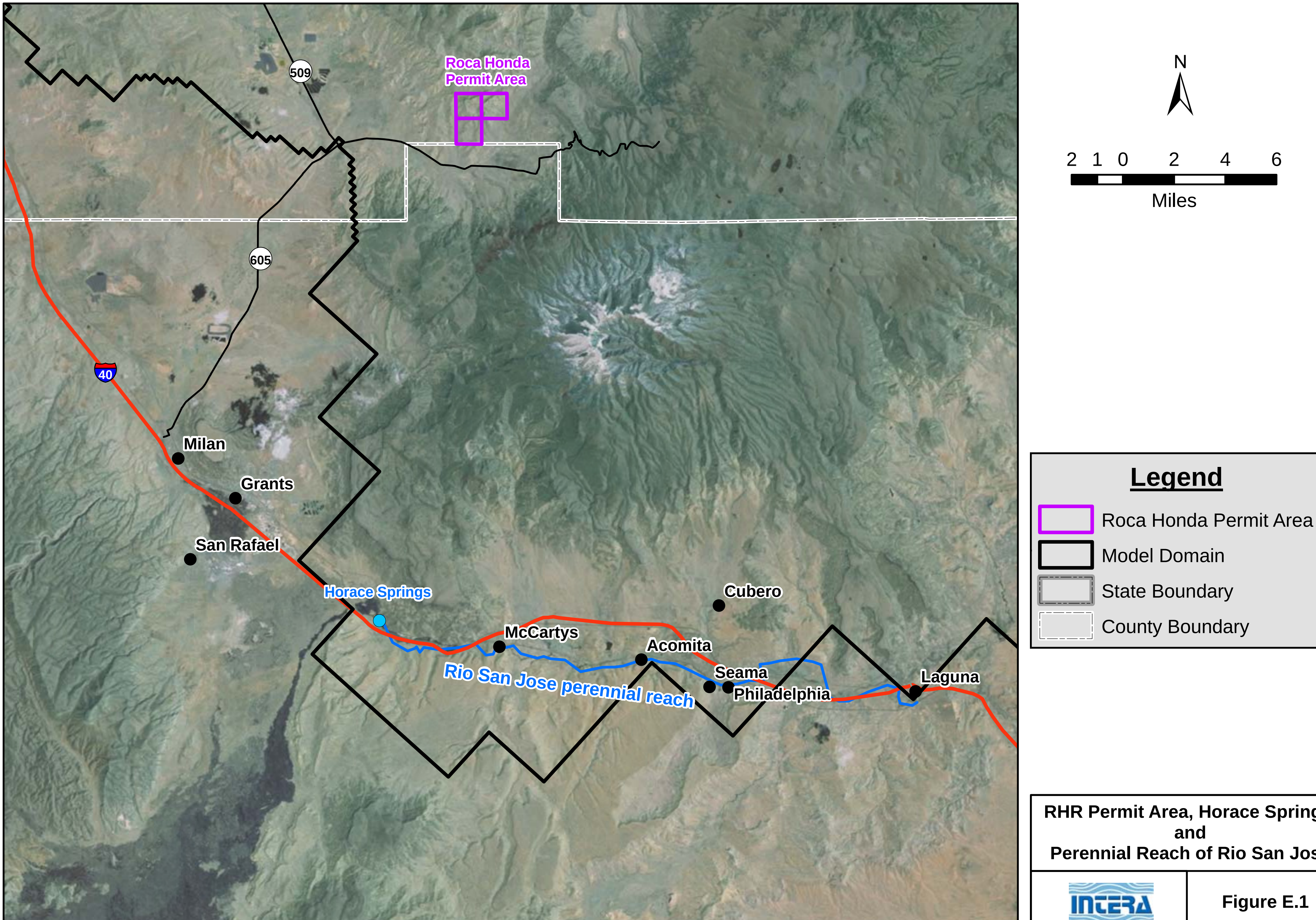
Appendix E

Hydrogeologic Evaluation of Horace Spring and Perennial Reach of the Rio San Jose for the RHR Model

APPENDIX E. HYDROGEOLOGIC EVALUATION OF HORACE SPRING AND PERENNIAL REACH OF THE RIO SAN JOSE FOR THE RHR MODEL

Groundwater discharge at Horace Spring and along the perennial reach of the Rio San Jose, which is located between Horace Spring and the Village of Laguna (Figure E.1), is the result of the interaction between the geology, topography, and watershed hydraulics for groundwater and surface water within the area (Risser, 1982; Baldwin and Anderholm, 1992; Frenzel, 1992; Wolf, 2010). Groundwater discharges at Horace Spring of 3 to 6 cubic feet per second (cfs) have been reported, with present-day discharge rates lower than past rates (Risser, 1982; Baldwin and Anderholm, 1992; Frenzel, 1992; Wolf, 2010). Groundwater discharge into the Rio San Jose between Horace Spring and the Village of McCartys (McCartys) has been estimated to be approximately 2.5 cfs (Risser, 1982). Groundwater discharges are far smaller or essentially negligible in the ephemeral Rio San Jose reaches upstream of Horace Spring and downstream of Laguna Pueblo (Risser, 1982; Risser and Lyford, 1983; Baldwin and Anderholm, 1992; Frenzel, 1992). By combining findings from previous investigations with new hydrogeologic analyses, this appendix presents the geologic and hydrologic controls on groundwater flow to Horace Spring and the perennial reach of the Rio San Jose.

Primary data sources on the Horace Spring and Rio San Jose hydrology include Risser (1982), Risser and Lyford (1983), Baldwin and Anderholm (1992), and Frenzel (1992). These USGS reports provide data showing the declining trend in groundwater discharge at Horace Spring, a gain of roughly 2.5 cfs in flow between Horace Spring and McCartys and roughly 0.5 cfs between McCartys and the Laguna Pueblo. Based on their hydrogeologic and geochemical analyses, Baldwin and Anderholm (1992) argued that groundwater discharging at Horace Spring did not come directly from the San Andres-Glorieta aquifer, but rather through alluvial sediments that were supplied by groundwater flow from the Malpais Valley and the upstream Rio San Jose valley, both of which received San Andres-Glorieta groundwater. Their geochemical analysis also indicated that the chemistry of groundwater discharging at Horace Spring had much higher concentrations of dissolved ions than groundwater from Jurassic aquifers in the area (Baldwin and Anderholm, 1992, pg 80). In contrast, groundwater from a well in the Dakota Sandstone had a much higher sulfate concentration than Horace Spring water (Baldwin and Anderholm, 1992). Using Baldwin and Anderholm (1992) as a foundation, Frenzel (1992) constructed a numerical flow model of the San Andres-Glorieta aquifer and the alluvial sediments in which he represented the groundwater flow path to Horace Spring by assigning hydraulic conductivity values up to 300 feet per day for the “cavernous basalt” that overlies the Malpais Valley and is within or adjacent to the perennial reach of the Rio San Jose. Frenzel (1992) stated that much of the groundwater discharging to the Rio San Jose came from the same source that supplies Horace Spring, but some of the groundwater may have originated from Jurassic and Cretaceous units.



