# RGDSS Memorandum
# DRAFT

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| **Subject:** | RGDSS Peer Review: Hydrogeologic Review of Manassa Fault and McIntire Spring, Conejos County, CO | |
| **Date:** | October 20, 2015 | |

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## Table of Contents


1 Introduction ..... 3
2 Approach ..... 3
3 McIntire Spring ..... 4
3.1 McIntire Spring: Background ..... 4
3.2 McIntire Spring Discharge and Confined Aquifer Artesian Pressure ..... 5
3.3 McIntire Spring and Confined Aquifer Water Chemistry ..... 8
3.3.1 Major Ion Water Chemistry ..... 8
3.3.2 Environmental Isotope Water Chemistry ..... 10
4 Manassa Fault ..... 13
4.1 Manassa Fault Background ..... 13
4.2 Manassa Fault: Geophysical and Geologic Interpretations ..... 16
4.3 Geologic Cross Sections in the Manassa Fault Area ..... 20
4.3.1 Cross-Section Methodology ..... 21
4.3.2 Cross-Section Results ..... 21

4.4 Manassa Fault, McIntire Spring, and the Conejos River ..... 23
5 Conclusions ..... 24
6 Recommendations ..... 26
7 Comments and Concerns ..... 27

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Tables: (In text of this memorandum)
Figures: (Attached at back of this memorandum)

# 1 Introduction

HRS was asked by the RGDSS peer review team (PRT) to review the hydrogeology of the area encompassing two features: the Manassa Fault and McIntire Spring. The study area for this review generally is the Conejos and San Antonio River valleys, the La Jara Creek watershed, and the San Luis Hills, all located in Conejos County, Colorado (see Figure 1).

The request for this review was initiated by the PRT in 2012. HRS made an initial review at that time that was discussed as part of documentation of hydrogeologic mapping improvements in the Conejos / San Antonio valley region[1]. More recent model calibration efforts in Phase 6 of the RGDSS in 2014 resulted in a PRT request that HRS review these features once again, and recommend whether any new data or new interpretations of data on the hydrogeology of the Manassa Fault and McIntire Spring provide insight to improve RGDSS model calibration. This memorandum discusses our review and provides recommendations.

# 2 Approach

The hydrogeologic interpretations made as part of this review were based on evaluation of the following sources of information:

- Interpretation of lithology and layer changes from geologist's lithologic logs (including the log of RGDSS Piezometer no. 3, located approximately 1.5 miles WNW of McIntire Spring.
- Interpretation of selected driller's reports from available logs of wells from the State Engineer's Office (SEO) well permit database.[2]

[1] HRS Water Consultants, Inc., July 17, 2012, Hydrogeologic Mapping Review of Conejos / San Antonio Region. RGDSS Memorandum,
[2] http://water.state.co.us/Home/Pages/default.aspx.

- Geophysical survey maps and reports developed by the U.S. Geological Survey as part of USGS' ongoing Rio Grande Rift research, and discussions with authors of those studies.
- The Rio Grande Water Conservation District water level database was used as a source of artesian head data for wells near McIntire Spring.
- Discharge data for McIntire Spring, obtained from the Division 3 Engineer's Office.
- Published maps and reports of the U.S. Geological Survey and others.
- We have referred to data contained in previous HRS studies in the Conejos River valley area.
- We have relied upon our experience and familiarity with the hydrogeology of the study area and surrounding localities in the San Luis Valley ("SLV").

As part of this review, HRS has made new comparisons and interpretations of existing data. These include development of two new geologic cross sections in the locality of the Manassa Fault and McIntire Spring, and a new comparison of McIntire Spring discharge and nearby confined aquifer head.

# 3 McIntire Spring

Questions were raised by the PRT as to whether the flow of McIntire Spring is sourced from the confined aquifer, and therefore whether the discharge fluctuations measured at McIntire Spring over time are an indicator of potentiometric (i.e. artesian) head changes in the confined aquifer.

## 3.1 McIntire Spring: Background

In the published literature on the hydrogeology of the San Luis Valley, and in our experience, water discharged at McIntire Spring is postulated to have its source in the confined aquifer. This

is documented at least since the Rio Grande Joint Investigation (1937) or W. J. Powell's U. S. Geological Survey study (1946-1953[3]), and probably before. Powell stated:

> The [McIntire] springs, which discharge at the base of the San Luis Hills near the contact of Alamosa formation and the volcanic rocks of the San Luis Hills, are believed to be sustained by artesian water rising to the surface along a fault plane."[4]

McIntire Spring was referenced by C.E. Siebenthal[5] (1910, USGS Water Supply Paper 240) as follows:

> "These springs rise in the bottom just at the foot of one of the San Luis Hills, and some of the springs appear to come up through crevices in the lava." (WSP-240, p. 101).

McIntire Spring was referenced in the Rio Grande Joint Investigation (1936-1937)[6] as follows:

> "Among the largest springs in the valley are the McIntire Springs, on the south side of the Conejos River… They rise along the Conejos River at the base of the San Luis Hills at the contact between the Alamosa formation and the volcanics of the San Luis Hills. According to Siebenthal this is probably a fault contact. Confined water moving southeastward in the Alamosa formation comes up along the contact and through the volcanics and escapes at the surface as the McIntire Springs." - Rio Grande Joint Investigation, Volume 1, p. 262.

McIntire Spring and its postulated relationship to the confined aquifer were referenced by Emery and others in 1973[7]:

> "Increased withdrawal of water from the confined aquifer has caused a decrease in the flow of most artesian springs [in the SLV]. For example, McIntire Springs near Lasauses had an average flow of 21 $ft^3$/sec in 1904 but the average flow between 1966 and 1970 was only 13.5 $ft^3$/sec." (CWCB Circular 18, p. 24.)

## 3.2 McIntire Spring Discharge and Confined Aquifer Artesian Pressure

A comparison of the flow of McIntire Spring over the period of record that coincides with confined aquifer head measurements shows a direct correlation between the rise and fall of

[3] Powell, W.J., 1958, Ground-Water Resources of the San Luis Valley, Colorado. U.S. Geological Survey Water-Supply Paper 1379, 284 pages.
[4] Ibid., p. 37.
[5] Siebenthal, C.E., 1910, Geology and Water Resources of the San Luis Valley, Colorado. U.S. Geological Survey Water Supply Paper no. 240, 128 pages.
[6] Robinson, T.W., and Waite, H.A., 1937, Ground water in the San Luis Valley, Colorado; a contribution to the Rio Grande Joint Investigation.
[7] Emery, P.A., R.J. Snipes, J.M. Dumeyer, J.M. Klein, 1973, Water in the San Luis Valley, South-Central Colorado. U.S. Geological Survey in cooperation with the Colorado Water Conservation Board. Colorado Water Resources Circular 18. 26 pages and 10 plates.

McIntire Spring discharge and the rise and fall of artesian pressure ("artesian head") on a seasonal and multi-year scale, in nearby confined aquifer monitoring wells including RGDSS Piezometer no. 3 ("P-3"), located approximately 1.7 miles west of McIntire Spring, and also well CON-2, located approximately 1.25 miles NW of McIntire Spring (see Figure 2). The P-3 period of record coincides with McIntire Spring records between 2002 and 2009. CON-2 has a longer period of record (1969 – present) although after 1970 the next recorded measurement was in April, 1983. The period of record of McIntire Spring encompasses March, 1936, to the present. The records for 1936 through February, 2015, were provided to HRS by the Division 3 Engineer's Office); (see Figure 3). Depth and completion intervals of P-3 and CON-2 are shown in Table 1.

**Table 1**

| Reported Completion: RGDSS P-3 and CON-2 | | | | |
|---|---|---|---|---|
| **Well** | **Permit No.** | **Total Depth (ft)** | **Screened or Open Depth Interval** | **RGDSS current aquifer layer assignment** |
| RGDSS P-3 | 223816 | 650 | 423 - 645 | L3 |
| CON-2 | 20111-R 30-WCB | 700 | 98 – 700 | L4 |

As shown on Figure 4, since approximately 2000 a seasonal or longer-term rise or fall of 1 foot of confined aquifer head in nearby confined aquifer wells correlates quite closely to a seasonal or longer-term increase or decrease in the range of 0.38 to 0.45 cubic feet per second (cfs) of discharge at McIntire Spring, based on comparison with RGDSS P-3 and monitoring well CON-2, respectively. The P-3 relationship to McIntire Spring discharge ($R^2 = 0.81$) is slightly stronger than the CON-2 relationship to McIntire Spring discharge ($R^2 = 0.76$), even though CON-2 is about ½ mile nearer to McIntire Spring (see Figure 5). This may be because RGDSS P-3 had daily records, and so the head measurements could be correlated to the same date as the McIntire Spring measurements. The frequency of CON-2 measurements and McIntire Spring measurements both varied from about 2 to 4 weeks, generally averaging about 3 weeks between measurements. For this comparison we chose CON-2 head observations and McIntire Spring

discharge observations as closely as possible to the same date, although the difference in measurement date varied from zero days up to 14 days, averaging about 7 days difference.

The strong seasonal and longer-term correlation, with no discernible lag time between change in nearby confined aquifer head and change in McIntire Spring discharge, suggests that McIntire Spring is sourced primarily, if not entirely, from the confined aquifer. It also suggests that the P-3 / CON-2 / McIntire Spring locality of the confined aquifer is of high transmissivity and low storativity, an observation corroborated by the results of the RGDSS P-3 aquifer test (T = 270,000 $ft^2$/day, S = 2.3 x $10^{-3}$) [8].

Several conclusions can be drawn from comparison of McIntire Spring discharge and nearby confined aquifer head:

- The linearity of the relationship between confined aquifer head and McIntire Springs discharge across the entire range of observed discharge - approximately 3.1 cfs (August, 2002) to 21.3 cfs (July, 1949) - strongly suggests that all, or at least a large majority, of McIntire Spring discharge has its source in the confined aquifer. If there were a substantial contribution of McIntire Springs discharge from the unconfined aquifer or from surface water sources, and if the elevation of those near-surface sources remained relatively constant over time, the head versus discharge relationship (Figure 5) would be expected to 'flatten' and be asymptotic to the surface water or unconfined source contribution in the lower range of discharge. This is not seen in the observed data.
- If all of the discharge from McIntire Spring is sourced from the confined aquifer, as the head - discharge relationship suggests, it appears likely that McIntire Spring would cease to flow at a confined head between 7,540 feet and 7,545 ft. This is only 7.5 to 12.5 feet lower than the lowest head observed at P-3 or CON-2 in the 2002 - 2015 time period. For comparison, the elevation of the Conejos River closely adjacent to McIntire Spring is 7,540 feet.[9]
- Extrapolation to higher confined aquifer head elevations suggests that the highest recorded discharge at McIntire Spring, 21.3 cfs in July, 1949, represents a local confined

[8] HRS Water Consultants, Inc., 2001, RGDSS Ground Water, Task 11 – Confined Aquifer Testing Piezometer no. 3, Johnson well 3080-F test. Final Memorandum, 24p.
[9] USGS 1:24,000 Pikes Stockade topographic map.

aquifer head elevation of about 7,594 to 7,597 feet. This is about 30 feet of head above ground surface at RGDSS P-3 (7565.24'). [10]

- The high transmissivity and low storativity in the area of RGDSS P-3, CON-2, and McIntire Spring, suggests that the Manassa Fault has enhanced secondary permeability due to fault-related fracturing of Hinsdale formation basalt lava flows in this area.

## 3.3 McIntire Spring and Confined Aquifer Water Chemistry

### 3.3.1 Major Ion Water Chemistry

A comparison of field water quality measurements of McIntire Springs and a nearby "cold" spring, as compared to RGDSS Piezometer no. 3, and the adjacent irrigation well 3080-F, yields the result shown in Table 2.

**Table 2**

| Water Quality Field Measurements at McIntire Spring, RGDSS P-3, and Pikes Stockade Cold Spring | | | | | |
|---|---|---|---|---|---|
| **Source** | **Date Sampled** | **Temperature deg C** | **pH** | **Specific Conductance (uS/cm at 25C)** | **Comments** |
| RGDSS P-3 / 3080-F | Oct. 2000 | 15.2 | 7.6 | 124 | By HRS during RGDSS aquifer testing. Approx 1.7 miles west of McIntire Spring |
| McIntire Spring | 4/19/1976 | 14 | 6.9 | 265 | USGS NWIS no. 371648105483400 |
| | 1984/05-04 0930 | 16 | 7.7 | 165 | |
| | 1984/05-04 0945 | 16 | 7.8 | 215 | |
| | Circa 1904 | 15.6 | -- | -- | 1904: as reported by Siebenthal, sampled by Headdon |
| Pikes Stockade Cold Spring | 8/22/1976 | 12 | 6.5 | 260 | USGS NWIS no. 371737105483400 |

As can be seen in Table 2, the USGS measurements at McIntire Spring differ in temperature and specific conductance from the 1904 and 1984 measurements as compared to the 1976 measurements. The 1904 and 1984 measurements compare more closely to the RGDSS P-3

[10] C. E. Siebenthal estimated the flow of McIntire Spring at about 21 cfs, circa 1904. Siebenthal, C.E., 1910, Geology and Water Resources of the San Luis Valley, Colorado. U.S. Geological Survey Water Supply Paper WSP-240, pp. 101-102.

measurements, but the 1976 measurement more closely resembles the Pikes Stockade measurements, which is probably from an unconfined aquifer or river source.

