Technical Report

Geologic Analogs of Engineered Barriers: Natural Examples of Very Long-Term Performance of Layered Geologic Materials

by

Susan D. Hovorka

Prepared for
Texas Low-Level Radioactive Waste Disposal Authority
under Interagency Contract CON-97-028.

Bureau of Economic Geology
Noel Tyler, Director
The University of Texas at Austin
Austin, Texas 78713-8924

August 1997

TABLE OF CONTENTS

FIGURES

ABSTRACT

Materials in the vadose zone are modified through time by a number of processes. These processes have the potential to adversely effect the performance of engineered barriers capping waste disposal facilities. In this study, the alteration of layered natural materials from 10 sites was described. In order for the materials to serve as partial analogs for typical arid-region engineered barrier, sites were selected to (1) have a difference between mean annual evaporation and rainfall greater than 40 inches rainfall and less than 50 days continuously below freezing; (2) be multilayered with maximum grain size contrasts (fine grained materials overlying gravel); (3) be well dated with ages less than 500,000 years. Site access and quality of exposure were also critical variables.

The selected sites are composed of fluvial and lacustrine deposits and range in age from 500 to 22,000 years. Fine grained materials include clay, silty clay, diatomite, and calcareous lake deposits. Coarse grained materials include gravel, gravel with sand matrix, and gravel with mud matrix.

Modification of sediments includes penetration by roots, cracking of fine grained materials in response to shrink/swell, infiltration of fines into gravel, precipitation of carbonate, limonite, manganese oxides and hydroxides, gypsum and halite, and oxidation and reduction of iron associated with fines. The two main variables that can be related to intensity of alteration are (1) geomorphic setting and (2) composition of fine materials. The most alteration was observed in deposits now in topographic lows; deposits on hillsides underwent the least alteration. Clayey deposits showed more evidence of shrink-swell and cracking than diatomites. Topographic effects and mineralogy have more influence on the amount of alteration than the age of the deposits. Infiltration of fine materials into gravels is common but little can be deduced about the rates and processes driving this type of alteration. Relationships to constrain the timing of infiltration could not be developed. It is probable that much or all of the infiltration of fine material into gravel occurred in the depositional environment.

INTRODUCTION

Engineered barriers constructed primarily of earthen materials are designed as a principal containment technology at disposal facilities throughout arid regions of the western United States. The disposal of low-level radioactive materials (as at the proposed Texas low-level radioactive waste disposal site in Hudspeth County, Texas), toxic and hazardous substances, and mixed wastes rely on similar methodologies.

This project documents the physical, chemical, and mineralogic changes in geologic deposits that have been modified by natural processes for thousands of years as analogs to what might happen to engineered barriers over a long time frame. The role of fine grained clays and marls in limiting vertical permeability and the extent to which *in situ* gravels function as capillary barriers to flow in the unsaturated zone were of particular interest. Results of this study are intended to be applicable to the other arid zone disposal sites as well to the Texas site. The purpose of this study is to improve conceptual understanding of natural processes that alter the performance of engineered barriers over a long time frame, and therefore increase confidence in cap performance. Improved understanding may also lead to innovations in engineering designs.

This final report summarizes approach, methods, activities, analytical results, and interpretations resulting from this project and makes recommendations for future work.

Methods

Engineered barriers use a variety of layering and grain size specifications. Bibliographic research was used to identify the common features of proposed, experimental, operational engineered barriers, as well as several designs for the proposed Texas low-level radioactive waste disposal facility. This information was compiled to determine the general stratigraphy, grain size, composition, and thickness required for a deposit to function as an analog. Climatic parameters were used to define the geographic areas suitable for analog sites to the Texas site.

A bibliography was compiled of archeological and Quaternary stratigraphic studies including about 250 references in the defined geographic area. Active researchers were contacted to identify additional potential sites. From this compilation, ten areas in Texas, New Mexico, Arizona, Utah, and California were selected for field evaluation. Layering and grain size specifications, climatic range, previous work, dating, site accessibility, and quality of outcrops were the key selection criteria.

The selected sites were evaluated in the field during July 1996. Published and in-progress research results, stratigraphic and dating information, topographic and geologic map data, and land access information were compiled for each site for use in the field. Each site was described, photographed, and sampled in the field. Quantitative and qualitative observations made on the outcrop analogs document the impact of the materials and layering in the analog site on long-term stability and hydrologic performance. More effective barriers were compared to those in which various types of failure have occurred. Description included (1) general characterization of the site, (2) description of the sedimentary stratigraphy, and (3) interpretation of the nature, amount and distribution of post-depositional alteration. Several measured sections for each site were used to describe the sedimentary stratigraphy in terms of bed thickness, texture, and sedimentary structures. Sample locations were identified on measured sections and each sample assigned a unique sample number consisting of a two or three letter site abbreviation, a section number, and the elevation in feet above the base of the section. Print photographs were used to document the general setting, the sequence in each exposure, and representative and significant lithologies in each section. Each unit was characterized in terms of alteration since deposition. Geologic observations were made to attempt to identify the conditions and processes under which these alterations took place.

Representative and significant unconsolidated and cemented Quaternary sediments were collected and 110 samples returned for analysis. Analyses for selected samples include inspection with binocular microscope, grain size analysis, acid insoluble residue, and examination for evidence of alteration using the scanning electron microscope (SEM).

Grain size and acid insoluble analyses were done on selected fine grained deposits by Mary Joe Schabel, Soils Laboratory, Department of Geography, University of Wisconsin at Milwaukee. Samples were air-dried, weighed and then treated with HCl until effervescence stopped. The supernatant was decanted, and the samples were washed until the supernatant pH was approximately neutral. The samples were then air-dried, weighed, dissaggregated, and set-up for hydrometer analysis. The Gee and Bauder (1986) particle-size analysis method was used (Schabel, 1997, written communication). One duplicate sample for ever ten samples was run; error in duplicates was 2 percent or less. The samples were wet-sieved for the sand fraction at the end of the hydrometer analysis. If the sieved sand percentage differed from the hydrometer percent values by more than 10 percent, the samples were rerun. Average error between the two analyses was $\pm$ 4 percent. High precision was not required, since the purpose is to compare the general texture of natural materials to those used in engineered barrier designs.

SEM analysis was done on the same samples at the Bureau of Economic Geology using a JEOL instrument. Fractured chips were mounted on brass stubs and gold-coated. Qualitative energy dispersive spectra (EDS) were collected with a Tracor system to aid in mineral identification.

Data packages for each site composed of bibliography, photocopied published and written communication, site locations from 1:24,000 USGS topographic maps, geologic setting; measured sections, sample locations, field notes, interpretation of alteration, and photographs were compiled and are archived at the Bureau of Economic Geology. Samples were also labeled and archived.

FEATURES OF ENGINEERED BARRIERS

The goal of this project is to identify natural sedimentary deposits that can be used as partial analogs to for prediction of the long-term integrity of engineered barriers. Natural sediments are not expected to be identical to engineered barriers, however, similarities in terms of grain size and layering of sediments are required, and observed patterns of failure in current engineered barrier designs pose some of the problems to be addressed. Therefore designs for engineered barriers and regional climatic parameters were compiled to serve as a basis for identification of analogs and a compilation of types of failure.

The regulatory requirements set forth in Environmental Protection Agency (EPA) documents for closure of hazardous, sanitary, and mixed waste landfills basically require the landfill owner to design and construct a barrier to minimize flow of water from the surface into the waste. Seven major types of engineered barrier designs are listed in a recent review paper (Hakonson, 1997):

- RCRA, subtitle C design, a multilayered barrier with compacted clay or geosynthetic clay as a hydrologic barrier;
- Handford barrier, multilayered design with crushed and basalt, composite asphalt, sand, gravel, silt, sandy soil;
- UMTRA rock armored barrier, which includes a compacted clay and silt hydraulic and radon barrier, sand, and a layer or riprap to prevent erosion;
- Capillary barrier, a multilayered barrier which impedes vertical flow because of contrasts the in hydraulic conductivity of fine grained material over coarse gravel;
- RCRA, subtitle D design, a single thick layer of compacted, low hydraulic conductivity soil covered by topsoil;
- Evapotranspiration cap, in which moisture flow through the barrier is limited by water up-take by plant roots and evapotranspiration through the leaves;
- Infiltration-control caps limit moisture flow through the barrier by enhancing runoff

A multilayered capillary barrier design (fig. 1) has been used for an experimental cap at the proposed Texas low-level radioactive waste disposal (Scanlon and others, 1997). Experiments with a geosynthetic clay liner and asphaltic concrete at 1.5 m depth are also underway at this site (Scanlon and others, 1997).

Failure of engineered barrier caps allows water to leak through the barrier and pool in the waste, potentially permitting contaminates to be mobilized and transported away from the site in groundwater, surface water, or other forms of surface transport. Some of the commonly listed failure concerns for engineered barriers include (Hakonson, 1997):

- Penetration of the low permeability intervals in the barrier by roots;
- Cracking of low permeability intervals in the barriers because of desiccation;
- Disruption of design elements by frost heave, animal burrowing, or waste compaction and subsidence;
- Breaching the cap or waste package by erosion or slope failure.

One failure scenario specific to capillary barriers is infiltration of fine material into underlying coarse material. Since the water storage capacity of a capillary barrier is generally improved by maximizing the textural contrast between layers (Stormont, 1997), this infiltration increases the risk of failure.

Layering

It is not possible or necessary for a geologic analog to precisely mimic an engineered design to provide useful information about possible or probable long term modification of that system. However, as a guide to the general stratigraphic characteristics of analog sites, the layering characteristics of 12 different representative proposed or experimental cap designs for hazardous or municipal solid waste were inventoried to determine the range and average. Total thickness of the barrier designs ranges from 1 to 7 m, with an average of 3. 5 m. Designs have 2 to 10 layers, averaging 5. One to three layers designated as low hydraulic conductivity units are present in all the designs. These vary in thickness from millimeter thick membranes to compacted soil 2 m thick, and include a

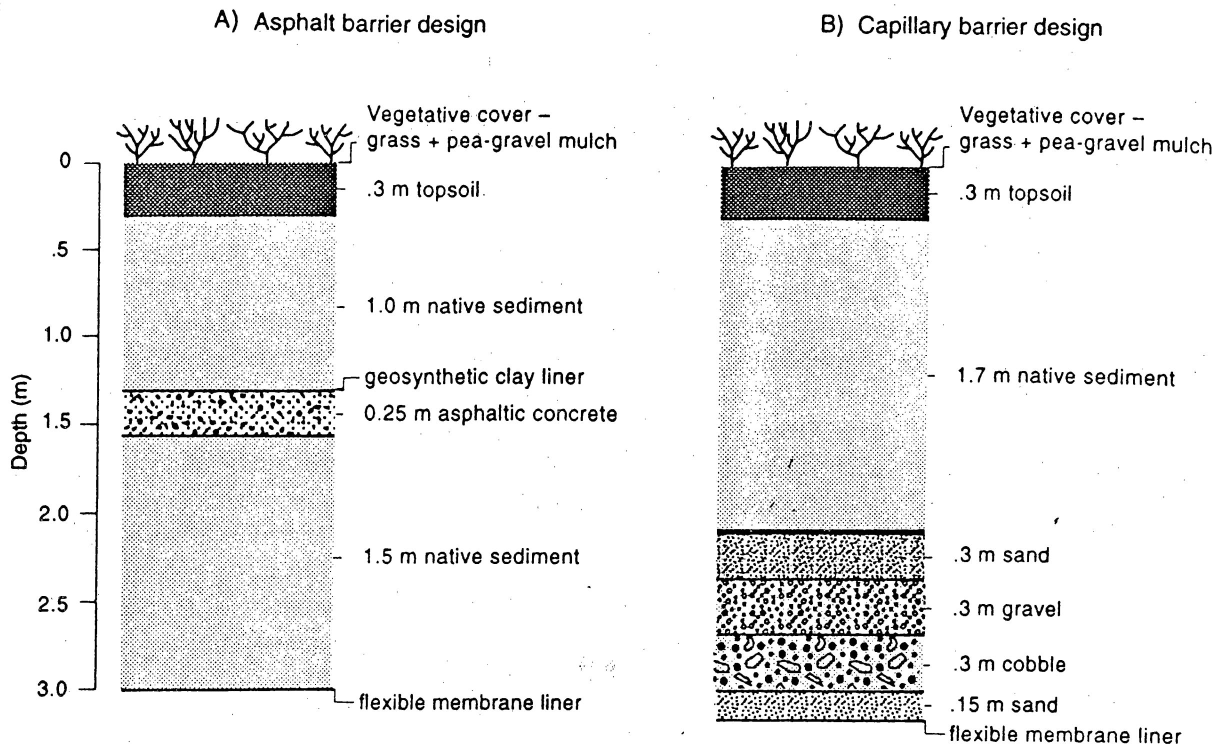


Figure 1. Representative engineered barrier designs installed as experimental caps at the Texas low-level radioactive waste disposal site (Scanlon and others, 1997).

variety of compositions. The coarse layers, which serve various functions for limiting erosion, venting gas, horizontal drainage, and as the coarse layer in capillary barrier design, include sand, gravel, and sand-gravel mixtures. Coarse layers range from 0.1 to 1.5 m thick, averaging 0.5 m. The design for an experimental barrier installed at the proposed Texas Low-Level site is shown in figure 1.

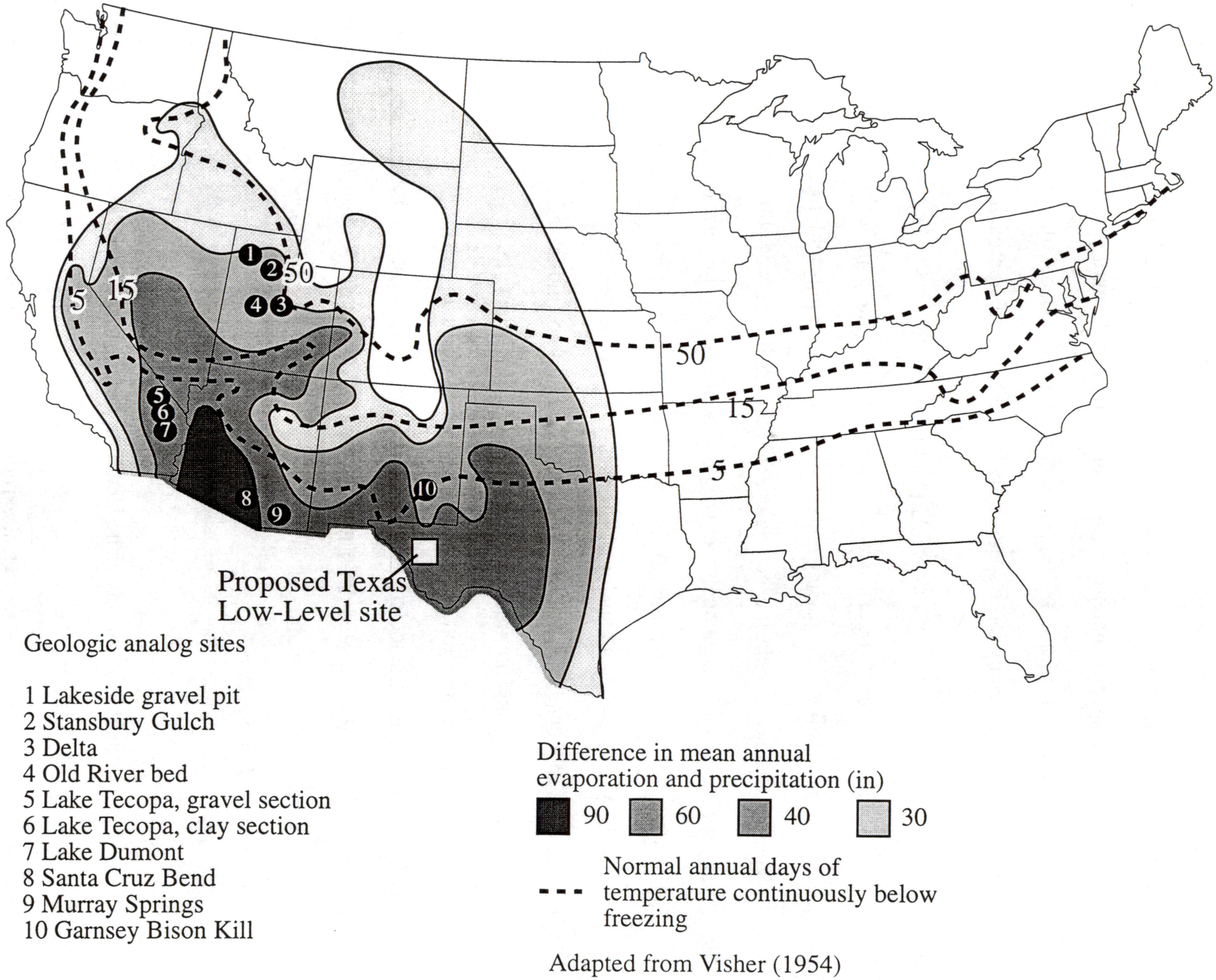
The optimum stratigraphy for analog sites was determined to have several meters of exposure that includes decimeter layers of contrasting low hydraulic conductivity material and gravel or sandy gravel. In addition, variability in bed thickness and texture within the site is desirable to observe any impacts this has on the long term alteration and moisture flux at the site. Variability in composition, thickness, and depth below surface of the low hydraulic conductivity unit is desirable for analogs, since cracking, rooting, and downward remobilization of fines are some of the major concerns for engineered barriers. In addition, reactive minerals or artifacts that have the potential for quantifying long term moisture flux were considered desirable in the analog sites.

Environments that commonly have appropriate stratigraphy and were prospected for analogs include pluvial lakes, alluvial deposits in valleys, and fan deltas. Archeological sites were considered as prospects because of their ages, emphasis on fine dating, and potential for reactive material usable for measuring alteration.

Climate

Moisture flux through sediments and consequent alteration depends on numerous local and regional variables. For the purposes of screening areas for sites to be considered as partial analogs to the proposed Texas low-level site, we used selected generalized regional climatic maps from Visher (1954). The difference between mean annual evaporation and precipitation was used as a general measure of aridity (fig. 2). Normal annual days of temperature continuously below freezing were used to screen areas for seasonality and eliminate those areas where deep freeze-thaw may be a dominant force in near surface alteration. The proposed Texas low-level site lies in the area where the

Figure 2. Sites for Geologic Analogs



difference between mean annual evaporation and precipitation is between 60 and 90 inches, and normal annual days of temperature continuously below freezing is less than 5. More detailed climatic mapping is available (U.S. Environmental Data Service, 1968), however in absence of site specific data such as elevation, relative humidity, albedo, surface roughness, evapotranspiration, (Burman and Pochop, 1994), detailed mapping may not group sites by climate any more specifically than the general approach.

ANALOG SELECTION

Potential areas in Texas, New Mexico, Arizona, Utah, and California were identified through literature review and telephone conversations with local specialists (table 1). These areas have similarities to engineered barriers in terms of climate, texture, and stratigraphic sequence. Data quality criteria for ranking these sites are: (1) reliability of dating (2) appropriate age (younger than 500,000 years), (3) access to the site can be obtained, (4) suitable for an analog to engineered barriers in terms of reported sedimentary textures and sequences, (5) suitable for use as an analog to engineered barriers at the Texas low-level site in terms of climate, (6) and exposure of adequate quality for data collection. As a result of this evaluation, ten sites were selected for field visits (table 2, fig. 2). Four of these are deposits were associated with pluvial lakes in the Great Salt Lake Basin, Utah; three were lake and associated deposits from pluvial lakes in the Amargosa River Valley, California; and three were alluvial valley deposits with locally developed ponds from Arizona and New Mexico.

