A CONCEPTUAL HYDROGEOLOGIC MODEL FOR FOSSIL SPRINGS, WESTERN MOGOLLON RIM, ARIZONA: IMPLICATIONS FOR REGIONAL SPRINGS PROCESSES

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ABSTRACT

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L. Megan Green

Fossil Springs is the largest spring system discharging along the western Mogollon Rim in central Arizona and is a rare and important resource to the region. The purpose of this study was to gain a better understanding of the source of groundwater discharging at Fossil Springs. This was accomplished by (1) constructing a 3-D digital hydrogeologic framework model from available data to depict the subsurface geology of the western Mogollon Rim region and (2) by compiling and interpreting regional structural and geophysical data for Arizona's central Transition Zone. EarthVision, a 3-D GIS modeling software, was used to construct the framework model. Two end-member models were created; the first was a simple interpolation of the data and the second was a result of geologic interpretations. The second model shows a monocline trending along the Diamond Rim fault. Both models show Fossil Springs discharging at the intersection of the Diamond Rim fault and Fossil Springs fault, at the contact between the Redwall Limestone and Naco Formation.

The second objective of this study was a compilation of regional data for Arizona's central Transition Zone. Regional structure was reexamined using geologic maps and geophysical data. The Diamond Rim fault was extended through the subsurface of the Verde Valley and the accompanying Diamond Rim monocline was delineated. Geological, hydrologic, and geochemical data for springs in the region were collected. Comparisons of these data were used to identify Fossil Springs and other springs in the region as having a small but significant deeply derived source, including Montezuma Well, Tonto Bridge Spring, Verde Hot Spring, Page Spring, and Summer Spring.

Conclusions from this study suggest that water discharging from Fossil Springs is sourced in the regional Limestone aquifer, transported to the springs via northeast striking fault conduits, and forced to the surface at the Diamond Rim fault, which acts as a barrier to flow. Additionally, deeply sourced constituents are transported upwards along deep seated structures, discharging high concentrations of CO_2 at Fossil Springs. The processes at Fossil Springs can be applied regionally to other springs identified as discharging deeply sourced constituents.

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PREFACE

Chapter 4 of this thesis is written as a journal manuscript and contains some material that is repeated from Chapter 1. Additionally, Chapters 2 and 3 can also be read as stand-alone chapters, but will benefit from the background information presented in Chapter 1. Chapter 5 summarizes conclusions from Chapters 2, 3, and 4.

CHAPTER 1: INTRODUCTION

1.1 Introduction

Fossil Springs is the largest spring system discharging along the Mogollon Rim in northern Arizona (Parker et al., 2005) and a major tributary to the Verde River; however, its sources have only been preliminarily studied and are poorly understood. Located in the Transition Zone physiographic province, this spring system is characterized by 115 individually mapped spring orifices with a seven year average discharge of 45 cubic feet per second (cfs) and provides important riparian habitat for many rare and endemic species of both plants and animals. Travertine dams form along the 14 mile stretch from the spring orifices to Fossil Creek's confluence with the Verde River, demonstrating elevated concentrations of calcium and CO_2 in comparison to other non travertine depositing springs in the area and a possible deeply derived source for these constituents (Crossey et al., 2006). Within the central Transition Zone, there are numerous other springs that provide insight into the aquifer system and place Fossil Springs in a regional context, such as Summer Spring, Montezuma Well, Page Spring, Tonto Bridge Spring, and Verde Hot Springs. A better understanding of the processes controlling groundwater and geochemical transport to regional spring systems will help to protect these valuable resources as continued population growth influences regional land and water resource management.

1.2 Purpose and Objectives

The importance of understanding processes controlling transport of groundwater and geochemical constituents to Fossil Springs is three-fold: (1) ecological restoration, (2) water supply, and (3) springs processes in Arizona's central Transition Zone. For the last 100 years, nearly all water discharging from Fossil Springs was diverted from the streambed and transported through a flume to the Arizona Public Service power plants at Irving and Childs, Arizona (Marks et al., 2006). In June of 2005, the power plant was decommissioned and full flows were returned to Fossil Creek. Researchers at Northern Arizona University, Arizona Game and Fish, United States Fish and Wildlife Service, and United States Forest Service are conducting intensive monitoring to understand the impact that the decommissioning will have on fish, invertebrates, and travertine deposition. Legislation has been proposed to designate Fossil Creek a "Wild and Scenic River". To protect these resources, a continuous supply of water must be assured, therefore the source of water discharging at Fossil Springs must be better understood.

With increasing population growth in the Strawberry, Pine, and Payson, Arizona area comes an increasing demand for a sustainable and reliable water supply. Population is expected to nearly double over the next 50 years (Parker et al., 2005) and groundwater supplies will likely be a component of a sustainable water portfolio for this growth. There is currently a very poor understanding of the regional aquifer system which might be tapped for this supply. A more complete understanding of this complex system must be gained for future water management decisions.

Travertine-depositing springs of the Southern Colorado Plateau have recently been identified as having endogenic, deeply-sourced, CO_2 contributing to high rates of deposition (Newell et al., 2005 and Crossey et al., 2006, Crossey et al., *in review*). The geologic CO_2 emission from the Colorado Plateau region reflects a complex tectonic evolution involving Laramide hydration of the lithosphere above the Farallon slab, addition of fluids from mid-Tertiary tectonism during slab removal, and fluid movement induced by neotectonic small-scale asthenospheric convection (Crossey et al., *in review*). Workers examining tectonically active regions (Liu et al., 2003; Minissale et al., 2002; Minissale, 2004) suggest that endogenic components may be contributing to travertine deposition in spring systems worldwide. Travertine-depositing springs in the Transition Zone physiographic province of central Arizona are related to similar geologic and structural characteristics and are sourced in the same aquifer system as those of the southern Colorado Plateau, suggesting that these processes are also active in this region. Geochemical and structural data collected at Fossil Springs and other springs within the central Transition Zone support hypotheses from these studies and expand the scope of that work.

The primary product of this thesis is the completion of a conceptual three-dimensional digital hydrogeologic framework model (DHFM), which is used to visualize the processes that control transport to Fossil Springs (see Chapter 2). This model was created in response to the lack of understanding previously available about regional and local aquifer systems in the modeled area. Surface and subsurface data were combined using EarthVision, a three-dimensional (3-D) geographic information system (GIS) software (Dynamic Graphics Inc., Alameda, California, 2002). The DHFM will serve as a tool for understanding and conveying the complex subsurface geology of the region to water managers and others who can directly benefit from this knowledge. Supporting discharge and geochemical data were collected for Fossil Springs and are presented and analyzed in Chapter 3.

The secondary product of this thesis places the hydrologic, structural, and geologic processes at Fossil Springs within a regional context. This thesis compiles a regional spring database for Arizona's central Transition Zone, with a focus on CO_2-rich springs with a hypothesized deeply sourced component. Reanalysis of structural data led to the extension of the Diamond Rim fault system north and west into the subsurface of the Verde Valley and the proposal of a Laramide age monocline trending along its length. Several new faults in the Sedona area, an Oak Creek monocline, and an uplift in the central Verde Valley were also proposed. The increased understanding of regional structure and geochemical data allowed for the expansion of the suite of springs interpreted to have endogenic components. This hypothesis is the focus of the draft manuscript presented in Chapter 4, which will expand the global database for CO_2-rich springs (Minissale, et al., 2002 Liu et al., 2003; Newell et al., 2005), as well as define a more detailed set of criteria for this process in the Transition Zone

1.3 Location

1.3.1 Study Area

The central portion of Arizona's Transition Zone province serves as the larger, regional focus of this thesis and is defined as the study area (figure 1). This area was selected to place Fossil Springs in a regional context and served as a comparison for findings made there. It encompasses a variety of other spring systems sourced in a variety of local and regional aquifers, with a focus on CO_2-rich Summer Spring, Page Spring, Montezuma Well, Tonto Bridge Spring, and Verde Hot Springs.

1.3.2 Model Area

The DHFM was created to investigate the geologic, hydrologic, and structural relationships contributing to transport to Fossil Springs. The model (figure 1) encompasses an area of about 600 square kilometers in the southeastern portion of the study area surrounding Fossil Springs. Boundaries were chosen to include the maximum amount of surface and subsurface data south of a large, regional fault system (the Diamond Rim fault).

1.4 Lithologic Units

In central Arizona, the Transition Zone serves as the boundary between the topographically high, Paleozoic rocks of the Colorado Plateau and the Proterozoic and Cenozoic rocks of the Basin and Range. The flat lying units of the Colorado Plateau dip less than 1° northeast, forming a surface water divide along the northwest- southeast trending Mogollon Rim (Spencer and Reynolds, 1989). The Basin and Range is typified by tilted fault block mountains separated by sediment filled basins (Leighty, 1998). Geologic formations present in the central Transition Zone (figure 2) have been identified and described by various workers (see table 1) and mapped at several scales (Gaeaorama, 2006; Langenheim et al., 2005; Richard et al., 2000; Weir et al., 1989; Ulrich et al., 1984; Anderson and Creasey, 1958) (figure 3). Table 1 provides a more detailed description of units present in the study area.

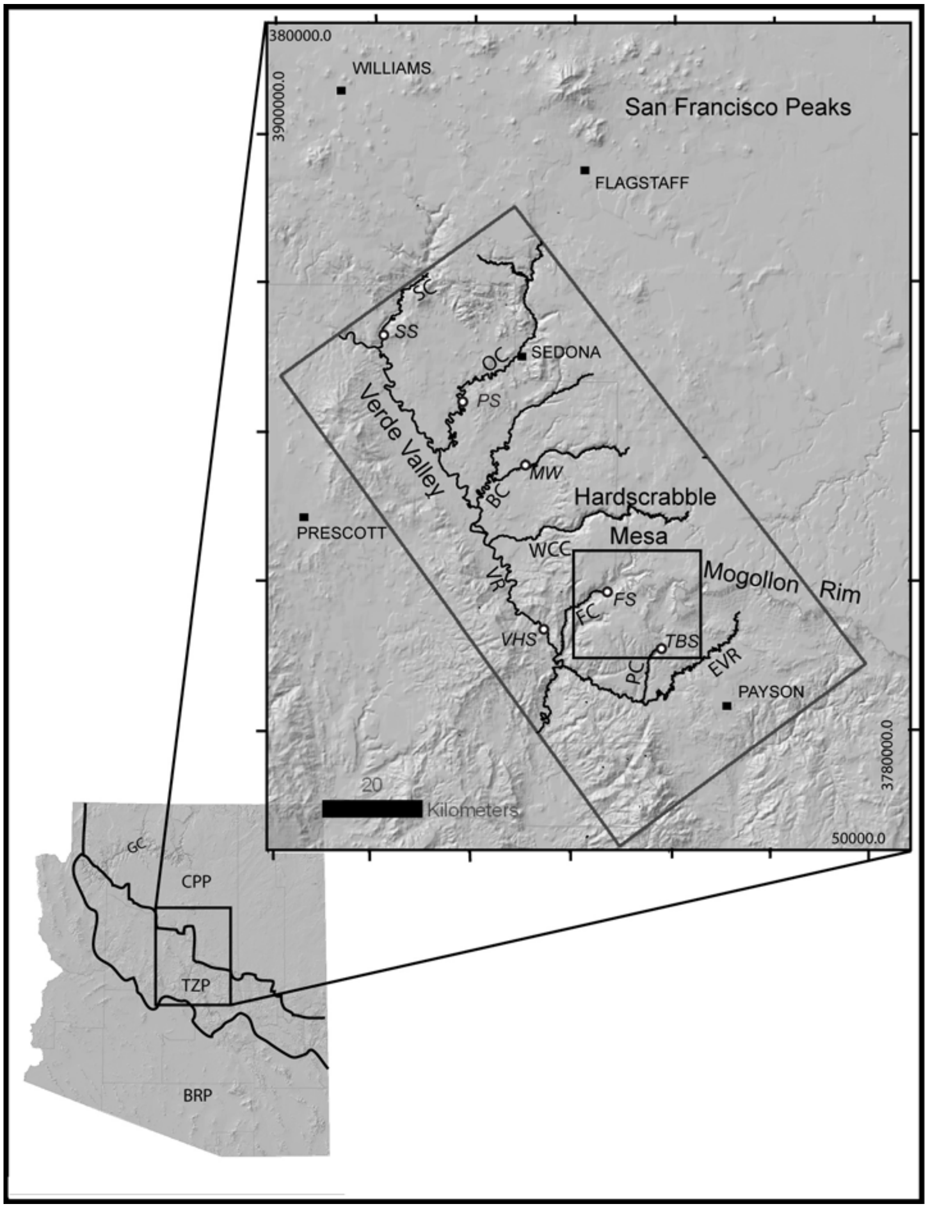


Figure 1. Location of the model and study areas in the Transition Zone of central Arizona, outlined by the black boxes in the larger map, which also shows CO_2-rich springs (circles) that are the focus of this study, cities (squares), and major geomorphic features. Springs: Summer Spring (SS), Page Springs (PS), Montezuma Well (MW), Fossil Springs (FS), Tonto Bridge Spring (TBS), and Verde Hot Spring (VHS). Streams draining the Mogollon Rim are major tributaries to the Verde River (VR): Sycamore Creek (SC), Oak Creek (OC), Beaver Creek (BC), West Clear Creek (WCC), Fossil Creek (FC), Pine Creek (PC), and East Verde River (EVR). The map of Arizona shows the Grand Canyon (GC) and three major provinces in Arizona: the Colorado Plateau (CPP), Transition Zone (TZP), and Basin and Range (BRP). The Mogollon Rim is the topographic escarpment forms the boundary between the Colorado Plateau and Transition Zone.

Metamorphic and igneous Proterozoic units (X) in the area have undergone several periods of deformation (Karlstrom and Bowring, 1991) and have been grouped together because groundwater movement through crystalline matrices is largely dependent on secondary porosity through fault and fracture flow rather than primary porosity (Parker et al., 2005). Erosional remnants of the Proterozoic rocks exist in at least two locations in the study area, the Christopher Mountain and Pine Mountain paleohighs (Parker et al., 2005; Teichert, 1965) (figure 3). Paleozoic units in the region are largely flat lying, sedimentary units typical of the Colorado Plateau and Grand Canyon regions and disconformably overly the Proterozoic basement. The Cambrian Tapeats Sandstone (Ct) is discontinuous throughout the study area, absent where it laps out against paleohighs and up to 30 meters thick in other areas (Middleton, 1989 and Hereford, 1977). The Tapeats Sandstone is overlain by the Devonian Martin Formation (Dm), which is also discontinuous and shows much variation in facies, ranging from dolomite and minor limestone to sandstone and siltstone throughout the region (Teichert, 1965). The Mississippian Redwall Limestone (Mr) is a massive limestone unit, likely with some karst development, that extends from the Mogollon Rim north to the Grand Canyon (Darton, 1910). The Pennsylvanian Naco Formation (Pn) is another limestone unit, distinguished from the Redwall Limestone by cherty nodules in its lower beds (Blakey, 1990). Upper Pennsylvanian and Permian limestone to sandstone units, the Supai and Schnebly Hill Formations (Pss), are grouped together in this study due to what are likely similar hydrologic characteristics and a lack of detailed mapping in this region (Blakey, 1990). Thickness of these units in the study area is up to 580 meters. Capping

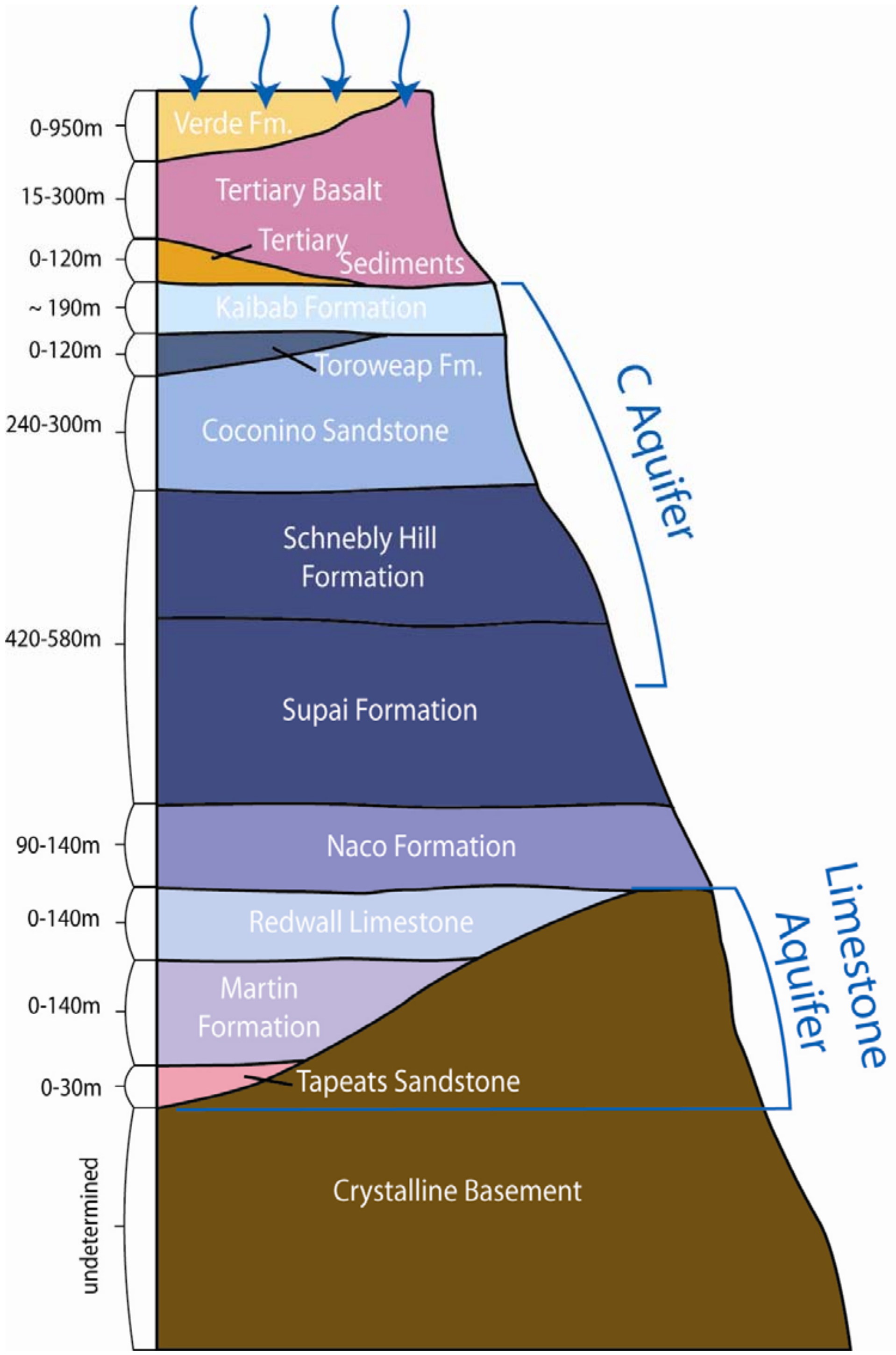


Figure 2. Generalized stratigraphic section of the geologic formations and hydrogeologic units present in the study area. Lithologic units can be seen in map view in figure 3, thicknesses are from Gaeaorama (2006) and Weir et al., (1989). The regional two-tiered aquifer system is composed of the C aquifer and Limestone aquifer. Recharge occurs on top of the Colorado Plateau as direct precipitation on the upper units and percolates down to the aquifers (after Parker et al., 2005).

