NEW MEXICO BUREAU OF GEOLOGY AND MINERAL RESOURCES

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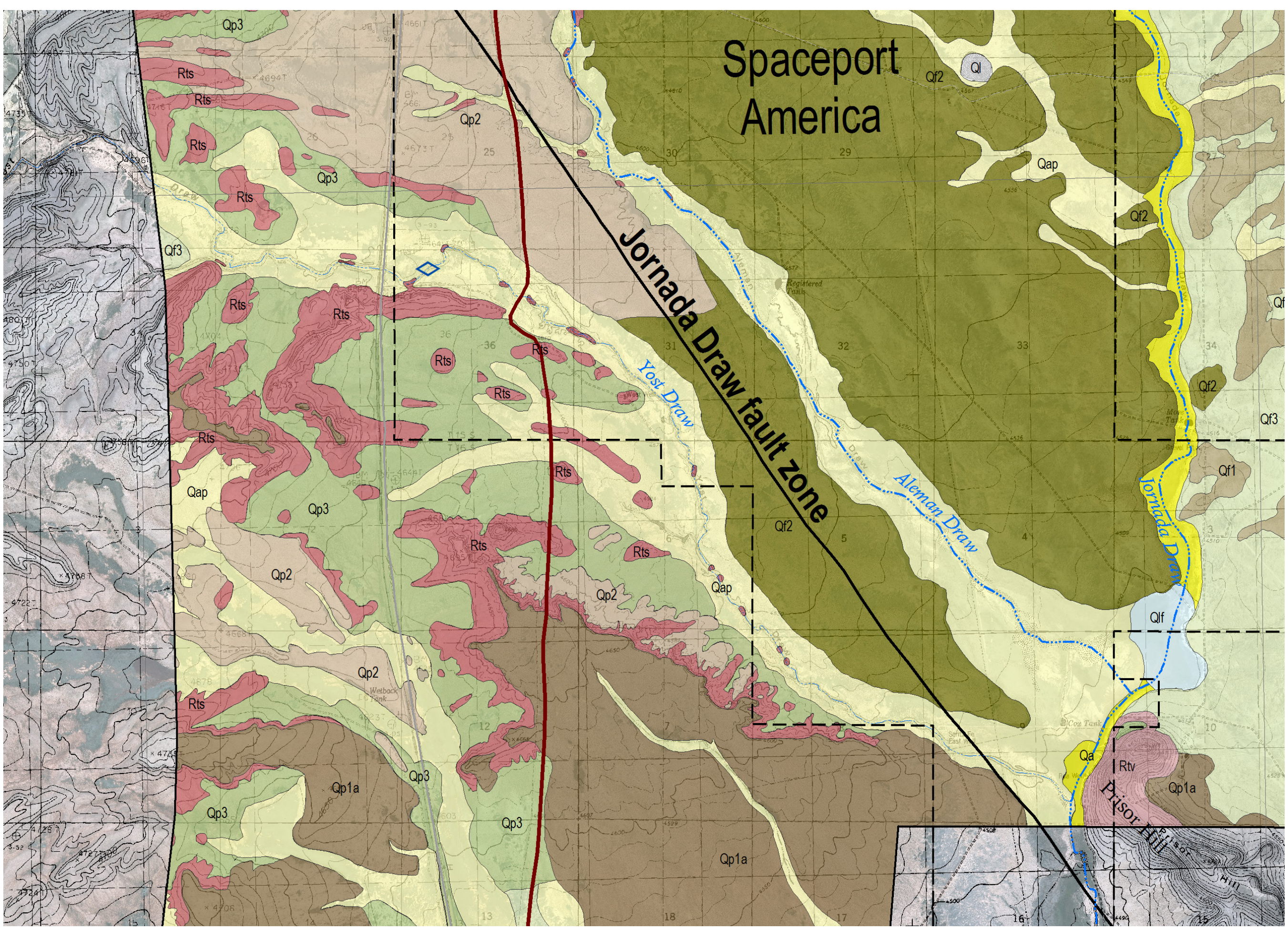
Trevor Kludt, Dave Love, Bruce Allen, and Talon Newton

Open-file Report 575
October 2015



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AQUIFER MAPPING PROGRAM

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PROJECT FUNDING

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CONTENTS

I. INTRODUCTION

El Camino Real de Tierra Adentro (El Camino Real) is a 1600 mile long trail linking Mexico City and San Juan Pueblo/Ohkay Owingeh, New Mexico, which was in use from 1598 to the 1880s (Figure 1). The Jornada Del Muerto, located in southern New Mexico, was reportedly one of the most feared sections along El Camino Real due, primarily, to the scarcity of water. It is thought that water availability largely influenced the travel route and locations of parajes (campsites) in the Jornada Del Muerto.

This report describes the second part of a two-part paleohydrologic study of the central Jornada Del Muerto conducted by the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) for the New Mexico Spaceport Authority (NMSA). This portion of the study focuses on the classification and mapping of landforms in proximity to the route of El Camino Real that potentially have implications for paleohydrologic conditions in the past. The landforms and relative stability of their surfaces also have implications regarding the ultimate location of the main route as it crosses the Jornada del Muerto. In addition to presenting a map of landforms within the study area, this document details the methods used to delineate these landforms as well as description and photos of the various landform components.

Project Background

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. In February of 2012, ten segments of El Camino Real 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 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

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

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 landform mapping portion of the project is located 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. In general, the landform mapping corridor is

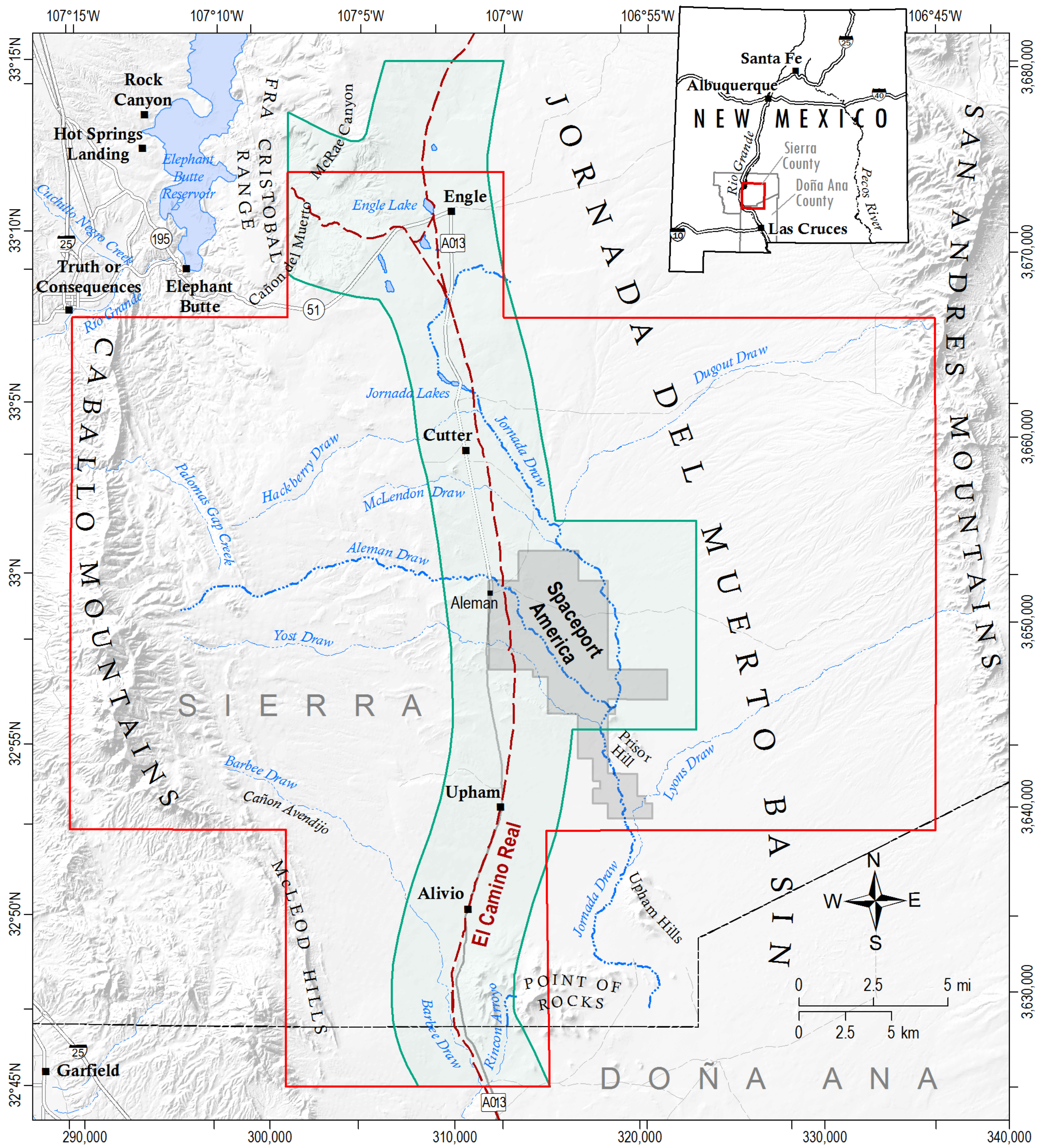


Figure 2. Study area boundaries for landform map.