ANALOG DESCRIPTION

Each of the ten areas was visited and representative available exposures examined. Holocene and Pleistocene lake deposits and alluvial sediments were examined for evidence indicative of the rates and processes of vertical and lateral moisture flux. Changes include fracturing, soil forming processes, penetration by roots and burrows, and mineral dissolution and precipitation. The role of fine grained clays and marls in limiting vertical

Table 1. Candidate sites evaluated

Site name	Age	Reliability of dating	Lithologies	Exposure quality	Site access	Citations	Contacts
Balmorea State Park, TX	6000 year old cienega deposits		Gravel, cienega deposits	Drainage construction, no good exposusures identified	State park		Chris Caran
Brazos River terraces, TX	Holocene, dated	?	Holocene avulged channels, fining upward with clay caps		On road	Waters, 1995	M. Waters
Canyon Lake, UT	5,100 and 1,900 B. P.		Marl, organic sediments, peat, sand in deltas, eolian and alluvial sand	?		Graf, 1989	Graf, Arizona State University, Geography
Chaco Canyon, NM						Wells and Love, 1983	Steve Wells, DRI, Reno, NV
Delta, UT	14.5 ka	C^{14}	Silt, clayey silt, silty clay, and silty marl.	Cutbank of the Sevier River and steep slope above rifle range	On highway, rifle range	Oviatt and others, 1994,	Jack Oviatt, Kansas State University
Double Adobe Archiological site, AZ	15 to 8 ka		Channel gravels, sand, and clay; cienega (marl?)	Backhoe trenches, poor natural exposures		Waters, 1983, 1985; Waters, 1989; Hawley, 1993	Michael Waters, Texas A& M Anthropology
Fish Lake Valley, CA/NV	12,330 to 590		Sand, debris flow, clay, silt sand and peat	Core and trench, may not be any exposures		Throckmorton and Reheis, 1993	Throckmorton and Reheis, USGS
Gallestina Canyon IV, AZ	540-3820	C^{14}	Very fine sand, clay, local gravel with pot shards	Arroyo	Zuni reservation, no access 1996	Unpublished S. Hall work notes	Steve Hall, Geography, U. Texas

Garnsey Bison Kill, NM	450-500 BP	C^{14}	Sand, gravel, clay	Arroyo	BLM, Elmer and Jane Garnesy in Roswell 505-622-9096, access from state park	Hall, 1985; Parry and Speth, 1984	Steve Hall
Hueco Tanks Sate Park, TX	Breached historic dams, also some prehistoric water contol features	?	Coarse gravels to very fine grained marsh deposits	poor	State Park		Chris Caran
Issacs Playa, NM	"old surface"	?	15 ft of clay, vertic propertie, on Camp Rice gravel.	Stock tanks but would have to trench	Desert Research project, BLM; Section 26 is private	Gile, Hawley and Grossman, 1981, p 171	John Hawley
Lake Bonneville /Oquirra Fault, UT	7,650 to 20,370 B. P	Laminated lake clays, buried soils, loess and colluvium, beach, fan		Trench at fault		Olig and others, 1994	Susan Olig, Bill Black, William Lund, Utah Geological survey
Lake Bonneville, UT	mostly >10ka	C^{14}, ashes, and stratigraphic framework	Gravel, silt, sand, lake beds	natural, road gravel pit	BLM, road	Oviatt and others, 1992; Elder, 1992; Horn, 1970; Machette, 1988	Charles Oviatt, Kansas State; Donald Curry, Univ. of Utah (geography); Dorothy Sack, University of Wisc, Madison (geography)
Lake Cahuilla, CA	1,239 to 2,450		Lagoon is silt; cobble and sand beach deposits dominant.	Trench and natural exposures		Clark and others, 1972; Mahoney, 1986 , Waters, 1983	
Lake Dumont, CA	30 to 18 ka	unpublished AMS radiocarbon dates	Gravel in subsurface, sand, and gypsiferous clay	Gully exposure	BLM, on highway	Ritter, 1987; Wells and Ritter, 1994	Kirk Anderson, Desert Research Institute

Lake Mojave CA (Silver Lake, Soda Lake, Afton Canyon, Lake Manix)	8-13 ka	?	Gravel, sand on exposed? beach ridges; clay, sand granules-coarse sand in core from Silver Lake.	Visited by T.C Gustavson, beach gravel exposures described, not much clay	BLM, road	Enzel and others, 1990, McFadden and others, 1992,1994	L. McFadden, U. New Mexico, Steve Wells, Desert Research Insitute, Diane Anderson
Lake Tecopa, CA	>160 ka	Tephras, paleomagnatic reversal stratigraphy	Sand and pebble gravel, marl and cemented lacustrine limestone; gray calcareous clay.	Badlands	BLM	Morrison, 1991, Hillhouse, 1987	Kirk Anderson, Deser Research Institute, Reno, NV.
Lakeside Gravel Pit, UT	Described as part of the Stansbury oscillation (22 to 20 ka)	good	Gravel, lake deposits	Gravel pit	good	none	Charles G. (Jack) Oviatt, Kansas State, Manhattan KS; Dave Miller, USGS Menlo Park, CA
Lingos Formation type area, TX	Alluvium, 35,000+, lake >13,000 to 8,000		Lake on Pliestocene alluvium in subsidence feature	?	Private, Property owner Smith, lives on property	Caran and Baumgardner, 1990	Chris Caran, Austin, TX
Modern Wilcox Playa, AZ		?	Playa: beach ridge	Backhoe trenches, 42 m corehole, natural exposures (?)			
Murray Springs, AZ	Peistocene basal gravel ; 10.8-9.7 ka Clanton clay cienega	detailed C^{14}	Channel sand and gravel; pond clay, organic material, and marls; and red eolian-alluvial sand and silt.	Arroyo, old archeologial trenches	BLM	Haynes, 1981; 1987; 1991.	Vance Haynes, Anthropology and Geosciences, University of Arizona, Tucson

Mustang Springs, TX	10.2 to 6.9 ka	?	Gravels, sand, silt and clay loam	Spring area trenched -- trenches all backfilled, no exposure	on county roads 1212 and 1208; Property owners (1987) Mr. and Mrs. Billy J. Louder	Meltzer, 1991; Meltzer and Collins, 1987	David J. Meltzer, Department of Anthropology, SMU, Dallas,
Old River Bed, UT	22 to 20 ka	By corellation	Granule sand with clay matrix, gravel in silty clay; silty clay and clayey silt	natural bluff and gully exposures	public lands	Gilbert, 1890	Charles G. (Jack) Oviatt, Kansas State, Manhattan KS;
Pedernales River alluvium	4500 to 1000	?	Sand and gravel pits in alluvium, minimal fines		Private ownership	Blum and Vallastro, 1989	Mike Blum Univ. of Nebraska, Lincoln, NB
Pluvial Lake Estancia (Laguna del Perro), NM	12-20 ka,		Varved gypsum-clay sequences, gypsum beach bar	outcrop and core hole data	?	Bachhuber, 1989; Allan, 1991; Hawley, 1993, Titus, 1969	
Pluvial Lake San Agustin, NM	18 ka;	Wave-cut notches, beaches		?		Hawley, 1993; Weber, 1980; 1982; Markgraf and others, 1983; 1984	
Santa Cruz Bend, AZ	Gravel >10 ka; clay 3.8 to 3.6 ka	C^{14}	Cobble-boulder gravel with sand matrix, bedded, locally calcareous, gray silty, slightly organic clay	Natural cut bank exposure	University of Arizona Argricultural Station	Huckell, 1996	Andrea Freeman, Desert Archeology, Tuscon, AZ
Stansbury Gulch, UT	Described as part of the Stansbury oscillation (22 to 20 ka)	good	Gravel, silt, lake deposits	Gully, gravel pit	Public?	Green, S. A., and Curry, D. R., 1988; Currey and others, 1983	Charles G. (Jack) Oviatt, Kansas State, Manhattan KS; Dave Miller, USGS Menlo Park, CA

Trukee River (Pyramid Lake), NV	Quaternary-Holocene	(no dates given in field guide)	?	Mostly sand, local silt and clay, tufa, soils fluvial pebbly sand	canyon exposures	Smoot, 1993	Joe Smoot, USGS
Tularosa Basin, NM	0 to 250,000	?	Gravel arroyo fill; mud in arroyo-mouth ponds, buried soils, .	Closely-spaced backboe trenches	White Sands Missil Range, NM	Blair and others, 1990	John Hawley, NMBMMR
Walker Lake, CA	300, 4,800 B.P.	C^{14}	Fine grained, look for marginal facies	Core, no exposures	?	Benson and others, 1991; Adam, and others, 1985	L. Benson, USGS; P. Meyers, U. Mich; Ron Spencer, U Calgary.
Walnut Creek, TX	Younger than First Street terrace, radiocarbon dated at 5000 years, modern deposit	inferred	Very coase point bar deposits, shoot bar filled with clay	Erosional cut at mouth of creek,	Through prision	none	Chris Caran, Austin TX

Table 2. Sites examined as geologic analogs for engineered barriers.

Site	Location	Coarse units	Fine units	Age	Alteration
Lakeside gravel pit	N41°13'00" W 112°52'15" Southwest shore of Great Salt Lake, UT	Multiple, thick pebble to cobble gravel deposits, intergranular space is mostly open.	Discontinuous marl and silty marl beds	22 to 20 ka	Most gravel has undergone little or no alteration, older gravels contain carbonate cement. Marl contains root tubules, local oxidation, widely spaced jointing.
Stansbury Gulch	N 40°46'44" W 112°30'00" South end of Stansbury Island in Great Salt Lake, UT	Boulder gravel, intergranular space is open or filled with loose carbonate sand or carbonate cement	Laminated white marl	20 to 22 ka	Roots penetrate gravel, and animal den in unconsolidated sand. Some gravel has undergone little or no alteration, other gravel has acquired extensive (early?) cement. Marl is damp, contains root tubules, local oxidation (?), minimal cracking.
Delta	N39°23'55" W 112°28'48" North of Delta, UT	No gravel	Silt, clayey silt, silty clay, silty marl	14.5 ka	Roots abundant in lower units by the river, limonite stain, carbonate filaments, sapping and jointing along cut bank.
Old River Bed	N35°35'55" W116°16' 20", West central Utah	Granule sand with clay matrix, gravel in silty clay	silty clay and clayey silt	22 to 20 ka	Moist clay with limonite and MnO stain on roots, fractures, and in patches in silty beds; gypsum precipitation near surface. Gastropod shell material preserved in granule sand.
Lake Tecopa, gravel section	Several localities, N 35°55'24" W 116°15'35" near Shoshone, CA	Cross bedded sand and pebble gravel, weakly consolidated, sand matrix	Silty marl and cemented lacustrine limestone	>30 ka?	Gravels: weak cement, local Liesegang banding, widely spaced joints, excavations for dwellings; marl top is indurated, highly fractured and has karst developed on it, underlying marls are friable with abundant root tubules.

Table 2. Continued

Lake Tecopa, clay section	N35°50'25"; W 116°16'6", 2 mi south of Shoshone CA	no gravel, sand with granule lenses	gray calcareous clay	>5 to 0.75 Ma	Clay is moist and gypsiferous at base, indurated but weathers to rubble above basin floor.
Lake Dumont	N35°35'55" W116°16'20" Armagosa River valley north of Baker, CA	Gravel in subsurface	Sand and gypsiferous clay	30 to 18 ka	Moist clay disrupted by displacive gypsum growth, crust of eolian salt and sand, local sapping along gullies.
Santa Cruz Bend	N32°15'27" W 111°00'5" North Tuscon, AZ	Cobble-boulder gravel with sand matrix	Bedded, locally calcareous, gray silty, slightly organic clay	>10 to 3.6 ka	Variable calcite cementation, rhyzolith formation in gravel; clay is cracked, vertical cracks are sand filled, abundant dry root fibers.
Murray Springs	N31°24'13"N, W110°10'40" Southeastern AZ	Cobble gravel in variably cemented granule matrix	Gleyed clay, marl and organic material	Pleisto cene, 9.7 ka	Abundant roots, cementation of gravel, ped formation in muddy units, minimal alteration in marls.
Garnsey Bison Kill Site	N33°35'55" W116°16'20"; east of Roswell, NM	Gypsum and dolomite cobble gravel in red mud matrix	Gray clayey sand and sandy clay	450-500 B.P.	Limonite stain and root traces in fine units, abundant modern roots.

permeability and the extent to which in situ gravels function as capillary barriers to flow in the unsaturated zone were of particular interest. The results of acid insoluble residue, grain size, SEM, and drying experiments on representative fine sediments are summarized in table 3. The major alteration in the fine grained (clay or marl) and coarse gravel units in each site are described in table 2. Each of the sites is described briefly in the following sections, which are organized geographically into Great Salt Lake Basin, Utah; pluvial lakes in the Amargosa River Valley, California; and alluvial valley deposits in Arizona and New Mexico. These descriptions are focused on observations relevant to understanding these exposures as analogs of engineered barriers. Site coordinates, detailed site access instructions, complete listings of literature, entire 7 1/2 minute USGS topographic maps, and observations about these well studied and significant outcrops are archived in data packages.

Lakeside Gravel Pit

General characterization of the site

This site is in a large abandoned gravel pit used during construction of the Southern Pacific railroad across Great Salt Lake (figs. 3, 4a). The gravel pit lies in a broad valley between structurally controlled bedrock ridges. Access to the site from Interstate 80 is 28.5 mi on paved and well-maintained public gravel roads across Hill Air Force Base Range and on unmaintained quarry roads.

The gravel pit as much as 25 m deep was cut into a gently sloping (north draining) valley above Great Salt Lake. The top of the exposure is at an elevation of about 4320 ft above sea level. Exposures on the south, east and west faces of the pit as well as remnants and benches within the pit expose complex stratigraphy.

Description of the sedimentary stratigraphy

This section exposes a series of five or more coarse gravel deposits and interbedded marls and soils (fig. 5). Most of the gravels are cross-bedded open-work boulder gravels

Table 3. Acid insoluble residue and grain size analyses.

Site	Sample #	Description	Carbonate	Acid insoluble fraction Sand	Silt	Clay
DEL 2	4	Gray clay with shells	43	1	24	32
GBK 1	1.2	Clayey silt and carbonate pebbles	28	40	20	12
LD	0.5	Red calcareous, gypsiferous clay	22	24	42	12
LG 1	0.2	Friable tan silt	42	19	36	3
LG 1	0.6	Gray clay	43	12	40	5
LG 1	0.7	Bonneville marl	51	22	23	4
LT 1	0.4	Hard yellow clay	35	23	37	5
LT 5	5.5	Gray clay	21	38	36	5
MS 1	2	Muddy gray sand	2	38	40	20
MS 1	2.08	Laminated clay	2	31	49	18
MS 1	2.2	Hard, white lake deposit	49	17	23	11
MS 2	1.3	Calcareous diatomite clay	68	2	14	16
MS 3	2	Clayey sand	4	25	50	21
SCB 1	3.6	Red mud	5	18	60	17
SCB 1	4.4	Friable brown silt	4	43	47	6
SI	1.3	Marl	36	10	44	10
SI	1.5	Marl	39	13	37	11
SI	2.15	Carbonate sand	21	61	18	39
SI 3	0.4	Marl	32	14	44	10
SO 1	3.5	Laminated olive clay	33	6	30	31

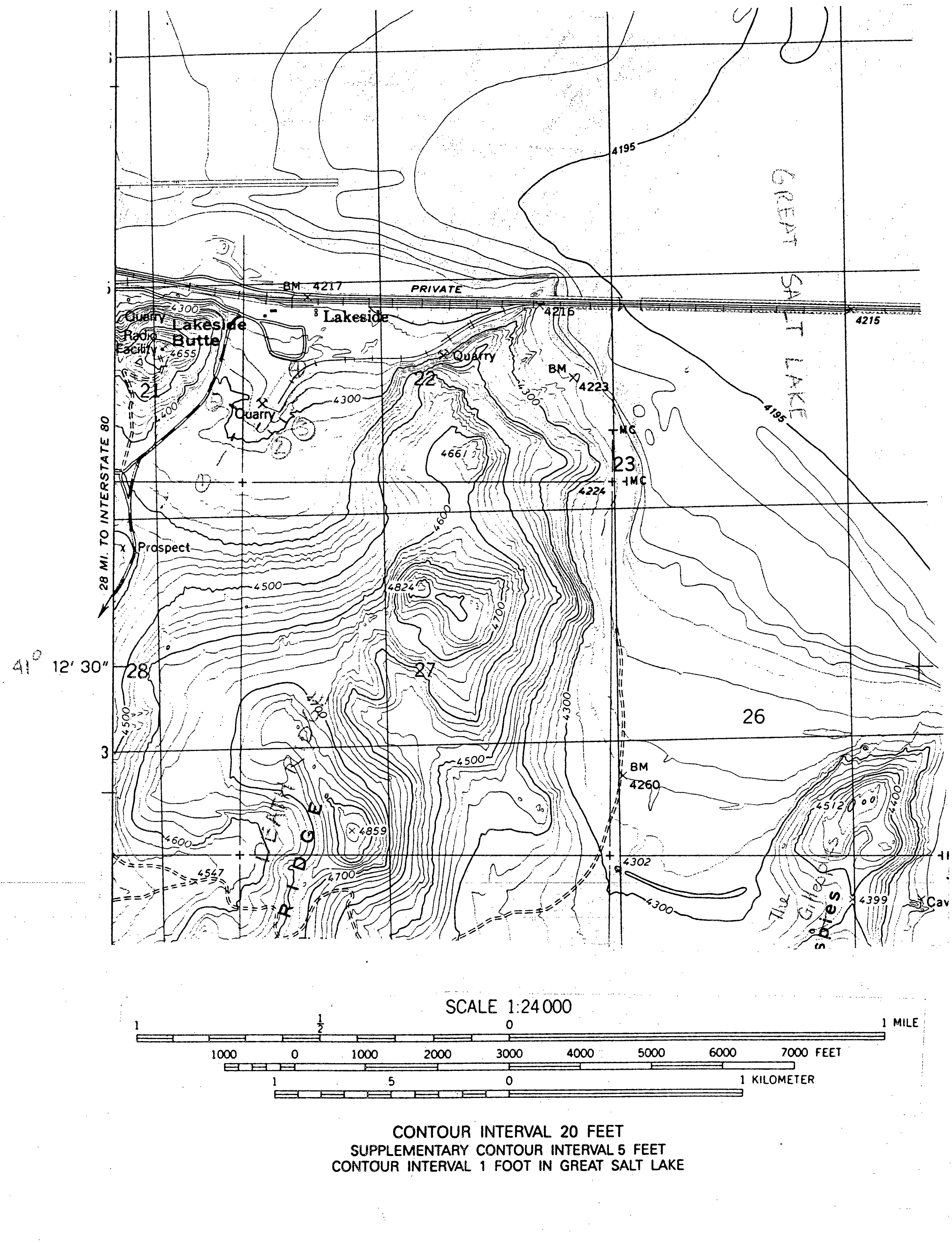
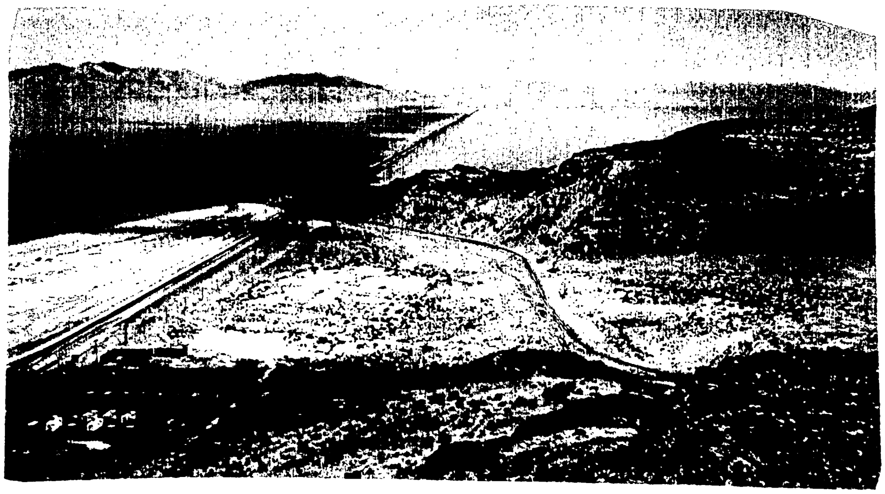


Figure 3. Location of the Lakeside Gravel pit site, USGS Lakeside, UT, 7 1/2 minute quadrangle.

(a)



(b)

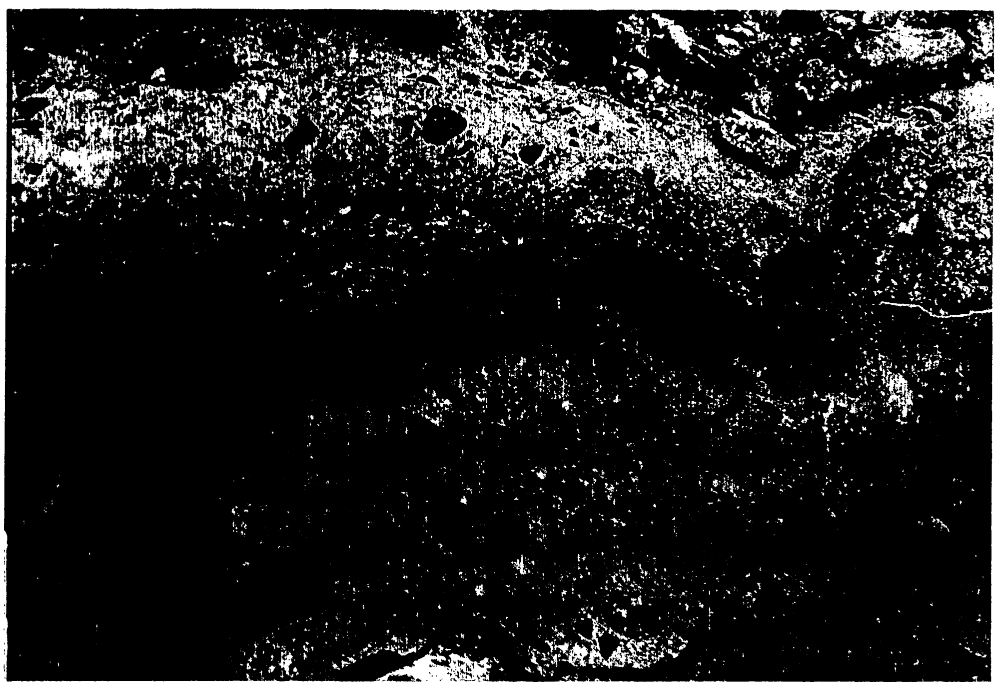


Figure 4. (a) Lakeside Gravel pit site looking east across Great Salt Lake. (b) Carbonate cemented gravel at top of gravel section, Stansbury Gulch

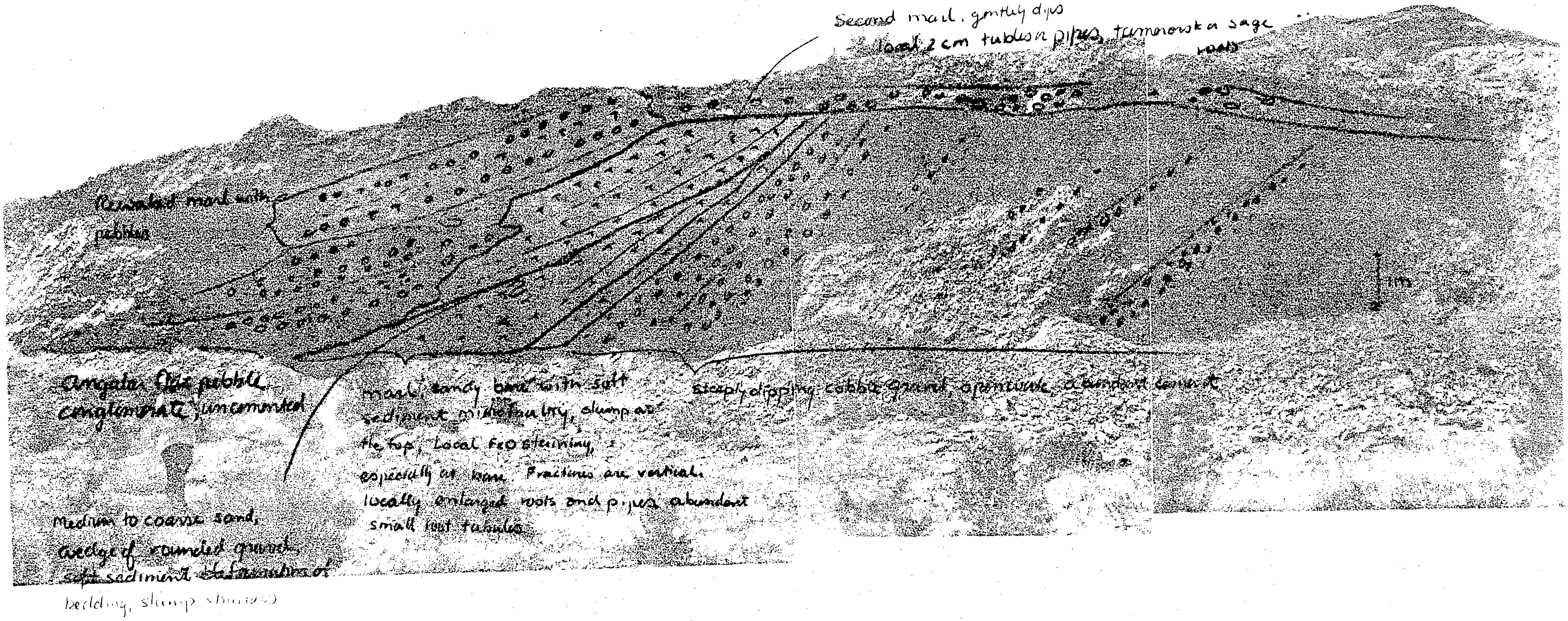


Figure 5. Photomosaic and interpreted drawing, Lakeside gravel pit site, section 5, showing shoreward dipping gravel bars and complex relationships between marl units.

