Understanding the source of water for selected springs within Mojave Trails National Monument, California

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ABSTRACT

While water sources that sustain many of the springs in the Mojave Desert have been poorly understood, the desert ecosystem can be highly dependent on such resources. This evaluation updates the water resource forensics of Bonanza Spring, the largest spring in the southeastern Mojave Desert. The source of spring flow at Bonanza Spring was evaluated through an integration of published geologic maps, measured groundwater levels, water quality chemistry, and isotope data compiled from both published sources and new samples collected for water chemistry and isotopic composition. The results indicate that Bonanza Spring has a regional water source, in hydraulic communication with basin fill aquifer systems. Neighboring Lower Bonanza Spring appears to primarily be a downstream manifestation of surfacing water originally discharged from the Bonanza Spring source. Whereas other springs in the area, Hummingbird, Chuckwalla, and Teresa Springs, each appear to be locally sourced as “perched” springs. These conclusions have important implications for managing activities that have the potential to impact the desert ecosystem.

KEYWORDS

Water resources; clipper mountains; bonanza spring; groundwater; forensics; isotopes

Introduction

General information and data regarding springs in the Mojave Desert are sparse, and many of these springs are not well understood. Bonanza Spring rises in the Clipper Mountains within the newly established Mojave Trails National Monument, San Bernardino County, California (Figure 1). Bonanza Spring is within the southeastern Mojave Desert, a sparsely populated area, and has generally been assumed to be a perched spring disconnected from the basin-fill aquifer system. Rapid growth and competition for water resources in the Mojave Desert is an ongoing issue and results in the need for a balancing of competing uses and priorities. These include providing water to an expanding population, preserving water-dependent ecological resources, and expanding needs of water for commercial development including alternative energy generation facilities.

In the case of Bonanza Spring, substantial groundwater development is proposed for export out of the region. Proposed groundwater development in this area is anticipated to be in excess of the groundwater recharge to the basin, resulting in basin aquifer drawdown from pumping with upgradient impacts to groundwater elevations above Bonanza Spring. Identification of future impacts from water resource utilization becomes problematic if initial baseline conditions are unknown or poorly understood. This analysis was performed with the intent to better understand the water source that sustains Bonanza Spring, neighboring Lower Bonanza Spring, and the desert ecosystem that is dependent on those resources. Bonanza Spring is the largest spring in the southeastern Mojave Desert. Despite its large size relative to other springs, Bonanza Spring is a fifth–sixth magnitude spring (Kresic, 2010), with its surface flow, not inclusive of evapotranspiration, varying around 10 gallons per minute. Small springs such as those identified in this investigation, frequently get overlooked in hydrologic investigations since their discharges are commonly inconsequential to the overall water budget of the area being studied. Such oversight is problematic when evaluating the sensitivity of critically important resources for vegetation and wildlife, both resident and migratory. Bonanza spring supports a substantial riparian area that belies its relatively small surface expression of water flow (Figure 2). That the spring is perennial is indicated by the presence of freshwater snails (Physidae sp.) that are...
reliant on fresh water to survive. These invertebrates are currently being identified to species level (Parker, 2017, pers. comm.) as many of these invertebrates can be endemic to the springs they live in.

While detailed regional hydrogeologic investigations in the Mojave region are typically sparse, the exception to this is in the area southwest of Bonanza Spring. This area of the Mojave has received attention because of the proposed Cadiz groundwater storage and recovery project (e.g., Metropolitan Water District of Southern California, 2001; Davisson, 2000; Davisson and Rose, 2000; CH2M Hill, 2011; and Geoscience Support Services, 2011). More recently, a Mojave Desert-wide spring survey (Andy Zdon & Associates, 2016) was completed on lands managed by the U.S. Bureau of Land Management (BLM) that included springs in the Clipper Mountains (Bonanza Spring, Lower Bonanza Spring, Hummingbird Spring, Lost Dutch Oven Spring, Falls Spring, Burnt Spring, and Chuckwalla Spring). Other springs of interest in the area include Vernandyles and Theresa Springs in the Marble Mountains, and the numerous springs in the Old Woman Mountains. These springs have been assumed in the past to be local springs – perched springs that rise as a result of surfacing of water that is recharged within its local watershed and not in communication with aquifers of more regional extent. The areas of the local watersheds for each of the key springs evaluated for this investigation are

Figure 1. Location of Bonanza Spring within Mojave Trails National Monument (adapted from Wilderness Society, 2017).

