APPENDICES

APPENDIX A

Chemistry and Water Level Data

Code	Meaning	Unit
^3H	Tritium	Tritium Units (TU)
^3H:^3He Age	Age of Water using dissolved gases	years
Ag	Silver	mg/L
Al	Aluminum	mg/L
As	Arsenic	mg/L
B	Boron	mg/L
Ba	Barium	mg/L
Be	Beryllium	mg/L
Br	Bromide	mg/L
$\delta^{13}C$	13C:12C ratio	per mil (‰)
C^{14}	14C Apparent age (uncorrected)	years
Ca	Calcium	mg/L
Cd	Cadmium	mg/L
Cl	Chloride	mg/L
Co	Cobalt	mg/L
Cond field	Specific Conductivity, field	µs/cm
Cr	Chromium	mg/L
Cu	Copper	mg/L
DO	Dissolved Oxygen, field	mg/L
F	Fluoride	mg/L
Fe	Iron	mg/L
δD	Deuterium:Hydrogen ratio	per mil (‰)
HCO_3	Bicarbonate	mg/L
HRD	Hardness (CaCO3)	mg/L
K	Potassium	mg/L
Li	Lithium	mg/L
Mg	Magnesium	mg/L
Mn	Manganese	mg/L

Code	Meaning	Unit
Mo	Molybdenum	mg/L
Na	Sodium	mg/L
Ni	Nickel	mg/L
NO_2	Nitrite (as NO2)	mg/L
NO_3	Nitrate (as NO3)	mg/L
$\delta^{18}O$	18O:16O ratio	per mil (‰)
ORP	Oxidation-Reduction Potential	mV
Pb	Lead	mg/L
pH Field	pH, field	pH units
PO_4	Phosphate	mg/L
Sb	Antimony	mg/L
Se	Selenium	mg/L
Si	Silicon	mg/L
SiO_2	Silica	mg/L
Sn	Tin	mg/L
SO_4	Sulfate	mg/L
Sr	Strontium	mg/L
Temp	Temperature, field	degrees celsius
TDS	Total Dissolved Solids	mg/L
Th	Thorium	mg/L
Ti	Titanium	mg/L
Tl	Thallium	mg/L
U	Uranium (total, by ICP-MS)	mg/L
V	Vanadium	mg/L
Zn	Zinc	mg/L
TAn	Total anions	meq/L
TCat	Total cations	meq/L
IONBAL	ion balance	% difference

Table A1. General chemistry data for well, and surface waters. Sample sites are shown on Figure 10.

Site ID	NAD83 UTM Easting	NAD83 UTM Northing	Sample point ID	Collection date	Water Type	Site Type	³H (TU)	Ag (mg/L)	Al (mg/L)	ALK (mg/L)	As (mg/L)	B (mg/L)
JM-005	327722	3640834	JM-005A	17-Oct-13	Na-Mg-Ca-SO$_4$	Well		<0.0025	<0.0025	161	<0.0025	0.9
JM-006	327628	3648143	JM-006A	17-Oct-13	Na-Ca-Mg-SO$_4$-Cl	Well		<0.0025	<0.0025	99	<0.0025	0.9
JM-007	331513	3653290	JM-007A	17-Oct-13	Na-Ca-Mg-SO$_4$-Cl	Well		<0.0025	<0.0025	108	<0.0025	0.9
JM-008	324827	3652693	JM-008A	17-Oct-13	Na-SO$_4$-Cl	Well	-0.1	<0.0025	<0.0025	126	0.0042	0.8
JM-035	297507	3660425	JM-035A	16-Oct-13	Na-SO$_4$-HCO$_3$	Well		<0.0025	<0.0025	312	<0.0025	0.2
JM-037	309033	3658022	JM-037A	23-Oct-13	Ca-Na-Mg-SO$_4$-HCO$_3$	Well		<0.0025	<0.0025	272	<0.0025	0.2
JM-038	306216	3654061	JM-038A	18-Oct-13	Na-Ca-Mg-SO$_4$-HCO$_3$	Well	3.2	<0.0025	<0.0025	283	<0.0025	0.5
JM-039	310661	3652987	JM-039A	18-Oct-13	Na-Ca-Mg-HCO$_3$-SO$_4$	Well		<0.0025	0.0088	253	<0.0025	0.3
JM-041	309159	3647472	JM-041A	18-Oct-13	Na-SO$_4$-Cl	Well	0.0	<0.0025	<0.0025	249	<0.0025	0.5
JM-042	307198	3649247	JM-042A	18-Oct-13	Na-Ca-HCO$_3$-SO$_4$	Well		<0.0025	<0.0025	309	<0.0025	0.5
JM-044	308701	3634398	JM-044A	23-Oct-13	Na-Mg-SO$_4$-HCO$_3$	Well		<0.0025	<0.0025	294	0.0042	1.3
JM-054	313070	3652465	JM-054A	16-Oct-13	Ca-Na-Mg-HCO$_3$-SO$_4$	Well	4.1	<0.0025	<0.0025	220	<0.0025	0.1
JM-058	311517	3625631	JM-058A	23-Oct-13	Na-Ca-SO$_4$-Cl	Well		<0.0025	<0.0025	82	0.0051	0.8
JM-059	296489	3653186	JM-059A	24-Oct-13	Mg-Ca-HCO$_3$	Well	3.4	<0.0005	0.0016	279	0.006	0.08
JM-500	295452	3666275	JM-500A	16-Oct-13	Ca-Na-HCO$_3$-SO$_4$	Spring		<0.0025	<0.0025	271	<0.0025	0.1
JM-501	310516	3663366	JM-501A	17-Oct-13	Ca-HCO$_3$	Playa		<0.0025	4.97	140	0.005	0.05
JM-501	310516	3663366	JM-501B	25-Mar-14		Playa						
JM-502	309551	3672347	JM-502A	17-Oct-13	Ca-HCO$_3$	Playa		<0.0005	0.219	97	0.003	0.02
JM-503	312413	3652920	JM-503A	18-Oct-13	Ca-SO$_4$	Seep	3.2	<0.0025	1.33	166	<0.0025	0.09
JM-503	312413	3652920	JM-503B	26-Mar-14		Seep						
JM-504	301489	3674351	JM-504A	04-Nov-13	Na-HCO$_3$-SO$_4$	Spring	0.1	<0.0005	0.006	345	0.0008	0.4
JM-506	312608	3652893	JM-506A	26-Mar-14		Seep						
JM-507	312964	3649428	JM-507A	25-Mar-14		Seep						
JM-508	303708	3672038	JM-508A	27-Mar-14		Spring						

Table A1—Continued

Site ID	Site Type	Ba (mg/L)	Be (mg/L)	Br (mg/L)	δ¹³C (‰)	C14 (% modern carbon)	C14_years (Years)	Ca (mg/L)	Cd (mg/L)	Cl (mg/L)	Co (mg/L)	CO$_3$ (mg/L)	Cr (mg/L)	Cu (mg/L)	DO (mg/L)
JM-005	Well	0.014	<0.0025	1.2				89.8	<0.0025	104	<0.0025	<5	<0.0025	<0.0025	7.85
JM-006	Well	0.013	<0.0025	2.1				139	<0.0025	178	<0.0025	<5	<0.0025	<0.0025	6.62
JM-007	Well	0.009	<0.0025	2.2				156	<0.0025	211	<0.0025	<5	<0.0025	<0.0025	4.96
JM-008	Well	0.015	<0.0025	1.2				46	<0.0025	112	<0.0025	<5	0.004	<0.0025	8.28
JM-035	Well	0.045	<0.0025	0.4				51.3	<0.0025	29.1	<0.0025	<5	<0.0025	<0.0025	0.13
JM-037	Well	0.021	<0.0025	1.0				130	<0.0025	106	<0.0025	<5	<0.0025	<0.0025	0.86
JM-038	Well	0.019	<0.0025	0.4				83.1	<0.0025	47.4	<0.0025	<5	<0.0025	<0.0025	9.51
JM-039	Well	0.023	<0.0025	0.2				64.8	<0.0025	25.8	<0.0025	<5	<0.0025	<0.0025	5.87
JM-041	Well	0.009	<0.0025	2.3				15.9	<0.0025	218	<0.0025	<5	<0.0025	<0.0025	0.45
JM-042	Well	0.032	<0.0025	0.3				58.5	<0.0025	25.2	<0.0025	<5	<0.0025	<0.0025	2.75
JM-044	Well	0.01	<0.0025	2.4	-12.4	85.8	1230	95.3	<0.0025	138	<0.0025	<5	<0.0025	0.0029	7.73
JM-054	Well	0.035	<0.0025	0.05	-15.6	96.1	320	49.1	<0.0025	7.9	<0.0025	<5	<0.0025	<0.0025	4.41
JM-058	Well	0.01	<0.0025	0.8				149	<0.0025	216	<0.0025	<5	0.008	<0.0025	7
JM-059	Well	0.217	<0.0005	0.1	-14.3	100	0	54	<0.0005	2.4	<0.0005	<5	0.001	0.0018	9.23
JM-500	Spring	0.295	<0.0025	0.2				119	<0.0025	26.3	<0.0025	<5	<0.0025	<0.0025	8.04
JM-501	Playa	0.294	<0.0025	0.03				46.4	<0.0025	2.03	<0.0025	<5	0.003	0.006	7.19
JM-501	Playa														
JM-502	Playa	0.142	<0.0005	0.01				36.7	<0.0005	1	<0.0005	<5	<0.0005	0.0021	10.6
JM-503	Seep	0.215	<0.0025	0.2				255	<0.0025	22.4	<0.0025	<5	<0.0025	0.0034	3.56
JM-503	Seep														
JM-504	Spring	0.026	<0.0005	0.3	-16.2	23.2	11740	3.56	<0.0005	28.2	<0.0005	8	0.002	<0.0005	0.18
JM-506	Seep														
JM-507	Seep														
JM-508	Spring														

