Final Staff Report
On the
Origin and Development of the Keeler Dunes

By

Great Basin Unified Air Pollution Control District

November 16, 2012

THIS PAGE LEFT INTENTIONALLY BLANK

Final Staff Report
On the
Origin and Development of the Keeler Dunes

By Great Basin Unified Air Pollution Control District
November 16, 2012

Executive Summary

The Great Basin Unified Air Pollution Control District (District) conducted seven separate investigations researching the origin and development of the Keeler Dunes employing a wide variety of methods and approaches. The investigations studied the development of the landscape in the dune area on multiple time scales ranging from geologic and geomorphic processes (on the order of thousands of years) to historical documents and photos (within the last 160 years) to analysis of dune elevations and sand flux data (recent, within the last 12 years).

The results of the investigations taken together clearly show that the landscape within the Keeler Dunes has changed dramatically in the last century and that the current active emissive Keeler Dunes developed after the historic desiccation of Owens Lake. Geomorphic mapping and analysis of the chronology and stratigraphy of the dunes area show that older vegetated and non-emissive dunes existed in the area as early as about 1,700 years ago associated with Late Holocene stands of ancient Owens Lake. These former dunes are thought to be significantly different in character and extent to the current active and mobile dune field and formed in relation to existing ancient shoreline features (Figure Ex-1).

Research of historic materials and photographs clearly indicate that the current active Keeler Dunes formed within the last 70 years with the main source of material coming from the Owens River and off of the dried bed of Owens Lake. As the sand sheet and dunes grew and migrated across the Keeler Fan, existing vegetation died and the landscape was changed to the largely barren and open deposits of emissive aeolian sand sheet and dunes that currently characterize the area and affect the population within the region. These sand deposits are currently being eroded on the upwind (north and west) margin but continue to move to the southeast towards the community of Keeler at a rate of about 10 meters (33 feet) per year.

In summary, the District's investigations on the origin and development of the Keeler Dunes conclusively indicate that the current active and emissive dune deposits are not natural but instead are the result of disruption of the natural hydrologic environment in the Owens Valley due to water diversion activities. The Keeler Dunes are a dramatic expression of the diversion of the Owens River and resulting desiccation of Owens Lake and are anthropogenic in origin.

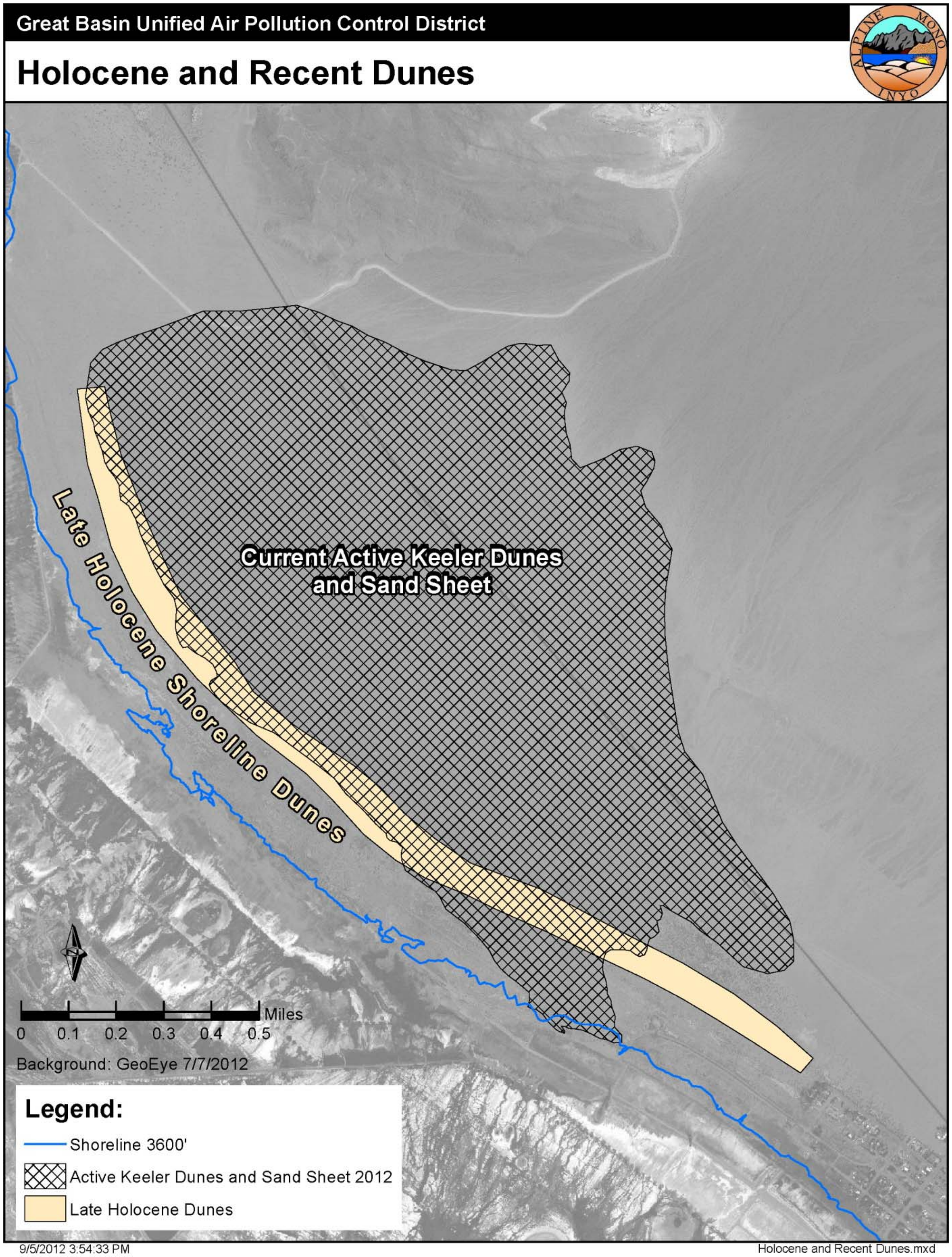


Figure Ex-1: Map showing the extent of the active Keeler Dunes and sand sheet deposit (from July 2012) with the general area with older dune features associated with Late Holocene shorelines.

Final Staff Report
On the
Origin and Development of the Keeler Dunes

By
Great Basin Unified Air Pollution Control District
November 16, 2012

Table of Contents

List of Figures

Figures for Executive Summary:

Figures for Section 1.0: Introduction

Figures for Section 4.1: Historical Document Research

Figures for Section 4.2: Ground-Based Analysis of Historic and Recent Photos

Figures for Section 4.3: Aerial Photograph and Satellite Imagery Analysis

Figures for Section 4.4: Geomorphic Mapping of the Keeler Dunes and Surrounding Area

Figures for Section 4.5: Chronology and Stratigraphy of the Keeler Dune Area

Figures for Section 4.6: Analysis of Surface Change in the Northeast Portion of Owens Lake

Figures for Section 4.7: Analysis of Dune Transects and Dune Movement (2002-2012)

Figures for Section 5.0: Summary of District Research

List of Tables

Table for Section 4.1: Historical Document Research

Table for Section 4.2: Ground-Based Analysis of Historic and Recent Photos

Table for Section 4.3: Aerial Photograph and Satellite Imagery Analysis

Tables for Section 4.5: Chronology and Stratigraphy of the Keeler Dune Area

List of Attachments

(Attachments are available as separate documents)

Attachment A: Research of Historical Documents and Records, report by Sapphos Environmental Inc. and A.W. von Schmidt Cadastral Survey of the Owens Lake Shorelands, report by Dr. Scott Stine.

Attachment B: Ground-Based Photo Analysis: Comparison of Historical and Recent Views, Final report by Sondra Grimm, Great Basin Unified Air Pollution Control District.

Attachment C: Aerial Photograph and Satellite Imagery Analysis (1944 to 2010), Final report and analysis by Nicholas Lancaster, Desert Research Institute.

Attachment D: Geomorphic and Geologic Map of Keeler Dune and Surrounding Area, Final report by Steven Bacon and Nicholas Lancaster, Desert Research Institute.

Attachment E: Late Holocene Stratigraphy and Chronology of the Keeler Dunes Area, Final report by Nicholas Lancaster and Steven Bacon, Desert Research Institute and Potential Sources of Sand for the Keeler Dunes, Final report by Nicholas Lancaster and Steven Bacon, Desert Research Institute.

Attachment F: Analysis of Surface Change in the Northeast Portion of Owens Lake, Analysis of Sand Motion Data, revised technical report by Duane Ono, Grace Holder, Chris Howard, and Mike Slates, Great Basin Unified Air Pollution Control District.

Attachment G: Analysis of Dune Transects and Dune Movement (2002-2012), report and analysis by David Groeneveld and Dave Barz, HydroBio ARS.

List of Appendices

(Appendices are available as separate documents)

Appendix 1:	Comments received on the September 7, 2012 Preliminary Staff Report on the Origin and Development of the Keeler Dunes.
Appendix 2:	District response to comments on the September 7, 2012 Preliminary Staff Report on the Origin and Development of the Keeler Dunes

List of Abbreviations and Acronyms

cal yr B.P.	calibrated years Before Present
CEQA	California Environmental Quality Act
District	Great Basin Unified Air Pollution Control District
ft	feet
LAA	Los Angeles Aqueduct
LADWP	City of Los Angeles Department of Water and Power
m	meters
NEPA	National Environmental Policy Act
PM_{10}	particulate matter less than 10 microns in diameter
SIP	State Implementation Plan

Glossary

Anthropogenic	Caused by human activity.
Aeolian/Eolian	A term used in reference to the wind. Aeolian/Eolian materials or structures are deposited by or created by the wind.
Aerial Photos/Imagery	Photos or imagery taken from above as in the air or in space.
Alluvial Fan	A fan-shaped wedge of sediment that typically accumulates on land where a stream emerges from a steep canyon onto a valley or flat area. In map view it has the shape of an open fan.
Barchan dune	A crescent-shaped dune lying at right angles to the prevailing wind and having a steep, concave leeward side with the crescent tips pointing downwind.
Cross-bedded	Sedimentary structures of inclined layers within a bed.
Deflation	The removal of particles from a soil by wind erosion.
Delta	A landform developed at the mouth of a river.
Deposition	The addition of sediment by aeolian, fluvial, alluvial or deltaic processes.
Desiccation	The process of drying.
Fluvial	Features and deposits formed by stream or rivers.
Fugitive dust	dust generated from a non-point source such as windblown dust off of Owens Lake
Geomorphology	The scientific study of landforms and the processes that shaped them.
Historic shoreline	The shoreline of Owens Lake prior to water diversions in the Owens Valley. For regulatory purposes the shoreline of Owens Lake is defined as 3,600 feet above mean sea level. The level of Owens Lake in the 1850s and 1870s, prior to water diversions of the Owens River was 3,597 ft above mean sea level.
Holocene	The Holocene is a geological epoch which began at the end of the Pleistocene (around 12,000 years ago) and continues to the present. The Holocene is part of the Quaternary period.
Inflation	The addition of sediment, generally by aeolian processes.
Lacustrine	Related to a lake

Little Ice Age	A period of cooling that extending from approximately the 13th century to the latter half of the 19th century. Occurred after the Medieval Warm Period.
Nebkha	A mound-like accumulation of wind-blown sediment, usually sand, collected within and behind, and stabilized by, vegetation.
Phreatophyte	A deep-rooted plant that obtains water from a permanent ground supply or from the water table.
Pluvial	An extended period of abundant rainfall that may last many thousands of years.
Poorly sorted	Composed of mixed sediment sizes such that there is a wide variety of particle sizes present
Quaternary	The most recent geologic period in the Cenozoic Era extending from 2.5 million years ago to the present and consisting of the Pleistocene and Holocene Epochs.
Regression	A geologic term used to describe a period of time in which the lake level falls relative to the land causing the shoreline to move to lower elevation and exposing lake bed.
Sand flux	The amount of sand motion in a given unit of time. For Owens Lake data, sand flux is generally given in grams per square centimeter (g/cm^2) per hour or year.
Stratigraphy	A scientific discipline concerned with the description of rock successions and their interpretation.
Superposition	The Law of Superposition in Geology states that sedimentary layers are deposited in a time sequence with the oldest at the bottom and the youngest at the top.
Transgression	A geologic term used to describe a period of time in which the lake level rises relative to the land causing the shoreline to move to higher elevation.
Well-sorted	Composed of uniform sediment size such that there is a narrow range in particle sizes present.

Final Staff Report
On the
Origin and Development of the Keeler Dunes

By

Great Basin Unified Air Pollution Control District

November 16, 2012

SECTION I.0 INTRODUCTION

The Keeler Dunes and associated sand deposits are a source of fugitive dust emissions that impact air quality in the communities of Keeler and Swansea. The Keeler Dune field and associated sand sheet is approximately 960 acres in size and is located adjacent to the dried bed of historic Owens Lake between the communities of Keeler and Swansea (Figure 1-1). Dust concentrations measured within the community of Keeler from the Keeler Dunes continue to exceed the Federal and State PM_{10} 24-hour standards of 150 and 50 $\mu g/m^3$, respectively.

The number of exceedances of the Federal PM_{10} standard in the community of Keeler that are attributed to Owens Lake bed emissions has decreased with time, from as many as 16 per year in 1994 to just over 1 per year from 2006 to 2012. This air quality improvement in Keeler is due to the implementation of dust control projects on the lake bed. However, the uncontrolled Keeler Dunes continue to cause an average of six PM_{10} standard exceedances every year since 1993 (Figure 1-2). These standard exceedances threaten the health, property and environment of the residents of the Keeler/Swansea area.

The 2008 Owens Valley PM_{10} State Implementation Plan (2008 SIP) (GBUAPCD, 2008) requires control of the dust emissions from the Keeler Dunes on or before December 31, 2013 in order to demonstrate attainment of the federal standard within the Owens Valley Planning Area by 2017. The Great Basin Unified Air Pollution Control District (District) is responsible for developing a dust control strategy and plan for the Keeler Dunes PM_{10} emissions.

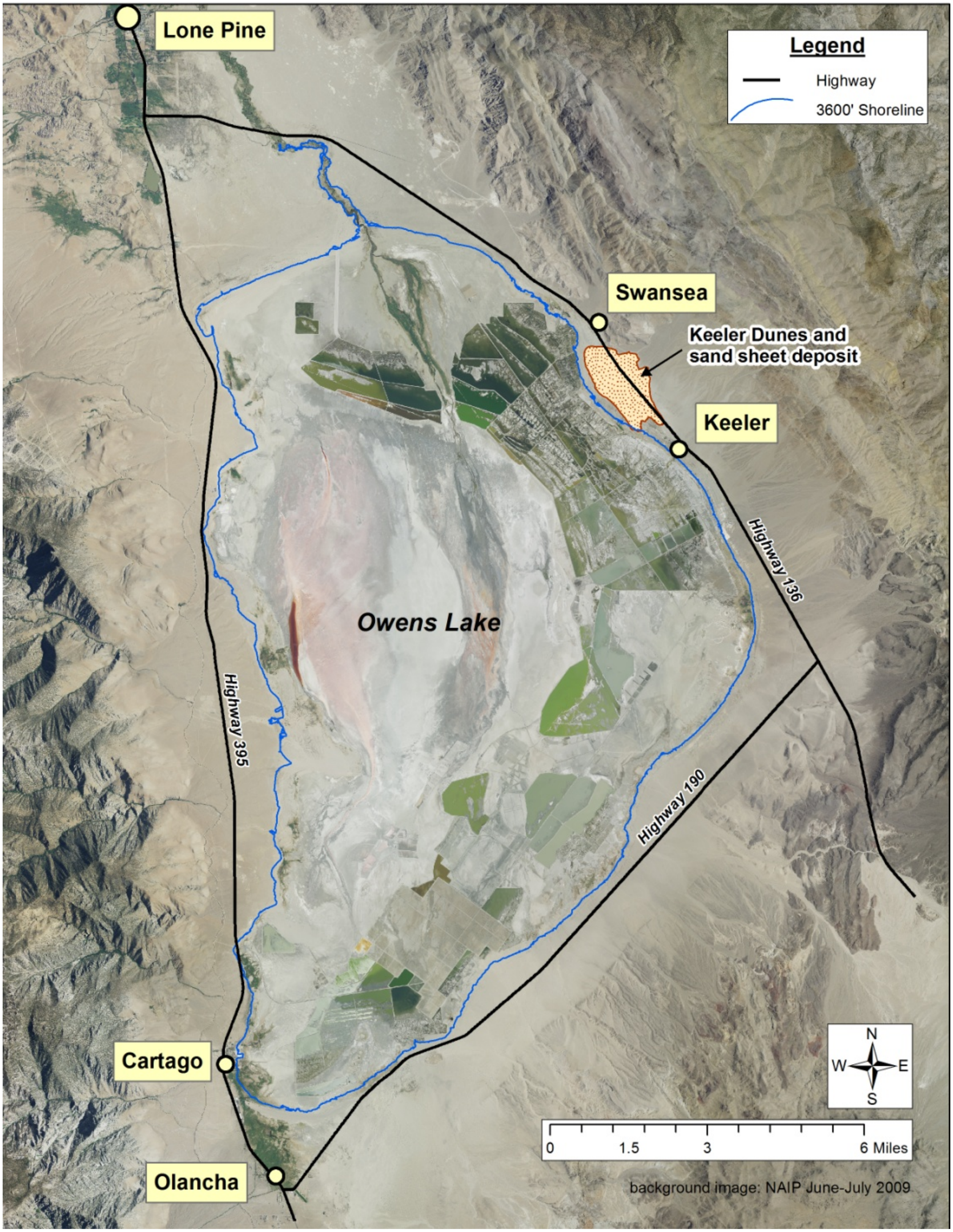


Figure 1-1. Map of the Owens Lake area showing the location of the Keeler Dunes and associated sand deposit and the communities of Keeler and Swansea.

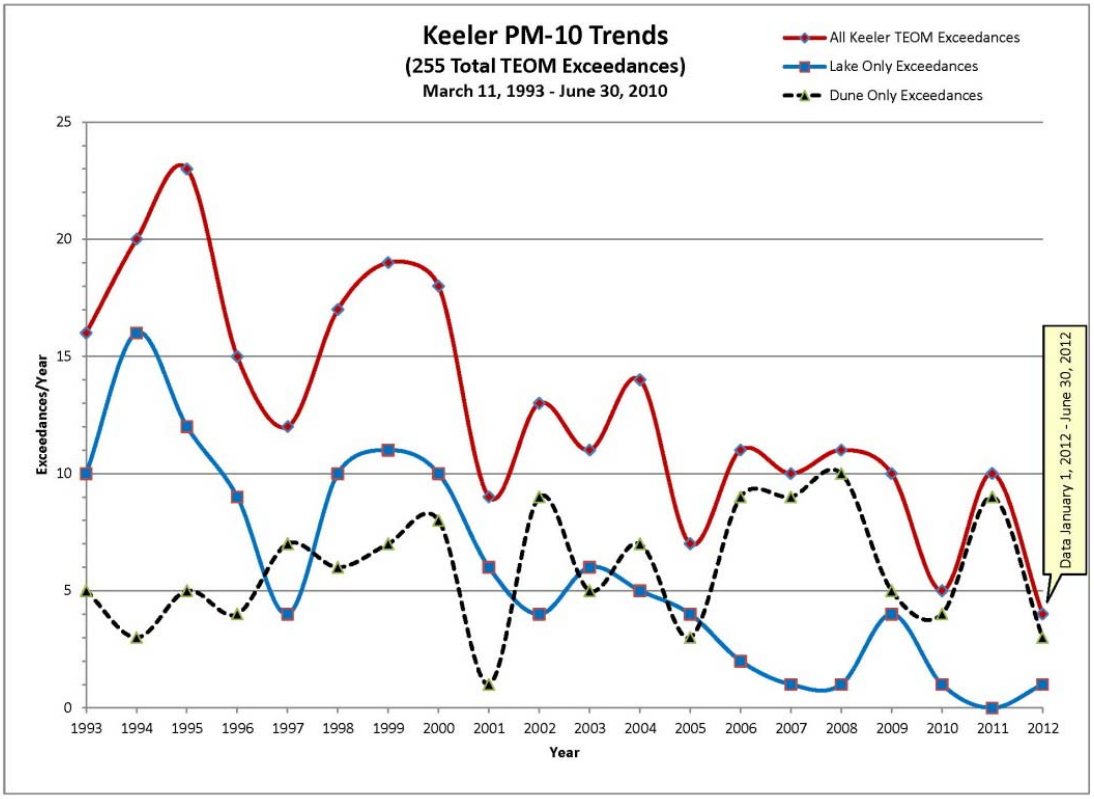


Figure 1-2. Plot of the number of exceedances per year of the Federal PM_{10} standard measured at the Keeler Monitoring site from 1993 to 2012. Data are broken out into exceedances that came from Owens Lake and those that came from the Keeler Dunes.

The District first began formal monitoring and data collection in the dunes in 2000 with the establishment of two sand motion monitoring sites as part of the Dust Source Identification (Dust ID) program. The number of monitors in the dunes was expanded to 12 in 2008[1] in response to commitments made by the District in its 2006 Settlement Agreement with the City of Los Angeles Department of Water and Power (LADWP) and the 2008 SIP (GBUAPCD, 2008). The purpose of the monitoring program is to gather information on the location and magnitude of emission activity within the area with the goal of developing a strategy for PM_{10} emission control.

In the 2003 and 2008 SIPs (GBUAPCD, 2003 and 2008), the District stated that the Keeler Dunes deposit formed by material that migrated off of the Owens Lake bed onto the lower portion Keeler alluvial fan after the lake became dry with the implication that the dunes were not

---

[1] Note: Five additional special purpose monitoring sites were added in 2011 for the development of a dust control strategy. These sites are not considered representative of the majority of the Keeler Dunes deposit.

natural. These statements were significant in that it meant that the dune deposit was formed as a result of exposure of lake bed material and was therefore an anthropogenic (man-caused) source of dust caused by diversion of waters that historically flowed into Owens Lake and prevented dust emissions and sand movement.

In 2008 the District began scientific investigations to learn about the history and formation of the dunes in order to determine if the statements regarding the dune origin were correct or if the dunes were natural. The District was not prejudiced in any way as to the outcome of the investigations and retained experts in dune geomorphology (dune form and shaping processes) and dune dynamics, Holocene pluvial lakes and paleoclimate, and remote sensing for the studies. A list of the project team and the curriculum vitas of the principle experts are provided in Section 7.0.

The answer as to the origin of the dunes is not just academic – it is critical for establishing the parties responsible for control of the PM_{10} emissions from the dunes. If the dunes are determined to have formed due to desiccation of Owens Lake and water gathering activities in the Owens Valley, then the City of Los Angeles would be responsible for implementation of dust controls. If the dunes are considered natural then the underlying property owner may be responsible for dust control since the source violates air quality standards and impacts the health, property and environment the residents of Keeler and Swansea. The third alternative is that the dunes were formed in part by natural causes and in part from desiccation of Owens Lake in which case the control project would have a mix of responsible parties. In all cases, the PM_{10} emissions from the dunes require control since they adversely impact the air quality and health of the residents of the two local communities, as well as the daily worker and visitor populations

The District Governing Board will hold a public hearing on December 13, 2012 to discuss the origin and development of the Keeler Dunes and directed District staff to complete a preliminary report (Preliminary Staff Report) to be made available to all interested parties along with the technical analyses, data and other materials from the completed studies. The Preliminary Staff Report and associated Technical Attachments were made available to all interested agencies and parties on September 7, 2012. Comments on these materials were due to the District by October 26, 2012[2]. The District carefully considered each comment and has provided detailed responses (see Appendix 2).

The Preliminary Staff Report was revised to provide additional information and clarifications to data and technical material based on the comments that were received. Many of the technical

---

[2] The original deadline for written comments was October 19, 2012. This deadline was extended one week to October 26, 2012 to provide additional comment time.

attachments were also revised to provide more information on the associated research and to address specific comments received. The revised staff report is presented here as the Final Staff Report on the Origin and Development of the Keeler Dunes. The supporting technical material and reports are provided as Attachments to the Final Staff Report.

The purpose of the public hearing in December 2012 is not to order the dust controls at this time, but rather it is to determine the origin and development of the dunes and ascertain whether anthropogenic actions have caused or contributed to their development and dust emissions. Depending on the outcome of this process, the District will issue appropriate dust control orders at a later date.

SECTION 2.0 PROJECT OVERVIEW

The Keeler Dunes Investigation is a multidimensional project with the main components of the project separated into three main categories.

1. Monitoring and data collection (dune and emissions characterization),
2. Dust control strategy development, and
3. Origin and development of the dunes and associated sand deposits

Each component part is separate but related to the other and is being conducted simultaneously. The results of the monitoring and data collection effort are being used for characterization of the dust emission location and activity and to learn about the dynamics of the dune system. This information is used to determine which portion of the dunes needs to be controlled and the level of control required to attain the PM_{10} standards in the local communities. Data from the monitoring sites has also been used to analyze the net direction and magnitude of sand motion and the amount of associated erosion and deposition.

The strategy for control measure implementation in the dunes and the required environmental analysis is being developed with the goal of minimizing the impacts to existing environmental resources. The preferred control strategy is modeled after a natural stable dune field and ultimately consists of the establishment of native vegetation. There have been multiple public workshops and meetings to gather input and concerns from interested residents and local agencies. The input from these meetings has been used to help guide the development of the dust control plan. The District has retained Sapphos Environmental Inc. to conduct the required state (CEQA) and federal (NEPA) environmental analysis on the dust control project.

Approximately seventy-five percent of the 194 acre Keeler Dunes dust control project area is located on federal property administered by the Bureau of Land Management (BLM) with the remaining twenty-five percent owned by the City of Los Angeles and managed by the Los Angeles Department of Water and Power (LADWP) such that both state (CEQA) and federal (NEPA) analyses are needed. A draft of the state Environmental Impact Report (EIR) is scheduled for distribution in December 2012 or early 2013 with the federal analysis to follow at a later date.

The District has been working with the BLM to ensure the dust control strategy incorporates its concerns and needs as much as possible. The District has also attempted to work with the LADWP on the development of the dust control plan as well as on other components of the project. Initially, in 2007 through 2010, the LADWP participated with the District in the Keeler Dunes investigations. However, starting in 2011, the participation from the City in a joint Keeler Dunes project ended and the LADWP began a series of independent investigations and projects in the dunes. Prior to the September 7, 2012 Preliminary Staff Report, the District requested but did not receive information and data on the work that the LADWP is conducting. Therefore, the Preliminary Staff Report only contained results, information and material completed by the District and does not contain information from the LADWP. Although the LADWP provided extensive comments on the District's Preliminary Staff Report (see Appendix 1) they did not include any data or information on the nature of their investigations or their findings. Thus as with the Preliminary Staff Report, the Final Staff report only contains results, information and material completed by the District and does not contain information from the LADWP.

This Final Staff Report focuses on the third element of the project; the origin and development of the Keeler Dunes. While circumstantially associated with the desiccation of Owens Lake, the precise origin of the Keeler Dunes was previously unknown. In order to learn how the landscape of the Keeler Dunes developed over time the District has conducted multiple scientific investigations. Each of these investigations will be reviewed and summarized in the following sections. The supporting reports, data and other materials for these investigations are available as a set of seven technical attachments to this report.

SECTION 3.0 COMPLETED WORK

The District's investigations related to the development and formation of the Keeler Dunes are presented in seven categories ranging in scope from a search of historical records to geologic and geomorphic mapping to several analyses of sand and dune movement over time. A summary of the work and results from each category is presented in Section 4.0. The completed reports, data, maps, photos, and other information associated with each category are available in Attachments A through G to this Final Staff Report.

The seven categories of research are listed below.

1. Historical documents research: reports by Sapphos Environmental, and Dr. Scott Stine **(Section 4.1, Attachment A)**

2. Ground-based photo analysis: comparison of historical and recent views– photos and report by the Great Basin Unified Air Pollution Control District **(Section 4.2, Attachment B)**

3. Aerial photograph and satellite imagery analysis (1944 to 2010): by Dr. Nicholas Lancaster, Desert Research Institute, Reno, Nevada **(Section 4.3, Attachment C)**

4. Geomorphic mapping of the Keeler Dunes and surrounding areas: Final report by Mr. Steve Bacon and Dr. Nicholas Lancaster, Desert Research Institute, Reno, Nevada **(Section 4.4, Attachment D)**.

5. Chronology and stratigraphy of the Keeler Dunes area and an analysis on potential sand sources for the Keeler Dunes: Final reports by Dr. Nicholas Lancaster and Mr. Steve Bacon, Desert Research Institute, Reno, Nevada **(Section 4.5, Attachment E)**

6. Analysis of surface change in the northeast portion of Owens Lake: Revised report by the Great Basin Unified Air Pollution Control District **(Section 4.6, Attachment F)**

7. Dune transect and movement analysis: by Dr. David Groeneveld, HydroBio ARS **(Section 4.7, Attachment G)**

SECTION 4.0 SUMMARY AND DISCUSSION OF RESULTS

Multiple sources of information were searched and studied in order to understand the development of the Keeler Dunes. Initially, the main focus of the research was on the landscape development within the last 100 to 160 years or since the modern anthropogenic desiccation of Owens Lake. However, research efforts were expanded in 2011 to study the pre-historical geologic and geomorphologic development of the terrain. Broadening of the time period of interest allowed for a more complete understanding of the spatial and temporal relationship of the landscape features of the area.

A summary and discussion of the results of each component portion of the associated research is presented in the following sections. For readers interested in learning more about the work that was conducted, a complete compilation of the reports, data and other related materials are available as attachments to this report. It is important to note that due to the nature of some of the materials (e.g. photos, satellite images, maps etc.), the reader is encouraged to view them on a high resolution computer monitor in order to view them with as much detail as possible.

4.1 Historical Documents Research

The eastern portion of the Owens Valley adjacent to Owens Lake was a busy area in the late 1800's and early 1900's. Much of the economy of Inyo County during this time was focused on this area with the presence of lead, zinc, silver, gold, and copper mining in the Inyo Mountains, salt mining on Owens Lake and in Saline Valley, steam boat traffic on Owens Lake, and the presence of the narrow gauge Carson and Colorado Railroad (later becoming the Keeler branch of the Southern Pacific Railroad). The total production of raw materials produced from the Keeler area between 1880 and 1948 has been estimated at $213 million (Sapphos, 2011).

The first non-Native American settlement along the eastern shore of Owens Lake was in the 1860's associated with the discovery of silver at Cerro Gordo and the development of a smelter at Swansea in 1869. Following the 1872 earthquake and an associated tectonic rise of the eastern part of the lake bed, the pier at Swansea was no longer accessible by steamboat and a second wharf and landing were constructed at Hawley. Hawley was renamed as Keeler after Julius M. Keeler who laid out the 42- parcel block plan in 1883 (Sapphos, 2011). The community of Keeler has been inhabited continuously since then and during the heyday of activity in the late 1800's it was reported that 7,500 people lived on the eastern shore of Owens Lake (Sapphos, 2011).

However, as Owens Lake dried with diversion of inflowing waters and local mining decreased the activity and population of the Keeler area declined. This decline was hastened by the end of the Natural Soda Product (NSP) plant operations in 1952 and the abandonment of the Keeler Branch of the Southern Pacific Railroad in 1960. By 1979, Keeler had a reported population of 39 residents (Sapphos, 2011). Today the community of Keeler consists of 66 residents and 40 households (2010 Census data) and no commercial businesses.

During the last 12 years, Keeler has been the base of operations for the dust control projects on the bed of Owens Lake and is the home for field operations for both the District and the LADWP. Although most of the buildings and structures associated with the railroad and mining industries are no longer standing a few remnants of the past are present in the area and attest to the rich cultural history since the 1860's.

The District searched through available historic records looking for information related to the landscape and conditions present within the area occupied by the Keeler Dunes. An initial search was made on the Internet and in published materials (books, newspaper articles, photos etc). A more formal search of a variety of sources was conducted by professional historians from Sapphos Environmental (Sapphos, 2011). The survey notes and plats from the 1850's von Schmidt public lands survey in the Eastern Sierra were researched by Dr. Scott Stine, a noted researcher on Holocene lakes and paleoclimatology in the Great Basin and a Professor Emeritus of Geography at California State University East Bay (Attachment A, Stine, 2012).

The large portion of the document search was focused on finding old photographs of the area so that a visual comparison could be made with the current conditions. For many of the historical photos, District staff went in the field and located the point where the original photo was taken. A new photo was taken at the same location and then compared to the original view. The results and an analysis of these reconstructed photos are presented in Section 4.2 and Attachment B.

Historical Documents

Multiple sources of information were searched in order to understand the development of the Keeler Dunes. The main focus of this research was on the landscape and conditions within the last 100-160 years or the time that included the modern anthropogenic desiccation of Owens Lake. The sources of information included in the research conducted by Sapphos are summarized in their technical memorandum (Attachment A, Sapphos, 2011).

> "The background investigations included a combination of existing literature reviews and original archival research to (a) research the history of the community of Keeler and (b) to trace the development of the Keeler Dunes. Research was conducted in public records and a number of repositories, including the California History Index of the Los Angeles Public Library; the collections of the Inyo County Free Library (August 28, 2011), the Eastern California Museum (August 29, 2011), the Bancroft Library at the University of California at Berkeley (September 6–7, 2011); and the archives of the Automobile Club of Southern California. Archival research included primary sources, such as historical aerial photography at the Benjamin and Gladys Thomas Air Photo Archives maintained by the Department of Geography of the University of California at Los Angeles; historic images; historic newspapers indexed by the ProQuest Newspaper Database; a focused review of the *Inyo Register* and *Inyo Independent*; and ephemera. Secondary sources included general histories; historical resources survey reports; previous research conducted in support of the 2008 Owens Valley PM10 Planning Area Demonstration of Attainment State Implementation Plan (SIP); technical materials relating to federal, state, and local historic preservation; and other materials, as available or appropriate." *(Sapphos, 2011, pg 2)*

During the search by Sapphos (2011) 94 historical documents, including books, maps, reports, articles, and photographs, dating from the 1860s to 2011 were reviewed for information relevant to the Keeler Dunes (Sapphos, 2011). Additionally, the notes and plats from the first official public land survey of the area by von Schmidt in 1855 to 1857 were reviewed for information of the terrain and landscape on the eastern side of Owens Lake (Stine, 2012).

Other published materials that were found and reviewed for information on the dunes include several books on the narrow gauge railroad that ended in Keeler (Table 4.1-1). The railroad was first established in 1883 as part of the Carson and Colorado[3] railroad line that originated in Mound House, Nevada and ended in Keeler, California. It later became part of the Southern Pacific Railway system and was referred to as the "Keeler Branch". The railroad line was a significant component of the area and was operated for 77 years until April 1960 when it was dismantled. A map of the path of the rail road line north of Keeler is shown in Figure 4.1-1 along with the location of the current Keeler Dunes and sand deposit. Notice that the railroad line went through the area where the southern Keeler Dunes are now located.

Table 4.1-1: Published books on the narrow gauge railroad that ended in Keeler.

Author	Date	Title
George Turner	1974, 4th ed.	Slim Rails Through the Sand, The Saga of the Carson and Colorado – Southern Pacific Narrow-Gauge Railroad Through the Desert.
Mallory Hope Ferrell	1982	Southern Pacific Narrow Gauge
Joe Dale Morris	2010	Southern Pacific's Slim Princess in the Sunset, 1940-1960
David F. Myrick	1962	Railroads of Nevada and Eastern California, Volume I: The Northern Roads
David F. Myrick	2007	Railroads of Nevada and Eastern California, Volume III: More on the Northern Roads

---

[3] The Carson and Colorado Railroad was supposed to extend to the south all the way to the Colorado River. The railroad line past Keeler was never built.

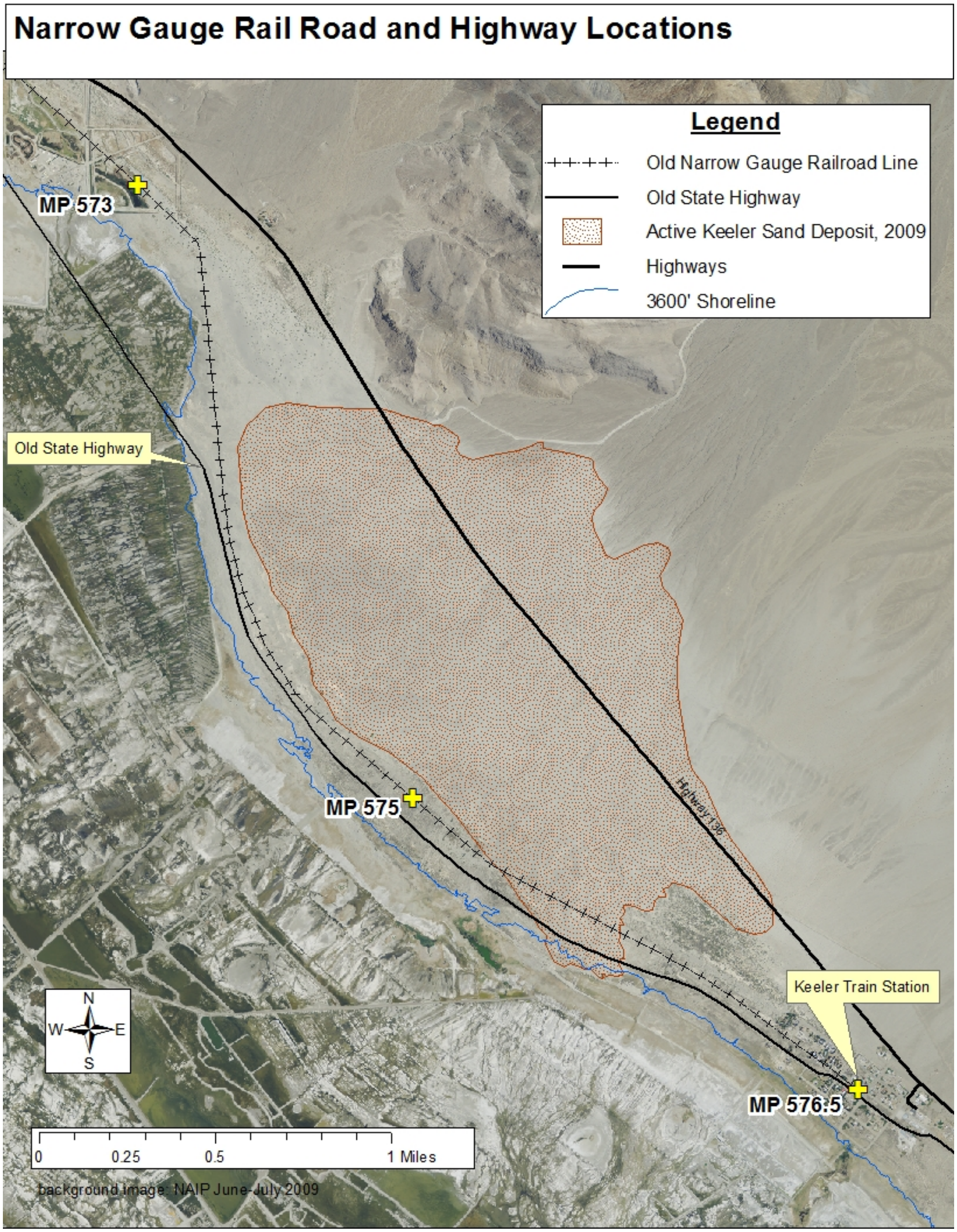


Figure 4.1-1. Map of the southern portion of the Southern Pacific narrow gauge railroad line ending in Keeler at milepost (MP) 576.5. Drifting sand was reported as a problem between mileposts 573 and 575 during the period from 1940 to 1960. The extent of the active Keeler sand deposit is shown as mapped in 2009.

Train timetables from the Southern Pacific Company from September 27, 1931 (Turner, 1974) and April 24, 1932 (Myrick, 2007) provide the narrow gauge train schedules between Mina, Nevada and Keeler, California. On these timetables from the 1930s there is no warning of sand along the route. However, in comparison, the Southern Pacific Timetable 179 from April 25, 1954 for the Keeler Branch[4] between Laws and Keeler specifically warn train operators to "Look out for drifting sand between MP [milepost] 573 and 575" (Morris (2010). Morris (2010) also states that the stretch of track from Dolomite to Keeler that was originally constructed with 35 pound rails was replaced with heavier 62 pound rails due to drifting sand. The Keeler train station is located at milepost 576.5 such that the "blowing sand" warning from 1954 corresponds to the location between Swansea and the northern portion of the Keeler Dunes (Figure 4.1-1). No mention of blowing sand or issues with the train line was found from before the 1940 to 1960 period.

In 1949, the route of State Highway 136[5] (formerly LRN 127) that went from Lone Pine to Keeler was realigned to bypass the community of Keeler (Mettam, 2009). The pre-1949 route from Keeler to Swansea ran parallel to and west of the train tracks on what is now known as the "Old State Highway". The realignment moved the highway to its current location up the Keeler alluvial fan and along the eastern side of Keeler. A second realignment of Highway 136 was conducted in 1954 in the Dolomite area in order to avoid three railroad crossings (Mettam, 2009) creating what is known as the "Dolomite Loop". The reason for the first realignment is uncertain but may have been to move the highway off of the soft lake bed soils and closer to Swansea.