4 miles wide and centers on the route of El Camino Real. In the northern portion of the study area, the corridor bulges to the west where side trails lead to the regional spring at Ojo del Muerto, in McRae Canyon. In the central portion of the study area, the corridor bulges to 8 miles wide to encompass the Spaceport America campus.

Landforms

Landforms develop through time on a landscape as a result of natural processes. The natural processes include erosion, deposition, deformation, igneous intrusions, and eruptions. In El Camino Real corridor and Spaceport America area, the landforms result from all of these processes. The location of El Camino Real trail and the hydrogeology of the region are strongly influenced by the landforms, underlying geology, and the length of time in which the features developed.

In southern New Mexico, the pioneering work of the Desert Project has detailed many of the landforms and landform components, their geologic contexts, soils, and temporal chronologies (Gile et al., 1981; Gile et al., 1996a, b; Gile et al., 2007). Researchers of the Desert Project have detailed the development of oldest to youngest geomorphic surfaces on both fluvial (river deposits) and piedmont-bolson (alluvial-slope-basin-floor deposits) environments and the development of soils on these surfaces in the region just south of the present study area. The concepts, descriptive vocabulary, and chronology developed by the Desert Project have been adopted and applied to surrounding regions, including the Jornada del Muerto (e.g. Seager and Mack, 2003 and references therein; Hawley and Kennedy, 2004, and references therein).

In this report, we use descriptive terms codified by Peterson (1981) as they apply to local conditions and features, with some modifications. Peterson's descriptions and illustrations, an outgrowth of the Desert Project, pertain to erosional and depositional landforms in the Basin and Range Province and their application to soils. Peterson does not cover other types of landforms such as volcanic edifices or accumulations of eolian sand.

Large-area geomorphic features of El Camino Real corridor and Spaceport America campus include (1) eroded bedrock cuestas, mesas, badlands, and canyons, (2) piedmont slopes and fan skirts, (3) volcanic edifices, (4) axial and tributary stream valleys and floodplain playas, and (5) playas and eolian lunettes. The mapped corridor is dominated by piedmont land surfaces, which cover more than 60 percent of the study area (Figure 2). The axial Jornada Draw and its major tributaries account for about 19 percent of the map corridor, and playas and their eolian lunettes account for 2 percent. Exposed bedrock features cover about 15 percent of the corridor area. Volcanic edifices account for about 2 percent.

Piedmont slopes, one of the dominant landforms within the study area, consist of conjoined alluvial fans debouching from mountain fronts and descending toward basin floors or axial drainages (Figures 3 and 4). Closest to eroded mountain fronts, proximal fans tend to be steep and have coarse and angular clasts such as boulders and cobbles. Individual alluvial fans are convex upward in profile. Medial and distal parts of fans and piedmonts tend to decrease in slope, become nearly planar in profile, and have smaller and more well-rounded cobbles

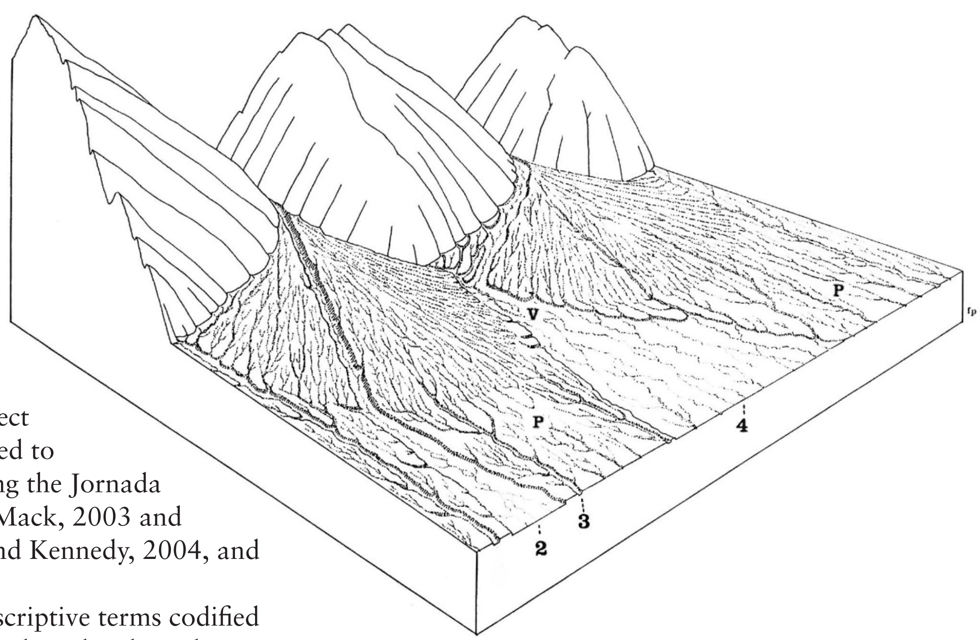


Figure 3. Well developed alluvial fans. In this illustration, the fan apex is at the mouth of a constricted valley, and three types of drainage systems are shown: (v and 4) inter-fan valley drainageway with on-fan tributaries, (2) fan-head trenches that broaden downslope, and (3) on-fan drainageways that have numerous on-fan tributaries (medial and distal fan channels, P). (Peterson, 1981).

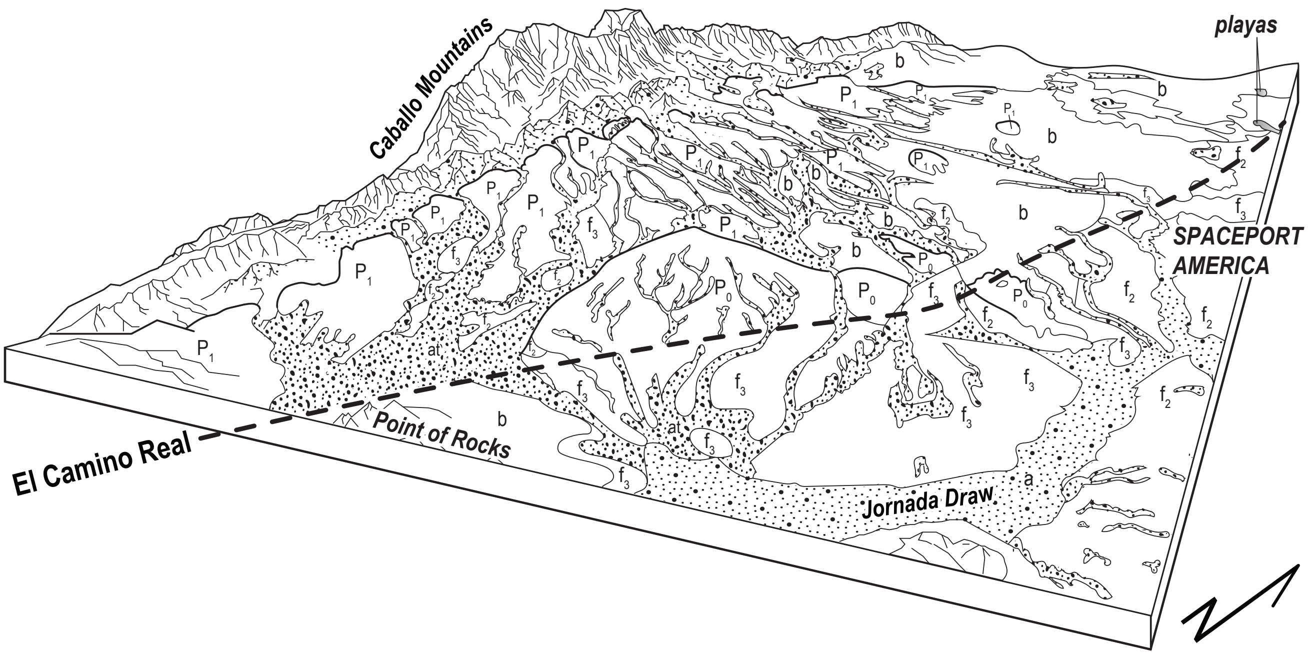


Figure 4. Path of El Camino Real across landforms of the Jornada del Muerto near Spaceport America. The trail crosses eroded, nearly planar bedrock (b), the lower margins of old piedmonts (P_0), old fan skirts (f_2, f_3), and minimizes the distance crossing problem-causing active alluvium (a—Jornada Draw; at—tributary alluvium). The eroded western edges of old piedmonts (P_0) are separated from their alluvial sources on the east side of the Caballo Mountains and are buried by inset fan skirts on their eastern margins. Younger piedmonts (P_1) are inset below the older piedmonts and are closer to their eroded mountain-flank sources.

and pebbles with more fine-grained (sand, silt, clay) matrix between. Broad distal piedmont alluvium is called a "fan skirt" (Figure 4). Scarps of the Jornada Draw fault zone and related Quaternary faults influence distal piedmont slopes, fan skirts, and orientations of playas along the route (Seager and Mack, 1995, 2003).