Figure 6. Bonneville gravels (a) uncemented cobble gravel with loose sand composed of broken calcite crust and unaltered sand size gastropod Amicola sp (personal communication, J. Oviatt, 1996). Space large roots cut through the gravel. (b) Calcite-cemented openwork gravel, Lakeside Gravel pit. Scale is 20 cm.

(fig 6 a) with steep dips away from the lake (fig. 5), preserving the shoreward side of very high energy gravel bars. At the north margin of the quarry, two marl deposits corresponding to the Bonneville and Provo lake highstands are recognized draping steeply dipping cross-bedded gravel deposits (Oviatt, 1996, personal communication). Grain size analysis of the two samples from the Provo marl (table 3) gave compositions of about half carbonate grain sizes in the silt range (47 to 71 percent silt). The upper surface of each gravel deposit is defined by a thin interval of less orderly bedding with horizontal boulders and more pebble and granule matrix including carbonate and gypsum sand between boulders, interpreted as a product of reworking of the bar during lake level change. In some of the bar deposits, the upper reworked fine layer thickens corresponding to thinning and shoreward pinch out of the bar deposit. This reworked material above the Provo marl is considered a "lagoon" deposit.It consists of of reworked marl, sand, and gravel deposited in a local depression behind relief created by the abandoned bars. One or more of the reworked bar-top deposits are slightly oxidized (10RY7/4) relative to other gray sediments, suggesting soil formation. Isolated thick bar-top units on a bench in the north part of the quarry also preserve a soil with carbonate (fig. 7a)

Interpretation of the nature, amount, and distribution of post-depositional alteration

Alteration in the fine grained deposits

Marls exhibited three types of alteration. Abundant small root tubules penetrate the sediment and are locally stained by black or yellow oxides or hydroxides. Widely spaced vertical fractures cut the sediment and locally sapping has enlarged these fractures. However sapping may be limited to quarry exposures. In one exposure (fig. 5), several 10's of centimeters of the somewhat sandy base of a steeply dipping marl overlying gravel cross beds was stained yellow by limonite. This yellow stain may reflect (1) preferential mineralization of the sandier base of the marl, (2) a capillary barrier hydraulic effect related to the grain size contrast leading to more alteration where moisture is trapped in the fine-grained lithology because of less suction in the gravel, or (3) a combination of these

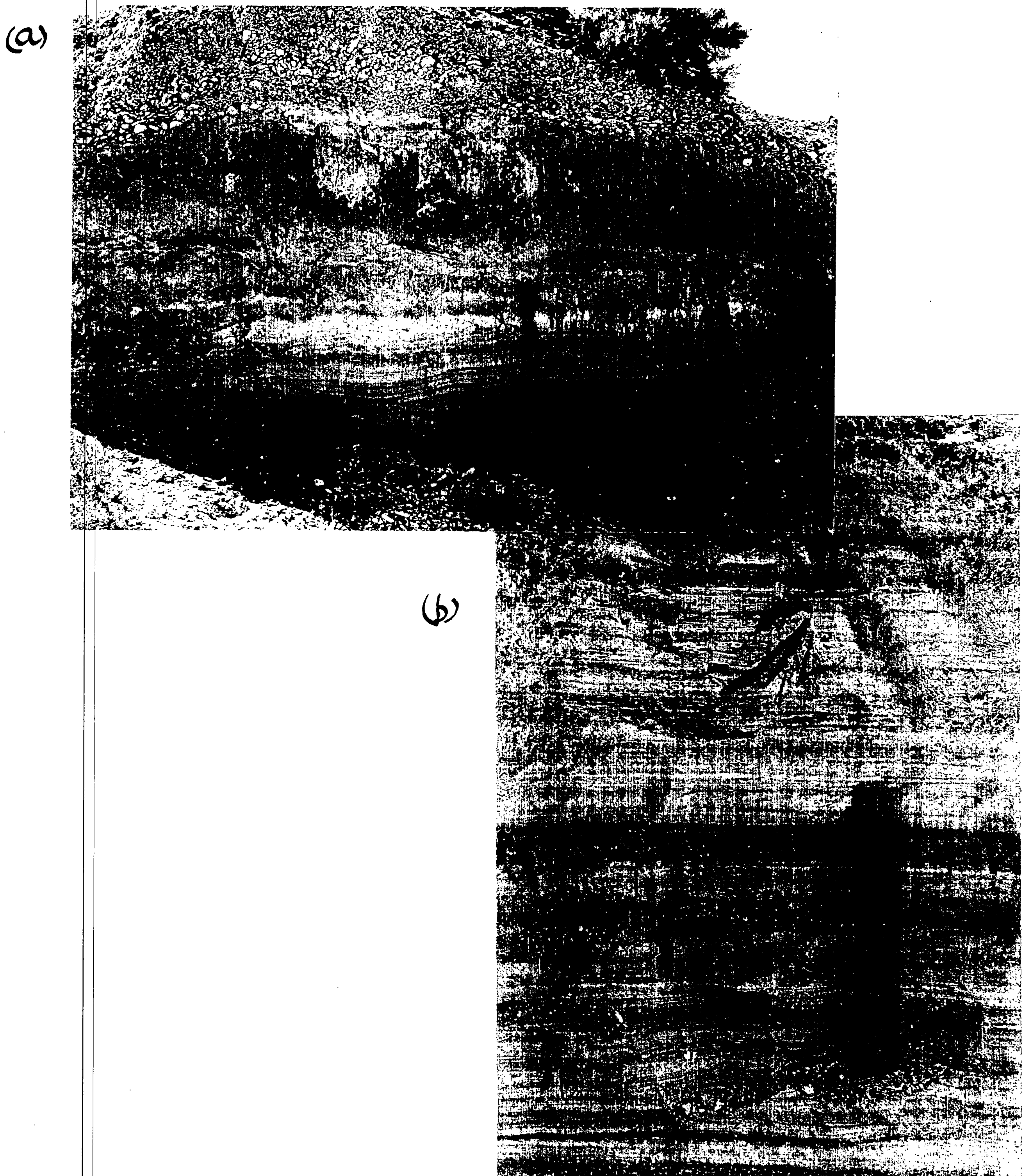


Figure 7. Bonneville fine grained deposits. (a) Soil profile on diatomite, Lakeside Gravel pit section 4. Scale is 20 cm.(b) Minimally altered laminated diatomite, Stansbury Gulch, section 4. Scale is 20 cm.

effects. However, SEM examination of the marls reveals pristine preservation of opal diatoms as well as ostracods and other carbonate shell material with little or no dissolution or cementation (fig. 8a and b).

Reworked sandy graveley silt and marl have undergone varying amounts of pedogenic alteration. The reworked sediments are nearly massive and poorly sorted. Profiles with the most intense pedogenic alteration contain pedogenic carbonate as cement and rhyzoliths (root casts) (fig. 7a). Root traces and vertical fractures are abundant in sections with soil textures.

Alteration in gravel

Much of the gravel in this section contains little fine matrix (fig. 6). Carbonate cement, however, is present throughout, varying in abundance from incomplete coats on grains to thick deposits that cement gravel. Cement appears as micrite in hand specimen, and as encrusting diatoms and calcite crusts in SEM image (fig 9 a, b). Thickness of cement is variable over small distances but no systematic trend within units was identified. Younger gravels appear to contain less abundant and less pervasive cements than older gravels. Roots, root tubules, or animal burrows were not identified in the gravel at this site. Several patches of limonite discoloring gravel were evident on quarry walls; exposure did not permit identifying the cause and three dimensional extent of the stain.

Stansbury Gulch

General characterization of the site

Stansbury Gulch is a classic exposure of pluvial lake stratigraphy at the south end of Stansbury Island in Great Salt Lake, in a small broad canyon with an intermittent drainage between resistant ridges of steeply dipping Paleozoic bedrock (fig. 10). Access from Interstate 80 is on a public gravel road across salt evaporation ponds that connect a former island in Great Salt Lake to the shore. A gravel pit at the base of the canyon and a borrow pit within the marl have enhanced exposure of Pleistocene lake sediments. Access

(a)

(b)

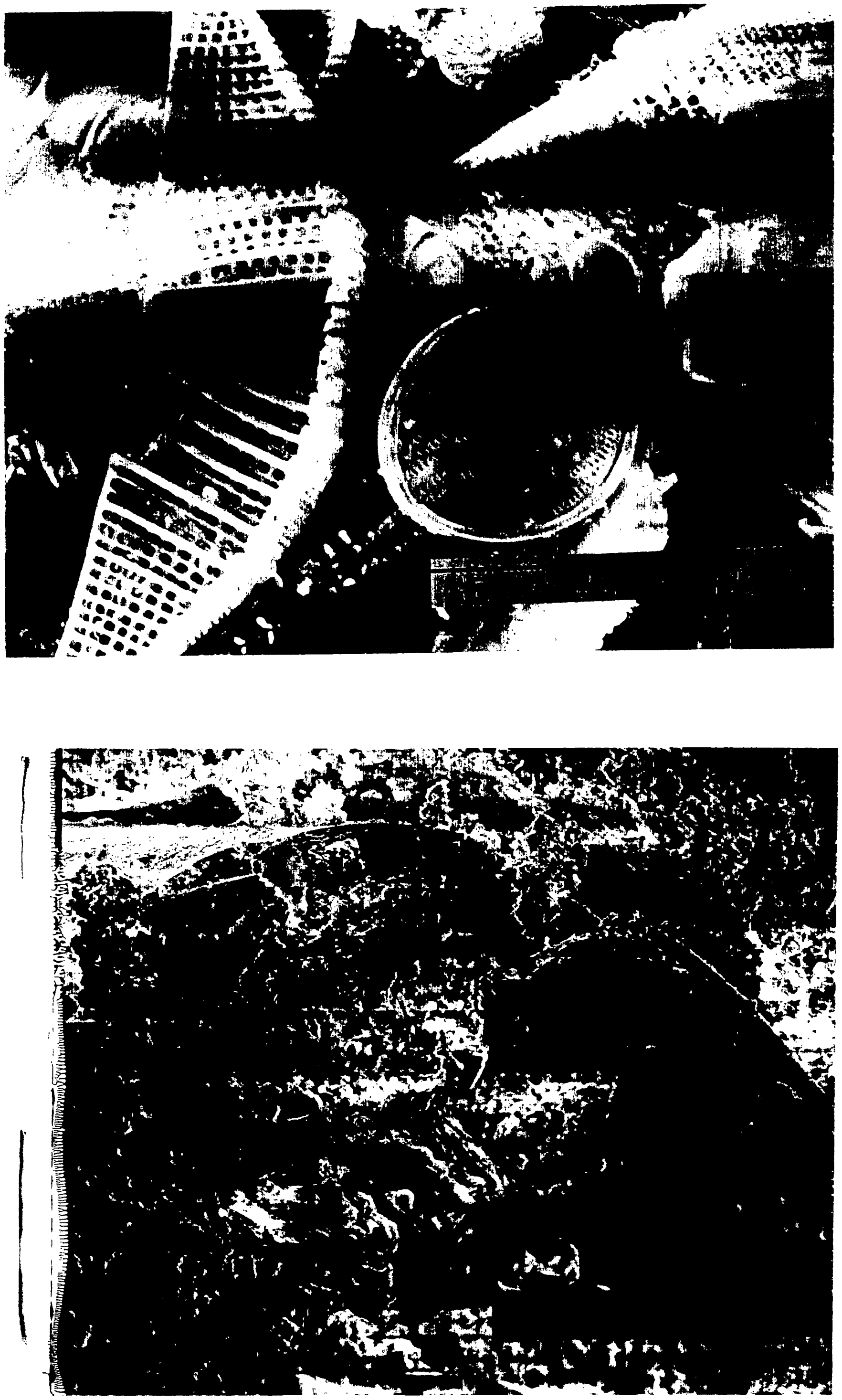
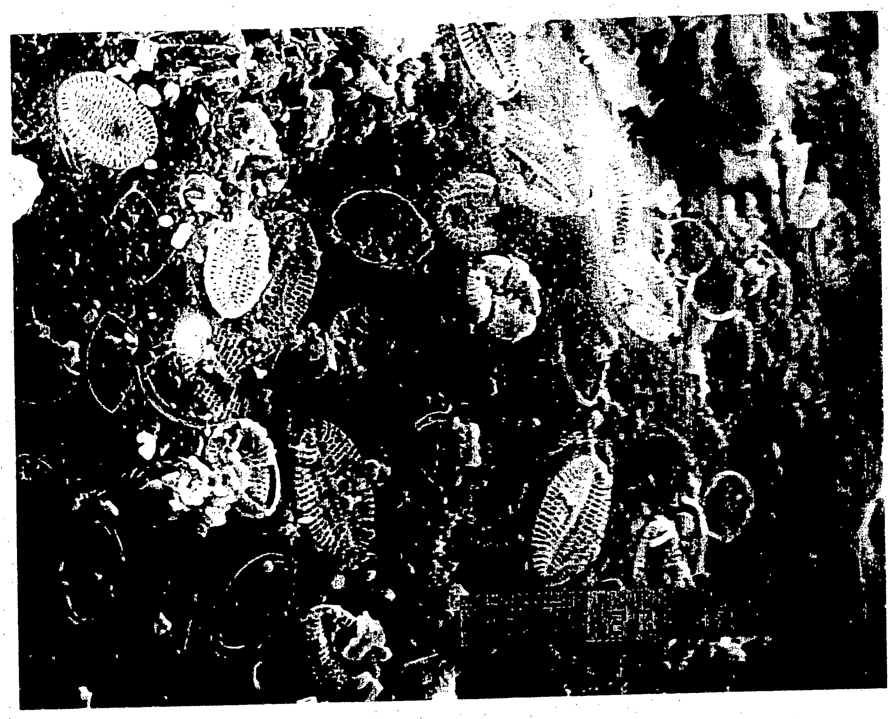


Figure 8. Scanning electron microscope images of (a) diatoms in minimally altered diatomite Stansbury Gulch 1.3 m and (b) calcite cement and crusts on ostracods, Lakeside gravel pit section 1, 0.6 m. Scale in microns.

(a)



(b)

Figure 9. Scanning electron microscope images of (a) diatoms encrusting a quartz sand grain in gravel, Stansbury Gulch 1.2 m and (b) calcite cement and crusts, Lakeside gravel pit section 1, 0.6 m. Scale in microns.

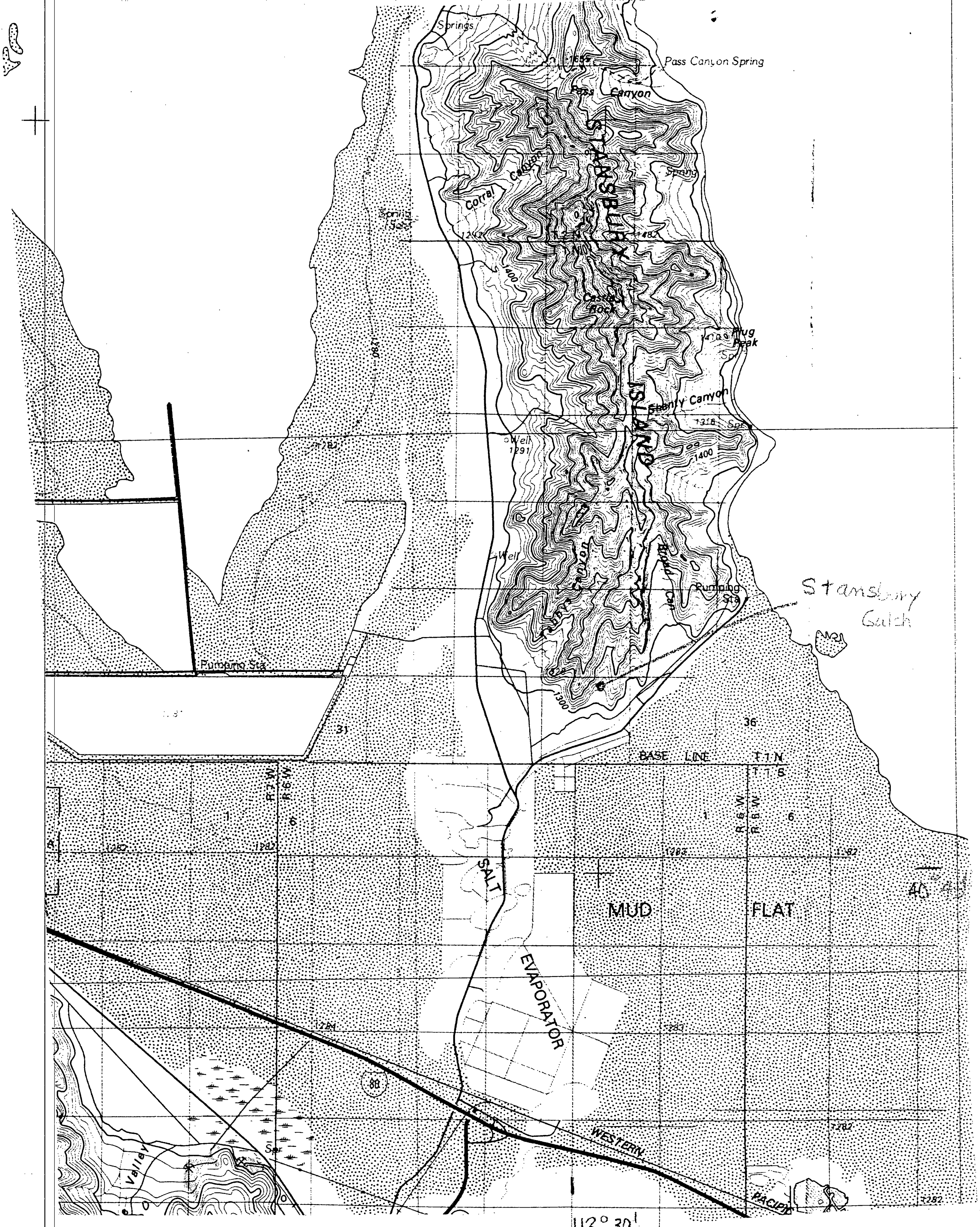


Figure 10. Location of the Stansbury Gulch site, USGS Tooele, UT, 30 x 60 minute sheet.

to exposures in upper part of canyon (about 100 m above mean lake level) is provided by 4WD dirt roads. Lake sediments mantle the steep bedrock slopes and dip steeply themselves. Rapid lateral changes in thickness, sequence, and composition were observed.

Exposure is south facing and vegetation on steep slopes includes a cover of cheat grass, sagebrush, and snake weed. The arroyo is steep and dry, intermittent flow is has polished the cemented gravel layer at the lip of the water fall and plunge pool. The Quaternary sediment mantle over steep bedrock is thin.

Description of the sedimentary stratigraphy

Gravels deposited during transgression related to the Stansbury shoreline (Dave Miller, personal communication) are poorly exposed in the gravel pit at the base of the slope and also have been exposed by hand excavation on the slope beneath marl (Currey and others, 1983, Green and Oviatt, 1988). In poor exposures, gravels appear to be boulder to gravel size and appear to have uncemented sand matrix. C^{14} dates on wood and shell beneath the gravel give ages of 20 and 22 ka (Currey and others, 1983).