Von Schmidt 1855-1857 Land Survey

The oldest documented records of the land in the Owens Lake area are those completed by Alexis W. von Schmidt who surveyed and mapped the region 1855-1857 under contract to the United States Land Office. The land survey consisted of laying out township and section lines, establishing corner markers, noting the character of the terrain and quality of the soil, and recording the work accomplished on plat sheets and in accompanying notes. Since the surveyors worked their way around each section (1 square mile) of land, the plats and notes provide useful information on the distribution and nature of the terrain. (Stine, 2012)

Stine (2012) researched the von Schmidt plats and notes from the 1855 to 1857 land surveys in the Mono Lake and Owens Lake areas to find information on the topography and geomorphology of the shoreline areas specifically focusing on areas where prominent dune

---

[4] The narrow gauge line from Mina to Laws was abandoned in 1943 leaving only the Keeler Branch from Laws to Keeler.

[5] Note: In 1933, the route from Lone Pine through Keeler was defined as LRN 127 (LRN stands for Legislative Route Number) that was used prior to 1964. In 1964 state routes were renumbered and the highway was designated as State Route 136. (http://en.wikipedia.org/wiki/California_State_Route_136 and http://en.wikipedia.org/wiki/California_State_Route_136)

fields (such as the Olancha and Keeler Dunes) are currently located. The lands of the Mono Basin were included in the analysis because of the demonstrably old (pre-1850's) sand dunes that exist there. Von Schmidt surveyed these dune areas in 1856, and his topographic characterization serves as a "calibration" on his descriptions of the Owens shorelands.

The public lands survey by von Schmidt followed a strict protocol that defined how the survey was conducted and the information that was recorded. The survey extended the Public Lands Survey System (PLSS)[6] into the region and documented and described the character of each township, range and section line. The character of the land was rated based on agricultural suitability and topography. Terms used to describe the topography include: "level", "rolling", "hilly", "hilly and broken", "steep and broken" etc. The term "level" was not used to describe lands that were flat or had no topographic relief but rather to describe a surface that had little micro-topography (i.e. little deposition on or dissection into it). From information gathered while researching the Mono Lake work (Stine, 2012) it is apparent that von Schmidt generally used the term "rolling" to describe a surface with dunes and also to describe a land that was gently undulating and that the term "level" was generally NOT used to characterize section lines that ran through or close to dunes that were known to have existed in the 1850's.

Figure 4.1-2 shows the land characterization from the von Schmidt land survey in the northern portion of the Owens Lake area in 1856. Section lines that were characterized as "level" are portrayed with a straight line and those characterized as "rolling" are shown with a dotted line. Careful study of the survey record indicates that Von Schmidt did not encounter the "rolling" topography at the present-day Keeler Dunes. Instead the section lines that extend through the present-day dune area are characterized as "level". The only sections lines characterized as "rolling" are located through the Owens River valley, west of Dolomite, along a portion of the northeastern historic shoreline, and along the eastern side of the Keeler alluvial fan. Interestingly, the section line between Sections 14 and 23 (T16S, R37E) along the northeastern shoreline of the historic lake bed (which is indicated as rolling) crosses an area that currently has a stable vegetated dune field that is thought to have developed along the historic shore of Owens Lake prior to lake desiccation. It is this type of dune field that the District is using as a model for stabilization of the emissive Keeler Dunes.

---

[6] PLSS is a way of subdividing and describing public lands and consists of six-mile block units (Townships) from a principle baseline and meridian. Each Township is subdivided into 36 Sections, each one mile on a side.

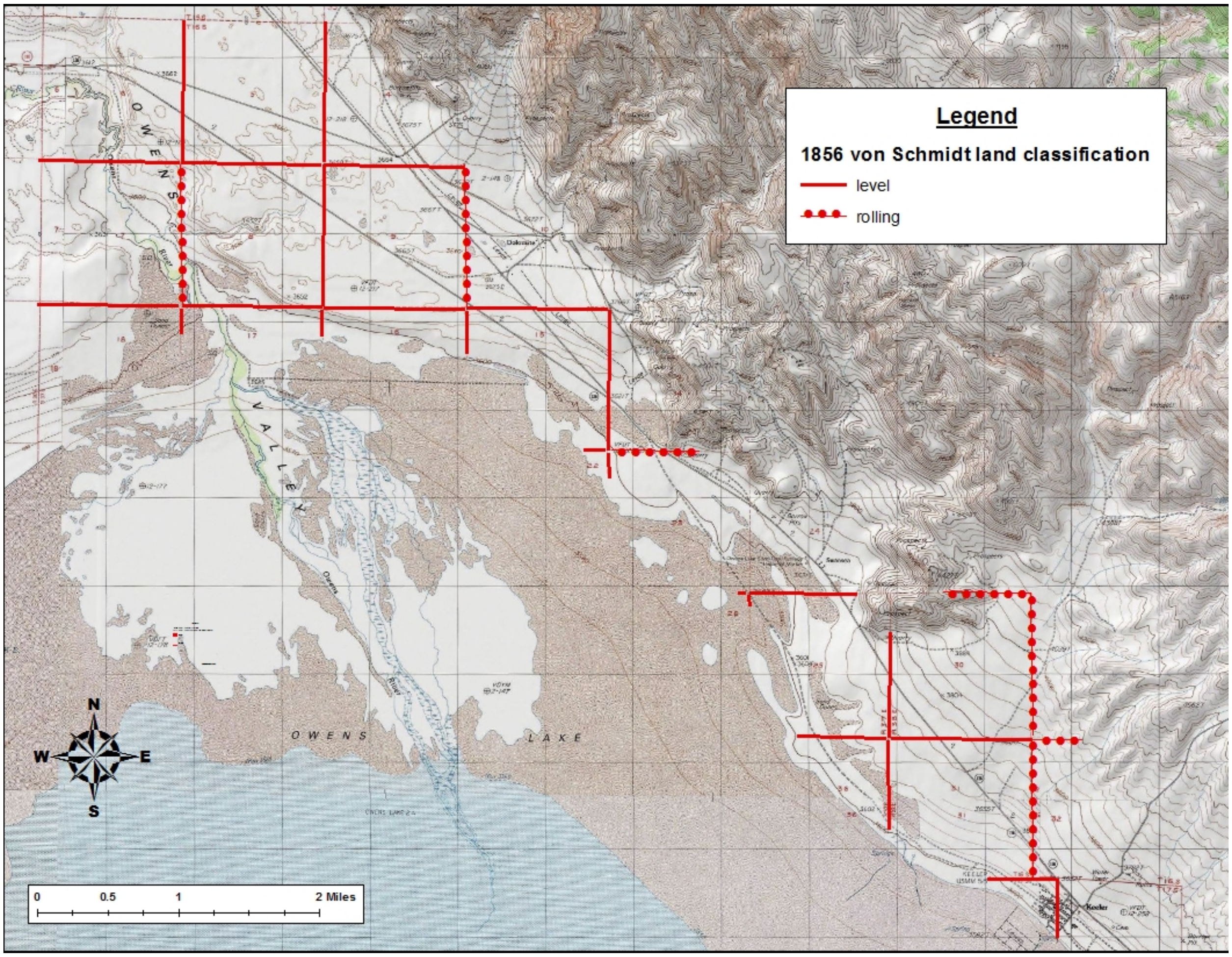


Figure 4.1-2. Topographic map of northern Owens Lake showing the land classification information from the 1856 public land survey by von Schmidt (Stine, 2012). Topographic base map layer is from ESRI 2012.

Other Historical Maps and Information

Early area maps typically reference only geographical features and do not include information regarding local environmental conditions. Several maps identified the Keeler area as lake beds and alluvial deposits. A geologic map based upon a 1912 field survey (Knopf, 1914 and 1918) depicted the Keeler area as a series of "lake beds" and "alluvial cones". The 1918 map noted the presence of soil, silt, and wind-blown sand near Independence which suggests that the field surveyors would have reported similar conditions had they existed in the Keeler area. The Keeler area was again labeled as "lake beds" in a 1954 California State Department of Natural resources publication and no dunes were identified. (Sapphos, 2011)

In comments made on the Preliminary Staff Report, the LADWP provided information from a report by Elliott (1904) on the "Catalogue of Mammals Collected by E. Heller in Southern California" that the District did not find in its search for historical documents. This report presents the survey results of Heller's 1902 trip through the Colorado and Mojave deserts and

Death Valley. Part of Heller's trip included the southern portion of the Owens Valley including the eastern side of Owens Lake. Although the Elliott (1904) report focuses on a description of the mammals found during the survey and not the overall geography, there is useful information presented on the nature of the terrain in the description of the habitats. Within this report there are four relevant references to the mammals and terrain around Owens Lake and Keeler (Elliott, 1904, pages 281, 289, 302 and 307). In these citations Elliot describes the presence of small mammals in the vegetated sand dunes and in particular states that the pocket mouse "was *found among the sand dunes at the edge of the lake, to which it appeared to be restricted.*" (Elliott, 1904, page 307). The descriptions found in Elliott (1904) fit with the information gathered from other studies and show that there were vegetated sand dunes along the historic shore of Owens Lake. As discussed in more detail in Section 4.3 and Technical Attachment C (Lancaster, 2012a) and Lancaster and Holder (2012), these vegetated shoreline dunes are separate and distinct from the dust producing active spreading and migrating dunes found in the Keeler Dune deposit.

Summary of Historical Documents Research

All of the historical materials were reviewed for information regarding the origin or historical presence of the Keeler Dunes. None of the located historical materials specifically referenced the name "Keeler Dunes" prior to 1987. Even though the history of Keeler and the surrounding areas is extensively documented in the historical record; there is no historical indication regarding the specific existence of the Keeler Dunes until the 1980's and railroad warnings appear to indicate that there were sand movement problems on the tracks in the vicinity of the Keeler Dunes in the 1940 to 1960 time period. These along with the results of research on the 1856 von Schmidt public lands survey and a mammalian survey in 1902 appear to indicate that, although there were vegetated dunes along the historic shoreline, the active and emissive Keeler Dunes are a new feature in the landscape of the area and were not present prior to the modern desiccation of Owens Lake.

4.2 Ground-Based Photo Analysis: Comparison of Historical and Recent Views

During the search for historical documents and records of the Keeler area twenty-two historic photos were found that show noteworthy views of various portions of the local landscape. These photos document the nature of the landscape at different times in the historic past and thus are important visual evidence to show the nature of the changes in the terrain over time. These photos were recreated in 2012 by finding the location of the original photograph and taking another photograph with the same view. Prior to discussing the results of that work, a brief overview of the basic concept and methodology behind rephotography is provided. Additional information is provided in Attachment B (Grimm, 2012).

Basic Concepts

A review of the history of photography shows that it is a medium of changing technology. But the basics of photography have not changed over the 150 plus years since camera systems were first introduced. Photography, in essence, is a form of visual communication that utilizes technology to capture and record light at a point in time.

The process of photography is based on the science of optics, and the laws of physics and chemistry. And as such there is a fundamental principle of photography that remains constant no matter the technology: objects reflect light that is focused by a lens onto some sort of light sensitive material where the light is recorded at a specific moment in time. This constant principle that is utilized by different technologies to capture light and communicate visual information enables comparisons to be made between photographs made at different times or by different technologies. A photograph becomes a record of visual information at a specific point in time of light reflecting from objects of a particular view taken from a specific vantage point. This remains true no matter what technology is used to make the photograph. The visual information remains the same even if the manner in which it is represented changes. This is how it is possible to compare black and white photographs to color, or how it is possible to compare a photograph made from a negative with a primitive pin hole camera to one made with a more contemporary digital camera.

Rephotography and Methodology for Documenting Landscape Change

Rephotography (also called repeat photography) is the process of making a rephotograph (also called a repeat photograph) of a view from a previously taken photograph. It is the process of a current photographer reoccupying the same place of a previous photographer, framing to match the same view, and taking a photograph. The result is two photographs representing the same visual information of a view from two different points in time. The two photographs are on different ends of the interval of time that is between them. And when placed side by side, it invites examination and evaluation of the relationships of objects within the view, it invites questions of what is present, and what is absent, and what has changed. Rephotography is a technique that has an incredible ability to illustrate and document change (Klett, 2010).

Rephotography has been used by researchers across a wide variety of disciplines and applications ranging from art to science. And one of its consistent and successful uses in the natural sciences has been to illustrate and document landscape change (Web et. al., 2010). The technique of rephotography can effectively evaluate and document landscape change and has been employed as such since it was first used to do so in the late 1800's by glaciologists as a method to monitor glaciers. There are numerous contemporary examples (Web et al., 2010) that show the utility of and just how rephotography is invaluable in documenting and evaluating all types of landscape change ranging from subtle to prominent. And even though it has expanded to become a prominent method in documenting numerous types of landscape change, rephotography still relies on the same basic method.

The general methodology of rephotography is simple and relies on the fundamental principle of photography (discussed in Grimm, 2012) and the concept that every vantage point is unique. The general method has the following ordered steps: research for historic photographs, identify and relocate the unique vantage point of the historic photograph, place a camera at that point, match and repeat the original view, and take a rephotograph. The degree of precision of the rephotograph to accurately repeat the historic photograph is directly related to ability to locate and reoccupy the unique historic vantage point.

The innate ability of the photograph to capture visual information at a specific moment in time offers a valuable and unique tool to examine changes in conditions of the landscape. A photograph and a replicate re-photograph of the same view at a later point in time represents and documents changes in the landscape of that view. The original photograph and its re-photograph bring the past and present into a dynamic juxtaposition that enables comparison and analysis of conditions of the landscape within the view and any change that has occurred.

Even though rephotography can illustrate and document change during a passage of time, it cannot in and of itself explain what caused the change. The interpretation of the change may require additional information external to the photographs themselves. Additional information from outside sources such as history references or other relevant research studies may be needed to give context to the change.

District's Rephotographic Survey

The re-photographic survey was completed by Sondra Grimm, a District staff member who is intimately familiar with the Keeler Dunes and the surrounding area due to the many years of working in the dunes and on the lake bed. A report on the photographic work and the methodology of conducting rephotographic surveys of historical photographs is provided in Attachment B (Grimm, 2012).

Most of the photos that were found in search of historical documents (see Section 4.1 and Attachment A) are focused on the community of Keeler, especially in relationship to the narrow gauge railroad or to the mining at Cerro Gordo. The most commonly found photos were of buildings and structures or of railroad steam engines. While extremely interesting from a historical prospective, by-in-large these photos were not useful in an evaluation of the development of the Keeler Dunes. However, out of the many photos that were reviewed in the historical documents search, twenty-two were found that show the area of or a portion of the area where the Keeler Dunes are currently located.

Eighteen of the twenty-two historic photographs were ground based and four were oblique aerial photographs. The historic photographs range in time from circa 1912 to 2007. A map of the historic photos locations and re-photos is given in Figures 4.2-1 and 4.2-2. The historical ground photographs were taken from sixteen different locations: one from the north end of Keeler, nine from around the old railroad engine terminal in Keeler, two from the bed of Owens Lake, three from the roadside of the current State Highway 136, and one near the old location of the State Highway from Lone Pine to Keeler. The historical oblique aerial photographs were taken from three general locations: one from approximately 40,000 on elevation feet over the Sierra Nevada, two over Keeler, and one from about 10,000 in elevation feet over the Inyo Mountains.

Fortunately, due to the presence of distinctive natural landmarks (mostly mountain crests and ridges and, in some cases, distinctive buildings), many these photos could be recreated to show the current view. These recreations provide compelling visual evidence of the dramatic changes in the terrain over the past 100 years. The oblique aerial photographs taken from an aircraft were not recreated from exactly the same vantage. Even so, these photos still provide important information on the terrain in the area.

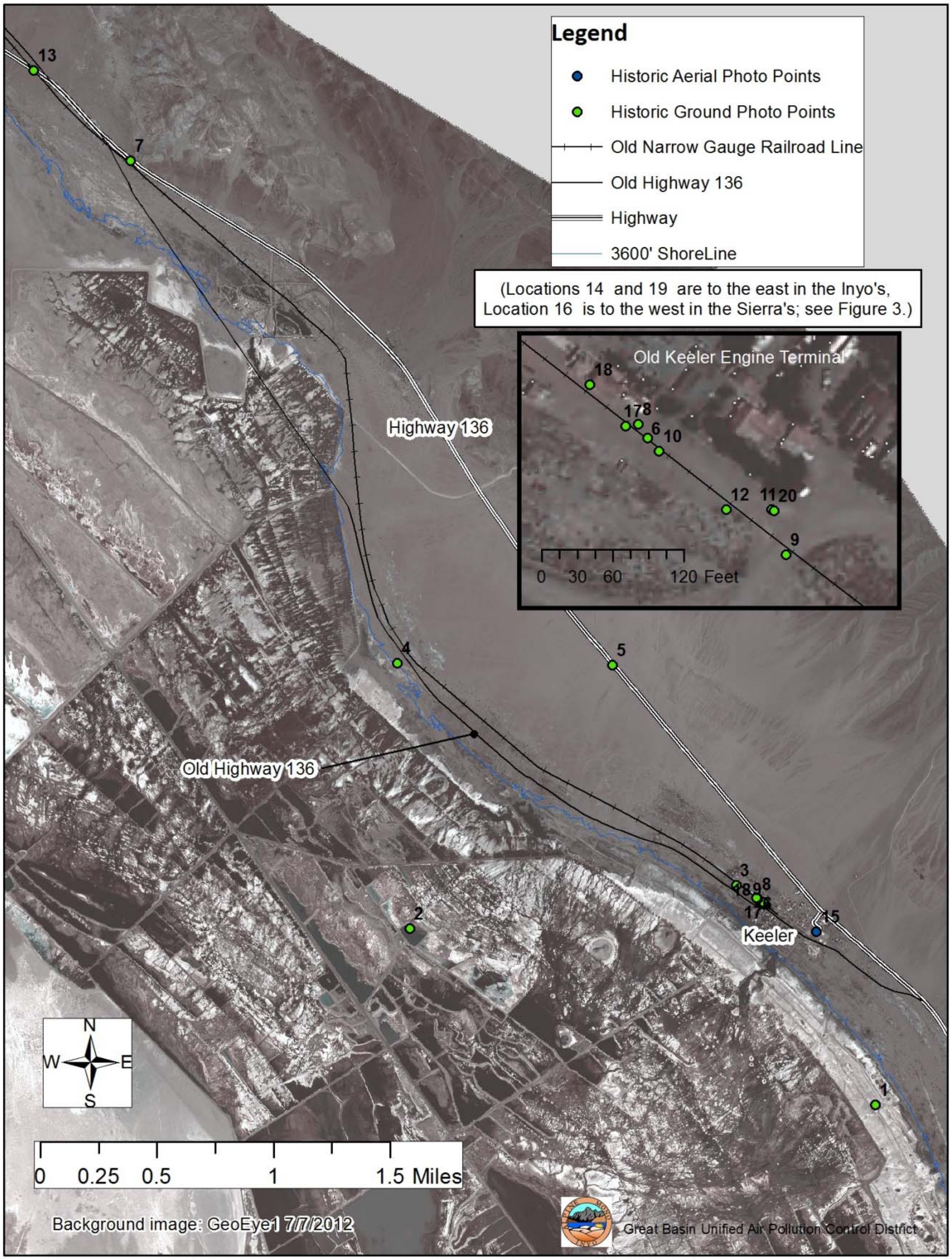


Figure 4.2-1: Map showing the locations of historic photos and re-photos used in the ground-based photos analysis. (from Grimm, 2012)

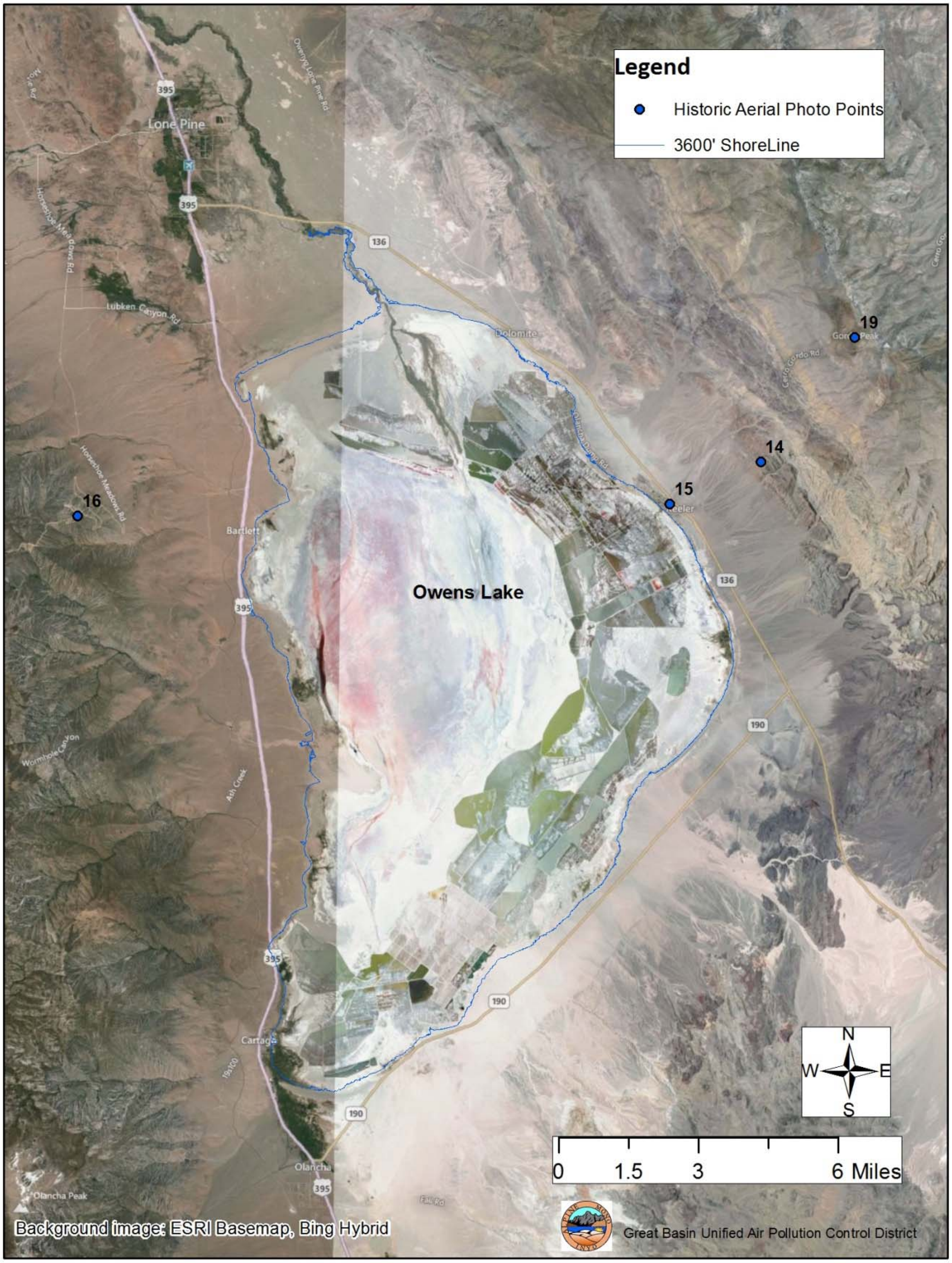


Figure 4.2-2: Map showing the locations of aerial oblique current rephotos used in the ground-based photos analysis. (from Grimm, 2012)

Great care was taken to determine the exact location of each historical photograph and every effort was made to replicate the historical photograph as accurately as possible. Special attention was given to recognized points of reference and their relative alignment, the vantage point and view, the camera lens, camera height, and to a lesser degree the time of day. It should be noted that the original vantage point of the historical photograph, may have drastically changed or even disappeared over time or was impossible to match. In this case, a new vantage point was chosen that best replicated the original historical view. For example, if the original vantage point was from atop a historical structure (from atop a train or tram tower) that is no longer present, then a new vantage point was chosen (from atop the cab of a truck or on top of a roof) that best duplicated the view from that vantage point.

The relevant visual information of each historical photograph and its re-photograph was examined and then compared. A summary table of the photos used in the analysis is provided in Table 4.2-1. A detailed description of the historic and recent photos is provided in Attachment B.

The historic photos used in the Grimm (2012) analysis range in age from circa 1912 (or early 1900's) to 2007 or approximately a 95 year period. As shown on Figure 4.2-1, most of the photo locations are from multiple vantage points that surround the position of the current Keeler Dunes. Other photo locations were taken at high elevation over the Sierra Nevada and Inyo Mountains or from tall structures in Keeler. Of the twenty-two historic photos included in the Grimm (2012) analysis, three are provided in this Final Staff report to illustrate the change in the landscape of the Keeler Dune area over time. These photos range in age from circa 1920 to 1953.

The oldest example, presented here in the Final Staff Report, is from pre-1920 from salt mining facilities that occurred along the historic shoreline of Owens Lake north of Keeler. The second example uses a photo taken of a narrow gauge steam engine from 1940. In this 1940 photograph, while the engine is prominent, the important portion of the photograph is the background behind the train showing the condition of the existing landscape. The third and last example is from1953 and shows a broad portion of the Keeler Fan terrain where the middle and southern portions of the Keeler Dunes are now located.

The historic photos and their 2012 re-photographs are provided electronically in Attachment B. The reader is strongly encouraged to examine and compare these images to determine the changes in the visible landscape over historic times. The digital copies the historic photographs and current rephotographs are provided only for the purpose of examination and comparison. To use them in any other way, written or otherwise, permission must be obtained from the appropriate source.

Table 4.2-1. Summary of historic photos and re-photos. Table is presented chronologically by the date of the historic photograph. (see Attachment B, Grimm (2012) for more a more detailed summary)

Photo Number	File Name	Historic Photo Date	Rephoto Date	Historic Photographer	Source	Source Reference	Location Description Photo Point
1	1_NatSoda_c1912	c. 1912 or c. early 1900s	8/9/2012	unknown	Eastern California Museum	http://www.virtualtransportationmuseum.com/gallery2/v/mining/nonmetalic/owenslake/RAM-2951.jpg.html	Located at IDC Lower works; on berm west of tracks; Keeler to ~SW.
2	2_IDC_pre1920	pre1920	8/14/2012	unknown	Eastern California Museum	Sapphos (2011)	View to NE toward IDC. Rephoto from atop the old pipeline monument.
2	2a_IDC_pre1920	pre1920	8/14/2012	unknown	Eastern California Museum	Sapphos (2011)	View to NE toward IDC. Rephoto from atop the old pipeline monument.
14	14_KeelerAerial_1936	1936	10/30/2012	G.M. Best photograph, R.C. Datin collection	R. C. Datin collection	Myrick, D. F. (2007)	Low oblique aerial with north view of Keeler and surrounding area
3	3_FlorenceCC22_1940	1940	8/15/2012	Frank J. Peterson	see Source Reference	Ferrell (1982)	North end Keeler, from porch or platform. Rephoto is from a small step ladder.
4	4_SandFence_c1948	c. 1948	8/24/2012	Ansel Adams	The Metropolitan Museum of Art	http://www.metmuseum.org/collections/search-the-collections/190014308	Along old sand fence parallel to Old St Hwy.
15	15_KlrHiView_1949	1949	10/18/2012	unknown	Pacific Railway Journey	Myrick, D. F. (1992)	From atop Cerro Gordo Aerial Tramway terminal, 3rd story
16	16_OLaerialNW_1951	1951	10/18/2012	Robert F. Symons	Pat Symons Rowbottom	Personal communication with Pat Symons Rowbottom.	From P-38 at 40,000'
5	5_No18toKeeler_031953	3/1953	7/3/2012	unknown	Eastern California Museum	Eastern California Museum, Independence, CA	South of DWP marker on current Highway 136.
5	5a_Nearing Keeler_031953	3/1953	7/3/2012	unknown	Eastern California Museum	Eastern California Museum, Independence, CA	South of DWP marker on current Highway 136.
6	6_RollingEtoKlr_051955	5/1955	8/24/2012	unknown	see Source Reference	Morris (2010) page 29	Old Keeler engine terminal.
7	7_BtwnKlr&Own_07061956	7/6/1956	8/7/2012	Harold F. Stewart	Courtesy of Stan Kistler	Morris (2010) page 185	Roadside current Highway 136, near spring by Tramway.
8	8_KlrJulySun_07291959	7/29/1959	8/24/2012	Harold F. Stewart	Courtesy of Stan Kistler	Morris (2010) page 231	Old Keeler engine terminal.
9	9_KlrEngineTerm_08251959	8/25/1959	8/15/2012	John B. West	John B. West	ALifeChasingTrains: http://lifewastedchasingtrains.com/main.php	Keeler Train station, from train top vantage. Rephoto is from atop a truck cab.
10	10_KlrEngineTerm_early1960	early 1960	8/24/2012	Robert A. Bader	Robert A. Bader Collection	Morris (2010) page 315 (middle black and white photo).	Old Keeler engine terminal.

Table 4.2-1. Continued

20	20_KlrEngineTerm_early1960	1960	10/1/2012	Rictor Swing	Photo restored by Rick Blanchard	Historic photo digital copy from photographer.	Old Keeler engine terminal.
11	11_KlrEngineTerm_1960_61	1960-61	8/24/2012	Robert A. Bader	Robert A. Bader Collection	Morris (2010) page 316 (lower left color photo).	Old Keeler engine terminal.
12	12_KlrEngineTerm_1960_61	1960-61	8/24/2012	Robert A. Bader	Robert A. Bader Collection	Morris (2010) page 315 (bottom black and white photo).	Old Keeler engine terminal.
17	17_KlrEnginTerm_061998	6/1998	10/1/2012	Orin Palmer	Rick Blanchard	High resolution photo scan directly from photographer.	Old Keeler engine terminal.
18	18_KlrEnginTerm_061998	6/1998	10/1/2012	Orin Palmer	Rick Blanchard	High resolution photo scan directly from photographer.	Old Keeler engine terminal.
19	19_OLaerialNE_04151998	4/15/1998	10/2/2012	Jim Wark	Airphoto-Jim Wark	High resolution photo scan directly from photographer.	Aerial from 10,000 feet including northwest Owens Lake.
13	13_RRcrossHwy136_052007	5/2007	8/7/2012	Joe Dale Morris	see Source Reference	Morris(2010) page 328.	Railroad intersection of current Highway 136.

Example 1: Historic Photo/Recreation of the Inyo Development Company Area (Figure 4.2-3):

The first example is a view from the bed of Owens Lake prior to 1920 looking toward the east-northeast along what is termed the “old wooden pipeline” (Figure 4.2-3). This pipeline structure was part of the facilities associated with the Inyo Development Company (IDC) for salt mining and processing. The photograph was taken from atop a concrete monument along the pipeline. Although the pipeline was removed in 2005-2006, the concrete monument was preserved such that the same vantage point was used for the recreated photographic view.

In the historic photograph (Figure 4.2-3A) the IDCs buildings and structures can clearly be seen at the shore of the lake in the center of the photograph. Above and beyond these facilities and shoreline is the Keeler Fan extending to the base of the Inyo Mountains. Although there are a few small minor dunes present along the historic shoreline, there are no dunes or open sand deposits visible on the Keeler Fan above the historic shoreline, instead, the fan is well vegetated.

In the recreation of the historic photo view (Figure 4.2-3B, taken on August 14, 2012) the vegetated band in the center of the photo marks the location of the historic shoreline behind which the active and emissive sand dunes and sand sheet deposits are clearly visible.

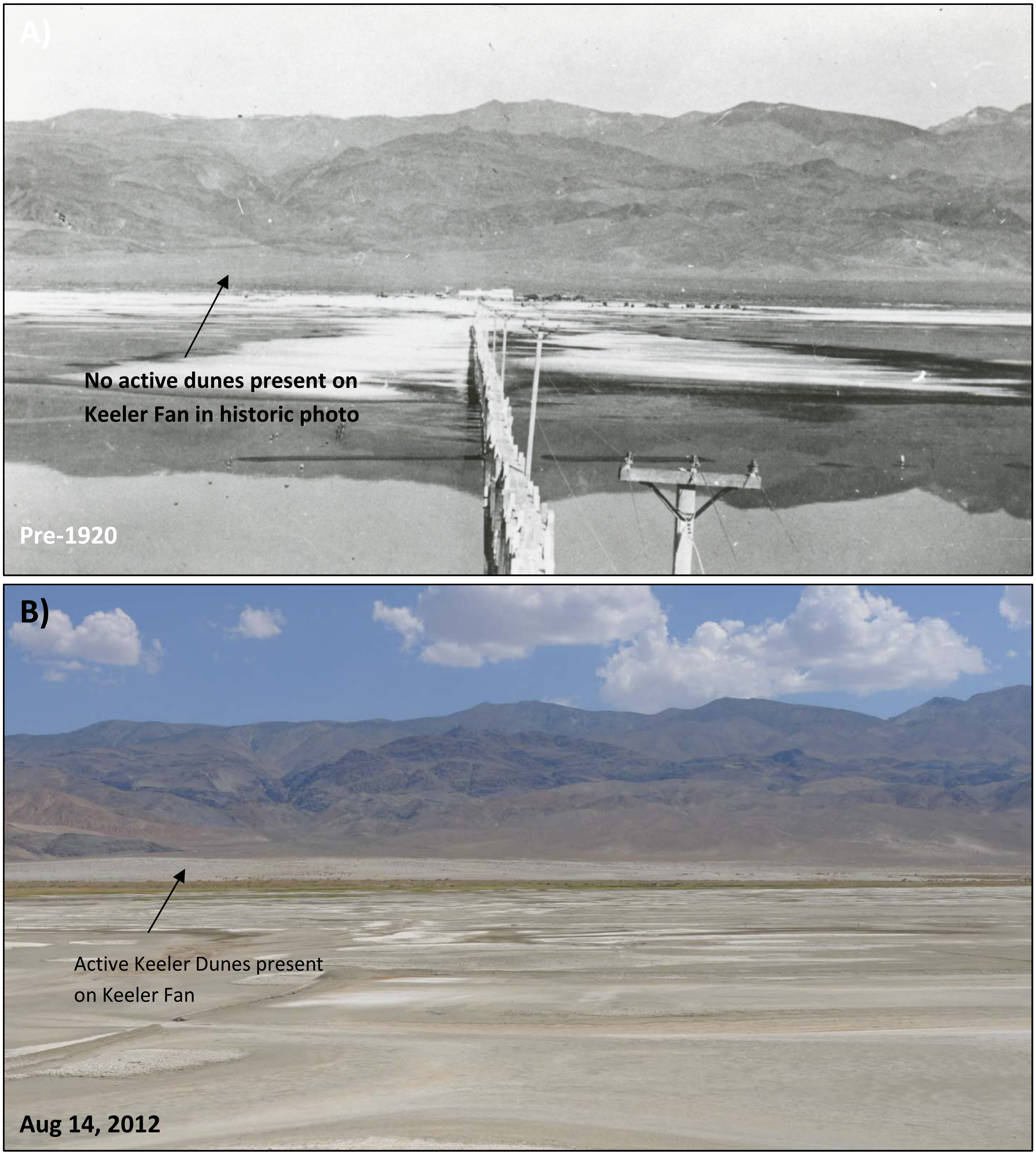


Figure 4.2-3: Historic photograph of the Inyo Development Company (IDC) facilities looking eastward from the lake bed: **A)** Historic photo from pre-1920 (ECM, 2011) and **B)** August 2012 photo (Grimm, 2012). Notice that in the historic photo, the Keeler Fan and area the area just northwest of Keeler (far right center of photos) do not have active dune and sand deposits of the Keeler Dunes as seen in the August 2012 photograph.

Example 2: Historic Photo/Recreation from the North End of Keeler (Figure 4.2-4): The second example consists of two photos taken from the north end of the community of Keeler with a view to the northwest toward the Keeler Fan. In the historic photo (Figure 4.2-4A) taken in 1940 by Frank Peterson (Ferrell, 1982), possibly from a porch or platform, there is no evidence of active aeolian sands on the Keeler Fan visible behind the engine in the background. The historic photo view was recreated by District staff on August 15, 2012 (Figure 4.2-4B) from a small step ladder. In this re-photo, sand can be seen on right (east) side of train, in the foreground and in the background up on the Keeler fan. The large unvegetated southern Keeler Dunes are prominent to the left (west) and back of where the train is present in historic view (Figure 4.2-4A).

In the search for historic photos of the area, there were many photographs found of the train engines and facilities in and around Keeler. Since Keeler was the last station on the railroad line many of the train activities were centered there. Twelve of the photos used in the Grimm (2012) analysis were from the community of Keeler with nine taken from around the old engine terminal. These photos span from 1940 to 1998, a fifty-eight year period. The one presented here in Example 2 was the oldest of these, taken in 1940. All of the subsequent photos taken from the engine terminal looking toward the northwest provide similar information and show that the current active Keeler Dunes were not present and visible from Keeler a late as 1998. All of the photos from Keeler are provided in Attachment B.

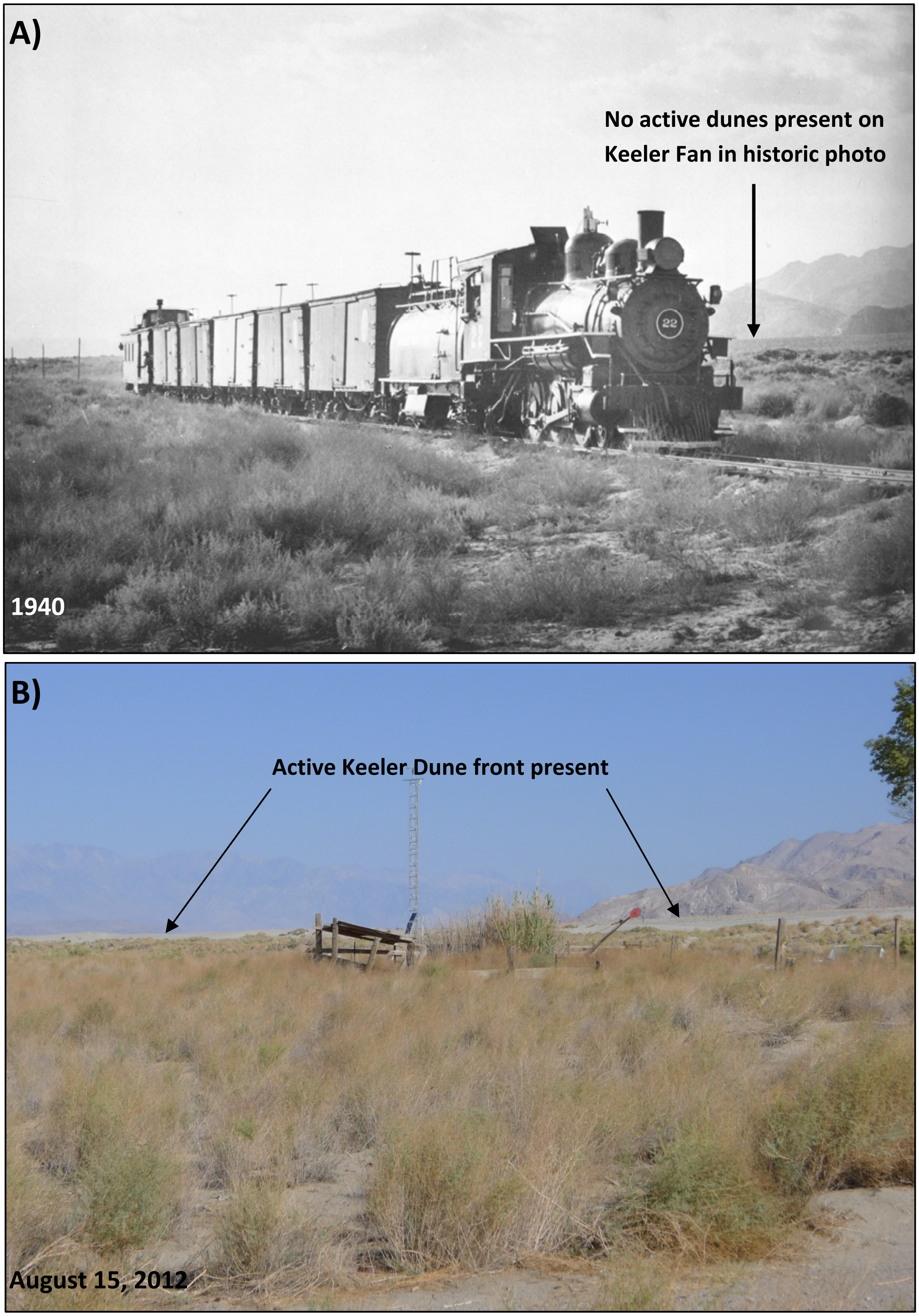


Figure 4.2-4: View from the north end of Keeler with a view to the northwest: **A)** Historic photo from 1940 (by Frank J. Peterson (Ferrell, 1982)) and **B)** August 15, 2012 photo (Grimm, 2012). Notice that in the historic photo, the Keeler Fan does not have active dune and sand deposits of the Keeler Dunes as seen in the August 2012 photograph.

Example 3: Historic Photo/Recreation from State Highway 136 (Figures 4.2-5 and 4.2-6): The third example consists of photos taken from State Highway 136 with a view to the southwest across the lower portions of the Keeler Fan and the Owens Lake playa. There are two original historic photos from 1953 (Eastern California Museum, ECM) that form a panorama when put together. Both of the historic photo views were retaken on July 3, 2012 by District staff (Grimm, 2012).

In Figure 4.2-5, one of the individual views is presented with the historic and recent photo pairs. Figure 4.2-6 presents the panorama of both photos views. The panorama view shows a broader portion of the landscape and enables a more complete evaluation of the changes on the southern portion of the Keeler Fan since 1953.