Alluvial aprons are short, steep combined alluvial fans that surround isolated uplands (Figure 5). Because the route of El Camino Real was (presumably) chosen to move heavy cargo and many animals over low-relief, non-boggy ground between known watering places, it commonly crosses medial-to-distal piedmont slopes and fan skirts (Figure 4).

Within the study area, piedmont features cover a wide swath of the landscape, forming a complex series of surfaces. To help clarify some of the apparent relationship between the various piedmont surfaces, the piedmont landforms are presented in terms of both slope location (e.g. medial vs. distal) and relative age for land surfaces above or below adjacent deposits and modern drainages (e.g. old vs. intermediate vs. young). In the resulting map, piedmont unit designations are "binomial" and are intended to indicate both relative age and landscape position.

Finally, this project has benefited from the detailed geologic work of many dedicated researchers, including Seager and Mack (2003), Mack and Seager (1995), Seager (1995a, b, c), Seager (2002), Seager (2005), Lozinsky (1986), Lozinsky and Hawley (1986), Lozinsky (1987), Lozinsky et al. (1995), Kelley and Silver (1952) and the early excellent work by Darton (1922). Many details of geologic history of the area are published in Lucas et al. (2012). Sierra County soil descriptions are given in Neher (1984), whereas more detailed aspects of regional soil descriptions and processes of formation are addressed in the many publications of the Desert Project (Gile et al., 1981, through Gile et al., 2007, and many references therein). Detailed descriptions of soils and stratigraphy within the Spaceport America campus are given in Hall and Goble (2012).

Methods

The principle framework used to define and distinguish the various landform units within the study area is found in "Landforms of the Basin and Range Province" (Peterson, 1981). Although this source provided definitions of the landform components and their relationships, a number of landform units are not found in the referenced bulletin, specifically

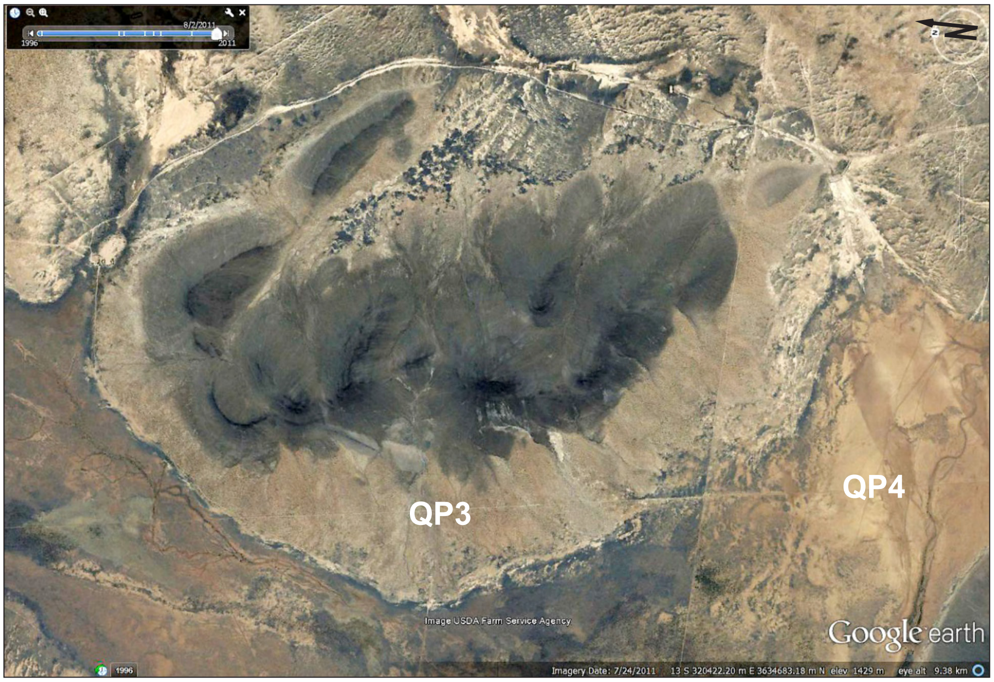


Figure 5. Alluvial apron. Upham Hills, the dark igneous rocks and sediments in the center of the image, surrounded by an alluvial apron. Proximal parts of alluvial fans form triangular features in the margins of the bedrock, but lower parts of fans merge together into a continuous slope (Qp3). Alluvium of Jornada Draw and Barbee Draw (Qp4) forms reddish-brown band across lower right part of image. North is to the left.

volcanic edifices and accumulations of eolian sand. The authors define and describe the volcanic units below. Regarding eolian sand deposits, we have included (lumped) them in with their underlying piedmont surfaces rather than map them individually. It should be noted, however, that east of the axial Jornada Draw drainage and northern playas, large areas are covered with sand sheets, distended parabolic arms of dunes, coppice dunes, and "patterned" vegetation complexes of eolian and alluvial deposits.

Landform units for the study area were defined based on several lines of evidence, including 1:500,000, 1:125,000 and 1:24,000 geological maps, and aerial photographs. The authors undertook field visits to validate a number of the mapped contacts, but did not field check all portions of the study corridor. The most detailed data available for the study area are found on the 1:24,000 series of geologic maps released by the New Mexico Bureau of Geology and Mineral Resources. These maps, including Engle (Mack and Seager, 1995), Cutter (Seager, 1995c), Upham (Seager, 1995b), Prisor Hill (Seager, 2005), Alivio (Seager, 1995a), and Upham Hills (Seager, 2002), cover just under 90% of the study area. Electronic versions of these maps, consisting of polygons representing the various geologic mapping units, were merged into a single coverage.

Portions of two quadrangles, Polecat Tank and Shannon Canyon NW, covering some 10.5% of the study area, had not previously been visited and mapped by geologists. Landform mapping units for this portion of the study area were generated by the authors. By reference to the two 1:125,000 geologic maps (Seager et al., 1982; Seager et al., 1987), the 1:500,000 state geologic map (New Mexico Bureau of Geology, 2003), the 1:24,000 geologic maps listed above, plus available air photos, the mapping units drawn in neighboring 1:24,000 series maps were extended into the unmapped portion of the study area (Figure 6). These units were extended using visual cues from the air photos and personal observations made during multiple field visits. Where necessary, additional polygons were created based upon the continuation of the various mapping units across the unmapped portion of the study area. These additional mapping units were digitized, and added to the geologic coverage discussed above.

Once these electronic files had been merged, an outline representing the study area was used to clip the merged geologic coverage, removing extraneous mapping data outside of the study area. Before proceeding, it was necessary to reconcile differences in the mapping unit polygons along the edges of the different maps where they abutted the mapping