RHR Permit Area, Horace Springs, and Perennial Reach of Rio San Jose

INTERA

Figure E.1

In an abstract, Wolf (2010) compared the water chemistry of Horace Spring to that of Ojo del Gallo Spring (supplied by the San Andres-Glorieta aquifer), a San Andres-Glorieta well, an Entrada Sandstone well, and two wells in the basalt-alluvial aquifer. The table of major anions and cations displayed on the poster accompanying the Wolf (2010) abstract shows good agreement between the various groundwater samples barring low dissolved silica from Ojo del Gallo and relatively high dissolved ions at one of the basalt-alluvial wells. Based on observed chemistry and simple geochemical modeling, Wolf (2010) concluded that the groundwater discharging at Horace Spring was likely a mixture of San Andres-Glorieta and basalt/alluvial aquifer groundwaters, which agrees in principle with both Frenzel (1992) and Baldwin and Anderholm (1992). Using a simple geochemical model, which was based on unstated assumptions about the relative proportions of each groundwater type, Wolf (2010) also concluded that Horace Spring water was "dominated" by San Andres-Glorieta groundwater and may contain up to 10% of groundwater from the Dakota Sandstone, despite presenting no data or analyses of groundwater from the Dakota Sandstone. In contrast, Baldwin and Anderholm (1992, pg 84) concluded,

> *Discharge from the San Andres-Glorieta aquifer at Horace Springs has been postulated. However, evaluation of hydrologic, geologic, and water-chemistry data seems to indicate that water discharging from Horace Springs is derived from the alluvial aquifer.*

The geologic cross-sections and hydrogeologic analyses described in this appendix are based on previous geologic and hydrogeologic investigations, including Thaden et al. (1967), Maxwell (1977), Risser (1982), Dillinger (1990), Maxwell (1990), Baldwin and Anderholm (1992), and Frenzel (1992). The findings from this new analysis described in detail in the following sections extend and corroborate the findings from Risser (1982), Baldwin and Anderholm (1992), and Frenzel (1992):

- Horace Spring and the perennial reach of the Rio San Jose are located within the McCartys Syncline, which uplifts the Dakota and Westwater aquifers roughly 1,000 feet above the Rio San Jose to the south and plunges to the north-northeast.
- On the western limb of the syncline, Horace Spring and the Rio San Jose are separated from the roughly 3- to 60-foot-thick Dakota aquifer by approximately 160 to 180 feet of alluvium and lower Mancos Shale units. The Westwater aquifer, which has a thickness of 20 to 40 feet in this area, is separated from the Dakota aquifer by up to 40 feet of Brushy Basin Member shale and siltstone (Thaden et al., 1967). Both the Mancos Shale and Brushy Basin have hydraulic conductivity values that are two to five orders of magnitude smaller than the hydraulic conductivity values of the Dakota or Westwater aquifers,

thereby limiting groundwater fluxes to Horace Spring from these aquifers to negligibly small values.

- The Gallup aquifer crops out high above the Rio San Jose and Horace Spring, so it lacks any hydraulic connection with them.
- The Rio San Jose flows across the Westwater upstream of Horace Spring on the western edge of the McCartys Syncline, where the Westwater's apparent thickness is approximately 155 feet. Flow in the Rio San Jose is ephemeral upstream of Horace Spring (Risser and Lyford, 1983), so there is little to no flow through the small hydraulic connection between the Westwater and the Rio San Jose. If the Westwater were discharging into the Rio San Jose at this location, flow in the river would be perennial. The ephemeral Rio San Jose flow along the hydraulic connection with the Westwater suggests that it is more likely that ephemeral flows in the Rio San Jose recharge the Westwater aquifer rather than groundwater from the Westwater supplies the river.
- The watershed area that contributes surface water flow to the Rio San Jose near Horace Spring is estimated to comprise nearly 1.5 million acres. Basalt flows in the Malpais Valley and the Rio San Jose valley occupy almost 350,000 acres. The basalt flows cover a former river valley and reach a maximum elevation approximately 1,000 feet above the elevation of the Rio San Jose. The basalt-covered portion of the Horace Spring-Rio San Jose watershed yields 20 cfs at Horace Spring and the Rio San Jose perennial reach if only 0.5 inch of precipitation per year infiltrates the porous, unvegetated basalt and follows the topographic gradient to the Rio San Jose.
- The thick, low-permeability units that separate the Dakota, Westwater, and San Andres-Glorieta aquifers from Horace Spring and the perennial reach of the Rio San Jose cannot realistically provide the observed 5 to 9 cfs groundwater discharges. For example, realistic recharge rates on the roughly 55,000-acre area of uplifted Dakota and Mancos units south of the Rio San Jose from Las Ventanas Ridge (west of Horace Spring) to Philadelphia, New Mexico, can provide the 0.5 cfs gain to the Rio San Jose flow noted by Risser (1982) for the reach between McCartys and Laguna.
- Instead, topography, geology, structure, and watershed calculations all corroborate the argument from Baldwin and Anderholm (1992) and Frenzel (1992) that the alluvial sediments in the Rio San Jose valley and in the Malpais Valley are the source of groundwater to Horace Spring and the perennial reach of the Rio San Jose.
- The Westwater aquifer appears to pinch out on the eastern limb of the McCartys Syncline. However, the next geologic map to the east of the limb (Laguna by Moench, 1963) shows surficial outcrops of all three Morrison Formation members. This suggests

that the Westwater is eroded away beneath the Rio San Jose between McCartys and Philadelphia, New Mexico.