In the 1953 historic photos (Figure 4.2-5A and 4.2-6A) there are small amounts of sands deposited around rock and small shrubs visible on the fan in the foreground. Additionally, a set of vegetated shoreline dunes are visible just behind the train along the historic shoreline. In the re-photo taken on July 3, 2012 (Figure 4.2-5B and 4.2-6B) the alluvial fan is almost completely covered by active aeolian sand deposits of the Keeler Dunes and there is noticeably less vegetation than in the 1953 photograph.

Figure 4.2-5: View from the State Highway 136 toward the southwest across the Keeler Fan and Owens Lake playa: **A)** Historic photo from 1953 (ECM) and **B)** July 3, 2012 photo (Grimm, 2012). Notice that in the 1953 photo, the Keeler Fan has only small amounts of sand deposited around shrubs and rocks on the fan surface. Active sands and sparse vegetation mark the August 2012 re-photo.

Figure 4.2-6: Panorama of same view as shown in Figure 4.2-5. The historic panorama **(A)** was made from two photos in March 1953 (ECM) from State Highway 136 toward the southwest across the Keeler Fan and Owens Lake playa: Panorama **(B)** was made from two similar photos taken on July 3, 2012 (Grimm, 2012). The Keeler Fan in 1953 has only small amounts of sand deposited around shrubs and rocks on the fan surface while there is an extensive active sand sheet and dunes present in the August 2012 re-photo.

Discussion

The majority (16 out of the 18)[7] of the historical photographs show no or little evidence of the presence of active aeolian sand or recognizable dune features while their re-photographs show clear evidence of the presence of sand and larger dune features. The historical photographs also show the presence of vegetation while their re-photographs, for the most part, show the same area to have less or no vegetation. In short, the photographic evidence indicates that the Keeler Dunes developed later than the historic photos. There is no visual evidence of the Keeler Dunes in the early 1900's to 1961 in the documented photo views. The exact time of development is not shown from any of the photographs, but it can be speculated to be after 1960, at least for the southern Keeler Dunes.

Two of the historical photographs do show the presence of sand and dune features: The circa 1948 Ansel Adams photograph shows the presence of deep sand in the sand fence that ran parallel to the old Highway 136 and the historic shoreline adjacent to the northern portion of the current Keeler Dunes (see Attachment B, photos: 4_SandFence_c1948.jpg and 4_SandFence_08242012.jpg). This area is virtually unvegetated in the 1948 photo except for small shrubs in the edge of the shoreline dunes or sand deposits on old evaporation pond berms. The re-photograph clearly shows that the deep sand along the remains of the sand fence is gone and the area is now vegetated. The comparison is consistent with observations (Lancaster, 2012) that this area had significant sand deposition in the 1940's that has subsequently eroded.

The re-photographic survey is presented in Attachment B in a format that best depicts the comparison of the visual evidence in each photograph. It is important to keep in mind that a close scrutiny was made of the photographs while examining their enlargements on a high resolution monitor. The photographs presented in Figures 4.2-3 to 4.2-6 are intended to be a summary only and are limited by the resolution and size required for their presentation here. It is strongly suggested that a review of the digital photographs be viewed on a high resolution monitor so specific features and conditions of the landscape can be examined and compared under enlargement.

---

[7] Of the two other historical photos included in Grimm (2012), one was taken in 2007 (only five years ago and well after the documented development and expansion of the Keeler Dunes) and the other was taken in 1948 along the northwestern portion of the Keeler Dune deposit from a location that is shown from air photos to have been covered in aeolian sands from the bed of Owens Lake (Lancaster, 2012).

4.3 Aerial Photograph and Satellite Imagery Analysis (1944 to 2010)

Air photos and satellite imagery provide a “snapshot” in time of the conditions present when the picture or image was acquired. As such they can be extremely useful in identification of the landforms present at the time of acquisition. The work discussed in this section of the Final Staff Report is the result of an analysis of photos and images over a 66-year period extending from 1944 to 2010. The beginning of this analysis from 1944 is 31 years after the beginning of operations of the Los Angeles Aqueduct (LAA) and approximately 20 years following the desiccation of Owens Lake to its current extent of the brine pool. The research and analysis was conducted by Dr. Nicholas Lancaster of the Desert Research Institute (DRI) (Lancaster, 2012). A summary of the results are presented here. The complete report by Lancaster (2012) and full resolution movie animations of the dune extent are available in Attachment C. Additionally, a report on the work is also available in a recent paper by Lancaster and Holder (2012).

The primary methodology used in this study was the comparison of identified dune and sand sheet positions and extents on aerial photographs and satellite images acquired at different dates. High-resolution scanned versions of the aerial photographs were used wherever possible until the advent of high-resolution digital satellite images in the late 1990’s. The aerial photographs were rectified and georeferenced to common geographic reference points before incorporation in a geographic information system (GIS). Dune and sand sheet extents, and major dune ridges were then identified and digitized from the images, and their dimensions measured using ARC-GIS. Table 4.3-1 gives the dates of the aerial photographs and satellite images used, together with an assessment of their image quality. (Lancaster, 2012).

Table 4.3-1: Aerial photographs and satellite images used in the Lancaster (2012) study.

Year	Agency/Source	Date	Image Quality
1944	LADWP	13-Oct-44	Excellent
1947	USGS	1-Aug-47	Very Good
1954	Army Map Service	3-Jul-54	Poor
1968	LADWP	19-Jul-68	Excellent
1970	Corona	17-Mar-70	Very Good
1975	BLM	3-Dec-75	Very Good
1982	USGS-HAP	24-May-82	Poor
1986	NHAP84	30-Aug-86	Good
1993	NAPP	23-Sep-93	Moderate
1998	NAPP	23-Aug-98	Moderate
2000	GBUAPCD	9-Sep-00	Excellent
2002	NAPP	8-Jun-02	Very Good
2004	Spencer Gross	7-Mar-04	Good
2006	Ikonos	1-Jun-06	Excellent
a2008	Ikonos	26-Apr-08	Excellent
2010	GeoEye	3-May-10	Excellent

There were 16 separate photo and image dates used in this study. An effort was made to distribute the photo and image dates as evenly as possible throughout the period of interest. Overall the analysis dates vary from 2 to 7 years apart except for the period from 1954 to 1968, a 14-year period, in which no photos were found. The oldest air photos found during the search for this portion of the project were taken by Fairchild Aerial Surveys for the Los Angeles Department of Water and Power in October 1944. The most recent date is from a high-resolution satellite image from May 2010.

It is important to bear in mind in the evaluation of the photographs and imagery that each photo used in the analysis represents an instantaneous snapshot of the area. The record used in this work is considered to provide a robust set of information for the overall developmental history of the dunes. However, there may have been changes in the dune field at times between the available photos (e.g. between 1954 and 1968) and imagery. These changes are not documented due to the discontinuous nature of the available data set. However, the District believes that the overall developmental trends and patterns in the Keeler Dune field are now well understood (Lancaster, 2012).

The varying quality and resolution of the aerial photographs used made precise identification and delineation of the dune areas difficult in some instances (Table 4.3-1). In addition, Lancaster (2012) notes that it was sometimes difficult to define the edges of individual dunes and adjacent sand covered areas, because of poor contrast between sand and alluvial materials. The measurements documented in Lancaster (2012) represent the best estimate given the uncertainties involved in the tracing of the dune areas.

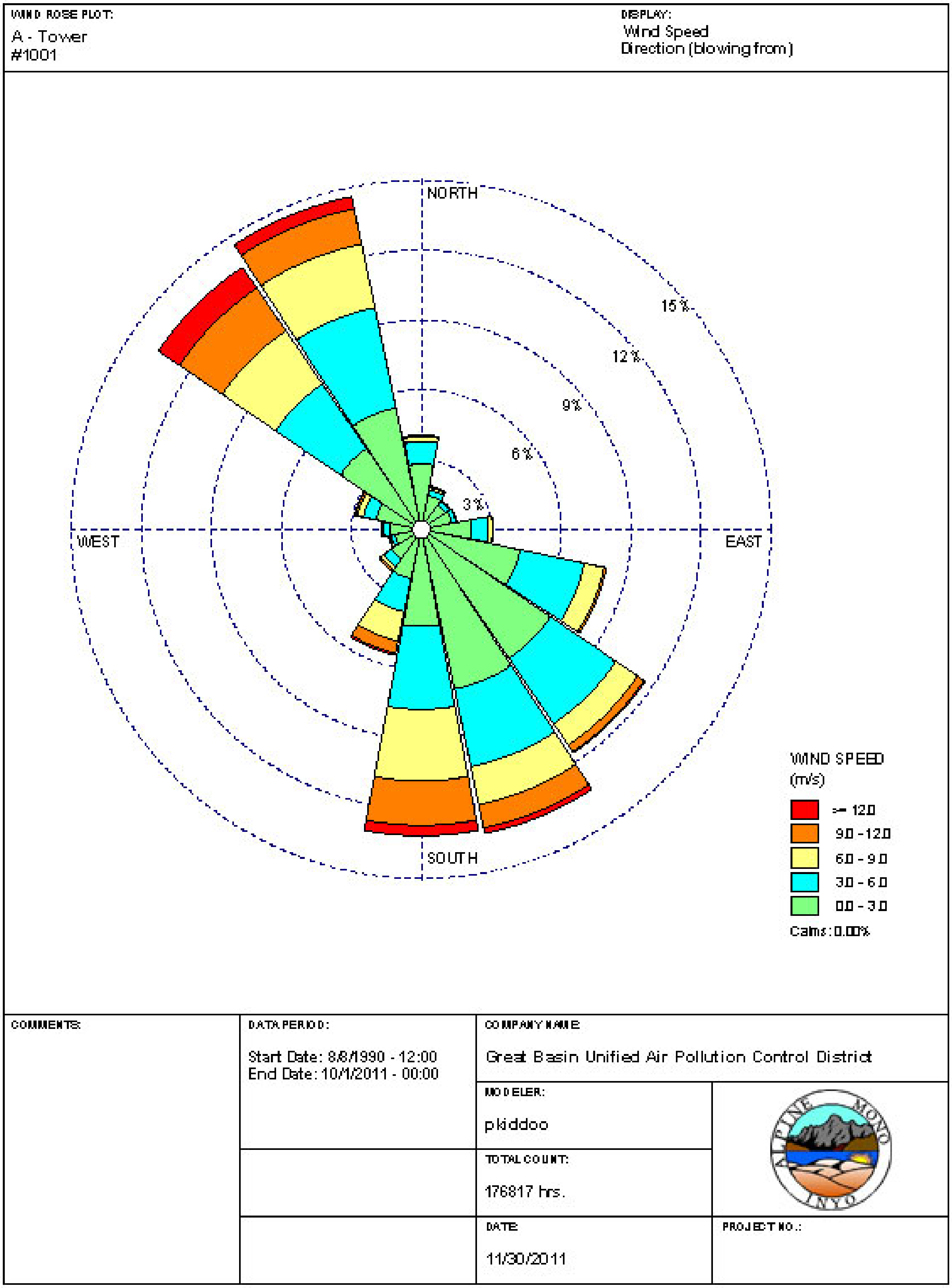
Results of Image and Photo Analysis

This section provides a description of the extent and geomorphology of the dune field and associated sand sheets at the times represented by the photo and image data used. The analysis is broken into four general time periods, each of which shows similar characteristics and evolutionary patterns. Figures 4.3-2 through 4.3-5 show overview maps of the dune extent for the four time periods[8]. Copies of the individual images used in the analysis are available in Lancaster (2012) and in Attachment C. A summary of the dune and dune field geomorphology is presented below for each developmental stage.

---

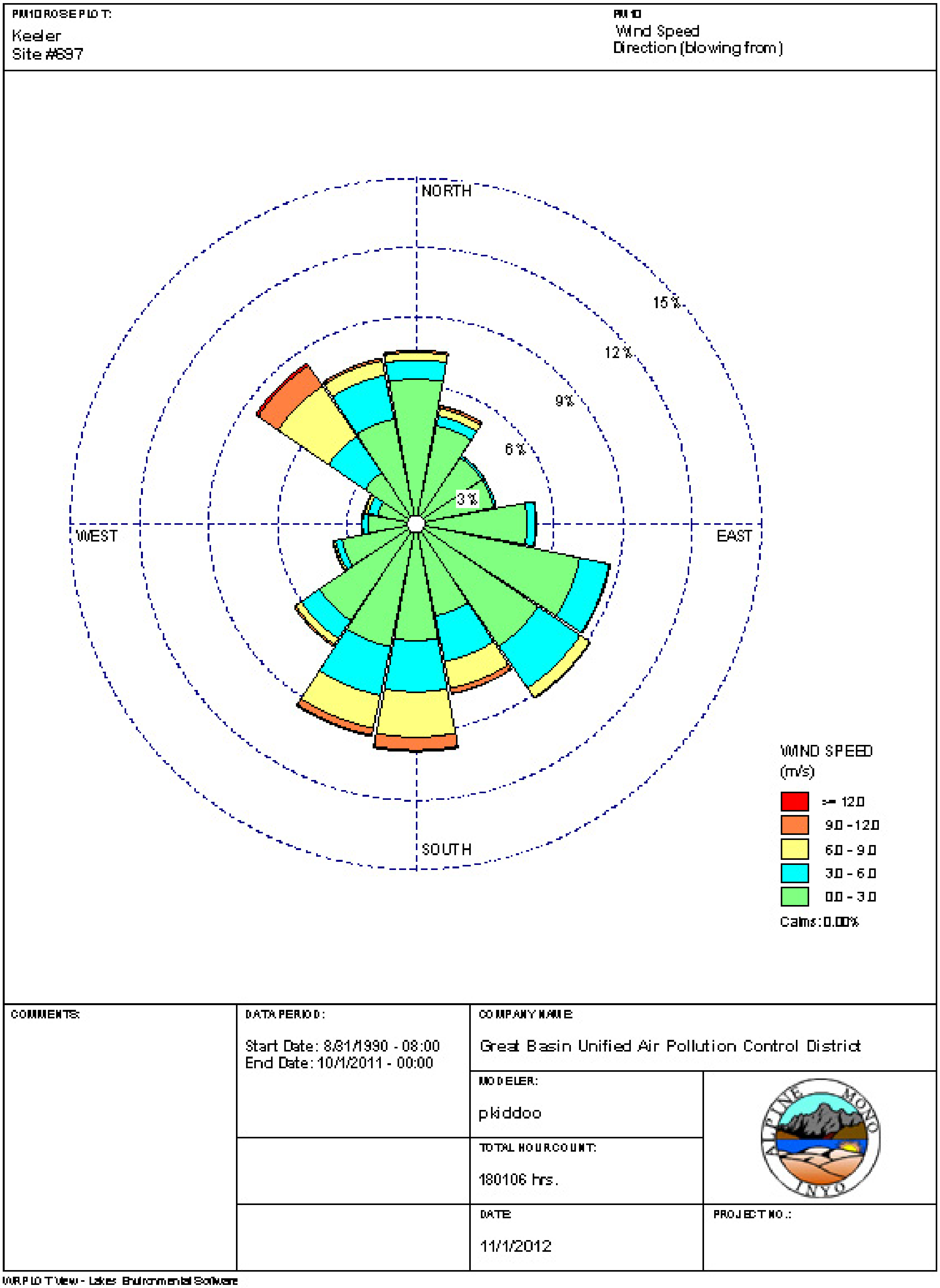
[8] Note: The photographs and imagery presented in this Section of the Final Staff Report are limited by the resolution and size required for their presentation here. It is strongly suggested that a review of the digital photographs and imagery be viewed on a high resolution monitor so specific features and conditions of the landscape can be examined and compared under enlargement.

Important to this analysis is a review of the predominant wind directions in the Keeler Dunes area. Figures 4.3-1 and 4.3-2 show a summary of the wind direction and wind speed data from the District's A-Tower site (located on the lake bed approximately 2 miles from the Keeler Dunes) and Keeler meteorological site (located at the north end of Keeler) from 1990 to 2011. In both the A-tower and Keeler data, there are two main general sectors from which the winds blow, from the northwest and from the south-southeast. Winds from the northeast and the west sectors are infrequent. However, the winds on the lake bed (A-Tower) are noticeable stronger and have more pronounced directional components than those measured in Keeler.



WRPLOT View - Lakes Environmental Software

Figure 4.3-1: Wind rose from the District's A-Tower meteorological site showing the prevailing wind pattern since 1990 on the northern portion of the lake bed.



PM10 ROSE PLOT:
Keeler
Site #697

PM10
Wind Speed
Direction (blowing from)

COMMENTS:

DATA PERIOD:
Start Date: 8/31/1990 - 08:00
End Date: 10/1/2011 - 00:00

COMPANY NAME:
Great Basin Unified Air Pollution Control District

MODELER:
pkiddoo

TOTAL HOURCOUNT:
180106 hrs.

DATE:
11/1/2012

PROJECT NO.:

WRPLOT View - Lakes Environmental Software

Figure 4.3-2: Wind rose from the District’s meteorological site in Keeler showing the prevailing wind pattern from August 1990 to October 2011 at the northern end of Keeler.

Four Periods of Development in the Keeler Dunes (1944-2010)

Period 1. 1944 to 1954 (Figure 4.3-3): From 1944 (or earlier) until the late 1950's, the dune field was small (~0.28 km^2; 0.11 square miles) and confined to a zone in the far northwest of the current dune area. Dune ridges, where identifiable, were short and small in number (4-5). Dune field location appeared to be strongly influenced by the prominent erosional shoreline scarp developed by late Holocene highstands of Owens Lake (Bacon and Lancaster, 2012). Dune field and dune geomorphology was influenced by the existing vegetation (*Sarcobatus vermiculatus*, *Suaeda moquinii*, and *Atriplex spp.*), which acted to anchor small dune ridges. A continuous sand sheet existed between the dune field and the Owens River delta. The southern portion of the study area (north of the community of Keeler) consisted of uniformly vegetated alluvial fan deposits without identifiable dunes or aeolian sands.

In the late 1950's or early 1960's, the dune field began to grow in size, and well-defined linear ridges started to extend from the core dune field towards the east. Three of these ridges have persisted to the present day, forming the dunes known as the Horseshoe and Linear dunes. The timing of development of these significant features is uncertain due to the time gap between 1954 and 1968 in which no photos were found. However, it is clear that at the beginning of this period these now-significant dune features were not present.

Period 2. 1968 to 1982 (Figure 4.3-4): From 1968 to 1982, the linear dune ridges were well developed, and increased in number (from 6 in 1975 to 9 in 1982). The dune field area expanded dramatically to the east and southeast, and grew in size to about 0.63 km^2 (0.24 sq. miles). This is twice as large as the 0.28 km^2 (0.11 sq. mile) 1940-1950's dune field.

Period 3. 1986 to 2000 (Figure 4.3-5): From 1982 to 1993 the dune field continued to rapidly increase in area, expanding toward the southeast, so that it covered an area of 0.84 km^2 (0.32 sq miles) in 1993. From 1982 onwards, crescentic dune ridges could, for the first time, be identified in the southern part of the dune field, as sand deposit thickness increased.

Period 4. 2002 to 2010 (Figure 4.3-6): From 2002 through 2010, dune field development was characterized by sand depletion along the northwest margin, but continued expansion and southeasterly migration of the southern dunes. As a result, the dune field area remained fairly constant, at around 0.77 km^2 (0.30 sq miles). Erosion became especially prominent following the construction of the shallow flood irrigation areas on the lake bed in the area of the former North Sand Sheet (NSS), resulting in widespread thinning of sand on the trailing (upwind) margin of the Keeler Dune field and exposure of alluvial fan deposits.

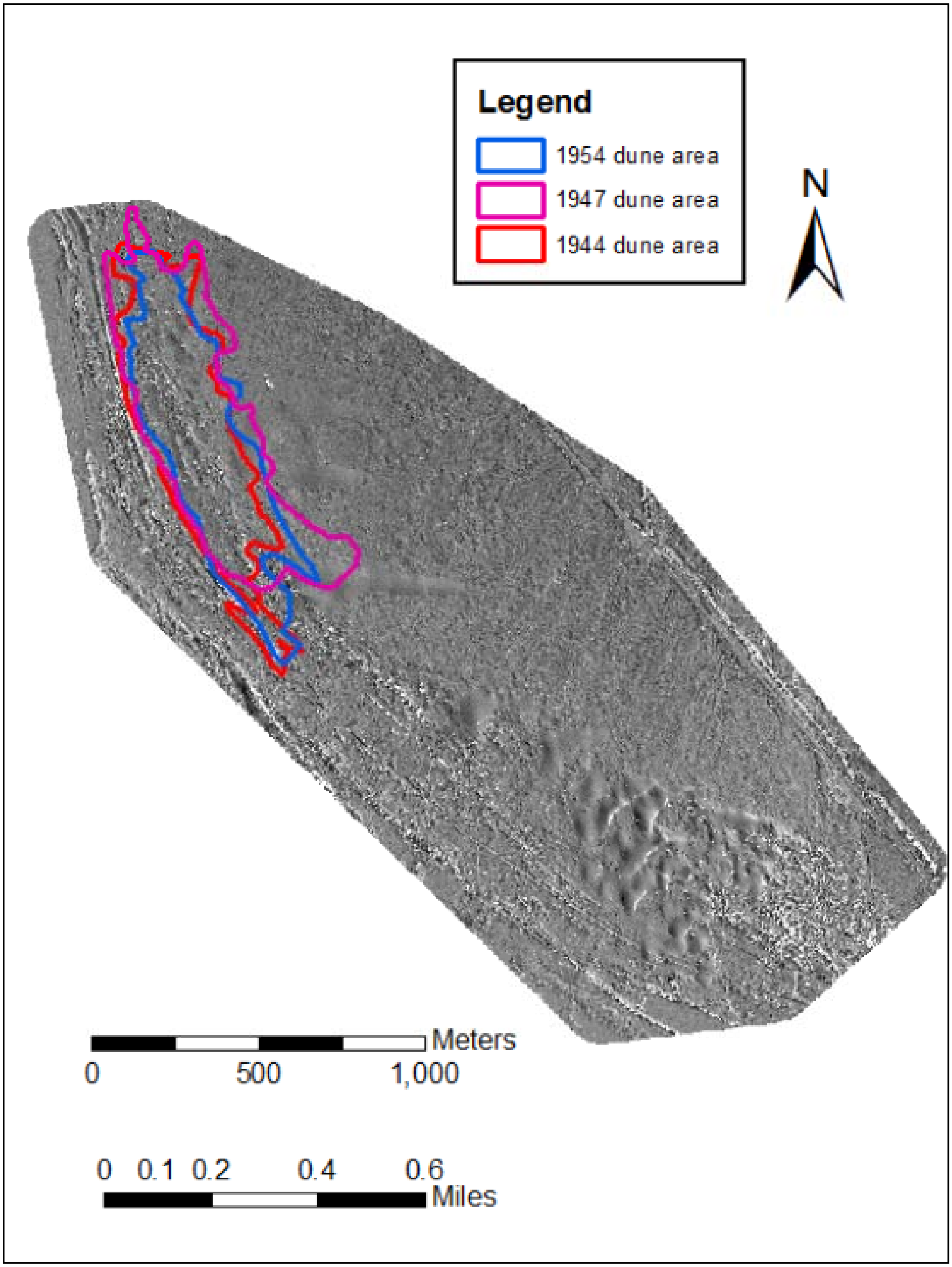


Figure 4.3-3. Map of dune extent in Period 1 (1944-1954) with 2010 LiDAR bare-earth image background. (from Lancaster, 2012)

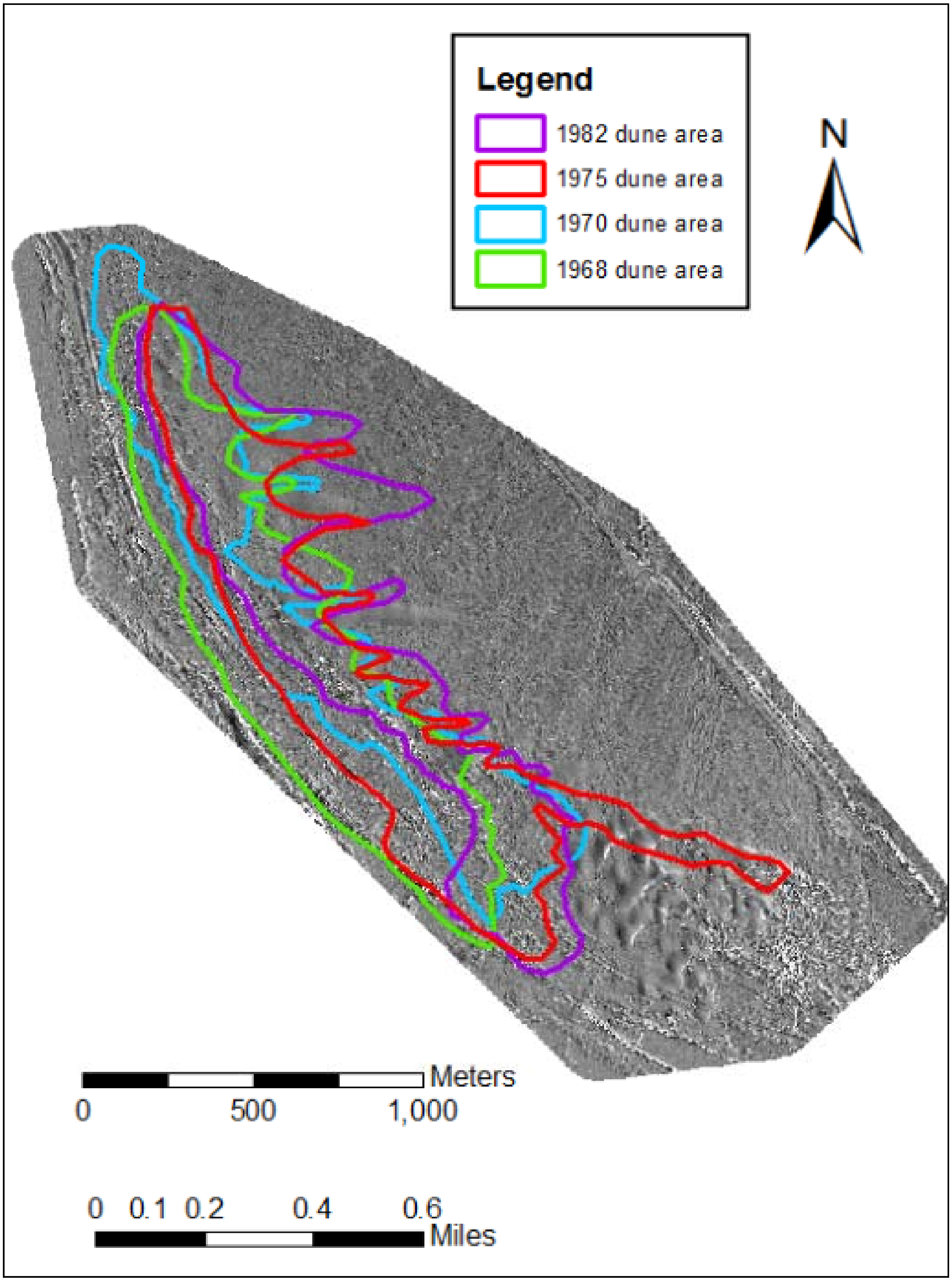


Figure 4.3-4. Map of dune extent in Period 2 (1968-1982) with 2010 LiDAR bare-earth image background. (from Lancaster, 2012)

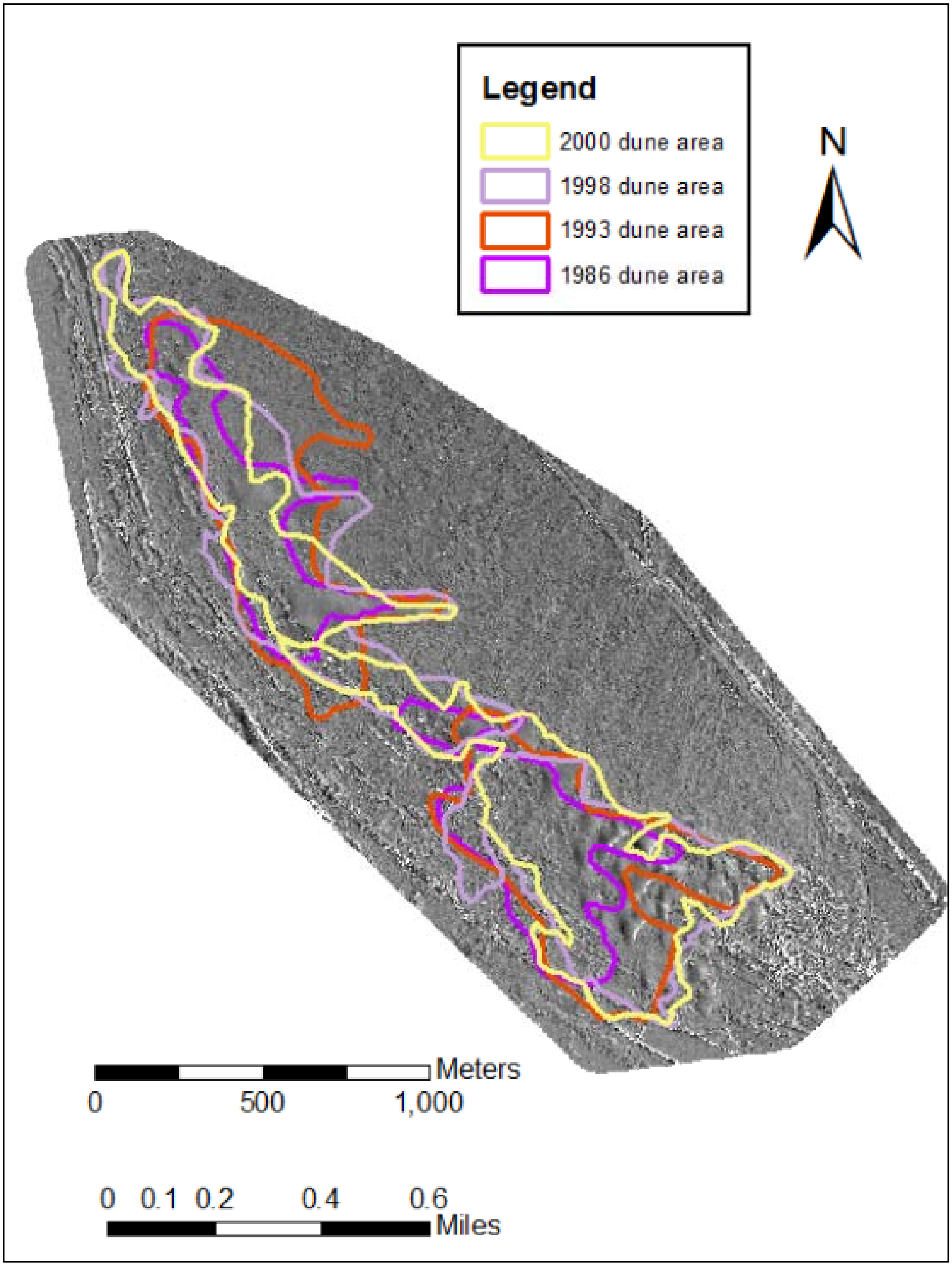


Figure 4.3-5. Map of dune extent in Period 3 (1986-2000) with 2010 LiDAR bare-earth image background. (from Lancaster, 2012)

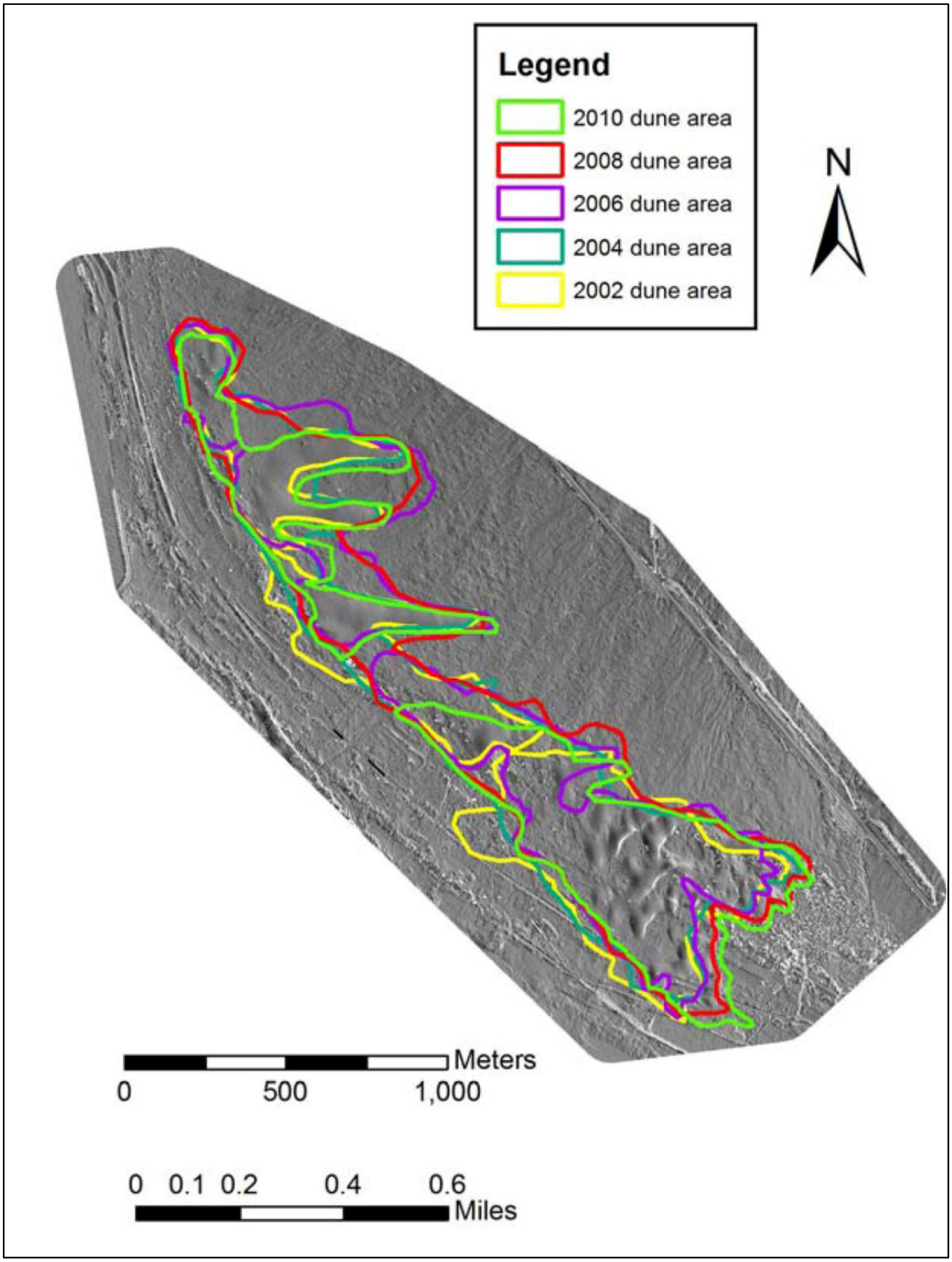


Figure 4.3-6. Map of dune extent in Period 4 (2002-2010) with 2010 LiDAR bare-earth image background. (from Lancaster, 2012)

Plots of the change in area, dune field length, number of dune ridges and total dune ridge length with time for data from the photo and image analysis are shown in Figure 4.3-7. There is good correlation of these parameters with time with correlation coefficients (R^2) ranging from 0.83 to 0.90. Notice that in Figure 4.3-7A the dune field area increases with time, and is quite well described by a second-order polynomial, showing the slowing of growth in the last 20 years while the field length of the dune area has increased linearly over time (Figure 4.3-7B). Within the dune field, the number of dune ridges has increased exponentially with time (Figure 4.3-7C) and, as anticipated, the total length of the ridges has likewise increased over time, in a similar fashion (Figure 4.3-7D).

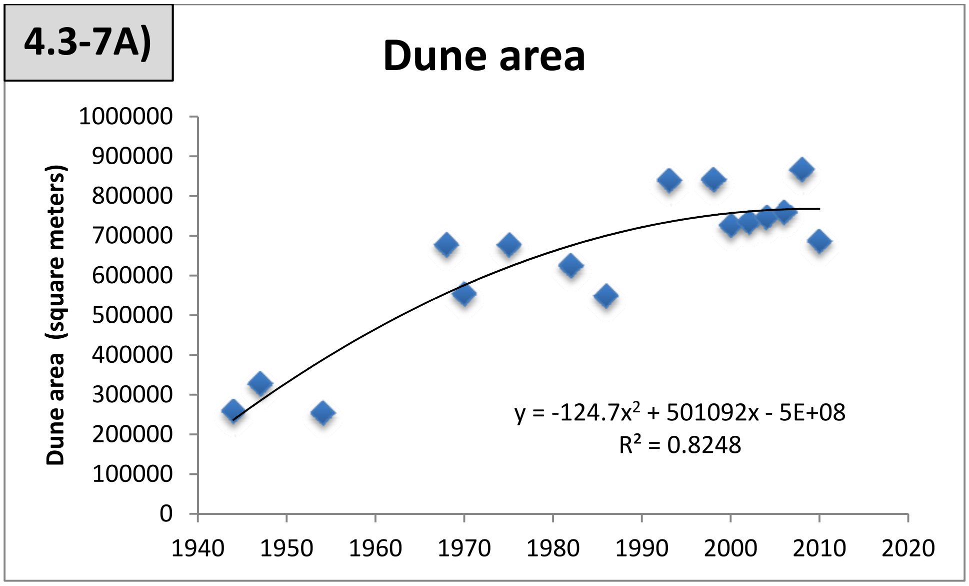


Figure 4.3-7A: Change in dune field area with time. (From Lancaster, 2012)

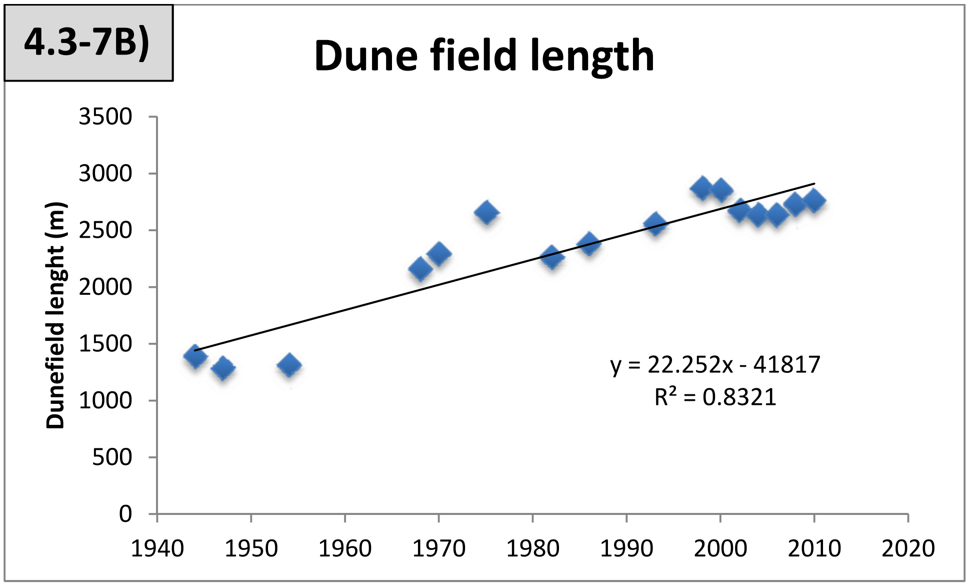


Figure 4.3-7B: Change in length of dune field with time. (From Lancaster, 2012)

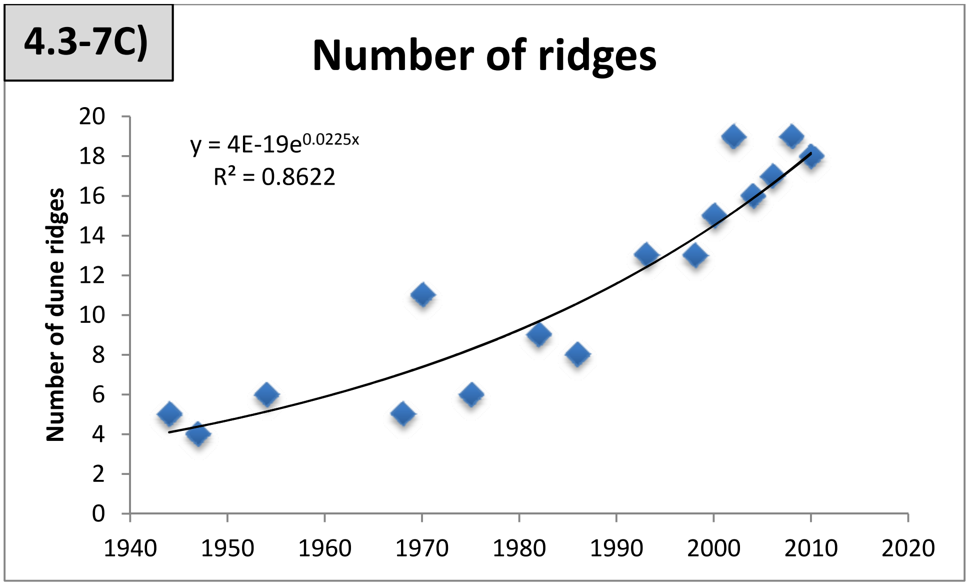


Figure 4.3-7C: Change in number of dune ridges with time. (From Lancaster, 2012)

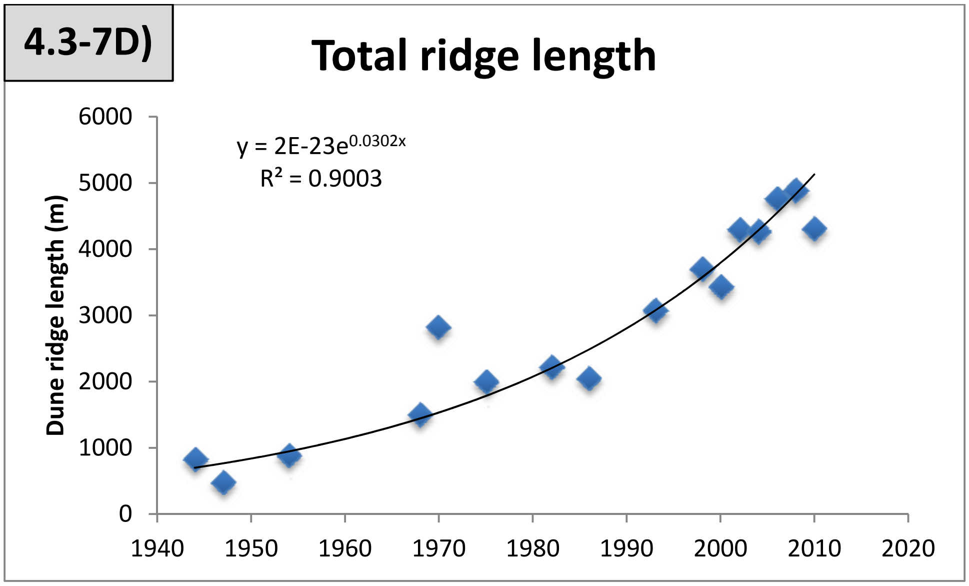


Figure 4.3-7D: Change in dune ridge length with time. (From Lancaster, 2012)

The relationships shown in Figure 4.3-7 seem to indicate that the dune field has not reached an equilibrium state and continues to evolve. The rapid and extensive nature of the documented changes indicates the relative youth of the dune field. (Lancaster, 2012) Mature dune fields tend to be stable both in terms of overall extent and also movement.