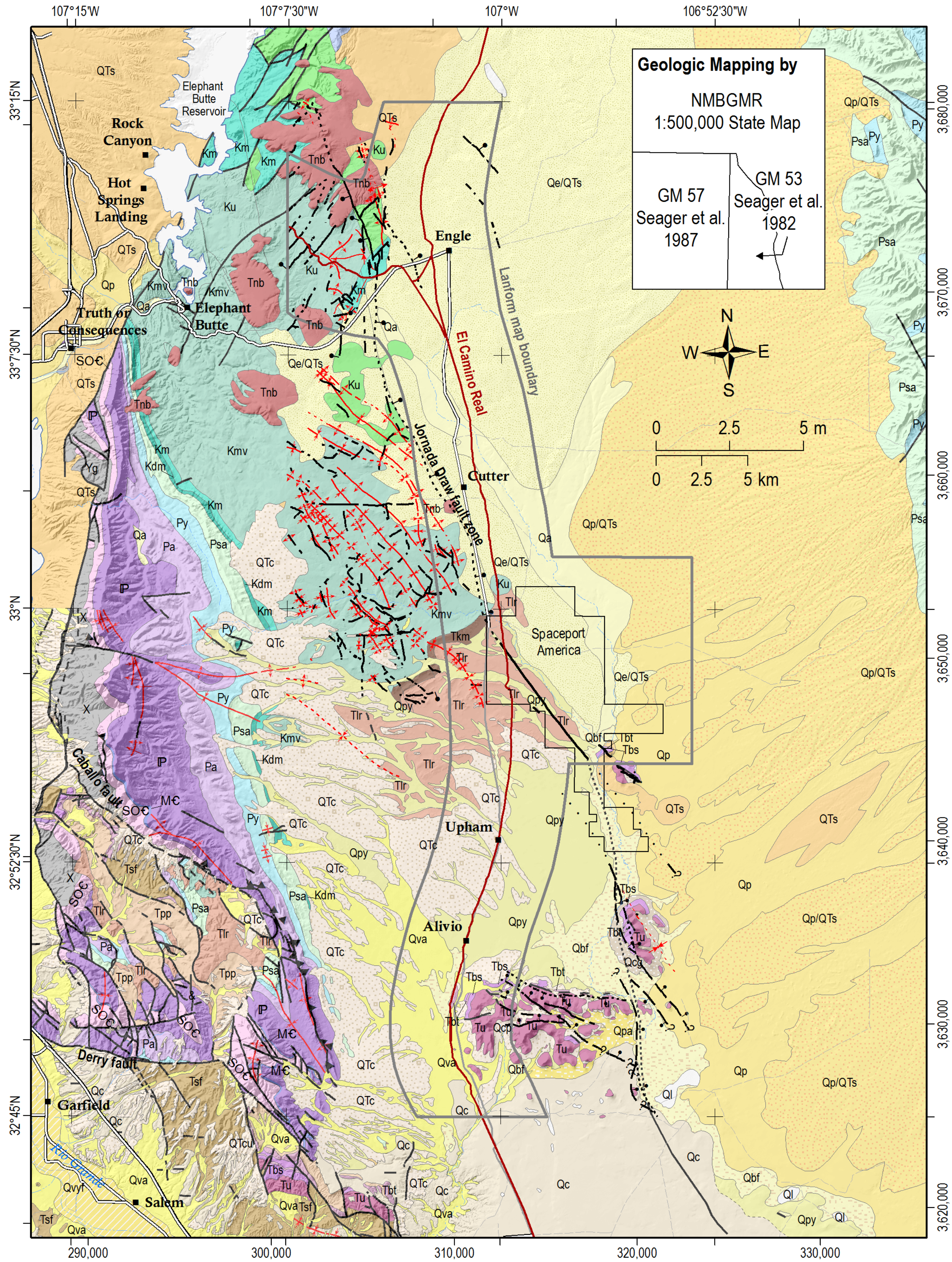


Figure 6. Compiled generalized geologic map of the central Jornada del Muerto Basin.

Geologic Units

Qa	*Young alluvium, and playa deposits (Holocene-upper Pleistocene)*
Qe	*Wind-blown sand and gypsum dunes*
Qva	*Undifferentiated deposits, Mimbres and Rio Grande Valley (Quaternary)*
Qp	*Piedmont deposits and landslides (Holocene and upper Pleistocene)*
QTs	*Sedimentary rocks and eolian deposits (lower Pleistocene and Pleiocene)*
Qvyf	*Rio Grande floodplain deposits (Holocene and latest Pleistocene)*
Qpa	*Undifferentiated closed basin deposits (Holocene-latest Pleistocene)*
Qbf	*Basin-floor sediments (Holocene-late Pleistocene)*
Ql	*Small playa deposits*
Tnb	*Basaltic rocks (Pliocene-Miocene)*
Qc	*Camo Rice Formation, sediments of La Mesa surface and fuvial faces (early-middle Pleistocene)*
Qcg	*Camp Rice Formation, Gypsum*
QTc	*Camp Rice Formation, undivided (middle-early Pleistocene)*
Tsf	*Santa Fe Group, undivided (upper Tertiary-Miocene)*
Tu	*Uvas Basaltic Andesite (lower Miocene-upper Oligecene)*
Tbt	*Bell Top Formation, undivided (Oligocene)*
Tbs	*Bell Top Formation, sedimentary rocks and tuffs (Oligocene)*
Tpp	*Palm Park Formation (middle Eocene)*
Tlr	*Love Ranch Formation (Paleocene-Eocene)*
Tkm	*McRae Formation (Paleocene-Eocene)*
Ku	*Cretaceous sedimentary rocks*
Kmv	*Mesa Verde Group (upper Cretaceous)*
Km	*Mancos Shale (middle Cretaceous) marine shales, mudstones, and limestones*
Kd	*Dakota Sandstone (lower Cretaceous) marine sandstones and mudstones*
Psa	*San Andres Formation (middle Permian)*
Py	*Yeso Formation (lower Permian)*
Pa	*Abo and Hueco Formations (lower Permian)*
IP	*Sedimentary rocks (Pennsylvanian)*
M€	*Sedimentary rocks (Mississippian-Devonian undivided)*
SO€	*Sedimentary rocks (Silurian-Cambrian)*
X	*Granitic rocks (Mesoproterozoic)*

Map Symbols

Contact	Anticline
Fault, exposed	Anticline, obscured
Fault, intermittent-obscured	Anticline, concealed
Fault, inferred	Syncline
Fault, concealed	Syncline, obscured
Thrust fault	Syncline, concealed
Thrust fault, inferred	Monocline

unit polygons on other maps. Where these polygons aligned, the boundary between the different polygons was dissolved. Where these polygons did not align properly, air photos were consulted and the outline of the polygons altered and these altered polygons were subsequently merged. In those instances where the classification of the geologic map units differed, the merged polygon was classified based on the dominant or largest of the constituent mapping unit polygons, or the more generalized designation.

The next step in the process was to reclassify the mapping units, converting the geologic unit classifications into landform units (Figure 7, Table 1, and Plate 1). In most instances, this process was fairly straight forward. Two of the geologic mapping classes, Paleogene (formerly Tertiary) and Cretaceous units, represent some 6% and 9% of the study area respectively. Multiple sub-classifications are found within each of these classes to delineate different stratigraphic members and/or adjacent but distinct volcanic units. In general, these units consist of bedrock outcrops and eroded bedrock surfaces found along the northern and eastern margins of the Caballo Mountains which extend into the study area along the western margin. The myriad of polygons representing these mapping units have been merged and reclassified into five landform units; volcanic edifice (Tb), basalt dike (Ti), paleogene volcanic bedrock (Rtv) sedimentary bedrock (Rts), and Cretaceous bedrock (Rks). The remainder of the study area, some 85%, is covered by Quaternary units which, due to the large extent of these mapping units and the complex interdigitation, required more analysis and inspection to reclassify into landform units.

The process of assigning the Quaternary geologic mapping units to a landform class was iterative, with adjacent geologic units first being joined with like units. Once the geologic mapping polygons were consolidated, larger aggregate units were created by merging related or similar geologic units. In some instances, it was necessary to break larger surfaces into smaller component surfaces. This occurred primarily on the large piedmont fan surfaces in the central and southern portions of the study area. These surfaces were often broken into an upslope 'Piedmont' component and a distal 'Fan Skirt' component. The delineation of the proximal and distal portions of a given piedmont fan was based on the judgement of the authors.

To illustrate this process, a few examples are provided. Geologic map unit Qpo [Older Piedmont-slope alluvium] (e.g. Seager, 1995b) represents 18% of the study area. All Qpo units represent older