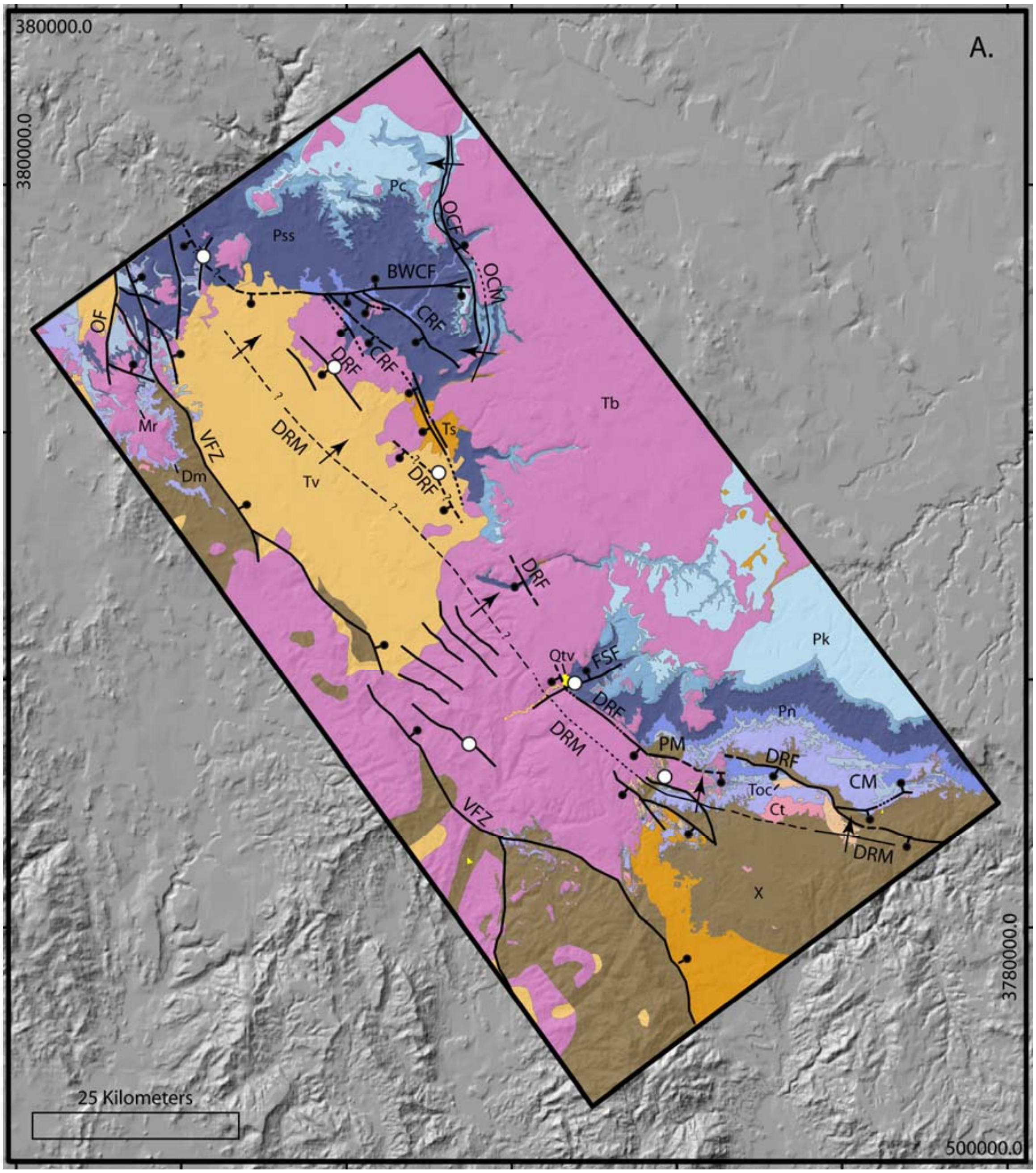


Figure 3. Geologic map (A) and explanation of map (B) of the study area in the central Transition Zone, Arizona. Major structures are shown. A more detailed description of lithologic units is in table 1.

B.

Explanation of Map Units

Qtr	Travertine (Holocene, Pleistocene and possibly Pliocene)
Tv	Verde Formation (Tertiary- Miocene to Pliocene)
Tb	Tertiary Basalts and Volcanic Rocks (Miocene)
Ts	Tertiary Sedimentary Units- undifferentiated (Eocene to Miocene)
Toc	Tertiary Older Conglomerate (Mogollon Rim formation) (Eocene)
Pk	Kaibab Formation (Permian)
Pt	Toroweap Formation (Lower Permian)
Pc	Coconino Sandstone (Lower Permian)
Pss	Supai and Schnebly Hill Formations (Pennsylvanian to Permian)
Pn	Naco Formation (Pennyslvanian)
Mr	Redwall Limestone (Mississippian)
Dm	Martin Formation (Devonian)
Ct	Tapeats Sandstone (Cambrian)
X	Crystalline Rocks(Middle- Lower Proterozoic)

CONTACT

NORMAL FAULT- bar and ball on downthrown side

NORMAL FAULT- approximate location

NORMAL FAULT- location inferred

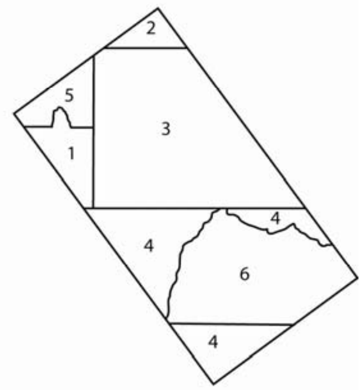
NORMAL FAULT- concealed

MONOCLINE- Showing trace of axis, dotted where concealed, dashed where inferred.

SPRINGS

Sources of Geologic Data

1. Anderson and Creasey, 1958
2. Ulrich et al., 1984
3. Weir et al., 1989
4. Richard et al., 2000
5. Twenter and Metzger, 1963
6. Gaeaorama, 2006



Explanation of Mapped Structures

DRF	Diamond Rim Fault Zone	This study; Gaeaorama, 2006; Langenheim et al., 2005; Weir et al., 1989
VFZ	Verde Fault Zone	Richard et al., 2000
OCF	Oak Creek Fault	Richard et al, 2000
BWCF	Bear Wallow Canyon Fault	Langenheim et al., 2005
CRF	Cathedral Rock Fault	This study; Weir et al., 1989
FSF	Fossil Springs Fault	Gaeaorama, 2006
OF	Orchard Fault	Langenheim et al., 2005
DRM	Diamond Rim Monocline	This study, Reynolds et al., 2001
OCM	Oak Creek Monocline	This study
PM	Pine Mountain Paleohigh	Gaeaorama, 2006; Reynolds et al., 2001
CM	Christopher Mountain Paleohigh	Gaeaorama, 2006; Reynolds et al., 2001

Table 1: Description of lithologic units in the central Transistion Zone study area.

	Lithologic Unit	Age	Thickness	Description	Hydrogeologic Properties	References
Tv	Verde Formation	Miocene to Pliocene	0 - 950 m	Intertonguing limestone and clastic facies deposited in lacustrine and fluvial settings. Present only in the western part of the study area.	Local aquifer	Nations et al., 1981
Tb	Tertiary Basalts and Volcanics	Miocene	15 - 300 m	Various ages and lithologies, undifferentiated for the purposes of this study. Basalt is composed of aggregate flows, in many locations the thickness is not not known.	Local aquifer	Leighty, 1998
Ts	Tertiary Sedimentary Units	Eocene-Miocene	0 - 120 m	Ts used where undifferentiated, composed of the Mogollon Rim formation (Toc, see below) and Beavertail Butte formation (Loseke, 2004). Generally, the Beavertail Butte formation is present below the rim and is a conglomerate with clasts of Pk and Pc, indicating a southerly transport. Often unconformably overlain by Tb.	May contain local aquifer units.	Potochnick, 1989 and Loseke, 2004
Toc	Tertiary Older Conglomerate	Eocene (37.5- 37.6 ± 0.8 Ma)	0 - 120 m	Informally named the Mogollon Rim formation, moderately consolidated conglomerate and sandstone. Exists on top of Mogollon Rim, clasts are largely Proterozoic rocks and locally Paleozoic. Indicates northwesterly transport. Overlain by Tb.	May contain local aquifer units.	Potochnick, 1989
Pk	Kaibab Formation	Permian	about 190 m	Limestone, dolomite, and basal sandstone and chert. Shows karst development.	C aquifer.	Blakey, 1990
Pt	Toroweap Formation	Early Permian	0 - 120 m	Only in western study area, does not extend east past Fossil Creek Canyon. Very fine to fine- grained sandstone, medium- scale sets of crossbeds.	C aquifer.	Blakey, 1990

Table 1. Continued.

	Lithologic Unit	Age	Thickness	Description	Hydrgeologic Properties	Citations
Pc	Coconino Sandstone	Early Permian	240-300 m	Very fine to fine-grained sandstone of eolian orgin. Characterized by massive cross bedding and steep cliffs.	C aquifer.	Blakey, 1990
Pss	Supai and Schnebly Hill Formations	Pennsylvanian-Permian	420- 580 m	Undifferentiated in the study area, contains the Schnebly Hill and Supai Formations, and the Hermit Formation in the Sedona area. A red bed sequence composed of highly oxidized fine-grained sediments: limestone, siltstone, shale, and sandstone.	Lower third is composed of silty beds that act as a confining unit. Upper two thirds is C aquifer.	Blakey, 1990
Pn	Naco Formation	Pennsylvanian	90- 140 m	Much variation in facies: major limestone and minor dolomite, shale, siltstone, sandstone, and conglomerate. Very fossilferous and cherty.	Dominantly unsaturated, faults and fractures act as conduits between the C and Limestone aquifers.	Blakey, 1990
Mr	Redwall Limestone	Mississippian	0-140 m	Massive limstone unit. Shows paleo and active kast development. Locally fossiliferous and cherty.	Limestone aquifer, shows secondary karst porosity.	Darton, 1910
Dm	Martin Formation	Devonian	0-140 m	Much variation in facies: fine to medium grained dolomite and limestone, cherty, fossiliferous, minor siltstone and sandstone. Discontinuous where laps against paleohighs.	Limestone aquifer, may have secondary porosity developed in karst.	Teichert, 1965
Ct	Tapeats Sandstone	Cambrian	0-30 m	Very coarse grained sandstone to conglomerate, discontinuous where laps against paleohighs.	Lowermost unit of Limestone aquifer.	Hereford, 1977 Middleton, 1989
X	Crystalline Basement	Middle- Early Proterozoic	undetermined	Various metamorphic and igeneous units.	Groundwater exists in fractures and faults, very little primary porosity.	Karlstrom, 1991

the Mogollon Rim, the Permian Coconino Sandstone (Pc), Toroweap Formation (Pt), and Kaibab Formation (Pk) are the youngest Paleozoic rocks (Blakey, 1990). The Toroweap Formation is only present in the western part of the study area and does not extend east of Fossil Creek Canyon. These units are commonly concealed by overlying basalts and sediments.

Mesozoic units are not present in the study area. Paleozoic formations are overlain by a complex series of Tertiary volcanic (Tb) and sedimentary units (Ts, Toc) and locally intruded by Tertiary dikes (Spencer and Reynolds, 1989). Tertiary sedimentary units underlie Tertiary basalts (Tb) and when undifferentiated (Ts) are generally attributed to either the Beavertail Butte formation (Loseke, 2004) or the Mogollon Rim formation (Potochnik, 1989 and 2001). The Mogollon Rim formation (Toc) has been extended as far west as Hardscrabble Mesa by recent studies (Gaeaorama, 2006) but may have an even larger areal extent. This conglomeratic unit represents a period of erosion in the late Eocene that occurred between the Laramide age uplift of the Basin and Range and Transition Zone relative to the Colorado Plateau and the inception of Mogollon Rim formation and extensional tectonics. While sparsely outcropping, this unit provides important insight into the structural history and complexities of the region and is discussed further in the following section. Tertiary volcanics rocks (Tb) have a complex and incompletely understood history that is not relevant to this study. Generally, the volcanic rocks represent two main periods of basaltic volcanism, the first between 12 and 16 Ma and the second about 8 Ma (Leighty, 1998). Overlying Tertiary basalts in the western study area is the Tertiary Verde Formation (Tv), deposited during late Tertiary extensional tectonism in fluvial and lacustrine settings (Nations et al., 1981). Because the purpose of this study is to examine regional flow systems in bedrock, surficial deposits younger than the Verde Formation are ignored due to their limited extent.

1.5 Structure

The central Transition Zone has a complex tectonic history. Because structures have a significant control over the transport of groundwater and, as we are proposing, CO_2 pathways to springs in this region, it is important to understand the processes contributing to the current hydrogeologic setting. The oldest rocks are lower Proterozoic meta-volcanic and meta-sedimentary units which were accreted to North America and deformed between 1.7 and 1.6 Ga into north- northeast trending folds and shear zones (Bowring and Karlstrom, 1990). Three major pulses of tectonism (ca. 1.74, 1.70, and 1.65-160 Ga) resulted in the assemblage of the southwestern North American craton. Two erosional remnants of Proterozoic crystalline rocks are present at the surface, the Pine Mountain and Christopher Mountain paleohighs (figure 3) (Teichert, 1965; Parker et al., 2005).

Paleozoic tectonism in Arizona was very minor, resulting in tilting and regional arching and sagging; however these trends affect the geometries of younger tectonics (Peirce, 1976). The main surface expression of Paleozoic activity is in broad uplifts such as the Kaibab and Defiance uplifts. During the early Mesozoic, the region was tilted slightly to the northeast, truncated, and then covered by Cretaceous marine strata (Peirce at al., 1979).

Late Cretaceous to early Tertiary Laramide contractional tectonics uplifted the Basin and Range and Transition Zone relative to the Colorado Plateau as a result of shallow subduction of the Farallon Plate under North America (Dickenson et al., 1988). At the beginning of the Tertiary, significant uplifts and monoclines had formed in the Transition Zone as a result of high angle thrust faulting, creating high topography in the Basin and Range and Transition Zone relative to the Colorado Plateau and a northeasterly dip on all units (Spencer and Reynolds, 1989; Krantz, 1989). These topographic highs are the source of the rim gravels (Mogollon Rim formation of Potochnik, 2001) deposited atop the Paleozoic and Mesozoic units and underlying Tertiary basalts discontinously along the Mogollon Rim. This unit is in the study area, and can be used to date the inception of extensional tectonics and differentiation between the Plateau and Transition Zone and has an age of 37.5- 37.6 ± 0.8 Ma (Potochnik, 1989).

As subduction waned and the Pacific-North American transform plate boundary was born (Nicholson et al., 1994), extensional tectonics became prevalent in central Arizona (Spencer and Reynolds, 1989). In the Oligocene, low angle detachment faulting accommodated most of the deformation and intermediate to felsic magmatism was reintroduced to the area. The Mogollon Rim scarp formed and started to retreat at 30 Ma (Mayer, 1979), most likely the result of normal movement along the Diamond Rim fault, and would eventually separate the Colorado Plateau from the Transition Zone. In the Miocene, detachment faulting ended, high-angle extensional faulting continued, and magmatism became more mafic as a result of a probable opening of a no- slab window beneath central Arizona (Severinghaus and Atwater, 1990; Spencer and Reynolds, 1989). During this time, the crust in the Transition Zone was thinned and subsidence of much of the region occurred. Many major structures in the study area are most recently a result of Tertiary extensional faulting, namely the Diamond Rim and Verde faults (Geaeorama, 2006 and Titley, 1962). These structures are often east-west or northwest-southeast striking and may represent reactivated basement faults (Reynolds et al., 2001).

1.6 Hydrogeology

Groundwater flow in the study area is confined to a regional, two-tiered aquifer system and various local aquifers (Cooley et al., 1969; Bills et al., 2000; Rice, 2007). Recharge to the regional aquifer system occurs largely along the southwestern margin of the Colorado Plateau and in the San Francisco Peaks (Bills et al., 2007), as either direct infiltration through permeable fractured basalt, cinders, or the Kaibab Formation, or seepage in streambeds (Feth and Hem, 1963). Water then percolates down through faults and fractures to recharge the two regional aquifers. Groundwater divides (figure 4) exist in both aquifers, directing flow either north to discharge at springs in the Little Colorado River or Grand Canyon or south to discharge at springs in the Transition Zone (Bills et al., 2007). Local aquifers (Rice, 2007) are likely recharged by direct precipitation onto the hydrologic unit.

Composed of the C aquifer and Limestone aquifer (Bills et al., 2007), the regional aquifer system is extensive throughout the Coconino Plateau, from the Grand Canyon to the Mogollon Rim (figure 2). Within the study area, the C aquifer (also known as the Coconino aquifer) is the upper, unconfined unit. Water-bearing formations include the Paleozoic Kaibab Limestone, Coconino Sandstone, Schnebly Hill Formation, and upper to middle Supai Formation (Parker et al., 2005). The lower, Limestone aquifer (Parker et al., 2005; also known as the RM aquifer or Redwall-Muav aquifer) is confined by the lower Supai Formation and Naco Formation (Mike Ploughe, Town of Payson, written

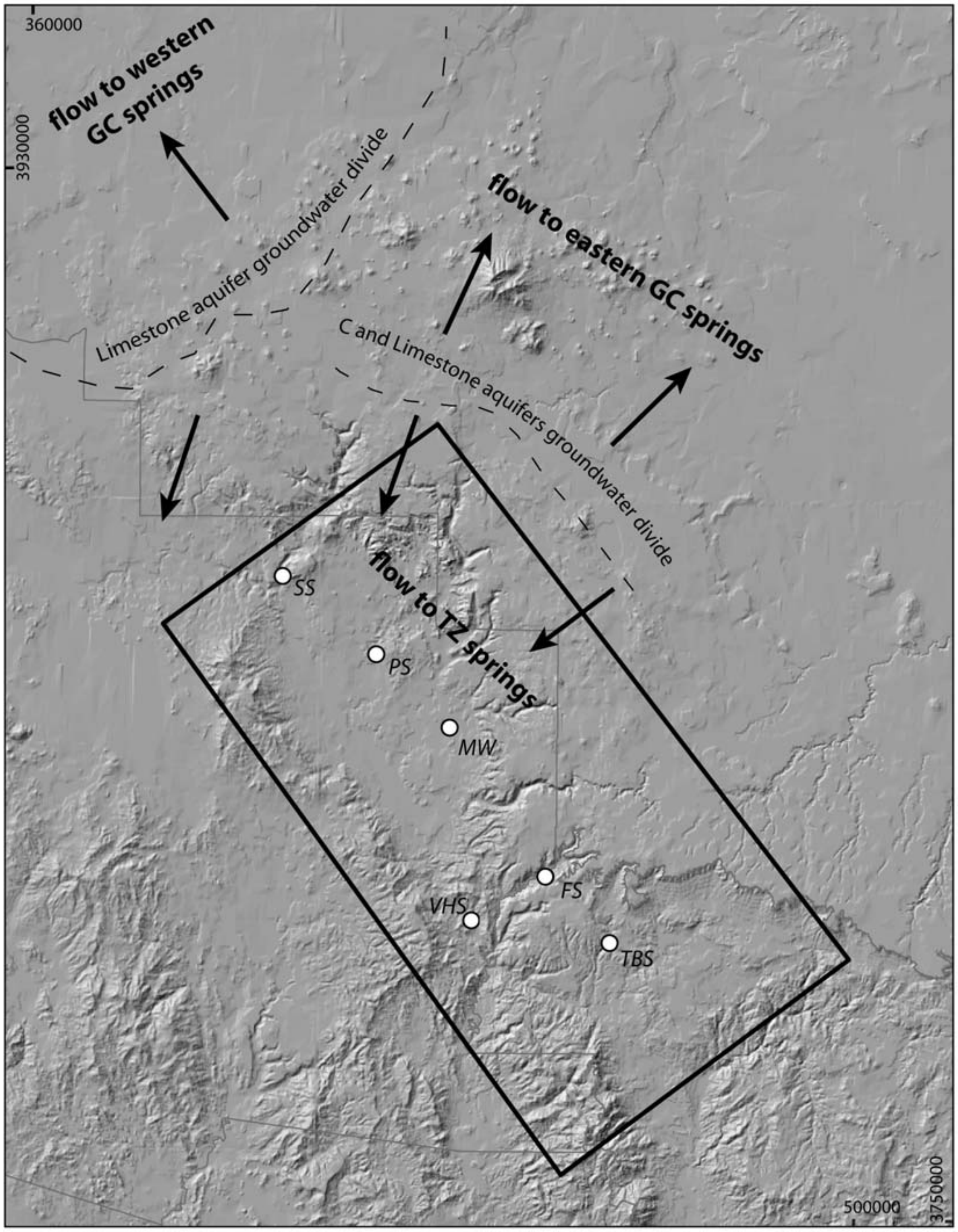


Figure 4. Groundwater divides and surface-water drainages in the study area. Groundwater divides for both regional aquifer systems are labeled on the map and groundwater flow direction is indicated by arrows of corresponding colors (from Bills et al., 2007). Major tributaries to the Verde River are labeled (from Rice, 2007). See figure 1 for names of springs (white circles). Elevation data from ALRIS.

communication, 2007). Saturated formations in the Limestone aquifer within the study area include the Redwall Limestone, Martin Formation, and discontinuous Tapeats Sandstone. Regionally, the Limestone aquifer also includes the Temple Butte Formation and Muav Limestone; however these formations are not present within the study or model areas (Bills et al., 2007).

