NEW MEXICO BUREAU OF GEOLOGY AND MINERAL RESOURCES

Hydrogeology of central Jornada del Muerto: Implications for travel along El Camino Real de Tierra Adentro, Sierra and Doña Ana Counties, New Mexico

Talon Newton, Trevor Kludt, Dave Love, and Ethan Mamer

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New Mexico Bureau of Geology and Mineral Resources

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AQUIFER MAPPING PROGRAM

New Mexico Bureau of Geology and Mineral Resources

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Cover photograph: Spaceport America with a mirage of horse wagons.

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EXECUTIVE SUMMARY

Between 1598 and the 1880s, El Camino Real de Tierra Adentro (El Camino Real) served as a 1,600 mile long trade route between Mexico City and San Juan Pueblo/Ohkay Owingeh, New Mexico. El Camino Real transects the Jornada del Muerto, located in southern New Mexico. This stretch of the trail is thought to have been one of the most feared sections along El Camino Real due, primarily, to the scarcity of water. Archaeologists have hypothesized that water availability largely influenced the travel route and locations of *parajes* (campsites) in the Jornada del Muerto. This report describes a study in the Central Jornada del Muerto, conducted by the New Mexico Bureau of Geology and Mineral Resources (NMBGMR). The study was funded the New Mexico Spaceport Authority (NMSA) and is the fulfillment of one of the measures specified in a mitigation plan that identifies a series of measures specifically intended to mitigate adverse effects to El Camino Real. These measures include actions that “will result in compilation of additional information about the properties and function of the trail and associated resources,” and “that will result in increased public awareness and appreciation of the trail.”

This study aims to assess the relationship between the location of the trail and *parajes* and water sources that would be available to travelers on the trail. The study area for the hydrogeologic study is located primarily in the central portion of the Jornada del Muerto Basin, extending from just North of Engle to just south of Point of Rocks and spanning the entire basin from the Caballo Mountains in the west to the San Andres Mountains to the east. This study focuses on the present-day hydrologic system in the area. We measured groundwater levels in wells, and sampled water from wells, springs and seeps for water chemistry and environmental tracer analyses. We used these data to construct a hydrogeologic conceptual model of the study area. We then identified shallow water sources and modeled/analyzed them in the context of the hydrogeologic conceptual model to assess spatial and temporal variability of water availability to travelers who traversed the Jornada del Muerto.

Structurally, the Jornada del Muerto, south of Engle, is a syncline (trough) due to the eastward tilting of the Caballo uplift and westward tilting of San Andres uplift. The syncline plunges to the south, exposing younger rocks in the south and older rocks to the north. The Jornada Draw fault zone runs from north to south near and roughly parallel to the hinge of the syncline. This normal fault, with down throw to the east, significantly affects the groundwater and surface water system. The rock units present in the study area are primarily composed of sandstones, siltstones, and conglomerates, all of which exhibit different resistances to weathering processes and different hydrologic properties. Important aquifers in the study area include quaternary alluvial deposits, the Eocene Love Ranch Formation (conglomeratic sandstone, sandstone, and mudstone), and Late Cretaceous strata that includes the McRae Formation (conglomerates, shale, sandstone), and the Gallup Sandstone.

During this study, many areas in New Mexico, including the Jornada del Muerto, received unusually large amounts of rainfall. During September of 2013 the study area received 19.2 inches of rain, more than twice the annual average for the area. Hydrologic responses to this wet period, which include changes in groundwater levels and filling of the playas provided important information about the local hydrogeologic system.

Groundwater flows from the mountains that bound the study area to the east (San Andres Mountains) and to the west (Caballo Mountains) towards the center of the study area, where most groundwater flows to the south. However, the area around Engle, where several playas are located, appears to be a groundwater divide. Groundwater north and west of Engle flows to the northwest towards Elephant Butte Reservoir. Groundwater level and geochemical data indicates that, within the study area, there are two different hydrologic systems, a shallow perched system and a deeper regional system. Wells with a depth-to-water (DTW) >200 feet below the surface produce water from the deeper regional system, while wells with a DTW <200 feet are associated with the shallow perched system. There are other metrics that can be used to differentiate the deep system from the shallow system. The sulfate to bicarbonate (SO_4/HCO_3) ratio, the stable isotopes of oxygen ($\delta^{18}O$) and hydrogen (δD), and tritium can all be used to identify the hydrologic regime. Groundwater from the shallow system is characterized by a SO_4/HCO_3 ratio of less than two, a oxygen ($\delta^{18}O$) and hydrogen (δD) value of greater than -7.8‰ and greater than -60‰ respectively, and tritium concentrations greater than three tritium units (indicating the presence of young modern water).

The shallow groundwater system is recharged by runoff of local precipitation that infiltrates primarily in streambeds. Groundwater level responses to extreme rainfall in September 2013 show that the spatial distribution of recharge to the system is highly variable, which is indicative of focused recharge in local ephemeral streams. This system, which is mostly located to the west of the Jornada Draw fault zone, is relatively small. Water is stored in the thin alluvium and upper strata of the underlying bedrock. Responses to large rain events are rapid, but depletion of the shallow aquifer system due to evaporation and leakage to the deeper system can also be relatively rapid, especially during times of drought. Most of the springs and seeps appear to be part of the shallow system.

Water in the deeper aquifer system, which is characterized by longer residence times, is likely recharged from downward percolation of water from the shallow aquifer system and from precipitation in the adjacent mountains that infiltrates into the subsurface, traveling along deep regional flow paths. Although it is not known how thick this aquifer is, this system is larger than the shallow perched system. This groundwater likely flows to the south beyond the study area. It should be noted that for the Ojo del Muerto spring, which is located at the north end of the study area, stable isotope and carbon-14 data suggest that this spring is part of a larger regional hydrologic system.

This hydrogeologic characterization enabled us to evaluate water sources that would have been available to travelers in the area in the context of the hydrogeologic framework. Water sources that are considered include playa lakes, springs, and seeps. The amount of water available would have heavily influenced the types of groups that attempted to access a given source. When flooded, the playas can hold millions of gallons of water and cover a vast area. From historical accounts, we know that the Ojo del Muerto could provide enough water for a large number of people. The other springs in the study area and the seeps are part of the shallow hydrologic system and do not provide a great deal of water. At seeps, groundwater can be accessed by digging a shallow trench into the streambed alluvium.

Reliability of shallow water sources that were likely used by travelers was assessed by characterizing the temporal variability of water availability relative to the temporal variability of precipitation. We assessed the reliability of the different water sources using simple mathematical models that were constrained by the hydrogeologic conceptual model and monthly precipitation amounts at Elephant Butte over the last 100 years. Although, playas can provide large amounts of water to travelers, they only fill on occasion. Our analysis indicates that there is a 35% chance of finding water in the playas during the months of September and October. The likelihood of finding water in the playas drops significantly throughout the rest of the year. Based on our groundwater models we found that the shallow springs and seeps are also not very reliable, and are susceptible to short-term drought. The Ojo del Muerto spring is the most reliable source of water in the study area. The groundwater flow model suggests that the long flow path allows the spring to flow continuously even in times of drought, an assessment supported by historical accounts of spring discharge.

This research provides new information on the nature of water supplies within the Jornada del Muerto and as such has implications for historical and archaeological research in the region. The nature and location of potential water sources were analyzed in the context of potential water demands of travelers and/or groups of travelers crossing the Jornada del Muerto during the historical period (ca. 1600–1900 A.D.). In historic accounts of travelers crossing the Jornada del Muerto, group size and composition varied considerably. Small groups of travelers such as merchants, riders carrying mail, and official dispatches would consist of 10 people or less and their mounts. Small scale commercial or military contingents, consisting of between 10 to 20 people with their mounts and carts, traversed the Jornada del Muerto while on patrol, escorting official delegations, and delivering official supplies and reports. Large traveling groups often contained dozens of carts and wagons and hundreds of livestock. Finally, the largest traveling groups consisted of large herds of New Mexican sheep being driven south to markets in Mexico. These herds routinely contained 2000 to 5000 animals plus herders, drovers, and support personnel. While precise numbers are hard to come by, water requirements for different sized groupings can be estimated. Based on estimates of daily water requirements for people and different types of livestock, water requirements for travelers were estimated to range from approximately 135 gallons per day for the smallest group to 23,000 gallons per day for the largest groups.

The three known *parajes* in the study area are located near water sources that include playas, springs or seeps. The *paraje*, Laguna del Muerto, which is located approximately in the middle of the 65 mile trek through the Jornada del Muerto, is located in the vicinity of several playas and approximately six miles from Ojo del Muerto. The results of this hydrogeologic study suggest that Ojo del Muerto was the key to travel across the Jornada del Muerto. The spring is reliable and produces ample amounts of good quality water. Near the midpoint in the

Jornada del Muerto crossing, travelers who reached this spring were guaranteed to find water to enable them to finish the remainder of the crossing. The playas also played an important role. When filled, they provided high quality water for even the largest of caravans. Although these playas often dry out, as long as large caravans did not attempt the crossing until after ample rainfall, those who reached the playas could water at this point and be ready to finish the remainder of the journey. The seeps provided, at best, small amounts of water intermittently. The trail passes right by these sources, and they were undoubtedly used when available. However, their limited potential and intermittent nature suggests that they were probably viewed more as an emergency supply.

The results of this study suggest that the formidable reputation of the Jornada del Muerto may be somewhat overstated. From our research, we have demonstrated that a reliable water supply lies near the midpoint of the Jornada del Muerto crossing, and that a series of playas and seeps offer additional water sources. The limited water within the Jornada del Muerto may have been a hardship, and the crossing arduous, but it appears to have been a hardship routinely surmounted.

Related reports

- Crossing the Jornada del Muerto:
  Hydrological and Geomorphological controls on traveling the El Camino Real Historic Trail
  Open-file Report 574, poster
  Trevor Kludt, Talon Newton, and Ethan Mamer

- Landforms of the Central Jornada del Muerto:
  Influencing the Path of El Camino Real de Tierra Adentro
  Open-file Report 575, report and landform map, with GIS data
  Trevor Kludt, Dave Love, Bruce Allen, and Talon Newton

I. INTRODUCTION

El Camino Real de Tierra Adentro (El Camino Real) is an approximately 1,600 mile long trade route between Mexico City and San Juan Pueblo/Ohkay Owingeh, New Mexico and was in use between 1598 and the 1880s (Figure 1). International trade shifted away from El Camino Real with the coming of the railroad by 1881 (and later, the interstate highway), although it continued to be used as a secondary transportation route through at least the 1940s. In some locations, it is still used as such today. It is commonly thought that the Jornada del Muerto, located in southern New Mexico, was one of the most feared sections along El Camino Real due, primarily, to the scarcity of water. Archaeologists have hypothesized that water availability largely influenced the travel route and locations of *parajes* (campsites) in the Jornada del Muerto. This report describes the paleohydrologic study in the central Jornada del Muerto, conducted by the New Mexico Bureau of Geology and Mineral Resources. This study aimed to assess the relationship between the location of the trail and *parajes* and water sources that would be available to travelers on the trail. We focused on two objectives: 1) to assess the present-day hydrologic system in the area to identify shallow water sources and analyze spatial and temporal variability of water availability to travelers who traversed the Jornada del Muerto, and 2) to identify landforms that may suggest available water sources along the trail that are now extinct. This report focuses on the hydrogeologic characterization. The landform map constructed by Kludt et al., (2015) provides a wealth of information that has implications for paleohydrologic conditions in the past. Detailed descriptions of other features can be found in Appendix B.

Data used to characterize the local and regional hydrogeologic system included geologic, hydrologic, and geochemical data. These data helped us

Figure 1. Route of El Camino Real de Tierra Adentro (modified from BLM, 2010).

to identify local and regional aquifers and flow paths, and estimate groundwater residence times. Understanding the hydrogeologic framework associated with specific existing water sources, including springs, seeps, and playas, enabled us to estimate how often this water would be available under the present climatic regime (over the last 100 years). The quantity of water provided by these sources was evaluated in terms of the size of party that a particular water source could sustain. Results suggest that, while water is scarce, with the proper navigation strategies that include timing and travel practices, most travelers could access enough water to make it through Jornada del Muerto along El Camino Real.

Significance

El Camino Real de Tierra Adentro has long been recognized as the primary route between the Spanish colonial capital of Mexico City and the northernmost Spanish provincial capitals in what would become New Mexico. In the United States, this trail was added to the National Trails System as a National Historic Trail (NHT) in 2000, and the entire length of El Camino in Mexico was inscribed on the UNESCO World Heritage List in 2010. In February of 2012, ten segments of El Camino in New Mexico (including several loci in/near the project area) were listed on the National Register of Historic Places. The portion of the route recognized and administered as El Camino Real de Tierra Adentro NHT extends 404 miles from El Paso, Texas, to San Juan Pueblo (Ohkay Owingeh), New Mexico, and is jointly administered by the Bureau of Land Management (BLM) and the National Park Service (NPS), regardless of land status. The Spaceport America project area encompasses approximately 26 square miles in the Jornada del Muerto, including segments of El Camino Real NHT and associated cultural resources. Per the consultations conducted prior to the initiation of the Spaceport America project, the New Mexico Spaceport Authority (NMSA) agreed to mitigate adverse effects associated with the construction and long-term operation of the Spaceport America on a suite of cultural properties in a 5-mile radius around the Spaceport America campus, including viewshed and noise impacts on the setting as well as "direct" or physical impacts on specific sites. The *Mitigation Plan for El Camino Real de Tierra Adentro Spaceport America* (FAA and NMSA, 2010) identifies a series of measures specifically intended to mitigate adverse effects to the Trail, including measures that "will result in compilation of additional information about the properties and function of the trail and associated resources," and "that will result in increased public awareness and appreciation of the trail."

The study which is the focus of this report represents the fulfillment of one of the measures specified in the mitigation plan, and has been funded by the NMSA. The principal objective of the mitigation measure is to assess the relationship between apparent water availability and the location of the Trail and associated *parajes*. The data gathered from hydrogeologic investigations will provide a greater understanding of cultural properties along El Camino Real as well as important information for long-term management of resources, and may be useful for future predictive modeling of resource locations.

Study Area

The study area for the hydrogeologic study is located primarily in the central portion of the Jornada del Muerto Basin (Figure 2), extending from just North of Engle to just south of Point of Rocks and spanning the entire basin from the Caballo Mountains in the west to the San Andres Mountains to the east. It should be noted that the far northwestern part of this study area is located west of a surface water divide, with water draining to the west into Elephant Butte.

Geology

General geologic description

Figure 3 and Figure 4 show a compiled geologic map of the study area and a geologic cross-section, respectively. The geologic map is a compilation of two 1:125,000 maps constructed by Seager et al. (1987, 1982) and the 1:500,000 NM state geologic map (NMBGMR, 2003). The cross-section was constructed from existing cross-sections in the area. Figure 5 shows the location of several cross-sections that were used to construct the fence diagram shown in Figure 6. Structurally, the Jornada del Muerto, south of Engle, is a syncline (trough) due to the eastward tilting of the Caballo uplift and westward tilting of San Andres uplift (Seager, 2005b). The syncline plunges to the south-southeast, meaning that the axis of the syncline dips to the south-southeast. Therefore, exposed bedrock increases in age from south to the north. The Jornada Draw fault zone runs from north to south near and roughly parallel to the hinge of the syncline (Figures 3, 4). This normal fault with down throw to the east significantly affects the groundwater system and will be discussed more below. In the northern section of the study area, north of Engle, strata that dips slightly to the north or northwest is cut by several NE-trending faults. These structures are an expression of the Cutter Sag transfer zone, related to the Rio Grande Rift (Mack and Seager, 1995; Lozinsky, 1987). The rock units present in the

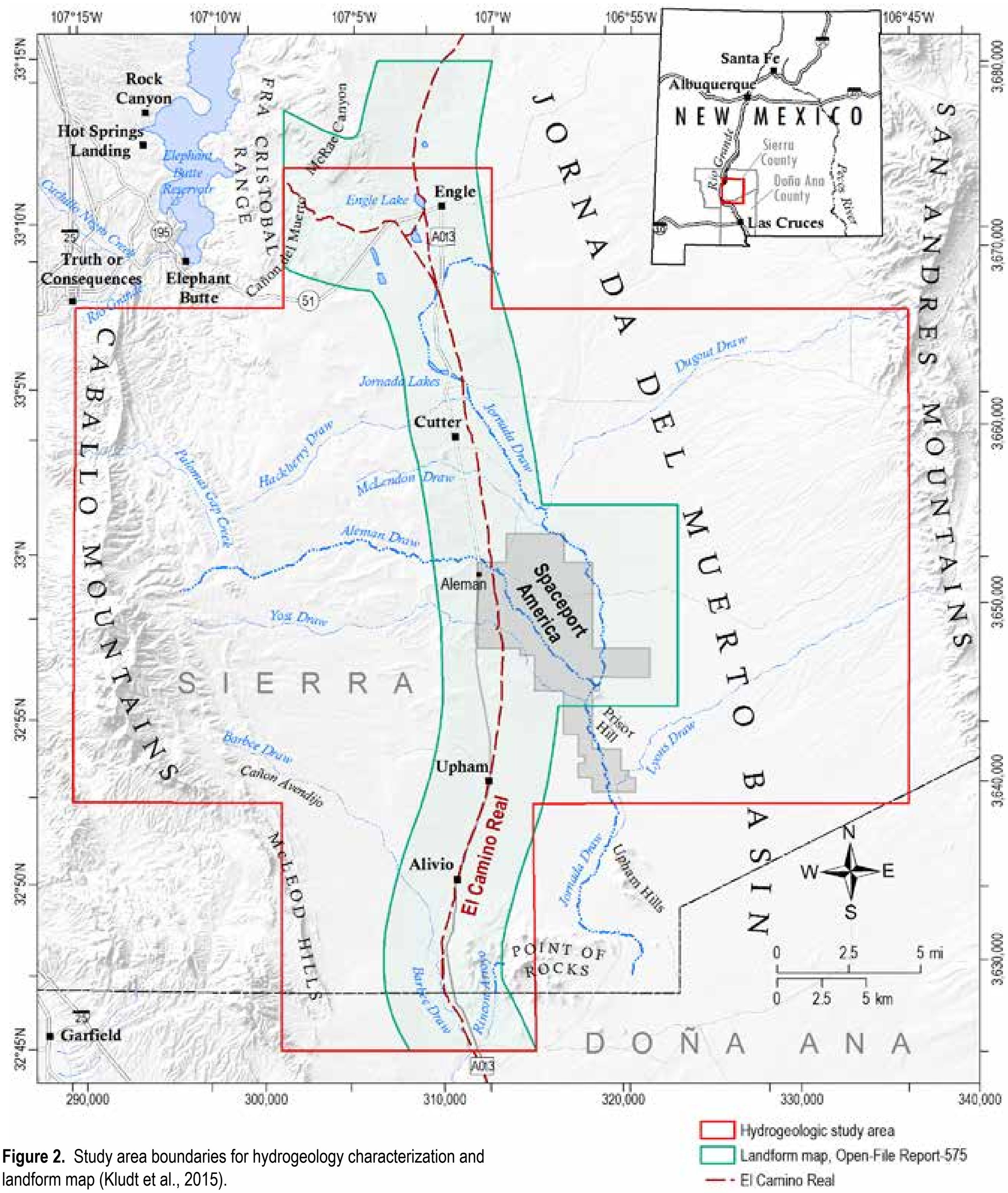


Figure 2. Study area boundaries for hydrogeology characterization and landform map (Kludt et al., 2015).

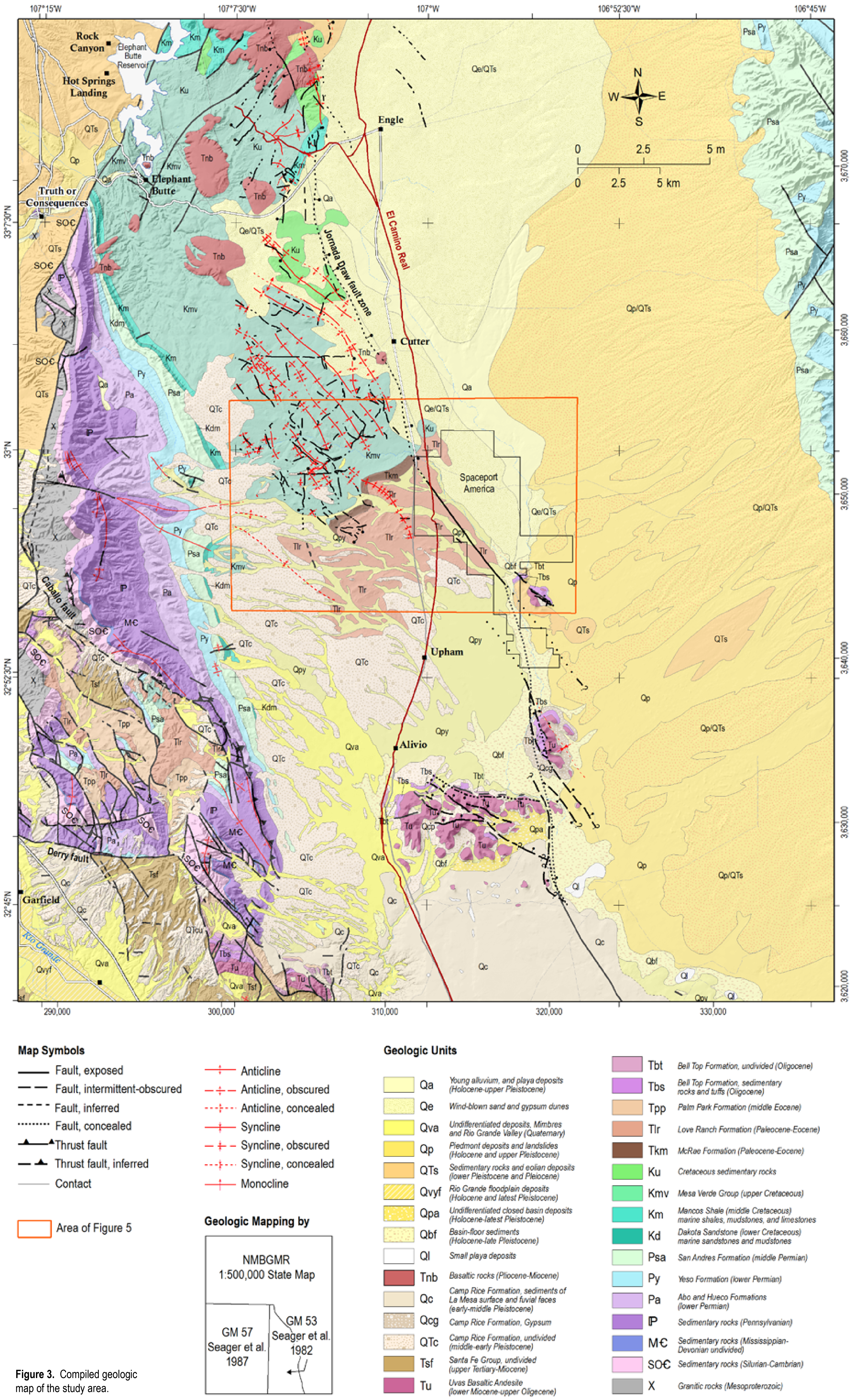


Figure 3. Compiled geologic map of the study area.