Table A1—Continued

Site ID	Site Type	F (mg/L)	Fe (mg/L)	δD (‰)	HCO₃ (mg/L)	HRD (mg/L)	K (mg/L)	Li (mg/L)	Mg (mg/L)	Mn (mg/L)	Mo (mg/L)	Na (mg/L)	Ni (mg/L)	NO₂ (mg/L)	NO₃ (mg/L)	δ¹⁸O (‰)	ORP (mV)
JM-005	Well	2.0	<0.02	-53	196	492	3.8	0.10	65.1	<0.005	0.011	238	<0.0025	<0.2	43.4	-7.1	232.1
JM-006	Well	1.9	<0.02	-61	121	693	4.3	0.10	84.0	<0.005	0.024	187	<0.0025	<0.2	61.4	-7.9	172.3
JM-007	Well	1.5	<0.02	-66	131	717	4.2	0.12	79.5	<0.005	0.018	269	0.0025	<0.2	22.1	-9.0	170.4
JM-008	Well	3.3	<0.02	-62	153	231	3.2	0.09	28.1	<0.005	0.033	203	<0.0025	<0.2	31.9	-8.5	150
JM-035	Well	0.7	<0.02	-58	380	181	2.3	0.43	12.9	0.098	<0.005	307	<0.0025	0.63	11	-7.8	20.7
JM-037	Well	1.5	<0.1	-52	332	495	3.8	0.06	41.6	<0.005	<0.005	127	<0.0025	<0.2	21.7	-6.0	119.8
JM-038	Well	3.2	0.102	-51	345	382	1.2	0.07	42.4	<0.005	0.009	160	<0.0025	<0.2	3.6	-7.4	39.2
JM-039	Well	2.7	<0.02	-52	309	278	1.4	0.04	28.3	<0.005	0.007	93.8	<0.0025	<0.1	8.8	-7.7	109.5
JM-041	Well	6.6	0.10	-63	304	59.3	2.2	0.30	4.7	0.009	0.053	608	<0.0025	<0.2	<0.2	-8.1	135
JM-042	Well	1.6	<0.02	-52	377	198	1.8	0.05	12.5	0.006	<0.005	142	<0.0025	<0.1	3.0	-7.5	203
JM-044	Well	3.0	<0.1	-54	358	534	1.9	0.16	71.8	<0.005	0.012	359	<0.0025	<0.2	56.8	-7.5	99.5
JM-054	Well	2.0	<0.02	-52	268	197	1.1	0.03	18.0	0.031	0.009	52.6	<0.0025	<0.1	2.1	-7.8	127.1
JM-058	Well	1.2	<0.1	-75	100	591	21.4	0.13	52.9	<0.005	0.021	346	<0.0025	<0.2	13.3	-10.0	
JM-059	Well	0.3	<0.02	-51	340	280	2.8	0.01	35.2	<0.001	<0.001	16.9	0.0008	<0.1	27	-6.8	93.8
JM-500	Spring	0.4	<0.02	-55	331	372	5.7	0.06	18.4	<0.005	<0.005	86.7	<0.0025	<0.1	5	-7.3	172.2
JM-501	Playa	0.3	0.342	-26	166	140	8.4	0.01	5.8	0.024	<0.005	3.3	0.0028	<0.1	<0.1	-3.4	193.7
JM-501	Playa			18												7.5	
JM-502	Playa	0.2	0.069	-47	111	101	4.4	0.00	2.3	0.013	<0.001	1.4	0.001	<0.1	<0.1	-7.0	184.4
JM-503	Seep	0.5	0.306	-38	202	783	6.9	0.02	35.5	0.017	<0.005	28.8	0.005	<0.2	0.3	-5.9	165.5
JM-503	Seep			-51												-7.5	
JM-504	Spring	3.5	<0.1	-61	406	11	4.3	0.31	0.5	0.008	0.01	261	<0.0005	<0.1	<0.1	-8.0	90.7
JM-506	Seep			-37												-3.9	
JM-507	Seep			-48												-7.0	
JM-508	Spring			-48												-6.0	

Table A1—Continued

Site ID	Site Type	Pb (mg/L)	pH Field	PO₄ (mg/L)	Sb (mg/L)	Se (mg/L)	Si (mg/L)	SiO₂ (mg/L)	Sn (mg/L)	SO₄ (mg/L)	Sr (mg/L)	T (deg C)	TDS (mg/L)	Th (mg/L)	Ti (mg/L)
JM-005	Well	<0.0025	7.66	<1	<0.0025	0.011	8.14	17.4	<0.0025	695	3.3	21.57	1360	<0.0025	<0.005
JM-006	Well	<0.0025	7.65	<1	<0.0025	0.015	7.8	16.7	<0.0025	697	3.4	24.13	1440	<0.0025	<0.005
JM-007	Well	<0.0025	7.64	<1	<0.0025	0.017	9	19.3	<0.0025	915	3.5	20.81	1750	<0.0025	<0.005
JM-008	Well	<0.0025	8.02	<1	<0.0025	0.01	7.16	15.3	<0.0025	377	1.6	22.4	900	<0.0025	<0.005
JM-035	Well	<0.0025	7.57	<1	<0.0025	<0.005	7.62	16.3	<0.0025	512	0.9	21.03	1140	<0.0025	<0.005
JM-037	Well	<0.0025	6.77	<1	<0.0025	0.014	9.07	19.4	<0.0025	345	4.3	18.91	967	<0.0025	<0.005
JM-038	Well	<0.0025	7.42	<1	<0.0025	0.009	7.44	15.9	<0.0025	369	2.9	18.05	903	<0.0025	<0.005
JM-039	Well	<0.0025	7.4	<0.5	<0.0025	0.005	8.78	18.8	<0.0025	175	1.9	19.95	577	<0.0025	<0.005
JM-041	Well	<0.0025	8.32	<1	<0.0025	0.005	5.24	11.2	<0.0025	859	1.4	20.92	1880	<0.0025	<0.005
JM-042	Well	<0.0025	7.48	<0.5	<0.0025	<0.005	6.72	14.4	<0.0025	163	1.5	19.4	612	<0.0025	<0.005
JM-044	Well	<0.0025	7.39	<1	<0.0025	0.015	15.8	33.8	<0.0025	788	5.4	19.5	1730	<0.0025	<0.005
JM-054	Well	<0.0025	7.34	<0.5	<0.0025	<0.005	8.35	17.9	<0.0025	76.7	1.5	19.29	363	<0.0025	<0.005
JM-058	Well	<0.0025	7.8	<1	<0.0025	0.008	34	72.7	<0.0025	1000	3.2	24.65	1930	<0.0025	<0.005
JM-059	Well	0.001	7.39	<0.5	<0.0005	0.002	12.6	26.9	<0.0005	14.8	0.5	19.76	351	<0.0005	0.001
JM-500	Spring	<0.0025	7.81	<0.5	<0.0025	<0.005	8.66	18.5	<0.0025	248	1.0	22.32	695	<0.0025	<0.005
JM-501	Playa	0.0029	7.74	<0.5	<0.0025	<0.005	15.1	32.3	<0.0025	4.5	0.5	14.19	190	<0.0025	0.14
JM-501	Playa														
JM-502	Playa	<0.0005	8.66	<0.5	<0.0005	<0.001	3.16	6.8	<0.0005	8.6	0.3	17.44	121	<0.0005	0.003
JM-503	Seep	<0.0025	7.66	<1	<0.0025	<0.005	9.34	20	<0.0025	644	3.0	16.76	1120	<0.0025	0.036
JM-503	Seep														
JM-504	Spring	<0.0005	8.55	<0.5	<0.0005	0.001	6.9	14.7	<0.0005	202	0.07	21.94	728	<0.0005	0.001
JM-506	Seep														
JM-507	Seep														
JM-508	Spring														

Table A1—Continued

Site ID	Site Type	TI (mg/L)	U (mg/L)	V (mg/L)	Zn (mg/L)	TAn (meq/L)	TCat (meq/L)	IONBAL (%)
JM-005	Well	<0.0025	0.02	0.01	0.02	21.4	20.3	-2.8
JM-006	Well	<0.0025	0.02	0.01	0.02	22.7	22.1	-1.2
JM-007	Well	<0.0025	0.01	0.01	0.0048	27.6	26.2	-2.8
JM-008	Well	<0.0025	0.02	0.03	0.0353	14.2	13.5	-2.6
JM-035	Well	<0.0025	<0.0025	<0.0025	1.23	18.0	17.1	-2.6
JM-037	Well	<0.0025	0.007	<0.0025	0.02	16.1	15.5	-1.8
JM-038	Well	<0.0025	0.010	<0.0025	0.0094	14.9	14.7	-0.9
JM-039	Well	<0.0025	0.007	<0.0025	0.0072	9.7	9.7	-0.3
JM-041	Well	<0.0025	0.003	<0.0025	0.0086	29.4	27.7	-3.0
JM-042	Well	<0.0025	0.0041	<0.0025	0.0045	10.4	10.2	-1.3
JM-044	Well	<0.0025	0.04	0.05	0.09	27.3	26.4	-1.7
JM-054	Well	<0.0025	0.005	0.00	0.04	6.4	6.3	-0.8
JM-058	Well	<0.0025	0.008	0.03	0.01	28.9	27.4	-2.6
JM-059	Well	<0.0005	0.002	0.03	1.9	6.4	6.4	-0.1
JM-500	Spring	<0.0025	<0.0025	<0.0025	0.0164	11.4	11.4	-0.3
JM-501	Playa	<0.0025	<0.0025	0.02	0.0092	3.0	3.2	2.7
JM-501	Playa							
JM-502	Playa	<0.0005	<0.0005	0.01	0.0018	2.2	2.2	0.6
JM-503	Seep	<0.0025	0.005	0.00	0.0034	17.4	17.1	-0.9
JM-503	Seep							
JM-504	Spring	<0.0005	0.0006	0.0005	0.0022	12.1	11.7	-1.8
JM-506	Seep							
JM-507	Seep							
JM-508	Spring							

Table A2. Water level measurements.