Local aquifer systems have recently been identified as the source for many intermittent or ephemeral springs in the region (Rice, 2007). Tertiary volcanic rocks serve as one such aquifer unit, transporting locally recharged water through fractures to springs (Flora, 2004). Alluvial and basin fill deposits, often related to modern drainage systems, also act as aquifers. Proterozoic igneous and metamorphic rocks are classified as local aquifers in this study, as flow is generally shallow, restricted to faults and fractures, and disconnected (Parker et al., 2005).

Springs within the study area discharge from a variety of lithologies (Flora, 2004; Rice, 2007); however, the majority issue from the sedimentary rocks of the regional aquifer system (Parker, 2005). Springs sourced in local aquifers tend to show a greater variability in discharge due to shorter residence times, while regionally sourced springs often have a larger, more constant discharge (Rice, 2007). Major springs in the study area supply the base flow to creeks in the region, which are tributaries to the perennial Verde River (figure 4). Many recent studies of Transition Zone hydrogeology (Bills et al., 2000; Parker et al., 2005; Langenheim et al., 2005) highlight the control of fracture and fault networks on the location of spring discharge, as they often act as either conduits or barriers to groundwater flow. The relationship between hydrogeologic units and these networks are essential to understanding the location and occurrence of travertine-depositing springs.

CHAPTER 2: 3-D CONCEPTUAL MODEL

2.1. Introduction

The subsurface geology of the western Mogollon Rim area and the sources of the water for Fossil Springs are only now beginning to be understood (Parker et al., 2005 and Gaeaorama, 2006). A complex geologic and structural history and the large amount of topographic relief in the area create a unique aquifer system. With increasing population growth in the Strawberry, Pine, and Payson, Arizona area comes an increasing demand for a sustainable and reliable water supply. Population is expected to nearly double over the next 50 years (Parker et al., 2005) and groundwater supplies will likely be a component of a sustainable water portfolio for this growth (Hydrosystems, Inc., Feb. 2006, draft); however, there is currently a very poor understanding of the regional aquifer system, which might be tapped for this supply. By conceptually modeling the bedrock structure and stratigraphy of the western Mogollon Rim area, a more complete understanding of this complex system will be made available for future water management decisions.

A Digital Hydrogeologic Framework Model (DHFM) was constructed using EarthVision v. 7.5 (Dynamic Graphics Inc., Alameda, California, 2002). The DHFM will serve as a tool for understanding and conveying the complex subsurface geology of the region to water managers and others who can directly benefit from this knowledge. It may also be used to construct groundwater flow models of the region providing an additional tool for water management decisions.

2.2 Methods

The western Mogollon Rim study area was delineated from surface and groundwater information and available data. Boundaries to the north and west were placed at inferred groundwater divides and southern and eastern boundaries were chosen to include the maximum amount of surface data south of the Diamond Rim fault (figure 1). A variety of surface and subsurface data were compiled to construct the three-dimensional digital hydrogeologic framework model (DHFM) of the western Mogollon Rim. These data were compiled into Excel spreadsheets and ArcGIS 9.2 (Environmental Systems Research Institute, Redlands, California 2004) map files, which were then imported for use in the modeling software, EarthVision, a three-dimensional (3-D) geographic information system (GIS) software. Modeling parameters were manually calibrated until the greatest correlation between well and surface outcrop data and representation in the DHFM was reached.

2.2.1 Data Collection

Subsurface Data

In areas with little or no available geophysical data, such as the western Mogollon Rim, logs recorded during the drilling of deep boreholes can often provide important insights into subsurface geology. The Arizona Department of Water Resources (ADWR) imaged records database was queried for well logs within the study area (Arizona Department of Water Resources, 2005). Of the hundreds of boreholes drilled in the area, over 50 had logs that contained relevant stratigraphic information, although none contained accurate locations or elevations. Logs with unclear or questionable information or unknown locations were removed from the data; the remaining three wells could be located on a map and showed the contact between the Paleozoic and Proterozoic rocks (figure 5). Data for the Milk Ranch Well, Strawberry Borehole, and Strawberry Hollow Well were entered into a spreadsheet, including X, Y, and Z coordinates at top of casing and top elevation of each stratigraphic unit (table 2).

Table 2. Data from three wells used for the western Mogollon Rim Model. All data are in meters above sea level, "top" data represent the elevation of the top of each geologic unit. Easting and Northing data are in UTM, zone 12.

	Strawberry Borehole	Strawberry Hollow Well	Milk Ranch Well
ADWR Well 55 #		587628	
Easting	452244	457086	458326
Northing	3806900	3805245	3804465
Elevation	1742	1681	1649
Well depth	1403	1279	1329
Water level	1382	1394	1462
Date	1/17/2003		
Top Supai Fm			
Top Naco Fm	1457	1602	
Top Redwall Ls		1497	1600
Top Martin Fm		1422	1564
Top Tapeats Ss		1331	1447
Top Basement	1266	1294	1427

Surface Data

Digital coverages for the western Mogollon Rim were collected and compiled into an ArcGIS map file, including the 10 meter digital elevation model (.dem), USGS digital quadrangle (.drg), digital orthoquarter quad (.doqq) retrieved from http://aria.cals.arizona.edu in North American Datum 1927 (NAD27). These data were collected for eleven quadrangles: Buckhead Mesa, Buckhorn Mountain, Calloway Butte, Cane Springs Mountain, Cypress Butte, Hackberry Mountain, North Peak, Payson North, Payson South, Pine, and Strawberry. Digital orthoquarter quads for the entire study area

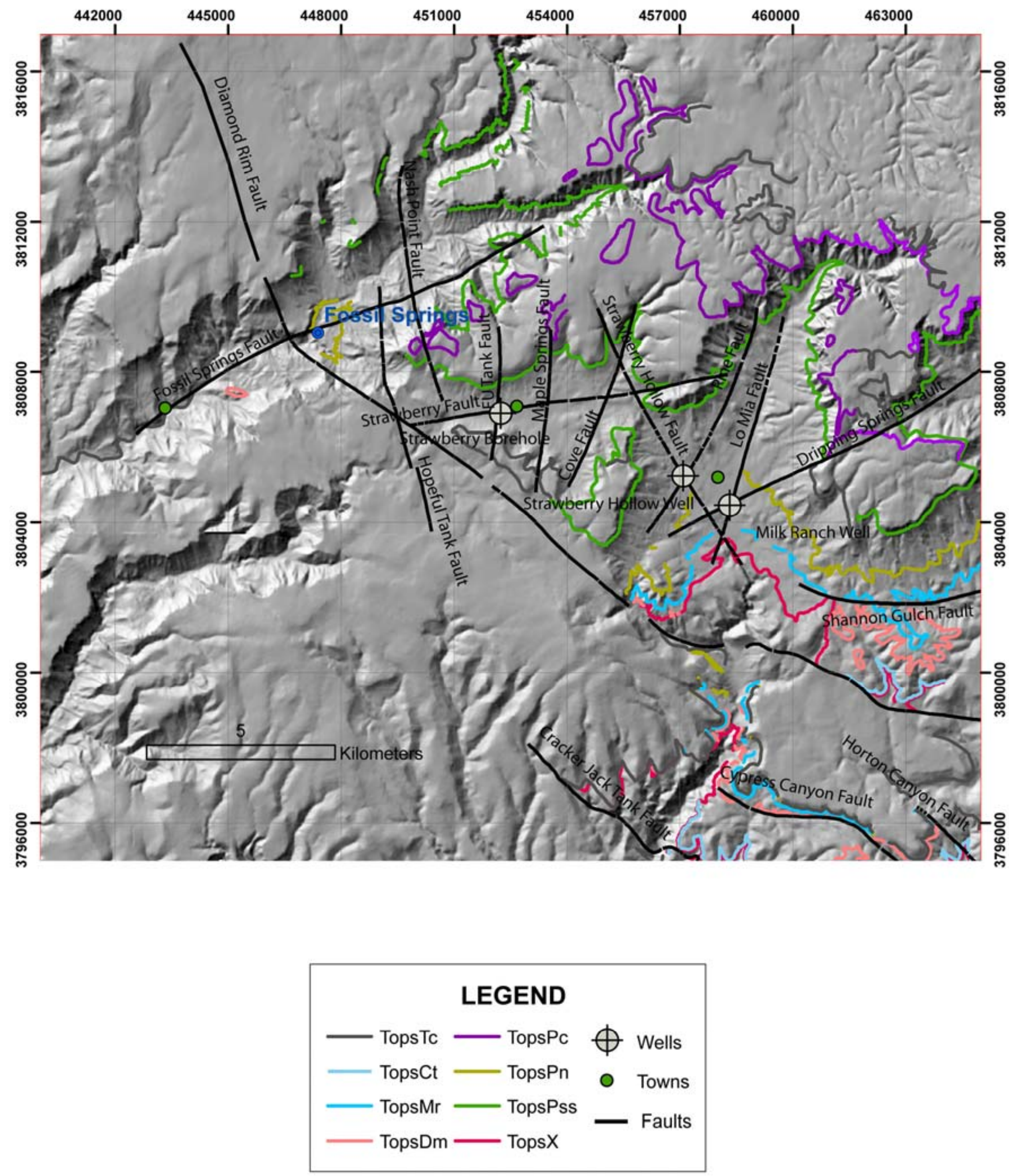


Figure 5. Location of surface and subsurface data points used to simulate the geology of the model area in the EarthVision Workflow Manager. Shown are the surface traces of faults, the upper contact of geologic horizons (tops), and the location of the three wells. Data from Gaeaorama (2006) and ARIA.

were compiled using the mosaic feature in ArcToolbox and used to create 10 meter contour lines.

Two geologic maps were used to determine surface outcrops in the study area. Weir and Beard (1984) provide a detailed (1:24,000) map of the Fossil Springs roadless area and Gaeaorama (2006) is a 1:55,000 scale map of the Pine, Strawberry, and Payson, Arizona areas commissioned by the Mogollon Rim Water Resources Management Study (MRWRMS). Maps were field checked and fault measurements were determined from field readings, where available, or estimations were made based on Transition Zone structural characteristics (Clay Conway, personal communication). Geologic contacts representing the top surface of each formation and fault surface traces were digitized as polylines in ArcGIS, each as an individual shape file for use in EarthVision (figure 6).

2.2.2 Modeling Techniques

Once data compilation was complete, horizons and faults were chosen for modeling. To create the DHFM, shape files (.shp) from ArcGIS were converted to data files (.dat) for use in EarthVision through a series of scripts and calculations (Appendix B: Model A Data Files). EarthVision's Work Flow Manager was used to compile data files and modeling parameters, which were manually calibrated until a best fit was reached between data and representation in the DHFM.

Faults

EarthVision models faults as 3-D planes that separate groups of geologic units into fault blocks (Dynamic Graphics, Inc. 2003-2005). Seventeen faults were simulated in the western Mogollon Rim Model: Fossil Springs fault, Diamond Rim fault, Strawberry fault, Strawberry Hollow fault, Nash Point fault, Pine fault, FU Tank fault, Hopeful Tank fault, Maple Springs fault, Dripping Springs fault, Lo Mia fault, Cove fault, Shannon Gulch fault, Horton Canyon fault, Cypress Canyon fault, and Cracker Jack Tank fault. Digitized surface traces were converted from ArcGIS files (.shp) to EarthVision files (.dat) through a series of calculations in DOS and EarthVision utilities. Direction and degree of dip were assigned to each fault (table 3) and were projected into the subsurface using the Dip/dip-azimuth plane creation utility in EarthVision (Appendix C: DHFM Additional Methods). A dip of 83 degrees was selected for every modeled fault based on regional data (Clay Conway, personal comm.) because field data could not be obtained.

Table 3. Seventeen modeled faults with degree of dip (dip) and dip direction (dip azm).

Fault	dip	dip azm
Fossil Springs fault	83	340
Diamond Rim fault	83	215
Strawberry fault	83	171
Strawberry Hollow fault	83	245
Nash Point fault	83	78
Pine fault	83	297
FU Tank fault	83	275
Hopeful Tank fault	83	260
Maple Springs fault	83	274
Dripping Springs fault	83	334
Lo Mia fault	83	286
Cove fault	83	281
Shannon Gulch fault	83	353
Cracker Jack Tank fault	83	238
Horton Canyon fault	83	45
Cypress Canyon fault	83	25

Horizons

"Horizon" is the term used in EarthVision to refer to a geologic unit simulated from "Tops", which are data points representing the upper surface of the unit (Dynamic Graphics, Inc. 2003-2005). Eight geologic horizons were modeled, from youngest to oldest: Quaternary deposits, Tertiary basalts, and sparse outcrops of Kaibab Formation were grouped together (Tb), Coconino Sandstone (Pc), Supai and Schnebly Hill Formations (Pss), Naco Formation (Pn), Redwall Limestone (Mr), Martin Formation (Dm), Tapeats Sandstone (Ct), and Proterozoic crystalline rocks (X). Groupings of units were determined either by relevance to hydrologic processes (Tb) or by availability of data (Pss).

ArcGIS shape files (.shp) were converted to tops data (.dat) files for each horizon through a series of calculations performed in DOS and EarthVision. A detailed explanation of this process is outlined in Appendix C: DHFM Additional Methods. Data sets for subsurface and surface data were kept separate during this process. EarthVision allows user-defined geologic relationships and modeling parameters to be set for each unit, initial parameters were chosen based on properties of each horizon.

Calibration

Initial parameters were input into EarthVision's WorkFlow Manager, the utility used to incorporate all functions necessary to create a 3D hydrogeologic framework model. After the initial model run, parameters and data were calibrated until the greatest correlation was reached between surface and subsurface data and representation in the model. This was done by overlying surface and subsurface data after each iteration of the model and manually editing data in the 3-D viewer of EarthVision.

Once a reasonable preliminary model was completed, a review of surface data was conducted to determine a reasonable interpretation of the subsurface in areas with little data (Hardscrabble Mesa, specifically). Regional and local geologic patterns at the surface indicate the possibility of a monoclinal structure trending along the surface trace of the Diamond Rim fault (Gaeaorama, 2006) of probable Laramide age (Reynolds et al., 2001). This suggests that the Diamond Rim fault has a complex history, including Laramide reverse faulting followed by more recent normal movement. This hypothesis has significant implications for the location and presence of Paleozoic and Proterozoic units below the basalt cap on Hardscrabble Mesa. With this in mind, two models were created: Model A represents the simple interpolation of geologic units made by following standard methods and interpolations in the EarthVision modeling code and Model B is based on both EarthVision interpolations and geologic interpretations based on regional surface data. To create Model B, control points were added based on geologic intuition (in locations where there were no borehole or outcrop data) to horizon data files along north south transects to force a monocline trending along the Diamond Rim fault (Appendix B: Model B Data Files). Models A and B are the same north of the Diamond Rim fault and east of Pine Creek canyon, they only vary in the subsurface of Hardscrabble Mesa.

2.3 Results and Discussion

The western Mogollon Rim DHFM is a tool that can be used to visualize the subsurface geology of the modeled area, although, like any model, it is most accurate where the most data are available. Because of the lack of data in the subsurface of some areas of the model, two models were created to represent the two end member scenarios. Model A represents the simple interpolation of available surface and subsurface data made by the EarthVision modeling code with minimal data editing. Model B is a result of regional geologic interpretations (Gaeaorama, 2006 and Reynolds et al., 2001) and shows a greater thickness of basalt, a monoclinal structure trending along the Diamond Rim

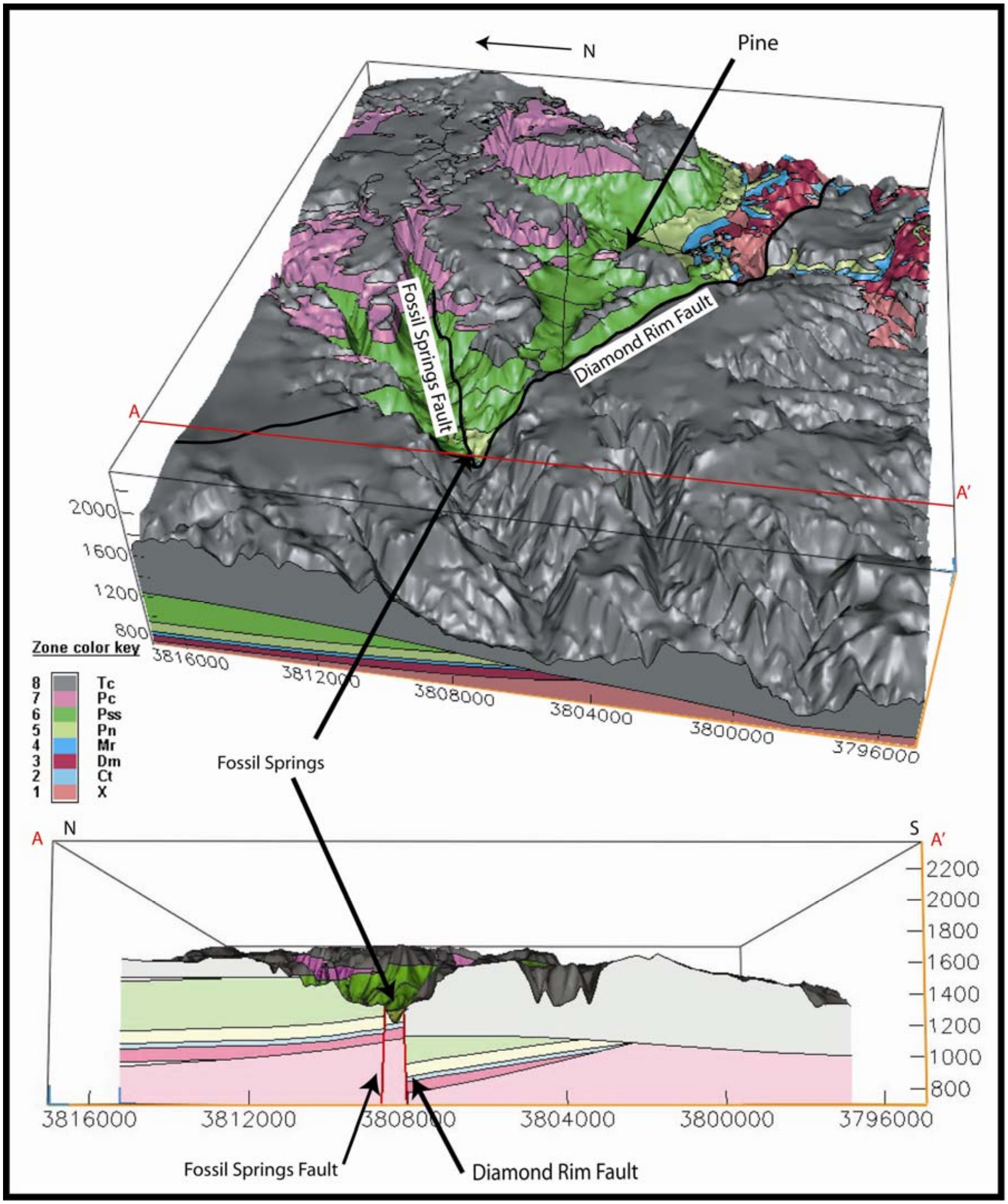


Figure 6. Oblique and cross-section views of Model A of the western Mogollon Rim digital hydrogeologic framework model. The lower view is a N-S cross section through Fossil Springs and the Diamond Rim fault.

fault, and a minimal section of Paleozoic units present under Hardscrabble Mesa. Model A (figure 6) shows good correlation with surface and subsurface data; however, where data were absent, the location and presence of units was determined numerically by the modeling code. Because the EarthVision modeling code defaults to the simplest geologic scenario in areas that are data poor, the interpretation of available data by EarthVision may be incomplete. The only exception in Model A was control points based on well data that were added to the Proterzoic rocks to force the presence of a 'basement high' in the area of Pine. Where the thickness of the basalt was not known, as in the area of Hardscrabble Mesa in the southwest quadrant of the model, the base of the basalt was extended 100 meters below its lowest surface elevation, resulting in a minimum thickness of basalt. This allowed for the presence of all Paleozoic units except Coconino Sandstone (Pc) south and west of the Diamond Rim fault, with a significant thickness of the Supai and Schnebly Hill Formations (Pss). As there is no evidence for the presence of the Supai and Schnebly Hill Formations south of the Diamond Rim fault, this introduces reasonable doubt in the validity of Model A. Along with uncertainty about the thickness of the Tertiary basalt and the presence of Paleozoic rocks in the subsurface of Hardscrabble Mesa, the need for the alternate scenario presented in Model B became evident.