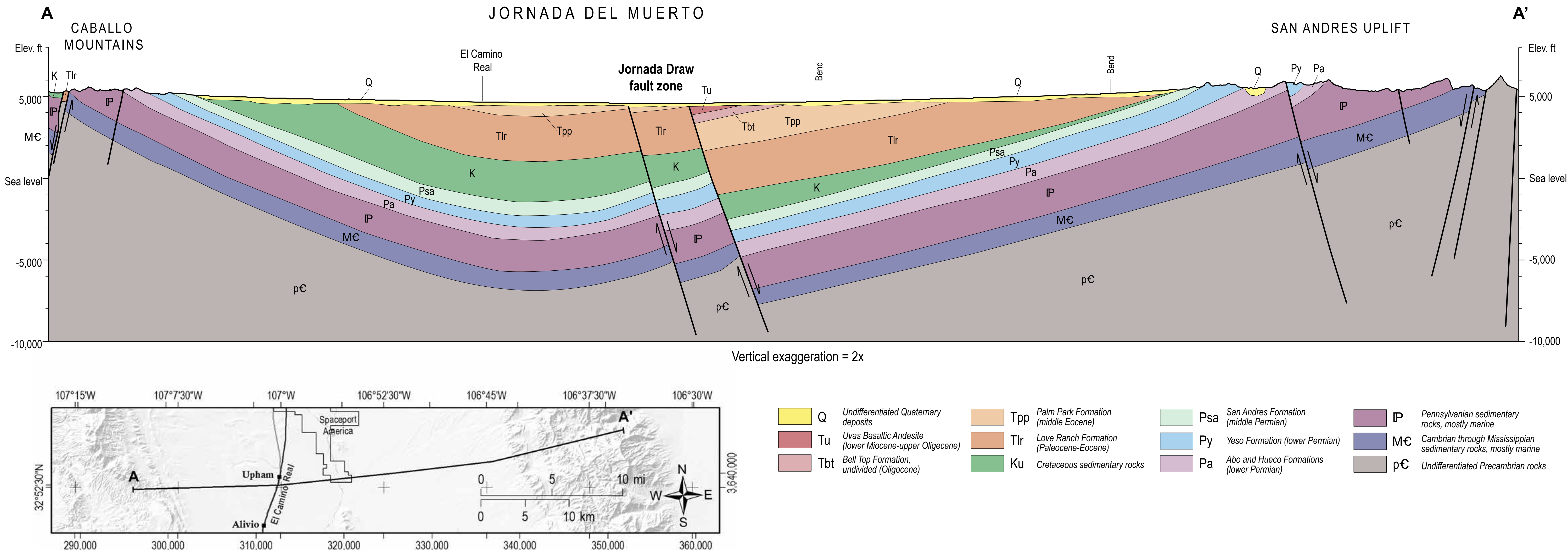
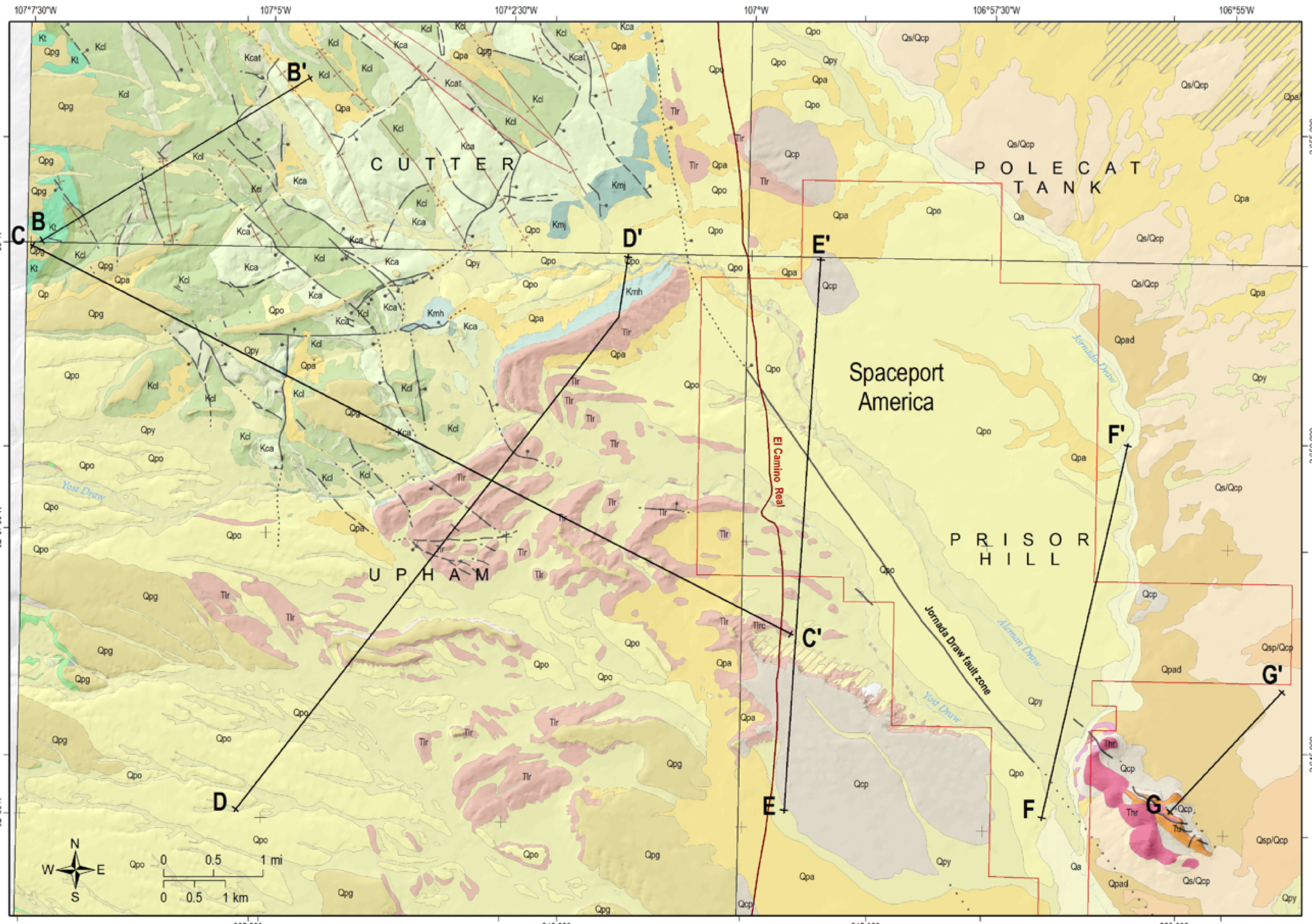


Figure 4. This geologic cross-section near Upham shows the subsurface geology across the simplest, least deformed part of the Jornada del Muerto.



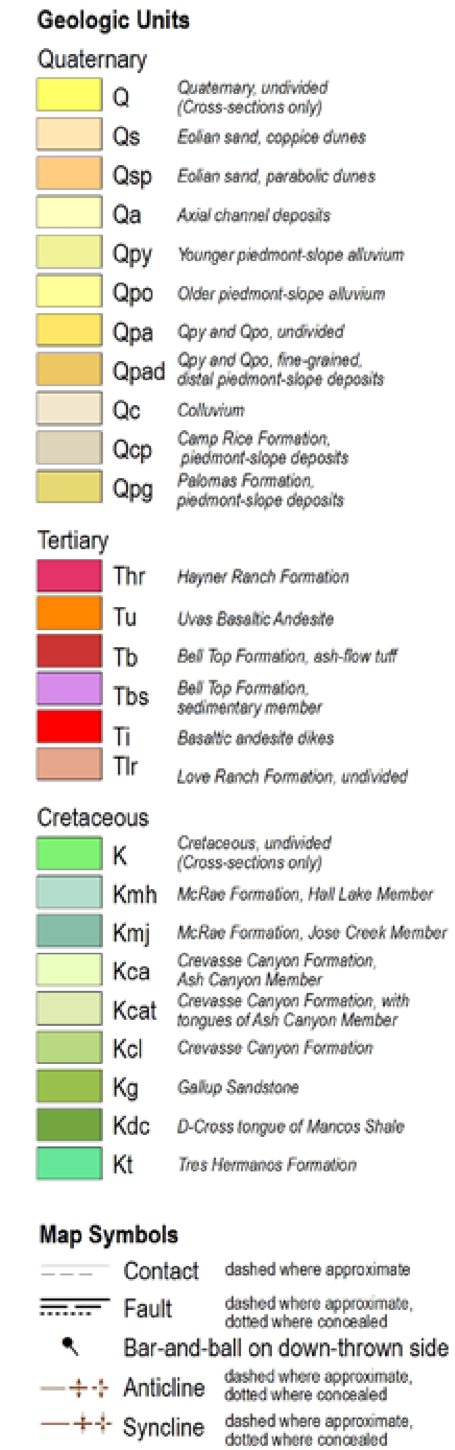


Figure 5. Compiled geologic map in the vicinity of the Spaceport America, showing cross-section lines represented on the fence diagram in Figure 6. See Figure 3 for location. The 1:24,000 scale quadrangles are Cutter by Seager, 1995a, Upham by Seager, 2005a, Prisor Hill by Seager, 2005b, and Polecat Tank by Love, 2014 unpublished.

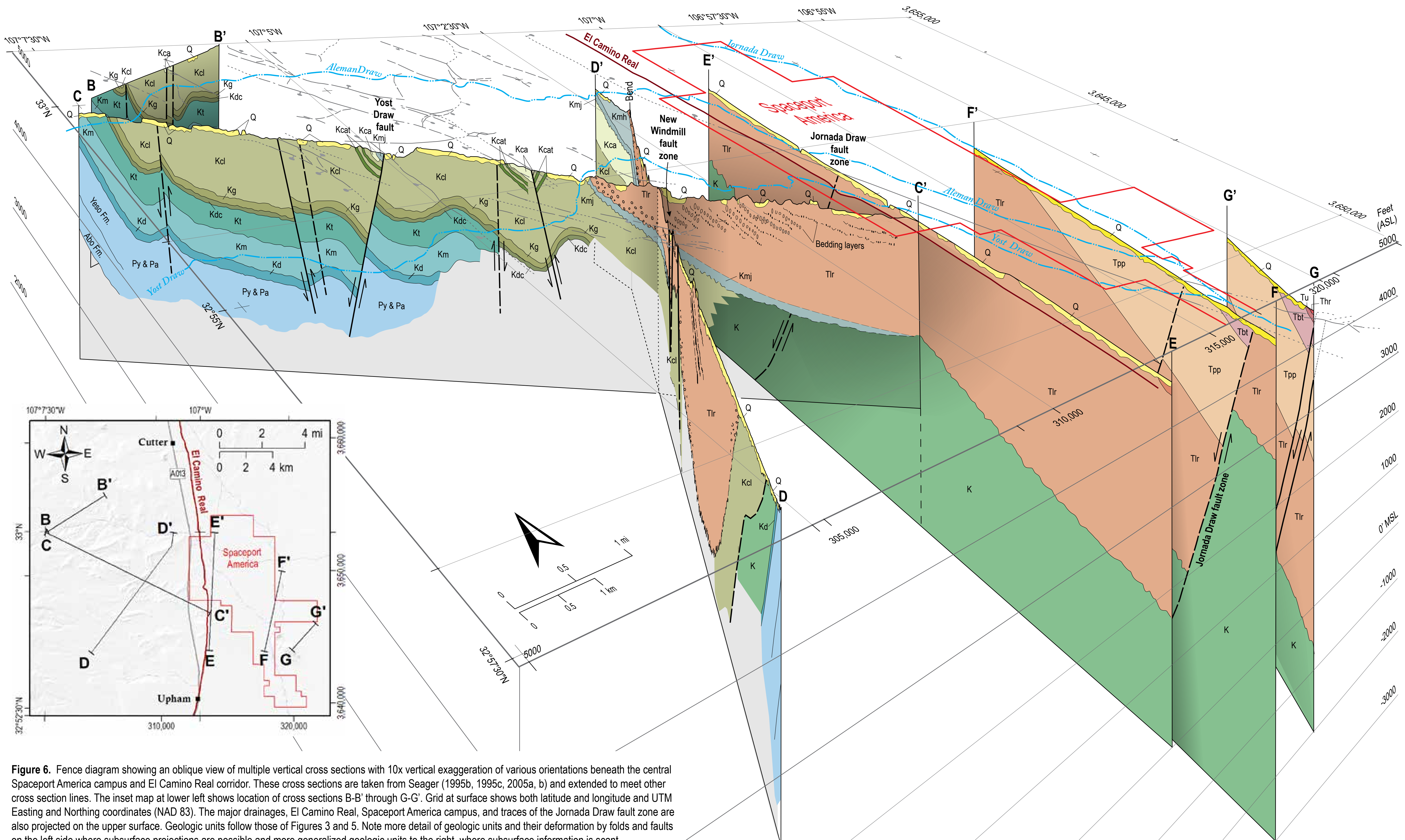


Figure 6. Fence diagram showing an oblique view of multiple vertical cross sections with 10x vertical exaggeration of various orientations beneath the central Spaceport America campus and El Camino Real corridor. These cross sections are taken from Seager (1995b, 1995c, 2005a, b) and extended to meet other cross section lines. The inset map at lower left shows location of cross sections B-B' through G-G'. Grid at surface shows both latitude and longitude and UTM Easting and Northing coordinates (NAD 83). The major drainages, El Camino Real, Spaceport America campus, and traces of the Jornada Draw fault zone are also projected on the upper surface. Geologic units follow those of Figures 3 and 5. Note more detail of geologic units and their deformation by folds and faults on the left side where subsurface projections are possible and more generalized geologic units to the right, where subsurface information is scant.

study area are primarily composed of sandstones, siltstones, and conglomerates, all of which exhibit different resistances to weathering processes. This structural setting, along with the different rock types, results in the formation of cuestas (Figure 7). Cuestas, which are erosional features, are characterized by a steep sloping surface where less resistant rocks are being eroded and a gentle sloping surface that is capped by a more resistant rock layer. The rocks that make up these cuestas generally also exhibit a range of different hydraulic conductivities, which have implications for groundwater flow processes. Cuestas are a common feature in the landscape within the study area.

Figure 8 is a stratigraphic column that shows the different rock units that can be seen on the surface and at relatively shallow depths in the subsurface within the study area. The rocks of most significance with respect to hydrogeology include alluvial and aeolian Quaternary deposits, the Eocene Palm Park and Love Ranch Formations, and Cretaceous McRae Formation. It should be noted the Santa Fe Group, which consists of ancestral Rio Grande deposits is only observed in the southern portion of the study area. However, the Santa Fe Group is an important hydrogeologic unit in the southern portion of the Jornada del Muerto.

Point of Rocks, located at the southern end of the study area, is composed of volcanic rocks from 25 to 40 million years old. On the surface, this feature is observed to be a barrier to ephemeral stream flow and is likely to impede groundwater flow in the subsurface also. Within the basin, south of the Spaceport America Campus, Quaternary alluvial deposits, including the Camp Rice Formation of the Santa Fe Group are observed on the surface. These deposits can be hundreds of feet thick in some areas. It can be seen in the cross-section (Figure 4) that these Quaternary deposits are approximately 200 feet thick in this area. These units are composed of sands, silts and gravels and make up a large part of the shallow groundwater system.

In the central section of the study area, west of the Spaceport America, the alluvium is very thin, and exposed rocks consist of the Eocene Love Ranch Formation (~40 million years old). In the center of the basin, to the north, late Cretaceous sedimentary rocks are exposed. These units include the McRae Formation (~80 million years old), and the Mesa Verde Group, which consists of the Gallup Sandstone and the Crevasse Canyon Formation. These formations are important aquifers in this area and will be discussed in more detail below.

The Caballo Mountains to the west are primarily composed of older strata that include Permian sedimentary rocks, including the San Andres, Yeso, Abo, and Hueco Formations. Many of these units are likely important for recharging some groundwater in the basin. In the eastern portion of the study area, the surface geology is dominated by Pleistocene and Holocene eolian and piedmont deposits.

Figure 4 is a cross section that transects the simplest, least deformed part of the Jornada del Muerto Basin and is the basis for the hydrologic conceptual model that will be discussed below. As 1:24,000 scale maps and cross sections by Seager (1995a, 1995b, 2005a, b) and Figure 3 shows, most areas north and south of the cross section are complicated by many

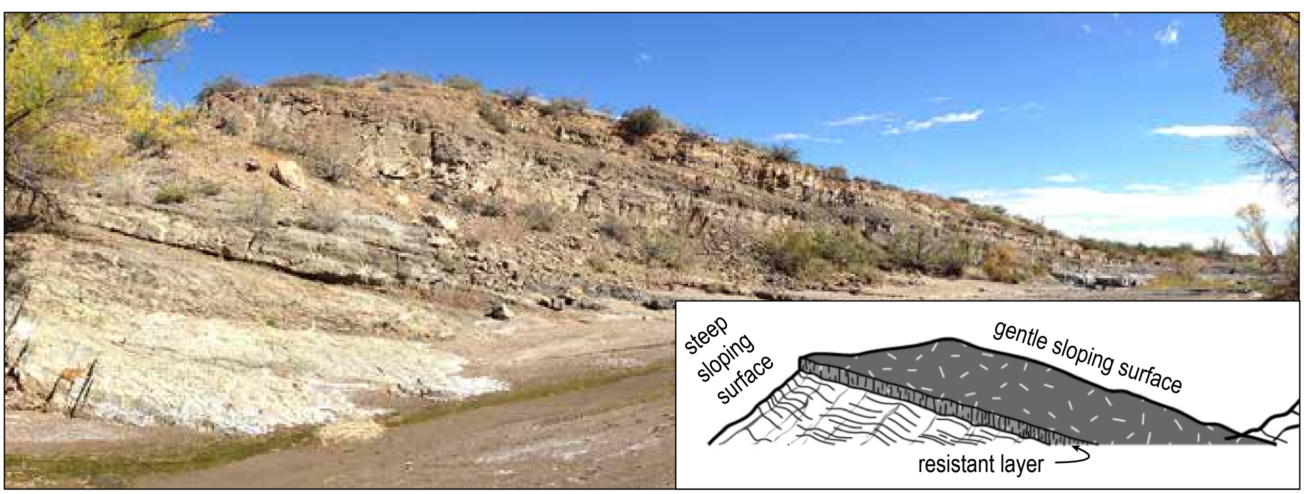


Figure 7. Cuestas are erosional features characterized by a steep sloping surface where less resistant rocks are eroded, and a gentle sloping surface that is capped by a more resistant rock layer. Cuestas are common features in the study area. Jose Creek member of the McRae Formation near Ojo del Muerto Spring.

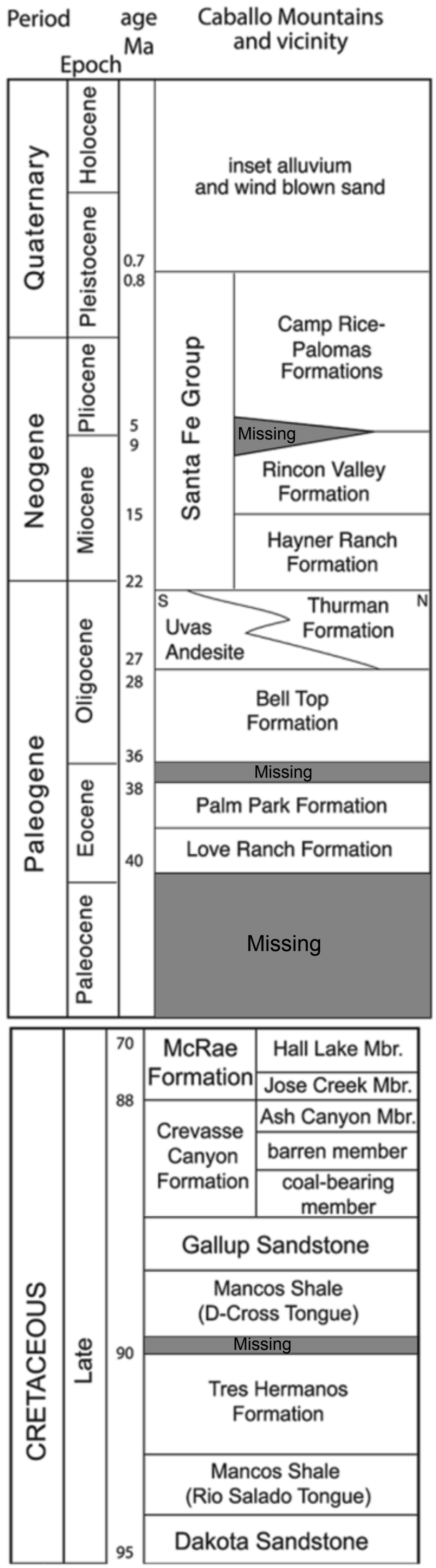


Figure 8. Stratigraphic column showing many of the rock units found in the study area.

more faults and folds exposed at the surface. These complications are shown instead on a "fence diagram" of the subsurface stratigraphy, faults, and folds in the vicinity of the Spaceport America (Figure 6). The fence diagram is an oblique perspective view tying together several vertical cross sections of the geologic units underlying El Camino Real corridor and Spaceport America. The diagram shows that the Cretaceous sedimentary rocks (K; green) and Eocene Love Ranch (Tlr; salmon) appear to dip to the south and appear to have a greater thickness preserved. In part this is due to the oblique projection of the cross sections.

Hydrostratigraphic units

The following geologic units make up the important aquifers in the study area, and their lithologies and stratigraphy greatly affects lateral and vertical groundwater occurrence and groundwater flow.

Quaternary deposits—Within the study area, these deposits include gravel, sand and silt. The Camp Rice Formation in the southern part of the study area is primarily piedmont slope deposits that consist of gravels, sand, silt and clay.

Love Ranch Formation—This formation is one of the primary aquifers in the study area and consists of gray to reddish-gray conglomeratic sandstone and sandstone and red to purple mudstone. The finer grained rocks in this unit likely define the lower boundary of localized perched aquifers.

Late Cretaceous strata—These units are exposed in the northern part of the study area and are part of the groundwater system. The McRae Formation in particular is a significant aquifer in the northern part of the study area and consists of conglomerates, shale and sandstone and is up to 1500 feet thick. The Gallup Sandstone is primarily medium grained sandstone with some coarse sandstone siltstone and shale and is approximately 250 feet thick. The Crevasse Canyon Formation can be up to 2500 feet thick and consists of interbedded conglomerate, sandstone, siltstone, and shale.

Hydrogeology

Although there has been hydrologic and hydrogeologic research done in the Jornada del Muerto, most of it has been done south of Point of Rocks (Hawley and Kennedy, 2004; Kambhammettu et al., 2010). The most recent work done in the study area was performed by Finch and Melis (2008) to evaluate groundwater supply for Spaceport America. Their work was focused on characterizing the groundwater system in the vicinity of the Spaceport America campus, evaluating the suitability of exploration wells as water supply wells, and calculating long-term effect of pumping for supplying water to the Spaceport America. The study area was smaller than the one for this study, but they made similar observations and came to similar conclusions to this study. In the central portion of the Jornada del Muerto, depth to water was observed to be shallowest in the center of the basin (~30 feet below the surface), and much deeper to the east and south (400 to 500 feet below the surface). They observed a groundwater divide near Engle, north of which groundwater flows north, and south of which groundwater flows south. Near the Spaceport America, most good quality groundwater is stored in the saturated alluvium, which is recharged primarily from mountain front recharge in the San Andres Mountains. Runoff from the mountains infiltrates through ephemeral streambeds to recharge the shallow hydrologic system. Around Prisor Hill is an area where shallow groundwater discharges by evaporation. Finch and Melis (2008) also concluded that the shallow alluvial aquifer was perched above a deeper aquifer system.

Precipitation Patterns

The most complete record of daily precipitation recorded in the area comes from Elephant Butte weather station (NOAA Coop ID: 292848), with records dating back to 1908. Average annual precipitation for the area, over the past 105 years, is roughly 9.4 inches/year. This region receives the majority of its precipitation from the North American Monsoon, which brings increased rainfall during the months of July, August, and September. On average, 70% of the annual precipitation falls during these months.

Figure 9 shows the probability of exceedance curves for (a) annual and (b) monthly precipitation amounts. These figures help to demonstrate the magnitude of the rainfall received in 2013. Receiving 19.2 inches, 2013 was the wettest year on record, more than twice the annual average for the area. The rainfall received this year has a probability of exceedance of 1%, and an average recurrence interval of 105 years. Additionally, September of 2013 was by far the wettest month on record, receiving 10.8 inches. Precipitation frequency modeling conducted by the National Oceanic and Atmospheric Administration (Bonnin et al., 2004) indicates that the total September 2013 rainfall for this area is on the scale of a 1,000 year rain event.

While it is exceedingly rare for rainfall events of the magnitude of September 2013 to occur, large storms that produce more than an inch of rain are particularly important, and have been more frequent in recent years. Six of the ten wettest months on record have occurred just in the last fifteen years. This is likely the result of a changing global climate. In terms of their potential impact on groundwater recharge, large storms produce enough water to overcome evaporation, allowing some of the rainfall to infiltrate into the local aquifers.

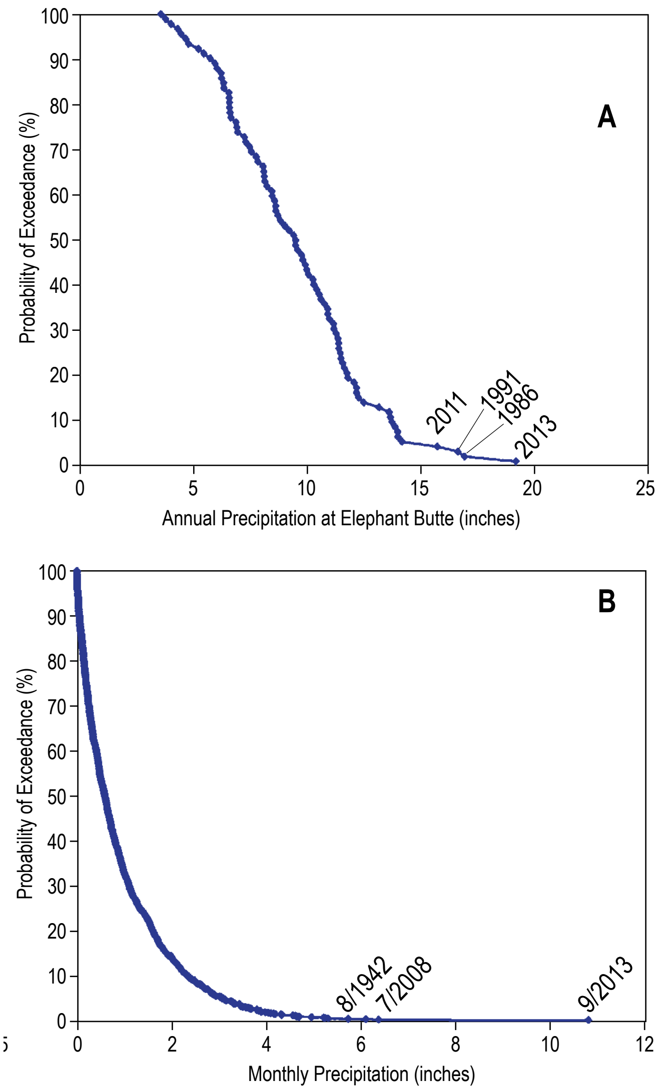


Figure 9. Probability of exceedance curves for (A) Annual precipitation and (B) monthly precipitation at Elephant Butte.