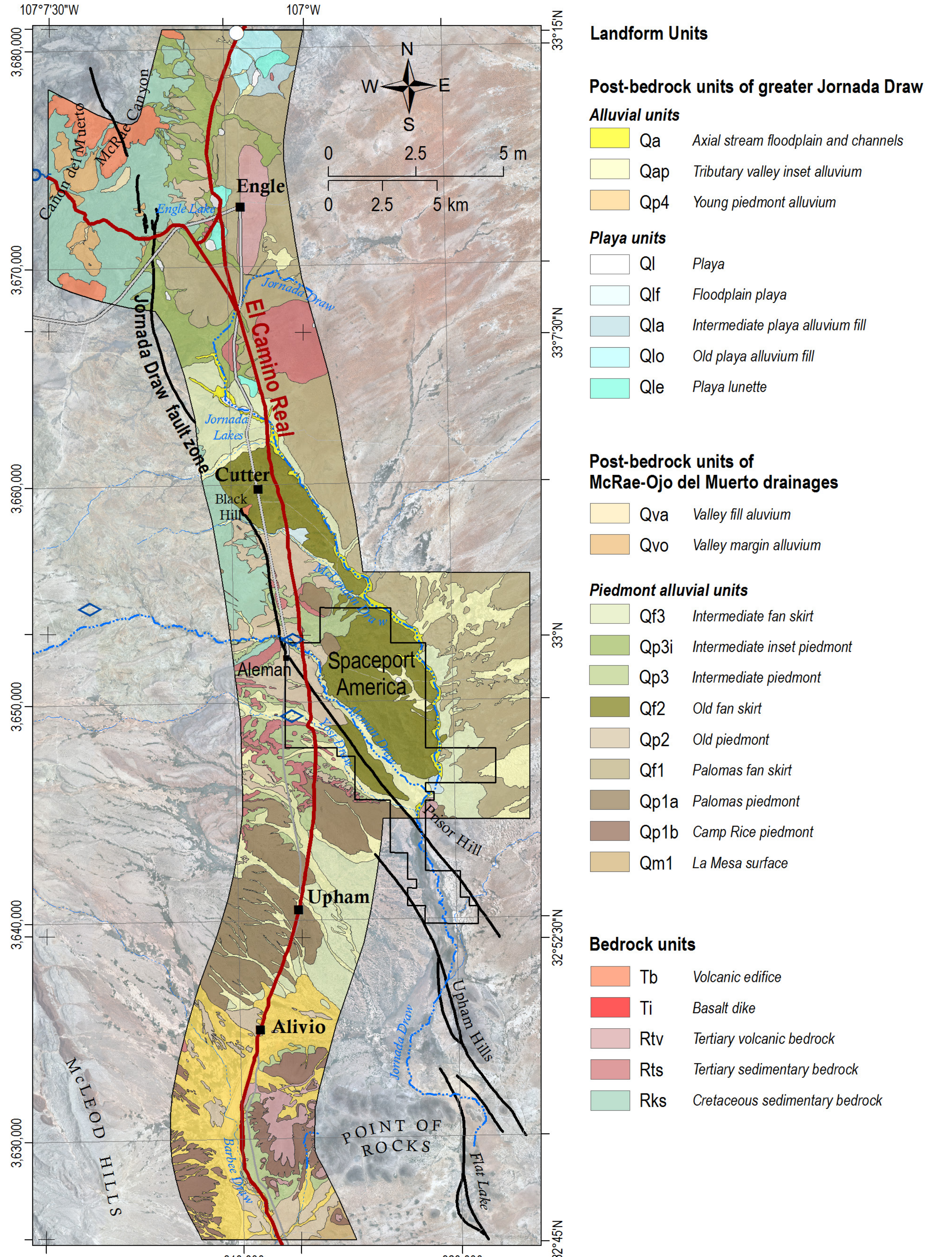


Figure 7. Landforms of the central Jornada del Muerto.

piedmont alluvium, but those units found at the distal end of alluvial fans were assigned to Qf2 [Old Fan Skirt] landform (48% of all Qpo units), while those further upslope were assigned to Qp2 [Older Piedmont] landform (29% of all Qpo units). Some Qpo units, intermixed with younger and/or indeterminate piedmont alluvium units (Qpy and/or Qpa), were assigned to Qf3 [Intermediate Fan Skirt] landform (15%). In another example, geologic map unit Qpg, [Palomas Formation, piedmont-slope deposits] were coded as Qp1a [Palomas Piedmont] landform (66% of all Qpg units) at upper piedmont locations, while 30% were coded as Qf1 [Palomas Fan Skirt] landform at the distal ends of the piedmont surfaces.

In all, a total of 24 landforms were defined for the study area, including 3 broad bedrock features, 2 volcanic features, 5 playa and lunette features, 5 alluvial features, 6 piedmont features, and 3 fan skirt surfaces (Table 1).

Correlation of Landform Units
(young above old)

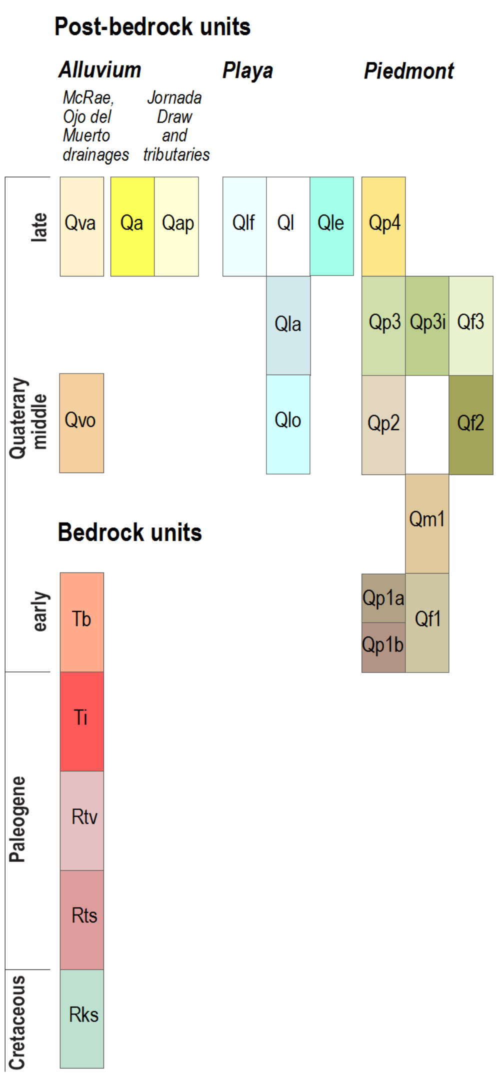


Table 1. Landform designations.

Landform	Designation	Unit label	Percentage of study area	Total
Young Alluvium	Tributary valley inset alluvium	**Qap**	8.70	
	Young piedmont alluvium	**Qp4**	7.96	16.66
Playas and Lunettes	Playa	**Ql**	0.26	
	Playa lunette	**Qle**	0.54	
	Old playa alluvium fill	**Qlo**	0.73	
	Intermediate playa alluvium fill	**Q1a**	0.38	1.91
Axial Stream Floodplain	Floodplain playa	**Qlf**	0.19	
	Axial stream floodplain	**Qa**	1.10	1.29
Valley Alluvium	Valley fill alluvium	**Qva**	0.13	
	Valley margin alluvium	**Qvo**	0.17	0.30
Intermediate-Level Piedmont	Intermediate inset piedmont	**Qp3i**	4.73	
	Intermediate fan skirt	**Qf3**	7.60	
	Intermediate piedmont	**Qp3**	4.24	
	Old fan skirt	**Qf2**	8.90	
	Old piedmont	**Qp2**	6.71	32.18
La Mesa, Jornada, or Cuchillo surfaces	Palomas fan skirt	**Qf1**	18.81	
	Palomas piedmont	**Qp1a**	7.33	
	Camp Rice piedmont	**Qp1b**	2.96	
	La Mesa surface on axial Camp Rice	**Qm1**	0.29	29.39
Bedrock/ Volcanic	Cretaceous bedrock	**Rks**	9.05	
	Paleogene sedimentary bedrock	**Rts**	3.69	
	Paleogene volcanic bedrock	**Rtv**	2.55	
	Basalt dike	**Ti**	0.01	
	Volcanic edifice	**Tb**	1.98	17.28

II. LANDSCAPE MAP UNITS: DESCRIPTION AND DISCUSSION OF FEATURES

Young Piedmont Alluvium and Tributary Valley Inset Alluvium deposits (Qp4, Qap)

The most recent piedmont deposits, mapped as young piedmont alluvium (Qp4), are found at the southern end of the study area near Point of Rocks. They are present along drainages such as Barbee Draw, flowing down piedmont slopes and fan skirts and across young alluvial fans. Barbee Draw descends a broad, inset piedmont fan, depositing Holocene alluvium across a wide swath and then bifurcating around Point of Rocks (Figure 8). Some of the small channels of this inset piedmont fan are aggrading more elevated and more vegetated natural levees that grow higher and persist on the landscape. These elevated reaches should not be confused with elevated remnants of Qp1b and Qp2 that have desert pavement and clasts covered with rock varnish.

Differentiated from this young piedmont designation are larger, clearly inset drainages that have Holocene valley alluvium and present-day arroyo channels. These tributary valleys with aggraded alluvium are low on the landscape and below older piedmont deposits and surfaces and commonly grade up-valley into young piedmont deposits. These valleys are mapped separately as tributary inset alluvium (Qap). In many locales, the tributary valleys act as ephemeral stream valleys, presently occupied by active arroyo channels. Along both Yost and Aleman valleys, we noted buried channels of arroyo-system proportions within the Holocene alluvial fill. Also in the alluvium along these valleys is geological evidence of higher water tables such as calcium carbonate precipitates, but not of marshes or wetlands (see discussion in Newton et al. 2015, Appendix B).

Playas and Lunettes (Ql, Qle, Qlo, Qla)

Unlike floodplain playas (Qlf), common playas (Ql) along the corridor and on the Spaceport America campus are depressions capable of storing runoff for months or years and have been excavated by wind and influenced by active (Quaternary) fault zones (Figure 9). At the northern end of the study corridor are three linked playa depressions (Figure 10). The

Figure 8. Young Piedmont Alluvium (Qp4). Fine-grained alluvial surface along Barbee Draw near Alivio. Point of Rocks on skyline to southeast.

depression holding the northern-most playa, Cedar Lake Playa, is 11 m below the sill or lip of the basin which, if filled, would spill over to the drainage leading south to next depression, Engle Lake. Similarly, the depression of the playa south of Engle Lake has a sill 16 m above the playa floor. It also has a well-developed lunette on its east side that rises 5 m above the playa.