The changes observed in the Keeler Dunes from the photos and imagery are summarized in the time line presented in Figure 4.3-8. Some of the most significant changes include an increase in the area of the dunes by a factor of 3 since 1944 and the development of well defined linear and crescentic dunes. The dune field continues to expand toward the southeast, but its upwind margins are now experiencing significant erosion. Of particular interest is that the Swansea dunes have experienced little change in size or morphology over the same time period. Instead, they have maintained morphology of a mix of scattered vegetation and open sand areas (Lancaster, 2012).

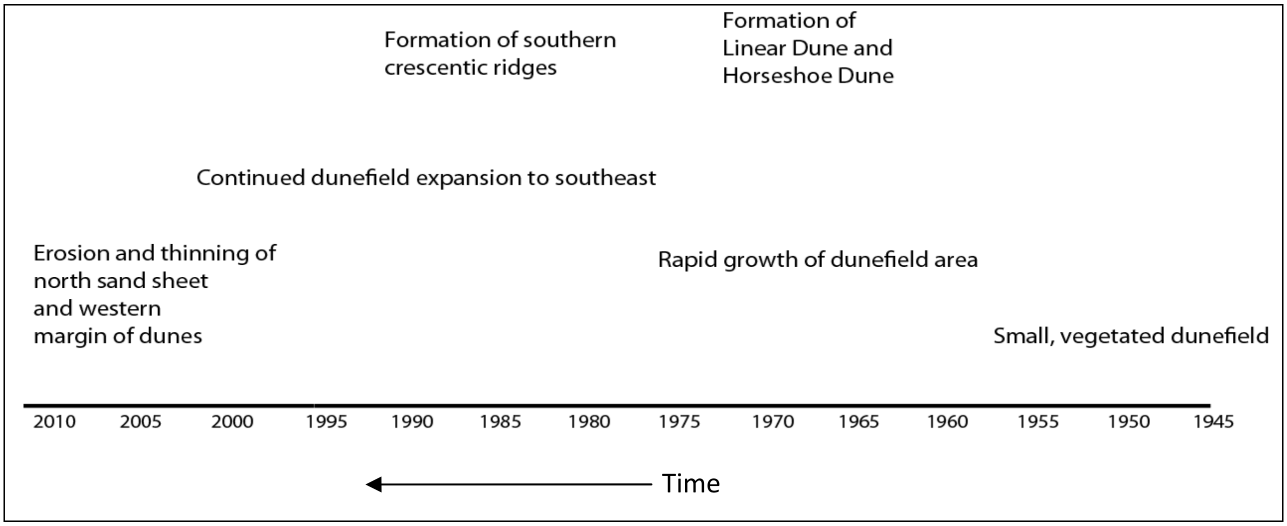


Figure 4.3-8: Development timeline for the Keeler Dunes area (from Lancaster, 2012).

Sand Supply

The significant expansion of Keeler Dunes areal extent and the increase in the number of identifiable dunes from the late 1950's to the 1990's required addition of sand from outside the dune field. Potential sources for this sand include washes draining from the Inyo Mountains to the east of the Keeler Dunes and fluvial sands of the Owens River delta, with associated sand sheets covering the northeast sector of Owens Lake. An evaluation of these potential sand sources is presented in Section 4.5 and in Lancaster and Bacon (2012b). Sediment volume, mineralogical composition and prevailing wind patterns, suggest the delta/lake bed as the primary source of sand.

The wind regime of the area is dominated by NW-NNW winds (Figures 4.3-1 and 4.3-2) which suggest this direction as that the main contributor for the sand added to the dune area in the last 50 years. In addition, the volume of additional material involved is much larger than is possible from the east given the size and frequency flow in the washes draining the Inyo Mountains Lastly, as shown in Section 4.5, the results of a mineralogical analyses show that the mineral composition of the dunes is dominated by quartz and feldspar; whereas sand-sized material from washes draining the Inyo Mountains contains a high proportion of calcite and low feldspar content. The Keeler Dune sands have a granitic or quartz-rich source like the Sierra Nevada. (Also see Lancaster and Bacon (2012a) provided in Attachment E)

Figure 4.3-9 shows the 1970 Corona satellite image of the Keeler Dunes and northern portion of Owens Lake along with the potential sand transport direction calculated by Lancaster (2012) from an analysis of available wind data and dune morphology. Following desiccation of Owens Lake, but prior to the construction of dust control measures, the sand supply to the dunes from the predominant wind direction was limited only by the transport capacity of the wind and surface moisture or surface cementation (crusting) that could restrict sediment availability. The resultant transport direction in the area of the Keeler Dunes based on analysis of sand flux data is discussed in Section 4.6 and Attachment F (Ono et. al. (2012)). From this analysis, net movement of sand within the dunes is toward the southeast.

However, the major question is: Why did the dune field expand so rapidly from the 1950's to the early 1990's; and how can this influx of sand be related to changes in sand supply from the Owens River source. Images from the 1940's to the early 1980's clearly show the sand sheet extended from the delta to the dunes and covered the area between the shoreline of Owens Lake and the dune field. Crossing this area is the old State Highway, which is variably covered by sand over time. After 1949 when State Highway 136 was relocated to its current position and the old roadway was no longer maintained, the amount of sand cover on the old highway roadway provides an index of the sand supply to the dunes (Figure 4.3-10). The data indicate that sand supply to the dunes peaked in the 1970's and 1980's and has since decreased. Since the late 1990's-2000 the proportion of old roadway covered by sand is less than 10%. This timeframe correlates well with the removal of the North Sand Sheet sediment supply source due to the implementation of dust controls on the lake bed. Following 2000, the dune field has been starved of incoming sand and is in a state of negative sediment budget, so that erosion is occurring on the upwind (west and northwest) margins. The continued expansion of the southern dunes towards the southeast is a result of reworking and movement of existing sand in these dunes.

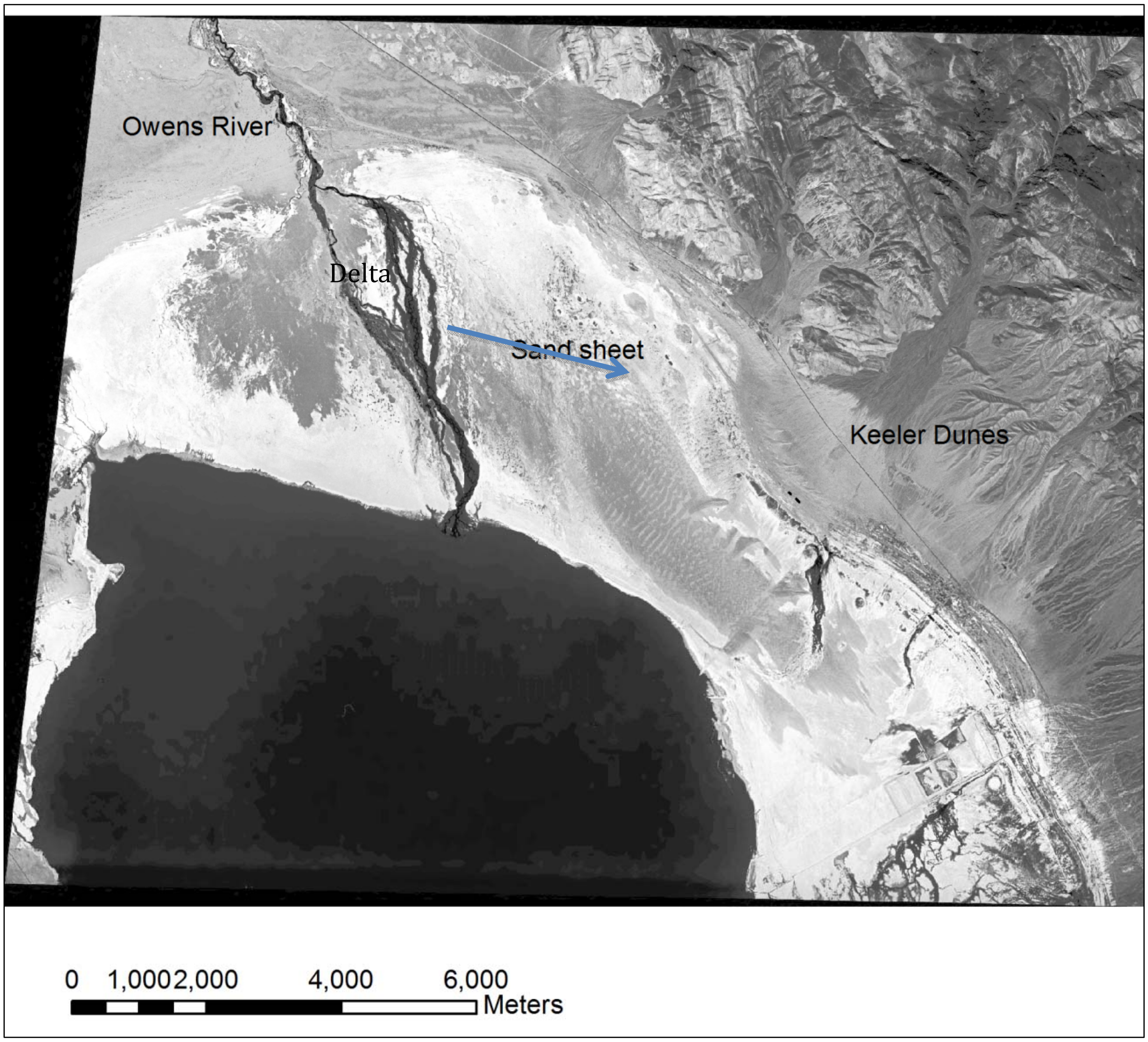


Figure 4.3-9: 1970 Corona image showing the Owens River delta and associated sand sheet located between the delta and the Keeler Dunes. The blue arrow indicates the predominant sand transport direction of 104° from Lancaster (2012).

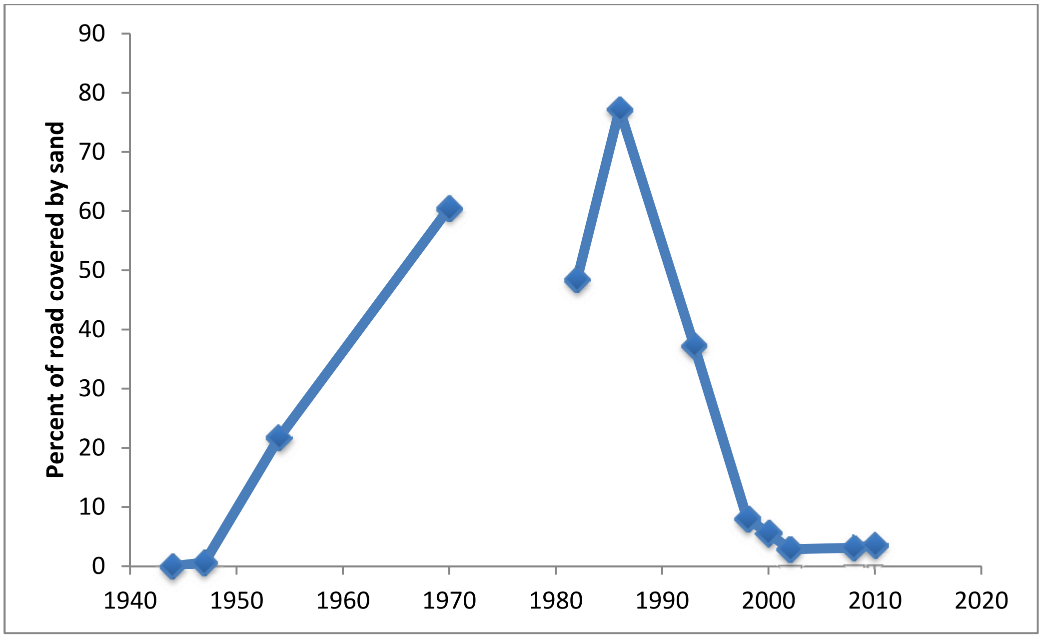


Figure 4.3-10: Percentage of the Old State Highway northwest of Keeler that was covered by sand. During the first peak (1970) the road was covered by sand sheets; second peak (1986) occurs when dunes cover road. Prior to the 1950's the road was maintained and sand cleared – so the low sand cover in the 1940's may not be representative of the sand moving across the area. (from Lancaster 2012a)

Conclusions

The following excerpt is an excellent clear and concisely written summary of the air photo and satellite images analysis conducted by Lancaster (2012).

> "The Keeler Dune field has developed to its present form since the mid-late 1950's, with rapid development in the 1970's and 1980's, when the southern dunes were formed. Presently it receives no sand input and is in a state of negative sediment budget, with net loss of sand, which is leading to erosion of its upwind margins, as well as depletion of sand. Analysis of dune morphologic changes over time indicates clearly that the dune field is still developing and has not yet reached an equilibrium with sand supply and wind conditions.
>
> Compared to other dune fields adjacent to present lakes in the region, (e.g. Mono Lake, Washoe Lake), which have developed directly adjacent to the leeward shore of the lake and which act like coastal sand dune complexes, the Keeler dune field appears more similar to desert dunefields, such as the Algodones dunes of southeast California, which has developed following desiccation of Lake Cahuila in the Salton Trough (Muhs et al., 1995; Stokes et al., 1997). Significantly, the dunes along the historic shoreline of Owens Lake are small and discontinuous, indicating a low supply of sediment to the lakeshore

prior to water diversions and subsequent desiccation of Owens Lake. The Keeler Dune field is not a lakeshore dune field, but a desert dune field adjacent to a lake basin, from which its sediments are derived.

The Keeler Dunes are characterized by a low cover of vegetation and dune forms that are characteristic of un-vegetated areas (e.g. the linear dune, the southern crescentic dunes). This implies a supply of sand and a degree of dune mobility that exceeds the capacity of the natural vegetation to establish and maintain itself.

By contrast, the Swansea dunes and the historic shoreline dunes are relatively small in area and sparsely- to well-vegetated, with morphology that is strongly controlled by the vegetation cover. This implies a supply of sand that is low in relation to the wind strength and the ability of the natural vegetation to establish itself and grow.

The state of the Keeler Dunes prior to the 1960's was similar in character, but not mode of formation, to the Swansea Dunes today (and in the past) – partly vegetated with a morphology that is strongly controlled by the vegetation cover. The area of dunes was very restricted. In the late 1950's to 1960's, the Keeler dune field area increased rapidly and new dunes formed, implying an input of sand from an external source. This process continued into the 1980's, when the southern area of very active crescentic dune ridges developed. Since 2002, when dust control measures were completed in the area of the North Sand Sheet, the dune field has been starved of sand, resulting in depletion of sand and erosion of its northern and western areas. By contrast, the Swansea dunes did not significantly change in area or morphology during this time.

Mineralogical analyses (Bacon and Lancaster, 2012) show that the additional sand was derived from the Owens River delta area. Periods of high flows in the Owens River are believed to have been responsible for transport of the additional sand to the delta area. In pre-diversion times, the delta would have been largely sub-aqueous and this sand would have been unavailable for wind transport because of high groundwater levels, riparian vegetation in the delta area and/or coverage of the lake bed and delta by water. Sand transport away from the delta would likely have been largely by wave action and near shore currents that built beaches and associated sand bars on the northern shores of the Owens Lake.

In pre-diversion times, sand input to the area of the Keeler Dunes would have been directly associated with transport of sand by wind from the immediate shoreline. Much of this sand was likely trapped by near-shore phreatophyte vegetation, resulting in the small and spatially-restricted shoreline dunes, the remnants of which can be identified today. Even in periods of drought that lowered lake levels, aeolian sand and dunes were likely restricted to the immediate vicinity of the shorelines.

Since lowering of the lake level by water diversion, the Owens River deposits sand on a sub-aerial delta fan, and this sand has been available for wind transport to the northeast quadrant of the lake via the North Sand Sheet, until dust control measures were put in place.

Water diversion therefore appears to have played a major role in changing the dynamics of sand supply to the marginal areas of Owens Lake. This has occurred as a result of changing the location where this sand is deposited from a sub-aqueous delta to a sub-aerial delta fan and by making the supply of sand from the Owens River much more available for wind transport across a largely dry lake bed." (excerpt from Lancaster, 2012)

4.4 Geomorphic Mapping of Keeler Dune Field and Surrounding Areas

The Desert Research Institute (DRI) conducted detailed geologic and geomorphic mapping of the Quaternary[9] deposits in the Keeler Dunes and northern shoreline areas of Owens Lake in 2011 and 2012 as part of an effort to learn how the emissive aeolian sand in the dune field fit into the overall geologic and geomorphic context of the region (Bacon and Lancaster, 2012). Prior to the mapping work completed by Bacon and Lancaster (2012) most of the previous detailed study of the Quaternary geomorphology in the Owens Lake region was completed in areas outside of the Keeler Dunes and Keeler alluvial fan where the features are more pronounced. The results from these previous studies and investigations are presented, discussed and summarized in Bacon et. al. (2006). In order to tie the mapped geomorphology of the Keeler Dunes area to the established geomorphic units and features determined from previous studies the areal extent of the mapping effort for this project was expanded to include the northern and northeastern margins of Owens Lake.

Two separate but overlapping maps were completed as part the work. Both maps and a technical report (Bacon and Lancaster, 2012) that describes the mapping methodology, map units and overall geomorphology are provided in Attachment D.

1. A large-scale map was created extending from the community of Keeler north and west around the northern margin of Owens Lake to the mouth of the Owens River and northern portion of the Owens River Delta (Figure 4.4-1). This regional map was created at a fixed map scale of 1:4,000 (1 inch = 330 feet) and covers an area of 16.4 square-miles (42.4 km^2). The purpose of completing this large-scale geomorphic map was to tie the mapped geomorphology from the Keeler Dunes area to the established geomorphic units and features found in previous studies.

2. A second map was created at a fixed map scale of 1:1,500 (1 in = 125 feet) that focuses on the Keeler Dune field using the airborne laser swath mapping (ASLM) or LiDAR digital topographic data acquired by Spatial Solutions from Bend, Oregon for the LADWP on January 29, 2010 (Figure 4.4-2). The focused map on the Keeler Dunes area covers 1.4 square-miles (3.5 km^2) and is centered on the emissive Keeler Dunes field.

---

[9] The Quaternary is the most recent of the three geologic time periods in the Cenozoic Era. The Quaternary Period is composed of the Pleistocene and Holocene Epochs and extends from approximately 2.5 million years ago to the present. The Quaternary units mapped in this project range from 25,000 cal yr B.P. to the present.

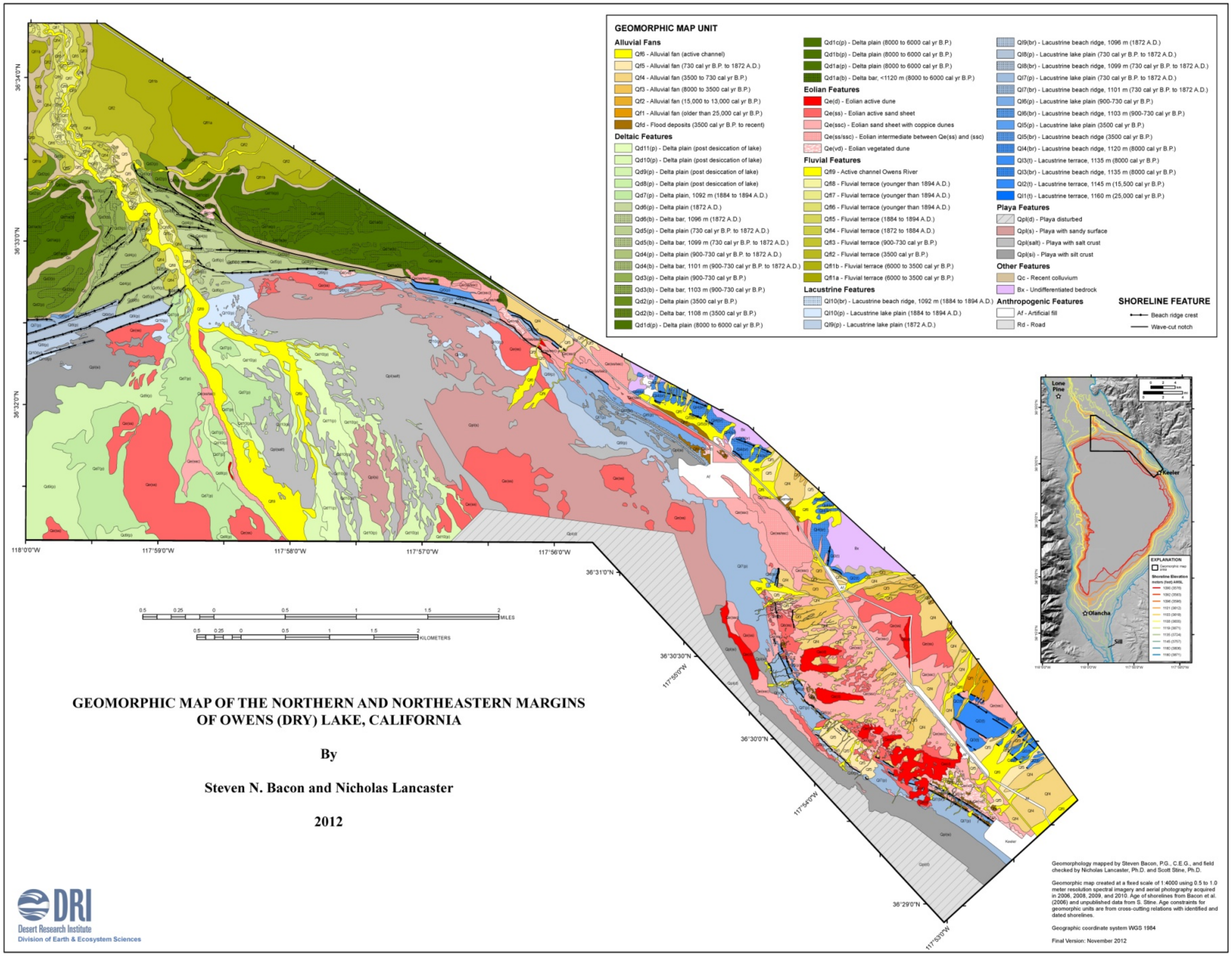
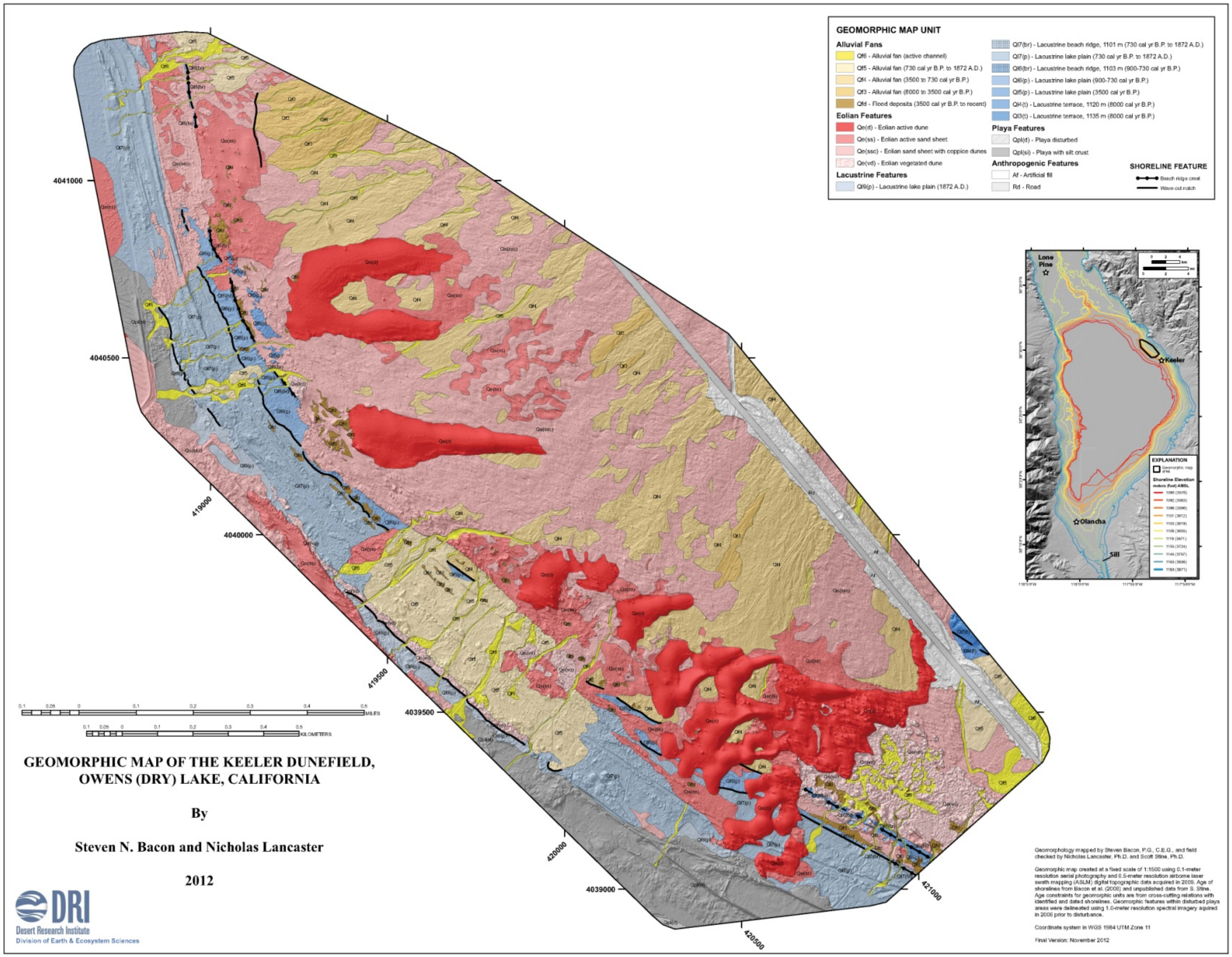


Figure 4.4-1. Geomorphic map of the northern and northeastern margins of Owens Lake. A large format map plate is available in Attachment D. (Map from Bacon and Lancaster, 2012)



GEOMORPHIC MAP OF THE KEELER DUNEFIELD,
OWENS (DRY) LAKE, CALIFORNIA

By

Steven N. Bacon and Nicholas Lancaster

2012

Geomorphology mapped by Steven Bacon, P.G., C.E.G., and field checked by Nicholas Lancaster, Ph.D. and Scott Stine, Ph.D.

Geomorphic map created at a fixed scale of 1:1500 using 0.1-meter resolution aerial photography and 0.5-meter resolution airborne laser swath mapping (ASLM) digital topographic data acquired in 2009. Age of shorelines from Bacon et al. (2006) and unpublished data from S. Stine. Age constraints for geomorphic units are from cross-cutting relations with identified and dated shorelines. Geomorphic features within disturbed playa areas were delineated using 1.0-meter resolution spectral imagery aquired in 2006 prior to disturbance.

Coordinate system in WGS 1984 UTM Zone 11

Final Version: November 2012

Figure 4.4-2. Geomorphic map of the Keeler Dune field. A large format map plate is available in Attachment D. (Map from Bacon and Lancaster, 2012)

Late Quaternary History of Owens Lake

Owens Lake in southern Owens Valley is currently a terminal playa that receives most of its water from the Sierra Nevada either through the Owens River or directly from tributary streams. During much of the late Pleistocene (140,000 to 25,000 years), pluvial Owens Lake was a perennial freshwater lake that periodically overflowed its sill to the south to form a chain of lakes occupying one or more of four successively lower-elevation basins (Smith and Street-Perrott, 1983). Both geomorphic and sediment core records indicate that pluvial Owens Lake had extreme lake-level fluctuations in response to changes in climatic and hydrologic conditions during the Pleistocene-Holocene transition (15,000 to 10,000 years), culminating with an early Holocene transgression (8000 years) and highstand below the basin sill (e.g., Bacon *et al.*, 2006). During the middle Holocene (6000 to 4000 years) the lake lowered to shallow and near desiccation levels that was followed by mostly shallow and oscillating lake levels which produced saline lakes in the late Holocene (3000 years to 1872) (Benson *et al.*, 1997; Smith *et al*., 1997; Li *et al*., 2000). (From Bacon and Lancaster, 2012)

Elevation and Shorelines in Owens valley

Late Pleistocene to early Holocene shoreline: The late Pleistocene to middle Holocene geomorphic history and spatial extent of pluvial Owens Lake shorelines has previously been reported (Beanland and Clark, 1994; Bacon *et al*., 2006; Bacon and Pezzopane, 2007; Orme and Orme, 2008). The oldest shorelines and associated features identified in Owens Valley have an age of ~160,000 years. These features are deformed across the Owens Valley fault zone, which is located in the center of the valley north of Owens Lake, and range in elevation from around 3871 ft (1180 m) east of the fault to near 3937 ft (1200 m) on the west (Jayko and Bacon, 2008). The last glacial maximum highstand shorelines have elevations that were controlled by a topographic divide (overflow sill) and subsequent downcutting that left two well-developed shorelines at elevations of about 3806 ft (1160 m) and 3757 ft (1145 m) at ~25,000 cal yr B.P. and ~15,500 cal yr B.P., respectively (Bacon et al., 2006). Subsequent lake levels lowered to near desiccation levels at ~11,600 cal yr B.P. prior to an early Holocene transgression that attained a brief highstand just below 3724 ft (1135 m) before dropping and stabilizing near 3674 ft (1120 m) at ~8000 cal yr B.P. (Bacon et al., 2006). (Figure 4.4-3).

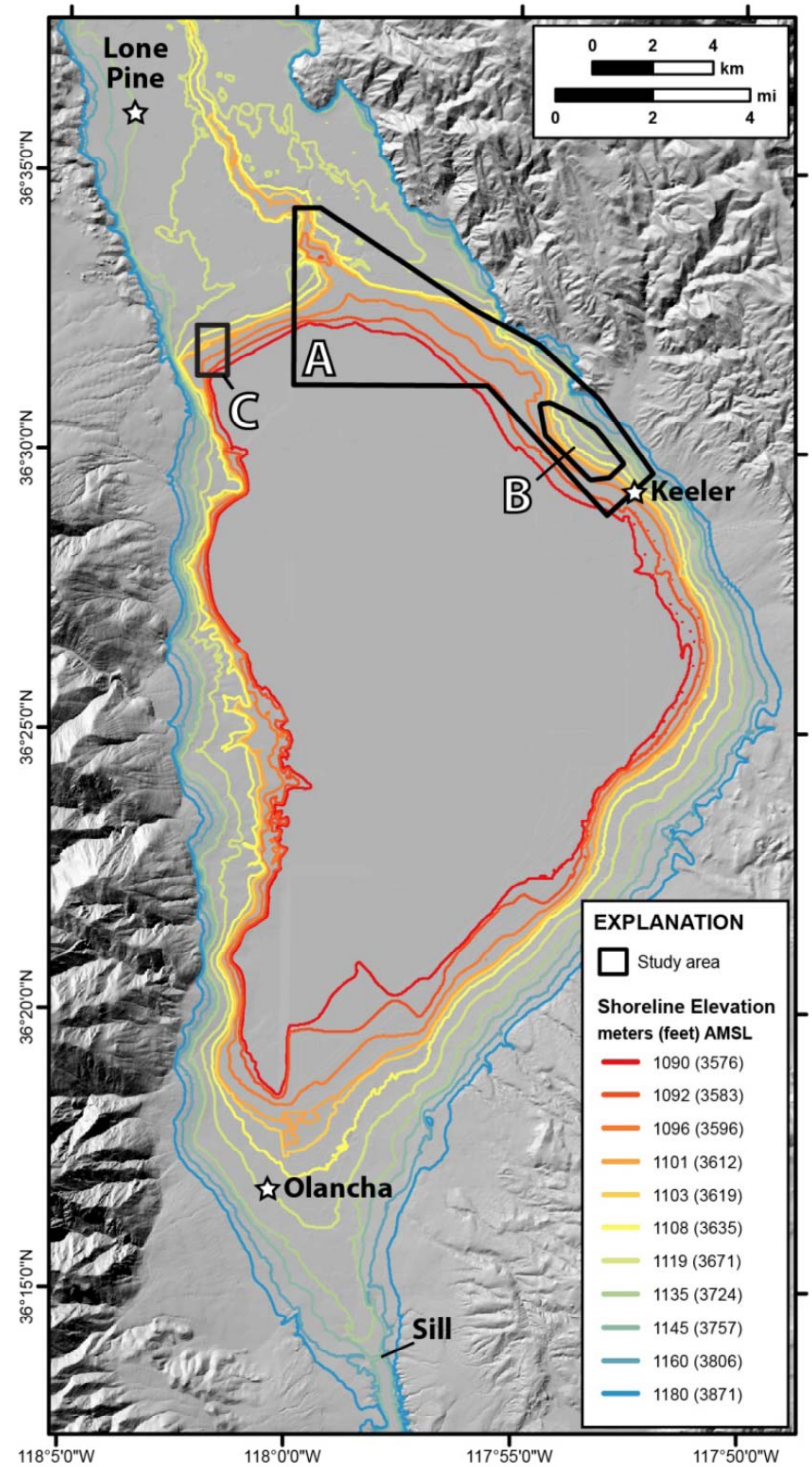


Figure 4.4-3. Map of southern Owens Valley showing the location and elevation of major late Pleistocene to historical shorelines of Owens Lake and the overflow sill of the basin at an elevation of 3757 ft (1145 m). Also shown are study areas of: (A) geomorphic mapping between the mouth of the Owens River and community of Keeler, (B) site-specific geomorphic mapping of the Keeler dunefield, and (C) type locality geomorphic record of late Holocene to historical shorelines. Elevation contours of shorelines are from U.S. Geological Survey 10-meter resolution digital elevation models. (From Bacon and Lancaster, 2012)

Late Holocene shorelines: The best preserved and complete geomorphic record of late Holocene and historical shoreline features is located in the northwest corner of the playa basin near the surface rupture of the historically active Owens Valley fault (Figures 4.4-3 and 4.4-4). At this locality and in many other areas in the basin, there are up to four well-developed late Holocene shorelines in the form of wave-cut notches and beach ridges preserved at elevations of approximately 3633 ft (1108 m), 3619 ft (1103 m), 3612 ft (1101 m), and 3605 ft (1099 m). The 3633 ft (1108 m) shoreline has not been directly dated and is inferred to be late Holocene in age, forming after 4300 cal yr B.P., based on relative degree of preservation, geomorphic cross-cutting relations, and topographic position in relation to older and higher shoreline features in the basin, however paleoclimatic proxy evidence from Owens Valley indicates a possible age closer to ~3500 cal yr B.P. (Bacon et al., 2006). Two of the three lower shoreline features also lack numerical age control and have not been previously described in detail. Only the 3619 ft (1103 m) shoreline has radiometric age control from charcoal of 900-730 cal yr B.P. that was preserved in sandy beach ridge sediments (S. Stine, unpublished data, 2011). The results of the companion study Late Holocene stratigraphy and chronology of the Keeler Dunes area by Lancaster and Bacon (2012a) have described in detail and refined the ages of shorelines below ~3633 ft (1108 m), as well as eolian landforms by directly dating deposits. (From Bacon and Lancaster, 2012)

Historical shorelines: Three well-preserved historical shorelines encompass Owens playa. The oldest of these shorelines formed around 1872 when Owens Lake was a perennial, closed-basin lake having a surface area about 110 square miles. At this time, Owens Lake had a pre-diversion, historical maximum lake level at 3597 ft (1096 m) with a water depth of 48.9 ft (14.9 m) (Gale, 1915). This lake level created laterally continuous and small-scale shoreline features around most of Owens Lake playa in the form of wave-cut notches, beach ridges, and associated shoreline dunes (Figure 4.4-4). In addition to the maximum historical lake level, other notable post-diversion lake levels were formed between 1884 and 1894 at an elevation of around 3584 ft (1092 m) and at a slightly lower lake level of about 3579 ft (1091 m) in 1912-1913 (Lee, 1915; Gale, 1915; Mihevc et al., 1997). These lower post-diversion lake levels formed conspicuous recessional shoreline features around and on the floor of Owens Lake playa that are mostly preserved along the northwestern, western, southwestern margins of the playa as sandy lake plains and beach ridges and wave-cut notches (Figure 4.4-4). After completion of the Los Angeles Aqueduct in 1913, Owens Lake began depositing salts onto the lake floor due to river and stream diversions to the aqueduct, and by 1926-1931 the lake had become a playa (e.g., Li et al., 2000). (from Bacon and Lancaster, 2012)

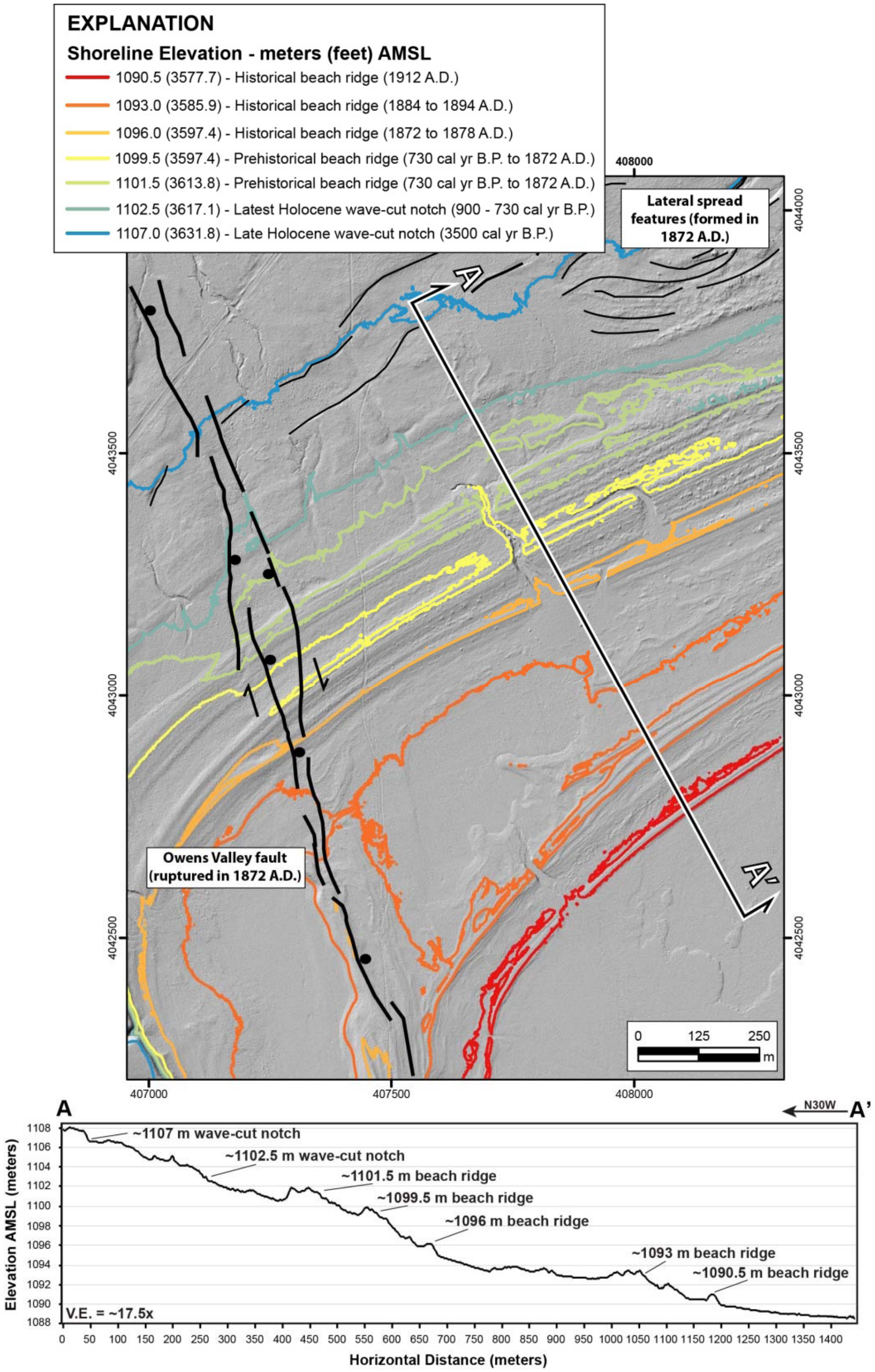


Figure 4.4-4. Map of northwestern corner of Owens playa showing the geomorphology and elevations of well-developed late Holocene and historical shorelines below an elevation of around 1107 m (3632 ft). Also shown is the trace of the Owens Valley fault that last ruptured in 1872 and geomorphic profile (AA') across shoreline features. This locality contains the best preserved and complete geomorphic record of late Holocene and historical shorelines in Owens Lake basin. Base map is 0.5-meter resolution airborne laser swath mapping digital topographic data from EarthScope (2011). Area shown is labeled 'C' on Figure 2-1. (From Bacon and Lancaster, 2012)

Correlation of Shorelines across the Owens Lake Basin

Owens Valley is a region of active tectonism, as demonstrated by M7.5-7.75 1872 Owens Valley earthquake (Beanland and Clark, 1994). The southern section of the Owens Valley fault extends along the entire western margin of Owens Lake basin (Figure 4.4-4). During the 1872 earthquake, vertical displacements occurred beneath Owens Lake that created a seismic seiche (tsunami) as well as laterally shifted the position of the eastern shoreline of the lake hundreds of yards (meters) to the west, raising the western shoreline (lake level) approximately 3 ft (1 m) in elevation (Smoot et al., 2000) and stranding the former shoreline. Eastside-down normal fault displacements of about 3 ft (1 m) coupled with the natural variability in the height of constructional shoreline features in Owens Lake basin of about 3-4 ft (1-1.5 m) have produced a range in elevation of shoreline features associated with the same lake level. As a result, the shoreline features of similar age and which are late Holocene and younger and adjacent to the Owens Valley fault or located across the basin at greater distance may have a difference in elevation up to 4 ft (1.5 m) (Bacon et al., 2006).