A more complete water quality comparison is made by plotting McIntire Spring major-ion data on a Piper trilinear diagram. We have compared McIntire Spring major-ion chemical data from the U.S. Geological Survey[11] with major-ion data from Dexter Warm Spring and from irrigation well permit no. 3080-F, which is 537 feet southeast from RGDSS Piezometer no. 3 (P-3) (see Figure 2). The Piper diagram shows that the major-ion concentrations of water from McIntire Spring and from 3080-F are very similar (see Figure 6). Well 3080-F is screened from 372' to 696' and reportedly is an open (uncased) borehole from 696' to 720' in Los Pinos / Santa Fe sediments and lava flows of Hinsdale Formation as shown by the lithologic log of RGDSS P-3 (RGDSS aquifer layer 3). Flow logging by the USGS (Well 3080-F was called "CON-4" by the USGS) showed that the majority of the produced water in Well 3080-F comes from the depth interval 480' to 715', but that "Specific-conductance and temperature logs indicate inflow at the top of the 9.0-inch-diameter casing at a depth of 57 ft."[12] Water produced from this well is predominantly from RGDSS model layer 3, which is interpolated to be in the depth interval 290' – 646' at this location.

The three McIntire Spring water samples and the 3080-F water sample all show water of Calcium-Bicarbonate type, which we have found to be common in the confined aquifer of the San Luis Valley, with the exception of deep, high-TDS confined aquifer water in the Closed Basin, which can range from Calcium-Sulfate type to Sodium-Chloride type water. Mayo et al, 2007, reach a similar conclusion: "Unconfined and active upper confined groundwaters outside the ancestral sump [in the Closed Basin] and unconfined low TDS groundwater in the ancestral sump tend to be of the $Ca^{2+}$ - $HCO_3^-$ type. These waters are only slightly evolved relative to stream and mountain spring waters."[13] The McIntire Spring sample showed slightly lower

[11] Williams, R.S., Jr., and Hammond, S.E., 1989, Ground-water quality in the San Luis Basin, Colorado and New Mexico, with emphasis on the Conejos River Subbasin: U.S. Geological Survey Water-Resources Investigations Report 89-4040, 43 p.
[12] Brendle, D., 2002, Geophysical Logging to Determine Construction, Contributing Zones, and Appropriate Use of Water Levels Measured in Confined-Aquifer Network Wells, San Luis Valley, Colorado, 1998–2000. USGS Water-Resources Investigations Report 02–4058, p. 25-27.
[13] Mayo, A.L, Davey, A., Christensen, D., 2007, Groundwater flow patterns in the San Luis Valley, Colorado, USA revisited: an evaluation of solute and isotopic data. Hydrogeology Journal (2007) 15: 383–408.

Sulfate concentration than did the sample from well 3080-F, but otherwise the major-ion chemistry is virtually identical. The Piper trilinear plot by Mayo, et al (2007) of major ion composition for "upper confined aquifer water" and for "Valley spring water" plot virtually identical to the Piper trilinear plot of data for McIntire Spring and Well 3080-F[14] (see Figure 7).

### 3.3.2 Environmental Isotope Water Chemistry

McIntire Spring water was sampled by the U.S. Geological Survey for Tritium ($^{3}H$), a naturally occurring isotope of Hydrogen, in May, 1984[15]. The sample showed a concentration of 5.75 Tritium units (TU), a low value indicating that the water discharging at McIntire Spring is almost certainly dominated by older, confined aquifer water. "Young" ground water, recharged in 1952 or later, shows Tritium concentrations much larger than is seen at McIntire Spring due to the relatively high Tritium concentrations in precipitation between 1952 and 1969, during the era of atmospheric thermonuclear bomb testing.[16] According to Mayo, et al, Tritium associated with mountain front recharge in the northwest region is in the range of 20 to 30 TU; and 10 to 15 TU in the northeast and southeast regions of the San Luis Valley. For the unconfined aquifer in the Conejos Valley region, a pattern of decreasing Tritium concentration is seen from the mountain front recharge area to the discharge areas, suggesting the ground water becomes progressively older along the flow paths toward the valley center.[17]

In regard to the age of confined aquifer water, Mayo, et al (2007) performed Carbon 14 ($^{14}C$) analysis on McIntire Spring water and on other confined and unconfined waters from the San Luis Valley. Mayo, et al (2007) stated:

> "McIntire Spring, located near the San Luis Hills in the southwest region [of the SLV] has a calculated $^{14}C$ age of about 2,000 years." … The general trend of increasing $^{14}C$ from the mountain fronts toward the center of the valley, both north and south of the Rio Grande, means that flow paths in the upper confined aquifer are from the mountain fronts to the valley center."[18]

[14] Ibid., p. 395.
[15] Williams and Hammond, p. 21.
[16] Ibid.
[17] Mayo et al, 2007, p. 403.
[18] Ibid, p. 404-405.

By contrast, $^{14}C$ ages of confined aquifer water from the Closed Basin (sump area) of the San Luis Valley exceed 20,000 years in some samples, and the oldest "upper confined aquifer" water tested near the Rio Grande but "appreciably away from the mountain front" is about 5,000 years old.[19] Based on the single $^{14}C$ age of 2,000 years for McIntire Springs water, and representative RGDSS Layer 3 aquifer parameter values of 20 ft/day hydraulic conductivity, 30% effective porosity, and confined aquifer head gradient in the range of 0.0015 to 0.0019 ft/ft [20], and using a form of Darcy's Law to compute the average linear velocity of water, we estimate, as a rough first approximation, that ground water discharged at McIntire Spring was recharged to the confined aquifer in the range of 14 to 26 miles distant. By comparison, known recharge areas for the confined aquifer are distant from McIntire Spring approximately the following straight-line distances:

- Conejos River near Mogote: 22 miles southwest.
- Alamosa River and La Jara Creek near Capulin: 16 miles west.
- Rio Grande near Del Norte: 40 miles northwest.

Overall, based on the chemistry and temperature of the water discharging from McIntire Spring, it can be concluded that all, or at least a large majority, of McIntire Spring discharge has its source from the confined aquifer. If there were a substantial contribution of McIntire Springs discharge from the unconfined aquifer or from surface water sources, the $^{14}C$ age probably would be less, and Tritium concentration most likely would be higher. Major-ion chemistry and temperature of McIntire Spring water is very nearly the same as water from nearby wells known to be screened in what is considered to be Layer 3 of the RGDSS model. High transmissivity in this region is considered the main reason for the virtually instantaneous response of rise and fall in McIntire Springs discharge due to rise and fall of nearby confined aquifer head. The water in the confined aquifer that discharges from McIntire Spring appears to have been recharged on the order of 2,000 years ago according to the single $^{14}C$ age date currently available. These conclusions are not contradictory. Changes in confined aquifer head (as well as the rate of depletions or accretions) are hydraulic pressure effects that propagate through the aquifer

[19] Ibid.
[20] HRS Water Consultants, Inc., 2002, RGDSS Task 32 Final Hydrogeologic Database Refresh, Map 6: Potentiometric Surface in the Confined Aquifer, 1997.

relatively quickly. The rate of movement of dissolved chemical constituents in ground water is a solute transport effect governed by mechanisms such as dispersion, diffusion, and advective movement of water. The rate of molecular movement is much slower than the rate of propagation of hydraulic pressure effects.

# 4 Manassa Fault

The Manassa Fault is the normal fault[21], or more likely fault zone, that bounds the San Luis Hills on the south and east from the Conejos / San Antonio River Valley to the north and west. It is known to be a normal fault because the San Luis Hills (Conejos Formation rocks capped in part by Hinsdale Formation lava flows; see Figure 1) are upthrown relative to the downthrown sediments and volcanic rocks buried beneath the Conejos / San Antonio Valley.

Questions were raised by the PRT as to how the Manassa Fault should be represented in the RGDSS model, where it may have an effect on discharge from the confined aquifer, and the geographic extent of any significant hydrologic effects it may have.

## 4.1 Manassa Fault Background

Questions have been posed for many years about what, if any, effect the Manassa Fault may have on the movement of ground water. Also there have been questions raised about the location of the Manassa Fault, whether it is a single fault, or whether it is better represented as several faults or as a zone of faulting. HRS has reviewed the existing mapping of the fault based on interpretation of geologic data (mostly driller's logs of water wells in the area) and geophysical data (U.S. Geological Survey aeromagnetic survey and gravity survey).

One of the earliest documented mentions of the Manassa Fault (although not so named) in the geologic literature is by C.E. Siebenthal (1910, USGS Water Supply Paper 240) as follows:

[21] Normal fault: a geologic fault in which the hanging wall has moved downward relative to the footwall.

SAN LUIS HILLS.

Stretching northeastward across the valley from Antonito to Fort Garland is a series of basaltic hills, flat topped and higher west of the Rio Grande, lower and more rounded east of the river, degenerating into a lava-capped mesa, the north border of which forms an escarpment along the south side of Trinchera Creek. At a point 5 miles southwest of Fort Garland this escarpment swings south, joining the San Pedro Mesa at San Luis. These hills and mesas form the southeast limit of the artesian basin, the sand and clay beds of which abut against the older formation, numerous springs coming up along the contact, particularly in the lower course of Conejos River. This

contact in all probability marks a fault scarp, the older strata forming the west ranges and the floor of the valley being deeply downthrown to the northwest in the formation of the depression in which the sands and clays of the artesian system were deposited.

- Siebenthal, WSP-240, pp. 38-39.

The faulting that we now call the Manassa Fault also was mentioned by Atwood & Mather[22] in the context of the San Luis Hills and the adjacent valley, again not so named:

> "Their mature or even youthful topography and their prominence above the general base-leveled surface result from the recency of the faulting which elevated them above their surroundings at so late a date in the Peneplain cycle of erosion that their degradation had little more than commenced when the cycle was terminated."

J. E. Upson, in his paper on the general geography and physiography of the San Luis Valley[23] also makes reference to the Manassa Fault (again not named) in the context of the San Luis Hills. Upson was the first researcher to propose that the Manassa Fault extends northeast beneath the San Luis Valley, and may be part of the Sangre de Cristo fault zone.

[22] Atwood, W.W., Mather, J.F., 1932, Physiography and Quaternary geology of the San Juan Mountains, Colorado. U.S. Geological Survey Professional Paper no. 166.

[23] Upson, 1939, Physiographic Subdivisions of the San Luis Valley, Colorado. Journal of Geology, Vol. XLVII, no. 7. Reprinted in New Mexico Geological Society Guidebook, 1970.

> "The dissection of the hills resulted from post-peneplain uplifts on normal faults situated along their northwest flank. The present writer believes that the faults are probably the southward continuation of those bordering the west flank of the Sangre de Cristo Range."

The Manassa Fault, depicted by Upson in map view along the northwest flank of the San Luis Hills and continuing northeast where it connects with the Sangre de Cristo fault zone, the major bounding fault system on the east side of the San Luis Valley, is also shown in a very general way, without specificity as to location, in several other publications, including the 1:500,000 – scale Geologic Map of Colorado (1979)[24], and also on Richard L. Burroughs' Ph. D. thesis[25], and on a map of "Major Structural Features of the northern San Luis Basin" in a publication related to geothermal resource identification[26].

Dr. Burroughs' Ph.D. thesis is the first publication we have found that mentions the Manassa Fault by that name:

> "The west side of this ridge [a postulated bedrock ridge from the San Luis Hills NE to Sierra Blanca] is probably bounded by a northeasterly extension of the Manassa Fault, upthrown to the east, which marks the western boundary of the San Luis Hills (figs. 2, 18). This fault may be a southwestern spur of the Sangre de Cristo fault, and like the Sangre de Cristo fault, a part of the eastern boundary of the deep Alamosa basin (Figs 1, 18). " - Burroughs, p. 105.

The Manassa Fault also is shown on a general geologic map of the San Luis Hills area in a Colorado State University Master of Science thesis on hot spring geology and mineralization near the Rio Grande River in the San Luis Hills[27]. Upwelling of geothermal water[28] is postulated to occur either at present or in the geologic past along fault zones at several locations in the San Luis Valley[29], including along the LaSauses Fault, which is the north-south trending fault

[24] Tweto, O., 1979, Compiler, 1979, Geologic Map of Colorado. U.S. Geological Survey.
[25] Burroughs, R.L., 1972, Geology of the San Luis Hills, South Central Colorado. University of New Mexico Ph.D. Thesis, 139 pages.
[26] Burroughs, R., 1981, A summary of the Geology of the San Luis Basin, Colorado – New Mexico, with Emphasis on the Geothermal Potential for the Monte Vista Graben. Colorado Geological Survey Special Publication 17, Figure 2.
[27] Bartlett, R. D., 1984, Geology of an Oligocene-Age Acid Hot Spring, San Luis Hills, Conejos and Costilla Counties, Colroado. Master's Thesis, Colorado State University.
[28] Geothermal water: water of elevated temperature, in some areas highly mineralized, most likely due to upwelling of ground water from depths greater than several thousand feet in the San Luis Valley area.
[29] Burroughs, 1981, A summary of the Geology of the San Luis Basin, Colorado – New Mexico, with Emphasis on the Geothermal Potential for the Monte Vista Graben. Colorado Geological Survey Special Publication 17, p. 14.

generally coincident with the Rio Grande as it cuts through the San Luis Hills. However, there is no known evidence of upwelling of ground water along the Manassa Fault from a depth sufficient to elevate the temperature of the springs along the northwest boundary of the San Luis, or to cause elevated mineral content of the spring water above what is normally seen in the confined aquifer at a depth of about 700 feet. This is shown by the field water quality measurements at McIntire Spring (see Table 1 and Table 2). According to Mr. Bartlett, author of the CSU Master's thesis:

> "I only recall seeing mineralization on the east side of the San Luis Hills – that seemed to be a significant volcanic center. In my research, I don't recall finding any references to mineralization on the west side - if there had been, I'm sure I would have checked it out because my thesis was funded by ASARCO.[30]

This information suggests that the majority of the hydrologic effects of the Manassa Fault on ground water movement likely are concentrated in Layer 3 of the RGDSS, composed primarily of interbedded layers of jointed and fractured Hinsdale Formation basaltic lava flows and interbedded sediments of the Los Pinos Formation. A significant contribution of ground water from deeper (i.e. Layer 4) probably would skew the water chemistry and temperature away from the confined aquifer Layer 3 values seen in Well 3080-F (see Table 2). The Manassa Fault offsets Layer 4, dominated by the Conejos Formation, as well as Layer 3. The apparent lack of ground water contribution from Layer 4 may indicate either that the fault (or fault zone) or the Conejos Formation, or both, are of low hydraulic conductivity as compared to Layer 3 materials.