Overlying these gravels are highstand deposits of white marl (fig. 7 b). Oviatt and Miller (personal communication, 1996) trace carbonate sand beds within the marl to shoreline gravel deposits identified as the Stansbury shoreline. Marl thickness is indeterminate because the complete section is not exposed in a single exposure, it may vary because of deposition on a slope and resultant slumping and erosion. Slumped bedding was observed in the lower part of the marl. Thickness is probably more than 1 m and less than 2 m. Marl is finely bedded with lamination several millimeters to centimeters thick defined by color variation (gray-white-yellowish tan 2.5Y 7/4 to 8/2). Marl is lightweight and may have a significant biogenic component. Acid insoluble and grain size analyses (table 3) showed 32 to 39 percent carbonate, and dominantly silt-size grains in the insoluble fraction, many of which are diatoms. Marl on the exposed surface is dry and friable. Several decimeters beneath the exposed surface the marl appears damp and is soft and slightly plastic. C^{14} dates on shell in the marls give ages of 19.8 to 15.5 ka (Currey and others, 1983).

Stansbury shoreline gravels form a wedge interpreted as laterally equivalent to sand beds within the marl (Currey and others, 1983). Gravels are bedded and cross bedded, heterogeneous and internally complex. Pebbly coarse sand in the downslope and lower parts of the wedge has cross beds that dip lakeward. This sand is overlain by boulder gravel (>10 cm somewhat rounded boulders derived from local quartzite). Large scale cross beds dip away from the lake. The matrix within the gravel varies vertically and laterally over short distances. Pebbles in a sand matrix are most common. One interval in the middle of the wedge contains only minor amounts of unconsolidated carbonate sand matrix composed entirely of small gastropod shells (Amicola sp, J. Oviatt, personal communication, 1996). Beds of gravely sand are interbedded with sandy gravel. Highly variable cementation in this unit is discussed in the following section. This is interpreted as barrier-beach gravel of the Stansbury oscillation.

Above the gravels about a meter of marl is preserved and exposed in the banks of the arroyo. This marl is similar to the marl previously described except that it is yellower (more oxidized) and silty and sandy at the top.

Interpretation of the nature, amount and distribution of post-depositional alteration

Alteration in the fine grained deposits

Marls exhibit minimal evidence of alteration in this exposure. Roots have penetrated most marl. Abundant living roots are found within the upper meter of marl, both along bedding plains and across the beds. In the lower part of marl exposures, MnO stained small root tubules are abundant. Dark lamination and preserved gray beds suggest that the marl may have been deposited under reducing conditions; yellow colors that increase in intensity and concentration upward through the marl may be related to later oxidation. Marl is compacted but is macroscopically uncemented. Alteration could not be identified in SEM view. Marl is massive and unfractured. Marl in this exposure appears moist and is crusted with salt, probably deflated salt dust that has adhered to the sediment surface. Moisture may be related to groundwater flow in the thin sediment mantle over steeply dipping bedrock.

Alteration in the gravel

Gravels have had a more complex and somewhat obscure cementation history. Gravels range from well-indurated and low porosity sandy pebble conglomerate to uncemented openwork boulders with very sparse apparently unaltered gastropod sand matrix (fig 6a). These shells look pristine when examined in SEM. However, an indurated layer occurs at the top of the gravel wedge and forms a waterfall in the arroyo (fig. 4 b). The timing of induration is unknown; it may be syndepositional beachrock cement as is common in Pleistocene lake deposits or formed later. The indurated layer is discontinuous but appears unfractured. Most abundant weakly cemented sands and gravels are stained by limonite and the boulders are coated with a white coat of calcite. Boulders in the uncemented interval are coated with a millimeter of white calcite also. Large woody roots (sage brush?) penetrate the gravel, (fig 6 a) and a large animal (?) den is present in the weakly cemented gravely sand at the base.

Delta

General characterization of the site

These exposures of pluvial lake deposits are on north side cutbank of the Sevier River near US highway 6 bridge Sevier River north of Delta, Utah (fig. 11). Cutbank exposure of about 20 m (4628 to 4700 ft) is excellent but mostly inaccessible because of steepness, the river at the base, and instability (fig 12 a and b). Steep slope exposures above the rifle range on the floodplain are somewhat weathered although some fresh gullying may be related to construction on the rifle range.

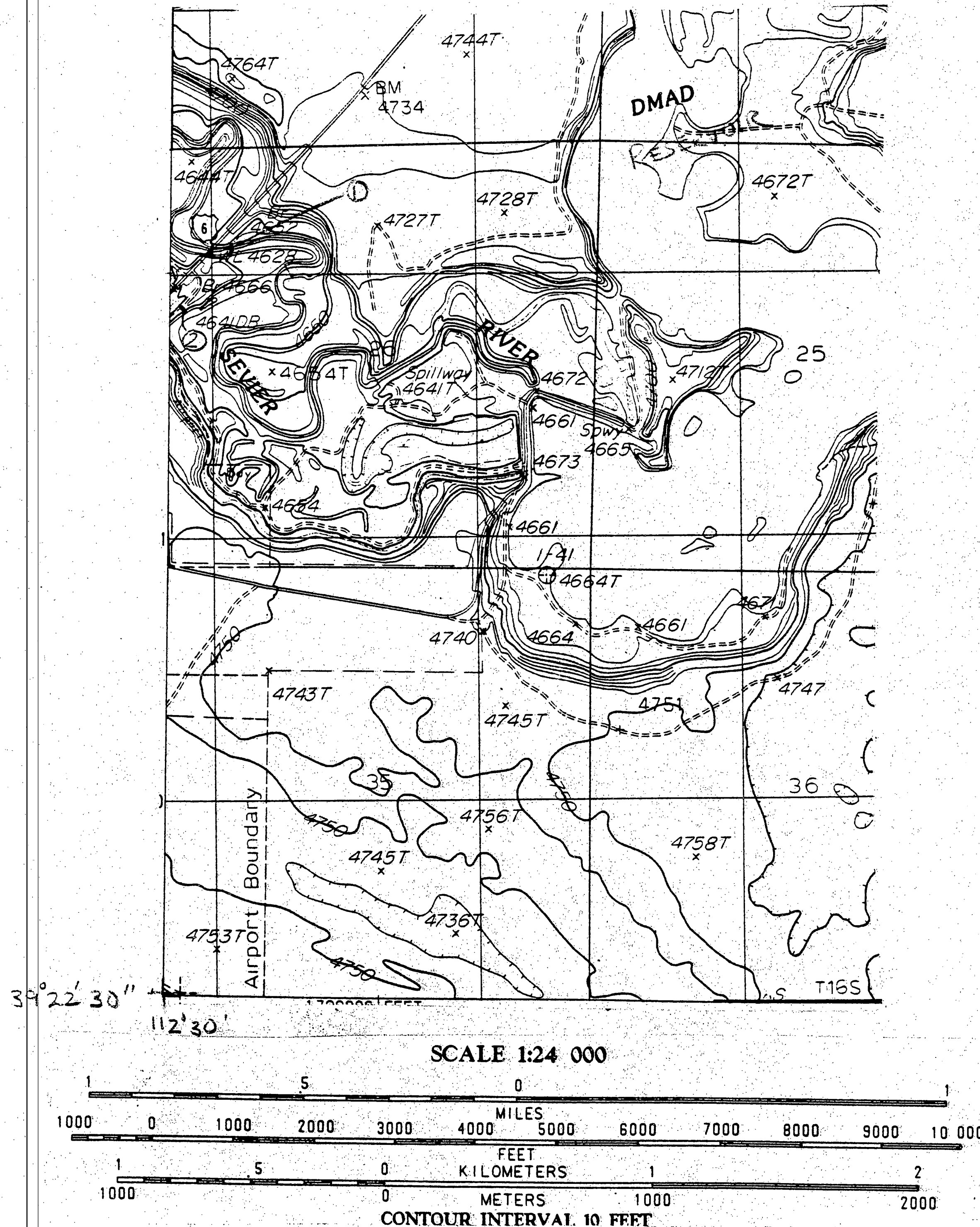


Figure 11. Location of the Delta exposure, USGS Strong, UT, 7 1/2 minute quadrangle (provisional).

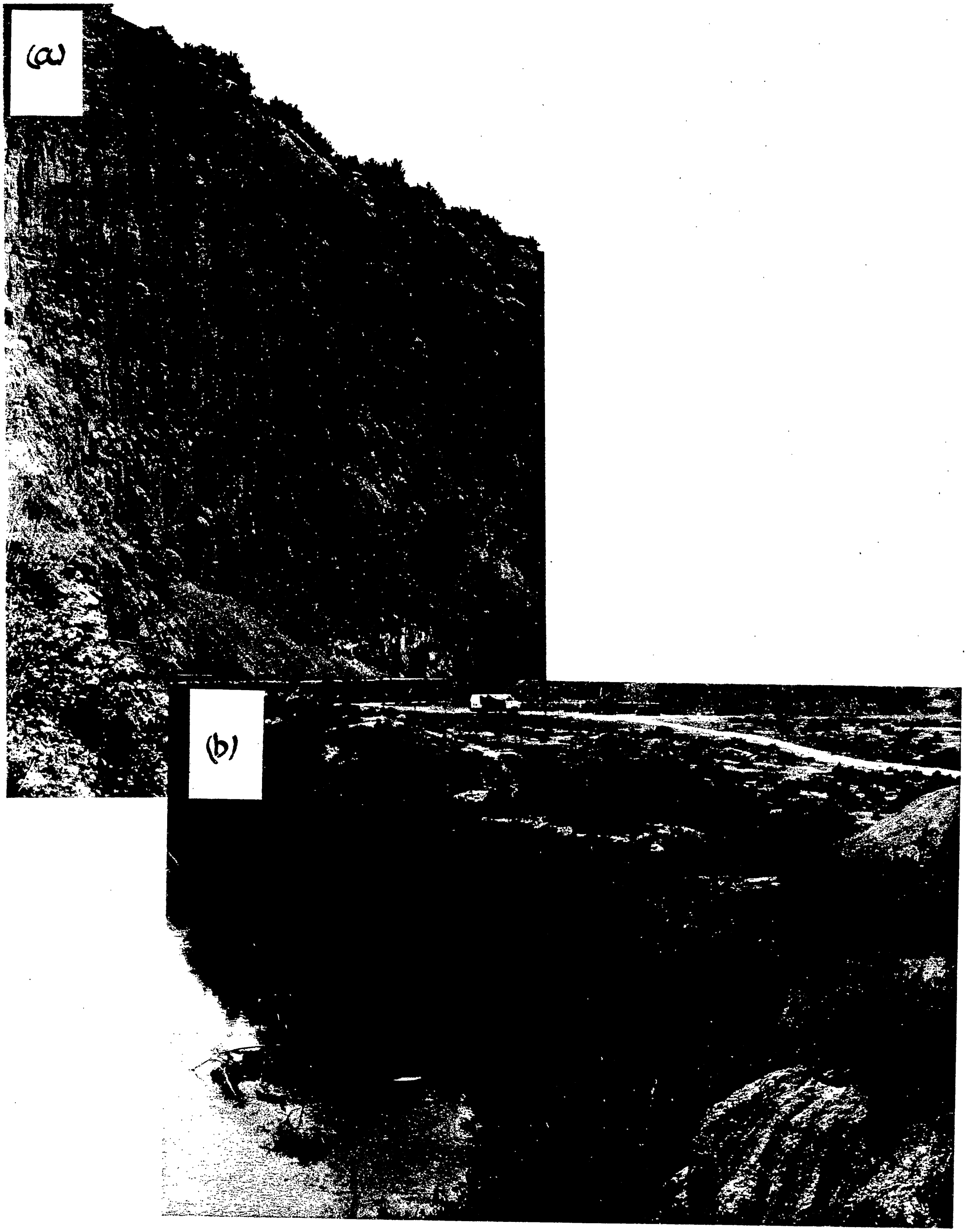


Figure 12. Delta exposure (a) underflow fan silts in the upper cutbank (b) lower cutbank with Pahvant Butte ash, marl, and unconformity with soil development (Oviatt and others, 1994).

Description of the sedimentary stratigraphy

This section exposes a sequence of silt, clayey silt, silty clay, and silty marl. Young gravel mantles the upper part of the section but is not found in place in this exposure. This section is the downdip end of a transect studied by Oviatt and others (1994), and the units exposed are described by them as Little Valley alluvium, overlain by an unconformity with soil development, the updip edge of the Little Valley marl, the Bonneville marl, Pahvant Butte ash, and a thick section of Bonneville regressive phase underflow silt and fine sand. A clay layer at the top of the white marl was the most clay-rich sample collected (56 percent clay, 42 percent silt, table 3). Dates on the regressive phase silts are 19 to 17 ka. Little Valley deposits are dated 60 to 140 ka (Oviatt and others, 1994).

Interpretation of the nature, amount and distribution of post-depositional alteration

Alteration in the fine grained deposits

Roots are abundant in lower units by the river, as well as limonite stain, and carbonate filaments. This section has some potential as an analog because of stratigraphic heterogeneity, however no sensitive indicators of alteration were identified, and it is difficult to separate soil effects from vadose zone alteration. Aragonitic mollusk shells are preserved in marls. The upper cut bank is fairly homogeneous in grain size; sapping and jointing are pervasive along the cut bank. In relatively fresh exposures above the recently constructed parking lot the silt has been extensively cracked.

No gravel is present in this section.

Old River Bed

General characterization of the site

This classic exposure described by G. K. Gilbert (1890) is interpreted as the oldest section of lake beds and is exposed in the "The Shut Off" of the Old River Bed south of where the dry valley is crossed by the old Pony Express and Stage Route. Natural cliff exposures lie along the relict river bed and escarpment (fig 13).

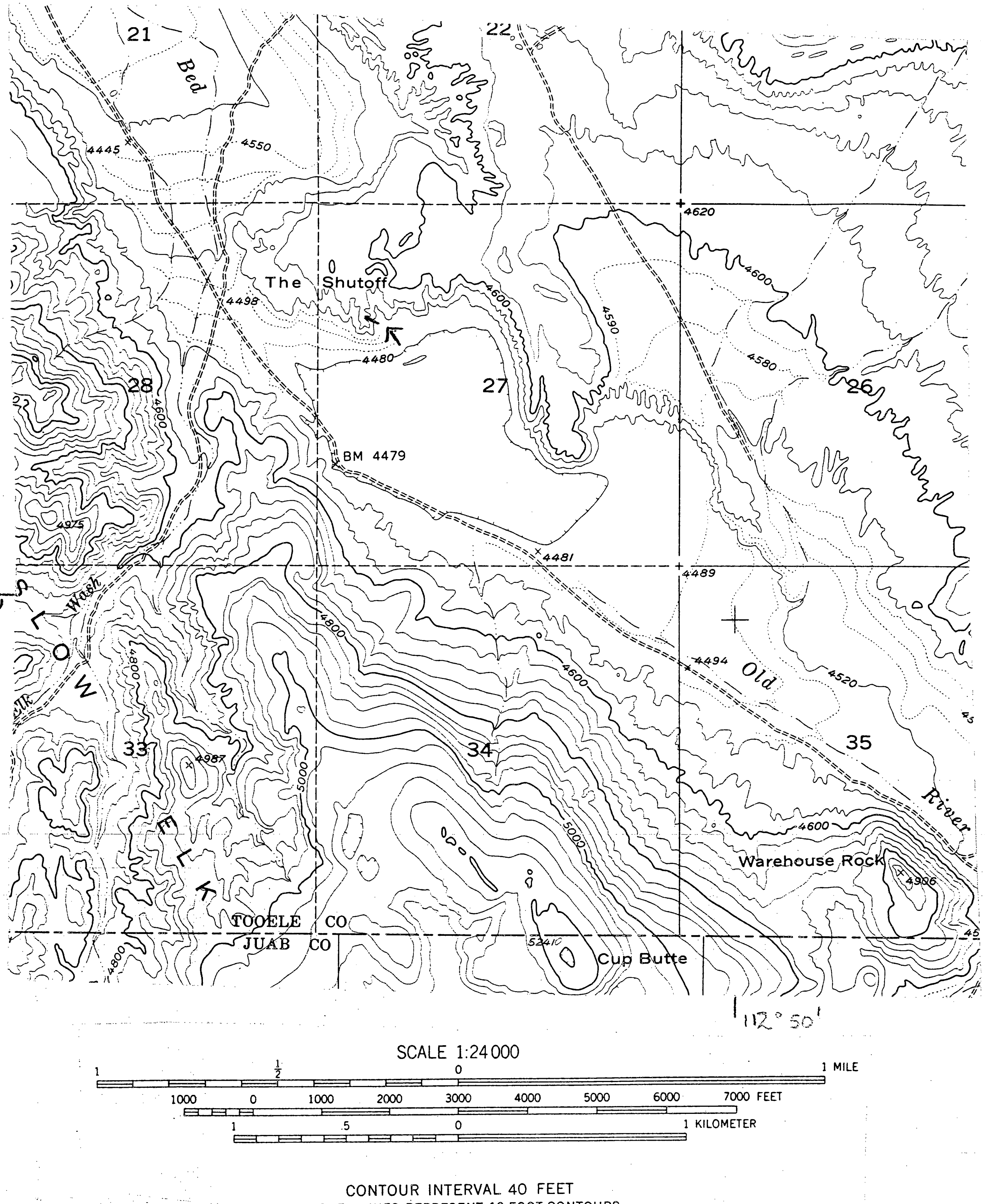


Figure 13. Location of the Old River Bed (Shutoff) exposure, USGS Coyote Springs, UT, 7 1/2 minute quadrangle (1955).

Description of the sedimentary stratigraphy

This site was examined to look for clayey lake sediments to compare with the diatomaceous units examined in the younger lake beds. Clay, silty clay, and sand form the "yellow clay" of Gilbert 1890. Gilbert mapped 90 ft of this unit; the upper 5 m were measured in this study. Grain size of a clay rich bed in this section gave 46 percent clay, 45 percent silt, and 9 percent sand (table 3). Gilbert (1890, Pl. XXXII) identified a discontinuous bed of "first gravel" on the west end of the of the ridge where sections were measured (fig 14a). In the area measured, a granule sand with abundant gastropod shells in a clay matrix may be the equivalent. Massive millimeter-laminated silt forms the "white marl" of Gilbert. Hard blocky sandy silt with sand beds and pebbles from the top of the exposure. Gravels at the top of the section are poorly exposed and their relationships to older units are unclear.

Interpretation of the nature, amount and distribution of post-depositional alteration

Alteration in the fine grained deposits

Weathering on natural exposures conceals much of the alteration on this section. Clay is moist at a depth of 20 cm below the surface near the base of the exposure. Limonite on roots and preferentially in silt layers, displacive gypsum and MnO on fractures may all reflect near surface processes (fig. 14b). Plants are preferentially rooted in sand beds suggesting that they are moist at shallow depths. The millimeter laminated olive silt near the base of the "white marl" interval is moist and plastic, suggesting it may wick water near the surface. Gastropod shells in gravel with clay matrix at the base of the white marl section are well preserved.

Gravels are poorly exposed and little can be determined about their hydraulic role in this setting.

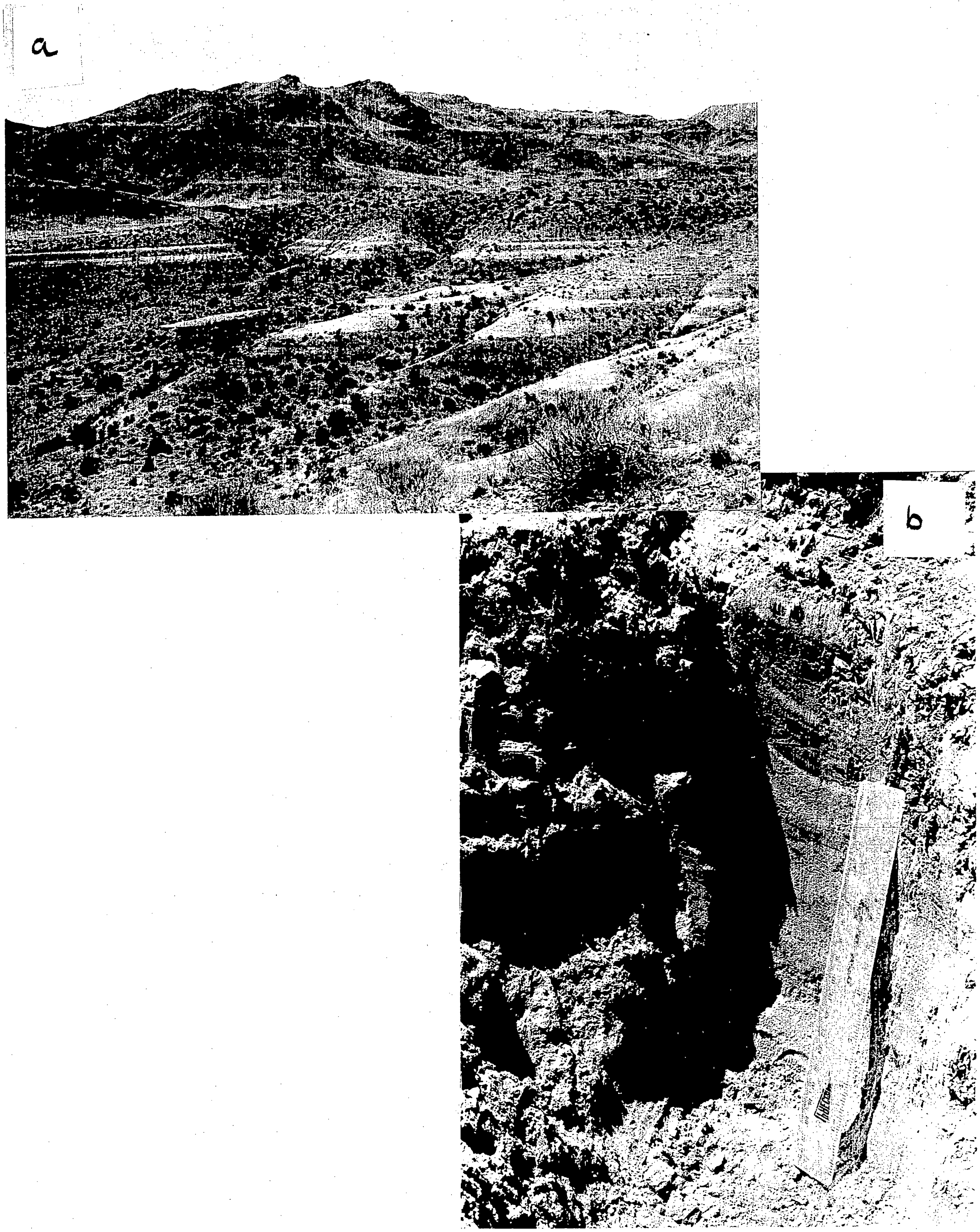


Figure 14. Old River Bed (Shutoff) exposure looking west (a) and (b) detail of "yellow clay" of Gilbert (1890) which was moist and fractured and weathered at this natural exposure. Scale is 20 cm.