Geologic relationships (Gaeaorama, 2006) and regional geologic structures (Reynolds et al., 2001) suggest that the Diamond Rim fault is a reactivated Laramide age thrust fault and/or monocline cored by a reverse fault that has only experienced normal movement during the Tertiary. The absence of the Coconino Sandstone and the Supai and Schnebly Hill Formations south of the Diamond Rim fault and the presence of the Mogollon Rim Formation (Toc) (Gaeaorama, 2006) indicate a period of northeast-

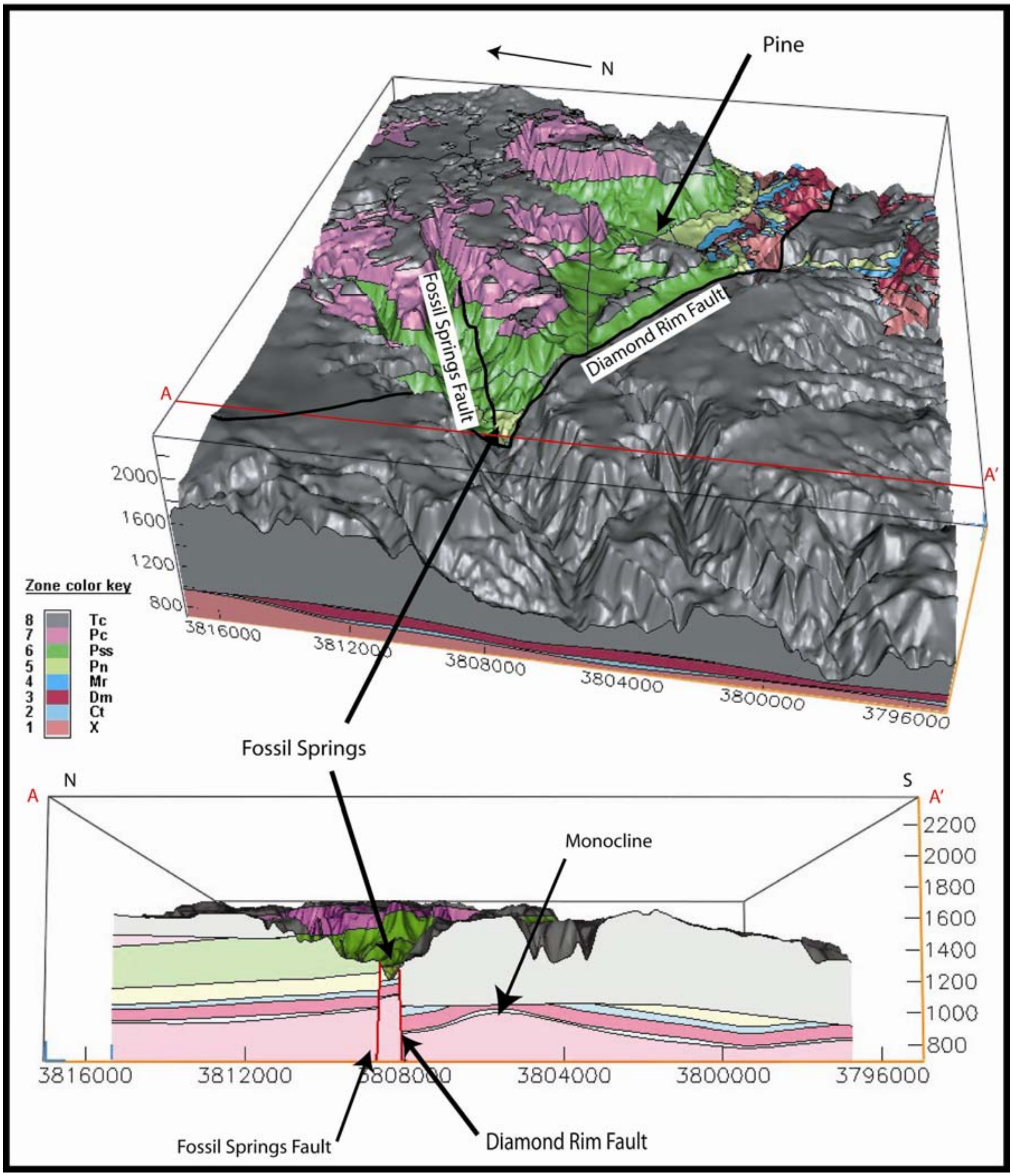


Figure 7. Oblique and cross-section views of Model B of the western Mogollon Rim digital hydrogeologic framework model. The lower view is a N-S cross section through Fossil Springs and the Diamond Rim fault, showing the monoclinal structure that indicates multiple movements of the fault.

directed erosion, suggesting that the hanging wall fault block was once uplifted with respect to the footwall. Most of the Paleozoic units were removed and then covered by basalt. This is represented in Model B by a greater thickness of Tertiary basalt and minimal thickness of Paleozoic units south of the fault (figure 7). Fossil Springs discharges at the intersection of the Fossil Springs fault and the Diamond Rim fault, as seen in both Model A and Model B. In both models, the confined units of the Limestone aquifer have been faulted against Tertiary basalts and Fossil Springs discharges at the contact of the Naco Formation and the Redwall Limestone. It is likely that as groundwater travels down gradient to the point of discharge, large amounts of water are channeled through fractures associated with the Fossil Springs fault and are forced to the surface when they encounter the less conductive Diamond Rim fault zone and basalt.

2.4 Conclusions

The western Mogollon Rim model is a 3-D visualization tool that can be used for instructional purposes and future water management decisions. The interaction of complex structure, the Pine bedrock high, and a possible Laramide-age monoclinal structure can be more easily understood and related to groundwater processes in three dimensions.

Although this model presents two probable scenarios for the subsurface of this region, the lack of data can not be wholly compensated for by numerical modeling codes or regional geologic interpretations. Future work includes exploration of the subsurface, specifically in the Hardscrabble Mesa area. A better understanding of the interactions of the fault networks in the area would also be useful to understanding the groundwater processes in this area. Eventually, a numerical groundwater flow model for this area should be used to constrain quantities of water and geochemical constituents issuing from Fossil Springs.

CHAPTER 3: DISCHARGE AND GEOCHEMICAL DATA

3.1 Introduction

New discharge and geochemical data were collected during this study to better constrain published and previously collected measurements. Between December, 2005 and June, 2007, Fossil Springs was visited every two months to collect discharge and geochemical data. Discharge was previously monitored by the USFS (Nelson, 2003) from 2002 through 2005, but the geochemistry of spring water has not been monitored in the past. To understand long-term processes operating at Fossil Springs, both flow and chemistry need to be continuously monitored. Although data from this study show little variability, a larger data set could be used to make predictions about the effects that climate change or the increased pumping of regional aquifers may have on Fossil Springs.

3.2 Spring Discharge

3.2.1 Methods

Discharge from the Fossil Springs complex was monitored from December, 2005 through June, 2007. Unpublished discharge data from November, 1999 through June, 2004 were provided by the Forest Service (Nelson, 2003) for comparison. The Swoffer 3000 flow meter (Swoffer Instruments, Inc., Seattle, WA) was used to measure water velocity at 1.5-foot intervals across the stream channel at 60% of the total depth. To calculate discharge, the velocity was multiplied by the area of each interval. Readings were taken approximately 15 meters downstream from the lowest spring orifice (Fig Tree

Spring) in a reach exhibiting laminar flow and recorded in cubic feet per second (cfs).

3.2.2 Results and Discussion

Forest Service data shows little variation through its period of record (standard deviation ≈ 3 cfs); however, data collected from December, 2005 through June, 2007 shows a large amount of variability (standard deviation ≈10 cfs) (table 4). Additionally, the largest discharge recorded by the Forest Service was 52 cfs, while discharges between 60 and 65 cfs were regularly recorded using the Swoffer 3000 flow meter. The flow meter was calibrated regularly during the monitoring period; however, no visible change in flow was noted while taking measurements. Because of this, the validity of measurements taken using the flow meter is questionable.

3.3 Geochemistry

3.3.1 Field Methods

Field water-quality parameters and water samples were collected on seven dates during the study period from the uppermost spring orifice in the northern channel (figure 8). Temperature (°C), conductivity (µS/cm), and pH were measured with a Troll9000 multi-parameter sensor manufactured by In-Situ, Inc. (Fort Collins, CO). The pH meter was calibrated to pH 7 and pH 10 buffers. On the dates that no data were recorded, the Troll9000 would not connect to the rugged handheld computer, either because of battery failure or exposure to moisture which caused cable connection failure.

Water samples were collected following standard procedures (U.S. Geological Survey, various dates). Stable isotope samples ($\delta^{18}O$, $\delta^{2}H$) were collected in 60mL glass

Table 4. Fossil Springs discharge data collected between 11/18/1999 and 6/16/2007 by various workers. Data collected by the Forest Service is available in a report on Fossil Creek instream flow assessment (Nelson, 2003). NAU-AES indicates data collected by Abe Springer at Northern Arizona University and NAU-LMG indicates data collected by Megan Green at Northern Arizona University.

Date	Field Crew	Discharge (CFS)
11/18/1999	Forest Service	47.10
1/20/2000	Forest Service	47.80
3/24/2000	Forest Service	47.09
4/19/2000	Forest Service	45.16
5/19/2000	Forest Service	46.70
6/20/2000	Forest Service	46.10
7/18/2000	Forest Service	46.63
8/23/2000	Forest Service	42.92
9/27/2000	Forest Service	43.46
10/24/2000	Forest Service	46.03
11/29/2000	Forest Service	45.65
12/8/2000	Forest Service	44.02
1/23/2001	Forest Service	48.85
2/21/2001	Forest Service	52.95
3/19/2001	Forest Service	49.96
4/25/2001	Forest Service	45.31
5/22/2001	Forest Service	51.68
6/26/2001	Forest Service	46.90
7/18/2001	Forest Service	46.21
8/28/2001	Forest Service	46.44
9/21/2001	Forest Service	42.11
10/26/2001	Forest Service	45.02
11/28/2001	Forest Service	42.08
12/12/2001	Forest Service	45.16
1/16/2002	Forest Service	46.31
2/27/2002	Forest Service	44.17
3/13/2002	Forest Service	39.73
4/16/2002	Forest Service	47.13
5/22/2002	Forest Service	42.16
6/21/2002	Forest Service	44.21
7/31/2002	Forest Service	46.52
8/2/2002	Forest Service	45.93

Date	Field Crew	Discharge (CFS)
9/26/2002	Forest Service	42.88
10/25/2002	Forest Service	44.99
11/20/2002	Forest Service	41.99
12/12/2002	Forest Service	42.51
1/15/2003	Forest Service	41.42
2/27/2003	Forest Service	51.08
3/27/2003	Forest Service	52.51
4/22/2003	Forest Service	40.47
5/13/2003	Forest Service	42.34
6/12/2003	Forest Service	41.00
7/25/2003	Forest Service	42.86
8/5/2003	Forest Service	40.80
9/24/2003	Forest Service	42.15
10/16/2003	Forest Service	46.10
11/24/2003	Forest Service	45.82
12/10/2003	Forest Service	41.64
1/28/2004	Forest Service	50.43
3/23/2004	Forest Service	40.81
4/15/2004	Forest Service	44.37
5/9/2004	Forest Service	42.04
6/15/2004	Forest Service	40.61
6/29/2004	NAU- AES	40.24
12/17/2005	NAU-LMG	65.78
2/11/2006	NAU-LMG	63.53
4/1/2006	NAU-LMG	60.39
6/9/2006	NAU-LMG	65.33
8/5/2006	NAU-LMG	60.75
10/14/2006	NAU-LMG	62.13
12/16/2006	NAU-LMG	47.91
3/3/2007	NAU-LMG	46.65
6/16/2007	NAU-LMG	37.47

Figure 8. The uppermost spring orifice collected in the Fossil Springs system and the location of water sample collection.

bottles with no headspace to allow for degassing of the samples. Samples to be analyzed for cations and anions were collected in 125mL high-density polyethylene (HDPE) acid washed bottles. Cation samples were filtered through a 0.45 micron membrane filter and acidified to a pH< 2.5 with nitric acid.

3.3.2 Laboratory Methods

Stable isotopes were analyzed by the Colorado Plateau Stable Isotope Laboratory at Northern Arizona University using a gas-source Finnigan Delta S™ Isotope Ratio

Mass Spectrometer (IRMS). Each sample was analyzed for $\delta^{18}O$ and $\delta^{2}H$ and reported in standard δ notation as a per-mil (‰) variation from the Vienna Standard Mean Ocean Water (VSMOW) (Ingraham et al., 2001).

Cation and anion samples were delivered to the Analytical Laboratory in the Department of Earth and Planetary Sciences at the University of New Mexico. Major cations (Ca, K, Mg, Na, Si, Al) and minor elements (only B, Ba, Sr were above minimum detection limits) were analyzed using a Jarell-Ash S-12 and Perkin Elmer 303. A Dionex 500X Ion Chromatograph was used to analyze major anions (F, Cl, NO_2, Br, NO_3, PO_4, SO4, HCO_3). Alkalinity was determined by titration. Charge balances and calculations were conducted using PHREEQC (Parkhurst, 1995).

3.3.3 Results and Discussion

Field parameters, stable isotope, and major ion chemistry data were collected on seven dates, between 4/1/2006 and 6/16/2007 (table 5). Data show little variability through the sampling period but can be used to indicate the source of water discharging from Fossil Springs. Major ion chemistry is bicarbonate, calcium, and magnesium rich and similar to regional data (Crossey et al., *in review*; Flora, 2004; Wirt et al., 2005) (figure 9). With the exception of springs containing solutes derived from buried evaporates (Verde Hot Springs and Springerville- West), major ion chemistry at Fossil Springs is similar to other travertine-depositing springs within the Transition Zone.

Stable Isotopes can be used to gain insight into source and evolution of spring water. In general, water depleted in ^{2}H and ^{18}O indicates water that is less evolved and has a recharge area in higher altitudes (Wirt and Hjalmarson, 1999). When plotted with regional isotope data (Bills et al., 2007), Fossil Springs stable isotope data plot on trend

Table 5. Fossil Springs field major ion chemistry, minor element and stable isotope chemistry, and field parameters for seven sampling dates. NR indicates none recorded.

Sample	Date	F ppm	Cl ppm	NO2 ppm	Br ppm	NO3 ppm	PO4 ppm	SO4 ppm	HCO3 ppm
Fossil Springs	4/1/06	0.12	12.5	0.44	0.47	0.63	0.64	26.3	476
Fossil Springs	6/9/06	0.13	13.8	0.25	0.20	0.70	0.54	23.4	476
Fossil Springs	8/5/06	0.12	7.1	0.32	0.03	0.28	0.37	26.0	470
Fossil Springs	10/14/06	0.15	12.3	0.33	0.27	2.76	0.35	26.3	458
Fossil Springs	12/16/06	0.34	12.2	0.37	0.12	0.66	1.23	26.5	467
Fossil Springs	3/3/07	0.10	7.3	0.06	0.02	0.27	0.03	26.0	464
Fossil Springs	6/16/07	0.16	12.4	0.72	0.36	0.74	0.40	26.4	458

Sample	Date	Ca ppm	K ppm	Mg ppm	Na ppm	Si ppm	Al ppm	Ch. Bal. %	log pCO2
Fossil Springs	4/1/06	86.5	1.56	35.0	12.7	5.57	0.067	-5.8	-1.12
Fossil Springs	6/9/06	86.1	1.52	34.9	12.4	5.48	0.067	-5.9	-1.12
Fossil Springs	8/5/06	88.2	1.49	36.1	12.6	5.53	0.067	-3.1	-0.99
Fossil Springs	10/14/06	92.9	1.59	37.2	12.9	5.49	0.232	-1.0	-1.07
Fossil Springs	12/16/06	95.5	1.56	37.0	12.5	5.34	0.246	-1.2	-1.40
Fossil Springs	3/3/07	94.2	1.56	37.8	12.6	5.40	0.243	0.3	-1.07
Fossil Springs	6/16/07	95.4	1.52	37.6	12.4	5.24	0.223	-0.1	-1.07

Sample	Date	B ppm	Ba ppm	Sr ppm	δD permil	O18 permil
Fossil Springs	4/1/06	0.322	0.116	0.224	-81.7	-11.6
Fossil Springs	6/9/06	0.303	0.115	0.221	-81.4	-11.5
Fossil Springs	8/5/06	0.340	0.117	0.224	-81.5	-11.6
Fossil Springs	10/14/06	0.562	0.120	0.224	-82.5	-11.6
Fossil Springs	12/16/06	0.621	0.118	0.220	NR	NR
Fossil Springs	3/3/07	0.642	0.119	0.220	NR	NR
Fossil Springs	6/16/07	0.514	0.117	0.220	-85.2	-11.56

Sample	Date	Discharge cfs	Temp °C	pH	Cond. µs/cm
Fossil Springs	4/1/06	NR	NR	NR	NR
Fossil Springs	6/9/06	NR	NR	NR	NR
Fossil Springs	8/5/06	NR	NR	NR	NR
Fossil Springs	10/14/06	NR	21.4	7.01	750
Fossil Springs	12/16/06	47.91	NR	NR	NR
Fossil Springs	3/3/07	46.65	21.4	6.74	752
Fossil Springs	6/16/07	37.47	22.1	6.64	757

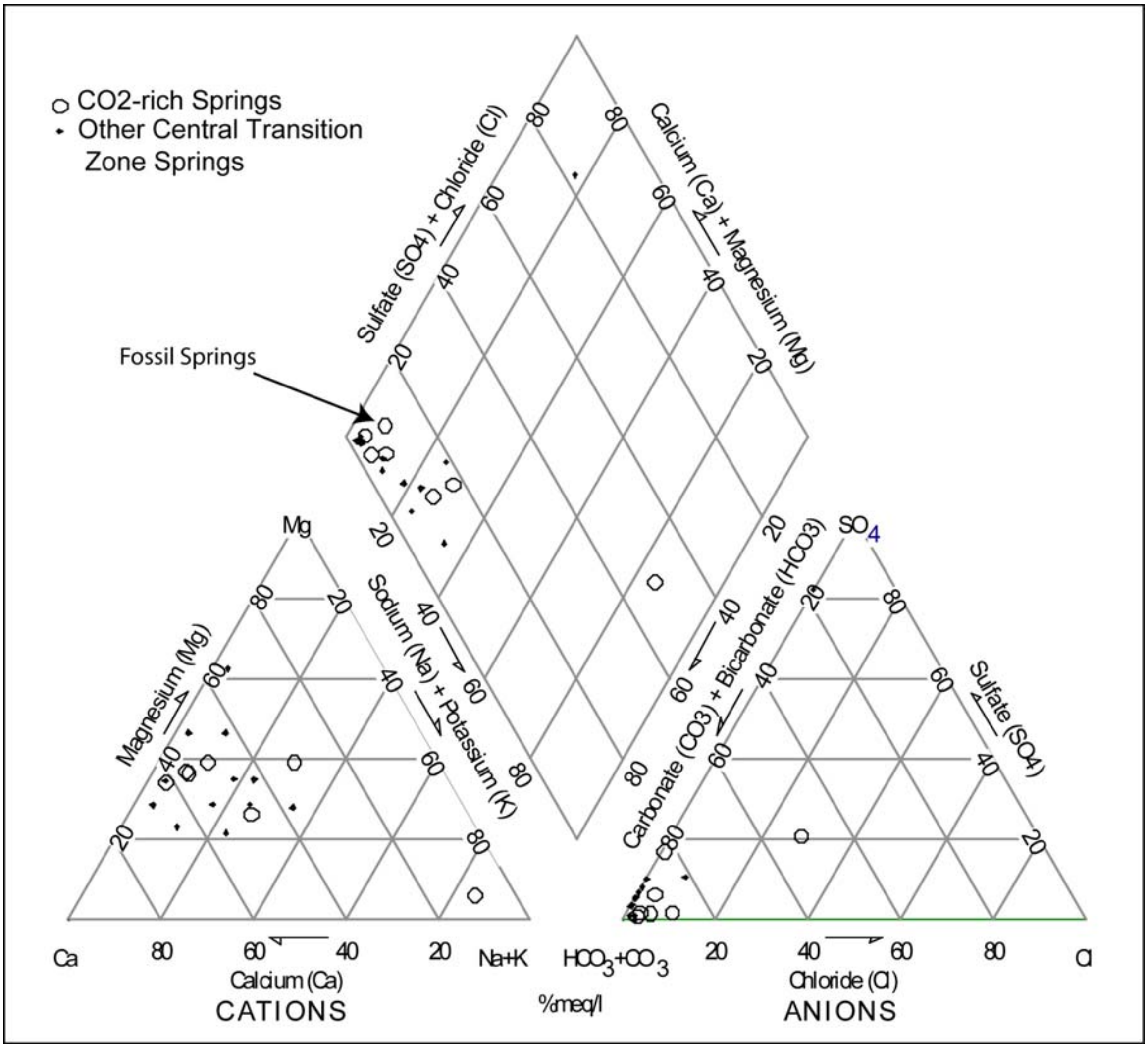


Figure 9. Piper diagram for springs in Arizona's Transition Zone. Springs with and endogenic source are indicated by individual symbols, all other springs are plotted as black dots. Data is from this study, Crossey et al., (*in review*); Flora (2004); and Wirt et al., (2005).

suggests a mixed source from local and regional flow systems, with the majority of the with Verde Valley springs streams and wells and Flagstaff area wells (figure 10). This recharge sourced on the Colorado Plateau.