## 4.2 Manassa Fault: Geophysical and Geologic Interpretations

Recent geological and geophysical studies that relate to mapping of the area encompassed by the Manassa Fault include geologic mapping of the aggregate thickness ("isopach") contours of the Alamosa confining clay series by the Colorado Division of Water Resources (1978)[31]. This map, an excerpt of which appears as Figure 8 of this report, shows the Manassa Fault as a zone of two "probable faults". This map also shows a "probable fault" labeled La Jara Fault, which parallels

[30] Douglas R. Bartlett, Feb. 25, 2015, email communication with E. Harmon.
[31] Moravec, G., and Schroeder, D., 1978, Isopach Map of the Blue Clay Series. Plate 5-1, Colorado Division of Water Resources. Map was revised as State's Exhibit 95, for the 1979 Rio Grande Rules & Regulations trial.

the Manassa Fault about four miles to the northwest, but with the opposite sense: the Manassa Fault (or fault zone) is downthrown on the west, and the La Jara Fault is shown as being downthrown on the east, thus forming a graben[32] (see Figure 8). This graben, if in fact it exists, is closely coincident with a well-defined thickening of the Alamosa confining clay series, as shown by the 1978 DWR mapping and also more recently and with better definition, on mapping done by HRS for the RGDSS[33]. Recent geophysical surveys in the study area by the U.S. Geological Survey have helped inform us as to the presence and location of these faults. Also, as part of our work on this project, HRS has developed two new geologic cross sections to help define the subsurface stratigraphy of the area. These cross sections are discussed in a later section of this report.

Geophysical surveys by U.S. Geological Survey researchers in the study area consist of a gravity survey[34] and an aeromagnetic survey[35]. Both of these surveys cover the entirety of the study area, and help inform the subsurface geology as it relates to faulting in the area. A combined interpretation of the gravity and aeromagnetic surveys, and some magnetotelluric ("MT") survey data collected in the San Luis Hills and areas further east, were discussed in a summary report (Drenth et al, 2013).[36] The aeromagnetic anomaly map and interpreted fault locations by Dr. V.J. S. Grauch, USGS, (email communication with Harmon, 2011) is shown on Figure 9. The authors of the 2013 combined aeromagnetic and gravity survey interpretations state as follows with respect to the Manassa Fault and the valley area west of the San Luis Hills (a scan of the noted Figure 10 from their paper is reproduced as Figure 10 of this report).

[32] Graben: a block of earth material located between two faults and displaced downward relative to the blocks of material on either side.
[33] HRS Water Consultants, Inc., 2012, Hydrogeologic Mapping Review of Conejos / San Antonio Region. Prepared for CWCB / CDWR. Plate 7, Layer 2 Thickness.
[34] Drenth B., Ph.D. Thesis. URL: http://crustal.usgs.gov/projects/rgb/SanLuisBasin/cslb_drenth_dissertation.html
[35] Bankey, V., Grauch, V.J, Webbers, A., 2005, Digital data and derivative products from a high-resolution aeromagnetic survey of the central San Luis basin, covering parts of Alamosa, Conejos, Costilla, and Rio Grande counties, Colorado, and Taos county, New Mexico. USGS Open-File Report 2005-1200.
[36] Drenth, B.J., Grauch, V., Rodriguez, B., 2013, Geophysical Constraints on Rio Grande Rift Structure in the central San Luis Basin, Colorado and New Mexico. *in* Hudson and Grauch, editors, 2013, New Perspectives on Rio Grande Rift Basins: From Tectonics to Groundwater. Geological Society of America Special Paper 494. Pp. 79-99.

> "On the western side of the San Luis Hills, anomaly patterns corresponding to areas of exposed volcanic rocks extend well beyond those outcrops, in a complex pattern of broadly east – west – trending anomalies. …we hypothesize that the east-west-trending anomalies reflect buried paleotopography in the areas that are covered. …The anomaly patterns extending west of the San Luis Hills gradually become broader and more subdued, reflecting deeper sources. This effect is demonstrated quantitatively by predominantly greater source-depth estimates in a ~10-km wide, north- northeast – trending zone west of the San Luis Hills (Fig.10), with a southeastern boundary that corresponds to the location of the Manassa Fault as defined by the gravity inversion." [37]

The gravity survey interpretation by Drenth et al, 2013, is shown on Figure 11. The aeromagnetic method distinguishes rock types, and general depths, by different levels of rock magnetization. Thus the aeromagnetic method is well suited for locating offsets in relatively magnetic volcanic rocks such as Hinsdale basaltic lava flows. The gravity method distinguishes rock types, and depths, by contrasts in rock density. Thus the gravity method is well suited for locating offsets in rock of different density in the subsurface. In this instance, it is better suited than the aeromagnetic method to locating fault offsets in relatively dense and deep rocks such as geologically old sedimentary rocks and Precambrian basement rock. The two USGS interpretations show differences in the interpreted location of the Manassa Fault in the area north of Manassa, probably indicating that the Manassa Fault actually is a fault zone, with several "steps" offsetting the Hinsdale basalts and also deeper formations. The HRS interpretation based on surface geologic mapping agrees relatively closely with the USGS gravity interpretation, probably indicating that this large-offset step of the fault nearest the San Luis Hills dips to the NW at a steep angle. Near the town of Manassa, the Drenth interpretation of the gravity survey indicates a westward bend to the Manassa Fault, generally parallel to State Highway 142; then a southwestward bend in the area west of U.S. 285 (see Figure 11).

The gravity interpretation also suggests that the Santa Fe Group as interpreted by Drenth et al (2013), which in this area is interpreted to include the Hinsdale / Los Pinos interbedded basalts

[37] Ibid, p. 89.

and sediments[38], is quite thick – as much as 600 to 800 meters (about 2,000 to 2,600 feet) – in the southern extension of the Monte Vista Graben that underlies the La Jara Creek – Alamosa River alluvial fan areas and the Mogote volcanic shield, but these same interbedded basalts and sediments are quite thin – perhaps less than 100 meters – in the majority of the Conejos / San Antonio River valleys approximately south of Highway 142 (see Figure 11). Thus the gravity interpretation suggests it would be advisable to re-visit the RGDSS deeper (Layer 3 and Layer 4) model layering in this area; although there could be some difficulty in doing so due to limited depth and coverage of well logs.

Neither the aeromagnetic survey nor the gravity survey interpretations postulate the existence of the La Jara Fault proposed by Moravec and Schroeder (Colorado DWR, 1978; see Figure 8). Although the estimates of depth to magnetic-anomaly source rocks, as interpreted by Drenth et al, GSA Special Paper 494, 2013 (see Figure 10) show a relatively abrupt change from shallower to deeper along a NE – SW trend generally coincident with the La Jara Fault proposed by Moravec et al, this change is not shown mapped as a fault by the USGS researchers.

There are other published maps and papers on the geology or hydrogeology of the study area. Williams and Hammond (USGS-WRI-89-4040) show the Manassa Fault location generally coincident with the interpretation of Moravec et al. However, WRI 9=89-4040 gives no new information as to the location of the fault, stating that their depiction is an "approximate location from Upson, 1939" (p. 11, figure 6 of WRI-89-4040). The most recent published, detailed geologic mapping of the San Luis Hills does not show any faulting at all in the study area.[39] A very general geologic map and cross section in a paper appearing in GSA Special Publication 494 by Machette, et al, show the presence of a structure named "La Jara Graben", although there is no discussion or support given for the presence of this graben or the fault shown on its west side[40] (this map and cross section are reproduced in this memorandum as Figure 12). The

[38] Lipman, P., Mehnert, H., 1975, Late Cenozoic Basaltic Volcanism and Development of the Rio Grande Depression in the Southern Rocky Mountains. in Cenozoic History of the Southern Rocky Mountains, Geological Society of America Memoir no. 144, p. 130.
[39] Thompson, R.A., Machette, M.N., 1989, Geologic Map of the San Luis Hills Area, Conejos and Costilla Counties, Colorado. USGS Map I-1906.
[40] Machette, M.N., Thompson, R.A., Marchetti, D.W., Smith, R.S.U., 2013, Evolution of ancient Lake Alamosa and integration of the Rio Grande during the Pliocene and Pleistocene. Geological Society of America Special Paper 494. Pp. 1-20.

authors state as follows: "Geologic logs of water wells indicate the presence of Servilleta Basalt at depth in the La Jara and Culebra grabens, on the west and east sides of the San Luis Hills, respectively."[41] We disagree with this interpretation. From our previous work on the RGDSS, and from work done as part of this review, we do not think the basalts encountered where these authors postulate the existence of a La Jara Graben are Servilleta Formation. Instead, these basalts more likely are eastward-dipping Hinsdale basaltic lava flows sourced from the Mogote volcano to the west. Our interpretation, which on this point generally agrees with the work by Moravec et al (1978) and Lipman and Mehnert (1975), is that the Servilleta basalts were not deposited generally north of the San Antonio River / Antonito area. Also, we question the geometry of the La Jara Graben as shown by Machette et al (see Figure 12) including whether there is a normal fault bounding the west side of this postulated graben at the location shown.

## 4.3 Geologic Cross Sections in the Manassa Fault Area

As part of our work on this hydrogeologic review, HRS has developed two new geologic cross sections to help define the subsurface stratigraphy and hydrogeology of the area including the Manassa Fault. Although HRS and previous researchers have developed cross sections in the general study area, so far as is known none have had the specific objective of identification or verification of subsurface faulting, and whether faulting extends through the confined aquifer layers in this area. The primary objective of developing the new cross sections was to develop a more thorough understanding of the Manassa Fault zone and the hydrogeology of RGDSS Layers 2, 3, and 4 (predominantly the Alamosa lacustrine clay series; and the Hinsdale/Los Pinos Formations) near the San Luis Hills of the San Luis Valley. A secondary objective was to better define the extent of the Alamosa confining clay series in the same area, and whether or not the available evidence shows that these deposits are offset by faulting. This will assist in improving the conceptual hydrogeologic model of the faults and springs in the area, particularly McIntire Spring, along the northwest margin of the San Luis Hills.

[41] Ibid, pp. 4-5.

### 4.3.1 Cross-Section Methodology

Two cross sections were considered necessary for refinement of the subsurface hydrogeology as part of this review. The two cross section locations we selected are: one trending NW-SE near McIntire Spring (hereinafter referred to as McIntire Spring Cross-Section); and one south of McIntire Spring trending E-W through the towns of La Jara and Sanford (hereinafter referred to as La Jara - Sanford Cross-Section). A review of existing data was performed to provide the perspective of earlier researchers on the geology of the study area, as discussed previously. Existing data include prior cross-sections constructed by HRS, a literature review, and a review of driller's logs obtained from the Colorado Division of Water Resources well permit database. Most logs shallower than 350 feet were not considered for a cross section unless deemed necessary for refinement of near-surface stratigraphy; or proximity to possible faults deemed them a useful addition. The two new cross sections are Figures 13 and 14 of this memorandum.

All logs on the two cross sections are labeled by well permit number for future reference. Well no. 223816, also referred to as RGDSS P-3, was considered accurate as it was professionally logged by a geologist at HRS as part of the RGDSS, unlike most of the logs reviewed. This log was then used as a base for interpreting surrounding well logs as they were logged by well drillers, with varying lithologic descriptions. Five faults were considered during interpretation of the cross-section, one developed in prior mapping by HRS (labeled "Geologic Evaluation" Fault), one determined through the Drenth, et al, gravity survey interpretation, (hereinafter referred to as "Gravity Survey" Fault), two determined by (Drenth, et al., from the aeromagnetic survey interpretation, hereinafter referred to as aeromagnetics ("AeroMag Survey") faults 1 and 2, and the La Jara Fault mapped as "probable" by Moravec et al (1978).

### 4.3.2 Cross-Section Results

The McIntire Spring Cross-Section (see Figure 13) shows a general thickening in sediment northwestward (basinward), which was expected based on our previous mapping in this area. The confining clays (Qala) thicken westward as well. The Hinsdale Formation (Thb, Tlp) volcanics are deeper at each indicated fault location, indicating generally good agreement

between the USGS geophysical survey interpretations and HRS' interpretations based on the well logs. The deepest volcanic unit identified was in 36WCB, at an elevation of 6,726 ft above mean sea level (MSL). Progressing northwest along this cross section, volcanic rocks appear to trend upward or are faulted upward at the location of 25 WCB as they are found at an elevation of 6816 ft MSL.

The La Jara-Sanford Cross-Section (see Figure 14) shows a general thickening of sediments, in particular the clay layers (Qala), westward (basinward) similar to the McIntire Spring Cross-Section. Hinsdale Formation (Thb, Tlp) volcanic rocks appear to be more laterally persistent near the La Jara Cross Section with the deepest found in well 18752-F. These rocks are at an elevation of 7094 feet, which is significantly higher than those corresponding to a similar location (in reference to the Aeromagnetic faults) along the McIntire Spring Cross Section. The western portion of the cross section is similar in structure to the McIntire Spring cross section, with thick sediments at well 14318 (considered analogous to wells 780R and 43WCB in the McIntire Spring Cross-Section). However, further west is well log evidence of volcanic rocks at much higher elevations, e.g. wells 10127F and 13928F. If so, this may lend credence either to the La Jara Fault per Moravec et al. (1978) located between wells 14318 and 13928F, or to the distal depositional edges of Hinsdale lava flows. Evidence for the presence of a fault in this vicinity may also exist in the McIntire Spring Cross-section with the presence of volcanic rocks in 25 WCB and sediments in 43WCB and 780R. Well 6876R (McIntire Springs Cross section) indicates a thin bed of volcanic rocks at 7,008 feet MSL; however, it is unclear whether these volcanic rocks were erroneously identified, or are thin and discontinuous, due to lack of corroborative evidence in surrounding wells.