Site ID	NAD83 UTM Easting	NAD83 UTM Northing	Elevation (ft above sea level)	Well depth (ft below ground surface)	Date measured	Depth to water (ft below ground surface)
JM-001	319283	3645249	4545	325	12/5/2012	91.30
JM-002	318396	3644997	4499	200	12/5/2012	71.66
JM-003	316205	3634489	4397	405	12/5/2012	320.14
JM-005	327722	3640834	4652	335	12/5/2012	271.24
JM-006	327628	3648143	4824	450	12/5/2012	361.23
JM-007	331513	3653290	5189	500	12/6/2012	353.41
JM-008	324827	3652693	4796	390	12/6/2012	320.67
JM-012	314718	3647895	4579	220	1/24/2013	47.38
JM-013	315266	3647787	4575	340	1/24/2013	72.71
JM-014	316071	3647688	4551	160	1/24/2013	78.35
JM-015	303497	3667536	4857	362	5/16/2013	143.00
JM-016	310158	3672371	4757	160	5/16/2013	96.01
JM-017	303509	3672087	4580	150	5/16/2013	25.69
JM-022	295159	3644428	5721	500	5/24/2013	323.75
JM-023	294734	3644741	5759	400	5/24/2013	99.65
JM-027	306977	3665051	4761		5/13/2013	55.71
JM-028	307941	3661502	4796	200	5/13/2013	93.67
JM-030	306131	3662558	4853	1100	5/13/2013	88.41
JM-031	302076	3662454	4937	140	5/13/2013	121.62
JM-032	303359	3658930	4906		5/13/2013	65.75
JM-033	301844	3656239	5070		5/13/2013	118.85
JM-035	297507	3660425	4926	175	5/14/2013	50.83
JM-037	309033	3658022	4774		5/23/2013	39.39
JM-038	306216	3654061	4813	40	5/15/2013	17.70
JM-039	310661	3652987	4705	60	5/15/2013	25.90
JM-040	310109	3650189	4692	150	5/15/2013	121.32
JM-041	309159	3647472	4735	220	5/15/2013	202.76
JM-042	307198	3649247	4791	160	5/16/2013	53.38
JM-043	304384	3666213	4829	300	5/16/2013	64.82
JM-044	308701	3634398	4518	265	5/22/2013	66.56
JM-045	312589	3640874	4568	200	5/22/2013	137.33
JM-046	306216	3640960	4737		5/22/2013	101.01
JM-047	304614	3639134	4763	180	5/22/2013	129.96
JM-048	312540	3640812	4571	210	5/22/2013	139.33
JM-049	301243	3650176	5135	134	5/24/2013	111.55
JM-052	295629	3648391	5610	265	5/28/2013	179.14
JM-053	313077	3652498	4653	285	5/28/2013	90.17
JM-054	313070	3652465	4652	150	5/28/2013	89.96
JM-059	296489	3653186	5387	220	10/24/2013	129.31
JM-045	312589	3640874	4568	200	5/22/2013	137.33
JM-045	312589	3640874	4568	200	10/23/2013	137.33
JM-046	306216	3640960	4737		5/22/2013	101.01
JM-046	306216	3640960	4737		10/23/2013	101.01
JM-047	304614	3639134	4763	180	5/22/2013	129.96
JM-047	304614	3639134	4763	180	10/23/2013	130.64
JM-048	312540	3640812	4571	210	5/22/2013	139.33
JM-048	312540	3640812	4571	210	10/23/2013	139.36
JM-049	301243	3650176	5135	134	5/24/2013	111.55
JM-052	295629	3648391	5610	265	5/28/2013	179.14
JM-052	295629	3648391	5610	265	10/24/2013	158.30
JM-053	313077	3652498	4653	285	5/28/2013	90.17
JM-053	313077	3652498	4653	285	10/16/2013	61.03
JM-054	313070	3652465	4652	150	5/28/2013	89.96
JM-054	313070	3652465	4652	150	10/17/2013	23.02
JM-059	296489	3653186	5387	220	10/24/2013	129.31

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APPENDIX B

Indications of Surface Water and Shallow Groundwater in the Study Area

Trevor Kludt, Dave Love, and Bruce Allen

Introduction

As part of the effort to delineate landforms and to define the paleohydrology of the project area, field work was undertaken in the study area, from Engle in the north to Point of Rocks in the south. This appendix contains observations regarding the presence of surface water in the project area, as well as indications of shallow ground water.

Surface water was noted in a number of locations, including seeps, springs, and playa basins filled by recent monsoon rainfall. In a number of locations, the presence of evaporites, iron oxide staining, and/or magnesium coatings in arroyo sidewalls indicate the presence of shallow ground water at these locations sometime in the past. Organic staining in deposits exposed in arroyo sidewalls at a few locations suggests that wet meadows or cienegas may have existed in these locations. However, during field work, no direct evidence was found indicating the presence of

previously undocumented paleo-springs in the study area.

The following appendix is divided into three sections. The first section discusses the geochemical indicators of shallow ground water, particularly as they are manifest in the study area. This section provides necessary geochemical background information for the evaluation of shallow ground water traces noted by the authors across the study area. The second section documents locations within the study area where surface waters and shallow ground water are accessible in the present or have been in the recent past (A.D. 1600 to the present). The third section documents locations which show indications of shallow ground water in the more distant past (pre-dating A.D. 1600).

The more recent locations are designated 'M' for modern on the accompanying map, while the older locations are designated 'P' for past (Figure B1). This temporal distinction is intended to focus attention on indications of surface waters or shallow ground water during the time period in which El Camino Real was in use. It should be noted that no samples were

Table B1. A 1 Indicators of high water tables and other forms of wetlands.

| Criteria for Shallow Ground Water	Figure No.
Abundant indicator plants (e.g. salt grass, sedges, allenrolfia, phragmites, equisetum)	M-2, M-5, M-6, M-7, M-8, M-9, M-10, M-12, M-13
Water loss due to phreatophytes (e.g. Saltcedar, willow, Cottonwood, Rabbitbrush)	M-1, M-2, M-5, M-6, M-7, M-8, M-9, M-10, M-12, M-13
Buildup of organic material	M-6, M-7, M-8, M-9, M-10, M-12
Buildup of minerals at or near the surface by groundwater contributions	M-2, M-7
Evidence of mineral precipitation	M-2, M-7, M-12, M-13, P-17, P-18, P-19, P20, P-23, P-24, P-25, P-26, P-27, P-28, P-29
Evidence of mineral alteration—by microbes or inorganically—Fe and Mn	P-17, P-18, P-19, P-20, P-28, P-29
Criteria for other forms of wetland	
Accumulations of clays and precipitates in playas.	M-14
Accumulations of clay along low-gradient stream valleys.	M-14, P-21
Shrink-swell clays with many scales of mud cracks and gilgai.	M-14
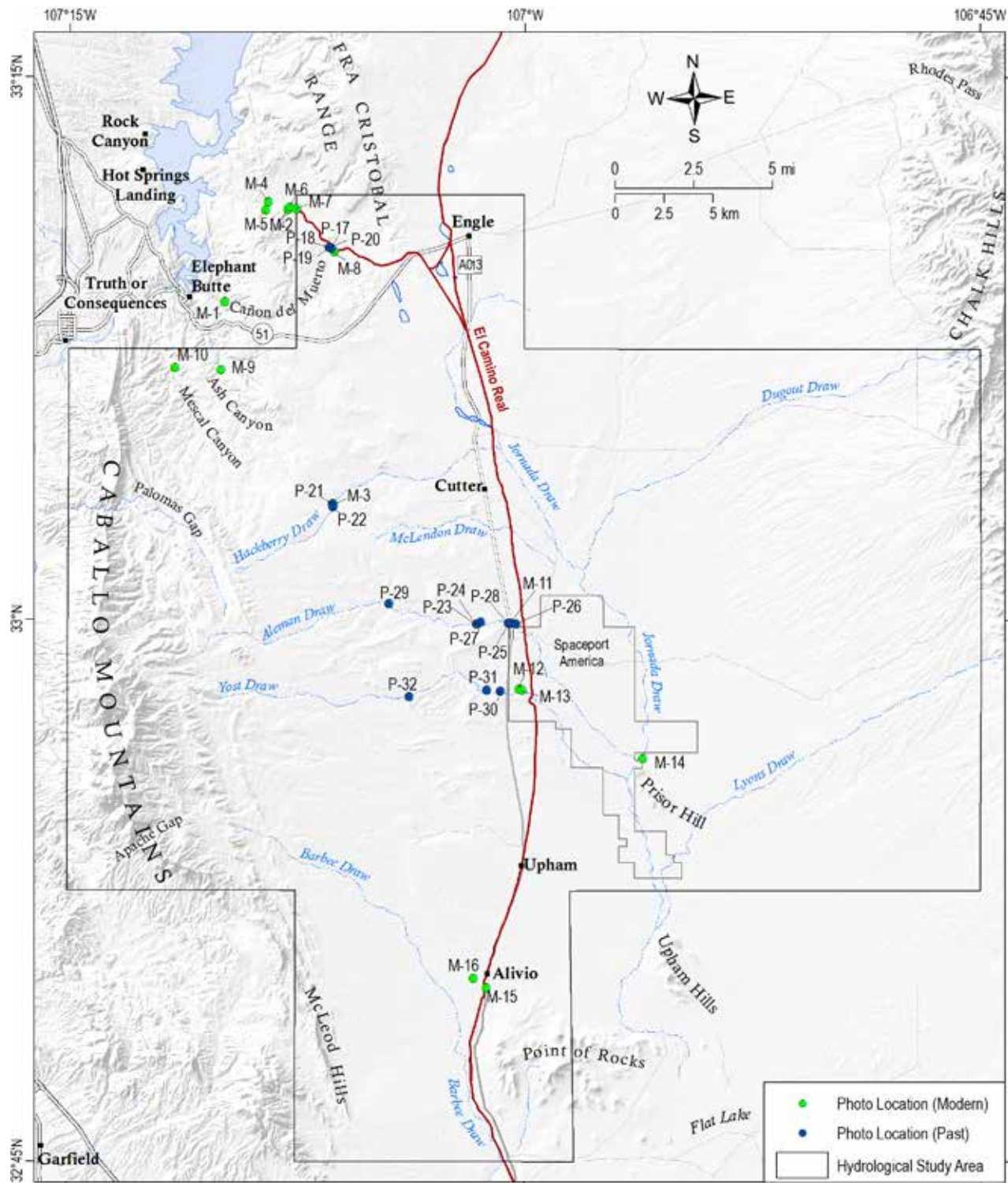
Figure B1. Surface water and shallow groundwater locations.

collected or processed to obtain radiometric ages, and that the ages presented here are estimates provided by the authors based on evident stratigraphic relationships, soil development, and/or previous experience.

For the most part, the locations discussed fall within the study area. Some are found outside of this boundary. The locations outside of this area have been included because they represent important regional water sources, or are illustrative of the numerous small scale springs/seeps found in the central portion of the study area.

Primer on Geochemical Indicators of Past Groundwater Levels

What are indicators of groundwater levels past and present? Where groundwater presently intersects the land surface, one finds springs, seeps, bogs, wet meadows, riparian vegetation, and/or accumulations of tufa, travertine, or evaporite minerals such as gypsum or halite. These features depend on conditions of water discharge and chemistry, surface environment, and the length of time such conditions have existed. Springs and seeps along active arroyo channels may be short-lived, depending on recent stream-flow conditions and precipitation events upstream. Their presence may be indicated by animal excavations looking for water and by evaporite minerals at the surface. Commonly organic matter accumulates in wet meadows and marshes over many centuries to form dark brown or black soils. In semiarid environments, tufa or gypsum may accumulate as mounds at the surface relatively quickly. Evaporite minerals such as gypsum ($Ca(SO_4)2H_2O$), other sulfate salts, or halite (NaCl) may precipitate where water is evaporated at the surface. Evaporite minerals may also accumulate along the capillary fringe above the water table or at shallow depths as a separate soil horizon. Soluble evaporite minerals at the surface may form and dissolve again or blow away seasonally. Cementation of sediments in the shallow subsurface may take longer, requiring many pore-volumes of water passing through to accumulate enough minerals to coat and glue preexisting sedimentary grains or fracture faces. Common cements precipitated from groundwater include calcite ($CaCO_3$), silica (SiO_2), clays (complex fine-grained layered silicate minerals), iron oxides (hematite Fe_2O_3; goethite, α-FeOOH), and manganese oxides (pyrolusite, MnO_2).

