Paleolimnology and paleoecology of the Coal Valley region, Lincoln County, Nevada

Anthony Dean Feig

University of Nevada, Las Vegas

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PALEOLIMNOLOGY AND PALEOECOLOGY OF THE
COAL VALLEY REGION, LINCOLN COUNTY, NEVADA

by

Anthony Dean Feig

Bachelor of Arts
University of New Mexico
1995

A thesis submitted in partial fulfillment
of the requirements for the degree of

Master of Science

in

Geoscience

Department of Geoscience
University of Nevada, Las Vegas
May 1998
Thesis Approval
The Graduate College
University of Nevada, Las Vegas

APRIL 28, 1998

The Thesis prepared by

______________________________________________
Anthony Dean Feig

Entitled

Paleolimnology and Paleoeocology of the Coal Valley Region, Lincoln County, Nevada

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Geoscience

______________________________________________
Examination Committee Chair

______________________________________________
Dean of the Graduate College

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Examination Committee Member

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Examination Committee Member

______________________________________________
Graduate College Faculty Representative
ABSTRACT

Paleolimnology and Paleoecology of the Coal Valley Region, Lincoln County, Nevada

by

Anthony Dean Feig

Dr. Frederick Bachhuber, Examination Committee Chair
Professor of Geoscience
University of Nevada, Las Vegas

During Pleistocene time, Coal Valley, Nevada, was situated between a pluvial climatic zone to the north and a non-pluvial climatic zone to the south. The Coal Lake section represents >20,000 years of continuous deposition, recording a saline lake phase (Early Coal Lake) present since at least 32,000 BP, evolving to a freshwater lake (Coal Lake Intermediate) ~28,000 BP. Maximum lake development (290 km² in area) was within 2000 years of ~20,000 BP, and was probably persistent through deglaciation. Ostracode ecology suggests that water salinity varied little through time, which may be indicative of consistently low ambient temperatures, high precipitation levels, and/or high basin seepage rates throughout the life of the lake. Coal Lake probably experienced more direct control by regional groundwater hydrology than by climate. The revised paleohydrologic index of Coal Valley is \( Z_{ov} = 0.11 \), compared to the previous value of 0.07, suggesting that the water balance of Coal Lake was higher than previously thought.
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<td>1</td>
<td>Geologic Map of Central Coal Valley</td>
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PLATE 1. Geologic Map of Central Coal Valley

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ACKNOWLEDGEMENTS

Financial support for this project was provided in large part by grants from the Bernada E. French Memorial Scholarship Fund; my thanks go to Mrs. Ann Wyman for administering this Fund. Additional support was provided by generous grants from the UNLV Graduate Student Association. The UNLV Geoscience Department provided me with two years of support in the form of a Teaching Assistantship. My profound thanks go the NSF Arizona Accelerator Laboratory for providing radiocarbon dates at greatly reduced cost, and also to Dr. John Geissman and the University of New Mexico Paleomagnetism Lab for cost-free use of the magnetometers there. Fred Bachhuber financed preliminary field work in whole, and subsequent field work in part. My thanks go to Dr. Gene Smith and the CVTS for use of their computer equipment.

Many people contributed in other ways to this work, and I offer my thanks to them. Dr. Wanda Taylor started this whole thing during a field trip to the Golden Gate Range, where she pointed out to me the strandlines in Coal Valley. She was subsequently very generous with her time, her library, and her equipment. My undying gratitude goes to Dr. Cathy Summa, who helped me to develop the initial concepts for this project. She also encouraged me to develop my skills as a scientist and an editor, and I learned a great deal about both from her. Dr. Michael Wells served on my committee, and his time and input were of great value to me. He also provided me with financial support during the summer of 1997. I am grateful to Dr. Darryl Randerson for taking the time to commute to campus to serve on my committee, and for monitoring all the literature databases that I didn't get to. Dr. Gene Smith constantly provided mentorship for this project in one way or another, and helped me learn to design and supervise research. Dr. Rodney Metcalf
was always there with an encouraging word. I thank Dr. Diane Pyper-Smith for serving on my committee. Dr. Margaret Rees provided me with financial support during the summer of 1996. She also showed me what a professional teacher really is, and I will always strive to her standard. Dr. Mohammad Nash provided indispensable expert advice on soils, hydrology, and computer modeling issues. Dr. Will Pratt aided in fossil identification. Dr. Norm Catto provided priceless advice in the field. Dr. David Weide provided helpful advice concerning mapping and aerial photographs. Joe P. Blaylock donated the use of his truck and his vast muscular mass for summer field work. Lisa Danielson, K. Jill Hammond, Leigh Justet, and Gil Simmons also helped out in the field. Jill Hammond agreed to conduct an undergraduate independent study based on this thesis, and she was a joy to work with. Andrew G. Smith and Sr. Alex Sánchez served as my personal Macintosh-IBM-UNIX Help Desks. Jason B. Cooper provided archeological information on Coal Valley, as well as insightful discussion. Dr. Clay Crow, Nathan Stout, Jason Smith, and Bill at the Copy Center provided cheerful and expert assistance upon each and every request. Dr. Frederick Bachhuber loaned to me his expertise, his time, and his patience for the last two years. Of all these things, I probably taxed his patience the most—but he never ran out. He gave me plenty of rope, but he never let me hang myself. I thank him.

I thank all those who contributed to my sanity: Christopher McGlone, Jason Cooper, Karin Von Gunner, Tim Bennett, Dave Lamme*, Bill Whiting, Maureen Stuart, Joe Satriani, Keith Wilse, Steve Thalken, Bob Noto, Steve Young, Cheryl Radeloff, Vangelis, Seth Goodman, R. Carlos Nakai, Rhonda Knupp, and Bill and Beverly Feig. Lastly, I thank my uncle, Gilbert Simmons, who many years ago kindled a young boy's interest in science. This is all his fault.

And finally, without Lisa Danielson to share everything with, my life would have been empty and meaningless, and certainly less gabbroic.
CHAPTER 1

INTRODUCTION

Understanding the nature and timing of past climate change enables us not only to assess anthropogenic impacts on the environment, but also provides us with some ability to predict and prepare for abrupt, potentially catastrophic future climate changes. To establish a basis to make such predictions it is necessary to understand natural climatic variability, both in the present and in the geologic past. Geologic data (Allen and Anderson, 1994; 1993; Anderson, 1994; 1993; Anderson and Kirkland, 1969; Bachhuber, 1992; Bradbury, et al., 1993; Dansgaard, et al. 1989; Dean and Stuiver, 1993) suggest that mean global temperature has varied by as much as +/-12 °C in the mid-latitudes during Pleistocene time. and further suggest that in some locations regional precipitation levels were ~2.5 times greater than present. Future climatic changes of such magnitude would have profound impact upon the world's ecology and economy.

Fortunately, lacustrine records have provided a wealth of data with which to reconstruct and model past climates and climatic changes. Lake Estancia in New Mexico, Searles Lake in southern California, and Lakes Bonneville and Lahontan are all examples of well-studied pluvial lakes. Even though these and many other ancient lacustrine systems have been examined, there remain yet many more unstudied sites with the
potential to yield usable climatic and environmental data. One such site is Coal Valley, a physiographically closed basin located in south-central Nevada, that contains the deposits of Pluvial Coal Lake.

Previous work

Climatic studies of the Great Basin region were conducted as early as the late nineteenth century (Russell, 1885; Gilbert, 1890). These works focused on the records of Lakes Lahontan and Bonneville. Russell (1885) identified two cycles of maximum water stands/desiccation in the Lahontan record. Gilbert (1890) also identified two lake cycles, and correlated them with glaciation in the midwestern U.S., linking maximum lake stands with glacial maxima. Since this time, many workers have studied sites in the Great Basin (e.g., Benson and Thompson, 1987; Currey, 1990; Davis, 1978; Eardley and Gvosdetsky, 1960; Jannik et al., 1991; Oviatt, 1987).

In Coal Valley, Carpenter (1915) attempted to determine the depth to the water table and surmised that it was greater than 250 feet (91 m). His was the first published report recognizing the existence of lacustrine sediments in the valley. Hubbs and Miller (1948) documented the late Quaternary history of the Great Basin region, and also recognized the existence of lacustrine sediments in Coal Valley. Hardman and Mason (1949) evaluated regional growing season zonations, labeling the majority of the valley floor as a "Lahontan Zone", allowing for "three cuttings of alfalfa, the production of many vegetables and hardy fruits, and of early maturing varieties of corn." (Hardman and
The geology of Lincoln County, Nevada, including the Coal Valley region, was first documented by Spurr (1903). Later work was conducted by Tschanz (1960), and Tschanz and Pampeyan (1961) drafted the preliminary geologic map of Lincoln County. These two workers later revised the map and provided a more rigorous accompanying description (Tschanz and Pampeyan, 1970).