Figure 2. Photograph of Bonanza Spring.
approximately 50 acres for Bonanza Spring (and Lower Bonanza Spring), 147 acres for Hummingbird Spring, 25 acres for Teresa Spring, and 20 acres for Chuckwalla Spring.

Due to the striking differences in physical character between Bonanza Spring and other springs in the Clipper Mountains, this study sought a greater understanding of Bonanza Spring and the causes for its physical differences.

**Previous studies**

Hydrologic investigations in the California desert have generally been focused on answering inquiries regarding a specific need. In the Bonanza Spring area (southeastern Mojave Desert), there have been three phases of investigation, as follows: 1) an early reconnaissance phase during the early decades of the 20th century, conducted to identify presence or absence of available water at springs and other desert waterholes to facilitate safe travel, and to identify potential bases of operation for more detailed scientific investigations in the region (Zdon, 2013); 2) investigations related to development of a water resource available for export (what is today known as the Cadiz Project). Investigations related to the Cadiz project have focused on the wellfield production and potential impacts to the alluvial aquifer in the Fenner Valley Groundwater Basin and surrounding hydrologically-linked groundwater basins; and 3) a recent effort to comprehensively document and understand individual springs on public lands throughout the region.

The early reconnaissance phase investigations in this area were conducted by Mendenhall (1909) and Thompson (1921, 1929). Mendenhall described the presence of Bonanza Spring in general terms and noted that the spring was in use by prospectors at that time. Thompson (1929) noted the presence of Bonanza Spring as a spring that yielded about 10 gallons per minute (similar to what it produces currently) that was piped to the community of Danby for use at the railroad. Thompson also noted the presence of other springs along the southern front of the Clipper Mountains including one spring near the Tom Reed Mine (likely what is known today as Burnt Spring) and another spring which may be what is known today as the perennial “Hummingbird Spring.” Moyle (1967) and Freiwald (1984) provided general descriptions of the regional geologic and hydrologic conditions in the project area.

Hydrogeological investigations associated with the Cadiz groundwater development project have been summarized in the environmental impact reports (e.g., Santa Margarita Water District, 2012; Metropolitan Water District of Southern California, 2001) that have been prepared for the proposed project and attached technical reports and documents. These investigations have occurred over several decades and the project-specific literature is substantial. Of principal note related to the current project are geochemical and recharge-estimation investigations by Lawrence Livermore Laboratory (Davisson and Rose, 2000), a limited field spring survey conducted in the Marble Mountains to support the draft environmental impact report (Kenney Geoscience, 2011) and an assessment associated with potential project-related impacts to springs (CH2M Hill, 2011). The field activities associated with these groundwater development related investigations were on a reconnaissance level and few springs in the Clipper Mountains, and neither of the springs in the Marble Mountains (Theresa and Vernandyles), were identified.

During 2015 and 2016, a spring survey was conducted (Andy Zdon & Associates, 2016) for U.S. BLM lands in their Needles, Barstow, and Ridgecrest Districts (Bonanza Spring is within their Needles District). Information regarding the location and physical characteristics of the springs in this study was found in the files of the Needles District of the BLM (U.S. Bureau of Land Management [BLM], 2015). For the purposes of that investigation, 436 springs were identified of which 312 were inspected during the period from September 2015 through February 2016. Of that number, two springs were identified in the Marble Mountains (one spring, Theresa Spring has had surface flow on two visits with substantial signs of Desert Bighorn Sheep activity and wildlife-watering infrastructure present) and seven springs were identified in the Clipper Mountains (including Bonanza Spring and Lower Bonanza Spring), shown in Figure 3.

Data collected at springs visited during the 2015–16 spring survey included measurement of field water quality parameters and sampling for stable isotope analysis on all springs where surface water was present. Surface water was present at Bonanza, Lower Bonanza, Hummingbird, and Chuckwalla Springs in the Clipper Mountains, and Theresa Spring in the Marble Mountains. These springs with surface water present are investigated in more detail in the current investigation. Surface water presence has also been documented at Vernandyles Spring in the Marble Mountains and the remaining springs noted in the Clipper Mountains. Several of these springs were not visited during the spring survey but were described based on BLM file records (U.S. BLM, 2015) and remote imagery.