Landscape features such as springs, wet meadows, tufa, and evaporate minerals were looked for along all major drainages in El Camino Real corridor.

Although springs and seeps are common locally, and wet meadows have formed locally down-gradient from Ojo del Muerto, evidence of past springs and wet meadows with dark boggy soils was not found. No evidence of tufa or travertine was found at the surface. Evidence of higher groundwater levels in the past are seen in alluvium along some of the present arroyos because their banks expose 3–5 m of deposits with varying amounts of precipitated minerals at various depths below the valley surface. These include bands of nodular calcite, crossbedded sandstones cemented with calcite, irregular masses and "fronts" of oxidized iron and manganese, and white powdery evaporite minerals (see following photo documentation). The summary of geochemical considerations presented below is meant to cover a few fundamentals that can be applied to observations along the corridor.

Oxidation Potential and Acidity of Natural Waters

Water dissolves or alters many preexisting rocks and minerals that are in contact as it flows across the surface and in the subsurface. Water may also precipitate new minerals depending on local circumstances. Such processes are controlled by chemical laws of thermodynamics. Natural water has a range in the amount of oxygen in it (Eh, commonly called oxidation-reduction conditions) and a range in amounts of acids or bases (pH). These two properties largely control the types of reactions that take place and the resulting ions dissolved in the water. The ions in turn react with each other and with changing Eh-pH conditions within the water to precipitate minerals along its path. The following diagrams show calculated stability fields for inorganic reactions under equilibrium conditions and provide a sound basis for interpreting observed mineral precipitates. In nature, however, complications ensue as some reactions are not in equilibrium, but may be based on local kinetics and on presence of microbes that can take advantage of local conditions to use constituents in the water for their own nutrient and energy extraction and growth.

In nature, Eh affects colors of iron-bearing minerals. For example, reducing conditions (low Eh like bog water) causes iron in solution to have a +2 charge and color minerals like clays green or grayish green. Oxidizing conditions causes iron to have a +3 charge and become much less soluble so that iron minerals precipitate orange or red coatings on grains (see Figure B2).
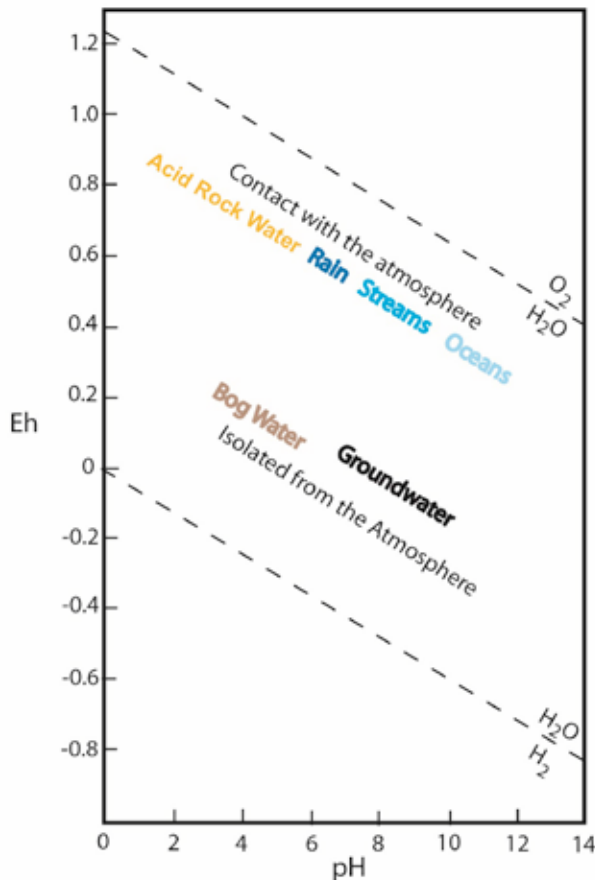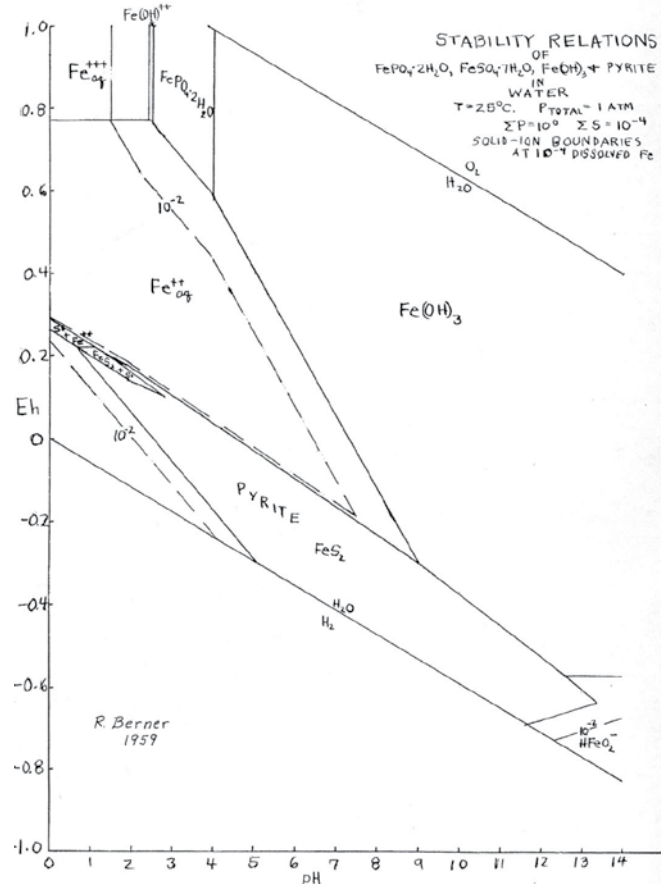
Figure B2. Diagram showing range of acid-base values (pH) and oxidation states (Eh) of natural waters at ordinary temperatures. The plot uses logarithmic increases for both pH and Eh. The upper and lower dashed diagonal lines indicate the upper and limits that water can exist at pH-Eh values. Diagram courtesy of Virgil Lueth.

Figure B3. Eh-pH diagram of types of iron ions and solid phases (pyrite, vivianite) in system of water, sulfur, and phosphorous, calculated under equilibrium conditions (Berner, 1962b). This diagram is used to illustrate the iron ions in solution such as Fe^{++} (aq) and $Fe(OH)_3$. Pyrite (FeS_2) is the stable solid phase at low Eh over a range of pH values. The solid phosphosiderite ($Fe(PO_4)2H_2O$) only precipitates under low pH and high Eh conditions not seen in the study area.

Iron and Manganese Coatings on Preexisting Grains

Iron and manganese are common in rock-forming minerals at and near the earth's surface. They both have different oxidation states depending on conditions of mineral formation and whether they have undergone weathering. As figures B3 to B5 show, in the presence of water, different ions and minerals are stable under different Eh-pH conditions.

Dissolution and Precipitation of Calcium Carbonate

The mineral calcite (calcium carbonate; $CaCO_3$) is a major rock-forming mineral in many environments and is a ubiquitous constituent of the land surface and dissolved in waters along the Jornada del Muerto. Thick limestone formations composed primarily of calcium carbonate are eroded from surrounding the mountains to bring boulders, cobbles, pebbles, and finer grains to the piedmont slopes. Dust brings silt- and clay-sized calcite particles to surfaces of other deposits where rain dissolves and reprecipitates the carbonate in the shallow subsurface as a soil horizon or takes it down to the water table, where it travels with the water until conditions change and calcite precipitates again. In many instances, surface water and groundwater are nearly saturated with dissolved $CaCO_3$. The main chemical reactions of calcite in contact with water are the formation of calcium ions, various carbonate species, and hydroxyl ions.

$$CaCO_3 + H_2O \rightleftharpoons Ca^{2+} + HCO_3^- + OH^-$$
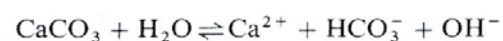
If the system is in contact with the atmosphere containing carbon dioxide (CO_2), that gas may either be
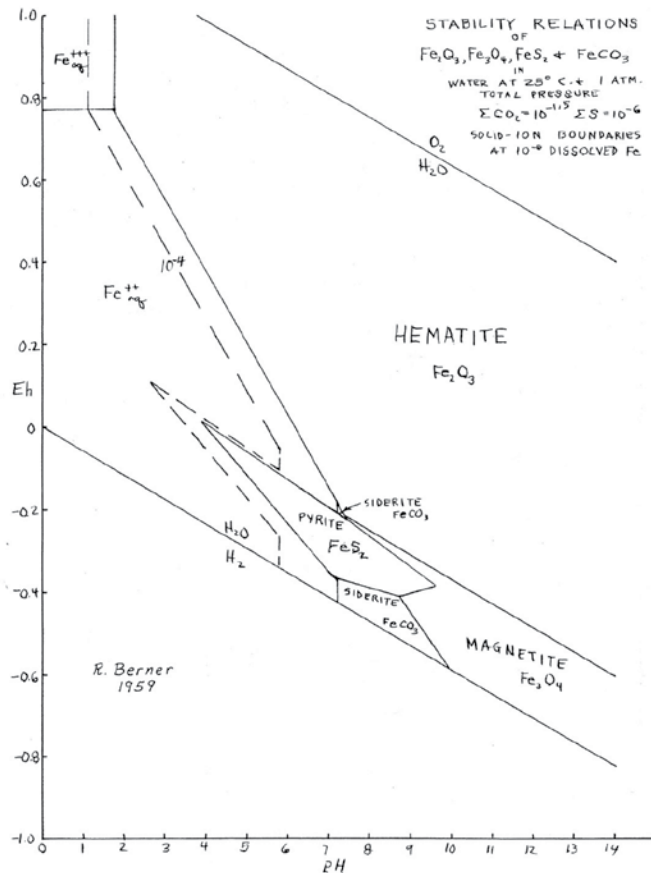
Figure B4. Eh-pH diagram showing dissolved ions of iron and solid phases in water also containing dissolved sulfur and carbon dioxide (Berner, 1962a). Note that hematite is the stable phase over the upper part of the Eh range for water. In nature, although hematite is common, a rust-colored hydrous mineral called goethite (α-FeOOH) and other hydrous iron phases are more common and are precursors to hematite. Also note that in the presence of dissolved CO_2, the field of pyrite stability is shrunk and siderite ($FeCO_3$) and magnetite (Fe_3O_4) are solids at low Eh and a range of high pH.