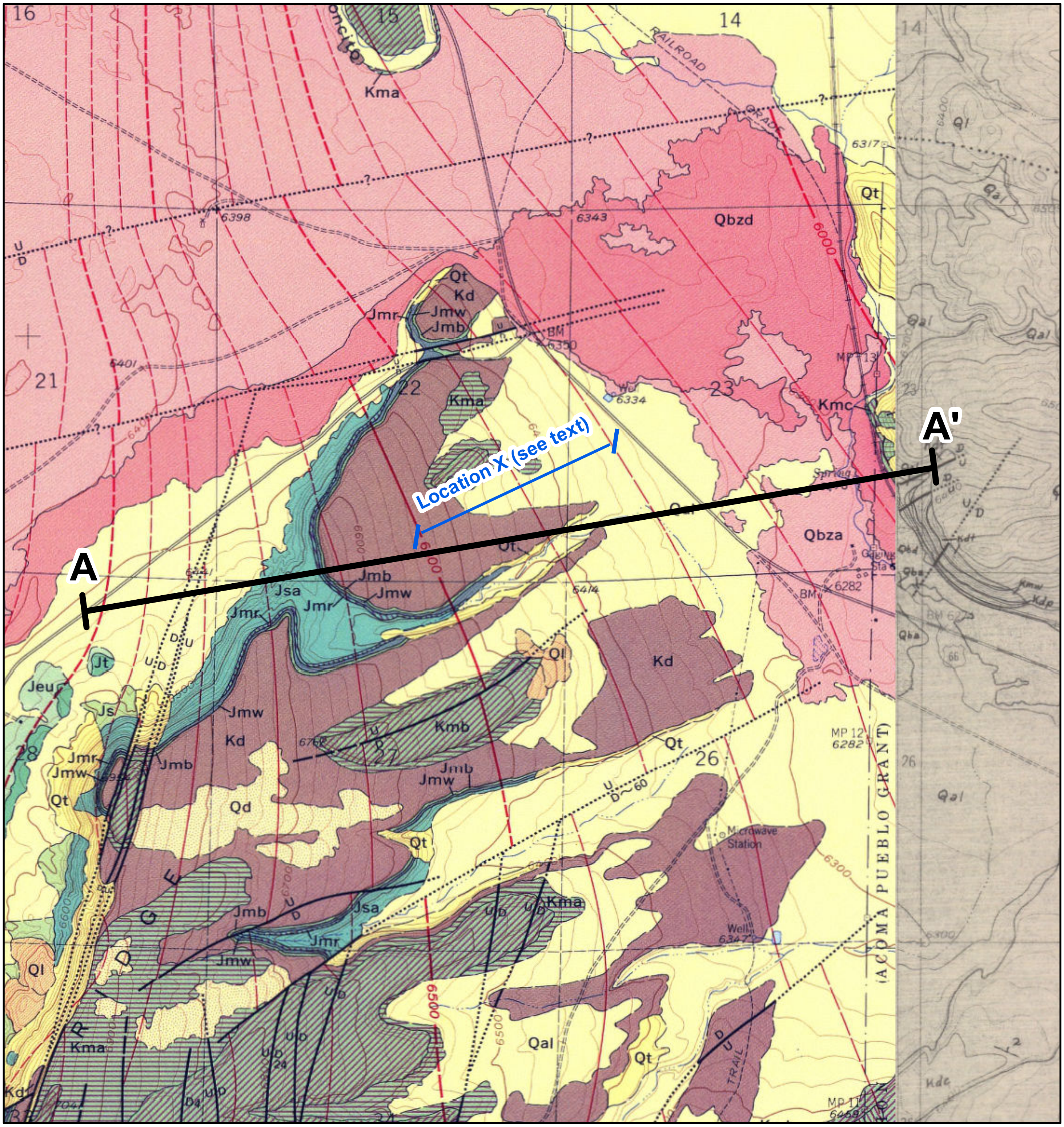
- Even if the Westwater is present on the eastern limb of the syncline, the Brushy Basin is roughly 300 feet thick, and so limits any groundwater discharge to the Rio San Jose to negligibly small values. Also, the Westwater thickness does not exceed 50 feet, so the resulting hydraulic connection is limited to an approximate apparent thickness of 150 feet.

E.1 GEOLOGIC ANALYSIS

The surficial geology of the area from San Raphael to Philadelphia, New Mexico, comprises Cretaceous sedimentary rocks, Jurassic sedimentary rocks, Quaternary basalt flows, and Quaternary alluvium. The spatial distribution of these units was altered by pre-Quaternary normal faulting, incision of the modern Rio San Jose, folding along the McCartys Syncline, volcanism, and erosion. Two geologic cross sections were developed to better understand the relationship between the Dakota and Westwater aquifers, the Jurassic and Cretaceous aquitards, Horace Spring, and the Rio San Jose.

E.1.1 Cross Section A-A’

Figure E.2a provides the location of Cross Section A-A’ (Figure E.2b). Figure E.2b illustrates the position of Horace Spring with respect to the key geologic features listed above. This cross section is based on the surface geology from a 2.5-mile-long, west-to-east transect (S80°W to N80°E) from New Mexico Highway 117 on the west to the slopes of Horace Mesa on the east on the Geologic Map of the Grants Southeast Quadrangle (Thaden, et al., 1967) and the McCartys Quadrangle (Maxwell, 1977) (Figure E.2a). As shown on Figure E.2b, geologic units beneath Horace Spring include the following, from oldest to youngest: Permian San Andres Formation; Triassic Moenkopi, Chinle, and Wingate Formations; and Jurassic Entrada, Todilto, Summerville, and Yellow Sandstone Formations. The Yellow Sandstone is also known as the Zuni Sandstone. The Jurassic Morrison Formation overlies the Zuni and consists of the Recapture, Westwater Canyon, and Brushy Basin Members. The Morrison Formation is unconformably overlain by the Cretaceous Dakota Formation (Dakota Sandstone) and in turn by at least four sandstone units of the Mancos Formation identified as the Mancos a, b, c, and d sandstone/shale units (shale/sand couplets), the upper three of which are also referred to as the Tres Hermanos a, b, and c sandstone units. These are overlain by the main Mancos Formation shale. Capping this sequence of Paleozoic and Mesozoic rocks are two Quaternary basalt flows having their origin in the Zuni flows (the Malpais flows) to the west and southwest, the Quaternary Basalt Zuni a and d. Quaternary alluvium and talus deposits are also present along the cross section. A legend for units and their respective map symbols is shown on Figure E.2b.



