures were used

* the detection limit was used in the REE normalization

*** higher concentrations of Eu in comparison to other REE may result from barium oxide interferences.
Eu concentrations are not used in the PCA

Table 7: Rare Earth Element Concentrations for Spring Waters (Virgin River Basin and Surrounding Area

all values in ppt

1st # concentration
2nd # standard deviation

Element	Detection Limit	Dodge	Creeper	Putting Green	Clover-UNK	Juanita	Oak-Low Mtn.	Pah Tempe	Grapevine
La	0.06	8.1	45.6	19.95	80.0	2.13	4.1	9.52	6.1
		0.3	0.3	0.06	0.4	0.02	0.3	0.09	0.4
Ce	0.04	4.0	156	5.3	29.3	0.52	0.90	9.43	0.49
		0.1	1	0.2	0.1	0.06	0.03	0.06	0.05
Pr	0.01	0.84	9.1	5.3	9.5	0.09	0.44	1.31	0.23
		0.01	0.1	0.2	0.3	0.01	0.02	0.04	0.06
Nd	0.08	3.6	39.0	26	41	0.5	2.1	5.45	1.11
		0.6	0.8	2	1	0.2	0.7	0.08	0.09
Sm	0.04	2.6	9.6	14.96	18.9	0.18	0.6	3.0	1.0
		0.5	0.3	0.09	0.8	0.08	0.2	0.6	0.1
Eu ***	0.02	10.1	0.72	0.95	12.1	1.4	4.7	1.50	19.9
		0.3	0.07	0.06	0.3	0.1	0.4	0.06	0.8
Gd	0.03	1.14	15.3	11.1	10.5	0.11**	0.84	2.2	0.15
		0.09	0.5	0.7	0.3	0.08	0.06	0.4	0.03
Tb	0.01	0.13	2.13	1.8	1.33	ND	0.13	0.35	0.03
		0.03	0.09	0.1	0.01		0.1	0.02	0.02
Dy	0.04	0.6	13.9	14.1	7.1	0.10	0.79	2.0	0.16
		0.1	0.5	0.5	0.3	0.03	0.06	0.4	0.06
Ho	0.02	0.18	3.0	3.5	1.56	0.015	0.22	0.57	0.023
		0.04	0.1	0.2	0.02	0.004	0.02	0.04	0.004
Er	0.03	0.45	8.5	11.1	4.4	0.04	0.7	1.6	0.14
		0.04	0.2	0.3	0.2	0.02	0.2	0.2	0.02
Tm	0.01	0.05	1.12	1.60	0.52	ND	0.10	0.28	0.03
		0.01	0.06	0.08	0.02		0.02	0.04	0.02
Yb	0.03	0.3	7.2	8.7	2.7	0.05	0.6	1.8	0.12
		0.1	0.2	0.4	0.2	0.03	0.1	0.1	0.09
Lu	0.02	0.06	1.1	1.25	0.34	ND	0.07	0.29	0.030
		0.02	0.1	0.07	0.05		0.01	0.01	0.004

ND - Not Detected

In order to attain these detection limits, preconcentration procedures were used

** concentration above detection limit, but accuracy is questionable based on RSD

*** higher concentrations of Eu in comparison to other REE may result from barium oxide interferences.
Eu concentrations are not used in the PCA

Table 7: Rare Earth Element Concentrations for Spring Waters (Virgin River Basin and Surrounding Area)

all values in ppt

1st # concentration
2nd # standard deviation

Element	Detection Limit	Stout Canyon	Cascade	Stave	Menu Falls	Toquerville	Oak Grove Camp	Boilers
La	0.06	9.5	5.3	8.5	5.3	2.6	16.8	17.6
		0.2	0.1	0.1	0.2	0.3	0.2	0.3
Ce	0.04	3.85	3.8	2.8	2.4	1.0	3.2	7.01
		0.077	0.1	0.1	0.1	0.1	0.2	0.05
Pr	0.01	0.93	0.85	1.2	0.57	0.17	2.82	2.7
		0.04	0.06	0.2	0.03	0.04	0.06	0.1
Nd	0.08	4.0	3.5	5.0	2.3	0.92	13.8	12.0
		0.3	0.4	0.2	0.1	0.05	0.5	0.3
Sm	0.04	4.3	2.5	1.3	0.7	0.6196	3.0	2.4
		0.4	0.4	0.3	0.1	0.0002	0.2	0.4
Eu ***	0.02	34	3.4	5.5	2.1	3.82	3.9	3.70
		1	0.2	0.3	0.1	0.07	0.2	0.08
Gd	0.03	0.93	0.9	1.6	0.7	0.21	4.1	3.2
		0.08	0.3	0.4	0.1	0.04	0.3	0.1
Tb	0.01	0.17	0.14	0.24	0.07	0.03	0.51	0.41
		0.03	0.03	0.03	0.02	0.03	0.05	0.04
Dy	0.04	1.00	0.9	1.9	0.35	0.08	4.2	2.9
		0.07	0.2	0.1	0.07	0.07	0.2	0.3
Ho	0.02	0.28	0.20	0.52	0.06	0.04	1.02	0.64
		0.03	0.01	0.03	0.01	0.03	0.08	0.01
Er	0.03	0.74	0.65	1.7	0.20	0.19	2.8	2.0
		0.07	0.02	0.1	0.05	0.04	0.3	0.2
Tm	0.01	0.10	0.05	0.26	ND	0.13	0.4	0.29
		0.02	0.03	0.06		0.02	0.07	0.05
Yb	0.03	0.5	0.34	1.80	0.09	0.6	2.4	2.0
		0.07	0.05	0.20	0.02	0.2	0.2	0.10
Lu	0.02	0.1	0.04	0.38	0.03	0.82	0.40	0.33
		0.02	0.01	0.03	0.01	0.03	0.02	0.01

ND - Not Detected
In order to attain these detection limits, preconcentration procedures were used
* the detection limit was used in the REE normalization
** concentration above detection limit, but accuracy is questionable based on RSD
*** higher concentrations of Eu in comparison to other REE may result from barium oxide interferences.
Eu concentrations are not used in the PCA

CHAPTER 6

DATA ANALYSIS RESULTS AND DISCUSSION

The primary focus of this research was to use Principal Component Analysis (PCA) as a tool to statistically analyze the spring water chemistry of selected springs in and near the Virgin River Basin. In order to provide supplementary insight into the potential understanding of spring waters in the study area, additional hydrologic tools were used to either support or refute the results of the PCA. This chapter presents an overview of each of the data analysis tools and the information resulting from their use in this study.

Major Ion Chemistry

Piper and Stiff diagrams were used to provide graphical displays of the major ion chemistry for the spring waters in the study area. Piper diagrams are a common type of graphical display of major ion chemistry . These diagrams allow the major chemical signatures of the spring waters in the study area to be graphically presented (Figure 8 and 9). Piper diagrams are trilinear diagrams on which the concentrations of the major ions are plotted in relative percent units. The diagrams presented in this report were developed using the hydrologic computer program, Rockware (1992). Stiff diagrams (Figures 10 and 11) were prepared and provide distinctive polygonal shapes that assist in rapid visual

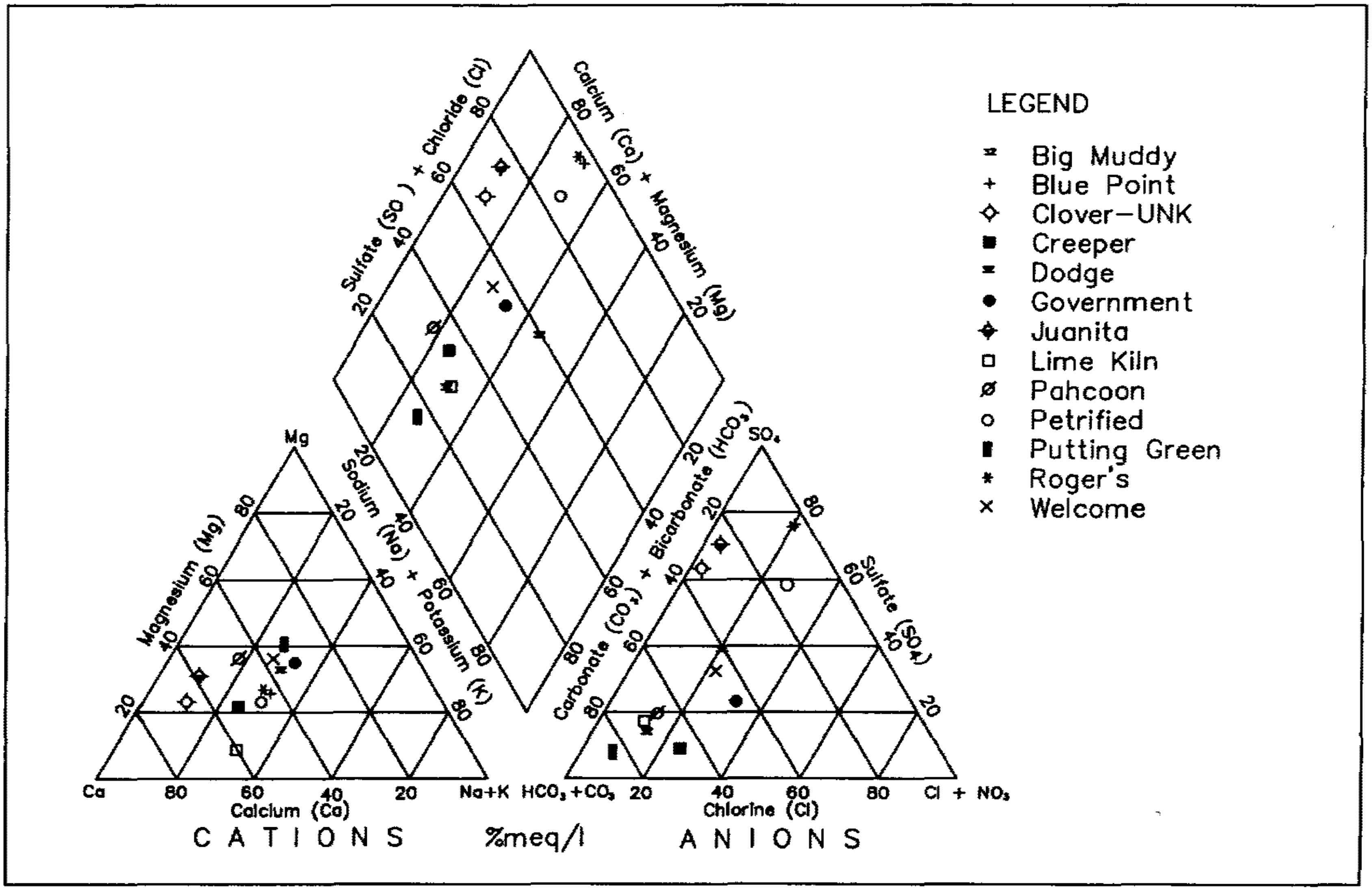


Figure 8: Piper Diagram: Lower Virgin River Basin Spring Waters

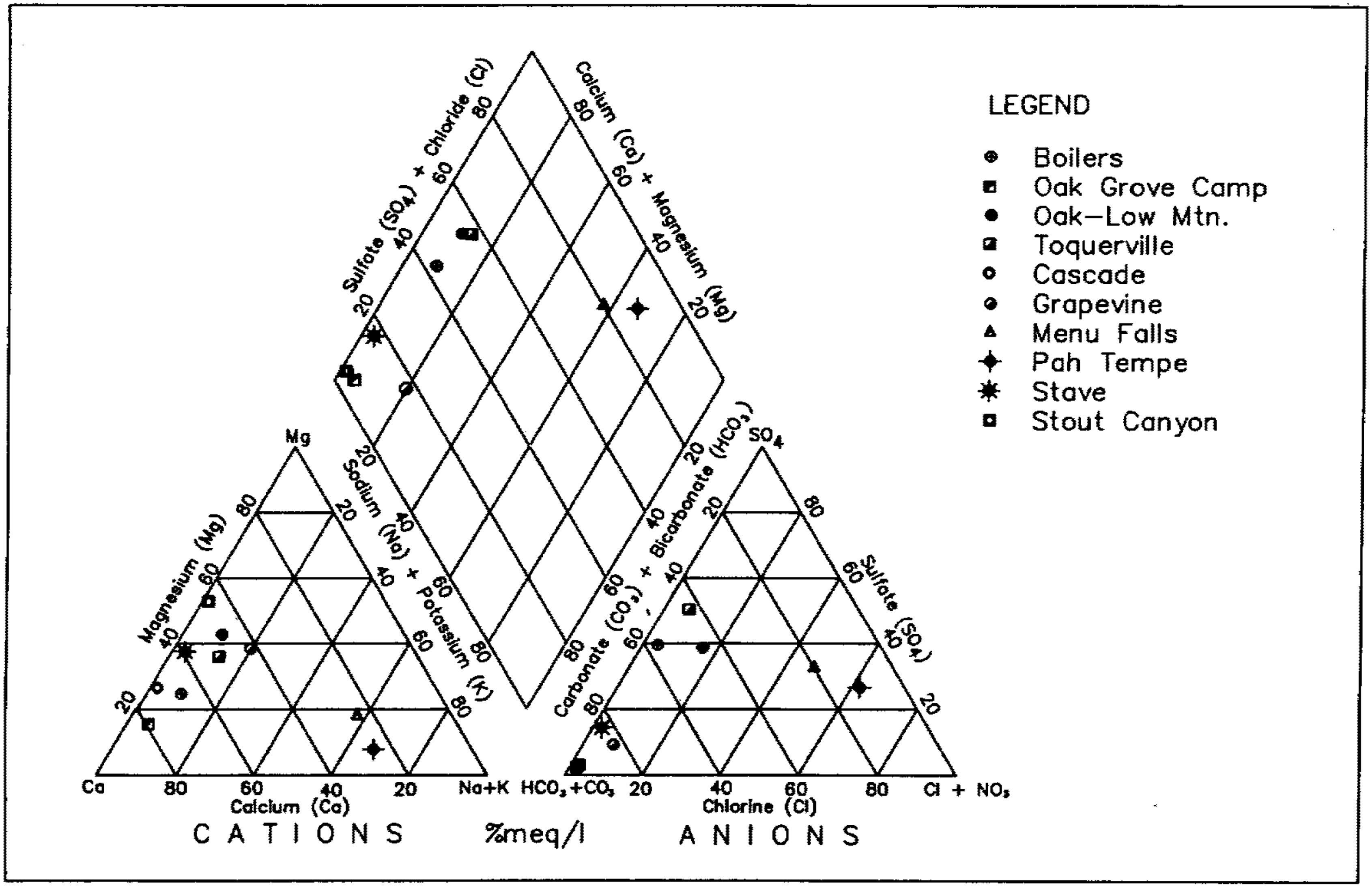


Figure 9: Piper Diagram: Upper and Central Virgin River Basin Spring Waters

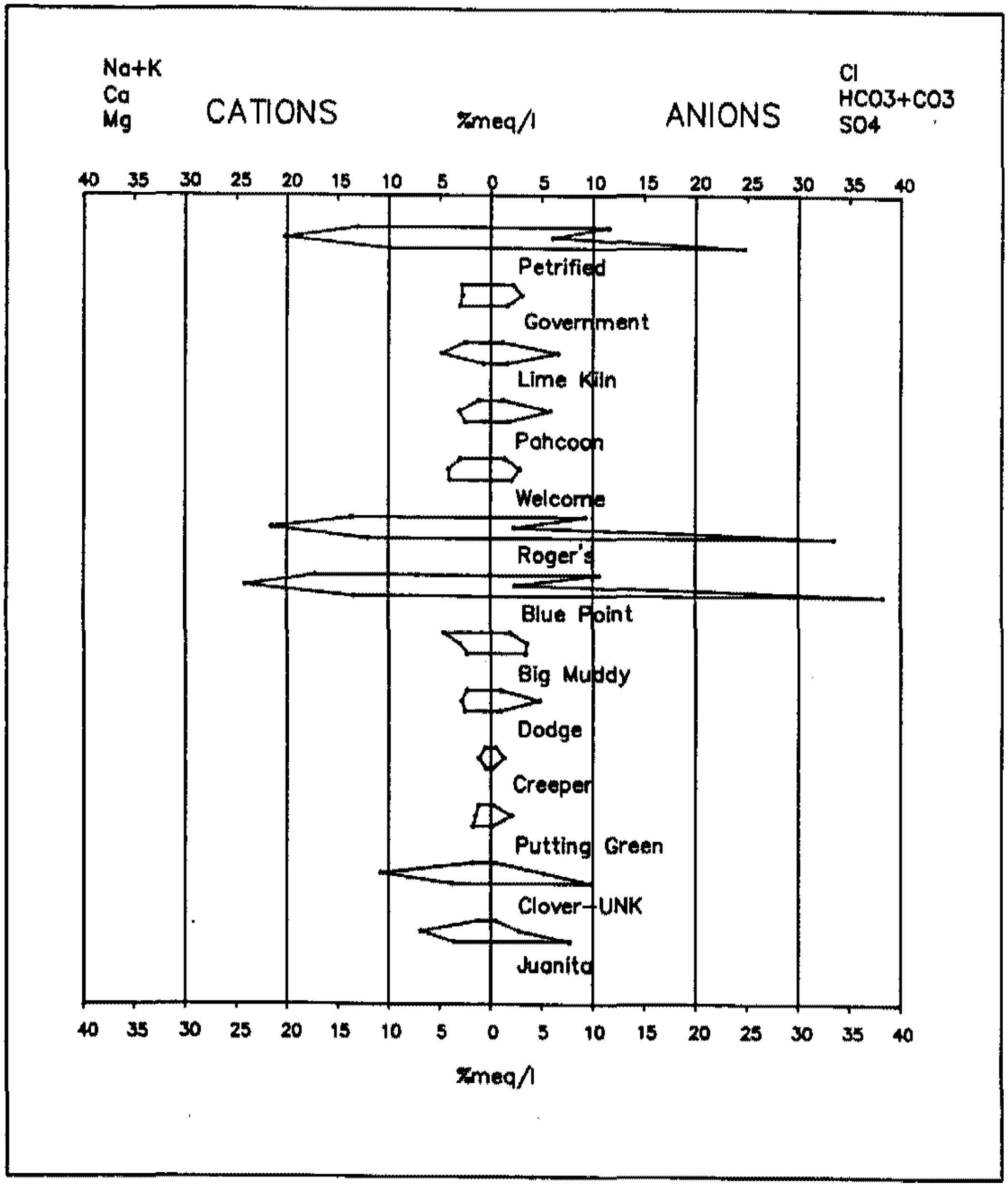


Figure 10: Stiff Diagram: Lower Virgin River Basin Spring Waters

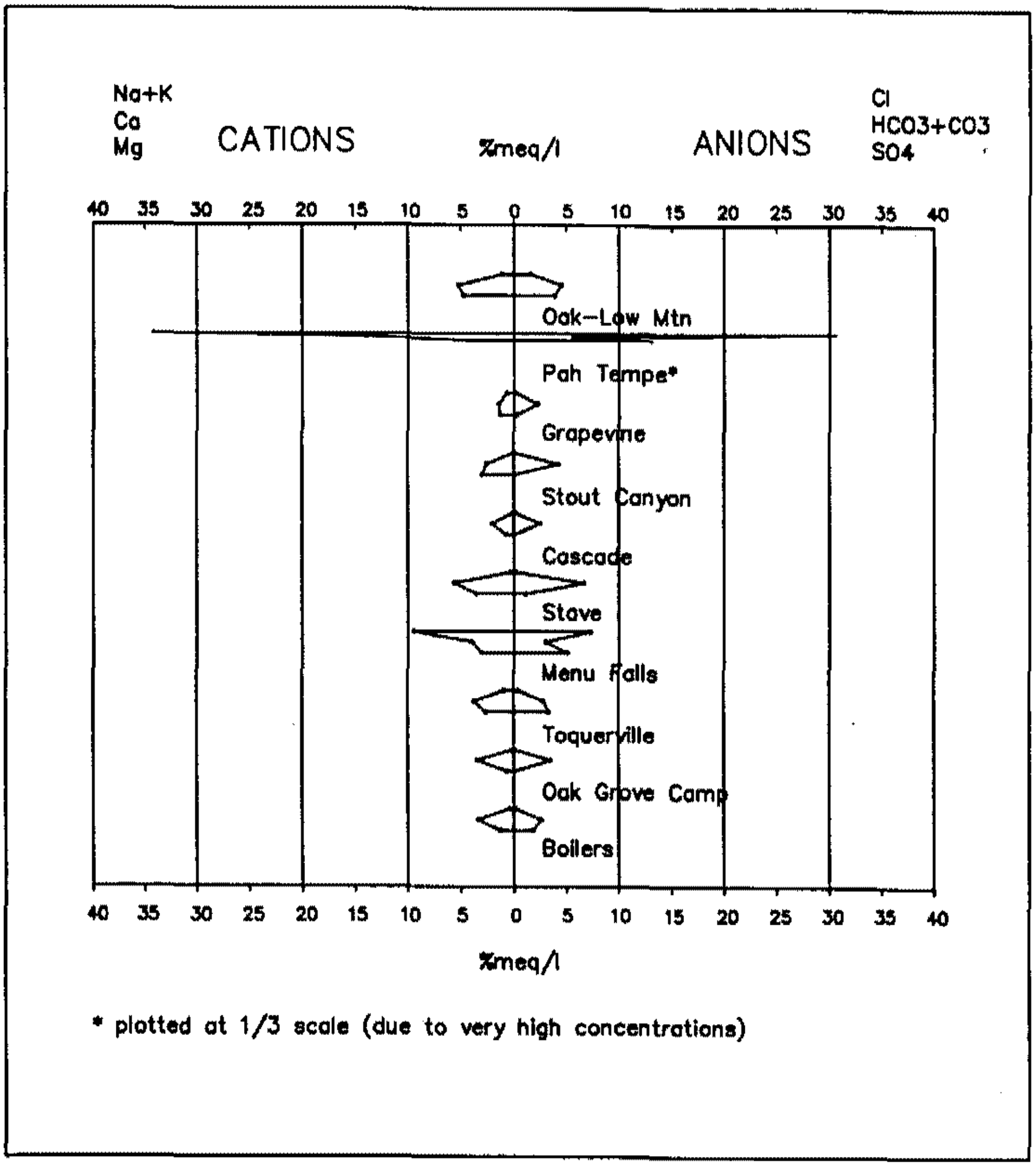


Figure 11: Stiff Diagram: Upper and Central Virgin River Basin Spring Waters

comparisons of the spring waters chemistry. The greater the concentrations plotted in milliequivalents per liter of the various major ions, the larger the area of the polygonal graphical display. Some interesting relationships between major spring water types are apparent from inspection of the Piper and Stiff diagrams. Significant similarities in major ion chemistry are evident between Roger's, Petrified, and Blue Point springs. These springs have considerable concentrations of major ion constituents in comparison to the other spring waters in the study area, with the exception of Pah Tempe Hot Springs which is a Na-Cl water that also contains high concentrations of dissloved solids. Unlike Pah Tempe, Roger's, Petrified, and Blue Point springs are primarily Ca-SO_4 waters. Generally, spring waters in the lower basin have higher dissolved solid concentrations and have higher concentrations of calcium and sulfate, whereas many of the upper basin spring waters are Ca-HCO_3 waters that are characterized by lower total dissolved solid concentrations. Again, a major exception to this is Pah Tempe Hot Springs east of the Hurricane Fault near La Verkin, Utah. Stout Canyon, which is at the headwaters of the East Fork of the Virgin River, is a Mg-Ca-HCO_3. Cascade Spring, on the other hand, which is the origin of the North Fork of the Virgin River is a Ca-HCO_3 water and has a slightly lower concentration of major ions than Stout Canyon Spring water (Figure 11). Menu Falls, in Zion National Park, is different from other spring waters in the region and is characterized as a Na-Cl water with higher major ion concentrations than the other springs in this area of the basin. Putting Green, Dodge, Grapevine, and Cascade springs have the lowest overall concentrations of major ions whereas Clover-UNK Spring has much higher concentrations than both Creeper and Putting Green springs. These three springs discharge from volcanic rocks in the Clover Mountains in eastern Nevada (Figure 7). Generally, the springs in the Lower Virgin River Basin are higher in calcium and sulfate compared to the springs in the Upper and Central Virgin River Basin which are typically Ca-HCO_3 waters. However, due to the great variability of spring water chemistries and the geology in the basin, there are exceptions to this generalization.

Principal Component Analysis

The large data set presented in Chapter 5, resulting from the chemical analysis of the spring water samples, was statistically reduced to simplify the data analysis. Principal Component Analysis (PCA) was used to determine the maximum number of factors or dimensions needed to illustrate the major chemical relationships between the different spring water samples. PCA can be used to reduce a large data set into a smaller set of factors and extracts key information for comparisons (Jolliffe, 1986 ; Stevens, 1986).

Principal Component Analysis is a multivariate statistical technique in which a number of related variables are transformed into a smaller set of uncorrelated variables. The principal component method dates back to the work of Pearson (1901) and then was subsequently used independently by Hotelling in 1933 (Jackson, 1991). Until the advent of computers, PCA was a very cumbersome technique. Personal computers, however, have simplified the use of this multivariate technique. PCA has been widely used in biological, physical, social and hydrologic sciences (Yu and Zou, 1993). Recently, PCA was used by Kreamer et al. (1996) to examine relationships between trace element geochemistry of spring waters in Death Valley National Park, California, and by Zukosky

(1995) in a groundwater flow pathway study in Grand Canyon National Park, Arizona. Also, Deverel and Millard (1988) used PCA to compare relationships between major ions, physical properties, and trace elements in shallow groundwater in the Western San Joaquin Valley, California. Additional research, utilizing PCA, is currently underway at the HRC at UNLV to conduct groundwater fingerprinting studies in the vicinity of the Nevada Test Site, Pahranagat Valley, Amargosa Desert, and Death Valley in southern Nevada and southeastern California.

Although PCA is only one type of multivariate statistical technique, it was chosen due to its simpler mathematical requirements in comparison to a techniques such as factor analysis (Stevens, 1986). PCA, for example, does not require the data to be normally distributed. The most dominant factor or component is provided first (i.e. linear combination of the measures containing the maximum amount of information), then the second most dominant component and so forth. The transformation of the original variables is placed into a new set of linear combinations of factors (Stevens, 1986). The large original data set is interpreted based on principal planes (Nishisato, 1994). The composite scores entailing the greatest variance creates the principal components.

PCA accesses a group of "n" variables:

$$y_1 = a_{11}x_1 + a_{12}x_2 + a_{13}x_3 \ldots a_{1n}x_n$$

such that:

y_1 = principal component (PC)

a_1 = coefficient of original variables in data set

x = original variables in data set

The first PC is y_1 and if $a_1'a_1 = 1$ then the y_1 has a variance that is the largest eigenvalue of the sample matrix (Morrison, 1967; Stevens, 1986). In an ideal situation the first PC would account for all of the variance in the data set. However, this is very unlikely with a large data set, so a second PC is extracted based on discrepancies resulting from the original data and the first principal component. The second linear combination (uncorrelated with the first principal component) illustrates the next highest amount of variance in the data set. The second component is defined in a similar fashion to the first, as:

$$y_2 = a_{21}x_1 + a_{22}x_2 + a_{23}x_3 \ldots a_{2n}x_n$$

As with the first PC, the elements of the eigenvector of the second PC are the coefficients of component two. The first and second PCs are orthogonal to each other by definition.