Mapping Methodology

Mapping of the landforms was conducted using accepted geologic and geomorphic methods that base delineations on several indices such as: tonal, textural, and topographic qualities, such as differences in surface color, degree of dissection and channel network development, plus presence and density of vegetation (Bacon and Lancaster, 2012). Mapping was performed by identifying geomorphic features that were spatially distinct and discernible using georeferenced satellite imagery and aerial photography. Map unit contacts were digitally created directly on base layers in a Geographic Information Systems (GIS) platform using ESRI's ArcMap software package.

Digitizing of unit boundaries in the larger map area of the north used a series of color satellite imagery with 0.5 to 1.0 meter-resolution from the years 2006 and 2008, in addition to color aerial photography with 0.3 meter-resolution acquired in 2011. Unit boundaries of the Keeler dunefield map area were digitized using color aerial photography with 0.1 meter-resolution acquired in 2009-2010 and using 0.5-meter resolution airborne laser swath mapping (ASLM) digital topographic data acquired in 2010. Landforms were correlated to each other and assigned relative geomorphic surface ages based on similarity of surface morphology, soil weathering characteristics, and direct ages on alluvial fans, as well as cross cutting relations with dated shorelines from previous studies. The mapping was conducted by S.N. Bacon of DRI and field checked by N. Lancaster (DRI) and S. Stine.

The ages of the identified shorelines of Owens Lake are from Bacon et. al. (2006), from unpublished data from S. Stine, and from this study (discussed in Section 4.5 and Attachment E). The constraints for the ages of the geomorphic units were established from cross-cutting relationships with identified shorelines. The mapping work focused on the Quaternary geomorphology; older bedrock units at the base of the Inyo Mountains were not differentiated. A technical report on the geologic chronology and stratigraphy of the Keeler Dunes area is provided in Attachment E (Lancaster and Bacon, 2012a).

The Quaternary geomorphic development of the Keeler Dunes and Owens Lake shorelines is complex and is a function of the dynamic regional geology. The Quaternary units range in age from greater than 25,000 cal yr B.P.[10] to modern. The mapped Quaternary units are separated into seven different types based on the origin of their formation and are coded by color on the maps. In addition, "Other" features (such as bedrock and colluvium) were differentiated and included on the completed maps.

<u>Geomorphic Map Categories</u>

1. Alluvial Fans – related to the formation and development of the alluvial fans in the area. (brown to yellow color scale)
2. Deltaic Features – features related to the formation and development of the Owens River delta. (green color scale)
3. Eolian Features – features related to eolian (or aeolian = wind-blown) activity. (red color scale)
4. Fluvial Features – features formed by the Owens River. (olive green to yellow color scale)
5. Lacustrine Features – features formed by ancient, historic or modern Owens Lake. (blue color scale)
6. Playa Features – features formed on the dried bed of modern Owens Lake. (grey and rose colors)
7. Other Features – recent colluvium and bedrock areas.
8. Anthropogenic Features – features formed by direct human disturbance, such as road construction, railroad activity etc.

Quaternary geomorphic map categories are abbreviated with the following descriptors: Qf – alluvial fan, Qd – deltaic, Qe – eolian, Qfl – fluvial, Ql - lacustrine, and Qpl – playa. Within each geomorphic map category, units are further broken out by the geomorphic formation or depositional environment (terrace, fan, plain, dune etc). Sixty-seven distinct landform units were distinguished during the mapping effort, each with a corresponding surface age when available. Following geologic convention, within each geomorphic category, the mapped units are presented and numbered in stratigraphic order with the oldest at the bottom and the

---

[10] cal yr B.P. – calibrated years Before Present. Geologic age dates are generally presented as the number of years before present or B.P. But because the "present" time continually changes the standard practice is to use 1 January 1950 as the origin year for radiocarbon dates.

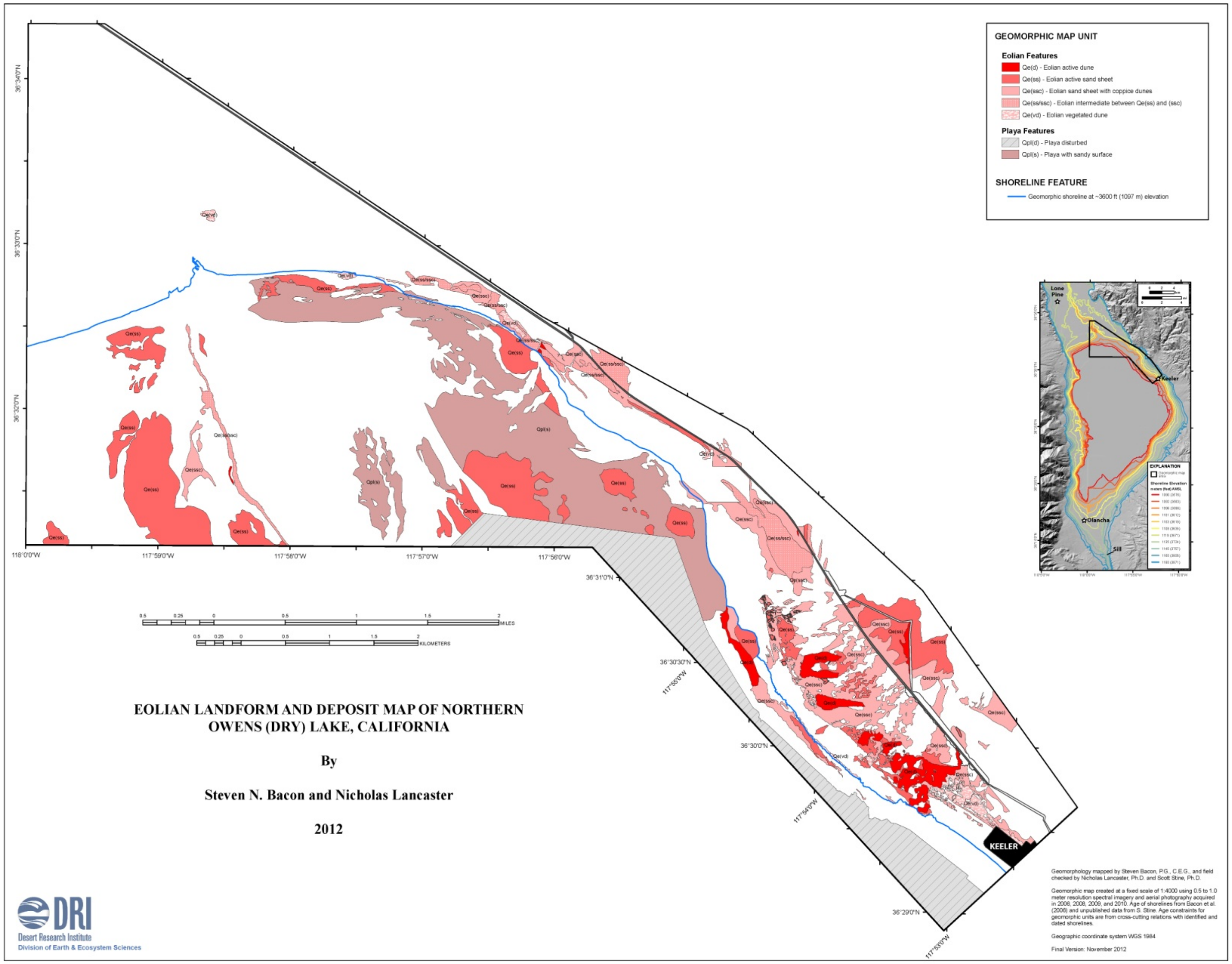
youngest on top (Figures 4.4-1 and 4.4-2, Attachment D). In order to be compatible with previous research on the Quaternary deposits in the region, elevations of the deltaic and lacustrine (lake) features are provided in meters (m) above mean sea level as well as in feet.

Among the most distinct and well-known types of Quaternary geomorphic features within the Owens Valley and in the mapped areas are those associated with the shorelines of ancient, historic and modern Owens Lake. These lacustrine features have been recognized and described in various levels of detail in publications and materials for well over one hundred years. The identified lacustrine features within the larger mapped area from the Bacon and Lancaster (2012) work are separated into ten distinct periods that extend in time from 25,000 (unit Ql1 at 1160 m (3806 ft) elevation) cal yr B.P. to 1894 A.D. (unit Ql10) (Figure 4.4-1).

Bacon and Lancaster (2012) were able to distinguish three types of lacustrine features depending on the depositional environment: beach ridge, terrace, and lake plain. Each of these is described in more detail in Attachment D. An inset map showing the locations of various shoreline elevations in the Owens Lake area is provided on both Figures 4.4-1 to 4.4-3.

Based on the results of the detailed geomorphic and geologic mapping, it is evident that the youngest units in the Keeler Dunes map area are the alluvial fan channels and the aeolian deposits (dunes and sand sheets) associated with the Keeler Dunes. The active sand deposits (sand sheet, coppice dunes, and dune) cross cut and are superimposed on (and are therefore younger than) lacustrine deposits mapped as unit Ql7 which range in age from 730 cal yr B.P. to 1872 A.D.

This mapping relationship is significant in that it constrains the timing of active dune development. The active sand deposits associated with the Keeler Dunes (map units Qe(d), Qe(ss), and Qe(ssc)) accumulated after 1872 A.D., following desiccation of historic Owens Lake. A map of the aeolian landforms and deposits in the northern portion of Owens Lake is provided as Figure 4.4-5. Most of the deposits shown on this map are modern in age.



EOLIAN LANDFORM AND DEPOSIT MAP OF NORTHERN OWENS (DRY) LAKE, CALIFORNIA

By

Steven N. Bacon and Nicholas Lancaster

2012

Geomorphology mapped by Steven Bacon, P.G., C.E.G., and field checked by Nicholas Lancaster, Ph.D. and Scott Stine, Ph.D.

Geomorphic map created at a fixed scale of 1:4000 using 0.5 to 1.0 meter resolution spectral imagery and aerial photography acquired in 2006, 2008, 2009, and 2010. Age of shorelines from Bacon et al. (2006) and unpublished data from S. Stine. Age constraints for geomorphic units are from cross-cutting relations with identified and dated shorelines.

Geographic coordinate system WGS 1984

Final Version: November 2012

Figure 4.4-5. Map of the aeolian landforms and deposits in the northern portion of Owens Lake and the Keeler Dunes. (from Lancaster and Bacon, 2012b)

4.5 Chronology and Stratigraphy of the Keeler Dune Area

The work completed for this portion of the project brings together the results from the geomorphic mapping with age date analyses, mineralogical analyses, and precise elevation measurements of the identified shoreline features to describe the chronology and stratigraphy in the Keeler Dunes. Also presented in this section is an analysis of the potential sand sources for the sands in the modern Keeler Dunes. The technical reports for this Section are provided in Attachment E and are companions to the mapping work discussed in Section 4.4 and provided in Attachment D.

4.5.1 Age Date Sampling

A major component of the work for this section involves interpretation of the ages established through quantitative age date analyses. Age dates for this project were obtained from two methods – Optical Stimulated Luminescence (OSL) and radiocarbon. The dates discussed here are the results of field work and lab analyses conducted in 2010, 2011, and 2012. Sample collection at two of the sample locations chosen for analysis in June 2012 were not conducted since the locations are located on land owned by the City of Los Angeles LADWP and permission has not yet been given by the LADWP. These two sample locations were designed to provide quantitative dates on the well defined 1103 meter shoreline present near the community of Keeler.

Fifteen OSL age dates analyses have been completed for samples within the Keeler Dune area and along the northeastern portion of the lake bed. The samples collected for OSL analysis in 2010 focused on the deposits within the Keeler Dunes area while the samples collected in 2012 were taken from the 1108 m shoreline near Swansea and from vegetated dunes near the District's Lizard Tail air monitoring station (informally called the Lizard Tail dunes). Maps showing the location of age date sample locations are provided in Figures 4.5-1 and 4.5-2.

The 2010 OSL dates provided in this section were conducted at DRI by the late Dr. Glenn Berger and Dr. Jose Luis Antinao (Antinao *et. al.*, 2012). The 2012 OSL analyses were conducted by Dr. Ed Rhodes at University of California at Los Angeles (Rhodes, 2012). Radiocarbon assays were run at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory for Dr. Scott Stine. Information on the methodology and results from the numerical age date analyses are provided in Attachment D.

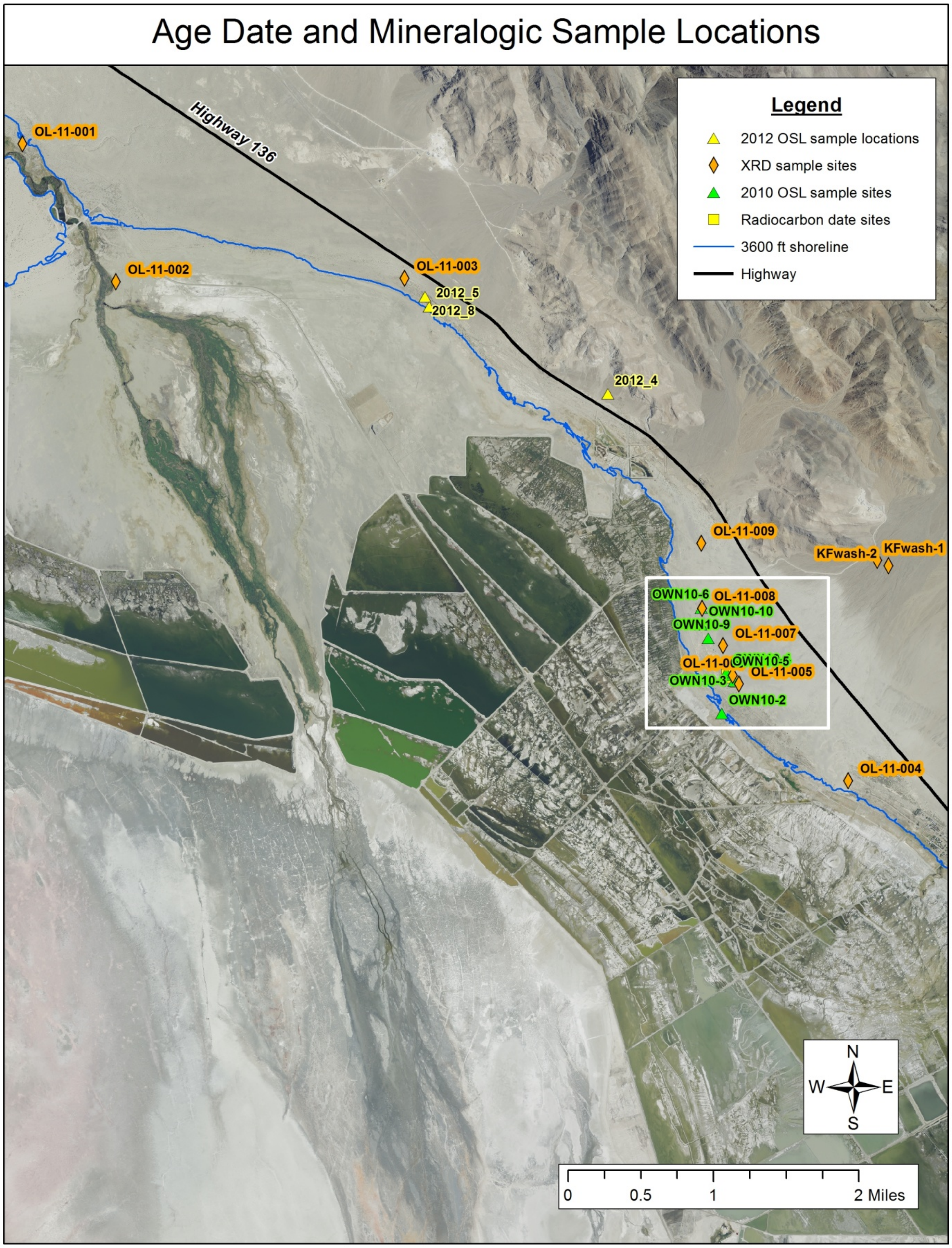


Figure 4.5-1. Map showing the locations of age date and mineralogical samples. The white box shows the location for Figure 4.5-2. Background image is 2009 NAIP.

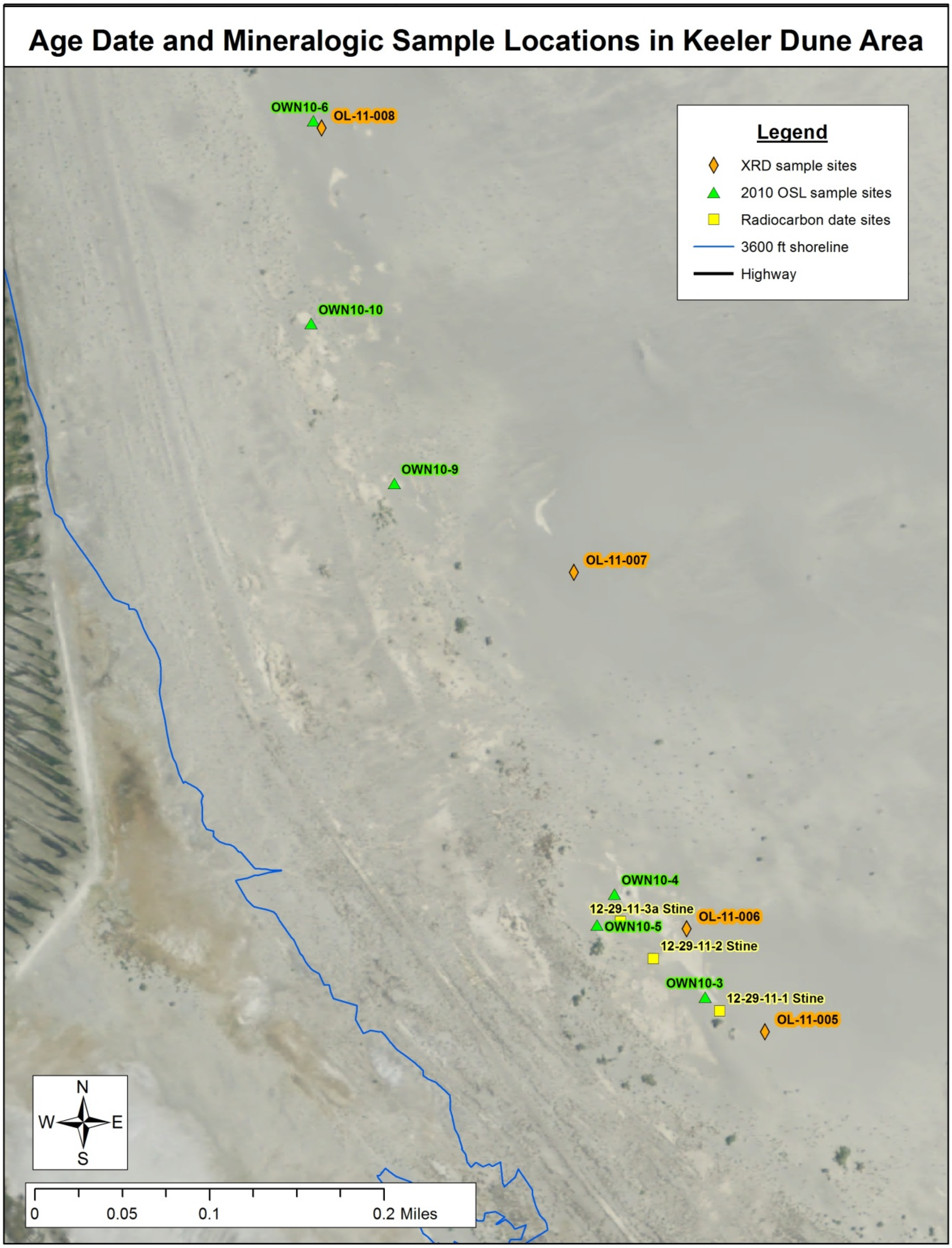


Figure 4.5-2. Map showing the locations of age date and mineralogical samples collected in the Keeler Dunes. The location of the map area is shown in Figure 4.5-1. Background image is 2009 NAIP.

Optical Stimulated Luminescence (OSL) Dating

The OSL dating technique has developed within the last decade as a valuable method for dating Quaternary sedimentary materials. The technique dates the sample's last exposure to sunlight prior to burial. Great care must be taken during sample collection to ensure that the samples are not "contaminated" by external light in the sampling process. Light "contamination" can lead to erroneously young ages. The OSL samples taken as part of this project were all collected by experienced lab personnel in order to ensure proper sampling methods were used.

All of the samples collected in 2010 for OSL age dating were collected in the Keeler Dune area (Figure 4.5-2) from sands that were capped by flood silt deposits thus protecting the underlying material from reworking and further exposure to sunlight. Samples were not collected from the active dunes since their "dating clock" is continually being reset due to their mobility. The samples collected in June 2012, for additional OSL dating, were taken from an 1108 m shoreline berm and from the dunes found in the northeast corner of the lake bed near the District's Lizard Tail air quality monitoring station (Figure 4.5-3).

Radiocarbon Dating

Radiocarbon dating is a radiometric technique that analyzes the decay of naturally occurring carbon-14 to ascertain the age of the material. The radiocarbon dates presented here were conducted on pieces of charcoal embedded within silt and sand units. Since the radiocarbon dates provide the age of the dated material (charcoal in this case) and not necessarily the surrounding sediments, the results need to be interpreted carefully. Information on the methodology and calibration used for the radiocarbon dates are provided in Attachment E (Lancaster and Bacon, 2012a).

4.5.2 Age Date Results

Tables 4.5-1 to 4.5-3 provide the results of the OSL and radiocarbon analyses collected as part of this study. The numerical age dates from the 2010 OSL samples are given in Table 4.5-1 and the results from the 2012 OSL analyses are provided in Table 4.5-2. The radiocarbon dates are provided in Table 4.5-3.

The results from the completed 2010 OSL age date analyses range from 35 to 1,710 years before 2011 (Table 4.5-1). In order to interpret the dates correctly it is important to consider the location and context of the dated samples. The two youngest dates are from vegetated dunes along the historic shoreline (sample OWN10-2) and from the Northern Dune in the Keeler Dunes (OWN10-6) with ages of 35 and 40 years before 2011 (or 1975 A.D. and 1971 A.D.), respectively. The oldest dates (1,710 and 727 yr. before 2011 or 301 A.D. and 1284 A.D.) are from the central portion of the Keeler Dune area (OWN10-4 and OWN10-5) from cross-bedded sands exposed below the eroded western portion of the Linear Dune. These samples were collected from sand exposed below flood silt deposits at elevations between 1103 and 1105 m (3,619 and 3,625 ft). Although there are no distinguishable Holocene lacustrine shoreline features mapped directly at the sample locations, these samples appear to correspond to dunes developed along the 1103 m (3,619 ft) shoreline. Geomorphic map units associated with the Ql5 (3,500 cal yr B.P.) and Ql6 (900-730 cal yr. B.P.) features are present within 100 to 150 meters to the northwest from the sample locations. The active and emissive portion of the Linear Dune is superimposed on, and cuts through, this former shoreline dune system.

The results from the dates of the samples collected in the Lizard Tail dunes are provided in Table 4.5-2 (samples 2012-5 and 2012-8). These samples were collected from two ridges of dunes located to the west of the air monitoring site (Figure 4.5-3). Site 5 was located on the southwestern, lake proximal ridge which is approximately 2 meters in height. Site 8 was located on the northeastern ridge away from the lake bed which reaches a height of 4-5 meters. Two analyses were conducted on samples from site 5, one from 0.75 m and one from 2.00 m depth. Four analyzes were conducted from samples at Site 8 at 0.87, 2.00, 3.00, and 3.73 m depths. The oldest age from the base of the dune at Site 5 yielded an age of 5000 yr before 2012. This age likely reflects that of the distal alluvial fan materials that underlie the dunes rather than the basal age of the dune. The ages from Site 8 range between 400 and 710 years before 2012.

The results from the three radiocarbon dates are presented in Table 4.5-3 (Figure 4.5-2). The samples analyzed consisted of small fragments of charcoal within the flood silts and range in age from 168 to 1,255 cal yr B.P. Again the age date results need to be interpreted based on location and stratigraphic context. Sample 12-29-11-3a, with a carbon dating age of 1,219 cal yr B.P., was collected from a unit thought in the field to be correlative to OSL site OWN10-5 (date of 727 yr before 2011). An interpretation for the difference in dates between the two samples is that while the unit was deposited 1,219 cal yr B.P. (as indicated by the radiocarbon date), the site was buried, and thus last exposed to light, 727 cal yr B.P. (as indicated by the OSL date).

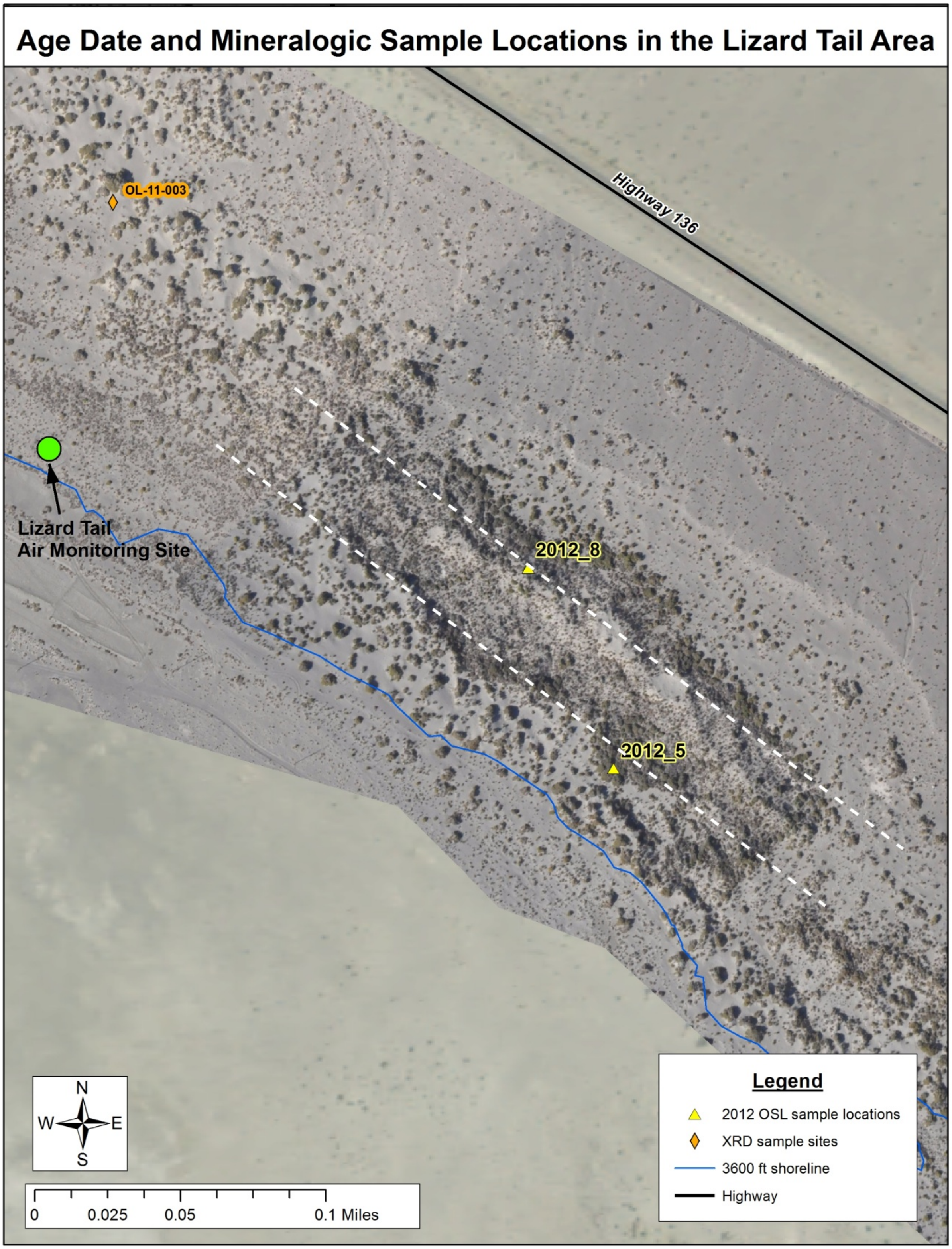


Figure 4.5-3. Map showing the locations of age date and mineralogical samples collected in the Lizard Tail dunes. The two dune ridges discussed in the report are shown schematically with dashed white lines. Background images are high resolution air photos from 2011 and 2009 NAIP.

Table 4.5-1. OSL age date results from samples collected on September 22, 2010 by Dr. Glenn Berger and analyzed at the Desert Research Institute at the E.L. Cord Geochronology Laboratory (Antinao *et al*, 2012). (See Figure 4.5-2 for sample locations)

Table 4.5-1. OSL Age Date Results (2010 samples)

Sample	Northing (m)	Easting (m)	Elevation (m)	Age (yr before 2011)	Error (1 sigma)	Calendar Years (AD)
OWN10-02	4039913.40	419251.92	1096	**35.1**	4	**1975**
OWN10-03	4040238.54	419384.05	1106	**81**	25	**1930**
OWN10-04	4040373.82	419307.43	1105	**1710**	250	**301**
OWN10-05	4040343.16	419296.98	1104	**727**	130	**1281**
OWN10-06	4041084.34	419033.10	1106	**40**	20	**1971**
OWN10-09	4040750.38	419106.90	1106	**172**	72	**1839**
OWN10-10	4040900.83	419025.74	1105	**423**	45	**1588**

Table 4.5-2. OSL age date results from samples collected on June20-21, 2012 by Dr. Ed Rhodes and analyzed at the University of California at Los Angeles. (See Figure 4.5-3 for sample locations)

Table 4.5-2. OSL Age Date Results (2012 samples)

Sample	Site	Northing (m)	Easting (m)	Elevation (m)/ Feature (depth of dune sample)	Age (yr before 2012)	Error (1 sigma)	Calendar Years (AD)
KD-12-01	2012-4	4043455	417995	1108 shoreline	**3690**	260	**1678**
KD-12-02	2012-4	4043455	417995	1108 shoreline	**3620**	260	**1752**
KD-12-08	2012-5	4044423	416019	Dune (0.75 m)	**300**	20	**1712**
KD-12-10	2012-5	4044423	416019	Dune (2.00 m)	**5000**	210	
KD-12-12	2012-8	4044534	415972	Dune (0.87 m)	**400**	30	**1612**
KD-12-14	2012-8	4044534	415972	Dune (2.00 m)	**420**	30	**1592**
KD-12-16	2012-8	4044534	415972	Dune (3.00 m)	**710**	40	**1302**
KD-12-17	2012-8	4044534	415972	Dune (3.73 m)	**620**	30	**1192**

Table 4.5-3. Radiocarbon age date results from samples collected in December 2011 by Dr. Scott Stine. (See Figure 4.5-2 for sample locations)

Table 4.5-3. Radiocarbon Age Date Results

Sample	Northing (m)	Easting (m)	Elevation (m)	RC age	RC Error	Calibrated Age (BP)	Calendar Years (AD)
12-29-11-1	4040264.19	419405.18	1104.172	190	30	**168±20**	**1782**
12-29-11-2	4040312.49	419343.97	1104.57	140	40	**176±3**	**1774**
12-29-11-3a	4040346.78	419313.62	1102.937	1255	35	**1219±47**	**731**

4.5.3 Stratigraphy

The interpretation of the age date results in the Keeler Dunes is not straight-forward due to the local topography of the area and its relationship to the development of the multiple former shoreline features. The oldest shoreline feature in the Keeler Dunes is present at the highest topographic elevation (1108 m, 3635 ft) with the younger shoreline features found at progressively lower elevations. The horizontal width of a shoreline zone associated with a particular shoreline "horizon" varies depending on the length of time associated with its development, slope of the land surface and other factors but is estimated to be approximately 50-70 m in the Keeler Dunes area. Over this horizontal distance, the general topographic relief (or vertical elevation change) generally varies several meters[11]. Thus for shoreline zones associated with the 1103 and 1101 m lake levels it is likely that there are areas with "overlapping" features. The aeolian deposits associated with these shoreline zones can be interpreted as a spatial sequence in which sands become progressively younger with decreasing elevation towards Owens Lake, as each dune sand unit was deposited against pre-existing dune topography.

Keeler Dune Area

The complex stratigraphy and chronology of the aeolian sand and flood silt deposits can be seen in the area along the western portion of the Linear Dune (Figure 4.5-2). There are three primary flood silt deposit elevations in this area (designated as units I to III, from lower to upper). The cross-sections from Lancaster and Bacon (2012a), and shown in Figures 4.5-4 and 4.5-5, illustrate the relationships of these flood silts with the aeolian sand units that are exposed.

The Linear Dune site provides evidence for aeolian and flood silt deposition spanning much of the last 2000 years. The OSL ages from the Linear Dune site appear to reflect inverted topography, where deposits are in reverse order (oldest on top) in terms of elevation relative to other deposits. This is not uncommon in alluvial environments where low relief areas are filled in with fine-grained sediment that solidifies to form an erosion resistant layer relative to softer sediment that surrounds and underlies it (Lancaster and Bacon, 2012a).

The sequence of aeolian deposit ages can be interpreted as a spatial sequence in which sands become progressively younger with decreasing elevation towards Owens Lake, as each dune sand unit was deposited against pre-existing dune topography (Fig. 4.5-6). The radiocarbon ages fall in stratigraphic order and provide good age control on the ages of the flood silt

---

[11] Section 4.4 and Attachment D, Bacon and Lancaster (2012), notes that for the historic shoreline at 3597 feet in elevation there is up to a 3-4 foot (1-1.5 m) difference in elevation across the basin. This is likely the case for the older shorelines identified in the region as well.

deposits. They also suggest that aeolian sands were deposited in the area prior to 1200 cal yr B.P., an interpretation consistent with OSL sample OWN-10-04. Aeolian sands were also deposited around 172, 423, and 727 cal yr B.P. (1839, 1588, 1281 A.D.). Recent dated sand deposits span the range from around 80 to 35 years ago (1931-1976).

The calibrated radiocarbon ages for the upper flood silts are statistically identical and provide good age estimates for the extensive flood silts at around 1106 m (3629 ft) elevation. It is clear that there was extensive flooding on the Keeler Fan in the period 1782-1835 A.D., or during the latter part of what is termed by geologists as “The Little Ice Age”.   During this period, floodwaters were ponded against a pre-existing dune area, at least in the area of detailed study adjacent to the Linear Dune (which did not form until the 1960s).

The well-constrained distribution of the flood silts indicates that some form of dune barrier has existed along the 1103 – 1106 m elevation associated with former shorelines at least for the past 2000 years. The form and extent of this dune barrier was likely vastly different from the more extensive dune field that formed between 1960 and 1980 (Lancaster, 2012a). Figure 4.5-7 shows the general interpreted extent[12] of the Late Holocene dunes associated with former shoreline features of Owens Lake in the vicinity of the Keeler Dunes.

It appears that these “old” dune barriers were associated with the band of phreatophytic vegetation that extended from Keeler to the active channel of the Keeler/Slate Canyon fan to the north, and lies immediately above and along the 1103 m (3619 ft) shoreline elevation. Sand blown from the lake bed has accumulated periodically in this zone to form prominent greasewood-anchored nebkhas, as seen on aerial photographs up to the late 1960’s. The vegetation band was then progressively buried from the north-northwest by large quantities of sand from the lake bed, culminating in the formation of more extensive dunes in the 1970’s.

OSL samples OWN-10-02 and -06 indicate that sand was deposited in the sand sheet area of Keeler dunes prior to 1980 and covered by flood silts soon afterwards. Significant floods on the Keeler fan occurred in 1979 and 1980, and it is likely that these flood silts were deposited at this time. (Lancaster and Bacon, 2012a)

---

[12] Note that these Late Holocene aeolian units are not exposed at the surface in most locations and thus are not shown on the geomorphic maps. However, in places (such as the western end of the Linear Dune) they are exposed in eroded cuts through the modern Keeler Dunes deposit.

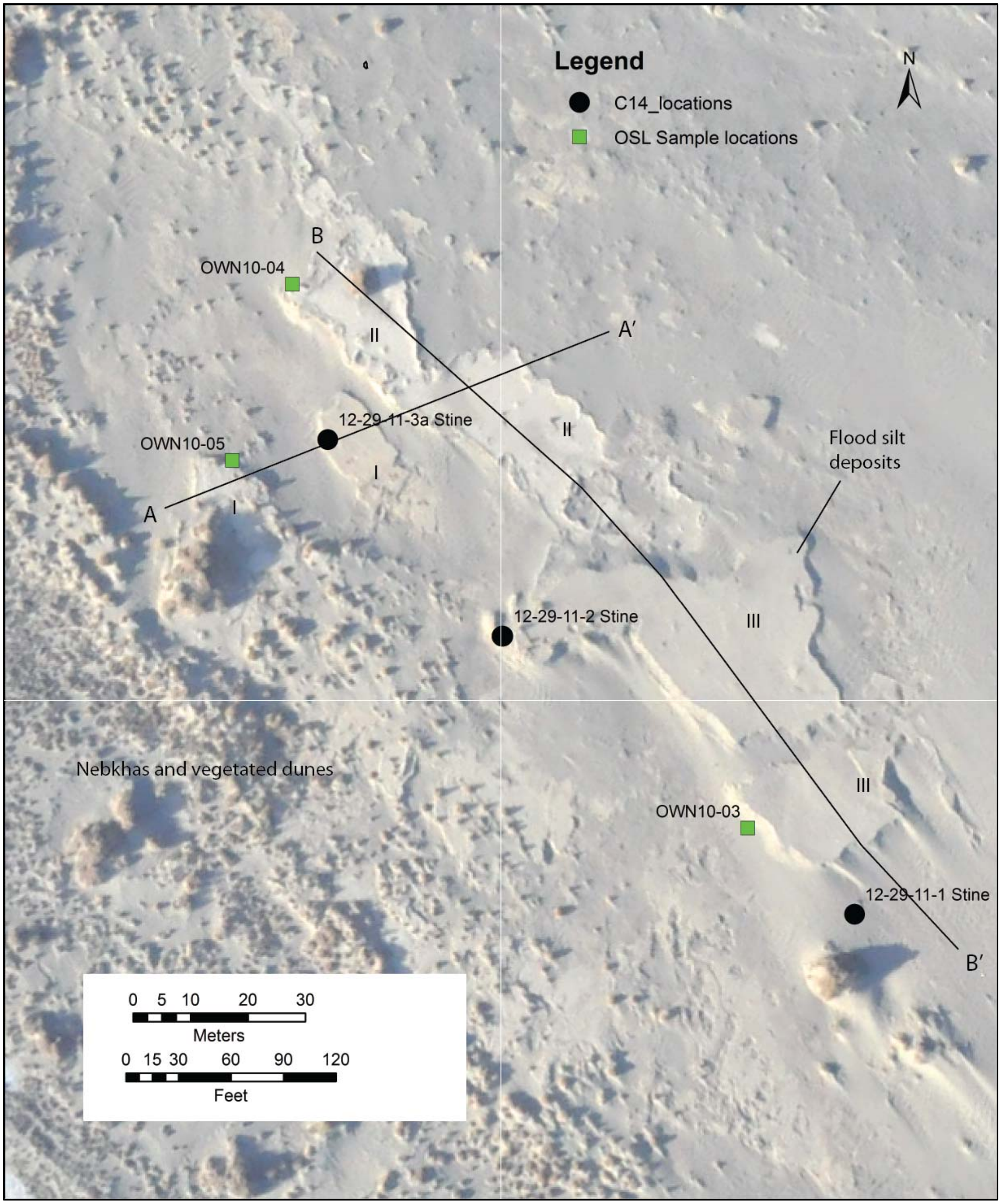


Figure 4.5-4: The Linear Dune site, showing location of OSL and radiocarbon dates and cross-section lines (cross sections are shown in Figure 4.5-5).