3.4 Conclusions

Discharge and geochemical data from Fossil Springs shows little variability in available data sets. These data suggest a dominantly regional source similar to other springs in the region. Fossil Springs provides important riparian habitat within the central Transition Zone and is at risk from increased development and groundwater exploitation in the region. To better understand changes over time, monitoring of discharge and geochemistry needs to be continued in the future.

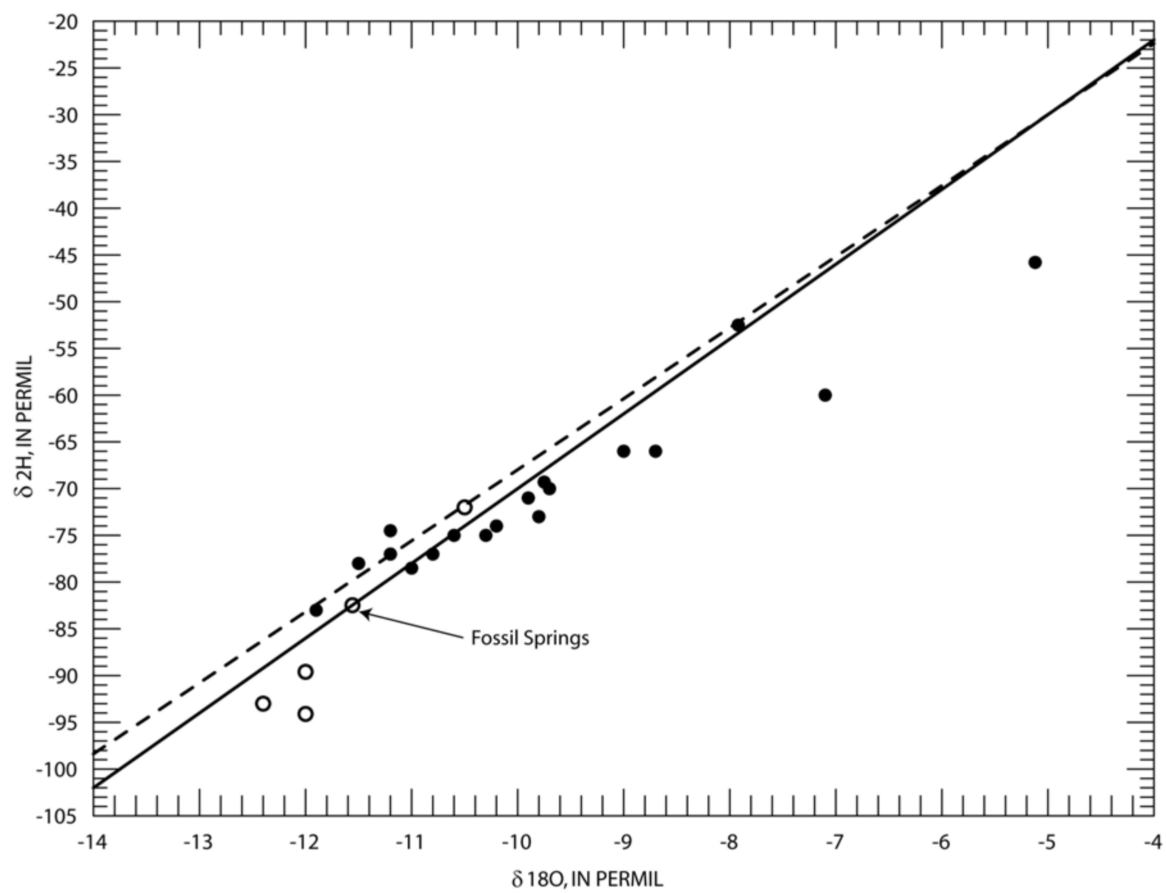


Figure 10. $\delta^{18}O$ and $\delta^{2}H$ isotope data for Fossil Springs and other springs in the region. Hollow dots represent discharging deeply sourced CO_2 (see Chapter 4), black dots are data from other springs in Arizona's Transition Zone. Dashed line is the Flagstaff Meteoric Water Line from 2003-2004 (Bills et al., 2007), solid line is the Global Meteoric Water Line (Craig, 1961).

CHAPTER 4: STURCUTRAL AND HYDROGEOLOGIC RELATIONSHIPS IN THE CENTRAL TRANSITION ZONE, ARIZONA: IMPLICATIONS FOR DISCHARGE OF DEEPLY SOURCED CO_2 FROM REGIONAL AQUIFER SYSTEMS

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4.1 ABSTRACT

Several high discharge springs in Arizona's central Transition Zone have been identified as having a small but significant endogenic source for discharged gasses (CO_2, ^3He). CO_2-rich springs in the region are associated with massive travertine deposits, mantle derived helium, slightly elevated temperatures, and high ionic concentrations. They discharge along regional, extensional, fault systems (Diamond Rim fault, Verde fault) which are associated Laramide monoclines from regional, confined aquifer systems. Gasses released during mantle degassing are conveyed upwards along these fault networks, trapped in the aquifer systems by confining units, and transported with regional groundwater flow to discharge at springs. To better define processes contributing

to the transport of gasses to these springs, structures in the region were examined. The known extent of the Diamond Rim fault has been projected north-westward and the associated Diamond Rim monocline has been delineated based geologic and geophysical data. Furthermore, it is speculated that the Diamond Rim fault and monocline are linked to similar structures in the Verde Valley. These known and inferred structures best explain the occurrence and distribution of CO_2 and non-CO_2-rich springs in the central Transition Zone of Arizona.

4.2 INTRODUCTION

Travertine-depositing springs of the Southern Colorado Plateau have recently been identified as having endogenic, deeply-sourced, CO_2 contributing to high rates of deposition (Crossey et al., *in review*; Crossey et al., 2006; Newell et al., 2005). The geologic CO_2 emission from the Colorado Plateau region reflects a complex tectonic evolution involving Laramide hydration of the lithosphere above the Farallon slab, addition of fluids from mid-Tertiary tectonism during slab removal, and fluid movement induced by neotectonic small-scale asthenospheric convection (Crossey et al., *in review*). Workers examining tectonically active regions (Minissale, 2004; Liu et al., 2003; Minissale et al., 2002) suggest that endogenic components may be contributing to travertine deposition in spring systems worldwide. Travertine-depositing springs in the Transition Zone physiographic province of central Arizona are related to similar geologic and structural characteristics and are sourced in the same aquifer system as those of the southern Colorado Plateau, suggesting that these processes are also active in this region. This study expands the regional database for CO_2-rich springs as well as defines a more detailed set of criteria for what controls this process in the Transition Zone of Arizona.

Specific hydrogeologic and structural relationships to springs in the central Transition Zone of Arizona (figure 11) are examined and used to define hydrologic pathways and compared with the regional conceptual model for CO_2-rich springs. The CO_2-rich springs are the highest discharge springs in the region and important resources, serving the conflicting roles of providing both important riparian habitat to rare and endemic species and water supply to growing communities. A better understanding of the processes controlling regional groundwater flow to the springs will allow for better management of the water resources.

The study area is characterized by steep, rugged terrain with topographic relief of over 1,500 meters and outcrops from Proterozoic to Tertiary in age. The area extends southwest from the Mogollon Rim (the physiographic edge of the Colorado Plateau) to the Verde Fault, and from the East Verde River to Sycamore Creek with a focus on the major springs (figure 11). Spatial relationships between spring locations, regional structure, and geochemical data were examined. Regional maps of geology (Gaeaorama, 2006; Langenheim et al., 2005; Richard et al., 2000; Weir et al., 1989; Ulrich et al., 1984; Anderson and Creasey, 1958) were compiled to reanalyze structural features, including a possible extension of the Diamond Rim fault system and previously unmapped monoclines. Geochemical and springs data were then used to examine spatial relationships between structures and springs.

4.3 GEOLOGIC SETTING

4.3.1 Lithologic Units

The Arizona Transition Zone, defined physiographically and geologically as an approximately 100 kilometer wide region of Tertiary volcanic and sedimentary rocks overlying Proterozoic basement and Paleozoic strata to the north (Leighty, 1998), also serves as the geological transition between the adjoining Colorado Plateau and the Basin and Range. The hydrology of the region reflects the topography, stratigraphy, and structure. The flat lying units of the Colorado Plateau dip less than 1° to the northeast, forming a groundwater and surface-water drainage divide along the northwest- southeast trending Mogollon Rim, the escarpment at the southern edge of the Colorado Plateau (Spencer and Reynolds, 1989). Geologic formations present in the central Transition Zone (figure 12) have been identified and described by various workers (table 6) and mapped at several scales (Gaeaorama, 2006; Langenheim et al., 2005; Richard et al., 2000; Weir et al., 1989; Ulrich et al., 1984; Anderson and Creasey, 1958) (figure 13). Table 1 provides a more detailed description of units present in the study area.

Metamorphic and igneous Proterozoic units in the area have undergone several periods of deformation (Karlstrom, 1991) and have been grouped together because groundwater movement through crystalline matrices is largely dependent on secondary porosity through fault and fracture flow rather than primary porosity (Parker et al., 2005). Paleozoic units in the region are largely flat lying, sedimentary units typical of the Colorado Plateau and Grand Canyon regions and unconformably overly the Proterozoic rocks. Erosional remnants of Proterozoic rocks exist in at least two locations in the study area, the Christopher Mountain and Pine Mountain paleohighs (figure 13) (Parker et al., 2005; Teichert, 1965). The Cambrian Tapeats Sandstone is discontinuous throughout the study area, absent where it laps out against paleohighs and up to 30 meters thick in other areas (Hereford, 1977 and Middleton, 1989). It is overlain by the Devonian Martin Formation (0-140m), which is also discontinuous and shows substantial facies variation, ranging from dolomite and minor limestone to sandstone and siltstone throughout the region (Teichert, 1965). The Mississippian Redwall Limestone (0-140m) is a massive limestone unit, likely with some karst development, that extends from the Mogollon Rim north to the Grand Canyon (Darton, 1910). The Pennsylvanian Naco Formation (90-140m) is another limestone unit, distinguished from the Redwall Limestone by cherty nodules in its lower beds (Blakey, 1990). Late Pennsylvanian and Permian limestone to sandstone units, the Supai and Schnebly Hill formations, are grouped together in this study due to inferred similarity in hydrologic characteristics and a lack of detailed mapping in this region (Blakey, 1990). Thickness of these units in the study area is up to 580 meters. Capping the Mogollon Rim, the Permian Coconino Sandstone, Toroweap Formation, and Kaibab Formation, in ascending order, are the youngest Paleozoic rocks (Blakey, 1990). The Toroweap Formation is only present in the western part of the study area and does not extend as far east as Fossil Creek canyon. These units are often concealed by overlying Tertiary basalts and sedimentary rocks.

Mesozoic units are not present in the study area, Paleozoic formations are overlain by a complex series of Tertiary volcanic and sedimentary units and locally intruded by Tertiary dikes (Spencer and Reynolds, 1989). Tertiary sedimentary rocks underlie Tertiary basalts and when undifferentiated are generally attributed to either the Beavertail Butte formation (Loseke, 2004) or the Mogollon Rim formation (Potochnik, 1989 and 2001). The Mogollon Rim formation (37.5 - 37.6 ± 0.8 Ma) has been extended as far west as Fossil Creek canyon by recent studies (Gaeaorama, 2006), but may have an even larger areal extent. This conglomeratic unit represents a period of erosion that occurred between the Laramide age uplift of the Basin and Range and Transition Zone and the inception of extensional tectonics at 30-25 Ma (Spencer and Reynolds, 1989). While sparsely outcropping, this Mogollon Rim formation provides important insight into the structural history and complexities of the region and is discussed further in the following section. Tertiary volcanic rocks of the region have a complex and incompletely understood history. Generally, the volcanics represent two main periods of basaltic volcanism, the first between 12 and 16 Ma and the second about 8 Ma (Leighty, 1998). Overlying the older Tertiary basalts and sedimentary rocks in the western study area is the Tertiary Verde Formation, deposited during late Tertiary extensional tectonism in fluvial and lacustrine settings (Nations et al., 1981). Because the purpose of this study is to examine regional structures and groundwater flow systems in bedrock, surficial deposits younger than the Verde Formation are not discussed.

4.3.2 Tectonic History

The central Transition Zone has a complex tectonic history. Because structures have a significant control over the transport of groundwater and, as we are proposing, CO_2 pathways to springs in this region, it is important to understand the processes contributing to the current hydrogeologic setting. The oldest rocks are lower Proterozoic meta-volcanic and meta-sedimentary units which were accreted to North America and deformed between 1.7 and 1.6 Ga into north- northeast trending folds and shear zones (Bowring and Karlstrom, 1990). Three major pulses of tectonism (ca. 1.74, 1.70, and

1.65-160 Ga) resulted in the assemblage of the southwestern North American craton. Two erosional remnants of Proterozoic crystalline rocks are present at the surface, the Pine Mountain and Christopher Mountain paleohighs (figure 12) (Teichert, 1965; Parker et al., 2005).

Paleozoic tectonism in Arizona was very minor, resulting in tilting and regional arching and sagging; however these trends affect the geometries of younger tectonics (Peirce, 1976). The main surface expression of Paleozoic activity is in broad uplifts such as the Kaibab and Defiance uplifts. During the early Mesozoic, the region was tilted slightly to the northeast, truncated, and then covered by Cretaceous marine strata (Peirce at al., 1979).

Late Cretaceous to early Tertiary Laramide contractional tectonics uplifted the Basin and Range and Transition Zone relative to the Colorado Plateau as a result of shallow subduction of the Farallon Plate under North America (Dickenson et al., 1988). At the beginning of the Tertiary, significant uplifts and monoclines had formed in the Transition Zone as a result of high angle thrust faulting, creating high topography in the Basin and Range and Transition Zone relative to the Colorado Plateau and a northeasterly dip on all units (Spencer and Reynolds, 1989; Krantz, 1989). These topographic highs are the source of the rim gravels (Mogollon Rim formation of Potochnik, 2001) deposited atop the Paleozoic and Mesozoic units and underlying Tertiary basalts discontinously along the Mogollon Rim. This unit is in the study area and can be used to date the inception of extensional tectonics and differentiation between the Plateau and Transition Zone and has an age of 37.5 - 37.6 ± 0.8 Ma (Potochnik, 1989).

As subduction waned and the Pacific-North American transform plate boundary was born (Nicholson et al., 1994), extensional tectonics became prevalent in central Arizona (Spencer and Reynolds, 1989). In the Oligocene, low angle detachment faulting accommodated most of the deformation and intermediate to felsic magmatism was reintroduced to the area. The Mogollon Rim scarp formed and started to retreat at 30 Ma (Mayer, 1979), most likely the result of normal movement along the Diamond Rim fault, and would eventually separate the Colorado Plateau from the Transition Zone. In the Miocene, detachment faulting ended, high-angle extensional faulting continued, and magmatism became more mafic as a result of a probable opening of a no- slab window beneath central Arizona (Severinghaus and Atwater, 1990; Spencer and Reynolds, 1989). During this time, the crust in the Transition Zone was thinned and subsidence of much of the region occurred. Many major structures in the study area are most recently a result of Tertiary extensional faulting, namely the Diamond Rim and Verde faults (Geaeorama, 2006 and Titley, 1962). These structures are often east-west or northwest-southeast striking and may represent reactivated basement faults (Reynolds et al., 2001).

4.4 ANALYSIS OF STRUCTURE IN CENTRAL TRANSITION ZONE STUDY AREA

4.4.1 Laramide Monoclines

Monoclines are the most notable Laramide age structures in Arizona's Colorado Plateau and Transition Zone Provinces (figure 14). Low angle subduction of the Farallon slab under the North American plate caused widespread uplift and east-northeast crustal shortening, resulting in north to northeast-striking monoclines in the southwestern

Colorado Plateau region (Huntoon, 2003). These monoclines formed in Paleozoic and Mesozoic strata, following the orientation of and reactivating high-angle reverse faults in Proterozoic rocks. Similar structures have been identified in the Transition Zone, but not within the study area (Krantz, 1989 and Reynolds et al., 2001).

We propose a southeast-northwest trending Laramide age monocline following the trace of the Diamond Rim Fault in the eastern portion of the study area, deforming all units younger than the Mogollon Rim formation, following Reynolds et al., 2001 (figure 14). In the area of Christopher Mountain, there are two significant outcrops of the Mogollon Rim formation (Gaeaorama, 2006). The northern outcrop overlies the Martin Formation and the southern outcrop overlies Proterozoic units. Given a northerly transport direction during deposition of the Mogollon Rim formation, this indicates a larger amount of uplift in the area of the southern outcrop. To the west, in the area of Pine Mountain, there is further evidence for the existence of a monocline. From north to south, the Mogollon Rim formation overlies a progressively older sequence of units (Naco Formation to Redwall Limestone), in the central area it overlies Proterozoic rocks, and farther south it overlies a progressively younger sequence of rocks (Tapeats Sandstone to Redwall Limestone). In both the Pine Mountain and Christopher Mountain areas, all outcrops of the Mogollon Rim formation are south of the Diamond Rim fault. In Fossil Creek canyon, just north of the Diamond Rim fault, the Mogollon Rim formation overlies the Schnebly Hill Formation, suggesting that during deposition of the Mogollon Rim formation, motion on the Diamond Rim fault was north side down, opposite to its current offset. Three-dimensional subsurface geologic modeling suggests that the simplest and most realistic interpretation of the area under the basalts of Hardscrabble Mesa, where there is little subsurface control, is to extend the monocline through this area.

4.4.2 Tertiary Normal Faults

In late Tertiary time, the central Transition Zone was dominated by east-southeast to southwest striking high-angle normal faulting as a result of the transition from subduction to transform motion at the North American- Pacific Plate boundary (Spencer and Reynolds, 1989). Major structures present in the study area (figure 13) are evidence of this event.

The Diamond Rim fault is an east-southeast striking, down to the southwest, regionally extensive, normal fault. Previously, only mapped in the eastern portion of the study area (Gaeaorama, 2006), this study connects two other unnamed faults (Langenheim et al., 2005 and Weir et al., 1989) and proposes two new fault segments to extend the Diamond Rim fault across the central Transition Zone, in the subsurface and concealed by Teritary basalts and the Verde Formation (figure 13). In the eastern portion of the study area, the Diamond Rim fault has offsets of up to 400 meters and the onset of normal movement has been dated to about 12 Ma (Mayer, 1979). The segment of the Diamond Rim fault near Page Springs was published by Langenheim et al. (2005) based on unpublished USGS maps and geophysical data. It was identified as having important control over the location of Page Springs but no other detail was provided. In West Clear Creek canyon, Weir et al. (1989) mapped a series of minor faults and one major fault offsetting the Paleozoic section. Southwest of the fault, the base of the Coconino Sandstone is at 1250 m in elevation and northwest of the fault it is at 1550 m, indicating at least 300 meters of offset is accommodated across the fault zone. Because these fault segments show a similar strike and offset to the Diamond Rim fault mapped in the eastern study area, we correlate the segments and infer additional segments in the area of Montezuma Well and Summer Spring because of the documented control that structure has on spring discharge locations regionally (Fry, 2006; Parker et al., 2005; Langenheim et al., 2005; Bills et al., 2000).

The Verde fault is the other regionally extensive fault in the study area, with comparable length and throw to the Diamond Rim fault. It is also a northwest striking normal fault and offset down to the northeast. It shows several hundreds of meters of Proterozoic throw, unknown Laramide displacement, and major normal displacement of 1-2 Km during the Late Miocene (Leighty, 1998). The Verde and Diamond Rim faults are the bounding structures of the Verde basin and the Hardscrabble Mesa area where Tertiary basalts accumulated (figure 13).

Other Tertiary normal faults in the region include the Oak Creek fault, Orchard fault, Bear Canyon Wallow fault, and Cathedral Rock fault, all in the western study area. The Oak Creek fault is a north striking, 50 Km long, down to the east, high-angle normal fault. It has a Proterozoic inheritance and has experienced both Laramide compression and Tertiary extension (Holm and Cloud, 1990).