Mifflin and Wheat (1979) produced what is arguably the authoritative work on Pleistocene environments in Nevada. In order to quantify the probability of lake formation in this region, as well as potential lake stability through time, they calculated the pluvial hydrologic indices of all the closed (and mostly closed) topographic basins in the state. The pluvial hydrologic index, Z, may be expressed in a number of ways (Table 1), but it is essentially a function of basin area, basin watershed area, areal extent of the lake (as observed by strandline or other geological features), precipitation input, water loss resulting from evapotranspiration and seepage out of the basin, and ambient temperature. The greater the Z value, the more conducive the environment is for lake development and support. Z values in Nevada range from 0.0 (no lake development) through 0.59 (extensive development such as that attained by Lake Bonneville). The results of Mifflin and Wheat suggest that the eastern half of Nevada was essentially zoned (Figure 1) such that pluvial lake sites in the northeastern portion of the state had high Z values, sites in the east-central portion had intermediate to low Z values, and the Z values for sites in southeastern Nevada were zero. This implies that no lakes existed in southern Nevada (supported by field evidence), and that lakes in northeastern Nevada existed well within
Table 1. Various expressions of hydrologic index \( Z \) after Mifflin and Wheat (1979).

<table>
<thead>
<tr>
<th>Expression</th>
<th>Description</th>
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<tbody>
<tr>
<td>( Z = \frac{A_L}{A_T} )</td>
<td>( A_L ) = maximum lake area as indicated by highest shore/strand feature, ( A_T ) = Tributary area of the basin (total basin area - lake area)</td>
</tr>
<tr>
<td>( Z = \frac{P_T - ET_T}{E_L - P_L} )</td>
<td>( P_T ) = average basin precipitation per unit area per unit of time, ( ET_T ) = average tributary basin evapotranspiration per unit area per unit of time, ( E_L ) = lake evaporation rate per unit area per unit of time</td>
</tr>
<tr>
<td>( Z = \frac{R_T}{E_L - P_L} )</td>
<td>( R_T ) = combined runoff of surface and groundwater per unit area per unit of time, ( E_L ) = lake evaporation rate per unit area per unit of time, ( P_L ) = direct precipitation upon the lake per unit area per unit of time</td>
</tr>
</tbody>
</table>
Figure 1. Climatic zonation of eastern Nevada as expressed by the hydrologic indices (Z values) of closed to semi-closed basins. Symbols denote individual basins. Data from Mifflin and Wheat (1979).
the climatic regimes that supported them. Coal Valley lies within the "intermediate zone". and Mifflin and Wheat report its Z value ($Z_{cv}$) as 0.07, indicating that this location was unlikely to contain a stable, long-lived body of water.

**Inferences based on previous work**

Because of the expression of climatic zonation of eastern Nevada, several reasonable inferences may be drawn about the regional paleoclimate. Foremost, if northeastern Nevada once contained stable pluvial lakes, and southeastern Nevada contained no pluvial lakes, then the region between, containing lakes with intermediate to low Z values, must have been a climatic "transitional zone" between the two other zones. Secondly, a lake whose $Z<0.1$ must have existed at its hydrologic (climatic) threshold; that is, at or near the very limit of the temperature, precipitation, and/or evaporation conditions that would allow its development and continued existence. Based on these inferences, it is logical to assume that the lakes in this transitional zone may have been very sensitive to climatic flux associated with the onset and termination of the last glacial maximum, and that the limnologic records of such environments may possibly yield high-resolution ecologic and climatic data. This assumes that other factors such as groundwater hydrology and tectonic activity did not have more direct control over the regional ecology than the climate itself.

Coal Valley was situated at what was probably a threshold location within this transitional zone, where the formation of a large body of water should have been in
response to a significant climatic event. This region was likely to have experienced a high amount of variability in temperature and precipitation, and the Coal Lake system should have been very sensitive to climate change. As a result, the geologic record of such a system may readily yield evidence of climatic change on the scale of millennia, and perhaps even centuries, depending on how long-lived the lake was. It is possible that the Coal Lake record may contain evidence of climatic flux, or that the entire lacustrine sequence was generated within one climatic regime. Alternatively, the climatic signature in Coal Valley may have been overprinted by the hydrologic record or other mechanisms.

Purpose and scope

The main purpose of this study is to reconstruct a limnologic and environmental history of pluvial Coal Lake. By identifying an ecologic record based on the paleontologic and sedimentologic sequences within the lacustrine section, the basis is then established from which to make inferences about the local climate during the late Pleistocene. It should also be possible, based on geologic and paleontologic evidence, to evaluate the validity of the assumption that Coal Lake existed at its climatic threshold and was a sensitive recorder of climatic flux. If the assumption is valid, then other lacustrine records within this transitional zone may also yield useful climatic data. Finally, study of the Coal Lake record may lead to a greater understanding of the response of hydrologic systems to climatic change, and particularly how they develop in a climatologically sensitive area such as Coal Valley.
Macroscale climate of the Pleistocene

The climate of North America during much of late Pleistocene time was markedly different than today. At about 70,000 years before present (BP), a large inland ice mass, the Laurentide Ice Sheet, established itself in northern North America, and continued building until about 60,000 BP (Frenzel et al., 1992; Crowley and North, 1991). From 60,000 BP to about 27,000 BP the Laurentide Sheet experienced multiple episodes of growth and shrinkage in response to climate change (Crowley and North, 1991), with at least two episodes of climatic flux between 35,000 and 25,000 BP (Frenzel et al., 1992). During this latter period, average annual temperatures in the southwestern United States were 8-10 °C cooler than present (Frenzel et al., 1992). The moisture supply was much greater than today, as a result of the low temperatures and attendant low evaporation rates (Frenzel et al., 1992). Biostratigraphic analyses of sediment cores recovered from low latitudes of the North Atlantic indicate that temperatures, at least in that region, were lower during the period of 30,000-28,000 than during the Last Glacial Maximum (LGM) of 18,000 BP (Crowley and North, 1991).

At about 35,000 BP, the latest cycle of Lake Lahontan gradually began to form (Morrison, 1991). Lake Bonneville formed at a much faster rate, but not until ~33,000 BP (Morrison, 1991). Also during this time, Searles Lake in southern California breached its basin (Morrison, 1991). In the Estancia Basin, New Mexico, the first freshwater lake phase appeared at ~23,000 BP (Bachhuber, 1989).

Between 22,000 and 14,000 BP, the Laurentide Ice Sheet covered large areas of

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North America with 3500 - 4000 m of ice (CLIMAP, 1981). Most of the western U.S. was situated within a zone of seasonal deep freezing, and average annual temperatures in this region were 8-12 °C lower than present (Frenzel, et al., 1992). Precipitation here was believed to be about 2.4 times greater than present (Benson and Thompson, 1987). The polar front airmass held a mean position of 34° N latitude (Delcourt and Delcourt, 1983), although today this airmass is located about 1200 km to the north in southern Canada (Crowley and North, 1991). One climate model suggests that the Laurentide ice sheet split the jet stream, sending a strong branch around the sheet's southern margin, south of the Great Basin (Kutzbach and Wright, 1985). The moist conditions and decreased temperatures (and consequently decreased evaporation rates) in the Great Basin region, and a polar jet stream branch located much further south of the Great Basin, may have all combined to enhance the development of extensive pluvial lakes in this area (Benson and Thompson, 1987).

During late Pleistocene-early Holocene time (18,000-9,000 BP), the Laurentide Ice Sheet retreated during a global warming event, or series of events, the mechanisms of which are unclear and remain controversial (Crowley and North, 1991). This deglaciation allowed for the development of essentially modern climates from about 9,000 BP to present.
Geography of Coal Valley

Location

Coal Valley is located in northwestern Lincoln County, Nevada, approximately 200 km north of the city of Las Vegas (Figure 2). This area is roughly bounded by 37°45'-38°15' N. latitude and 115°10'-115°30' W longitude. About 80% of the valley lies north of the city of Las Vegas (Figure 2). Location map of Coal Valley within Lincoln County, with the northern 20% extending into Nye County. Coal Valley is accessible via Mail Summit Road, an unimproved secondary road ~8 km north of the intersection of State Highways 93 and 375. Another unimproved secondary road (unmarked) allows access to Coal Valley ~16 km north of the intersection of State Highways 93 and 375.

Topography

Coal Valley is an elliptically-shaped valley with its major axis oriented approximately north-south. The valley floor is ~30 km long and ~16 km wide and has an average elevation of about 1500 m above sea level. The valley is bounded on the west by the Golden Gate Range (maximum elevation 2422 m), on the east by the Seaman Range (maximum elevation 2623 m), and on the south by Mt. Irish (maximum elevation ~3000 m) (Plate 1). The Golden Gate Range separates Coal Valley from the topographically higher Garden Valley, with two major drainages into Coal Valley from Garden Valley: Murphy Gap to the south, and Water Gap to the north (Plate 1). The Seaman and Golden
Figure 2. Location map of Coal Valley.
Gate Ranges join to form the northern boundary of Coal Valley (Plate 1). The eastern side of the basin slopes gently toward the Seaman range, but the western side of the basin meets the Golden Gate Range somewhat more abruptly. The surface area of Coal Valley is in excess of 800 km² (~300 mi²).

The lowest elevations occur on the playa surfaces in the southwestern portion of Coal Valley, averaging ~1500 m above sea level (Plate 1). Strandline features are observable up to the 1535 m topographic contour line, and this is the maximum level I have extrapolated for Coal Lake (see Chapter 2).