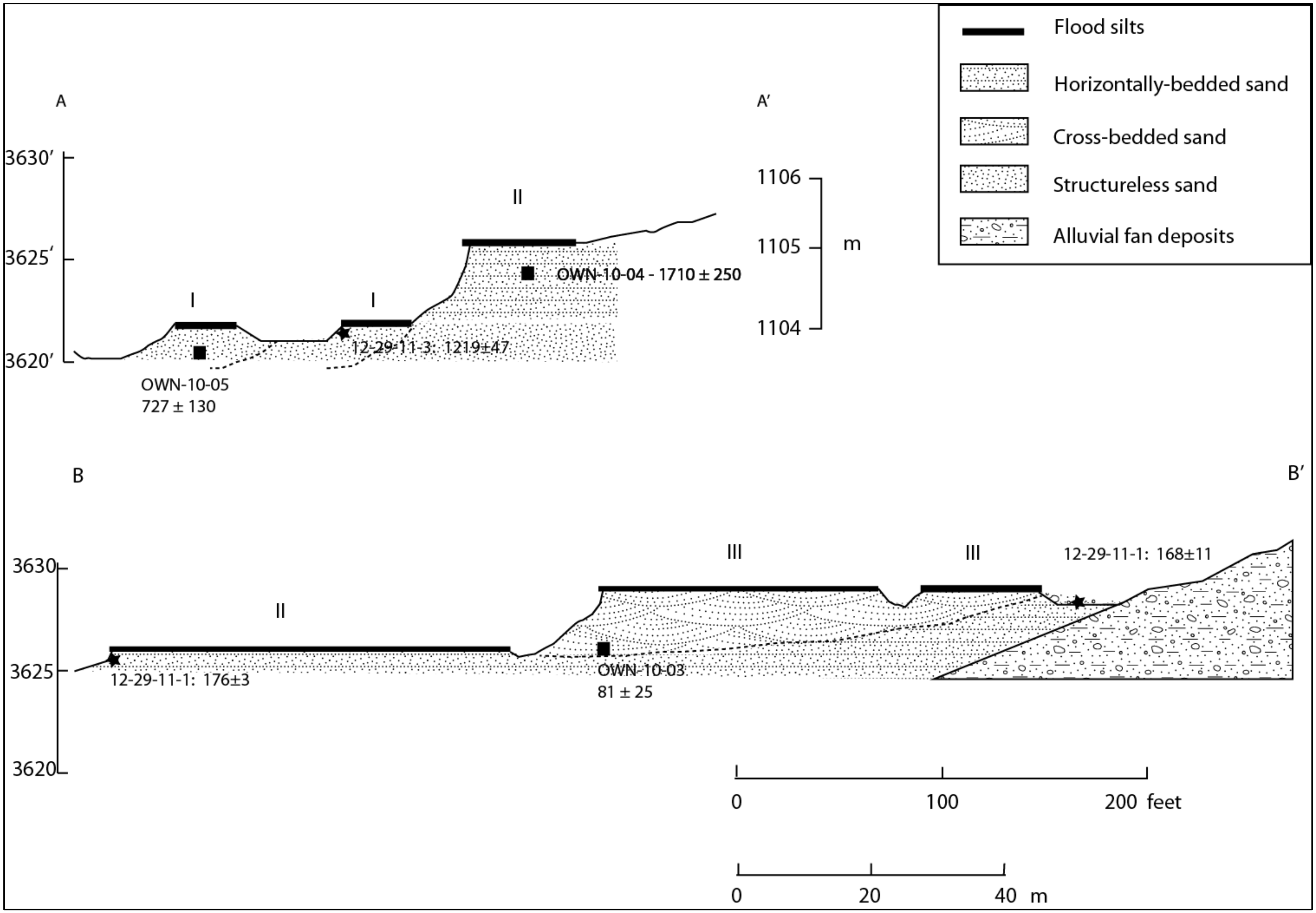


Figure 4.5-5: Generalized topographic and geologic cross-sections for area shown along the western portion of the Linear Dune. Location of cross-section lines is shown in Figure 4.5-4. Profile based on 0.5 m LiDAR topographic data, augmented by differential GPS surveys. (From Lancaster and Bacon, 2012a)

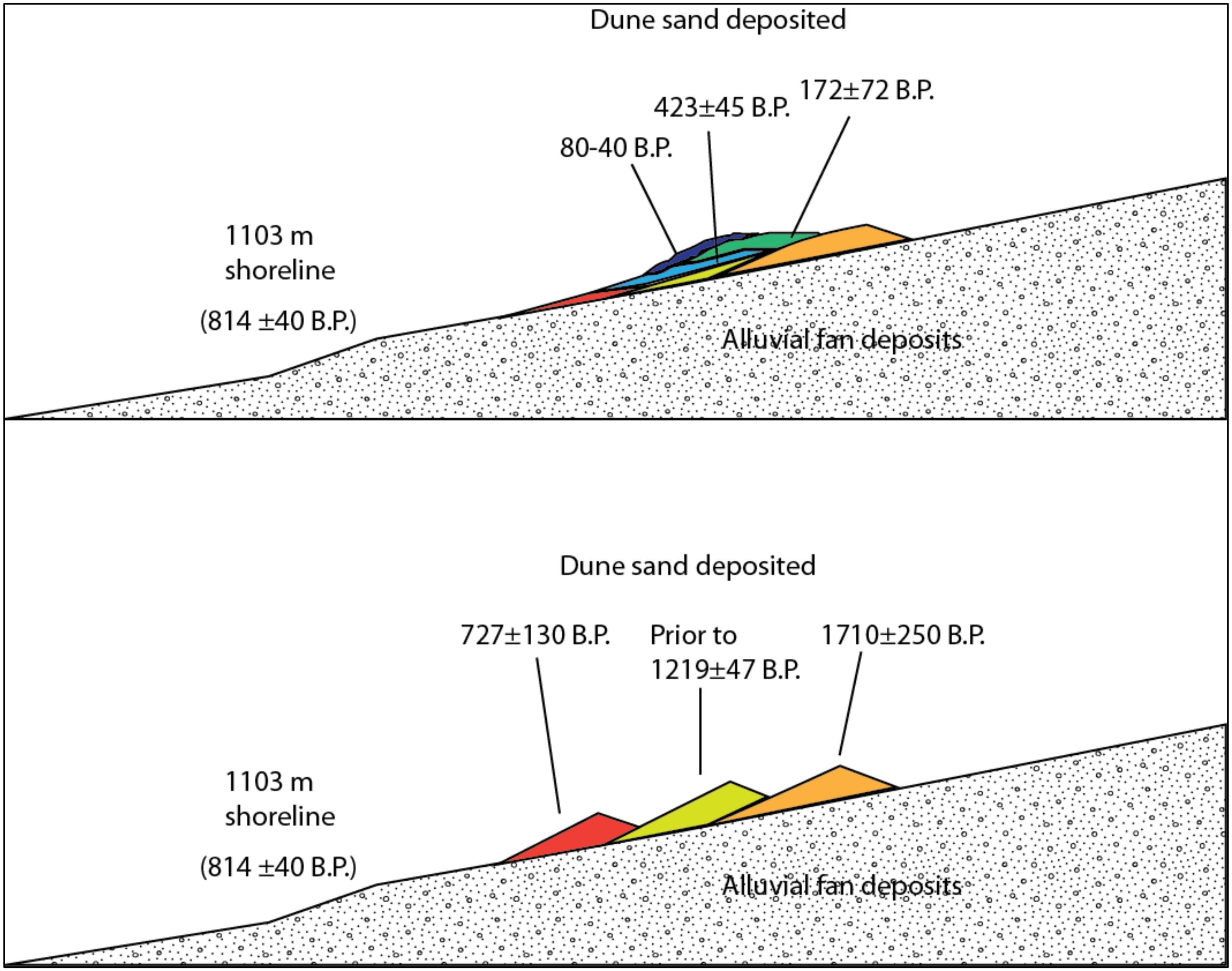


Figure 4.5-6: Schematic illustration of aeolian sand deposition on the Keeler Fan. (From Lancaster and Bacon, 2012a)

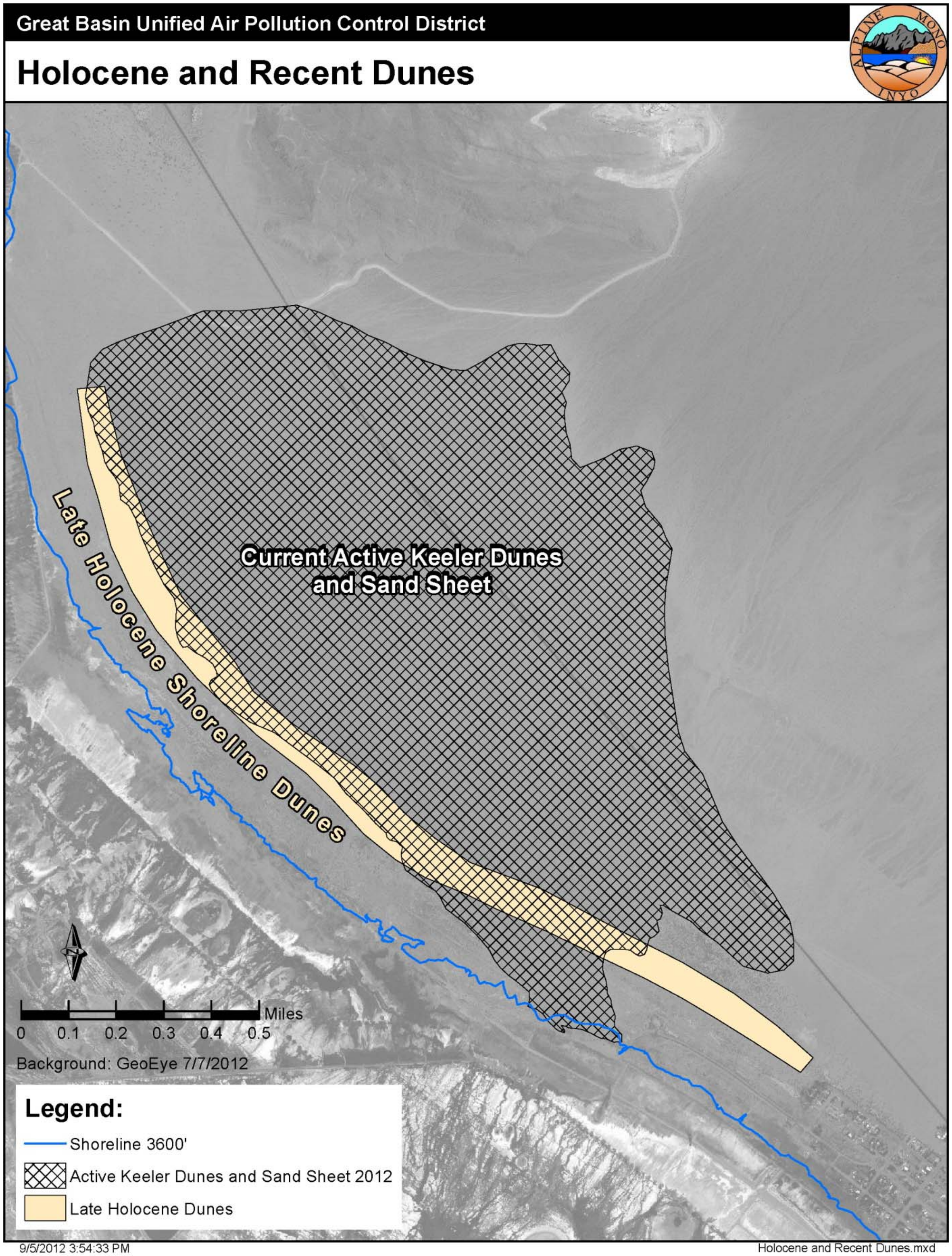


Figure 4.5-7: Map showing the extent of the active Keeler Dunes and sand sheet deposit (from July 2012) with the generalized location of older dune features associated with Late Holocene shorelines.

Lizard Tail Dunes Area

Two sites were sampled for OSL dating in the Lizard Tail dunes, in the vegetated dunes of unit Qe(vd) (see Section 4.4 and Attachment D) adjacent to the Lizard Tail meteorological station (Figure 4.5-3). As discussed above, Site 5 was located on the southwestern, lake proximal ridge, which is approximately 2 m high; whereas Site 8 was located on the northeastern ridge away from the lake, which reaches a height of 4 – 5 m (Figure 4.5-8). The shoreward ridge is cut by the 1872 shoreline at an elevation of 1097 m; while both ridges lie topographically below the 1103 m shoreline notch cut into late Holocene alluvial fan unit Qf4, with an age range of 3500 – 830 cal yr. B.P. Samples for OSL dating were collected from several depths down to the base of the dunes using a sand auger, with a special sampling head to allow collection of undisturbed samples that were not exposed to daylight. At Site 5, two samples were analyzed. Sample KD-12-08 from a depth of 0.75 m provided an age of 300±20 B.P., while the age of sample KD-12-10 from 2 m depth was 5000±210 B.P. As mentioned above, this older age from the lower sample likely reflects that of the distal alluvial fan materials that underlie the dunes, rather than the basal age of the dune. At Site 8, four samples were analyzed, at depths of 0.87, 2.0, 3.0, and 3.73 m. Ages range between 400 ± 30 and 710±40 B.P. It appears that two periods of accumulation occurred in the dunes at this site: ~300-420 B.P. and ~600-720 B.P. as shown in Figure 4.5-8.

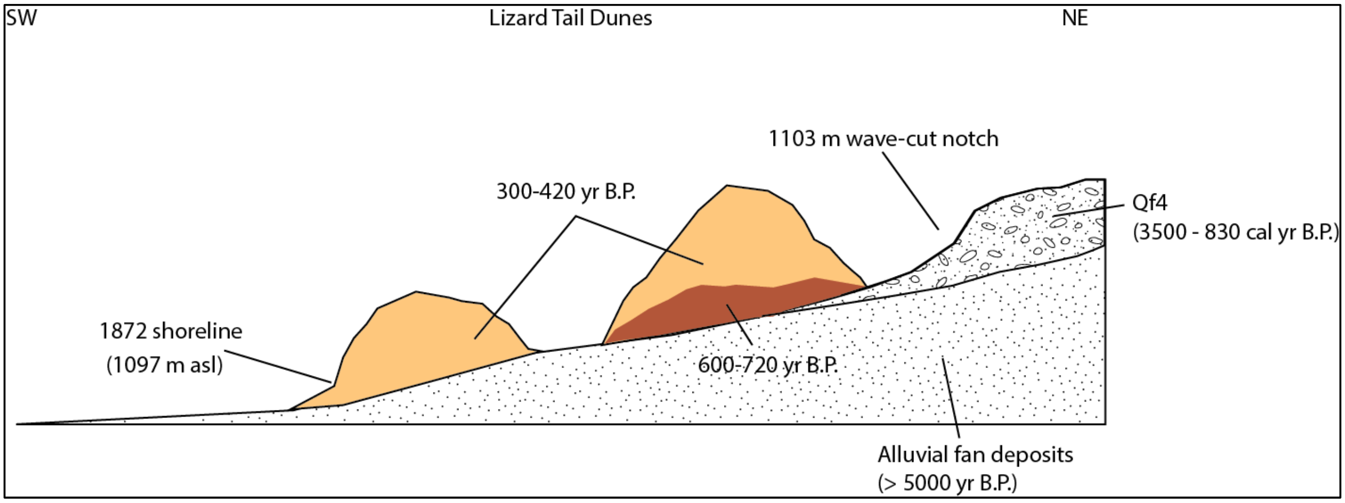


Figure 4.5-8. Schematic cross section of the Lizard Tail dunes area.

Stratigraphic Discussion

These studies provide evidence for episodic aeolian and flood silt deposition over the last 2000 years. The OSL ages from the Linear Dune site appear to reflect inverted topography, where deposits are in reverse topographic order (oldest on top in terms of elevation) relative to other deposits.

The sequence of aeolian deposit ages can be interpreted as a spatial sequence in which sands become progressively younger with decreasing elevation towards Owens Lake, as each sand unit was deposited against pre-existing dune topography (Figure 4.5-6). The radiocarbon ages fall in stratigraphic order and provide good control on the ages of the flood silt deposits. They also suggest that aeolian sands were deposited in the area prior to 1200 B.P., an interpretation consistent with OSL sample OWN-10-04. Aeolian sands were deposited around 172, 423, and 727 B.P. (1839, 1588, 1281 AD, respectively). Recent dated sand deposits span the range from around 80 to 35 years ago (1931-1976) reflecting the deposition of the modern dunes.

The calibrated radiocarbon ages for the upper flood silts are statistically identical and provide good age estimates for the extensive flood silts at around 1106 m elevation. It is clear that there was extensive flooding on the Keeler Fan in the period 1782-1835 A.D. (during the latter part of what is called the Little Ice Age). The floodwaters were ponded against a pre-existing topographic barrier, most likely a small dune, at least in the area of detailed study adjacent to the Linear Dune (which did not form until the 1960s).

OSL sample OWN-10 -06 (Figure 4.5-2), collected from sands on the Northern Dune, indicates that sand was deposited in the sand sheet area of Keeler Dunes around 1971 and covered by flood silts afterwards. Significant floods on the Keeler fan occurred in 1979 and 1980, and it is likely that these flood silts were deposited at this time.

The OSL ages from the Lizard Tail dunes indicate two periods of aeolian sand accumulation: 620-710 yr B.P. (1192 to 1302 AD) and 300-420 yr B.P. (1592-1712 AD). These periods are also represented in the Keeler Dunes area, suggesting aeolian sand accumulation in the area around 300-450 and 600-730 yr B.P. (1563-1712 and 1282-1412 A.D.). The older of these periods immediately follows the 1103 m lake highstand that occurred at around 814 yr B.P. (1136 A.D.), and likely was the result of the lowering of the lake level and exposure of lake plain sediments at this time.

The age dates from the samples from the Keeler Dune area and the Lizard Tail dunes are plotted on Figure 4.5-9 (from Lancaster and Bacon, 2012a) to show the correlation with the tree ring record from the last 2000 years and a sediment core record from the last 1000 years. The tree ring record was compiled from data collected in the Bristlecone Pines in the White Mountains (see Lancaster and Bacon 2012a) and the core record from Owens Lake (Li et.

al.,2000). The tree ring record has been shown to be a good proxy for precipitation and therefore also to lake level. Similarly, the sediment core data from Li et. al. (2000) is also considered to be a general proxy for lake depth based on the overall chemistry and particle size of the sediment.

Significantly, there appears to be a very good correlation between the ages of the shoreline dune sands and the “Dry” intervals as recorded on the tree ring record. The correlation with the interpreted water level from the sediment core record is not as strong but generally shows that the Holocene dune deposits formed during low water levels. These indicate that there is an overall climatic response of the system in the development of the identified Holocene shoreline dunes with an overall pattern in which shoreline dunes form during periods when the lake is low. Based on geomorphic mapping and age date analyses, these dunes appear to have been restricted to former shoreline areas and were most likely vegetated and relatively stable. Although the Keeler Dunes appear to have formed in a similar manner, from material moving off of the exposed lake bed following the historic desiccation of Owens Lake, the identified Holocene dunes are not thought to be similar in character to the modern Keeler Dunes which by contrast are a recent formation and are laterally extensive.

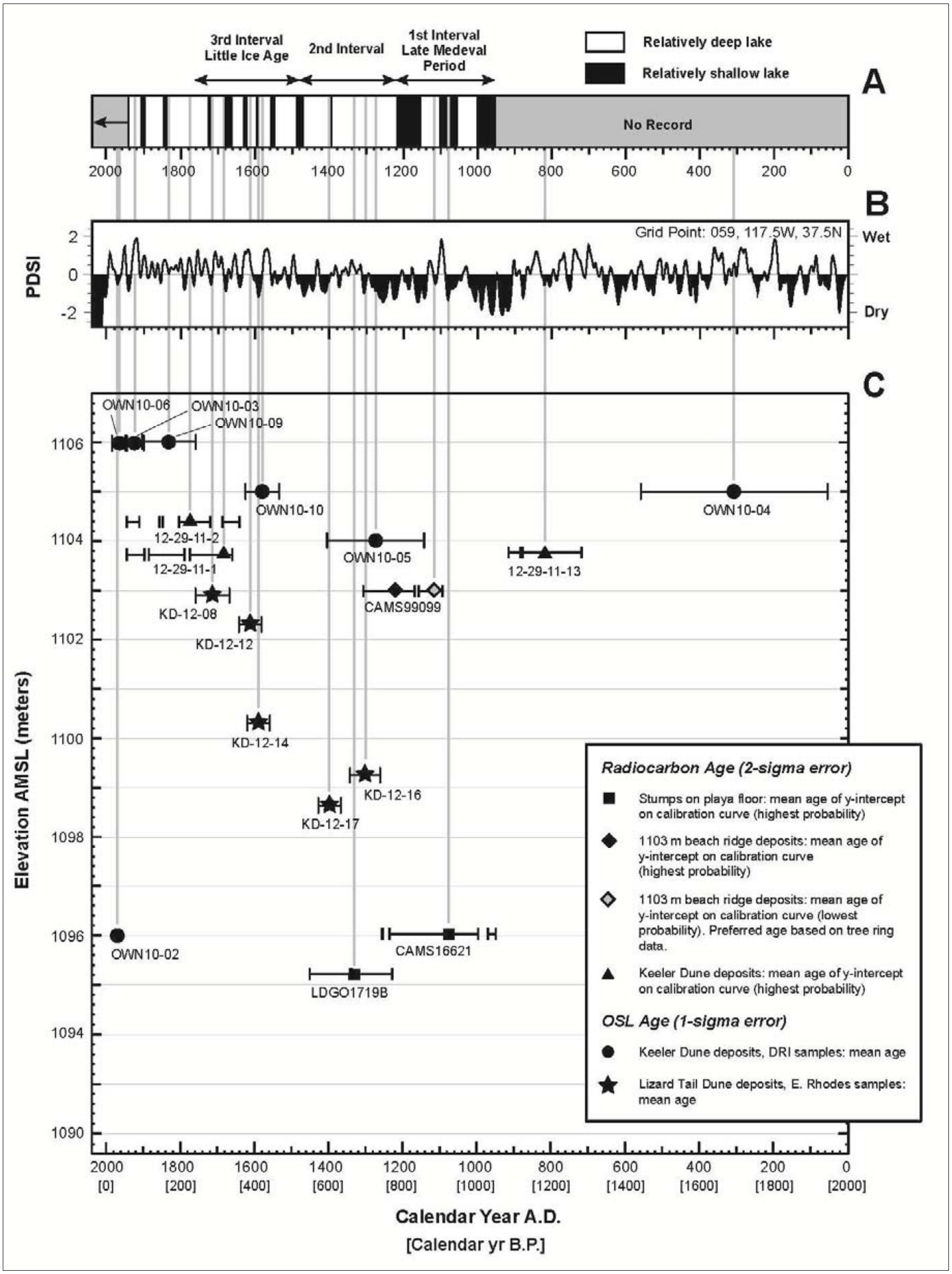


Figure 4.5-9. Correlation between the age date analyses from (A) the sediment core record from Li et. al. (2000), (B) the tree ring record from the bristlecone pines, and (C) Owens Lake dune deposits. (From Lancaster and Bacon, 2012a)

4.5.4 Bulk Mineralogical Results

Surface sand samples were collected from locations in the Keeler Dunes as well as locations in the Swansea and Lizard Tail Dunes. Sand was also collected from fluvial (river deposited) sand adjacent to the Owens River channel and the Owens River delta and from active alluvial washes originating from the Inyo Mountains. Sample locations are given in Table 4.5-4 and on shown on Figure 4.5-10.

Table 4.5-4. Sample locations for XRD analysis. Northing (Y) and Easting (X) coordinates given in NAD83, UTM Zone 11. (from Lancaster et. al., 2012)

Table 4.5-4: Locations of samples collected for mineralogical analysis.

Sample	Northing	Easting	Description
OL-11-001	4046226	411516	sand from old channel of Owens River
OL-11-002	4044698	412549	adjacent to Owens River delta channel
OL-11-003	4044736	415742	NW end of Swansea Dunes
OL-11-004	4039172	420654	Southern dunes, crest
OL-11-005	4040245	419447	west end of linear dune
OL-11-006	4040340	419375	cross bedded sand
OL-11-007	4040669	419271	west end of Horseshoe dune
OL-11-008	4041079	419038	north sand sheet
OL-11-009	4041803	419030	Swansea dunes
KF wash 1	4041613	420975	Keeler Fan
KF wash 2	4041553	421101	Keeler Fan

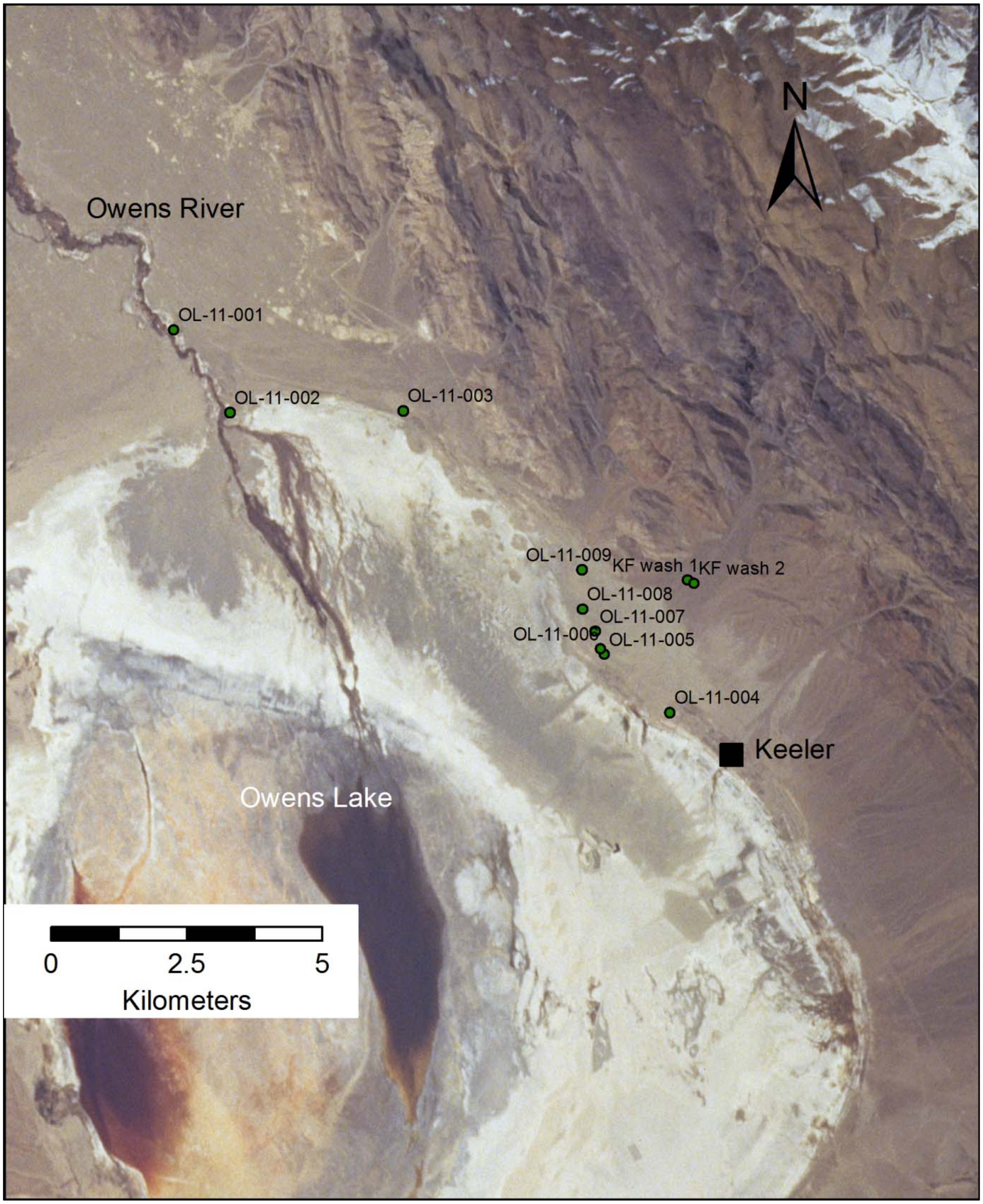


Figure 4.5-10. Location of samples collected for bulk XRD analysis of mineralogy. (From Lancaster et. al. 2012)

The bulk mineralogy of the samples was analyzed using X-Ray Diffraction (XRD). Samples were analyzed at the Soils Lab at DRI in Reno, Nevada. The details of the methods are provided in Lancaster et. al. (2012).

The results of the XRD bulk mineralogy analyses are provided in Table 4.5-5. The XRD data fall into two main groups: (1) samples from the Keeler Fan washes; and (2) sands from the Keeler and Swansea Dunes and the Owens River delta. All nine samples from Group 2 were very similar in mineral composition but significantly different from those in Group 1 (see Table 4.5-5).

The sands from Group 1 were similar to each other. Results indicate that quartz is the dominant mineral (>50%), and calcite is the only other major mineral (>20%) present. Plagioclase and mica are present in minor amounts (<10%), and K-feldspar and hematite may be present in trace amounts (<5%).

For Group 2 (Keeler-Swansea dunes, Owens River delta), the following minerals were identified: quartz (major), plagioclase (major), K-feldspar (minor), calcite (minor to trace), and amphibole (trace). Table 4.5-5 shows the results of the semi-quantitative analysis. Quartz content varies between 30 and 41%; with plagioclase between 38 and 43%; and K-feldspar ranging from 12 to 16%. The compositional data are plotted as ternary diagrams in Figures 4.5-11 and 4.5-12.

Table 4.5-5. Results of semi-quantitative bulk XRD analysis for Keeler Dunes samples

Sample Number	Semi-quantitative XRD results					
	Quartz **- % -**	**Plagioclase** **- % -**	**K-feldspar** **- % -**	**Calcite** **- % -**	**Other ^{1,2}** **- % -**	**Total** **- % -**
Keeler Dunes						
OL-11-004	39	38	10	11	2	100.0
OL-11-005	38	40	14	7	1	100.0
OL-11-006	35	43	13	8	1	100.0
OL-11-007	41	39	12	7	1	100.0
OL-11-008	39	39	14	7	1	100.0
Swansea Dunes						
OL-11-009	38	40	15	6	1	100.0
OL-11-003	37	40	15	6	2	100.0
Owens River						
OL-11-001	40	43	15	1	1	100.0
OL-11-002	38	42	16	3	1	100.0
Owens River						
KF-wash 1	57	8	3	25	7	100.0
KF-wash 2	54	6.5	3	30	6.5	100.0

(1) Other for OL samples is amphibole

(2) Other for Keeler fan samples includes 6% mica (muscovite) and 1% hematite

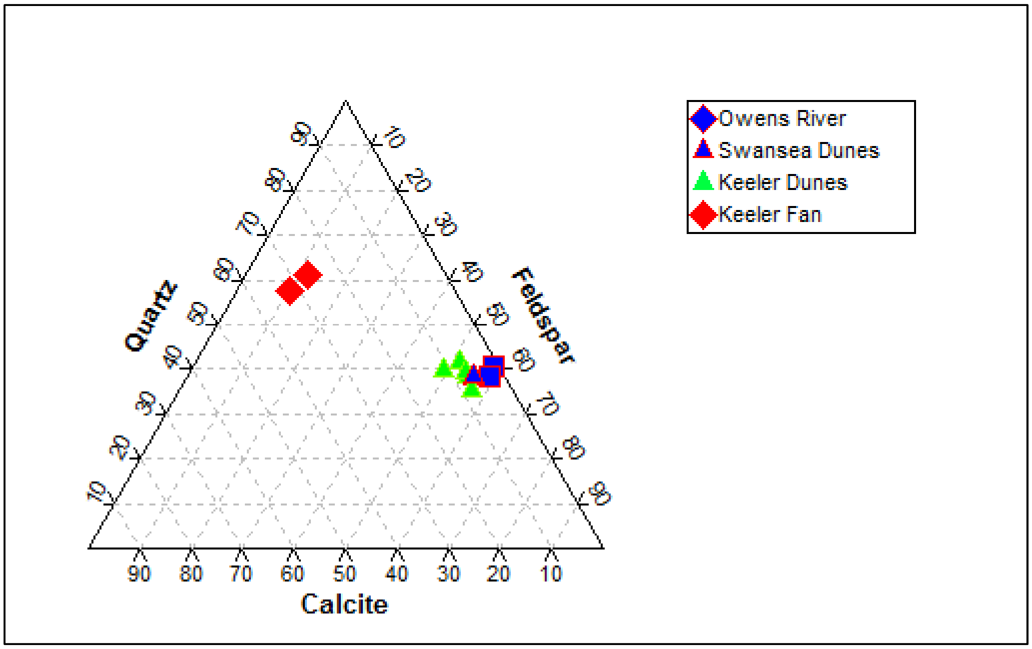


Fig.4.5-11: Ternary diagram showing proportions of quartz, calcite, and feldspar in collected samples.

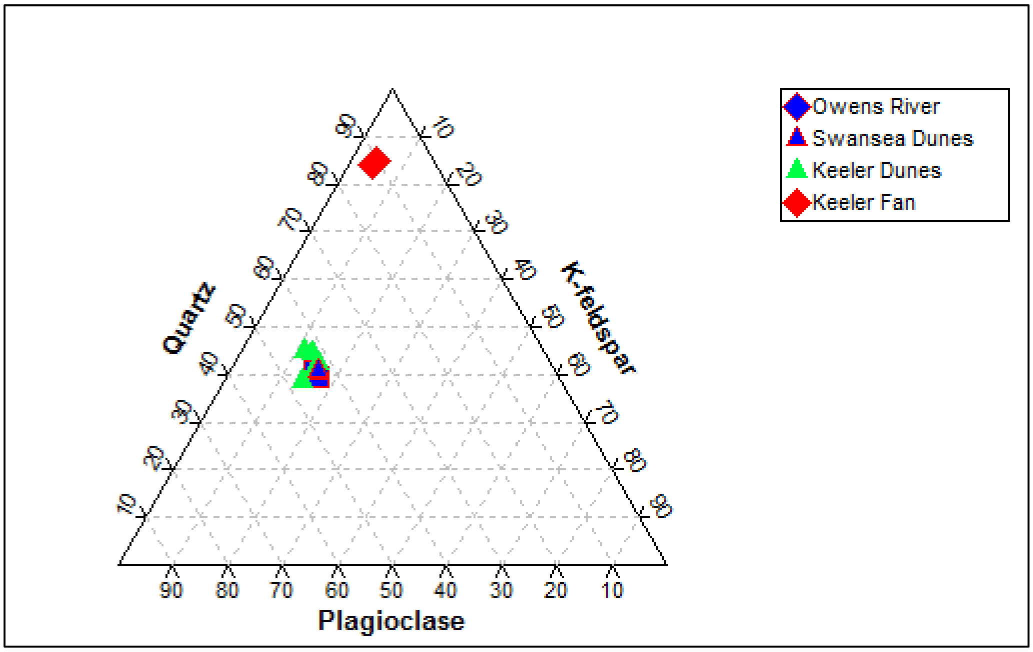


Fig. 4.5-12: Ternary diagram showing proportions of quartz, K-feldspar and plagioclase in collected samples.

The relative proportions of quartz, K-feldspar and plagioclase in the sands from the Owens River, as well as the Keeler and Swansea dunes indicates that they are derived from a granodiorite source rock – as found in the Sierra Nevada (Figure 4.5-13). The sand contains a high percentage of plagioclase and K-feldspar (> 50%), indicating that it is has not been exposed to significant chemical weathering and is mineralogically very immature. This indicates a short transport path and residence time in the fluvial and aeolian environments (in other words, this is young sand that has not been transported very far).

There is no discernible difference between the sand from the Swansea Dunes and the Keeler Dunes, based on this analysis. Likewise, there is no difference mineralogically between the sand that comprises all parts of the Keeler Dunes today and older sands (e.g. the cross bedded sand) that have been dated in this case to 1710 cal yr B.P.

By contrast, the sand from the Keeler Fan washes is quite different with dominant calcite derived from Early Permian and Pennsylvanian-age marine sedimentary rocks (e.g. Lone Pine Formation; Keeler Canyon Formation) in the Inyo Mountains. The sands are characterized by low feldspar content, suggesting that they have been derived from pre-weathered and transported sediments. Stone et al. (2004) report detrital quartz sandstone units in both the above formations, suggesting a source for the quartz in the Keeler Fan wash sediments. Other possible sources of quartz include the Miocene Fanglomerate of Slate Canyon and Jurassic felsite intrusions, as indicated by the ternary plot (Figure 4.5-13).

The similarity of the overall mineral composition of the samples from the Keeler and Swansea Dunes to that from the Owens River indicates that the main source of the sand is the Owens River with minor additions from the Inyo Mountains as suggested by the presence of minor to trace amounts of calcite.

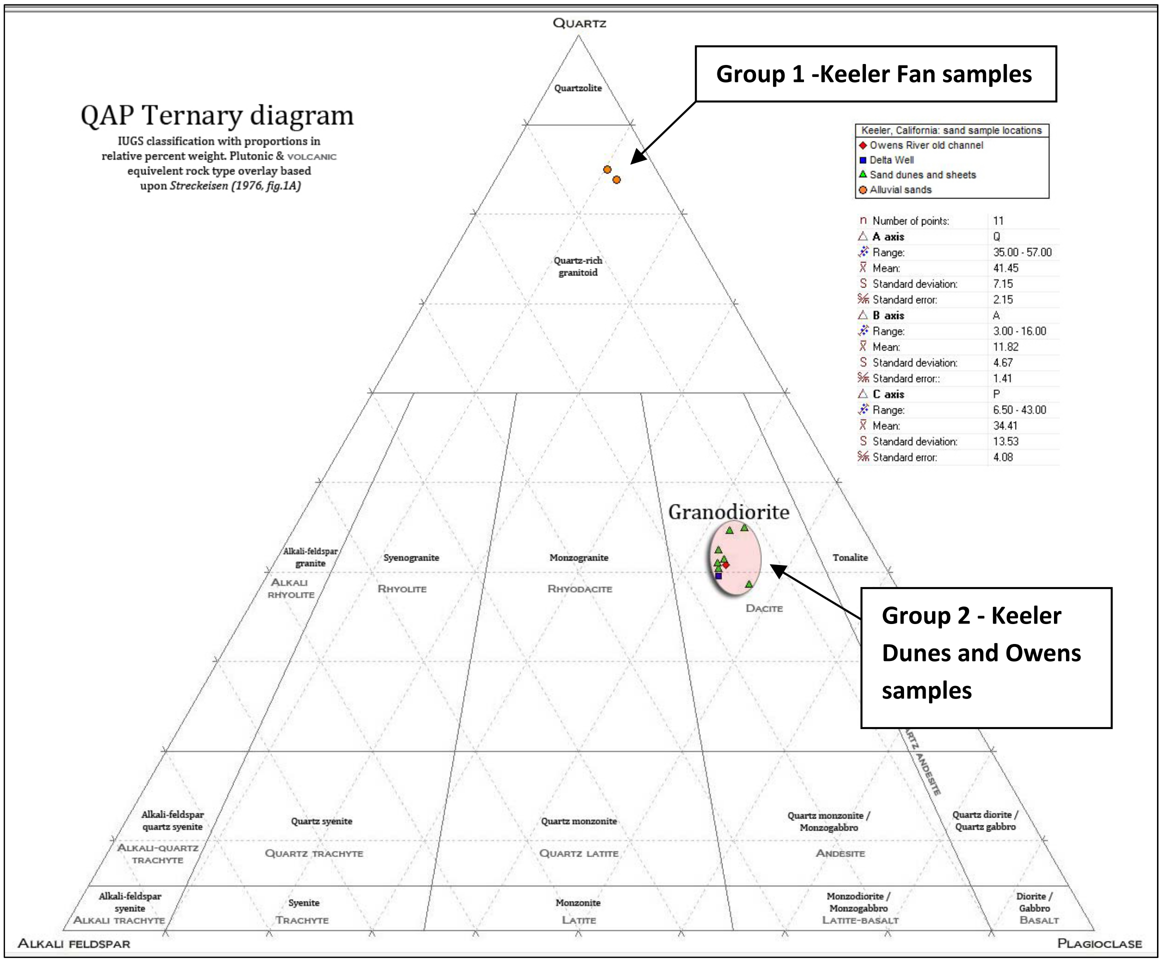


Figure 4.5-13: Ternary diagram showing proportions of quartz, plagioclase feldspar and K-feldspar (alkali feldspar) in sampled sands – plotted with fields used in igneous rock classification – sands are clearly derived from a source rock with granodiorite composition, as found in the Sierra Nevada. (from Lancaster et. al., 2012)

4.5.5 Potential Sources of Sand for the Keeler Dunes

The observed and documented growth and expansion of the Keeler Dunes over the past 50-60 years requires an external source of sand supplying the system (see Section 4.3 and Attachment C). Since 1944 (the date of the earliest aerial photographs available), the Keeler Dunes have undergone significant changes resulting in an increase in the area of the dunes by a factor of three. Much of the increase in dune field area and volume appears to have occurred between 1954 and 1965, with further expansion in the 1980's (Lancaster and Holder, 2012) (Figure 4.5-14). Identifying the source of sand required for the expansion of the dune field area and volume is important to understand how the expansion occurred and to constrain the boundary conditions associated with the expansion.