Geologic Quadrangle Map:
Grants SE Quadrangle, 1967
by R.E. Thaden, S. Merrin, and O.B. Raup;
Preliminary Geologic Map of the McCartys Quadrangle,
Valencia County, New Mexico, 1977
by C.H. Maxwell

N

2,000 1,000 0 2,000
Feet

INTERA

Sources:
Topo – USGS, NGMD website

A-A' Schematic Geologic Cross Section Location Map

INTERA

Appendix E.2a

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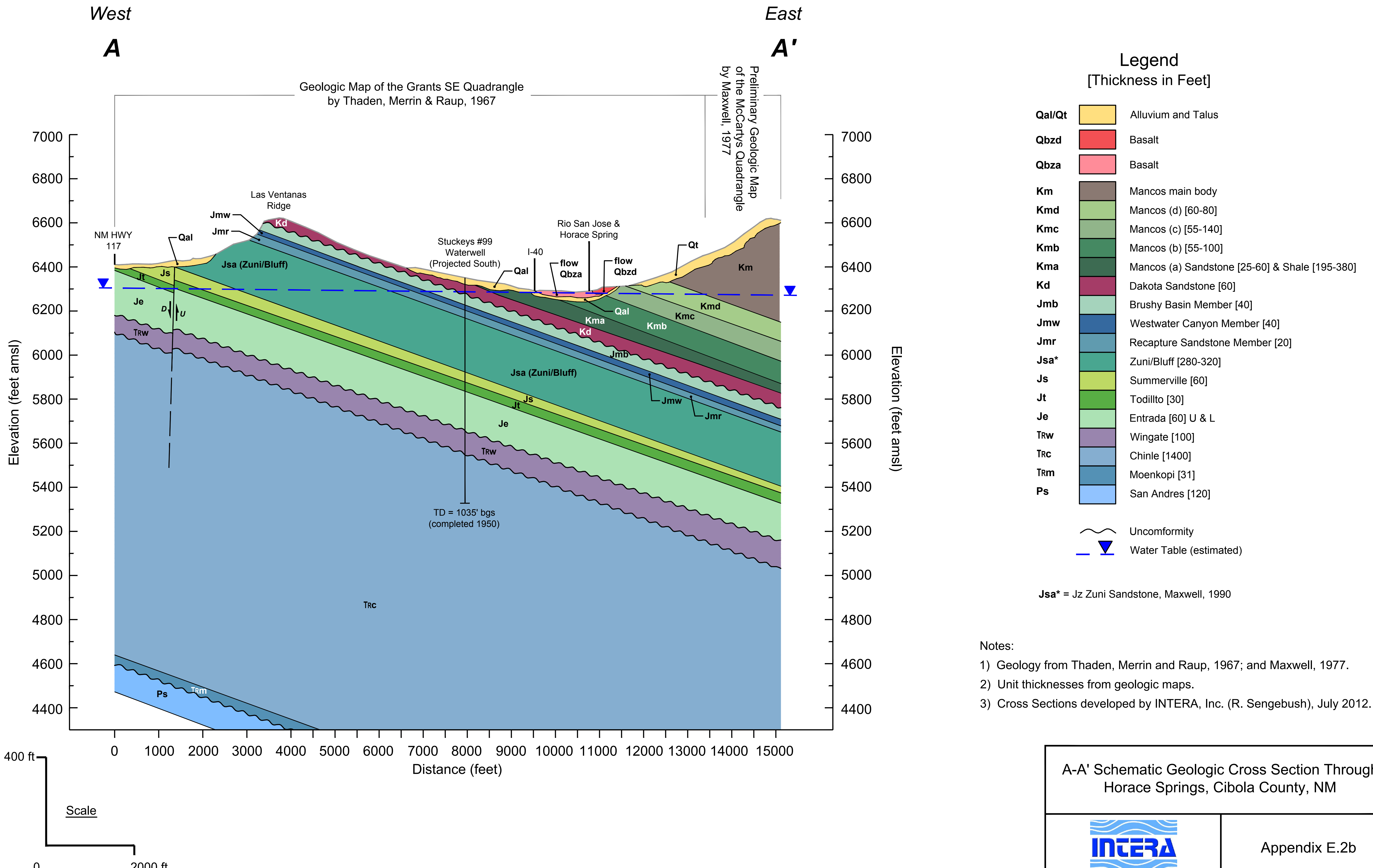
August 7, 2012



Notes:

1) Geology from Thaden, Merrin and Raup, 1967; and Maxwell, 1977.
2) Unit thicknesses from geologic maps.
3) Cross Sections developed by INTERA, Inc. (R. Sengebush), July 2012.

A-A' Schematic Geologic Cross Section Through Horace Springs, Cibola County, NM

INTERA

Appendix E.2b

August 7, 2012

From west to east, the cross section has topographic relief of about 300 feet. At the western end of the section is the Las Ventanas Ridge, a north-to-south trending, west-facing hogback with a scarp slope that includes the Zuni Sandstone, the Recapture Member, the Westwater Canyon Member, and the Brushy Basin Member of the Morrison Formation. The east-facing slope of the hogback is capped by the Dakota Sandstone. This dip slope correlates closely with the actual dip of the Dakota as defined by 100-foot structural contours on the base of the Dakota on the geologic map (Thaden et al., 1967) (Location X on the map in Figure E.2a). The true dip of the Dakota as defined along the cross section is 3.4°, although this dip steepens somewhat toward Las Ventanas Ridge. An average dip of 4° was used throughout Cross Section A-A'. The base-Dakota contours also reveal that the rocks are cut by northeast-trending normal faults with normal separation from 50 to 160 feet. Additional, similar faults are mapped to the northwest on the top of Horace Mesa (Dillinger, 1990). These faults display both down-to-the-east and down-to-the-west normal separation. An additional normal fault (concealed by talus) trends west to east along the south-facing slope of Horace Mesa, with down-to-the-south separation. These faults are consistent with the northeast-trending structural grain of the region, including the major San Rafael fault which forms the southwestern edge of the Zuni Uplift.

The cross section extends eastward up onto the Las Ventanas Ridge, down the slope of the Dakota Formation and across the alluvium toward the low point of the cross section within the flood plain of the Rio San Jose. This alluvium forms a thin deposit over the Dakota Formation. The section then intersects the two Zuni basalt flows, Qbza and Qbzd. Horace Spring is shown on the geologic map discharging from within the Qbza basalt flow along the bank of the Rio San Jose into the river. Both basalt flows are interpreted to be relatively thin, having flowed southeastward within the Rio San Jose valley. At the east edge of the basalt flows, the ground elevation increases steeply to the west-facing flank of Horace Mesa. The cross section and the geologic map depict outcrops of Kmc and the Kmd dipping east under Horace Mesa. This suggests that the Kma and Kmb units are present but concealed under the basalt and alluvium west of the Rio San Jose. The slopes above these outcrops are covered with talus deposits, but the main body of the Mancos is interpreted to be present under the talus toward the top of the mesa.