Overall, the two new geologic cross sections appear to lend support to the locations of the Manassa Fault zone in the area north of the town of Manassa, as interpreted by the USGS geophysical surveys. It is notable that these faults do not appear to extend upward to depths shallow enough to cause fault offset to the Alamosa formation clay deposits. Previous HRS work (HRS, 2012) has shown that Alamosa formation clays are relatively continuous, although

quite thin, beneath the Conejos River in the reach from the San Antonio confluence east of the town of Manassa, downstream at least as far as the McIntire Spring area.

The new cross sections also support the possibility of a fault generally coincident with the La Jara Fault per Moravec et al. (1978), although we disagree with Moravec's interpretation that this fault extends southwest into the Mogote escarpment (see Figure 8). Definite mapping of this fault would depend on better subsurface data, such as a deep test well or wells (estimated at 800 to 1,000 feet deep near La Jara) or high-resolution seismic reflection studies E-W or SE-NW in this area. In general, we believe the existing data tend to support the existence of the La Jara Fault.

## 4.4 Manassa Fault, McIntire Spring, and the Conejos River

Emery et al (1973) reference the Manassa Fault and its supposed relationship to observed gain in flow in the Conejos River:

> "The Conejos River is apparently in hydraulic connection with both the unconfined and the confined aquifers. In the reach between Manassa and Lasauses the Conejos River flows along the fault and(or) depositional contact of the valley fill and the volcanic San Luis Hills. Geologic and hydrologic data indicate that in this reach, the confined aquifer, as well as the unconfined aquifer, discharges water into the Conejos River." (CWCB Circular 18, p. 22.)

The work done in this review does not indicate any contradiction with the statement above from Emery, et al. Although the unconfined aquifer is, at most, only a few tens of feet thick in this area, earlier work for the RGDSS (HRS, 2012) has shown the likelihood of gain from surface and near-surface return flow through the unconfined to the Conejos River. At the same time, at least four factors in combination act to enhance the upward movement of water from the confined aquifer (dominantly Layer 3) to the Conejos River and McIntire Springs in this area:

1. The high upward gradient in the confined aquifer in this area, which is at least partly due to typical basin recharge and discharge patterns[42], and partly due to the presence of relatively low hydraulic conductivity Conejos Formation materials that form the core of the San Luis Hills.
2. The presence of enhanced vertical hydraulic conductivity due to fracturing of Hinsdale Formation volcanic rocks and Los Pinos Formation sediments in the Manassa Fault zone.
3. Thinning of the Alamosa Formation confining clays from 200 feet or more near La Jara and Sanford to a feather edge near the Conejos River and the San Luis Hills.
4. Enhanced hydraulic conductivity due to the presence of coarse rubble and talus material along the base of the west slopes of the San Luis Hills, sourced from landslides and other mass-wasting processes that have been at work since the San Luis Hills have been in existence as a topographic high area, probably since Miocene time (approximately 5 to 23 million years before present).[43]

# 5 Conclusions

Based on this hydrogeologic review, we have arrived at the following conclusions.

1. Based on similarity of major-ion water chemistry, water temperature, Tritium measurements, and the strong correlation between McIntire Spring discharge and confined aquifer head in this local area (RGDSS P-3 and well CON-2), we conclude that McIntire Spring discharge is indicative of the confined aquifer head in this area, and is most indicative of the head in RGDSS Layer 3. The data show that there is little, if any, contribution to McIntire Spring from the unconfined aquifer or surface water. McIntire Spring discharge is predominantly Layer 3 confined aquifer ground water, although a minor percentage of its flow may be from Layers 2 or 4.

[42] Toth, J., 1963, A Theoretical Analysis of Groundwater Flow in Small Drainage Basins. Journal of Geophysical Research, Vol. 68, no. 16, August, 1963, pp. 4795 – 4812.
[43] Machette, M.N., Thompson, R.A., Marchetti, D.W., Smith, R.S.U., 2013, Evolution of ancient Lake Alamosa and integration of the Rio Grande during the Pliocene and Pleistocene. Geological Society of America Special Paper 494. Pp. 2-3.

2. McIntire Spring does not exist solely due to upwelling of ground water through the Manassa Fault. Instead, McIntire Spring exists where it is because of a combination of factors, including:

    - Typical basin-wide recharge and discharge patterns.[44]
    - The presence of relatively low hydraulic conductivity Conejos Formation materials that form the core of the San Luis Hills.
    - Enhanced vertical hydraulic conductivity (Kv) in the area of the Manassa Fault zone.
    - Alamosa confining clay series thins to a feather edge in this area.
    - Enhanced Kv in a rubble or talus zone eroded from the western slopes of the San Luis Hills.

3. The gain observed in the Conejos River between its confluence with the San Antonio River and its confluence with the Rio Grande River is due to a combination of factors: Layer 1 ground water discharge, overland flow, and surface drainage, as well as from upward leakage from the confined aquifer, predominantly Layer 3.

4. Geophysical survey interpretations by the U.S. Geological Survey (aeromagnetics and gravity surveys) indicate that the gravity-survey interpretation of the Manassa Fault agrees quite well with the interpreted location of faulting based on evaluation of logs of wells in the study area. The aeromagnetics interpretation shows two other faults, indicating that the Manassa Fault is a zone of several normal faults in a stepwise configuration, not just a single fault. There are at least three faults that comprise the Manassa Fault zone, and there may be more, that are near-vertical and offset the sediments and volcanic rocks in the Conejos River valley down to the west in a stepwise fashion. These can be seen on the cross sections (see Figures 13, 14, and 15). Some fault steps do not directly underlie the Conejos River, but instead are further northwest.

[44] Toth, J., 1963, A Theoretical Analysis of Groundwater Flow in Small Drainage Basins. Journal of Geophysical Research, Vol. 68, no. 16, August, 1963, pp. 4795 – 4812.

5. Work done for this review lends credence to the postulated presence of the La Jara Fault, NE trending through the La Jara area, downthrown to the southeast (Moravec et al, 1978), and the possible presence of a shallow graben bounded on the SE by the Manassa Fault zone and on the NW by the La Jara Fault. This possible graben has been shown to contain confining layers consisting of Alamosa Formation fluviolacustrine sand and clay deposits that generally thicken to the NE (HRS, 2012). A map view of the interpreted locations of the faults that bound this postulated graben is shown on Figure 15.

6. Based on this review, we conclude it is probable that the majority of the hydrologic effects of the Manassa Fault on ground water movement are concentrated in Layer 3 of the RGDSS, composed primarily of interbedded layers of jointed and fractured Hinsdale Formation basaltic lava flows and interbedded sediments of the Los Pinos formation. A significant contribution of ground water from deeper (i.e. Layer 4) probably would change the water chemistry and temperature away from the confined aquifer Layer 3 values seen in Well 3080-F (see Table 2). The Manassa Fault zone offsets Layer 4, dominated by the Conejos Formation, as well as Layer 3. The apparent lack of ground water contribution from Layer 4 may indicate either that either the fault zone in Layer 4, or the Conejos Formation, or both, are of low hydraulic conductivity as compared to Layer 3 materials.

# 6 Recommendations

Based on this review, we make the following recommendations to the RGDSS for future enhancements to the hydrogeologic mapping and ground water modeling of the study area.

1. The Manassa Fault should be represented in the model as a zone of elevated hydraulic conductivity in Layers 2 and 3, approximately in the area shown on Figure 15. Such a zone is reasonable, because from geologic and geophysical evidence the Manassa Fault zone appears to crosscut volcanic rocks and sediments that comprise Layer 3. Based on

the available well logs, there is no evidence that the Manassa Fault zone offsets or cuts across the Alamosa Formation confining clay layers, including in the areas beneath the Conejos River where the clay confining layer is thin, but apparently generally continuous. However, the Alamosa confining clay layers do thin to a feather edge in this area, so upward ground water movement is likely from the confined aquifer upward through or around the edges of the confining clay.

2. Based on this review, evidence from well logs and from USGS geophysical survey interpretations lend credence to the postulated presence of the La Jara Fault, NE trending through the La Jara area, down to the southeast; per Moravec et al, (1978); the possible presence of a shallow graben bounded on the SE by the Manassa Fault zone and on the NW by the La Jara Fault; thickening of Los Pinos or Santa Fe Formation sediments beneath the Mogote volcanic shield and the La Jara / Alamosa alluvial fans; and thinning of Los Pinos or Santa Fe sediments generally south of State Highway 142 (Romeo – Manassa area). It is advisable that the model layering in these areas be reviewed for needed updates to improve the conceptual hydrogeology as depicted in the RGDSS ground water model.

# 7 Comments and Concerns

The conclusions and recommendations in this report have been based, in part, on driller's logs of existing water wells. Although useful for our purposes, some of these well logs contain descriptions of lithology that are not consistent with other, nearby well logs. In future, HRS recommends that replacement of confined aquifer wells be accompanied by a basic geophysical logging suite, consisting, at a minimum, of short and long normal resistivity (or induction), SP, and natural gamma (gamma ray) logging. We recommend consideration of requiring this minimum suite of logs as a condition of approval for confined-aquifer well replacement.

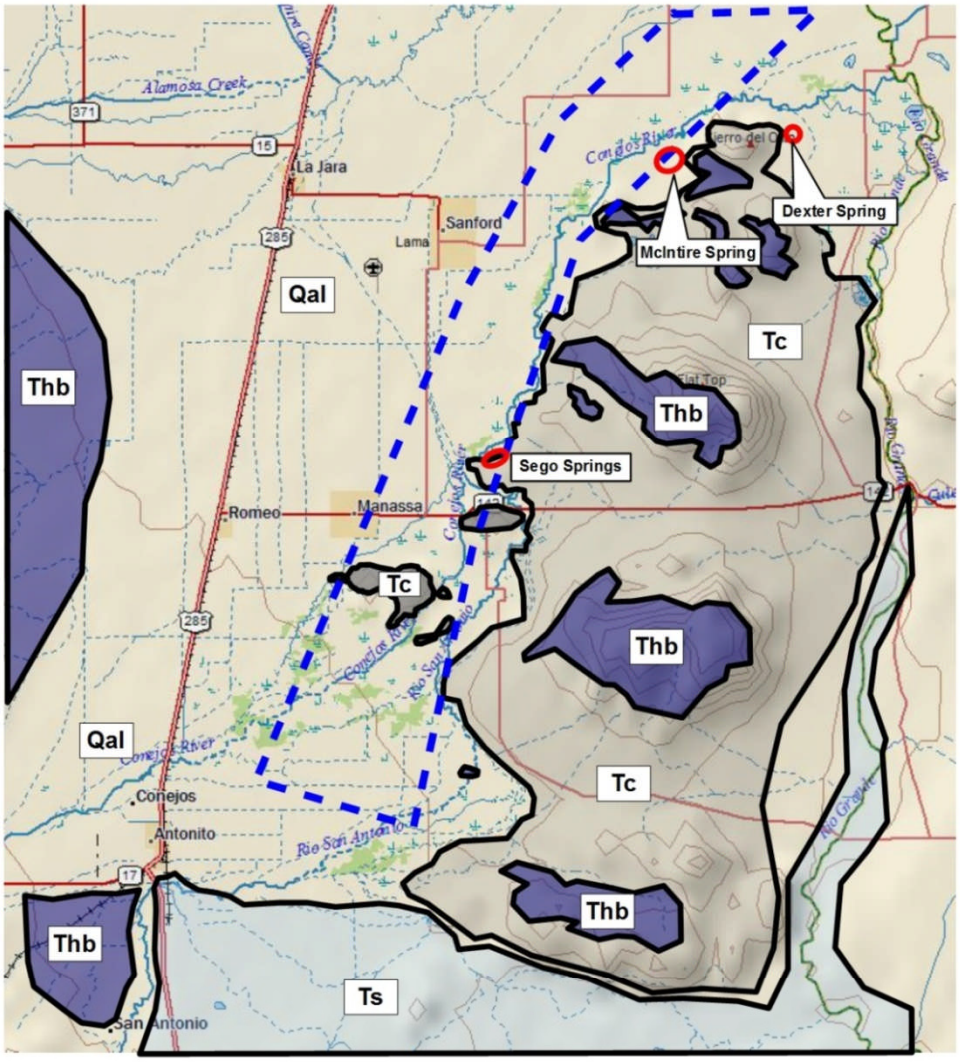

Alamosa Creek
La Jara
Sanford
Lama
Dexter Spring
McIntire Spring
Sego Springs
Romeo
Manassa
Conejos
Antonito
San Antonio
Qal
Thb
Tc
Ts
Alluvial deposits
Servilleta Formation
Hinsdale Formation
Conejos Formation
General location of Manassa Fault Zone
RGDSS
Generalized Geologic Map
And General Location Map of
Manassa Fault Zone
HRS Water Consultants, Inc. 99001-60