Figure B5. Eh-pH diagram showing dissolved ions of manganese and solid phases in water also containing dissolved carbon dioxide (Eckstrand, 1962). Note that under middle to low Eh conditions and pH below 9, Mn^{+2} ions remain dissolved. As waters become oxygenated (upward on diagram, and upward toward the surface of the water table), manganite and/or pyrolusite precipitate, forming black sooty coatings on preexisting grains of sediment.

given off by the water or taken up by the water to change the amounts of various carbonate species:

$$H_2O + CO_2$$
$$\updownarrow$$
$$CaCO_3 + H_2CO_3 \rightleftharpoons Ca^{2+} + 2HCO_3^-$$

This exchange depends on changes in temperature, pressure, organic activity, and decay of organic matter (Krauskopf, 1979). For example, if temperature rises, CO_2 is given off by water, driving the equation to the left and precipitating calcite. If decay of organic matter produces acids, calcite is dissolved, moving the equation to the right.

The dominant carbonate species in solution depends on the pH of the water and dissolution of calcium carbonate can shift the pH to being more basic (pH greater than 7). See Figure B6.

Figure B6. Diagram showing the concentrations of different dissolved carbonate species in water depending on pH of the system. H_2CO_3 is carbonic acid, most abundant an pH <6. HCO_3^- is the bicarbonate ion, most abundant between pH 6 and 11. CO_3^{-2} is most abundant in very basic solutions.

As mentioned above, calcium carbonate (commonly called caliche) builds up as a subsurface soil horizon 0.5–3 m below stable surfaces in semi-arid landscapes. The older surfaces have increased amounts of pedogenic (soil-generated) carbonate, designated with descriptors of stages from I (least) to VI (most). The stages IV through VI take millions of years to form. In stages II-VI, nodules of calcium carbonate can form in soils, but they also can form beneath water tables. Unfortunately the term "caliche" has also been applied to calcium carbonate precipitated along gullies—"gully bed caliche" or cementation. At some localities, it is difficult to determine whether the carbonate nodules are from soil-forming processes, from groundwater processes, or from both (Table B2 and Figure B6).

Evaporite minerals at the capillary fringe

Some chemical constituents in water are more soluble than others and are less apt to come out of solution than others. When water is evaporated, these constituents may form "salts" or evaporite minerals ("evaporites") which are combinations of cations such as Ca^{+2}, Na^+, K^+, Fe^{+3}, Mg^{+2}, Mn^{+2}, and anions such as Cl^-, SO_4^{-2}, CO_3^{-2}. The most common evaporites identified along the trail corridor are gypsum ($Ca(SO_4)2H_2O$), halite (NaCl), and thenardite (Na_2SO_4).

Table B2. Stages of calcium carbonate accumulation in desert soils by Gile et al. (1981) and Monger et al.(2009).

The stages of carbonate accumulation _1/

Stage and general character	Diagnostic carbonate morphology	
	Gravelly sequence	Nongravelly sequence
I Weakest expression of macroscopic carbonate	Thin, discontinuous pebble coatings	Few filaments or faint coatings
II Carbonate segregations separated by low carbonate material	Continuous pebble coatings, some interpebble fillings	Few to common nodules
III Carbonate essentially continuous; plugged horizon forms in last part	Many interpebble fillings	Many nodules and intermodular fillings
IV Laminar horizon develops	Laminar horizon overlying plugged horizon	Laminar horizon overlying plugged horizon
V Initial brecciation, recementation, and pisolith formation in the upper part of the laminar-plugged zone		
VI Multiple generations of brecciation, recementation, and pisoliths are common. Stage VI horizons also have higher bulk densities and carbonate contents than do stages IV and V.		

1/ The stages of carbonate accumulation follow Gile et al. (1966) and Birkeland et al. (1991). Pisoliths are subangular to spherical bodies, ranging from 2 mm to more than 10 mm in diameter, that have concentric coatings of carbonate around a nucleus that commonly consists of fragments of laminar and/or massive carbonate.
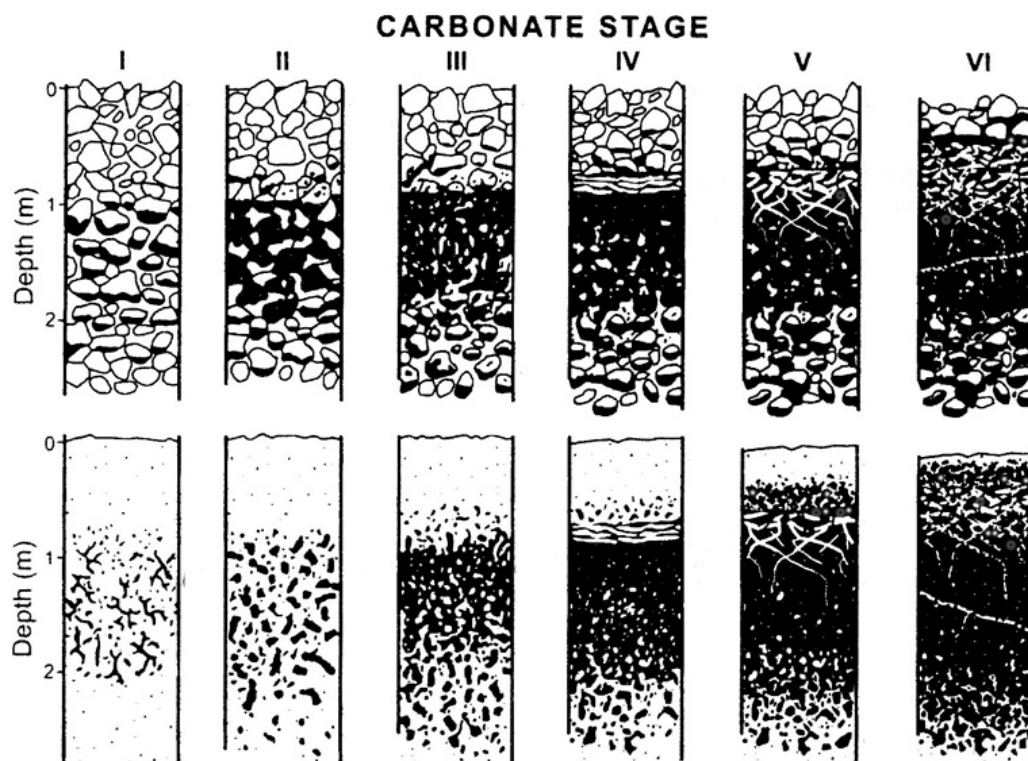
CARBONATE STAGE

Figure B6. Stages of calcium carbonate accumulation in desert soils. Upper row, coarse parent material; lower row, fine-grained parent material (modified from a diagram by Bruce Harrison in Schaetzl and Anderson, 2005).

Modern Surface Water and Shallow Groundwater Locations

Figure M-1. Unnamed spring, Jose Canyon. This spring is located just outside of project corridor, 3.6 miles southwest of Ojo del Muerto spring. The spring emerges in a gravel bed beneath the road. The spring comes up along a fault and is found in a syncline that funnels water toward the fault. No obvious spring deposits at the site, indicating that minerals in the water do not precipitate when reaching the atmosphere.

Figure M-2. McRae Canyon. Overlooking canyon to the northwest from hillside above present location of Ojo del Muerto spring. Note water in drainage channel and white evaporites on sandbars in arroyo. Historic Fort McRae located around curve above channel to left.

Figure M-3. Vertical dike. Dike (Ti; dark brownish gray under shovel) cutting gray, well cemented sandstone of the Cretaceous Crevasse Canyon Formation at Big Red Windmill, Hackberry Draw. No difference in cementation or flow of shallow subsurface water is observed at this dike. While there is no indication that this dike has obstructed flow, this illustration has been included because a similar dike in McRae Canyon may have influenced the location of historic Ojo del Muerto spring (see Figure M-4).
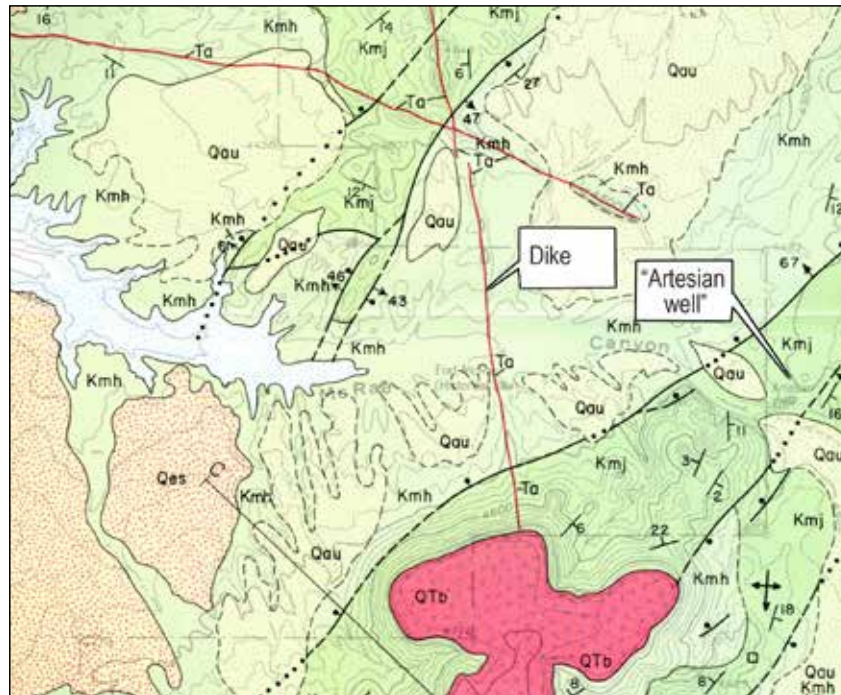
Figure M-4. Geologic map showing north-trending andesite dike (Ta; our Ti) crossing McRae Canyon at Fort McRae Historic Site. This map is a portion of the Elephant Butte quadrangle by Lozinsky (1987). The dike crosses faults and intrudes Cretaceous Jose Creek member (Kmj) and Hall Lake member (Kmh) of the McRae Formation (our Bks). Other map symbols include Plio-Pleistocene basalt lava flows (QTb), undifferentiated alluvium (Qau; similar to our Qvo), eolian sand sheets (Qes), and the reservoir level (blue stipples at 4,400 feet elevation). The dike runs just east of Fort McRae and reportedly forced water to the surface at the fort until construction of a reservoir upstream from the Fort by AT&SF Railroad Co. in the 1880s diverted this flow (Department of the Interior, 1893). Note, "Artesian Well" marked on map to the east of Fort McRae is the present location of the Ojo del Muerto spring.

Figure M-5. Google Earth ™ image showing the remains of Fort McRae in lower left, with dike crossing drainage to east. Where dike crosses the channel is the historic location of the Ojo del Muerto spring. Present location of spring is upstream to the right.

Figure M-6. Present location of Ojo del Muerto spring, McRae Canyon. View is downstream along channel. Major outflow from spring enters channel from left in center of photo, just downstream from the larger cottonwood tree on the left bank of the channel.

