HYDROGEOLOGIC AND GEOCHEMICAL INVESTIGATION OF ROBUST SPRING DISCHARGE AT WINGATE RANCH, EASTERN SAN GABRIEL MOUNTAINS, CALIFORNIA

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SIGNATURE PAGE

THESIS:	HYDROGEOLOGIC AND GEOCHEMICAL INVESTIGATION OF ROBUST SPRING DISCHARGE AT WINGATE RANCH, EASTERN SAN GABRIEL MOUNTAINS, CALIFORNIA
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ABSTRACT

Wingate spring system discharges from a major landslide in Kerkhoff Canyon, a tributary of San Antonio watershed located in the eastern San Gabriel Mountains in Southern California. Flow measurements taken during summer 2011 and from October 2012 through June 2014 yield hydrographs following abnormally wet and dry recharge periods, respectively. Discharge from the main Wingate Spring varied from 281 to 334 gallons per minute (gpm) during 2011 and from 141 to 206 gpm during the 2012-2014 period. This spring demonstrates remarkably robust, sustained flow, which is reflected by an average low base flow recession constant (0.0015 days^{-1}), as compared to landslide-fed springs in nearby Icehouse Canyon (0.0068 days^{-1}), Upper San Antonio Canyon (0.0154 days^{-1}), and Lower San Antonio Canyon (0.0074 days^{-1}).

To investigate groundwater flow paths and reasons for the robust flow, the local bedrock and surface deposits were mapped, and spring water samples were collected for geochemical analysis. Wingate Springs occur below a point where the crystalline bedrock topography beneath the Cow Canyon Landslide deposits creates a funnel that channels shallow groundwater flow from the landslide. Furthermore, the springs discharge down-gradient from a buried strike-slip fault that displays a 30 meter-wide gouge/breccia zone in exposures to the southeast. This transversely oriented structure may act both as a conduit for deep groundwater flow and a dam that blocks groundwater derived from Ontario Ridge to the east. Optimally oriented fracture networks that intersect the fault may also provide pathways through which groundwater discharges during drought periods.

Geochemical analyses of alkalinity, anions, and isotopes from several springs on Wingate Ranch provide insight to the sources or flow paths of the groundwater. A combination of $\delta^{18}O$, deuterium and tritium isotopic analyses aides interpretation of flow paths and degree of mixing

between near-surface and deeper bedrock groundwater sources within the study area. $\delta^{18}O$ - deuterium analyses plot on the local meteoric water line, indicating that an original meteoric water source has not been disturbed by later fractionation or mixing with anomalous groundwater. Comparison of these data with results from other watersheds in San Antonio Canyon demonstrates a systematic correlation to average watershed elevation. Tritium analyses of four spring samples from the Wingate Ranch area yield apparent groundwater "ages" ranging from 18.9 to 24.7 years. These values cannot be taken as true ages because it is not known how much recent meteoric water has mixed into the samples. Nevertheless, the tritium results show that water that feeds Wingate Springs has resided a relatively long time in the ground. This result is consistent with mapped geologic relations that show likely groundwater sources from deep-seated fault and fracture networks.

Wingate Springs provide a unique laboratory for studying the hydrogeologic controls of an important sustainable groundwater supply in recently uplifted crystalline mountain terrain.

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INTRODUCTION

Purpose and Objectives

The intent of this study is to document the robust spring flow observed at Wingate Ranch (Figure 1), and determine if the unusual discharge is directly linked to precipitation and landslide drainage, or if it is connected to a larger deeper source. To facilitate this understanding, spring discharge was systematically gauged over the course of two years. Base flow recession is the rate at which groundwater discharges from an aquifer after recharge events have ceased for the particular area. Recession constants corresponding to three base flow periods were then calculated from the observed decay in spring flow, and flow data was compared to that from other springs in the Mt. Baldy area. Local precipitation records were used to assess any correlations. In order to understand the nature of the flow of springs at Wingate Ranch, the understanding of the local geology and hydrology needed to be refined. This was achieved through mapping features in source areas adjacent to Wingate Ranch, including: extent of alluvium and landslide deposits, bedrock type and foliation, fracture and fault networks, and delineation of geologic structures which may play a role in the groundwater flow distribution. Spring water samples were also analyzed for Wingate Springs, Garden of Eden Spring, and Kerkhoff Wall Spring (Figure 2). The basic ion geochemistry along with $\delta^{18}O$, deuterium and tritium isotopic analyses help identify or exclude possible sources and flow paths for spring water.

Location, Topography and General Hydrogeologic Setting

The study area is located at Wingate Ranch, which occupies approximately 28 acres of privately owned mountain riparian land roughly half of a mile south of Baldy Village in the eastern San Gabriel Mountains (Figure 1). The property is bisected by the Los Angeles-San Bernardino county line. Wingate Ranch lies along a stretch of the San Antonio Creek and north of its junction with the mouth of Kerkhoff Canyon. Figure 2 shows the United States Geological Survey (USGS) 7.5 minute Mt. Baldy quadrangle topographic map overlain by local property boundaries to provide a perspective of the physiographic features in the area. The property adjacent to and north of Wingate Ranch is the Mt. Baldy School, which was originally deeded to Scripps College of Claremont College system (Nourse, 2011).

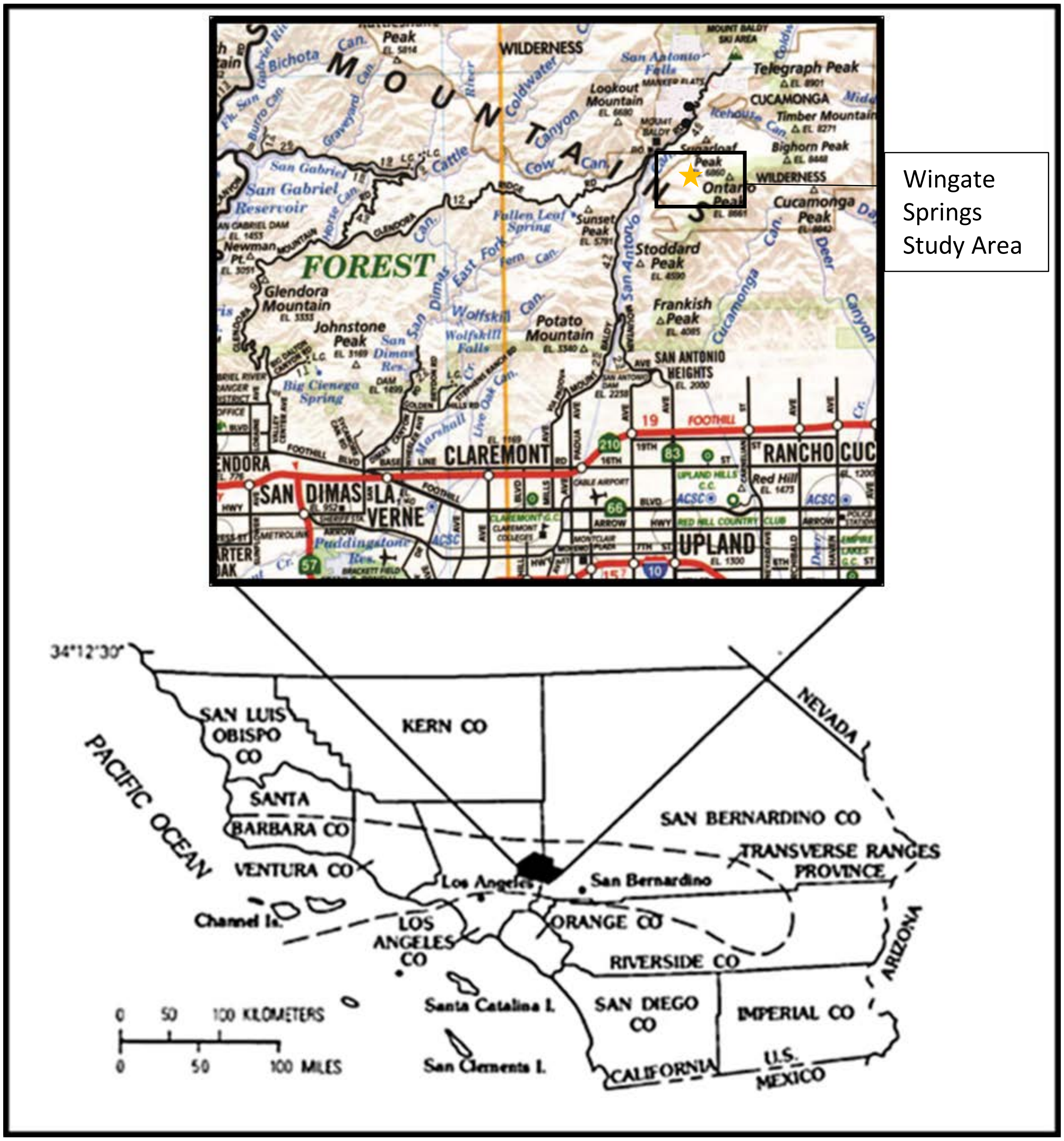

Figure 1. *Location map of Wingate Springs study area. Yellow star is the approximate location of Wingate Springs. (Modified from Evans, 1982 and City Data Maps).*

Several springs discharge from the hillside to the east of San Antonio Creek. These springs flow year-round and follow a convoluted network of small stream channels that eventually drain into the main creek. The largest group of these springs in the study area provides domestic water supply to Wingate Ranch and adjacent Brant Ranch. Historically, these springs have a robust flow that is sustained even through periods of drought. The location of these springs down-gradient from a sharp bend in Kerkhoff Canyon (a tributary of San Antonio Creek; east side of Figure 2) is not coincidental, as will be discussed later. The upper reaches of Kerkhoff Canyon drain the steep west-facing slopes of Ontario Ridge, transecting elevations from eighty five hundred feet to four thousand feet.

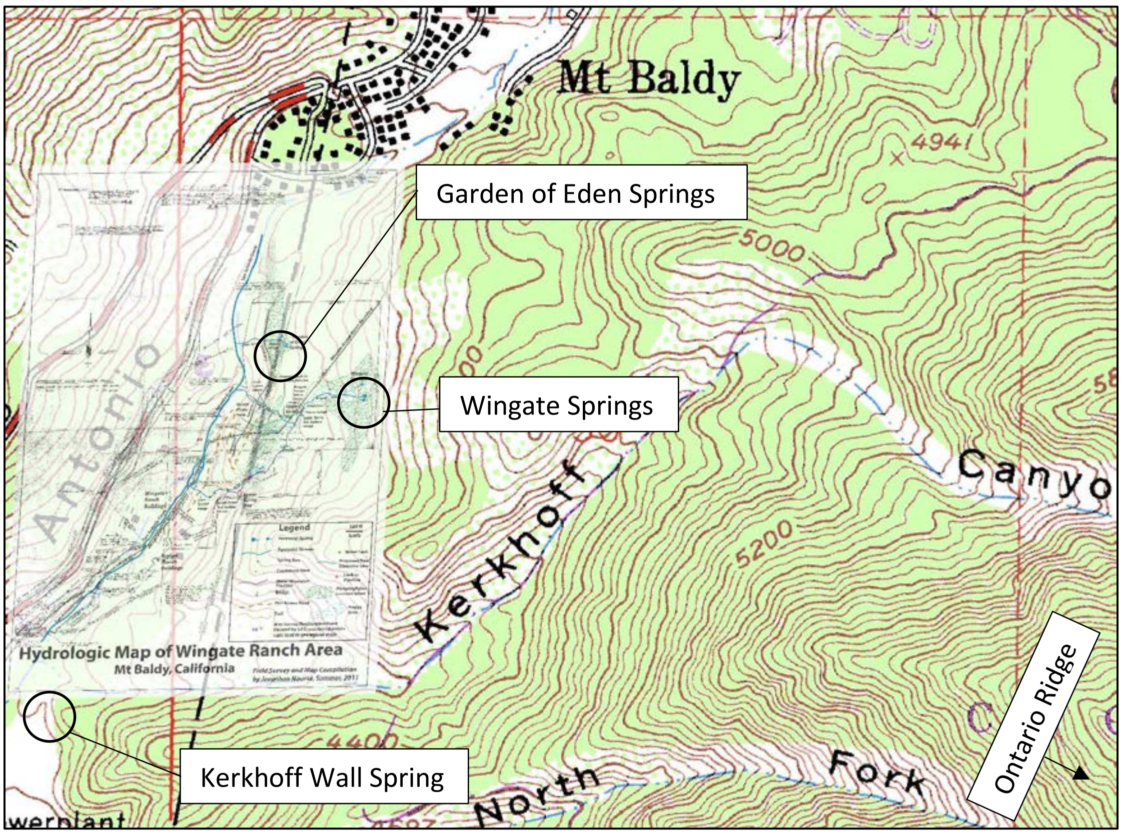

Figure 2. *Hydrologic overlay map of Wingate Ranch property on a portion of the 7.5 minute Mt. Baldy USGS Topographic Quadrangle (reproduced from Nourse, 2011). This shows the location of Wingate Ranch and associated springs in relation to Kerkhoff Canyon. The hydrologic map is shown enlarged as in Figure 4.*

The San Gabriel Mountains are part of the Transverse Ranges and are therefore highly fractured and faulted from the many tectonic forces acting in this region (Nourse et al., 1994). As shown on Figure 3, there are four main rock units in this study area: Quaternary alluvium seen mostly as flood channel deposits, Quaternary talus deposits, Quaternary landslide deposits, and Mesozoic crystalline bedrock (map symbol KTmy). The attitude of these last units and the features associated with them represents the majority of the targeted field measurements because the fracture network and associated faults within the rock structure may represent conduits for the sustained flow observed at Wingate Springs. The Quaternary landslide deposits also play an important role because Wingate Springs discharge from this unit. Landslide deposits litter the San Antonio Canyon and provide the water for the majority of spring locations. It is for this reason that Wingate Springs are more of an exception than the rule for spring flow studies.

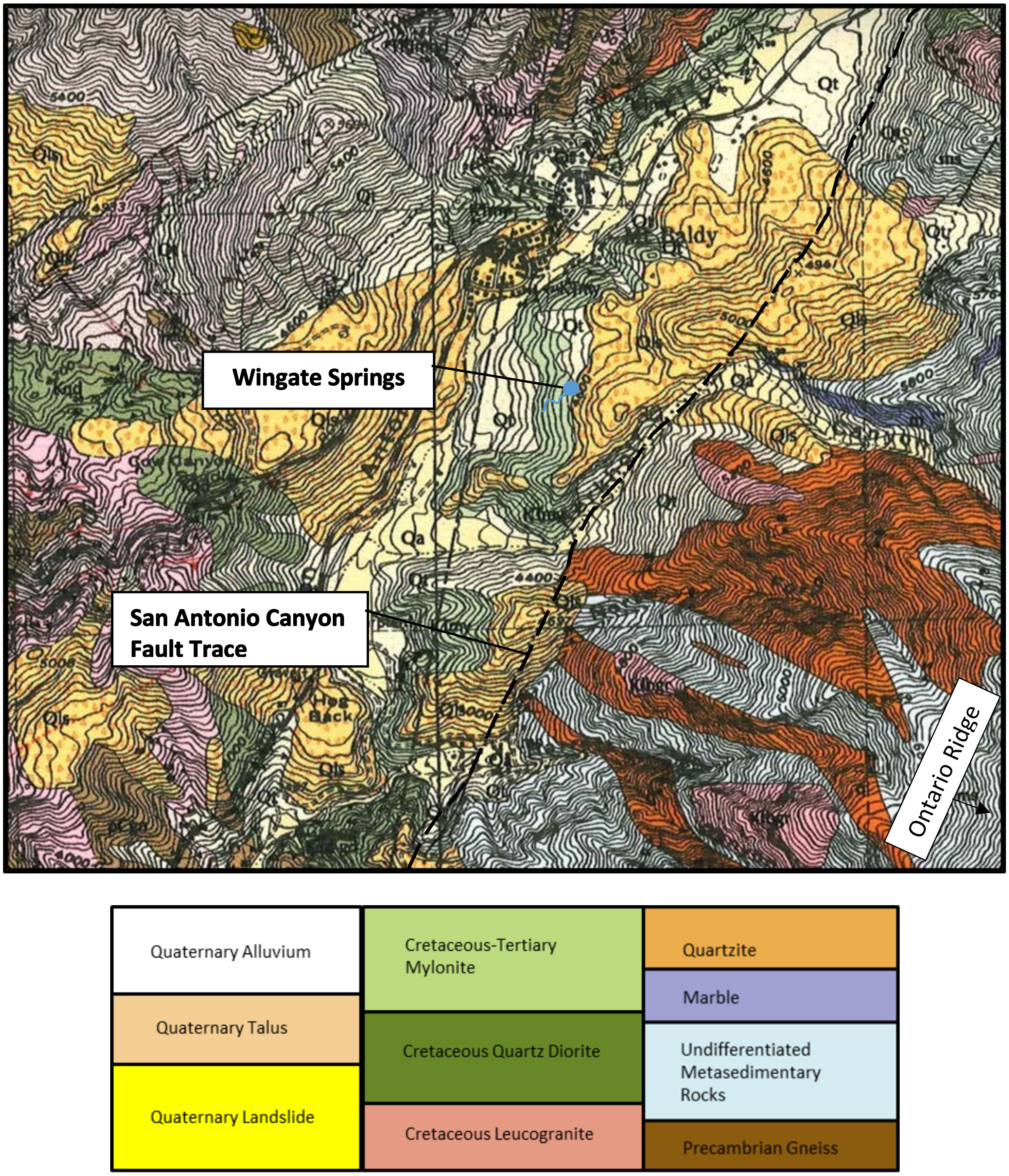

Figure 3. *Bedrock geology and surface deposits surrounding the study area (reproduced from Nourse et al., 1998). The box shows the approximate location of Wingate Ranch; important springs are shown with blue dots. Mapped units are as follows: Qa = Quaternary alluvium, Qt = Quaternary talus, Qls = Quaternary landslide, KTmy = Cretaceous-Tertiary mylonite, Kqd = Cretaceous quartz diorite, Klgr = Creatceous leucogranite, q = Quartzite, m = marble, ms = Undifferentiated metasedimentary rocks, PCgn = Precambrian gneiss.*

Previous Investigations

Studies Near Wingate Ranch and Kerkhoff Canyon

Previous investigations in the Wingate Ranch area are limited in scope, consisting of geologic mapping in the Kerkhoff Canyon area conducted by Dr. Jon Nourse in the 1990s (Nourse et al., 1998), and one short-term hydrologic study of Wingate Springs by the same author in 2011, completed at the request of the property owner Richard Wingate. Nourse's investigation took place between the months of June and early October, 2011, after an abnormally wet winter. The focus was a feasibility study on spring diversion infrastructure. Spring flow measurements were taken using both a flow meter and a bucket to establish flow volume per time. Flow information collected by Nourse is included in the analysis for this study.

Figure 3 shows part of Nourse et al., 1998 1:24,000 scale geologic map that covers the Kerkhoff Canyon area. Symbols for bedrock and soil units described previously and mapped in more detail in this study are noted in the caption. A hydrologic map completed by the same author in 2011 shows the layout of Wingate Ranch at a more detailed scale along with the important spring locations and stream networks relative to water diversion infrastructure (Figure 4). These maps provided an important base for the current study.

Spring Flow Studies in Adjacent Areas

Several hydrology studies have been completed in the areas surrounding Kerkhoff Canyon. Three are similar in scope to this project, but focus on other locations within the San Antonio Canyon area. Pratt (1995) completed the first detailed study of Icehouse Canyon hydrology. Her investigation detailed the regional geologic and tectonic setting of Icehouse Canyon (just north of Kerkhoff Canyon) within San Antonio Canyon, along with climate and local geology. As part of this study, a water budget analysis was conducted. Precipitation and evapotranspiration rates were measured and analyzed within Icehouse Canyon and compared to rates from previous years for Icehouse Canyon as well as for the entire San Antonio Canyon drainage. Data was also collected from the stream at different gauging locations in Icehouse Creek to understand the gaining or losing stream segments and the overall surface flow and its relationship with subsurface geology. The stream's response to precipitation in Icehouse Creek will be used as a comparison for that seen at Wingate Springs.

Carey (2009) calculated base flow recession constants for different gauging stations and springs throughout Icehouse Canyon Creek. Her study of Icehouse Canyon was conducted for more than a year and analyzed how different segments of Icehouse Creek reacted to both precipitation (wet season) and drought (dry season). Flow data was measured and analyzed to provide base flow recession constants. Her study indicated that springs feeding Icehouse Creek were dependent on the amount of precipitation received. Carey's data set was augmented with older data from San Antonio Canyon and Icehouse Canyon in a GSA field trip guidebook article (Nourse et al., 2010). The base flow recession constants from these two drainages springs will be compared to data from my study.

A recent study was completed by Bloom (2012), who measured the flow rate of multiple springs situated in landslide deposits throughout Lower San Antonio Canyon to compare base flow recession constants to other springs in the area. Bloom's data offers a great comparison to this study's springs due to the close proximity and similar material through which the springs discharge. She concluded that the difference in base flow recession constants can be attributed to the aquifers that supply the individual springs.

Strand (2006) also studied base flow recessions, but her study was limited to the San Dimas watershed which is located to the southwest of San Antonio Canyon Basin, which includes

Kerkhoff Canyon. One focus of the study was on the impacts of wildfires and their effects on base flow recession in creeks within the San Dimas Watershed in order to see if these effects could be predicted. Strand's findings showed that base flow recession increases during the year following a fire. San Dimas Basin was compared to San Antonio Basin and some of this data was utilized for the historical data analysis and base flow understanding in my study.