**Figure 1**

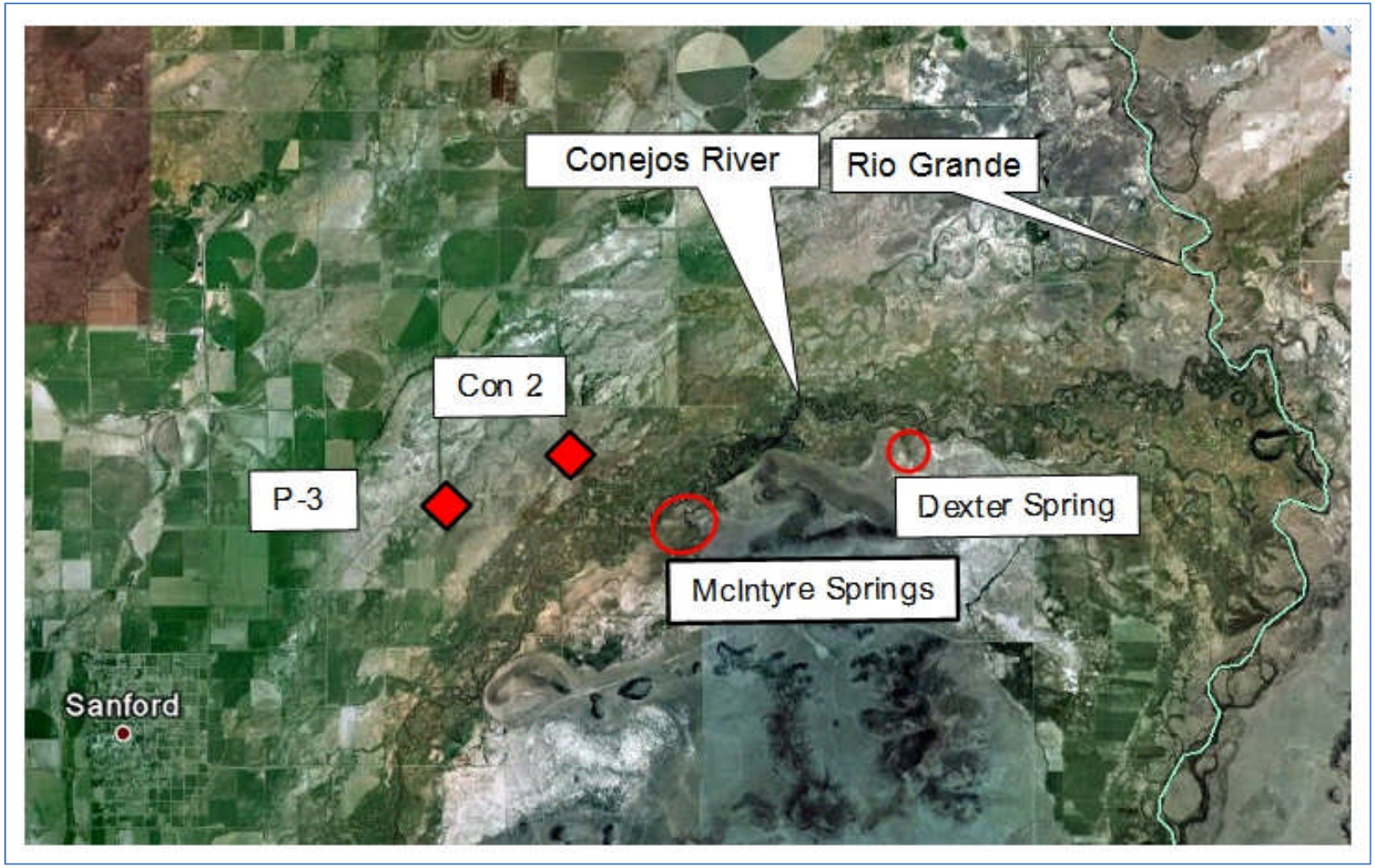



**Figure 2: Location of Springs, streams, RGDSS Piezometer no. 3, and monitoring well CON-2.**

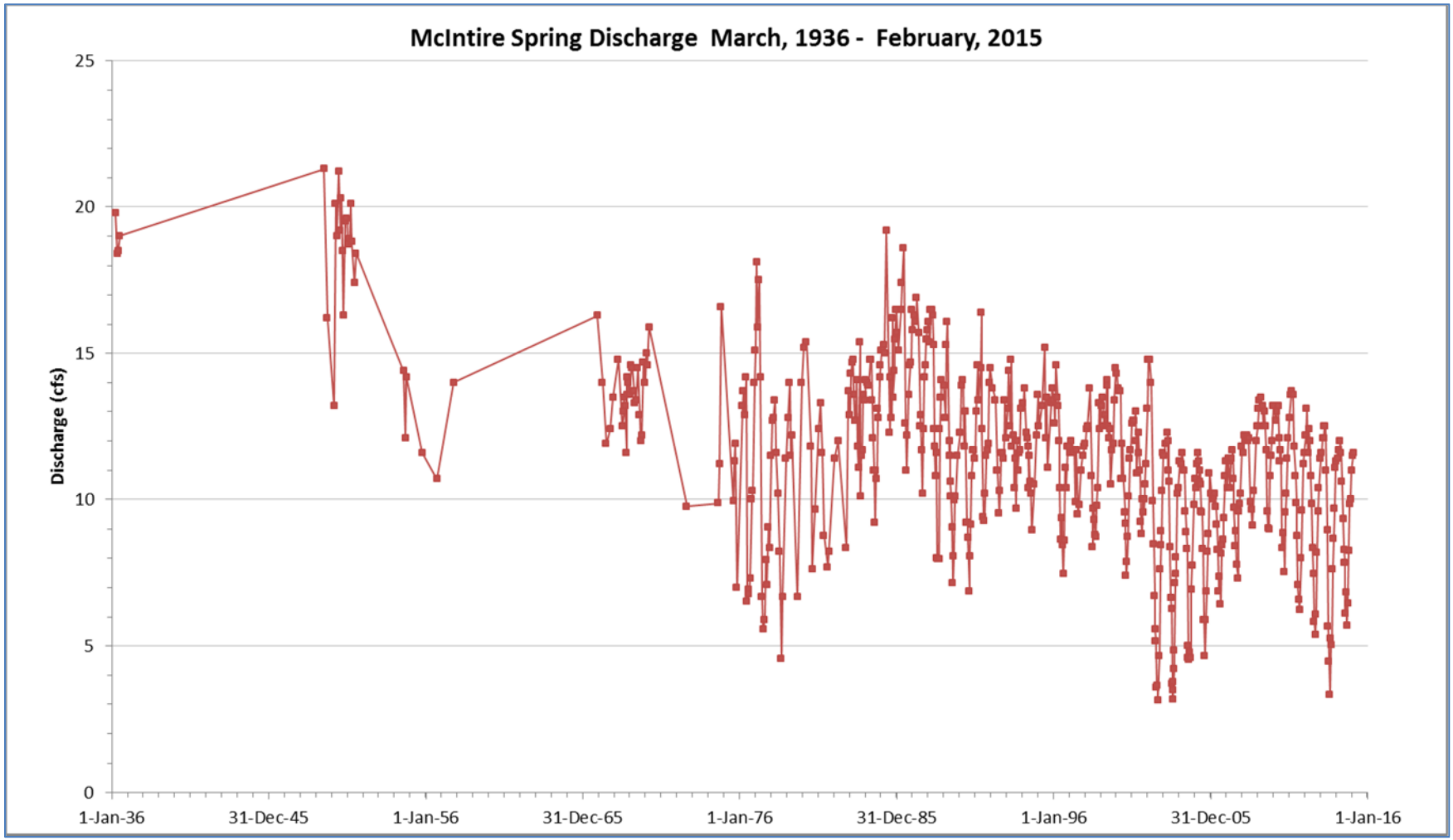

McIntire Spring Discharge March, 1936 - February, 2015
Discharge (cfs)
25
20
15
10
5
0
1-Jan-36
31-Dec-45
1-Jan-56
31-Dec-65
1-Jan-76
31-Dec-85
1-Jan-96
31-Dec-05
1-Jan-16

Figure 3

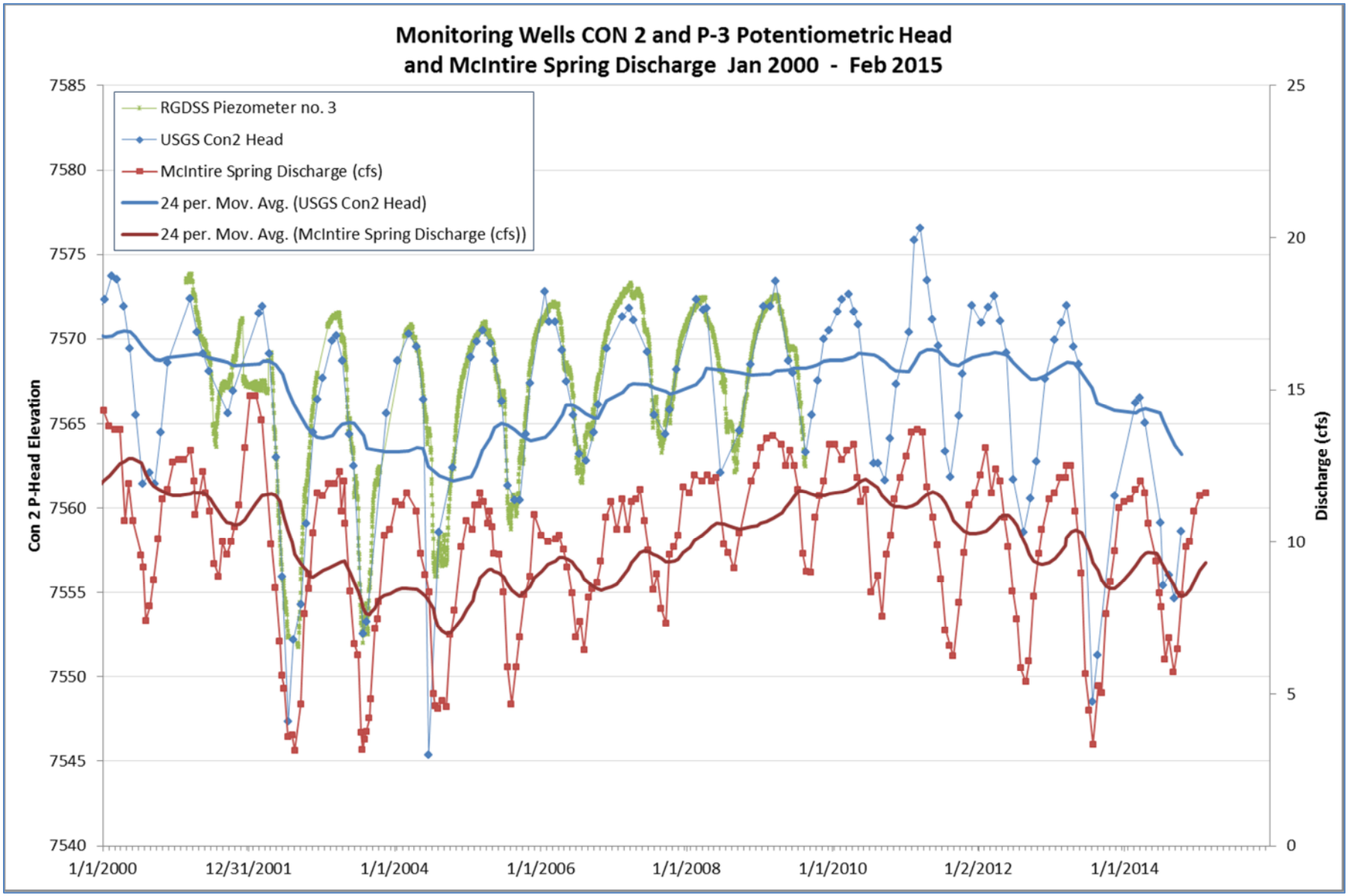

Monitoring Wells CON 2 and P-3 Potentiometric Head
and McIntire Spring Discharge Jan 2000 - Feb 2015
RGDSS Piezometer no. 3
USGS Con2 Head
McIntire Spring Discharge (cfs)
24 per. Mov. Avg. (USGS Con2 Head)
24 per. Mov. Avg. (McIntire Spring Discharge (cfs))
Con 2 P-Head Elevation
Discharge (cfs)
7585
7580
7575
7570
7565
7560
7555
7550
7545
7540
25
20
15
10
5
0
1/1/2000
12/31/2001
1/1/2004
1/1/2006
1/1/2008
1/1/2010
1/2/2012
1/1/2014

Figure 4

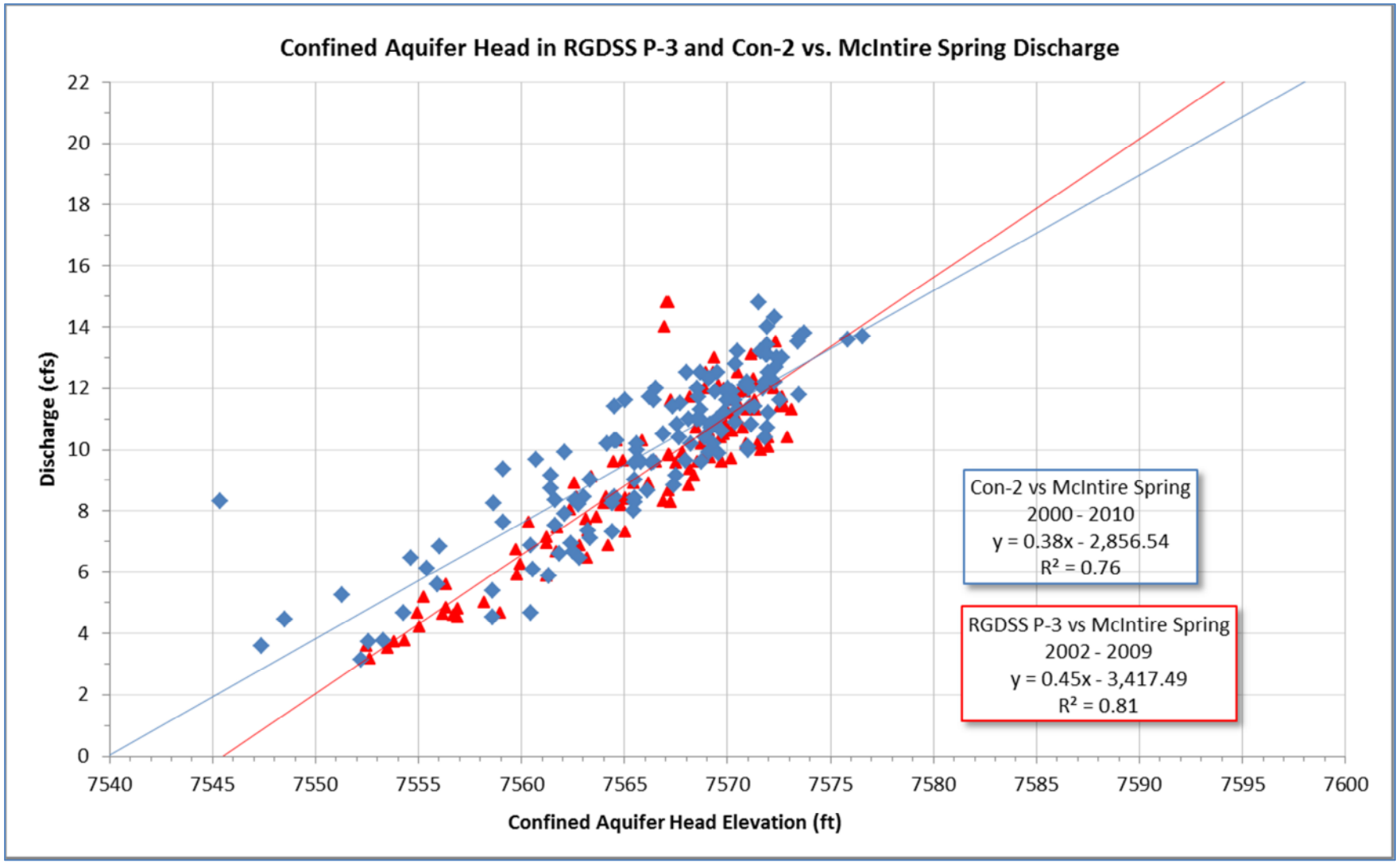

Confined Aquifer Head in RGDSS P-3 and Con-2 vs. McIntire Spring Discharge
Discharge (cfs)
Confined Aquifer Head Elevation (ft)
0
2
4
6
8
10
12
14
16
18
20
22
7540
7545
7550
7555
7560
7565
7570
7575
7580
7585
7590
7595
7600
Con-2 vs McIntire Spring
2000 - 2010
y = 0.38x - 2,856.54
R² = 0.76
RGDSS P-3 vs McIntire Spring
2002 - 2009
y = 0.45x - 3,417.49
R² = 0.81