Climate

The present climate of this area is semiarid with low humidity and precipitation, and a high daily and seasonal range in temperature (Eakin, 1963). Even though temperature and precipitation data are not available for any location within Coal Valley itself, data do exist for Adaven, a site in the adjacent Garden Valley at 2260 m (6200') elevation; and also for Alamo, a site outside of and ~40 km south of Coal Valley, at an elevation of approximately 1275 m (3500') (Figure 2). Because Coal Valley lies between Adaven and Alamo in terms of both altitude and latitude, I have made the assumption that temperatures for Coal Valley, in general, have values between those of Adaven and Alamo. Precipitation data for Adaven and Alamo are significantly different; this is attributed to the fact that Adaven is located within Cherry Creek Canyon, and therefore affected by local canyon-type exposure and topography, skewing precipitation data to higher values (Eakin, 1963). I suggest that precipitation rates for central Coal Valley are...
more similar to those of Alamo, since Alamo is located within the interior of Pahranagat Valley (which has a similar geometry and topography to Coal Valley). Temperature and precipitation data for Adaven and Alamo from 1931-1960 are listed in Table 2.

Geologic setting

Coal Valley is a major structural (extensional) basin within the Basin and Range Province, with a total depth to bedrock in the central basin of ~2000 m (Snyder, 1983). Quaternary- and Tertiary-age alluvium fills the basin. In the eastern part of the basin, Tertiary-age volcanic rocks occur beneath alluvium, extending almost to the center of the basin. The alluvial and volcanic units are underlain by Early to Middle Paleozoic-age marine sedimentary successions (Howard, 1978; Snyder, 1983; Tschanz and Pampeyan, 1970). These same Paleozoic sandstone, carbonate and shale successions make up the bulk of the Golden Gate Range and Mt. Irish (Tschanz and Pampeyan, 1970). The Seaman Range contains bedrock successions of similar age and composition, but these are overlain by extensive Tertiary-age lava flows, tuff flows, and volcanic breccias (Tschanz and Pampeyan, 1970). The post-Sevier Seaman Pass normal fault passes through Seaman Wash and strikes northwestward across the valley floor (Tschanz and Pampeyan, 1970). It is uncertain if the fault actually cuts the Quaternary valley fill, or if the scarp was formed by some other process, such as erosion (W.J. Taylor, personal communication, 1995).
Table 2. Temperature (in °C) and precipitation data (in cm) for Adaven, NV. and Alamo, NV. from 1931-1960. From Eakin (1963).

<table>
<thead>
<tr>
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<th>Average winter temperature</th>
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<tr>
<td></td>
<td>2.2</td>
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<td>May-October</td>
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<td>-1.6 (Jan.)</td>
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<td>13.4 (Apr.)</td>
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<td>21.2 (Jul.)</td>
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<tr>
<td></td>
<td>14.8 (Oct.)</td>
<td>26.2 (Jul.)</td>
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<table>
<thead>
<tr>
<th></th>
<th>Coldest month</th>
<th>Warmest month</th>
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<tbody>
<tr>
<td></td>
<td>January</td>
<td>Adaven</td>
</tr>
<tr>
<td></td>
<td>January</td>
<td>July</td>
</tr>
<tr>
<td></td>
<td>Adaven</td>
<td>July</td>
</tr>
<tr>
<td></td>
<td>Alamo</td>
<td></td>
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<table>
<thead>
<tr>
<th></th>
<th>Average highest precip/month</th>
<th>Average lowest precip/month</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.98</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>1.96</td>
<td>0.38</td>
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<table>
<thead>
<tr>
<th></th>
<th>Wettest month</th>
<th>Driest month</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>February</td>
<td>Adaven</td>
</tr>
<tr>
<td></td>
<td>Adaven</td>
<td>June</td>
</tr>
<tr>
<td></td>
<td>Alamo</td>
<td>June</td>
</tr>
</tbody>
</table>

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CHAPTER 2

PALEOLIMNOLOGIC INVESTIGATIONS

Field Reconnaissance and Mapping

The purpose of field reconnaissance and mapping was to identify and differentiate the various Quaternary-age units in the basin; (1) older alluvium underlying lacustrine deposits, (2) unmodified lacustrine deposits, (3) younger alluvium adjacent to or overlying (and sometimes containing) lacustrine sediments, (4) eolian "dune" features containing reworked lacustrine deposits, and (5) modern playa surfaces. I mapped the basin at a scale of 1:100,000 over a topographic base map, concentrating on the area that contained Coal Lake deposits. Plate 1 shows the various surficial features of and immediately surrounding pluvial Coal Lake. The highest strandline feature is at 1535 m (5030 ft); by tracing out this contour line, a maximum area for Coal of 290 km² (112 mi²) may be extrapolated. However, it is likely that this estimate is too low; Coal Lake probably extended closer to Water Gap (Plate 1) than the modern 1535 m contour line, and Holocene alluvium in this vicinity has since buried the lacustrine sediment and associated geomorphic features.

Exposed lacustrine deposits, dune features, and modern playa surfaces combined cover an area of ~30 km² (Plate 1). The playa surfaces cover lacustrine deposits generally
at the lowest elevations in the basin, and lie almost wholly within the closed 1500 m
contour line (Plate 1). Dune features are generally sublinear to subarcuate in shape and lie
between playa surfaces (Plate 1). These dunes are composed of reworked lacustrine
sediments and bioclasts, and are identified by characteristic ripple-marks and low-angle
crossbeds.

I have identified two basic types of alluvium, an older undifferentiated
(Pleistocene) unit and a younger (Pleistocene-Holocene) unit. The older alluvium is the
lower bounding unit of Coal Lake deposits, and is also found exposed in the peripheral
areas of the basin (Plate 1). Younger alluvium both postdates and is coeval with Coal
Lake deposits, and is in places also composed of reworked lacustrine sediments.

Sampling Locations and Methods

A total of five sites were sampled, distributed throughout the basin as shown in
Figure 3. The North-central site featured the greatest amount of outcrop exposure (2 m).
The West and South sites showed outcrop exposures of about one meter each, and the
North and Central sites showed no outcrop. Exposed outcrop was sampled by excavating
stepwise pits (Figure 4a), and subsurface samples were recovered using a hand soil auger
(Figure 4b). Sampling intervals were generally at 5 cm for outcrop exposures and at 10
cm for the subsurface sections. After collection, samples were allowed to air dry for one
week. Each sample was then divided into "A" and "B" specimens, with "A" specimens
Figure 3. Locations of sampling sites in Coal Valley.
Figure 4a. Stepwise excavations exposing fresh surfaces of lacustrine outcrop for sediment sampling at the North-central Site. View is to the east-northeast.

Figure 4b. Soil augers used for subcrop sampling. The modern playa exposed at the surface of the Central Site is shown in view.
intended for sedimentologic analysis and "B" specimens intended for paleontologic analysis.

Sedimentology

In general, the lacustrine deposits of Coal Valley are white-colored, fine-grained, and moderately well-sorted fine sand to clay. Compositionally, lacustrine sediments are fairly uniform throughout the basin, consisting generally of 40-70 percent quartz, 10-30 percent calcium carbonate, and 5-15 percent lithic fragments. X-ray diffractometry shows that the lithic group includes the minerals magnetite, spinel, hypersthene, sanidine, anorthite, and biotite, in varying quantities (Hammond, et al., 1996).

Some sedimentologic variance does exist between each site. Figures 5-9 summarize grain sizes, sorting, and radiocarbon ages from the stratigraphic sections of each sampling location. In these stratigraphic sections, negative values denote depth of intervals underlying the exposed surface of Coal Valley, and positive values denote height of intervals in outcrop above the exposed surface. Negative-value samples were recovered along the sides of hand-dug test pits and with a soil auger.

Paleontology

The lacustrine stratigraphic sequence contains a diverse and highly variable sequence of fossils. All invertebrate and algal fossil forms found in the Coal Lake sequence are extant today, and I based fossil identifications on comparisons to the extant taxa. I attempted
Figure 5. Stratigraphic summary of the North Site. Depositional environments included for reference only; discussion follows in later section.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Stratigraphy</th>
<th>Grain Size Range</th>
<th>Sorting</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm</td>
<td>playa</td>
<td>fine silt to clay (modern playa)</td>
<td>very well</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-325 cm</td>
<td></td>
<td>medium sand to clay</td>
<td>moderately poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-650 cm</td>
<td></td>
<td>pebble to silt size</td>
<td>very poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>younger alluvial</td>
<td>medium sand to clay</td>
<td>moderate to very poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>pebble to silt size</td>
<td>poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>medium sand to clay</td>
<td>moderate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Figure 6. Stratigraphic summary of the North-central Site. Radiocarbon age and depositional environments included for reference only; discussion follows in later section.
Figure 7. Stratigraphic summary of the Central Site. Radiocarbon age and depositional environments included for reference only; discussion follows in later section.
Figure 8. Stratigraphic summary of the West Site. Radiocarbon age and depositional environments included for reference only; discussion follows in later section.
Figure 9. Stratigraphic summary of the South Site. Radiocarbon age and depositional environment included for reference only; discussion follows in later section.
fossil identification down to species level whenever possible, but in certain cases it was not possible to classify beyond genus or family. Ostracodes are the most abundant animal fossils in Coal Valley, and occur locally in great numbers; however, ostracode species diversity is lower than that of other pluvial lake sites, such as the Estancia Basin (see Bachhuber, 1972). Pelecypoda and gastropoda remains are also common in some stratigraphic intervals. At one location, abundant megafossil detritus occurs at the surface exposure. Diatoms and other algal forms are abundant throughout the stratigraphic sequence. Plant fragments are less abundant, and I did not attempt to identify these. The Coal Valley fossil fauna assemblage is shown in Figure 10.