Cedar Lake playa has two apparently older deflation levels partially covered with old alluvium graded to the playa floor at that time. The higher inset alluvium has a broken petrocalcic horizon and is designated Qlo. The lower inset alluvium, intermediate between the old alluvium and present playa, is designated Qla. The lunette (Qle) downwind of Cedar Lake appears to ascend more than one level. Similar stepped deflation levels have not been noted surrounding other playas, but more investigation is required to determine whether stepped deflation occurs in other locations.

Figure 9. Jornada Lakes Playa, with view to northwest. Playa recently filled by substantial rainfall during September, 2013. Photo taken October, 2013.

Figure 10. Time-series images of playas. Engle Lake is top right playa. Images show dry basins on left (7/24/2011) and full basins on right image (12/14/2013). North is to top. Note playa lunette (Qle) to east of central unnamed playa.

Axial Stream Floodplain and Floodplain Playas (Qa, Qlf)

The axial stream within the corridor and Spaceport America campus is the Jornada Draw (Qa). It has a gradient of 0.0008 [88 ft drop over 19.9 miles run] and although it floods occasionally following local intense precipitation, inset or even gullied channels are local and small. Much of the sediment transported and temporarily stored is fine-grained sand, silt, and clay and organic flotsam. Mesquite thickets are common along most reaches as are thick stands of tobosa grass (*Pleuraphis mutica)*. In some reaches, flow spreads out into broad, nearly flat areas called floodplain playas (Qlf, Figure 11). These areas slow water but do not store it in ephemeral ponds. These low-gradient areas have clayey soils that break into platy shards and larger mudcracks. They have microtopography of mounds and depressions called gilgai (Figure 11).

Valley Margin Alluvium and Valley Fill of Cañon del Muerto and McRae Canyon (Qvo, Qva)

Cañon del Muerto and McRae Canyon in the northwest portion of the study area are dominated by bedrock landforms (Rks, Rtv, Rts, Ti, Tb) and are deeply dissected. However, some alluvial deposits are preserved locally (Figure 12). The mapped piedmont deposits (Qvo) descend from the margins of lava flows and drainage divides toward the axial drainage and are similar to piedmont deposits on Cretaceous bedrock farther south along the corridor. The axial alluvium (Qva) has an angular unconformity with Cretaceous bedrock at its base is as much as 5 m thick. Exposures of the alluvium commonly show evidence of shallow water levels in the past (see photographs in Appendix B, Newton et al., 2015). These include white evaporite (thenardite; Na_2SO_4) and calcite ($CaCO_3$) coatings on grains, orange iron-hydroxy-compound coatings (such as Goethite: αFeOOH) and dark brown and black coatings of manganese oxides (MnO_2).

Figure 11. Floodplain playa (Qlf) near Prisor Hill, in central portion of the study area. Small anastomosing channels drain clayey deposits covered with Tobasa grass *(Pleuraphis mutica).*

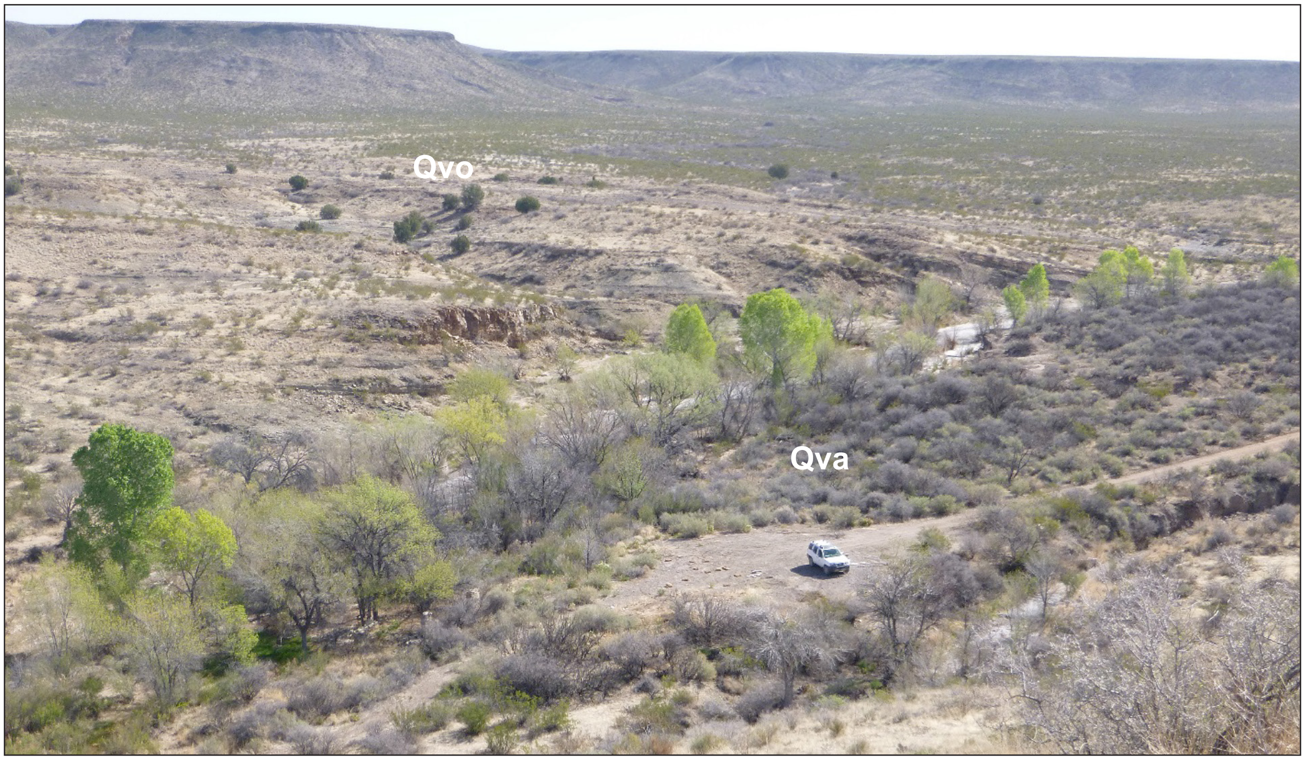


Figure 12. View to northeast of present location of Ojo del Muerto spring, McRae Canyon. Qva deposits to south of arroyo, extending under vehicle. Qvo deposits sloping south under creosote bush cover along planar surface below mesas on skyline.

Intermediate-Level Piedmont Deposits and Surfaces (Qp2, Qp3, Qp3i, Qf2, Qf3)

Inset below the higher Palomas-age piedmont remnants are two lower levels of piedmont. These are further divided into medial portions of the piedmont slopes (Qp2, Qp3, Qp3i) and the distal fan skirt portions (Qf2, Qf3). Old piedmont slopes graded to levels below those of Jornada/Palomas piedmont surfaces are designated Qp2. They are intermediate, but higher on the landscape than other broad drainage features descending toward the axial Jornada Draw valley from both the Caballo and San Andres Mountains (Figure 13). Much of the Spaceport America campus is on the distal reaches of these older piedmont deposits, the rather planar old fan skirt (Qf2). Similarly Qp3 and Qp3i commonly are inset below or appear to be younger than piedmont Qp2. In some cases Qf3 spreads out as fan skirts on top of or partially on top of older fan skirts or descends in small drainages toward incised Jornada Draw. Piedmont and fan-skirt Qp3 and Qf3 therefore incorporate some elements of the older landscape features and some of younger landscape features.

Figure 13. Qp2 surface with gravelly desert pavement northwest of Alivio. Point of Rocks on skyline in background.

La Mesa, Jornada, or Cuchillo surfaces, and Underlying Deposits (Qm1, Qp1a, Qp1b, Qf1)

The La Mesa surface is a major planar landform along the Rio Grande valley immediately south of the study area (Qm1). A small portion of this surface crosses into the mapped corridor and is included in the landform map. This surface marks the top of aggradation of Rio Grande sediments across basins of southern New Mexico and adjacent parts of Texas and Chihuahua, Mexico approximately 800,000 years ago. The route of El Camino Real crosses the planar La Mesa surface between San Diego Mountain along the Rio Grande and the eroded escarpment south of Paraje del Perrillo in the southern end of the study area (Figure 14). The ancestral river deposits beneath La Mesa surface are called the Camp Rice Formation (Qp1b), which is mapped as such where the stable La Mesa surface no longer exists. An equivalent surface, traceable up the Rio Grande valley to the Truth or Consequences airport and farther north, is called the Cuchillo surface, and the deposits beneath are called the Palomas Formation (Qp1a and Qf1). Both the Camp Rice and Palomas Formations have ancestral Rio Grande and piedmont facies. The high piedmont surfaces are called the "Jornada surfaces" or Camp Rice and Palomas piedmonts. The Jornada surface caps older piedmont slopes from the San Andres Mountains to the east of the study area. In the area near Spaceport America the oldest piedmont cuestas are farthest from the Caballo Mountains and the youngest piedmonts are closer to their mountain sources, but their distal ends are inset or buried to the east.