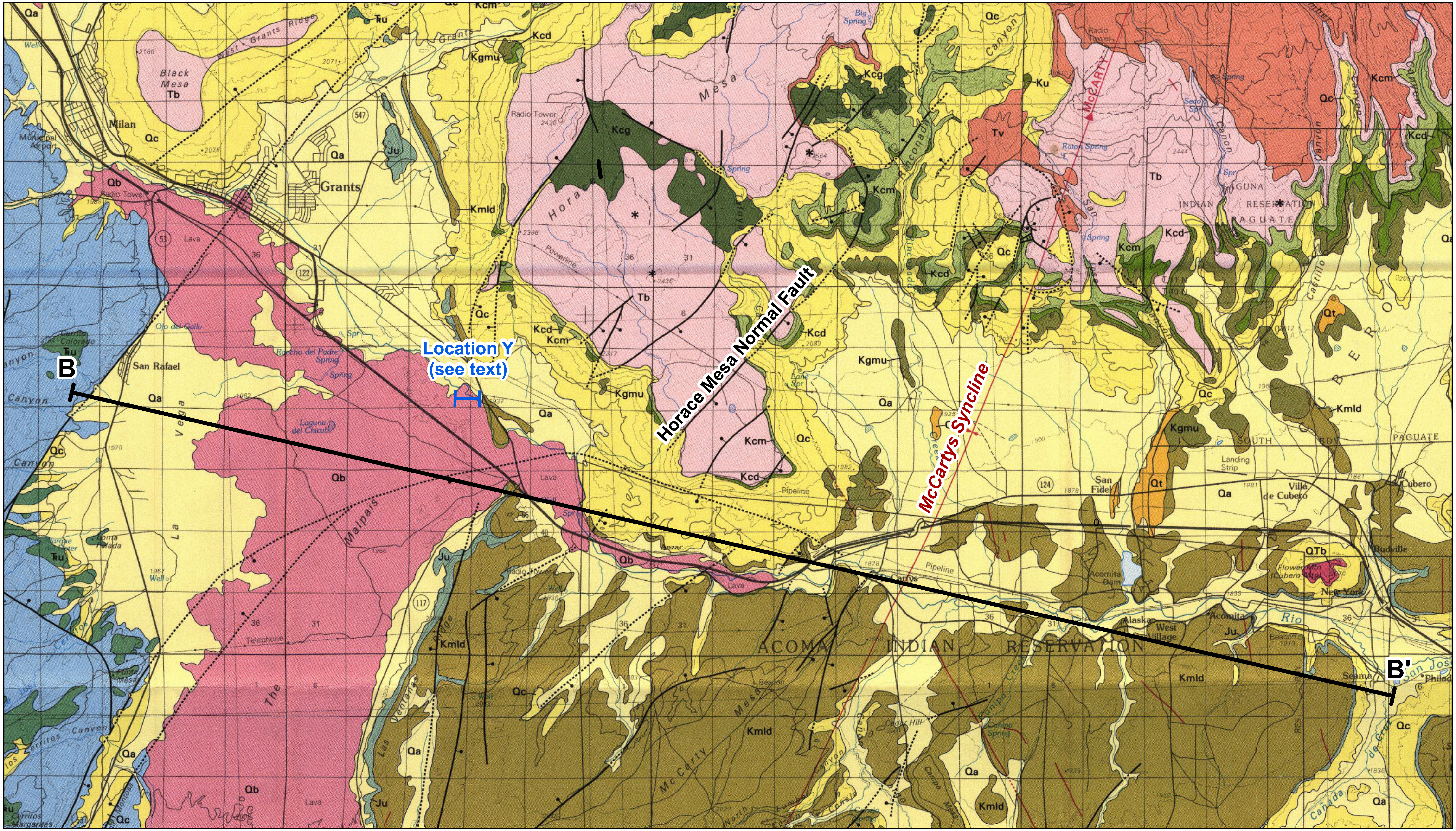
As shown on the cross section, Horace Spring emerges at the ground surface from basalt, but that basalt is underlain by Cretaceous sandstone and shale, probably within the Kma, Kmb, or Kmc units, depending on their thicknesses in these locations. The thicknesses of these units are shown as a range on the geologic map (unit d, 60 to 80 feet; unit c, 55 to 140 feet; unit b, 55 to 100 feet; and unit a, 25 to 60 feet). Although the actual thicknesses are not known, the stratigraphic position of the units is constrained by the outcrops of Kmc and Kmd on the slope of Horace Mesa such that the Cretaceous units beneath the basalt must be within or below unit Kmc. The cross section shows the position of the spring overlying unit Kmb, a unit of the Mancos Shale. The cross section also reveals that the Westwater Canyon Member in the vicinity of Horace Spring is hundreds of feet below ground surface and beneath the Mancos Shale

The cross section also depicts a water well in Section 23, Township 10 North, Range 9 West, projected 2,700 feet to the south. The well is identified as the Stuckey's #99 well with a total depth of 1,035 feet, completed in 1950 and no longer in use. The depth to water and screened interval information for this well are not available but, based on the total depth of the well and this cross section, it appears the well penetrates into the Chinle Formation. Production was likely from any and/or all of the sandstone units within and above the Chinle, such as the Wingate, Entrada, Zuni, Morrison, and Dakota. These units are likely to form confined aquifers, but there may also be a shallow, unconfined alluvial aquifer present beneath the basalt flows. The well could also access groundwater in the alluvium and basalt aquifer depending on how it is completed.

A northeast-trending, down-to-the-southeast normal fault is mapped across the top of Horace Mesa (Dillinger, 1990) (Figure E.3a, Horace Spring Normal Fault). This fault is mostly covered by the talus on the west-facing slope of Horace Mesa, but is mapped again where the Cretaceous rocks crop out near the base of the mesa about 1,750 feet southeast of Horace Spring. The amount of separation on this fault is unknown, but it is significant enough to be mapped as a solid line across the Tertiary basalt unit that forms the top of Horace Mesa. The fault is dotted west of Horace Spring. This structure may be interpreted to extend southwest past the Rio San Jose and connect with a fault trace in an arroyo cut through the Dakota outcrop west of the Rio San Jose. It is possible that this fault creates a barrier to flow in the Horace Spring area either by cementation/mineralization along the fault zone or by juxtaposing low-permeability rocks (e.g., Mancos) against more permeable rocks (alluvium) (i.e., a fault spring; Fetter, 2001). This fault is not shown on cross section A-A' because it is located south and sub-parallel to the line of section; however, it is shown on Figure E.3b with a question mark as it has not been specifically mapped in this area. At least three other faults are mapped (Dillinger, 1990) east of Horace Spring that could have a similar effect of bringing shallow aquifer water to the surface and into the reach of the Rio San Jose between Horace Spring and McCartys. (Figure E.3a)

E.1.2 Cross Section B-B'

The location for cross section B-B' is provided on Figure E.3a. The Geologic Map of the Grants 30' x 60' Quadrangle (Dillinger, 1990) was used for stratigraphic and structural information depicted in the cross section B-B' (Figure E.3b). Figures E.3b and E.3c illustrate this geologic cross section trending west to east (N73°W to S73°E) for approximately 25 miles.