Figure M-7. Sandstone beds exposed as eroded ledges in bottom of McRae Canyon, just upstream from primary outlet of the spring, at the present day location of Ojo del Muerto Spring. X-ray diffraction analysis (XRD) of white evaporate crust seen in photo identified as a combination of thenardite and halite (Na_2SO_4, $NaCl$).

Figure M-8. Seep in arroyo, near JM-508, McRae Canyon. Photo was taken March, 2014, six months after heavy monsoon rains. The extensive algal growth indicates that water has been present at the surface for a substantial period of time. In addition, the lack of evaporite minerals in the channel indicates that the water is low in dissolved salts, suggesting that the water in the channel is recently derived from rainfall rather than from a deeper subsurface flow path. This intermittent water supply is approximately half way between Ojo del Muerto spring and the large playas near Engle. It extends upstream at least 1.5 km from JM-508.

Figure M-9. Ash Canyon Spring (JM-509). This spring lies outside of the project area to the west. At this location, ground water rises to the surface above bedrock. Shallow alluvium discontinuously covers bedrock along the channel length. Numerous such seeps/springs occur along this and neighboring canyons.

Figure M-10. Mescal Spring (JM-500) in Mescal Canyon. This spring lies to the west of Ash Spring, and discharges under similar circumstances. Additional seeps/springs are located in this canyon.

Figure M-11. Shallow ground water in channel deposits, Aleman Draw seep (JM-506). The arroyo channel consists of shallow sand and gravel over Eocene bedrock (Love Ranch Formation). Location is just downstream from railroad trestle crossing Aleman Draw. Photo (and water sample) were taken October, 2013, one month after major monsoon rainfall.

Figure M-12. Hole dug in arroyo channel by animals to access shallow ground water, Yost Draw. Arroyo channel consists of shallow sand/gravel over Eocene bedrock (Love Ranch Formation). Location is east of CR A-13, and south of Aleman Draw.

Figure M-13. Collecting water sample from shallow ground water, Yost Draw seep (JM-507). Note evaoporites along capillary fringe in channel alluvium, indicating shallow water table. White powdery crust is made of sulfate evaporites such as gypsum ($CaSO_4 \cdot 2H_2O$), thenardite (Na_2SO_4), or bloedite($Na_Z Mg(SO_4)2 \cdot 4H_2O$). Depth to water at this location during March 2014 was 15–20 cm. Location is east (downstream) of animal water hole seen in figure M12.

Figure M-14. Bifurcating channels on floodplain playa (Qlf) in Jornada Draw northwest of Prisor Hill. Playa is presently dry, but undergoes periodic inundation. Note multiple sets of polygonal cracks forming fissures in the dry clay and rubbly texture of broken clay platelets at the surface of the channels. Tobosa grasses hide uplifted blocks of clay called "gilgai." These features are common in clays that swell when they are wet and shrink when they are dry.

Figure M-15. Hand dug concrete lined cistern. Cistern is located in the southern portion of the project area. Shaft is 5 ft wide by 7 ft deep, but may be deeper as base of shaft filled with sediments and debris. Materials excavated during the construction of the cistern were apparently used to create an earthen berm to channel runoff from Barbee Draw into the mouth of cistern. The water was probably used for livestock. While this indicator of surface water is not strictly speaking geological in nature, it does show that periodic sheet wash was frequent enough and substantial enough to induce people to attempt to harvest and store these waters.

Figure M-16. Second hand dug concrete lined cistern. Shaft is 4 ft wide by 8 ft deep and excavated into small remnant of Qp2 surface. Shaft may be deeper. As with the cistern described in figure M15, this water feature appears to have been filled with runoff from Barbee Draw.

Locations with Indicators of Past Shallow Groundwater

Figure P-17. Stains and mineral precipitation in late Quaternary alluvium (Qva). Staining indicates higher levels of the water table exposed in an arroyo wall along Cañon del Muerto drainage. Maroon sandstone at base is Cretaceous McRae Formation (Rks). Lower alluvium is pebbly sand with many cross-cutting channels. Rusty brown and dark gray irregular masses of iron and manganese oxides indicate chemical precipitation in past shallow groundwater. Finer-grained alluvium above top of rod is coated with evaporite minerals and calcium carbonate along a subsurface horizon, probably indicating a paleo-capillary zone above the water table. Rod is 1.5 m long, marked in 10 cm increments.

Figure P-18. Closer view of stains and cementation in late Quaternary alluvium (Qva). Staining exposed in an arroyo wall along Cañon del Muerto drainage. Rusty brown and dark gray irregular masses and stains of iron and manganese oxides indicate alteration within the saturated zone of past shallow groundwater.

Figure P-19. Arroyo cut, McRae Canyon. Multiple levels of iron and manganese oxide coatings are visible in the center of the profile. Lower white evaporite in capillary fringe above bedrock may indicate lateral movement of local groundwater along contact. Closeup of manganese and iron oxide coatings in arroyo cut bank, McRae Canyon.

Hackberry Draw

Figure P-20. Rust and evaporate minerals in lower arroyo wall may indicate shallow groundwater in past. Location is in Hackberry Draw. Shovel handle is 1 m long.
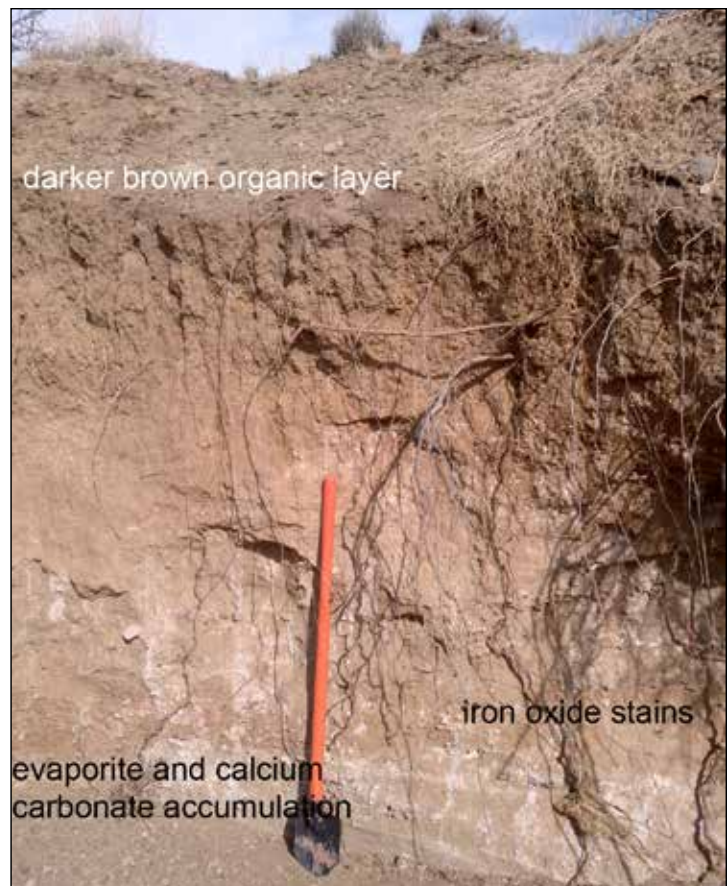
Figure P-21. Elevated organic matter exposed in arroyo profile. Pale gray and dark brown horizons at top of shovel handle indicate elevated organic content and may represent zone of wet soils and possibly a shallow groundwater level in the Holocene epoch. Photo was taken in Hackberry Draw.

Figure P-22. Fault zone, Aleman Draw. Fault zone with evaporite minerals and calcium carbonate precipitated along fractures in fault zone cutting Cretaceous sedimentary rocks (Rks) in Aleman Draw.

Aleman Draw
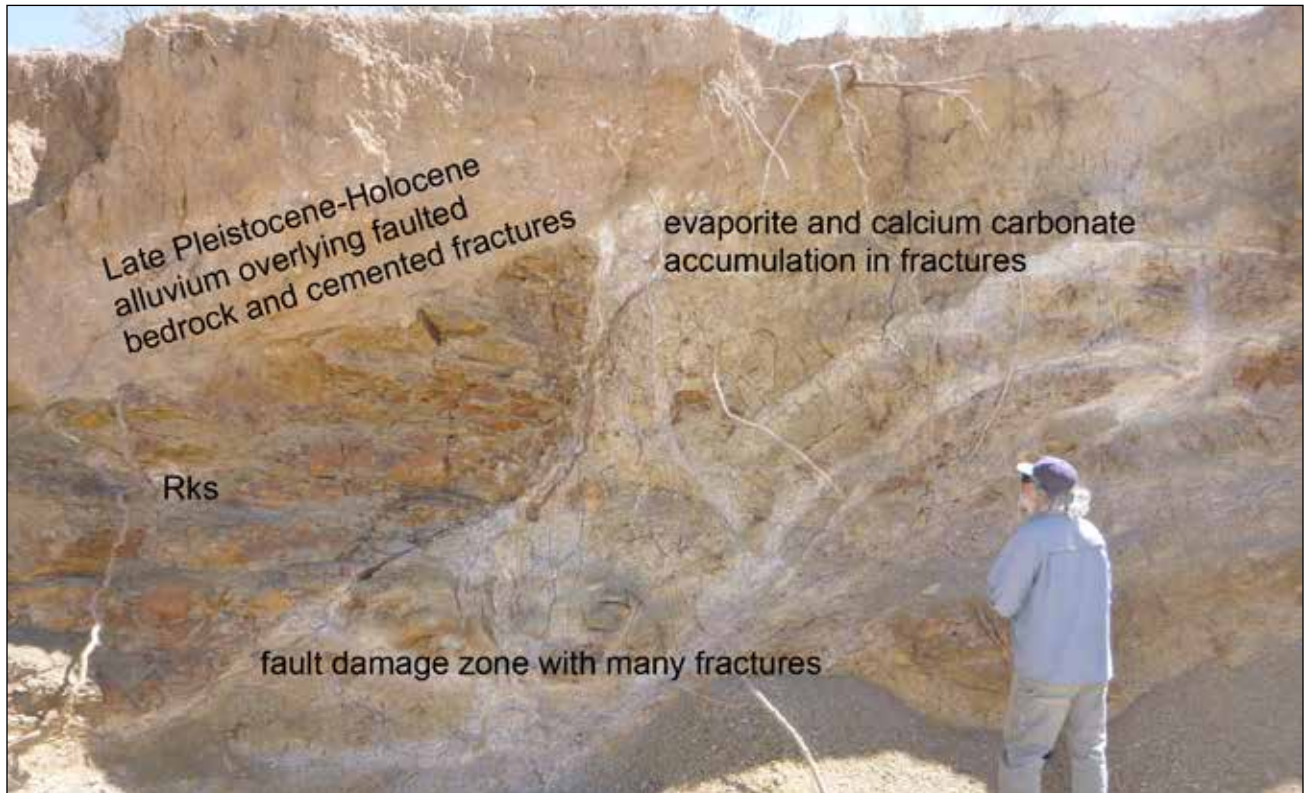
Figure P-23. Close up of fault zone with calcium carbonate and evaporite minerals in Aleman Draw. Note Quaternary alluvium on upper left truncates fault and Cretaceous bedrock. Precipitated minerals along the fault zone indicate that groundwater moved along the fractures, although direction of movement has not been determined.