II. METHODS

Data Description

Existing and previously reported data used in this study include published geologic maps, subsurface geologic data from well records and lithologic logs, hydrologic consultants' reports, weather station data, and historical depth-to-water and water quality data from published and unpublished sources. New data collected by the NMBGMR includes:

- Accurate measurement of coordinates for field site locations
- Characterization of the geologic setting of spring and well sites
- One-time and repeated depth-to-water measurements in wells
- Geochemical, isotopic, and environmental tracer sampling from wells, springs, streams, and precipitation

In May of 2013, we measured the depth to water in many wells within the study area. These data and static water levels provided from the New Mexico Office of the State Engineer (NMOSE) records were used to assess the groundwater occurrence and movement in the study area. During October of 2013, we re-measured water levels in thirteen wells. Locations of all sites that were measured are shown in Figure 10 and noted in Table 1 and 2. We collected water samples from fourteen wells, three springs, two playas, and three seeps. Seeps are localized areas in ephemeral streambeds where shallow groundwater can easily be accessed by digging a shallow hole. Some or all of these samples were analyzed for a variety of analytes, including major cations and anions, the stable isotopes of oxygen and hydrogen, tritium, and carbon-14. These data helped us to assess the different hydrogeologic processes that take place in the study area. Details about the new data collected for this study are described and interpreted in this report. Details about water sampling procedures employed, analysis methods and systematics are described in Timmons et al. (2013).

In this report, we use the terms "regional" and "local" to describe large and small scale observations, respectively. When the terms regional or large-scale are used, we are referring to an area covering tens of square miles. Local or small-scale terminology refers to an area that is less than a few square miles, such as a canyon or small watershed.

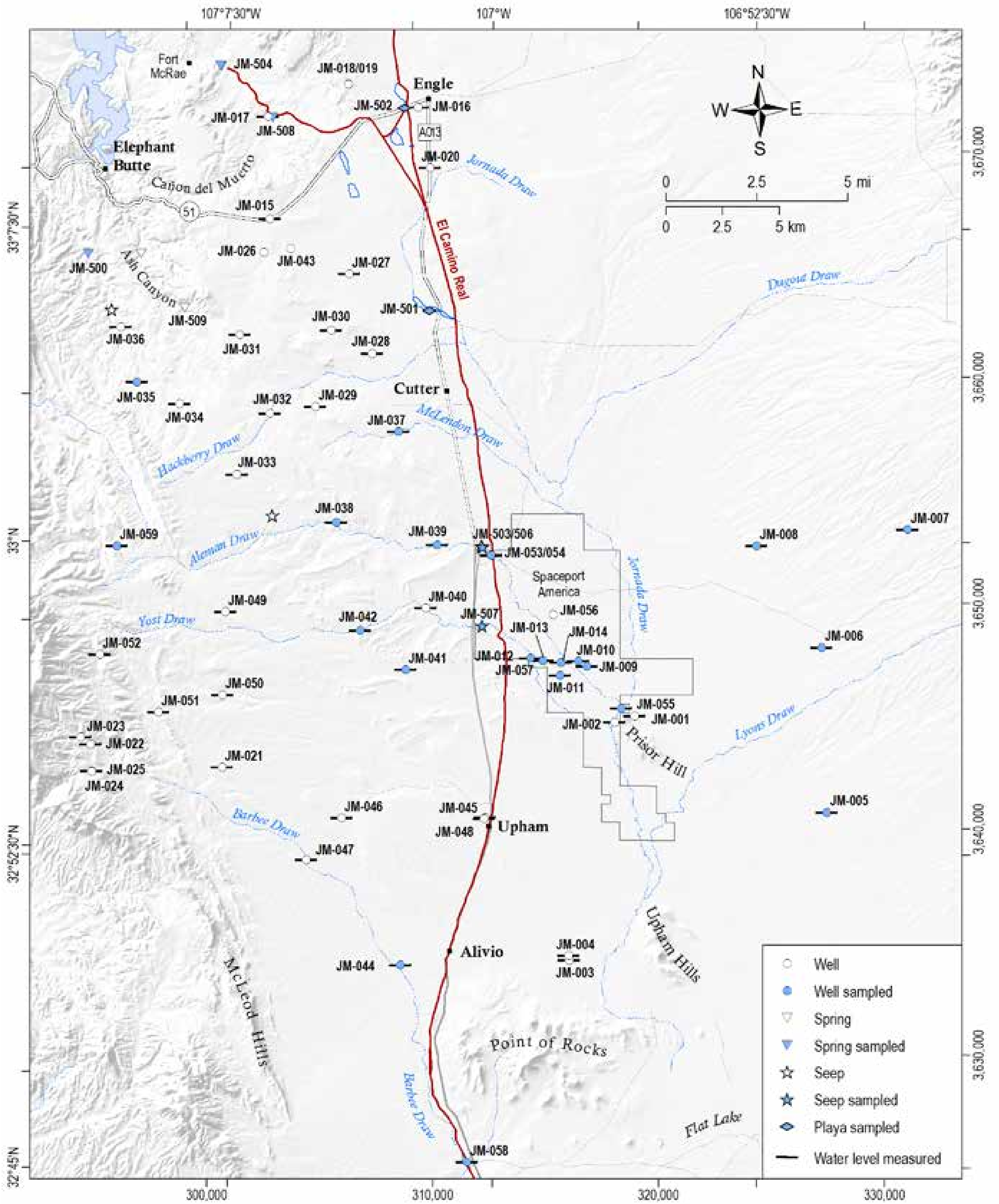


Figure 10. Locations of wells, springs, seeps and playas that were visited, measured and/or sampled. See Tables 1 and 2.

Table 1. Well inventory with location, site and construction information (sites shown on Fig. 10)—Continued.

WELL LOCATION				SITE INFORMATION			WELL CONSTRUCTION					
	NAD83											
Site ID	UTM easting	UTM northing	Elevation (ft asl)[1]	NMOSE well record	Water sample	Water level	Well depth (ft bgs)[2]	Screen top (ft bgs)[2]	Screen bottom (ft bgs)[2]	Drill date[3]	Driller static water (ft bgs)[2]	Static water elevation (ft asl)[1]
JM-001	319283	3645249	4545	LRG-07300		x	325			1/1/62	149	4396
JM-002	318396	3644997	4499	LRG-07301		x	200			1/1/59	120	4379
JM-003	316205	3634489	4397	LRG-07303 POD2		x	405	345	405	8/20/09	300	4097
JM-004	316195	3634692	4398	LRG-07303		x	365			1/1/15	320	4078
JM-005	327722	3640834	4652	LRG-07302	x	x	335			1/1/80	290	4362
JM-006	327628	3648143	4824	LRG-06224	x	x	450			1/1/57	410	4414
JM-007	331513	3653290	5189	LRG-06223	x	x	500	450	500	10/5/95	375	4814
JM-008	324827	3652693	4796	LRG-06225	x	x	390			1/1/81	360	4436
JM-009	317215	3647487	4543	LRG-14148	x	x	140	90	130	6/22/07	68	4476
JM-010	316840	3647727	4545	LRG-14359	x	x	120	70	100	4/22/08	68	4477
JM-011	316022	3647102	4554	LRG-14278	x	x	160	50	150	11/19/07	78	4476
JM-012	314718	3647895	4579	LRG-14149	x	x	220	60	200	6/1/07	32	4548
JM-013	315266	3647787	4575	LRG-14277	x	x	340	130	329	11/30/07	145	4430
JM-014	316071	3647688	4551	LRG-14358	x	x	160	70	150	4/25/08	75	4477
JM-015	303497	3667536	4857	RG-54777		x	362			12/31/68		
JM-016	310158	3672371	4757	RG-92010		x	160			6/17/10		
JM-017	303509	3672087	4580	RG-54651		x	150			12/31/05		
JM-018	307073	3673477	4878	(none)			600			1/1/59		
JM-019	307079	3673464	4877	(none)			530			1/1/59		
JM-020	310632	3669681	4761	RG-54779		x	500			12/6/80		
JM-021	300969	3643298	5085	LRG-06250		x	160			12/31/76	100	4985
JM-022	295159	3644428	5721	LRG-06248		x	500			12/31/79	300	5421
JM-023	294734	3644741	5759	LRG-06246		x	400			12/31/78	105	5654
JM-024	295184	3643233	5582	LRG-06247		x	535				400	5182
JM-025	295185	3643220	5583	(none)			195					
JM-026	303207	3666069	4870	(none)								
JM-027	306977	3665051	4761	RG-38268		x						
JM-028	307941	3661502	4796	LRG-06895		x	200			1/1/74	105	4691
JM-029	305383	3659187	4871	RG-06243		x					95	4776
JM-030	306131	3662558	4853	RG-38267		x	1100			1/1/56	80	4773
JM-031	302076	3662454	4937	RG-91531		x	140			1/1/50		
JM-032	303359	3658930	4906	LRG-06242		x					60	4846
JM-033	301844	3656239	5070	LRG-06241		x					145	4925
JM-034	299362	3659420	4979	RG-50058		x	40	20	40	11/15/88	21	4958
JM-035	297507	3660425	4926	LRG-06591	x	x	175			1/1/1892	60	4866
JM-036	296825	3662870	4750	LRG-06588		x	11			12/31/05		
JM-037	309033	3658022	4774	(none)	x	x						
JM-038	306216	3654061	4813	LRG-06880	x	x	40			1/1/70	10	4803
JM-039	310661	3652987	4705	LRG-06881	x	x	60			1/1/45	25	4680
JM-040	310109	3650189	4692	LRG-06882		x	150			5/16/94	56	4636

1 ft asl = feet above sea level
2 ft bgs = feet below ground surface
3 Drill dates of January 1 indicates year only was found with well record

Table 1. Well inventory—Continued.

WELL LOCATION				SITE INFORMATION			WELL CONSTRUCTION					
	NAD83											
Site ID	UTM easting	UTM northing	Elevation (ft asl)[1]	NMOSE well record	Water sample	Water level	Well depth (ft bgs)[2]	Screen top (ft bgs)[2]	Screen bottom (ft bgs)[2]	Drill date[3]	Driller static water (ft bgs)[2]	Static water elevation (ft asl)[1]
JM-041	309159	3647472	4735	LRG-06883	x	x	220					
JM-042	307198	3649247	4791	LRG-06884	x	x	160				85	4706
JM-043	304384	3666213	4829	(none)			300					
JM-044	308701	3634398	4518	LRG-06894	x	x	265			1/1/78	60	4458
JM-045	312589	3640874	4568	LRG-07299		x	200			1/2/00	150	4418
JM-046	306216	3640960	4737	(none)		x						
JM-047	304614	3639134	4763	LRG-06887		x	180			1/1/74	128	4635
JM-048	312540	3640812	4571	LRG-06893		x	210			1/1/79	142	4429
JM-049	301243	3650176	5135	LRG-06244		x	134				110	5025
JM-050	301036	3646501	5066	LRG-06252		x				1/1/09	130	4936
JM-051	298203	3645782	5346	LRG-06249		x	724			1/1/40	630	4716
JM-052	295629	3648391	5610	LRG-10885		x	265	205	265	10/24/00	65	5545
JM-053	313077	3652498	4653	LRG-10808		x	285	245	285	8/10/95	45	4608
JM-054	313070	3652465	4652	LRG-6228S	x	x	150					
JM-055	318701	3645600	4500	LRG-14145	x	x	250	120	240	6/6/07	42	4459
JM-056	315751	3649800	4586	LRG-14147						6/29/07		
JM-057	314718	3647895	4579	LRG-14150	x	x	410	340	400	7/14/07	160	4419
JM-058	311517	3625631	4327	LRG-06890	x	x	300			1/1/45	220	4107
JM-059	296489	3653186	5387	LRG-06245	x	x	220				150	5237

[1] ft asl = feet above sea level
[2] ft bgs = feet below ground surface
[3] Drill dates of January 1 indicates year only was found with well record

Table 2. Surface water inventory with location (sites shown on Fig. 10).

		NAD83				
Site ID	Site name	UTM easting	UTM northing	Elevation (ft asl)[1]	Site type	Water sample
JM-500	Mescal Spring	295452	3666275	4544	Spring	x
JM-501	Jornada Lake	310516	3663366	4692	Playa	x
JM-502	Engle Lake	309551	3672347	4728	Playa	x
JM-503	Aleman Draw seep	312413	3652920	4663	Seep	x
JM-504	Ojo del Muerto	301489	3674351	4463	Spring	x
JM-506	Aleman Draw seep	312608	3652893	4652	Seep	x
JM-507	Jost Draw seep	312964	3649428	4622	Seep	x
JM-508	Unnamed spring	303708	3672038	4575	Spring	x
JM-509	Ash Canyon Spring	299677	3663671	4760	Spring	

[1] ft asl = feet above sea level
[2] ft bgs = feet below ground surface
[3] Drill dates of January 1 indicates year only was found with well record

III. HYDROGEOLOGY RESULTS

This section describes and interprets hydrologic and geochemical data to develop a hydrogeologic conceptual model. Figure 10 and Table 1, 2 shows the wells and springs that we measured and/or sampled. Specific locations of interest include Ojo del Muerto Spring, Mescal Spring, Aleman and Yost Draws, and the well labeled JM-041.

Surface Water

Surface water in the study area is scarce and limited to a few springs, ephemeral streams, and playas that occasionally store water for several months at a time (Figure 10). The location and nature of these surface water features are largely dependent on the local topography and geology. Important surface water features are described below.

Streams

Jornada Draw, which is an expression of the Jornada Draw fault zone, runs north to south approximately along the hinge of the syncline that defines the Jornada del Muerto Basin. Several ephemeral streams drain precipitation from the Caballo Mountains to the west and the San Andres Mountains to the east. Notable ephemeral streams are Aleman Draw and Yost Draw to the west of the Spaceport America. Dugout Draw and Lyons Draw drain water from the San Andres Mountains. Streams from both the east and west join Jornada Draw, which carries water to the east of Point of Rocks and terminates at a large Playa called Flat Lake. Barbee Draw drains water from the southern Caballo Mountains to the south, east of Point of Rocks. These ephemeral streams flow only after a significant rain event.

Springs and Seeps

Mescal Spring (JM-500), Ash Canyon Spring (JM-509), and Ojo del Muerto Spring (JM-504) are located in the northern region of the study area and all are located in ephemeral streams that drain water to the northwest toward Elephant Butte (Figure 10). Mescal Spring and Ash Canyon Spring (Figure 11) both discharge diffusely from the bottom of the stream bed in the vicinity of where bedrock is exposed. Water returns to the subsurface in areas where bedrock is significantly buried. Therefore, these springs are likely the result of the intersection of the shallow water table and the ground surface. Groundwater flowing along the bedrock surface in alluvium is forced to the surface where the depth to bedrock decreases due to the presence of geologic features such as cuestas, faults, or folds.

Ojo del Muerto Spring, on the other hand, appears to discharge at a specific point within the streambed (Figure 12A). Water also discharges through a shallow well that was drilled on the bank adjacent to the streambed (Figure 12B). This focused discharge suggests that the hydrogeologic framework for Ojo del Muerto Spring is different from that for the other springs discussed above. As will be discussed below, evidence suggests that this spring discharges water that flows along a relatively long, isolated flow path. It is also important to note that the present location of this spring is not where travelers along El Camino Real likely encountered it. Smith(1893) is the official decision for litigation that brought the present day location of Ojo del Muerto Spring into question. Surveys done in 1869 and 1872 place Ojo del Muerto Spring at the Fort McRae military post, which was located approximately two miles to the west of the present day location of the spring (Figure 10). We are assuming that the present day Ojo del Muerto Spring discharges water from the same recharge source that supplied water to the original spring. Smith (1893) also mentioned that in 1883, "the Railway Company have excavated and walled a reservoir 24 feet in diameter, 12 to 14 feet deep, and have equipped the same with a powerful Knowles pump, making a draft on the spring of from 16,000 to 25,000 gallons daily." The discharge rates are consistent with the regional hydrogeologic system, discussed in more detail below.

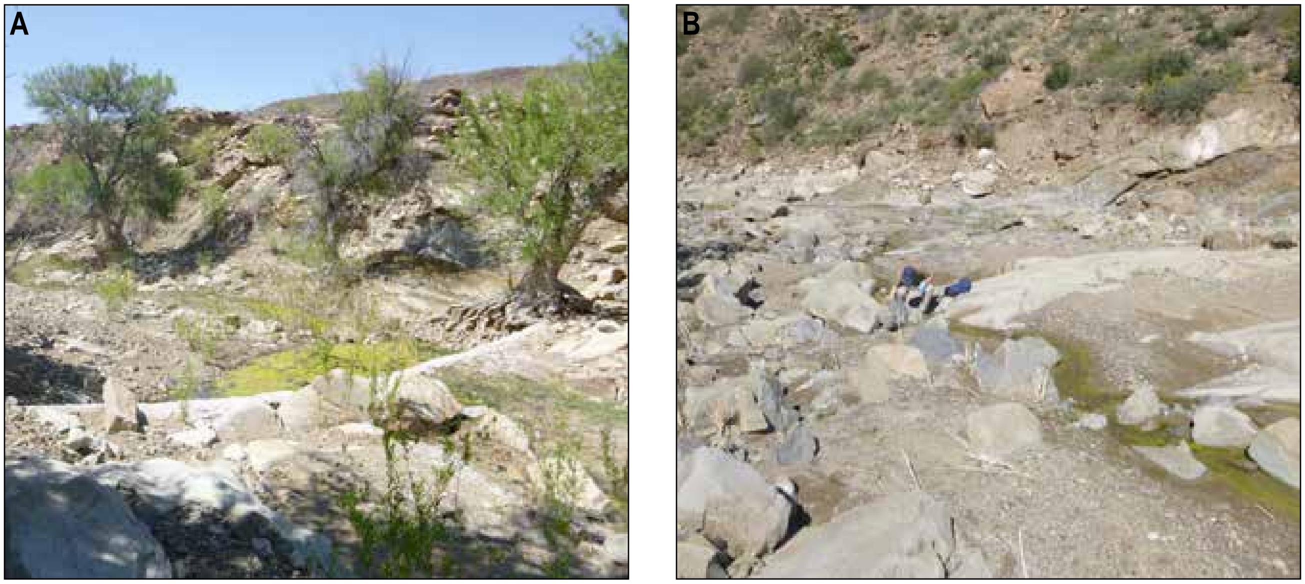


Figure 11. A—Ash Canyon Spring (JM-509) and **B**—Mescal Spring (JM-500).

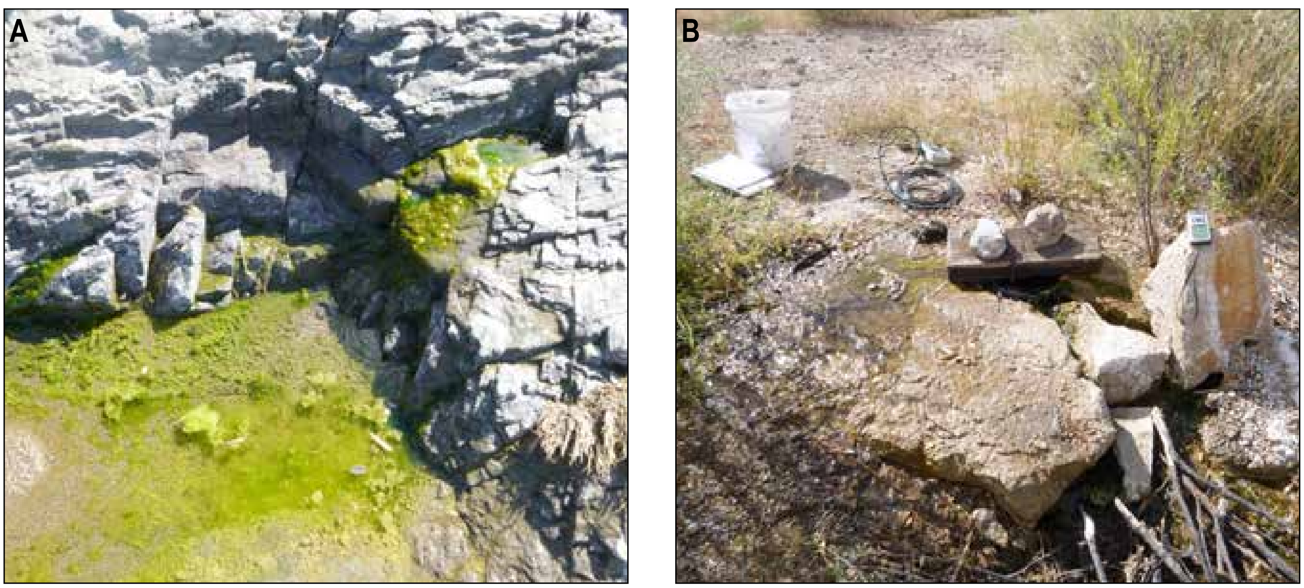


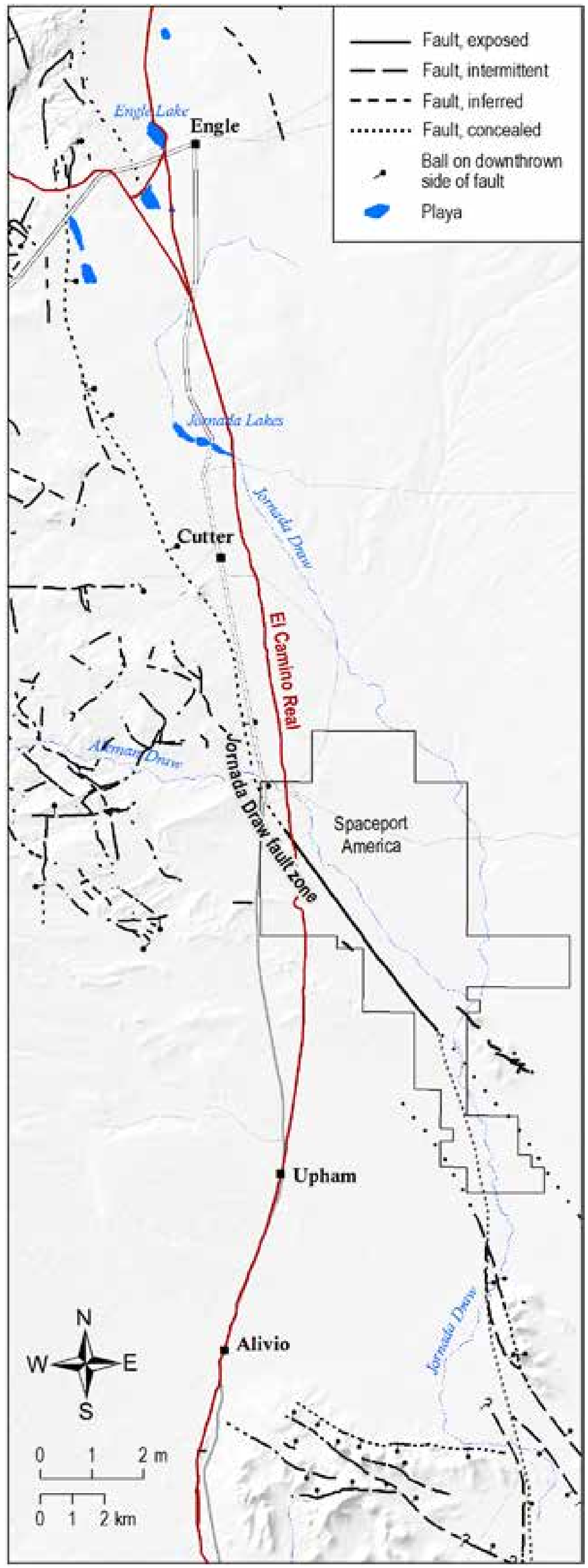
Figure 12. A—Discharge area of Ojo del Muerto (JM-504) in the stream bed; **B**—Water at Ojo del Muerto Spring discharging from shallow well adjacent to streambed.

There are several seeps located in the study area (Figure 10). Seeps are located in Aleman Draw, Yost Draw, and in Canyon del Muerto. Seeps are characterized by moist sand with white precipitates on the bottom of the stream bed, due to evaporation of shallow groundwater (Figure 13). In late 2014, we dug less than one foot below the surface at both locations to access water for sampling. It is very likely that travelers along El Camino Real utilized these seeps as a local water supply. The hydrogeologic setting for these seeps is similar to those that characterize Mescal and Ash Canyon springs. The local water table is forced towards the surface due to geologic structures such as cuestas, faults, and folds.