**Geologic framework**

Bonanza Spring is located at an elevation of 2,105 feet above mean sea level. Average annual temperatures at the
The closest nearby meteorological stations with long-term records are 17.1°C (62.8°F based on a record from 1958 to 2011) at Mitchell Caverns in the Providence Mountains (elevation 4,350 feet above mean sea level), and 23.1°C (73.6°F based on a record from 1941 through 2016) at Needles in the Colorado River Valley to the east (elevation 890 feet above mean sea level). Since Bonanza Spring lies at an intermediate elevation to these two stations, an average annual temperature at Bonanza Spring of 21.0°C (69.8°F) is estimated for the purposes of comparing average ambient temperature to spring temperature.

Regionally, there is a northwest trending fault zone with a secondary east to west trend also present, all parallel to the prevailing structural regime. The geologic units in the region are very diverse, ranging from Precambrian metamorphic rocks to Tertiary-aged volcanic rocks and playa and alluvial deposits in the valley floors (Figure 3).

In the Clipper Mountains, the principal rock types present are Tertiary volcanic rocks consisting of rhyolite, andesite, basalt, and other pyroclastic rocks. These rocks comprise the bulk of the range including the highest elevations. They are the only outcropping rock unit comprising the western half of the Clipper Mountains. Elsewhere in the Clipper Mountains, Precambrian granitic and gneissic rocks outcrop (generally in the eastern third of the Clipper Mountains, and are present immediately below Hummingbird Spring serving as a restriction to flow forcing water to the surface). A small area of Tertiary-aged intrusive hypabyssal rhyolite and andesite is also present near Hummingbird Spring (Bishop, 1963). Hypabyssal rocks are intrusive rocks, emplaced at shallow to medium depth, having characteristics more like their extrusive, volcanic counterpart.

The rocks in the Clipper Mountains are cut by a series of roughly parallel, northwest trending faults. Due to the level of geologic mapping (only in rock units), the faults are mapped as ending at the alluvial interface, although it is likely they extend further. One of these faults trends southeast toward Bonanza Spring and extends northwest toward Clipper Valley.

The Clipper Mountains are surrounded by the broad desert valleys consisting of Fenner Valley to the south and east, the Clipper and Lanfair Valleys to the north, and the Cut Wash valley area that separates the Clipper Mountains from the Marble Mountains to the west. The valley areas are covered by coalescing alluvial fans forming broad slopes between surrounding mountains and the valley floors. The surrounding mountain ranges generally consist of the Marble Mountains to the west comprised of Tertiary-aged volcanic rocks and Lower Cambrian sedimentary rocks; the Providence Mountains comprised of diverse rock types to the northwest, the primarily granitic New York Mountains to the north, the

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**Figure 3.** Geologic map and spring locations (adapted from California Department of Conservation, 2017) Qa Quaternary-aged alluvium (unconsolidated basin fill) Qpc Quaternary-aged older alluvium (sandstone, conglomerate) Tv Tertiary-aged volcanic rocks (rhyolite, basalt) Tvp Tertiary-aged volcanic rocks (rhyolite, dacite) Ti Tertiary-aged hypabyssal rocks grMz Mesozoic-aged granitic rocks Pzca Paleozoic-aged carbonate rocks pC Precambrian-aged metamorphic rocks grpC Precambrian-aged granitic rocks **Faults presented as white lines on map.**
Piute Mountains to the east that are comprised of Precambrian igneous and metamorphic, and Tertiary-aged volcanic rocks, and the Old Woman Mountains to the south that are comprised largely of Precambrian igneous and metamorphic rocks (Bishop, 1963).