Vathanasin (1999) examined historical and recent hydrological data from the San Dimas Experimental Forest. His analysis focused on precipitation, evaporation, and runoff data. One of his more profound findings was quantifying the amount of evapotranspiration that the area experiences. Vathanasin found that San Dimas Canyon loses more than 80% of its precipitation to evaporation from sun exposure and plant respiration. Some of his historic precipitation findings were used for comparison to the precipitation experienced in Kerkhoff Canyon.

Comparative Water Chemistry Studies

Another senior thesis was completed in Icehouse Canyon, which describes seasonal influences on stream chemistry (Cunningham, 1992). Water temperature at the Spring 1 location of Carey's 2009 study was monitored, but no flow data was recorded. Cunningham's stream chemistry data provided a good comparison for water chemistry results from this study.

A congruent group senior thesis study (Soto et al., 2013) is currently being conducted in Evey, Palmer, and Icehouse Canyons. Soto's group is analyzing the differences in spring flow and geochemistry of waters that interact in bedrock, through fault-fracture networks and from cobble clast landslide deposits. Like this Wingate Springs study, much of their investigation is affected by fault and fracture geometries. Preliminary geochemical data was used to compare the two areas.

SITE CHARACTERIZATION

Overview of the Wingate Ranch Property

Evaluation of hydrogeologic and climate characteristics is important for any hydrologic study. Understanding the Wingate Spring system and why this particular spring has such robust flow involves some challenges, given the complex geology and its particular geometries (Nourse, 2011). The hydrologic map drafted by Nourse (2011) and reproduced in Figure 4 provides a good starting point for my current study. This map shows locations of two key sets of springs (Wingate Springs and Garden of Eden Springs) that discharge from landslide deposits. Also mapped are areas of continually water saturated ground ("boggy areas"), phreatophytes (water-seeking trees), significant water diversion dams and pipes, and streams that carry excess discharge into San Antonio Creek.

One obvious aquifer in this area is a portion of the Cow Canyon Landslide (Morton et al., 1987) that supplies groundwater and from which the springs discharge (see the largest mapped Qls unit on Figure 3). Although springs are expected to surface from such sources, this particular spring surfaces in the middle of the deposit, and not because of an obvious impermeable barrier. Different structural and hydrogeological processes must account for the unusually large amount of flow from Wingate Springs.

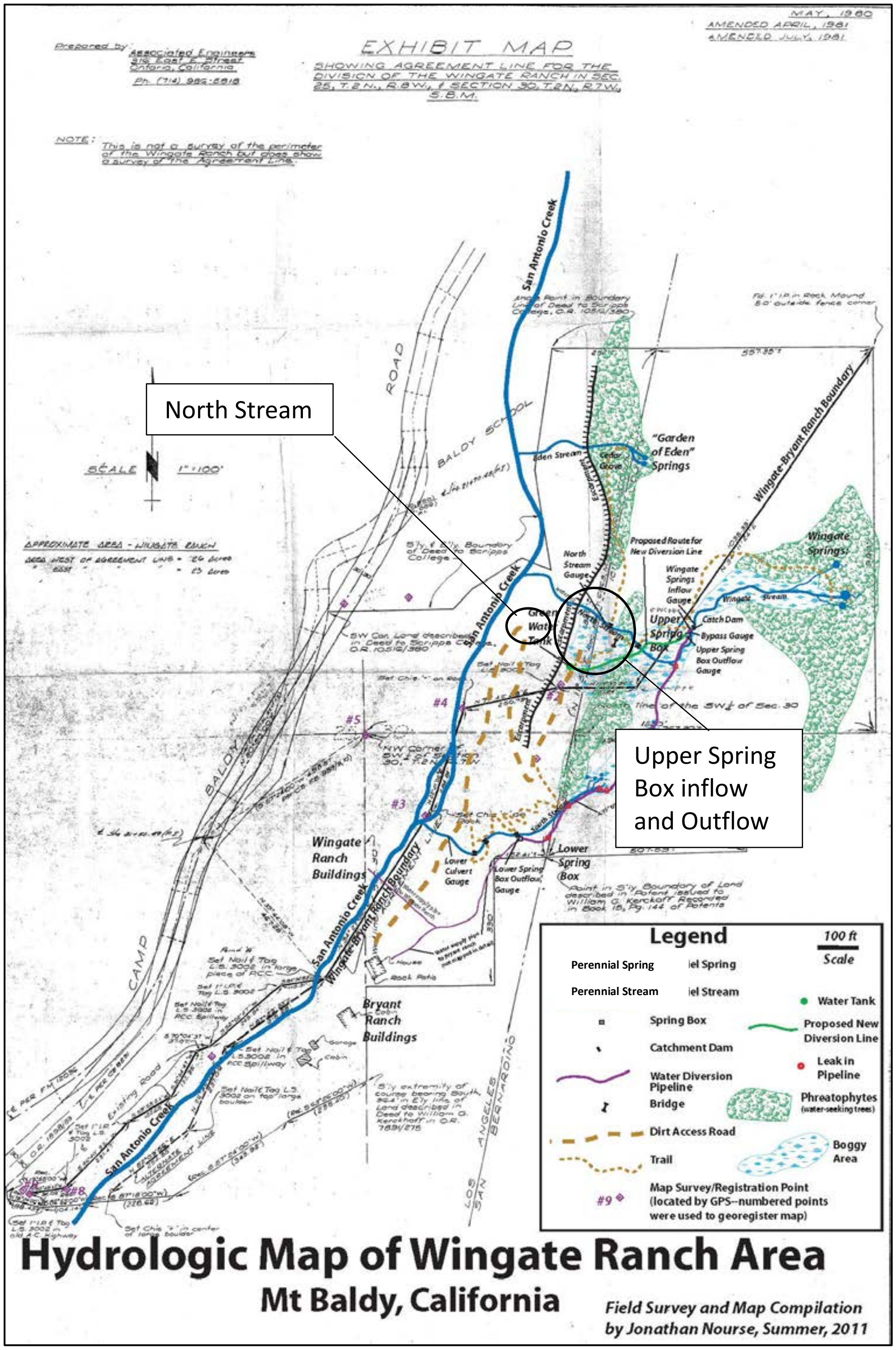

***Figure 4**. Wingate Ranch hydrology map, illustrating the location of Wingate Springs, Garden of Eden Spring, along with their surface flow paths (reproduced from Nourse, 2011). Particularly important to this study are the locations of Wingate Springs Inflow gauge, Upper Spring Box Outflow, and North Stream gauge.*

Groundwater flow is frequently localized and exceedingly preferential to specific geologic conditions that control porosity and permeability. Fractured rocks in the area are another potential groundwater source that beg further investigation. Within San Antonio Canyon and probably within Kerkhoff Canyon up-gradient from Wingate Springs, groundwater flow and the hydraulic properties of crystalline bedrock aquifers are controlled in part by faults and associated fracture networks. The orientations and geometries of these fracture networks have huge impacts on groundwater flow which typically results in localized, preferential pathways. Furthermore, large fractures or faults with gouge can impede flow or become a complete barrier due to high concentrations of clay. All of these factors create potentially complicated flow paths for groundwater that discharges at Wingate Springs (Nourse, 2011). One of the objectives of my study is to identify and map such features.

Geography and Climate

Wingate Springs are located on the east side of San Antonio Canyon and are one of its major downstream contributors (Figure 4). Wingate Springs are believed to acquire the majority of their water from within the Kerkhoff Canyon drainage basin (Nourse, 2011), which is approximately 2.6 km^2 or 1 mi^2 (Google Earth, 2014). The study area is bounded to the east by Kerkhoff Canyon and the crystalline rocks of Ontario Peak, to the south and north by crystalline bedrock overlain by alluvial and landslide deposits of Cow Canyon Landslide, and to the west by San Antonio Canyon. Kerkhoff Canyon has only one drainage wash which is almost always dry except at very high precipitation events.

The climate is semi-arid with periods of drought and high precipitation. Temperatures range from high 80^{o}s F in the summer to the low 20^{o}s F in the winter. Wingate Springs are situated at an elevation of 4,320 feet (ft). above mean sea level (amsl). In the San Gabriel

Mountains, this elevation is usually below most of the annual snow fall. The average annual precipitation at Sierra Powerhouse rain gauge (elevation 3,120 ft) is 31.8 inches, most of which falls as rain Figure 5).

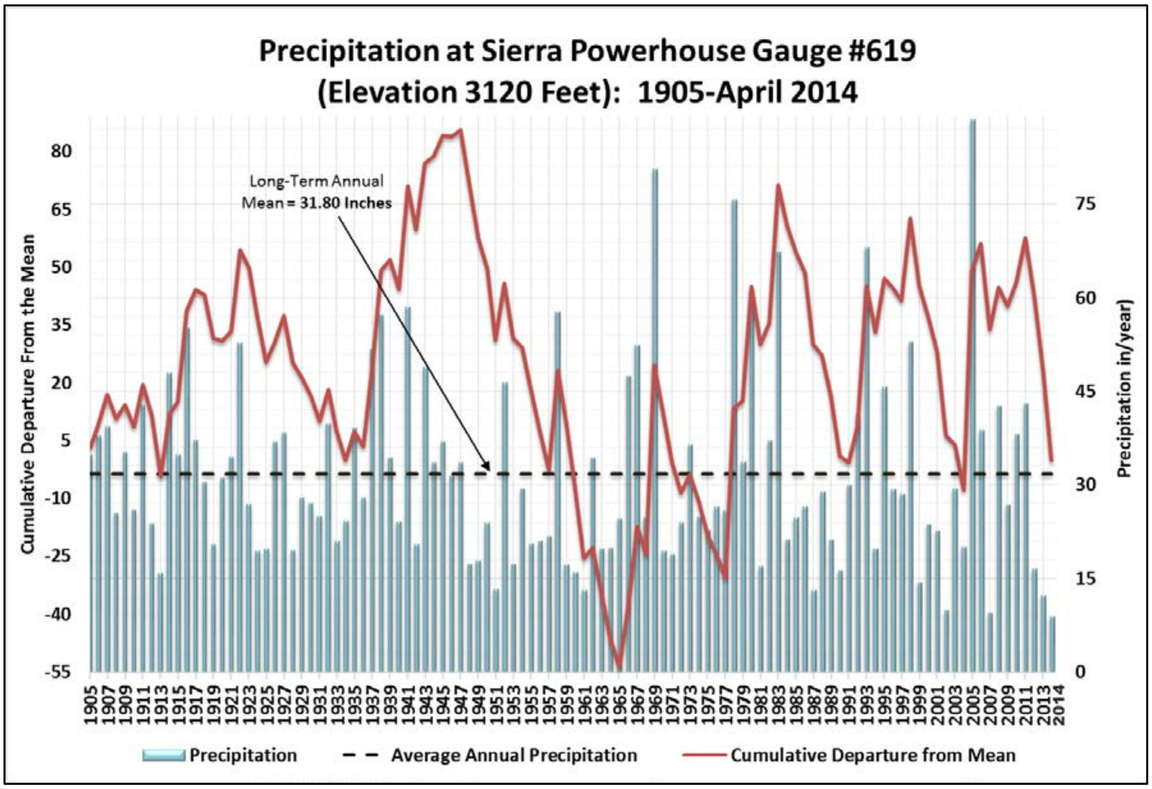

Figure 5. *Historical records of annual precipitation at Sierra Powerhouse (Gauge 619) from 1905 to present. Precipitation values (blue bars) are plotted along with cumulative departure from mean (red line) and the 110 year average (black dotted line) (modified from Vathanasin, and Nourse, 1999).*

At higher elevations, precipitation records are incomplete. Average precipitation generally increases as elevation increases to the north and east. The best data set available for recent years was provided by Pat Chapman at Chapman Ranch (elevation 4,560 ft). Her records show a mean annual precipitation of 35.72 inches between 1979 and 2014. Limited records indicate a 40-45 inches/yr average at Icehouse Canyon (Nourse, unpublished data). Annual snow fall above 6,000 ft elevation is 51.5 inches. Most of the precipitation (90%) that falls in this area is received between the months between October and May (NOAA, 2014).

Regional and Local Geology

Bedrock Units

There are two main bedrock units within this study area: Ontario Ridge metasediments (part of the Placerita formation) and Cretaceous-Tertiary mylonitized granite, granodiorite, and diorite. The left-lateral San Antonio Canyon Fault separates these units. Rocks in this study area are Mesozoic plutonic and pre-plutonic metasedimentary units. The main group of metasedimentary rocks on Ontario Ridge is assigned to the regionally extensive Placerita suite (Dibblie, 1982 and Powell, 1993). The Placerita mainly consists of marble, graphitic schist, biotite-sillimanite schist, and amphibolite-grade metaquartzite, all of which was intruded by Cretaceous granitoid rocks. Ontario Ridge in the vicinity of San Antonio Canyon, has large portions of the Placerita intruded by the tonalite and leucogranite with minor bodies of monzogranite and granodiorite (Morton and Matti, 1987, and 1990).

Figure 3 is a local geologic map of Kerkhoff Canyon and Wingate Springs area (Nourse et al., 1998). The KTmy unit (colored light green on the map) is known as the Vincent Thrust mylonite and consists of mylintonized granite, granodiorite, quartz diorite, and gneiss or amphibolite. It has been retrograded and sheared through movement along the Vincent Thrust (Nourse, 2002). The greenish color of the unit is a result of chlorite and epidote alteration of hornblende- and biotite-rich protoliths (Nourse, 2002). Most of the yellow colored units on the map represent portions of the Cow Canyon Landslide or Spring Hill Landslide. The San Antonio Canyon Fault bisects the northeast tending section of Kerkhoff Canyon, as illustrated by a dotted line on Figure 3.

Alluvial and Colluvial Deposits (Qa and Qt)

In general, the San Gabriel Mountains have had multiple generations of quaternary deposits which have settled on the canyon bottoms and are dispersed throughout the adjacent valleys. In Kerkhoff Canyon, the alluvium mostly consists of large boulders 1 to 3 meters wide at the canyon head and gradates down towards the mouth of the canyon. Talus deposits also litter the canyon. In some areas these deposits are extensive and, not unlike other tributaries to the San Antonio Canyon, these deposits make great conduits for groundwater flow. Alluvium and colluvium are shown in white on Figure 3.

Landslides (Qls)

Cow Canyon Landslide is one of the largest landslides within San Antonio Canyon (Morton et al., 1987). Cow Canyon Saddle is the divide between the San Gabriel River drainage and San Antonio Canyon. There are possible composite sources contributing to the landslide from Cherry Canyon and Kerkhoff Canyon. However due to the abundance of quartzite in the deposit, Ontario Ridge (located on the east side of San Antonio Canyon) is the most likely origin. Other noteworthy landslides include Hog Back, which is located southwest of the Cow Canyon Landslide (located outside of the study area). This landslide spilled across San Antonio Canyon Creek, and was eventually eroded through (Morton et al., 1987). Icehouse Canyon Landslide is a major contributor of groundwater to Icehouse Creek and the main San Antonio Canyon Creek. Springs discharging from this landslide provide an interesting comparison to Wingate Springs, which discharge from Cow Canyon Landslide. One other landslide that is noteworthy is the Spring Hill Landslide. Spring Hill Landslide is mostly constrained in Barrett and Cascade Canyons, but a small portion sits along the ridge between Barrett and Kerkhoff Canyons. The significance of this particular landslide is that it is rich in sulfur bearing minerals like pyrite and pyarrite. These minerals, when broken down, release sulfate ions that are readily absorbed by groundwater and can be detected in samples. This landslide is distinguished from others by a red-orange color and sulfur smelling clasts.

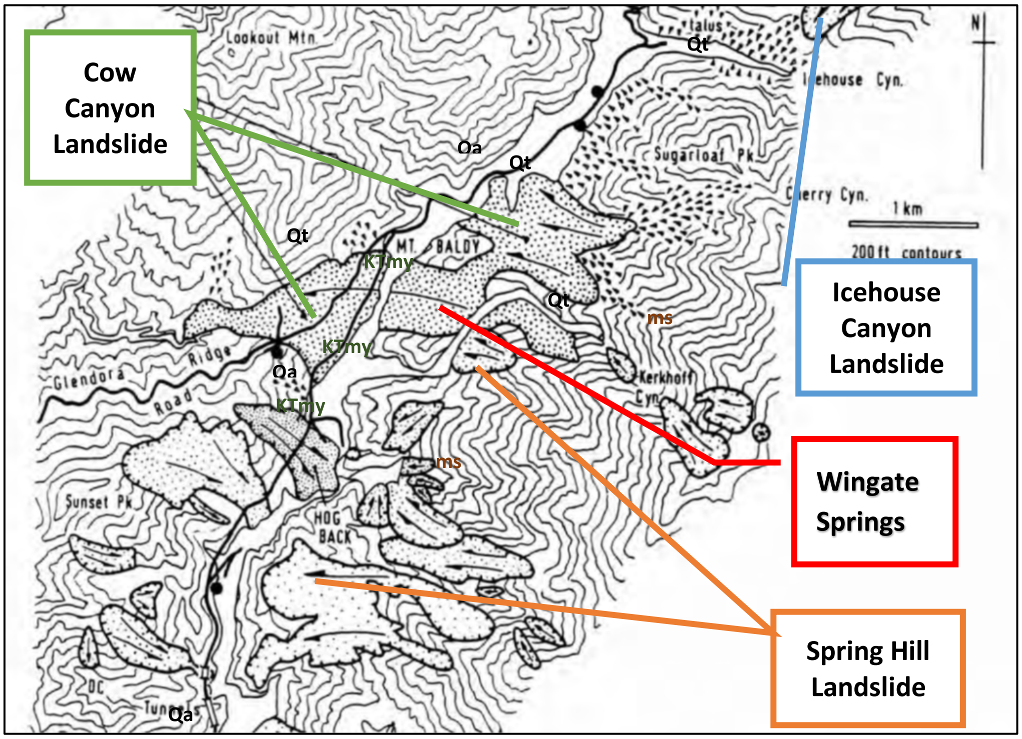

Figure 6. *Cow Canyon Landslide in the vicinity of Kerkhoff Canyon and Wingate Springs. Qa = Quaternary alluvium, Qt = Quaternary talus, ms = Undifferentiated metasediments, KTmy = Cretaceous-Tertiary mylonite (modified from Morton et al., 1987).*

Local Hydrology

Kerkhoff Canyon drainage is a tributary to the main San Antonio Creek. Beginning on the north facing slopes of Ontario Peak, it has incised a steep, rugged canyon. The elevation ranges from about 8,000 to 3,750 ft amsl at the Kerkhoff and San Antonio Creek intersection. Kerkhoff Canyon has been offset about 3,260 ft to the northeast due to the sinstral strike-slip motion of the San Antonio Canyon Fault. This offset creates a near 90 degree bend in the drainage to the southwest of Ontario Peak. The canyon drainage is approximately 2.6 square kilometers, but almost never has flowing surface water except during large storms.

The local climate is dominated by warm, dry conditions from May to October, and cool, occasionally wet conditions between November and April. As much as 10 ft of snow has been known to accumulate at elevations higher than 5,000 ft amsl during the winter but is usually gone before June. Figure 5 shows the 110-year running average for precipitation in the San Antonio Canyon.

Any watershed in the San Gabriel Mountains is controlled by the rates of annual precipitation, evaporation, and transpiration; Icehouse and Kerkhoff Canyons are no different. It can be expected, therefore, that differences in precipitation would be reflected by corresponding spring flow variations. It can be argued that this topographically lower spring (Wingate) has the ability to collect more water or pull water from a greater area, however, Icehouse Canyon has the larger area and generally has more snowpack due to the elevation gain. The question becomes: why does the robust flow in Wingate Springs have a lower base flow recession constant than some of the springs in Icehouse Canyon and other canyons within the main San Antonio Canyon? The entire area is frequently subjected to drought conditions such as that from 2011 to 2014, when precipitation recorded at Sierra Powerhouse (Figure 5) was less than half the 110 year mean of 31.8 inches. The fact that Wingate Springs continue to flow intensely during drought periods suggests that the drainage is continuously supplied by significant groundwater sources other than just the apparent Cow Canyon Landslide aquifer. In contrast, segments of Icehouse drainage typically dry up during summer and fall.

Groundwater flow systems in the study area are controlled by the basic geology of the watershed. Approximately 30% of the bedrock is covered by varying thicknesses (a few feet to hundreds of feet) of mostly porous, unconsolidated rock deposits, landslide deposits, talus, and alluvium. Permeability is the ability of water to flow within a particular media or in this case, multiple units which can play an important role in the storativity of groundwater and the occurrence and flow rates of surface water within the drainage. The permeability and porosity of a unit can be significantly altered by fractures and faulting. All of these units have a different permeability and porosity. As shown on Figure 7, the bedrock in this area is riddled with faults and fractures which can be potential hydrologic pathways and/or barriers to groundwater flow.

METHODS

The Wingate Spring system is located in a highly dynamic area. To properly study this location, three basic data collection practices were utilized: geologic mapping, spring flow measurements, and water sampling for chemical analysis.