N

0 1.5 3

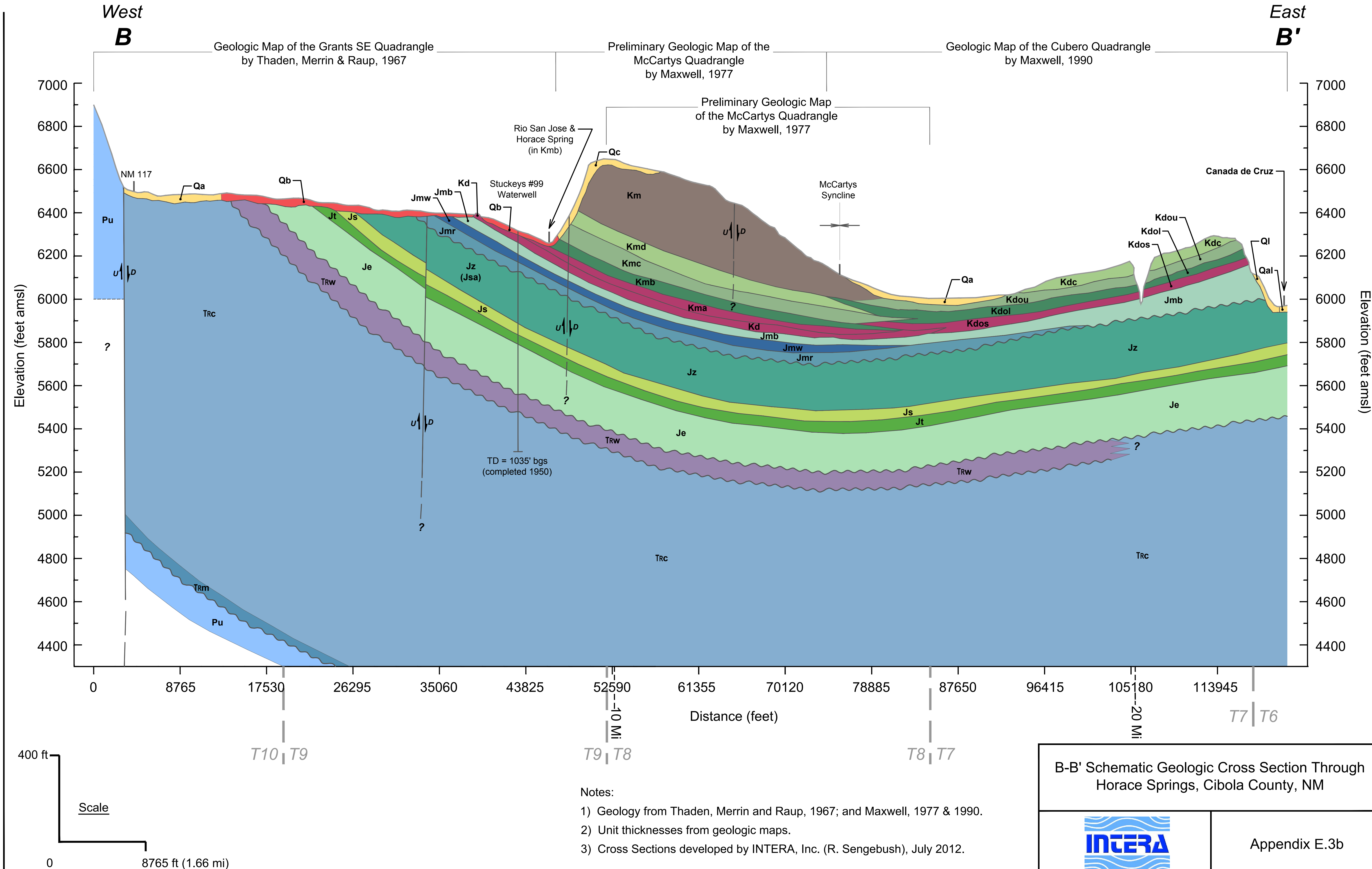
Miles

Geologic Map of the Grants 30' x 60' Quadrangle,
West-Central New Mexico, 1990
by J.K. Dillinger

B-B' Schematic Geologic Cross Section Locaton Map

INTERA

Appendix E.3a



Notes:

1) Geology from Thaden, Merrin and Raup, 1967; and Maxwell, 1977 & 1990.
2) Unit thicknesses from geologic maps.
3) Cross Sections developed by INTERA, Inc. (R. Sengebush), July 2012.

B-B' Schematic Geologic Cross Section Through Horace Springs, Cibola County, NM

Appendix E.3b

Legend
[Thickness in Feet]

Qa/Qal/Qc/Cl	Alluvium and Talus
Qb	Basalt
Km	Mancos main body
Kmd/Kdc	Mancos (d) [60-80]
Kmc/Kdou	Mancos (c) [55-140]
Kmb/Kdol	Mancos (b) [55-100]
Kd/Kma/Kdos	Dakota Sandstone [60]; Mancos (a) Sandstone [25-60] & Shale [195-380]
Jmb	Brushy Basin Member [40]
Jmw	Westwater Canyon Member [40]
Jmr	Recapture Sandstone Member [20]
Jz/Jsa*	Zuni/Bluff [280-320]
Js	Summerville [60]
Jt	Todillto [30]
Je	Entrada [60] U & L
TRw	Wingate [100]
TRc	Chinle [1400]
TRm	Moenkopi [31]
Pu	Permian, undivided

Uncomformity

Water Table (estimated)

Jsa* = Jz Zuni Sandstone, Maxwell, 1990

B-B' Schematic Geologic Cross Section Through Horace Springs, Cibola County, NM

INTERA

Appendix E.3c

Topographically, this section begins at 6,900 feet elevation on the eastern flank of the Zuni Mountains, and extends across the northern edge of the Malpais basalt fields and along the path of the Rio San Jose, ending at the confluence of Canada de Cruz and the Rio San Jose near the Laguna Pueblo village of Seama. The purpose of this cross section is to illustrate the regional stratigraphy and structure along the Rio San Jose, through Horace Spring, and through the McCartys Syncline, a north-plunging, regional syncline. The synclinal axis trends north to south, so the cross section is essentially perpendicular to the dip of the limbs of the syncline. The geology of this cross section is based on the Geologic Map of the Grants 30' x 60' Quadrangle (Dillinger, 1990) and on larger scale geologic quadrangles by Thaden, et al. (1967), Maxwell (1977), and Maxwell (1990). The strike of the base of the Dakota formation near Horace Spring is N30°W with a dip of 8° NE (from structural contours), and the apparent dip of the bedding along the trend of Cross Section B-B' is 6°NE.