Additional components can be extracted until all of the variance in the data set is accounted for. Each successive component illustrates the maximum amount of variance left in the original data, not accounted for by the previously extracted components. Basically, PCA allows a large set of variables to be reduced to a smaller set of uncorrelated variables (principal components) (Stevens, 1986). The smaller set of variables is then used to interpret the overall relationships of the original data set.

Results of Principal Component Analysis

The computer program, Statistica for Windows was used to perform the PCA (Statistica, 1993). Several combinations of chemical constituents were introduced into the PCA for this research. The results of the PCA are presented graphically in Figures 12 through 21. Typically, two dimensional graphs of the first two factors have been plotted because the first two factors accounted for most of the variance in the data set. The third factor, as well as other factors, were assessed, but rarely provided any new groupings of the spring waters.

Approximately 200 PCA plots were made from the data set generated in this research. PCA plots indicating the most common spring water groupings are included within this section. Appendix D contains the same plots as shown in this section with additional information on the origination of the plots. Included with each plot are the percentage of variance accounted for by each principal component (factor) and the factor loading of each chemical constituent. These additional data provide information relating to each chemical constituents' importance in the calculation of each component. The first page of Appendix D contains definitions of important terms associated with PCA.

The chemical concentrations presented in Tables 4-7, were used in the PCA. Field parameters were not inputted into the PCA with the exception of alkalinity which provided the combination of bicarbonate and carbonate concentrations. Initially, all of the chemical concentrations for all of the springs were entered into the PCA (Figure 12). The first two factors accounted for 51% of the variance in the original data set. The variables correlating to factor one were primarily the major ions as well as a few other trace elements whereas the REEs dominated in importance in factor 2. The configuration of the data plotted in Figure 12 indicates that water from Pah Tempe Hot Springs differs significantly from the other spring waters because it plots distinctively separate from the other springs. Also, Petrified, Blue Point, and Roger's springs cluster together indicating

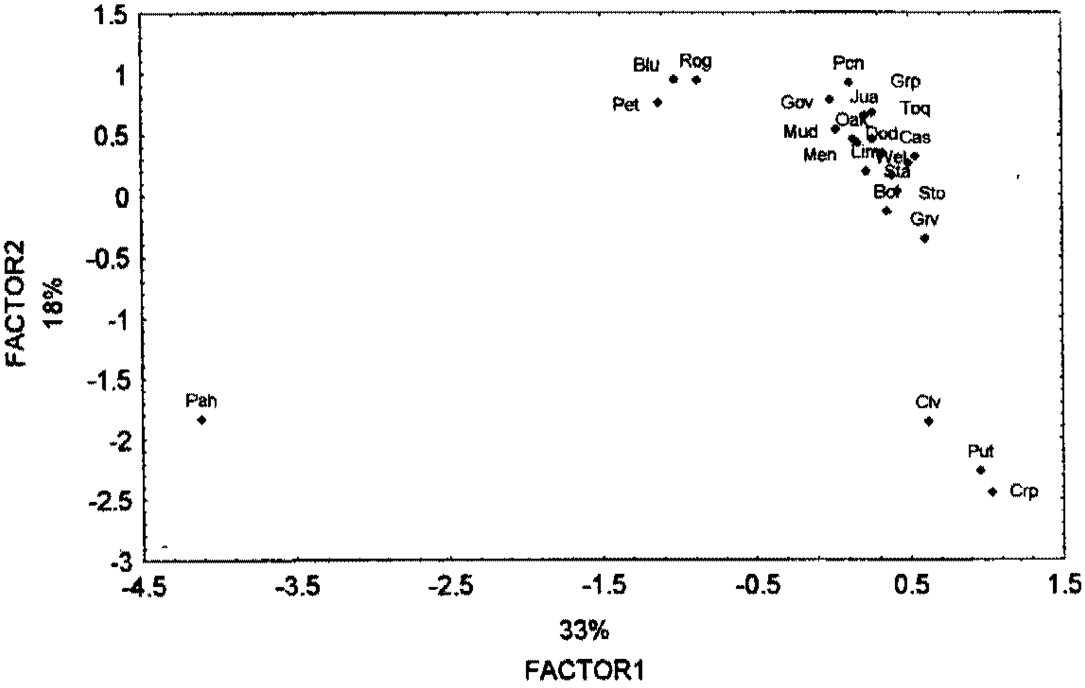


Figure 12: All Chemical Concentrations, All Springs

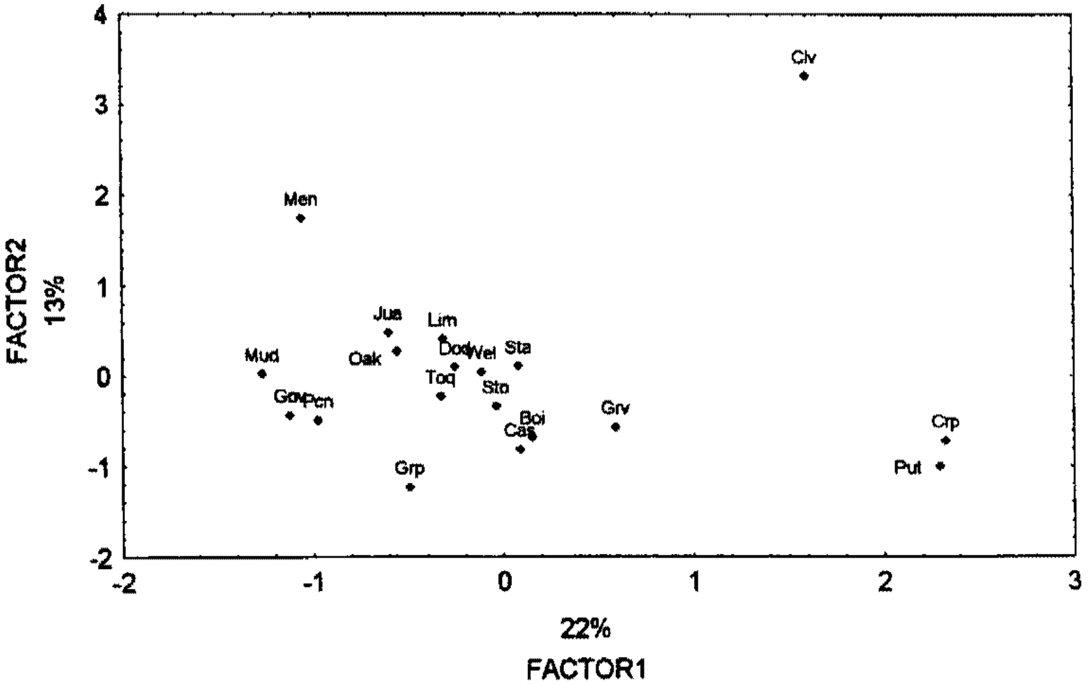


Figure 13: All Chemical Concentrations, without Pah Tempe, Petrified, Roger's, and Blue Point Springs

that these three springs have similar water chemistries. The separation of the Petrified, Blue Point, and Roger's springs and Pah Tempe springs from each other and from the remaining springs in the study was common throughout the PCA. Another group that plotted separately from the other springs was the springs discharging from volcanic rocks in the Clover Mountains in the northern part of the Lower Virgin River Basin in Nevada (Figure 12). The remainder of the springs clustered as one large group (Figure 12). Information from Figure 12 indicated potential relationships between water chemistry at spring sites that graphically plotted together. Data plotted in Figure 12 are thought to be the result of the spring water chemistry such that springs that plot near each other have similar chemical composition, whereas, springs that plot separately exhibit different water chemistry.

In order to see potential sub-clustering of the mass of spring waters that grouped together when entire data set was entered into the PCA, springs that plotted separately from the majority of springs were removed from the data set. For example, Figure 13 is a representation of the same chemical constituents as entered to generate Figure 12 without data from Pah Tempe, Petrified, Blue Point, and Roger's Springs. In this plot, springs in the Clover Mountains (Creeper, Clover-UNK, and Putting Green) plotted the furthest from the rest of the springs. However, Clover-UNK differed greatly in factor 2 from Creeper and Putting Green. The variables providing the most variance in factor 2 for Figure 13 were calcium, sulfate, and strontium whereas the REEs contributed the most to factor 1. Apparently, the major cations and anions were not as important in Figure 13 as was the case in separating Roger's, Blue Point, and Petrified springs in Figure 12.

Menu Falls also plots somewhat away from the other springs which was commonly the case in other plots generated by the PCA. Compared with many other springs in the Central and Upper Virgin River Basin, Menu Falls has higher major ion concentrations. The springs that plot together in Figure 13 can be separated into Lower Basin, and Central and Upper Basin springs. The same separation is apparent in many of the other PCA plots generated in this study. The separation between spring water based on relative location in the study area may result from the overall increase in total dissolved solids in the Lower Virgin River Basin as compared to the Central and Upper Basin springs. Higher concentration of major cations may explain why Menu Falls plots more with the Lower Basin Springs (Figure 13). Figure 14 contains the same variables and springs as Figure 13, but is presented in a three dimensional manner. Again, there is apparent separation between the Lower Basin springs and the Central and Upper Basin springs. The major exception to this, however, is the separation of Menu Falls from other Central and Upper Basin Springs.

Figure 15 is a plot of the PCA using only the trace element concentrations of the spring water variables. The clustering of springs in Figure 15 is almost identical to that of Figure 14 which also included the major ion data in addition to the REE concentrations. REEs are primarily responsible for most of the variance in factor 2 in Figure 15, with a mixture of trace elements accounting for the variance in factor 1, as is indicated (*) in the factor loading table located in Appendix D. Figure 16, on the other hand, contains all the spring sites, but the REEs are not included in the PCA performed to generate the plot. Figure 16 is very similar to Figure 13 except that now the Clover Mountain springs

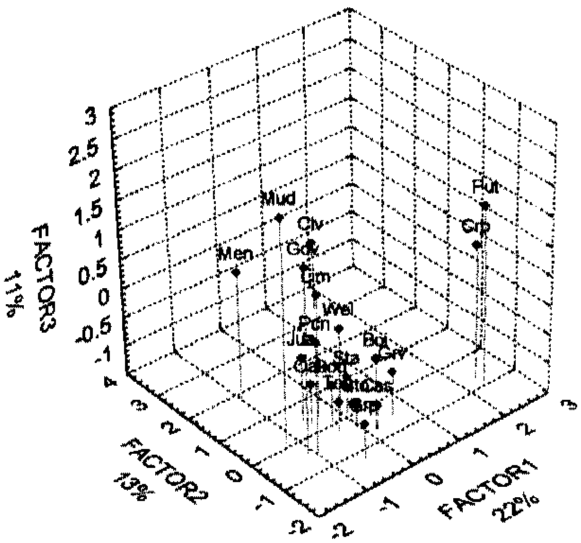


Figure 14: 3-D Plot, All Chemical Concentrations without Pah Tempe, Petrified, Roger's, and Blue Point Springs

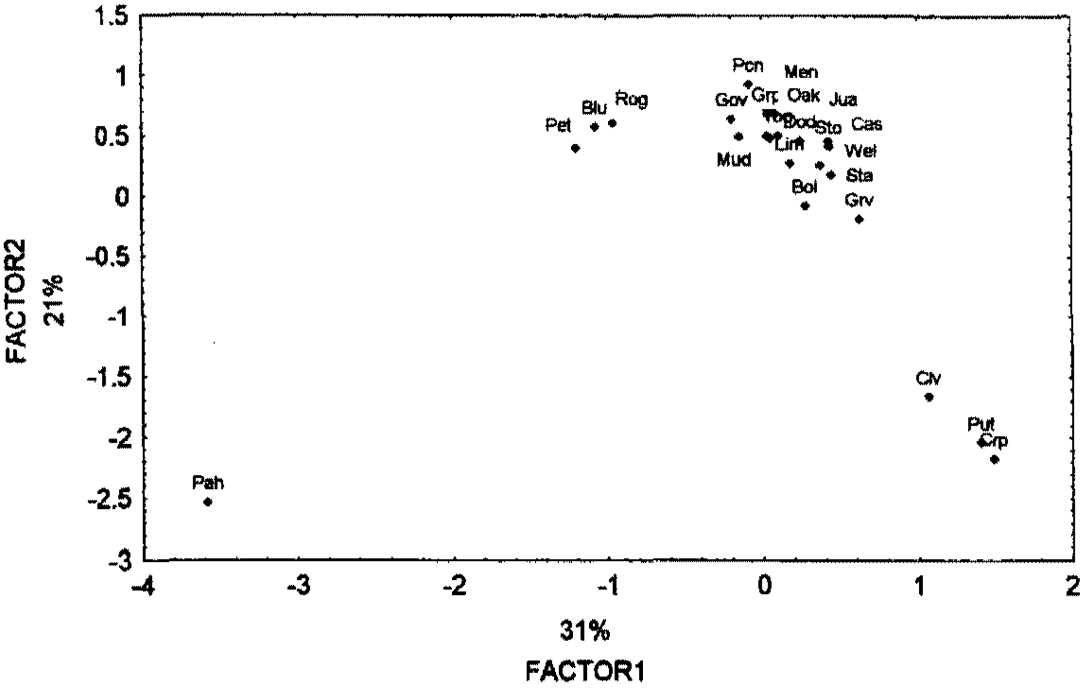


Figure 15: All Trace Elements, All Springs

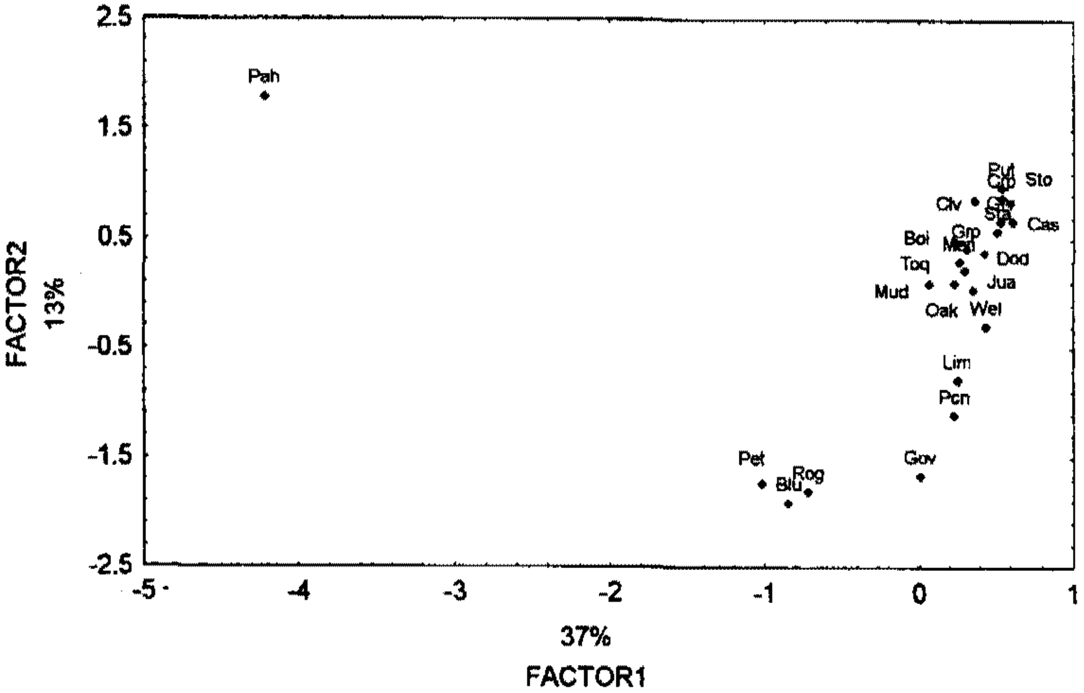


Figure 16: Trace Elements without REE Concentrations

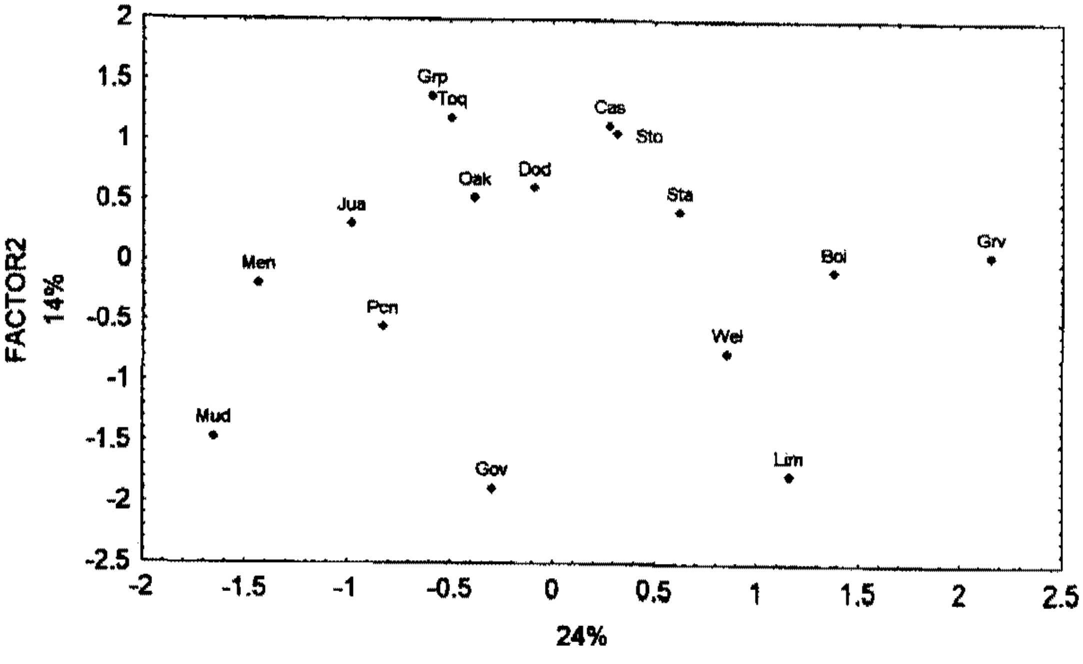


Figure 17: All Chemical Concentrations, without Previous Groupings

(Creeper, Clover-UNK, Putting Green) plot amongst the other major group of springs. This indicates the importance of the REEs in distinguishing between these spring waters. Without REE concentrations no significant differences would be observed between the Clover Mountain springs and the rest of the springs in the drainage basin.

Figure 17 includes all data without the springs that previously grouped together, as shown in Figures 12-16. This is an attempt to display any additional sub-clustering of the spring waters. Figure 18 includes the same data set as that used to generate Figure 17 without the major ion concentrations. The plots are almost identical and suggest that the major ions are of minor importance in determining the statistical grouping of these spring waters. Four minor groupings are displayed in these two plots. First, Cascade Spring at the headwaters of the North Fork of the Virgin River and Stout Canyon Spring near the headwaters of the East Fork of the Virgin River cluster together (Figures 17 and 18). Stout Canyon Spring discharges from rock composed of Kaiparowits (sandstone and shale) and Wasatch (sandstone and limestone) Formations. Cascade Spring, on the other hand, discharges only from the Wasatch Formation. A second group of springs includes Grapevine Spring (Zion National Park) and Toquerville Spring (Toquerville, UT). The groundwater that discharges from these springs flow through basalts and Navajo Sandstone (Hamilton 1975; Utah Board of Water Resources, 1993). Oak-Low Mtn. Spring (Virgin Mountains) and Dodge Spring (Beaver Dam Mountains) group near one another and both discharge in an area of volcanic rocks. The last small grouping of springs includes Menu Falls (Upper Basin, Zion National Park) and Juanita Spring (Lower Basin, west of Virgin Mountains). These springs are located in extremely different areas

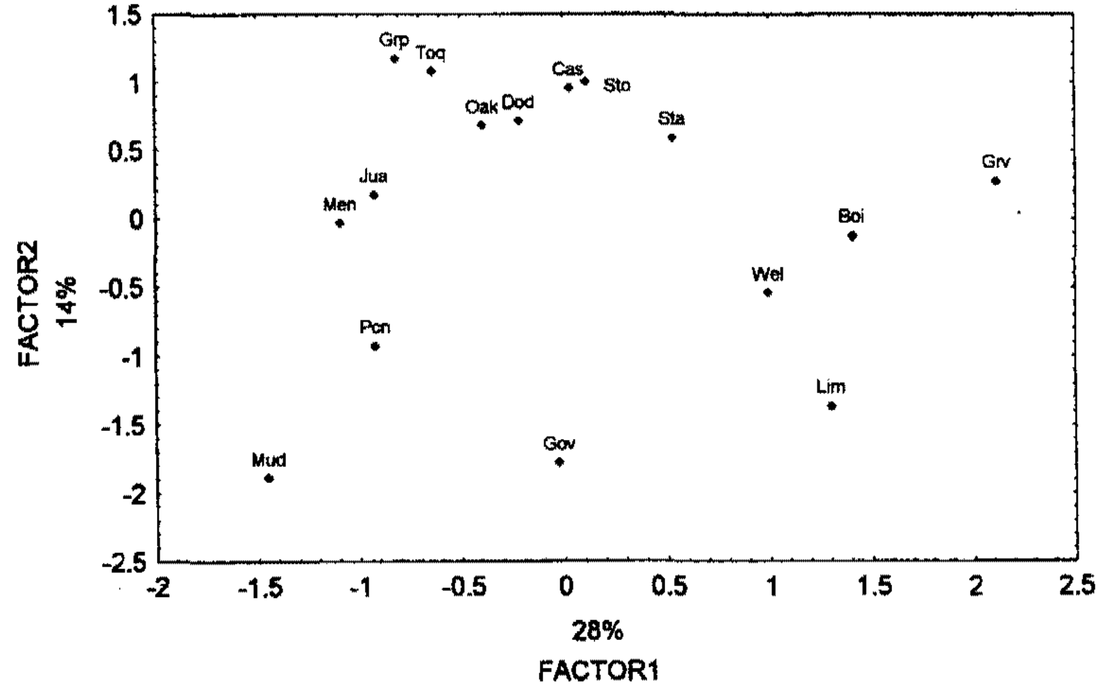


Figure 18: All Trace Element Concentrations without Previous Groupings

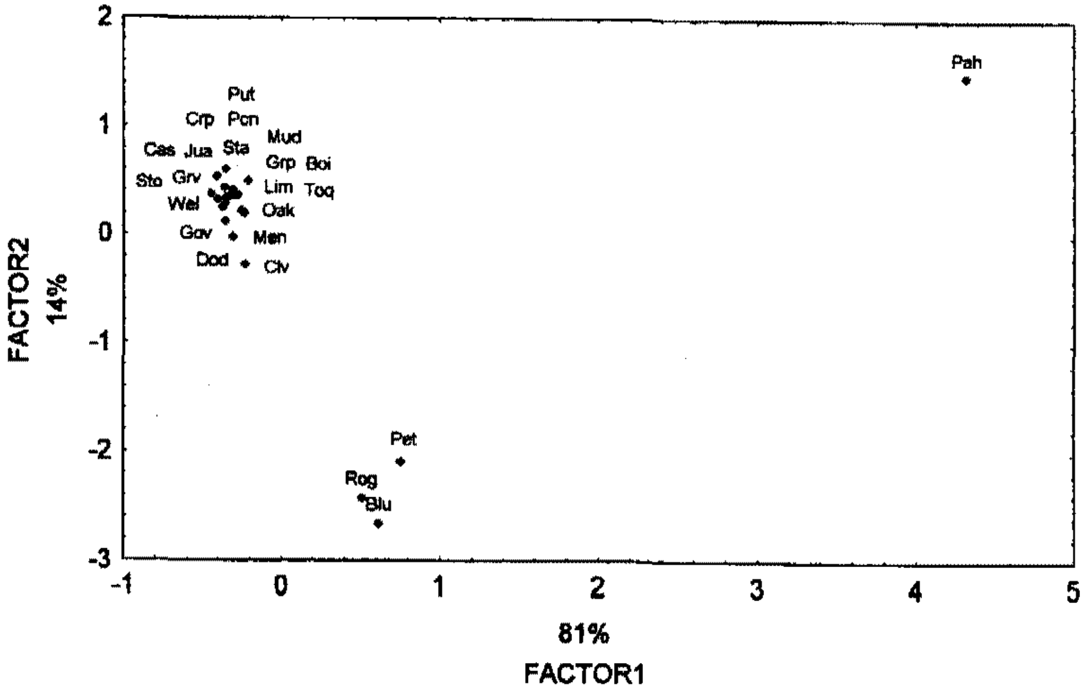


Figure 19: Selected Trace Elements, All Springs

of the basin and discharge from different geologic materials. Juanita is located in the lower portion of the basin and Menu Falls is located in the Navajo Sandstone in Zion National Park. The only similarity noted about these two springs other than plotting together because of their water quality, is that white mineral deposits (i.e. calcite) were present at both of their discharge areas. The clustering of these springs by PCA indicates their waters are similar in composition, but the potential for any geologic connection is extremely low due to their locational differences. This indicates the importance of using other hydrologic tools in addition to PCA.

Other statistical scatterplots were generated by using only trace element data without the REEs (Figure 19) and only major ion data (Figure 20). The resulting displays have almost identical spring clustering (Figures 19 and 20). This suggests that the spring waters can be differentiated by not only major ion chemistry, but also their trace element concentrations. Figure 21 contains the same trace element as in Figure 19, but without Pah Tempe, Petrified, Roger's, and Blue Point springs. For the most part the major group of springs remained in a cluster, however, Big Muddy and Menu Falls plotted separately from the other springs which suggests some differences in their trace element water chemistries.