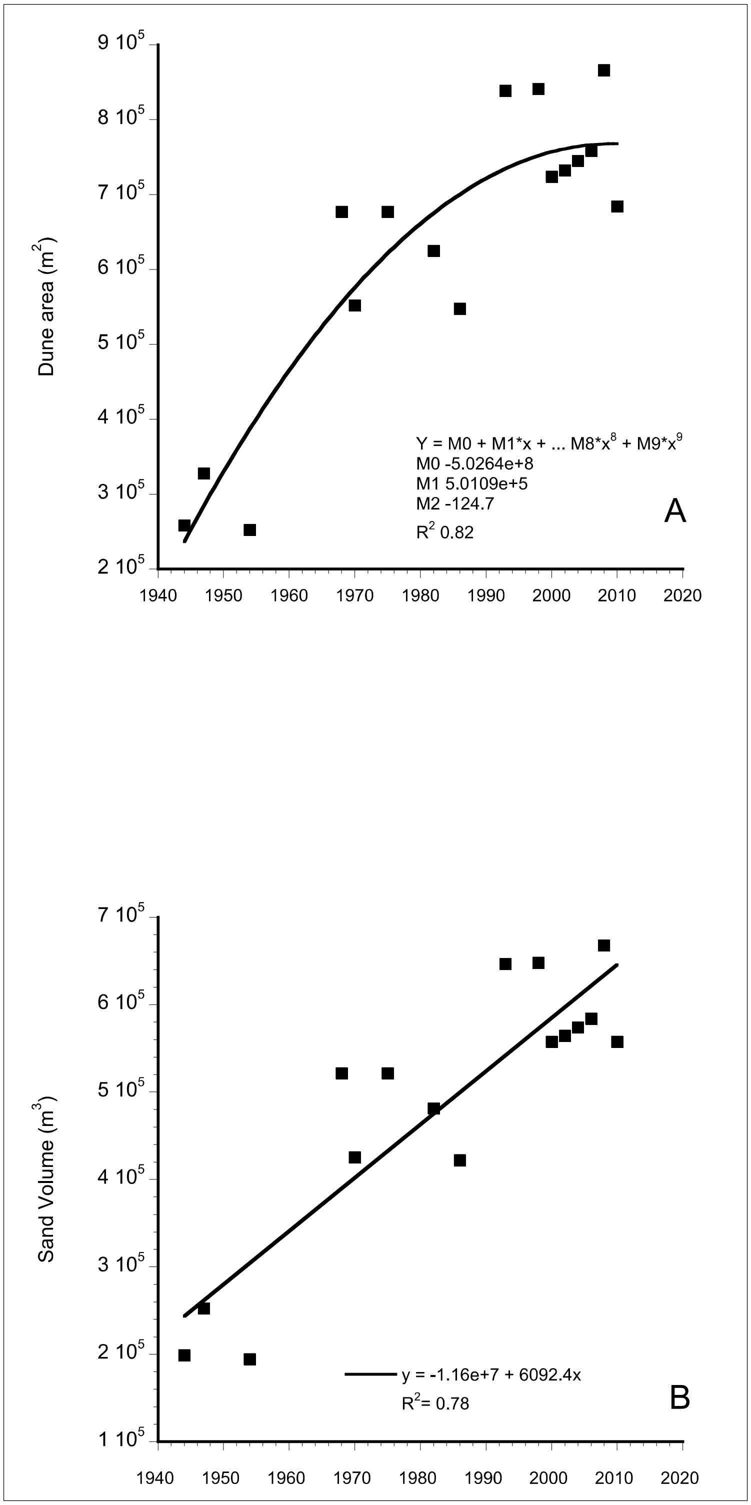


Figure 4.5-14. Changes in (A) area and (B) volume of Keeler Dune field over time. (From Lancaster and Bacon, 2012 and Lancaster and Holder, 2012)

The source of this sand for the Keeler Dunes was investigated by Lancaster and Bacon (2012b). Possible potential source materials include:

(1) alluvial material coming from the Inyo Mountains,
(2) erosion of pre-existing aeolian sands in the vicinity of the present Keeler Dunes,
(3) Swansea Dune area, and
(4) Owens Lake bed and delta.

A summary of each source and its potential for supplying the current Keeler Dunes is provided below. The technical report (Lancaster and Bacon, 2012b) that describes this work is provided in Attachment E.

(1) Alluvial fans derived from Inyo Mountains:

The Keeler Dunes are situated on the apex of the distal part of a large alluvial fan (informally called the Keeler Fan) that originates in Slate Canyon in the Inyo Mountains to the east of Owens Lake. Ephemeral flows of water and sediment derived from the headwaters of this fan system have been noted by observers in the Keeler area for many years. Flows generally follow localized heavy rains in summer or less frequently, winter seasons. Active channels on the fan lie to the north and south of the dune field, with flows generally directed towards Swansea and Keeler.

One of the main active channels from Slate Canyon discharges onto the Owens playa immediately northwest of Keeler Dunes. There is evidence for flooding onto this area on August 1968 aerial photographs (see Figure in Lancaster and Bacon 2012). Other documented significant flood events in the area occurred in 1979, 1982, and other years, including August 2012.

The mineral composition of sand derived from this potential source area is however incompatible with that of the Keeler Dunes, based on bulk XRD mineralogy (see Section 4.5.4, above, and Lancaster et al, 2012). In addition, the potential volume of material derived from these ephemeral flood events is estimated to be low, based on the small area flooded in each event.

(2) Erosion of pre-existing aeolian sands in the vicinity of the present Keeler Dunes:

Parts of the area on the western edge of the present Keeler Dunes are underlain by aeolian sands deposited in prior episodes of accumulation as documented by Lancaster and Bacon (2012a). The composition of these sands is identical to that of the modern dunes. The sands are preserved below thin layers of flood silts and are estimated to cover an area of 100,000 m^2. The maximum measured thickness of these deposits is 1.5 m, giving a maximum estimated volume of 150,000 m^3. Reworking of portions of these deposits could provide material for the expansion of the Keeler Dune field.

However, the volume of material contain is not consistent with the volume of sand estimated to be involved in the expansion of the Keeler Dunes. Expansion of the dune field between 1954 and 1975 involved an additional 327,000 m^3 of sand. If all the pre-existing sands were eroded, they would only provide about 50% of the needed sand volume. However, many of the outcrops of the older aeolian sands are not eroded as they capped by flood silt deposits and therefore unavailable for reworking. Most of the older flood silt units were, in addition, buried by the modern active dunes until 2000, based on examination of aerial photographs.

<u>(3) Swansea Dunes area:</u>

Undulating sand sheets, with a variable vegetation cover and development of coppice dunes comprise an area extending northwest and west along the shoreline from Swansea toward Lizard Tail. These dunes have a composition similar to the Keeler Dunes, but there is no geomorphic evidence for transfer of sand from these dunes to the Keeler Dune. These dunes appear to have been largely stable in area for the period of aerial photograph and satellite records, although changes in vegetation cover have occurred. In addition, evidence from OSL dating of dunes in the western part of this area (the Lizard Tail Dunes) suggests that these dunes have been stable for past 300-400 years.

<u>(4) Owens Lake bed and delta:</u>

The composition of the Keeler and Swansea dunes as determined by bulk XRD mineralogy is identical to sand from the Owens River delta and fluvial deposits (Lancaster et al., 2012). This suggests strongly that the Keeler Dunes are derived from this source, either directly by deflation and wind transport of sand deposited by major flood events in the Owens River (e.g. 1939, 1969, 1982), or by wind erosion and deflation of sandy lacustrine and deltaic sediments deposited prior to the lowering of Owens Lake by water diversions.

Measurements of winds and sand flux on the northern part of the lake bed and sand sheets indicate that sand is transported by winds from the W-NNW and SSW-SSW sectors (Figure 4.5-15 and Ono et. al., 2012). In any year, sand is transported back and forth by the wind, but with a net (or vector) of movement at this location towards the east (082° azimuth). The sand flux measurements indicate that very significant quantities of sand are transported in this manner (Cox and Holder, 1997).

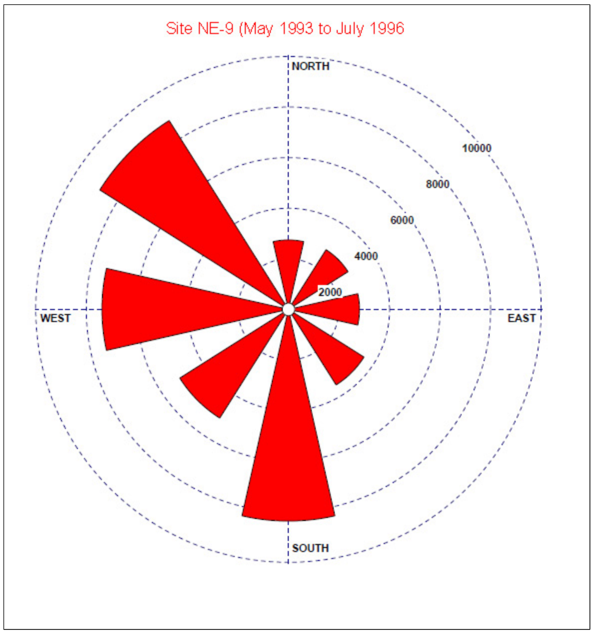


Figure 4.5-15. Summary of sand transport in the area between the North Sand Sheet and the Keeler Dunes. Net sand transport is towards 82°. From data in Cox and Holder (1997).

Based on the results of the geomorphic mapping (see Section 4.4 and Attachment D), the amount of area on the lake bed and in the delta that show evidence of significant erosion since exposure due to the modern desiccation of Owens Lake can be estimated. Figure 4.5-15 shows a generalized geomorphic map of the northeastern portion of Owens Lake below the 3600 foot elevation from 1998 (immediately prior to the construction of dust controls on the lake floor) as well as the reconstructed lake bed structure from 1872 to 1924. The extent of modification of the exposed lake bed due to the historic exposure is evident by comparison of Figure 4.5-16A to Figure 4.5-16B. A map of the aeolian units that are present on the northeastern portion of the lake bed is provided in Section 4.4 (Figure 4.4-5).

The maps provided in Figure 4.5-17 allow an estimate calculation of amount of area that has been affected by wind erosion on the northeastern portion of the lake bed. Figure 4.5-17a illustrates the reconstructed lake bed features separating the units above the 3560 ft elevation[13] into either a deltaic or lake plain deposit. Figure 4.5-17b shows how these features were as of 1998 (prior to dust controls) and thus how they have been modified for 74 years following complete desiccation of the lake. From this comparison, it is apparent that 8.7 square miles of lake plain on the eastern side of the delta (Ql(1)) has been eroded to form the current mapped playa (Qpl(1)). Additionally, a significant portion (0.8 square miles) of the delta

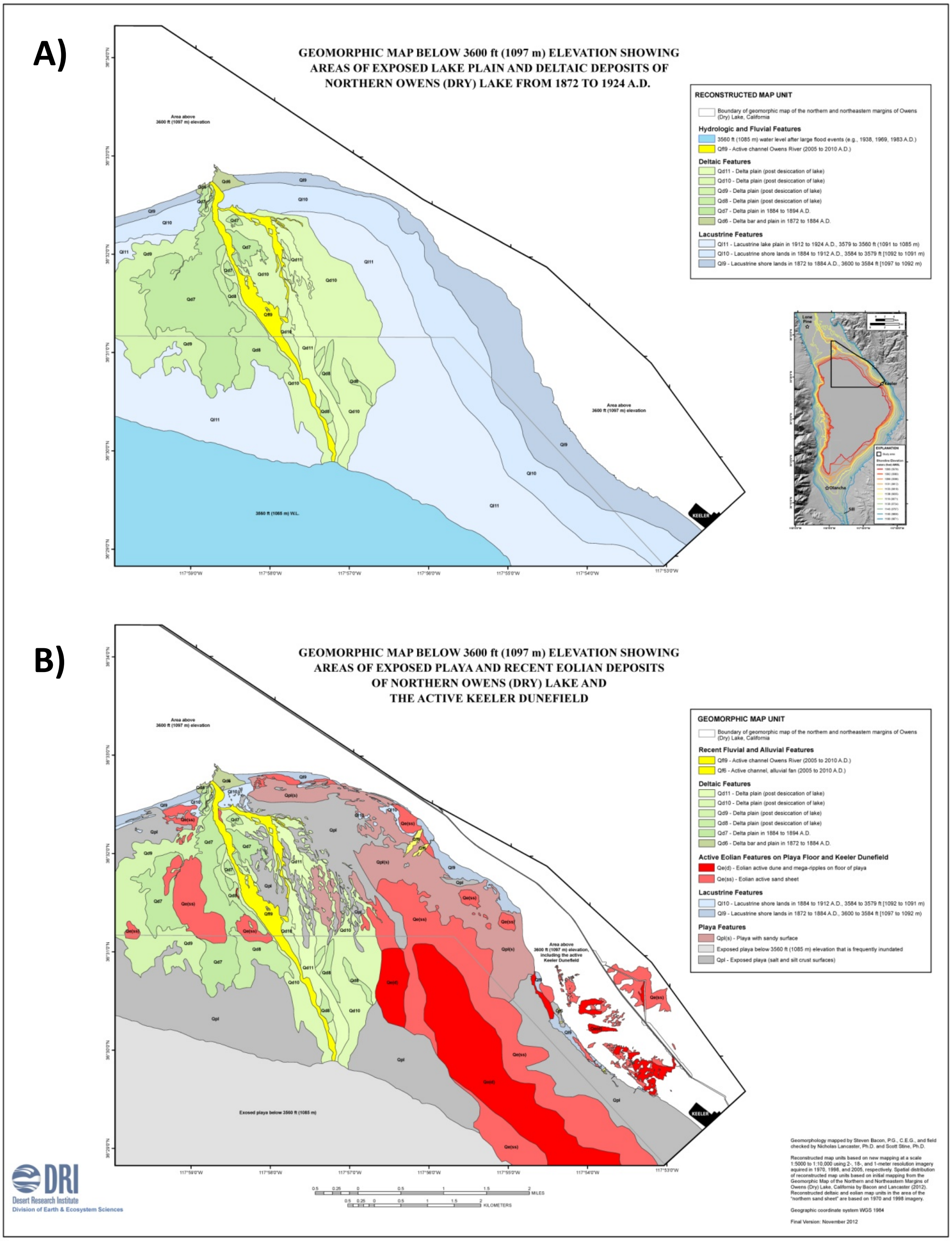
---

[13] This is the approximate elevation in 1924 when the lake level was receded to essentially the extent of the current brine pond.

deposits have been eroded to form the unit Qpl(3). The combined total of this eroded area is 9.5 square miles. These calculations indicate that only 6.1% of the original lake plain still remains in small areas along the north shore of the playa. In the area of the delta that was exposed by reduction in the lake level from 1096 to 1085 m, some 2 km^2 or 13% of the original extent of deposits had been eroded by the wind to expose underlying playa sediments. If the deltaic deposits consisted of 100% sand sized material and only a 0.5 m thickness of material had been removed in this way, it would have generated roughly 1 million cubic meters of sand for transport downwind to form other deposits, such as the North Sand Sheet (10.7 km^2 in extent, as shown on Figure 4.5-17) and the Keeler Dunes.

The area east and northeast of the exposed delta and below the historic shoreline is today comprised of areas of eroded lake plain that expose underlying playa sediments (1.64 km^2), together with areas of sand sheets (Qe (ss) on Figure 4.5-16b) with an area of 3.20 km^2. The eroded lake plain is considered to be a likely source area for the Keeler Dune field. If this part of the original lake plain was covered with the equivalent of 0.50 m thickness of sand, the eroded material would comprise 820,000 m^3 of sand. The estimated mean volume of the Keeler Dunes has ranged from 200,000 m^3 in the 1940s-1950s to 500,000 m^3 in the 1970s and 600,000 m^3 in the period 1990-2010. It is therefore quite feasible to generate sufficient sand to increase the area and volume of the Keeler dunes since the 1950s by erosion of sandy lake plain deposits exposed by lowering of lake levels. Although variable image quality makes definitive determinations of sand sheet extent and characteristics difficult, it is noteworthy that aerial photographs of the area in the 1940s and early 1950s show an extensive sand sheet between the delta and the shoreline in the vicinity of the Keeler Dunes. This sand sheet was progressively eroded by 1970. 1982 photographs also appear to show a relatively extensive sand sheet, which had largely been eroded in its western parts by the 1990s. (Lancaster, 2012; and Lancaster and Bacon, 2012b)

In summary, the sand mineralogy and reconstructions of the former lake plain extent strongly indicate that the Owens River delta and/or adjacent sandy lake plain sediments exposed by low lake levels provided the major source of sand for the Keeler Dunes. The progressive or episodic erosion of these materials by predominant winds transported this material in a net easterly-southeasterly direction towards the area of Keeler Dunes, where it was deposited as a result of reduced wind energy. Additional contributions may have come from sands deposited in the delta region by large flood events in the Owens River.



Geomorphology mapped by Steven Bacon, P.G., C.E.G., and field checked by Nicholas Lancaster, Ph.D. and Scott Stine, Ph.D.

Reconstructed map units based on new mapping at a scale 1:5000 to 1:10,000 using 2-, 18-, and 1-meter resolution imagery aquired in 1970, 1998, and 2005, respectively. Spatial distribution of reconstructed map units based on initial mapping from the Geomorphic Map of the Northern and Northeastern Margins of Owens (Dry) Lake, California by Bacon and Lancaster (2012). Reconstructed deltaic and eolian map units in the area of the "northern sand sheet" are based on 1970 and 1998 imagery.

Geographic coordinate system WGS 1984

Final Version: November 2012

Figure 4.5-16. Geomorphic maps of the northeastern portion of Owens Lake. **A)** map of the reconstructed lake plain units that formed from 1872 to 1924. **B)** Generalized geomorphic map of the northeastern portion of Owens Lake from Bacon and Lancaster (2012). (Figure from Lancaster and Bacon, 2012b)

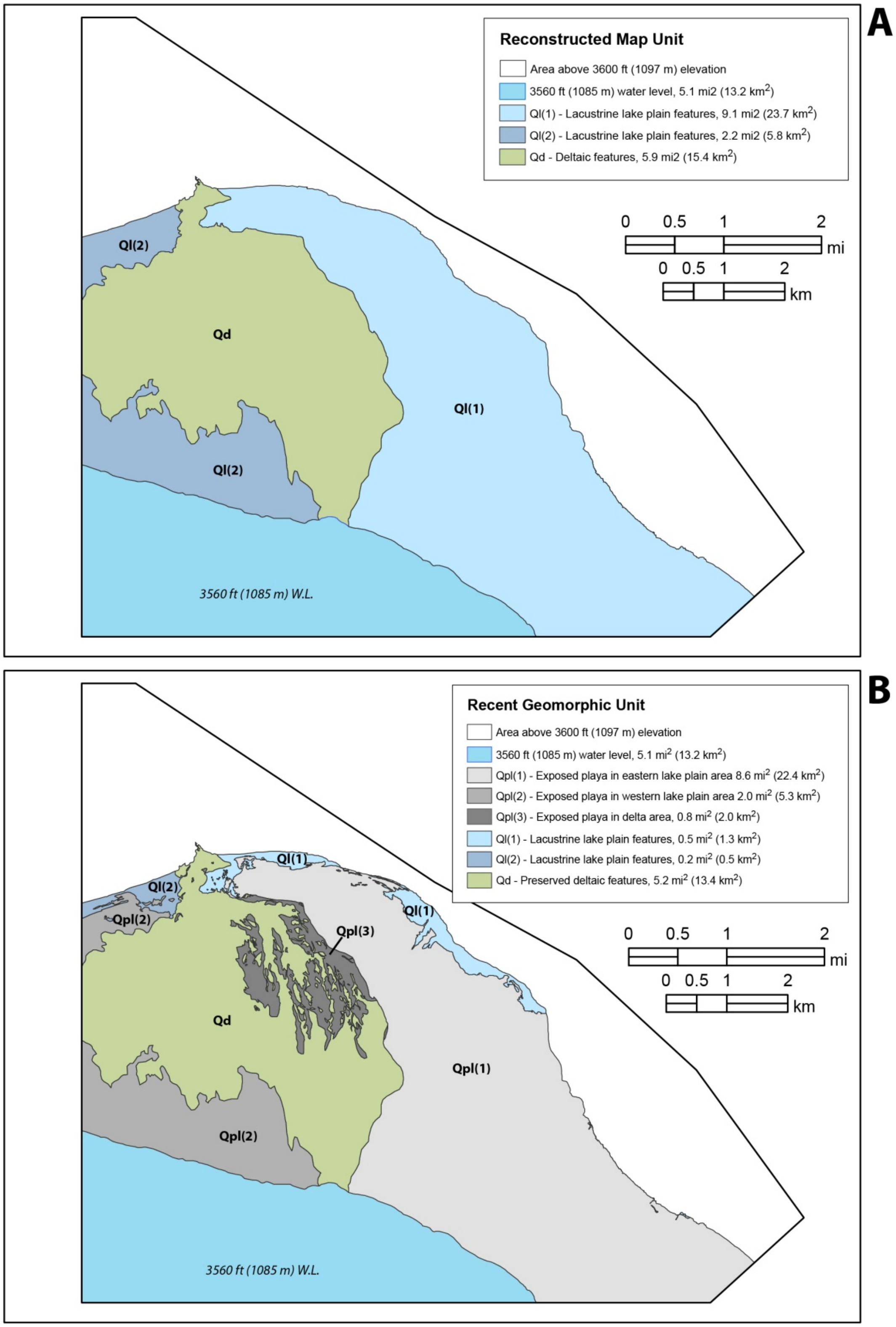


Figure 4.5-17. Map showing the A) reconstructed and B) the recent lake plain and deltaic geomorphic deposits on the northeastern portion of Owens Lake below 3600 feet elevation. (Figure from Lancaster and Bacon, 2012b)

4.6 Analysis of Surface Change in the Northeast Portion of Owens Lake

The District has monitored sand motion on and adjacent to Owens Lake in various capacities since the mid-1980's. Up until 1999-2000, sand motion monitoring was associated with specific dust control measure research projects on the lake bed such that the initial record is both spatially and temporally discontinuous. Beginning in 1999-2000, the District began implementing a large-scale sand motion monitoring program across the Owens Lake bed as part of the Dust Source Identification Program (Dust ID). The Keeler Dune area was included in this large-scale monitoring network with two sites installed in 2000. Additional sand motion monitoring sites were installed in the dunes in 2008-2009 when the District began the focused Keeler Dunes Investigation.

An analysis of sand motion data from the northeastern portion of Owens Lake over two separate time periods was conducted by District staff (Ono et.al., 2012). For each time period the annual and overall surface change was estimated using hourly sand flux values from the sand motion monitoring sites and wind direction data to determine the annual net sand movement of sand within the analysis area. A detailed explanation of the methodology used for the calculations and data analysis are provided in Ono et. al. (2012) and in Attachment F.

The first time period analyzed was from January 2000 to December 2001. Data from this period was evaluated using a 1-square kilometer grid (Figure 4.6-1). This time period represents the two-years prior to the implementation of the Shallow Flooding dust control measure on the northeast portion of the lake bed. During this period there were only two sand motion monitoring sites in the Keeler Dunes (sites 7223 and 7247). Many of the lake bed monitoring sites were removed in 2002 due to the operation of Shallow Flooding and are therefore not present in the second study period from 2009-2012.

The second time period analyzed extends from July 2009 to June 2012. During this time period, the Shallow Flooding dust control measures on the lake bed were in full operation and the sand motion monitoring network in the Keeler Dunes was expanded from the original two sites to twelve sites. The data from this period was evaluated using an array of 125 x 125 meter grid cells configured to overlay the irregular distribution of sand motion monitoring sites (Figure 4.6-2).

Figure 4.6-1. Map showing the kilometer grid and sand motion monitoring sites used in 2000-2001 analysis. Sand motion monitoring sites are labeled by Sensit site number. The dust control areas shown on the map are for reference and were not implemented during the 2000-2001 study period.

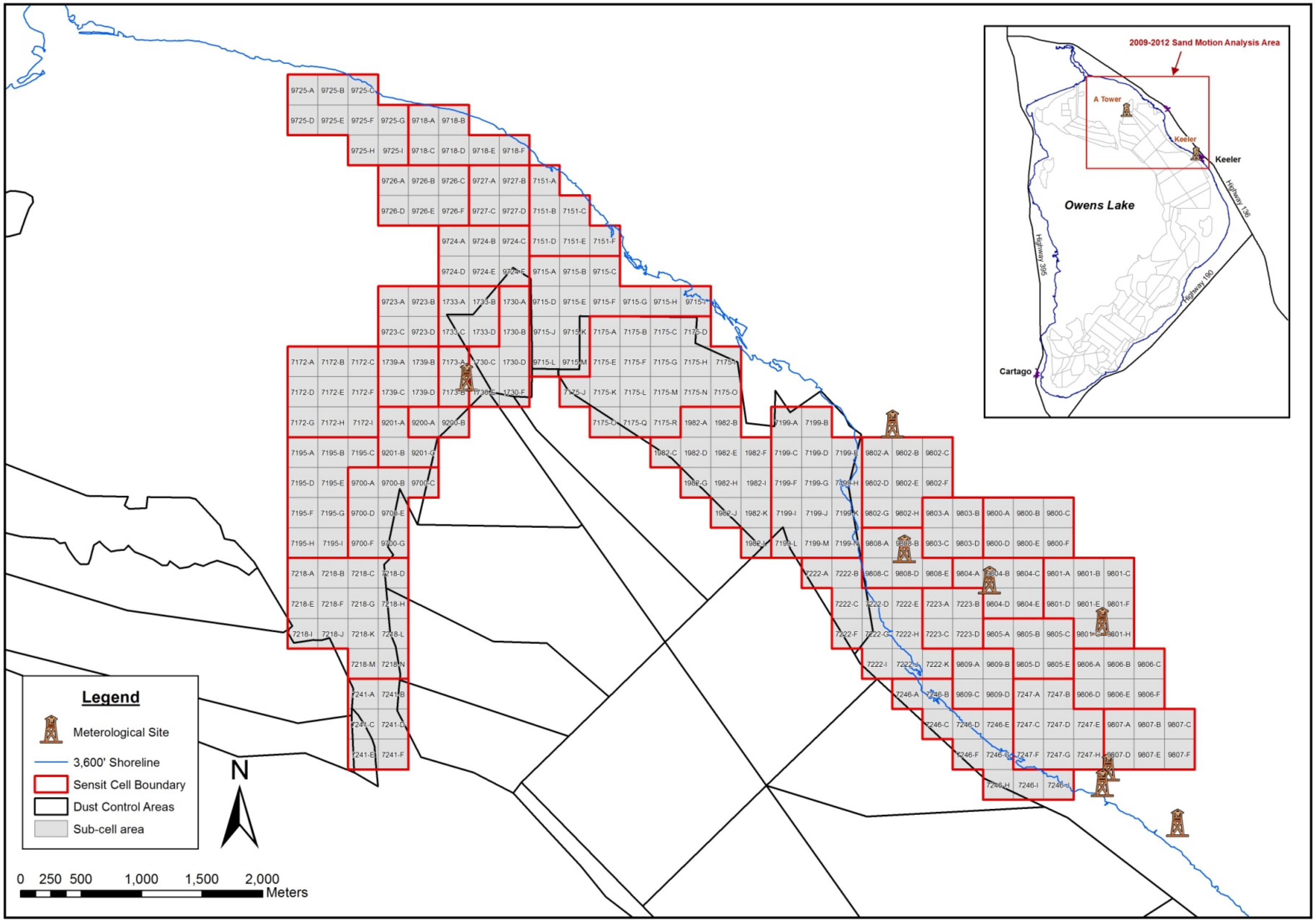


Figure 4.6-2. Map showing irregular grid pattern used in the sand motion monitoring for 2009-2012. The bold red outlined areas show the areas designated for the sand motion monitoring sites. Each inner grid cell used in the analysis is 125 x 125 m.

2000 to 2001 Surface Change

Figures 4.6-3 to 4.6-5 show contour color-shaded maps of the surface changes estimated for calendar years 2000 and 2001 and for the average of both years. The areas with overall deposition are shown in shades of blue and the areas with net erosion are shown in yellow-red. Arrows show the relative magnitude and direction of the net sand movement at each sand flux measurement site over the sampling period.

In the 2000-2001 time period surface elevation changes ranged from deflation of 1.41 cm per year to inflation of 0.97 cm per year. Overall, the study area was losing surface sand at an average rate of 0.10 cm per year (Ono et. al., 2012). The general pattern evident in Figures 4.6-3-4.6-5 is one of erosion in the central portions of the north sand sheet and deposition along the east and west edges of the future dust control area (shown as the black outline of the dust control measures). The largest deposition area corresponds to area along the eastern shoreline of the playa and the southern portion of the Keeler Dunes. The area of moderate erosion present in the northwestern portion of the Keeler Dunes corresponds to the area indicated in Lancaster (2012a) as being stripped of sand starting in the late 1990's (see Section 4.3)

Interestingly, the area of high deposition on the lake bed in 2000 corresponds to the location of the District's SURF (Shallow Un-confined Re-circulated Flood) (Agrarian, 2001) dust control measure test. This test was conducted from October 1999 to September 2000 and consisted of 320 acres of lateral Shallow Flooding. Notice that the distribution of high lake bed erosion is interrupted by the SURF test. The SURF test area and the location of former dunes that used to be present on the lake bed are shown on Figure 4.6-3. Notice that the amount and extent of the deposition in the SURF area is dramatically reduced in 2001 following the end of the project (Figure 4.6-4).

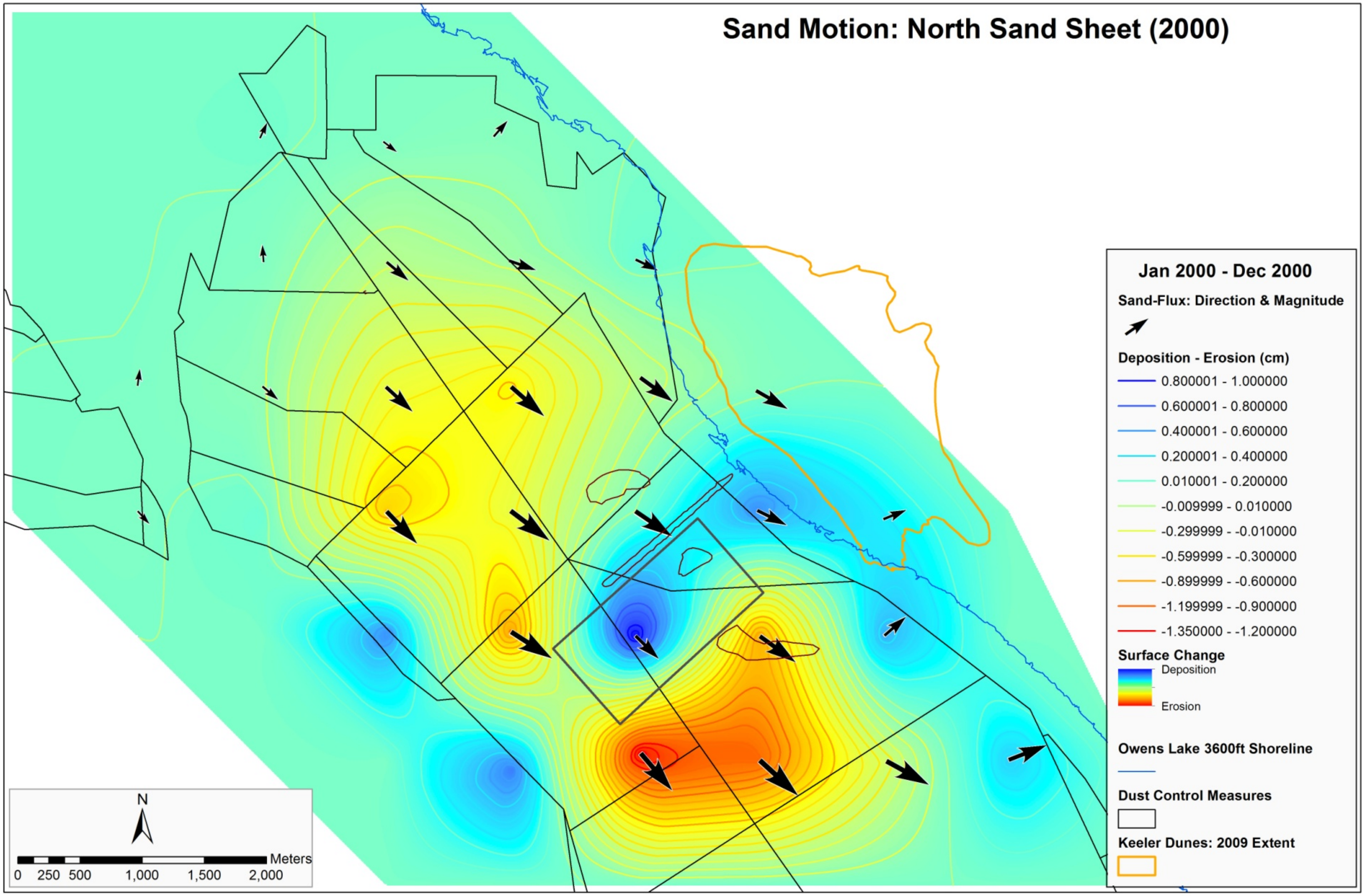


Figure 4.6-3. Surface change on the northeastern portion of Owens Lake from January 2000 to December 2000. The location of the dunes on the lake bed and the outline of the extent of the Keeler Dune deposit are shown as is the location of the District's former SURF project (rectangle in center of map).

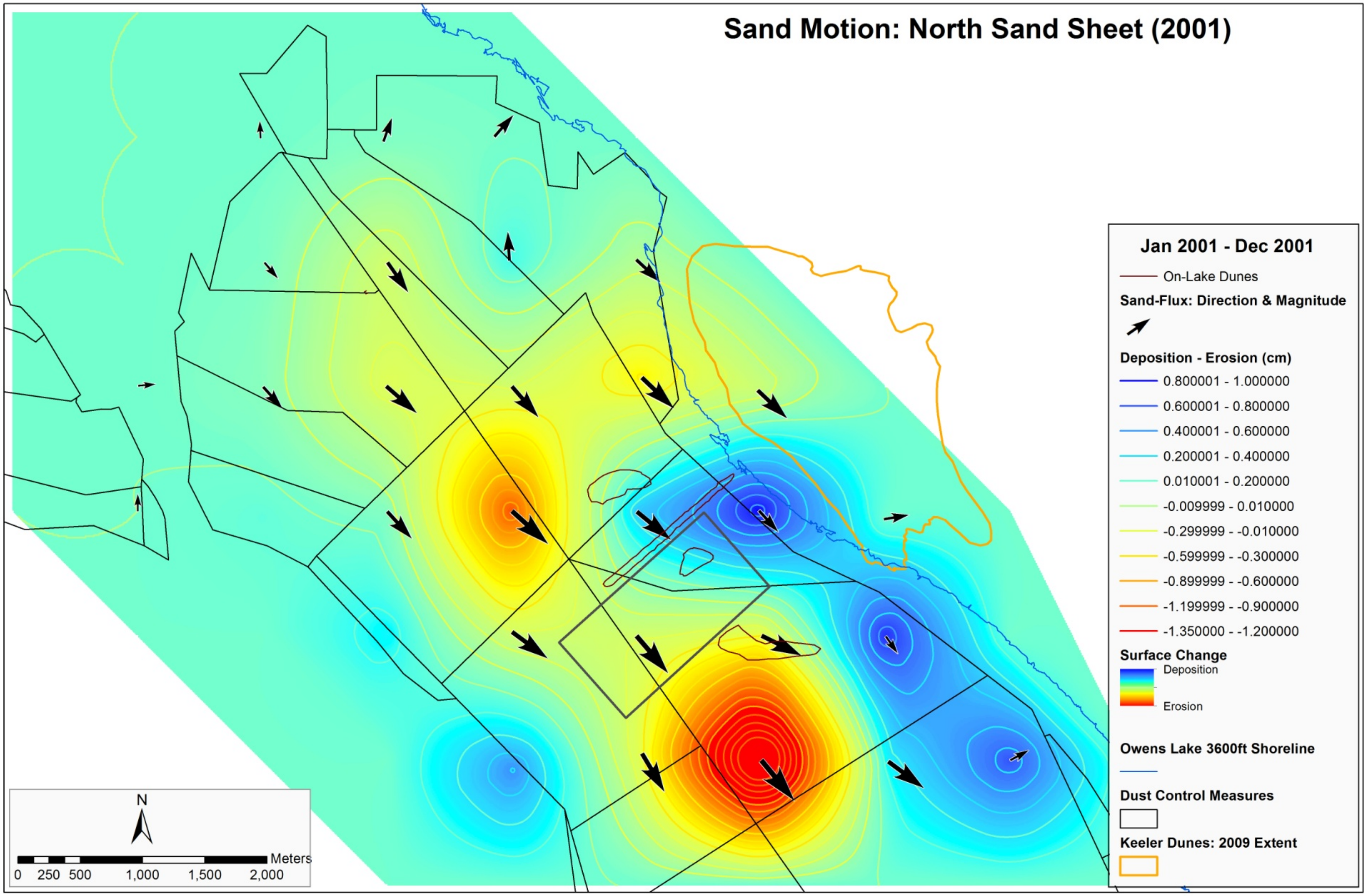


Figure 4.6-4. Surface change on the northeastern portion of Owens Lake from January 2001 to December 2001. The location of the dunes on the lake bed and the outline of the extent of the Keeler Dune deposit are shown as is the location of the District's former SURF project (rectangle in center of map).

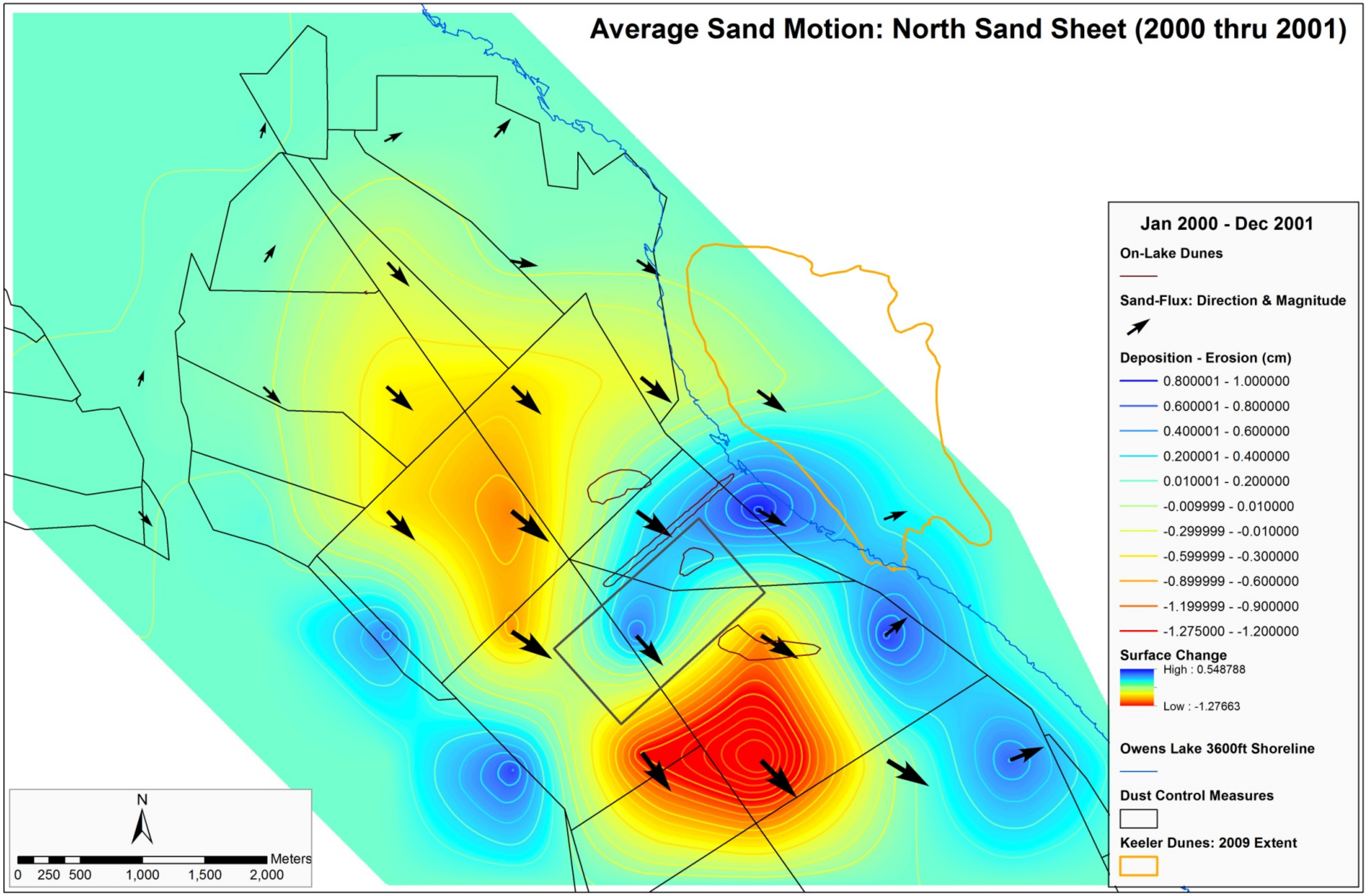


Figure 4.6-5. Average surface change on the northeastern portion of Owens Lake from January 2000 to December 2001. The location of the dunes on the lake bed and the outline of the extent of the Keeler Dune deposit are shown as is the location of the District's SURF project (rectangle in center of map).