**Ostracoda**

Ostracodes are small, bivalved crustaceans, usually less than 2 mm in size (Pennak, 1989), which have long been used as indicators of paleoecological settings and paleoenvironmental change (Delorme, 1989). I collected ostracode specimens from each sampling site location at intervals of 5-10 cm, for a total of 253 intervals, and then processed these specimens by recording their dry weight, followed by disaggregation in water for at least 24 hours. I wet-sieved the specimens in stacked 1000, 300, and 106 micron sieves, then oven-dried them and recorded the weight of the sediment retained on each sieve. I then hand-picked each sediment specimen to identify microfossils and to make determinations of absolute fossil abundances in relation to specimen mass. This collection procedure applies to all specimens, except those processed for diatoms.
Figure 10. Coal Valley invertebrate fossils. (a) female *Candona caudata*, (l) interior right valve, (r) interior left valve. (b) female *Candona rawsoni*, (l) interior left valve, (r) exterior right valve. (c) *Pisidium* sp., exterior right valve.

a. Scale bar=0.5mm

b. Scale bar=0.5mm

c. Scale bar=1mm
Four genera and six species of ostracodes occur in the Coal Valley sediments. All ostracodes are extant and have been previously reported from Quaternary deposits (Bachhuber, 1989; 1972; Delorme, 1989; 1971; 1970a; 1970b; 1970c; 1970d; 1969). The Coal Valley ostracode assemblage contains the following species (classification adopted from Delorme, 1989).

**Phylum ARTHROPODA**

**Class CRUSTACEA**

**Subclass OSTRACODA**

**Order PODOCOPINA**

**Family CANDONIDAE**

**Genus CANDONA**

- *Candona caudata*
- *Candona rawsoni*

**Family ILYOCYPRIDIDA**

**Genus CYTHERISSA**

- *Cytherissa lacustris*

**Family LIMNOCYTHERIDAE**

**Genus LIMNOCYTHERE**

- *Limnocythere ceriotuberosa*
- *Limnocythere staplini*

**Family CYCLOCYPRIDIDAE**

**Genus CYCLOCYPRIS**

- *Cyclocypris cf. ampla*

The paleoecological importance of ostracodes, based on the environmental tolerances of extant species, is well established (Bachhuber, 1989; Delorme, 1989; 1978; Forester, 1986). While all Coal Valley ostracodes are primarily lacustrine species, and therefore indicative of lacustrine conditions, certain taxa are highly diagnostic indicators of water temperature, chemistry, and salinity. Figure 11 summarizes the ecology of the Coal Valley ostracodes.

*Candona caudata.* This benthic species is locally abundant throughout all sections.
Figure 11. Summary of ecologic data pertaining to Coal Valley ostracodes. Open parentheses indicate absence of specific data. Data from Bachhuber (unpublished data), Delorme (1989; 1983; 1978a-e; 1969), and Forester (1986; 1983).

<table>
<thead>
<tr>
<th>Salinity (ppm X 1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. caudata</td>
</tr>
<tr>
<td>C. rawsoni</td>
</tr>
<tr>
<td>L. staplini</td>
</tr>
<tr>
<td>L. vero.</td>
</tr>
<tr>
<td>C. lacustris</td>
</tr>
<tr>
<td>C. ampla</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>pH</th>
<th>Alkalinity</th>
<th>SO₄ Content</th>
<th>Dissolved Oxygen Content (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6 7 8 9 10</td>
<td>Low High</td>
<td>Low High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>saline</td>
<td>fresh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>fresh</td>
<td>saline</td>
</tr>
<tr>
<td></td>
<td></td>
<td>low alkalinity</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( )</td>
<td>( )</td>
</tr>
<tr>
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</tbody>
</table>

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and is consistently associated with Candona rawsoni. In modern settings, C. caudata is widely distributed throughout North America and Europe, and has a total dissolved solute (TDS) tolerance range of 20-2054 parts per million (ppm) (Delorme, 1978) (Figure 11). As a result, it is primarily a freshwater species, but can tolerate slightly brackish conditions. This species tends to inhabit alkaline-rich water (Bachhuber, F.W., personal communication, 1996), and in modern lakes has a pH- distribution range of 5.2-9.4 (Delorme, 1989; 1978), and prefers a dissolved oxygen range of 2.3-14.0 ppm (Delorme, 1978) (Figure 11). The modern (Delorme, 1970c) and fossil (Bachhuber, F.W., unpublished data) occurrences of C. caudata in various locations suggest that this species populates cold (−0 °C winter average) water.

Candona rawsoni. This benthic, mud-burrowing species is the single most abundant ostracode taxon in Coal Valley. C. rawsoni also has a wide distribution throughout North America and Europe, and is commonly found in ephemeral bodies of water, as well as permanent lakes and rivers (Delorme, 1970c). In modern environments, this species has a TDS tolerance range of 141-42,770 ppm (Delorme, 1969), a pH- distribution range of 7.2-12.0, and a dissolved oxygen range of 0.2-25.9 ppm (Figure 11). In terms of anion chemistry, C. rawsoni is distributed in both alkaline-enriched and alkaline-depleted, SO₄-enriched waters (Forester, 1986) (Figure 11). This ostracode does not inhabit freshwater lakes that have low seasonal salinity variation (Forester, et al., 1987), and as a result, high abundances of C. rawsoni fossils are likely indicative of brackish to moderately freshwater conditions with high rates of summer evaporation (Bachhuber, F.W., personal communication).
*Limnocythere ceriotuberosa.* This benthic species is highly restricted in numbers and distribution in Coal Valley. *L. ceriotuberosa* is almost exclusively a lacustrine taxon (Delorme, 1989), distributed throughout Canada (Delorme, 1971), and is found within lakes of the Great Basin (Forster, 1987). In modern settings, this species has a TDS tolerance range of 500-2500 ppm, and a pH range of ~7.8–9.7 (Delorme, 1989) (Figure 11). No published data exist on dissolved oxygen range, but this range is likely to be narrower and have a higher minimum value than either *L. staplini* or *C. rawsoni* (Bachhuber, F.W., personal communication, 1997) (Figure 11). This ostracode has a strong preference for alkaline-enriched, SO₄-depleted water (Forster, 1986) (Figure 11).

*Limnocythere staplini.* This benthic species is locally abundant in the Coal Valley stratigraphic section, but never approaches the abundance of Candonae. *L. staplini* is distributed throughout North America, mostly in lakes (Delorme, 1971). This ostracode has a TDS tolerance range of 149-199,000 ppm (Delorme, 1969), a dissolved oxygen range of 0.6-14.0 ppm (Delorme, 1969), and a pH range of ~6.8 to ~11.0 (Delorme, 1989) (Figure 11). The alkalinity tolerance of *L. staplini* varies in part with salinity; in highly saline conditions, it is restricted to alkaline-depleted, Cl- or SO₄-enriched water (Forster, 1983; 1986) (Figure 11). This species is found in alkaline-enriched conditions, but in low numbers (Bachhuber, F.W., personal communication).

*Cytherissa lacustris.* This benthic species is also highly restricted in numbers and distribution in Coal Valley. In modern settings, *C. lacustris* has a worldwide distribution in cold, deep, boreal lakes (Delorme, 1970d). This ostracode has a TDS tolerance range of 11-215 ppm, a pH range of 6.4-8.8, a dissolved oxygen range of 3.0-13.4 ppm, and
prefers alkaline-enriched waters (Delorme, 1978) (Figure 11). Temperature may also impact the occurrence of *C. lacustris*: Delorme (1978) reports occurrences at temperature maxima of 23.0 °C for bottom-water and 25.2 °C for surface water. As a result of its narrow ecologic ranges, *C. lacustris* is a highly diagnostic paleolimnologic indicator.

*Cyclocypris* cf. *ampla*. This ostracode is highly localized and occurs in both high and low abundances in Coal Valley. In modern settings, *C. ampla* is distributed throughout the interior plains of Canada (Delorme, 1970b), and probably throughout North America. This species has a TDS tolerance range of 10-5000 ppm and a pH range of 5-13 (Delorme, 1989) (Figure 11). The occurrences of this ostracode in the Coal Valley stratigraphic section do not yield any discernible patterns of associations with more diagnostic taxa, except that it occurs with relatively high numbers of *C. caudata*.

**Mollusca**

The molluscan assemblage of Coal Valley consists of one genus of pelecypod and 5 genera of gastropod, all of which are extant fauna. These fauna are not as ecologically diagnostic as ostracodes, in part because little is known about their chemical, salinity, and temperature tolerance ranges. The molluscan assemblage contains the following species (adopted from Burch, 1982, and Pennak, 1989).

**Phylum MOLLUSCA**

**Class PELECYPODA**

Family *SPHAERIIDAE*

Genus *PISIDIUM*

*Pisidium* sp.