Figure 5

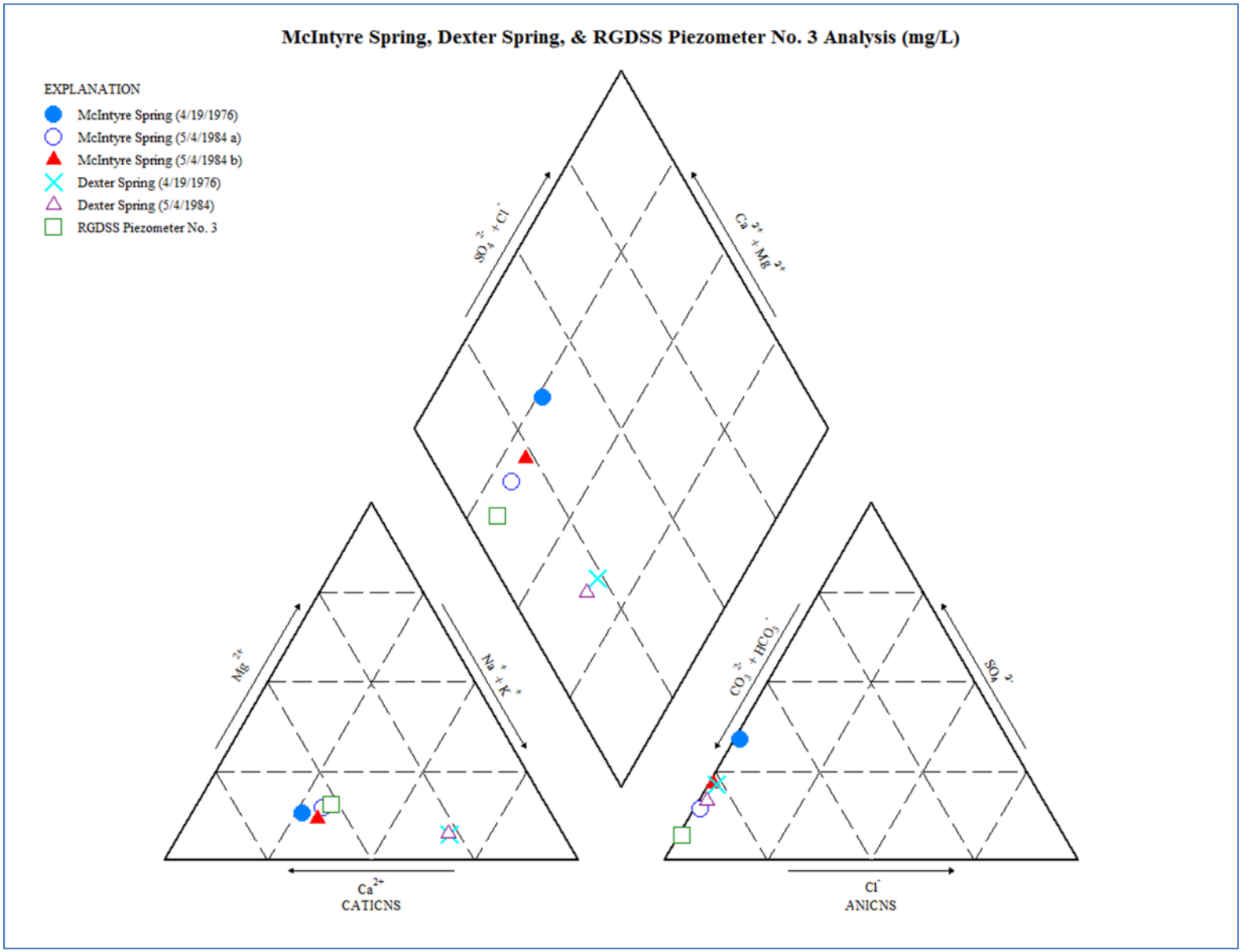

McIntyre Spring, Dexter Spring, & RGDSS Piezometer No. 3 Analysis (mg/L)
EXPLANATION
McIntyre Spring (4/19/1976)
McIntyre Spring (5/4/1984 a)
McIntyre Spring (5/4/1984 b)
Dexter Spring (4/19/1976)
Dexter Spring (5/4/1984)
RGDSS Piezometer No. 3
$SO_4^{2-} + Cl^-$
$Ca^{2+} + Mg^{2+}$
$Mg^{2+}$
$Na^+ + K^+$
$Ca^{2+}$
CATICNS
$CO_3^{2-} + HCO_3^-$
$SO_4^{2-}$
$Cl^-$
ANICNS

Figure 6

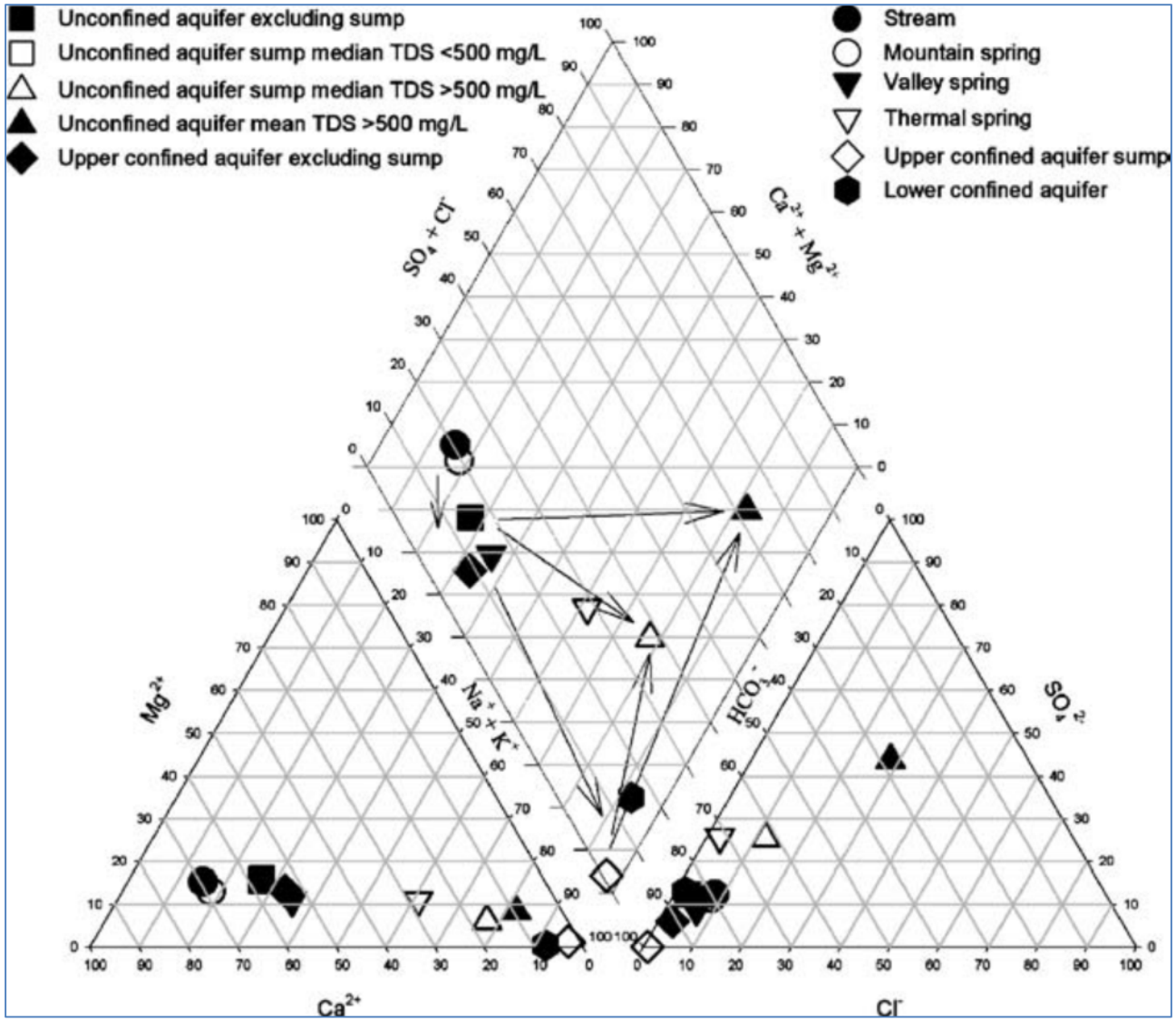



**Figure 7: This appeared as Figure 9 in Mayo, et al (2007) Fig. 9, with the caption, "Trilinear plot of solute compositions of surface and groundwater in the San Luis Valley Closed Basin. Arrows depict chemical evolution along generally accepted groundwater flow paths."**

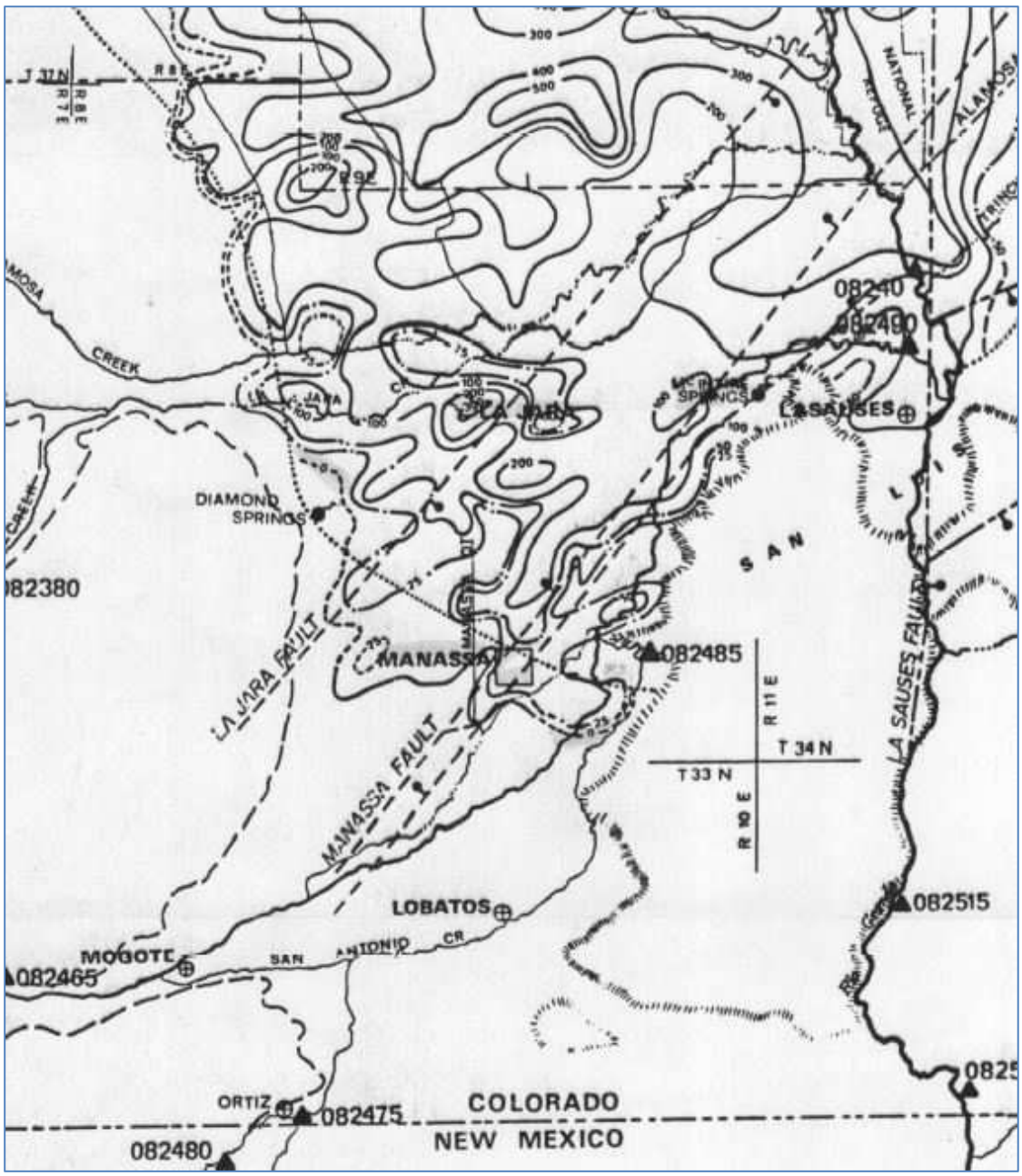



**Figure 8: Excerpt from Moravec, G., and Schroeder, D., 1978, Isopach Map of the Blue Clay Series, Plate 5-1, Colorado Division of Water Resources.**