**Hydrogeology**

The principal surface water bodies in the Bonanza Spring area (primarily Clipper and Marble Mountains) are the springs in the region (Figure 3) and the playas in the vicinity of Cadiz Valley that receive water during occasional summer and winter precipitation events that eventually evaporates. Generally, most of the springs in the Mojave Desert are “local” or “perched” springs that are the result of precipitation in their local watershed that percolates into the ground, only to reach the surface where bedrock restrictions to underflow force water to the surface. They are typically in wash bottoms, or may form small, intermittent seeps on hillsides. These local springs are wholly dependent on flow within their respective watersheds. Generally, there will be no planar, perched groundwater-table that extends across ridges and valleys in these desert ranges. Larger, perennial springs may be observed along geologic structures or along geologic contacts and are in hydraulic communication with regional aquifer systems including basin-fill aquifers.

The direction of groundwater movement usually parallels the slope of the ground surface, from points of recharge in the higher elevations to points of discharge such as springs, or evapotranspiration from the salt-encrusted playas. In the Bonanza Spring area, groundwater underflow moves southwest from the New York and Providence Mountains generally at elevations above the Bonanza Spring (Geoscience Support Services, 2011), southward toward Fenner Valley then southwest to Cadiz Valley. Davisson and Rose (2000) described the New York and Providence Mountains as a source of recharge to the Fenner Valley and beyond. Precipitation and periodic snowmelt runoff from the higher surrounding mountains recharge the basin alluvium.

In the Clipper Mountains, sparse water runoff from the south slope will flow toward Fenner Valley where it will either percolate back into the subsurface, evaporate, or in larger runoff events such as flash floods resulting from summer monsoonal rainfall events, reach the Fenner Valley floor and continue southwest toward the playa in Cadiz Valley. Most springs in the Clipper Mountains are located on the south-facing slopes (including Bonanza Spring). Sparse runoff on the north side of the Clipper Mountains will flow northward toward Clipper Valley, and then eventually southward around the east or west ends of the range.

Based on the field reconnaissance activities that have been conducted for this investigation and those previously (Andy Zdon & Associates, 2016), it appears that the springs in the Clipper Mountains emanate from multiple sources. These sources include independent locally perched, and regional basin systems. In the case of Bonanza Spring, field reconnaissance suggests a more complex sourcing.

Bonanza Spring rises along a structural trend at the interface of volcanic rocks and older basin fill deposits along the south side of the Clipper Mountains. The spring is within the low foothills of the southwest margin of the Clipper Mountains. The principal massif of the Clipper Mountains lies to the east, with drainage from substantially higher elevations and of larger topographic extent. Springs along this more mountainous area are of substantially smaller size than Bonanza Spring (with flow typically less than one gallon per minute). Downgradient from Bonanza Spring is Lower Bonanza Spring. This is likely a resurfacing of flow from Bonanza Spring along with possible additional seepage from the underlying formations. There is a substantial riparian area covering more than five acres for the spring complex that is anomalous given the limited watershed/catchment for the spring (approximately 50 acres) and is indicative of a regional source. In comparison, Hummingbird Spring to the east has a much larger catchment extending to near the crest of the range, and with a more substantial bedrock restriction to flow, but with much less flow suggestive of a local source. Additionally, Bonanza Spring has exhibited a relatively steady flow that has been noted back to that reported by Thompson in 1929, which contrasts with other area springs with more seasonal flow. A spring flow system that is more regional in nature would leave Bonanza Spring potentially more susceptible to regional pumping impacts than springs such as Hummingbird.

**Methods**

For this analysis, water samples collected from Bonanza Spring, Lower Bonanza Spring, Hummingbird Spring, and Teresa Spring were analyzed for general minerals, trace metals (conducted by Alpha Analytical, Inc., in Sacramento, California) and stable isotope, and tritium (conducted by Isotech Analytical Laboratories, Inc., in Champaign, Illinois).

Samples for general minerals analysis were collected in 1-L high-density polyethylene (HDPE) sample bottles provided by the laboratory (no preservative was used). Samples for trace metals were collected in 250-mL
HDPE sample bottles provided by the laboratory (nitric acid preservative was used). Samples were maintained on ice and shipped to the laboratory in proper holding times (with the exception for nitrate).