Data Collection

Geological Mapping

Geologic mapping of the landslide and the drainage of Kerkhoff Canyon was conducted to better understand the geometry of the structures within the bedrock and the extent of the Cow Canyon Landslide from which the springs discharge. The study area was mapped previously by Ehlig (1958) and Nourse et al., (1998), but in recent years fire and earthquakes have cleared un-mapped areas of Kerkhoff Canyon and its associated bedrock. Special interest went into mapping faults, fractures and foliations at both a local and broader scale since fracture and fault geometries are essential to understanding hydrologic systems. These features can act as either conduits or barriers to groundwater flow, depending on the extent of mineralization and the clay content present within them. Foliation orientations were mapped in an attempt to distinguish any regional folding which could have some effect on groundwater flow.

Figure 7. *Northwest trending fractures within KTmy unit.*

Mapping tools used in this study included:

- Brunton Compass
- Trimble 100 Range Finder
- Garmin CS30 handheld Global Positioning System
- Topographic maps from the USGS, 7.5 minute Mount Baldy Quad
- Camera
- Various software programs (ArcGIS, Goggle Earth and Illustrator)

The Brunton compass was used to measure the strike and dip of fractures, faults and foliation, along with some trend and plunge measurements. The location of the measurement was recorded with a GPS coordinate so the structure could later be plotted on a map. The

Trimble Range Finder was used to map outcrops or contacts too far away or too dangerous to get to by foot (Figure 8). The range finder was calibrated by Trimble and was used to record the vertical distance, horizontal distance and the azimuth of each point of reference. These points were also used in conjunction with handheld GPS. The data then had to be accurately calculated, measured and plotted on the topographic map. To do so, all geologic data and their corresponding GPS coordinates were uploaded and transferred to ArcGIS and Illustrator to digitize the geologic map.

Figure 8 *- Using a Trimble Range Finder to help map KTmy contact within Kerkhoff Canyon.*

Flow Measurements

In order to measure the spring flow from Wingate Springs, two instruments were utilized: a calibrated flow meter made by Global Water, and a meter stick. The flow meter measures the velocity of the water and the meter stick was used to determine the cross-sectional area of the flow. The area was measured in square inches, and the flow rate was measured in feet per second. These measurements were later converted and combined to calculate the flow rate in gallons per minute (gpm).

The flow meter uses a propeller which rotates when water runs through it. On one end of the propeller is a magnet. The rotation creates an electrical signal which is then sent up the meter to the computer. The computer processes the speed at which the propeller is moving and converts it to feet per second on the screen. By measuring the cross-sectional area over which the flow was measured with the meter, discharge can be obtained in cubic feet per second (cfs) by multiplying the cross-sectional area by the flow velocity. The user is responsible for taking a representative flow measurement across the discharge area. Lingering too long in either a slow or fast flowing area will skew the overall average flow rate. In an attempt to reduce user error, the entire discharge cross-sectional area was measured multiple times to minimize the extreme highs and lows recorded by the meter for that sample location.

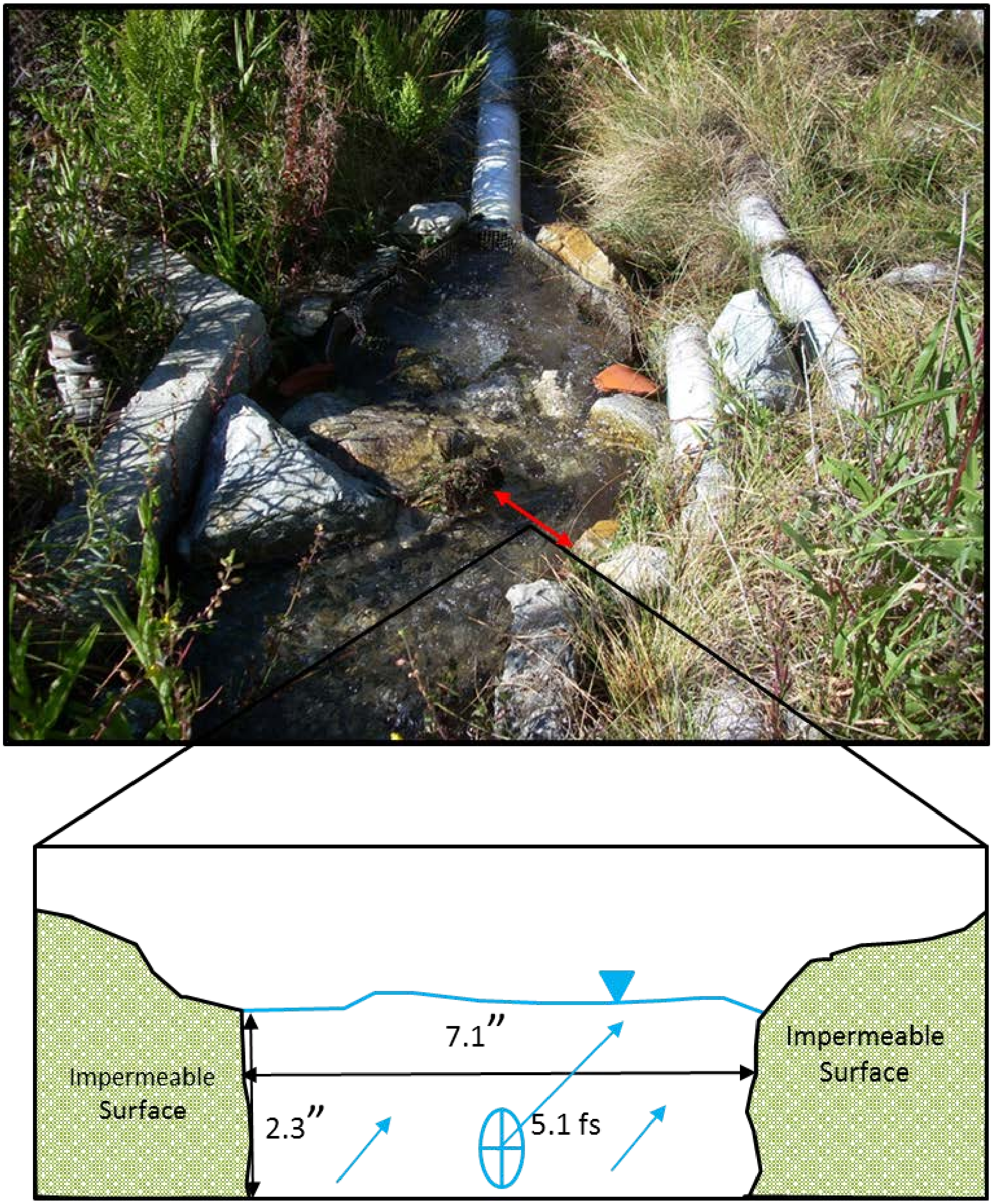

Figure 9. *Wingate Spring inflow gauging location and schematic of cross-sectional area of spring flow values are example measurements, blue arrows indicate flow. Stream bed is not completely impermeable due to the unconsolidated landslide deposit the springs flow out of.*

The rate of flow from the springs was measured at three locations shown on Figure 4. These flow gauging locations, Upper Spring Box Inflow, Upper Spring Box Outflow and North Stream, were chosen to correlate with those from the previous short study of the same springs (Nourse, 2011). The base flow constant was derived using only Upper Spring Box Inflow for this study. The stations were chosen for the maximum amount of flow over relatively impermeable features and easily approximated cross-sectional areas. Two of the three locations were located at the Upper Spring Box; one station before the spring water entered the box, and one station after. The flow station after the box, or "Upper Spring Box Outflow", is shown in Figure 10. Flow was measured as it discharged from the spring box outlet pipe, which was a 6-inch diameter PVC pipe. In order to gauge this station properly, measurements of the pipe and the height of the water flowing out of it were recorded along with the metered flow rate. Figure 9 shows the gauging location named "Wingate Spring Inflow" which is located just prior to the Upper Spring Box. The cross-sectional area can be approximated by a rectangle with the sides being bound by two large rocks. The water from the spring box is diverted by an old water supply system to be used by the current property owners.

Figure 10. *Upper Spring Box Outflow gauging location.*

Figure 11. *North Stream gauging location.*

The third gauging location, “North Stream”, is shown on Figure 11. At this station, the amount of water that bypassed the upper spring box was measured. This eventually makes its way to the main San Antonio Creek. These three locations were the main points of data collection for flow volume in this study.

Water Sampling

Water sampling was conducted with the hopes the results would provide information on possible flow paths and source for the springs. In an ideal study, sampling locations would be adequately distributed, as well as to avoid spatial gaps in sampling locations. For this study, however, sampling was limited to locations where active springs were flowing. Samples were taken primarily of spring water, but also included stream flow and local precipitation. Table 1 summarizes the samples and locations.

__Table 1.__ List of Samples Analyzed in This Study

Sample ID	Type of sample	Analysis			
		Ion Chromatography	Alkalinity	δ18O/δD	Tritium
Cascade Cyn	Stream			X	
Cedar Glen Spring	Spring			X	
Columbine Spring	Spring			X	
Cow Cyn rain storm	Precip			X	X
E. Palmer Spring 1	Spring	X	X	X	X
Evey Canyon 0	Stream	X	X	X	
Evey Canyon 1	Spring	X	X	X	X
Evey Canyon 2	Spring	X	X	X	X
Evey Mid 1	Stream	X	X	X	
Garden of Eden Spring 1	Spring	X	X	X	X
Icehouse Canyon Lot#20 Spring	Spring			X	
Icehouse Canyon Spring 1	Spring	X		X	
Icehouse Spring 2	Spring	X		X	
Kerkhoff Wall Spring 1	Spring	X	X	X	X
Lower Barrett	Stream			X	
Lower Evey Creek	Stream	X		X	
Lower Hogback	Spring			X	
Lower Manker Spring 0	Spring			X	
Lower Manker Spring 1	Spring			X	
Mid Cascade Creek	Stream			X	
Barrett Creek 2	Stream	X		X	
North Stream	Stream	X		X	X
Barrett Creek 1	Stream	X		X	
USAC-A	Stream			X	
Wingate Spring 1	Spring	X	X	X	X

At some locations, samples were taken on several dates in order to evaluate the seasonal chemistry. There was no problem gathering seasonal samples form Wingate Springs, but other locations became dry in the summer or difficult to sample due to reduced flow. Mapping through Kerkhoff Canyon revealed two locations that may have spring flow during a normal year, but no flow was observed during this study due to the drought conditions.

All samples were taken with nitrile gloves to minimize possible contamination and were field filtered utilizing a 30 mL Luer-Lok syringe and a disposable Luer-Lok 0.45 micron (µm) filter except for tritium samples. The tritium samples were not required to be field filtered. They were sent off to be analyzed at the Environmental Isotopes Laboratory at the University of Arizona. The sample containers were issued and prepared by Dr. Stephen Osborn of the Cal Poly Pomona Geological Sciences Department. The $\delta^{18}O$/ δD, alkalinity, and anion samples were taken directly from the spring source (where it first surfaces) in 30 milliliter (mL) high-density polyethylene (HDPE) vials. Tritium samples were taken using a 500 mL HDPE bottle. During each sampling, an additional 30 mL sample was taken that included a 2% optima grade nitric acid (HNO_3) preservative. This was used for the cation analysis. Field readings were taken at each sample location using YSI pH100 EcoSense and EC100 EcoSense meters for pH and electrical conductivity, respectively. The meters were used as a check against more accurate lab analyses. Samples were capped and labeled with date, time and location. The alkalinity and ion samples collected could not have any head space within the bottle so care was taken in capping the samples to ensure there were no bubbles. They were then bagged in freezer-grade “Ziplock” bags and stored in black trashcan bags (Hefty Brand), put on ice and kept out of direct sunlight. The samples were taken directly to the Cal Poly Pomona Hydrology Lab to be stored in a refrigerator where they were later prepared for analysis.

Laboratory Analysis of Samples

The water samples gathered in the field for alkalinity and anion determination were analyzed in the Hydrology Laboratory in the Geological Sciences Department at California State Polytechnic University. These samples were prepared by Dr. Stephen Osborn, Professor in the Geological Science Department, who also oversaw all analytical work performed for this study. A portion of the spring water samples collected were sent to the Environmental Isotopes Laboratory in the College of Science at the University of Arizona, Tucson. These samples were prepared and run by Dr. Chris Eastoe, and students. Both $^{18}O/^{16}O$ and D/H isotope ratios were measured and are reported as $\delta^{18}O$ and δD relative to Vienna Standard Mean Ocean Water (VSMOW), which is described in more detail later. The accuracy of the results have a detection limit of 0.6 and 0.9 per mil ($^{0}/_{00}$) for $\delta^{18}O$ and δD, respectively. The Tritium results are recorded in Tritium Units (TU) at a detection limit of 0.6 TU.

Alkalinity Determination

Alkalinity is the capacity of a solution (e.g., water) to neutralize an acid. The alkalinity of each water sample taken for this project was measured through the process of titration. During titration, the sample is very slowly diluted with an acid solution (i.e., drip by drip) until the pH begins to decrease rapidly. The alkalinity can then be calculated using the following equation:

$$\text{Alkalinity} = \frac{(Volume\ of\ Acid\ added\ mL)(Normality\ of\ Acid)\times 50{,}000}{(Volume\ of\ Sample\ mL)}$$

All samples were titrated within 48 hours of collection using a Brand Digital Bottle Top Titrater with and Orion Star A211 Bench Top pH meter utilizing 0.1 normal HCl.

***Table 2**. Typical Alkalinity Ranges for Natural Waters*

Alkalinity (mg/L of $CaCO^3$)	
Rainwater	<10
Typical Surface Water	100-200
Surface Water in Regions with Alkali Soils	100-500
Groundwater	50-1000
Sea Water	100-500

Ion Chromatography

After analyzing a small portion of the sample for alkalinity, five additional milliliters were used to analyze both the major and minor ions for each sample. An ion chromatograph was used to analyze ion concentrations of F, Cl, NO_3, and SO_4 in the various samples and compare the samples to known, lab derived quantities for high, average and low values. The machine is a DionEx ICS-1100 with a column AS-23. Normalization of the data was accomplished by analyzing the three known standards at the beginning of the run and periodically throughout (e.g., about every ten samples) as a calibration check. A sample of deionized water was also analyzed along with the other samples. The measured values for the known samples (standards) were then used to both normalize the results and to check the calibration of the machine. Major and minor ion concentrations can provide insight into the amount of time a sampled water spent in the subsurface by comparing the measured values to known values for the same type of rock or aquifer.

Oxygen and Hydrogen Isotope Analyses

The number of protons and neutrons within a nucleus of an atom is what makes each elements mass different. Elements with the same number of protons but different number of neutrons are known as isotopes. Some of the most common, naturally occurring isotopes include: hydrogen, carbon, oxygen, nitrogen, and sulfur. Hydrological systems have particular signatures of these isotopes, and analyzing their abundance relative to one another (as a ratio) can produce important information about the processes that govern the dynamics of water movement Oxygen and hydrogen isotope ratios are common tracers used in groundwater and surface water studies.

$\delta^{18}O$ and δD

Oxygen has three isotopes: ^{16}O, ^{17}O, and ^{18}O. The superscript numbers refer to the atomic mass of the isotope. Most of the world's oxygen is present in the form of oxygen-16 (^{16}O). The ratio of oxygen-18 to oxygen-16 is 1:500 (Drever, 1997). To measure the isotopic ratio in a sample, a mass spectrometer is used. Stable isotope abundance is usually reported as delta (δ). These values have units of per mil (‰), or parts per thousand, and are calculated relative to a standard:

$$\delta_A = \frac{R_A - R_{Stand}}{R_{Stand}} \times 10^3$$

Where: δ_A is the isotopic ratio of the sample, and R_{Stand} is the absolute isotopic ratio in the standard. The reported values specify whether a particular sample is positive or negative in $\delta^{18}O$ relative to the standard. For instance, a sample with a $\delta^{18}O$ of +20 is equal to an $^{18}O/^{16}O$ ratio that is 2% (or 20 per mil) greater than the standard (Carey, 2011). Mean ocean water samples are used as standards because oxygen isotopic variations in seawater are very small (+/- 1.5 ‰) (Welham, 1987). The current standard used most continuously is known as Vienna Standard Mean Ocean Water (VSMOW).

Hydrogen isotopic concentrations are used in conjunction with oxygen isotopic concentrations because both isotopes are found in water. ^{2}H is the stable isotope conformation of hydrogen, also known as deuterium (D). A relationship exists between $\delta^{18}O$ and δD values. Kehew (2001) describes this relationship as:

$$\delta D = \delta^{18}O + 10 \text{ VSMOW}$$

This equation also defines what is known as the Global Meteoric Water Line (GMWL). Figure 12 explains where different waters should plot along or off the GMWL.

The amount of $\delta^{18}O$ in a sample is the result of natural processes by way of fractionation. Fractionation is the change in isotopic ratio due to chemical or physical processes. Examples of the process that cause fractionation include: evaporation, precipitation events, and the movement of vapor masses inland and latitudinally. The amount of fractionation that takes place depends on various reaction rates, environmental factors, and the temperature.

Temperature affects fractionation the most (Mazor, 1991). Temperature has such an effect on fractionation due to the bond strength between the light and heavy oxygen isotopes. This decreases as the temperature rises, and the net effect of temperature is expressed in the following empirical function from Mazor (1991):

$$\delta^{18}O = 0.7T_a - 13‰$$

Where: T_a is the local mean annual air temperature. Temperature is also the main control on isotopic concentrations in precipitation. Seasonal variations in $\delta^{18}O$ concentrations are due to the dependence on temperature, and therefore called the temperature effect (Dutton et al., 2005). Given this "temperature effect", lower temperatures lead to a depletion of $\delta^{18}O$ in precipitation, while warmer temperatures lead to enhancement. Seasonality signals manifest themselves with more negative $\delta^{18}O$ values in winter (see Figure 12).

Short term isotopic separations are controlled by phase separation processes (like the transition of water into ice, liquid, and vapor). Kinetic factors, like evaporation, usually govern the enrichment of $\delta^{18}O$. Higher temperatures, and arid areas, lead to more evaporation. During evaporation, the heavier isotopes (i.e., $\delta^{18}O$ and deuterium) are preferentially partitioned into the aqueous phase (Kehew, 2001), leaving the lighter isotopes free to evaporate (i.e., ^{16}O).

Therefore, there is a general depletion of $\delta^{18}O$ from summer to winter and from the equator to the poles. The “latitude effect” describes this progressive depletion of heavy isotopes in precipitation at high latitudes (Gibbs, 2008; Hoefs, 1987; Mazor, 1991). Evaporation causes water to plot off the GMWL on a separate evaporation line that has a lower slope than that of the GMWL. This is illustrated on Figure 12. Each evaporation line is determined primarily by the prevailing temperature and the air humidity. Its intercept with the GMWL can change depending on evaporation conditions (Gat et al., 1991).

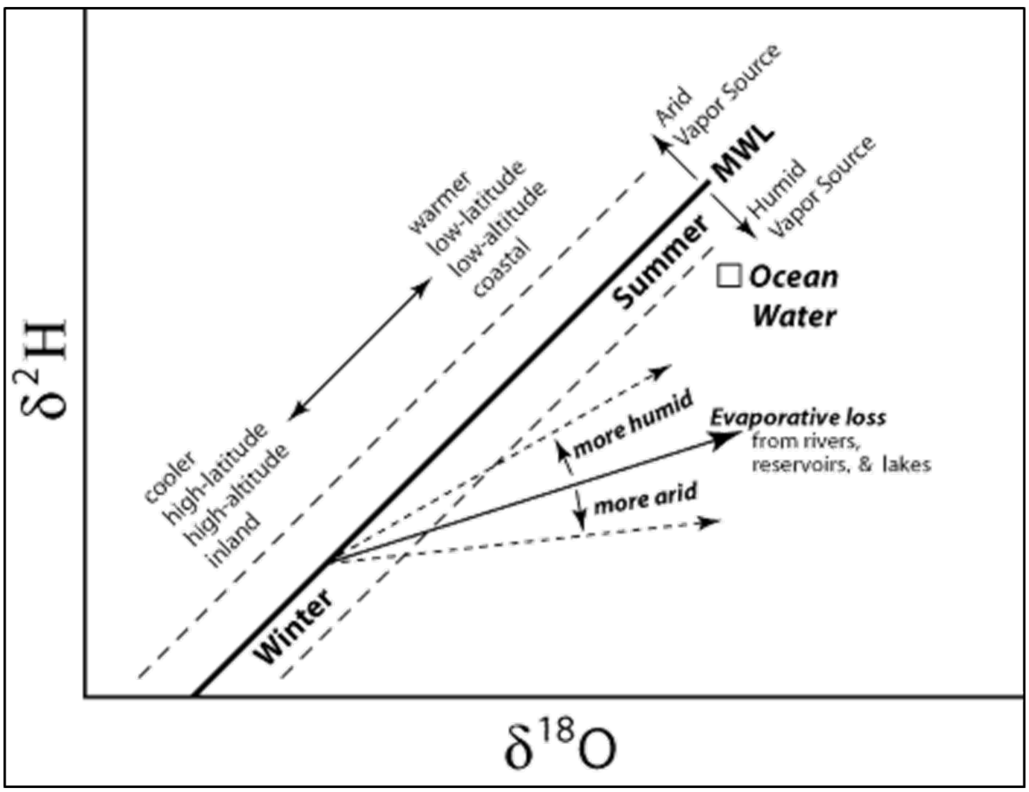

***Figure 12**. Fractionation of oxygen and hydrogen away from the Meteoric Water Line (Gibbs, 2008).*

Results for the samples taken of precipitation near the Wingate Springs study area at Cow Canyon Saddle were used in conjunction with local data from Osborn (sampled during 2013 and 2014) in order to establish a Local Meteoric Water Line (LMWL).