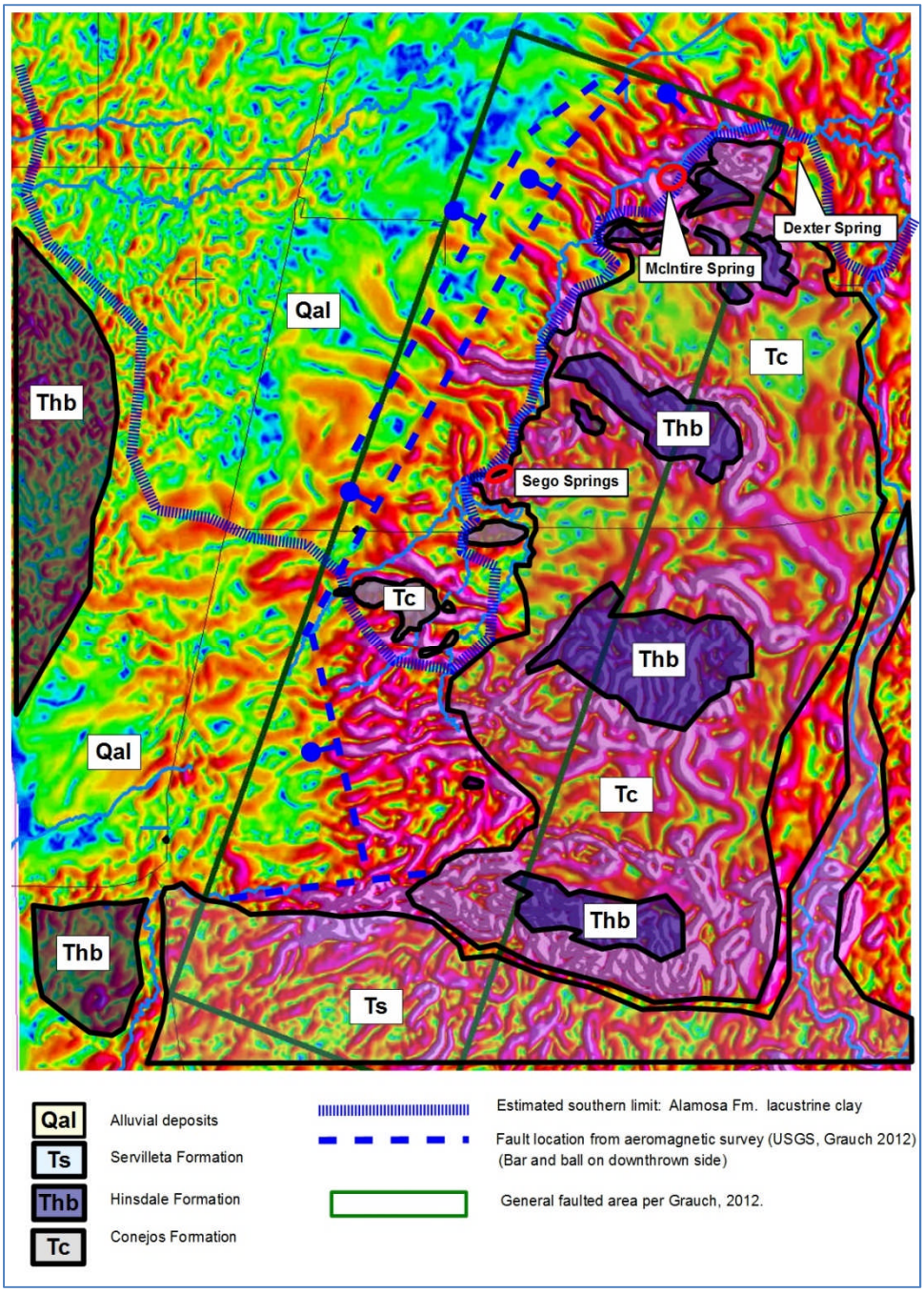



**Figure 9: Aeromagnetic anomaly map (Horizontal gradient, reduced to the pole) and interpreted fault locations per Grauch, 2011. Geology and streams overlaid by HRS.**

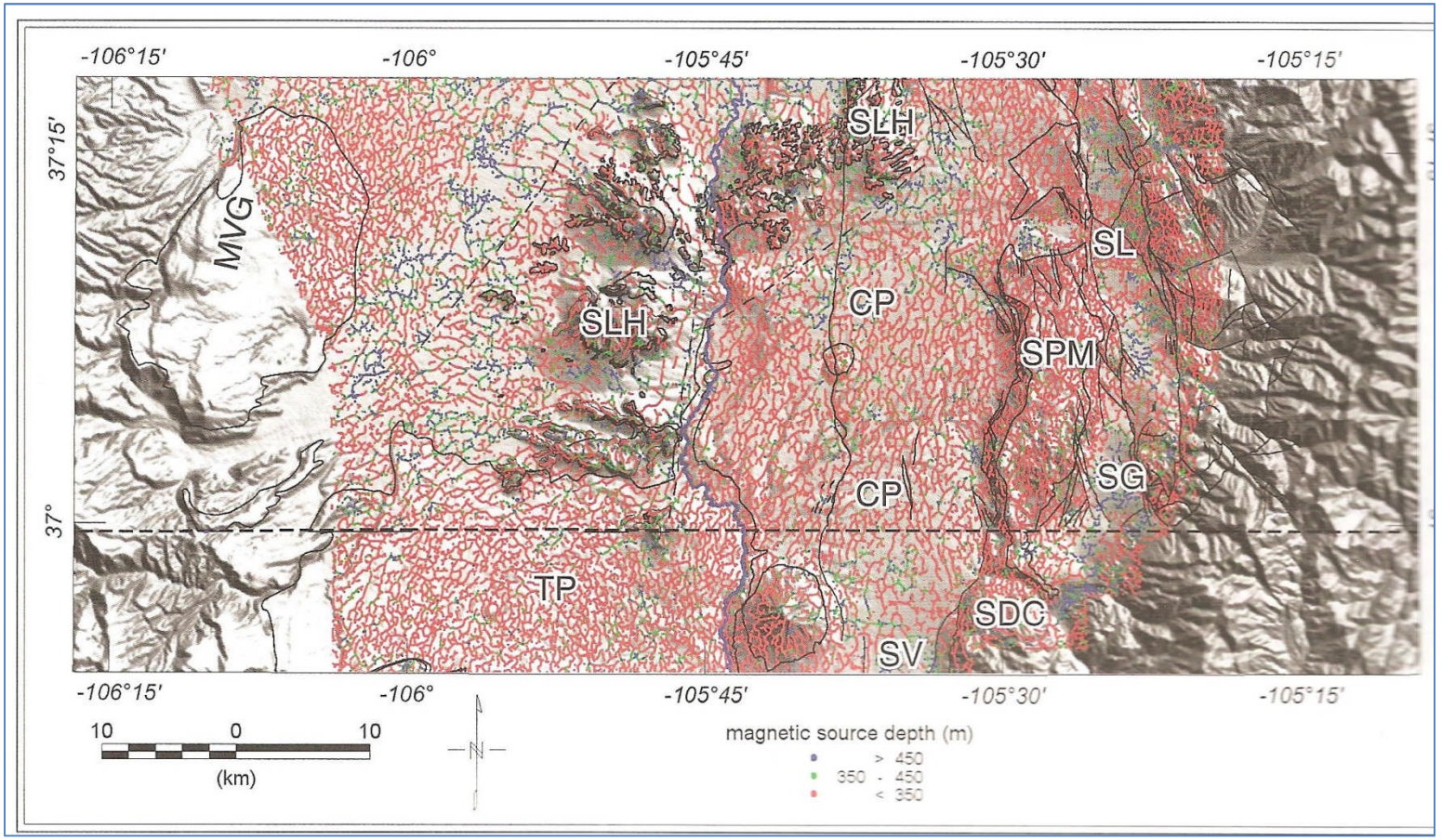



**Figure 10: Estimates of depth to magnetic sources, as interpreted by Drenth et al, GSA Special Paper 494, 2013.**
**This figure appeared as Figure 10 in Drenth et al, GSA Specal Paper 494, 2013.**

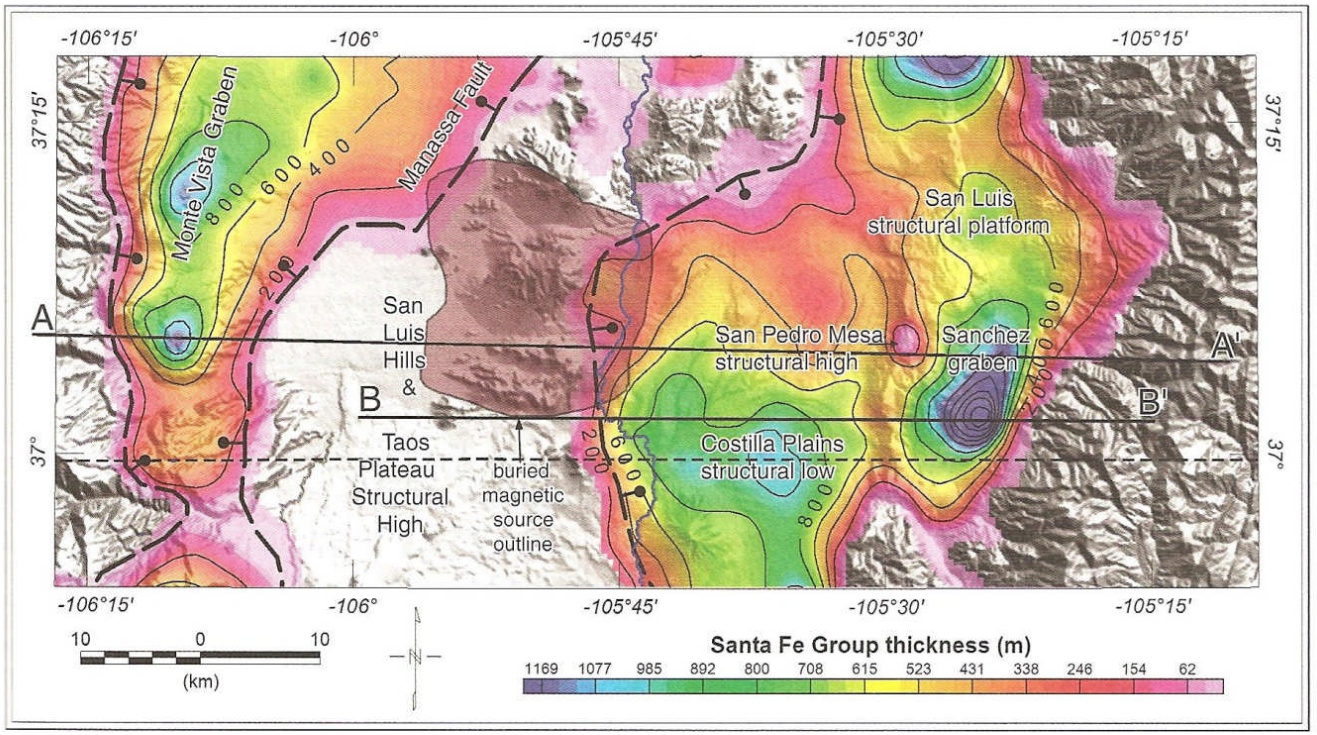



Figure 14. Summary of selected new geologic conclusions determined from geophysical data analysis. Colors and contours indicate estimated thickness of Santa Fe Group sediments from gravity inversion (contour interval 200 m). Locations of newly inferred basin- and graben-bounding normal faults shown by dashed lines with ball on downthrown side. Location of profile model A–A′ (Fig. 13) shown, as well as magnetotelluric profile B–B′ (Fig. 12).

**Figure 11: Fault location and interpreted Santa Fe Group thickness from gravity survey interpretation per Drenth et al, 2013. This figure is a reproduction of Figure 14 with its caption, from GSA Special Paper 494, 2014, p. 95.**

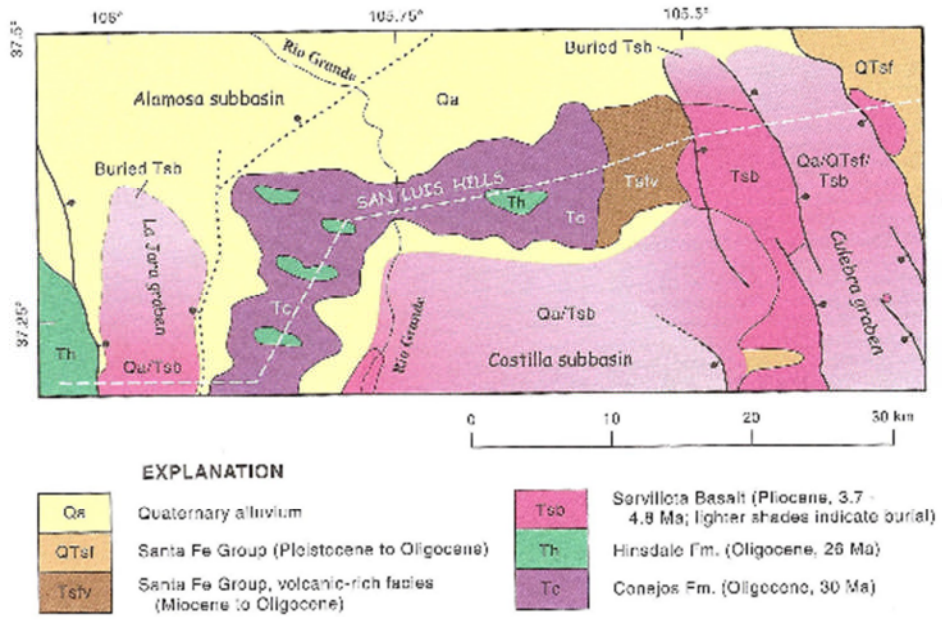



Figure 2. Schematic geologic map of the San Luis Hills showing Pliocene Servilleta Basalt (unit Tsb) that flowed northward around east and west margins of the hills. Slashes indicate stacked units (e.g., Qa/Tsb indicates Qa over Tsb). White dashed line shows topographic traverse of Figure 9.