4.4.3 Interpretation

Our reinterpretation of the structures of the central Transition Zone is based on compilation and review of previous mapping, we did not remap the study area ourselves. In both the southwestern Colorado Plateau (Huntoon, 2003) and the northwest and southeast Transition Zone (Krantz, 1989), Tertiary normal faulting reversed the sense of offset on Laramide monoclines, reactivating Proterozoic faults a second time. Often, offset propagated laterally past previous faults and conjugate faulting formed grabens. We suggest a similar history for the Diamond Rim fault and monocline in Arizona's central Transition Zone. It is likely that reverse offset first occurred during the Proterozoic assemblage of the North American craton, followed by a long period of inactivity. Laramide compressional tectonics created the Diamond Rim monocline, reactivating the Proterozoic fault and uplifting the southwestern fault block. A period of erosion and deposition of the Mogollon Rim formation atop units Proterozoic to Pennsylvanian in age accompanied and followed formation of the monocline. A shifting western North American Plate boundary and the development of the Basin and Range province lead to extension and a final reactivation of the Diamond Rim fault during the Tertiary, reversing the sense of motion and down-dropping the southwestern fault block. Coeval and later movement on the Verde fault led to the formation of the Verde basin.

4.5 HYDROLOGY

4.5.1 Hydrologic Setting

Groundwater flow in the study area is confined to a regional, two-tiered aquifer system and various local aquifers (Cooley, 1969; Bills et al., 2000; Rice, 2007). Recharge to the regional aquifer system occurs largely along the southwestern margin of the Colorado Plateau and in the San Francisco Peaks (Bills et al., 2007), as either direct infiltration through permeable fractured basalt, cinders, or the Kaibab Formation or seepage in streambeds (Feth and Hem, 1963). Water then percolates down through faults and fractures to recharge the two regional aquifers. Groundwater divides (figure 15) exist in both aquifers, directing flow either north to discharge at springs in the Grand Canyon or south to discharge at springs in the Transition Zone (Bills et al., 2007). Local aquifers (Rice, 2007) are likely recharged by direct precipitation onto the hydrologic unit.

Composed of the C aquifer and Limestone aquifer (Bills et al., 2007), the regional aquifer system is extensive throughout the Coconino Plateau, from the Grand Canyon to the Mogollon Rim. Within the study area, the C aquifer (also known as the Coconino aquifer) is the upper, unconfined unit (figure 12). Water-bearing formations include the Paleozoic Kaibab Formation, Coconino Sandstone, Schnebly Hill Formation, and upper to middle Supai Formation (Parker et al., 2004). The lower, Limestone aquifer (Parker et al., 2004; also known as the RM aquifer or Redwall-Muav aquifer) has an upper confining unit of the lower Supai Formation and Naco Formation. Saturated formations in the Limestone aquifer within the study area include the Redwall Limestone, Martin Formation, and discontinuous Tapeats Sandstone. Regionally, the Limestone aquifer also includes the Temple Butte Formation and Muav Limestone (Bills et al., 2007); however, these formations are not present within the study area.

Local aquifer systems have recently been identified as the source for many intermittent or ephemeral springs in the region (Rice, 2007). Tertiary volcanic rocks serve as one such aquifer unit, transporting locally recharged water through fractures to springs (Flora, 2004). Alluvial and basin fill deposits, commonly related to modern drainage systems, also act as aquifers. Proterozoic igneous and metamorphic basement rocks are classified as local aquifers in this study, as flow is generally shallow, restricted to faults and fractures, and disconnected (Parker et al., 2005).

Springs within the study area discharge from a variety of lithologies (Flora, 2004; Rice, 2007), however the majority issue from the sedimentary rocks of the regional aquifer system (Parker, 2005). Springs sourced in local aquifers tend to show a greater variability in discharge due to shorter residence times, while regionally sourced springs commonly have a larger, more constant discharge (Rice, 2007). Many recent studies of Transition Zone hydrogeology (Fry, 2006; Parker et al., 2005; Langenheim et al., 2005; Bills et al., 2000) highlight the control of fracture and fault networks on the location of spring discharge, as they often act as either conduits or barriers to groundwater flow. The relationship between hydrogeologic units and these networks are essential to understanding the location and occurrence of travertine-depositing springs.

In the western United States, helium isotope data have been used to correlate areas of low mantle velocity with travertine-depositing cool springs, suggesting a mantle-derived source for gases (He^3 and CO_2) discharging from these springs (Newell et al., 2005; Crossey et al., *in review*). Arizona's central Transition Zone has been identified as one such region. Crossey et al. (2006) proposed a model for the western United States in which deeply circulated (endogenic) fluids are transported upwards from the mantle via magmatism and seismicity to mix with shallower, regional aquifer (epigenic) waters. Epigenic waters are derived from surface recharge and are generally cool (<20 ºC), neutral to slightly alkaline, and have low CO_2 content. Endogenic waters are deeply-derived and have undergone deep crustal circulation and mixing, often have elevated temperatures (20-35 ºC), high salinity, radiogenic strontium isotopic signatures, low pH, and high CO_2 and mantle derived ^3He (Crossey et al, 2006). Springs discharging endogenic waters are often associated with travertine deposits and basement penetrating faults.

Mixing models for the Colorado Plateau suggest that up to 37% of dissolved inorganic carbon discharging from CO_2-rich springs is derived from deep sources and have been used to better define the source of CO_2 (*Crossey et al., in review*). The complex tectonic history of the region has resulted in the addition and storage of CO_2 in the lithospheric mantle, most recently and significantly a result of Laramide subduction of the Farallon slab (*Crossey et al., in review).* The partially molten (Duffield et al., 2000) and tectonically active mantle is currently degassing, releasing the stored CO_2 to be conveyed upwards and discharged at springs.

4.5.2 Geochemistry Methods

Available geochemical data for springs were collected from published literature (Crossey et al., *in review*; Rice, 2007; Wirt, 2005; Flora, 2004). Charge balances and calculations were conducted using PHREEQC (Parkhurst, 1995). Geochemical data from all regional springs are presented in table 7, including major ion data, stable isotopes, field parameters, and helium data, when available (table 7).

Helium isotope data are used to indicate a mantle source for gasses discharging with spring water. ^{3}He is sourced in the mantle, while ^{4}He is the dominant helium isotope present at Earth's surface (Newell et al., 2005). Values are reported as the corrected ratio of helium isotopes in the sample gasses collected from springs to helium isotopes in air (Rc/Ra). Values higher than 0.1 Rc/Ra are considered to have significant mantle contribution. Crustal brines exhibit very low ratios (0.02-0.05) due to the accumulation of 4He (alpha decay). Values higher than 0.1 Rc/Ra are considered to have significant mantle contribution if the sample is nonairlike.

DISCUSSION

4.6.1 Factors Controlling Transport to CO_2-rich Springs

The complex structures that control groundwater flow in the central Transition Zone result in the complex mixing of constituents from various sources. Within the study area, travertine-depositing Fossil Springs, Tonto Bridge Spring, Montezuma Well, and Verde Hot Spring and non-travertine-depositing Summer Spring all reveal a mantle signature based on noble gas analysis (Newell et al., 2005; figure 16). Detailed geologic comparisons of these five CO_2-rich springs indicate that they are (1) related to Tertiary normal faults with a possible Laramide or Proterozoic inheritance, (2) discharge from the confined Limestone aquifer, and (3) have a dominantly regional geochemical source (table 8). These criteria reveal that, although travertine is a good indicator of deeply sourced CO_2, it is not a necessary characteristic for all springs discharging deeply derived components, such as Summer Spring. Other springs in the region that fit the three criteria may also discharge deeply sourced CO_2, one such spring is non-travertine-depositing Page Springs. No helium data are available for Page Springs, but it discharges along the Diamond Rim fault, is sourced in the Limestone aquifer, and shows similar geochemistry to travertine-depositing springs in the region, suggesting that although it is not travertine-depositing it does discharge deeply sourced CO_2. The lack of travertine at some CO_2-rich springs in the region remains unexplained; however it is likely related to the specific lithologies of the aquifer units the CO_2 charged water travels through.

This region has a northeast-southwest trending fault geometry related to Tertiary extensional tectonics. The five largest discharge springs in the region follow this trend: Tonto Bridge Spring, Fossil Springs, Montezuma Well, Page Spring, and Summer

Spring. These springs all discharge along the Diamond Rim fault system, likely a good conduit for transport of endogenic gasses because of its complex history and deep-seated nature. At Fossil Springs, this fault juxtaposes the regional Limestone aquifer units against less permeable basalts, serving as a horizontal barrier that traps regional groundwater flow and forces it to discharge at the surface in the deeply dissected Fossil Canyon. The Diamond Rim fault system also acts as a vertical conduit, transporting deeply circulated waters and CO_2 and ^3He to the springs discharging at topographic lows.

All CO_2 rich springs in the central Transition Zone are sourced in the regional Limestone aquifer, with the possible exception of Verde Hot Springs, which has an unknown source. The regional Limestone aquifer is hydraulically confined and linked to other regional endogenic springs discharging in the Grand Canyon (Blue Springs, Havasu Springs). The upper confining unit (upper Naco Formation and lower Supai Formation) limits the upward movement of deeply-derived gases into the overlying C aquifer in the central Transition zone.

Geochemistry indicates a mixed endogenic and meteoric source for water discharging from springs in the study area. Helium isotopes indicate that discharged gasses are a result of deeply sourced fluids and stable ^2H and ^{18}O isotopes indicate recharge from precipitation on the Colorado Plateau (figure 16). The majority of the constituents discharging from these springs are likely a result of the latter process; however, a small but significant component is related to deeply derived fluids.

4.6.2 Sources of CO_2 and Springs

Zones of recent seismicity and volcanic activity have long been identified as locations of high CO_2 discharge (Barnes et al., 1978). There are three possible sources for excess CO_2; organic material, metamorphism of carbonate rocks, and mantle degassing. In areas that have not experienced recent significant metamorphism and don't have organic-rich rocks, the only likely source for excess CO_2 is degassing of the mantle.

Through spatial patterns, helium isotopes, and water chemistry data, springs of the western United States have been shown to discharge endogenic CO_2 (Newell et al., 2005, Crossey et al., 2006). These springs are commonly associated with travertine deposits related to the high volumes of CO_2 discharged. Globally, the set of travertine-depositing springs with an endogenic source is expanding. The largest travertine complex in southwestern China is formed by springs discharging water with endogenic CO_2 at very high partial pressures (Liu et al, 2003). Quaternary travertine deposits related to thermal and cold springs in Italy are associated with major regional structures (Minissale et al., 2002). Their source has been identified as a complex mixing of meteoric waters and magmatic, metamorphic, and geothermal fluids (Minissale, 2004).

Using hydrogeologic and geochemical data, we have shown that a set of six springs in Arizona's central Transition Zone also discharge deeply-sourced CO_2. These springs can be used to test and expand the model proposed by Crossey et al. (2006) for the Grand Canyon region as applied to Arizona's central Transition Zone. In the Grand Canyon, CO_2-rich springs are located along basement-penetrating faults and associated with large volumes of travertine. In the Transition Zone, CO_2-rich springs are also located along basement penetrating faults (the Diamond Rim and Verde faults); however, two of the springs are not travertine-depositing. In the Grand Canyon region, deeply sourced fluids are conveyed upwards via both recent magmatism and active seismicity. Magmatism and seismicity in the Transition Zone are older and inactive as compared to the Grand Canyon, posing a potential problem when applying this process to the Transition Zone. Cross sections constructed for travertine and non-travertine depositing springs in the Transition Zone (figure 12) show that waters recharge on the Colorado Plateau. It is possible that the Diamond Rim fault may not be serving to transport deeply sourced CO_2 directly to the springs in the Transition Zone, but rather that faults and magmatism in the area of the San Francisco Volcanic Field (Duffield et al., 2000) serve as the conduit for deeply sourced constituents, transporting them upward to the regional Limestone aquifer where they are mixed with meteoric waters and transported down gradient. In this scenario, the Diamond Rim fault is acting as a trap, rather than a conduit, forcing a mixture of endogenic and meteoric waters to discharge at land surface.

4.6.3 Model for Northern and Central Arizona Springs

CO_2-rich springs in Arizona's central Transition Zone are related to deep seated regional structures (Diamond Rim and Verde faults). Winter precipitation on the Colorado Plateau percolates down through faults and fractures in volcanic rocks and C aquifer sandstones to the regional Limestone aquifer. CO_2 and He^3 derived from mantle degassing related to Laramide subduction (*Crossey et al., in review*) is transported upwards along deep seated fault networks and trapped in the Limestone aquifer by confining units. This process may be occurring either very near the discharge point for the springs, along the Diamond Rim fault, or further upgradient in the San Francisco Volcanic Field. Meteoric and endogenic sources are mixed as they travel down gradient, either north from the San Francisco Peaks to springs discharging in the Grand Canyon (Havasu Springs, Blue Springs) or south from the Mogollon Rim to springs discharging in the Transition Zone (Fossil Springs, Montezuma Well, Tonto Bridge Spring, Verde Hot Spring, Page Spring, and Summer Spring) (figure 12). If waters have travelled through $CaCO_3$ rich aquifer units (limestone), such as at Fossil Springs, Montezuma Well, and Tonto Bridge Spring, the high concentration of CO_2 in the water allow for increased rates of dissolution. When water discharges at the springs, the CO_2 partial pressure is higher than that of the atmosphere and as degassing occurs downstream, travertine is deposited (Crossey et al., 2006). However, travertine is not a necessary result of the transport of endogenic CO_2 to springs and can only be used as an indicator.

4.7 SUMMARY

A new set of springs in the Transition Zone of central Arizona have been identified as having a small but significant endogenic source. These springs can be identified by a number of factors, including: massive travertine deposits, slightly elevated temperatures, high ionic concentrations, and a mantle helium signature. They almost always discharge from a confined, regional aquifer system along deep seated extensional faults, which serve as a conduit for CO_2 transport. The inferred extension of the Diamond Rim fault and delineation of the Diamond Rim monocline has allowed for a better understanding of the interaction of hydrologic and structural processes.

The complex interaction of regional, confined aquifer units, deep-seated, regional structures, and recent magmatism control the location and occurrence of endogenic CO_2 discharges in springs. Travertine deposits associated with these springs provide a record of the paleohydrology of the region. Rates of travertine-deposition can provide insight into the temporal relationship between aquifer processes and neotectonics. Our model for the CO_2-rich springs of northern and central Arizona extends the model of Crossey et al. (2006) from the Grand Canyon to the central Transition Zone.

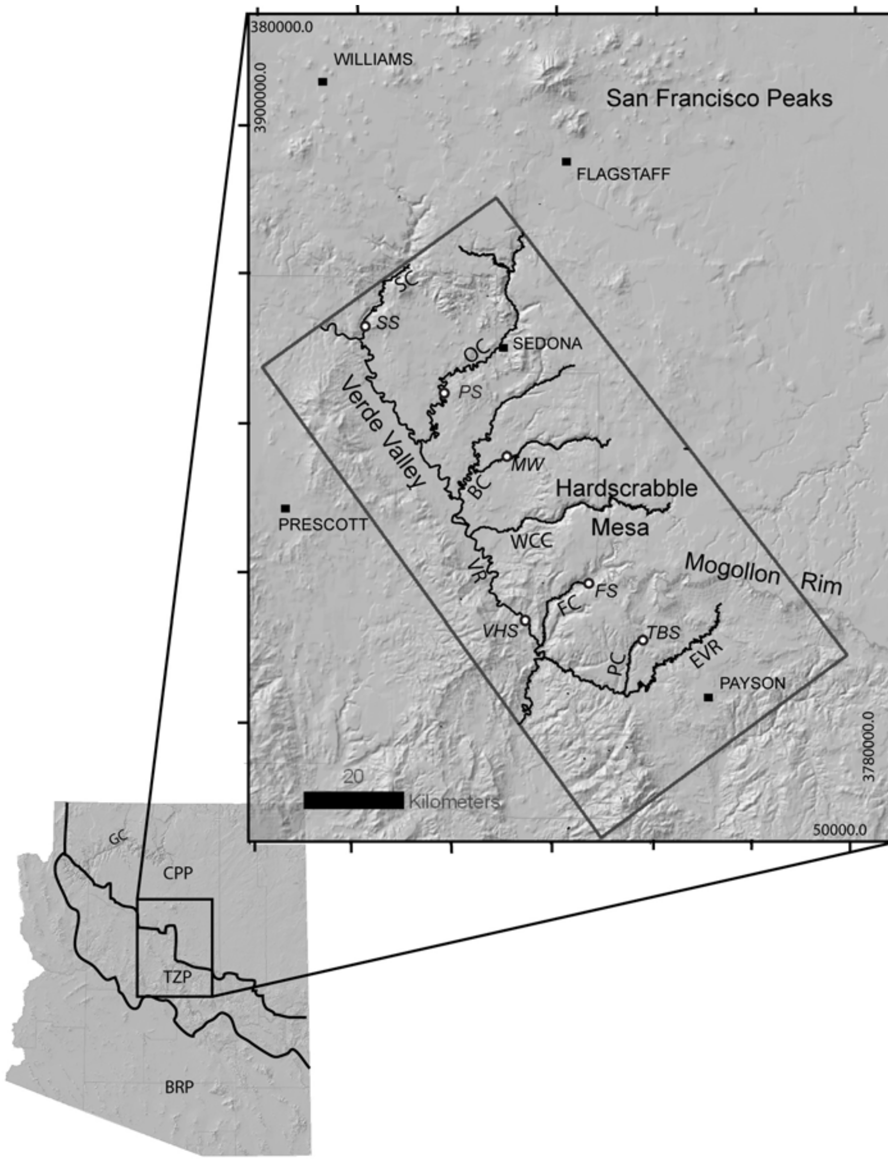


Figure 11. Location of the study area in the Transition Zone of central Arizona, outlined by the black box in the larger map, which also shows CO_2-rich springs (circles) that are the focus of this study, cities (squares), and major geomorphic features. Springs: Summer Spring (SS), Page Springs (PS), Montezuma Well (MW), Fossil Springs (FS), Tonto Bridge Spring (TBS), and Verde Hot Spring (VHS). Streams draining the Mogollon Rim are major tributaries to the Verde River (VR): Sycamore Creek (SC), Oak Creek (OC), Beaver Creek (BC), West Clear Creek (WCC), Fossil Creek (FC), Pine Creek (PC), and East Verde River (EVR). The map of Arizona shows the Grand Canyon (GC) and three major provinces in Arizona: the Colorado Plateau (CPP), Transition Zone (TZP), and Basin and Range (BRP). The Mogollon Rim is the topographic escarpment forms the boundary between the Colorado Plateau and Transition Zone.

Figure 12. Cross-section views along the hydrologic flow-paths to two regional springs, travertine-depositing Fossil Springs (B-B') and non-travertine-depositing Page Springs (A-A') in Arizona's central Transistion Zone. Blue arrows indicate hydrologic processes, abbreviations and geologic units are explained in figure 13B. Location of cross-sections are shown in figure 13A.