Samples for oxygen and hydrogen isotopes were collected in 1-L HDPE sample bottles provided by the laboratory. Samples were shipped to Isotech Laboratories in Champaign, Illinois where the $^{18}$O/$^{16}$O and D/H ratios were measured as a gas using standardized mass spectrometry methods. Tritium ($^3$H) analysis was conducted using the tritium enhanced enrichment (TEE) method to obtain lower reporting limits. Tritium can be used qualitatively for dating groundwater as substantial increases in atmospheric $^3$H was produced as a result of nuclear bomb testing beginning in the late 1940’s and early 1950’s. The presence of $^3$H in groundwater is then indicative of the modernity of that water. Tritium is expressed in absolute concentration using tritium units (TU).

As is standard, the oxygen and hydrogen isotope results are reported as normalization to Standard Mean Ocean Water (SMOW), which is an internationally recognized standard in stable isotope analysis, and expressed in $\delta$ ("del") notation following its convention. Values for "del" are typically reported as negative numbers where lighter isotopic compositions have larger "del" values.

During site visits, field water quality parameters of temperature, pH, electrical conductivity, and dissolved oxygen were measured at the sources of the springs. Field instruments were checked for calibration daily, if not at higher frequencies.

**Results**

**Geochemistry**

Groundwater quality in the Clipper Mountains area tends toward moderate total dissolved solids contributed by appreciable levels of sulfate and bicarbonate. To place this water quality in context, more regional data were compiled from Andy Zdon & Associates (2016), U.S. Geological Survey (2017), Metropolitan Water District of Southern California (2001), and Davisson (2000). A Piper diagram of Bonanza Spring waters and regional waters are provided in Figure 4.

Spring water at Bonanza Spring is a Na-HCO$_3$ type (this is consistent with water at Lower Bonanza Spring as well). This is similar to most waters in the region except those waters at Hummingbird Spring (Ca-HCO$_3$ type). The total dissolved solids concentration in water from Lower Bonanza Spring was nearly three times that of that from the Bonanza Spring source and likely indicates that Lower Bonanza Spring is a more evaporated form of Bonanza Spring water that is present as spring outflow resurfaces downstream of the spring source. Of note is that while Hummingbird Spring appears to be a local spring, located within the same geologic units from which Bonanza Spring resides, Hummingbird Spring’s water are different in chemical character (greater relative calcium abundance).

The Bonanza Spring water is also similar in type to waters from the basin fill in the Fenner and Cadiz Valleys (Mathaney et al., 2012; Metropolitan Water District of Southern California, 2001). Water from Teresa Spring in the Marble Mountains was also noted to be a Na-HCO$_3$ type. Field water quality parameters noted for Bonanza Spring were a temperature of 27.5°C, or 81.5°F, with a pH of 7.83, and electrical conductivity of 675 µS. Of note is the temperature of the water being considerably higher than that measured during the same sampling event at Lower Bonanza Spring (24.5°C or 76.1°F), Hummingbird Spring (23.8°C or 74.8°F), and Teresa Spring in the Marble Mountains (19.2°C or 66.6°F). Shallow groundwater temperatures will typically mimic the average annual ambient air temperature at that location. For Bonanza Spring, the water directly at the source location is 6.5°C warmer than the average annual temperature. This indicates that the water at Bonanza Spring has been at significant depth below ground surface during its history. Subsurface temperatures are affected by climatic conditions to depths of about 100 feet below surface. As has been reported in Nevada (but is likely comparable at this location), below 100 feet, normally temperatures increase about 1°F every 55 feet (Garside and Schilling, 1979). This indicates that the water issuing from Bonanza Spring has been at a depth of at least 750 feet below ground surface. This would be a low estimate of depth below ground surface as it can be assumed that some cooling of the water would have occurred as it reached the surface where the water temperature was measured. It is unclear how groundwater in an unconfined, perched setting could fall as precipitation, reach the local groundwater surface at depths more than 750 below the source of Bonanza Spring, only to rise to ground surface and discharge to the surface, all in such a limited area of approximately 50 acres.