Lake Tecopa gravel section

General characterization of the site

Ancient Lake Tecopa was the terminus of the Amargosa River and existed from 2 million to 160,000 years ago, when its basin was breached (Morrison, 1991). Subsequent erosion has exposed lake sediments in extensive badlands with older units exposed in center of area where Amargosa River incision is deepest (figs. 15 and 16 a) (Hillhouse, 1987). Dwellings have been excavated into youngest margin gravel deposits (fig. 16 b). Chronology is defined by tephra layers (Morrison, 1991). Complex basin evolution involving multiple lake stands separated by incision and cut and tilted by faulting require more prolonged examination that was undertaken for this study. Diagenesis involves brines and spring input.

Description of the sedimentary stratigraphy

Section 1 (Castle in clay) is composed of massive to millimeter-laminated gray sandy silt at the base, cross bedded sand and pebble gravel (fig 16 a), weakly consolidated, sand matrix; silty marl and cemented lacustrine limestone (fig 17 a). This is probably in the Amargosa Alloformation of Morrison (1991), 620 to 160 ka. The deposition of this unit may reflect river input as well as springs in the northern part of the basin. Modern springs feed a swimming pool north of the town of Shoshone.

Section 5 contains gray calcareous clay, poorly cemented silt and very fine sand, a tephra bed at top, and an angular cobble residuum with desert varnish on the ridge top (fig 18 a). Grain size analysis of a fine grained unit gave 48 percent sand and 46 percent silt. Carbonate concentration is high (21 percent) but does not produce good cementation. This is probably the Spanish Trail or Greenwater Fan Alloformation of Morrison (1991), dated between 5 to 0.74 Ma.

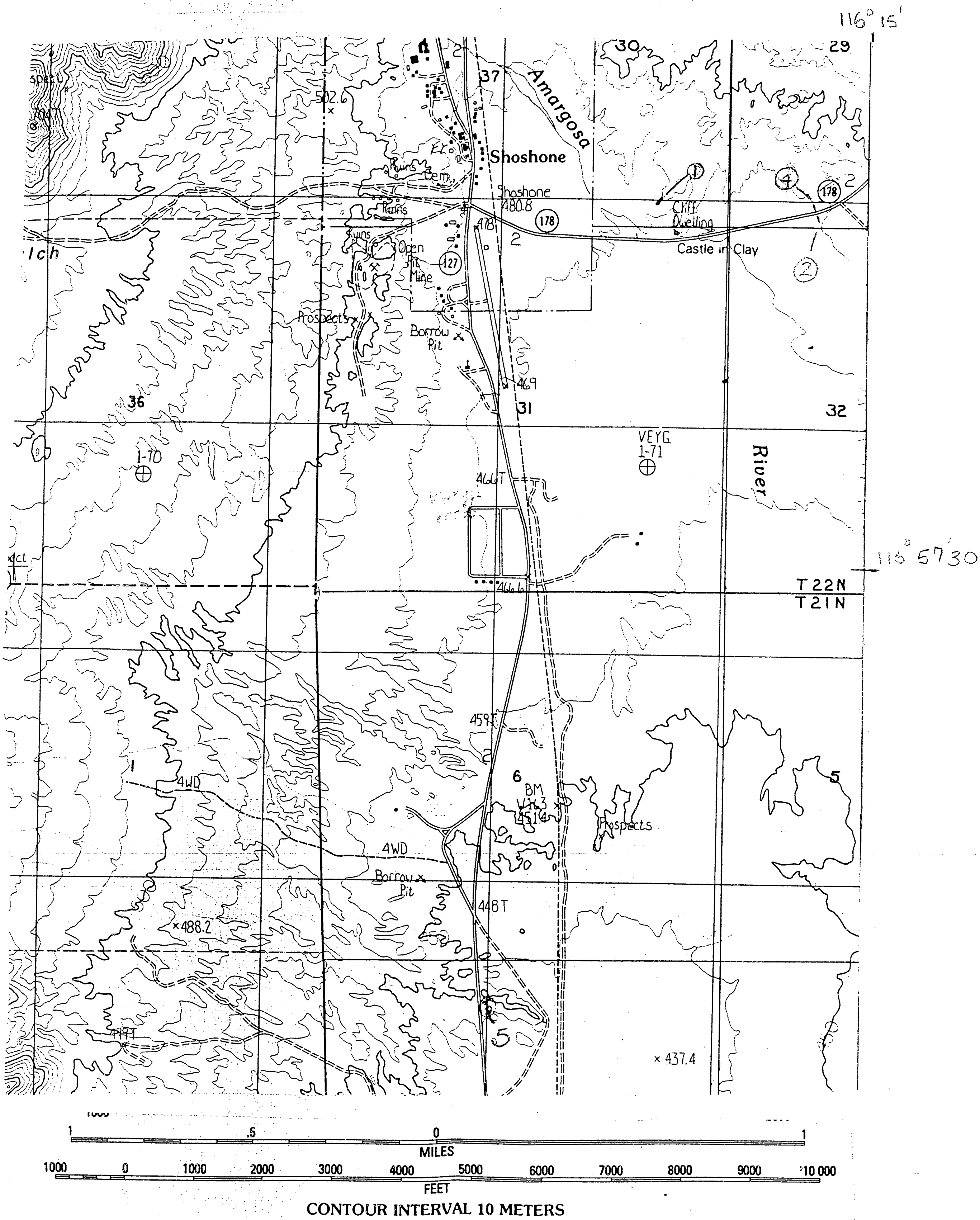


Figure 15. Location of the Lake Tecopa exposures, USGS Shoshone, Ca, 7 1/2 minute quadrangle (1984).

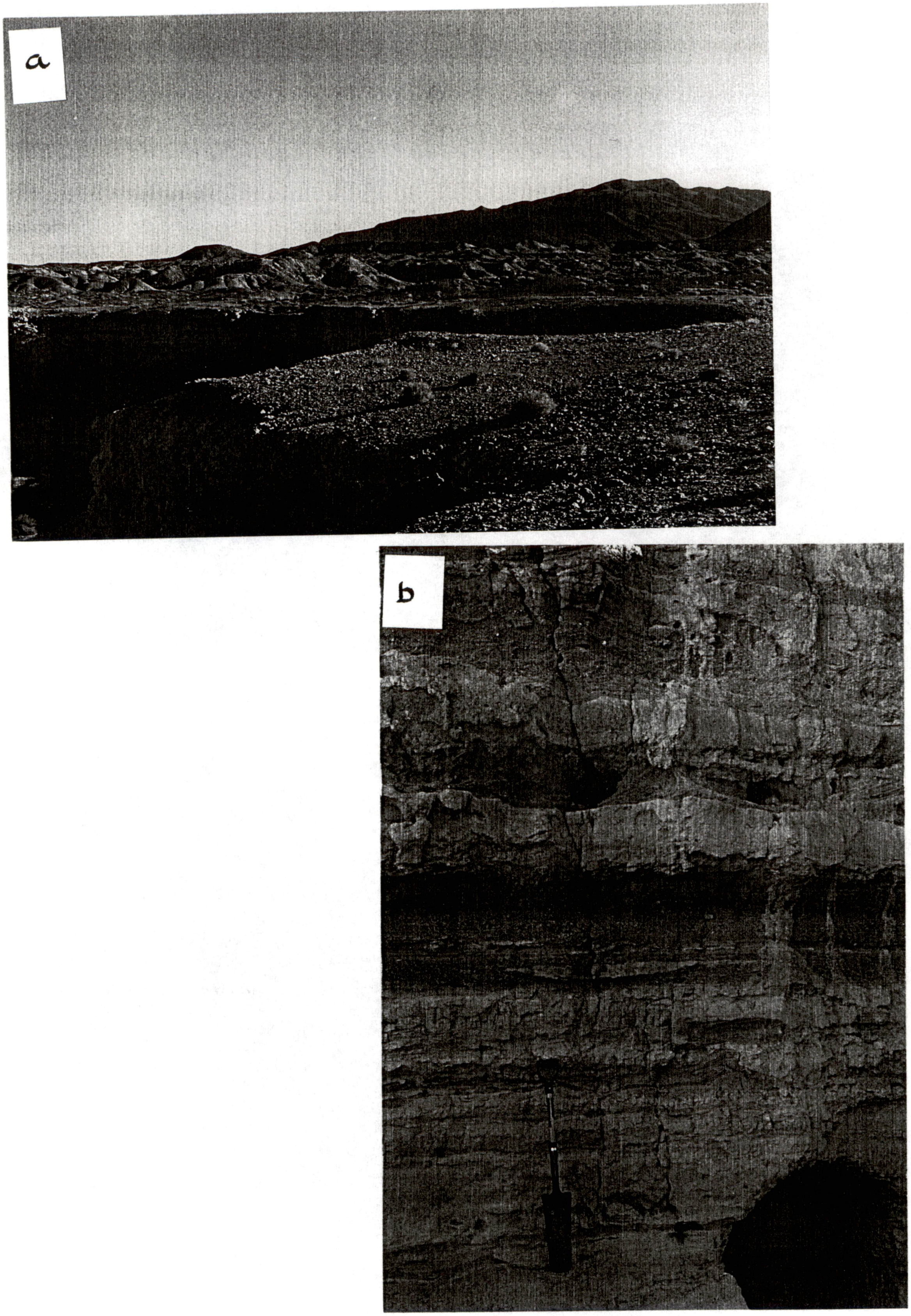
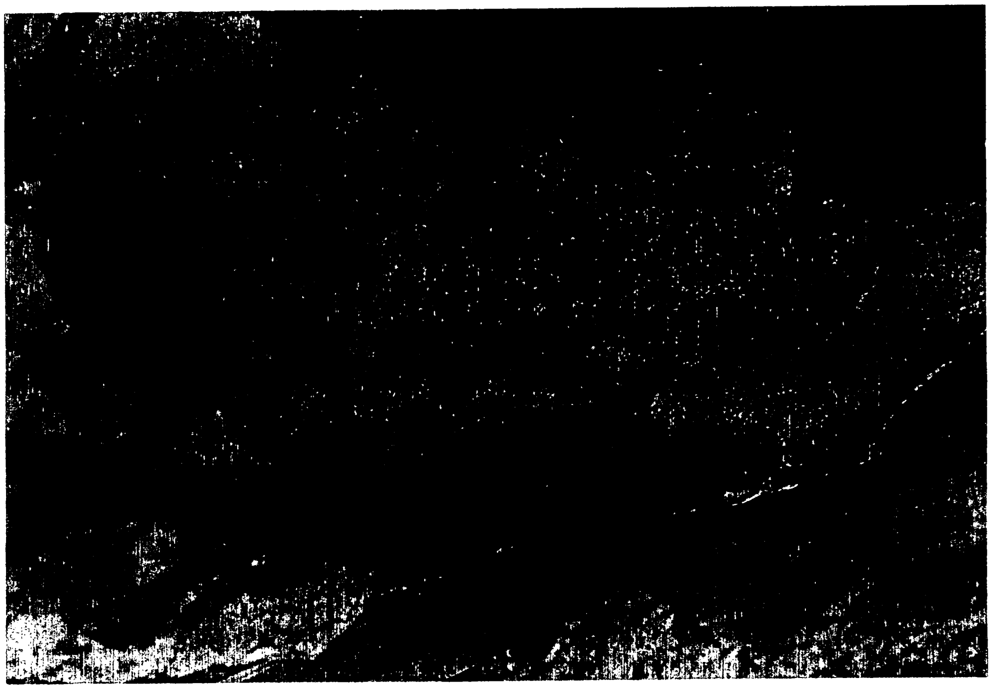


Figure 16. Lake Tecopa gravel (Castle in clay) exposure section 1 (a) from top of marl beds looking north across badlands (b) through indurated gravels showing fracturing, and an excavated cliff dwelling.

(a)



(b)

Figure 17. Lake Tecopa gravel (Castle in clay) exposure section 1 (a) Indurated marl beds at the top of the exposure, cracking is formed during lake exposure following deposition (b) weakly indurated sand better cemented along Liesegang banding.

(a)

(b)

Figure 18. Figure 18. Lake Tecopa clay exposure (section 5), (a) clays and weakly indurated volcaniclastic at the top; (b) cracking and folded clays at arroyo floor may be near groundwater discharge point.

Interpretation of the nature, amount and distribution of post-depositional alteration

Alteration in the fine grained deposits

Gray sandy silt near low point in basin floor is moist and gypsiferous at base, indurated but weathers to rubble above basin floor (fig 18 b). Displacive gypsum growth may be part of weathering pattern in silts and fine sands. Fine grained material at section 1 (Castle in clay) cliff base is indurated and has a salt crust. The salt crust suggests local groundwater seeps from this unit directly above the Amargosa River flood plain. Mineralogically and texturally immature silty clays have undergone some diagenetic alteration to form minor amounts of authigenic clay cements (fig. 19). Paleomagnetic and mineralogic studies indicate burial diagenesis was responsible for alteration (Larson and Patterson, 1993; Leising and others, 1995)

Alteration in the gravel

Gravel in the northern part of the basin is younger than the lake deposits in the basin center but also may be more influenced by spring discharge as suggested by lake deposits and occurrence of modern springs in this area. Limonitic root traces in slightly pink sandy silt layers may indicate paleosol formation. Sand and gravels are weakly cemented, display local Liesegang banding (fig 17 b), and widely spaced (1 m) joints. Liesegang banding suggests alteration and cementation occurred under saturated conditions before incision of badlands. Jointing may be related either to tectonic stresses or to unloading around local topography. Excavations for dwellings are located in gravels and sands (fig 16a); induration is sufficient to support them. Marl at the top of the cliffs is indurated, highly fractured, and has karst developed on it. Underlying marls are friable with abundant root tubules. No prominent diagenetic effect related to grain size contrasts was observed.

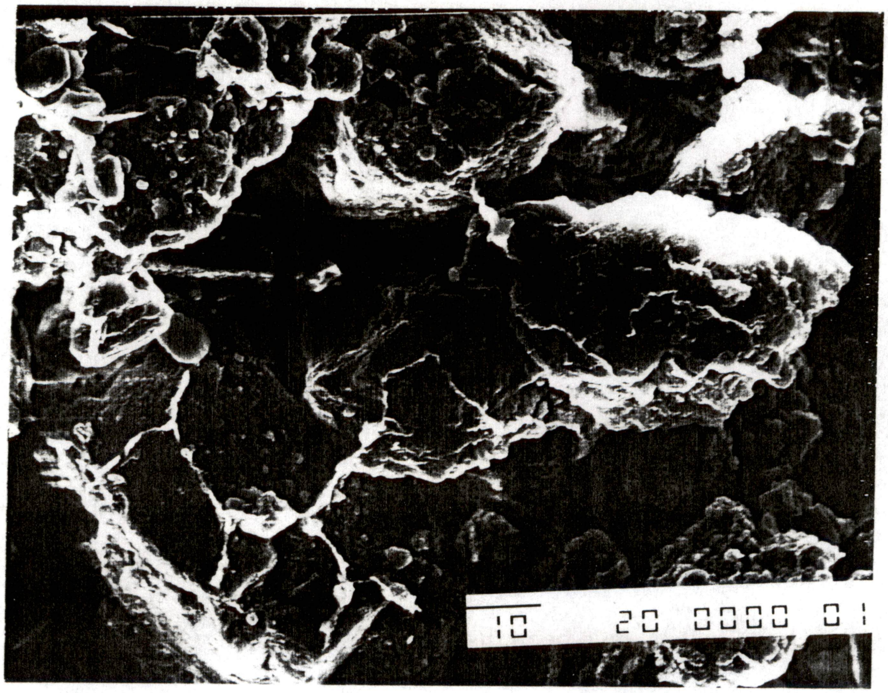


Figure 19. Scanning electron microscope image of authigenic clay coat on detrital clay and fresh quartz and feldspar silt, Lake Tecopa clay exposure (section 5), 5.3 m. Scale in microns.

Lake Dumont

General characterization of the site

Incised alluvial terraces into pluvial lake clays and marginal gravels have been recently examined in core by the Desert Research Institute, and AMS radiocarbon dates on core yield dates of 27 ka (K. Anderson, written communication, 1996). Only minor amounts of the lake clays crop out along low terraces on the basin margins (figs. 20, 21a).

Description of the sedimentary stratigraphy

A few meters of clayey sediments (15 percent clay, 54 percent silt, 31 percent sand) crop out. This unit has 21 percent carbonate but is not well indurated. Several generations of fine and coarse younger alluvium and one or more paleosols can be recognized cross cutting the pluvial lake deposits. Although core data indicate that grain size contrasts exist in this section, no outcrops of gravels were found.

Interpretation of the nature, amount and distribution of post-depositional alteration

Alteration in the fine grained deposits

Lake clay deposits have been disrupted by displacive gypsum growth, and obscured by crusts of eolian salt and sand (fig 21b). Sapping along gullies is common.

Fan gravels associated with the lake deposits in core were not exposed.

Santa Cruz Bend

General characterization of the site

The Santa Cruz River in downtown Tucson has a strongly incised valley cut through older alluvial deposits. Archeological investigations along the river have dated this alluvial record (Huckell, 1996). The exposure examined is on a still active cutbank below the University of Arizona experimental farm (fig. 22 and 23). The land surface is urbanized and vegetation includes mesquite and palo verde.

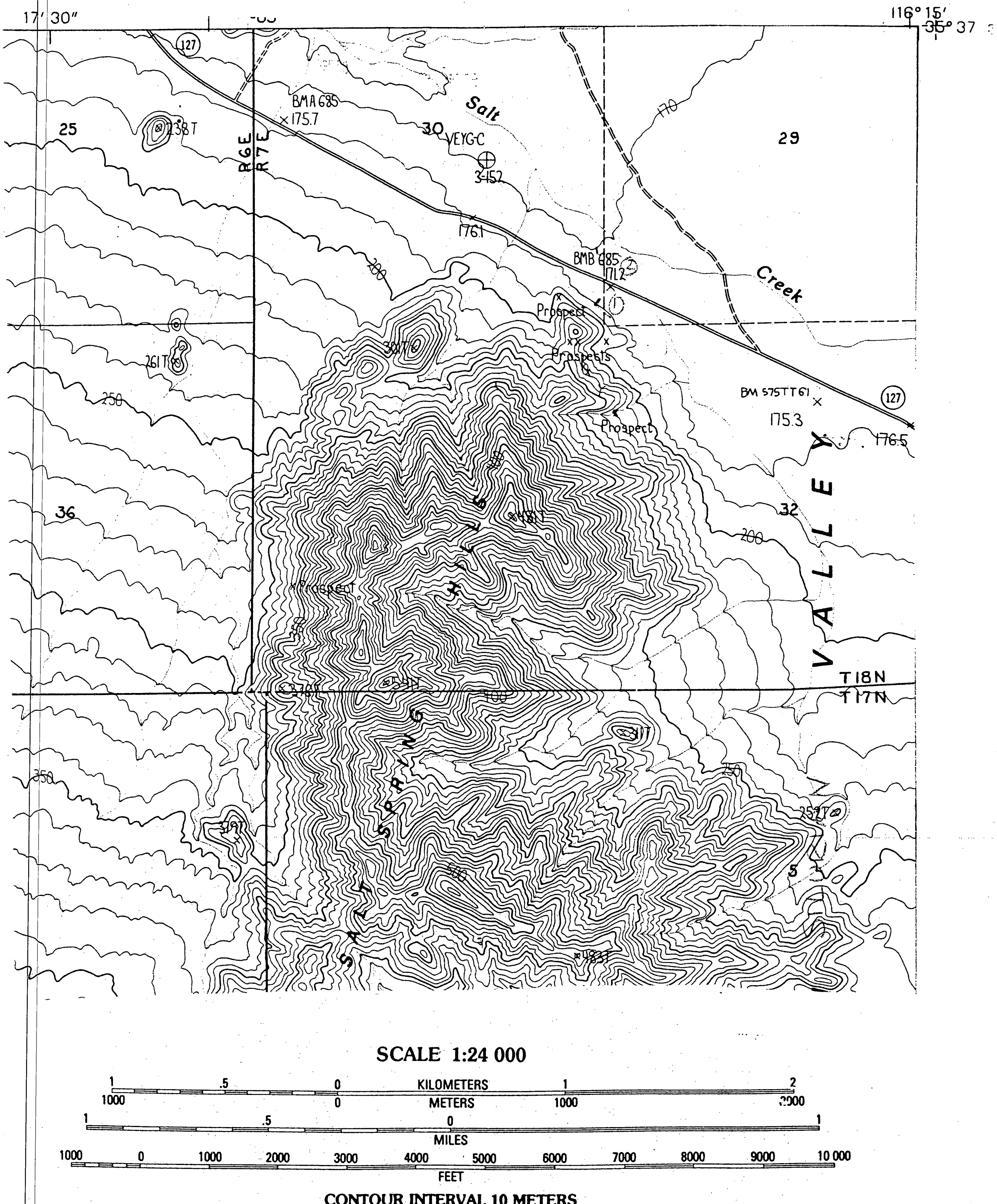
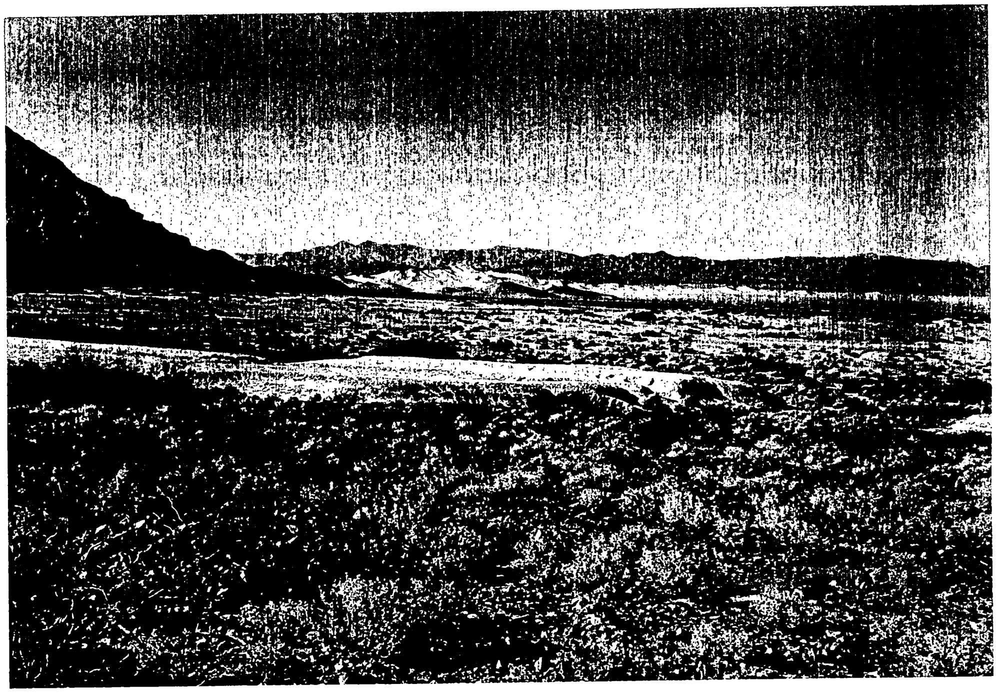


Figure 20. Location of the Lake Dumont exposures, USGS Sheep Creek Spring, CA, 7 1/2 minute quadrangle.

a



b

Figure 21. Lake Dumont exposures (a) looking north (b) salt crust and weathered surface of exposure. Notebook is 18 cm long.