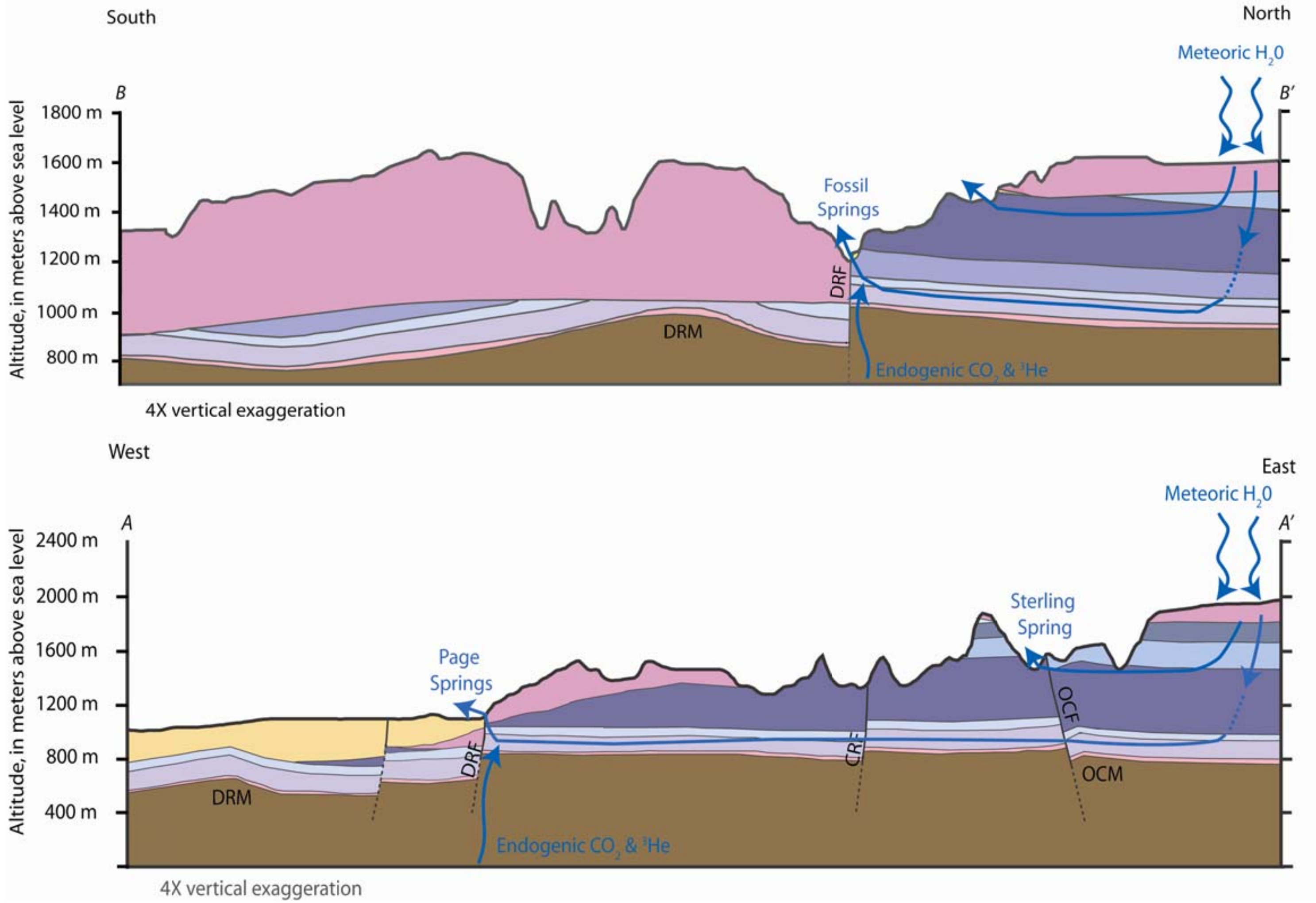
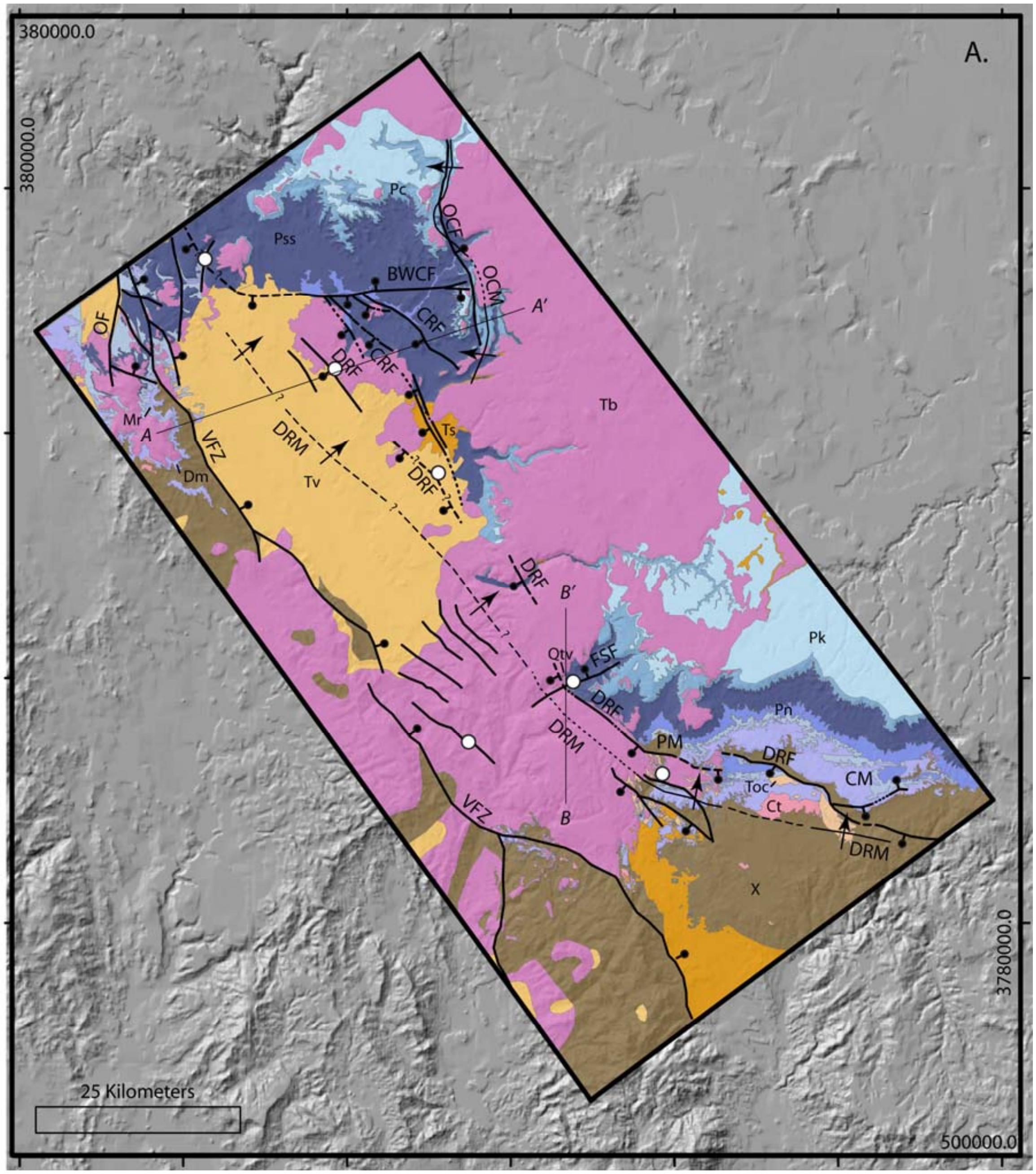


Figure 13. Geologic map (A) and explanation of map (B) of the study area in the central Transition Zone, Arizona. Major structures are shown. A more detailed description of lithologic units is in table 6.



B.

Explanation of Map Units

Qtr	Travertine (Holocene, Pleistocene and possibly Pliocene)
Tv	Verde Formation (Tertiary- Miocene to Pliocene)
Tb	Tertiary Basalts and Volcanic Rocks (Miocene)
Ts	Tertiary Sedimentary Units- undifferentiated (Eocene to Miocene)
Toc	Tertiary Older Conglomerate (Mogollon Rim formation) (Eocene)
Pk	Kaibab Formation (Permian)
Pt	Toroweap Formation (Lower Permian)
Pc	Coconino Sandstone (Lower Permian)
Pss	Supai and Schnebly Hill Formations (Pennsylvanian to Permian)
Pn	Naco Formation (Pennysylvanian)
Mr	Redwall Limestone (Mississippian)
Dm	Martin Formation (Devonian)
Ct	Tapeats Sandstone (Cambrian)
X	Crystalline Rocks(Middle- Lower Proterozoic)

CONTACT

NORMAL FAULT- bar and ball on downthrown side

NORMAL FAULT- approximate location

?- -- ? NORMAL FAULT- location inferred

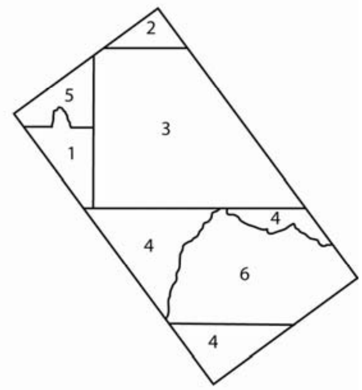
NORMAL FAULT- concealed

MONOCLINE- Showing trace of axis, dotted where concealed, dashed where inferred.

SPRINGS

Sources of Geologic Data

1. Anderson and Creasey, 1958
2. Ulrich et al., 1984
3. Weir et al., 1989
4. Richard et al., 2000
5. Twenter and Metzger, 1963
6. Gaeaorama, 2006



Explanation of Mapped Structures

DRF	Diamond Rim Fault Zone	This study; Gaeaorama, 2006; Langenheim et al., 2005; Weir et al., 1989
VFZ	Verde Fault Zone	Richard et al., 2000
OCF	Oak Creek Fault	Richard et al, 2000
BWCF	Bear Wallow Canyon Fault	Langenheim et al., 2005
CRF	Cathedral Rock Fault	This study; Weir et al., 1989
FSF	Fossil Springs Fault	Gaeaorama, 2006
OF	Orchard Fault	Langenheim et al., 2005
DRM	Diamond Rim Monocline	This study, Reynolds et al., 2001
OCM	Oak Creek Monocline	This study
PM	Pine Mountain Paleohigh	Gaeaorama, 2006; Reynolds et al., 2001
CM	Christopher Mountain Paleohigh	Gaeaorama, 2006; Reynolds et al., 2001

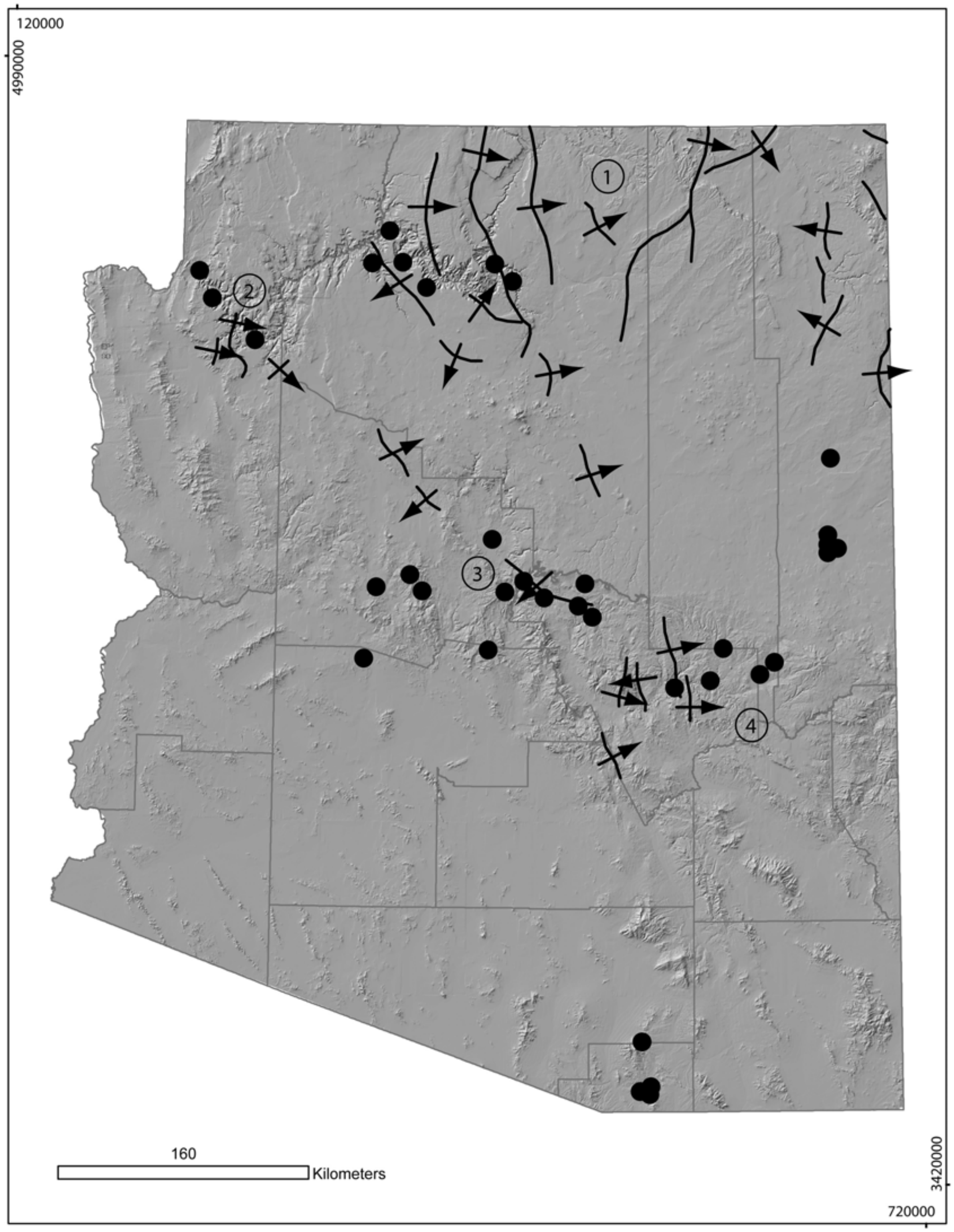


Figure 14. Spatial relationship between regional Laramide monoclines (lines indicate surface trace, arrows indicate dip direction) and spring deposited travertine (dots). 1: Southwestern Colorado Plateau monoclines and Grand Canyon travertine-depositing springs. 2: Northwestern Transition Zone, Hualapai Plateau monoclines and travertine. 3. Central Transition Zone travertine-depositing springs (Montezuma Well, Fossil Springs, Tonto Bridge Spring, Verde Hot Springs) and the Diamond Rim Monocline. 4. Southeastern Transition Zone, Salt River Canyon monoclines and travertine.

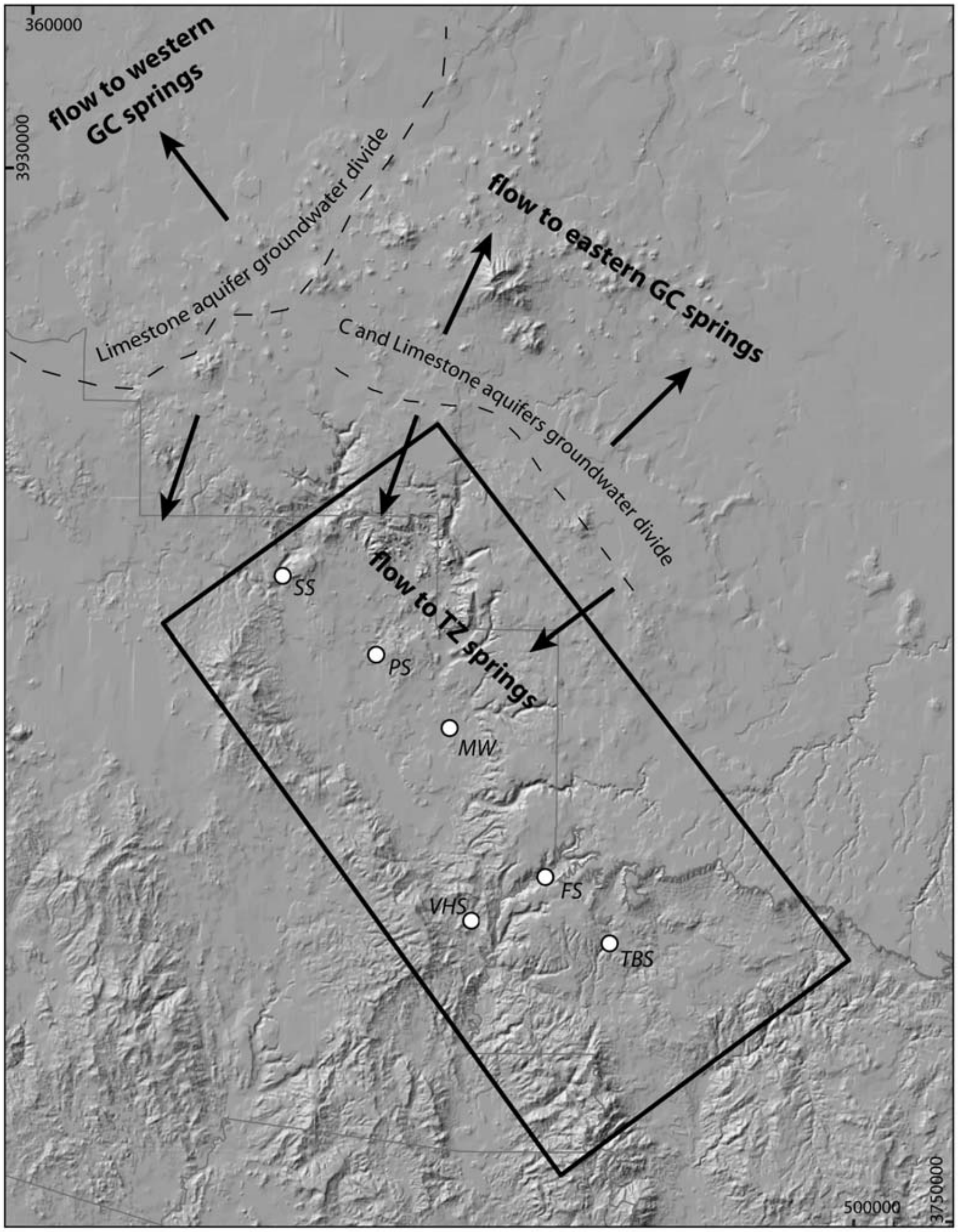


Figure 15. Groundwater divides and CO_2-rich springs in the central Transition Zone study area. Groundwater divides for both regional aquifer systems are labeled on the map and groundwater flow direction is indicated by arrows, either north to Grand Canyon springs or south to Transition Zone springs (from Bills et al., 2007). Springs: Summer Spring (SS), Page Springs (PS), Montezuma Well (MW), Fossil Springs (FS), Tonto Bridge Spring (TBS), and Verde Hot Spring (VHS).

Table 1: Description of lithologic units in the central Transistion Zone study area.

	Lithologic Unit	Age	Thickness	Description	Hydrogeologic Properties	References
Tv	Verde Formation	Miocene to Pliocene	0 - 950 m	Intertonguing limestone and clastic facies deposited in lacustrine and fluvial settings. Present only in the western part of the study area.	Local aquifer	Nations et al., 1981
Tb	Tertiary Basalts and Volcanics	Miocene	15 - 300 m	Various ages and lithologies, undifferentiated for the purposes of this study. Basalt is composed of aggregate flows, in many locations the thickness is not not known.	Local aquifer	Leighty, 1998
Ts	Tertiary Sedimentary Units	Eocene-Miocene	0 - 120 m	Ts used where undifferentiated, composed of the Mogollon Rim formation (Toc, see below) and Beavertail Butte formation (Loseke, 2004). Generally, the Beavertail Butte formation is present below the rim and is a conglomerate with clasts of Pk and Pc, indicating a southerly transport. Often unconformably overlain by Tb.	May contain local aquifer units.	Potochnick, 1989 and Loseke, 2004
Toc	Tertiary Older Conglomerate	Eocene (37.5- 37.6 ± 0.8 Ma)	0 - 120 m	Informally named the Mogollon Rim formation, moderately consolidated conglomerate and sandstone. Exists on top of Mogollon Rim, clasts are largely Proterozoic rocks and locally Paleozoic. Indicates northwesterly transport. Overlain by Tb.	May contain local aquifer units.	Potochnick, 1989
Pk	Kaibab Formation	Permian	about 190 m	Limestone, dolomite, and basal sandstone and chert. Shows karst development.	C aquifer.	Blakey, 1990
Pt	Toroweap Formation	Early Permian	0 - 120 m	Only in western study area, does not extend east past Fossil Creek Canyon. Very fine to fine- grained sandstone, medium- scale sets of crossbeds.	C aquifer.	Blakey, 1990

Table 6. Continued.

	Lithologic Unit	Age	Thickness	Description	Hydrogeologic Properties	References
Pc	Coconino Sandstone	Early Permian	240 - 300 m	Very fine to fine-grained sandstone of eolian orgin. Characterized by massive cross bedding and steep cliffs.	C aquifer.	Blakey, 1990
Pss	Supai and Schnebly Hill Formations	Pennsylvanian-Permian	420 - 580 m	Undifferentiated in the study area, Contains the overlying Supai Formation and the underlying Schnebly Hill Formation. A red bed sequence composed of highly oxidized fine-grained sediments: limestone, siltstone, shale, and sandstone.	Lower third is composed of silty beds that act as a confining unit. Upper two thirds is C aquifer.	Blakey, 1990
Pn	Naco Formation	Pennsylvanian	90 - 140 m	Much variation in facies: major limestone and minor dolomite, shale, siltstone, sandstone, and conglomerate. Very fossilferous and cherty.	Dominantly unsaturated, faults and fractures act as conduits between the C and Limestone aquifers.	Blakey, 1990
Mr	Redwall Limestone	Mississippian	0 - 140 m	Massive limstone unit. Shows paleo and active kast development. Locally fossiliferous and cherty.	Limestone aquifer, shows secondary karst porosity.	Darton, 1910
Dm	Martin Formation	Devonian	0 - 140 m	Much variation in facies: fine to medium grained dolomite and limestone, cherty, fossiliferous, minor siltstone and sandstone. Discontinuous where laps against paleohighs.	Limestone aquifer, may have secondary porosity developed in karst.	Teichert, 1965
Ct	Tapeats Sandstone	Cambrian	0 - 30 m	Very coarse grained sandstone to conglomerate, discontinuous where laps against paleohighs.	Lowermost unit of Limestone aquifer.	Hereford, 1977 Middleton, 1989
X	Crystalline Basement	Middle- Early Proterozoic	undetermined	Various metamorphic and igeneous units.	Groundwater exists in fractures and faults, very little primary porosity.	Karlstrom, 1991

Table 7. Summary of available water chemistry data for springs (SP), lakes (LK), and groundwater (GW) in Arizona's central Transition Zone, including major ions, trace elements, stable isotopes, and field parameters.