The PCA grouped springs into similar clusters independent of the data used in the calculations. Three significant clusters of springs were evident. Roger's, Blue Point, and Petrified springs, for example, consistently plotted in close proximity to one another no matter which variables (elements or ions) were included in the PCA. This indicates that these springs have waters with very similar chemistries. An in depth discussion of a

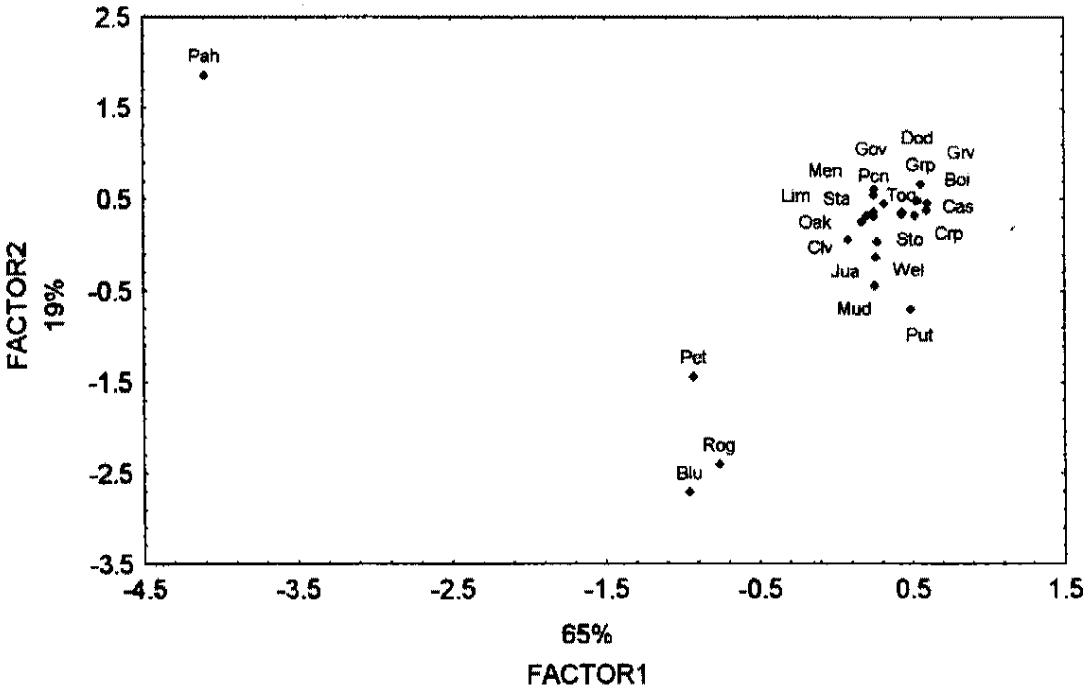


Figure 20: Major Ions, All Springs

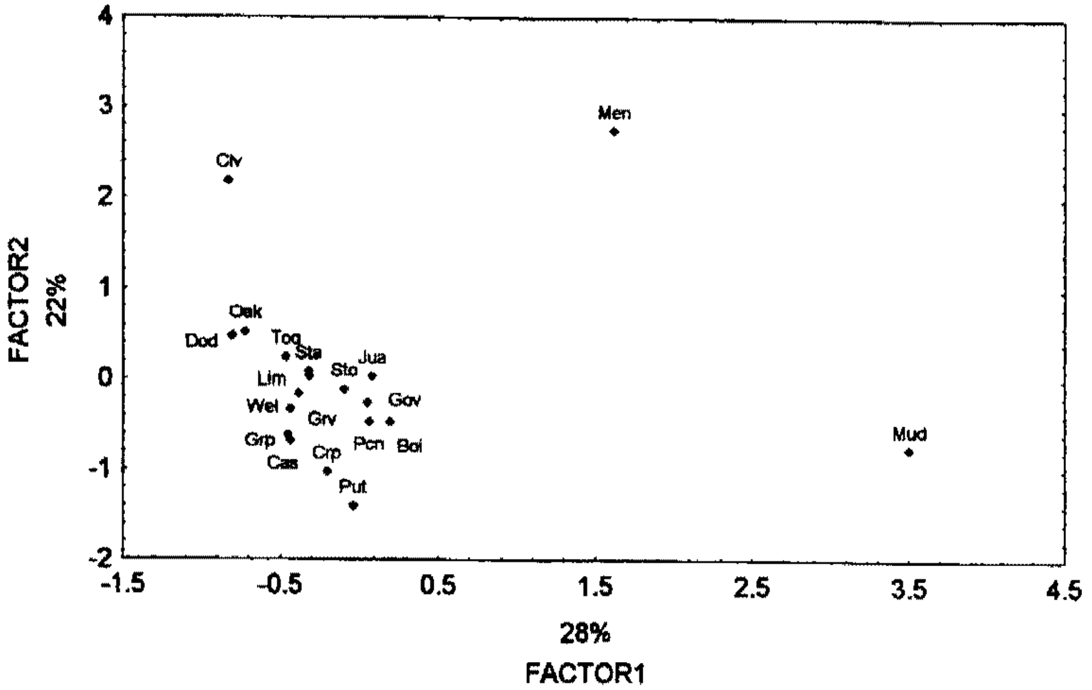


Figure 21: Selected Trace Elements without Pah Tempe, Petrified, Roger's, and Blue Point Springs

potential connection between these springs is presented later.

Pah Tempe Hot Springs always plots alone (e.g., Figure 12), with the exception of when only REEs are used in the PCA. In this case, the PCA resulted in all springs, except the Clover Mountain springs, plotting closely together. The similarities that Pah Tempe has with most of the other springs in the Virgin River Basin with respect to REE concentrations is discussed further in the REE Normalization section. REEs appear to be important as another distinguishing factor for water types. This is evident by the Clover Mountain springs (Creeper, Clover-UNK, Putting Green) clustering separately only when REE data are included in the statistical analysis.

Rare Earth Element Concentrations

Rare earth elements have been used to study the evolution and petrogenesis of igneous rocks (Taylor and McLennan, 1988) as well as geochemical processes in the oceans (Elderfield and Greaves, 1982). More recent studies have focused on the use of REEs in understanding the groundwater-rock interactions in aquifer systems (Smedley, 1991; Gosselin et al., 1992). The literature indicates that REEs are mobilized to some degree by weathering, secondary alterations, and diagenesis, and the occurrence of REEs in solution may be increased by these processes (Smedley, 1991). Currently, it is thought that water-rock interaction imparts a comparable REE signature to the groundwaters that is related to that of the rocks through which the water flows (Smedley, 1991).

The REEs have unique chemical properties as a group, making them ideal for geochemical studies. The REEs consist of fifteen elements (La to Lu) which are also known as the lanthanide series elements. These elements are divided into two major groups based on mass; the light REEs (LREEs) La through Eu, and the heavy REEs (HREEs) Gd through Lu (Taylor and McLennan, 1988). The REEs act uniquely as a group and occur together in nature because of their trivalent valence state. The small changes in chemical behavior from one REE to the next is due to the gradual decrease in ionic radius with atomic number, which is known as the lanthanide contraction. Fractionation between HREEs and LREEs may result from geologic processes, as a consequence of the differences in ionic radii between individual REEs and REE bonding capacities with anions (Fee et al., 1992). Rare earth elements have become very important tools for geochemical investigations and have been studied extensively in rocks and minerals.

Recently, the study of REEs in aqueous systems has been facilitated by the improvement of analytical technology that allows for more accurate measurements of these elements at pmol/kg concentrations in natural waters (Smedley, 1991; Stetzenbach et al., 1994). Studies have utilized REE concentrations to assess geochemical processes in groundwater. REE studies indicate that REE patterns in groundwater are at least in part acquired from the rocks through which the water flows (Smedley, 1991; Gosselin et al., 1992; Johannesson, 1996). This technique has been used to provide an understanding of groundwater flow pathways in the carbonate rock province in southern Nevada (Johannesson et al., 1994; Johannesson et al., in review).

Rare Earth Element Normalization

REE concentrations for each spring water were normalized to the composite shale tabulated in Sholkovitz (1988). The normalized REE concentrations for each spring were then plotted versus atomic number of the REEs to display REE normalization patterns (Appendix E). The REE concentrations used to generate the normalization plots are presented in Table 7.

Some of the elements exhibited apparent anomalies. Anomalies are extreme differences in normalized concentrations of a REE in comparison to its nearest neighbor on the periodic table. Commonly these anomalies are analytical in nature resulting from isobaric interferences from other isotopes or oxides or hydroxides of the other elements, during the mass spectrometric determination. The interferences can be difficult to detect by standard techniques, and therefore, can cause false positive REE concentration measurements, for instance, BaO^+ interferes with Eu analyses by ICP-MS (Jarvis et al., 1989). Because BaO^+ interferences were not corrected for, Eu was removed from the REE normalization patterns in this study. Lanthanum concentrations may also be higher due to high concentration of barium. In this case ^{138}Ba interferes with determination of ^{139}La because the barium signal is typically many orders of magnitude greater than La (E. R. Sholkovitz, 1994, written comm.). Also, Sm tends to exhibit anomalous normalized concentration for some samples although the reason for this significant alteration in the REE pattern is not currently known, however, interference from CsO^+ is suspected (K. H. Johannesson, 1996, pers. comm.).

The REE patterns of the 23 different spring waters sampled for this study were compared to each other to detect similarities and differences in their REE shale-normalized patterns. Representative plots of the REE normalizations are presented in Figures 22 through 25. REE normalization plots for all of the spring waters sampled in this study are displayed in Appendix E. The majority of the REE patterns for the spring waters throughout the study area were roughly similar to seawater, but typically exhibited more concentrated values (Elderfield and Greaves, 1982). The general pattern is characterized by a depletion in the normalized LREEs compared to the normalized HREEs. Many of the springs in the study area exhibited this seawater-type pattern and examples of this pattern are shown in Figure 22. The relative location of the springs in the Virgin River Basin (i.e., Upper, Central, or Lower) apparently does not affect the overall shape of the REE normalization patterns. In addition, Pah Tempe Hot Springs (Figure 23) has a very similar pattern and REE concentrations compared to the majority of the spring waters in the Virgin River Basin, specifically those spring waters plotted in Figure 22. The similar REE pattern between Pah Tempe and other springs suggests the water discharging at Pah Tempe Hot Springs may have originated in a similar fashion to spring waters discharging at other locations in the Upper Virgin River Basin. However, when taking the location of Pah Tempe into account, it is possible that water originating in the Upper Virgin River Basin that eventually discharges at Pah Tempe Hot Springs interacts with a shallow magma reservoir that heats the water and possibly modifies the major ion chemistry of the water, but does not substantially affect the REE concentrations.

Based on the PCA and the REE normalization plots of the Clover Mountain springs, the REEs may provide an additional tool for differentiating between spring water

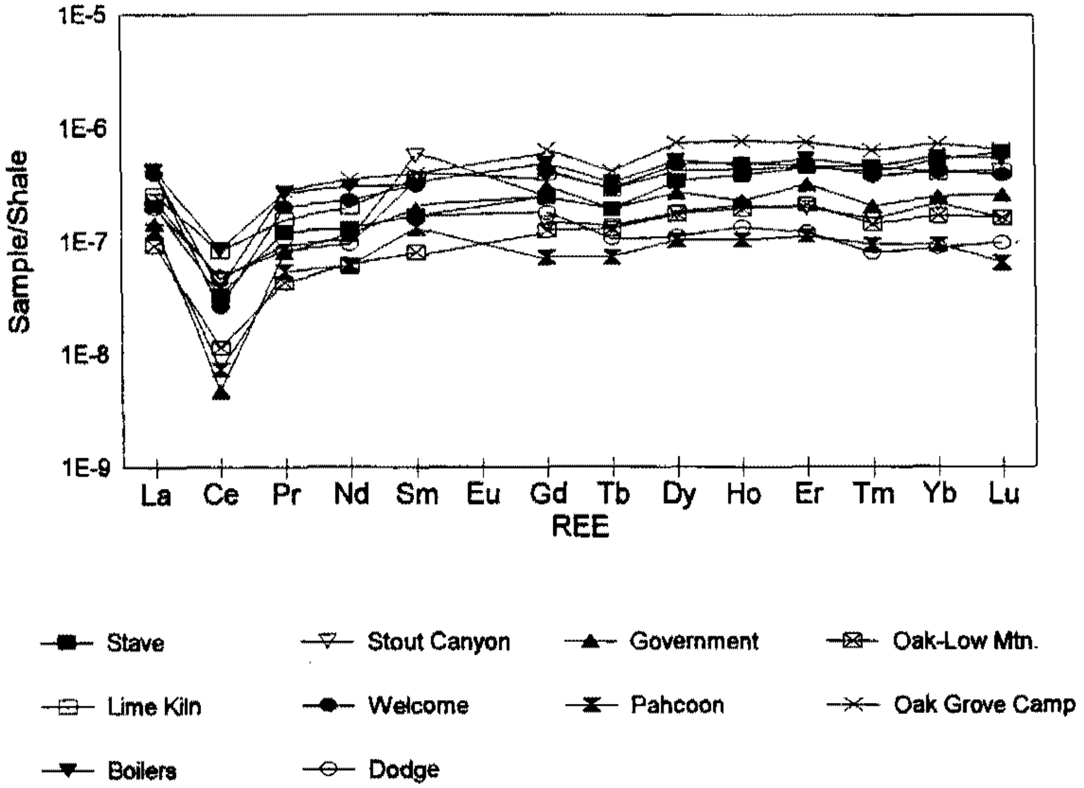


Figure 22: REE Normalization Plot Typical of Spring in the Virgin River Basin

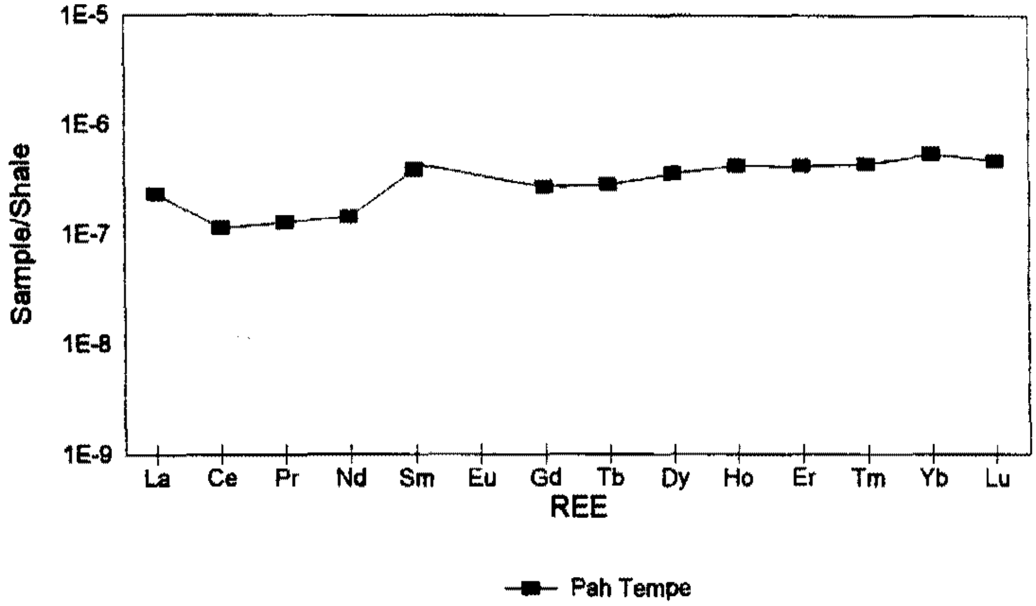


Figure 23: REE Normalization Plot of Pah Tempe Hot Springs

discharging in volcanic rocks as compared to other rock types (Figure 24). Like the previous REE normalization plots, these spring waters are depleted in the LREEs compared to the HREEs. However, their concentrations are almost an order of magnitude higher and there is also slight depletion in the heaviest of the HREEs (Figure 24). Dodge Spring (Beaver Dam Mountains) also discharges in an area of volcanic rocks and has a similar REE normalization pattern to Clover-UNK, but exhibits an overall lower concentration of REE. It is possible that Dodge Spring water has more limited contact with the volcanic rocks before discharging and therefore does not acquire as high of a REE concentration as the Clover Mountain springs. Springs discharging from some volcanic rocks in southwestern Nevada have similar patterns and concentrations to Putting Green, Creeper, and Clover-UNK springs (Johannesson et al., 1996). The REEs provide a means of examining subtle chemical processes in water and provide an additional discriminatory factor when grouping waters based on chemical data.

The differences in the REE normalization patterns exhibited by different spring water corresponded to some degree to the results of the spring water clustering based on water chemistry from the PCA. For example, Petrified, Roger's, and Blue Point consistently grouped together in the PCA and also displayed similar REE normalization patterns that were unique compared to the other springs in the study area (Figure 25). In comparison to most other springs in the basin their REE concentrations are lower and the REE normalization patterns are flatter.

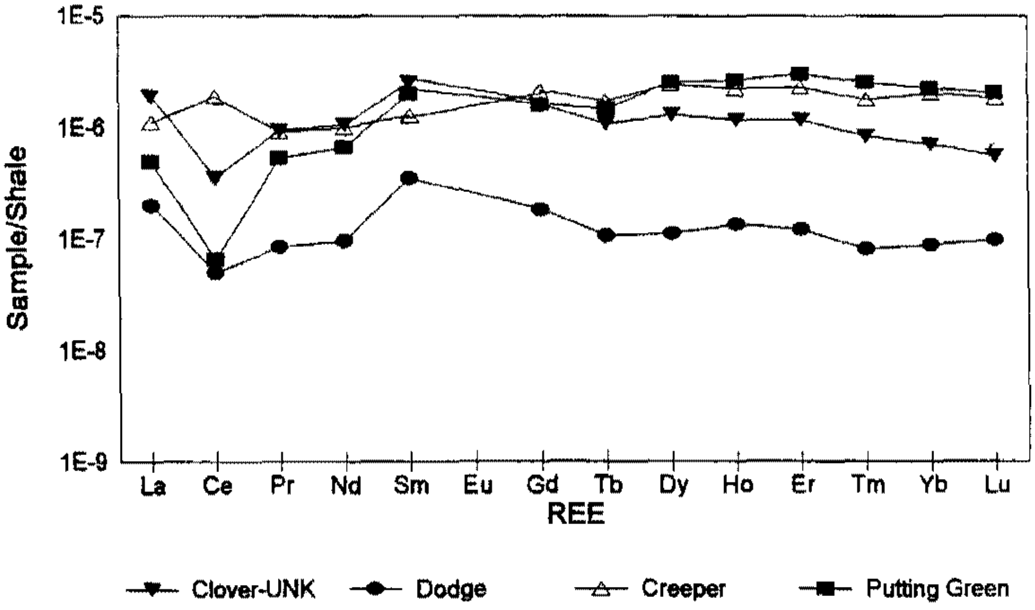


Figure 24: REE Normalization Plot of Clover Mountain Springs

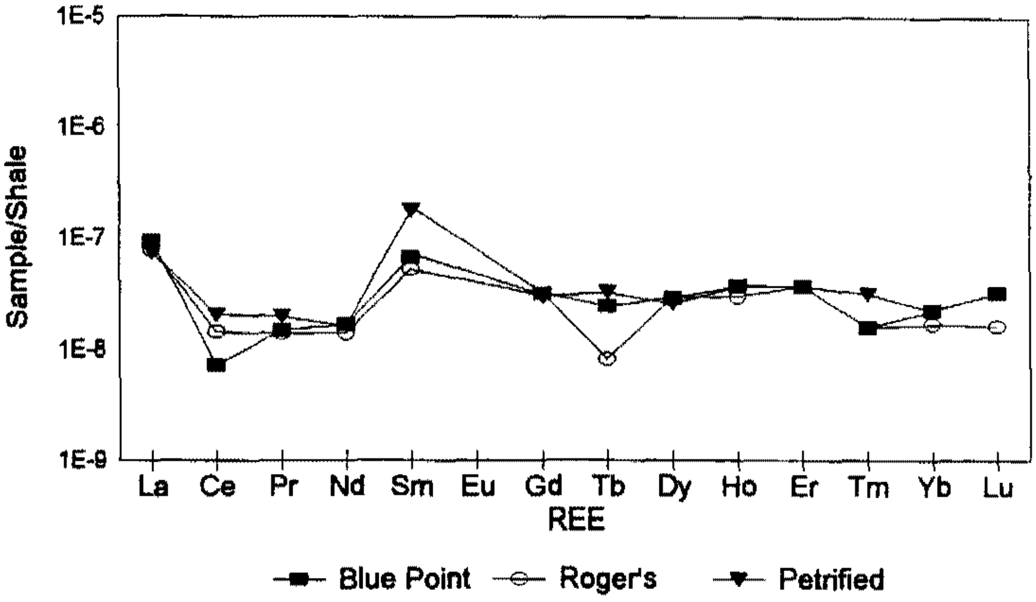


Figure 25: REE Normalization Plot of Petrified, Blue Point, and Roger's Springs

PHREEQE

PHREEQE was used to determine the saturation indices with respect to specific minerals for each spring water sampled in this study as well as for Virgin River water samples reported in Sandberg and Sultz (1985). PHREEQE is a geochemical computer program based on an ion-pairing aqueous model. The model is designed to assess the potential for geochemical reactions and to solve thermodynamic equations (Parkhurst et al., 1990). PHREEQE was used in the current study to simulate mineral equilibrium calculations for the spring waters. In addition, mineral equilibrium for Virgin River water samples reported in Sandberg and Sultz (1985) was determined to allow for the comparison of the mineral equilibrium of spring waters and river water in the Virgin River Basin. Similarities in mineral equilibrium between Virgin River water and spring water may provide insight into connections between groundwater and surface water in the Virgin River Basin.

Mineral equilibrium calculations for each spring water generated saturation indices with respect to calcite, gypsum, fluorite, aragonite, dolomite, and anhydrite. A saturation index is a dimensionless representation used to evaluate deviation from chemical equilibrium. A positive saturation index indicates the water is supersaturated with respect to a certain mineral, for example, calcite. Negative saturation indices mean the water is undersaturated.

Saturation indices for calcite, gypsum, and fluorite were compared graphically in Figures 26 through 29. In Figure 26 the saturation index of gypsum is plotted against the

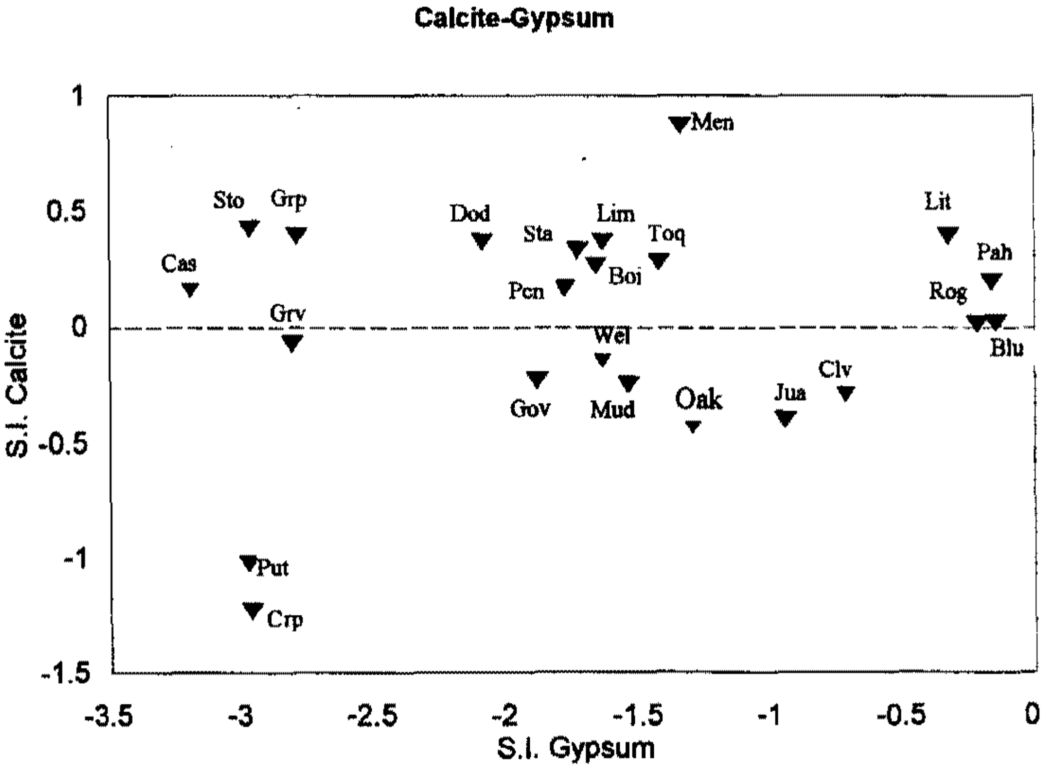


Figure 26: Virgin River Basin Spring Water Mineral Equilibrium Plot: calcite vs. gypsum

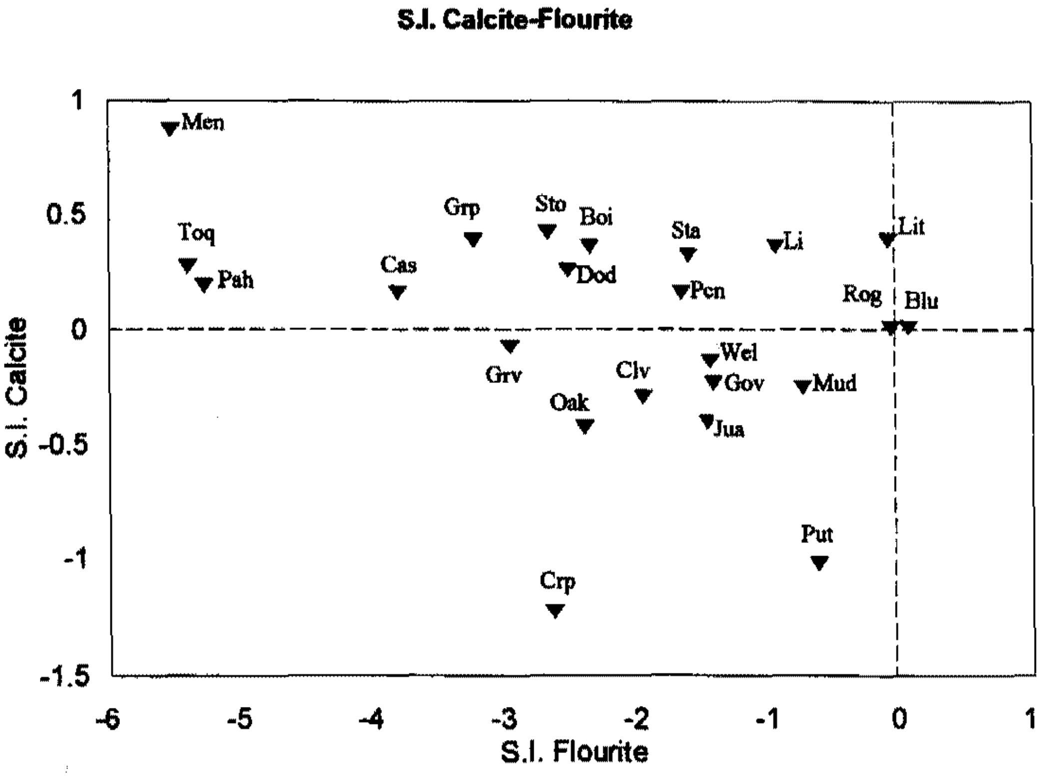


Figure 27: Virgin River Basin Spring Water Mineral Equilibrium Plot: calcite vs. fluorite

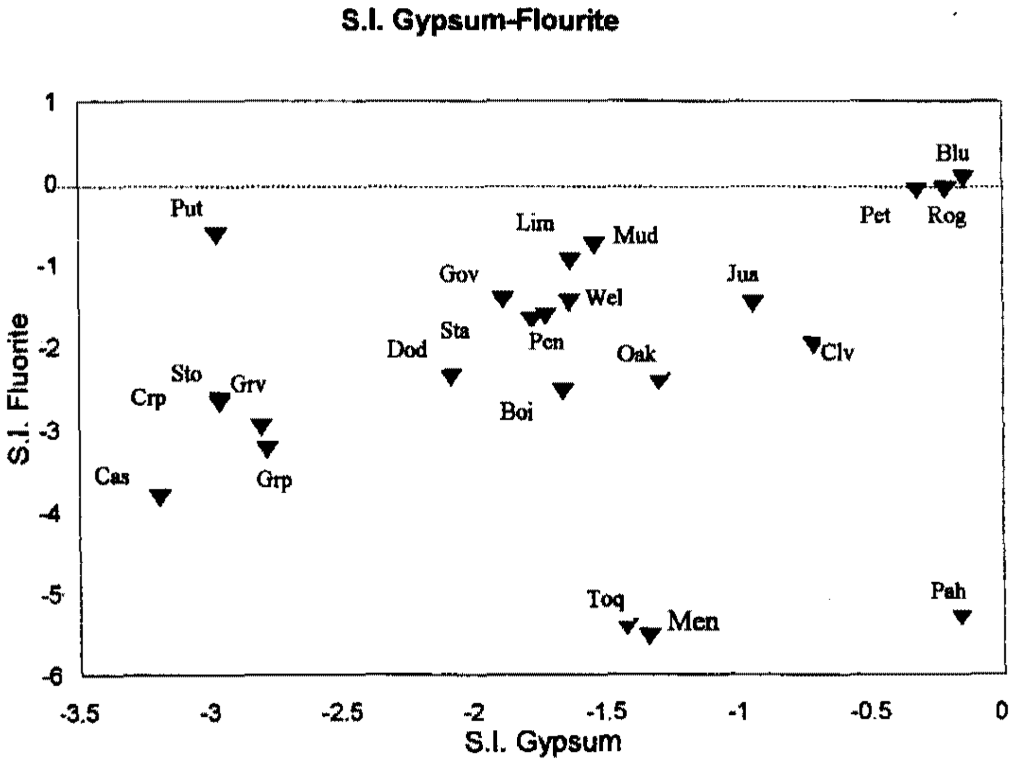


Figure 28: Virgin River Basin Spring Water Mineral Equilibrium Plot: fluorite vs. gypsum