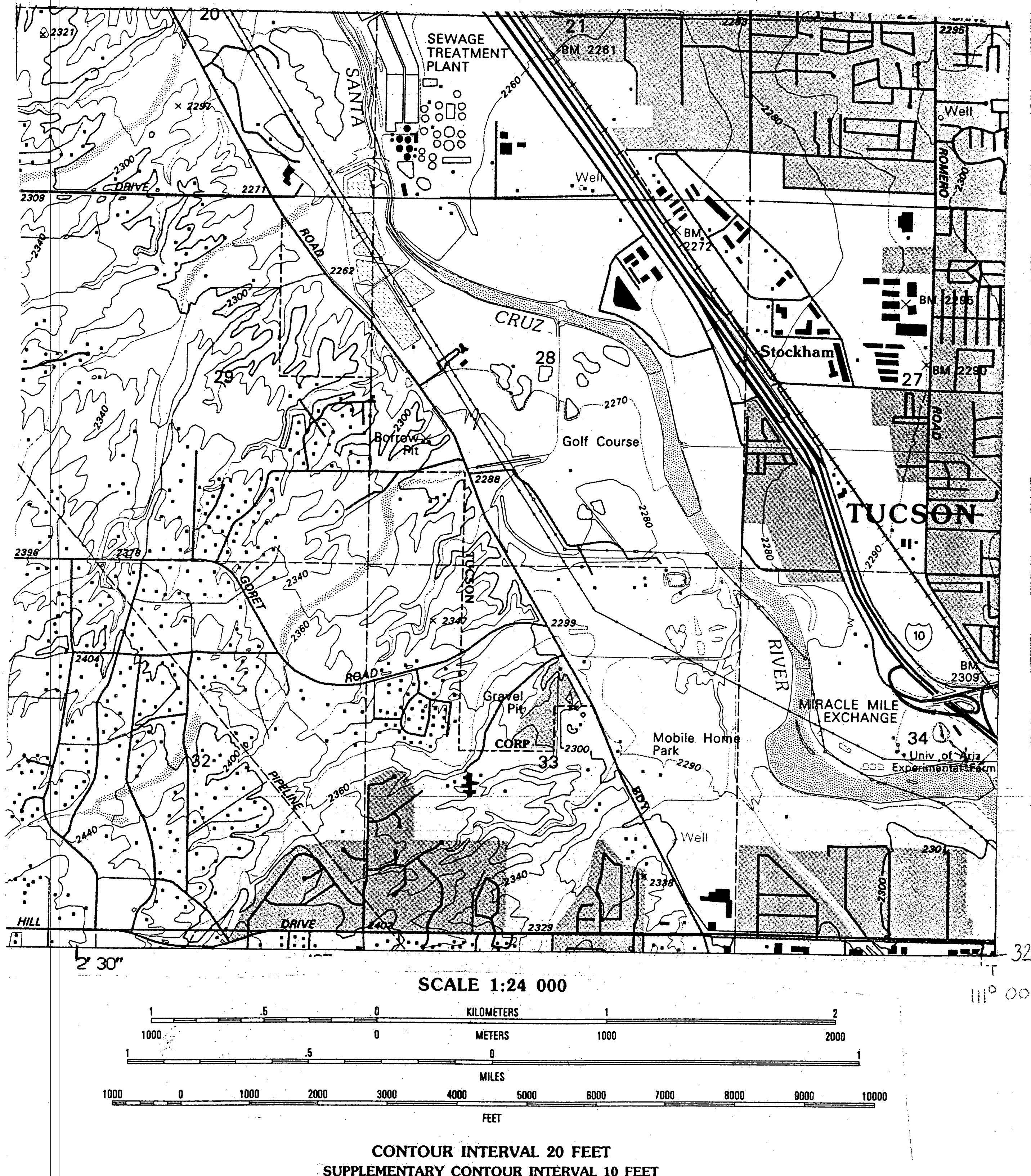


Figure 22. Location of the Santa Cruz Bend exposure, USGS Jaynes, CA, 7 1/2 minute quadrangle.

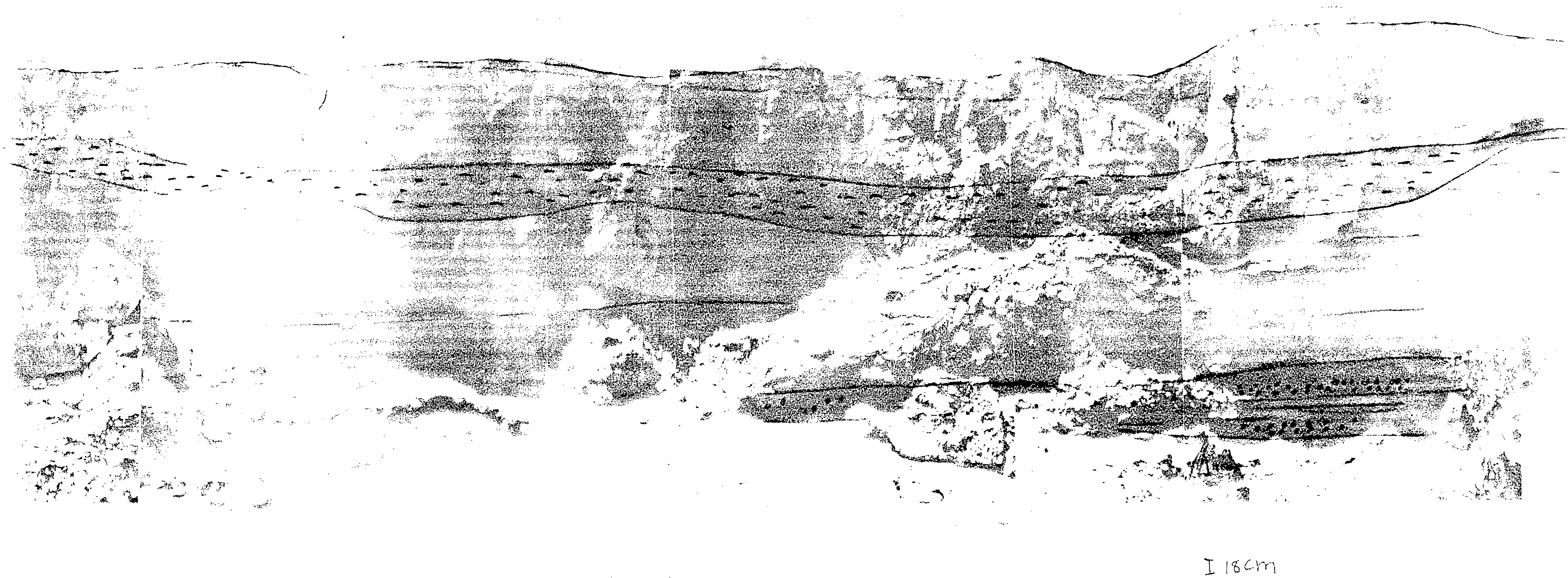


Figure 23. Photomosaic and interpreted drawing, Santa Cruz Bend exposure, fine grained charco deposits over Pleistocene gravels.

Description of the sedimentary stratigraphy

Basal gravel exposed near river level are composed of cobble gravel in sand and granule matrix. Calcite cement is variable and rhyzoliths are common (fig. 24 a). This unit is not dated, but a possible Pleistocene age is suggested. The gravel is overlain by medium sand with gravel lenses, and become finer upward with abundant root molds. Local horizontal calcite cemented zones may be pedogenic or groundwater caliche. Radiocarbon dating of charcoal from the upper part of this unit (Huckell, 1996) yielded 4,610 to 3,740 years b.p.

The fine grained unit in the section is brown clayey silt (0 to 0.75 m thick) filling incised channels (fig 24 b). These deposits are interpreted as charcos; backwater sloughs in an alluvial system (Huckell, 1996). Dates on charcoal from these units are around 3,800 years b.p. Grain size analysis of a representative sample of the fine grain unit gave 19 percent sand, 63 percent silt and 18 percent clay (table 3). Only 5 percent carbonate in the charco sediment reflects lack of soil formation and induration. Sand and silt filled cracks cross-cut these deposits.

Overlying the fine grained unit is 1.5 m of massive fine sandy silt (45 percent sand, 49 percent silt, 6 percent clay; table 3).Carbonate (4 percent) cements and forms weakly calcified root tubules. Huckell (1996) notes strong rodent bioturbation in this unit and resulting variable radiocarbon dates on charcoal.

Interpretation of the nature, amount and distribution of post-depositional alteration

Alteration in the fine grained deposits

The fine grained "charco" deposits are laminated and have sharp contact with adjacent sediments indicating minimal disturbance by early soil formation or later disruption such as burrowing. They are also not very fine grained with a maximum of 18 percent clay measured. The performance of the charco deposits as barriers has been compromised by vertical fractures filled with silt and sandy silt. The timing of cracking is not clear, since no

(a)

(b)

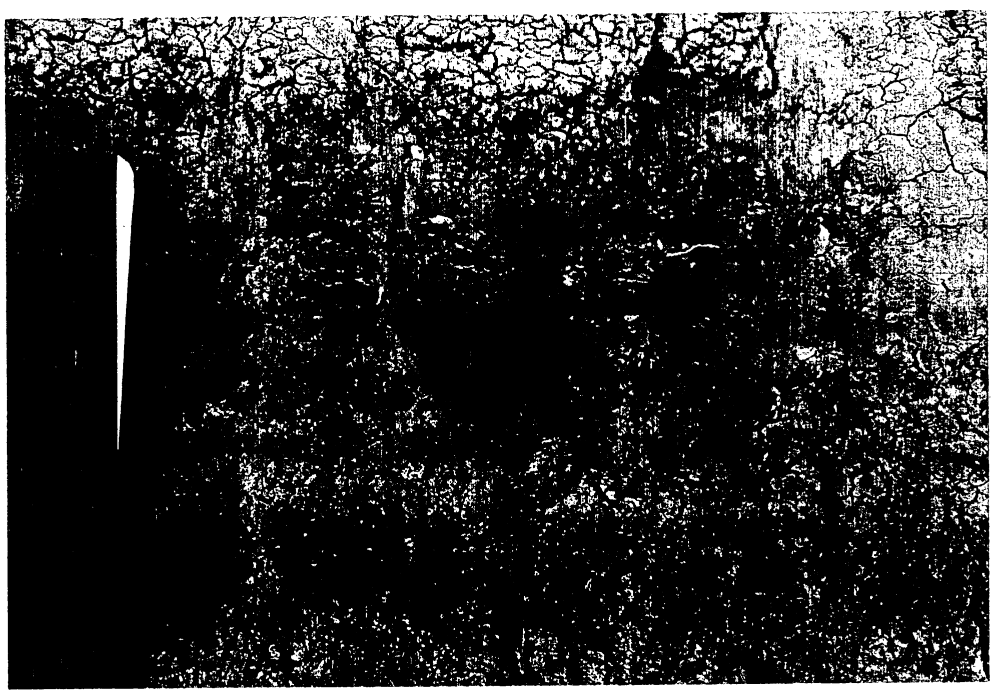


Figure 24. Santa Cruz Bend (a) variable cementation in Pleistocene gravels, probably rhyzoliths (b) fine grained charco deposits are cracked and cracks filled with fine sand and silt, increasing permeability. Timing of crackling is not known.

silt source layer is preserved and the cracks lack classic upward-widening mud crack morphologies. The most probable time for cracking is in the depositional environment. The fine grained units are now dry and are intensly cracked, forming blocky structure in the natural exposures, however it is difficult to tell without excavation how much of the cracking is relate to exposure. No sensitive indicators of flux through the fine grain deposits were identified. This site might be useful for measuring the effect an imperfect fine grained barrier has on vertical flow in the unsaturated zone, because the thickness of the charco deposits varies laterally over short distances and other sediments remain more contstant in thickness and composition.

Alteration in the gravel

Gravel at the base of the section is variably cemented by calcite. Calcite concentrations are probably rhyzoliths (root casts). Calcite concentration may reflect preferential flow along roots or biogenically mitigated more intense calcite precipitation near roots. Roots are no longer present in these gravels and therefor reflect earlier conditions. Large root casts are not found in strata overlying the gravels, suggesting that the plants may be related to an old surface before deposition of the younger sediments.

Murray Springs

General characterization of the site

The Murray Springs site in Cochise County, southeast Arizona is a well-known archeological site and has been slightly developed by BLM with trails and bridges over the draw. The site is accessible from NM 90 on Moson Road with the access road and parking developed on the abandoned Southern Pacific railroad grade (fig. 25).

Arroyos developed along Curry Draw, an ephemeral tributary to the San Pedro River, expose 5.5 m of sediment. The undissected upland slopes gently toward the San Pedro River. Prior to incision of the arroyo in 1911, the draw occupied a gentle swale (Haynes, 1987). An abandoned railway embankment north of the site may somewhat

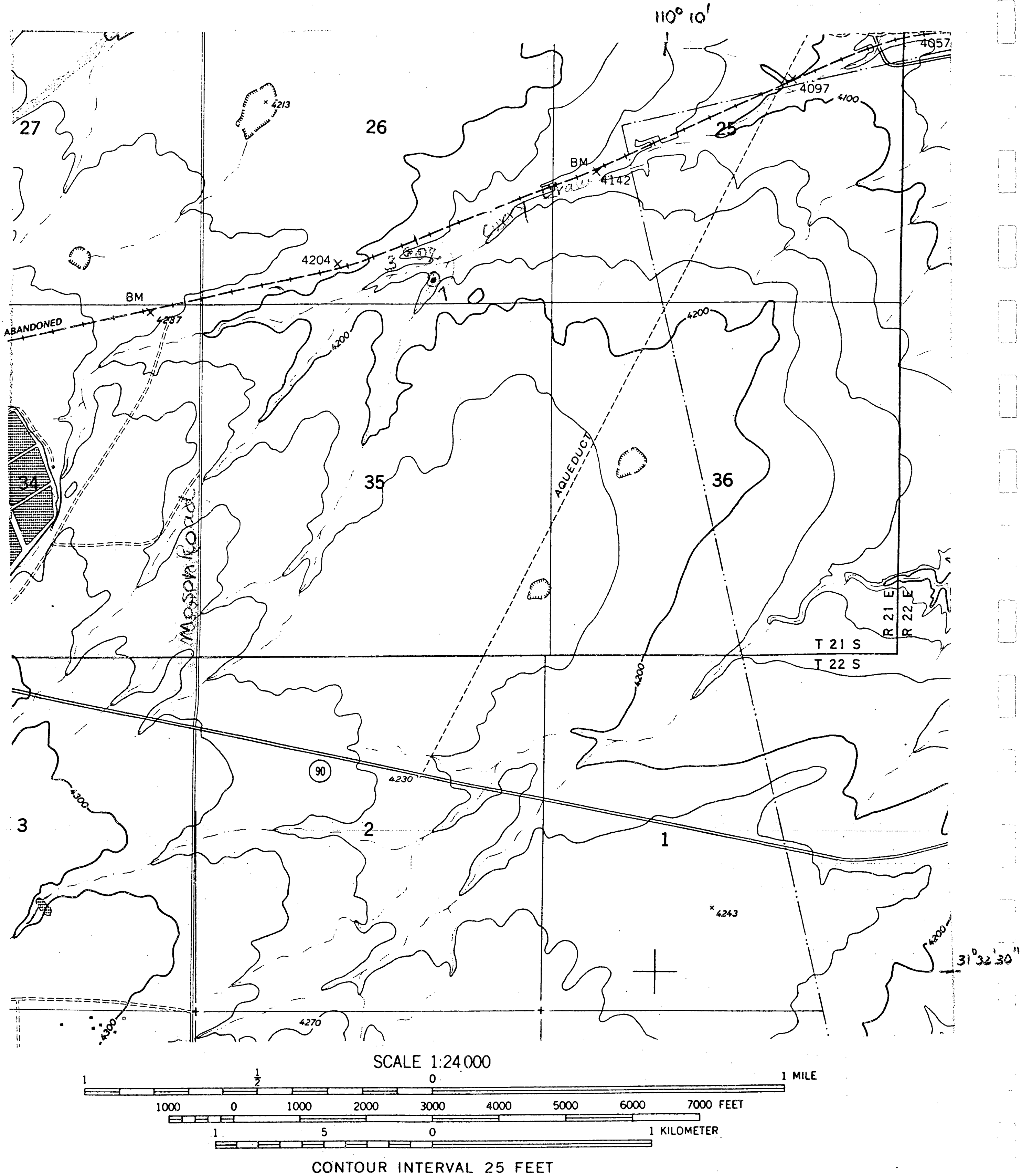


Figure 25. Location of the Murray Springs site, USGS Jaynes, AZ, 7 1/2 minute quadrangle.

modify the modern near surface drainage and hydrology. The swale is fairly densely vegetated by grasses, squash, and mesquite (fig. 26 a)

Description of the sedimentary stratigraphy

Complex stratigraphy is related to multiple alluvial episodes under varying climatic conditions through the Quaternary resulting in accumulation of channel sand and gravel; pond clay, organic material, and marls; and red eolian-alluvial sand and silt (fig. 26 b).

The basal unit exposed is cobble gravel in variably cemented granule matrix (fig 27a). Cobbles are rounded and lithologically heterogeneous. Where this unit is well cemented and exposed in the channel floor, small potholes are developed in it (fig 27 b). Overlying this is red hard clayey granule sand. Bedding and resistance to erosion is defined by variable textures ranging from graveley sand to clayey drapes. The upper part is locally gleyed (5Y 6/3), firmer, and more limonitic. This is probably the Millville Formation of Haynes (1987).

The middle unit exposed is fine grained, gleyed clay, marl and organic material mapped as the Murrey Springs and Lehner Ranch Formations (Haynes, 1987). This unit is heterogeneous because of deposition on an irregular surface, complex topography and environment changes during deposition, and erosion following deposition (Haynes, 1987). The exact relationships between the exposures examined for this study and the stratigraphy defined by Haynes (1987) on the basis of excavations and C^{14} dating was unclear. Section 1 measured in the southern gully contains a thin sequence (28 cm) of muddy gray sand overlain by laminated dark clayey silt (5YR 6/2-5/2), overlain by calcareous silty gray clay. Acid insoluble and grain size analyses of dark clayey silt (table 3) gave 2 percent carbonate with 18 percent clay, 50 percent silt, and 31 percent sand in the insoluble fraction. A sample of marl contained 68 percent carbonate with 49 percent clay and 45 percent silt in the insoluble fraction. The top of the fine grained interval is about 1.5 m of white marl.