Of note is that Davisson and Rose (2000) assumed the local catchment for Bonanza Spring as being the whole of the Clipper Mountains although this is very unlikely as it would require substantial volumes of water to flow laterally across the distant range-front of the Clipper Mountains and across several geologic northwest-trending geologic structures, instead of following the path of least resistance down-slope toward the basin fill.
Isotopic composition

The $\delta^{18}O$ and $\delta D$ abundances in precipitation systematically vary with increasing latitude and elevation. This results in lower $\delta^{18}O$ and $\delta D$ isotope values at higher elevations and further distance inland in general. Additionally, this results in lower $\delta^{18}O$ and $\delta D$ values in groundwater from north to south from central Nevada to southeastern California (Davisson et al., 1999). There is also a regional effect where monsoonal precipitation occurs in areas north of the Gulf of California, causing precipitation in higher elevation areas of the Mojave Desert. This summer monsoonal rain has higher isotope values than winter season equivalents because of warmer temperatures (Zdon et al., 2015). These same effects provide a means to use these patterns to potentially derive recharge sources of groundwater in the Bonanza Spring area. This methodology has been used previously in the area (Davisson, 2000) to evaluate source areas for groundwater in the Fenner Valley.

Andy Zdon & Associates (2. 6) sampled waters from springs for $\delta^{18}O$ and $\delta D$ in the Clipper Mountains, Piute Mountains, Old Woman Mountains and Marble Mountains as part of their Mojave Desert-wide spring survey. That work provided a previously-lacking regional stable isotope dataset that assists in looking at individual locations in more detail. As part of this investigation, Bonanza Spring, Lower Bonanza Spring, Hummingbird Spring and Teresa Spring were sampled and also analyzed for other constituents including $^3H$.

Overall, the variable precipitation sources yield a systematic difference in $\delta D$ and $\delta^{18}O$ abundance in accumulated precipitation in the Mojave Desert. This has been demonstrated in previous work on multi-year annual precipitation collection throughout the Mojave (Friedman et al., 1992). In the work by Friedman and others, over seven years of annual precipitation was collected at 32 different sites ranging from approximately −200 to 7,500 feet elevation, as far north as the Owens Valley and south to the United States–Mexico border. Systematic variations were shown to exist in $\delta D$ and $\delta^{18}O$ for annualized, wintertime, and summertime accumulations, consistent with the regional precipitation sources and elevation effects (Friedman et al., 1992).

Illustrated in Figure 5 is the contoured pattern of $\delta D$ variations in wintertime precipitation from this previous work. Also mapped are spring locations where stable isotopes and their corresponding $\delta D$ values were measured. Topographic effects on the $\delta D$ values are seen in the contoured patterns where low $\delta D$ values in precipitation occur north of the Transverse Ranges. Also $\delta D$ values are low in the northern Mojave associated with northern winter storm tracks causing precipitation in areas such as Owens Valley. Furthermore, inspection of the
variation of springs’ δD values plotted in Figure 5 shows a general correlation with these wintertime isotope precipitation patterns. Exceptions are where spring waters are extensively evaporated and caused enrichment of the isotope abundance (such as is frequently found in “local” springs, or in localized high elevation areas with lower δD values). Nevertheless, low δD values in both precipitation and spring water are prevalent in the northern Mojave Desert and high in the southeastern Mojave, suggesting spring water variations at this geographic scale are controlled by geographic position (Andy Zdon & Associates, 2016).

Friedman et al. (1992) also produced similar contour plots of summertime precipitation and mean annual precipitation isotope values. In both of these cases the general correlation with spring water isotope values is poor. Accordingly, the implication is that spring water sources in the Mojave reflect less of a mean annual precipitation source, but rather wintertime precipitation having the greater influence overall.

Andy Zdon & Associates (2016) illustrated the geographic dependence of isotope abundances in Mojave spring water by dividing the study region of that spring survey into four quadrants as shown in Figure 6.
Northwest, northeast, southwest, and southeast quadrants were defined that separate groups of springs as they might be influenced by summer monsoonal versus winter maritime precipitation sources. The quadrants presented are based on field measured stable isotope values from Mojave Desert springs and from precipitation patterns as described earlier.

Further in Figure 7, the values of δD and δ18O in each quadrant are plotted compared to the Global Meteoric Water Line (GMWL). It is readily noted that the southern quadrants have higher δD and δ18O values than the northern (Andy Zdon & Associates, 2016). Computed average δD values for each quadrant are shown in the list below and indicate that isotope values increase in spring water from the northwestern Mojave toward the southeast:

<table>
<thead>
<tr>
<th>Quadrant average</th>
<th>δD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest</td>
<td>−91.6</td>
</tr>
<tr>
<td>Northeast</td>
<td>−86.4</td>
</tr>
<tr>
<td>Southwest</td>
<td>−77.7</td>
</tr>
<tr>
<td>Southeast</td>
<td>−71.6</td>
</tr>
</tbody>
</table>

It can also be observed that most springs samples plot somewhat to the right of the GMWL, suggesting most have experienced some extent of evaporative enrichment of their isotope values. Stable isotope results for springs in the Clipper Mountain area are presented in Figure 8.