Table 8: Virgin River Sites (From Sandberg and Sultz, 1985)

Site Name	Site #	Site Name	Site #
Virgin River at Littlefield, AZ	1	Virgin River above North Creek, UT	33.1
Virgin River above Beaver Dam, AZ	3	Virgin River below confluence of North and East Forks, UT	38
Virgin River near Bloomington, UT	6	North Fork Virgin River above confluence with East Fork, UT	39
Virgin River below Ash Creek, UT	21	North Fork Virgin River at mouth of Zion Narrows, UT	43.2
Virgin River below Pah Tempe Springs, UT	29	East Fork Virgin River above confluence with North Fork, UT	56
Virgin River above Pah Tempe Springs, UT	31	East Fork Virgin River at Mt. Carmel Junction, UT	60

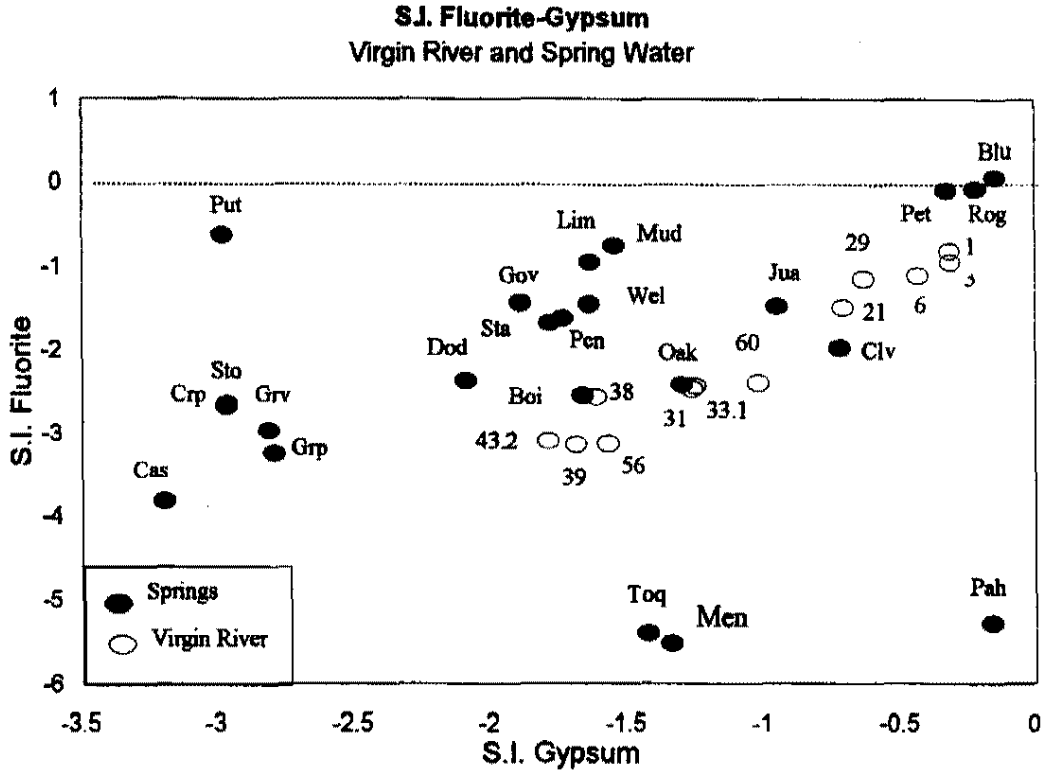


Figure 29: Virgin River Basin Spring Water and Virgin River Water Mineral Equilibrium Plot: gypsum vs. fluorite

saturation index of calcite. With the exception of Putting Green, Creeper, and Menu Falls springs, the remainder of the springs are nearly in equilibrium with respect to calcite and fall into a range of +/- 0.5 of being in equilibrium with calcite. The calcite undersaturation of Putting Green and Creeper, which discharge from volcanic rocks, may due to the lack of calcite availability in the areas where these two springs discharge. Menu Falls Spring is oversaturated with calcite as is evident at the spring site by the presence of travertine deposits. The gypsum saturation index values of the spring waters range from approximately -0.1 to -3.3 which is greater than the range of calculated values of the calcite saturation index. Spring waters in the lower basin (Petrified, Roger's, Blue Point) are nearly at equilibrium with gypsum as compared to springs near the headwaters of the Virgin River Basin (Cascade and Stout Canyon). The overall trend of the spring waters in the lower basin being nearly in equilibrium with gypsum is likely caused by an increase in the local availability of evaporites (i.e., gypsum) in the lower basin as compared to the Upper Virgin River Basin.

Other plots, including saturation indices of calcite versus fluorite (Figure 27), and gypsum versus fluorite (Figure 28), indicated the importance of fluorite saturation as a distinguishing factor between spring waters. In general, springs in the lower portion of the basin were nearly saturated with fluorite, while spring waters in the upper portions of the basin were more undersaturated. The differences in fluorite saturation in the Virgin River Basin spring waters may be caused by the availability of calcium. In natural waters, if sufficient calcium is present, the waters will likely be in equilibrium with fluorite because of the solubility product of fluorite compared to that of calcite (Hem, 1992).

The degree of mineral saturation in the Virgin River Basin spring waters is likely dependent on water-rock interactions encountered by the spring waters in their flow paths. Gypsum and fluorite saturation indices provided the greatest separations between spring waters based on their mineral equilibriums (Figure 28). The mineral equilibrium of Virgin River water with respect to fluorite and gypsum was also determined by PHREEQE to provide a comparison of surface water and groundwater in the Virgin River Basin. Virgin River water chemistry reported by Sandberg and Sultz (1985), was entered into PHREEQE to determine the mineral equilibrium of the river water. Figure 29 displays the comparison of spring waters in the study area to Virgin River water with respect to the saturation indices of gypsum and fluorite. As with the spring waters there is a trend in the river water samples (Table 8) for the water to be nearer to equilibrium with gypsum and fluorite as the river flows from the upper to the lower Virgin River Basin. Again, this may be caused by an increase in the availability gypsum as the water flows through the basin. Also, the abundance of calcium in the spring waters may control near equilibrium conditions the spring waters have with respect to fluorite.

Many additional studies could be conducted using PHREEQE and the chemical concentrations presented in this thesis including modeling the mixing of spring waters in the Virgin River Basin. Also, using a geochemical model such as PHREEQE or NETPATH may provide valuable information on discerning the source of spring waters in the Virgin River Basin. This type of analysis could be very important in determining the source of springs, such as the Littlefield Springs, that are believed to be a result of influent Virgin River water upstream from where the springs discharge and a much smaller portion of local recharge (Trudeau, 1979).

Stable Isotopes (deuterium and oxygen-18)

Spring water samples for stable isotope analysis (deuterium and oxygen-18) were collected at all of the spring sites in the study with the exception of Blue Point Spring. Isotopic concentrations were measured at the Desert Research Institute in Las Vegas, Nevada. Deuterium and oxygen-18 (D and ^{18}O) isotope abundances are reported as del (δ) values in permil ($^{o}/_{oo}$) units. Del (δ) values are the positive or negative deviations of isotope ratios away from a standard, specifically, SMOW (Standard Mean Oceanic Water) (Fetter, 1988). Further information may be gained by using a locally derived meteoric water line.

Results of the deuterium and oxygen-18 isotopic analyses are presented in Table 9. Values for $\delta^{18}O$ ranged from -8.6 $^{o}/_{oo}$ at Government Spring to -14.1 $^{o}/_{oo}$ at Menu Falls Spring. The average $\delta^{18}O$ value from the spring waters sampled in the current research was -12.3 $^{o}/_{oo}$. The range of δD values was -72 $^{o}/_{oo}$ to -104 $^{o}/_{oo}$ at Government Spring and Pah Tempe Hot Springs, respectively. The mean δD value was -91 $^{o}/_{oo}$ for the spring waters sampled in the study area. A δD value for the deuterium isotope of -91 $^{o}/_{oo}$, means that the spring water is depleted in the deuterium isotope by 91$^{o}/_{oo}$ or 9.1 % in comparison to SMOW (Domenico and Schwartz, 1990).

Values for δD and $\delta^{18}O$ are plotted against one another and compared to the global meteoric water line (MWL) (Craig, 1961) (Figure 30). Government, Dodge, and Pahcoon springs fall below the MWL which is likely due to the difficulty of sampling these springs directly at their orifices. It is likely that evaporative processes caused the deviation from the meteoric water line in these three spring waters. Spring waters, such as Pah Tempe, Big Muddy, Petrified and Roger's springs plot just to the right of the MWL and may be caused by exchange of the spring waters with minerals in the rocks through which the waters flow (Domenico and Schwartz, 1990). Domenico and Schwartz (1990) suggest that isotopic exchange between minerals and groundwater is important in deep, regional flow systems, as could be the case with Petrified and Roger's springs and also, Big Muddy Spring, which is believed to be a discharge point of the White River flow system in southern Nevada (Prudic et al., 1993; Burbey and Prudic, 1991). In addition, isotopic exchange between minerals and groundwater is also thought to be important in geothermal systems (Domenico and Schwartz, 1990), such as the spring water discharging at Pah Tempe Hot Springs. Isotopic exchanges could be responsible for the water discharging at Pah Tempe Hot Springs, plotting to the right of the global meteoric water line. The interaction of groundwater with rocks could change the $\delta^{18}O$ values due to the oxygen in the rocks. However, rocks contain little if any hydrogen, so δD values will be unaffected by water-rock interaction.

Table 9: Stable Isotope Data (oxygen-18 and deuterium) for Spring Waters

Spring	VSMOW 18O	VSMOW D
Government	-8.6	-72
Lime Kiln	-11.8	-85
Petrified	-12.6	-95
Welcome	-11.8	-87
Pahcoon	-9.9	-80
Big Muddy	-12.8	-96
Roger's	-12.3	-92
Oak-Low Mtn.	-12.2	-89
Dodge	-9.6	-76
Juanita	-11.9	-86
Stave	-12.9	-92
Putting Green	-12.7	-91
Stout Canyon	-13.4	-97
Menu Falls	-14.1	-104
Clover-UNK	-11.7	-85
Creeper	-12.4	-91
Pah Tempe	-13.6	-107
Oak Grove Camp	-13.5	-96
Toquerville	-12.9	-93
Boilers	-13.0	-93
Cascade Falls	-13.1	-96
Grapevine	-13.0	-93
	+/- 0.2	+/- 1

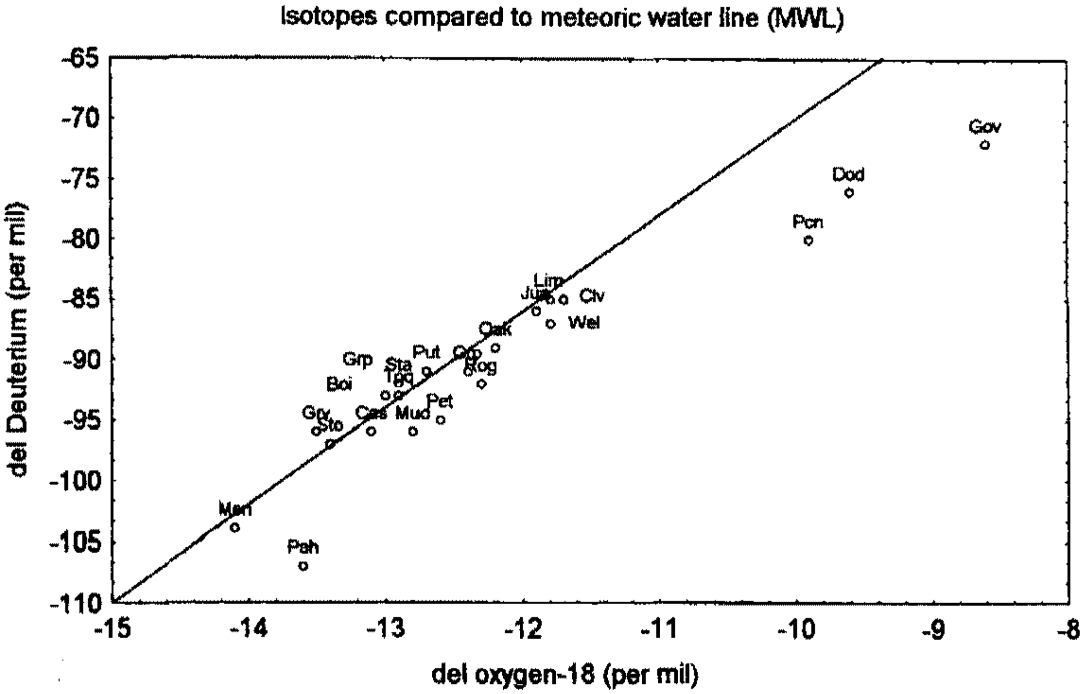


Figure 30: Stable Isotope Plot of Spring Waters (oxygen-18 and deuterium)

Major Spring Water Groups

Roger's, Blue Point, and Petrified Springs

The results of the data analysis tools presented in this research overwhelmingly indicate the waters discharging at Petrified, Blue Point, and Roger's springs are chemically similar. The similarity in chemical concentrations suggests that these springs may potentially be hydrologically connected. It is likely that Roger's and Blue Point springs are from the same source because they discharge along the same fault zone (Mifflin, 1968) and are only approximately one mile from one another. The potential hydrologic connection between Blue Point and Roger's springs, and Petrified Springs (Littlefield Springs) is not as easily accepted even though the springs are chemically very similar.

The source of Petrified Spring, which is a spring in the Littlefield Springs area, is thought to be related to an influent stretch of the Virgin River southwest of St. George, Utah, and northeast of the Virgin River Gorge in Arizona (Trudeau, 1979). The flow of Littlefield Springs is estimated to be a relatively constant at 65 cfs (1.8 m^3/s) (Glancy and Van Denburgh, 1969). These authors argue that the Littlefield Springs originate upstream in an influent area of the Virgin River and travel through carbonate rocks until they discharge downstream in a six mile stretch from the Virgin River Gorge to just southwest of Littlefield, Arizona. The chemical data presented here suggest that groundwater discharging at the Petrified Springs in the Littlefield Springs area may also flow toward and eventually discharge at Blue Point and Roger's springs. If the Virgin River is a losing stream as it flows toward Lake Mead, it may provide the 1200 acre-feet per year of flow discharging at Blue Point and Roger's springs. A hydrologic model presented by Prudic et al. (1993) also suggests that the discharge of these two springs is a result of the Virgin River flow system. However, groundwater head data indicate groundwater from the Virgin River system will not likely reach Roger's and Blue Point springs (J. Thomas, 1996, pers. comm.). In addition, deep carbonate rocks would likely be needed to transmit major amounts of groundwater from the Virgin River Basin to Roger's and Blue Point springs and this is probably not the case considering the knowledge of geology in the area (J. Thomas, 1996, pers. comm.). Moreover, if there was a direct hydrologic connection between the Littlefield Springs and Blue Point and Roger's springs, then spring waters discharging at Juanita Spring would be expected to group with these spring waters (Petrified, Blue Point, and Roger's springs) based on the location of Juanita Spring. Juanita Spring lies almost directly between the Littlefield Springs and Blue Point and Roger's springs and discharges from alluvium. The lack of chemical similarity between spring waters discharging from Juanita Spring and waters discharging from Petrified, Blue Point, and Roger's springs indicates a direct hydrogeologic connection between these spring waters is unlikely. However, the differences in elevation at Juanita Spring in comparison to Littlefield Springs may be the reason for the lack of similarity in spring water chemistry.

Another potential source for the spring waters discharging at Blue Point and Roger's Springs is flow from the Mormon Mountains. A zone of higher hydraulic conductivity geologic materials is located in a region that stretches from the Lake Mead area north to the Mormon Mountains and to the Beaver Dam Mountains (J. Thomas, 1996, pers. comm.). These more conductive deposits could potentially provide an avenue for groundwater flow from the Mormon and Beaver Dam mountains in the north to the Muddy Mountains and consequently, may contribute groundwater flow to Roger's and Blue Point springs (Prudic et al., 1993; J. Thomas, 1996, pers. comm.).

Other studies suggest that the discharge at Blue Point and Roger's is from an extension of the Muddy River Flow system. The topography of the area suggests that flow from the Muddy River Springs to Blue Point and Roger's springs is possible (Thomas et al., 1986). However, geologically this may not be possible because below the Muddy River Springs area, low permeability Cenozoic rocks and fine-grained clastic sediments (Anderson and Laney, 1975) near the land surface, that have low transmissivities, could prevent groundwater from reaching the Lake Mead area (Prudic et al., 1993). Also, isotopic data from Muddy Spring does not support the potential for discharge of the Muddy River flow system at Blue Point and Roger's Spring (Thomas et al., 1991). The chemical data in this research did not indicate any major similarities between Big Muddy Spring water and that at Petrified (Littlefield Springs), Blue Point or Roger's springs. Another possibility, however, is that the spring flow of Blue Point and Roger's springs is from recharge in the Muddy Mountains. However, this is unlikely based on the small amount of precipitation this area receives (Prudic et al., 1993).

The groundwater-surface water interactions in the Lower Virgin River Basin below Littlefield Springs is in question. Geochemical data from two separate studies, indicate that the groundwater is not being recharged from the Virgin River, but possibly from sources outside the basin (Las Vegas Valley Water District et al., 1992). Metcalf

(1995) conducted a study on the Lower Virgin River Basin and concluded that there was no significant evidence for groundwater increasing the flow of the Virgin River downstream from Littlefield, Arizona.

The research presented here, based on spring water chemical data, supports a potential connection between the water in the Virgin River Basin and the water discharging at Blue Point and Roger's springs west of the Overton Arm of Lake Mead. Even though this seems reasonable according to the similarities in spring water chemistry between Petrified Spring near Littlefield, Arizona, and Blue Point and Roger's springs, additional research is needed to understand if such a connection is hydrogeologically possible. Assuming no direct hydrogeologic connection, the reason for Petrified, Blue Point, and Roger's springs displaying analogous chemistries is likely a result of similar geologic materials being present in the areas where these groundwaters flow and eventually discharge. Limestone with abundant gypsum is present in both the Littlefield Springs area as well as at Roger's and Blue Point springs.

Clover Mountain Springs

Creeper, Putting Green, and Clover-UNK springs are located in the Clover Mountains and discharge from volcanic rocks. The Clover Mountain springs have similar chemistries to the majority of other springs in the Virgin River Basin except when REEs are included in the analysis. The separation of the Clover Mountain springs from other springs in the study area, based on REE concentrations, indicates the importance of REEs as a distinguishing factor between spring waters with similar major ion and trace element (without REE) concentrations. The difference in the Clover Mountain springs' REE normalization patterns and REE concentrations is likely due to the abundance of volcanic rocks where these groundwaters flow and discharge.

An understanding of the groundwater system in the Clover Mountains may be important in discerning the recharge of groundwater in the Lower Virgin River Basin. Well data suggest that water from the Clover Mountains and Meadow Valley Wash areas may be important in recharging the groundwater in the Mesquite, Nevada region of the Lower Virgin River Basin (Southern Nevada Water Authority, pers. comm., 1996).

Pah Tempe Hot Springs

Pah Tempe Hot Springs had very different water chemistry from other springs in the study area except when only REE data were used in the analysis. The similarity in REE concentrations and REE normalization patterns between Pah Tempe Hot Springs and the majority of other springs sampled in this study, indicates that Pah Tempe spring waters may have originated like other spring waters in the basin. However, due to the deep circulation of these spring waters the major ion and trace element (without REE) chemistry may have been altered. This suggests the potential to use the REEs as a conservative tracer in groundwater systems. Knowledge of groundwater flow in the area of Pah Tempe Hot Springs will be valuable as a potential diversion of the hot spring's water is being considered (Washington County Water Conservancy District, 1994).

Majority of Spring in the Study Area

A majority of the spring waters sampled for this research displayed similar chemistry as shown by the PCA and REE normalization plots when all 23 springs were included in the analysis. When primary spring groups (i.e., Pah Tempe; Petrified, Blue Point, and Roger's; Clover Mountain springs) were removed from the analysis some subgroups were evident, but for the most part the remaining spring were separated from one another on an individual basis, indicating some differences between the spring waters. There was a division of the spring waters in this group as a whole with separation between the Lower Basin springs as compared to the Central and Upper Basin spring waters. The separation between springs based on location may be due to the increase in evaporites moving from the Colorado Plateau in the Upper Basin to the Basin and Range Province in the Lower Virgin River Basin. The lack of spring subgroups may be related to the large areal extent and geologic diversity of the study area and the lack of sampling points in close proximity to one another.

CHAPTER 7

CONCLUSION AND FUTURE RESEARCH

The demand for Virgin River Basin water is dramatically increasing due to substantial urban growth in the southwestern United States, primarily in the areas of Las Vegas, Nevada, and St. George, Utah. Historically, agriculture has been the dominant water user in the basin, but with poor economic return in comparison to urban developments, the use of water for agricultural purposes will likely decrease in the future. The geologic and climatic uniqueness of the basin provides beauty and species diversity, making preservation of the natural basin a great concern and places additional demands on the water resources in the basin. The broad range of demands on the basin, and the current lack of structured governmental policies between the three basin states, will make the management of water resources in the Virgin River Basin very difficult. It is important for the basin to be managed according to basin boundaries, not only political boundaries which has typically been the case in previous research conducted on the water resources in the Virgin River Basin. Studies, such as this one, that provide information about the entire river basin will be vital to supply knowledge in order to best management the water resources in the basin.

The research described in this thesis provides a large baseline data set for springs in the Virgin River Basin and other springs in close proximity to the Lower Virgin River Basin. Even though the success of using water chemistry to suggest potential groundwater source and groundwater flow in the Virgin River Basin was somewhat limited, valuable information on the overall spring water chemistry in the Virgin River Basin was established. Major ion chemistry contributed as much understanding to the groundwater system in the study area as did the trace elements excluding the REE.

The primary spring water groups (i.e., Pah Tempe; Petrified, Blue Point, and Roger's; Clover Mountain springs), based on chemistry data, suggested the importance of water-rock interactions in creating water chemistry "signatures" for the groundwaters in the study area. The spring groupings displayed by PCA and the REE normalization patterns resulted from similarities and differences in spring water chemistry which is potentially controlled by the rocks through which the groundwaters flow. Even though some of the results indicated strong correlations between certain springs (i.e., Petrified, Roger's, and Blue Point), additional hydrologic and geologic tools are needed to support or refute suggestions of a direct connections between these springs. The results presented from the use of water chemistry data analysis tools all provided similar suggestions as to analogous water chemistry of these three springs.

The information provided by this study will be helpful in the eventual development of a basin-wide hydrologic model. The large areal extent of the Virgin River Basin and its complicated geology represents a particularly difficult system in which to understand the groundwater movement and spring sources. Deciphering the groundwater flow regime is especially difficult because only 23 spring sites were used as data collection points for the entire Virgin River Basin (5,900 sq. miles, 15,280 sq. kilometers). Water chemistry can provide potential insight into an understanding of groundwater flow pathways, but in order for the Principal Component Analysis (PCA) of spring water chemistry to provide a more concrete understanding of the hydrogeology in the Virgin River Basin, additional data must be collected and other hydrologic tools should be used to support or refute the results of this study. A more in depth look into groundwater head values would provide another method to assist in determining the potential for connection between spring waters in localized areas. Additional research should include periodic resampling of previously sampled sites to provide information on seasonal fluctuation of spring water chemistry as well as the sampling of new spring sites in the Virgin River Basin and surrounding areas. Moreover, sampling well water for groundwater chemistry could provide useful information for the understanding of the groundwater system in the Virgin River Basin.

A more effective way of utilizing PCA for the interpretation of groundwater chemistry would be to focus on small areas of the basin to gain an understanding of groundwater movement of more localized groundwater flow first, and then to enlarge the study area as interpretations warrant. For instance, concentrating on a sub-basin and then expanding to an adjacent sub-basin may allow for easier interpretations in areas of more concentrated data collection.

The large spring water chemistry data set collected for this research will allow for numerous analyses utilizing several different hydrologic tools. Other hydrologic analyses would likely provide more insight into the groundwater flow system in the Virgin River Basin. For additional interpretation of a potential groundwater connection between

Petrified, Roger's, and Blue Point, the analysis of Virgin River water upstream from the Petrified Spring would be valuable. Sampling the Virgin River at several points along its flow path would potentially provide valuable information in understanding the groundwater-surface water relationship in the Virgin River Basin. Uranium isotope samples for uranium series disequilibrium analysis have already been collected, but not analyzed. Isotopic values for uranium may provide insight into groundwater age, source, and movement in the Virgin River Basin. Also, the further use of geochemical modeling programs such as PHREEQE or NETPATH to model the mixing of waters in the study area would give additional information on the water resources in the basin.

REE normalization patterns may be more useful if the REE concentrations of the spring waters were normalized to a standard other than the global shale as was used in this study. A REE standard directly related to the geologic materials found in the Virgin River Basin may contribute to the understanding of water-rock interactions in the Virgin River Basin. However, because of the complexity of the geologic materials in the Virgin River Basin, deciding on an appropriate standard for REE normalization would be difficult. At this point the use of North American Shale may provide smoother REE normalization patterns as compared to the global shale used to normalize the REE concentrations in this research, but will not significantly change the REE patterns.

The results of this study based on water chemistry suggested some insight into the groundwater system of the Virgin River Basin. However, it is important to combine this type of water chemistry data analysis with other combinations of hydrologic techniques to provide the most accurate interpretation of the groundwater flow system in the Virgin

River Basin. The use of other techniques as previously mentioned, should allow for a better understanding of the water resources in the Virgin River Basin. Also, the simultaneous analysis of groundwater and surface water samples would give more details on the overall water system in the basin.

APPENDICES

APPENDIX A

SPRING SITE GEOLOGY

KEY
Spring Name
Location

Geologic Characteristics (References).

Roger's Spring
Lake Mead, Muddy Mountains, NV

Located along fault at contact between sandstone, siltstone, and clay with abundant gypsum and rock salt underlain by basalt, and Devonian limestone and dolomite (Longwell et al., 1965; 1:250,000), at fault contact of conglomerate and Mississippian limestone (Mifflin, 1968).

Blue Point Spring
Lake Mead, Muddy Mountains, NV

Located along a fault and contact between sandstone, siltstone, and clay with abundant gypsum and rock salt underlain by basalt, and Devonian limestone and dolomite (Longwell et al., 1965; 1:250,000). Located at junction of 2 faults near Mississippian limestone (Mifflin, 1968).