(a)

(b)

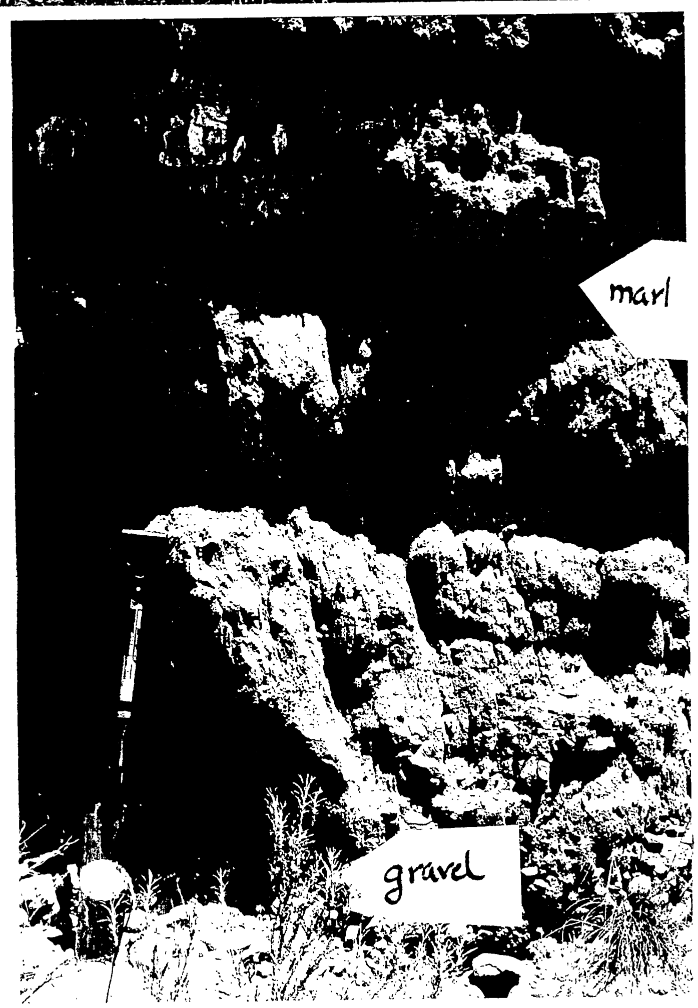


Figure 26. Murray Springs site, Curry Draw, (a) Moderately abundant vegetation indicates a shallow water table (b) marl beds overlie Pleistocene gravel at exposure base.

(a)

(b)

Figure 27. Murray Springs gravels (a) typical Pleistocene gravel with a sand matrix; (b) Calcite cemented Pleistocene gravel eroded in arroyo floor, cementation may indicate past or ongoing groundwater discharge.

In the northern gully, the marl is absent. Gray marly clay forms the base of the fine grained interval. A distinctive organic-rich bed ("black bed" of Haynes [1987]) is the middle unit. In section ,2 another gray clayey marl overlies the organic-rich bed.

The top of the interval in all three sections is red (7.5 YR 5/4) silty clayey sand with local cobble lenses.

Interpretation of the nature, amount and distribution of post-depositional alteration

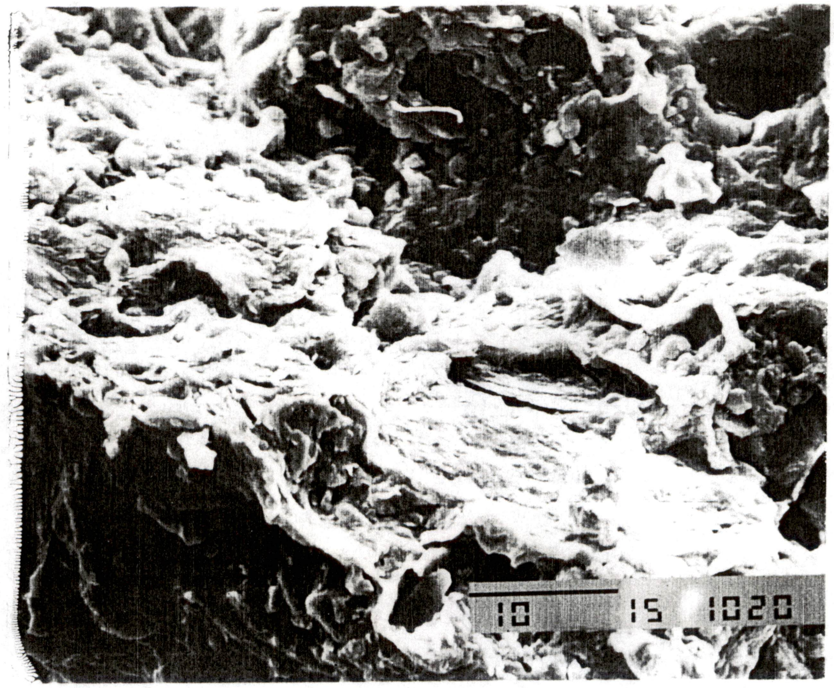
Alteration in the fine grained deposits

Modern roots penetrate the entire section. The vegetation is somewhat lush in the swale, including mesquite, tall grass, and wild squash plants suggesting that soil moisture content may be higher than in adjacent areas of creosote bush, gray and sage brush. High moisture content may be related to continuation of the hydrologic regime that created springs and ponds in this area.

Permeability of marls may have been modified by formation of root tubules. Some large tubules are filled with red alluvium derived from overlying units, documenting the effectiveness of transport along the tubules. Marls have been little modified and are low density showing that they have not been strongly compacted or cemented. Gastropods near the base of the marl units are preserved without leaching. The upper part of one marl is discolored and clayey and the upper contact with alluvium is sharp and irregular, suggesting formation of a soil on top of the marl unit. Marl is jointed and the joints influence its weathering pattern.

Silty clays and marly clays have been more intensely altered. One thin clay unit was cracked and the cracks infilled with sand and marl. This cracking may have occurred in the depositional environment or under burial conditions. Clays also contain abundant modern roots and some root traces. Soil fabrics resulting from shrink-swell and clay illuviation (peds) are well developed in most clays (fig 28a). Clays also have been more strongly modified by outcrop weathering compared to marl. Clays crumble and flake whereas assocoated marls form massive cliffs. The organic-rich layer exhibits no soil texture but has

(a)



(b)

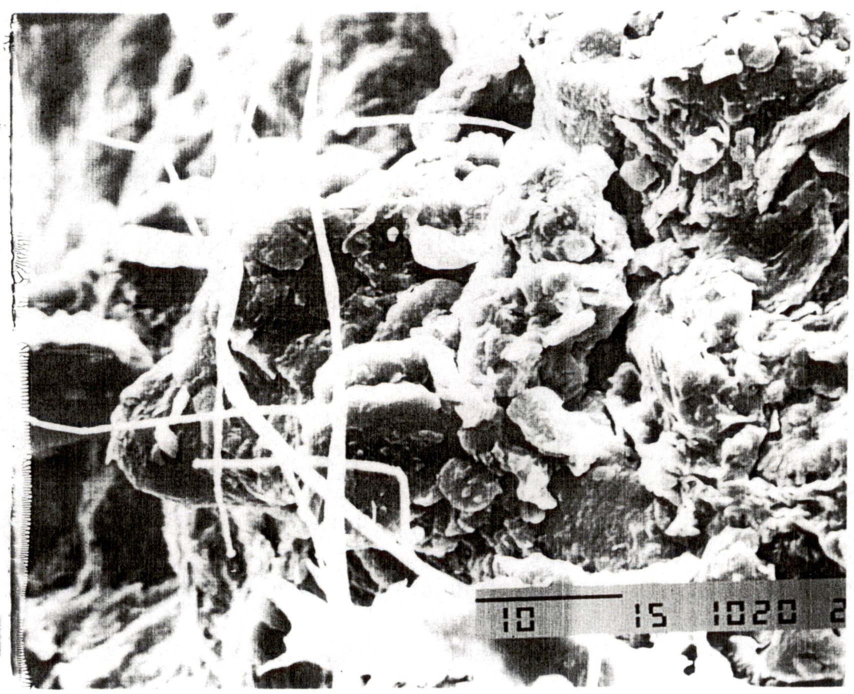


Figure 28. Scanning electron microscope images (a) authigenic clay in marl, Murray Springs section 1, 2.0 m. (b) fungal filaments indicating modern and moisture flux, Murray Springs section 1, 2.0 m. Scale is in microns.

become crumbly in outcrop. The top of the lower coarse-grained unit where it underlies marl is clayey and gleyed. It exhibits well-formed peds. Fungal filaments are indicators of moisture and nutrient flux (fig. 28b).

Alteration in the gravel

Gravel has a sand and clay matrix weakly to strongly cemented with calcite rhyzoliths. Roots from creosote and other large shrubs penetrate the entire exposed section. Local lithification because of calcite cementation of gravel is observed in the floors of the arroyos may be a product of spring discharge in this area where discharge has been focused a several times in the areas geologic history.

Garnsey Bison Kill Site

General characterization of the site

The Garnsey Bison Kill archeological site is east of Roswell, NM on BLM land east of Bottomless Lakes State Park (fig. 29). Access is from the Park Road.

Permian gypsum on the east side of the Pecos River has been dramatically modified by karst development, forming the Bottomless Lakes (fig 30 a). The Holocene stratigraphy is exposed in a 2 to 4 m deep arroyo incised in a 40 m-deep valley east of Dimmit Lake. This valley is developed in folded, fractured, probably collapsed bedded gypsum bedrock. At least two terraces are developed in alluvial fill. Grassland vegetation covers the area (fig 30a).

Description of the sedimentary stratigraphy

Alluvial stratigraphy is complex in response to the irregular gypsum bedrock topography. Gypsum and dolomite cobble gravel in red mud matrix is found in the floor of the arroyo. Angular clasts appear to be locally derived. Fine-grained bedded white gypsum is the most abundant clast lithology. Selenite (coarsely crystalline fibrous gypsum) forms clasts and disaggregated fibers. Dolomite occurs as large clasts and is the dominant sand-

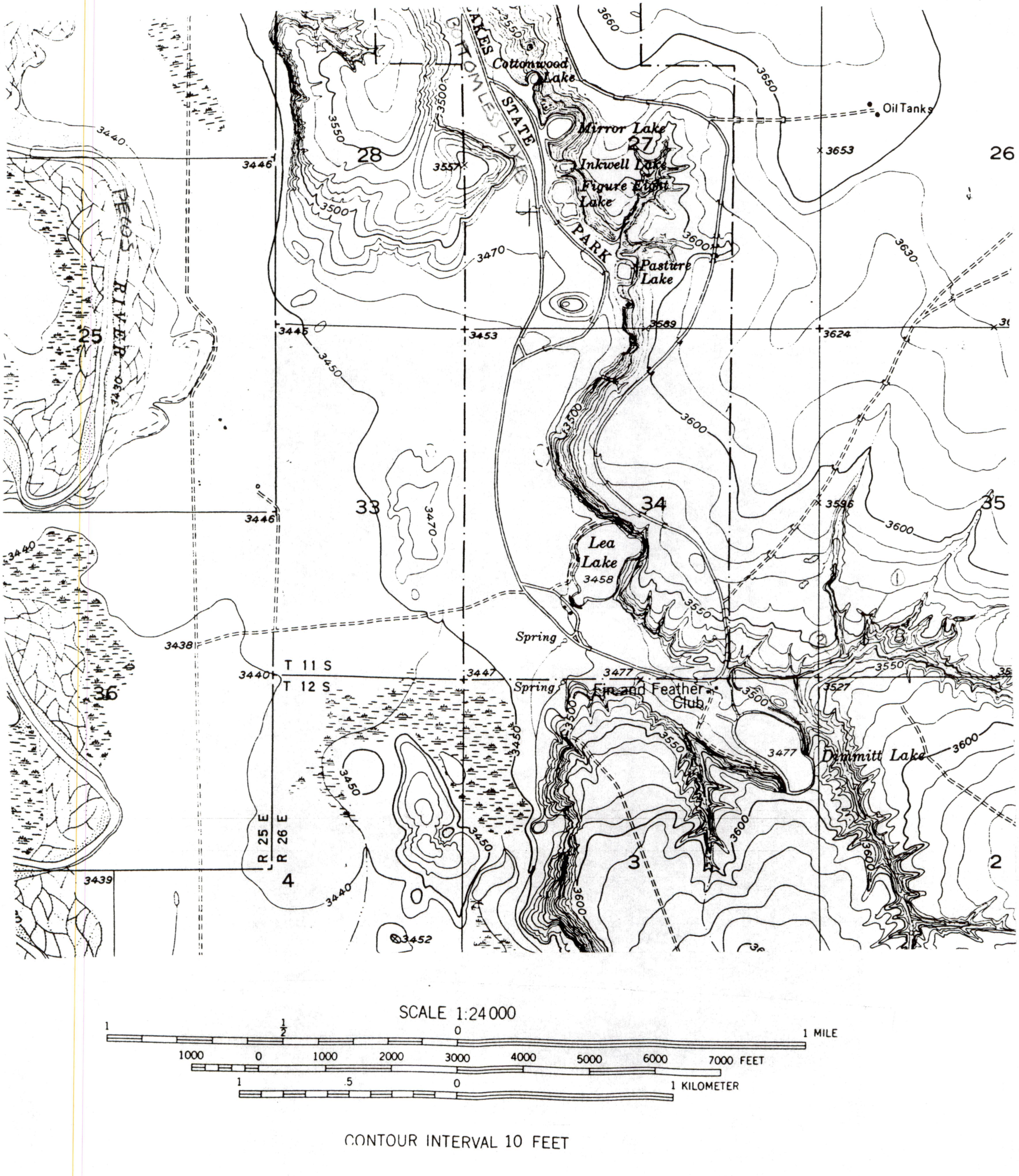


Figure 29. Location of the Garnsey Bison Kill site, USGS Bottomless Lakes, NM, 7 1/2 minute quadrangle.

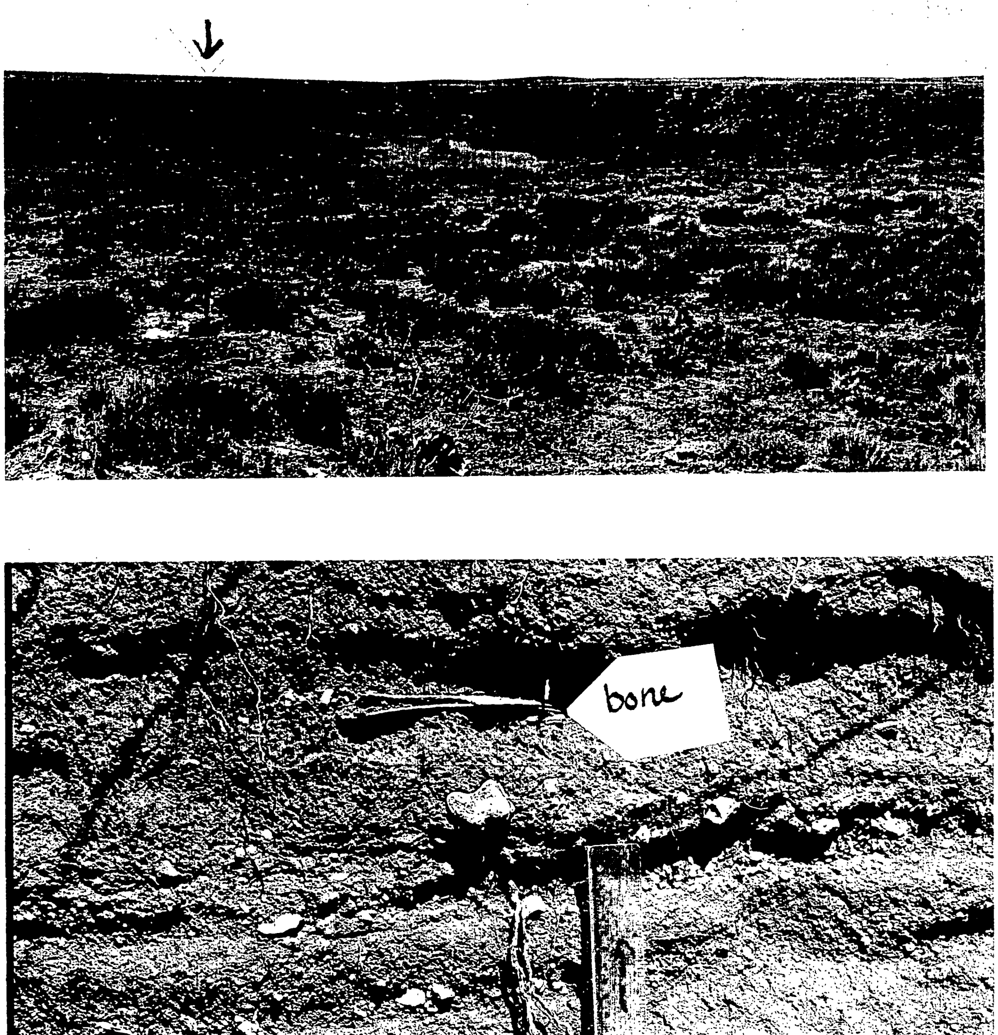


Figure 30. Garnsey Bison Kill site (a) exposures in arroyos (arrow), evaporite collapse feature Dimmit lake in center. (b) gypsum-bone gravel overlying gleyed clayey sand. Scale is 20 cm.

size grain. Bones and bone fragments are found within the gravels at many locations in the arroyo (fig. 30 b).

Overlying the gravel is a unit of interbedded clayey sand, sandy clay, and gravel. In the upstream (eastern) part of the area examined, finer grain size material dominates and is gleyed, with strong limonite mineralization along the traces of fine roots. Lenses of sandy gravel 10-to-30-cm thick fine upward into muddy sand. Poorly sorted clayey sand forms the interbedded units. Western exposures in the arroyo contain better sorted cross bedded sand and gravel, indicating fluvial deposition.

The upper unit is finer grained clayey sand with less gravel and less gypsum, and appears to be less locally derived. Acid insoluble and grain size analyses of this sediment showed 28 percent carbonate, with 56 percent sand, 28 percent silt and 16 percent clay in the acid insoluble fraction.

Interpretation of the nature, amount and distribution of post-depositional alteration

Alteration in the fine grained deposits

Modern roots are abundant throughout the section. Limonite stain on root traces is especially well developed in gleyed clayey sand units. Gleying may be partly facies controlled with more reduction occurring in ponded areas where muddy sand accumulated. However, other areas of bleached sand are irregular and occur near bedrock outcrops, suggesting that they may be related to groundwater discharge from gypsum bedrock, with reduction possibly occurring as a product of processes such as minor amounts of bacterial sulfate reduction.

Alteration in the gravel

Gravels are all muddy, and relationships in this muddy section suggest that the sorting in this arroyo was never very good, and mud filled most pores between cobbles during or immediately after deposition. Geomorphic setting and deep root development suggest that groundwater may intermittently and locally perch in the alluvium above low permeability bedrock. However, gypsum does not appear to be more highly altered in gravels than in bedrock outcrops. I would expect that if gravels were wet, gypsum would recrystallize or dissolve. Bone is soft and fragile; quantitative estimates of alteration in bone might be useful fro understanding moisture flux in this area.

DISCUSSION

Coarse grained deposits

One objective of this study was to evaluate the performance of natural grain size contrasts to perform as capillary barriers and to assess the processes of degradation of the grain size contrasts by infiltration of fine material into the pores of coarse material. Natural analogs identified in this study are imperfect to meet this objective for several reasons including (1) lack of natural tracers suitable for evaluating performance, (2) probable syndepositional infiltration of fine into coarse material, (3) possible to definite saturation of deposits at times in the geologic past, making separation of vadose processes and saturated zone processes problematic.

The best preserved and most dramatic grain size contrast in the study sites is in the Lakeside gravel pit. Here marl, composed dominantly of silt size carbonate and opal grains, overlies well-sorted pebble gravel with minimal matrix. These deposits are relict from previous high lake levels, so the modern groundwater regime is very different from the one in which the deposits were formed.

The silt-over-gravel grain size contrast may be functioning as a capillary barrier to surface flow. Evidence for this is (1) observed moisture in the marl beds where the underlying gravels appeared dry and dusty (2) abundant fine roots and root traces in marl beds, few or no roots in gravel beds, indicating that marl is a recurrent source of moisture, and (3) limonite staining in the lower part of marl beds suggesting alteration where moisture is stored. Staining, however, may also reflect compositional variations in the lower parts of marl beds. Even though marl lies directly on top of gravel, there is little evidence of infiltration of silt into gravel. The uppermost few centimeters of gravel beneath marl beds typically have a denser white carbonate coat than underlying gravel coat, this may be a product of infiltration and then evaporation and cementation by stored water. Very steep dips on the gravel /marl contacts are interesting. Dip is required on many capillary barrier designs to release water stored at the barrier and prevent build up of head and consequent moisture break through. However structural failure in wet, fine grained clayey material is a concern . The steeply dipping marl beds at the Stansbury Gulch site have evidence of deformation and slumping when they had high moisture content in the depositional environment, however in spite of loading by younger deposits, and saturation by lake high stands, these marl beds show no evidence of creep or other deformation. The organic carbonate-diatom composition may have an influence on shear strength of these materials.

Gravels are cemented, indicating that at some time fluids moved through them. However, the carbonate composition of the cements, lack of vertical variability in carbonate concentration, and pervasivness of cement suggests that cementation may have occurred when ground water saturated the gravels during several episodes of high lake level. Local areas of limonite stain in gravels may indicate discharge through gravels at an unknown time, possibly in the vadose environment before or during quarrying. Additional geochemical and radioisotopic study of cement could be used to more completely separate ancient and modern alteration as indicators of moisture flux.

The Lake Tecopa gravel section, Santa Cruz Bend, Murray Springs, and Garnsey Bison Kill have adequate grain size contrasts to serve as potential analogs to assess how altered, natural bedded layers function as capillary barriers. The grain size contrast in all of these analog sections is degraded from the contrast that would be designed in an engineered barrier because infiltration of fines into gravel. Analogy with very young gravel deposits suggests that much of the infiltration probably occurred in the depositional environment during waning energy phases. Fine grained deposits are dominated by silt, which does not provide very strong hydraulic contrast. In all sections, environments have been wetter, and gravels saturated. Cementation degrading capillary performance may have occurred in near saturated conditions. An example of evidence of saturated condition is the Liesegang banding at contacts in the Lake Tecopa gravel section. Saturated conditions in the gravels certainly existed during deposition of overlying marls. In addition, gravels in these exposures occur near the base of the sections and may at times be saturated by ground water flowing into the rivers and arroyos responsible for creation of the exposures. This is an especially high risk in alluvial settings (Murray Springs, Garnsey Bison Kill, and possibly Santa Cruz Bend) where the gravels are confined to incised valleys in less permeable bedrocks and therefore may perch and channel groundwater along the alluvial valley. Denser modern vegetation associated with alluvial valleys at Murray Springs and Garnsey Bison Kill supports this idea. Santa Cruz Bend is in a highly modified urban area.