Bedrock and Volcanic Group (Rks, Rtv, Rts, Ti, Tb)

This group includes Cretaceous sedimentary rocks (Rks), Paleogene (formerly Tertiary) sedimentary rocks (Rts), Paleogene volcanic and volcaniclastic rocks (Rtv), igneous dikes (Ti), and volcanic edifices (Tb). The Cretaceous and early Paleogene rocks crop out from the Spaceport America campus north and west to the boundaries of the corridor, as do the dikes. The bulk of the Paleogene sedimentary rocks crop out from Aleman Draw southward to Alivio (Figure 15).

Figure 14. View west of La Mesa Surface (Qm1) in southern portion of the study area. Point of Rocks on skyline to right. Copice dunes on stage IV pedogenic carbonate horizon.

Figure 15. Love Ranch conglomerate (Rts) exposed in Yost Draw, with younger valley alluvium (Qap) deposits above. East of County Road A-13. Bars on staff are 10-cm increments.

Figure 16. Cretaceous bedrock (Rks) exposed along Ash Canyon, near Ash Spring. Lava flow (Tb) on piedmont in middle distance, with Caballo Mountains on skyline. Photo taken facing west southwest.

The Paleogene volcanic rocks crop out at Prisor Hill, Upham Hills, and Point of Rocks. The volcanic edifices are all west of Engle and Cutter.

The first three units have alternating layers of more erodible and less erodible units and have been deformed by faulting, folding, and tilting. Differential erosion has produced similar landform features wherever these rocks are exposed. These features include cuestas, hogbacks, hills, mesas, badlands, and canyons. Cretaceous sedimentary rocks are predominantly alternating beds of sandstone and mudstone with some coarser beds of conglomerate. The tilted mudstones erode more rapidly than the coarser, more cemented layers, so that cuestas, mesas, hills, and badlands form easily and remain on the landscape (Figure 16). The alternating beds of Cretaceous rocks appear to be thinner than the overlying Paleogene conglomerates, sandstones, and mudstones, and more deformed, so that the cuestas, mesas, and canyons are more numerous and smaller, whereas the badlands are more extensive. The cuestas developed along Paleogene resistant conglomerates and sandstones tend to be more continuous and have higher relief. The Paleogene volcanic rocks form even higher cuestas, mesas, and hills.

Although basaltic dikes (Ti) are minor features on the landscape, they show up as long, linear, narrow features from above, having two parallel resistant sides and a less resistant core. They locally play a role in diverting groundwater flow up, down, or laterally so they are included as separate landscape features (see Newton et al., 2015).

Several volcanoes and their lava-flow "skirts" (Tb) dot the landscape west of Engle and Cutter. Not all of the volcanoes in the region have been radiometrically dated. The two that have, Black Hill 0.6 miles SW of Cutter and an unnamed cinder cone 3.5 miles SW of Engle, have age determinations of about 2 to 2.4 million years old (Bachman and Mehnert, 1978; Seager and Mack, 2003). The landforms consist of cinder cones, a shield volcano, and eroded cliffy escarpments around the margins of the flows. They erupted on a broad surface already established at the time, and the canyons developed between them show how much erosion has taken place since the volcanoes first covered the landscape.

III. SUMMARY AND DISCUSSION

Landforms found within the study area have been described and discussed in the preceding sections. In all, twenty-four landforms were defined, including three bedrock landforms, two volcanic landforms, five playa and lunette surfaces, five alluvial surfaces, six piedmont surfaces, and three fan skirt surfaces. As noted at the outset, it is thought that landforms and the availability of water within the Jornada del Muerto influenced the location of El Camino Real trail as well as the location of *parajes* (campsites) along the trial. All else being equal, we would expect the route of El Camino Real to favor surfaces within the study area more amenable to sustained traffic and to avoid, wherever possible, surfaces that would impede the flow of wheeled carts and wagons.

As discussed in the companion report (Newton et al., 2015), traffic along El Camino Real often included wheeled carts and draft animals. Caravans with dozens of heavily laden large-wheeled carts and hundreds of mules, horses, cattle, and sheep, were common during the 17th and 18th centuries (Scholes, 1930a, b, c, Moorhead, 1957). Early carts were massive cargo haulers, with two axels, four immense iron-shod wheels that were each 8 inches wide, pulled by eight draft animals, usually mules (Scholes, 1930 a) (Figure 17). These freight wagons had a width of 12 ft (3.6 m) (Paul Harden, personal communication July 15, 2015). Later, the large wagons were replaced by pack mules and/or smaller and narrower wagons, much like the famous 'Prairie Schooners' seen on the Santa Fe Trail (Moorhead, 1957). The passage of this wheeled traffic cut deep ruts and swales that can still be seen today, evidence of the concentrated impact that this traffic had on the landscape.

"Trafficability" is a term used to describe the interaction between vehicles and underlying soils, and can also be considered for foot traffic and herds of animals (Karafiath and Nowatzki; 1978, Anderson et al., 2005; Suvinen, 2006; Hemmat et al., 2014; Herbin et al., 2011). Foot and wheel

Photo credits: 'Argentine freight wagon', 1926, the Field Museum.

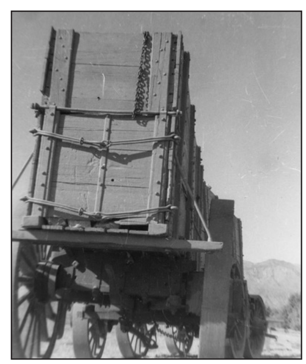
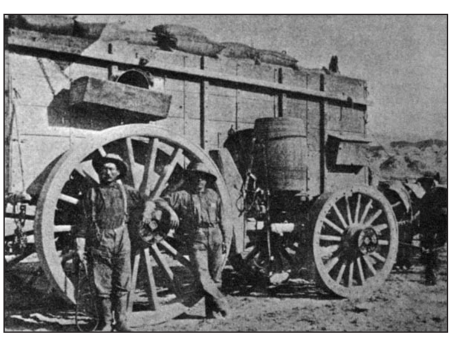


Photo credits: Stephen Morgan.



(Photo credits: 'Large cart' (Spears 1892).

Photo credits: '20 mule team with sacked ore' (Spears 1892).

Figure 17. Large-wheeled carts similar to those used on El Camino Real.

interaction with the soil determines traffic mobility which then characterizes the dynamics between the two. The interactions depend on properties of animal feet, or vehicle wheels, conditions of motion (speed, number of passes, turning radii, etc.), soil properties, relief, aspect, surrounding land use, and climatic conditions. Dry, frozen, or coarse-grained soil can support single-pass traffic well. However, conditions can change drastically when soil properties change over time (as with repeated passes of multiple wagons) and during wet conditions. As concerns the Jornada del Muerto, three different surfaces are most problematic for the passage of wheeled carts: mud, loose sand, and jagged areas of exposed bedrock.

Active alluvial surfaces are potential quagmires, and the route of the trail should avoid these surfaces where possible. In the study area, the most active alluvial surfaces include axial stream floodplain (Qa), tributary valley inset alluvium (Qap), and young piedmont alluvium (Qp4). Repeated crossing of these dry, fine-grained deposits can easily generate large amounts of dust and deepening ruts. Such flat, dusty, blown-out areas are liable to accumulate runoff during wet episodes and may become boggy. In the past, when carts and wagons were pulled by hooved livestock, such areas would have hindered vehicles or livestock from performing their tasks, to the extent that vehicles may have become damaged or entrapped and livestock exhausted (Figure 18).

(Photo credit: Toronto Archives, Fonds 1244, Item 24).

Figure 18. Coal wagon stalled on muddy Ashdale Avenue, 1908.

All of these active alluvial surfaces are flat to slightly inclined, and consist of fine-grained sand, silt, and clay, with few or no larger clasts or gravel. The surface of these landforms is easily penetrated by both hooved and wheeled traffic, to the extent that heavy traffic will pulverize the deposits, creating areas of soft powder. These areas are susceptible to inundation and flooding, and when wet, become treacherous with deep, clingy mud. During our field visits, we saw many instances of deep ruts left by motor vehicles trying (unsuccessfully) to cross these surfaces when wet.