**Class GASTROPODA**

Family *LYMNAEIDAE*
Genus STAGNICOLA  
*Stagnicola elodes*  
*Stagnicola* sp.  

Family PLANORBIDAE  
Genus HELISOMA  
*Helisoma trivolvis*  

Genus ARMIGER  
*Armiger crista*  

Family VALVATIDAE  
Genus VALVATA  
*Valvata perdepressa*

*Pisidium* sp. (or *Pisidiidae* sp.). In general, *Pisidium* is restricted to freshwater (Pennak, 1989), and has a modern worldwide distribution (Bachhuber, 1972; Cox, et al., 1969). This species is locally common to abundant in Coal Valley, and consistently occurs with *C. caudata* and *C. rawsoni*.

Gastropods are highly localized, varying from a few individuals to large numbers and diversity, depending on their location in the basin. With very few exceptions, gastropods occur only in intervals that also contain high numbers of *C. caudata* and *C. rawsoni*. As a result, it is reasonable to infer that the gastropods indicate relatively freshwater conditions in Coal Lake.

Fam. *Lymnaeidae*. This "pond snail" family is represented in Coal Valley by one genus, *Stagnicola*. At least two species of this genus are present, *S. elodes*, and another unidentifiable *Stagnicola* sp., probably of the same ecological "group" (see Burch, 1982, p. 200) as *S. elodes*. These snails tend to inhabit a wide variety of aquatic conditions, but usually quiet standing waters such as ponds, swamps, and vegetated areas near water bodies (Burch, 1982). The genus *Stagnicola* is widely distributed throughout North America (Burch, 1982).
Fam. Planorbidae. This family is represented in Coal Valley by two species within two genera. *Armiger crista* and *Helisoma trivolvis*. *A. crista* is found throughout Canada and the Northern United States (Burch, 1982). The genus *Helisoma* is widely distributed throughout a variety of aquatic habitats in North America (Burch, 1982). With some exceptions, only juvenile *H. trivolvis* were preserved intact; adult valves were highly fragmented.

Fam. Valvatidae. The representative species of this family, *Valvata perdepressa*, is rare in Coal Lake sediments, occurring locally in very small numbers. Its modern distribution is in aquatic environments throughout the northern United States and Canada (Burch, 1982).

*Diatoms*

I processed a total of seventeen specimens from the West Site for diatom analysis. Samples were prepared by boiling ~1 cm$^3$ of sediment in a 10% HCl solution for ~15 minutes, then centrifuging and decanting them. The specimens were boiled again in a 30% H$_2$O$_2$ solution for ~15 minutes, then centrifuged and decanted. The remaining material was suspended in distilled water, then a drop of the suspension was placed on a glass slide that was prepared with Hyrax mounting medium. I determined abundances of the diatoms in terms of either being present or absent in the sediment specimen. Diatom flora are abundant throughout the section, and the Coal Valley diatom assemblage includes members of the following families (classification modified from Czarnecki and Blinn, 1978).
Division BACILLARIOPEYTA
Class BACILLARIOPHYCEAE
Order BACILLARIALES
Family NITZSCHIACEAE
Genus NITZSCHIA
  Nitzschia hungaria
  Nitzschia punctata aff. N. punctata var. elongata
  Nitzschia frustulum var. purpussila
Order EPITHEMIALES
Family EPITHEMIALES
Genus DENTICULA
  Denticula elegans
  Epithemia argus
Order FRAGILARIALES
Family FRAGILARIALES
Genus FRAGILARIA
  Fragilaria construens
  Fragilaria sp.
Genus SYNEDRA
  Synedra punctella
Order NAVICULAE
Family NAVICULACEAE
Genus ANOMEONEIS
  Anomeoneis costata
Genus CALONEIS
  Caloneis limnosa
  Caloneis schumaniannii
Genus DIPLONEIS
  Diploneis smithii
Genus MASTOGLOIA
  Mastogloia braunii
  Mastogloia eliptica
Genus NAVICULACEAE
  Navicula crucicula var. obtusata
  Navicula radiosa var. tenella
  Navicula ammophila var. degoneranus
  Navicula anglica
  Navicula cincta
Family CYMBELLACEAE
Genus AMPHORA
  Amphora ovalis var. libyia
  Amphora proteus
Genus CYMBELLA
  Cymbella pusila
Order SURIRELLALES
Family SURIRELLACEAE
Genus CAMPYLODISCUS
  *Campylodiscus clypeus* var. *bicostata*
Genus SURIRELLA
  *Surirella striatula*
  *Surirella ovalis*

The preceding list is the result of a "first-run" identification in the absence of a physical reference collection. Owing to the difficulty of identifying diatoms to the species level without such a reference collection, I did not attempt a definitive paleoecologic determination based on diatom species occurrences. Despite this, I believe that the Coal Valley diatom record has the potential to yield significant paleoecologic information, possibly of a higher resolution than the ostracode record.

*Megafauna*

Only one megafauna fossil was found in Coal Valley. The South Site contained the scattered tusk fragments and one tooth fragment of what has been tentatively identified as Genus *Mammuthus*, probably *Mammuthus columbi* (Columbian Mammoth). *Mammuthus* fragments were exposed at the surface, and also embedded within the outcrop.

*Biostratigraphy*

The North Site shows a paucity of fossils, both in terms of absolute numbers and distribution throughout the section. The South Site contains the greatest density of fossils.
of all site locations, and the only megafauna fossil, but it is the shortest sampled interval (50 cm). As a result, I do not present detailed biostratigraphic data from these sites here, concentrating instead on the North-central, Central, and West Sites.

**North-central Site**

This section is notable for the pattern of fossil occurrences within it (Figure 12). Fossils are generally absent below 0 cm, with the exception of the interval from -238 cm to -208 cm. This interval contains only a few (<10) valves of *Pisidium* and *L. staplini*. At 0 cm, ostracode and *Pisidium* valves appear, and increase to their maximum values at +20 cm (*L. staplini*), +50 cm (*C. rawsoni* and *C. caudata*), and +85 cm (*Pisidium*) (Figure 12). Throughout the section, *L. staplini* and gastropods shows three main, coeval cycles, in population size, while population sizes of *C. rawsoni*, *C. caudata*, and *Pisidium* remain relatively abundant (Figure 12). The ostracode *C. cf. ampla* appears at +110 cm and +120 cm, and *L. ceriotuberosa* appears at +175 cm and +195 cm (Figure 12).

**Central Site**

In the lower half (-320 cm to -200 cm) of this section, *C. caudata* and *C. rawsoni* are continuous and abundant (Figure 13). The ostracode *L. staplini* maintains a continuous presence, albeit of low abundance, except at one interval, and *Pisidium* and gastropods are rare (Figure 13). The occurrence of *L. ceriotuberosa* is discontinuous, and *C. lacustris* occurs at two stratigraphic intervals (Figure 13). In the upper half (-200 cm...
Figure 12. Biostratigraphy of the North-central Site. Y-axis values are height of outcrop/depth of subcrop, expressed in centimeters. The zero value on the Y-axis corresponds to the contact between outcrop and subcrop.
Figure 13. Biostratigraphy of the Central Site. Y-axis values are depth of subcrop, expressed in centimeters.
to -25 cm), *C. caudata* is absent from -165 cm to -115 cm, but *Pisidium* reaches its greatest numbers in this interval (Figure 13). The ostracodes *C. rawsoni* and *L. staplini* are present throughout, and gastropods show their highest numbers from -100 cm to -25 cm. The ostracode *L. ceriotuberosa* declines from initially high values low in the section and eventually disappears upsection (Figure 13).

West

This section contains large numbers of fossils throughout, although the basal interval of the section (-345 cm to -330 cm) contains no *L. staplini*, and low numbers of *Pisidium* and *C. caudata* (Figure 14). The ostracode *C. rawsoni* is abundant throughout the section, and gastropods only occur within the basal interval and at +30 cm (Figure 14). The bivalve *Pisidium* shows three apparent cycles in population size. The ostracodes *C. caudata* and *L. staplini* appear to have similar population-size cycles similar to *Pisidium*, although these cycles are not coeval, and are much more weakly developed (Figure 14). The ostracode *L. ceriotuberosa* occurs at -240 cm, -220 cm, and at -100 cm (Figure 14). Figure 15 shows the diatom family occurrences of the West Site.

Radiocarbon stratigraphy

Coal Valley radiocarbon ages were determined by the Arizona Accelerator Mass Spectrometer Laboratory in Tucson AZ in 1996 (identification numbers AA-22062 to AA-22066 inclusive). Table 3 summarizes the ages with error ranges for each sample, as well
Figure 14. Biostratigraphy of the West Site. Y-axis values are height of outcrop/depth of subcrop, expressed in centimeters.