Alteration of fine grained deposits

Fine-grained clastic sediments of any age and in all natural settings examined have been fractured. Shrink swell because of moisture variation is a probable cause in all the settings. The timing of formation and extent of this fracturing away from the exposure face is uncertain for all the sites. Sand-filled cracks in clayey silt "charco" layers at Santa Cruz Bend, are examples of cracks that probably originated because of wetting and drying. Filling with coarser material has probably increased the vertical hydraulic conductivity of this unit under all conditions. Exposures, both natural and man made, have changed the local stress field, and fractures have opened up and spalling has occurred. This process was especially well displayed at the Delta exposure, where silts in vertical cut-bank exposures have probably not undergone much shrink-swell but are cracking and spalling parallel to the river bank. In most natural exposures, rapid surface weathering obscures the character of fine grain clastic sediments so that little can be determined about their performance. Excavation to depths of more than a meter would be required to assess the performance of fine grained materials at depth in engineered barriers. Cracking, formation of blocky fabrics, precipitation of iron and manganese oxides and hydroxides on cracks, extensive penetration by roots were observed in all the fine grained materials examined. Surface alteration of fined grained materials appears to be rapid, as it was at the Delta exposure where construction has modified topography within the last year or so.

Alteration of marls in terms of cracking is much less that fine silty clastics. Marls at Lakeside gravel pit, Stansbury Gulch, Delta, Lake Tecopa gravel section, and Murray Springs all are fractured by widely spaced near-vertical joints, but show no evidence of shrink-swell or creep deformation. Opal diatoms and carbonate skeletal materials are preserved in all the Lake Bonneville marls examined. Root tubules vertically and horizontally through the marl beds and iron oxide staining are the dominant alteration in Bonneville marls. Marls from Lake Tecopa gravel section and Murray Springs have abundant lake-precipitated carbonate grains and/or carbonate cements, making the diagenetic alteration of these marls difficult to determine. These marls, in contrast to the Bonneville marls, also have been variably lithified and altered by exposure and cementation, probably at least partly occurring in the depositional environment.

Role of geomorphic setting

Minimal alteration is observed in pluvial lake sediments stranded well above most of the modern ground water. Lakeside gravel pit, Stansbury Gulch, Lake Tecopa gravel sections have minimal observed interaction with modern ground water. Salt crusts at Stansbury Gulch on some marl sections and at the base of the Lake Tecopa gravel section document local moist units. In these sections, both gravels and fine grained materials are relatively minimally altered. Jointing in response to regional stresses or unloading at the exposure face can be observed. Live roots are sparse and are observed at the Lakeside gravel pit and Stansbury Gulch concentrated in the fine grained layers, which may serve as capillary barriers storing water. However, the dry sand and gravels in cliff exposures in these settings were attractive to large burrowers, including an animal den at Stansbury Gulch, excavated caves for human occupation at Lake Tecopa gravel section, and quarrying at Lakeside gravel pit.

Most alteration is observed in alluvial settings: Murray Springs, Santa Cruz Bend, Garnsey Bison Kill site, and Delta. The density and depth of penetration by roots is generally greater where groundwater is shallow in these settings. Variable cementation, discoloration by iron oxide, and past and present shrink-swell of clays are also common and pervasive elements altering both fine and coarse deposits. However, very intense alteration has not occurred in any sites: reactive grains such as gastropod shells and bone are preserved as the original material. Geochemical analysis of these materials might help quantify the amount and timing of alteration in these sections.

Role of age

Age of the deposit plays little role in the intensity of observed alteration. At Garnsey Bison Kill (500 years) and Santa Cruz Bend (3,800 years), young alluvial deposits are cemented, fine grained material is cracked, and roots and burrows have penetrated and disturbed layering as much as in older deposits. These processes operate rapidly and the effects also probably do not cumulate through time, because of (1) overprinting (new roots tend to follow the same path as old roots, limiting the ultimate density of root tubules) and (2) episodic low frequency alteration only after prolonged flooding followed by drying. Geomorphic setting and bed composition are more important in determining intensity of alteration than age of deposit.

RECOMMENDATIONS FOR FURTHER STUDY

Table 4 lists the strengths and weaknesses of the sites investigated as natural analogs of engineered barriers. No site is a perfect analog, and an exact match between natural and engineered sites was not expected. These sites serve as useful partial analogs in terms of documented sedimentary textures and sequences.

Modern geomorphic setting is critical in how useful the analog will be. Relict pluvial lake sites have an advantage over alluvial sites in that modern groundwater and arroyo vegetation appears to be less important, making the site a better analog to vadose

Table 4. Evaluation of the suitability of sites examined as geologic analogs for engineered barriers.

Site	Advantages	Disadvantages
Lakeside gravel pit	Well-developed grain size contrasts, Minimal modern ground water interaction.	Unusual marl/diatom mineralogy of fines, complex stratigraphy, diagenesis in lake paleo-environment.
Stansbury Gulch	Well-developed grain size contrasts, Moderate modern groundwater interaction.	Unusual marl/diatom mineralogy of fines, complex stratigraphy, salt crusts, diagenesis in lake paleo-environment
Lake Tecopa, gravel section	Some grain size contrasts, moderate modern groundwater interaction	No clayey or silty fines, marls are modified probably in depositional environment
Santa Cruz Bend	Variable thickness of siliciclastic fines over sand overlying gravel	Fines are separated from gravel by sandy sediments, gravel has a complex history. May be substantial involvement of modern groundwater adjacent to modern river.
Murray Springs	Variable thicknesses and compositions of fines over sand overlying gravel	Fines are separated from gravel by sandy sediments, old gravels have a complex history. May be substantial involvement of modern groundwater adjacent in spring discharge area.
Garnsey Bison Kill Site	Reactive phases including gypsum and bone have potential to be used as tracers for long term moisture flux	Muddy matrix in gravel and minimal clay in sand provide inadequate grain size contrasts. May be substantial involvement of modern groundwater in this setting.
Lake Tecopa, clay section	Volcaniclastics under lake clays might be found in another section	Inappropriate stratigraphy, weathered natural exposure.
Old River Bed		Weathered natural exposure, inadequate grain size contrasts
Delta		Poor exposure in modern cubank, inadequate grain size contrasts
Lake Dumont		Gravel in subsurface is not exposed, salt crusts.

engineered facilities. I recommend screening any future analog sites for geomorphic setting and groundwater regime.

Lake deposits including diatomites and carbonates are identified as fine grained alternatives to silts and clays. Marl deposits appear to be structurally more stable to shrink swell and weathering than deposits containing clay. Inspection of sites suggests that marls may serve as fine grained units in capillary barrier systems, however quantitative and experimental data are needed.

All the deposits examined during this study have undergone substantial modification since deposition, and complex evolution limit determination of the timing and rates of alteration. Future analog studies might focus on very young deposits, for example mine ponds and tailings, to determine the rates of alteration. .

CONCLUSIONS

Fracturing, soil forming processes, penetration by roots and burrows, calcite dissolution and precipitation, precipitation of iron and manganese oxides, and bleaching were the major changes noted. The geomorphic setting exerts a dominant control on the amount and type of alteration. Analogs in alluvial settings where moisture has been intermittently ponded in the river or gully floor, on the surface, or as shallow ground water above bedrock have more alteration than abandoned lake deposits on hill slopes. The amount of alteration also varies depending on the composition of the fine grained layers. Clay beds containing a significant component of expansive clays have been cracked and exhibit soil fabrics. Fine grained sediments with a significant component of carbonate and diatomite appear to have been only slightly altered. These observations compliment site-specific observations and suggest that further experimentation with the composition of the fine-grained layers may be warranted.

ACKNOWLEDGMENTS

The funding from this project was obtained by DOE through the Texas Low Level Radioactive Waste Disposal Authority (TLLRWDA) under Interagency Contract CON 97-028. Jay Raney served as project manager. Grain size analyses were conducted by Mary Joe Schabel, Soils Laboratory, Department of Geography, University of Wisconsin - Milwaukee. C. E. Mear of the Texas Archeological Research Laboratory (TARL) conducted a search of the archeological literature.

I thank the following experts for helping me identify and interpret the field sites: Jack Oviatt, University of Kansas, Manhattan, Kansas for information on Lake Bonneville deposits and for generously allowing me to join his field party [Vicki Pedone (UC Riverside) and Dave Miller (USGS)] to Stansbury Island and Lakeside gravel pit; Andrea (Max) Freeman, Desert Archeology for taking me to and providing essential data on the Santa Cruz Bend site and for sending me to the Murray Springs site; and Kirk Anderson, Desert Research Institute for information on Lake Tecopa and Lake Dumont areas. Chris Caren, Austin, Texas provided the locations of several prospective sections. Steve Hall (University of Texas Geography Department) provided information and references and Elmer and Jane Garnsey allowed me to visit the Garnsey Bison kill site on the property they lease from BLM. Eddie Collins (BEG) made a preliminary visit to this site. Dr. Tim Lowenstein, SUNY Binghamton, Dr. Vance Holliday, University of Wisconsin; Dr. John Hawley, NMBMMR), Dr. Mike Collins, TARL, Dr. Mike Blum (Univ. of Nebraska, Lincoln) all provided suggestions and referrals for potential sites. Dr.T. C. Gustavson (TARL) made a reconnaissance visit to Lake Mojave sites.

REFERENCES

Adam, David P; Hevly, Richard H.; Diggs, Robert E, 1985, Pollen data from a 2.93-meter Holocene lacustrine section from Walker Lake, Coconino County, Arizona: Open-File Report, U. S.Geological Survey, 13 p.

Allen, B. D., 1991, Effect of climatic change on Estancia Valley, New Mexico; sedimentation and landscape evolution in a closed drainage basin, *in*: Julian, Betsey, Zidek, Jiri, Field guide to geologic excursions in New Mexico and adjacent areas of Texas and Colorado, Bulletin New Mexico Bureau of Mines and Mineral Resources, No. 137, p. 166-171.

Bachhuber, F. W., 1989, The occurence and paleolimnologic significance of cutthroat trout (Oncorhynchus clarki) in pluvial lakes of Enstancia Valley, central New Mexico: Geological Society of America Bulletin, v. 101, p. 1543-1551.

Benson, L. V; Currey, D. R.; Lao, Yong; Hostetler, S. W., 1992: Lake size variations in the Lahontan and Bonneville basins between 13,000 and 9000 ^{14}C yr B.P: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 95, p 19-32.

Blair, T. C.; Clark, J. S.; Wells, S. G., 1990; Quaternary continental stratigraphy, landscape evolution, and application to archeology; Jarilla Piedmont and Tularosa graben floor, White Sands Missile Range, New Mexico; with Suppl. Data 90 08.: Geological Society of America Bulletin, v. 102; no. 6, p. 749-759.

Blum, M. D.; Valastro, S. Jr. 1992, Quaternary stratigraphy and geoarchaeology of the Colorado and Concho rivers, Geoarchaeology. 7. (5). p. 419-448.

Burman, R. and Pochop, L. O., 1994, Evaporation, evapotranspiration, and climatic data; Developments in Atmospheric Science 22, Elsevier, Amsterdam, 250 p.

Caran, S. C.; Baumgardner, R. W. Jr., 1990, Quaternary stratigraphy and paleoenvironments of the Texas Rolling Plains, Geological Society of America Bulletin. 102., No. 6, p. 768-785.

Clark, Malcolm M; Grantz, Arthur; Rubin, Meyer, 1972, Holocene activity of the Coyote Creek fault as recorded in sediments of Lake Cahuilla: The Borrego Mountain Earthquake of April 9, 1968. U. S. Geological Survey Professional Paper P- 787 p. 112-130.

Currey, D. R., Oviatt, C. G., and Plyler, G. B., 1983, Lake Bonneville stratigraphy, geomorphology, and isostatic deformation in west-central Utah; in Gurgel, K. P., ed., Geologic excursions in neotechtonics and engineering geology in Utah, Guidebook part IV, The Geological Society of America Rocky Mountain and Cordilleran Sections Meeting, Salt Lake City, Utah, Utah Geological and Mineral Survey Special studies 62, p. 63-69.

Elder, A. S., 1992, The paleoecology and geomorphology of Holocene deposits of the southern Malad River, Box Elder County, Utah: Utah State University, United-States; Master's, 57 p.

Enzel, Yehouda; Brown, W. J.; Anderson, R. Y.; McFadden, L. D.; Wells, S. G. , 1992; Short-duration Holocene lakes in the Mojave River drainage basin, Southern California: Quaternary Research (New York). 38; 1, Pages 60-73.

Gee, G. W., and Bauder, J. W., 1986, Particle-size analysis, *in* Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, American Society of Agronomy -Soil Science Society of America, Madison, WI, Agronomy Monograph No. (2nd ed.), p. 383-396.

Gilbert, G. K., 1890, Lake Bonneville; U. S. Geological Survey Monograph 1, 438 p.

Gile, L. H., Hawley, J. W., and Grossman, R. B., 1981, Soils and geomorphology in a Basin and Range area of southern New Mexico -- Guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 p.

Graf, W. L., 1989, Holocene lacustrine deposits and sediment yield in Lake Canyon, southeastern Utah: National-Geographic-Research, v. 5, no. 2, p. 146-160.

Green, S. A., and Curry, D. R., 1988, The Stansbury shoreline and other transgressive deposits of the Bonneville lake cycle; in Machette, M. M., and Currey, D. R., In the footsteps of G. K. Gilbert -- Lake Bonneville and neotectonics of the eastern Basin and Range Province, Guidebook for field trip 12, 100th Annual Meeting of the Geological Society of America, Denver, CO, p. 55-57.

Hakonson, T. E., 1997, Capping as an alternative for landfill closures — perspectives and approaches: *in* Reynolds, T. D., and Morris, R. C., editors, Landfill Capping in the Semi-arid West: Problems, Perspectives, and Solutions: Environmental Science and Research Foundation, Idaho Falls, ID, p. 1- 18.

Hall, S. A., 1990, Holocene landscapes of the San Juan Basin, New Mexico; geomorphic, climatic, and cultural dynamics, *in* Laska, Norman P., Donahue, Jack. Archaeological geology of North America: Geologial Society of America.

Hawley, J. W., 1993, Geomorphic setting and late Quaternary history of pluvial lake basins in the southern New Mexico region: Open File Report New Mexico, Bureau of Mines and Mineral Resources, 28 p.

Haynes, C. V., 1981, Geochronology and paleoenvironments of the Murray springs Clovis sites, Arizona: National Geographic Society research Reports, v. 13, p. 243-251.

Haynes, C. V., 1987, Curry Draw, Cochise County, Arizona: A late Quaternary stratigraphic record of Pleistocene extinction and paleo-Indian activities: Geological Society of America Centennial Field Guide — Cordilleran Section, p. 23-28.

Haynes, C. V., 1991, Geoachiological and paleohydrological evidence for a Clovis-age drought in North America and its bearing on extinction: Quaternary Research, v. 35, p. 438-450.

Hillhouse, J. W., 1987, Late Tertiary and Quaternary geology of the Tecopa Basin, southeastern California.: Miscellaneous Investigations Series - U. S. Geological Survey, MAP1728, Pages: 16, 1 sheet.

Horn, R. V., 1970, The Holocene Ridgeland Formation and associated Decker Soil (new names) near Great Salt Lake, Utah: U.S.Geological Survey Bulletin B-1457, p. C1-C11

Huckell, B. B, 1996 (draft), Quaternary alluvial stratigraphy of a portion of the Santa Cruz River Basin: The Santa Cruz Bend Reach: In Mabry, J. B., ed. Archeological investigations of early village sites in the middle Santa Cruz Valley: analyses and synthesis; Anthropological Papers No. 19, Center for Desert Archeology, Tucson.

Larson, E. E. and Patterson, P. E., 1993, The Matuyama-Brunhes reversal at Tecopa Basin, southeastern California, revisited again: Earth and Planetary Science Letters. 120; 3-4, Pages 311-325.

Leising, J. F.; Tyler, S. W.; Miller, W. W., 1995, Convection of saline brines in enclosed lacustrine basins; a mechanism for potassium metasomatism: Geological Society of America Bulletin. 107; 10, Pages 1157-1163.

Markgraf, Vera; Bradbury, J. P.; Forester, R. M.,; Singh, G; Sternberg, R. S., 1984, San Augustin Plains, New Mexico: Age and paleoenvironmental potential reassessed: Quaternary Research, v. 22, p. 336-343.

McFadden, L. D.; Wells, S. G.; Brown, W. J.; Enzel, Y, (Univ. New Mexico, Dep. Geol.) 1992, Soil genesis on beach ridges of pluvial Lake Mojave; implications for Holocene lacustrine and eolian events in the Mojave Desert, Southern California: Catena (Giessen), v. 19, no. 1, p. 77 97.

McFadden L. D.; Wells, S. G.; Brown, W. J.; Enzel Y, Amundson, R, and Wang, Y. 1994, Formation and pedogenic isotope studies of soils on beach ridges of Silver Lake Playa, Mojave Desert, California, *in* Mc Gill, S. F. and Ross, T. M., geological investigation of an active margin, Geologial Society of America Cordillerin Section Guidebook, San Beranadino County Museum Association, Redlands CA, p. 188-194.

Machette, M.N. In the footsteps of G. K. Gilbert; Lake Bonneville and neotectonics of the eastern Basin and Range Province; guidebook for field trip twelve. Miscellaneous-Publication Utah Geological and Mineral Survey, p. 89-95.

Meltzer, D. J., 1991, Altithermal archiology and peleoecology at Mustang Springs, on the Southern High Plains of Texas; American Antiquity, v. 56, p. 236-267.

Meltzer, D. J., and Collins. M. B., 1987, Prehistoric water wells on the Southern High Plains: Clues to Altithermal climate; Jounal of Fieild Archeology, v. 14, p 8-28.

Morrison, R. B., 1991, Quaternary stratigraphic, hydrologic, and climatic history of the Great Basin, with emphasis on Lake Lahontan, Bonneville, and Tecopa; In: Morrison, R. B. (editor), Quaternary nonglacial geology; conterminous U.S. In the collection: The geology of North America. K-2; Pages 283-320. Geol. Soc. Am.. Boulder, CO, United States.

Olig, S. S.; Lund, W., R.; Black, B. D., 1994, Large mid-Holocene and late Pleistocene earthquakes on the Oquirrh fault zone, Utah, Geomorphology, v. 10., no. 1-4, p. 285-315.

Oviatt, C. G.; Currey, D. R.; Sack, Dorothy, 1992, Radiocarbon chronology of Lake Bonneville, eastern Great Basin, USA: Palaeogeography,-Palaeoclimatology,-Palaeoecology, v. 99, no. 3-4, p. 225-241.

Oviatt, C. G., McCoy, W. D., Nash, W. P., 1994, Sequence stratigraphy of lacustrine deposits: A Quaternary example from the Bonneville basin, Utah: Geological Society of America Bulletin v. 106, p. 133-144, p. 133-144.

Parry, W. J., and Speth, J. D., 1984, The Garnesy Spring campsite: Late prehistoric occupation in southeastern New Mexico: Museum of Antropology, University of Michigan Technical Reports 15, 85-108.

Scanlon, B. R., Mullican, W. F., Reedy, R. C., and Angle, E. S., 1997, Prototype barrier designs for low-level radioactive waste disposal in Texas;: *in* Reynolds, T. D., and Morris, R. C., editors, Landfill Capping in the Semi-arid West: Problems, Perspectives, and Solutions: Environmental Science and Research Foundation, Idaho Falls, ID, p. 231-242.

Smoot J. P., 1993, Field trip guide; Quaternary Holocene lacustrine sediments of Lake Lahontan, Truckee River canyon north of Wadsworth, Nevada: Open File Report U. S. Geological Survey, OF 93-0689, 35 p.

Stormont, J. C., 1997, Incorporating capillary barriers in surface cover systems, *in* Reynolds, T. D., and Morris, R. C., editors, Landfill Capping in the Semi-arid West: Problems, Perspectives, and Solutions: Environmental Science and Research Foundation, Idaho Falls, ID, p.39-68.

Titus, F. B., 1969, Late Tertiary and Quaternary hydrogeology of the estancia basin, central New Mexico , Ph. D thesis, Albuquerque, NM, 179 p.

Throckmorton, C. K.; Reheis, M. C, 1993, Late Pleistocene and Holocene environmental changes in Fish Lake valley, Nevada California; geomorphic response of alluvial fans to climate change: Open File Report U. S. Geological Survey, OF 93-0620, 82 p.

U. S. Environmental Data Service, 1968 (1975), Weather atlas of the United States, reprinted Gale Research Company, Detroit, 262p.

Visher, S. S. 1954, Climatic atlas of the United States, Harvard University Press, Cambridge, 403 p.

Waters, M. R., 1985, The geoarcheology of Whitewater Draw, southeastern Arizona: University of Arizona Anthopological Papers, 45.

Waters, M. R., 1989, Lake Quaternary lacustrine history and paleoclimatic significance of pluvial Lake Cochise, southeastern Arizona: Quaternary Research, v. 32, p. 1-11.Wells, S. G., and Love, D. W., 1983, Chaco Canyon County: A field Guide to the geomorphorphology, quaternary geology, papeoecology, and environmental geology of northwestern New Mexico, 253 p.