Because the cross section covers four geologic maps that were created by different geologists at different times, the geologic unit nomenclature varies across the section. For example, the Cretaceous units near Horace Spring identified as Kma, Kmb, Kmc, and Kmd are absent at the east end of the section, and the time-equivalent units there are mapped as Kdos, Kdol, Kdou, and Kdc. Furthermore, the Recapture and Westwater Canyon Members of the Morrison Formation are absent at the east end of the cross section. These members are generally known to pinch out stratigraphically south of Laguna (Freeman and Hilpert, 1956; Thaden, et al., 1967). These members are shown on the cross section as merging into the Brushy Basin Member in the center of the cross section. In addition, the cross section shows an increase in thickness of the Brushy Basin Member from about 40 feet at the west end to about 300 feet at the east end, based on the geologic maps.

These lateral changes in lithology and nomenclature are relevant to this discussion because of the interaction of these units with the Rio San Jose as the units cross the path of the river over both the western and eastern limbs of the McCartys Syncline. Referring to the mapped trace of Cross Section B-B' (Figure E.3a), it is evident that the Rio San Jose cuts the Westwater Canyon Member on the west limb of the syncline, with the river potentially in hydraulic connection with the Westwater aquifer. Flow in the Rio San Jose is ephemeral upstream of Horace Spring (Risser and Lyford, 1983), so there is little to no water present to move through the hydraulic connection between the Westwater and the Rio San Jose. If the Westwater were discharging into the Rio San Jose at this location, flow in the river would be perennial. The ephemeral Rio San Jose flow along the hydraulic connection with the Westwater suggests that it is more likely that ephemeral flows in the Rio San Jose recharge the Westwater aquifer rather than groundwater supplies the river. The Rio San Jose does not appear to cut these members on the eastern limb, presumably because these members were eroded away from this part of the eastern limb. Instead, the Brushy

Basin Member directly overlies the Zuni Sandstone Formation in this area. Moench (1963) maps surficial outcrops of all three Morrison Formation members on the geologic quadrangle immediately east of cross-section B-B'.

The hydraulic connection between the ephemeral Rio San Jose and the Westwater Canyon Member is located at an apparent thickness of the member along the path of the river, shown as Location Y on the map in Figure E.3a. Location Y is approximately 1.5 miles north of the trace of Cross Section B-B'. The apparent thickness was calculated as follows:

> Based on structural contours on the base of the Dakota Formation, the strike of the beds is N10°W, dip 19°NE.
>
> The true thickness of the Westwater Canyon Member is estimated to be 40 feet in this location (Thaden, et al., 1967).
>
> The apparent thickness, along strike, of the bed at the ground surface is 123 feet.
>
> The trend of the Rio San Jose in this location is N63°W.
>
> The apparent dip of the beds along this trend is 15°NE
>
> The apparent thickness of the bed along the Rio San Jose is 154 feet.

Thus, the hydraulic connection between the Westwater Canyon Member and the ephemeral Rio San Jose is limited to a length of 154 feet at the west end of the McCartys Syncline. Even though the Westwater is considered by some geologists to be absent along the eastern limb of the McCartys Syncline, the RHR groundwater model conservatively assumes that the Westwater is present throughout this area. Given that the Westwater thickness is similar on both syncline limbs, the RHR groundwater model assumed that the Rio San Jose is in contact with the Westwater along an apparent thickness of 155 feet.