Spring	type	F ppm	Cl ppm	NO2 ppm	Br ppm	NO3 ppm
Fossil Springs	SP	0.2	11.1	0.4	0.2	0.9
Tonto Bridge Spring	SP	0.181	6.30	----	0.062	----
Pieper Hatchery Spring	SP	0.100	1.90	----	----	<0.08
Hackberry Spring	SP	0.200	13.00	----	----	<0.08
Clover Spring	SP	0.100	1.50	----	----	<0.08
Pivot Rock Spring	SP	0.057	1.86	<0.025	0.010	0.500
Sterling Spring	SP	0.100	2.50	----	----	0.800
Summer Spring	SP	0.068	5.00	----	0.053	----
Grapevine Spring	SP	0.58	28.9	<0.025	0.28	0.40
Montezuma Well	SP	0.155	37	----	0.067	----
Page Spring	SP	0.1	6.74	----	----	0.69
Verde Hot Spring	SP	1.23	482.2	----	2.304	----
Del Rio Spring	SP	0	19.0	----	----	----
Granite Sp lower	SP	0.001	21	----	----	----
Lee Spring	SP		24	----	----	----
LV-1 Spring	SP	0.001	9.0	----	----	----
Mint Springs	SP	0.001	7	----	----	----
Muldoon Canyon Spring	SP		0.001	----	----	----
Pine Spring	SP		11	----	----	----
Seven Springs AZ	SP	0.195	12.2	----	0.147	----
Springerville Lyman Lk	LK	2.635	66.5	----	0.699	----
Springerville Salado Sp	SP			----	----	----
Springerville-west	SP	0.368	5.2	----	0.058	----
Stillman Lake 1	LK	0	24	----	----	----
A-20-06 02BDB- coconino	GW	<0.1	1.6	----	----	----
A-20-08 20CCA- coconino	GW	<0.1	2.0	----	----	----
A-20-08 30CDA- coconino	GW	0.1	2.6	----	----	----
A-20-07 28BCC- coconino	GW	0.1	5.3	----	----	----

Table 7. Continued.

Spring	PO4 ppm	SO4 ppm	HCO3 ppm	Ca ppm	K ppm	Mg ppm	Na ppm
Fossil Springs	0.5	25.85	466.8	91.3	1.5	36.5	12.6
Tonto Bridge Spring	----	2.80	394	71.7	3.3	28.5	9.8
Pieper Hatchery Spring	----	<1.6	122.03	26.6	0.87	6.84	1.37
Hackberry Spring	----	23.00	224.54	36.7	3.2	13.8	20.7
Clover Spring	----	1.70	244.07	35.9	0.3	20	2.17
Pivot Rock Spring	0.02	1.58	----	----	----	----	----
Sterling Spring	----	2.00	222.1	41.8	0.52	14.3	2.69
Summer Spring	----	3.80	330	72.2	1.2	27.5	5.8
Grapevine Spring	<0.05	33.50	----	----	----	----	----
Montezuma Well	----	9.00	576	115	5.9	38.8	70.5
Page Spring	----	2.85	213.56	38.12	0.6	18.08	9.1
Verde Hot Spring	----	482.2	1513	106	34.5	44.3	1150
Del Rio Spring	----	12.0	136	30.0	2.6	15.0	17.0
Granite Sp lower	----	13	226	48.0	2.9	22.0	20
Lee Spring	----	20.2	442	71	0.9	47	20
LV-1 Spring	----	11.0	354	88.0	1.7	19.0	18.0
Mint Springs	----	5.1	122	21.0	0.5	5.0	10
Muldoon Canyon Spring	----	23	330	55	2.6	25	57
Pine Spring	----	17.7	639	72	0	80	8
Seven Springs AZ	----	----	384	54.6	4	32.6	23.7
Springerville Lyman Lk	----	113.2	703	101.9	20.0	77.0	97.0
Springerville Salado Sp	----	----	----	----	----	----	----
Springerville-west	----	15.0	199	18.2	5.6	12.1	41.1
Stillman Lake 1	----	----	246	45	3	20	18
A-20-06 02BDB- coconino	----	1.6	127	20.0	1.4	12.0	4.8
A-20-08 20CCA- coconino	----	1.5	----	53.0	0.6	36.0	3.7
A-20-08 30CDA- coconino	----	1.3	----	70.0	0.9	49.0	3.5
A-20-07 28BCC- coconino	----	1.8	240	44.0	0.5	21.0	3.3

Table 7. Continued.

Spring	Li ug/l	Sr ug/l	Si ppm	PCO2	δD (‰) permil	O18 permil	d13C (‰)
Fossil Springs	<MDL	0.2	5.5	-1.18	-82.5	-11.6	-11.7
Tonto Bridge Spring	3.9	134		-1.36	-74.5	-112.0	-9.1
Pieper Hatchery Spring	1.5	31	3.2	-2.39	-77.0	-11.2	-9.4
Hackberry Spring	9.1	393	28.6	-2.04	-66.0	-9.0	-7.6
Clover Spring	<MDL	70	6	-3.23	-72.0	-10.5	-9.0
Pivot Rock Spring	----	----	----	----	-78.0	-11.5	----
Sterling Spring	<MDL	80	5.2	-2.04	-83.0	-11.9	-8.6
Summer Spring	15	107	----	-1.51	-93.0	-12.4	----
Grapevine Spring	----	----	----	----	-73.0	-9.8	----
Montezuma Well	----	----	----	-0.98	-89.6	-12	-7.6
Page Spring	----	----	----	-2.31	----	----	19.7
Verde Hot Spring	----	----	----	0.13	-94.1	-12.0	-4.1
Del Rio Spring	----	----	----	-3.21	-71	-9.9	-11.5
Granite Sp lower	----	----	----	-1.99	-70	-9.7	-10.4
Lee Spring	----	----	----	-2.34	-74	-10.2	-6.4
LV-1 Spring	----	----	----	-1.70	-77.0	-10.8	-12.2
Mint Springs	12	150	----	-1.67	-60.0	-7.1	-8.2
Muldoon Canyon Spring	----	----	----	-1.34	-75.0	-10.3	-7
Pine Spring	----	----	----	-1.52	-78.5	-11.0	-11
Seven Springs AZ	----	----	----	-1.76	-52.5	-7.9	-20.24
Springerville Lyman Lk	----	----	----	-1.22	-45.8	-5.1	----
Springerville Salado Sp	----	----	----	----	----	----	----
Springerville-west	----	----	----	-2.39	-69.3	-9.8	-16.96
Stillman Lake 1	----	----	----	-2.68	-66.0	-8.7	-7.6
A-20-06 02BDB- coconino	----	----	19.0	-3.07	-83.5	-11.95	----
A-20-08 20CCA- coconino	----	----	9.4	----	-87.5	-12.18	----
A-20-08 30CDA- coconino	----	----	12.0	----	-85.6	-11.77	----
A-20-07 28BCC- coconino	0	110	14.0	-1.65	-82.8	-11.91	----

Table 7. Continued.

Spring	Rc/Ra	Disch. l/sec	Temp °C	pH	Cond. µs/cm	info
Fossil Springs	0.31	1246.0	21.6	6.8	753	This study
Tonto Bridge Spring	0.13	6.3	19.5	6.9	629	Crossey et al., in review
Pieper Hatchery Spring	----	12.62	10.7	7.4	226	Flora, 2004
Hackberry Spring	----	0.07	8.2	7.3	443	Flora, 2004
Clover Spring	----	3.1	8.2	8.5	226	Flora, 2004
Pivot Rock Spring	----	0.14	14.7	6.8	399	Flora, 2004
Sterling Spring	----	18.92	9.8	7.3	369	Flora, 2004
Summer Spring	0.34	160	19.3	6.98	541	Crossey et al., in review
Grapevine Spring	----	0.02	12.1	7.7	686	Flora, 2004
Montezuma Well	1.16	40	23.2	6.7	1004	Crossey et al., in review
Page Spring	7.6	326	19.7	7.6	326	This study
Verde Hot Spring	0.6	0.76	38.6	6.1	5010	Crossey et al., in review
Del Rio Spring	----	50.6	20	8.3	330	Wirt et al., 2005
Granite Sp lower	----	----	18.9	7.3	458	Wirt et al., 2005
Lee Spring	----	----	16	7.9	751	Wirt et al., 2005
LV-1 Spring	----	----	20.5	7.2	601	Wirt et al., 2005
Mint Springs	----	----	15	6.7	179	Wirt et al., 2005
Muldoon Canyon Spring	----	----	18.2	6.8	704	Wirt et al., 2005
Pine Spring	----	----	8	7.2	959	Wirt et al., 2005
Seven Springs AZ	----	----	13.4	7.26	656	Crossey et al., in review
Springerville Lyman Lk	----	----	9.1	6.95	1633	Crossey et al., in review
Springerville Salado Sp	0.58	----	----	----	----	Crossey et al., in review
Springerville-west	----	----	13.8	7.62	397	Crossey et al., in review
Stillman Lake 1	----	----	16.1	8	474	Wirt et al., 2005
A-20-06 02BDB- coconino	----	----	12.8	8.1	199	Blasch et al., 2006
A-20-08 20CCA- coconino	----	----	11	7.3	488	Blasch et al., 2006
A-20-08 30CDA- coconino	----	----	10.9	7.2	635	Blasch et al., 2006
A-20-07 28BCC- coconino	----	----	10.6	6.9	379	Blasch et al., 2006

Table 8. Matrix of characteristics associated with a representative sampling of springs in Arizona's central Transition Zone., 1 indicates that feature is associated with the springs, 0 indicates that it is no, ND indicates that no data are available. Springs with a mantle gas signature (Rc/Ra>0.1) are also associated with travertine deposits, normal faults, Laramide monoclines, and discharge from the regional Limestone aquifer.

	Associated with:								
Spring	travertine deposits	normal faulting	reverse faulting	Laramide monocline	Confined aquifer	Limestone aquifer	C Aquifer	local aquifer	Rc/Ra >0.1
Clover Spring	0	0	0	0	0	0	1	1	ND
Fossil Springs	1	1	1	1	1	1	0	1	1
Grapevine Spring	0	0	0	0	0	0	0	1	ND
Hackberry Spring	0	1	0	0	0	0	0	1	ND
Montezuma Well	1	1	0	1	1	1	1	1	1
Page Springs	0	1	0	1	1	1	0	1	1
Pieper Hatchery Spring	0	0	0	1	0	0	1	0	ND
Pivot Rock Spring	0	0	0	0	0	0	1	0	ND
Sterling Spring	0	0	0	0	0	0	1	1	ND
Summer Spring	0	1	0	0	1	1	0	1	1
Tonto Springs	1	1	0	0	1	1	0	1	1
Verde Hot Springs	1	1	0	0	ND	ND	ND	ND	1

CHAPTER 5: CONCLUSIONS

5.1 Summary

Surface and subsurface geologic data, geochemical and discharge data, and regional springs data were used to investigate the processes controlling hydrogeologic transport to Fossil Springs. Two 3-D framework models (A and B) were created to represent the end member scenarios of location and presence of hydrogeologic units in the subsurface of the western Mogollon Rim area. Both models show a juxtaposition of Limestone aquifer units against less permeable basalts at the intersection of the Diamond Rim and Fossil Springs faults, forcing water to the surface at Fossil Springs. Model B indicates the potential presence of a monoclinal structure trending along the Diamond Rim fault (as proposed by Reynolds et al., 2001) (figure 8), suggesting that it is a more extensive feature than previously recognized and likely extends laterally in the subsurface further than its previously mapped extent.

Discharge and geochemical data indicate a dominantly regional source for the water discharging from Fossil Springs. Recharge occurs on the Colorado Plateau, on the San Francisco Peaks and along the Mogollon Rim, and percolates down through the overlying rocks to the Limestone aquifer. Major ion chemistry and stable isotope data are similar to other regional springs; however, elevated ^{3}He isotopes in gas samples indicate an endogenic source. Within Arizona's central Transition Zone, other springs have been identified as having an endogenic source; Tonto Bridge Spring, Montezuma Well, Page Spring, Verde Hot Spring, and Summer Spring. Other than elevated ^{3}He, most or all of these springs are travertine-depositing, related to major extensional fault systems

(Diamond Rim and Verde faults), have a dominantly regional source, and discharge from the regional Limestone aquifer.

5.2 Conclusions

The primary product of this thesis work is an interactive 3-D hydrogeologic framework model for the western Mogollon Rim that is now available for educational purposes and water management decisions (Appendix A). This model has been presented to local stakeholders and will hopefully be used to direct land and water management decisions for the benefit of Fossil Springs.

The secondary contribution is the identification of Fossil Springs and other springs in the region as having a small but significant endogenic source, including Montezuma Well, Tonto Bridge Spring, Verde Hot Spring, Page Spring, and Summer Spring. These springs can be identified by a number of factors, including: massive travertine deposits, slightly elevated temperatures, high ionic concentrations, and a mantle helium signature. They almost always discharge from a confined, regional aquifer system along deep seated extensional faults, which serve as a conduit for CO_2 transport. The inferred extension of the Diamond Rim fault and delineation of the Diamond Rim monocline using existing maps and geophysical data has allowed for a better understanding of the interaction of hydrologic and structural processes.

A more detailed process for hydrologic and geochemical transport to these springs has been outlined. Winter precipitation on the Colorado Plateau percolates down through faults and fractures in volcanic rocks and C-aquifer sandstones to the regional Limestone aquifer. CO_2 and He derived from mantle degassing during recent volcanism is transported upwards along deep seated fault networks and trapped in the Limestone aquifer by the lower confining unit. Meteoric and endogenic sources are mixed as they travel down gradient to springs discharging in the Transition Zone.

5.3 Future Work

Through this study, greater insight has been gained into groundwater processes in the western Mogollon Rim and larger central Transition Zone, however there is still much to learn about this complex area. 3-D modeling of the entire region would better explain the relationship between structure and aquifer units. Geophysical mapping and detailed structural analysis should be used to constrain the extent of the Diamond Rim Fault under the volcanic rocks and sediments in the Verde Valley section of the Verde Basin. Continued monitoring of discharge and spring geochemistry for all springs in the region will make it possible to understand the changes in this dynamic system and the impacts that groundwater exploitation cause as population expands. Travertine deposits associated with Fossil Springs and other springs are a record of the paleohydrologic conditions of the region. If rates of travertine-deposition are determined, they can provide insight into the temporal relationship between aquifer processes and neotectonics.

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APPENDIX C

DHFM Additional Methods

APPENDIX C1. Creating 3-D Fault Files

This method can be used to convert two-dimensional geologic maps in ArcGIS v.9.2 into three-dimensional data files for use in EarthVision modeling software. An individual file should be created for each fault using Steps 2 and 3. For use in Windows.

1. **Create a 3-D grid of land surface:**
    A. Obtain a Digital Elevation Model (.dem) and import to an ArcGIS map file (.mxd).
    B. Create surface contours using the 3D Analyst utility (3D Analyst> Surface Analysis> Contour). For more details see the ArcGIS Desktop Help.
    C. Copy and paste all files associated with “contour”.shp into the EarthVision working directory.
    D. Open DOS command prompt and navigate to the working directory. Use the following series of commands to create a 3-D data file (.dat):
        ev_shape2ev –d “contour.dat” –s “contour”.shp –l “contour”.dbf –z “name of field with elevation data in .dbf file”
    E. Open EarthVision and navigate to the working directory. Open Modeling> 2Dminimum tension gridding. Scattered data is “contour”.dat.
    Uncheck extrapolate outside data area and leave everything else as default.
    Calculate: Normal minimum tension. The output file will be “contour”.2grd.

2. **Create a 3-D data file for a fault:**
    A. From a georeferenced geologic map, digitize the surface trace of each fault as a polyline in ArcGIS (see the ArcGIS Desktop help for more detail).
    B. Copy and paste all files (.ann, .dbf, .prj, .sbn, .sbx, .shp) associated with the fault file into the EarthVision working directory.
    C. Open the DOS command prompt and navigate to the working directory. Use the following series of commands to create a 2-D annotation file (.ann):
        Ev_shape2ev –a “fault”.ann –s “faults”.shp
    D. Calculate the X values for each data point by back interpolating to the surface grid. Open EarthVision and navigate to the working directory. Open Utilities> Formula Processor. Enter the following and Calculate the formula:
        “fault”.dat <X>= “fault”.ann<X>
        “fault”.dat <Y>= “fault”.ann<Y>
        “fault”.dat <Z>=bakint(“contour”.2grd, “fault”.ann<X>, “fault”.ann<Y>)

    E. Check the file header by going to File> List files and selecting “tops”.dat and clicking on Header. Check that each field is in the appropriate column and has the correct units.

3. **Project a fault into the subsurface:**
    A. Using field measurements or published data, determine the direction (dipazm) and degree of dip (dip) from horizontal for the fault plane.
    B. Open the “fault”.dat file in excel and add the dip and dipazm values in columns 4 and 5, respectively, for every data point. Save changes and close the file. Manually edit the header for each file (File>list files>Header), adding a column for dip and dipazm with correct positions and unknown units.
    C. Use the projection utility to project the faults into the subsurface. Go to Utilities>DGI gifts to open a new menu, then Utilities> Dip/Dip-Azimuth Surface Creation. The scattered data is “fault”.dat. Specify an output file name. Determining values for each of the strike and dip field is best done by trial and error.
    D. The projected file is ready to be entered into the EarthVision Workflow Manager.

APPENDIX C2. Creating 3-D Horizon Files

This method can be used to convert two-dimensional geologic maps in ArcGIS v.9.2 into three-dimensional data files for use in EarthVision modeling software. An individual file should be created for each geologic horizon using Step 2. For use in Windows.

4. **Create a 3-D grid of land surface:**
    - A. Obtain a Digital Elevation Model (.dem) and import to an ArcGIS map file (.mxd).
    - B. Create surface contours using the 3D Analyst utility (3D Analyst> Surface Analysis> Contour). For more details see the ArcGIS Desktop Help.
    - C. Copy and paste all files associated with “contour”.shp into the EarthVision working directory.
    - D. Open DOS command prompt and navigate to the working directory. Use the following series of commands to create a 3-D data file (.dat):

      ev_shape2ev –d “contour.dat” –s “contour”.shp –l “contour”.dbf –z “name of field with elevation data in .dbf file”
    - E. Open EarthVision and navigate to the working directory. Open Modeling> 2Dminimum tension gridding. Scattered data is “contour”.dat. Uncheck extrapolate outside data area and leave everything else as default. Calculate: Normal minimum tension The output file will be “contour”.2grd.

5. **Create a 3-D data file for a geologic horizon:**
    - A. From a georeferenced geologic map, digitize the upper contact (tops) of a single geologic unit as a polyline in ArcGIS (see the ArcGIS Desktop help for more detail).
    - B. Copy and paste all files (.ann, .dbf, .prj, .sbn, .sbx, .shp) associated with the tops file into the EarthVision working directory.
    - C. Open the DOS command prompt and navigate to the working directory. Use the following series of commands to create a 2-D annotation file (.ann):

      Ev_shape2ev –a “tops”.ann –s “tops”.shp
    - D. Calculate the X values for each data point by back interpolating to the surface grid. Open EarthVision and navigate to the working directory. Open Utilities> Formula Processor. Enter the following and Calculate the formula:

      “tops”.dat <X>= “tops”.ann<X>
      “tops”.dat <Y>= “tops”.ann<Y>
      “tops”.dat <Z>=bakint(“contour”.2grd, “tops”.ann<X>, “tops”.ann<Y>)
    - E. Check the file header by going to File> List files and selecting “tops”.dat and clicking on Header. Check that each field is in the appropriate column and has the correct units. This file will be ready to enter into the EarthVision Workflow Manager.