Tritium

Tritium samples were collected to gather an approximate age relationship between recent precipitation and spring water and to trace different waters. This analysis does not precisely age date the water sample it just provides a qualitative measure of how long the water sample has been isolated from the atmosphere. Tritium analysis of water is relatively new, and can be used it is used to help determine the timing of recharge in groundwater aquifers, or in this case, to help determine how long water has been in the ground. By comparing the tritium concentrations of the water collected in the field to those of precipitation also collected near the study area, an estimation can be made as to how long the water from each of the sample locations has been in the ground, up to about 60 to 70 years. This is accomplished by using the Tritium Decay Law.

Hydrogen is the first element on the Periodic Table and can exist in multiple forms: common hydrogen (^1H or protium), hydrogen-2 (^2H or deuterium), and hydrogen-3 (^3H or tritium). 99.98% of all naturally occurring hydrogen is protium, or common hydrogen. Deuterium comprises about 0.02%, while tritium occupies about a billionth of a billionth of natural hydrogen (Carey, 2011). With two neutrons in its nucleus, tritium is unstable and consequently decays radioactively to helium-3 (^3He) through this process known as beta decay. During this process, a beta particle (high-energy electron) is released. This decay rate is measured in half-lives. A half-life is the amount of time it takes for a set quantity to decrease to half its initial value. Tritium has a half-life of 12.32 years.

Tritium concentrations are expressed in Tritium Units (TU) where one TU is the equivalent of one tritium atom (or one THO molecule) per 1,018 atoms of hydrogen (or 1,018 H^2O molecules). One TU is also equivalent to 0.1181 Becquerel per kilogram (Bq/kg), where one Becquerel is equal to one decay per second (Tritium Laboratory, 2010).

Several mechanisms exist to produce tritium. It occurs naturally through cosmic ray bombardment of nitrogen and deuterium in the upper atmosphere (Carey, 2011):

$$^{14}N + {}^{1}n \rightarrow {}^{12}C + {}^{3}H \text{ and } {}^{2}H + {}^{2}H \rightarrow {}^{3}H + {}^{1}H$$

Naturally occurring tritium in the atmosphere produces rainfall with concentrations of roughly 30 atoms per square centimeter of Earth's surface per minute, or a concentration of 3-10 TU in the northern hemisphere and 1-5 TU in the southern hemisphere (Kazemi et al., 2006; Happle, 2010). Natural tritium concentrations tend to be greatest near the poles and lower close to the equator. Another natural source of tritium is through the neutron radiation of lithium in rocks (especially granitic rocks) (Kazemi et al., 2006):

$$^{6}Li + n \rightarrow {}^{3}H + \alpha.$$

The average rock-produced tritium is less than 0.2 TU (Kazemi et al., 2006). Naturally occurring tritium concentrations repreent the background level. The most important and significant sources of tritium is from thermonuclear tests. These tests began in 1952 and were highest around 1963 and 1964. Tritium concentration values differ in the northern and southern hemispheres. This is because most of the tests were conducted by countries in the northern hemispheres. All of the tritium that was added in the atmosphere from these tests create a traceable marker which can be used for age dating. At the peak in the northern hemisphere in 1963, tritium concentrations originating from thermonuclear weapons were three orders of magnitude greater than the natural background tritium concentrations. In 1963, a treaty stopped the testing of nuclear bombs in the atmosphere. Since then, the high tritium levels have nearly decayed beyond detection and atmospheric tritium is returning to pre-bomb background levels.

The chemical bonding of atoms is controlled by protons and not neutrons, which enables tritium to behave like common hydrogen, and it can therefore be readily incorporated into hydrologic and biologic cycles by replacing a regular hydrogen atom. To be considered tritniated water, at least one hydrogen atom of a water molecule needs to be replaced by a tritium atom. The amount of tritium in the atmosphere at the time of precipitation is the principal control of the amount of tritium in the precipitation. Most of the methods for analyzing tritium concentrations report only qualitative results. Exact ages of waters cannot be determined using tritium and are at best very soft values. However, values can be used as an indicator for distinct water sources.

RESULTS AND DATA ANALYSIS

Preview of a New Hydrogeologic Data Set

The data collected in this study reveals insight to the hydrologic system controlling the flow of Wingate Springs. A composite summary graph (Figure 13) is presented below to illustrate spring discharge in relation to specific rainfall events from June 2011 through June 2014. There is a one year time gap when flow was not gauged. Figure 13 shows the calculated spring flow rates at the three locations described previously. Precipitation values have also been plotted against the flow data to assess possible correlations between flow and individual storm events. Relationships between these hydrologic parameters are described in detail below with reference to additional graphs. Also presented below are tables that provide a summary of the alkalinity, anion/cation, $\delta^{18}O$ and δD, and tritium results of sampled spring water at Wingate Springs, Evey Canyon, Icehouse Canyon, and Barrett Canyon. The data is graphically illustrated to help emphasize the specific chemistry of the water at Wingate Springs. Lastly new geologic observations are described in the form of a geologic map, cross-sections and stereonet plots, with a focus on illustrating potential groundwater flow paths in three dimensions. Figure 22 is a detailed geologic map, modified from Nourse et al., (1998). This map will be referred to throughout the Geologic Observations section. The cross-sections illustrated in Figure 32 are representations of the underlying geology and its associated hydrologic properties.

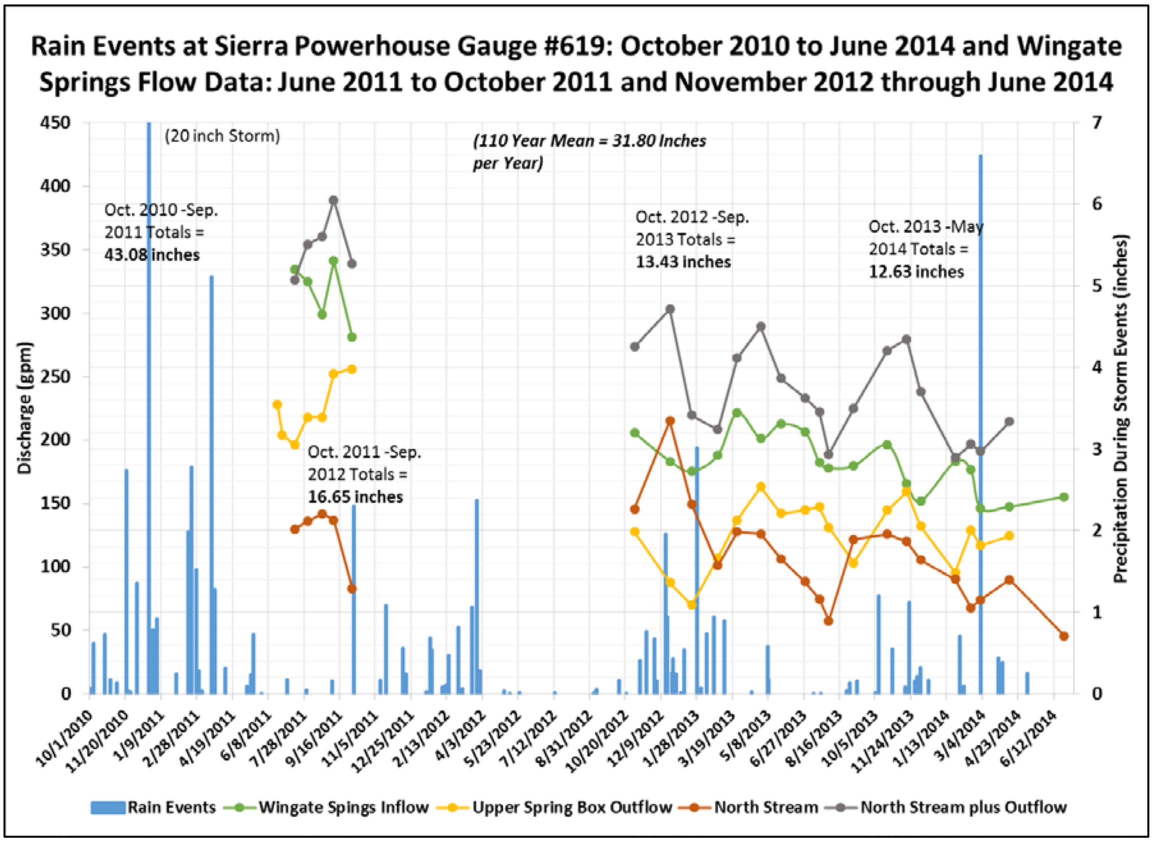

***Figure 13**. Discharge from Wingate Spring gauge locations specific rain events during the period of study.*

Precipitation

Precipitation values were recorded daily over a 110-year period at Sierra Powerhouse (Gage #619, Elevation 3,310 ft) located along San Antonio Creek about a mile south of Wingate Springs (refer to Figure 5). Precipitation data from Chapman Ranch (elevation 4,460 ft) was also analyzed. Both of these sources were plotted and compared but, due to gaps in the Chapman

Ranch data, it was only used to cross reference the Powerhouse data. The calculated 110-year mean of annual precipitation at Sierra Powerhouse is 31.8 inches. Mean annual precipitation at Chapman Ranch was 38.4 inches between 1979 and 2014, but this calculated value is missing data from 7 dry years between 1986 and 1992. Hence, the Sierra Powerhouse gauge offers the best available measure of historical precipitation at Wingate Ranch.

Detailed records of the last four rainfall seasons are graphed in Figure 14. This chart shows values of rainfall for individual storm events. Also noted are annual precipitation totals for the 2010-2011, 2011-2012, 2012-2013 and 2013-2014 hydrologic years. A hydrologic year is defined as the time interval between October 1 of one year and September 30 of the subsequent year.

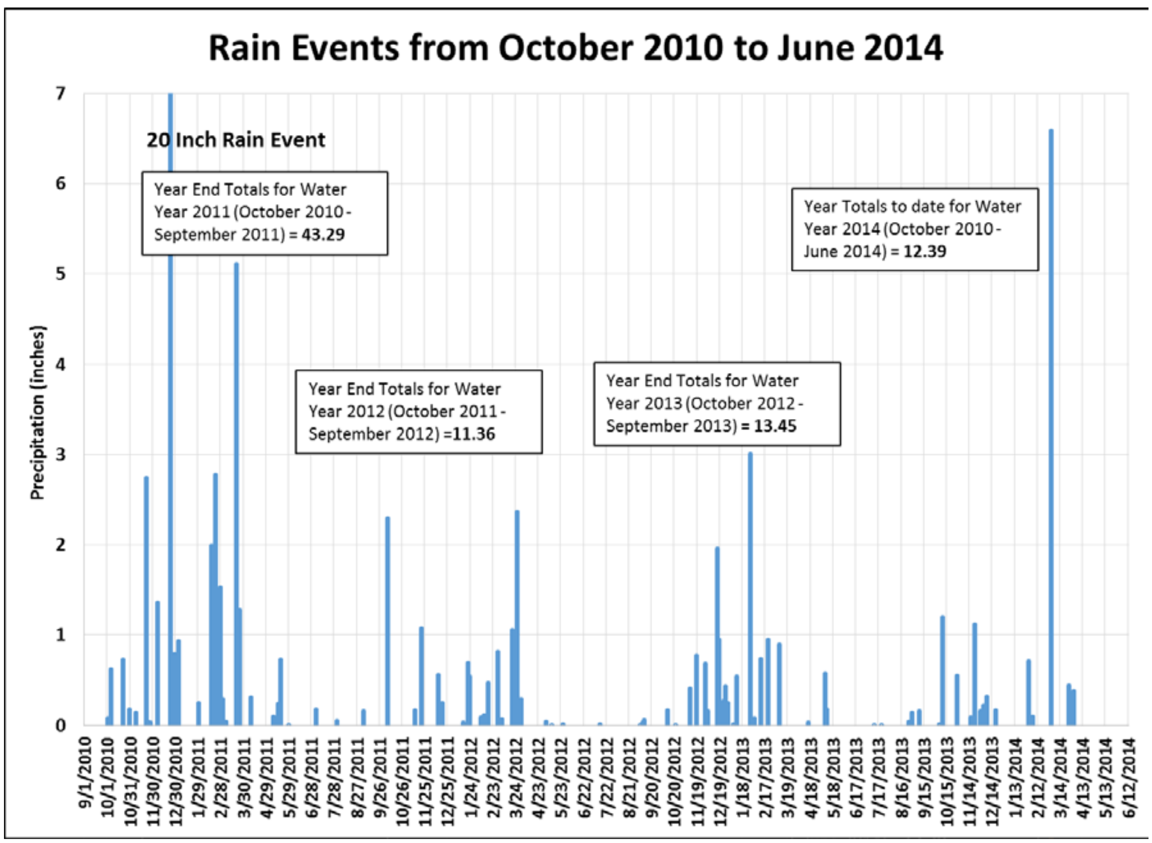

Figure 14. Individual *precipitation events from October 2010 to June 2014.*

Five of seven years before the summer of 2011 recorded higher than average precipitation at Sierra Powerhouse (Figure 5). The 2004-05 and 2010-11 water years recorded some especially intense storms exceeding 10 inches. Spring of 2011 was then followed by three years of extreme drought; less than half the average rainfall. A complementary view of these “feast and famine” trends is provided by a graph of cumulative departure from the mean vs. time (Figure 5). In general, values greater than the 110 year mean of 31.8 inches represent positive storage of groundwater in the watershed, whereas values below 31.8 inches indicate a deficit in storage. The transition from a wet period to a drought is demonstrated by the decreasing values and a negative slope in the cumulative departure from mean curve since the end of the 2011 wet season (Figure 5). Droughts of similar magnitude occurred during previous decades (e.g., 1984-1992 and 1999-2004).

Flow Data

Flow data collected throughout the course of this investigation reveal some interesting spatial and temporal trends. Described below are discharge measurements from three locations that were gauged at approximately 2-to 4-week intervals during the period of study. These three locations include: 1) Wingate Spring Inflow; a good measure of the main Wingate Spring discharge a few meters above its diversion into Upper Spring Box, 2) Upper Spring Box Outflow; equivalent to the amount of water diverted into the domestic water supply system, and 3) North Stream Gauge; a measure of the flow not captured by the Upper Spring Box plus additional groundwater that seeps in below the spring box. Figure 4 shows the map locations of these three sites. Hydrographs of flow vs. time are presented for these three gauges (Figure 13). On the same graph, North Stream plus Upper Spring box is also presented. This graph typically displays the highest discharge values because it includes significant seepage from the water saturated ground situated between the Upper Spring Box and North Stream Gauge.

Spring Discharge in Relation to Precipitation

To help illustrate possible connections between precipitation recharge and spring discharge, flow data from 2010 to 2014 has been plotted on top of individual precipitation events that occurred during the same period (Figure 13). Included are discharge measurements for three gauging locations from the study Nourse completed during summer 2011. My data for the period October 2012 through June 2014 is plotted on the same graph, following a one year gap in the discharge measurements.

Figure 15 shows the flow data from Nourse (2011) and this study plotted against the cumulative departure from the 110 year mean of 31.8 inches/yr. The seven years prior to Nourse's study were generally wetter than average, but the years since have seen a deficit in precipitation. Despite the fact that my study was conducted in severe drought years, the flow measured at Wingate Springs is still half of that measured after the abnormally wet conditions experienced in water year 2010 - 2011. The rainfall total for that year was 43.3 inches. Mean rainfall for the previous seven years was 41.13 inches/yr.

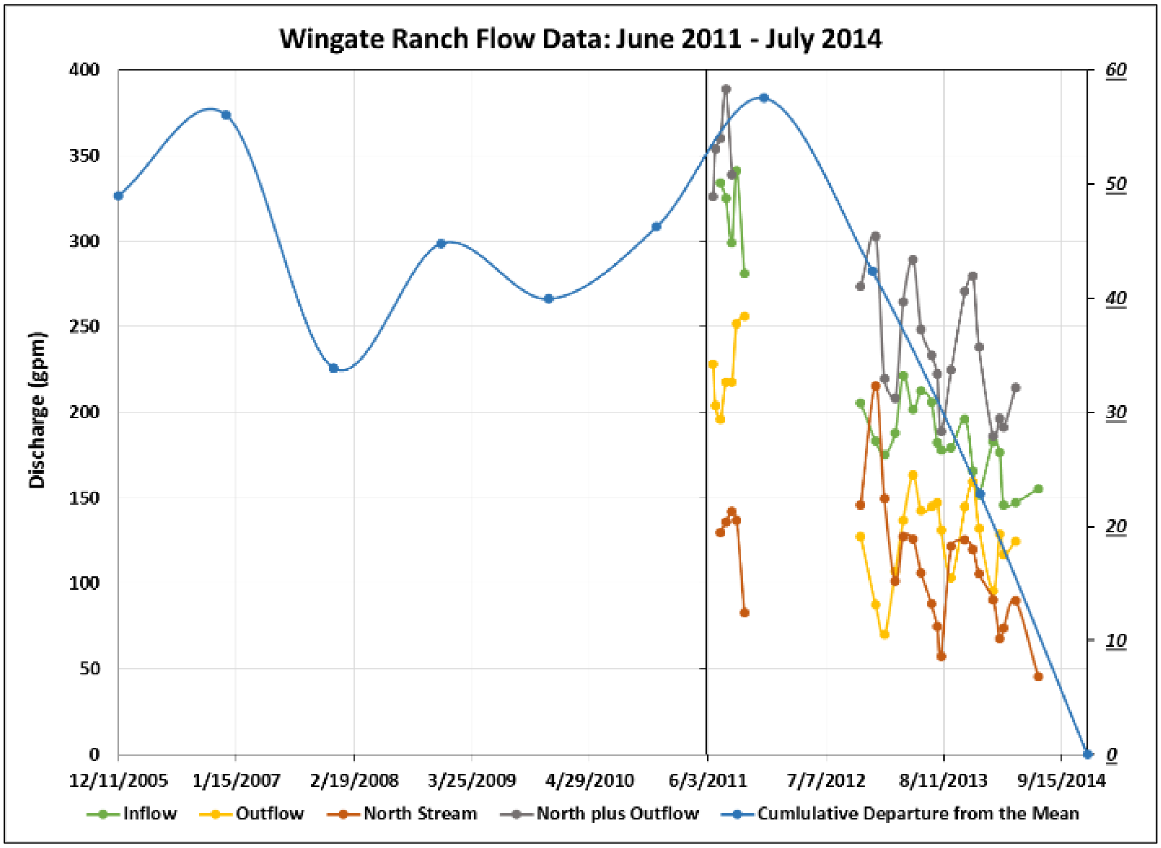

Figure 15. *Wingate Springs flow data with cumulative departure from the mean precipitation data for 110 years. Pre 2011 shows wet conditions greater than 31.8 inches of precipitation, post 2011 shows a steady decline into drought conditions below 31.8 inches of precipitation.*

It is somewhat fortuitous for this investigation that drought conditions exist so as to establish an absolute baseline for Wingate Springs. The general expectation is that these data represent very low base flow conditions. In other words, the groundwater released by various aquifer sources should be minimized because little precipitation recharge has occurred during the past three years. Also, with such low discharge, one might expect the effects of recharge by individual storms to be pronounced and measurable. However, the observed effects do not have such a straightforward interpretation.

The response of the springs following specific rainfall events and extreme wet years is complicated. Data acquired in 2011 by Nourse missed the immediate response of the extremely wet year prior to measurements (Figure 13). Nevertheless, these data represent the latent effects of that wet year. An increase in flow due to high precipitation would be expected in general, and seems to be manifested by measured discharges significantly higher than those during the current drought. However, Nourse's data set documents major fluctuations of Wingate Spring discharge despite no obvious recharge events. There was virtually no rain during the five month period of observation in summer 2011, but the flow rate jumped from 299 gpm to 341 gpm during early September 2011.

The two years of data collected for this study further complicates the relationship between the springs and the response to specific rainfall events. Wingate Spring flow does appear to increase during the weeks following a major rain storm. This increase is not immediately apparent; significant delay between the end of the storm and the increase in discharge has been observed. In fact, Wingate Spring has even shown an increase in discharge three months after rain events, as shown in Figure 13 after rain events of early February 2013 and late February to early March 2014. Similar anomalous fluctuations were also observed during the first few months of data collection in my study. Most of the anomalies happen in the spring months. Such fluctuations might be caused by irregular snow pack and snow melt cycles. This would help explain why the variations tend to occur in the spring months. However, still unexplained are major fluctuations observed in the summer months.

The Wingate spring system is very dynamic and flow can be difficult to measure due to the down slope spring discharge configuration. The spring is located within a landslide unit and not directly above an impermeable surface like many of the Icehouse Canyon springs. Because of this configuration, the spring water becomes diffuse within the landslide material and saturates the meadow below. Although flow at the Wingate Spring Inflow gauge is usually higher than that of both the Outflow and the North Stream, if the flow from the latter two is combined, it is typically greater than the Wingate Spring Inflow.

Differences in flow response between the three gauges are best exemplified by the large rainfall event of February 28 through March 2, 2014 where North Stream experienced a more rapid increase in flow than both the Wingate Springs Inflow and Outflow. However, this variation was short lived. This suggests that the surrounding effluent area (drainage of shallow groundwater from surrounding material) affects the flow of North Stream more than that of Wingate Spring Inflow. This is an important piece of information. Because Wingate Spring Inflow does not have a quick reaction to precipitation, it is likely influenced by a much deeper and larger source. Still, flow at Wingate Spring is not entirely independent of precipitation. The reaction to precipitation events for Wingate Spring is much more sustained than that for North Stream. This is seen in Figure 13, where readings were taken during the March 2, 2014 precipitation event and two weeks post event.