Figure P-24. Secondary calcium carbonate precipitation high in arroyo cut bank, near railroad trestle, Aleman Draw. The cemented calcium carbonate indicates elevated groundwater levels in the Pleistocene (>11,000 years ago).

Figure P-25. Angular unconformity along Aleman Draw. Angular unconformity between maroon sandstone and mudstone of the Love Ranch Formation (Rts) and overlying late Quaternary alluvium (Qap) along Aleman Draw at Aleman, NM. Note white deposits of evaporite in alluvium above the unconformity, indicating shallow groundwater during the Holocene. Rod is 1.5 m long.
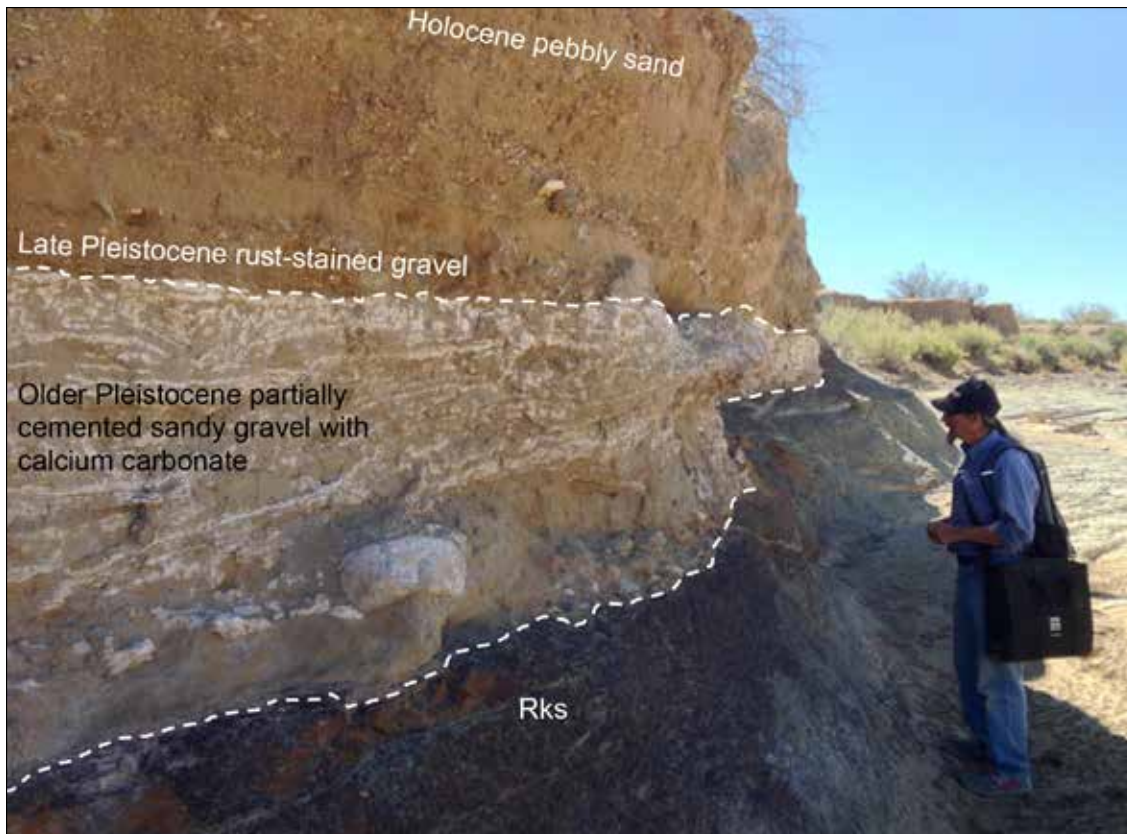
Figure P-26. Two unconformities exposed in Aleman Draw. Lower maroon and gray unit is McRae Formation (Rks). The overlying pale tan unit with pebbly base is Quaternary alluvium (older than 100,000 years). Whitish blobs and stringers are calcium carbonate cement showing elevated groundwater levels in the Pleistocene (>11,000 years ago). The uppermost reddish-brown unit with a pebbly base is late Quaternary arroyo alluvium (Qap) with no indication of shallow groundwater.
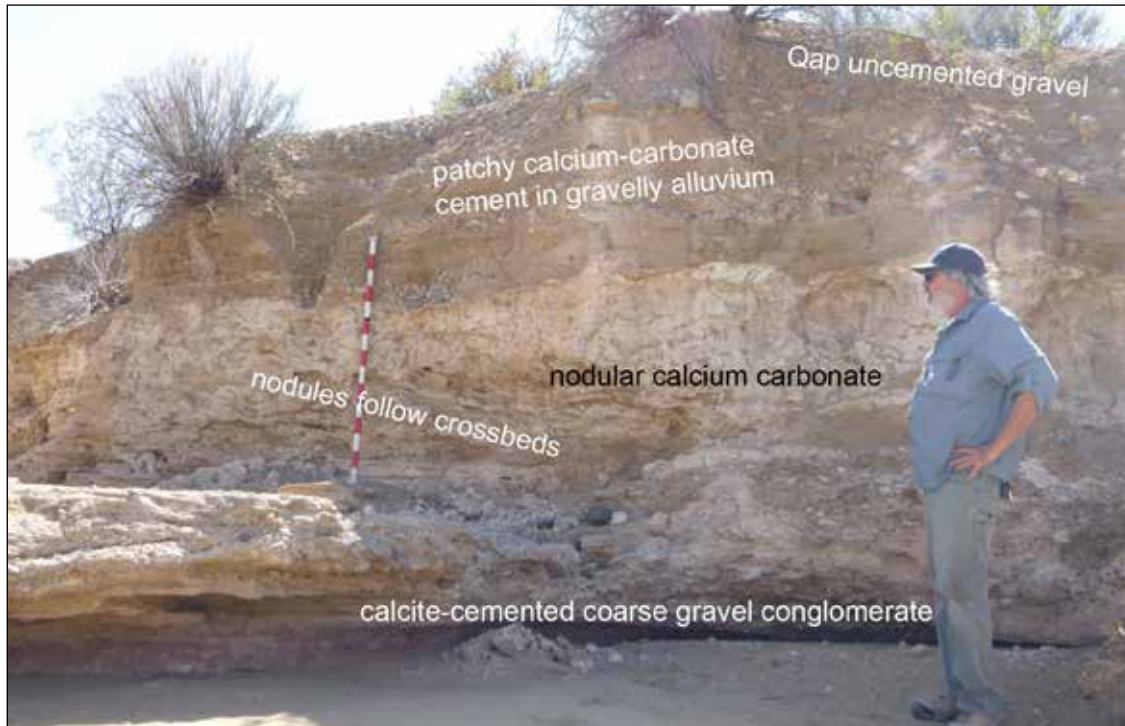
Figure P-27. Multiple Pleistocene-age episodes of calcium-carbonate cementation and shallow groundwater-levels revealed in wall of Aleman Draw west of the railroad trestle. Lower coarse gravel and sand are cemented with poikilotopic (coarse crystals) of calcite. Middle unit of white, fine-grained, nodular calcium carbonate may be from a separate episode of growth of nodules in a capillary fringe zone after initial precipitation pedogeni-cally in a soil. Crossbedded sand and gravel above 1.1 m on 1.5 m rod is partially cemented with fine-grained calcium carbonate. Coarse gravelly alluvium (Qap) at top is not cemented nor stained.

Figure P-28. Indications of shallow groundwater in the past in exposures along the North Fork of Putnum Draw. Lower half-meter is clayey alluvium with white evaporite minerals and calcium carbonate accumulation indicating shallow groundwater—possibly a wet meadow. Rusty iron-oxide stained alluvium is in contact with the clay and also indicates shallow groundwater during the Holocene. Dark brown alluvium above top of 1.5 m rod indicates a period of soil development before burial by more recent alluvium (Qap).
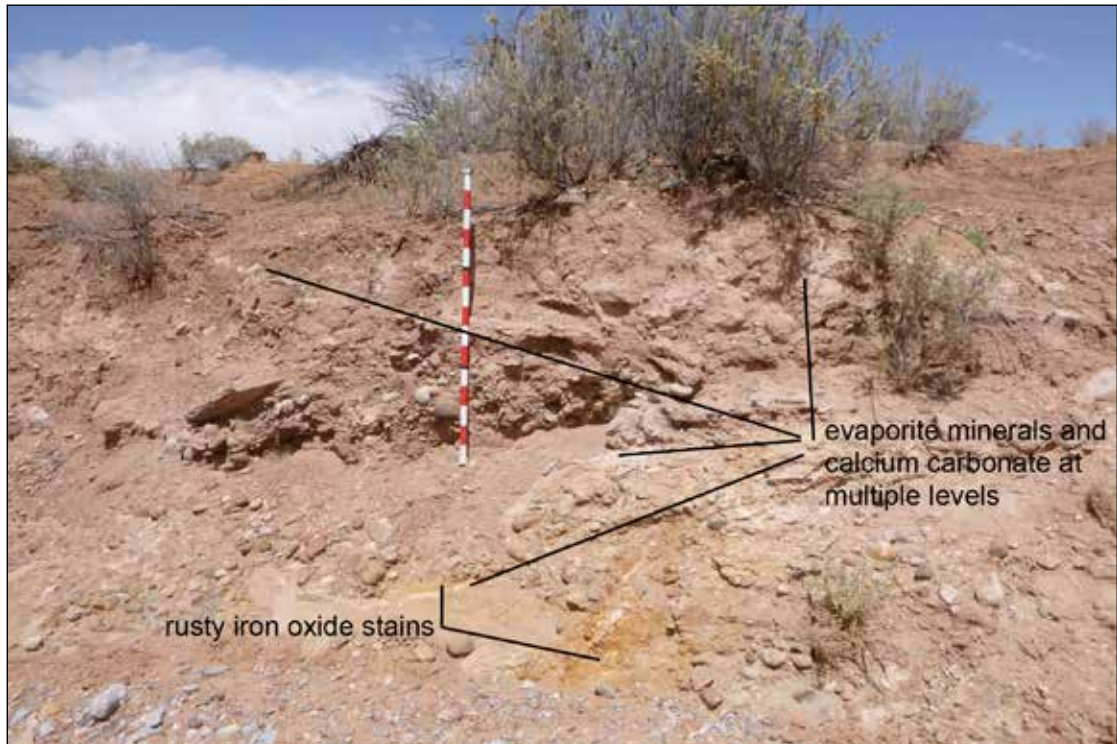
Figure P-29. Rust stains (iron oxide) and evaporite minerals exposed in late Quaternary deposits in arroyo wall of Yost Draw. Rusty iron oxide suggests an oxidizing wet environment at the top of a zone of shallow groundwater.