Deep sand is another bane to wheeled carts and wagons. Depending on factors such as moisture content, depth, and vegetation, loose sandy surfaces do not support wheeled or hooved traffic well. Passage across these surfaces generally entails breaking through the surface and sinking into the soft, unconsolidated sands below. Pulling laden wagons across such surfaces is exceedingly difficult, as the following passage illustrates. In 1847, heading southward near the northern entrance to the Jornada del Muerto, Susan Shelby Magoffin noted in her journal:

> *"By the goodness of God we have come this far in safety. We are almost at the mouth of the Jornada (the long journey without water) have been traveling slowly the roads being exceedingly heavy, with two or three severe hills; one we passed this morning, about a half mile in length, and the sand so heavy all the teams doubled and were then just able to get over with resting half a dozen times. 'Tis an ugly road very, but they say 'twill be better after this; I hope so indeed, for the poor animals work so hard." (Drumm, 1982 p. 194).*

Two points are worth noting about this passage: the obvious difficulty in crossing just ½ mile of heavy sand, and that conditions would improve 'after this', presumably meaning once the caravan left the sandy reaches of the Rio Grande valley behind and began to cross the hard-packed piedmont fringes within the Jornada del Muerto.

Eolian sands within the study area have not been mapped as a specific landform, but eolian dunes and sand sheets are extensive on the fan skirts and piedmont surfaces to the east of Jornada Draw, from Engle on southward to Point of Rocks. In places, the coppice dunes and sand sheets cover the majority of the land surface. Coppice dunes are also present in the north central portion of the study area, east of Black Hill and west of Jornada Draw, on old fan skirt (Qf2) deposits.

Bedrock and/or volcanic landforms are another potential impediment to wheeled traffic, and are found within the study corridor. They are commonly jagged and contain features such as cuestas, hogbacks, mesas, badlands and canyons. These portions of the study area have been deformed by folding, faulting, and tilting of alternating beds of sandstone and mudstone with some coarser beds of conglomerate. While these surfaces do not preclude foot or mounted traffic, wheeled traffic across them is limited due to the abrupt transitions associated with these landforms. Wheeled traffic should, therefore, avoid these landforms as much as feasible.

When the route of El Camino Real is placed on the landform map (Figure 7, Plate 1), it is possible to see whether the route avoids the surfaces discussed above. Of the 24 landforms mapped for the corridor, the trail does not cross eight of these landforms, including basalt dikes, volcanic edifices, playas, and valley fill and valley margin alluvium. Most of these landforms are of limited size, but represent some of the least favorable for wheeled traffic. The volcanic and bedrock surfaces are avoided where possible, as can be seen in the central portion of the corridor, where the trail passes over a series of sedimentary bedrock exposures (Rts). These bedrock outcrops are found near Yost Draw, and the trail appears to pass through this region on account of the seeps in Yost and Aleman Draws while missing the most rugged series of outcrops to the west (Newton et al., 2015). The side branch of El Camino Real that descends McRae Canyon to the regional spring Ojo del Muerto mostly traverses the eroded Cretaceous bedrock (Rks) surfaces while apparently avoiding the soft sands found in the valley alluvium landforms (Qva, Qvo).

The route of El Camino Real does cross active alluvial surfaces (Qa, Qap, Qp4) – this is unavoidable. Drainages enter the trail corridor from the west, joining Jornada Draw to the east. Unless the trail was to follow Jornada Draw, the route must cross these arroyos as it progresses though the study area. While the route does cross active alluvial surfaces, the route appears to skirt these surfaces as much as possible, a pattern that can be readily seen in the southern portion of the study corridor. As the trail progresses northward from the southern project boundary, the route mounts the western fringes of the piedmont apron of Point of Rocks (Qp3 and Rtv). It follows this fringe for some three miles, at which point the route leaves the piedmont fringe and crosses just over one mile of the active alluvium of Barbee Draw (Qp4). By hugging the piedmont fringe, the trail avoids a long stretch of potential boggy ground (Figure 19 and 20).

Deep sand is the other bane to wheeled carts and wagons noted above. Eolian sand is found in many locations within the study corridor, but is most prevalent east of Jornada Draw in the north and central portions of the corridor. The trail runs to the west of these sandy portions of the study corridor. The trail does, however, cross an area of coppice dunes located on fan skirt deposits (Qf2) in the central portion of the corridor. At the northern end of the study corridor, the trail crosses two small areas of playa lunette deposits. As noted in the companion hydrogeological

Figure 19. Borrow pit near Engle showing well developed horizontally fractured white carbonate horizons just below the reddish brown eolian deposits at the surface.

Figure 20. Palomas Piedmont surface (Qp1a) near Yost Draw, just south of Spaceport America. Note predominance of rocks and pebbles at the surface that would better support heavy foot and wheeled traffic.

report (Newton et al., 2015), the playas were likely an important water source for people and livestock crossing the Jornada del Muerto, and the proximity of the trail to these water sources may reflect this importance.

In the final analysis, an inspection of our landform map shows that the route of the trail appears deliberate. It avoids (where possible) the most problematic surfaces while crossing the firm and nearly planar piedmont surfaces. These 'preferred' intermediate piedmont surfaces have developed on deposits containing pebbly sands with desert pavements and advanced stages of soil development due to the stability of their surfaces, a stability commonly measured in tens of thousands to millions of years. To the extent possible, the route avoids alluvial landforms which flood episodically and consist of clay-rich deposits which would be impassible when wet and would generate clouds of dust when dry. The route also avoids the eolian dunes and sand sheets found to the east of Jornada Draw and the worst of the rough and tumble bedrock and/or volcanic surfaces. This is not to say that the route does not ever cross any of these landforms, but rather that the route appears to be laid out to avoid these landforms as much as feasible.

From the earliest periods, the route of El Camino Real left the relative safety (water!) of the Rio Grande and crossed the open, flat country of the Jornada del Muerto. If this crossing was treacherous and fraught with danger, surely a better alternate route could have been found. Considering that this 'detour' was not altered and indeed remained the preferred route for over 200 years suggests that it was the best alternative, due in some measure to the suitability of the gently sloping piedmont surfaces found in the Jornada for large-wheeled carts and draft animals.

IV. SUGGESTIONS FOR FUTURE RESEARCH

A number of issues have been raised by the work presented here which point to potential research directions and opportunities. A short list of potential topics is presented below, arranged by general topic.

Hydrogeology, Geomorphology, and Landforms:

1) Extend hydrogeologic investigations across the Jornada del Muerto from Paraje Fra Cristobal in the north to San Diego in the south to encompass entire route of El Camino Real through the Jornada. Identify water sources, landforms, and route of El Camino Real.
2) Investigate where El Camino Real crosses large tributaries of Jornada Draw such as Aleman, Yost, and Barbee Draws to determine (if possible) how long the modern arroyos have existed and whether El Camino Real crossed these valleys before they were incised. The incised arroyos probably have not been present for 400 years.
3) Investigate cycles of cut and fill along large tributaries of Jornada Draw to gain longer-term perspective of arroyo behavior during the past few thousand years.
4) Investigate the uncommon routes of various drainages in the central Jornada ('deranged' drainage patterns). Preliminary examination of some of the stream courses suggests deflection of drainages by faults and other tectonic deformation, as well as eolian accumulations.

Historical/Archaeological:

5) Investigate historic and prehistoric sites near the route crossings along large tributaries of Jornada Draw such as Aleman, Yost, and Barbee Draws to determine whether a trail across the Jornada existed before Oñate crossed on what was to become El Camino Real.
6) Investigate the distribution of archaeological sites on or near shorelines of the northern playas, particularly large playas such as Flat Lake and Cedar Lake. In neighboring areas (i.e. Hueco Bolson) basin floor playas are bordered by major Puebloan sites. Do the playas in the Jornada follow this pattern, and if not, why?
7) Investigate eolian landforms, particularly distended parabolic arms of dunes and lunettes downwind from playas to determine when wind-blown deposits were particularly active and how they relate to archaeological sites in the vicinity.

Route of El Camino Real and Durability of Landform Surfaces:

8) The discussion of the route presented above suggests that following the Rio Grande would have been more difficult for wheeled traffic than crossing the Jornada. Is this contention accurate? Can an analysis of potential alternate routes along river demonstrate this?
9) Are there instances of the route of El Camino Real encountering any of the landform surfaces argued to be impediments to wheeled traffic, such as dense/heavy sands and/or fine grained alluvium, in other areas or regions? If so, what do historic accounts of passage through these areas tell us?
10) The weight of the early freight wagons was immense, and repeated crossings of the Jornada must have compressed soils along route. Can this differential compression still be seen, and if so, can it be used to map out the trail (main route and alternates)?
11) If the Ojo del Muerto spring complex was as important to travel across the Jornada del Muerto as we believe, trails leading to this area from the main corridor should be present. Investigate the potential route or routes of any side trails that lead from the playas near Engle westward in the direction of Ojo del Muerto spring.
12) Further investigate the issue of 'trafficability' and landform surfaces or soils in more detail. Determine the potential for preservation of sections of the trail versus the eventual degradation and/or eradication of these segments, either by natural and human-caused processes.

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