North Stream tends to show a more rapid response which correlates to individual storm events. The same is the true during generally, wet vs. dry periods. This observation suggests that North Stream is more influenced by shallow groundwater discharge from the landslide material and wet meadow surrounding the springs.

While Wingate Spring Inflow gauging location appears to fluctuate a small amount with precipitation, Upper Spring Box Outflow and North Stream demonstrate much more variability after precipitation events. This variability may arise from the fact that these two locations are basically splitting the volume of spring water from Wingate Springs. The Upper Spring Box Outflow can only collect what comes into its inlet and almost all the water that gets diverted away from the inlet ends up in North Stream. This relationship is also seen in Figure 13: as Upper Spring Box discharge increases, North Stream decreases, and vice versa. The other interesting fact is that when the Outflow and North Stream are added together they are always more than the Wingate Spring Inflow, (also illustrated in Figure 13).

Base Flow Recession of Wingate Spring

The nature of the springs in San Antonio Canyon are defined in part by their individual base flow recession constants. The measure of the rate at which groundwater discharges out of a defined basin after most or all precipitation stops for the year is known as the base flow recession. Best results are seen during periods with little to no rainfall where spring discharge decays over time in the form of an exponential curve. The base flow recession constant is calculated from flow measurement data collected at regular intervals over this time period. The shorter the interval (e.g., days, weeks, months) the data is collected over, the better the flow curve is going to be represented and the more accurate the base flow recession constant will be.

A base flow recession analysis was conducted on flow data from Wingate Spring Intake gauge to allow comparison with similar analyses from other springs in San Antonio watershed. The main Wingate Spring Inflow was chosen because it is the primary upstream groundwater source, directly tied to an upstream point of spring discharge. Also, this is the least impeded gauging location and represents the best sample for the springs. For this study, measurements were taken roughly every month. Due to the Wingate Spring's location on private property, access was limited and had to be scheduled. Results of the base-flow analysis are graphed on Figure 16.

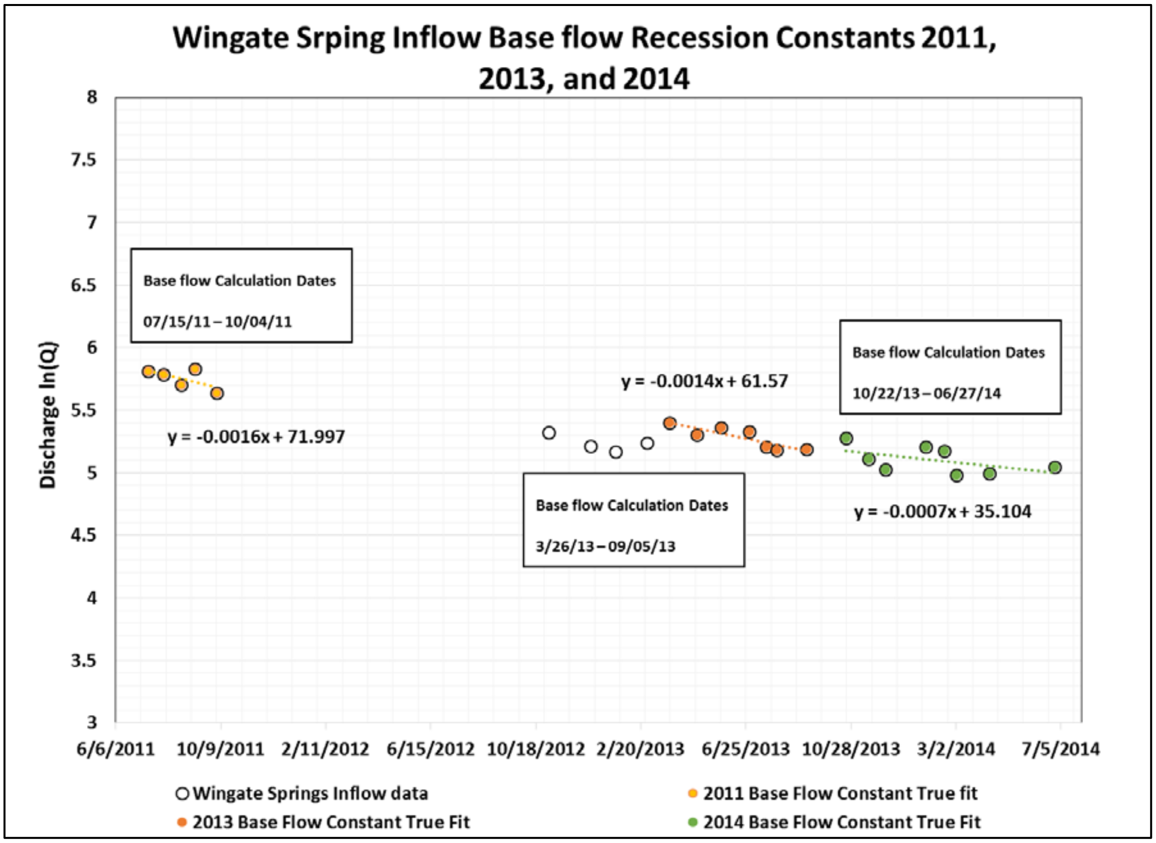

***Figure 16**. Base flow recession graphs for Wingate Spring for the years 2011, 2013, and 2014.*

The base flow recession constant (expressed in units of days^{-1}) is the slope of the recession line on a plot of natural log (ln) time the discharge vs. time. The exponential decay equation for base flow recession: $Q = Q_o e^{-at}$ may easily be manipulated to that of a straight line:

$$\ln Q = \ln Q_0 - at$$

Where Q = flow at specific time, and Q0 = flow at peak or end of wet season, and a = base flow constant, and t = time. When the data is graphed as the natural log of discharge versus time, the slope of the line is equal to the negative value of the base flow recession constant, a (Fetter, 2001).

With the exception of October 2013 through June 2014, data from only the dry (recession) months were plotted to calculate base flow recession constants. Much care was taken to select base flow recession beginning and ending points for data collected in 2011 and 2013 for the Wingate Spring Inflow gauge location. This was done to avoid major storm inputs. It was difficult to choose end points for the 2013 through 2014 data due to many intervening storms. Start and end times of the recession periods are noted on Figure 16.

Base flow recession data from Nourse's hydrologic study in 2011 on Wingate Springs may be visually compared on Figure 16 with two other recession events documented during my current study. The base flow recession constant for the 2011 recession (0.0016 $days^{-1}$) indicates a greater rate of drop off than the recessions calculated for 2013 and 2014 (0.00114 and 0.0007 $days^{-1}$, respectively). There are multiple explanations for the larger base flow recession constant calculated for the earlier data set: 1) Data was only taken for a four-month period and did not include earlier months. This data may only represent post snow melt, which might increase the rate of decay seen in the data. 2) The previous wet year increased maximum flow rates, which then would cause a sharper decline in flow than in a normal or drought year. This is because there will be more groundwater in the unconsolidated material (landslide) through which groundwater more readily flows, so the base flow recession constant will seem greater right after an extreme wet period. 3) A combination of 1) and 2) where the extremely wet year followed by minimal data illustrated a steeper drop in recession constants. Although the base flow constants are different between Nourse's 2011 study and this one, there is still a clear difference between Wingate Springs and other springs in San Antonio Canyon (as described below in the next section).

One indicator of a deeper source for spring water discharge is a low base flow constant because this shows that the spring has a large, continuous supply of water. The overall flow through Wingate Springs Inflow is relatively consistent. Although the volume fluctuates with wet and dry years, the overall recession is minimal. It then becomes clear that this spring is being consistently fed by another source other than local and recent precipitation and rapid drainage from the Cow Canyon Landslide aquifer. The annual recession shown on Figure 16 suggest a water source that is only slightly affected by surface water, and therefore must have a deeper/older source.

Base Flow Comparison with Other Springs in San Antonio Watershed

Wingate Springs does not display the classic exponential decay of a base flow recession during the dry (drought) months as some of the other springs in the San Antonio Canyon do. Most other springs in San Antonio Canyon show steeper decays over shorter times. As described previously, there are several pulses of discharge at Wingate Springs with no obvious connection to rain events. Still, it is possible to generate base flow recession curves for select time intervals. For comparison, base flow recession curves for springs in Icehouse Canyon to the north are shown in Figure 17. Spring #1 and Spring #2 illustrate typical recession constants for this area. These springs are also situated within landslide deposits. Another comparison is provided by data from Evey Canyon (Soto et al., 2013), but flow data is very limited here (Figure 18).

Base flow recession constants compared to this study's reveal that discharge at Wingate Spring does not decrease as rapidly as other springs in the area. Icehouse Canyon and Evey Canyon springs show a steeper slope with base flow constants averaging around 0.00763 $days^{-1}$ for Icehouse (Carey, 2009), and around 0.0035 $days^{-1}$ for Evey Canyon (Soto et al., 2013). Wingate Springs show values ranging from 0.0007 to 0.00016 $days^{-1}$ with an average of 0.0015 $days^{-1}$. Below are some of the base flow recession graphs for Icehouse Canyon Spring #1 and #2, Evey Canyon Spring, Lower San Antonio Canyon Springs A, B, C and Hogback Springs.

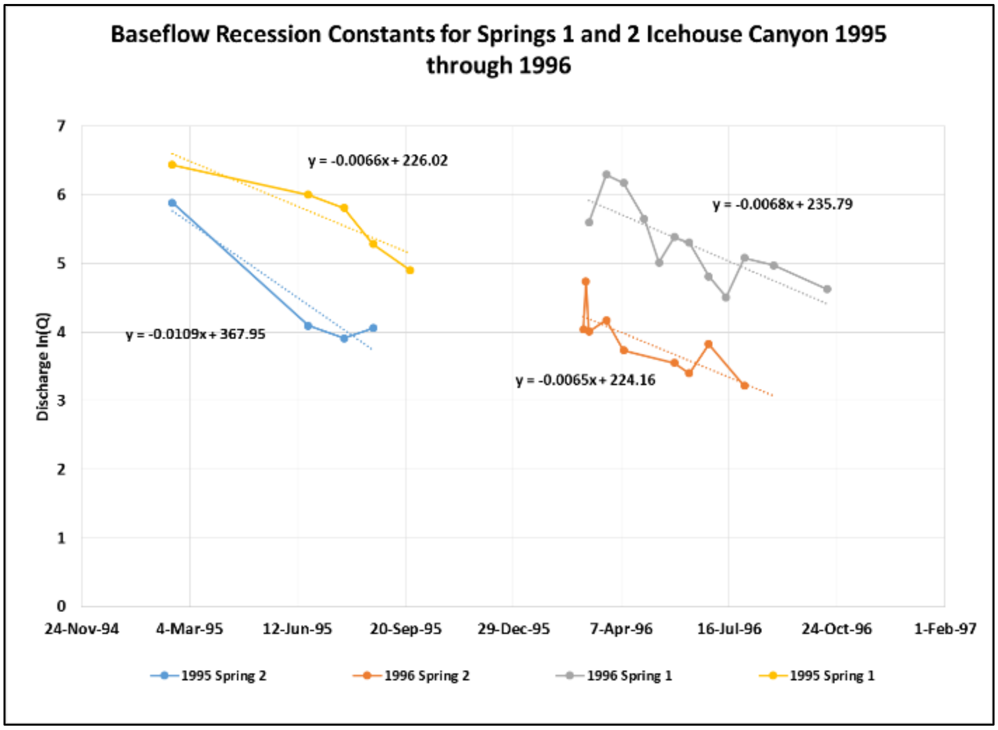

Figure 17. *Base flow recession constants for Icehouse Canyon Springs #1 and #2. (Carey, 2009; Nourse et al., 2010).*

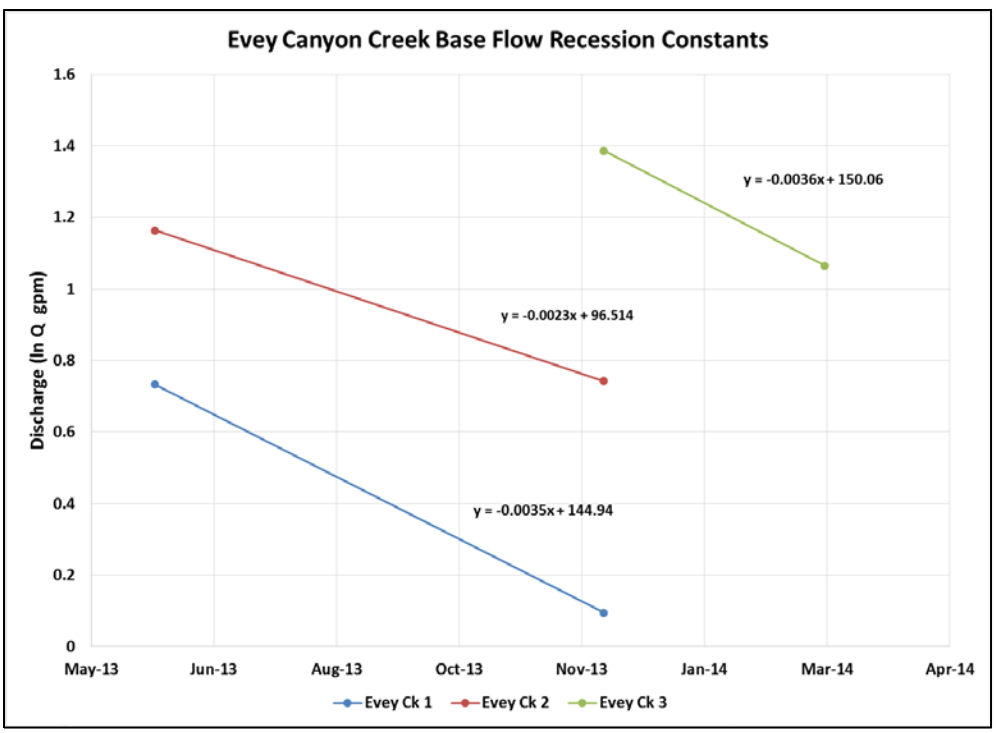

Figure 18. *Base flow recession constants from Evey Canyon (Soto et al., 2013).*

Table 3. *Comparison of base flow recession constants for various springs and streams in the eastern San Gabriel Mountains. Data sets include Strand (2006), Carey (2009), Nourse et al., (2010), Bloom (2012), and Soto et al. (2013).*

Base flow Recession Constant Comparissons for Springs in San Antonio Canyon and San Dimas Draingae Basin	
Location	**Baseflow Recession (days^{-1})**
Wingate Springs 2011	0.0016
Wingate Springs 2013	0.0014
Wingate Spring Average (2011 & 2013)	0.0015
Wingate Springs 2014 (Incomplete data)	0.0007
Icehouse Canyon Average	0.0068
Upper San Antonio Canyon Average	0.0185
Lower San Antonio Canyon Average (2012)	0.0074
Evey Canyon (Incomplete data)	0.0031
Wolfskill Creek (San Dimas Drainage)	0.0190
Middle Fork (San Dimas Drainage)	0.0320
East Fork (San Dimas Drainage)	0.0246

Table 3 shows the average base flow recession constants for springs in Icehouse Canyon, Lower San Antonio Canyon, Upper San Antonio Canyon, Evey Canyon, and three spring-fed creeks in San Dimas Canyon Drainage: East Fork, Middle Fork, and Wolfskill Creek. After comparing Wingate Spring to the other springs in Table 3, it is clear that Wingate Spring has a significant lower base flow recession constant than the other springs in the area. The largest base flow recession constants of this group all lie in San Dimas Drainage where lower elevations and small hills may lead to more evapotranspiration and therefore less flow sooner (Strand, 2006). Icehouse Canyon, Upper San Antonio Canyon, and Lower San Antonio Canyon exhibit moderate base flow recession constants, with averages of 0.0068 days^{-1} (Carey, 2009), 0.0185 days^{-1} and 0.00746 days^{-1} (Bloom, 2012) respectively.

Wingate Springs has a base flow constant of 0.0015 $days^{-1}$ when the average is taken between 2011 and 2013. The base flow constant for 2014 is determined from incomplete data, which might help explain the extremely low constant of 0.0007 $days^{-1}$. Without averaging the base flow constants for Wingate Springs for the years 2011, 2013, and 2014, a decreasing trend is seen after two dry years. In 2011 after an extreme wet year, the base flow recession constant is 0.0016 $days^{-1}$, the base flow constant in 2013 is 0.0014 $days^{-1}$. For 2014, it is 0.0007 $days^{-1}$. After continuous drought years. This trend is interesting and will need to be studied more, but the fact that the base flow recession constants seem to decrease with drought might be a result of the immense size of the water source, or maybe after two good wet years the base flow recession has yet to level out. Either way, the discharge out of Wingate Springs is not characteristic of springs within San Antonio Canyon.

Although the springs in the San Dimas Drainage area do not reside in San Antonio Canyon, they were used as a comparison between geographical locations. As stated in Strand's 2006 and Vathansins's 1999 studies, possible reasons for different base flow recession constant values could be due to the direction of the canyons. Evapotranspiration values have been seen to reach over 80% in canyons trending North-South, which would drastically reduce the amount of recharge available for groundwater flow and ultimately spring discharge.

Icehouse Canyon, Upper San Antonio Canyon and Wingate Spring are much more comparable to each other due to similar precipitation values, elevation, and watershed areas. Upper San Antonio Canyon covers the most area at about 4.71 square miles, while Icehouse Canyon has an area of about 3.91 square miles. Kerkhoff Canyon, which may supply Wingate Springs, is about 1 square mile. This difference in watershed area is deceiving at first because even though Kerkhoff Canyon has the smallest of the three areas, Wingate Springs has the lowest base flow recession. This seems counter intuitive. However, while the area is small, the potential volume of groundwater supply may be large. Tritium sampling is one way to help understand groundwater flow paths.

Water Chemistry Analyses

Alkalinity Measurements

Alkalinity analysis of water samples may suggest how long the water flowed through the ground (flow path) which helps in identifying spring source and flow paths. Table 4 shows the calculated values for alkalinity of the Wingate Spring, Garden of Eden Springs and Kerkhoff Wall Spring (collectively referred to as Wingate Springs here), along with samples collected from Evey and East Palmer Canyons (Soto et al., 2013). All of the Wingate Springs samples show results of a low to moderately alkaline water which points to a water source that is relatively clean. Whereas the Evey Canyon samples are a little more alkaline. This slight difference may mean that the Evey Canyon samples had a longer flow path or that the rocks through which they flowed were more alkaline. It also could be due to biological processes. This is also a first indication that these two waters may have different source locations.

Table 4 - Alkalinity Results

Alkalinity Results	
Sample ID	**mg/L**
Wingate Spring 1	125.858
Kerkhoff Wall Spring 1	187.53
Garden of Eden Spring 1	160.47
Evey Canyon Creek-mid	247.13
Evey Canyon Spring 1	194.39
Evey Canyon Spring 2	192.89
Evey Creek Canyon Site	192.42
East Palmer Spring 1	216.01

Ion Chromatography

The ion chromatograph results presented in Table 5 allow comparison of three spring samples from the Wingate Ranch study area to various spring and stream samples collected in other tributaries of San Antonio Canyon. The data from Evey and Palmer Canyons were presented by Soto et al. (2013). None of the water samples show evidence of marine influence. The three samples from my study area have comparable sulfate concentrations between 26 and 31 mg/L. The Kerkhoff Wall spring sample is somewhat more elevated in chloride, possibly due to its proximity to Kerkhoff Canyon alluvial deposits that may provide a component of groundwater from a near-surface source. The Barrett Canyon and Cascade Canyon samples, located one and two drainages, respectively, south of Kerkhoff Canyon, have elevated sulfate values between 39 and 205 mg/l. This anomaly is possibly caused by groundwater interaction with pyrite-bearing bedrock and clasts in the Spring Hill Landslide. This data may suggest that Wingate and Kerkhoff Wall Springs are sampling a different groundwater source.

The Wingate samples show little evidence for shallow or anthropogenic waters due to low concentrations of NO_3, whereas these values are elevated in the Evey and East Palmer Canyon samples. This is one indication that groundwater from these different watersheds may have different sources and flow paths. All higher elevation springs in Icehouse, Wingate, and Barrett Canyon have minimal nitrate values, possibly indicating that anthropogenic contamination is restricted to Evey and East Palmer Canyons.

Table 5 *- The Ion Chromatography Results*

Ion Chromatography Results (mg/L)					
Sample ID	**F**	**Cl**	**NO3**	**Br**	**SO4**
Garden of Eden Spring 1	0.4120	0.6957	0.3433	N.D	26.1627
Wngate Spring 1	0.2783	0.6811	0.5419	N.D	30.9045
Kerkhoff Wall Spring 1	0.4419	1.3185	0.7888	N.D	30.8329
Evey Canyon Spring 0	1.4715	4.8318	7.9255	N.D	28.5144
Evey Canyon Creek mid 1	1.4090	5.2189	2.9892	N.D	30.3940
Evey Canyon Spring 1	1.3067	5.1369	3.2635	N.D	24.7839
Evey Canyon Spring 2	1.3759	4.9303	3.4366	N.D	26.5496
Lower Evey Creek 1	1.4721	5.9489	1.3150	N.D	38.1346
East Palmer Spring 1	1.3684	5.8875	4.3883	N.D	20.6911
Icehouse Spring 1	0.1963	0.6551	0.4464	N.D	17.6099
Icehouse Spring 2	0.1775	0.5586	0.5808	N.D	13.9164
Cedar Spring 1	0.1157	0.5583	0.2732	N.D	22.5519
Cascade Creek	0.5250	2.0210	0.1433	N.D	204.5296
Barret Canyon Creek 1	1.0657	0.1333	0.4122	0.0210	38.6591
Barret Canyon Creek 2	1.1169	0.1738	0.6551	0.0187	41.8881

δ^{18}O - Deuterium Isotopic Analyses

Stable isotopes of spring water from three different locations within the Wingate Ranch area were analyzed. Results from Wingate Spring samples (Wingate, Garden of Eden, and Kerkhoff Wall Springs are compared with other spring and stream samples from San Antonio watershed in Table 6. The data are graphed on Figure 19. An important reference line is the best-fit to several samples of local precipitation that were collected and analyzed during the course of this study (see also Gonzalez, 2012, and Soto et al., 2013). These samples define the Local Meteoric Water Line (LMWL) for the San Antonio Canyon area.