Playas

There are several playas (small ephemeral lake beds) in the study area (Figure 10) that served as sources of water to El Camino Real travelers. Most of these playas are located on the hanging wall, east of the Jornada Draw fault zone (Figure 14) (Seager and Mack, 1995), where a thin layer of basin fill was deposited to accommodate the vertical offset. Large

Figure 13. **A**—Yost Draw seep (JM-507) and **B**—Aleman Draw seep (JM-506). Water was accessed for sampling less than a foot beneath the surface.



storm events during September 2013 filled these playas with large volumes of water that remained for several months later. We discuss these playas in more detail below.

Groundwater

The primary water source in the study area is groundwater. Wells located throughout the area provide water for residents, livestock, and municipal uses, in addition to Spaceport America. This section will present hydrologic and geochemical data to characterize the regional and local groundwater system.

Occurrence of Groundwater

In the study area, groundwater occurs in shallow alluvium and underlying shallow bedrock, including the Love Ranch and Palm Park Formations and the Mesa Verde Group. In the vicinity of the Spaceport America, saturated alluvium can be as deep as 150 feet below the surface (Finch and Melis, 2008). Depth to water varies from less than twenty feet to greater than 300 feet below the surface (Figure 15). As mentioned above, in the ephemeral stream beds of Aleman Draw and Yost Draw, groundwater appears to sit on top of shallow bedrock. Shallow Cretaceous and Paleocene rocks in the study area, west of the Jornada Draw fault zone, consist of layers of coarse to fine sedimentary rocks that likely host perched aquifer systems. Shallow groundwater likely sits on top of rock units of lower permeability and flows horizontally through more permeable rocks. The depth to water in wells in this area is generally shallower than those observed in wells to the east to the fault zone. To the east of the Jornada Draw fault zone, these rocks are significantly deeper due to the downward offset of the hanging wall of the fault, resulting in greater depths to groundwater in this area (Figure 15). Depth to water also appears to decrease to the south.

Groundwater Flow Conditions

Figure 16 shows water level elevation contours that were calculated from water level measurements. Groundwater flows from high elevation to low elevation. Groundwater flows from the mountains that bound the study area to the east (San Andres Mountains) and to the west (Caballo Mountains) towards the center on the study area, where most groundwater flows to the south, as is observed for most streams described above. However, the area around Engle, where several playas are located, appears to be a groundwater divide. Groundwater north and west of Engle flows to the northwest towards Elephant Butte Reservoir.

Figure 17 shows measured water level elevations as a function of well depth. In general, higher water level elevations are associated with shallower wells, indicating a downward hydraulic gradient. This observation suggests that much of the shallow groundwater in the study area occurs in a system of perched aquifers. Depth to water measurements and other data that will be discussed below suggest that perched groundwater is usually found at depths less than 200 feet below the surface. This shallow perched groundwater system appears to be isolated to some extent from the deeper system (DTW >200 feet).

This assessment is supported by the depth-to-water measurements in the wells JM-053 and JM-054 (Figure 15). These wells are located approximately fifty feet from each other but are drilled to different depths. JM-054 is drilled to a depth of 150 feet below the surface and completed in saturated alluvium, while JM-053 is drilled to a depth of 285 feet and is completed in a sandstone. During May of 2013, both of these wells exhibited similar depth to water measurements of 91.74 and 90.43 feet below the surface for JM-053 and JM-054 respectively. In October of 2013 water levels in both of these wells increased significantly due to extreme rainfall in September 2013. However, the water level in the wells increased by different amounts. Depth to water measurements were 62.6 and 23.5 feet below the surface for JM-053 and JM-054, respectively. Finch and Melis (2008) made a similar observation where depth to water in the deeper well (JM-053) was about 100 feet lower than that in the shallower well (JM-054). These observations again suggest that the shallow aquifer system is perched system. Leakage from the shallow aquifer system to the deeper system likely occurs, and during long periods with no significant recharge events, these two hydrologic systems likely equilibrate and exhibit similar water levels as observed in May 2013.

Figure 18 shows the change in water levels for wells measured in May and October 2013. Water level increases are due to the extreme rainfall that occurred in September 2013. It can be seen that this recharge event resulted in very significant water level changes in some wells (up to ~140 foot rise), while water levels in other wells hardly changed a month after September rains. These water level responses

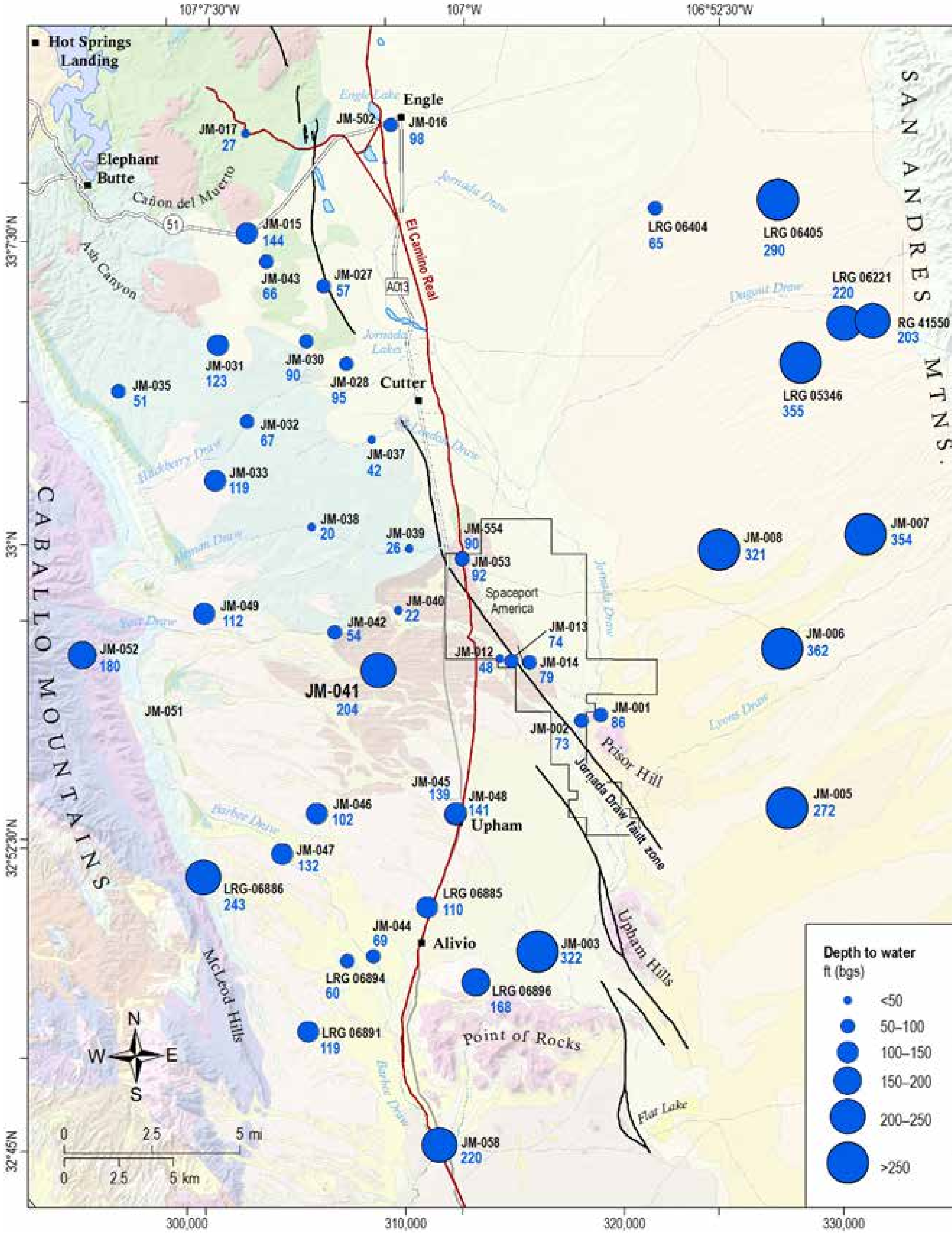


Figure 15. Depth-to-water ranges from less than 20 feet to greater than 300 feet below the ground surface. Groundwater is deeper to the east of the Jornada Draw fault zone. The well JM-041 has depth-to-water that is significantly deeper than those of other wells in the area. Points designated with a prefix of "LRG" or "RG" are approximate static water levels from the Office of the State Engineer well records, measured when the well was drilled. See Figure 3 for geologic unit descriptions.

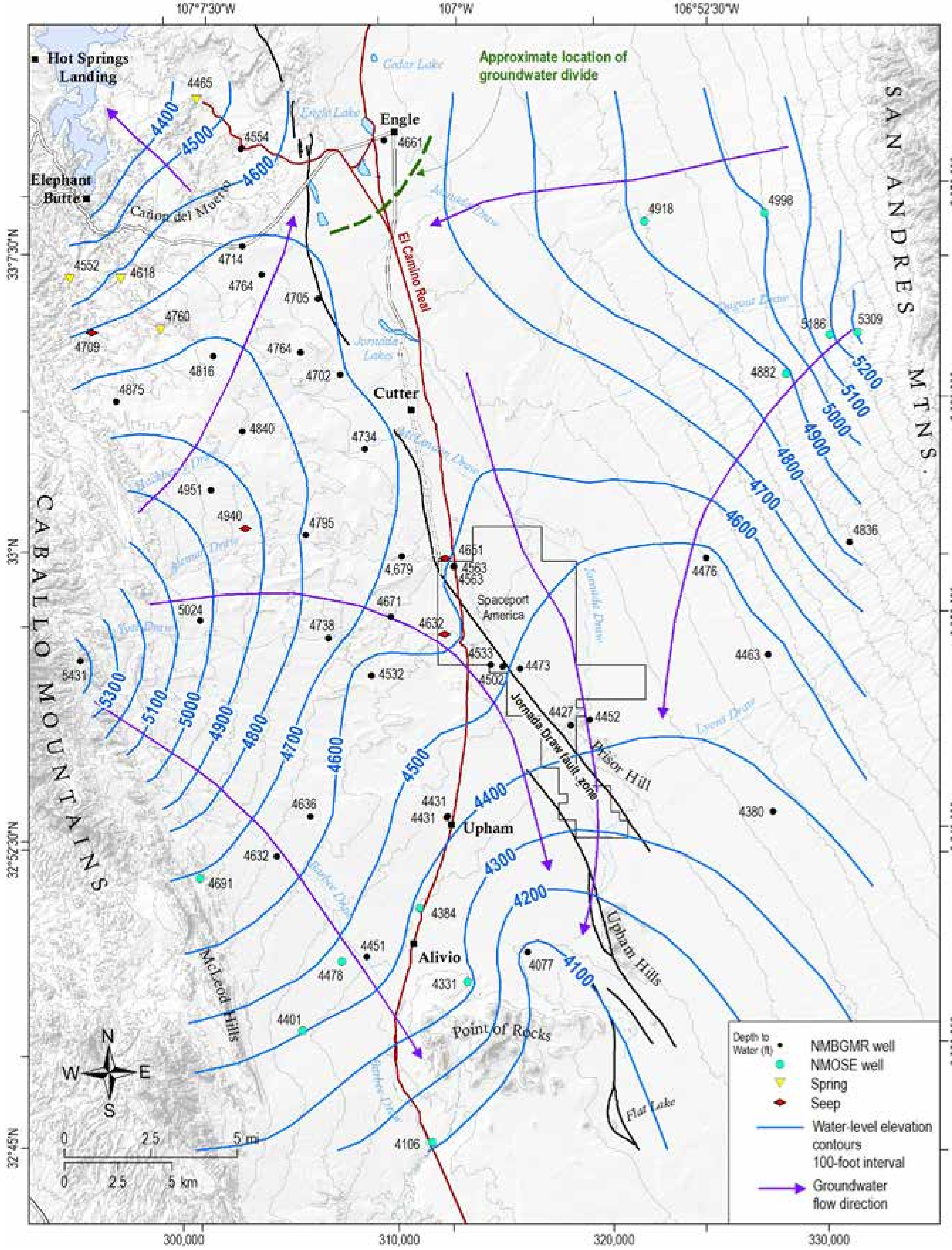


Figure 16. Groundwater elevation contours show that regional groundwater flow in the study area is primarily to the south. However, a groundwater divide near Engle is evident. Groundwater in this area flows to the northwest toward Elephant Butte. Water elevations in feet above sea level are shown for each well. NMBGMR wells were measured by NMBGMR staff and NMOSE wells show static water levels on well records (locations are approximate).

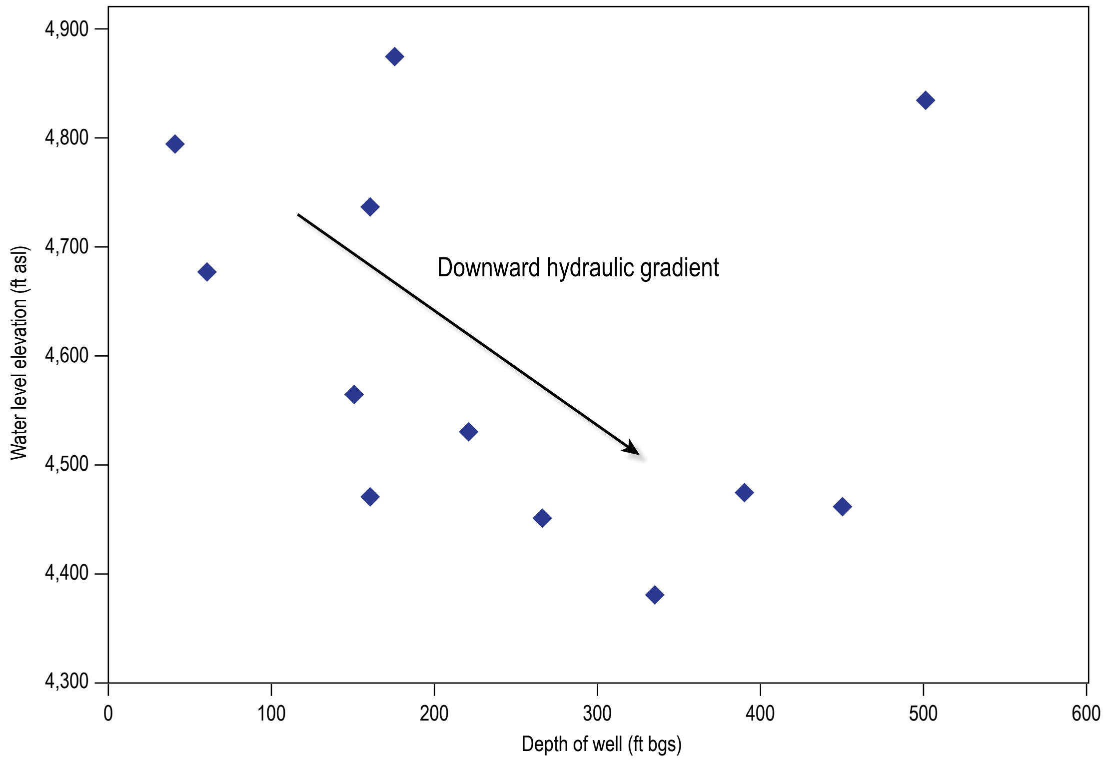


Figure 17. Water level elevations as a function of well depth show a downward vertical gradient, indicating that the shallow system is a perched aquifer system. Water level elevations are in feet above sea level; well depths are in feet below gound surface.

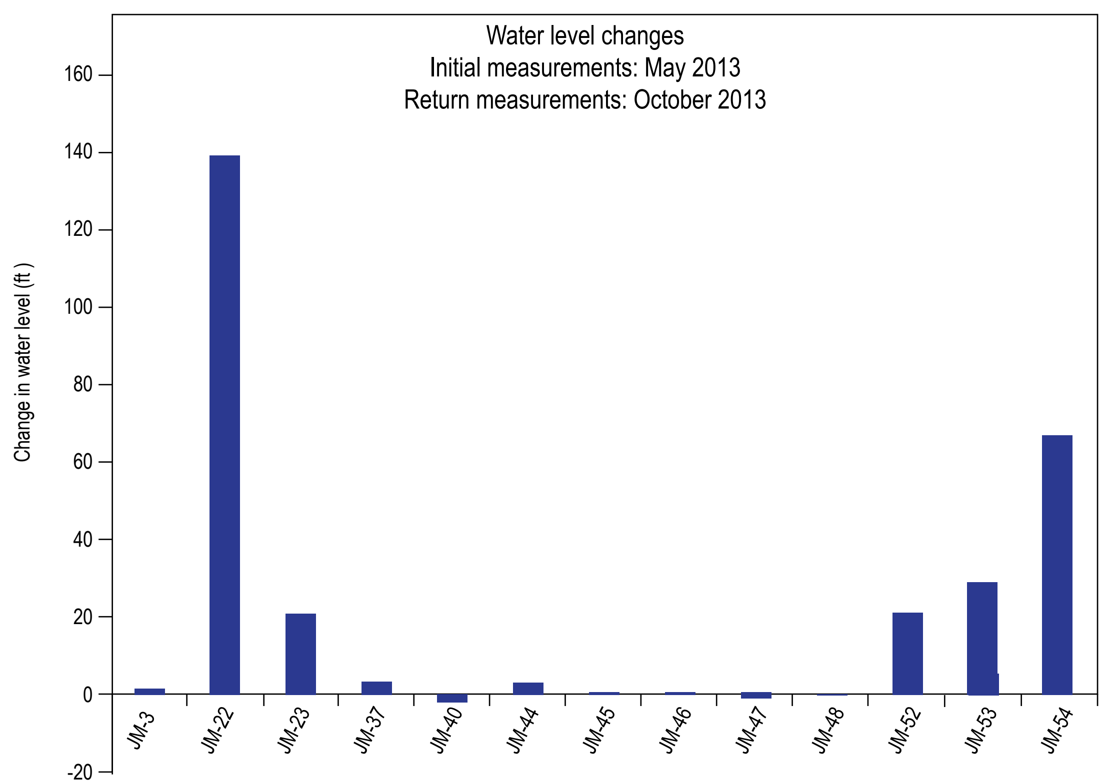


Figure 18. Difference in water levels in wells that were measured in May and October 2013 show a range of responses to the September 2013 monsoons.

shows that recharge to the shallow aquifer can happen quickly but is spatially variable. Much of this fast recharge occurs in ephemeral stream beds.

Water Chemistry

We collected water samples from fourteen wells, two springs, two playas, and one seep (Figure 10). Table 3 shows field parameters that were measured during sample collection. Specific conductance, which is proportional to the amount of dissolved ions in solution, ranges from 2,480 µS/cm to 202 µS/cm. In general, groundwater with the highest specific conductance values is located in the southern part of the study area. JM-058, which is located just southwest of Point of Rocks, exhibits the highest specific conductance. This spatial trend will be discussed in more detail below. Most water samples show relatively high dissolved oxygen (DO) values and positive oxidation reduction potential (ORP), indicating oxidizing conditions. Measured pH values range from 6.77 to 8.66, which is typical for groundwater.

Total dissolved solids (TDS) values range from 121 to 1930 mg/L (Figure 19). Samples collected from the playas exhibit the highest quality water with the lowest TDS values, suggesting that most water in the playas is comprised of local runoff generated by the September storm events discussed above. It should be noted that NM secondary drinking water regulations suggest a maximum TDS value of 500 mg/L. TDS values and measured concentrations of other constituents, such as hardness, sulfate, and sodium are observed to exceed U.S. Environmental Protection Agency (EPA) and New Mexico guidelines to some degree (Table 4). While much water in the central portion of the Jornada del Muerto may not satisfy current standards, water that would be available to travelers along El Camino Real would be satisfactory for consumption by humans and livestock. Figure 19 shows that the highest TDS values are generally located in the eastern and southern portions of the study area, where depth to water is deeper and would not be available to travelers on El Camino Real.

The relative concentrations of the major cations and anions in groundwater is reflective of the rocks and sediments that make up and the aquifer system and the physical and chemical reactions that take place in the system over time. Figure 20 is a Piper diagram that enables us to plot and compare waters that have different relative concentrations of the major cations and anions. The samples have been

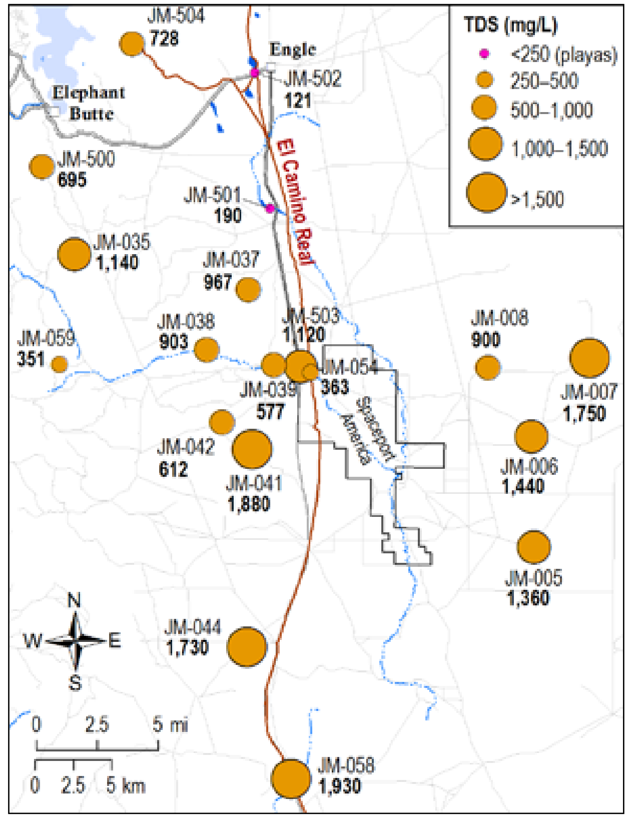


Figure 19. Total dissolved solids in groundwater varies significantly over the study area. In general, the lowest TDS values are found in the center of the study area near the Spaceport America. TDS values increase to the east and south.

Table 3. Field parameters for water samples.

Point ID	Site names	Well depth (ft bsl)[1]	SC (µS/cm)	DO (mg/L)	ORP (mV)	pH
JM-007		500	2305	4.96	170.4	7.64
JM-005		335	1845	7.85	232.1	7.66
JM-006		450	1947	6.62	172.3	7.65
JM-007		500	2305	4.96	170.4	7.64
JM-035		175	1544	0.13	20.7	7.57
JM-037			1390	0.86	119.8	6.77
JM-038		40	1159	9.51	39.2	7.42
JM-041		220	2743	0.45	135	8.32
JM-042		160	930	2.75	203	7.48
JM-044		265	2265	7.73	99.5	7.39
JM-054		150	563	4.41	127.1	7.34
JM-058		300	2480	7		7.8
JM-059		220	558	9.23	93.8	7.39
JM-500	Mescal Spring		994	8.04	172.2	7.81
JM-501	Jornada Lakes Cutter Playa		283	7.19	193.7	7.74
JM-502	Engle Lake (playa)		202	10.6	184.4	8.66
JM-503	Aleman Draw seep		1092	3.56	165.5	7.66
JM-504	Ojo del Muerto Spring		1100	0.18	90.7	8.55

[1] ft bgs = feet below ground surface

Table 4. Minimum, maximum, and average values for selected water quality parameters along with EPA and NM guidelines.

	Min (mg/L)	Max (mg/L)	Average (mg/L)	EPA & NM guidelines
TDS	121	1930	1017	500 mg/L – secondary drinking water regulation
Hardness	11	783	325	>300 mg/L = extremely hard
SO_4	4.5	1000	450	250 mg/L – secondary drinking water regulation
Na	1.37	608	205	>20 mg/L for individuals restricted to a total sodium intake of 500 mg/day

categorized based on the depth to water in the well. "Shallow" water represents wells with a depth-to-water of 200 feet or less. "Deep" water represents samples collected from wells with a depth-to-water greater than 200 feet below the surface. For the major cations (left triangle), most water samples exhibit low relative concentrations of Mg (<30%). Most deep and shallow well samples plot along a trend that approaches very high relative Na concentrations, while Ca concentrations decrease. This is the result of water-mineral interactions that will be discussed below. Relative cation concentrations cannot be used to distinguish shallow waters from deep waters. The playas and Aleman Seep show Ca as the dominant cation. For anions (right triangle), all water samples exhibited very low relative Cl concentrations. The major anion distribution ranged from HCO_3 being the dominant anion to SO_4 being dominant. As can be seen in Figure 20 , the "deep" water samples are generally higher in SO_4 than shallow waters. This can also be seen in Figure 21, which shows the SO_4/HCO_3 ratio as a function of depth-to-water. Shallow water exhibits a SO_4/HCO_3 ratio that is less than two, while deep waters tend have a SO_4/HCO_3 ratio greater than two. For the playas and Aleman Seep, HCO_3 is the dominant anion.