Valves/5 g of sediment

Depth (cm) 0 1000 2000 0 1000 2000

-20 no data
-30 no data
-40 no data
-50 no data
-60 no data
-70 no data
-80 no data
-90 no data
-100 no data
-110 no data
-120 no data
-130 no data
-140 no data
-150 no data
-160 no data
-170 no data
-180 no data
-190 no data
-200 no data
-210 no data
-220 no data
-230 (1914)
-240 (3975)
-250 (2736)
-260 (6752)
-270 (6752)
-280 (2754)
-290 (2757)
-300 (4681)
-310 (4681)
-320 (4681)
-330 (4681)
-340 (4681)

C. caudata
C. rawsoni
Pisidium
L. cenotuberosa
L. staplini

27,760 +/- 330 BP
32,280 +/- 490 BP

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Figure 15. Diatom occurrences within the West Site stratigraphic section: an X denotes the presence of members of a given diatom family at a given interval.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Cymbellaceae</th>
<th>Epithemiales</th>
<th>Fragiliniales</th>
<th>Naviculaceae</th>
<th>Nitzschioideae</th>
<th>Surirellaceae</th>
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<tr>
<td>-20</td>
<td>X</td>
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</table>
Table 3. Laboratory identification numbers and ages in years BP (from 1950 A.D.) of dated specimens. Also shown are the types of material submitted, and site and stratigraphic locations.

<table>
<thead>
<tr>
<th>Identification</th>
<th>Age, +/- error</th>
<th>Material</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA-22062</td>
<td>20.280 +/- 140</td>
<td>Ostracodes (<em>C. Caudata, C. rawsoni</em>)</td>
<td>North-central, +70 cm</td>
</tr>
<tr>
<td>AA-22063</td>
<td>40.660 +/- 1390</td>
<td>Bivalves (<em>Pisidium sp.</em>)</td>
<td>Central, -170 cm</td>
</tr>
<tr>
<td>AA-22064</td>
<td>27.760 +/- 330</td>
<td>Ostracodes (<em>C. Caudata, C. rawsoni</em>)</td>
<td>West, -290 cm</td>
</tr>
<tr>
<td>AA-22065</td>
<td>32.280 +/- 490</td>
<td>Ostracodes (<em>C. Caudata, C. rawsoni</em>)</td>
<td>West, -330 cm</td>
</tr>
<tr>
<td>AA-22066</td>
<td>37.220 +/- 925</td>
<td>Gastropods (<em>H. trivolvis</em>)</td>
<td>South, +5 cm</td>
</tr>
</tbody>
</table>
as the material submitted and location within stratigraphic section. In general, radiocarbon ages that are older than 35,000 BP should be treated with a certain amount of caution; additionally, a number of circumstances exist that may cause Coal Lake $^{14}$C ages to be unexpectedly old. Foremost, the basin is surrounded by thick sections of Paleozoic carbonate rocks, and the weathering and subsequent deposition of this ancient carbonate into Coal Lake would lead to a hardwater or reservoir effect, i.e., a surplus of $^{14}$C-depleted carbonate anions in the water column. This would reduce the total amount of $^{14}$C available for construction of shell material by various fauna. The hardwater effect has implications for all Coal Lake dates, in addition to other site-specific circumstances.

Another potential factor skewing the ages of Coal Lake dates is ion exchange between shell material and groundwater, subsequent to the desiccation of the lake.

The date from the South Site of 37,220 +/- 925 BP (AA-22066) was obtained from the shell fragments of the snail *H. trivolvis*. The hardwater effect may be particularly exaggerated in this specimen as a result of its large body size, which is much greater than the dated ostracode or *Pisidium* specimens. Additionally, aquatic snails tend to yield $^{14}$C dates inconsistent with true $^{14}$C ages, such as those derived from tree rings (Brennan and Quade, 1997; Riggs, 1984).

The date from the Central Site of 40,660 +/- 1390 BP (AA-22066) is the most problematic of the Coal Lake dates. Although somewhat beyond what is usually considered the reliable age range of $^{14}$C dates, it was not reported as infinite (meaning that the sample is not depleted of $^{14}$C, and the analytical laboratory was able to assign an age to it). This date was obtained from *Pisidium* shell fragments, which due to their body size
may have experienced a hardwater effect exaggerated with respect to the ostracode specimens, but not as pronounced as that in the snails. It is also possible that the location of the Central Site itself may have complicated this date. The section recovered from this site underlies the modern playa surface in the centermost portion of the basin. Anion exchange between water and shell material may be unusually high in this location, due to the concentration and greater residence time of precipitation runoff from the surrounding watershed.

Although the possibility exists that the South Site and Central Site dates may be valid, the simplest and most reasonable course of action at present, in the absence of other geochronological information, is to remove them from further consideration.

**Ostracode Biology and Water Salinity Through Time**

The variations of population diversity and abundances of ostracode species in the Coal Lake section, together with the known ecologic data of these species, allow for a limited extrapolation of the water chemistry of Coal Lake throughout its lifetime.

Ecologic data may be expressed in a variety of ways, including the maximum ranges of tolerances of various environmental conditions, as shown in Figure 11. I have provided an interpretation of Coal Lake water salinity, expressed in terms of the maximum tolerance ranges of the six Coal Valley ostracode taxa. For example, the ostracode *C. rawsoni* has a salinity tolerance range of 141-42,770 ppm, and *C. caudata* has a salinity tolerance range of 20-2054 ppm. The overlap of the salinity tolerances of these ostracode species is the
range 141-2054 ppm. As a result, if these two taxa occur together in a given interval, then the water salinity of the lake during the time that this interval represents must be at some value between 141-2054 ppm. It is important to note that the analysis presented here is not rigorous; it is meant to define a (somewhat broad) range of possible environmental conditions.

In general, the water salinity of lacustrine sections containing ostracodes appears to have fluctuated little throughout time. At the North-central Site, inferred reductions in salinity are observable at +10 cm, whereas upsection of this interval salinity does not appear to have significant variances (Figure 16). The Central Site shows more evidence for water salinity changes throughout the section (Figure 17), but these variations are not significant in terms of differentiating between a saline, brackish, or freshwater lake. The base of this section shows the greatest salinity variations, expressing the development of an infrahaline phase (suggested by the occurrence of C. lacustris) from a less fresh (slightly brackish) phase, at about -290 cm (Figure 17). From -250 cm to about -160 cm salinity appears to remain constant. From about -160 cm to -130 cm salinity fluctuates slightly, and then seems remain constant, at levels slightly higher than those lower in the section, to about -90 cm (Figure 17). These data suggest that at this point, the lake returns to a lower salinity level (Figure 17). At the West Site, water salinity also appears to show little variation through section, with only slight increases apparent at -240 cm, -220 cm, and -100 cm (Figure 18).
Figure 16. Inferred water chemistry of the upper 200 cm of the North-central Site. Salinity at each interval is expressed as a potential range, denoted by a horizontal bar with its median point shown.
Figure 17. Inferred water chemistry of Central Site. Salinity at each interval is expressed as a potential range, denoted by a horizontal bar with its median point shown.
Figure 18. Inferred water chemistry of the West Site. Salinity at each interval is expressed as a potential range, denoted by a horizontal bar with its median point shown.
CHAPTER 3

DISCUSSION

Depositional Environments

Several different environments of deposition may be identified in the Coal Lake sections, including fluvial, deltaic, saline lacustrine, freshwater lacustrine, younger alluvial, and modern playa.

The North Site is located basinward of the high strandline (Figure 3), yet shows a paucity of fossils, and the grain size throughout the North section ranges from pebble to clay-size particles (Figure 5). The large grain size range, together with the lack of fossils, suggest that this site represents an alluvial rather than a lacustrine environment. Since this site is basinward of strandline features (Plate 1), the alluvium here is post-lacustrine, subsequent to deflation of the original lake sediments out of the area. The upper 90-100 cm of this section contains the fine silt to clay (Figure 5), and paucity of fossils consistent with a playa environment. In addition, desiccation cracks are visible at the exposed surface. By contrast, the entire South Site section represents a lacustrine environment, as interpreted from grain size analysis (Figure 9) and the high abundance of fossils.

The interval spanning 0 cm to ~100 cm in the North-central Site section contains a
narrow grain size range (Figure 6), as well as abundant freshwater lacustrine ostracode fossils (Figure 12). As a result, this interval represents a freshwater lacustrine environment, and in fact probably represents the period of maximum biologic productivity and areal extent of Coal Lake. Even though the interval above ~100 cm contains coarser grain sizes, the biostratigraphy (Figure 12) indicates that this interval is also lacustrine. A very weakly developed soil horizon is observable in the uppermost 30 to 20 cm of this section (M.H. Nash, personal communication, 1996). Because of the consistently high abundance of lacustrine taxa, the interval of 0 cm to +195 cm represents a single freshwater lacustrine phase. By contrast, the entire subcrop interval represents two earlier phases in the development of Coal Lake, when it did not yet extend to the vicinity of the North-central site. The lowest and coarsest interval of this section (Figure 6) contains no fossils, and represents a fluvial (or alluvial?) environment. As Coal Lake grew, a transition may have occurred between a high-energy fluvial environment, to a lower-energy deltaic environment, marked by the grain size change at approximately -370 cm (Figure 6). In addition, within the interval from -260 cm to 0 cm, rare bivalve and very rare ostracode fossils may be observed (Appendix 2). The occurrence of bivalves indicates the development of a nearshore freshwater environment, and the single occurrence of the benthic ostracode *C. caudata* indicates that for a brief period, a sufficiently low-energy environment developed to allow a small community to exist at this site.