Table 6 - *Oxygen and Deuterium Isotopic Results*

δ18O ‰ and δD ‰ Results				
Sample	**δ18O ‰**	**δD ‰**	**Date**	**Elevation**
Garden of Eden Spring 1	-10.5	-70	6/29/2013	4,320
Wingate Spring 1	-9.8	-70	6/29/2013	4,350
Kerkhoff Wall Spring 1	-10.1	-68	6/29/2013	3,820
Evey Canyon 1	-8.1	-52	N/A	3,040
Evey Canyon 2	-7.8	-52	N/A	2,920
East Palmer Spring1	-7.9	-52	N/A	2,550
Evey Canyon 0	-7.8	-52	N/A	2,750
Evey Mid 1	-7.5	-52	N/A	2,550
Cascade Cyn	-9.3	-62	13/13/2013	4,140
Columbine Spring	-11.0	-74	10/8/2013	6,660
Mid Cascade Creek	-9.3	-62	12/13/2013	4,000
Icehouse Cyanon Lot#20 Spring	-10.8	-73	10/9/2013	5,390
Cow Canyon Rain Event	-7.0	-39	10/9/2013	4,333
Lot#20 Spring	-10.8	-73	7/17/2013	5,390
Lower Barrett	-10.1	-67	12/13/2013	3,600
Cedar Glen Spring	-11.1	-75	10/8/2013	6,300
USAC-A	-10.9	-75	1/7/2014	6,400
Lower Evey Creek	-8.0	-53	8/5/2013	2,300
Lower Manker Spring 0	-10.7	-70	1/7/2014	5,800
Icehouse Creek Spring 1	-11.0	-75	7/19/2013	5,400
Lower Manker Spring 1	-10.7	-74	1/7/2014	5,790
Icehouse Canyon Spring 1	-10.9	-75	10/8/2013	5,400
Cedar Glen Spring	-11.1	-75	7/19/2013	6,300
Lower Hogback	-10.3	-69	12/13/2013	3,580
North Barrett Creek	-10.3	-68	12/13/2013	3,900
South Barrett Creek	-10.1	-67	13/13/2013	3,920
Icehouse Canyon 2	-10.9	-74	7/19/2013	5,480

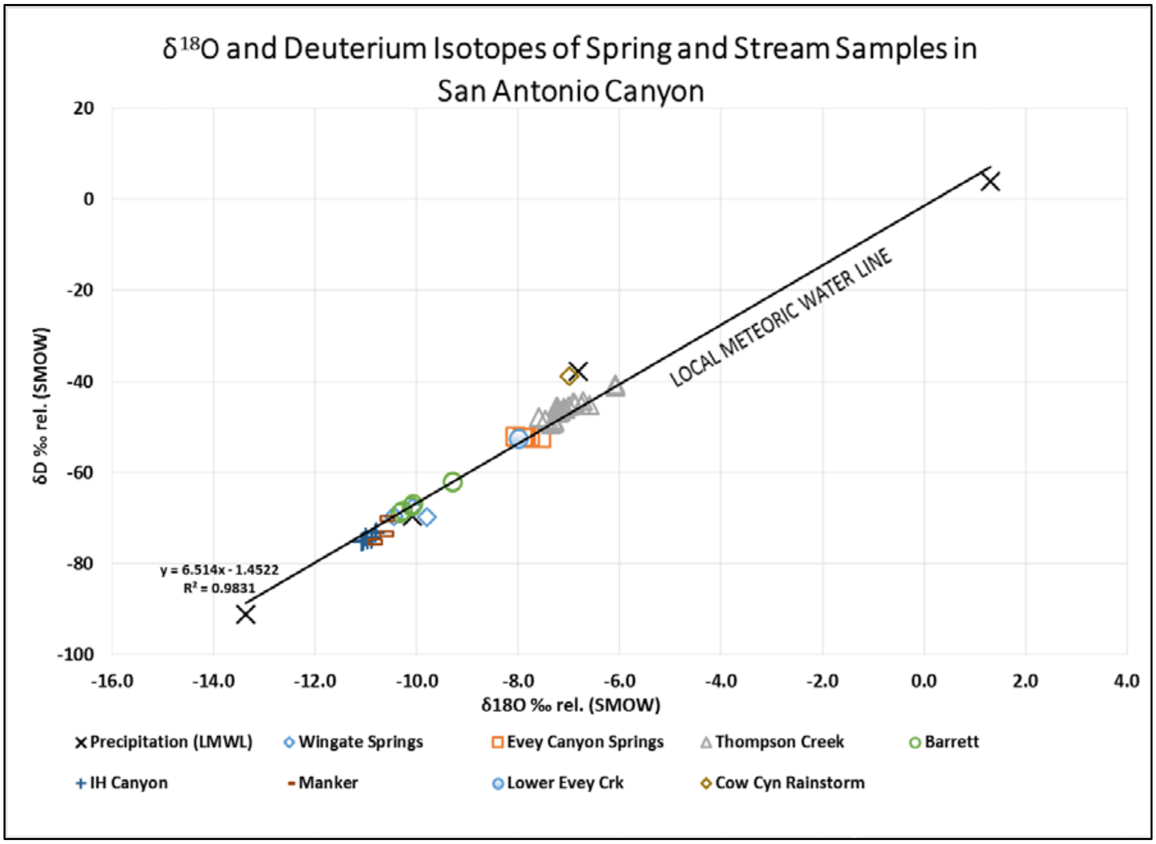

Figure 19 *– δ^{18}O-deuterium analyses from various localities in San Antonio watershed, plotted on the Local Meteoric Water Line (LMWL) (Sources of data: Soto, 2013; Gonzalez, 2013; Nourse and Osborn, unpublished).*

All of the samples from San Antonio watershed samples are grouped on or very close to the LMWL. This indicates that: 1) meteoric water (precipitation in the form of rain or snow) was the dominant source of these waters, 2) little isotopic fractionation has occurred since these waters originated as precipitation, and 3) there is little evidence of mixing with anomalous groundwater that has experienced some kind of fractionation process (e.g., seawater, hydrothermal fluids, metamorphic waters, etc.). In other words, all of the waters from San Antonio watershed including the Wingate Springs samples, have retained their original meteoric isotopic signature.

The other thing to note is that samples from specific localities cluster at different places along the LMWL. This indicates that the initial fractionation process (precipitation) occurred at different temperatures. In general, samples with higher $\delta^{18}O$ and deuterium values represent warmer temperatures, whereas those with lower values represent colder temperatures. The simplest interpretation is that different values of the stable isotopes probably reflect different elevations of precipitation recharge to the various aquifers. Is elevation an important controlling factor in the San Antonio watershed data set?

To test possible elevation controls on the clustering of stable isotopic data from different watersheds in San Antonio watershed, I examined topographic maps and determined the range of elevations for each watershed. Table 7 summarizes these variations. When the elevations are compared with specific data clusters on Figure 20, there is indeed a systematic correlation. Higher elevation watersheds generally yield lower $\delta^{18}O$ values, and vice versa.

Table 7. *Elevation distribution in various sub-watersheds of San Antonio Canyon*

Watershed	Minimum Sample Elevation feet (amsl)	Maximum Elevation of Watershed Divide feet (amsl)	Average Elevation feet (amsl)	Aveage $\delta^{18}O$
Thompson Creek	1,620	3,500	2,560	-8
Evey-Palmer Canyons	2,300	5,400	3,850	-7.8
Barrett-Cascade Canyon	3,900	8,963	6,432	-9.8
Wingate Ranch/ Kerkhoff Canyon	3,860	8,963	6,412	-10.1
Icehouse Canyon	5,400	8,985	7,193	-10.8
Manker Canyon	5,800	10,064	7,932	-10.7

Another way to test possible elevation controls is to plot $\delta^{18}O$ values of specific samples against elevations of the sample sites. This is done on Figure 20. The general relationship described above is borne out by this data set, although there is some scatter and overlap. This makes sense because the elevations where samples were collected do not actually represent the elevation of precipitation fractionation. The isotopic analyses effectively reflect the average fractionation elevation that originally occurred somewhere above the sampling site.

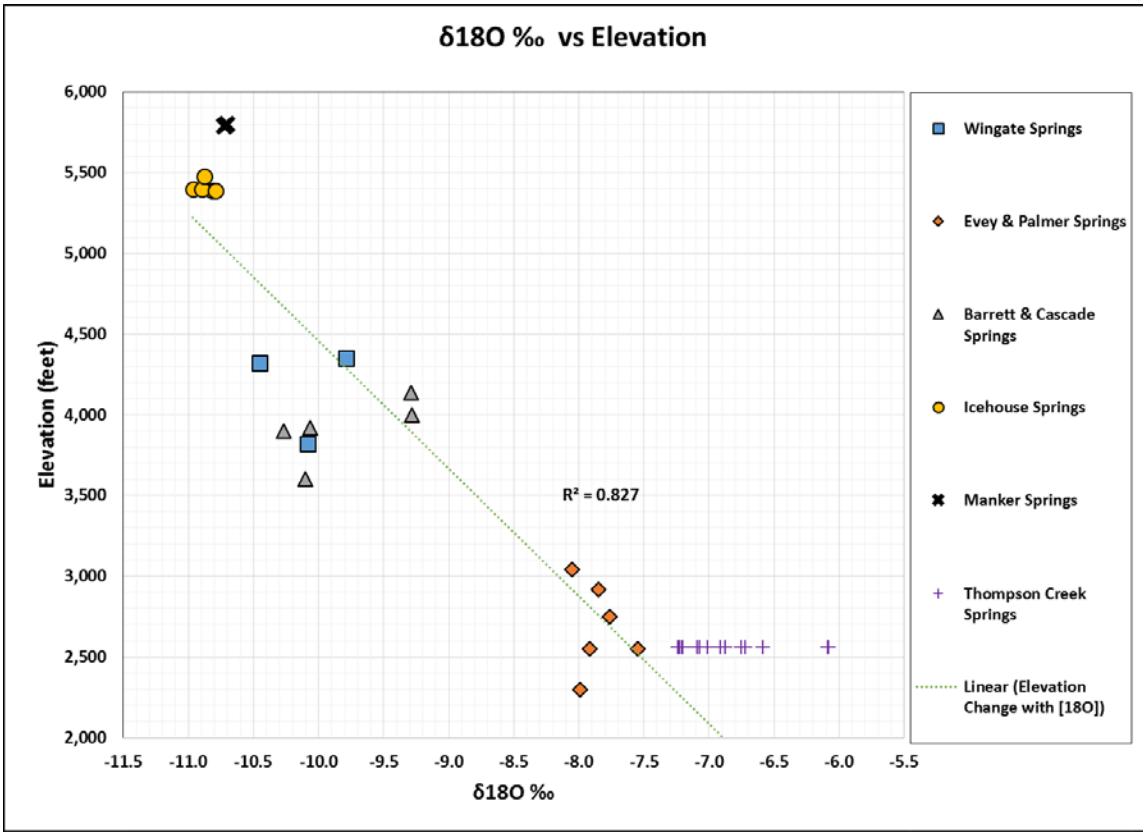

Figure 20 *–Plot of $\delta^{18}O$ concentration vs. elevation for samples collected in various watersheds of San Antonio Canyon.*

Tritium Analyses

Table 8 shows the results of tritium analyses in TU (tritium units) for spring samples collected during the course this study. Two precipitation samples were also collected at the Cow Canyon Saddle in October 2013 and at the Cal Poly Pomona campus in May 2012. Analytical results of these two rain samples were used to calculate tritium age dates for three spring samples from Wingate Ranch and various other spring samples from the San Antonio watershed. In Table 8 the 6.5 TU sample represents the overall average for the entire Southern California region. This value could be used on a much larger scale, but is probably not appropriate for my study. The TU value for the precipitation collected at the Cal Poly Pomona campus could be used, and would be a good representation due to general proximity to the San

Gabriel Mountains. However, for that same reason, the Cow Canyon Saddle sample is the closest and most accurate precipitation sample for this study area. That sample was collected just 0.5 miles northwest and at about the same elevation as the Wingate Springs, so it provides the best reference frame.

***Table 8**. Tritium Results*

Trituim Results							
Sample location	**TU (Tritium Unit)**	**TU avg for Southern California Rain**	**Estimated GW "Age" (years)**	**TU of Pomona Rain 5/13**	**Estimated GW "Age" (years)**	**TU of Cow Canyon Saddle Rain 10/13**	**Estimated GW "Age" (years)**
Garden of Eden Spring 1	**4**	6.5	8.7052	9	18.9350	11.5	18.9350
Wingate Spring 1	**3.9**	6.5	9.1591	9	14.9939	11.5	19.3890
Kerkhoff Wall Spring 1	**2.9**	6.5	14.4711	9	20.3060	11.5	24.7010
North Stream	**3.8**	6.5	9.6248	9	15.4597	11.5	19.8547
Evey Cyanon Spring 1	**2.3**	6.5	18.6274	9	24.4622	11.5	28.8572
Evey Cyanon Spring 2	**1.5**	6.5	26.2914	9	32.1262	11.5	36.5213
East Palmer Spring 1	**3.7**	6.5	10.1030	9	15.9378	11.5	20.3329
Icehouse Canyon Spring 1	**3**	6.5	13.8633	9	19.6981	11.5	24.0932
Cedar Glen Spring	**1.9**	6.5	22.0530	9	27.8878	11.5	32.2828
Columbine Spring	**1.9**	6.5	22.0530	9	27.8878	11.5	32.2828
Lot #20 Spring	**2.3**	6.5	18.6274	9	24.4622	11.5	28.8572

Tritium analysis does not provide an exact age of the groundwater sampled, but rather an estimate of how long the water has been in the ground and helps trace different waters. This estimate can be affected in many ways. For instance, if the recent precipitation came into contact with older groundwater, then the sample will be contaminated by both ages, making the measured age younger than the old groundwater and older than the recent precipitation. In this case there is an estimate of mixing which needs to be understood when calculating estimated ages using tritium. With this type of tritium analysis, small fluctuation in measured values can yield large variations in estimated ages, as seen in Table 8.

A fundamental result to be gleaned from the tritium data (Table 8) is that calculated groundwater “ages” from all of the San Antonio watershed samples are on the order of decades. These values cannot be interpreted as true ages because it is unknown how much recent precipitation with near-zero tritium age has mixed in, nor can we know the original amount of tritium when the groundwater fell as rain, possibly “decades” ago. Nevertheless, it can be concluded that the springs at Wingate Ranch are tapping a significant source of groundwater that has resided in the ground long time. The same thing can be said about other springs included in Table 8.

With the calculated estimate for groundwater ages at Wingate Ranch we can infer some qualities of that water that are supported by known geologic conditions. For example, a confined aquifer might yield very old type water (low to near-zero tritium values). There are no wells within the spring area, so well water contamination is not likely. At Wingate Springs one must consider several possible groundwater flow paths that follow precipitation recharge. This recharge to groundwater might come from infiltration through the sediment of Cow Canyon Landslide or Kerkhoff Canyon alluvium. Such near-surface groundwater might be expected to have efficient connectivity to rainfall, yielding relatively young tritium ages. This does not appear to be the case, thus, a strong argument can be made for significant groundwater contribution from fractured bedrock aquifers.

Alkalinity values (Table 4) also suggest that groundwater discharging from springs in San Antonio Canyon have relatively long flow paths which may indicate longer residence time underground. Alkalinity values of less than 10 mg/L is usually classified as rainwater. Groundwater values can range from 50 – 1,000 mg/L, so the longer the flow path, the more alkalinity in the water. The more alkalinity in the sample, the older that sample can be. By plotting alkalinity against tritium we can see a very general trend; the higher the alkalinity, the “older” the water may be (Figure 21). East Palmer Spring in Figure 21 is anomalous, but it is located within another watershed. Evey and Wingate Springs are waters within San Antonio Canyon and can there for be more easily compared. Figure 21 illustrates that samples with higher alkalinity (Evey Canyon Spring samples; 192 mg/L), usually also have longer residence time (36.5 years) underground compared to Wingate Springs which have lower alkalinity values (125 mg/L) and lower qualitative ages of around 19.4 years.

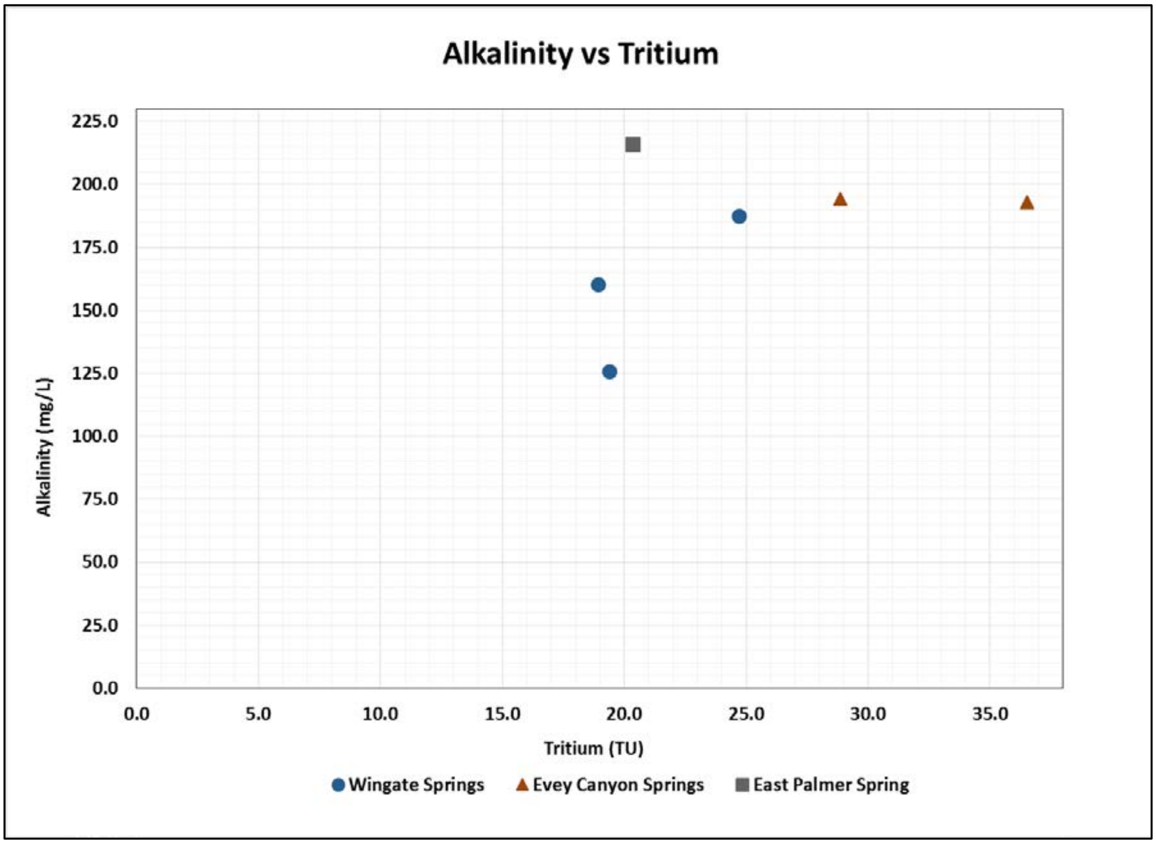

Figure 21. *Alkalinity vs. Tritium plot. Generally, as alkalinity increases so does the qualitative age of the water. Longer flow paths = longer residence time in the ground.*

There are abundant fractures and faults in this area having trends of northeast and northwest. These trends would be good conduits for groundwater flow and recharge to depth. The average range of porosities for this area in fractured crystalline rock is between 0.0 and 0.1 ρ_t, and landslide material is between 0.25 and 0.40 ρ_t. These values differ greatly but also may suggest that this spring water is coming from a deeper source because although the fractured crystalline rock has a lower porosity than that or landslide deposits, it also means that the water source would not be as affected by precipitation events as landslide deposits. The slower flow rates would also fit in with the tritium results due to the estimated ages of the waters that fall in the range of decades.

Another way to compare and contrast groundwater sources and pre-sampling flow paths is to graph $\delta^{18}O$ vs TU. This is done in Figure 22 for the Wingate Ranch, Icehouse Canyon and Evey-Palmer Canyon watershed samples. The data exhibit distinct clusters that represent significant differences between the watersheds. For example, the clusters of Wingate Springs and Icehouse Canyon samples are far removed from that of Evey Canyon samples. One general explanation for observed variation in $\delta^{18}O$ is different elevations of fractionation (condensation) for the precipitation that supplied the original water. Evey and Palmer watersheds have a much lower average elevation (3,850 ft) compared to Kerchoff Canyon/Wingate Ranch (6,412 ft) and Icehouse Canyon (7,193 ft). It is interesting that the condensation elevation implied by these data varies systematically with watershed elevation.