Projected data points on the diamond portion of the Piper diagram show that "deep" waters group together, while "shallow" water are more variable in

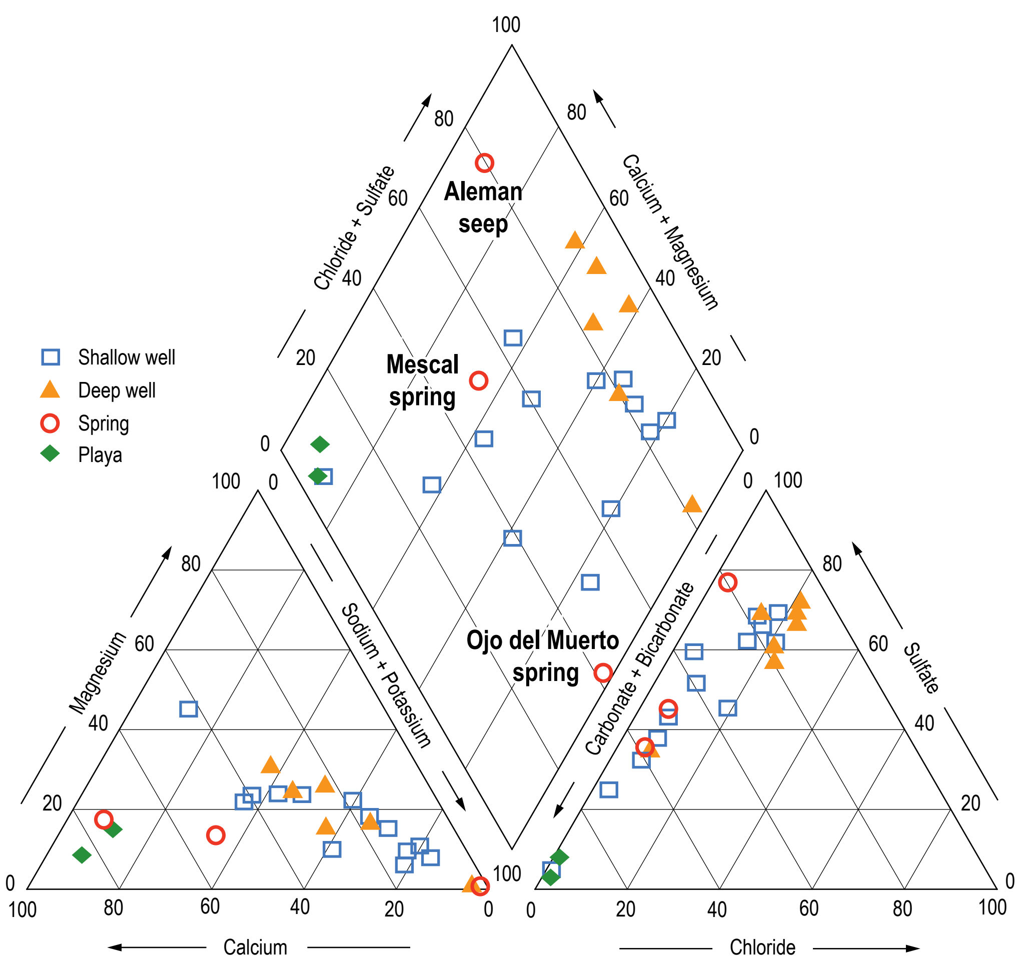


Figure 20. Piper diagram showing relative concentration distribution of major cations and anions. "Deep" water represents samples collected from wells with a depth to water greater than 200 feet and "Shallow" water was sampled from wells with a depth to water less than 200 feet below the surface.

terms of the distribution of the major ions. Samples collected from playas are easily differentiated from most of the groundwater samples, with Ca and HCO_3 being the dominant cation and anion respectively. This Ca-HCO_3 signature observed for the playas represents local runoff from September 2013 storms. The different water chemistry seen in groundwater is again due to water mineral interactions in the subsurface. It is important to note that Mescal Spring plots on the Piper diagram with relative ion concentrations similar to those observed for several shallow groundwater samples. The sample collected from Aleman Seep shows a unique Ca-SO_4 signature. Interestingly, another sample that stands out was collected from Ojo del Muerto Spring, which shows high relative Na and HCO_3 concentrations. These samples will be discussed in more detail below. In general, the anions, specifically the SO_4/HCO_3, can be used to differentiate "deep" groundwater from "shallow" perched groundwater.

Specific processes that control water chemistry were assessed by analyzing the relationships between different ions. Figure 22 shows HCO_3+SO_4 as a function of Ca+Mg, where the 1:1 line indicates that the water chemistry is primarily controlled by the dissolution of gypsum and carbonates. It can be seen that most samples plot above this line, indicating an excess of HCO_3 and SO_4, which is likely due to the dissolution of other minerals in addition to gypsum and carbonates. The molar ratio of Na/Cl is greater than one for most samples (data not shown), which also suggests the dissolution of other minerals that contain Na besides halite (NaCl). A strong linear correlation between lithium (Li) and sodium (Na) (Figure 23) suggests that much of the Na in the water is likely due to the dissolution of sodium salts such as trisodium hydrogendicarbonate dihydrate (trona, $Na_3(CO_3)(HCO_3)2H_2O$) and sodium sulfate (thenardite, Na_2SO_4), both of which, are evaporite minerals associated with saline pluvial lake deposits. Pluvial lakes are land locked basins that fill with water during wet periods. Evidence of large pluvial lakes has been found in the central Jornada del Muerto (Hawley, 1993). These deposits are present in the Love Ranch Formation and Cretaceous rocks. Lithium salts are often also found in evaporite deposits associated with pluvial lakes. Therefore, the trend seen in Figure 23 is probably due to the dissolution of rocks where both Na-bearing evaporite minerals and Li salts are present. It should be noted that thenardite was found in surficial precipitates near Ojo del Muerto (JM-054).

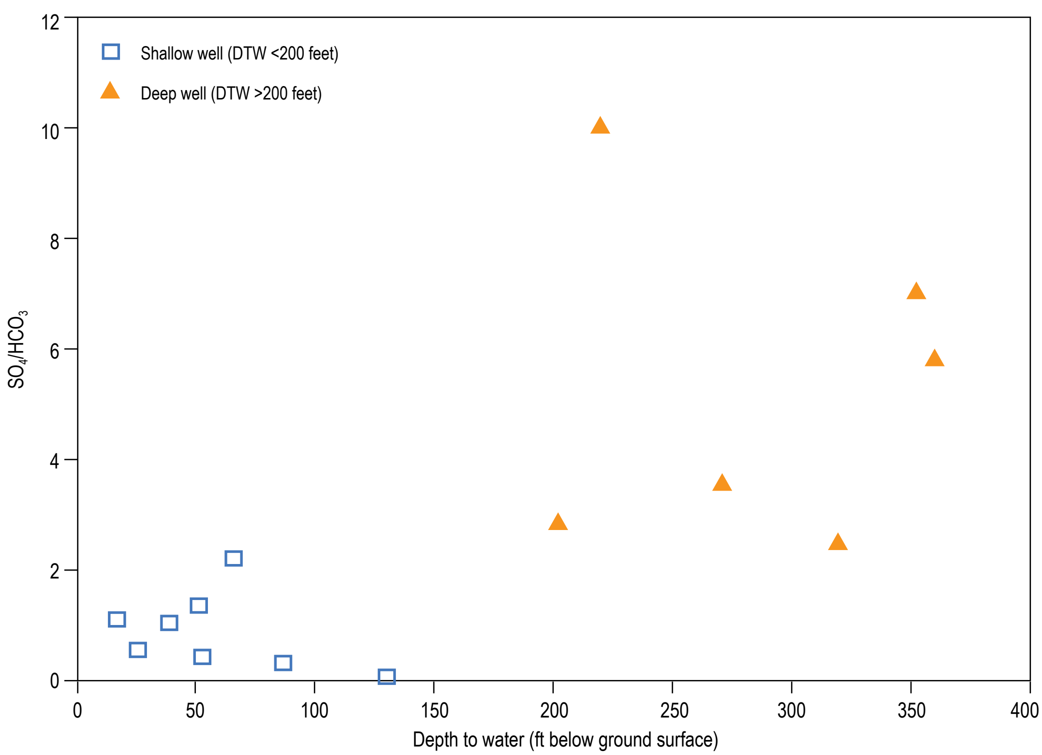


Figure 21. SO_4/HCO_3 ratio as a function of depth-to-water. Groundwater sampled from wells with a depth-to-water greater than 200 feet below the surface is characterized by higher SO_4/HCO_3 ratios. Shallow water exhibits a SO_4/HCO_3 ratio that is less than two, while deep waters tend have a SO_4/HCO_3 ratio greater than two.

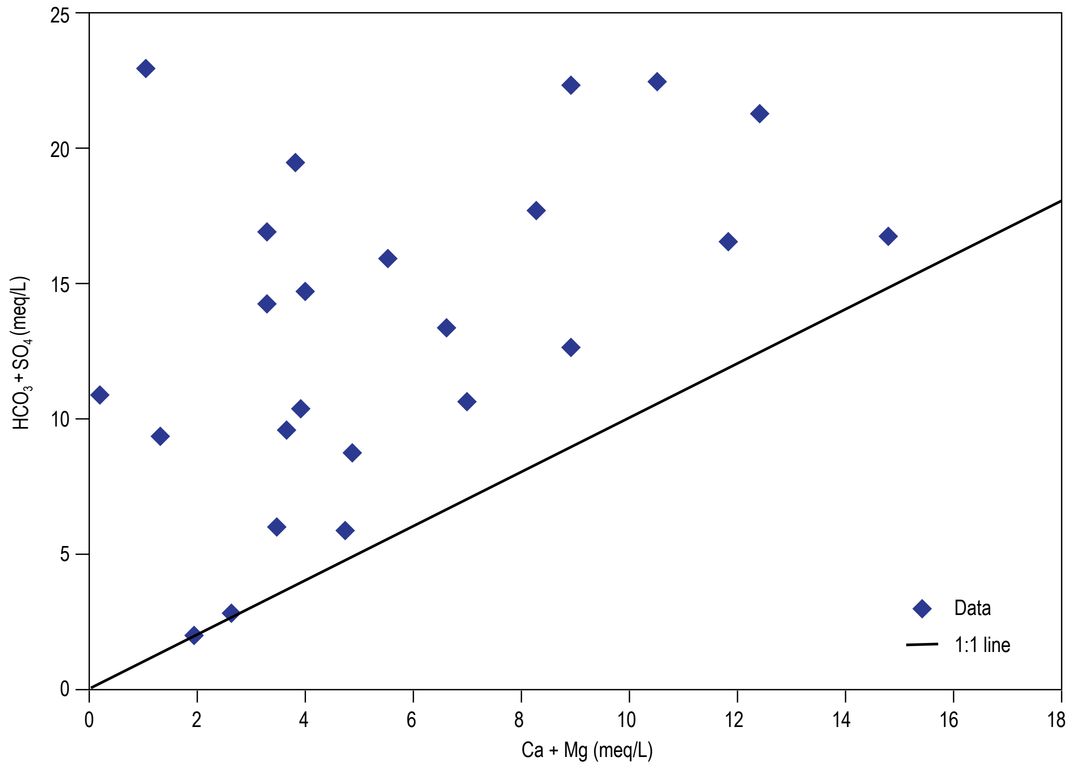


Figure 22. HCO_3+SO_4 as a function of Ca+Mg. The 1:1 line indicates that the dissolution of gypsum and carbonates is the primary process that controls water chemistry. The observed HCO_3+SO_4 values suggests that other water-mineral interaction processes play a role in determining water chemistry.

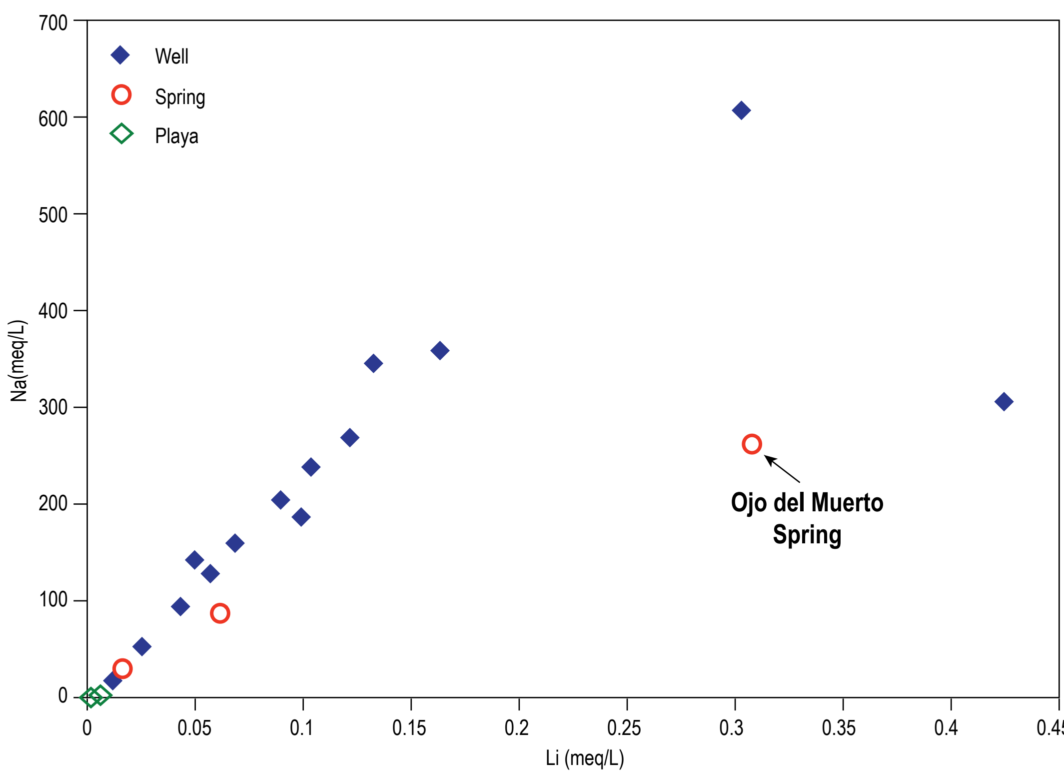


Figure 23. Strong linear correlation between Na and Li concentrations indicates that the increase in Na is due to the dissolution of Na rich evaporite minerals.

Samples collected from the playas show that local runoff exhibits low TDS values and a $Ca\text{-}HCO_3$ signature. Water that infiltrates into the subsurface and recharges the groundwater system increases in Na and SO_4 concentrations due to water/mineral interactions. Water chemistry is primarily controlled by the dissolution of gypsum and evaporite minerals from pluvial lake deposits. Water in the deeper aquifer system can be differentiated from shallow perched water by elevated SO_4/HCO_3 ratio (>2). Therefore an increase in SO_4 is likely due to larger residence times. The increase in Na, presumably due to the dissolution of Na evaporite minerals, does not appear to be a function of depth-to-water. Mescal Spring has a chemical signature similar to that of "shallow" groundwater. Ojo del Muerto exhibits a chemical signature that differs from that of all other samples, with a $Na\text{-}HCO_3$ chemical signature.

Stable Isotopes of Hydrogen and Oxygen

Stable isotopes of hydrogen and oxygen are useful tools for tracking precipitation through a hydrologic system. The nucleus of most oxygen atoms contains 16 subatomic particles: 8 protons and 8 neutrons. A small fraction of all oxygen atoms (approximately 0.2%) contains 10 neutrons, for a total of 18 subatomic particles in the nucleus. This isotope of oxygen is referred to as oxygen-18, or ^{18}O. Most hydrogen atoms consist of a single proton in the nucleus orbited by a single electron. A very small fraction of hydrogen atoms (approximately 0.016%) also contains one neutron in the nucleus, for a total of two subatomic particles. This isotope of hydrogen is referred to as deuterium and abbreviated as D.

The isotopic composition of a water sample refers to the ratio of the heavier isotopes to the lighter isotopes (R) for the hydrogen and oxygen that make up the water molecules. Because these stable isotopes are actually part of the water molecule, small variations in these ratios act as labels that allow tracking of waters with different stable isotopic signatures. All isotopic compositions in this report are presented as relative concentrations, or the per mil deviation of R of a sample from R of a standard shown in equation below:

$$\delta = \left(\frac{R_{sample} - R_{standard}}{R_{standard}} \right) * 1000‰$$

A negative value of $\delta^{18}O$ or δD indicates that the water sample is depleted in the heavier isotopes with respect to the standard. Standard Mean Ocean Water (SMOW) is the reference standard for stable isotopes of hydrogen and oxygen.

Because a water molecule is made up of both hydrogen and oxygen, it is advantageous to evaluate δD and $\delta^{18}O$ data simultaneously by plotting the data on a graph with δD on the y-axis and $\delta^{18}O$ on the x-axis (Figure 24). On such a plot, the isotopic compositions of precipitation samples collected worldwide plot close to a line called the global meteoric water line (GMWL) due to the predictable effects of evaporation and condensation (Craig, 1961). In general, precipitation in warmer regions will plot toward the heavier end of the GMWL (less negative values), and precipitation from cooler regions will plot towards the lighter end (more negative values). At any given location, a seasonal trend may be evident with winter precipitation plotting on the GMWL toward the lighter end and summer precipitation toward the heavier end. The GMWL represents a global average variation in the isotopic composition of precipitation. For most hydrogeologic studies that concern a discrete geographic region, it is preferable to characterize the local precipitation and construct a local meteoric water line (LMWL), whose slope and y-intercept (deuterium excess) may vary slightly from those of the GMWL due to local climatic conditions. For this study, we did not construct a LMWL. Mamer et al. (2014) constructed a local meteoric water line (LMWL) for the northern Tularosa Basin from precipitation collected from several elevations several times over three years. This LMWL was almost identical to the GMWL. Therefore, for this study, we used the GMWL to represent the local precipitation trend.

Stable isotopes of oxygen and hydrogen are also useful for assessing evaporative and condensation processes. As water evaporates, the isotopic composition of the residual water evolves away from the meteoric water line (global or local) along an evaporation line, whose slope depends on the conditions under which evaporation has taken place.

The isotopic signatures of water samples are plotted on a δD vs. $\delta^{18}O$ graph along with the global meteoric water line (GMWL) (Figure 24). No precipitation was collected for this study, but it can be seen that the sample collected from the playa, Engle Lake, which is local runoff from September rains plots on the GMWL. Other playa samples plot to the right of the GMWL, indicating that the water has undergone evaporation. Assuming an initial isotopic composition similar to that of Engle Lake, the isotopic composition would evolve along the evaporation line shown.

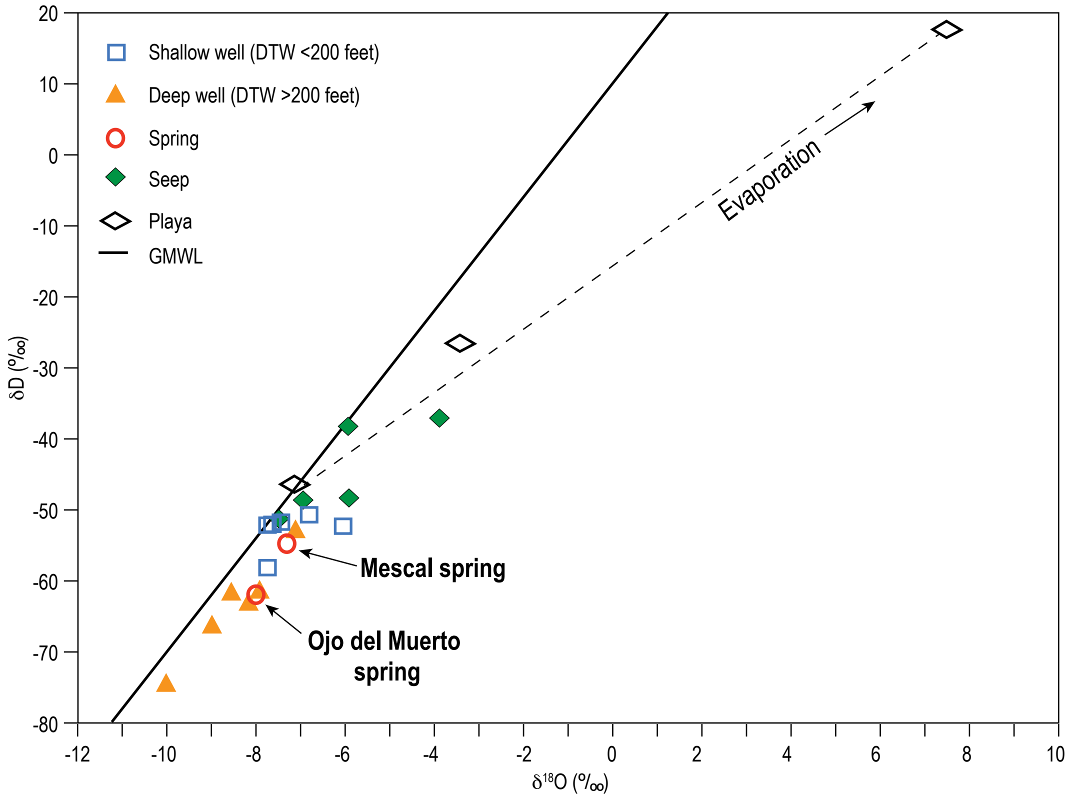


Figure 24. Stable isotope data for water samples collected from wells, springs, seeps, and playas, along with the Global Meteoric Water Line (GMWL).

Again, the wells that were sampled were divided into "deep" wells (DTW >200 feet) and "shallow" wells (DTW <200 feet). These data suggest that the stable isotopes of oxygen and hydrogen can be used to differentiate shallow waters from deep waters. For most well samples, shallow waters are characterized by δD and $\delta^{18}O$ that are greater than -60‰ and -7.8‰ respectively (Figure 25). Most deep waters sampled exhibit isotopic values that are lighter (more negative values) than those values. Shallow waters show values that are typically observed for summer precipitation in southern New Mexico (Newton et al., 2012; Mamer et al., 2014). Therefore, this shallow groundwater is primarily derived from local summer precipitation. Stable isotope data for shallow water that is offset to the right of the GMWL has undergone evaporation.

Most deep water samples exhibit lighter isotopic signatures with more negative values, which suggests that these waters are part of a larger regional groundwater system. These isotopically light waters likely represent winter precipitation (snow melt) from higher elevations in the adjacent mountains and/or precipitation that fell during the Pleistocene, when mean annual temperatures were significantly cooler (Phillips et al., 1986).

Based on the isotopic signatures of deep and shallow groundwater, we can assess the groundwater regime for the springs and seeps that were sampled. The seep samples show isotopically heavier values and generally plot with the shallow groundwater samples. Mescal Spring plots with "shallow" water, and Ojo del Muerto plots near "deep" water samples. These data allow us differentiate the different springs and seeps by identifying the associated hydrologic system. Mescal Spring and the seeps appears to be part of the shallow perched system, while Ojo del Muerto is part of a deeper, more regional system. As with the water chemistry data, stable isotope data allows us to differentiate deep groundwater (DTW <200 feet) from shallow groundwater (DTW <200 feet). Water in the shallow system is primarily recharged by local summer precipitation, while water in the deeper system is likely older water and may be recharged at higher elevations.

Water Age

A subset of water samples that were collected were analyzed for tritium and carbon-14. Tritium concentrations in groundwater can help to identify the

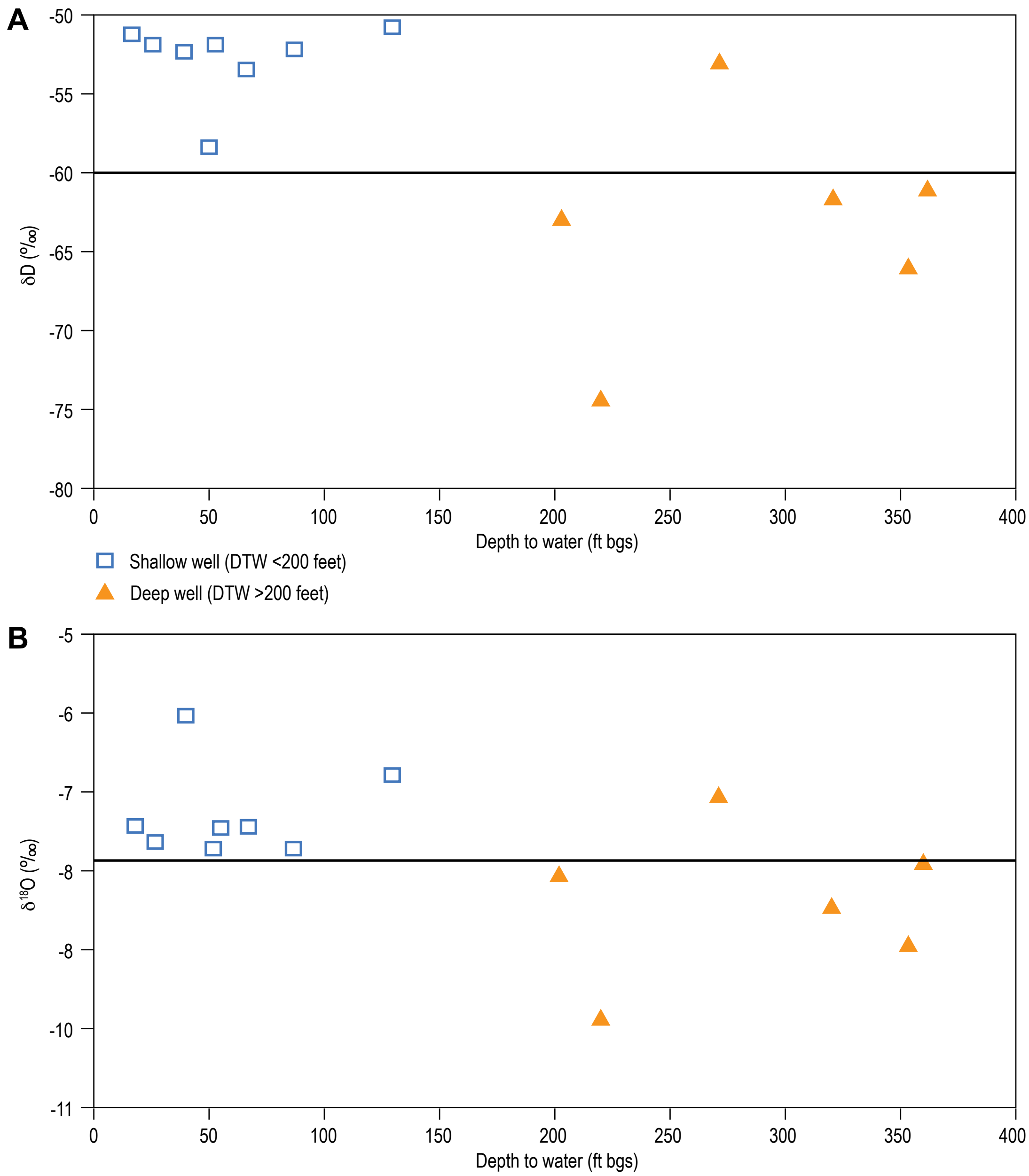


Figure 25. Stable isotopic values (**A**—δD, **B**—$\delta^{18}O$) as a function of depth-to-water. Isotopic compositions of groundwater can be used to differentiate between "deep" and "shallow" waters. Depth to water is in feet below ground surface.

presence of young waters (<50 years old). In the study area, water samples exhibited tritium concentrations of less than 0.1 TU and greater than 3 TU (Figure 26). Samples with tritium concentrations less than 0.1 TU are likely much greater than 50 years old. These samples were collected from Ojo del Muerto, and the wells JM-041 and JM-008, both of which have a DTW greater than 200 feet. Wells that exhibit greater than 3 TU include JM-038, JM-054 and JM-059, all of which have a DTW that is less than 200 feet below the surface. This water is likely a mixture of modern recharge (<5 to 10 years old) and submodern recharge (prior to 1950). This young age is consistent with this water representing a shallow perched hydrologic system. Aleman Draw seep also shows a tritium concentration greater than three TU, suggesting that it is part of the shallow perched system.