In general, the grain size ranges within the Central Site are comparable to the upper 100 cm of the North-central site, although fossil density is somewhat lower. The upper 50 cm contains a grain size range (Figure 7) consistent with a playa feature, and
desiccation cracks on the exposed surface are observable as well. The remaining interval contains grain size ranges (Figure 7) and ostracode taxa (Figure 13) consistent with a lacustrine environment; coarser intervals may represent periods of lake regression. The portion of the section below -260 cm at the Central Site contains no *Pisidium sp.* fossils, but *C. lacustris* does occur twice (Figure 13). As a result (see Chapter 2 for ecological information), this interval expresses an overall deep-water, low-temperature lake environment, with maximum development at the intervals containing *C. lacustris*. The biostratigraphy of the overlying interval between -250 cm and -110 cm suggests that it represents a shallower-water (higher energy) environment, with a return to deeper-water conditions above -110 cm.

The upper 415 cm of the West Site section compares well with the Central Site section in terms of grain sizes (Figure 8) and fossil content (Figure 14). As a result, this interval represents a lacustrine environment. The gypsiferous diatomite below -315 cm (Figure 8) may be interpreted to represent a saline lake environment, based on the lack of freshwater ostracode fossils, and the presence of gypsum and saline diatoms. Gypsiferous sediments do not occur in any other section.
Figure 19. Stratigraphic correlations of the South, Central, West, and North-central Sites.
Stratigraphic correlations, Two Explanations for One Gypsiferous Diatomite, and the chronology of Coal Lake

Despite the complications associated with the Coal Valley $^{14}$C dates, it is possible to attempt some correlations between the site sections (Figure 19). Of the three, the West Site probably contains the oldest section, and the Central Site contains a section generally contemporaneous with, but younger than, the West Site section. Radiocarbon chronology indicates that the North-central Site contains the youngest exposed (remaining) lacustrine sediment in Coal Valley.

At present, the lowest elevations in Coal Valley occur in the vicinity of the West Site (Plate 1). This modern surface expression may be the result of Holocene eolian activity, or it may be the result of paleotopography; this area was a depression (Figure 20), or contained a set of depressions, during Pleistocene time, perhaps as a result of pre-Wisconsin lacustrine and/or eolian activity in the basin. Assuming the latter, and recognizing that gypsiferous diatomites do not occur in any other section, it is then reasonable to speculate that the gypsiferous diatomite represents an early, saline phase of Coal Lake, which was first established at the West Site and grew outward from there to the Central Site and beyond. This saline lake phase must have been confined to that vicinity: water was not accumulating in the Central Site area during the time of saline Coal Lake. This Early Coal Lake phase is the first expression of Coal Lake, forming prior to 32,000 BP (Figure 19). This phase is expressed at the North-central site by the presence of the fluvial environment located at the base of this section. Radiocarbon ages suggest
Figure 20. Potential paleotopographic profiles of Coal Valley. The north direction is into the paper. Dashed line represents water level. (a) A bowl-shaped basin in which the center is the lowest point; (b) a bowl-shaped basin, with an additional depression on its west side; (c) the same basin with water level reduced.
that the transition from saline to freshwater occurred between ~32,000 BP and ~28,000 BP (Figure 19). To make this transition, water must have been added to the basin, and I suggest that during and after this event, energy conditions at the West Site and the Central Site were rather similar, as opposed to the differences between the sites during the time of Early Coal Lake. That is, a sufficient amount of water was added to the system to overprint significant lithologic differences between the two sites. The Central Site was a shallower, higher energy, more near-shore environment than the West Site, but the lithologic similarities between the two sites (Figure 19) suggest that the difference was minimal. However, the biostratigraphic records from each section indicate that the living environments must have been dissimilar enough to (1) prevent the occurrence of the ostracode *C. lacustris* at the West Site, and (2) prevent the occurrence of *Pisidium sp.* at the Central Site below -250 cm. This may be explained by the idea that although the West Site may have been the deepest part of Coal Lake, water circulation in the area may have been restricted by the same topographic (in this case bathymetric) circumstances that contained the evaporite here *a priori*. As a result, the salinity levels here may have been unsuitably high for *C. lacustris* (see Chapter 2). Figure 19 shows a correlation between the lower half of the Central Site section and the West Site section.

I have drawn principal correlations between the West Site and Central Site sections based on the occurrences of the rare ostracode *L. ceriotuberosa* (Figure 19). In general, the entire Central Site section, as well as the entire interval above the evaporite in the West Site section, both represent the same lacustrine phase, Coal Lake Intermediate. During this phase, freshwater lacustrine conditions existed at the Central and West Sites.
However, at the North-central Site, the transition from Early Coal Lake to Coal Lake Intermediate is marked by the change from a high-energy fluvial environment to a lower-energy deltaic regime, which was persistent throughout the Intermediate phase.

The end of the Coal Lake Intermediate phase is marked by the appearance of freshwater taxa in the North-central Site section starting at \(-10\) cm and continuing throughout the rest of the section. This base of this interval is probably from a time period within 1000 to 2000 years of the radiocarbon date of 20,280 BP obtained from this site. The interval as a whole represents the final lake phase, Coal Lake Maximum. The biostratigraphic record suggests that the transition from Coal Lake Intermediate to Coal Lake Maximum was not gradual (Figure 12). During this phase, Coal Lake grew to its maximum extent of 287 km² and its maximum depth of \(-40\) m. This phase was probably persistent until deglaciation of 14,000-9,000 BP, although most of the lacustrine record beyond 20,000 BP has likely been deflated out. The Central Site and the West Site apparently do not express the Coal Lake Maximum phase, although the South Site section may correlate to the upper North-central Site section in some manner.

Although the idea of variable topography/bathymetry is interesting, a simpler and probably more reasonable scenario is that gypsiferous diatomite deposits may in fact exist at the Central Site, underlying the lowest interval recovered. This scenario is simple, and is consistent with the idea of the gradual development of Coal Lake from the center of the basin, where water levels would be expected to have been the deepest. However, it does not explain the (apparent) greater grain size variability of the Central Site, as compared to the West Site. Also, if paleotopography (paleobathymetry) is not an issue, why doesn’t
the ostracode *C. lacustris* appear in the West Site section? Perhaps favorable salinity conditions for this taxon existed exclusively at the Central Site. One explanation for this, without invoking variable topography/bathymetry, is the possibility of a different sediment source for the West Site. Perhaps similar mechanisms that allowed for the variability of heavy mineral suites in the lacustrine section (Hammond, et al., 1996) also allowed for variable gypsum input. Additionally, evaporation rates may have been higher in the nearshore (West Site) environment, thus increasing the salinity (and gypsum content) of the water in this area. Until proven otherwise, the assumption that the gypsiferous diatomite exists in the central basin is the most reasonable. Future study of the Coal Lake system requires deeper coring of all sites, or excavation of trenches using heavy equipment.

**Paleoenvironmental and Paleoecological Interpretations**

The water chemistry observations derived from ostracode occurrences suggest that the Coal Lake Intermediate phase was dominated by freshwater conditions, and that fluctuations in salinity were infrequent and low in magnitude. This suggests that water input into the basin was constant throughout this period. Further, the absence of multiple, recurring evaporite deposits, together with the lack of fossil evidence suggesting multiple, long-term saline phases, implies that water seepage out of the basin was high throughout all lake phases, at a rate roughly equal to water input into the basin.

A lake is the surface expression of the local groundwater regime, and may be fed
by the water table, as an effluent lake, or may feed the water table, as an influent lake (Moore, 1986). The freshwater nature of Coal Lake, as implied by the ostracode ecology, may be attributable to a consistently high groundwater budget from ~28,000 BP through (probably) to deglaciation. The transition from the Early Coal Lake phase to the Coal Lake Intermediate phase may be more directly a result of changes in local hydrology, which in turn is controlled by the regional climate. The relatively fresher and infrahaline phases of Coal Lake, as expressed by the ostracode biostratigraphy, may indicate periods of peak effluence.

It should be noted that an investigation of the Coal Lake diatom record would probably yield a higher resolution record of water salinity conditions than the ostracode record.

A Regional Perspective of Climate

Coal Lake was a saline body about 3000 years (Morrison, 1991) after the formation of freshwater Lake Lahontan, and about 1000 years (Morrison, 1991) after the formation of freshwater Lake Bonneville. Searles Lake breached its basin during the time of Early Coal Lake (Jannik, 1991). Additionally, the saline phase of Coal Lake was contemporaneous with the saline La Salina Complex of the Estancia Basin (Bachhuber, 1992). As a result, the development of Early Coal Lake at ~32,000 BP is consistent with the documented pluvial history of the southwestern U.S., in terms of the migration of pluvial climates from higher latitudes to lower latitudes (Bradley, 1985; Mifflin and Wheat, 1979; Morrison, 1991). That is, the climatic conditions necessary to support pluvial
environments were established first in higher latitudes and then migrated south. By
comparing the timing of Lakes Bonneville and Lahontan with Coal Lake (as well as Lake
Estancia), the rate of this "climatic migration" was about 1° of latitude per 1000 years, on
average. Although interesting, this idea must be substantiated by investigations of other
pluvial systems in the Great Basin, such as those adjacent to Coal Valley (Figure 1).

Tephra in Coal Valley?