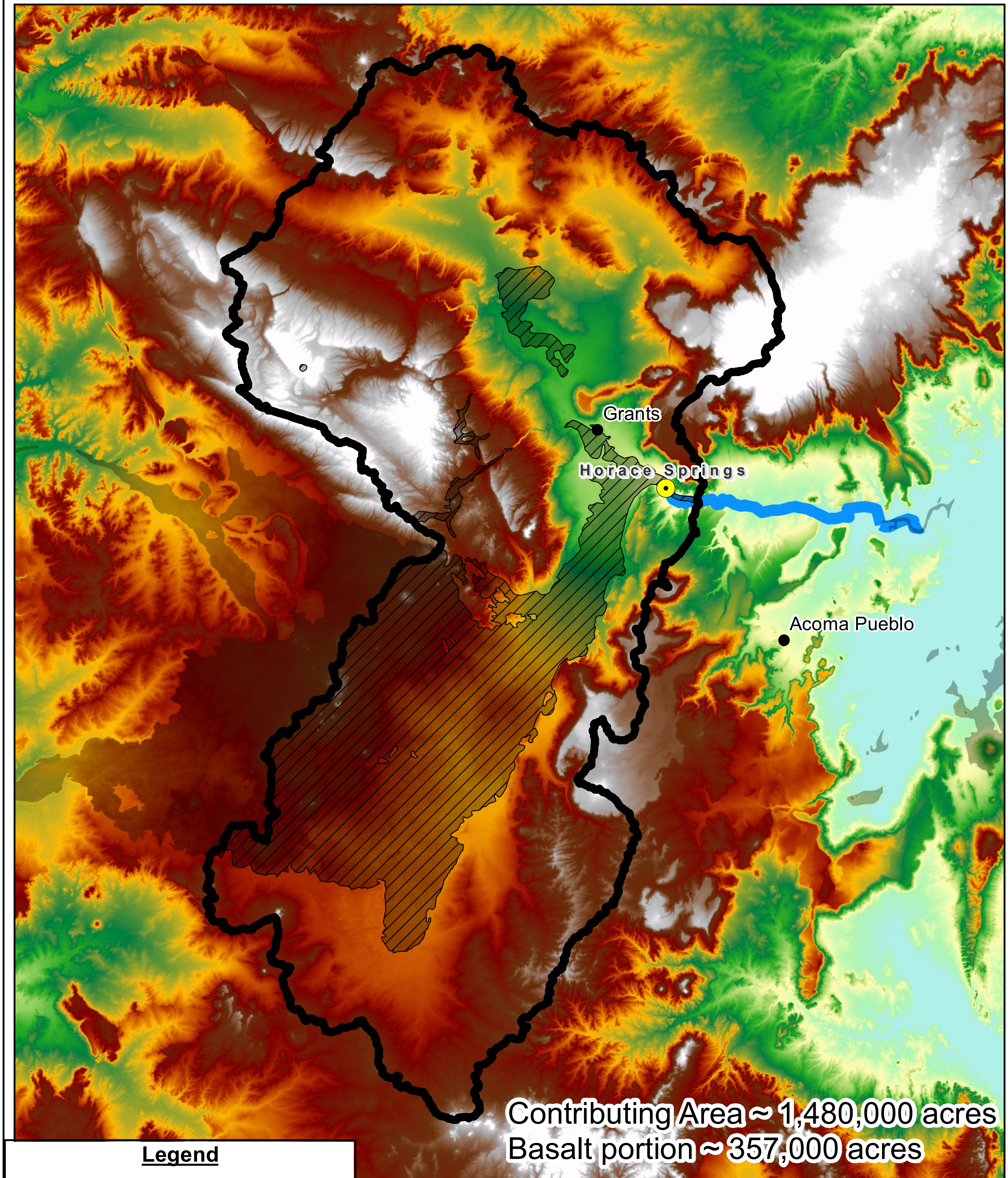
E.2 SOURCES OF WATER FOR HORACE SPRING AND THE RIO SAN JOSE

Based on the geology described above (Figures E.2b and E.3b) and the typical low-permeability values used for the Mancos and Brushy Basin aquitards, it is highly unlikely that groundwater discharges of 5 to 9 cfs measured for the Rio San Jose from Horace Spring to Laguna can originate from the Dakota and Westwater aquifers. Nor is it likely that the San Andres-Glorieta aquifer can provide such discharge rates given that this formation is more than 1,000 feet below ground surface and below the low-permeability Chinle Formation in this area.

Regarding other sources of water for Horace Spring that are consistent with the geology, Risser and Lyford (1983), Baldwin and Anderholm (1992), and Frenzel (1992) all pointed to basalt and alluvial aquifers within the Rio San Jose valley and the Malpais Valley. These authors contended that groundwater in the alluvium and basaltic aquifers of the Malpais Valley area flows northward and eastward, while water in the alluvium and basaltic aquifers along the Rio San Jose flows eastward. These aquifers converge in the vicinity of Horace Spring because of a reduction in the aquifer cross-sectional area, faulting, and topography. The basin-fill sediments within the San Raphael graben and the Malpais Valley are juxtaposed against the uplifted Jurassic units on the graben's eastern edge (e.g., Las Ventanas ridge), especially the low-permeability Chinle Formation. Thus, the erosional cut made by the Rio San Jose in the western limb of the McCartys Syncline acts as a funnel or drain to capture groundwater flowing from the upstream Rio San Jose and Malpais valleys. The analyses presented below provide additional support for this conclusion by quantifying the potential groundwater recharge from the watersheds that drain towards Horace Spring and the perennial reach of the Rio San Jose.

As illustrated in Figure E.4, the watershed that directs surface water flows to the Rio San Jose near Horace Spring encompasses nearly 1,500,000 acres. This area was calculated using the watershed delineation tool in ArcMap 10. Differences in ground surface elevation span thousands of feet between the watershed margins and the Rio San Jose near Horace Spring. The high-elevation areas also receive higher amounts of precipitation, such as the Zuni Uplift areas that recharge the San Andres-Glorieta aquifer (Baldwin and Anderholm, 1992) in the northwestern part of the watershed depicted in Figure E.4. The Zuni Uplift also tilted the San Andres-Glorieta aquifer so that the area west of San Raphael slopes down into the Malpais Valley, where separation of more than 1,000 feet along the San Raphael fault juxtaposes basin-fill sediments and the low permeability Chinle Formation in the San Raphael graben against the highly permeable San Andres-Glorieta aquifer (the western end of cross-section B-B' on Figures E.3a and E.3b). This juxtaposition likely allows for the calcium bicarbonate-rich groundwater from the San Andres-Glorieta aquifer to migrate into the basalt-alluvium aquifer of the Malpais and Rio San Jose valleys.

Almost 350,000 acres of the watershed is covered by the basaltic flows observed in the Malpais and Rio San Jose valleys (Figure E.4). The basalt flows cover a former river valley and reach a maximum elevation approximately 1,000 feet above the elevation of the Rio San Jose, which suggests topographic-driven groundwater flow along the valleys towards Horace Spring (see Figure 11 of Baldwin and Anderholm, 1992). The basalt-covered portion of the Horace Spring-Rio San Jose watershed comprises porous, unvegetated basalt that likely minimizes evapotranspiration and maximizes infiltration.



Legend

- Basalt in Contributing Area
- Horace Spring Possible Contribution Area
- All Basalts
- Rio San Jose River (Perennial)

Elevation (m)

High : 3405

Low : 1697

22 11 0 22

Miles

N

Surface Watershed for Rio San Jose near Horace Spring

INTERA

Figure E.4

Our calculations reveal that if 0.5 inch of precipitation per year infiltrates the basalt-covered portion of the watershed and follows the topographic gradient to the Rio San Jose, it can yield 20.5 cfs at Horace Spring and the Rio San Jose perennial reach: 347,000 acres x 0.5 in/yr = 20.5 cfs. This is an overly conservative estimate of the infiltration rate expected for the basalt as Frenzel (1992) estimated the recharge rate in the basalt flows to be 15% of average annual precipitation for the Grants area.

As described by Risser (1982), Baldwin and Anderholm (1992), and Frenzel (1992), evapotranspiration will remove some of the groundwater discharging into the Rio San Jose from the upstream Rio San Jose and Malpais valleys. However, they also anticipated that infiltrating water would gather at the contact between the basalt and underlying, less permeable sediments and follow the topographic gradient along the covered river valley towards the lowest elevation in the watershed: the Rio San Jose and Horace Spring. The actual discharge of groundwater at Horace Spring and along the Rio San Jose reach from Horace Spring to McCartys is most likely controlled by the incision of the Rio San Jose into the basalt flow and local sub-surface barriers to flow such as faults or juxtaposition of high and low permeability materials.

The large area of Dakota and Mancos units south of the Rio San Jose from Las Ventanas Ridge (west of Horace Spring) to Philadelphia, New Mexico, may also collect enough recharge to provide some groundwater discharge to the Rio San Jose reach between McCartys and the Laguna Pueblo. Watershed and DEM maps were used to calculate a watershed area of roughly 55,000 acres. Only a very small recharge rate is required to generate 0.5 cfs that could be discharged into this Rio San Jose reach.

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