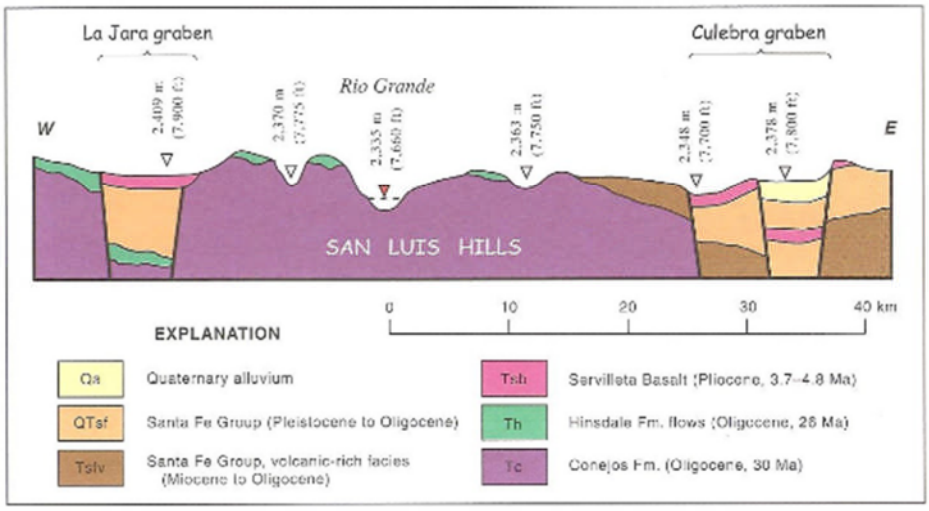



Figure 9. Schematic cross section showing probable Lake Alamosa outlets (topographic lows) adjacent to and within the San Luis Hills along an east-west traverse (location shown in Fig. 2). Eventual outlet through the Fairy Hills sill (dashed line, elevation 2335 m; 7660 ft) shown by red triangle.

**Figure 12: Schematic geologic map and cross section (figures 2 and 9) reproduced From Machette et al, GSA Special Paper 494, p. 4 and p. 12.**

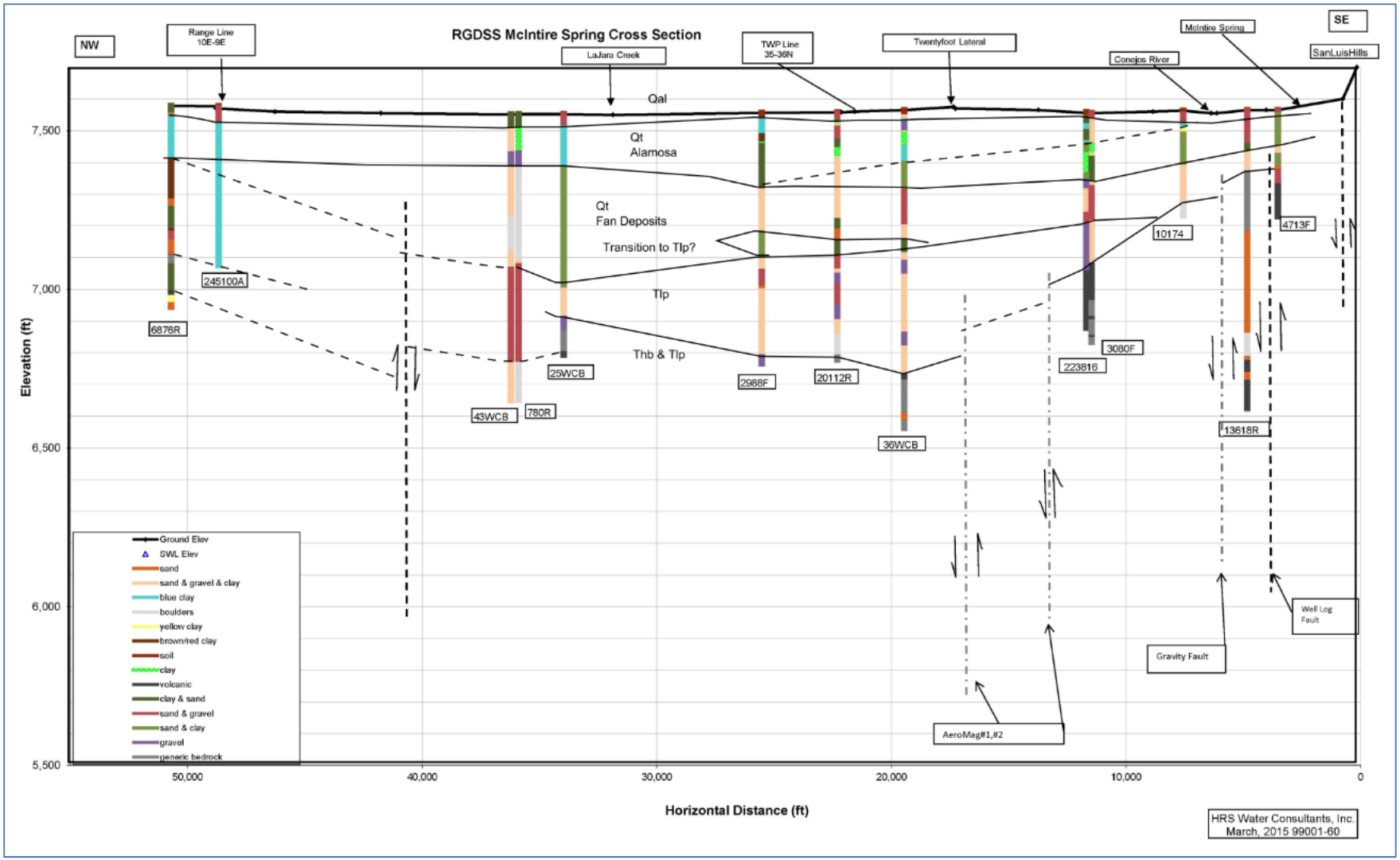



**Figure 13. McIntire Spring Cross-Section**

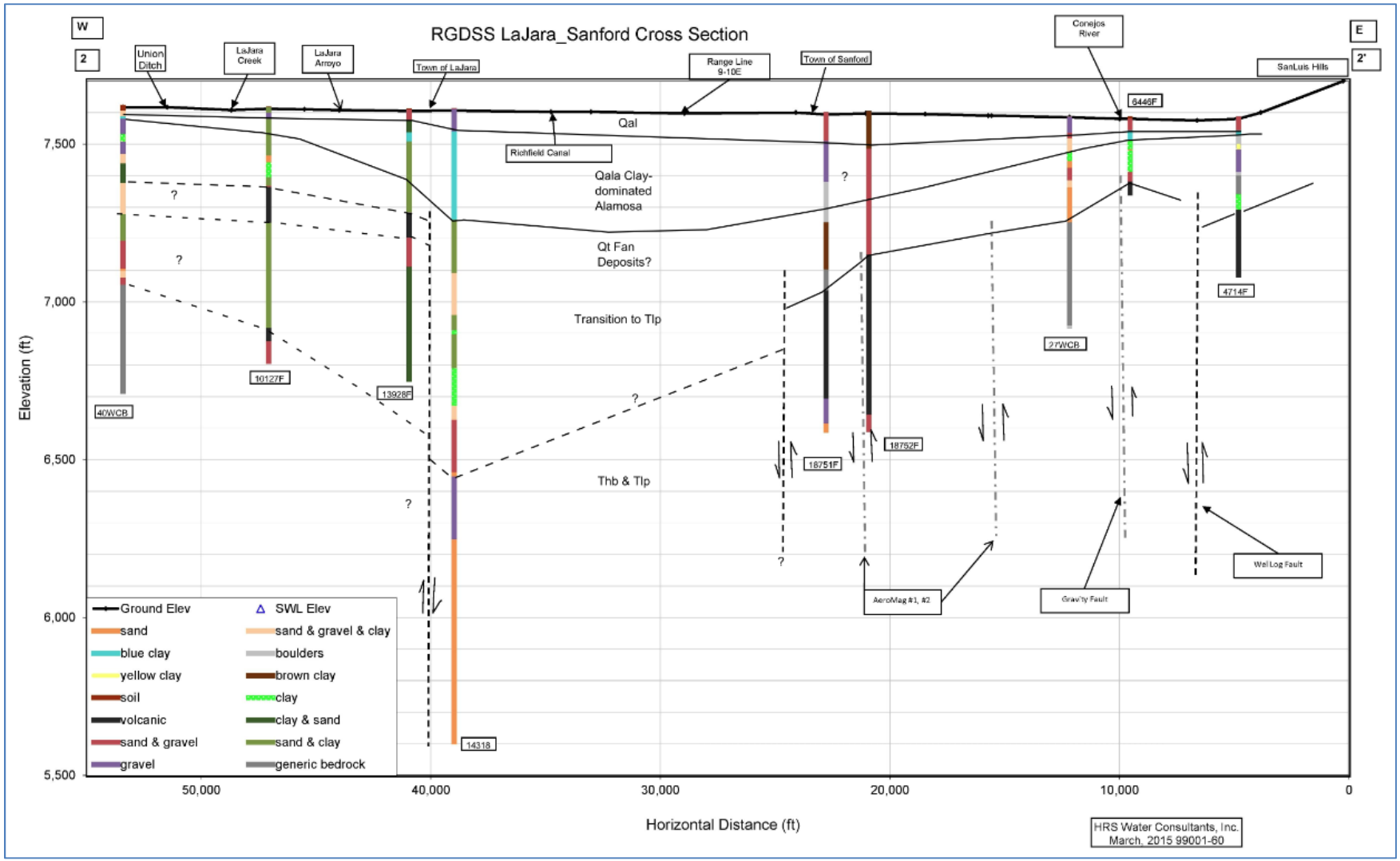



**Figure 14. LaJara-Sanford Cross-Section**

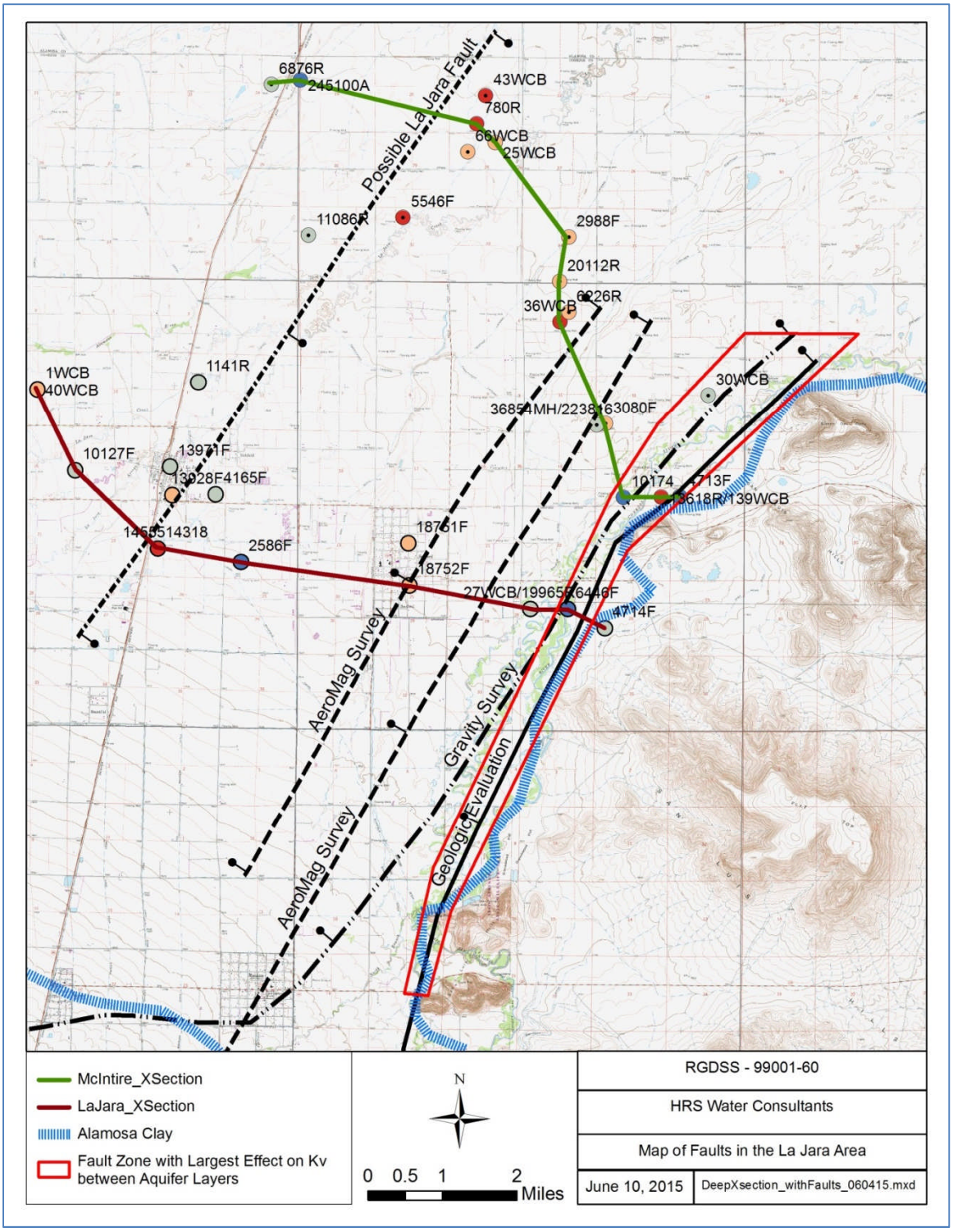



**Figure 15. Map of Faults and Cross-Sections**