Only four samples were analyzed for carbon-14, and these data are shown on Figure 26. It should be noted that these are apparent ages and have not been corrected for hydrogeologic process, such as the dissolution of carbon-dead carbonate rocks that usually make the carbon-14 age look older than it really is. However, the range of these apparent ages is large

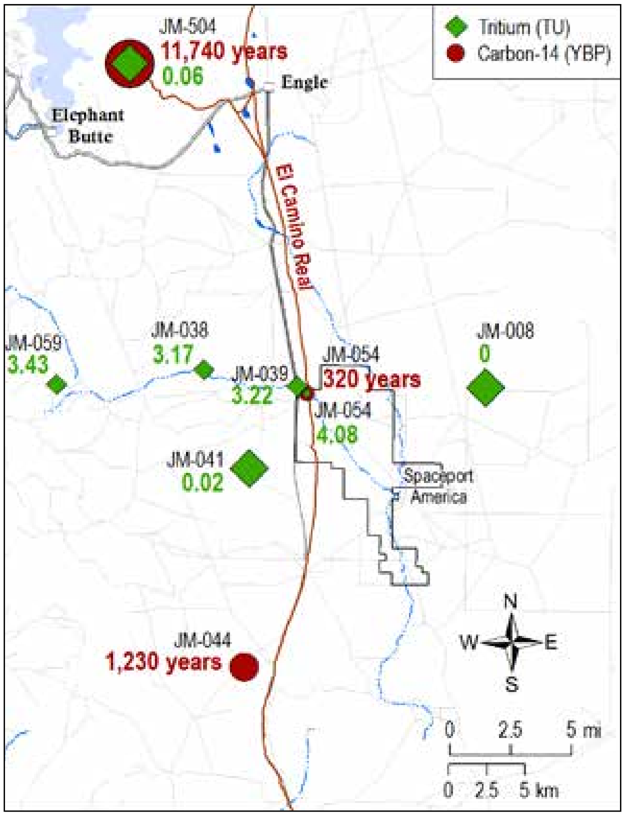


Figure 26. Tritium concentrations in tritium units (TU) and apparent carbon-14 age dates, years before present (YBP).

enough to make relative comparisons and to identify very old water versus modern recharge. The two samples with the youngest apparent carbon-14 ages were sampled from JM-054 and (320 years before present) and JM-059 (0 years before present (YBP)), both of which were observed to have a DTW less than 200 feet below the surface. Both of these water samples also exhibit tritium concentrations greater than 3 TU. These young carbon-14 dates and high tritium concentrations are consistent with a local perched hydrologic system. The well JM-044, which has a depth to water less than 200 feet, has an apparent carbon-14 age of 1230 YBP. This well is located in the southern portion of the study area. The oldest age date observed was sampled from Ojo del Muerto, with an apparent age of 11,740 YBP. This old age again suggests that this spring is part of the deeper regional system.

Discussion

Geologic, hydrologic, and geochemical data discussed above has increased our understanding of the hydrogeologic system in the Jornada del Muerto. This section integrates the data discussed above to characterize the hydrogeologic system and to construct a conceptual model.

Shallow versus Deep Hydrologic System

The data and discussion presented above show that, within the study area, there are two different hydrologic systems, a local perched system and a deeper regional system. It can be seen in Table 5 that there are several metrics that can be used to differentiate the deep system from the shallow system. The SO_4/HCO_3 ratio, the stable isotopes of oxygen and hydrogen, and tritium can all be used to identify the hydrologic regime. Carbon-14 age dates also show expected differences for these waters, but we did not collect enough samples to establish an age boundary. Apparent carbon-14 ages for samples collected from wells with DTW measurements less than 200 feet below the surface range from 0 to 1,230 YBP. No samples from "deep" wells were analyzed for carbon-14. However, water sampled from Ojo del Muerto, which groups with the deeper regional system by criteria set for tritium and stable isotopes, has an apparent age of 11,740 YBP. This old apparent age also suggests that this spring discharges from a larger regional system. It should be noted that for any one metric, there is some overlap, where water from the deep system may exhibit a value that suggests that it is from the shallow system. However, if multiple metrics are used for the well samples, a depth-to-water of greater or less than 200 feet can be predicted accurately. Therefore, these metrics can be used to identify water from the "deep" system versus the "shallow" system.

Table 5. Criteria to differentiate the shallow perched hydrological system from the deep regional system.

	Depth to water (ft)	SO_4/HCO_3	$\delta^{18}O$ (‰)	δD (‰)	^3H (TU)
Shallow perched system	<200	<2	>-7.8	>-60	>3
Deeper regional system	>200	>2	<-7.8	<-60	<1

Hydrogeologic Conceptual Model

Figure 27 shows the same geologic cross-section that is seen in Figure 4, but with 10x vertical exaggeration to focus on the shallow subsurface. A dotted line shows a depth of 200 feet below the surface, and in this area it is approximately coincidental with the contact between Quaternary deposits and older rocks. It can be seen that to the west of the Jornada Draw fault zone, most wells are completed in the Quaternary alluvium and exhibit depth to water of less than 200 feet below the surface. However, well JM-003 (Figure 27), as well as well JM-041 (Figure 15), which both show depth-to-water values of greater than 200 feet, suggest that there is a deeper hydrologic system in the Cretaceous, Paleocene and Eocene rocks underlying the Quaternary. This observation is consistent with the "shallow" and "deep" systems discussed above. To the west of the fault zone, the water table is deeper than 200 feet, and there does not appear to be a "shallow" water table in the alluvium. It should be noted that the shallow system shown in Figure 27 may not be completely confined to the Quaternary alluvium in the central portion of the study area. To the north, Cretaceous and Paleocene-Eocene rocks are closer to the surface and in some places exposed. Therefore, much of the shallow groundwater likely resides in the upper portions of these units.

The shallow groundwater system is recharged by runoff of local precipitation that infiltrates primarily in streambeds. Groundwater level responses to extreme rainfall in September 2013 (Figure 18) show that the spatial distribution of recharge to the system is highly variable, which is indicative of focused recharge in local ephemeral streams. This system is relatively small. Water is stored in the thin alluvium and upper strata of the underlying bedrock. Responses to large rain events are rapid, but depletion of this aquifer system due to evaporation and leakage to the deeper system can also be relatively rapid, especially during times of drought.

Water in the deeper system, which is characterized by longer residence times as discussed above, is likely recharged from downward percolation of water from the shallow system and from precipitation in the adjacent mountains that infiltrates into the subsurface and travels along deep regional flow paths. Although it is not known how thick this aquifer is, this system is larger than the shallow perched system. This groundwater likely flows to the south beyond the study area.

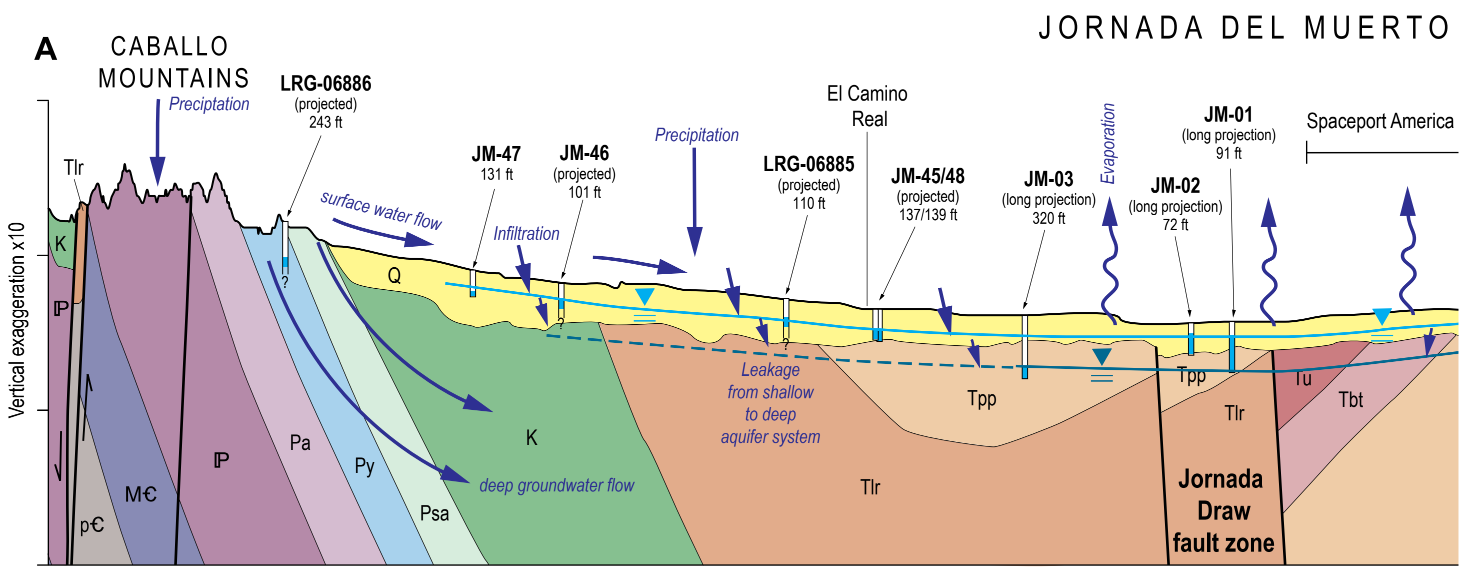
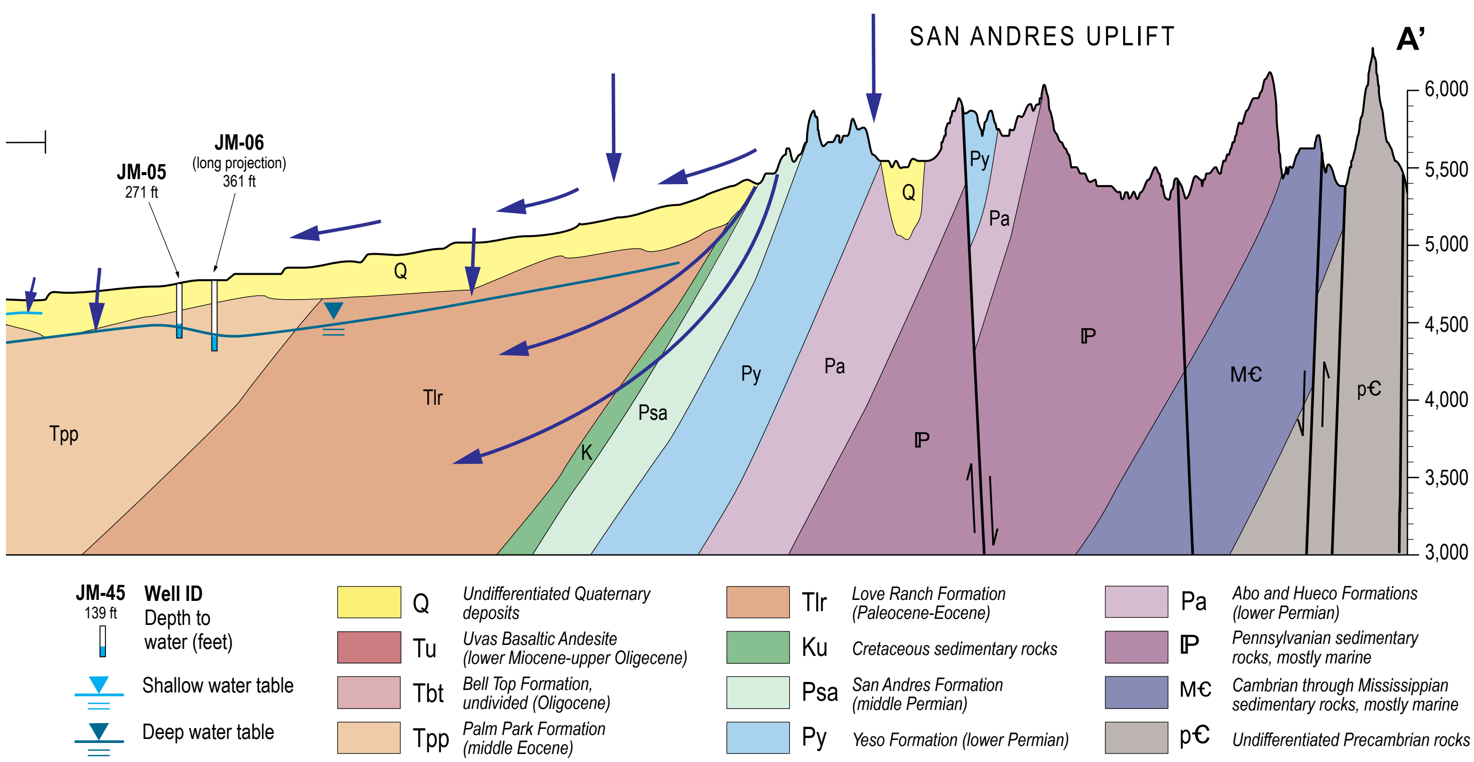


Figure 27. This conceptual hydrogeologic model is presented on a geologic cross-section. To the west of the Jornada Draw fault zone, a perched groundwater system exists in the Quaternary alluvium and the upper portion of the underlying bedrock and is characterized by a depth-to-water of less than 200 feet below the surface. This system is recharged primarily from local precipitation and runoff that infiltrates through ephemeral stream beds. Discharge from this system mostly occurs as evaporation near the center of the basin. This shallow system is relatively small and has limited storage, and therefore responds quickly to short-term wet and dry periods. The deeper regional groundwater system resides in Cretaceous and Paleogene bedrock, and is characterized by a depth-to-water that is greater than 200 feet below the surface. This system is recharged by leakage from the perched system and precipitation in adjacent mountains.

For this study, an understanding of the regional and local hydrogeologic framework is necessary to characterize individual water sources that would be available to travelers on El Camino Real. A spring that discharges from small perched aquifer system will likely be very responsive to short wet and dry periods and may be prone to dry up during multi-year droughts. Conversely, a spring that discharges from the larger regional system will be more stable and may not respond to annual or decadal climate fluctuations as much. The characterization of these water sources for use by travelers along El Camino Real is discussed below and in Kludt et al. (2015).

Paleohydrology of the Jornada del Muerto

In discussions presented below, we analyze the implications of these findings on how travelers likely navigated across the Jornada del Muerto. These analyses assume that the hydrogeologic and climate conditions 200 to 300 years ago were similar to the conditions we observe today. Landform mapping (Kludt et al., 2015) showed no evidence that hydrogeologic conditions have changed significantly over the last few hundred years. Much of the study area is comprised of piedmont slopes of different types, which are very stable and can be millions of years old. Historic accounts of travelers crossing the Jornada del Muerto mention the same springs and seeps described in this study. Therefore, it appears that the assumption that the hydrogeologic system has not changed much over the last few hundred years is valid. The local climatic regime, on the other hand, may have been different from what is depicted by precipitation records over the last 100 years. Assessing the paleoclimate in the area was beyond the scope of this study. All hydrologic modeling and analyses that were used to predict the reliability of these water sources discussed below, were based on the temporal variability of precipitation observed over the last 100 years using NOAA weather station data.



IV. EVALUATION OF THE SHALLOW WATER SUPPLY IN THE JORNADA DEL MUERTO

The above hydrogeologic characterization enabled us to evaluate shallow water sources that would have been available to travelers in the area in the context of their hydrogeologic framework. Water sources that are considered include playa lakes, springs, seeps and streams. This section describes analyses, including mathematical models that were used to assess water supply in the Jornada del Muerto.

Playa Lakes

A playa is an ephemeral lake that is a topographic low in an undraining desert basin. Playas generally flood after large seasonal storms provide adequate surface water runoff. When flooded, they often contain substantial amounts of water and may also play a crucial role in recharging the groundwater system in the desert. Basin-wide recharge from infiltration of precipitation through surficial deposits in a desert is usually assumed to be negligible because of small precipitation and large evaporation rates. However, when runoff floods the playa lakes, a significant amount of this water has a chance to slowly infiltrate, recharging the aquifers which feed springs and seeps.

There are four major playas in the northern portion of the study area, which are located just to the east of the Jornada Draw fault zone (Figure 28). This location is unique in that it sits on top of a groundwater divide, where groundwater flows northwest to Elephant Butte (Figure 16), or south through the Jornada del Muerto. Engle Lake (a) (Figure 29) is the northern most playa in the study area, and can be seen north of Highway 51, just northwest of Engle. There is a smaller playa 0.6 miles to the south of Engle Lake, designated Engle Lake (b). An unnamed playa is located two miles southwest of Engle Lake (b). Jornada Lake, which is the largest playa, reaching a maximum surface area of 250 acres, is located 5.6 miles south of Engle Lake (Table 6). When the playas in the area are flooded, combined, we estimate they can hold more than 100 million gallons of water (300 acre-feet).

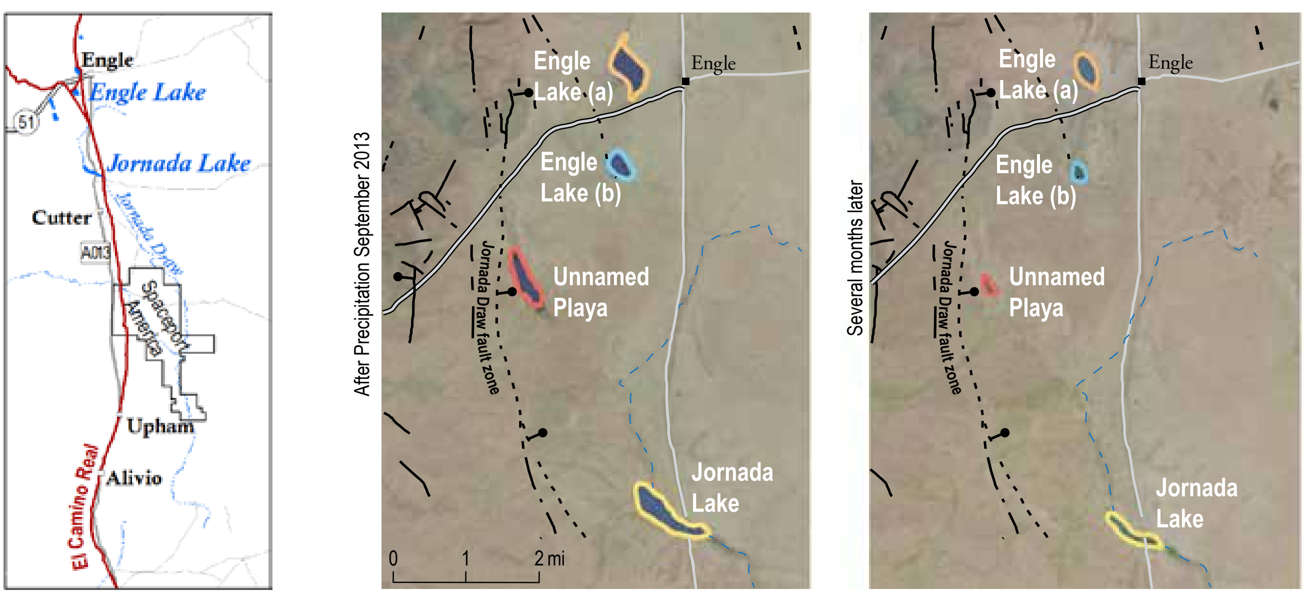


Figure 28. The playas are located in the northern portion of the study area on top of a groundwater divide. Satellite images showing the change in the wetted surface area of playas over time.

Figure 29. Playa (Engle Lake (a)) filled with water after recent rains in September 2013.

Table 6. Size of playa lakes and their drainage basins studied in this report.

	Max flooded surface area (acres)	Approximate drainage basin area (acres)
Engle Lake (a)	140	3,650
Engle Lake (b)	60	1,100
Unnamed Playa	160	2,500
Jornada Lake	250	55,000

Modeling of Playa Water Availability

To understand how important these playas were as a water source, we assessed the recurrence of flooding events that resulted in a significant amount of standing water in the playas. We defined a threshold precipitation event that is necessary to fill playas by using historic satellite imagery obtained from Landsat (Figure 28). Landsat images are recorded every 16 days, covering the majority of the earth's surface, and have been collected for more than 30 years. These images consist of several spectral bands that have a variety of applications, including detection of water bodies (landsatlook.usgs.gov). The frequency at which these photos are taken is high enough to determine when (within 16 days) the playas have filled, as well as how long they contained water over the past 30 years.

Historic precipitation records from the past 30 years recorded at Elephant Butte weather station (~12 miles from the playas) (NOAA station: 292848), were used to compared rain events with playa filling events. Our analysis of these data suggest that it takes at least two inches of rainfall over the period of a week (7 consecutive days) to result in filling the playas. This criterion assumes that when the surface soil is moist, runoff is increased. Using the Landsat data, we found that this threshold criterion accurately predicted fifteen of twenty-one playa flooding events and gave only four false positives over the thirty year playa record (Figure 30). Inaccuracy of this method may be associated with the high spatial variability of monsoon thunderstorms (i.e., rain collected at a nearby weather station does not necessarily represent that which fell near the playas) and other factors such as soil moisture.

Water availability in the playas depends, not only on a threshold precipitation event to fill them, but also on how long the water remains in the playas. Because the playas are a closed surface water system (no surface water outputs), evaporation and infiltration are the only processes that control the amount time that water might remain in the playas. If the underlying sediments are impermeable enough as to make them hydraulically disconnected from the groundwater system then we expect to see water volume decline at the same rate as evaporation. However, playas can be connected to the groundwater system and can provide a significant amount of groundwater recharge in desert environments. Previous research on playas in New Mexico (Havens, 1966) measured 20% to 80% infiltration of ponded water in six playas. This infiltration would decrease the amount of time that water is available in the playas.

Following the most recent playa flooding event in September 2013, continuous water level measurements were recorded in Jornada Lake from early November 2013 through February 2014 (data not shown, see Appendix D, on CD only). This data set, combined with Landsat imagery showing change in surface area, was used to find the change in volume over the four month interval. To determine local evaporation rates, historic pan-evaporation rates from Elephant Butte weather station (NOAA, 2014) were taken into account, as well as rates reported from previous evaporation studies of the Elephant Butte reservoir (Eichinger et al., 2003; Herting et al., 2004; Moreno, 2008). Playa area and volume decline were modeled using these evaporation rates (0.01 in/day). The modeled evaporation accounted for 85% of the decline measured at Jornada Lake, with the remaining 15% of the playa volume potentially infiltrating into the groundwater system. If this is the case, these ephemeral lakes may play a significant role in recharging the shallow groundwater. More research is required to accurately determine the impact that these playas have on the groundwater in the region. We were not able to conduct the same analysis on the other playas in the area.