The Bonanza Spring δD value is of note in that it is closer to the northeast quadrant springs as described...
above than the southeast quadrant springs such as neighboring Hummingbird, Chuckwalla, and Teresa Springs. Indeed, the stable isotope values for Bonanza Spring are more typical of values measured in spring water samples in the area of the Mescal Range and Ivanpah Mountains to the north (Andy Zdon & Associates, 2016). Additionally, as reported by Rose (2017), the volumetric average isotopic signature of precipitation collected on the Clipper Mountains is much higher than the isotopic signature at Bonanza Spring. This is indicative of a recharge area north of the Clipper Mountains such as the New York and Providence Mountains and is consistent with a substantial portion of the assumed recharge area for Fenner Valley. As part of this investigation, springs in the New York Mountains and Providence Mountains (within Mojave National Preserve) were not surveyed in the Mojave Desert-wide survey as the work was conducted solely on lands managed by the BLM, but these results are also consistent with results from prior sampling within the Mojave National Preserve (e.g. Davison and Rose, 2000).

In order to qualitatively evaluate ages of spring water from Bonanza, Hummingbird, and Teresa Springs, water samples were collected from those springs and analyzed for $^3$H. In evaluating the $^3$H data, the values are indicative of average values. For example, a spring with multiple sources (such as a more regional old source and from recent precipitation) will result in a composite $^3$H value. $^3$H was not detected at reporting limits of 0.56 TU in the water samples from Bonanza (and Lower Bonanza) and Hummingbird Springs. This indicates that the water is primarily submodern or older in age, having been recharged prior to 1952 (Clark and Fritz, 1999).

In the case of Bonanza Spring, the assumption of local recharge is problematic in that this model requires very slow movement of groundwater from the point of recharge to the spring given the small watershed. For example, the distance from the crest of the watershed to the source is approximately 1,000 feet. Assuming that precipitation recharged a local perched aquifer zone that fed the spring (if it existed), it would require very low permeability earth materials (hydraulic conductivity of substantially less than approximately 0.04 feet per day), which is improbable given that these low permeability materials would otherwise inhibit groundwater recharge and promote direct runoff from precipitation events and promote seepage in the overlying coarse-grained, higher-permeability overburden. The hydraulic conductivity would have to be much lower than that used in the scenario described above as based on the spring water temperatures present, this travel path does not account for the requirement that the water reach substantial depth as described earlier, only to resurface in a very short distance. This appears to be contradicted by existing field conditions.

At Hummingbird Spring, $^3$H was not identified in the spring sample collected indicating that it is water primarily of pre-1952 origin. Beyond this, the scale of age difference in waters of Bonanza Spring and Hummingbird Spring is not known. Given the substantially larger watershed for Hummingbird Spring, the smaller size of the spring (as compared to Bonanza Spring), and the

![Figure 7. Distribution of $\delta^D$ and $\delta^{18}O$ values for spring water relative to Global Meteoric Water Line (GMWL). Note northern waters generally have lower $\delta^D$ and $\delta^{18}O$ values than their southern counterparts.](image)
same source area geologic unit as at Bonanza Spring further highlights the anomalous nature of increased flow at Bonanza Spring if it were a local spring.

The geomorphology of the respective watersheds above Bonanza and Hummingbird Springs are substantially different. Watershed topography above Hummingbird Spring is more variable over a larger area, than that for Bonanza Spring. The Hummingbird Spring watershed includes cliff-forming rock units and relatively flat, sandy washes. The uncertainty of how and where in the watershed recharge would occur makes comparing estimated maximum flow velocities problematic between Bonanza Spring and Hummingbird Spring.