Big Muddy Spring
Moapa Valley, NV

Located in Quaternary alluvium, surrounded by Tertiary Muddy Creek Formation sandstone, siltstone, and clay with abundant gypsum, nearby outcrops of sandstone, shale and thin limestone of Pennsylvanian and Mississippian Bird Spring Formation (Longwell et. al, 1965; 1:250,000). Alluvium near Mississippian, Pennsylvania, and Permian, Bird Spring Formation (Mifflin, 1968).

Grapevine Spring
Zion National Park, UT

Spring flow is from the base of a basalt flow aquifer covered with approximately a vertical sequence of 16 basalt flows. The spring originates at the boundary between basalts and the sedimentary Moenave Formation (Dinosaur Canyon Member). Vertical flow is expected to be large because of contraction joints in the basalts. Moenave and Kayenta formations act as aquitards and confine the majority of the groundwater flow to overlying Basalts and Navajo Sandstone (Hamilton, 1975). Located at junction between volcanic rocks of Pleistocene age (basalt flows and cinder cones; basalt flows occupy canyons and structural benches and in many cases capping mesas. Cinder cones are associated with normal faults. Dated basalts range in age from approximately 0.26 to 1.4 million years before present) and slide deposits of Holocene age (fragmented rockfall debris, including talus from Mesozoic sedimentary rocks and Quaternary Basalts) (Hamilton, 1987; 1:31,680).

Menu Falls Spring
Zion National Park, UT

Located in Navajo sandstone of Jurassic age (sandstone, white, gray, tan, pink, medium to fine-grained, crossbedded increasingly to top, maximum thickness attained at west temple an estimated 200 ft. (51 m)) just above alluvium (silt, sands and gravel in flood plain, stream channel and alluvial fan deposits) (Hamilton, 1987; 1:31,680), calcite deposits.

Stave Spring
Zion National Park, UT

Located at junction between Temple Cap Formation (sandstone gray and tan, crossbedded, overlying sandstone, red-brown, flat-bedded, with thin basal red shale, thickness of 0 to 260 ft in the park) and Carmel Formation Limestone, tan and gray; sandstone and siltstone, banded pink and gray; gypsum, and sandstone, fine-grained; constituting four members. Thickness approximately 850 ft in park (Hamilton, 1987; 1:31,680).

Petrified Spring
Littlefield, AZ

Observable flow originates in Littlefield Limestone, limestone, sandstone, and siltstone, some gypsum in area assumed to be secondary in origin, travertine deposits are common in area. (Trudeau, 1979).

Putting Green Spring
Clover Mountains, NV

Located in fluvial sediments, volcanics mostly tuffs, nonwelded to welded.

Creeper Spring
Clover Mountains, NV

Several small orifices are located in clay-like sediments, surrounding area consists of red-colored volcanics.

Clover-UNK Spring
Clover Mountains, NV

Located in area of volcanics, fault zone transmitting.

Dodge Spring
Beaver Dam Mountains, UT

Located in area of volcanics, dacite.

Juanita Spring
Virgin Mountains, NV

Located in valley fill of Muddy Creek Formation (Miocene and lower Pliocene (?), altered claystone and sandstone; white, very light gray, and grayish pink; silica and calcium carbonate deposited in pores and fractures (Hoover et al., 1992; 1:24,000); deposits along Juanita Springs Fault (down drop to west).

Oak Spring
Low Mountain, Virgin Mountains., AZ

Located in area of lower Paleozoic carbonates, basalts.

Pah Tempe Hot Springs
La Verkin, UT

Located in sidewall of Virgin River canyon composed of Permian Limestone (Kaibab), Large amounts of gypsum and some calcite deposits (Cordova, 1981).

Stout Canyon Spring
Stout Canyon, UT; Dixie National Forest

Cretaceous Kaiparowits Formation (Arkosic sandstone, and sandy shale)/Tertiary Wasatch Formation (Limestone and calcareous sandstone, conglomeratic at base, generally light-colored) siltstone and mudstone; Cretaceous Wahweap Sandstone (Buff, gray, or yellow sandstone, minor shale) (Cordova, 1981).

Cascade (Spring) Falls
Navajo Lake, UT

Located in Tertiary Wasatch Formation; Limestone and calcareous sandstone, conglomeratic at base, generally light-colored (Sandberg and Sultz, 1985).

Toquerville Spring
Toquerville, UT

Located on west side (down thrown) of Hurricane Fault, stage 1 Basalt flow on top of Quaternary alluvium. From Navajo Sandstone (Utah Board of Water Resources, 1993).

Oak Grove Camp Spring
Pine Valley Mountains, UT

Located in area of Tertiary intrusion through Navajo sandstone.

Boilers Spring
St. George, UT

Located in alluvium recycled from Kayenta and Moenave gypsiferous sands and silts (Triassic ?) (Hintze, 1963; Clyde, 1987).

Lime Kiln Spring
Virgin Mountains, AZ

Located in area of outcrops of metamorphic rocks (gneiss) near limestones.

Government Spring
Virgin Mountains, NV

Located in area of Tapeat Sandstone (Middle and Lower Cambrian) sandstone and quartzite, probably near shore marine; and Chisholm Shale (Middle Cambrian) Shale, quartzite, and limestone, black to gray and gray green, marine. (Hoover et al., 1992; 1:24,000).

Pahcoon Spring
Beaver Dam Mountains, UT

Located near outcrops of Moenave Formation (Triassic ?), mainly shale and siltstone; some mudstone and sandstone (Cordova et al., 1972), and Kayenta Formation (Jurassic), red shale and siltstone (Larsen et al., 1986).

Welcome Spring
Beaver Dam Mountains, UT

Located in alluvial sediments near outcrops of Redwall Limestone (Mississippian), Bonanza King Formation (Cambrian - laminated white boundstone in upper half, silty limestone near base, and Tapeats Quartzite (Hintze, 1986; 1:48,000).

APPENDIX B

SPRING SITE DESCRIPTIONS

This section gives information on individual spring sites and includes comments noted in field notebook during field reconnaissance and/or spring water sampling.

KEY
Spring Name (Location)
(Water Type)
Description

Roger's Spring (Lake Mead, Muddy Mountains, NV)
(calcium, sulfate)

Roger's spring is located in the Lake Mead Recreation Area west of the Overton Arm of Lake Mead near Stewart's Point. The area around this spring has been developed as a picnic area. The access to this spring is easy via the paved road that follows the coastline of Lake Mead. Flow from this spring comes from limestone and is estimated to be 880 gpm (56 L/s) (Mifflin, 1968).

Blue Point Spring (Lake Mead, Muddy Mountains, NV)
(calcium, sulfate)

Blue Point spring is located in the Lake Mead Recreational and flows from alluvium, just to the northeast of the Muddy Mountains, toward Lake Mead west of the Overton Arm near Stewart's Point. The access to this spring is easy via the paved road that follows the coastline of Lake Mead. The spring orifice is about one-half mile west of the paved road where several palm trees grow. Flow has been estimated by Mifflin (1968) to be 400 gpm (25 L/s). The spring is approximately one mile north or Roger's spring. The Valley of Fire State Park is to the northwest of the Blue Point spring.

Big Muddy (Moapa Valley, NV)
(sodium, bicarbonate, sulfate)

Big Muddy spring is located in the alluvium along the Muddy River in the Moapa Valley. The spring is just one of a group of large regional springs discharging approximately 8 to 10 miles northwest of Interstate-15 along Highway 168. Groundwater in this area is believed to be transmitted through Paleozoic carbonate rocks exposed in the area. The spring waters range in temperature from 80° F to 90° F and have potential for recreational purposes and low temperature agricultural applications (Robinson and Pugsley, 1981). Many of the springs in this area can be accessed by taking Warm Springs Road from Highway 168 just east of Warm Springs. Big Muddy spring is located at the L.D.S. Recreation Area. This spring has been developed for recreational purposes and is often diked up to provide swimming facilities. Total flow from the springs in the Warm Springs area (Muddy River Springs) of the Moapa Valley is estimated to be 37,000 acre-ft/yr (Eakin, 1966).

Grapevine (Zion National Park, UT)
(calcium, magnesium, bicarbonate)

Grapevine spring is located at an elevation of 4500 ft (1370 m) at the intersection of Grapevine Wash and the Left Fork of North Creek in the western part of Zion National Park. Spring flow is from the lower end of Cave Valley at the base of a basalt escarpment at the contact between basalt and Moenave Sandstone. Gaining access to this spring requires a semi-difficult hike of approximately 1 ½ hours down a very steep gradient, descending 450 ft. (137 m). The best trail is a game trail marked by a parking area just west of Grapevine Wash. Follow the trail east across the wash where after a short hike the trails descends into the canyon of the Left Fork of North Creek. High permeability of this basalt aquifer results in rapid response to variations in precipitation (Hamilton, 1975). Flow has been reported as 360 gpm (23 L/s) (Cordova, 1981) but likely fluctuates due to precipitation events. The beautiful discharge area of the spring (approximately 60 ft (18 m) above the Left Fork of North Creek) is covered by lush green ferns and other vegetation. (NOTE: Beware of rattlesnakes).

Menu Falls (Zion National Park, UT)
(sodium, chloride, sulfate)

Menu Falls Spring is located in the main canyon of Zion National Park north of the visitor's center. The spring is on the east side of the paved road in the main canyon approximately 5 ½ miles from jog in the road that will take you north into the main canyon or on east to the east entrance of Zion National Park. There is a pull-off area just west of the spring. A walkway and deck area have been developed to view this spring. The spring issues from rock several feet above the viewing area. White mineral deposits (calcite) were apparent on the rocks near the spring flow. Flow was estimated to be about 3 to 5 gpm (0.2 to 0.3 L/s). (NOTE: The deck that directly overlooks the spring flow had recently been painted at the time of sampling. Paint fumes were very noticeable.).

Stave Spring (Zion National Park, UT)
(calcium, bicarbonate)

Stave Spring is located near the eastern boundary of Zion National Park, north of the east entrance to the park. There are several hiking trails in this area to provide access to the spring. The quickest access is probably by driving east (2.5 miles) of the park's entrance and turning north (5.2 miles) to go to the Ponderosa Ranch. From this point there is dirt road access to the park boundary and then a marked hiking trail can be followed to Stave spring. It takes about 20 minutes to hike to the spring. The spring has been developed and a spring flow of approximately 1 to 2 gpm (0.1 to 0.2 L/s) flows from a small pipe near the contact of two sedimentary formations.

Petrified Spring (Littlefield, AZ)
(calcium, sulfate)

Petrified Spring is actually in an area of spring discharge collectively known as the Littlefield Springs. Several orifices are located in a six mile stretch that begins in the Virgin River Gorge northeast of Littlefield, Arizona and ends near the town of Littlefield, Arizona. The Petrified Spring discharges out of the alluvial bank of the Virgin River just south of the Interstate-15 Virgin River Bridge at Littlefield. The spring was accessed by exiting the interstate at the Farm Road exit just northeast of Littlefield and following a service road west to a small parking area along the river. The spring is to the right (north) on the upper bank of the river. An area below this spring flow is often used for recreational purposes. Water is diverted from the Littlefield Springs area for agricultural purposes. During dry summer months the flow from Littlefield Springs accounts for the majority of the flow in the Virgin River.

Putting Green (Clover Mountains, NV)
(magnesium, calcium, bicarbonate)

Putting Green spring (not named according to map) has several orifices discharging from a flat grassy area in the Clover Mountains. The flow comes from fluvial sediments near surrounding outcrops of volcanic rocks. The total flow from this meadow area was estimated at 10 to 20 gpm (0.6 to 1.3 L/s). This spring was accessed by the use of a helicopter and is located just to the west of the Virgin River Basin boundary

Creeper Spring (Clover Mountains, NV)
(calcium, bicarbonate)

Creeper Spring (not named according to map) is located in the Clover Mountains and was accessed by the use of a helicopter. Several small orifices are located in clay-like sediments on a side slope. The flow (approximately 0.5 cfs (14 L/s)) of groundwater from this slope is creating a scarp, as the highly saturated soil is slowly "creeping" down the slope. Outcrops near the spring discharge consists of volcanic rocks that are red in color.

Clover-UNK (Clover Mountains, NV)
(calcium, sulfate)

Clover-UNK (not named according to map) is located in the Clover Mountains. The discharge (approximately 0.25 cfs (7 L/s)) is from fluvial deposits in a small stream channel surrounded by volcanic outcrops. This spring was accessed by the use of a helicopter.

Dodge Spring (Beaver Dam Mountains, UT)
(calcium, magnesium, sodium, bicarbonate)

Dodge spring is located in volcanic rocks in the northern Beaver Dam Mountains about 1.5 miles west of the Beaver Dam Wash and 2 miles east of the Nevada state line, approximately 22 miles north of the Arizona state line. The actual orifice was not found, so the spring water samples were taken from stream flow (approximately 5 to 10 gpm (0.3 to 0.6 L/s)). A fairly recent fire had burned most of the vegetation in the area. A helicopter was used to gain access to this spring.

Juanita Spring (Virgin Mountains, NV)
(calcium, sulfate)

Juanita spring discharges on private property from alluvial deposits at the base of the Virgin Mountains. The spring is located 3.5 miles east of the Virgin River. The Black Ridge is located southwest of Juanita Spring and the Bunkerville Ridge to the northeast. North of the spring at higher elevations in the Virgin Mountains, there are outcrops of Precambrian metamorphic rocks and also limestone outcrops. Flow was estimated at 500 gpm (32 L/s) and mineral deposits were evident on surrounding soil. This spring was actually accessed by helicopter, but can easily be accessed by a paved road south of the Virgin River at Riverside, Nevada. The road parallels the Virgin River to the southwest for about 7 miles then curves to the southeast for about 3.5 miles where Juanita spring is noticeable from the growth of vegetation and palm trees. The spring has been developed for use by the property owner, but the sample was actually taken directly from alluvial flow.

Oak Spring (Virgin Mountains, AZ)
(calcium, magnesium, bicarbonate, sulfate)

Oak spring is located in the eastern Virgin Mountains near Low Mountain in Mohave County, Arizona. The spring flow (1 to 2 gpm (0.1 to 0.2 L/s)) was sampled in a cistern where it was apparently piped from a nearby area. The cistern was located just east of a small meadow. Carbonates and basalts were present in the area. A helicopter was used to access this spring. Travel by 4-wheel drive vehicle would be possible but several hours of driving would be required to reach the spring.

Pah Tempe Hot Springs (La Verkin, UT)
(sodium, chloride, sulfate)

Pah Tempe Hot Springs, also known as La Verkin Hot Springs, discharges directly from Kaibab Limestone in the bed and sidewalls of the Virgin River canyon along the Hurricane Fault between Hurricane and La Verkin, Utah just 0.5 miles east of Highway 9. This spring area has been developed by private owners into a recreational resort. The spring flow was estimated to be 4700 gpm (300 L/s) (Cordova, 1981). The water quality of this spring is very poor. Total dissolved solid concentrations are extremely high and cause severe degradation in the overall quality of the Virgin River downstream from these hot springs. There is a great deal of controversy surrounding the impact of Pah Tempe Hot Springs on the Virgin River Basin downstream from this area. The springs discharge approximately 109,000 tons of dissolved solids each year (U.S. Bureau of Reclamation, 1979).

Stout Canyon Spring (Dixie National Forest, Stout Canyon, UT)
(magnesium, calcium, bicarbonate)

Stout Canyon spring is in the headwaters region of the East Fork of the Virgin River in the Dixie National Forest in Utah. The spring is located in Stout Canyon and discharges from alluvium in an area of the Wasatch Formation (Tertiary) and the Kaiparowits Formation and Wahweap Sandstone (Cretaceous). The flow in this area was estimated to be 0.5 cfs (14 L/s). The spring can be accessed by taking Highway 89 north of Mt. Carmel Junction, Utah to the Long Valley Junction and turning west on Highway 14 to Stout Canyon Road. The dirt road is followed south for approximately 4 miles to arrive at the spring site.

Cascade (Spring) Falls (Navajo Lake, UT)
(calcium, magnesium, bicarbonate)

Cascade Spring is at the headwaters (8900 ft) of the North Fork of the Virgin River. The spring is located 6400 ft south of Navajo Lake in the Kolob Terrace area of the Dixie National Forest in southwestern Utah. The spring flows from Tertiary Wasatch Formation (Sandberg and Sultz, 1985). The majority of the water discharging from Cascade Springs originates from the inflow of water at the east end of Navajo Lake into the underlying porous basalts (Wilson and Thomas, 1964). Flow has been reported to fluctuate with the water levels in Navajo Lake (1 to 6 cfs (28 to 170 L/s)) (Sandberg and Sultz, 1985).

Toquerville Spring (Toquerville, UT)
(calcium, magnesium, sulfate, bicarbonate)

Toquerville Spring is a group of several orifices on the west side of the Hurricane Fault on the northern edge of Toquerville, Utah. Flow from the Toquerville springs discharges from the bed and sides of Ash Creek in two main locations (Upper Toquerville and Lower Toquerville springs). The Lower Toquerville Springs were sampled in this study. The combined flow of Toquerville Springs is estimated to be 30 cfs (850 L/s) (Utah Board of Water Resources, 1993). The source of the springs is not known but suggestions have been made that the flow comes from a basalt aquifer and/or Navajo Sandstone (Utah Board of Water Resources, 1993). The water is very high quality and is diverted for both agricultural and public uses.

Oak Grove Camp Spring (Pine Valley Mountains, UT)
(calcium, bicarbonate)

Oak Grove Camp Spring is located on the eastern slope of the Pine Valley Mountains northwest of Leeds, Utah in the Dixie National Forest. The access road parallels Leeds Creek most of the way to Oak Grove Campground. The spring is located a short hike north of the circle drive at the campground. Flow from this spring has been developed for use at the campground. A smaller orifice near the fenced spring development was sampled for this study. The flow at this specific discharge point was approximately 2 to 5 gpm 0.1 to 0.3 L/s), however there is additional flow from several other orifices. The area is thick with grasses and Pine trees. Up gradient from the spring location there is evidence of Tertiary intrusion through Navajo Sandstone. The spring appears to discharge for alluvial sediments below these intrusions.

Boilers Spring (St. George, UT)
(calcium, bicarbonate, sulfate)

Boilers spring is located just west of Interstate-15, approximately 0.5 miles north of the Washington exit, north of St. George, UT. The spring is used for recreation and can be accessed on short dirt roads paralleling Interstate-15. The spring discharge has formed a pool in alluvium of recycled Kayenta and Moenave Formations. Spring discharge was estimated to be approximately 700 gpm (45 L/s).

Lime Kiln Spring (Virgin Mountains, AZ)
(calcium, bicarbonate)

Lime Kiln Spring is located in Lime Kiln Canyon in the Virgin Mountains of Arizona at a point about 2 miles east of the Nevada/Arizona state line, The spring is about 10 miles south, southeast of Mesquite, Nevada. The spring can be accessed by following a paved road that turns into dirt from west side of Mesquite and crosses the Nevada/Arizona state line in the Virgin Mountains and climbs south into Lime Kiln Canyon (approximately 11 miles). Both metamorphic and sedimentary rocks outcrop in this area. The flow was estimated to be 2 to 3 gpm (0.1 L/s).

Government Spring (Virgin Mountains, NV)
(magnesium, sodium, calcium, bicarbonate)

Government Spring is located on the western slope of the Virgin Mountains in the Bunkerville Ridge area. The spring can be accessed by a paved road south of the Virgin

River at Riverside, Nevada. The road parallels the Virgin River to the southwest for about 7 miles then curves to the southeast for about 6 miles where an abrupt turn on a dirt road (4-wheel drive) cuts to the northeast. Juanita Spring is about halfway between curve to southeast and the dirt road turnoff to Government Spring. The road winds for about 6 more miles to the north, northeast. Another access is from a dirt road that leaves the pavement and heads to the southeast (6 to 7 miles) about 2 miles southwest of Riverside, Nevada. Government Spring has been developed as water storage for livestock and wildlife. The spring water is piped into a large cement storage area. The sample was taken directly from flow (1 to 2 gpm (approx. 0.1 L/s)) out of the pipe as the actual orifice could not be sampled.

Pahcoon Spring (Beaver Dam Mountains, UT)
(calcium, magnesium, bicarbonate)

Pahcoon Spring is located in the northeastern Beaver Dam Mountains in southwestern Utah approximately 4 miles southwest of Gunlock, Utah. The spring can be accessed by dirt road (5 miles) from the paved road that cuts through the Paiute Indian Reservation just north of the Santa Clara River gaging station. The spring is less than 0.5 miles east of the main dirt road. The spring has been developed for livestock water storage purposes. The spring appears to be piped into a cement storage structure and was sampled at that point. The cement storage structure had just been dredged to remove silt. The spring discharges (2 to 3 gpm (approx. 0.1 L/s)) in alluvial sediments near outcrops of Moenave and Kayenta Formations.

Welcome Spring (Beaver Dam Mountains, UT)
(calcium, magnesium, bicarbonate)

Welcome Spring is located in the Beaver Dam Mountains in southwestern Utah, north of Littlefield, Arizona. The spring can be accessed by traveling on the paved road north (12 miles) out of Beaver Dam, Arizona and turning west onto a dirt road (2 miles) and then turning right for another 2 miles. The spring has been developed for livestock water storage. A cement storage structure is located at the end of the road. The sample was taken east, up the wash approximately ½ mile from a cement structure where the water was freely flowing. Flow was estimated to be about 5 to 10 gpm (0.3 to 0.6 L/s).

APPENDIX C

FIELD RECONNAISSANCE

APPENDIX C Virgin River Basin Spring Reconnaissance

Spring Name	General Location	DATE	LAT. (N)	LON. (W)	Elevation meters	Alkalinity mg/l	Temp. C	pH	EC µS
Roger's	Lake Mead, NV	5/15/95	36 23 20	114 26 56	NA	128	30.1	6.8	3350
Blue Point	Lake Mead, NV	5/15/95	36 23 20	114 26 07	530	138	29.1	6.8	4000
Government	Virgin Mtns, NV	5/24/95	36 38 73	114 10 91	591	184	20.8	7.4	853
Key West South	Virgin Mtns, NV	5/24/95	NA	NA	NA	Not sampled - outflow from tank - stagnant water			
Key West North	Virgin Mtns, NV	5/24/95	NA	NA	NA	Not sampled - outflow from tank - stagnant water			
Tombstone	Wolf Hole Mtns, AZ	6/4/95	NA	NA	NA	Not sampled - outflow from tank - stagnant water			
Maple	Black Rock Mtns, AZ	6/4/95	36 46 55	113 43 53	NA	308	29.7*	7.6	2090
Quail	Wolf Hole Mtns, AZ	6/4/95	NA	NA	NA	no flow			
Lime Kiln	Virgin Mtns, AZ	6/24/95	NA	NA	NA	419	23.3	7.3	977
Little Wolf	Wolf Hole Mtns, AZ	6/4/95	36 45 99	113 42 20	NA	555	23.6	7.4	7470
Littlefield	Littlefield, AZ	5/24/95	36 53 60	113 54 96	NA	368	26.9	7.1	3590
Jones	Moapa Valley, NV	5/22/95	36 43 11	114 43 11	991	221	29.9	7.7	1018
Baldwin	Moapa Valley, NV	5/22/95	36 43 24	114 43 38	NA	226	31	7.6	996

* storage tank LAT. (N) = latitude north LON. (W) = longitude west NA = not available, no measurement

APPENDIX C Virgin River Basin Spring Reconnaissance (cont.)

Spring Name	General Location	DATE	LAT. (N)	LON. (W)	Elevation meters	Alkalinity mg/l	Temp. C	pH	EC µS
Little Baldwin	Moapa Valley, NV	5/22/95	36 43 24	114 43 38	NA	237	29.2	7.4	1074
Iverson	Moapa Valley, NV	5/22/95	36 43 26	114 42 93	NA	217	31.4	7.6	1015
Welcome	Beaver Dam Mtns, UT	6/2/95	37 05 85	113 54 67	760	340	18.6	7.1	927
Badger	Beaver Dam Mtns, UT	6/2/95	37 10 43	113 55 87	1296	347	19.5	8.0	1049
Camp	Beaver Dam Mtns, UT	5/19/95	37 10 93	113 46 77	NA	193	24.3	7.9	2.78
Pahcoon	Beaver Dam Mtns, UT	5/19/95	37 14 49	113 49 48	1216	174	24	7.7	647
Jackson	Beaver Dam Mtns, UT	5/19/95	37 16 60	113 53 43	1188	236	17.7	7.4	1503
Jackson (tank)	Beaver Dam Mtns, UT	5/19/95	37 16 60	113 53 45	1188	186	18	7.5	2260
Red Hollow	Beaver Dam Mtns, UT	5/19/95	37 18 13	113 55 97	NA	Not sampled - outflow from tank - stagnant water			
Peach	Mormon Mtns, NV	5/18/95	36 57 29	114 17 40	952	39	27.3	8.0	121.1
Gourd	Mormon Mtns, NV	5/18/95	36 57 59	114 17 42	1004	Not sampled - outflow from tank - stagnant water			
Abe	Tule Desert, NV	5/18/95	37 02 11	114 14 81	933	228	28.8	7.7	789
Tule	Tule Desert, NV	5/18/95	37 02 36	114 14 74	NA	114	22.1	8.1	516

* storage tank LAT. (N) = latitude north LON. (W) = longitude west NA = not available, no measurement

APPENDIX C Virgin River Basin Spring Reconnaissance (cont.)

Spring Name	General Location	Date	Latitude (N)	Longitude (W)	Elevation meters	Alkalinity mg/l	Temp. C	pH	EC µS
Spring Mtn. Meadow	Bull Valley Mtns, UT	6/2/95	37 28 51	113 38 50	1672	307	18.2	7.7	702
Kane	Bull Valley Mtns, UT	6/2/95	37 26 92	113 37 19	NA	264	15.3	7.7	593
Sawyer	Pine Valley Mtns, UT	6/3/95	37 26 30	113 16 35	NA	239	21.7	7.7	531
Oak Grove Camp	Pine Valley Mtns, UT	6/3/95	37 19 17	1132720	2085	213	14.8	7.2	463
Pah Tempe	La Verkin, UT	6/3/95	37 11 32	11 316 18	NA	1040	32	6.1	13270
Toquerville	Toquerville, UT	6/3/95	37 15 98	113 16 76	NA	177	23.7	7.4	702
Smith Mesa	Smith Mesa, UT	6/3/95	37 18 48	113 07 56	NA	221	19.9	7.6	1858
Coyote	Hurricane Cliffs, AZ	6/4/95	32 56 08	113 22 02	NA	no flow			
Gould	Hurricane Cliffs, UT	6/4/95	37 07 34	113 14 37	NA	215.5	19.4	7.4	3610
Lemmon	Zion Natl. Park, UT	6/30/95	NA	NA	NA	313	18.6	7.6	617
Menu Falls	Zion Natl. Park, UT	6/29/95	NA	NA	NA	193	24.1	7.6	1588
Stave Spring	Zion Natl. Park, UT	6/30/95	37 15 69	112 54 30	2191	416	15.2	7.4	820
Stout Canyon	Stout Canyon, UT	6/29/95	NA	NA	NA	269	15	7.7	507
Left Fork North Creek	Zion Natl. Park, UT	6/30/95	NA	NA	NA	113	25	7.8	312

* storage tank LAT. (N) = latitude north LON. (W) = longitude west NA = not available, no measurement

APPENDIX D

PRINCIPAL COMPONENT ANALYSIS

Key to PCA Plot Information - Basic Information (Statistica, 1993)

Eigenvalue:

The table of eigenvalues presented with each plot gives the variance of each successive factor extracted by the principal component analysis. Accumulative percentages of the variance accounted for by the factors are given.