Using the results from analyses described above, we constructed a model to predict when, over the past 100 years, the playas contained water (Figure 31). By applying the flooding threshold criterion to the precipitation record collected at Elephant Butte we were able to estimate when the playas filled. Next, we were able to estimate how long after each flood event the playas might have stored water. This duration is based on the flooded surface area, the observed duration that the playas remained flooded over the past 30 years with Landsat imagery, and estimated evaporation rates. Using this information we were able to find the likelihood, by month, that water would be present in the playas.

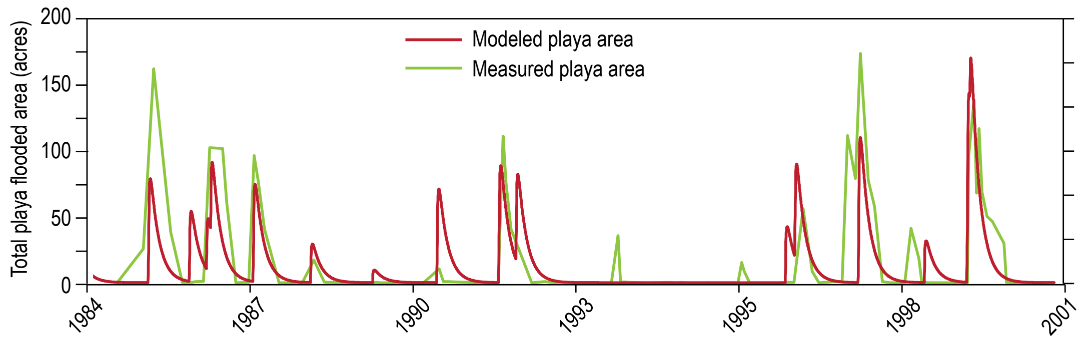


Figure 30. Measured and modeled combined playa wetted areas.

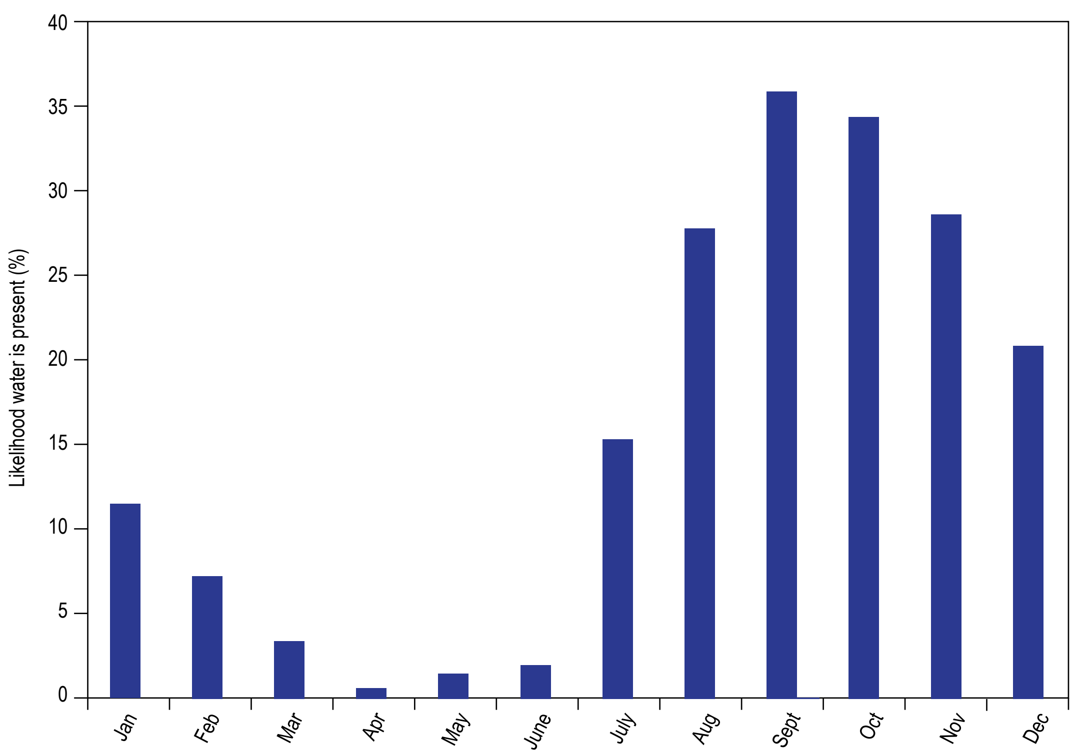


Figure 31. Likelihood of water being present in the playas throughout a given month, averaged from 1908–2013.

Playa lakes, when filled, have the capacity to supply large amounts of water. The playas, however, do not fill every year. Even after a good monsoon season, there is no guarantee that the playas will have water, since they only fill after major storm events. At best, we found that during September and October in any given year, there is a ~35% chance of finding water in the playas (Figure 31). During the months of August, November and December the probability of water being present drops to 20%. The chances of finding water in the playas in March through June are less than 5%.

Springs and Seeps

Within the study area there are springs and seeps that likely provided water for travelers along the Jornada del Muerto. For this study we sampled two springs and one seep (Figure 10, Table 2). Ojo del Muerto Spring (JM-504) is located in the north, just east of old Fort McRae (Figure 10). Mescal Spring (JM-500) discharges into the Mescal Canyon in the northwestern portion of the study area. The Aleman Draw seep (JM-503) is located in the center of the study area in Aleman Draw, just west of Spaceport America. From the hydrolgeologic characterization discussed above, it is apparent that there are two different hydrologic systems, a shallow, local and a deeper, regional aquifer system. An understanding of the different springs in the context of the hydrogeologic conceptual model has helped us to construct basic groundwater flow models to evaluate the temporal variability of these water sources.

Ojo del Muerto

Ojo del Muerto (JM-504) is situated in an arroyo that drains west toward the Rio Grande. It is believed to be one of the most reliable springs in the area and is commonly mentioned in traveler accounts for its "copious supply of water" (Smith, 1893). According to historic accounts, the spring location has shifted in the recent past. Previously, the spring is reported to have emerged 2 km west of the current discharge location. The original location was very close to Fort McRae, which was constructed to protect travelers using the spring (Figure 10). At this location an intrusive dike runs north-south, perpendicular to flow paths. This dike probably acts as a barrier to flow, and forces the deeper groundwater up resulting in the spring. When the railroad was being laid down a large cistern was built in the vicinity of the spring and a tremendous volume of water was pumped (Smith, 1893). This possibly disturbed the aquifer system and led the change in the spring's location. We do not know how much water this spring produced in the past. The court documents cited above indicate that the AT&SF Railway Company pumped from 16,000 to 25,000 gallons per day, or some 11 to 17 gallons per minute (18 to 27 acre-feet per year). When we visited the present outlet of the spring in November 2013, we visually estimated the flow rate to be about 10 gallons per minute (16 acre-feet per year).

Modeling of Ojo del Muerto

Modeling of relative discharge rates over time for this spring requires knowledge of the recharge area, recharge mechanism, groundwater flow velocities and the groundwater flow path. Data discussed above, including the geology, age dates, and water chemistry, help to provide some of this necessary information. An apparent carbon-14 date of 11,740 years before present and the absence of tritium (Figure 26) indicate a relatively long flow path with little or no mixing of younger water along this flow path.

Ojo del Muerto is chemically distinct from the other springs and wells sampled for this study. Its water chemistry plots in the lower right quadrant on the Piper diagram, with a sodium-bicarbonate chemical signature (Figure 20). This chemical signature is likely a result of cation exchange that occurs in clays and shales, where cations in the water, such as Ca^{2+}, are exchanged for Na+ that was bound to mineral surfaces. Groundwater north of the study area, which was analyzed in an earlier study, show similar chemical signatures (Geohydrology Associates Inc, 1989). These wells were screened in the McRae Formation, which is also the geologic unit, from which the spring discharges. The McRae Formation in this area, consists of volcaniclastic sandstone and shale, and behaves as a deeper, regional aquifer system in the northern part of the study area.

Geologic cross sections up-gradient of the spring helped to determine potential recharge locations. Figure 32 shows a conceptual model of the likely flow path for water that discharges at Ojo del Muerto. We are assuming that Engle Lake (a) and (b), and the unnamed playa are the primary recharge areas for the hydrologic system associated with the spring. Although playa sediments generally have very low hydraulic conductivity values (~0.03 ft/day), meaning that it is difficult for water

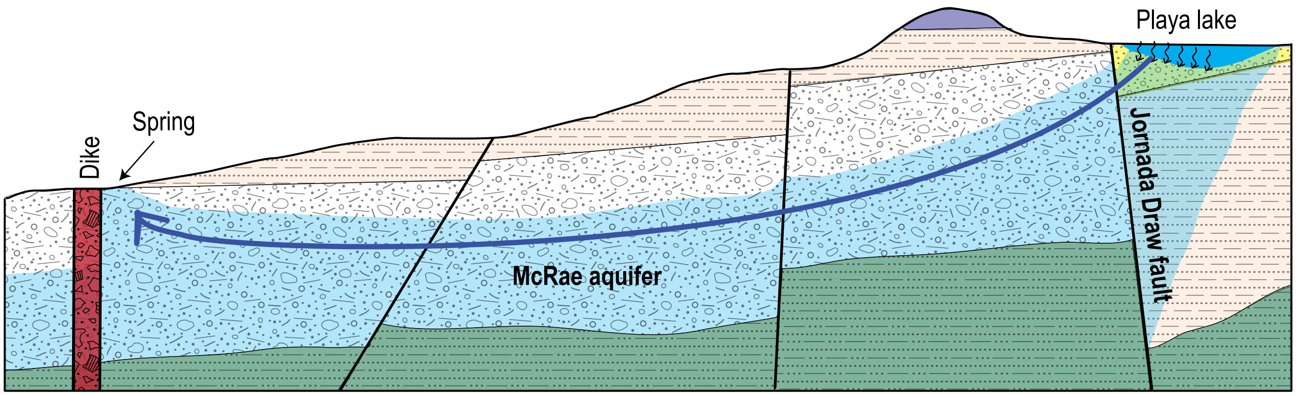


Figure 32. This conceptual model of Ojo del Muerto Spring assumes the playa is the recharge source and the dike forces water to discharge from the McRae aquifer which is part of the deeper, regional aquifer system..

to move through them, significant volumes of water can infiltrate creating very steady sources of recharge over large time periods. We evaluated the potential for these playas to provide significant recharge by extrapolating the water level trend in Jornada Lake (described above) to represent the entire length of time that there was water in the playa. Assuming an average evaporation rate of 0.01 inches per day, we estimate a recharge volume of approximately 12 million gallons per playa filling event for Jornada Lake. The playas fill, on average, once every 3 years, resulting in a long-term average recharge rate of 4 million gallons per year (12 acre-feet per year) for Jornada Lake. The estimated discharge rate for Ojo del Muerto (10 gallons per minute or ~16 acre-feet per year) is close to this estimated recharge rate. These back-of-the-envelope calculations suggest that the playas in the study area can contribute a significant amount of recharge to the groundwater system. Given the apparent carbon-14 age date for water discharging from Ojo del Muerto, of ~11,740 years, recharge rates through the playas were likely higher during wetter periods, due to a higher rate of playa filling events. Therefore, we feel that that the assumption that the playas provide recharge to the hydrologic system associated with Ojo del Muerto is valid.

We built a rudimentary groundwater flow model to understand how flow and discharge conditions for this spring change with time (Figure 33). Our model assumes recharge originates from the playas, 9 km from the spring discharge point. The modeled playa flooding data was used as the model input. During the modeled periods of time in which the playas are estimated to have been flooded, an infiltration rate of 0.01 inches per day was applied. This infiltration rate was estimated with water level data in Jornada Lake as described above. Several aquifer pumping tests

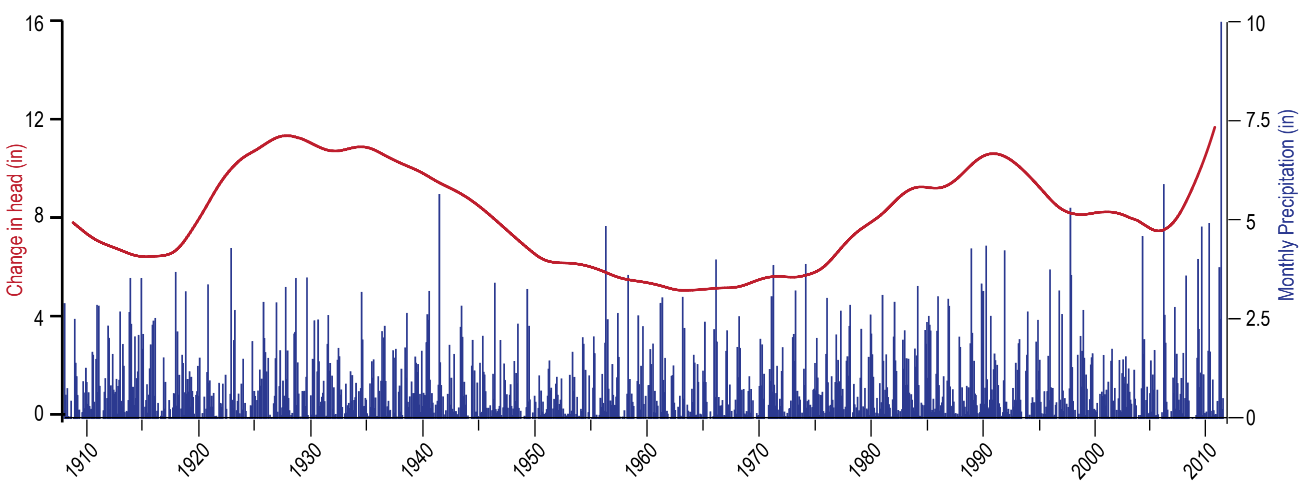


Figure 33. Modeled water level fluctuations that are proportional to discharge from Ojo del Muerto, show small scale variability responding to variable recharge.

at wells in the study area were recently conducted, providing us with accurate hydraulic conductivity estimates for the McRae Formation (Geohydrology Associates Inc. 1989). We used a hydraulic conductivity value of three feet per day.

The resulting model simulates water levels at the end of the flow path with input at a discrete point up gradient at the recharge zone. We did not model spring discharge, but simulated water levels at the spring location, which are proportional to discharge rates. Modeling results show a system that has a relatively steady discharge and is very slow to react to changes in precipitation. Water levels at the spring location respond to wet and dry periods gradually over several years. The attenuated response of water levels to short-term precipitation patterns suggests that spring discharge is rather stable and that Ojo del Muerto was a very reliable spring over the last 100 years.

Springs and Seeps in Shallow Aquifer System

Aleman Seep, and Mescal Spring, along with several other small seeps and springs throughout the Jornada del Muerto have very different flow systems than that of the Ojo del Muerto spring. At the Ojo del Muerto, the water chemistry, and tracer age indicates that there is one unique recharge location and that water flows through an isolated flow path in a confined aquifer. Aleman Seep, Mescal Spring and the other seeps and springs in this area have very different water chemistry, tracer age, and discharge history. As a result, these water sources rely on different recharge mechanisms, and are evaluated differently from the Ojo del Muerto spring.

Environmental tracer sampling, or age dating, performed at these springs and seeps suggests that the discharging water is quite young. The high levels of tritium (.3TU) found in these waters suggest that recent precipitation plays a large role in the flow associated with these water sources. Water discharging from these springs and seeps seems to originate largely as runoff. Storms that provide a significant amount of water result in runoff, or overland flow. Precipitation that falls in the watersheds up gradient of the springs and seeps infiltrates into the alluvium in the stream beds. The streambed deposits gradually pinch out as exposed bedrock outcrops. At these points we find springs and seeps emerging (Figure 34). The presence of large stands of cottonwoods and other vegetation suggests that water in these locations is present, even if the springs are not continuously discharging. Local springs and seeps do not provide a great deal of water. At seeps, groundwater can be accessed by digging a shallow trench into the streambed alluvium to access water.

Modeling of Local Shallow Springs

We again ran a simple groundwater flow model to assess the reliability of these local springs and seeps. Water levels were calculated along a shallow flow path as a response to local precipitation. Unlike the Ojo del Muerto, recharge was modeled at the surface all along the flow path to simulate infiltration through the stream bed. Precipitation records from Elephant Butte were used as input. Modeling results can be seen in Figure 35.

Increases due to precipitation happen quickly, as reflected by the "spikey" nature of the change in head, but water levels also decline rapidly during dry periods. "Zero head" represents an arbitrary depth below which a spring may stop flowing or seep is no longer easily accessible. It can be seen that because of

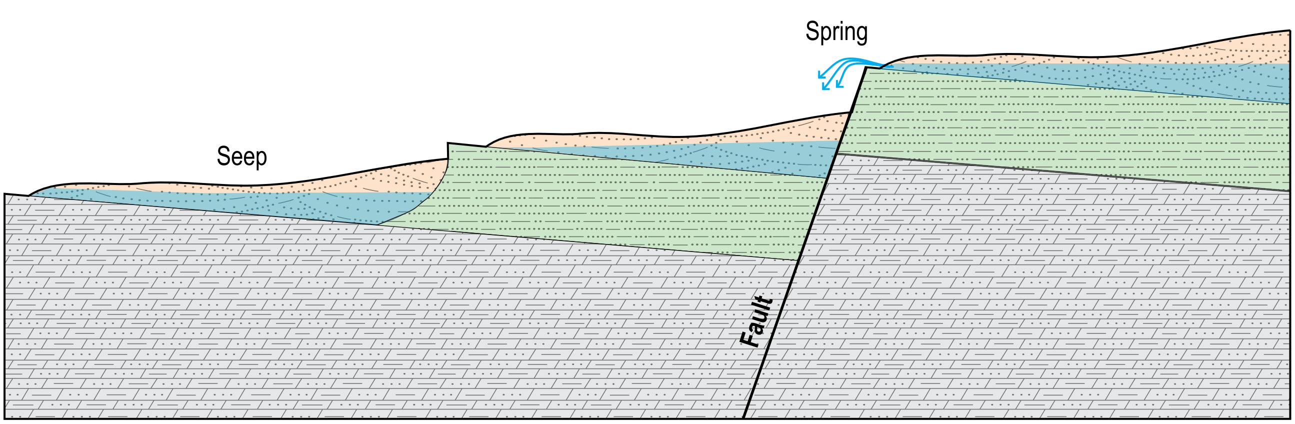


Figure 34. Conceptual model of streambed springs and seeps. This model shows groundwater flowing along bedrock being forced to the surface when stream bed sediment thins due to underlying structure of bedrock

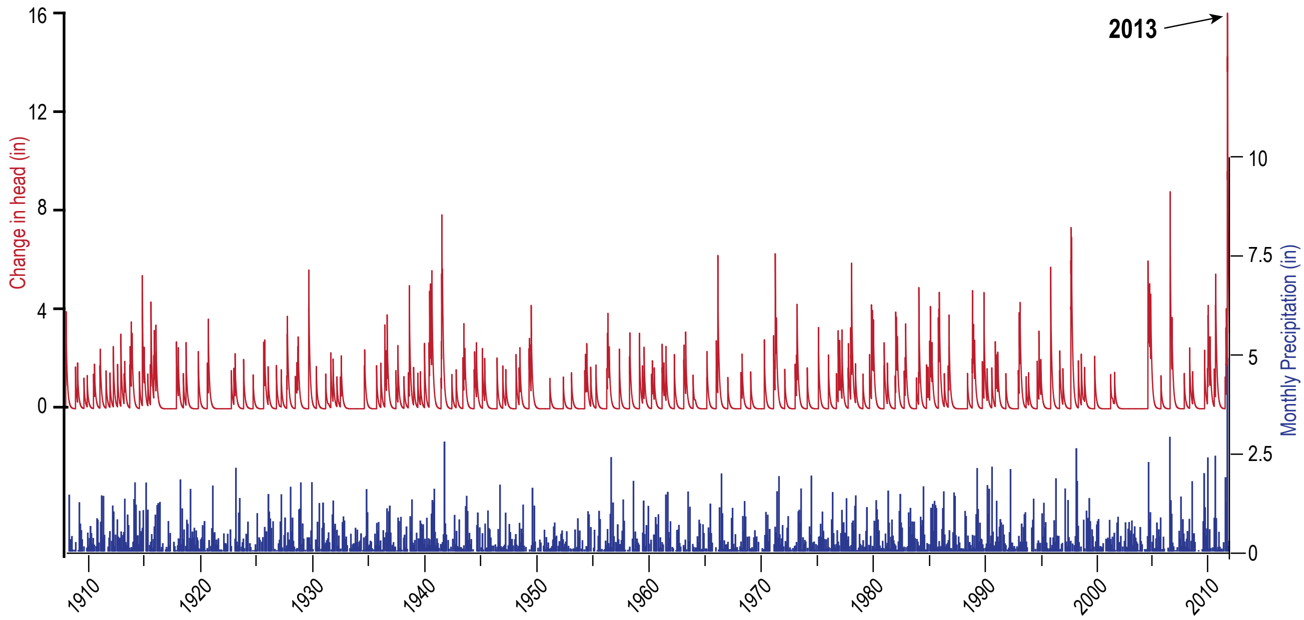


Figure 35. Hydrologic modeling results for shallow seep and springs show that water levels at the seep/spring location respond quickly to precipitation events but also decline rather quickly. Record breaking rains of September 2013 can be seen. When modeled head is zero, water is no longer easily accessible.

the nature of the hydrologic system associated with these springs and seeps, the availability of water from these water sources is highly dependent on short term precipitation rates. The hydrologic system is very shallow and cannot store a large amount of water. Therefore, these shallow springs and seeps are not a very reliable water source. They will often dry up during short periods of drought.

Summary of Water Supply Assessment

Quantity

One of the most important characteristics of a water source is its quantity. The amount of water available would heavily impact the types of groups that would attempt to access a given source. When flooded, the playas can hold millions of gallons of water and cover a vast area. This would allow thousands of travelers and livestock to utilize the playas simultaneously. From historical accounts we know that the Ojo del Muerto was heavily relied upon by travelers as it supplies a significant amount of water, and could provide enough water for a large number of people. As for the shallow springs and seeps, these sources do not provide a great deal of water. At seeps, groundwater can be accessed by digging a shallow trench into the streambed alluvium to access water. While this method would have been sufficient for a small group, it would be impractical to supply large herds with water in this fashion. It should be noted that local ephemeral streams can provide significant amounts of water when they run.

Reliability

Reliability of shallow water sources that were likely used by travelers was assessed by characterizing the temporal variability of water availability relative to the temporal variability of precipitation. Our assessment of the reliability of the different water sources is based on the hydrologic modeling discussed above. Figure 36 shows modeling results for playas, the local springs and seeps, and the regional spring at Ojo del Muerto. Monthly precipitation amounts at Elephant Butte over the last 100 years are also shown. The reliability of these water sources can be evaluated by comparing the temporal variability of water availability from a specific source to the temporal variability of precipitation. Streams, which are not shown, only run after large storm events, and therefore are likely the least reliable water source.

Based on the playa modeling discussed above, we found the playas only fill on occasion. The model indicates that the best chance travelers had to find water in the playas was during September and October. Even during this ideal period there is still only a 35% chance of finding them filled. The likelihood of finding water in the playas drops significantly

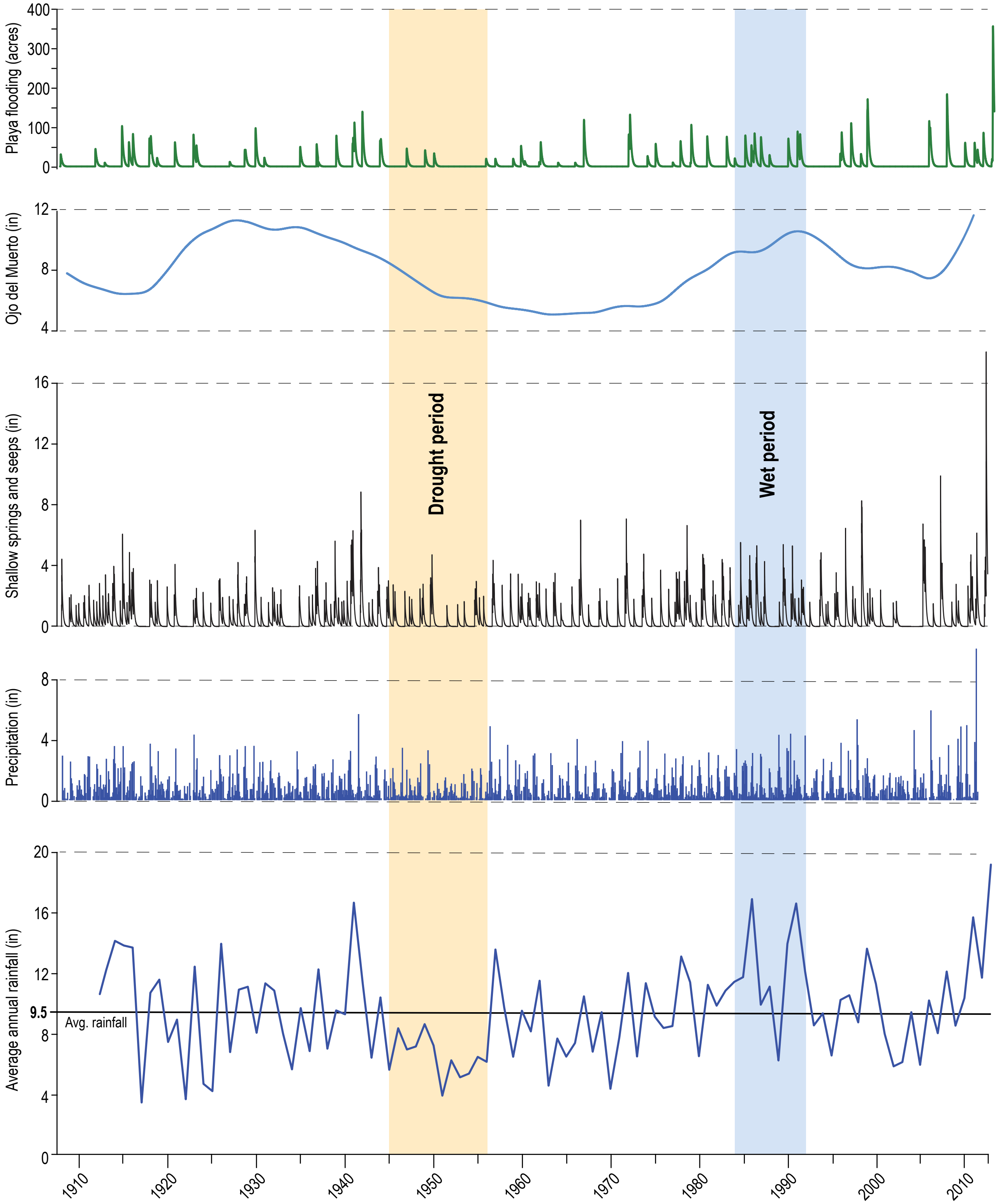


Figure 36. Modeled qualitative discharge from the Ojo del Muerto, unconfined springs and seeps, and playa flooding shows the relative reliability of each water source. Two precipitation records are included; monthly, and annual records. Regional dry (1945–1956) and wet (1984–1992) periods have been highlighted to demonstrate their impact on the water sources.

throughout the rest of the year (Figure 30). Based on our groundwater models we found that the local springs and seeps are also not very reliable, and are susceptible to short-term drought. The Ojo del Muerto spring is the most reliable source of water in the study area. The groundwater flow model indicates that the long flow path allows the spring to flow continuously even in times of drought, an assessment supported by historical accounts of spring discharge.