Tritium was identified in the water sample collected from Teresa Spring at a concentration of 1.38 ± 0.29 TU. Water from Teresa Spring therefore is either of younger origin (post-1952) or a mixture of mostly younger (local) with older (local and or more regional) waters. When combined with the results from the stable isotope analysis, the source is most likely exclusively locally sourced.

**Summary/Conclusions**

Based on the analysis and integration of the new and historic data collected within the geologic and hydrogeologic framework of the region, the sources of the springs evaluated appear to be as follows:

1. Bonanza Spring – water within Bonanza Spring is from a basin-fill water source, deriving its water from recharge north of the Clipper Mountains, such as the Providence and New York Mountains, and could be impacted if groundwater levels decrease at, or near, the spring (as estimated in Santa Margarita Water District (2012)). Groundwater from these northern regional sources (such as the New York and Providence Mountains) moves southward toward Fenner Valley, generally around the Clipper Mountains, but also seeping through the subsurface within the volcanic rocks of the range, only to resurface at the spring. This conclusion is based on the following data:
   a. groundwater elevations in the basin-fill north of the Clipper Mountains is at higher elevations than Bonanza Spring (Geoscience Support Services, 2011);
   b. isotopic signatures consistent with past studies (e.g., Davison (2000)) of waters in Fenner Valley and Mojave National Preserve indicating waters derived from sources north of the Clipper Mountains such as the New York Mountains or Providence Mountains;
   c. isotopic signatures of precipitation collected in the Clipper Mountains are much higher than those at Bonanza Spring (Rose, 2017);
   d. site field conditions related to large size of the spring and associated small watershed size indicate that the spring flow observed is not

![Figure 8. δD and δ18O value for Bonanza Spring relative to all other waters in the region.](image-url)
compatible with its watershed and the low volume of precipitation anticipated in that watershed;
e. absence of $^3$H indicating that the spring water has a composite age greater than 65 years old despite the limited size of the watershed;
f. Bonanza Spring flow has been consistent for more than 100 years despite multi-year wet periods and longer periods of drought (as indicated by the literature), and
g. Bonanza Spring water temperature is indicative of waters that have been at depths of greater than 750 feet below the spring vent and risen to groundwater surface despite being in such a small catchment.

2. Lower Bonanza Spring – Evaporated waters from Bonanza Spring with some potential for the inclusion of additional inflow from the underlying formations indicated by cooler water temperatures, same water-type with higher dissolved solids concentrations due to evaporation; and stable isotope results indicative of having undergone greater evaporation; and,

3. Hummingbird, Teresa, and Chuckwalla Springs – local, perched springs based on limited flow relative to spring watershed size, stable isotope signals, and in the case of Teresa Spring, presence of $^3$H indicative of a component of younger recharge.

Based on the results of this investigation, recommendations for future groundwater management in this region include the following:

- Future groundwater development in the region, should it occur, should be cognizant of the likelihood of a hydraulic connection between the recharge area for Fenner Valley, and Fenner Valley itself with Bonanza Spring. Based on the existing source characterization of Bonanza Spring, a reduction in groundwater level could result in an uncertain, but potentially substantial decrease in free-flowing water from the spring source.
- Numerical modeling in the area (e.g., as presented in Santa Margarita Water District (2012)) indicates that expansion of a cone of depression in areas of substantial pumping, and limited recharge, can occur for periods long after pumping ceases (100 years or more). This is due to the continued drawing in of more distant groundwater to infill the recovering cone of depression. Therefore, if future groundwater development occurs that puts substantial stresses on the aquifer system, future groundwater-level monitoring protective of Bonanza Spring should be designed to obtain sufficient early warning of potentially damaging groundwater level decline to allow for changes in effective groundwater management protective of the spring resource.

In addition to the recommendations listed above, long-term monitoring of the spring will be important for future groundwater management and resource protection. This monitoring should include evaluations of additional water development in the area to assess possible impacts to both baseline spring flow and groundwater level records. Currently, there are no groundwater monitoring wells between the location of proposed groundwater development in Fenner Valley and Bonanza Spring. Additional monitoring wells between a proposed well field in Fenner Valley and the spring would provide a means to identify early changes to the groundwater system indicative of future impacts on Bonanza Spring. Additionally, reliance on observable changes at the spring as a trigger for changes in groundwater management or usage will not be an effective protective measure due to the delays in groundwater changes described above.

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