Factor Scores:

Factor scores give the coordinates where each variable will plot in a graphical representation.

Factor Loadings:

Factor loadings are the correlations between the variables and the factors generated ("new variable"). The original variables that provide the majority of the relationship to generated factors are indicated by a star (*).

NOTE: Figure numbers in this appendix correspond to those found in the text.

Spring Name Abbreviations

Petrified	Pet	Government	Gov
Lime Kiln	Lim	Pahcoon	Pcn
Welcome	Wel	Roger's	Rog
Blue Point	Blu	Big Muddy	Mud
Dodge	Dod	Creeper	Crp
Putting Green	Put	Clover-UNK	Clv
Juanita	Jua	Oak-Low Mtn.	Oak
Pah Tempe	Pah	Grapevine	Grp
Stout Canyon	Sto	Cascade Falls	Cas
Stave	Sta	Menu Falls	Men
Toquerville	Toq	Oak Grove Camp	Grv
Boilers	Boi		

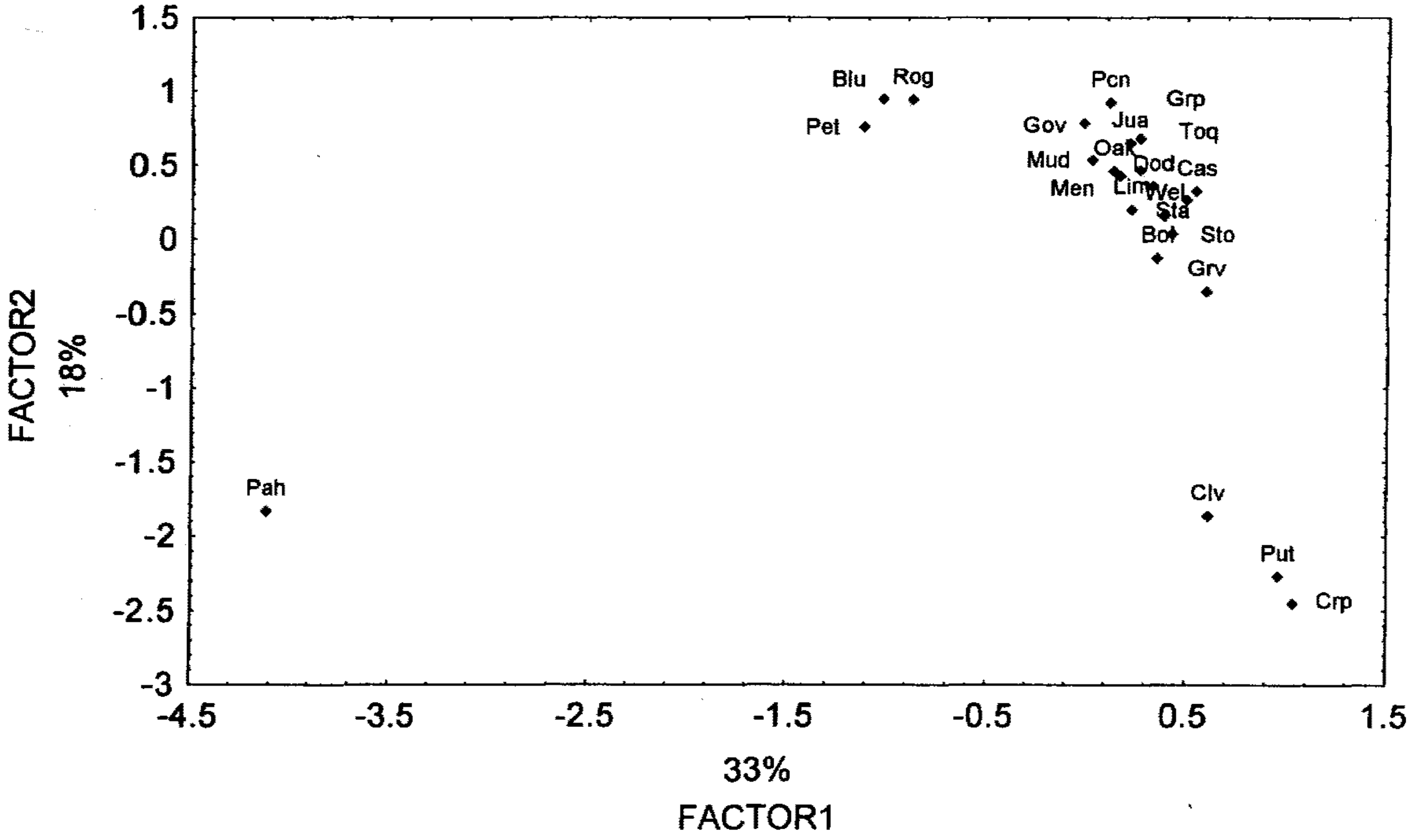


Figure 12: All Chemical Concentrations, All Springs

Figure 12
fs61
Eigenvalues (nofield.sta)
Extraction: Principal components

	Eigenval	% total Variance	Cumul. Eigenval	Cumul. %
1	21.80277	33.03450	21.80277	33.03450
2	12.15941	18.42334	33.96218	51.45785
3	5.60233	8.48838	39.56451	59.94622
4	4.33634	6.57022	43.90085	66.51644

Factor scores

	FACTOR1	FACTOR2
Pet	-1.12232	0.75702
Gov	-0.01263	0.78159
Lim	0.22269	0.19946
Pcn	0.11508	0.92254
Wel	0.38672	0.15700
Rog	-0.87495	0.94370
Blu	-1.02160	0.94820
Mud	0.02589	0.53490
Dod	0.32924	0.35076
Crp	1.03401	-2.44832
Put	0.96105	-2.26695
Clv	0.61510	-1.86422
Jua	0.21523	0.64942
Oak	0.13236	0.46017
Pah	-4.11721	-1.83098
Grp	0.26243	0.68079
Sto	0.49570	0.26365
Cas	0.54329	0.31895
Sta	0.42541	0.03545
Men	0.16561	0.42726
Toq	0.26236	0.46425
Grv	0.60124	-0.35444
Boi	0.35528	-0.13020

Factor Loadings (nofield.sta)
Extraction: Principal components
(Marked loadings are > .700000)

		Factor 1		Factor 2			Factor 1	Factor 2
Alkalinity	*	-0.74851		-0.23403	ZN		-0.08161	0.22099
NA	*	-0.89372		-0.27922	GA		-0.66601	-0.13918
K	*	-0.90107		-0.27115	AS	*	-0.72148	0.16847
CA	*	-0.87819		-0.08056	SE		-0.61827	0.33060
MG	*	-0.74980		0.14755	RB	*	-0.90588	-0.26454
CL	*	-0.88448		-0.29325	SR	*	-0.87359	-0.17784
SO4	*	-0.79687		0.03750	AG		-0.60410	0.05289
F		-0.17713		0.17490	CD		-0.10741	0.04970
BR	*	-0.85189		-0.25987	IN	*	-0.85873	-0.32625
NO3		-0.08032		0.23244	CS	*	-0.88435	-0.26560
Y		0.24268	*	-0.85849	BA		0.13921	0.13175
LA		0.26154		-0.68790	TL		0.05592	-0.08089
CE		0.20081		-0.58662	PB		-0.29759	-0.01747
PR		0.31750	*	-0.81290	BI	*	-0.85638	-0.32742
ND		0.33136	*	-0.82025	U		0.06509	0.14792
SM		0.27137	*	-0.78148	RU	*	-0.88661	-0.29995
GD		0.31515	*	-0.85100	RH		-0.02610	-0.23944
TB		0.30560	*	-0.85650	PD		-0.62030	0.28993
DY		0.32151	*	-0.83582	SN	*	-0.86957	-0.12074
HO		0.30370	*	-0.83665	SB		0.20420	-0.40782
ER		0.30738	*	-0.82019	TE	*	-0.85453	-0.33832
TM		0.27974	*	-0.81395	HF		0.11591	-0.12299
YB		0.27056	*	-0.82231	IR		0.33861	-0.19278
LU		0.27772	*	-0.72369	PT		0.06810	0.20645
TH		0.04582		-0.18766	AU		-0.07387	0.23546
LI	*	-0.92281		-0.21527	GE	*	-0.85677	-0.32501
BE	*	-0.77389		-0.45818	ZR	*	-0.81341	-0.34011
AL	*	-0.71222		-0.27517	NB	*	-0.73359	0.06267
V		-0.07333		0.32302	MO		-0.15064	0.41559
CR		-0.33830		0.31854	TA		-0.52363	0.16900
MN		-0.48816		-0.39106	W		-0.35870	-0.11463
CO	*	-0.85593		-0.02731	RE		-0.19659	0.51868
NI	*	-0.70485		0.14085	Expl.Var		21.80277	12.15941
CU	*	-0.69977		0.14078	Prp.Totl		0.33035	0.18423

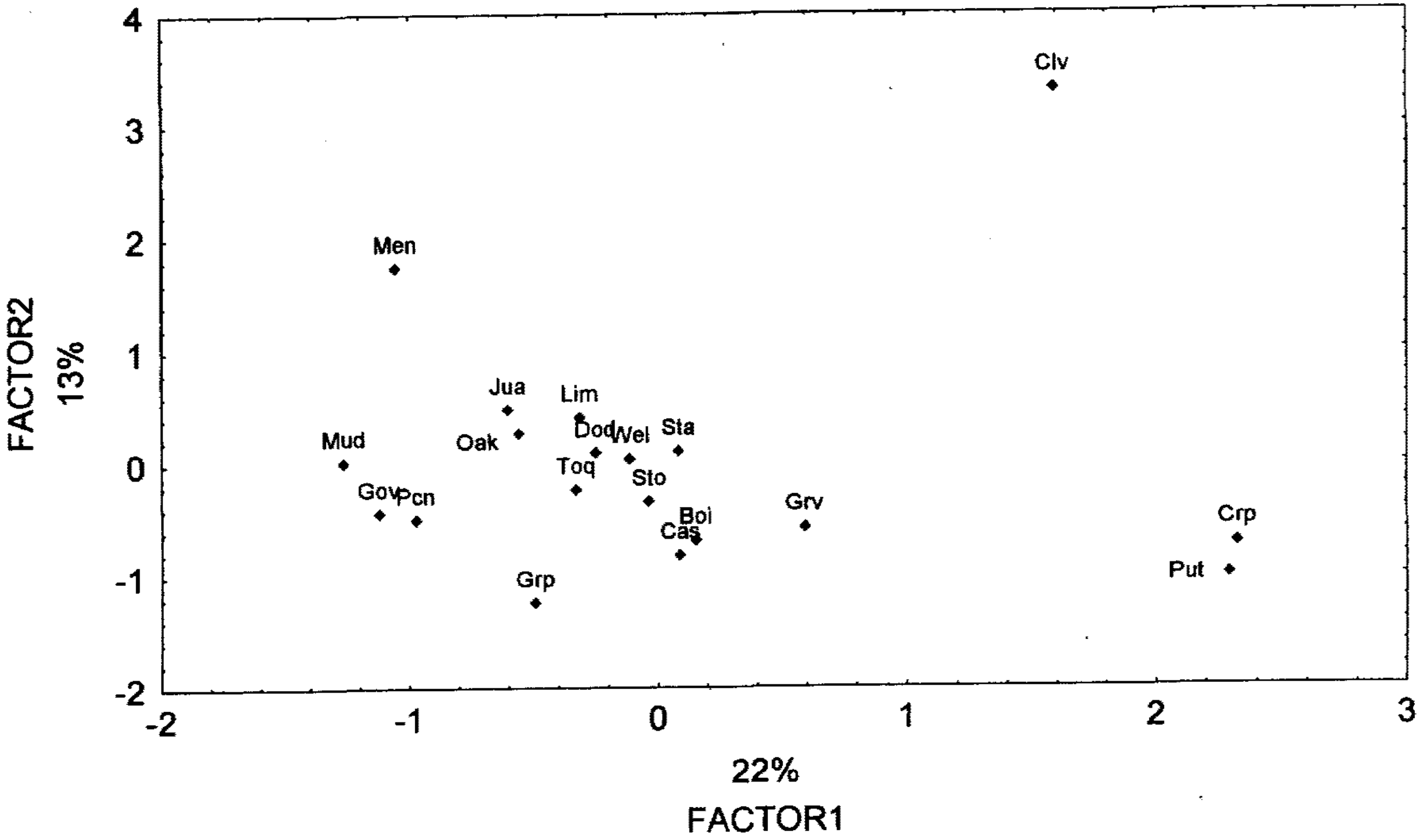


Figure 13: All Chemical Concentrations without Pah Tempe, Petrified, Roger's, and Blue Point Springs

Figure 13
fs62
Eigenvalues (nofieldx.sta)
Extraction: Principal components

	Eigenval	% total Variance	Cumul. Eigenval	Cumul. %
1	14.14994	21.76913	14.14994	21.76913
2	8.40747	12.93457	22.55741	34.70370
3	7.42546	11.42379	29.98287	46.12749
4	6.29092	9.67834	36.27379	55.80583

Factor scores

	FACTOR1	FACTOR2
Gov	-1.12348	-0.43497
Lim	-0.31536	0.41501
Pcn	-0.97473	-0.49210
Wel	-0.11367	0.04170
Mud	-1.26820	0.02497
Dod	-0.25202	0.09750
Crp	2.32211	-0.71714
Put	2.29171	-1.00044
Clv	1.59386	3.31383
Jua	-0.60177	0.48360
Oak	-0.55893	0.27525
Grp	-0.49395	-1.23323
Sto	-0.03669	-0.33587
Cas	0.08746	-0.81452
Sta	0.08327	0.11045
Men	-1.05717	1.74700
Toq	-0.32761	-0.22850
Grv	0.59227	-0.57199
Boi	0.15290	-0.68054

Factor Loadings (nofieldx.sta)
Extraction: Principal components
(Marked loadings are > .700000)

	Factor 1	Factor 2			
Alkalinity	-0.24756	0.37526	CU	-0.12557	0.38316
NA	-0.37925	0.46491	ZN	-0.27435	-0.08217
K	-0.53087	0.20376	GA	-0.11261	-0.18434
CA	0.01165	* 0.82017	AS	-0.45704	-0.04785
MG	-0.30145	0.49775	SE	-0.46195	-0.08108
CL	-0.41296	0.40110	RB	-0.33570	0.12623
SO4	-0.09919	* 0.81155	SR	0.03993	* 0.85565
F	0.10408	-0.13948	AG	-0.52311	0.09209
BR	-0.28622	0.14922	CD	-0.07533	-0.13909
NO3	-0.34906	-0.24405	IN	-0.32622	0.38651
Y	* 0.86429	0.18496	CS	-0.34729	0.07847
LA	0.68927	0.51240	BA	-0.10642	-0.10974
CE	0.59392	-0.03459	TL	0.12412	-0.12330
PR	* 0.83832	0.29497	PB	-0.20029	-0.12237
ND	* 0.85230	0.27330	BI	-0.30451	0.38925
SM	* 0.79981	0.34586	U	-0.16133	0.09272
GD	* 0.88287	0.10558	RH	0.13289	* 0.84177
TB	* 0.88661	0.04171	PD	-0.51364	0.02935
DY	* 0.88295	-0.05875	SN	-0.30883	-0.00676
HO	* 0.88064	-0.07627	SB	0.35949	0.66454
ER	* 0.86513	-0.09636	TE	-0.04901	0.69094
TM	* 0.85025	-0.14083	HF	0.01033	-0.32273
YB	* 0.85434	-0.16433	IR	0.22305	0.00770
LU	* 0.76317	-0.20830	PT	-0.27745	0.04651
TH	0.04599	0.45615	AU	-0.25521	-0.11556
LI	-0.44439	0.05861	GE	-0.21301	0.01376
BE	0.63526	-0.26061	ZR	-0.25967	-0.06914
AL	-0.22716	-0.25734	NB	-0.06735	0.34228
V	-0.38602	-0.22403	MO	-0.40145	0.02012
CR	-0.41123	-0.34019	TA	0.04234	* 0.74796
MN	0.14554	0.34736	W	-0.21750	-0.07909
CO	0.03613	0.62722	RE	-0.51274	0.45675
NI	-0.10182	0.68261	Expl.Var	14.14994	8.40747
			Prp.Totl	0.21769	0.12935

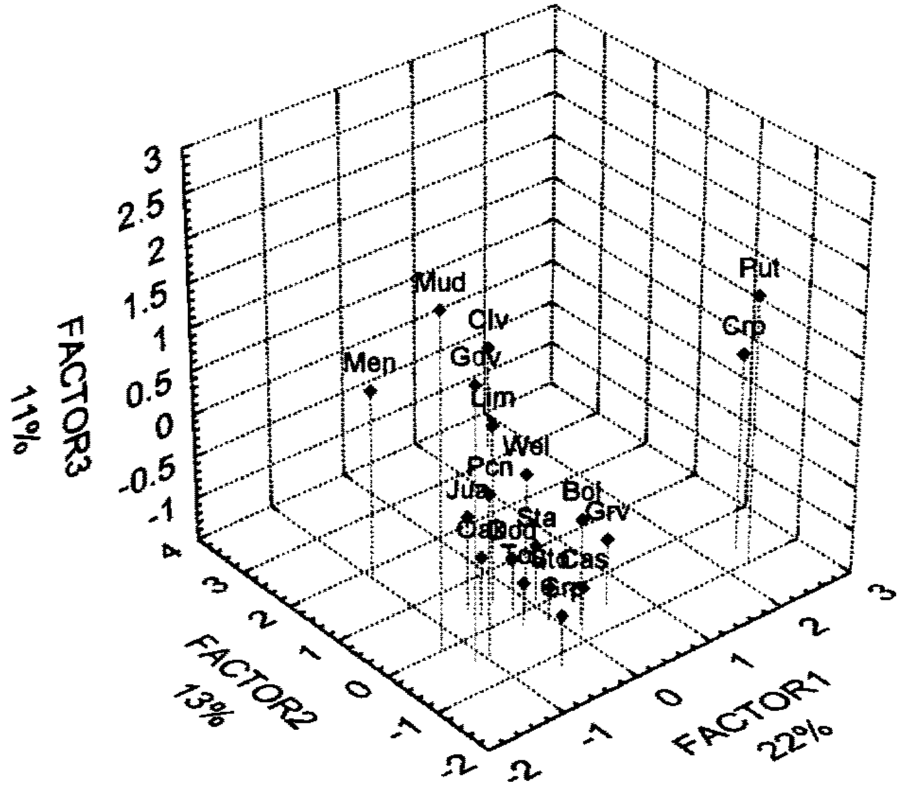


Figure 14: 3-D Plot, All Chemical Concentrations without Pah Tempe, Petrified, Roger's, and Blue Point Springs

Figure 14
fs62
Eigenvalues (nofieldx.sta)
Extraction: Principal components

	Eigenval	% total Variance	Cumul. Eigenval	Cumul. %
1	14.14994	21.76913	14.14994	21.76913
2	8.40747	12.93457	22.55741	34.70370
3	7.42546	11.42379	29.98287	46.12749
4	6.29092	9.67834	36.27379	55.80583

Factor scores

	FACTOR1	FACTOR2	FACTOR3
Gov	-1.12348	-0.43497	1.65473
Lim	-0.31536	0.41501	0.57931
Pcn	-0.97473	-0.49210	0.38990
Wel	-0.11367	0.04170	0.07745
Mud	-1.26820	0.02497	2.35113
Dod	-0.25202	0.09750	-0.87279
Crp	2.32211	-0.71714	0.83057
Put	2.29171	-1.00044	1.59990
Clv	1.59386	3.31383	-0.30643
Jua	-0.60177	0.48360	-0.40411
Oak	-0.55893	0.27525	-0.80589
Grp	-0.49395	-1.23323	-0.89910
Sto	-0.03669	-0.33587	-1.12089
Cas	0.08746	-0.81452	-0.98284
Sta	0.08327	0.11045	-0.86155
Men	-1.05717	1.74700	0.75154
Toq	-0.32761	-0.22850	-0.99585
Grv	0.59227	-0.57199	-0.72085
Boi	0.15290	-0.68054	-0.26424

Factor Loadings (nofieldx.sta)
Extraction: Principal components
(Marked loadings are > .700000)

	Factor 1	Factor 2	Factor 3
Alkalinity	-0.24756	0.37526	-0.17904
NA	-0.37925	0.46491	0.47927
K	-0.53087	0.20376	0.58370
CA	0.01165	* 0.82017	-0.19360
MG	-0.30145	0.49775	-0.11537
CL	-0.41296	0.40110	0.36500
SO4	-0.09919	* 0.81155	0.02320
F	0.10408	-0.13948	* 0.74904
BR	-0.28622	0.14922	0.40500
NO3	-0.34906	-0.24405	0.27398
Y	* 0.86429	0.18496	0.28384
LA	0.68927	0.51240	0.05514
CE	0.59392	-0.03459	0.17035
PR	* 0.83832	0.29497	0.17757
ND	* 0.85230	0.27330	0.19457
SM	* 0.79981	0.34586	0.19643
GD	* 0.88287	0.10558	0.27444
TB	* 0.88661	0.04171	0.30868
DY	* 0.88295	-0.05875	0.33301
HO	* 0.88064	-0.07627	0.33053
ER	* 0.86513	-0.09636	0.34899
TM	* 0.85025	-0.14083	0.34215
YB	* 0.85434	-0.16433	0.33756
LU	* 0.76317	-0.20830	0.20998
TH	0.04599	0.45615	0.16176
LI	-0.44439	0.05861	0.60134
BE	0.63526	-0.26061	0.39820
AL	-0.22716	-0.25734	-0.15727
V	-0.38602	-0.22403	0.01859
CR	-0.41123	-0.34019	-0.03236
MN	0.14554	0.34736	0.08771
CO	0.03613	0.62722	-0.24630
NI	-0.10182	0.68261	-0.34051
CU	-0.12557	0.38316	-0.18415
ZN	-0.27435	-0.08217	0.36741
GA	-0.11261	-0.18434	-0.20423
AS	-0.45704	-0.04785	0.37598
SE	-0.46195	-0.08108	0.23495
RB	-0.33570	0.12623	0.50303
SR	0.03993	* 0.85565	0.01629
AG	-0.52311	0.09209	0.44938
CD	-0.07533	-0.13909	0.08227
IN	-0.32622	0.38651	0.26944
CS	-0.34729	0.07847	0.38381
BA	-0.10642	-0.10974	-0.39684
TL	0.12412	-0.12330	-0.15584
PB	-0.20029	-0.12237	0.39687
BI	-0.30451	0.38925	0.24107
U	-0.16133	0.09272	0.19149
RH	0.13289	* 0.84177	-0.21107
PD	-0.51364	0.02935	0.53286
SN	-0.30883	-0.00676	0.42621
SB	0.35949	0.66454	0.10135
TE	-0.04901	0.69094	0.04837
HF	0.01033	-0.32273	0.60380
IR	0.22305	0.00770	-0.19777
PT	-0.27745	0.04651	0.28258
AU	-0.25521	-0.11556	0.08805
GE	-0.21301	0.01376	0.59303
ZR	-0.25967	-0.06914	0.49978
NB	-0.06735	0.34228	-0.46049
MO	-0.40145	0.02012	0.50378
TA	0.04234	* 0.74796	0.24387
W	-0.21750	-0.07909	0.54668
RE	-0.51274	0.45675	0.33233
Expl.Var	14.14994	8.40747	7.42546
Prp.Totl	0.21769	0.12935	0.11424

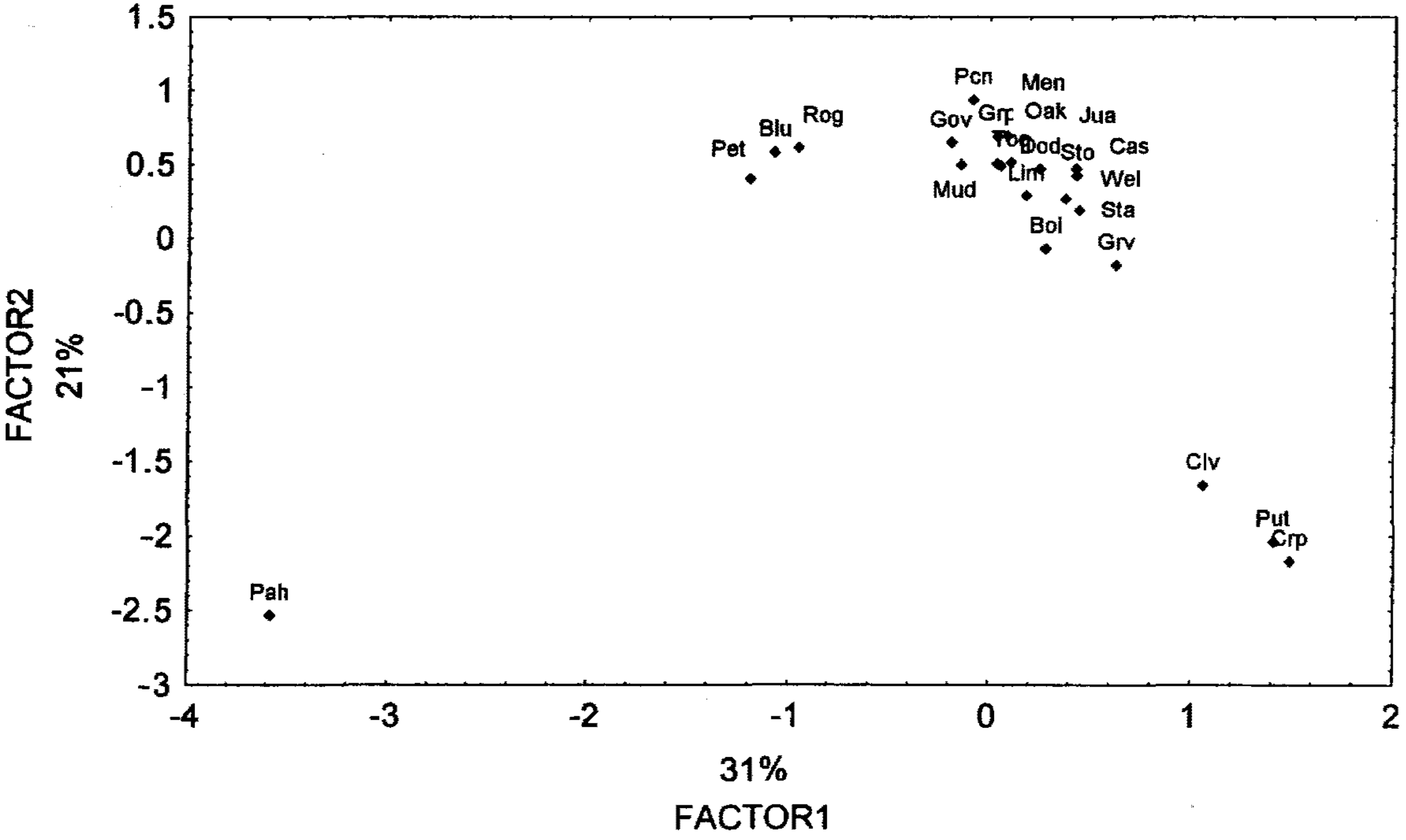


Figure 15: All Trace Elements, All Springs

Figure 15

fs40

Eigenvalues (alltrace.sta)