Wingate and Icehouse samples cluster closer to one another for various reasons. Precipitation sources of the Wingate and Icehouse spring waters were condensed at roughly equal temperatures, probably reflecting similar average watershed elevations (6,410 ft and 7,190 ft, respectively). Minor differences in TU values suggest similar residence times in the ground, although this is speculative because the relative proportion of young rainwater that mixed with older groundwater is unknown.

Wingate and Icehouse Canyon springs can be separated in two groups and therefore thought of as different waters, or they might be distantly linked by a common source. These waters are most likely different due to the distance and a major topographic divide between them. Having said that, the San Antonio Canyon Fault (SACF) intersects the Icehouse Canyon Fault and other fracture networks near the mouth of Icehouse Canyon. Faults can be both excellent barriers or conduits to groundwater flow. It is suspected that a portion of the groundwater discharged at Wingate Springs is released by the SACF (refer to Figure 33 for Cross-sections). Likewise, there is circumstantial evidence that some of the springs in Icehouse Canyon derive their groundwater from the Icehouse Fault zone (Nourse, unpublished data). This is possible because of upgradient hydrologic pressures and the conduit of parallel flow through and along the faults. If this is true, one can speculate that the two faults are hydrologically connected. In this perspective it is possible that groundwater derived from Icehouse Canyon has found its way into the gouge zone of the SACF, and then was carried down-gradient to Wingate Ranch. Potentially, the concentrations of $\delta^{18}O$ and tritium at Wingate Springs may represent a mixture that contains a component of Icehouse Canyon groundwater.

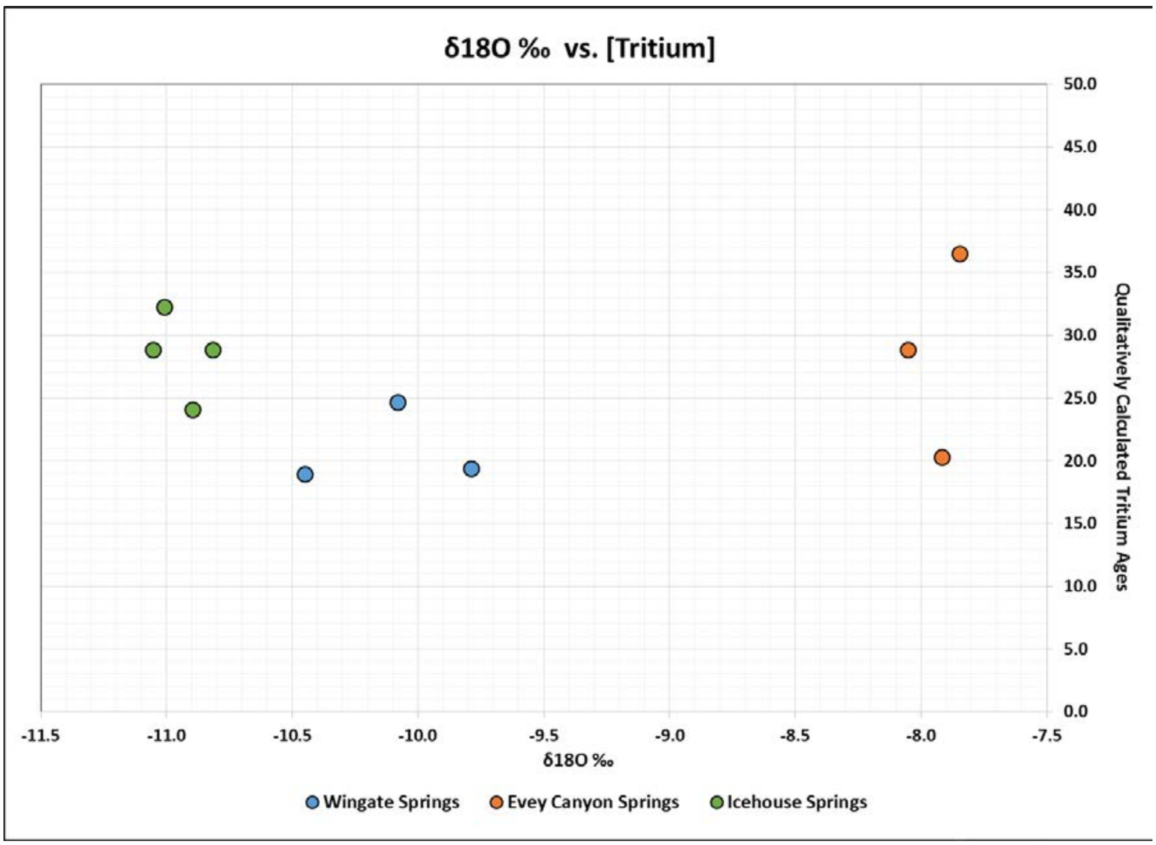

Figure 22 *– Graph demonstrating the relationship between $\delta^{18}O$ and Tritium for springs sampled at Wingate Ranch (this study) and Icehouse Canyon and Evey/Palmer Canyons (Soto et al., 2013; and Nourse and Osborn, unpublished).*

Geological Observations

Refined Geologic Contacts

My mapping at 1:3,000 scale (shown on Figure 23) reveals some significant differences from the regional geologic map of Figure 3 that represents a compilation of work by Ehlig (1958) and Nourse et al., (1998). First, the KTmy boundaries have been better located on either side of Kerkhoff Canyon. These refined contacts between the KTmy and alluvium, and more importantly the Cow Canyon Landslide, define bedrock flow barriers and help explain why Wingate Springs has such robust flow.

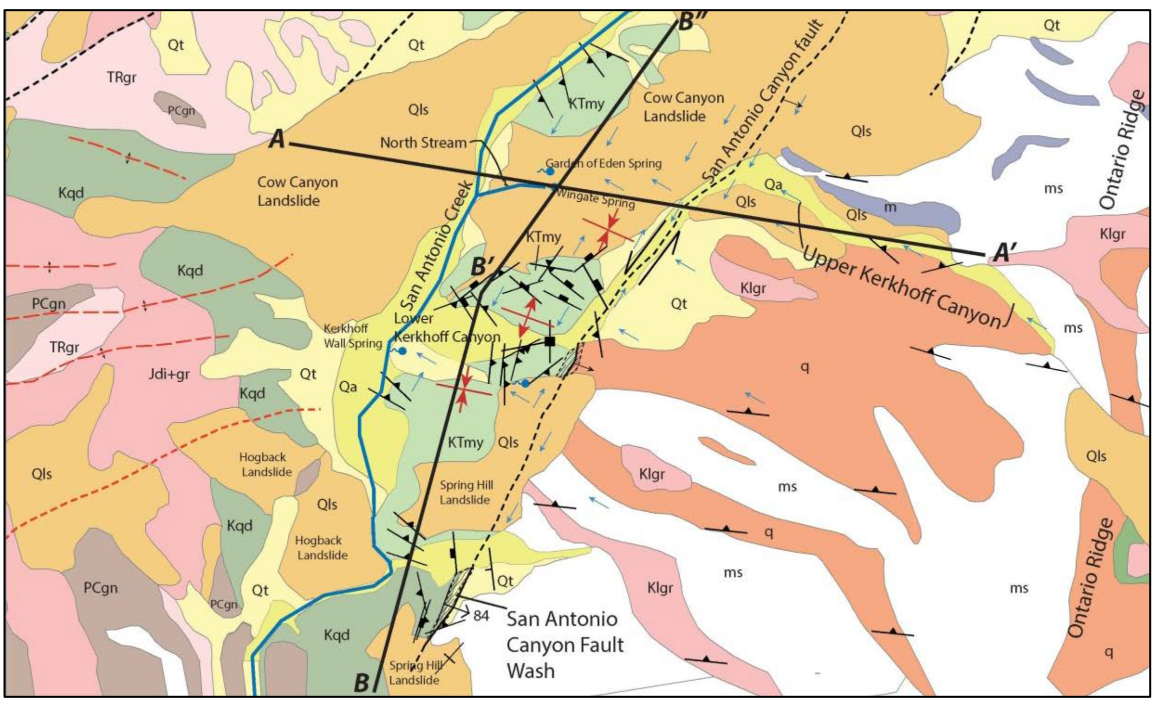

Figure 23. *Simplified geologic map of the Wingate Ranch, Kerkhoff Canyon and Barrett Canyon area, modified from the original base map of Nourse et al., (1998) presented in Figure 3. The key features shown are refined geologic contact locations, general structural trends and inferred groundwater flow paths (blue arrows). Refer to Figure 3 for description of unit labels.*

The contact between Cow Canyon Landslide and KTmy bedrock is especially important in the vicinity of Wingate Springs and Garden of Eden Springs. Due to the lush and dense vegetation surrounding these springs, mapping in the immediate area revealed little to no outcrops (Figure 24). Results of the mapping data on the ridge above Wingate Springs, and in Kerkhoff Canyon to the southeast, reveal a possible mechanism for the channeling of groundwater. Nourse and other's map of Figure 3 shows a continuous KTmy outcrop along the slope east of Wingate and Garden of Eden Springs. This outcrop is correctly shown to be overlain by landslide debris (the yellow Qls unit), but its extent is more limited. My field observations show that the previously mapped KTmy outcrop at Wingate Springs is actually composed of porous and permeable Cow Canyon Landslide debris. The northern and southern parts of the outcrop do exist, and their contacts with overlying landslide deposits slope to the south and north, respectively. The map geometry implies existence of a north-northeast trending KTmy bedrock ridge with a pronounced saddle that has been filled in by the Cow Canyon Landslide.

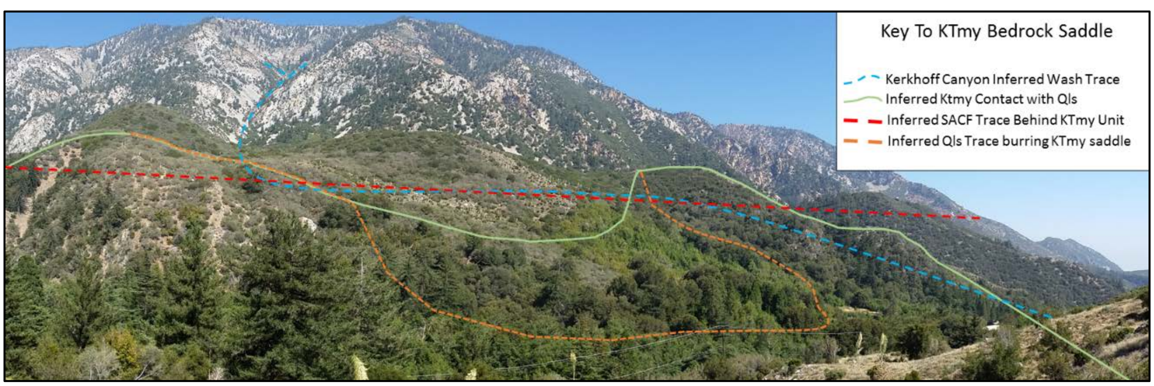

Figure 24. ***Infered*** *KTmy basal contact saddle overlain on a panoramic photo taken west of Wingate Springs from Glendora Ridge Road.*

The basal contact relationship of Cow Canyon Landslide deposit and KTmy bedrock is crucial because it is close to this contact that groundwater discharges from Wingate Springs and Garden of Eden Springs. By inference, there is probably a shallowly buried Ktmy bedrock exposure beneath the gently-sloping, water saturated meadow west of Wingate Spring. Bedrock outcrops that one might expect to see along San Antonio Creek are probably covered by reworked landslide debris.

San Antonio Canyon Fault

The San Antonio Canyon Fault (SACF) is, for the most part, elusive and very difficult to map in the Wingate Ranch area because of cover by alluvium, talus and/or landslide debris. For this reason, its exact location and orientation was inferred and shown as a dotted line on Nourse and other's geologic map (see Figure 3). The fault trace generally coincides with a sharp bend or jog in Kerkhoff Canyon, where the west-trending canyon trace appears to be offset left laterally about half mile. Location and orientation of this fault is now better constrained through projection of actual outcrops that I investigated to the south. The SACF is important to the Wingate Springs study because it provides a likely hypothetical barrier to groundwater flow derived from Ontario Peak. Its footwall also may serve as a conduit to channel groundwater that originates at depth along strike.

Due to large talus and landside deposits, the fault remains a buried, projected structure within the southwest-trending segment of Kerkhoff Canyon. Directly south of this segment, its location is constrained to be within a 50 m talus-covered interval between outcrops of KTmy and metasedimentary rock. Farther southwest, an excellent exposure of the fault zone exists in a small box canyon now named "San Antonio Canyon Fault Wash," located directly south of Barrett Canyon. The SACF was precisely located here, where I acquired abundant structural measurements. The SACF proper is defined by a perfectly preserved zone of fault gouge and breccia at least 30 m wide (Figure 25), bounded on the western edge by a 2-3 cm band of ultracataclasite (Figure 26). The cataclasite strikes N20E and dips 84SE, and projects northeast directly into Kerkhoff Canyon through a point a few hundred meters east of Wingate and Garden of Eden Springs.

Figure 25. *Oblique view showing extent of the breccia-gouge zone (the light-green pulverized rock) marking the San Antonio Canyon Fault. The more coherent rocks on the right are fractured quartz diorite. To the left are poorly exposed, inaccessible metasedimentary rocks.*

Figure 26. *Views southwest along the strike of the San Antonio Canyon Fault. Both photographs were taken from the same location. The dark streak is an ultracataclasite zone (S20W/80SE) that separates pulverized and brecciated rock (possibly KTmy?) to the southeast from fractured and faulted quartz diorite to the northwest.*

Structural data from fault exposure in San Antonio Canyon Fault Wash are presented in stereonet form to better illuminate the likely character of the buried structure that may affect groundwater flow paths near Wingate Springs. Most measurements were taken from precarious outcrops of foliated quartz diorite that composes the footwall of the SACF at this locality. This rock is pervaded by minor faults and joints, many of which are expressed as open fractures in the host rock (Figure 27). Several measurements confirm that the foliation in the quartz diorite dips consistently southwest (Figure 28).

Figure 27. *Southwest dipping quartz diorite composing the footwall of the San Antonio Canyon Fault. This view to the south-southwest illustrates abundant faults and fractures that pervade this rock.*

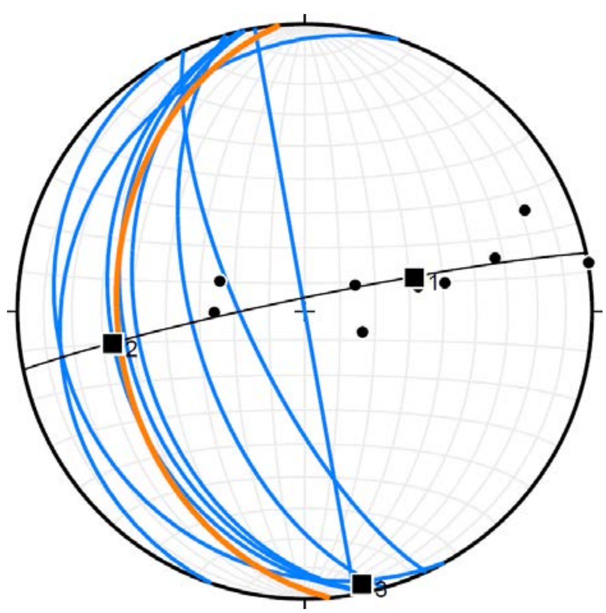

Figure 28. *Stereonet of quartz diorite foliations in the footwall of the San Antonio Canyon Fault.*

My structural observations show that the fault zone is not simply composed of impermeable fault gouge. The pervasively fractured quartz diorite footwall contains abundant minor faults and associated fractures with predominantly north-northeast strikes and steep southeast dips (Figure 29). A secondary, conjugate set of steeply dipping west-northwest striking faults also exists (Figure 30). Both fault sets exhibit striations with shallow rakes, confirming the previously inferred strike-slip nature of the SACF. In terms of groundwater flow, these faults provide a mechanism for the footwall to conduct water in directions both parallel to and transverse to the fault, as discussed later.

Figure 29. *One of the many southwest-trending strike-slip faults that pervade the quartz diorite in the footwall of the San Antonio Canyon Fault zone.*

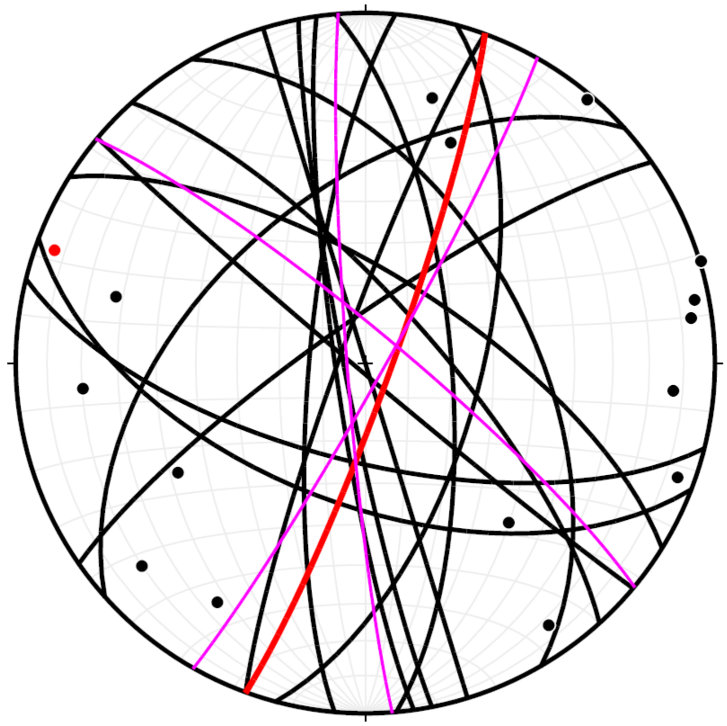

Figure 30. *Stereonet faults mapped in the footwall of the San Antonio Canyon Fault. This plot includes measurements from the KTmy unit of Kerkhoff Canyon and the quartz diorite unit of San Antonio Canyon Fault Wash. The red line shows the measured cataclasite illustrated in Figure 26; pink lines represent best fit congruent faults.*

Faults, Fractures, and Foliations in the KTmy Unit

The KTmy unit is the most abundant bedrock exposed in the near vicinity of Wingate Springs. This rock was originally a greenschist facies mylonite derived from granodiorite, quartz diorite, diorite and leucogranite protoliths (Nourse, 2002). Currently it has a very messy appearance due to a complex brittle structural overprint. KTmy forms the footwall of the San Antonio Canyon Fault in the Wingate Springs area, and also underlies the Cow Canyon Landslide that is inferred to be an important source of spring water. Brittle structures within the KTmy unit are potentially additional mechanisms to focus groundwater discharge at Wingate Ranch.

There are many different faults and fractures that pervade the KTmy unit. These are likely a smaller scale manifestation of two major fault zones (San Gabriel and San Antonio Canyon Faults) that intersect in the approximate vicinity of Mt. Baldy Village (Nourse, 2002). The San

Gabriel Fault Zone runs nearly east and west, but has been truncated by the San Antonio Canyon Fault within San Antonio Canyon (Nourse et al., 1998; Nourse, 2002). The San Antonio Canyon Fault records left-lateral oblique reverse motion, which is suggested by three distinct factors: (a) disruption of northwesterly fault trends in upper North Fork Lytle Creek drainage, (b) uplift and tilting of stream terraces in lower San Antonio Canyon, and (c) seismicity associated with the 1988 and 1990 Upland earthquakes (Heaton and Nourse et al., 1994).

Multiple faults and fractures from this area have been mapped and plotted on the stereonets of Figures 30 and 31. Most of the fractures were measured from exposures of the KTmy unit south and southeast of Wingate Ranch. The two plots are similar in that they both illustrate moderately to steeply dipping planes with northeast and northwest strikes. In general, these structures probably represent a conjugate fault network, consistent with orientations of the San Gabriel and San Antonio Canyon Faults.

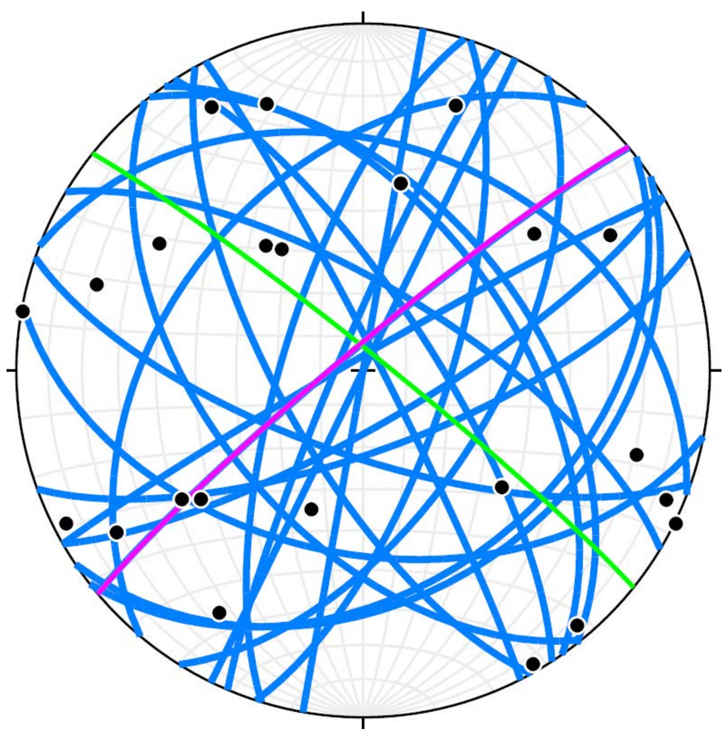

Figure 31. *Stereonet plot showing measured fracture or joint planes and corresponding poles from various KTmy outcrops west of the San Antonio Canyon Fault. Approximated best-fit planes are shown in purple and green.*

Another potentially important structure in the KTmy unit is mylonitic foliation. There is a tendency for this rock to break along the weak foliation plane. The stereonet of Figure 32 displays foliation data from the KTmy unit. The diffuse distribution of poles is broadly consistent with folding along gently southeast-plunging axes. This interpretation is supported somewhat by the distribution of foliations on my geologic map (Figure 23). Of particular interest is the suggestion of a synform structure centered about Wingate and Garden of Eden Springs. This structure coincides approximately with the buried bedrock saddle described earlier. Presuming that water-saturated fractures track this synform, the three-dimensional geometry presents another mechanism to channel groundwater toward Wingate Spring.