Given the chronologic scenario outlined for Coal Lake, it would be reasonable to
expect to find at least one tephra layer within the lacustrine sediments. The Wono Ash
(25 ka) and the Mt. Saint Helens G-Marble Bluff Ash (35 ka) occur in the Lake Lahontan
record (Morrison, 1991). However, I observed no ash layers in any of the Coal Lake
sections. This most likely is the result of sampling technique; a thin ash layer (<1 cm) is
likely to be fairly well-mixed with other sediments during the augering process and
therefore rendered visually unrecognizable. Further, the high abundance of heavy
minerals throughout the lacustrine section (Hammond, et al., 1996) greatly complicates ash
identification by X-ray diffractometry. Positive documentation of tephra in Coal Valley
requires (1) sample recovery by a means that will preserve stratigraphy, and/or (2)
electron microscopy of recovered sediment.

Volcanic ash simply may not have been circulated to Coal Valley between 40,000
BP and 20,000 BP. This seems unlikely, given the volcanic history of the region (E.I.
Smith, personal communication, 1996). Further, models of wind patterns for winter for
18,000 BP (Kutzbach and Wright, 1985) suggest that volcanic ash originating from the west coast of North America would have had the opportunity to settle out in the Central Nevada region. It is reasonable to assume that wind circulation was not vastly different from ~25,000 BP to 18,000 BP. Any future work in Coal Valley should focus on the documentation of tephra layers as an aid to further refine Coal Lake chronology.

Recalculations of $Z_c$

Mifflin and Wheat (1979) calculated a $Z$ value for Coal Lake ($Z_c$) of 0.07, based on a basin area of 1005 mi$^2$ and a lake area of 69 mi$^2$. Accounting for the revised maximum area of Coal Lake of 112 mi$^2$, based on the recognition of a topographically higher strandline, $Z_c$ becomes 0.11. This value is comparable to those for the Buffalo, Diamond, and Smith Basins of the Lahontan complex (Figure 21). In their original calculation of $Z_c$, Mifflin and Wheat (1979) added the surface areas of Garden and Coal Valleys, assuming that all water entering Garden Valley was transported into Coal Valley, and eventually into Coal Lake. The topography of Garden Valley suggests that standing water did not accumulate there, and that it was a major watershed of Coal Lake, as it is currently part of the watershed of modern Coal Valley. However, given the seepage rates out of Coal Valley suggested by the biostratigraphic record, it is reasonable to assume that Garden Valley has, or had, similarly high rates. The alluvial units of the two valleys are of comparable composition, and therefore should be comparable in terms of hydrologic properties. As a result, not all of the water entering Garden Valley would have ended up
Figure 21. Location map showing Buffalo, Diamond, and Smith Basins.
in Coal Lake, thus decreasing the value of the basin area, $A_T$. This increases the value of $Z_{cv}$, making Coal Valley even more favorable (in terms of numerical models) to lake formation than previously thought.

Alternatively, if the input of Garden Valley is ignored altogether, then

$$Z_{cv} = \frac{287 \text{ km}^2}{800 \text{ km}^2} = \frac{112 \text{ mi}^2}{312 \text{ mi}^2} = 0.36.$$  This, however, approaches the $Z$ value calculated for Lake Bonneville (0.59), and is in fact greater than the $Z$ value calculated for Lake Lahontan (0.24) (Mifflin and Wheat, 1979). A $Z_{cv}$ value of this magnitude is not supported by the sedimentologic, biostratigraphic, or field geomorphic records of Coal Valley, especially when compared to the more extensive strandline complexes and stratigraphic records left by Lakes Bonneville and Lahontan.
CHAPTER 4

CONCLUSIONS

The development of Coal Lake may be constrained to three general phases. Early Coal Lake, a saline phase, developed sometime before 32,000 BP, probably within a few thousand years. Based on the localized occurrence of gypsiferous deposits, it is possible that Early Coal Lake first developed southwest of the geographic center of the basin, at the West Site, and was restricted to that area. However, it is probably a safer assumption that water accumulated in the center of the basin first, and that the gypsiferous sediments representative of Early Coal Lake underlie the lowest interval recovered from the Central Site. Between 32,000 BP and 28,000 BP (probably closer to 28,000 BP), the transition to freshwater Intermediate Coal Lake occurred. The beginning of this phase is marked in the biostratigraphic records in sections recovered from areas near the central basin, and by sedimentologic changes in more distal locations. The Intermediate Coal Lake Phase continued until probably within 22,000 to 20,000 BP. This time period marks the beginning of the Coal Lake Maximum phase. This phase probably developed rapidly in response to the climatic conditions associated with the Last Glacial Maximum (LGM), filling the basin with water to a depth of at least 40 m. This phase is observable in only one of the recovered stratigraphic sections. Although most of the sediment younger than
20,000 BP is believed to have been deflated from the basin. Coal Lake itself was probably persistent through to deglaciation, between 14,000-9,000 BP. Since that time, widespread eolian activity has actively removed much of the lacustrine section, and playa surfaces have formed. In one location, a very weakly developed soil horizon may be observed.

The development of Coal Lake is consistent with the pluvial history of the Great Basin. Coal Lake postdates the formation of Lake Lahontan by at least 3000 years, and Lake Bonneville by at least 1000 years. This suggests the possibility that the climatic conditions necessary to support pluvial lakes were established from north to south at an average rate of 1° of latitude per 1000 years, at least in the eastern Great Basin.

The ostracode record indicates that the salinity levels of accumulated water varied little through time, suggesting that Intermediate Coal Lake and Coal Lake Maximum were consistently freshwater environments throughout time. The Coal Lake ostracode record did not yield evidence of rapid and recurring climatic flux, despite the "climatic threshold" location of Coal Valley and its low Z value. The lacustrine environment probably experienced more direct control by regional groundwater hydrology than by regional climate itself. A high resolution climatic signature may be revealed by detailed examination of the diatom stratigraphy, and by the paleomagnetic record as well (see Appendix 1). Coal Lake reached a maximum area of ~ 290 km², compared to the 178 km² reported by earlier workers. The paleohydrologic index of Coal Valley (Zcv) is revised to a new value of 0.11, as compared to an earlier report of 0.07. Both of these Z values assume that 100% of the surface area of the adjacent Garden Valley contributed to the Coal Lake watershed; the actual Zcv may be much greater.
APPENDIX I

PALEOMAGNETISM AND ROCK MAGNETISM

The magnetic properties of lake sediments often contain valuable information concerning changes in regional precipitation, vegetation, sediment sources, water levels, biologic productivity, and weathering within a catchment (Rowe, 1995; Thompson and Oldfield, 1986). Variations in concentration, grain size, and mineralogy of magnetic material over a stratigraphic interval have been linked to climatic change (Peck, et. al, 1994; Rowe, 1995). It is important to note, however, that the physical meaning of lacustrine rock magnetic records are still being evaluated because they are site-specific (Rowe, 1995).

I conducted a pilot study of the paleomagnetic and rock magnetic properties of Coal Lake sediments at the University of New Mexico Paleomagnetism Laboratory. I subjected thirty-one oriented specimens to alternating-field (AF) demagnetization, and 127 unoriented specimens to saturation isothermal remanent magnetization (SIRM) acquisitions. The AF-demagnetized samples were from the North-central Site, over a stratigraphic interval of ~83 cm, with a sampling interval of ~2.2 cm. Figure 22 shows the raw unsmoothed declination and inclination curves obtained from this interval at the 20

65
Figure 22. Magnetic declination (top) in degrees, and magnetic inclination in degrees (bottom).
Figure 23. Selected SIRM acquisition curves obtained from the North-central Site. The shapes of these curves indicate that magnetism resides primarily in magnetite for all specimens, with some contribution from other iron oxides likely.
milliTesla (mT) demagnetization step. Figure 23 shows selected SIRM acquisition curves from the North-central Site.

Figure 24 shows the smoothed paleosecular variation (PSV) declination and inclination records from Lakes Estancia and Lahontan. For ~20,000 BP, the declination and inclination records from Coal Valley compare favorably to those of Estancia and Lahontan. This suggests that the $^{14}$C age obtained from the North-central Site is reasonably accurate, and that Coal Lake sediments have the potential to yield a reliable, long-term PSV record for mid- to late-Wisconsin time. SIRM acquisitions suggest that in all specimens the magnetism resides primarily in magnetite.
APPENDIX 2

COMPLETE BIOSTRATIGRAPHY OF THE NORTH-CENTRAL SITE

Figure 25 shows the biostratigraphy of the complete North-central Site section, from -410 cm to 0 cm, in addition to the portion of the section presented in Figure 12, from 0 cm to +190 cm.
Figure 25. Biostratigraphy of the entire North-central Site section. Y-axis values are height of outcrop/depth of subcrop, expressed in centimeters. The zero value on the Y-axis corresponds to the contact between outcrop and subcrop.
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UMI
PLATE 1
Wisconsin-Holocene Geology of Central Coal Valley, Nevada

- **H₂**: Youngest Holocene alluvium
- **Hp**: Holocene playa surface
- **He**: Holocene eolian (dune) features
- **H₁**: Older Holocene alluvium
- **W₁**: Pleistocene lacustrine deposits

Maximum extent of Pluvial Coal Lake

**SCALE 1:100,000**
**COUNTOUR INTERVAL 50 m**

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