Extraction: Principal components

	Eigenval	% total Variance	Cumul. Eigenval	Cumul. %
1	17.20931	30.19177	17.20931	30.19177
2	12.03827	21.11977	29.24758	51.31154
3	4.78716	8.39853	34.03474	59.71007
4	3.89054	6.82550	37.92528	66.53557
5	2.69841	4.73405	40.62368	71.26962

Factor scores

	FACTOR1	FACTOR2
Pet	-1.20687	0.40302
Gov	-0.20501	0.63165
Lim	0.18186	0.28623
Pcn	-0.08301	0.92656
Wel	0.37132	0.26168
Rog	-0.96455	0.60618
Blu	-1.08281	0.57625
Mud	-0.14732	0.49600
Dod	0.25569	0.47470
Crp	1.46579	-2.19241
Put	1.38672	-2.05758
Clv	1.06279	-1.65518
Jua	0.07883	0.68090
Oak	0.03028	0.50126
Pah	-3.58975	-2.50034
Grp	0.06417	0.71586
Sto	0.48090	0.47222
Cas	0.42212	0.46319
Sta	0.44094	0.18308
Men	0.04730	0.48521
Toq	0.10198	0.50957
Grv	0.61731	-0.19069
Boi	0.27132	-0.07736

Factor Loadings (alltrace.sta)

Extraction: Principal components

(Marked loadings are > .700000)

		Factor 1		Factor 2			Factor 1	Factor 2
Y		0.43433	*	-0.81847	SR		-0.82420	-0.37140
LA		0.42192		-0.63531	AG		-0.62789	-0.07889
CE		0.32453		-0.55471	CD		-0.13618	0.01059
PR		0.49907	*	-0.75411	IN	*	-0.79506	-0.49523
ND		0.51405	*	-0.75917	CS	*	-0.83227	-0.44634
SM		0.45203	*	-0.73069	BA		0.12010	0.19570
GD		0.50136	*	-0.79754	TL		0.06719	-0.06357
TB		0.49230	*	-0.80595	PB		-0.30429	-0.10017
DY		0.50208	*	-0.78350	BI		-0.79263	-0.49554
HO		0.48488	*	-0.78703	U		0.03759	0.16685
ER		0.48447	*	-0.77062	RU	*	-0.82594	-0.47946
TM		0.45372	*	-0.76916	RH		0.04169	-0.23267
YB		0.44514	*	-0.77977	PD		-0.68122	0.13248
LU		0.42553		-0.67565	SN	*	-0.85083	-0.31305
TH		0.08705		-0.16260	SB		0.30426	-0.36527
LI	*	-0.87658		-0.41116	TE	*	-0.78771	-0.50632
BE		-0.68366		-0.60876	HF		0.13637	-0.10528
AL		-0.66793		-0.40734	IR		0.38283	-0.09873
V		-0.14991		0.30800	PT		0.02658	0.22943
CR		-0.42500		0.23793	AU		-0.12344	0.22090
MN		-0.40355		-0.47442	GE	*	-0.79502	-0.49517
CO	*	-0.83647		-0.22640	ZR	*	-0.74878	-0.49525
NI	*	-0.71635		-0.03871	NB	*	-0.73329	-0.10717
CU	*	-0.70972		-0.03651	MO		-0.23053	0.35024
ZN		-0.13126		0.17569	TA		-0.54131	0.02320
GA		-0.65414		-0.27762	W		-0.35428	-0.19160
AS	*	-0.74553		-0.01257	RE		-0.28744	0.44273
SE		-0.67954		0.16756	Expl.Var		17.20931	12.03827
RB	*	-0.85312		-0.45131	Prp.Totl		0.30192	0.21120

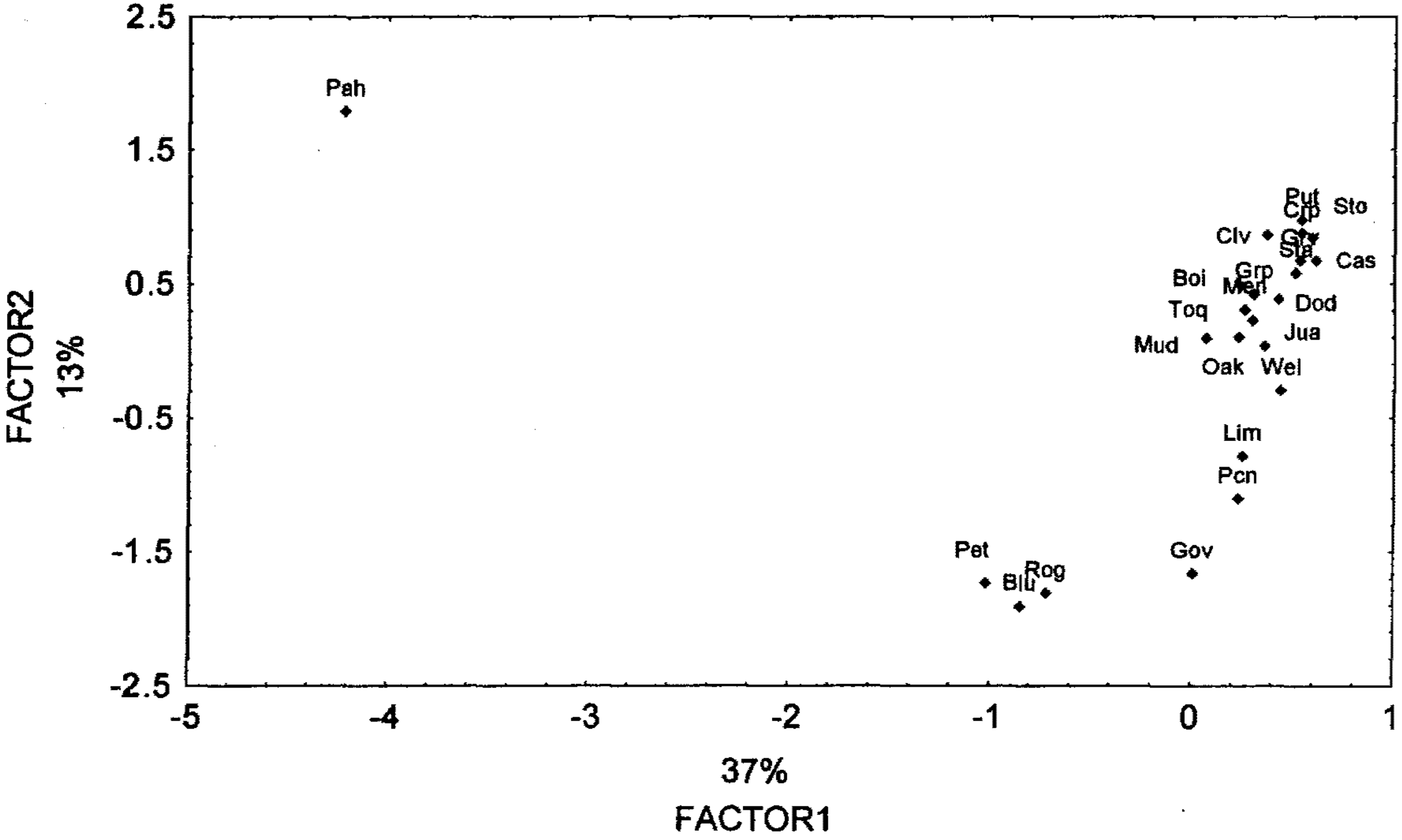


Figure 16: Trace Elements without REE Concentrations

Figure 18
fs41
Eigenvalues (altmore.sta)
Extraction: Principal components

	Eigenval	% total Variance	Cumul. Eigenval	Cumul. %
1	16.12373	37.49705	16.12373	37.49705
2	5.71129	13.28208	21.83503	50.77914
3	3.68564	8.57127	25.52067	59.35040
4	2.82940	6.58000	28.35007	65.93040

Factor scores

	FACTOR1	FACTOR2
Pet	-1.01713	-1.73328
Gov	0.00785	-1.66344
Lim	0.25075	-0.78450
Pcn	0.22911	-1.10737
Wel	0.43922	-0.29292
Rog	-0.71703	-1.80847
Blu	-0.84482	-1.90780
Mud	0.06843	0.09522
Dod	0.42905	0.38337
Crp	0.53811	0.87477
Put	0.53981	0.97542
Clv	0.36740	0.85911
Jua	0.35605	0.03998
Oak	0.22894	0.10007
Pah	-4.21985	1.78741
Grp	0.30383	0.41814
Sto	0.59155	0.83828
Cas	0.60919	0.66830
Sta	0.51064	0.57873
Men	0.25860	0.30350
Toq	0.29796	0.22544
Grv	0.53106	0.66929
Boi	0.24029	0.48075

Factor Loadings (altrnore.sta)
Extraction: Principal components
(Marked loadings are > .700000)

		Factor 1		Factor 2
Y		0.10336		0.42800
TH		0.02840		0.20761
LI	*	-0.96507		0.09075
BE	*	-0.85162		0.41381
AL	*	-0.76307		0.37281
V		-0.03384		-0.29222
CR		-0.31308		-0.16809
MN		-0.54803		0.23620
CO	*	-0.86847		-0.24783
NI		-0.69227		-0.47059
CU		-0.68550		-0.45924
ZN		-0.06733		-0.48008
GA	*	-0.70512		0.24057
AS	*	-0.70708		-0.42167
SE		-0.58624		-0.68561
RB	*	-0.95561		0.18656
SR	*	-0.90579		-0.05118
AG		-0.61126		-0.10548
CD		-0.12368		-0.10745
IN	*	-0.91493		0.30366
CS	*	-0.93451		0.19051
BA		0.17821		0.24165
TL_		0.04501		0.14418
PB		-0.32465		-0.22784
BI	*	-0.91260		0.30858
U		0.08987		-0.30995
RU	*	-0.93990		0.23571
RH		-0.04044		0.25677
PD		-0.59847		-0.57863
SN	*	-0.90665		-0.05078
SB		0.14983		0.26327
TE	*	-0.91221		0.31356
HF		0.08524		-0.00911
IR		0.32313		0.45210
PT		0.10041		-0.37057
AU		-0.04361		-0.32528
GE	*	-0.91481		0.30015
ZR	*	-0.87133		0.34122
NB	*	-0.73074		-0.23315
MO		-0.10209	*	-0.77430
TA		-0.50963		-0.55267
W		-0.39148		0.21571
RE		-0.12286		-0.87728
Expl.Var		16.12373		5.71129
Prp.Totl		0.37497		0.13282

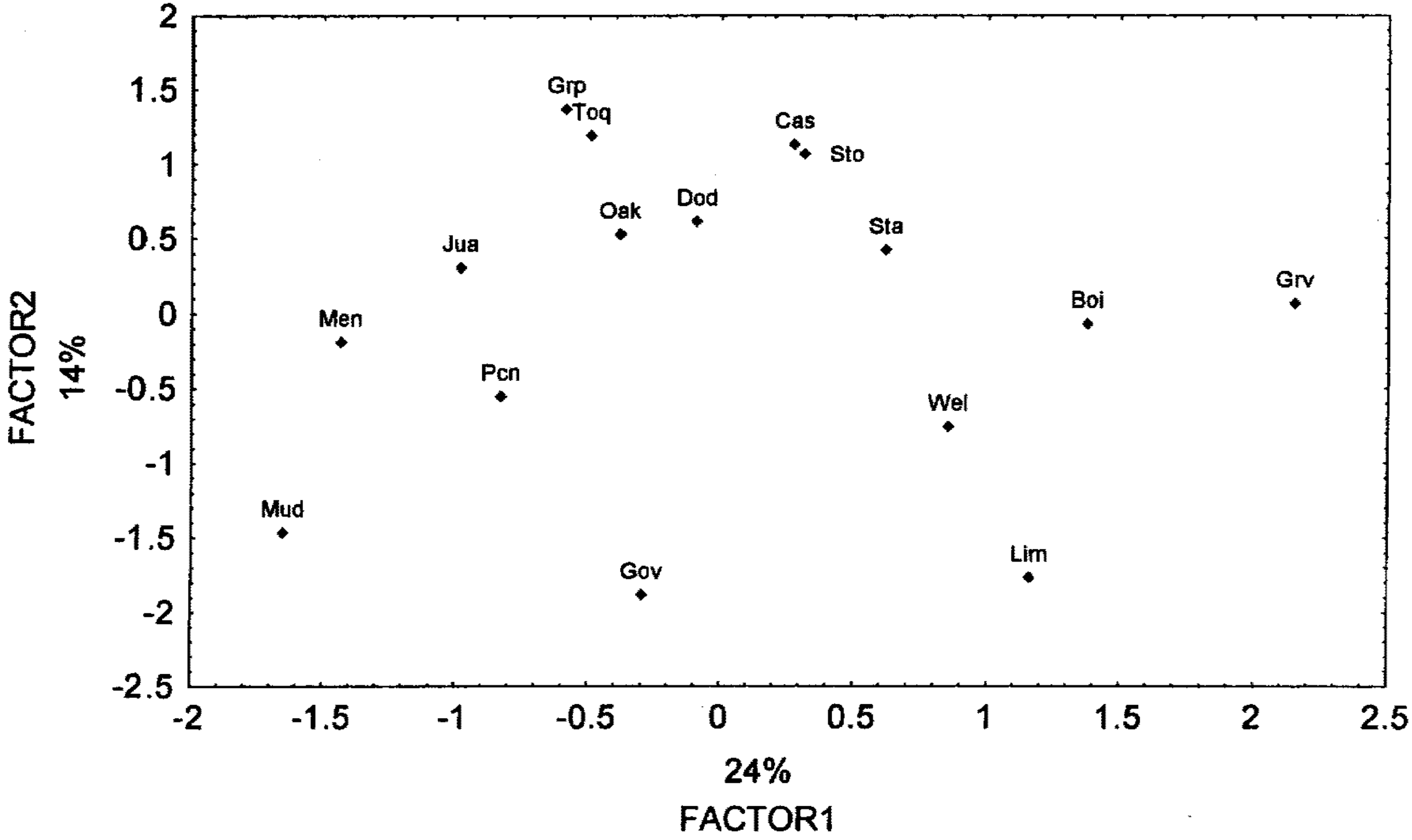


Figure 17: All Chemical Concentrations, without Previous Groupings

Figure 17
fs50
Eigenvalues (uploall.sta)
Extraction: Principal components

	Eigenval	% total Variance	Cumul. Eigenval	Cumul. %
1	15.54406	24.28759	15.54406	24.28759
2	8.82592	13.79049	24.36997	38.07808
3	6.60349	10.31796	30.97347	48.39604
4	6.22036	9.71931	37.19383	58.11536

Factor scores

	FACTOR1	FACTOR2
Gov	-0.29606	-1.88244
Lim	1.16199	-1.76593
Pcn	-0.82946	-0.55513
Wel	0.85421	-0.75769
Mud	-1.65153	-1.46416
Dod	-0.09224	0.61368
Jua	-0.98261	0.30598
Oak	-0.38375	0.52660
Grp	-0.58871	1.36835
Sto	0.31419	1.06623
Cas	0.27531	1.12948
Sta	0.61900	0.42127
Men	-1.43501	-0.18962
Toq	-0.49413	1.19163
Grv	2.15192	0.06399
Boi	1.37687	-0.07224

Factor Loadings (uploall.sta)
Extraction: Principal components
(Marked loadings are > .700000)

	Factor 1	Factor 2		Factor 1	Factor 2
Alkalinity	0.16060	-0.23255	ZN	-0.03954	-0.50917
NA	-0.47529	-0.41959	GA	0.02085	0.26177
K	-0.67599	-0.44438	AS	-0.51257	-0.32917
CA	0.01051	-0.14709	SE	-0.30409	-0.40639
MG	-0.39178	0.01502	RB	-0.59492	-0.23876
CL	-0.46720	-0.31637	SR	-0.60727	-0.24326
SO4	-0.54224	-0.12884	AG	-0.47372	-0.46125
F	-0.25085	* -0.74645	CD	0.30937	-0.21832
BR	-0.15839	-0.65849	IN	-0.39518	-0.18099
NO3	-0.23030	-0.30065	CS	-0.44846	-0.19866
Y	* 0.85031	-0.33572	BA	0.05984	0.38592
LA	* 0.80636	-0.17523	TL	0.51535	0.01189
CE	0.63732	-0.07870	PB	-0.01638	-0.51682
PR	* 0.85208	-0.21649	BI	-0.38593	-0.14505
ND	* 0.86385	-0.24697	U	0.30361	-0.57100
SM	0.61493	-0.03691	RH	-0.39834	0.31853
GD	* 0.86730	-0.28917	PD	-0.29576	-0.65618
TB	* 0.87845	-0.31499	SN	0.20528	-0.62819
DY	* 0.87411	-0.27174	SB	-0.23021	-0.22599
HO	* 0.88543	-0.24088	TE	-0.37679	0.04785
ER	* 0.88288	-0.28743	HF	-0.40930	-0.44871
TM	* 0.86928	-0.21979	IR	-0.18702	0.51493
YB	* 0.85749	-0.21261	PT	0.15230	-0.64522
LU	0.41768	0.11520	AU	-0.22650	-0.14381
TH	-0.08302	-0.10846	GE	-0.50833	-0.33447
LI	-0.56887	-0.45474	ZR	-0.12185	-0.57988
AL	-0.25279	0.23228	NB	-0.29256	0.58467
V	-0.29084	-0.06801	MO	-0.01458	-0.80593
CR	-0.38505	0.18296	TA	-0.53083	-0.43787
MN	0.34567	-0.42617	W	-0.35686	-0.34032
CO	0.42711	-0.23717	RE	-0.36931	-0.65010
NI	0.11476	0.02528	Expl.Var	15.54406	8.82592
CU	-0.08200	0.00131	Prp.Totl	0.24288	0.13790

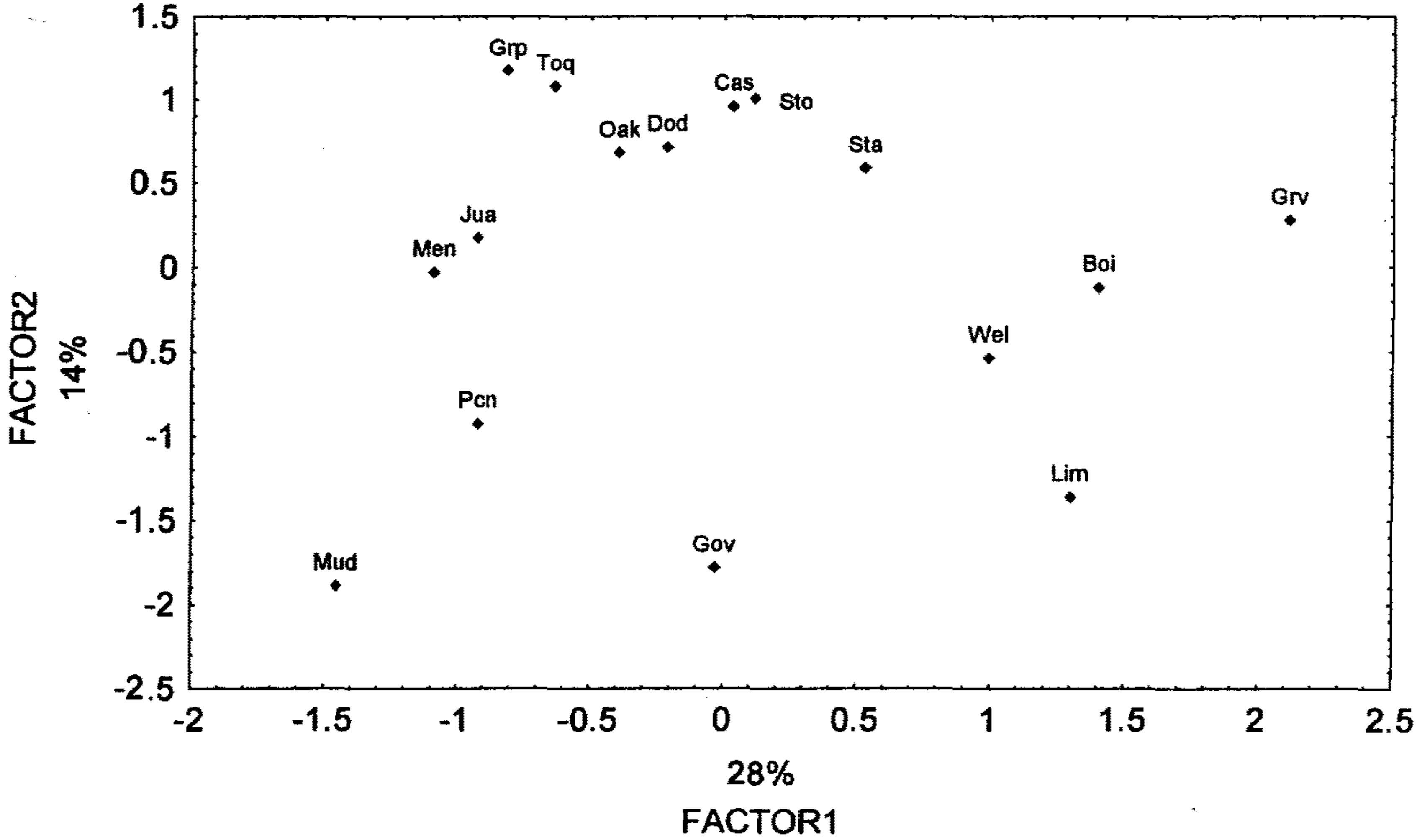


Figure 18: All Trace Element Concentrations without Previous Groupings

Figure 18
fs63
Eigenvalues (p63.sta)
Extraction: Principal components

	Eigenval	% total Variance	Cumul. Eigenval	Cumul. %
1	14.94861	27.68261	14.94861	27.68261
2	7.44225	13.78195	22.39086	41.46456
3	5.80160	10.74371	28.19246	52.20627
4	5.09321	9.43188	33.28568	61.64015

Factor scores

	FACTOR1	FACTOR2
Gov	-0.02787	-1.78066
Lim	1.30016	-1.36484
Pcn	-0.92082	-0.92593
Wel	0.99425	-0.53930
Mud	-1.45292	-1.88582
Dod	-0.21506	0.71431
Jua	-0.92542	0.17327
Oak	-0.39474	0.68058
Grp	-0.81669	1.17274
Sto	0.11169	1.00653
Cas	0.03044	0.95615
Sta	0.53040	0.58865
Men	-1.09248	-0.02955
Toq	-0.63846	1.08004
Grv	2.11477	0.27619
Boi	1.40273	-0.12236

Factor Loadings (p63.sta)
Extraction: Principal components
(Marked loadings are > .700000)

		Factor 1	Factor 2				
Y	*	0.91856	-0.21817	SR	-0.55489		-0.28646
LA	*	0.85420	-0.08454	AG	-0.39994		-0.48656
CE		0.65932	0.01013	CD	0.36200		-0.22167
PR	*	0.90823	-0.11922	IN	-0.30748		-0.14633
ND	*	0.92356	-0.14401	CS	-0.41701		-0.31199
SM		0.60510	0.01562	BA	-0.01810		0.38225
GD	*	0.93635	-0.16489	TL	0.53146		0.06547
TB	*	0.94418	-0.19334	PB	0.06423		-0.50157
DY	*	0.93550	-0.15730	BI	-0.30199		-0.10827
HO	*	0.94038	-0.11823	U	0.37995		-0.47925
ER	*	0.94292	-0.16131	RH	-0.39556		0.36977
TM	*	0.91595	-0.09990	PD	-0.21325		-0.67602
YB	*	0.90935	-0.09466	SN	0.33686		-0.60978
LU		0.41358	0.17724	SB	-0.20788		-0.33899
TH		-0.00982	-0.04344	TE	-0.32163		0.08061
LI		-0.51825	-0.58968	HF	-0.39099		-0.53910
AL		-0.30045	0.23069	IR	-0.24972		0.52734
V		-0.33208	-0.15887	PT	0.22219		-0.60696
CR		-0.44378	0.05194	AU	-0.25527		-0.23561
MN		0.39543	-0.33081	GE	-0.47413		-0.47375
CO		0.47268	-0.07490	ZR	-0.08318		-0.63105
NI		0.14580	0.13028	NB	-0.36949		0.60900
CU		-0.09124	0.05353	MO	0.08693	*	-0.78738
ZN		0.03590	-0.49336	TA	-0.46136		-0.53069
GA		0.00938	0.22997	W	-0.32378		-0.47062
AS		-0.49282	-0.49065	RE	-0.27240		-0.64335
SE		-0.27605	-0.45480	Expl.Var	14.94861		7.44225
RB		-0.54537	-0.35043	Prp.Totl	0.27683		0.13782

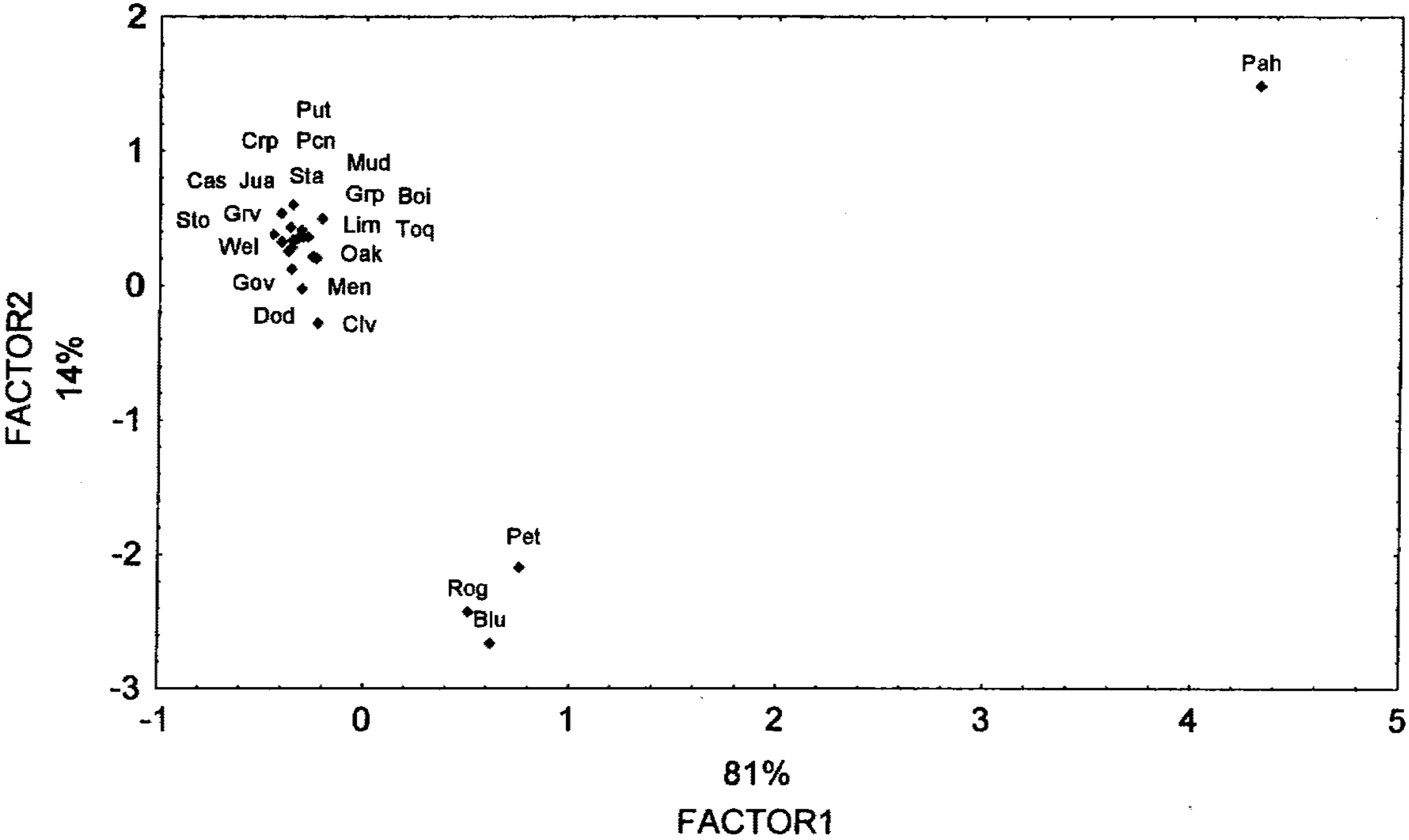


Figure 19: Selected Trace Elements, All Springs

Figure 19
fs58
Eigenvalues (p58.sta)
Extraction: Principal components

	Eigenval	% total Variance	Cumul. Eigenval	Cumul. %
1	13.78880	81.11057	13.78880	81.11057
2	2.41415	14.20089	16.20295	95.31146