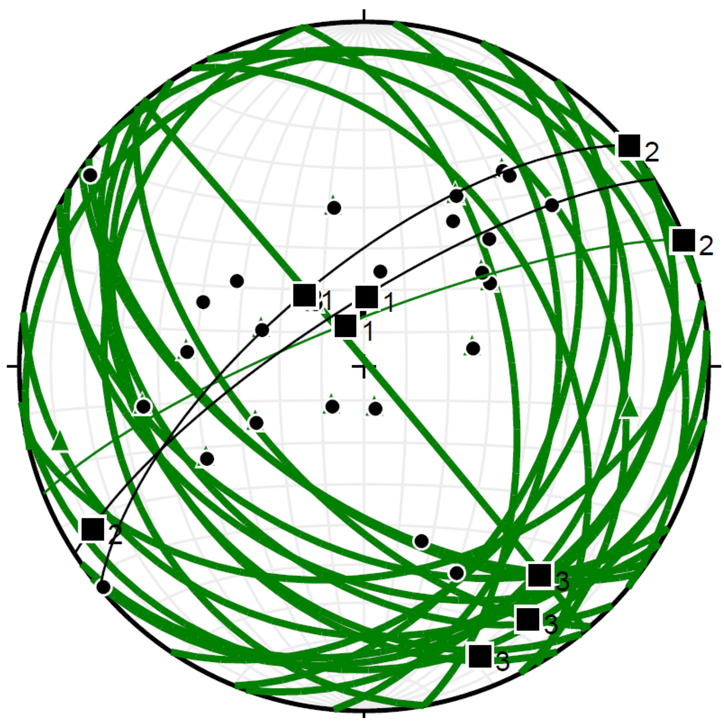

Figure 32. *Stereonet plot of planes and corresponding poles to mylonitic foliation in the KTmy unit. These data are consistent with broad folding along gently southeast plunging axes.*

Structures in the Metasedimentary Units of Ontario Ridge

Other than two foliations acquired during a difficult hike into upper Kerkhoff Canyon, bedrock structures of the Ontario Ridge block were not mapped in my study. Fortunately, a body of data exists from previous mapping by Ehlig (1958) and Nourse et al., (1998). Their contacts and foliation measurements are included on my geologic map of Figure 23. In general, the metasedimentary rock units dip moderately to steeply north and northeast. Metamorphic foliations in these units show very consistent dips of 45 to 70 degrees to the north-northeast. These structures in upper Kerkhoff Canyon and Ontario Ridge likely provide significant fracture porosity, and a mechanism to both store and transmit groundwater. Also worth noting is that the fracture network is oriented almost perpendicular to the San Antonio Canyon Fault (Figure 23). Located down-gradient from Ontario Ridge, the SACF probably forms an important hydrologic barrier, effectively representing an underground dam.

Hydrogeologic Cross-Sections

I constructed two schematic Cross-sections (Figure 33) to illustrate the three-dimensional configuration of rock and soil near Wingate Springs, and the likely groundwater flow paths. Section A-A’ is oriented west-northwest, transverse to SACF; Section B-B’-B” is oriented north-northeast, parallel to SACF. Both sections intersect the buried saddle in the KTmy unit described earlier. The intent of these cross-sections is to show mechanisms that concentrate groundwater discharge at Wingate and Garden of Eden Springs. For reference, my schematic hydrogeologic map on Figure 23 illustrates inferred groundwater flow paths with blue arrows. My interpretations are discussed in detail below.

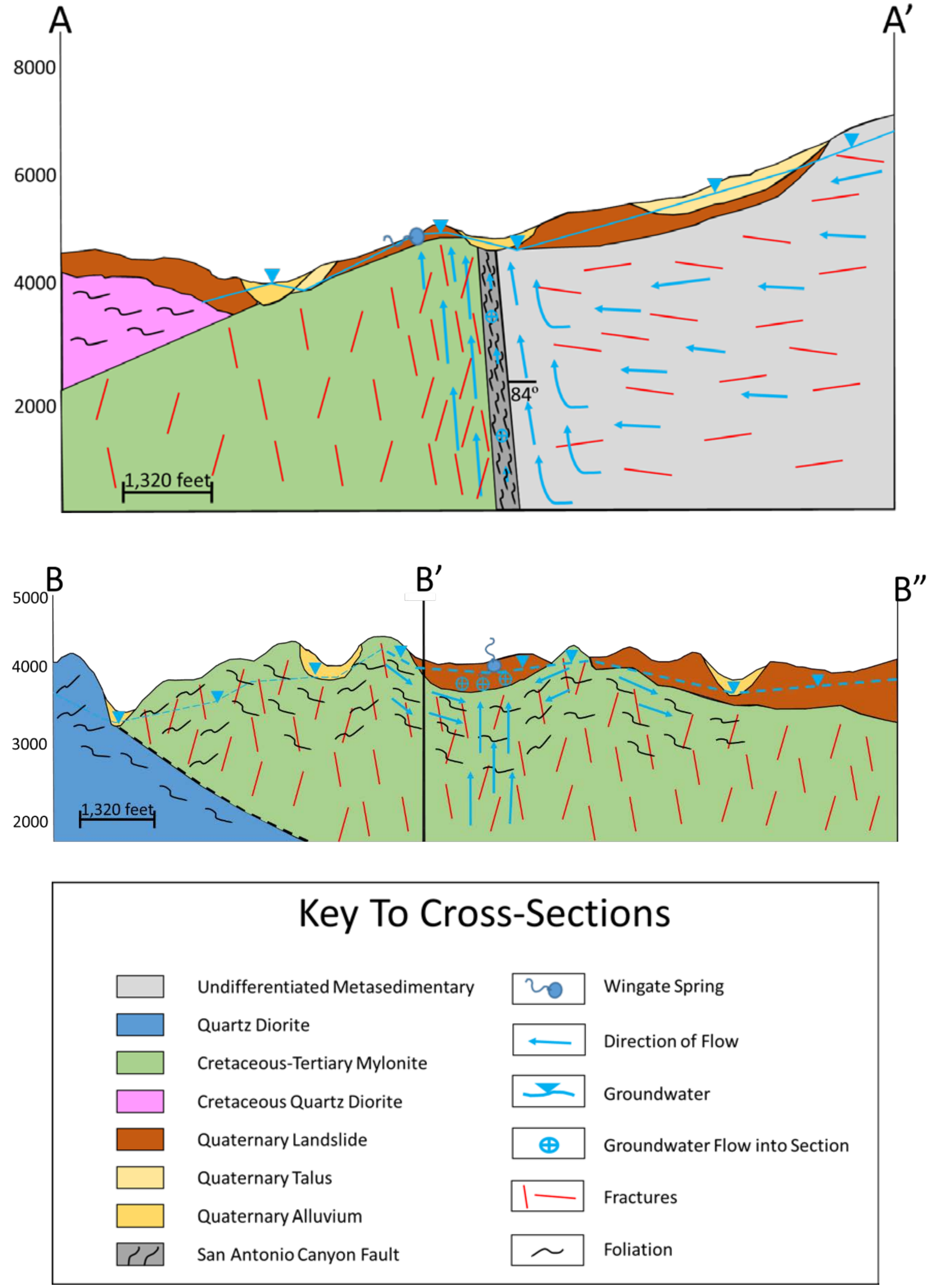

Figure 33. *Hydrogeologic cross-sections through the study area. See Figure 23 for location of section lines.*

DISCUSSION OF RESULTS

The geologic and hydrologic processes that formed Wingate Springs are both fascinating and complicated. Wingate Springs exhibit very low base flow recession constants, ranging from 0.0007 to 0.0016 days^{-1}, which are unique compared to other springs located within San Antonio Canyon. The flow data also suggest that Wingate Springs discharge is not directly related to storm events because seasonal variations are moderate, unlike other springs in the area. In addition, Wingate Springs still show robust and sustained discharge despite a three year drought. Some additional thoughts and interpretations are discussed below.

General Summary of Some Unusual Discharge Relationships

The general relationship between rainfall and discharge rates at Wingate Springs over a four year period is similar to that from other springs of San Antonio Canyon watershed in that more flow occurs during the wet seasons and less during the drought or dry seasons. However, unlike springs of Icehouse Canyon, Upper San Antonio Canyon (Nourse et al., 2010) and Lower San Antonio Canyon (Bloom, 2012), the discharge drops off at a much slower rate during dry seasons. Base flow recession recorded by Wingate Springs presents some highly unusual qualities, possibly unique for San Antonio watershed.

Despite some expected differences in discharge from Wingate Springs following a very wet year compared to discharge during extreme drought, base flow recession does not follow the normal decay that is exhibited in many of the measured springs within San Antonio Canyon (Table 3), and Wingate Spring discharge commonly shows abrupt increases not obviously connected to storm events . The graphs of Figure 13 indicate increases of flow during certain dry periods which are not seen in other springs in San Antonio Canyon. Other water sources must be contributing to the springs to make up for the exceptionally low base flow recession constants for the Wingate Springs, and poorly understood discharge fluctuations.

Precipitation Controls on Spring Discharge

Precipitation events during the past four years have been compared to discharge fluctuations of the main Wingate Spring and North Stream. Flow data suggest that individual storm events have little short-term relationship to flow of Wingate Springs. This is illustrated in Figure 13 where large storm events occurred and discharge at Wingate Spring Inflow gauge was not affected. North Stream does appear to show a more rapid response to precipitation in some cases. For example, we gauged and sampled North Stream for tritium analysis immediately after the major 6-inch rainstorm of February 28 through March 2, 2014. At this time, North Stream discharge had jumped considerably compared to its pre-storm level, while flow at Wingate Spring was unchanged.

The gain in flow at North Stream on March 2 was thought to be caused by recent saturation and drainage from the boggy area between Wingate Spring and North Stream. In other words, North Stream flow was expected to contain a large component of modern precipitation at this time. However, that precipitation event seems to have caused little dilution of tritium values (Table 8). The TU value for North Stream was 3.8, compared with 3.9 for Wingate Spring. This result is not yet understood.

Discussion of Anion Results

Water chemistry results (alkalinity measurements and ion chromatography) show the water from Wingate Springs is low in total dissolved solids. This indicates a water source that is extremely clean and pure. pH values are also consistent with uncontaminated mountain groundwater. Several other samples collected from Barrett and Cascade Canyons to the south yielded anomalous sulfate values distinctive from the Wingate Springs samples. Further investigation is required, but a likely contributing factor is a major landslide deposit on Spring Hill. The Spring Hill Landslide is characterized by its burnt orange color and sulfurous smells. Sulfur-bearing minerals like pyrite and pyrrhotite are in abundance in this landslide. The overall color of the landslide is burnt orange from iron staining, but yellowish samples have been found which smell sulfurous. Just south of Kerkhoff Canyon there is a small portion of this landslide that outcrops along the Barrett-Kerkhoff Canyon divide. I did note a wet area near the base of this deposit that should be sampled in the future. Groundwater flowing through the Spring Hill Landslide will pick up these sulfur components that will be expressed in the spring water.

Insights from δ^{18}O-Deuterium and Tritium Analyses

Concentrations of δ^{18}O in the spring waters sampled from several distinct watersheds in San Antonio Canyon (Figure 19) display a systematic relationship with elevation. As shown on Figure 20, δ^{18}O concentrations and elevation have a relationship such that the higher the source elevation of the sample, the more depleted in δ^{18}O concentration. This is due to fractionation effects associated with condensation from water vapor to rain or snow. During precipitation, water condensed at colder temperatures will have lower concentrations of δ^{18}O compared to warmer water. In terms of geography, one would expect rain precipitated in the higher elevation watersheds to be colder. Additionally, more of the precipitation may condense as snow or hail, at least during winter and early spring. Wingate Spring and Icehouse Canyon samples have more depleted δ^{18}O values than samples collected in Evey Canyon, Palmer Canyon and Thompson Creek watershed.

Figure 20 has the data separated into two distinct groups. Samples from Evey Canyon Springs typically show a $\delta^{18}O$ concentration around -8.0 $^{0}/_{00}$ and are all located at roughly the same elevation (about 2,500 ft amsl). Wingate Springs however, recorded values of around -10.0 $^{0}/_{00}$ which corresponds with a higher elevation of around 3,800 ft amsl. Just like with alkalinity and ion concentrations, $\delta^{18}O$ concentrations demonstrate that these two sources are again different. Table 5 illustrates all the oxygen and deuterium results.

Isotope results plotted on Figure 19 show that all of the spring samples analyzed from various watersheds of San Antonio Canyon originated as meteoric water, and have not experienced later fractionation and/or mixing with anomalous groundwaters. The intent of the tritium analyses was to test how long this meteoric water has resided in the ground prior to discharge at the various springs. The results shown in Table 8 have some interesting implications.

Measured tritium values in all of the springs are significantly reduced (TU=1.5-4.0) compared to the most representative modern rainfall value at Cow Canyon saddle (TU=11.5). The spring samples have a significant component of tritium which has been lost through the radioactive decay processes; these groundwaters are therefore understood to be older than modern (recent) recharge. The calculated ages cannot be interpreted as true groundwater ages or residence times because the amount of mixing with younger rainwater is unknown. These calculated "ages", on the order of decades, should be taken as minimums. Nevertheless, it can be concluded that these spring samples contain significant components of old groundwater that likely was released from deep seated fractures and faults in the bedrock units.

Potential Water Sources Revealed by Geologic Mapping

Wingate Springs' robust flow can be attributed to many factors, and it is a great area to study the dynamics of geology and hydrogeology. Geologic mapping reveals several possible groundwater sources that may contribute to spring flow in different proportions, all fortuitously focused at Wingate Springs. The porous and permeable Cow Canyon Landslide has long been considered a major source of spring water. Also important are a buried saddle within the KTmy bedrock, local fracture networks, and the San Antonio Canyon Fault, all of which may funnel deeper groundwater to the main discharge point that is Wingate and Garden of Eden Springs. A large component of the spring water sampled during 2013-14 was likely contributed by the fractures and faults in the area. Results of tritium analyses support this contention. As discussed above, the tritium data indicate significant contribution of "old" groundwater.

The cross-sections of Figure 33 in conjunction with my hydrogeologic map on Figure 23 help illustrate the poorly consolidated soil units, bedrock and fracture geometries and how they might aid groundwater transportation. Aquifers and spring discharge locations have some similar general requirements. Both need a groundwater source, preferential flow paths and some kind of barrier to the flow. In the case of Wingate Springs, the groundwater source is water contained in the Cow Canyon Landslide and fractured/faulted rock. Flow paths include water-saturated zones in low areas of various soil units and optimally oriented fracture networks. Key groundwater barriers are most likely the buried bedrock saddle and the SACF.

The fractured and faulted rocks close to the SACF present both a barrier and conduit to groundwater flow. Conjugate fractures known to exist in the footwall KTmy unit have the potential to store and transmit more groundwater due to the creation of preferential pathways. Optimally oriented fracture networks probably contribute significant water to Wingate Springs, as illustrated in Cross-Section B-B'B" (Figure 33). At the same time, the SACF proper is marked by a zone of impermeable fault gouge about 30 m in width, consisting of pulverized quartz diorite or KTmy. This steeply southeast-dipping fault would in fact make a great barrier to flow. Cross-Section A-A' (Figure 33) illustrates how the SACF may help dam up groundwater flowing through fractures and alluvium of upper Kerkhoff Canyon and Ontario Ridge to the northwest. The dipping fault likely forms a steep ramp for the dammed groundwater to spill over the KTmy bedrock beneath the Cow Canyon Landslide.

The hypothetical location at which the groundwater is channeled from fractured bedrock and upper Kerkhoff Canyon alluvium coincides with a low spot or saddle in the KTmy. Mapping reveals KTmy outcrops to the north and south of Wingate Springs with the middle portion buried by Cow Canyon Landslide (Cross-Section B-B'B"; Figure 33). In this perspective, additional shallow groundwater is contributed by the landslide deposit. Porous and permeable Cow Canyon Landslide potentially provides a large unconfined aquifer. Its basal contact with the buried bedrock saddle coincides with Wingate and Garden of Eden Springs (Figure 24). This geometric effect creates a funnel, ideal for focusing groundwater flow.

Fracture flow is thus believed to be central to the occurrence of Wingate Springs. The faults and fractures described in this report can hold lots of water and have very distinct flow paths (parallel to mapped fault trends). If these fracture planes carry down to depths of hundreds or even thousands of feet, the potential water source for springs that are fed by fracture porosity will have a very large aquifer to pull from. The tritium results show evidence of waters that are decades old, and therefore probably come from depth. The very low base flow recession constants described earlier support the notion of a robust, almost perpetual aquifer source, probably related to bedrock fractures.

CONCLUSIONS

The data collected during this study provides insight into the origins of robust spring flow at Wingate Ranch. Detailed conclusions about this study are as follows:

- Spring discharge is not simply controlled by specific precipitation events or trends. Throughout the entirety of this investigation drought conditions persisted. Although spring discharge dropped off compared to the wet year of 2011, after three full years of drought the main Wingate Spring was flowing at nearly 150 gallons per minute, which is quite anomalous for San Antonio Canyon.
- The main Wingate Spring demonstrates an average base flow recession value of 0.0015 $days^{-1}$, with a range from 0.0016 $days^{-1}$ in 2011 to 0.0014 $days^{-1}$ in 2013. These values are anomalously low compared to previously studied springs in Upper San Antonio Canyon, Lower San Antonio Canyon, Icehouse Canyon and Evey Canyon that owe their existence to drainage from landslides. Base flow constants average 0.0185 $days^{-1}$ in Upper San Antonio Canyon (Nourse, 2010), 0.0074 $days^{-1}$ in Lower San Antonio Canyon (Bloom, 2012), 0.0068 $days^{-1}$ in Icehouse Canyon (Carey, 2009), and 0.0031 $days^{-1}$ in Evey Canyon (Soto et al., 2013). This implies that there is a deeper groundwater source at Wingate Ranch to sustain the spring flow.
- $\delta^{18}O$ and deuterium isotopic analyses of the Wingate Springs samples plot on the local meteoric water line, indicating that their original source was meteoric water and has not been contaminated or fractionated since. Comparison with many other spring samples from San Antonio watershed yields a systematic relationship between $\delta^{18}O$ and watershed elevation. This is likely related to colder temperatures of condensation at higher source elevations.

- Tritium analyses yield calculated “ages” on the order of decades for the Wingate Ranch spring samples. Values between 18.9 years and 24.7 years result from calculations that utilize nearby modern rain as a baseline. Although the degree of mixing with younger waters is not known, these data indicate a significant component of a deep seated (older) groundwater is tapped by Wingate Springs. This groundwater source is most likely derived from the San Antonio Canyon Fault (SACF) and associated fracture networks within the local bedrock.
- Geological mapping of potential sedimentary and fractured bedrock aquifers in relation to points of significant spring discharge provides abundant evidence for groundwater contributions from multiple sources: 1) relatively shallow drainage from Cow Canyon Landslide, 2) groundwater that has infiltrated steeply dipping fractures of Ontario Ridge, 3) groundwater residing in fractures in the footwall of the SACF, and 4) possible far-traveled groundwater derived from deep levels of the SACF or up-gradient regions along strike with the SACF.
- The geologic coincidence of a major fault barrier/conduit to groundwater flow with a buried bedrock saddle and fortuitously oriented fractures creates a unique mechanism for focusing robust spring discharge at Wingate Ranch.

RECOMMENDATIONS

Environmental studies such as this one are crucial for our future. Water is a commodity and will be evermore so in the coming years. Understanding how water flows and why it discharges in certain areas will be not only beneficial for consumption but also for profit. To acquire more accurate age dates, different analyses will have to be performed. One such type is tritium and helium, which is a much more quantitative analysis that can be performed on the different spring waters throughout the San Antonio Canyon. Another idea is to try to establish much more extensive mapping to help make a more complete groundwater model and geologic map of the surrounding area. Another recommendation is to perform this same study during an El Niño wet year, so as to get comprehensive flow rates, and tritium data which may show significant younger age differences. This data can then be analyzed against this study's data which may reveal closer age dates and groundwater sources. Seismic refraction data can be gathered along the ridge above Wingate Springs to help confirm the hypothesis of a low point in the KTmy bedrock. Lastly, a comparison study within Barrett and Cascade Canyons could yield much different water chemistry results. Studies such as this one will need to be refined and cross referenced with others like it.

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