Yost Draw

Figure P-30. Oriented poikilotopic concretions. Concretions found in sandstone cemented along unconformity between maroon Love Ranch Formation (Rts) and Quaternary alluvium (Qap) in Yost Draw. These oriented concretions with macro-calcite indicate subaqueous precipitation of calcium carbonate and the paleo-flow direction (downstream).

Figure P-31. Large concretions cemented by calcium carbonate and iron oxides developed in sandstones of the Cretaceous Crevasse Canyon Formation (Rks) probably developed under saturated conditions during late Cretaceous time. The sandstone is also cemented with lesser amounts calcium carbonate and clay.

References

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APPENDIX C

Model Descriptions

Playa Modeling

The first model we discuss attempts to simulate the filling and decline of the playas in the area. Four playas; Engle Lake (a) and (b), Jornada Lake, and an unnamed playa, were examined for this study. Landsat imagery, which are satellite photos taken every 16 days, allowed us to create a record of surface area of the playas throughout the past 30 years. This was done by using an area measuring tool to trace the extent of each playa, when they filled, and as they slowly dried up. The satellite imagery showed an interesting phenomenon. We found that, not all of the playas would flood after a large storm event. Sometimes one playa would fill while the others would remain dry, while sometimes the other three would flood, leaving one dry (Figure 1). Several

hypotheses have been proposed to explain this irregularity. As the playas dry, the playa sediments desiccate and create large cracks in the playa bed. These cracks may result in rapid draining of the water. The development of these cracks to varying degrees in different playas may result in varying responses of different playas to the same precipitation regime. A second hypothesis takes localized precipitation into account. Localized summer thunderstorms associated with the North American Monsoon likely result in an uneven spatial distribution of precipitation, causing some playas to fill while others remain dry. To study the playa flooding we used the precipitation record from Elephant Butte, located roughly 15 km away from the playa area. We found that even from this relatively proximal precipitation record, there were occasional flooding events that corresponded
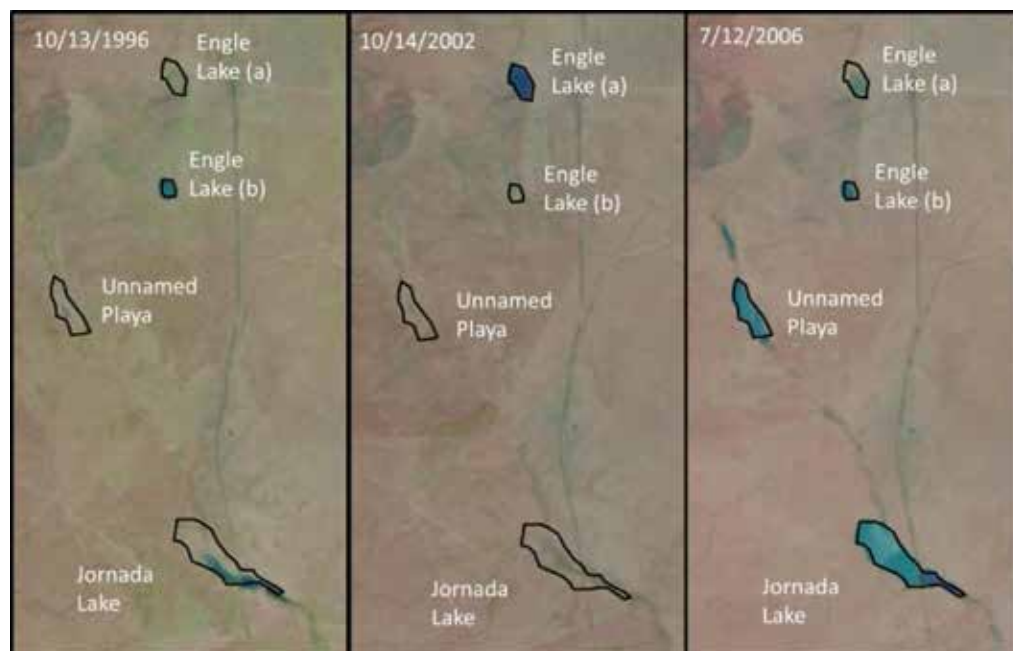
Figure C-1. Above are three Landsat captures of the playa region captured after storms in 1996, 2002, and 2006. This figure emphasizes the irregularity of which playas flood following a storm.

with very small storms. To smooth the data for modeling purposes, the four playas areas were treated as a single playa.

Using the temporal record of flooding, as well as the precipitation record collected at Elephant Butte, we filtered the data to find a relationship between the magnitude of storms and the filling of the playas. By matching the record of flooding events with significant storms we found that the best fit threshold for flooding to occur came when more than two inches of rain fell over the period of a week. Next, we fit an exponential regression to match the rate at which the playas dried up following being filled. This takes into account the magnitude of the filling event, matches the observed decline in the area of the playas with time as result of evaporation and surface water infiltration, and predicts how long water remains in the playas (Figure 2).
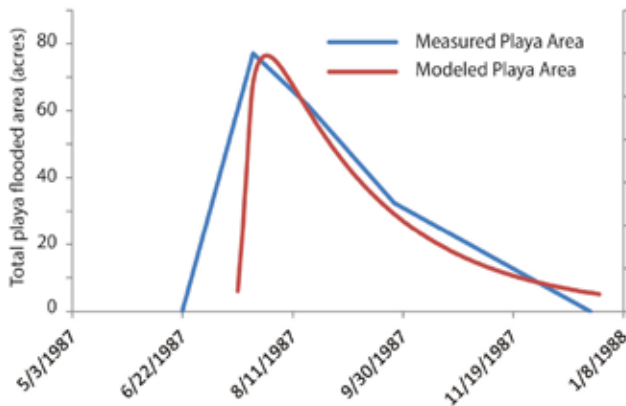
Figure C-2. Comparing the measured playa area to the modeled playa area.

Modeling of springs

Two rudimentary 1D Boussinesq groundwater flow models were constructed in Excel to estimate discharge at the springs, assuming saturated, horizontal flow through a homogeneous aquifer. One model describes the local springs and seeps, and the other models the regional spring, Ojo del Muerto. There are several inputs for each model we had to estimate; these include hydraulic conductivity (K), gradient length the aquifer flow path (x), location of recharge, and the amount of recharge infiltrating to the aquifer (R). In a confined case specific yield (h/x) and aquifer thickness (b) are used.

$$\frac{\partial^2 h}{\partial x^2} = \frac{S_y}{Kb}\frac{\partial h}{\partial t} + R$$

Local Springs and Seeps Modeling

We assume the water discharging at the local springs and seeps originates within the individual watersheds, up gradient of the water source. This assumption is based on the groundwater age (Figure 26), and water chemistry (Figure 24) of the discharging water (OFR 573, page 31). As result, we determined the recharge mechanism for these water sources originates as overland runoff, from large storms. The modeled flow path runs parallel to the stream, where these springs and seeps occur. This means the location of recharge is assumed to cover the entire model. As runoff is the primary water source for the model we determined the 'length of the aquifer' by finding the average distance to the boundary of the watershed from the discharge point, which is approximately 4 km (2.5 mi). The watersheds for the springs and seeps were delineated using the Spatial Analyst toolbox in ArcGIS.

To determine available recharge, runoff calculations for this region were used to estimate the minimum rainfall required to create overland flow. Using these equations, we can estimate when runoff is likely to occur due to excess precipitation (developed by the USDA Natural Resources Conservation Service). Runoff calculation equations are:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

$$S = \frac{1000}{CN} - 10$$

Where Q is the runoff, P is rainfall, S is the potential maximum retention after runoff begins, and CN is the curve number which is determined by the USDA, and that takes into account vegetation type, and land slope.

Using this method we found storms producing more than and 0.97 inches of rain result in runoff. As result, we filtered the precipitation data for storms that met or exceeded this threshold. In the southwest, approximately 5% of runoff is estimated to recharge the shallow aquifers (Wilson and Guan, 2004). The final recharge value that is entered into the model throughout the modeled domain is 5% of the precipitation produced by storms large enough to result in runoff (>0.97 in). The gradient of the system was found by taking the difference between the highest elevations in the watershed and the elevation of the spring, and dividing by the aquifer length. Hydraulic conductivity is calibrated to be roughly 16 m/day as the sediment is a highly conductive sand and gravel

alluvium. The model solves for head along a transect of the drainage basin each day throughout the entire period which we have precipitation data. The boundary conditions on either side of this 1D model are fixed head.

Regional Spring Modeling

The Ojo del Muerto spring is thought to have a very different recharge mechanism. The age of the groundwater and the water chemistry tells us that the water discharging at the spring entered the aquifer approximately 11,000 years ago. This tells us that the flow path which supplies water to the spring is very long and isolated from the surface runoff. Based on water chemistry analyses we determined that chemical signature of the spring matches other wells in the area that tap the McRae aquifer (Geohydrology Associates, 1989). Using geologic cross sections, and the water table map we look for areas where the McRae aquifer is not confined, or sections which would allow infiltration through the impermeable layers above it. We determined that the most likely location for groundwater to recharge this system is from the playa lakes.

With this information another Boussinesq model was constructed, which models the head along a profile from the playas and spring (Figure 30, OFR 573, page 38). The length of the aquifer flow path being modeled is the distance between the playas and the discharge point, 9 km. The gradient of the model was found using the difference in elevation at the playas and the spring, divided by the aquifer length. Recharge to the model occurs only at the playas so only one cell on the edge of the model receives recharge. Because we assume that the recharge to the spring is the result of infiltration from the playa lakes we use the model that estimated when the playas were full to account for recharge. For recharge to occur the water must infiltrate through the playa sediments, which generally have very low conductivity values (~0.01 m/d). As result, when the playas are full, 0.01 m/d of recharge is assigned to the model. Even with very low values, significant volumes of water can infiltrate creating very steady sources of recharge when the playas are flooded in this otherwise dry environment.

Next, we estimated the hydraulic conductivity value for the aquifer by using the travel time water takes to move from the recharge location, to the spring (11,000 years, based on uncorrected C14 dates). The estimated hydraulic conductivity was 1 m/day. This agrees with hydraulic conductivity tests conducted in the McRae which range from 0.5 to 1.7 m/day (Geohydrology Associates, 1989). The boundary conditions on either side of this 2D model are fixed head, playa elevation, and spring elevation.

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