Factor scores

	FACTOR1	FACTOR2
Pet	0.75598	-2.09488
Gov	-0.31275	0.37608
Lim	-0.30404	0.35711
Pcn	-0.36303	0.43145
Wel	-0.35329	0.33508
Rog	0.50873	-2.42712
Blu	0.61665	-2.66204
Mud	-0.21147	0.49484
Dod	-0.30805	-0.02745
Crp	-0.40852	0.53274
Put	-0.35343	0.59795
Clv	-0.23170	-0.27897
Jua	-0.37315	0.25303
Oak	-0.25337	0.21352
Pah	4.32315	1.48154
Grp	-0.31036	0.40881
Sto	-0.35900	0.11982
Cas	-0.44785	0.37895
Sta	-0.35891	0.28157
Men	-0.23866	0.19939
Toq	-0.27858	0.35902
Grv	-0.40584	0.32445
Boi	-0.33254	0.34511

Factor Loadings (p58.sta)
Extraction: Principal components
(Marked loadings are > .700000)

		Factor 1		Factor 2
LI	*	0.99448		-0.04655
BE	*	0.92181		0.34784
AL	*	0.81657		0.42697
CO	*	0.86030	*	-0.48895
NI		0.65126	*	-0.74889
CU		0.64869	*	-0.73685
RB	*	0.99463		0.07206
SR	*	0.91682		-0.28148
IN	*	0.97016		0.23088
CS	*	0.97358		0.08776
BI	*	0.96835		0.23646
RU	*	0.98822		0.13292
SN	*	0.90266		-0.08871
TE	*	0.96925		0.23043
GE	*	0.96522		0.23404
ZR	*	0.92881		0.33903
NB	*	0.71864		-0.56227
Expl.Var		13.78880		2.41415
Prp.Totl		0.81111		0.14201

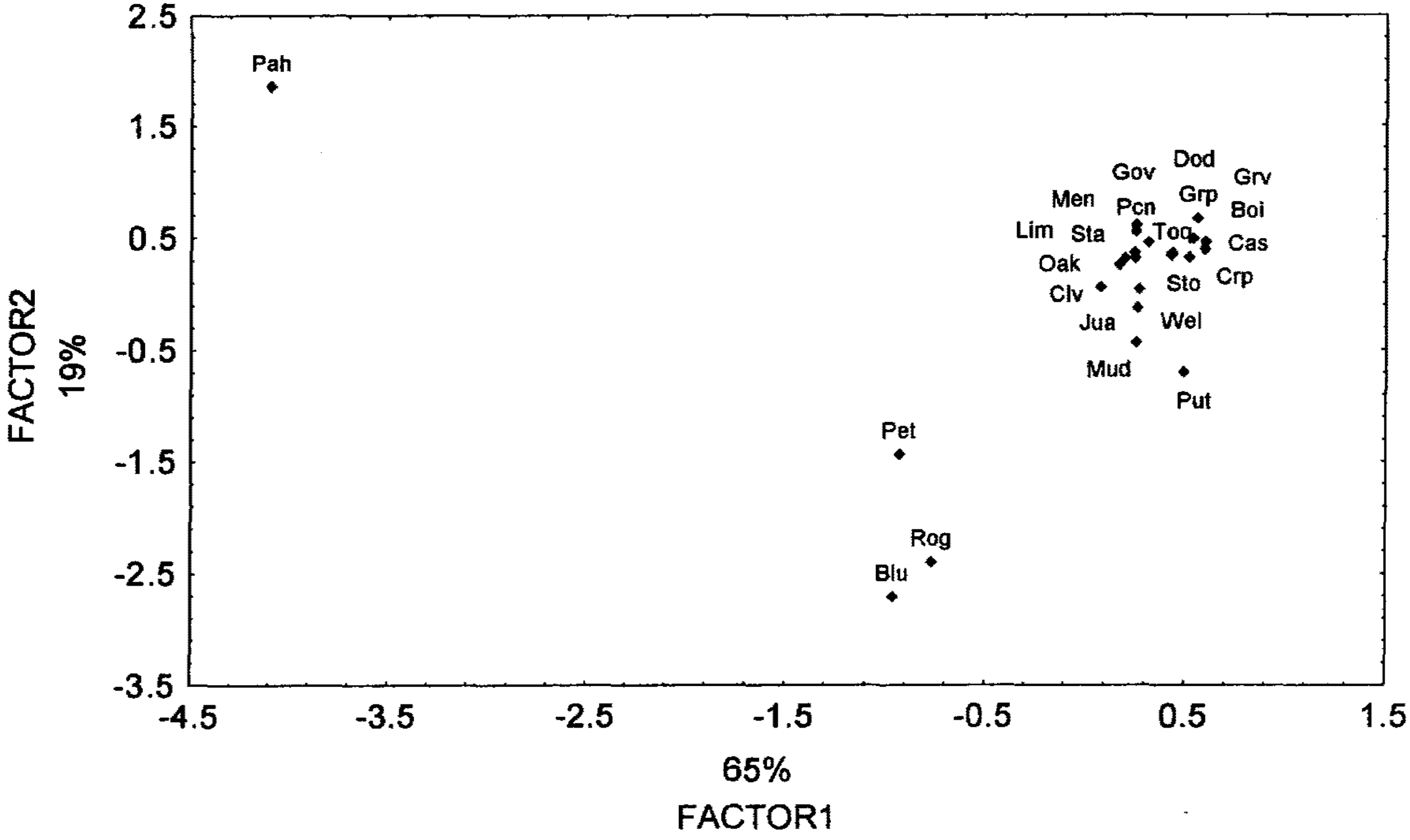


Figure 20: Major Ions, All Springs

Figure 20
fs2
Eigenvalues (catanion.sta)
Extraction: Principal components

	Eigenval	% total Variance	Cumul. Eigenval	Cumul. %
1	6.52731	65.27309	6.52731	65.27309
2	1.89787	18.97866	8.42517	84.25175
3	1.01019	10.10187	9.43536	94.35362

Factor scores

	FACTOR1	FACTOR2
Pet	-0.92810	-1.43749
Gov	0.25611	0.60743
Lim	0.20388	0.31225
Pcn	0.25245	0.54876
Wel	0.27090	0.03544
Rog	-0.76388	-2.40103
Blu	-0.95989	-2.70938
Mud	0.25591	-0.44042
Dod	0.31538	0.45420
Crp	0.59657	0.39067
Put	0.49114	-0.70231
Clv	0.08076	0.05532
Jua	0.26334	-0.13073
Oak	0.17322	0.25272
Pah	-4.09886	1.85987
Grp	0.55964	0.67077
Sto	0.43742	0.35960
Cas	0.59869	0.46148
Sta	0.25142	0.31076
Men	0.24903	0.35862
Toq	0.43422	0.33854
Grv	0.53727	0.48573
Boi	0.52138	0.31921

Factor Loadings (catanion.sta)
Extraction: Principal components
(Marked loadings are > .700000)

	Factor 1	Factor 2
NA	* -0.96364	0.21218
K	* -0.96599	0.21112
CA	* -0.94401	-0.28313
MG	* -0.78389	-0.55906
CL	* -0.95416	0.26038
SO4	* -0.84217	-0.50098
F	-0.17980	* -0.87623
BR	* -0.91496	0.30762
NO3	0.00997	0.22981
Alkalinity	* -0.81895	0.42611
Expl.Var	6.52731	1.89787
Prp.Totl	0.65273	0.18979

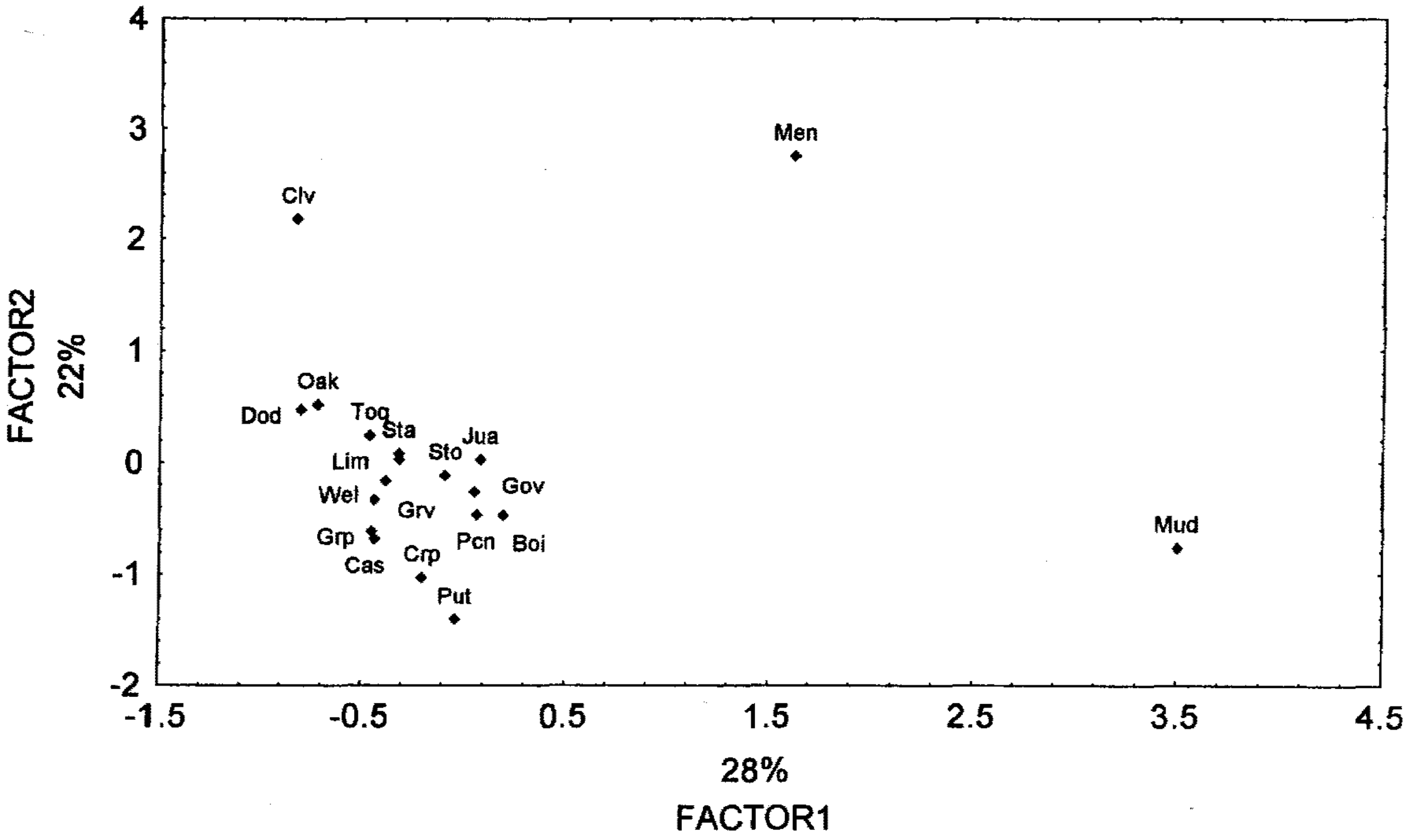


Figure 21: Selected Trace Elements without Pah Tempe, Petrified, Roger's, and Blue Point Springs

Figure 21
fs59
Eigenvalues (p59.sta)
Extraction: Principal components

	Eigenval	% total Variance	Cumul. Eigenval	Cumul. %
1	4.55809	28.48809	4.55809	28.48809
2	3.49545	21.84657	8.05355	50.33466
3	2.53072	15.81698	10.58426	66.15164
4	1.57147	9.82169	12.15573	75.97333

Factor scores

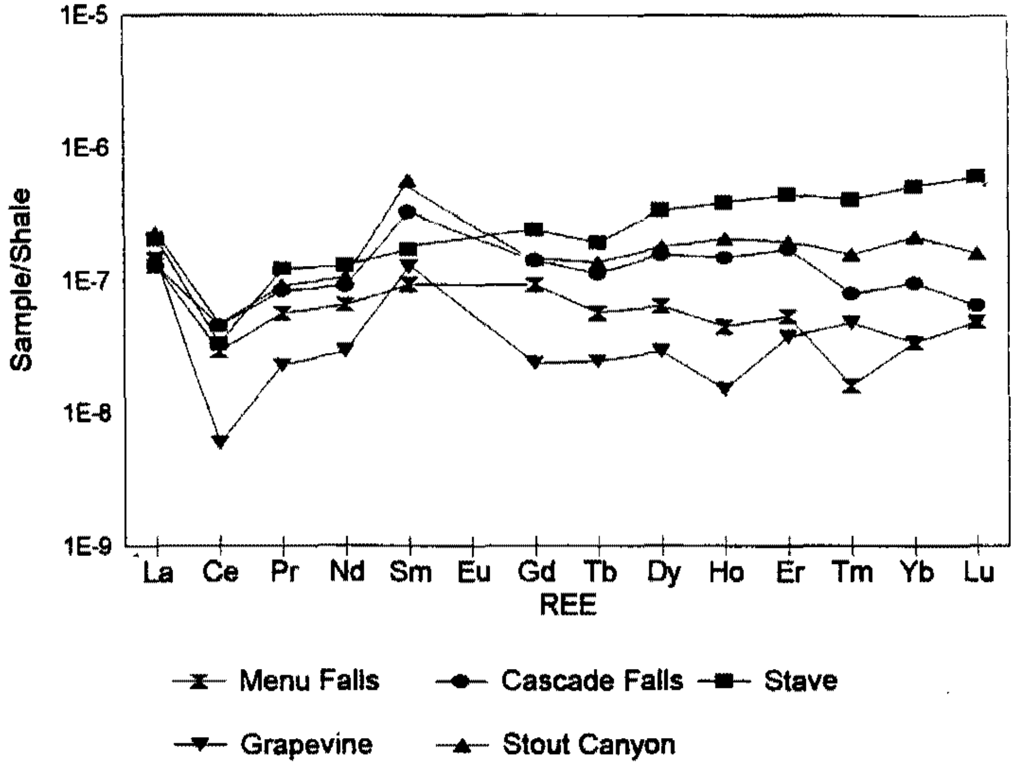
	FACTOR1	FACTOR2
Gov	0.05190	-0.26064
Lim	-0.31728	0.02681
Pcn	0.06645	-0.46781
Wel	-0.38306	-0.16369
Mud	3.50087	-0.76002
Dod	-0.80741	0.47604
Crp	-0.20356	-1.02854
Put	-0.03828	-1.40571
Clv	-0.82984	2.18209
Jua	0.08233	0.02958
Oak	-0.72431	0.51663
Grp	-0.45521	-0.61617
Sto	-0.09105	-0.11510
Cas	-0.43972	-0.68278
Sta	-0.31963	0.08233
Men	1.61776	2.74965
Toq	-0.46475	0.24165
Grv	-0.43910	-0.33171
Boi	0.19391	-0.47263

Factor Loadings (p59.sta)
Extraction: Principal components
(Marked loadings are > .700000)

	Factor 1	Factor 2
LI	* 0.92615	-0.06426
BE	-0.02250	-0.40063
AL	-0.19467	-0.10936
CO	-0.36605	0.53693
NI	-0.19618	0.61376
CU	-0.21113	0.33801
RB	* 0.95542	0.09342
SR	0.02554	* 0.71944
IN	0.44735	0.65404
CS	* 0.89539	-0.00366
BI	0.43182	0.66007
SN	0.42916	0.05869
TE	0.20935	* 0.86119
GE	* 0.87310	-0.19305
ZR	0.52712	-0.29753
NB	-0.27369	0.52814
Expl.Var	4.55809	3.49545
Prp.Totl	0.28488	0.21847

APPENDIX E

Rare Earth Element (REE) Normalization Patterns for Spring Waters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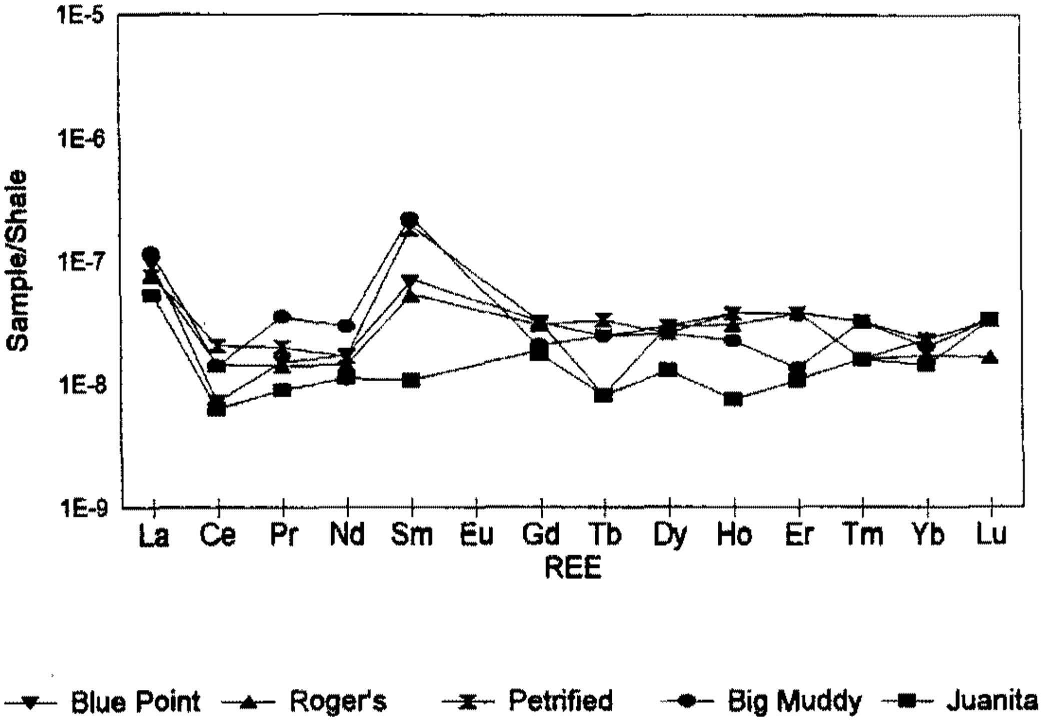
1E-6
1E-7
1E-8
1E-9
Sample/Shale
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
REE
Menu Falls
Cascade Falls
Stave
Grapevine
Stout Canyon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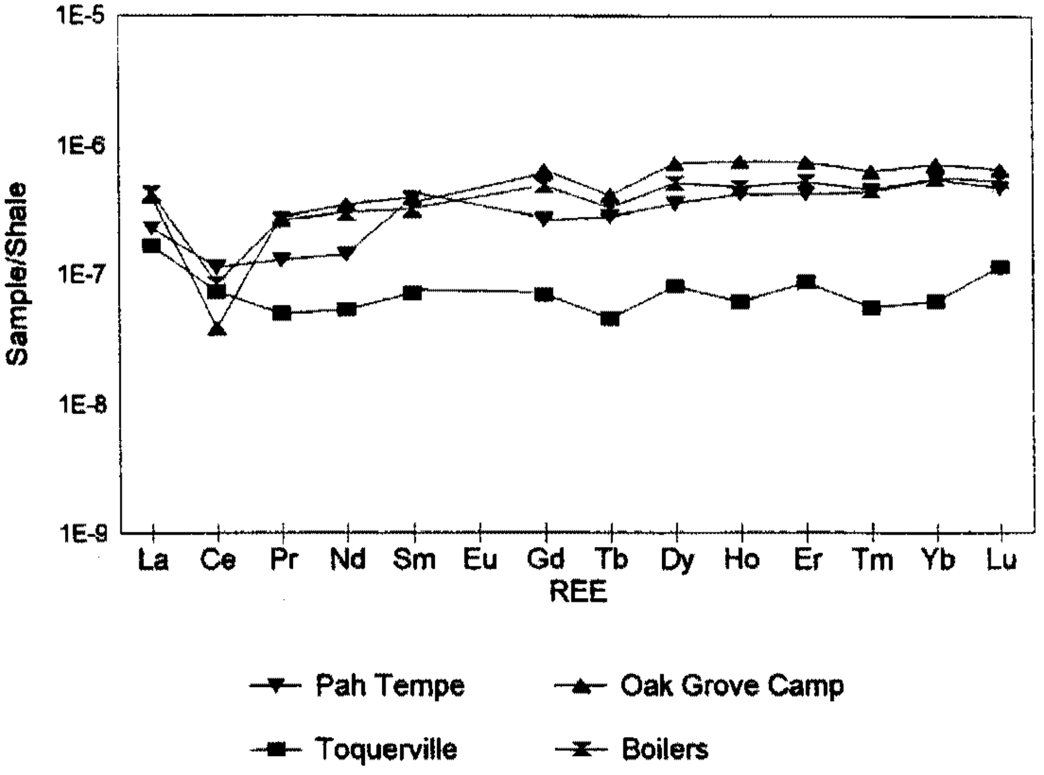
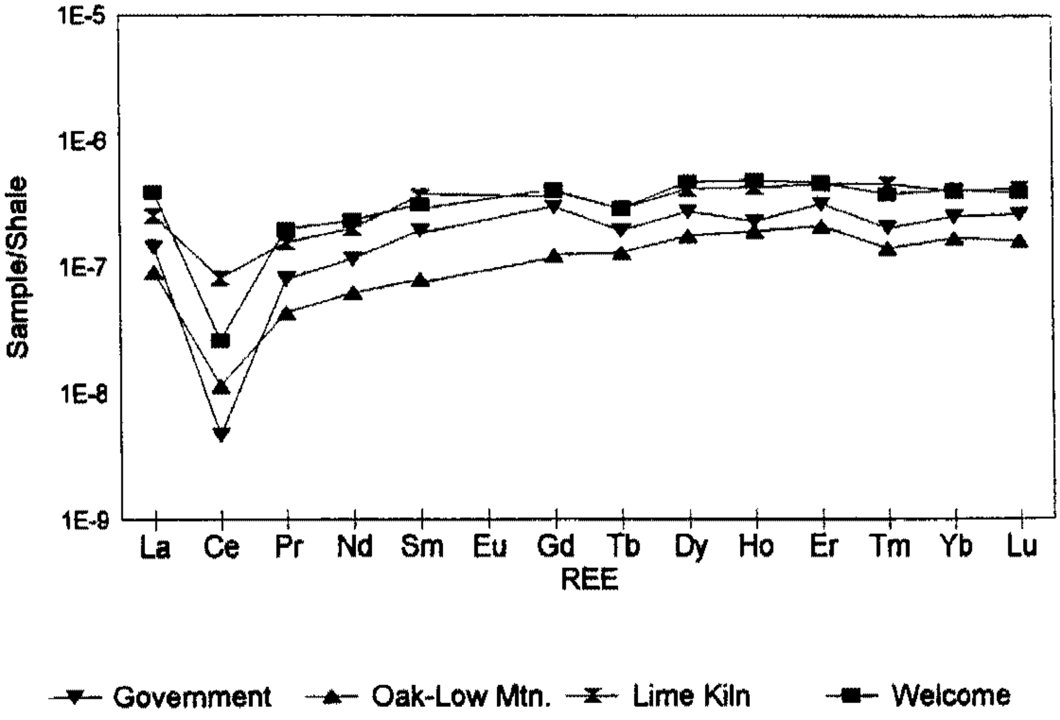
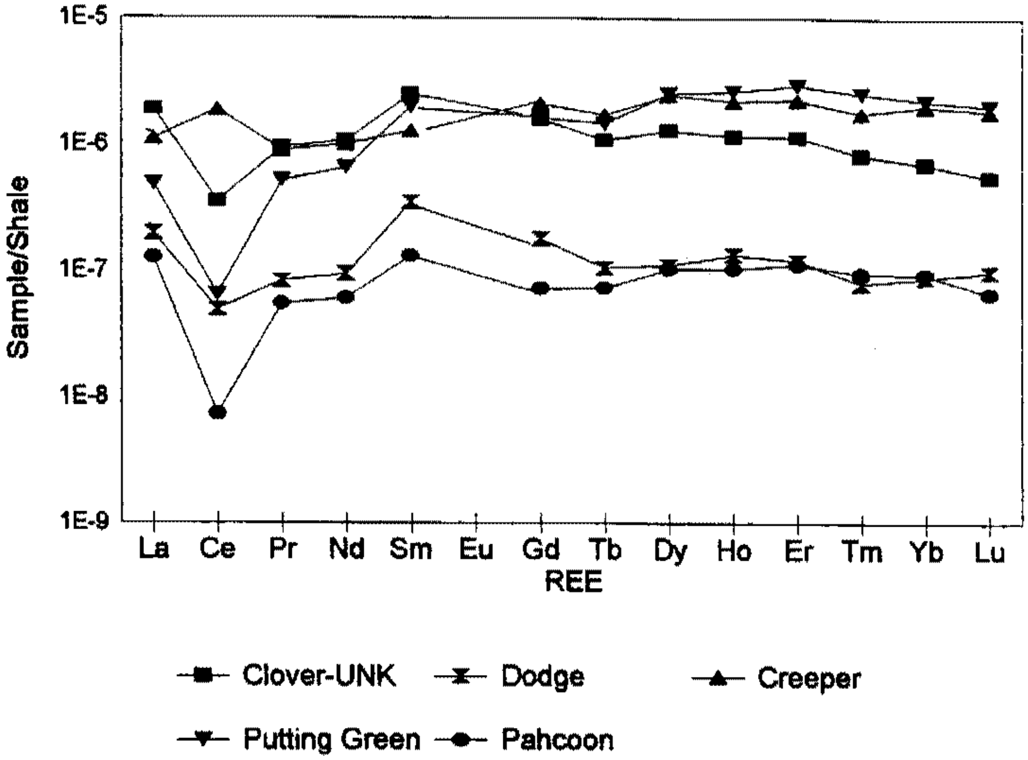
1E-6
1E-7
1E-8
1E-9
Sample/Shale
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
REE
Blue Point
Roger's
Petrified
Big Muddy
Juanita


1E-5
1E-6
1E-7
1E-8
1E-9
Sample/Shale
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
REE
Pah Tempe
Oak Grove Camp
Toquerville
Boilers


1E-5
1E-6
1E-7
1E-8
1E-9
Sample/Shale
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
REE
Government
Oak-Low Mtn.
Lime Kiln
Welcome


1E-5
1E-6
1E-7
1E-8
1E-9
Sample/Shale
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
REE
Clover-UNK
Dodge
Creeper
Putting Green
Pahcoon

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