These model results can give insight to how these different water sources likely responds to extended wet and dry periods. Throughout New Mexico, and much of the southwest there have been two major decadal scale precipitation anomalies that are frequently mentioned in climate studies concerning the area; the 1950s drought, and the 1980s wet period.

In the Jornada del Muerto, the dry period extended from 1945 through 1956, during which the area received, on average, only 6.5 inches of rain annually, or 31 percent less than average. During this drought our model suggests the playas may have filled only three or four times, and that each filling event was likely very brief. As the playas are assumed to be the primary recharge location for the regional spring, the model suggests that during this period its discharge dipped to its lowest point. The modeling work on the shallow springs and seeps also show reduced and less frequent flow during the drought.

The wet period for this region extended from 1984 through 1992. During this period the Jornada del Muerto received on average 2.8 inches more rainfall annually, or 30% more than average. This period was punctuated by the playas filling on an almost annual basis, as observed from Landsat Imagery and supported by the modeling. Frequent playa input to the regional springs model suggests higher discharge at the Ojo del Muerto spring. The increased rain also impacted the shallow springs and the model suggests that they flowed more frequently and with greater magnitude.

V. WATER IN THE JORNADA DEL MUERTO: SUPPLY VS DEMAND

In the previous sections, information has been presented concerning the geology and hydrology of the area surrounding the Spaceport America. This research provides new information on the nature of water supplies within the Jornada del Muerto and as such has implications for historical and archaeological research in the region. Modeling efforts described above allow for an assessment of the shallow water sources that were available to users of El Camino Real. In the following section, some of the more direct implications of this research are discussed. The supply of surface water will be compared to potential demands of travelers and/or groups of travelers crossing the Jornada del Muerto during the historical period (ca. 1600–1900 A.D.).

Supply: A Ranking of Water Sources

As discussed in the previous chapter, the primary water sources within the study area are playas, the regional spring Ojo del Muerto, and a series of shallow seeps/springs. Two general attributes of these water sources are thought to be relevant to the discussion presented here; the quantity of water provided by the different water sources, and the degree to which these water resources could have been relied upon.

When full, the playas can provide many millions of gallons of water for a period of months. However, they are reliant on major rain events to fill and often dry out between major rainstorms. The regional spring at Ojo del Muerto can provide some 15,000 to 25,000 gallons of water per day, or some 6.5 million gallons per year. The long flow path between the spring and the recharge area and the long transit time mean that output is fairly steady. The shallow seeps and springs in the study area are more difficult to characterize. These sources are ephemeral and compared to the playas and the regional spring, provide little water on an annual basis.

To compare these different water sources, we have scored them based on their reliability and the quantity of water they would have provided, where a higher score represents a higher quantity or greater reliability (Table 7). The scores for reliability and quantity for each water source were added together, allowing us to rank the different water sources. It can be seen that the Ojo del Muerto spring is ranked highest, due to its reliability and substantial output. The playas are ranked second, even though the quantity of water available at the playas is the highest. This is due to fact that the playas often dry out, and are therefore less reliable that the regional spring. Shallow springs and seeps rank a distant third. They produce the least amount of water and are intermediate in terms of reliability of the group.

Table 7. Water sources were scored for reliability and quantity, where the higher the score, the the more reliable and the larger the quantity respectively. Scores for reliability and quantity were added together for each source so that water sources could be ranked. Ojo del Muerto was ranked as the best water source, and streams were ranked last as the worst water sources.

Water Source	Reliability score	Quantity score	Total score	Ranking
Ojo del Muerto	3	2	5	1
Playas	1	3	4	2
Shallow springs and seeps	2	1	3	3

Demand for Water: Travel Across the Jornada del Muerto

In historic accounts of traveling across the Jornada del Muerto, many different parties are described, ranging from individuals or small groups to large convoys of wagons, carts, people and livestock. For all of these travelers, deciding to risk a crossing was probably made based on an assessment of water resources likely to be encountered during the crossing, and how well these resources would meet the specific needs of the given travelers and their livestock.

To facilitate an analysis of potential water supply verses likely demand, a four-part classification of travelers crossing the Jornada del Muerto is presented. It is intended to highlight the most commonly described groupings noted in historical accounts. The categories presented are somewhat arbitrary and in the historical accounts the various groups can and do expand and contract during their passage as members join or leave. However, by noting how many people and livestock are associated with these basic categories, water requirements for different groupings can be estimated.

The first category of traveler to be considered is that of the solo traveler or "micro" group. This class of traveler consists generally of less than ten people and their mounts. Small group movement along El Camino includes people passing through the Jornada del Muerto to visit distant settlements, engaging in commerce, carrying mail and official dispatches, patrolling the trail to prevent hostilities or in pursuit of hostile Indian raiding parties, or returning from such visits (Scholes, 1930 a, b, c; Hand and Carmony 1996; Moorhead, 1957). Examples of this class of traveler include such noteworthy individuals as Bernardo Gruber, a German trader whose death at a watering point within the Jornada del Muerto is thought to be the genesis of the Spanish place name "el alemán" (*the German*) (Sanchez, 1993).

The next category of traveler to be considered is that of small scale commercial or military contingent. Consisting of between ten to twenty people, their mounts and carts, these small groups traversed the Jornada del Muerto while on patrol, while moving from one staging area to the next, while escorting official delegations, while delivering official supplies and reports, and while trading with settlements outside of the Jornada del Muerto. Examples of this class include the numerous supply trains and troop movements involving soldiers stationed at Fort McRae during the 1860s (Hand and Carmony, 1996), the traders who joined with the Wislizenus' caravan before crossing the Jornada del Muerto (Wislizenus, 1848), and the Postal Caravan of 1810 (Moorhead, 1958).

The third category is of moderate size, and includes convoys containing hundreds of people, dozens of carts and wagons, and hundreds of livestock. An example of this type of traveling group is the caravan that accompanied Don Juan de Oñate during his entrada into New Mexico. This caravan consisted of some 83 wagons and carts, soldiers, colonists, and a large herd of livestock (Moorhead 1957; Simmons, 1993). An additional example is the caravan described by Wislizenus (1848), consisting of some 50 wagons, 400–500 animals, and dozens of people.

Perhaps the most well-known example of this category are the official supply caravans used to support the missions at the northern terminus of El Camino Real during the 17th century (Scholes,1930 a,b,c; Moorhead 1957, 1958; Ivey, 1993). The composition of these caravans was standardized by decree, and included at least 32 wagons, a staff of some 50 individual soldiers, cooks, drivers, and other support personnel, and hundreds of livestock. In addition to the required wagons and staff, colonists and merchants would often join the caravans, swelling the size of the traveling group even further (Scholes, 1930 a,b,c; Moorhead, 1957).

It is worth noting that these official triennial caravans, as they repeatedly made the round trip journey from Mexico City to the missions in Northern New Mexico, are perhaps the primary actors responsible for establishing the route of El Camino Real. Wagon ruts left by the de Sosa expedition in 1590 in the Rio Grande valley were still visible when Oñate passed El Paso in 1598 (Moorhead, 1957). With each successive caravan, the ruts of the trail would become more indelibly etched, and the trail would become more familiar to the drovers and drivers. The distribution of campsites along the trail would become more formalized to the extent that the campsites, initially ad hoc stopping locations, became named landmarks.

The final category encompasses the largest groups to travel El Camino, namely the herds of livestock being driven to market. These herds routinely contained 2,000 to 5,000 animals (predominantly sheep) in addition to the necessary herders, drovers, and support personnel (Dunmire 2013). A single herd, driven south across the Jornada del Muerto in 1800, consisted of 18,784 sheep and 213 horses (Moorhead, 1957). Other researchers note that during the late colonial period, herds of 30,000 sheep were not unheard of (Baxter, 1993).

Demand for Water as a Function of Group Size and Composition

Conceptually, it would seem a simple matter to determine how much water would be needed by a given group. In practice, it is not—the list of conditioning factors is long and varied. These factors include, but are not limited to, age, weight, sex, and physical condition of the person or animal. Other factors include the level of physical activity and exposure to the elements, whether food is consumed, and if so what food, and the water and protein content of that food. Environmental conditions, such as air temperature and humidity, water temperature, turbidity, salinity, amount of dissolved solids in the drinking water also affect the amount of water needed by individuals each day (Grandjean, 2004; Sawka et al., 2005; Gleick, 1996; Duberstein and Johnson, 2012; Dyer, 2012; Markwick, 2007; Ward and McKague, 2007). It should be noted that some of the factors listed above increase the amount of water needed by a given individual, and some factors work to decrease the amount of water needed

In Table 8, daily water requirements are presented for people and the types of livestock taken across the Jornada del Muerto. In all cases, the water requirements are presented as a min/max range, an indication of how the various factors listed above influence water requirements. It can be seen that daily water requirements for people vary from 0.4 to 1.3 gallons. Large animals such as horses, cattle, and presumably mules require from 5 to 15 gallons of water per day. Smaller livestock such as sheep, goats and pigs require less water, on the order of 1 to 2 gallons per day. To simplify subsequent calculations, the water requirement for people will be rounded to 1 gallon /person /day, larger livestock to 5 gallons/animal/day, and small livestock to 2 gallons/animal/day.

Using these estimates, water needs for the four travel groups can be calculated (Table 9). When group composition and individual water needs are combined, total daily water needs for the different groupings range from a low of approximately 135 gallons of water per day for micro groups to 23,000 gallons of water per day for large groups

Table 8. Range of water requirement estimates for people and livestock from several different sources.

Species	Water (gallons/ per animal per day)	References
People	0.5–1.3	Gleick, 1996; Sawka et al., 2005; Grandjean,2004
Horse	2.5–15	Clemson Cooperative Extension, 2013; Duberstein and Johnson, 2012; NRC, 1989; Markwick, 2007; Ward and McKague, 2007
Cattle	5–21	Clemson Cooperative Extension, 2013; Gadbery, n.d.; Dyer, 2012; Markwick, 2007; Ward and McKague, 2007
Sheep	0.5–3	Clemson Cooperative Extension, 2013; Markwick, 2007; Ward and McKague, 2007
Goats	1–2	Clemson Cooperative Extension, 2013
Pigs	1–2	Clemson Cooperative Extension, 2013; Ward and McKague, 2007

Table 9. Approximate water needs for different group sizes traveling on El Camino Real.

Group size	**People** volume of water *(gallons)*	**Large livestock** volume of water *(gallons)*	**Small livestock** volume of water *(gallons)*	**Total daily water needs** *(gallons)*
Micro	**10** / *10*	**25** / *125*	0 / 0	135
Small	**100** / *100*	**200** / *1,000*	**200** / *400*	1,500
Medium	**250** / *250*	**300** / *1,500*	**1,000** / *2,000*	3,750
Large	**500** / *500*	**500** / *2,500*	**10,000** / *20,000*	23,000

with market herds. While these estimates should be viewed as rough approximations, the differences are suggestive. Since crossing the Jornada del Muerto could take up to a week, water within the Jornada del Muerto may have been of major importance to those crossing, particularly for larger groups with sizeable livestock herds.

Small groups, with modest water needs, would presumably have been satisfied with minor water sources such as the seeps in the Aleman/Yost Draw area. Larger groups, with more substantial water needs, would have targeted more abundant water sources such as the playas and the regional spring at Ojo del Muerto. While larger groups may not have been satisfied with the water resources sufficient for smaller groups, the smaller groups would certainly have been satisfied with water resources sufficient to provision the larger groups. This suggests that smaller travel groups had more leeway when preparing to cross the Jornada del Muerto, and could make the crossing under a wider set of conditions. Conversely, larger groups would have faced different prospects. With larger membership and often driving large herds, these groups would be much more reliant on the water sources within the Jornada del Muerto to enable successful crossing. They would have likely ventured out onto the Jornada del Muerto only when ample water supplies were either certain or imminent. Failure to account for water supplies could have led to tragedy, particularly for large groups shepherding large herds across the Jornada del Muerto.

Location of Trailside Campsites in Relation to Water Sources

A series of trailside campsites, or *parajes*, have been identified within the Jornada del Muerto crossing (Marshall and Walt, 1984; National Park Service, 2004). Between the riverside *parajes* of San Diego in the south and Fra Cristobal in the north, six different campsites have been identified. The precise location of four of these *parajes*, Las Tusas, Cruz de Anaya, and Las Peñuelas, could not be ascertained, and are probably located north of the study area. The location of the three remaining *parajes*, Laguna del Muerto, La Cruz de Alemán, and Perrillo, were clear from the descriptions provided by Marshall and Walt (1984), and are found in the study area (Figure 37).

It is worth noting that all six of the *parajes* are associated with water, springs, seeps, or playas. When the locations of three known campsites are mapped with those of water sources discussed in this above, the correspondence is illuminating (Figure 37). The *paraje* at Laguna del Muerto is associated with a series of playas, while the Aleman campsite is associated with nearby seeps. The Perrillo campsite has no labeled water source nearby. This location is just outside of the study area, and was not explored in detail. However, air photos showing clustered vegetation and historic records indicate that there is a seep in the nearby arroyo. Although the Ojo del Muerto spring is mentioned by Marshall and Walt (1984), and was an important water source, no campsite is recorded for this location. However, the Ojo del Muerto is only six miles from the Laguna del Muerto *paraje*.

Strategies for Traveling El Camino Real

Historic accounts of travelers crossing the Jornada del Muerto indicate that a number of strategies were employed to increase the likelihood of success. These strategies included carrying water for the crossing, nighttime crossings, fall and winter crossings, forced marches, "leapfrogging," and scouting.

Carrying water is an obvious method of providing water during a crossing, but the volume of water that can be reasonably carried is rather limited. Weighing over 8 pounds per gallon, water is relatively heavy. Travelers could be expected to bring enough water for themselves, either in individual canteens or in larger casks (Wilson et al., 1989; Moorhead, 1958; Carmony, 1996), but would have been hard pressed to transport enough water to supply any livestock in the convoy. For large herds, transporting sufficient water would not have been feasible, considering the large amount of water needed per animal (Table 8).

Another means of minimizing water needs while crossing the Jornada del Muerto is that of planning to cross during the evening (Drumm, 1982; Moorhead, 1958; Wislizenus, 1848). Nighttime crossings are

Figure 37. Locations of known *parajes* and water sources near El Camino Real in the Jornada del Muerto. The numbers indicate the ranking of the water sources (Table 7).

mentioned frequently in the historical record, with trips generally starting from either the northern or southern end of the Jornada del Muerto late in the afternoon and continuing through till the next morning. Rest stops are taken around noon, during the hottest part of the day. Traveling at night and resting at noon will minimize the amount of heat stress for travelers and their livestock, and reduce the amount of water that must be supplied to replace that lost during the exertion.

In the same vein, travel across the Jornada del Muerto was often timed to occur during fall or winter, the coolest months of the year (Drumm, 1982). Travel during this period has two distinct advantages. First, temperatures are low, minimizing any potential heat stress during the crossing. This, of course, translates into a reduction in the amount of water that would be needed by either the travelers or their livestock. Second, planning to cross the Jornada del Muerto in the fall or winter is to cross after the summer monsoon season. Rainfall from these storms could well replenish water resources within the Jornada del Muerto, particularly the central playas, greatly easing the stress of crossing.

Another method to minimize the amount of time spent out in the Jornada del Muerto during a crossing is that of the forced march (Moorhead, 1957; Wislizenus, 1848). In a forced march, travelers proceed night and day with the aim of covering the most amount of ground in the least amount of time. For long stretches like the Jornada del Muerto, a forced march can shave the amount of time exposed to the elements on the trail by a day or more. Since each end of the trail is located along the Rio Grande, shaving time off the transit shortens the time between more or less secure water along the river.

"Leapfrogging" was and additional technique that was used by travelers along the trail. In this technique, larger groups would be broken up into smaller groups that would then proceed across the Jornada del Muerto separately. As each group progressed up the trail, some of the travelers would care for the animals or take them to water, while others would travel back to the previous camp site, and collect gear and/or stock which had been left behind, and bring them to the new camp (Wislizenus , 1848). Depending on group size and composition, this process may have been repeated.

It is hard to imagine the large market herds passing through the Jornada del Muerto in the early 19th century without some form of leapfrogging being done to move the massive herds across the expanse of the Jornada del Muerto (Baxter, 1993). By breaking the larger herds into smaller clusters, it would have been easier to maintain order at the watering holes, and prevent the water holes from being damaged and compromised. While this concern is not as important for the large playa watering locations, it is certainly germane for the seeps and spring locations.

The final means by which travelers were able to minimize risks in crossing the Jornada del Muerto was that of scouting. From the earliest days, native scouts were assigned to all of the Mission Caravans, and were probably instrumental in assessing water availability and overall conditions up the trail (Ivey, 1993; Scholes, 1930a, b, c). For larger groups, it appears that specialized scouts were employed, while for smaller groups, scouting may have been an occasional activity, depending on circumstances and the state of the trail ahead. Depending on the amount of traffic on the trail, it may also have been possible to gain important information concerning the state of water supplies along the trail and across the Jornada del Muerto from other travelers. It was probably common practice to discuss the details of trail conditions whenever travelers were encountered coming up the trail from the opposite direction (Drumm, 1982).

Discussion

So, what can we reasonably say about supply and demand? First and foremost, there actually is a supply worth considering. At the outset of this project, we expected that surface and near-surface water resources would prove to be marginal and transitory, an expectation conditioned to a large degree by the formidable reputation of the Jornada del Muerto. To our surprise, we found a number of water sources capable of supplying significant amounts of water. Playas in the central portion of the Jornada del Muerto appear to fill every third or fourth year, and potentially represent millions of gallons of water. The Ojo del Muerto spring reliably delivers some 15,000 gallons of water per day. Clearly, supplies of this magnitude did not go unnoticed.

With a supply in hand, our thoughts turned to potential demand. From our research it is clear that supplies within the study area fluctuate both in time and space, and that multiple strategies were needed to ensure that demand paralleled supply. Historical accounts by travelers crossing the Jornada del Muerto provide insight into the strategies and tactics they employed. Depending on group size and composition, these strategies included carrying water, crossing at night, avoiding the heat of summer, forced marches, and scouting. Since water was a limiting resource, the challenge of crossing the Jornada del Muerto was essentially one of tailoring demand to supply.

Our appreciation of the (at times) ample water supply within the Jornada del Muerto also leads us to question the appropriateness of the dire reputation held by the Jornada del Muerto. It has long been considered imposing; a place of dread and danger. Many accounts of travelers crossing the Jornada del Muerto seem to emphasize this notion of dread, often rendering the Spanish "*Jornada del Muerto*" as "Journey of the Dead" or "Journey of the Dead Man.

> *… an intrepid traveller (sic)undertook to traverse this desolate tract of land in one day, but having perished in the attempt, it has ever after borne the name of La Jornada del Muerto, 'the Dead Man's Journey,' or, more strictly, 'the Day's Journey of the Dead Man'. One thing appears very certain, that this dangerous pass has cost the life of many travellers (sic) in days of yore …*
>
> *(Gregg, 1844).*

> *Jornada del Muerto (the day's journey of the dead man) was along a detour of the highway for a distance of about eighty miles, made necessary by the obstruction of a mountain at the river's edge. In dry seasons there was no water supply along this journey, and a Mexican who tried to make it in a day, without supplies, perished on the road. Hence the name. It was a dangerous pass and cost the lives of many travelers*
>
> *(Drumm, 1982).*

> *Jornada del Muerto means, literally, the day's journey of the dead man, and refers to an old tradition that the first traveler who attempted to cross it in a day perished in it. The word Jornada (journey preformed in one day) is especially applied in Mexico to wide tracts of country without water, which must for this reason be traversed in one day*
>
> *(Wislizenus, 1848).*

> *Three halting points on the gravedecked trail of the "dead man's journey" gave the only relief of dreariness—the "Alamand", because some Germans tried to dig a well and were surprised and killed by Indians; the "Water holes", because sometimes a little water collected there for a short time after a heavy rain, and lastly, on the lower third of the trail, below where it branched off to lonely Fort McRae, near the Ojo del Muerto, the "Spring of Death", was the famous "Point of Rocks", the chosen lair for the Indians when they tried to jump a wagon train or other travelers on the Jornada. Graves along the roadside were plentiful near this place.*
>
> *(Parker, 1913).*

The results of this study suggest that the formidable reputation of the Jornada del Muerto may be somewhat overstated, or more precisely, that the rendering of the Spanish "Jornada del Muerto" may be in error. From our research, we have demonstrated that a reliable water supply lies near the midpoint of the Jornada del Muerto crossing, and that a series of playas and seeps offer additional water sources. The limited number of water holes within the Jornada del Muerto may have been a hardship, and the crossing arduous, but it appears to have been a hardship routinely surmounted. With this in mind, another interpretation presents itself.

> *… on May 25 (1598), [Oñate's party] reached a creek at two leagues which they called the "Arroyo de los Muertos" for reasons unrecorded but which may conceivably have be the origin of the name Jornada del Muerto.*
>
> *(Moorhead, 1958, describing Oñate's initial crossing of the Jornada del Muerto).*

Considering that the major spring is named the "*Ojo del Muerto,*" and the nearby playas are known as the "*Lagunas del Muerto,*" perhaps the name Jornada del Muerto refers to a journey to the *Del Muerto* spring area rather than a more sensational and sinister "journey of the dead".

VI. FUTURE WORK

The research presented in this report and attached appendices expand the knowledge of the geology, hydrogeology, and paleohydrology of the Jornada del Muerto Basin in central New Mexico. Future work can extend this knowledge in four specific areas. First, the hydrological portion of the study can be expanded to encompass the remaining portions of El Camino Real passing through the Jornada del Muerto: the northern portion from Engle to *paraje* Fra Cristobal and the southern portion, from *paraje* Perillo to *paraje* San Diego (Figure 34). This work should include documenting surface and near surface water resources such as springs, playas, seeps, and wells.

In conjunction with this work, the landform map can be expanded to cover the remaining portions of El Camino Real route, as well. This work would be simplified by the availability of Natural Resourcess Conservation Service (NRCS) 1:24,000 scale soil maps covering the northern portion of the Jornada del Muerto. The soil units can be used as the basis of the extended landform surfaces.

The third focus would be research into paleoclimatic patterns within the Jornada del Muerto Basin, with the aim of quantifying precipitation totals during the past 300 years. Research presented in this report indicates that rainfall events of a certain magnitude are required to fill the playas. Identifying when such rainfall events occurred in the past would be useful in assessing water availability during any given year. Potential data sources would include tree rings and seasonal deposits found in playa bed deposits.

Finally, early eye-witness accounts of crossing the Jornada del Muerto would be an invaluable resource for understanding the trials and hardships endured by these early travellers. State sponsored triennial caravans frequently made the trek from Mexico City to Santa Fe, and official accounts of these journeys should be available in the archives in Santa Fe or Mexico City. Cataloging the conditions encountered during the numerous crossings would go a long way in answering questions concerning group sizes and composition, timing of crossings, tactics employed, and water availability.

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