2009 to 2012 Surface Change

Figures 4.6-6 to 4.6-10 show the contour color-shaded maps of the surface changes estimated for the three year period starting in July 2009 and ending in June 2012. The analysis separated the data into the dust years that are used for the Owens Lake Dust ID Program, which start on July 1 of each year and end on June 30 of the following year. Overall, surface elevation changes ranged from a deflation of 12.04 cm per year to inflation of 5.98 cm per year. (It should be noted that the surface changes are for smaller areas than the square kilometer grids used for the 2000 and 2001 study periods so there is a larger range of values.) Overall the study area was deflating at a rate of 0.13 cm per year, which is close to the 0.1 cm estimated for the 2000 and 2001 study period. Attachment F of this Final Staff Report and Appendix B in Ono et.al. (2012) summarize the results for each site for the 2009 through 2012 study period.

The erosion and deposition patterns observed in the vicinity of the Keeler Dunes from the analysis are consistent for each of the three year study periods (Figures 4.6-6 to 4.6-8). The overall pattern observed has the highest erosion along the western portion of the dune area extending from the vicinity of the Northern Dune southeastward along the western edge of the deposit. Sand deposition is seen in the southeastern end of the dunes and in the eastern half of the sand deposit. These patterns are consistent with general observations made on the ground and in Lancaster (2012) and HydroBio (2012) that there has been significant deflation of material on the west and spreading and migration of the active Keeler sand sheet and dunes to the east and southeast, respectively.

Overall, during the 2009-2012 study period the surface changes were highest in the Keeler Dunes with less change observed on the lake bed north of the Shallow Flooding dust control area. This observation is evident in each of the three dust years (Figures 9-13) and is particularly pronounced when looking at the erosion areas. The amount of erosion occurring within the Keeler Dunes was three to four times as that on the lake bed.

Also evident by looking at the individual dust years is that the 2009-2010 year had the highest amounts of surface change loss as evidenced by looking at the magnitude and extent of erosion. The amount and extent of deposition is more variable with some areas having higher deposition in 2009-2010 and others in 2011-2012.

Also of interest on Figures 4.6-6 to 4.6-8 is the surface changes estimated for the northeast portion of the lake bed north of the Shallow Flooding DCM. The north-south oriented elongated zone of moderate erosion (yellow) seen on Figure 4.6-6 for 2009-2010 is located between the Moat and Row test conducted by the LADWP on the west and the Shallow Flooding DCM on the east. This pattern suggests that there may have been some overall affect in the sand motion patterns resulting from the test. Once the test area was removed in mid-2010 the surface change pattern changed such that the Moat and Row area eroded in 2010-2011 (Figure 4.6-7).

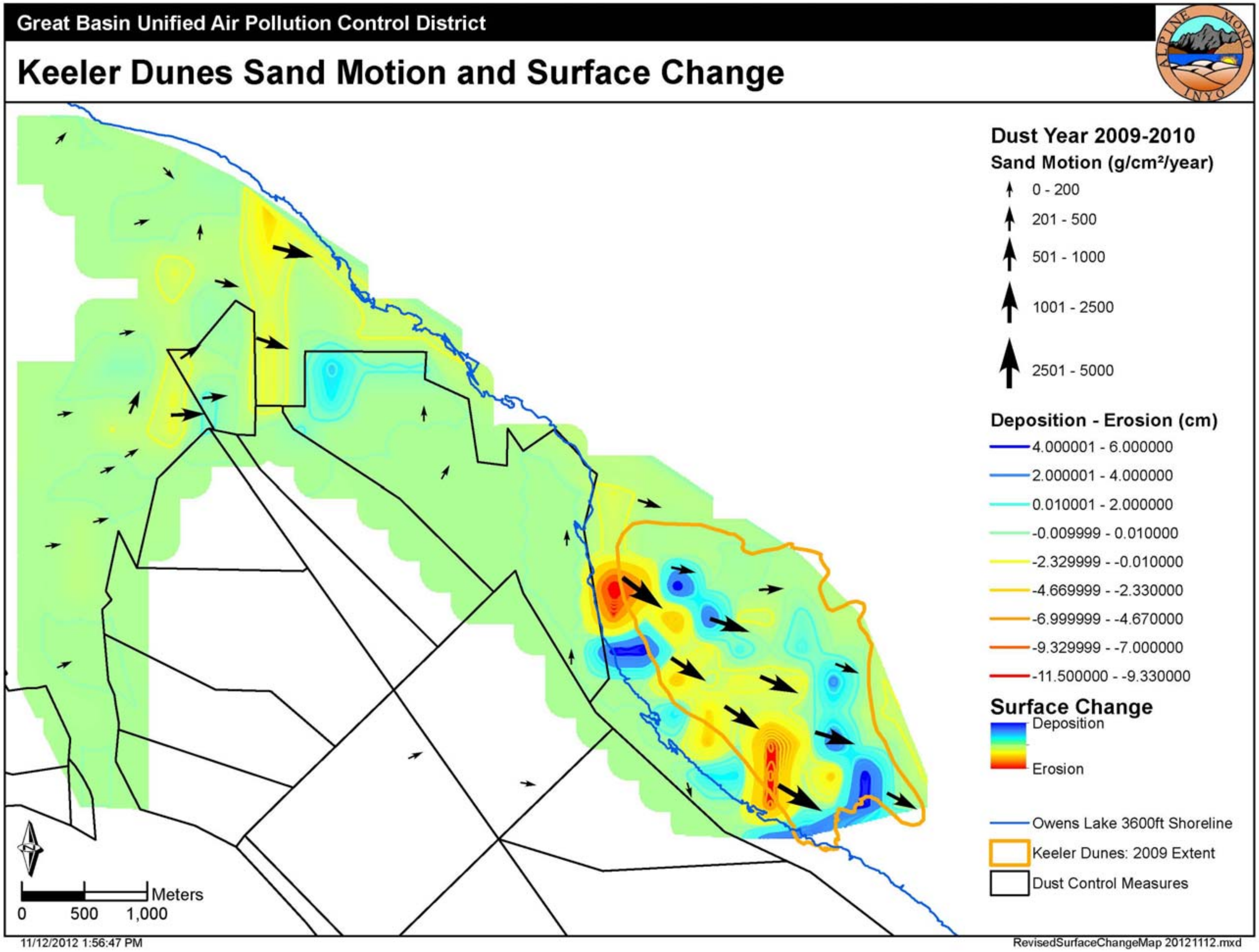


Figure 4.6-6. Surface change on the northeastern portion of Owens Lake from July 2009 to June 2010.

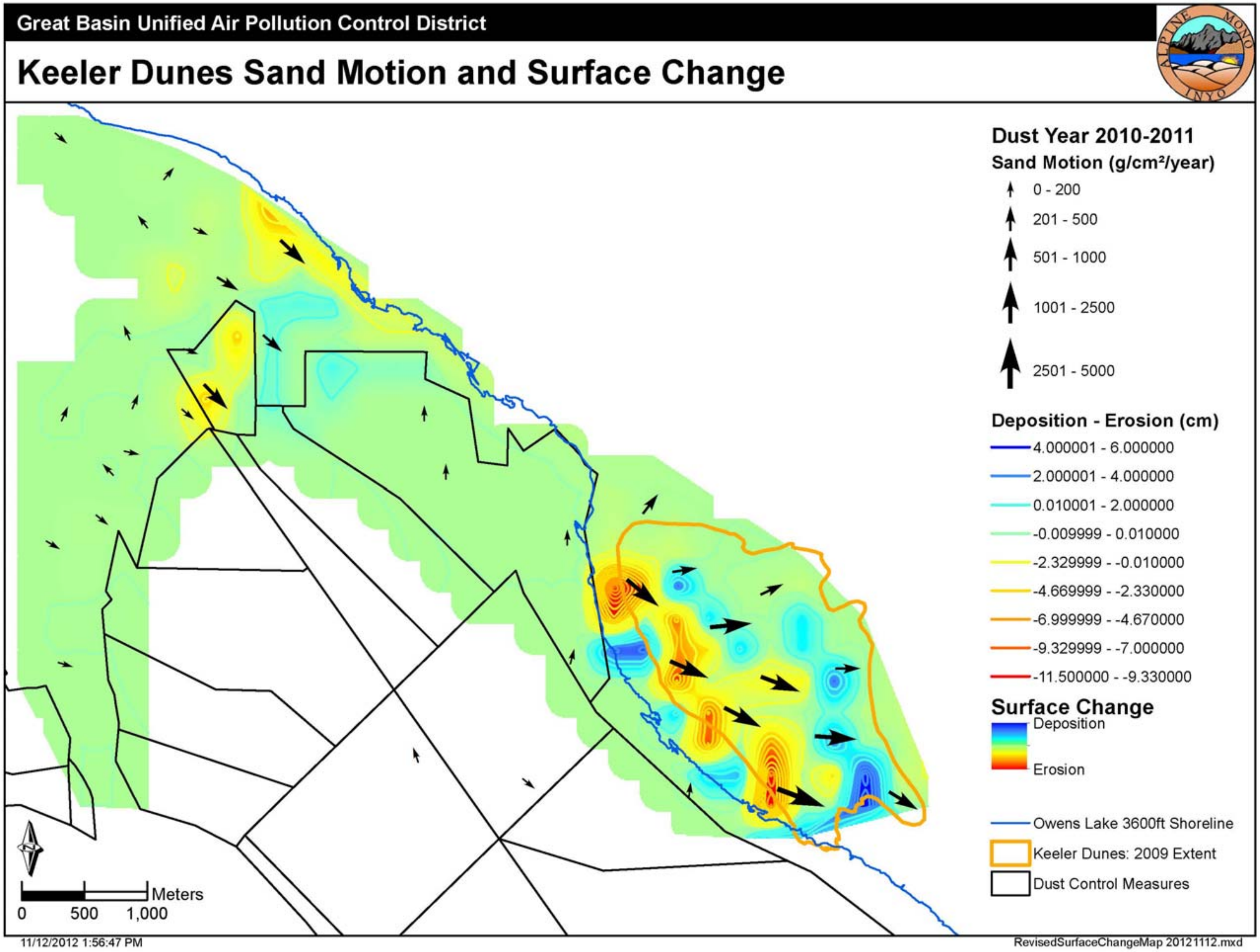


Figure 4.6-7. Surface change on the northeastern portion of Owens Lake and Keeler Dunes from July 2010 to June 2011.

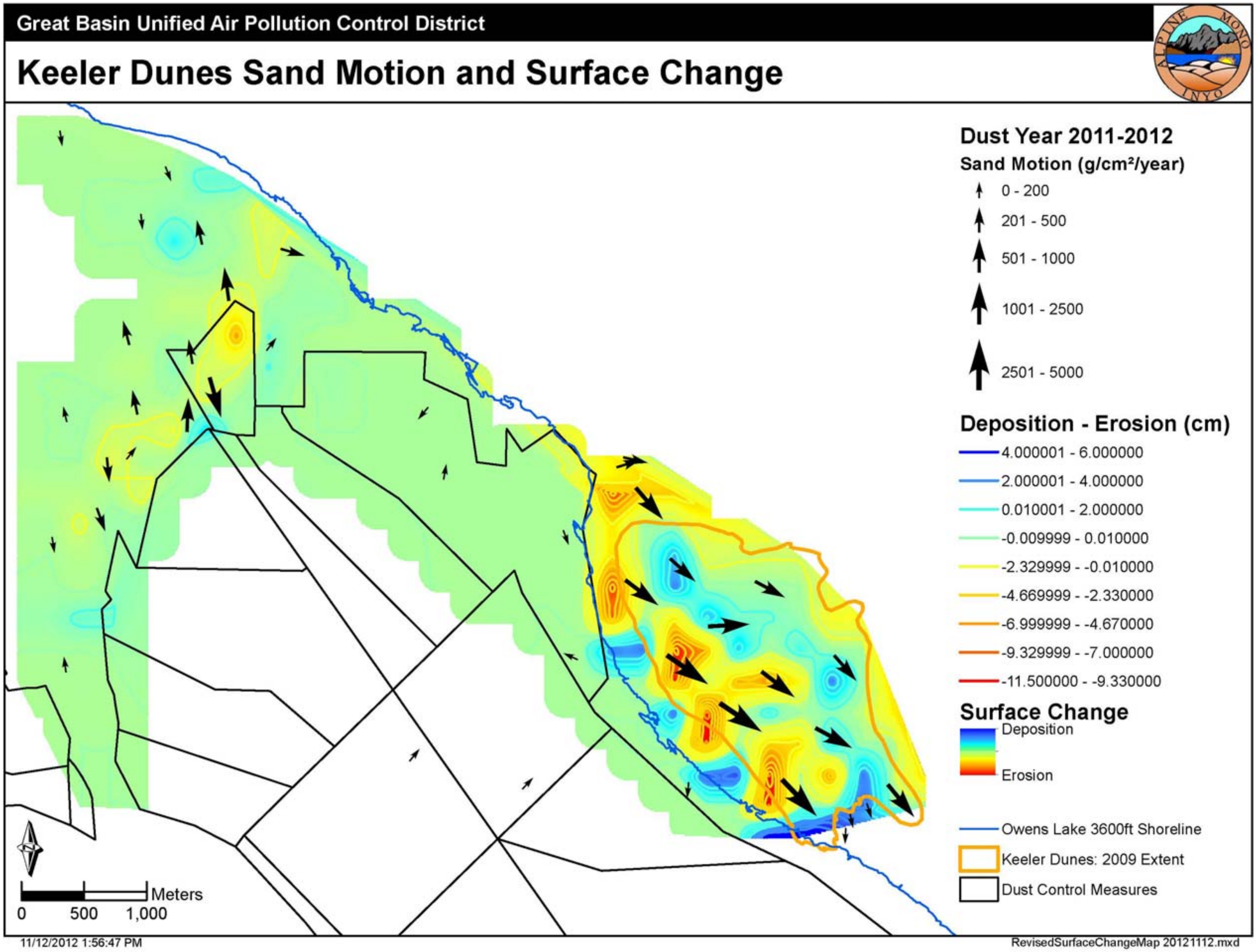


Figure 4.6-8. Surface change on the northeastern portion of Owens Lake and Keeler Dunes from July 2011 to June 2012.

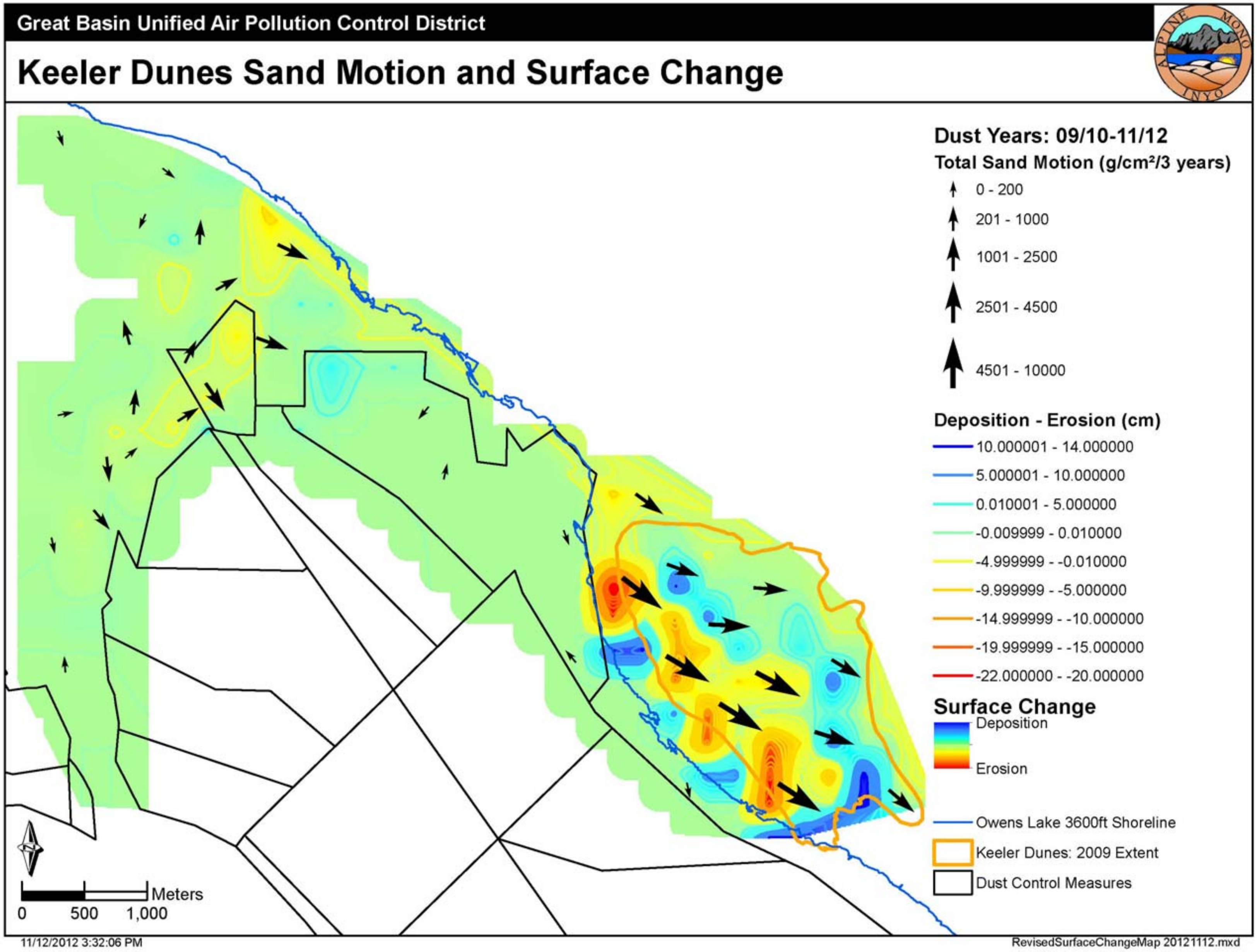


Figure 4.6-9. Total surface change on the northeastern portion of Owens Lake and Keeler Dunes from July 2009 to June 2012.

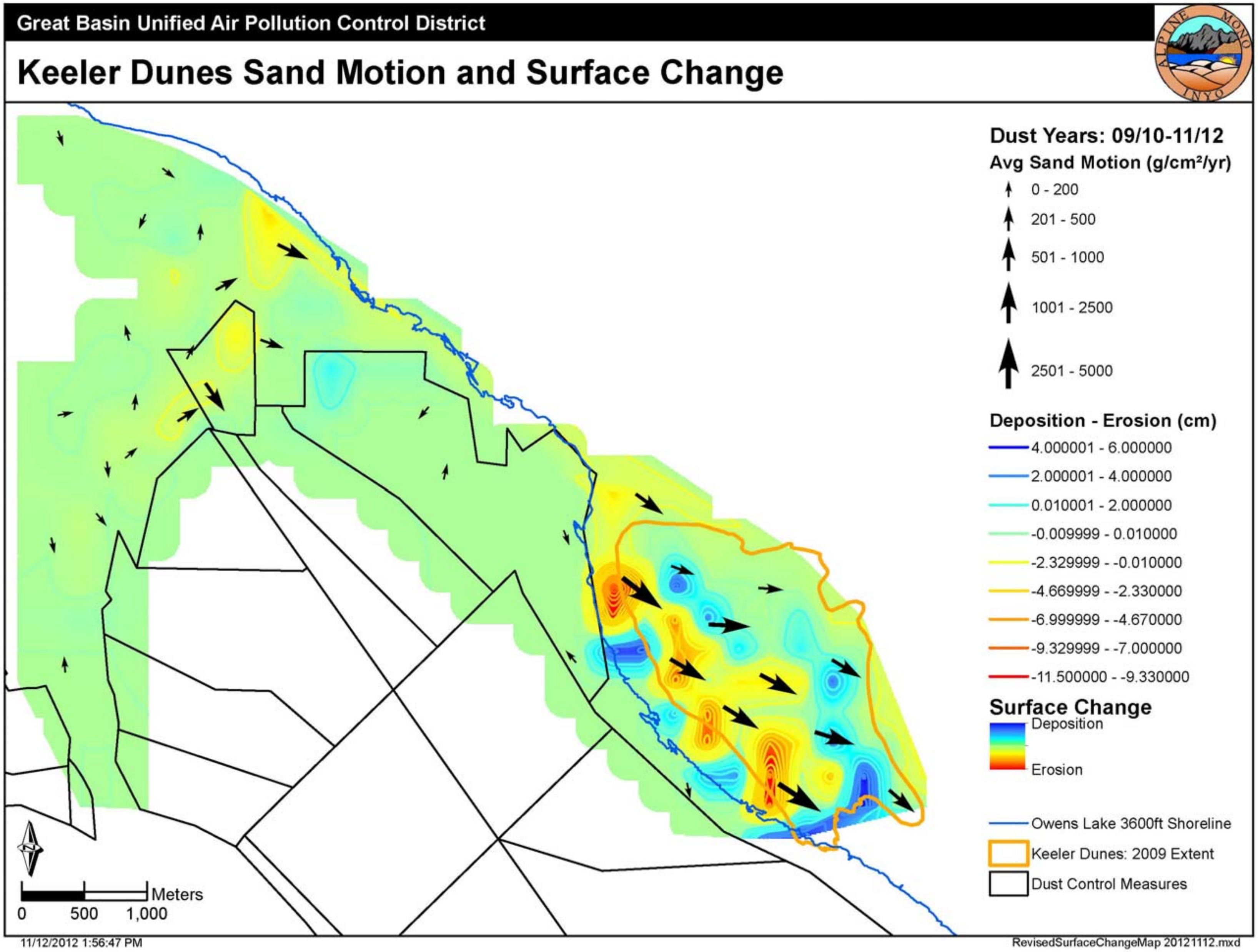


Figure 4.6-10. Average surface change on the northeastern portion of Owens Lake and Keeler Dunes from July 2009 to June 2012.

Summary

The results of the extensive calculations made using the sand motion monitoring data from the two study periods show distinct patterns of erosion and deposition across the northeastern portions of the lake bed and in the adjacent Keeler Dunes. These patterns were evaluated with respect to on-the-ground observations and with respect to dust control measure research activities. In both cases, the patterns in the data correspond well to those observed in the field and to the timing of lake bed research projects. Due to the gridded nature of the cells and the spatial scale used in the analysis, the resulting calculations do not provide an exact match of features on the ground but when interpreted with feature locations provide strong support for the observed patterns. These patterns provide additional confirmation that, since 2000, material is moving southeastward off the northeast portion of the Owens Lake bed and up onto the alluvial fan in the area of the Keeler Dunes. In addition, within the dune field itself, the sand is also moving toward the southeast. (from Ono et. al., 2012)

The methodology applied here to sand motion monitoring data is a useful tool in the evaluation of surface changes caused by erosion and deposition of sand across an active emissive area. Employing this methodology can provide valuable insight into the spatial and temporal relationships of sand movement over a broad scale. (from Ono et. al., 2012)

4.7 Analysis of Dune Transects and Dune Movement (2000-2011)

In 2008, HydroBio Advanced Remote Sensing (HydroBio) began work on a project studying the rate of movement on the Keeler Dunes utilizing data from measurement of dune profiles and evaluation of 10 years of aerial imagery. High resolution air photo mosaics, constructed from images collected in 2009 and 2010, were used along with Quickbird satellite imagery from 2002 through 2008 to evaluate recent dune movement. Dune profiles were measured as a series of laser level survey transects across four dunes from 2008 to 2012 to gain information about changes in dune shape and movement over the four year study period. A series of three reports were prepared by HydroBio discussing the results of their work (HydroBio, 2009, 2010, and 2012). The overall results of their work are presented here. The complete reports are available in Attachment G.

Dune Transect Results

Four dunes were selected for the transect surveys (Figure 4.7-1). The dunes chosen are distributed throughout the dune field and include, two dunes in the northern portion of the dune field (the “Northern Dune” (Dune B) and the “Linear Dune” (Dune C)) and two dunes in the southern portion of the dune field (Dunes D and E). Multiple transects were placed on each dune in order to determine the changes in dune shape and to gauge how much material was moving on the dunes through examination of inflation and deflation along the transects (Figure 4.7-1). These sites were visited in October for three consecutive years from 2008 to 2010. The fourth and most recent survey occurred in late February 2012.

Surveys show that the northern dunes are thin but still capable of significant movement. This has become particularly apparent in 2012, as the eastern transects of Dunes B and C have shown significant shift of mass from previous surveys (Figures 4.7-2 and 4.7-3). And while it is obvious that material is starting to accumulate on the eastern alluvial fan, the majority of the blown material is moving to the southeast (HydroBio, 2012).

Northern Dune – Dune B

The transect analysis shows that Dune B elevations remained relatively stable from 2008 to 2010 and then changed significantly from October 2010 to February 2012 field visit (Figure 4.7-2B). Consistent with visual observations of the Northern Dune, the 2012 results shows a significant shift in sand distribution on the dune with scouring on the western transect and deposition on the central part of the eastern transect. Shrubs along the eastern side of Dune B experienced partial burying, mounding, and micro dunes trailing off toward the southeast. Transect 1 was scoured of sand that had built up around vegetation as at least three isolated spikes in elevation disappeared.

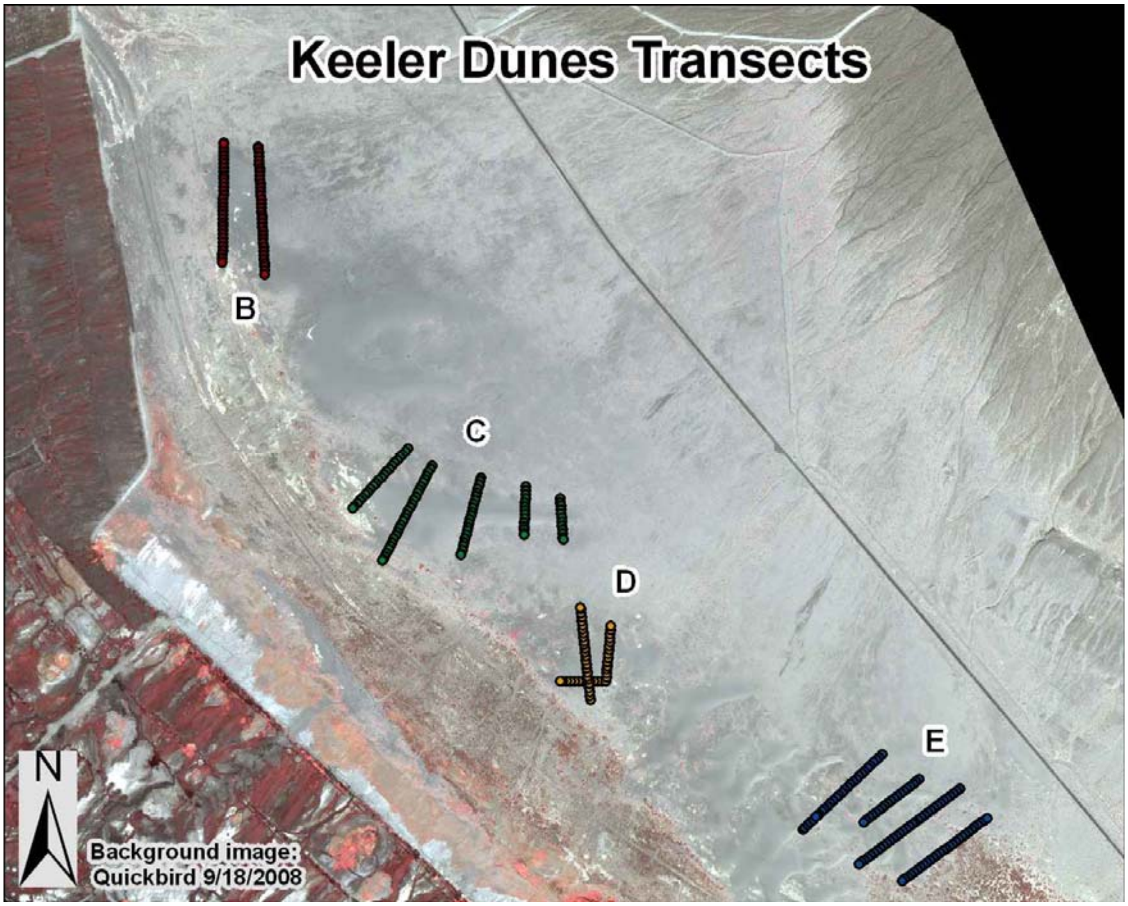


Figure 4.7-1. Locations of dunes and survey transects for the 2008 – 2012 profile analysis displayed on the September 2008 Quickbird image**.** (Figure from HydroBio, 2012)

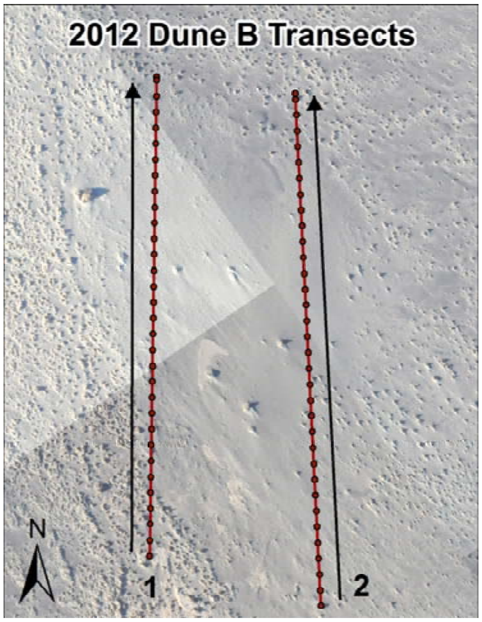


Figure 4.7-2A. Map of survey transects on the Northern Dune (Dune B). (Figure from HydroBio, 2012)

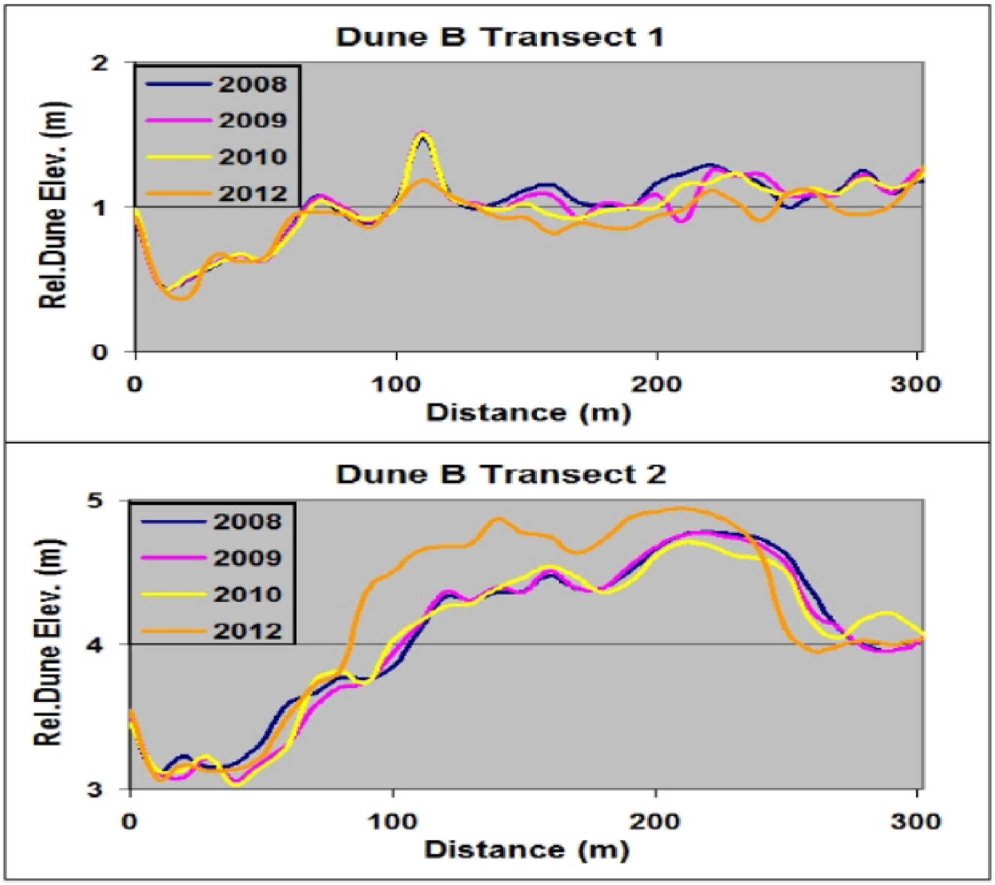


Figure 4.7-2B. Graphs of relative dune elevations along survey transects from the Northern Dune (Dune B) for the 2008 – 2012 profile analysis**.** (Figure from HydroBio, 2012)

Linear Dune – Dune C

The Linear Dune is an east-west trending dune feature located approximately in the middle of the main part of the Keeler Dune field. This dune is about 500 meters in length. The western portion of the dune has been observed to be eroding over the past several years exposing fine-grained silt deposits from flooding events. The locations and data from five transects across the Linear Dune (Dune C) are shown in Figure 4.7-3. Noticeable in the profiles is that the Linear Dune has lost approximately 0.5 to 0.75 meters in elevation from 2008 to 2012 and at the same time has shifted southward.

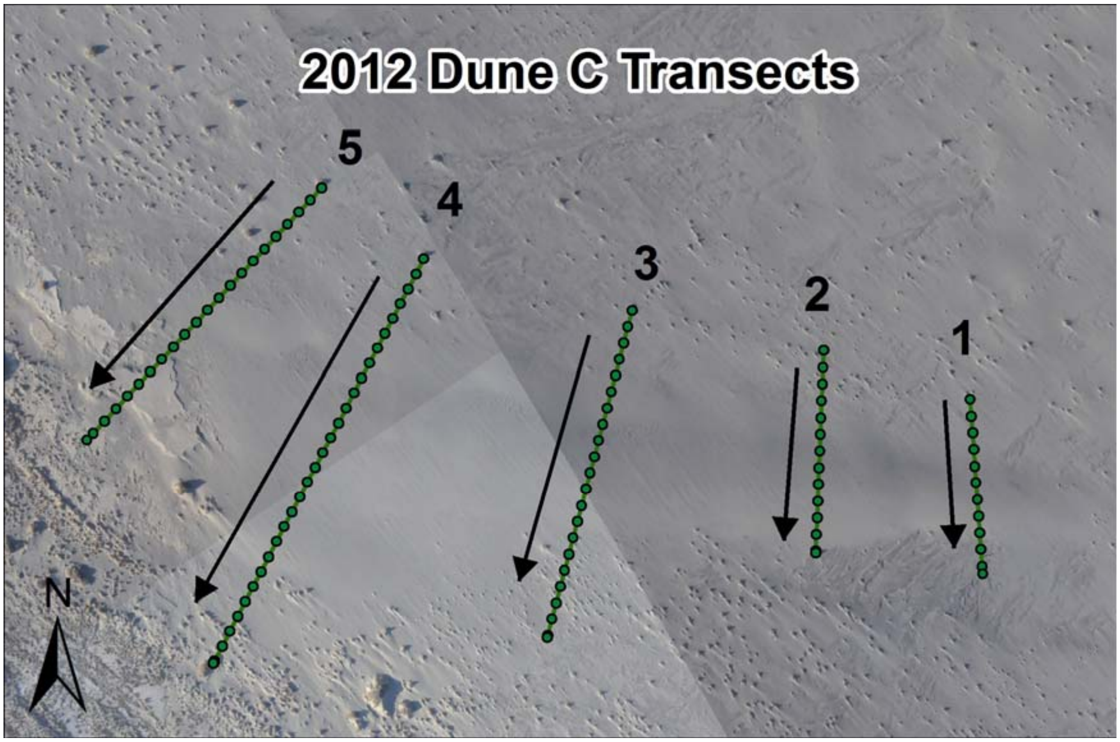


Figure 4.7-3A. Map of survey transects on the Linear Dune (Dune C). (Figure from HydroBio, 2012)

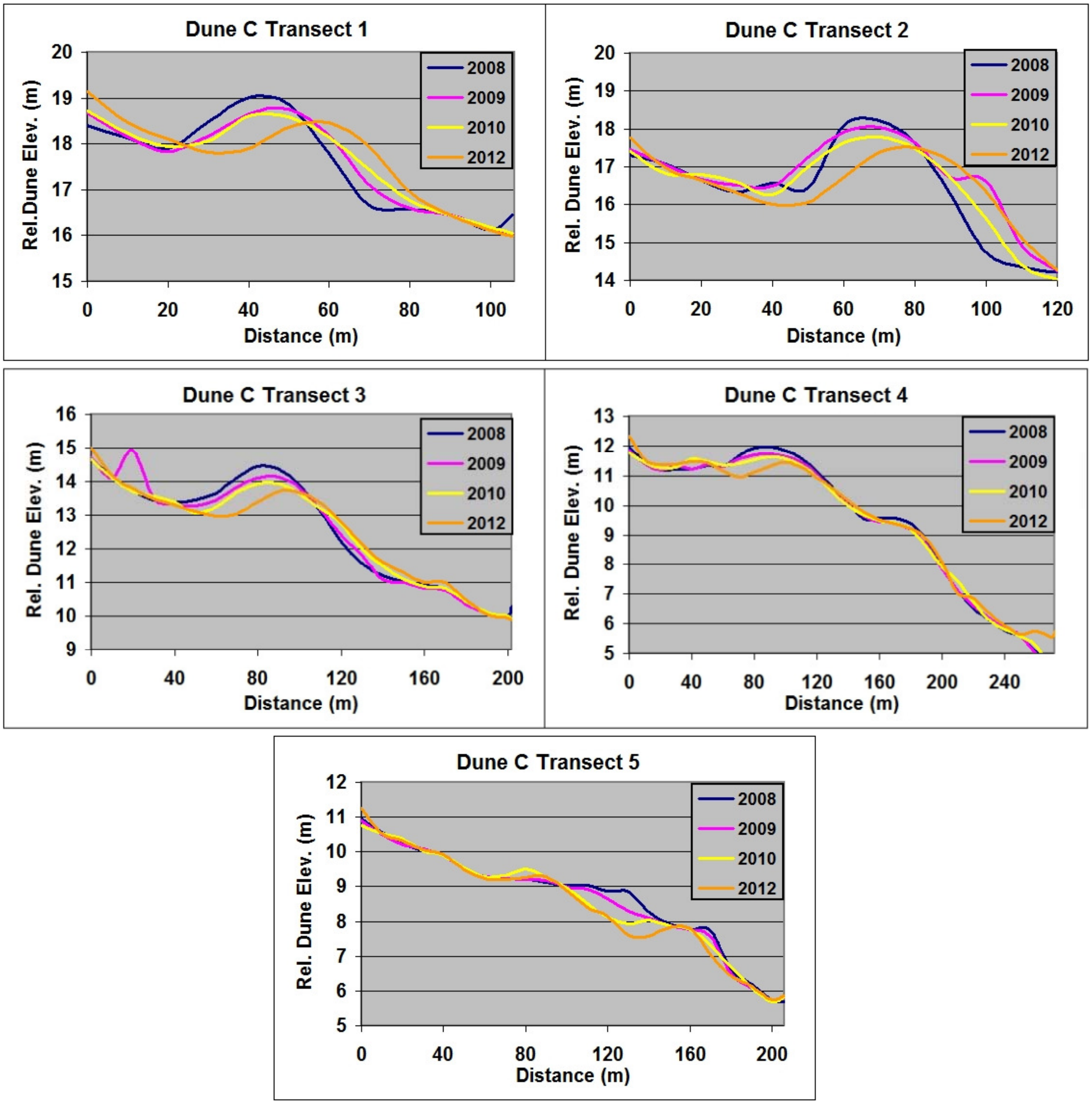


Figure 4.7-3B. Graphs of relative dune elevations along survey transects from the Linear Dune (Dune C) for the 2008 – 2012 profile analysis**.** (Figure from HydroBio, 2012)

Dune D

Dune D is located between the northern and southern portions of the dune field. Dunes to the north are generally large isolated dune forms such as the Northern Dune, Horseshoe Dune and Linear Dune. Within the southern dune complex, to the south, the individual dune forms tend to be relatively small in extent and frequently coalesce to form an interconnected dune area. Dune D is similar in character to the northern dunes in that it lacks a classic dune shape but like the dunes to the south, it is relatively small and interconnects with the southern dunes through continuous sand deposits along the eastern portions of the feature. HydroBio (2012) conducted elevation surveys on three transects across Dune D as shown in Figure 4.7-4. As evident from the survey transects, there has been a dramatic change in Dune D over the past four years with deflation along the north and west and deposition to the south and east.

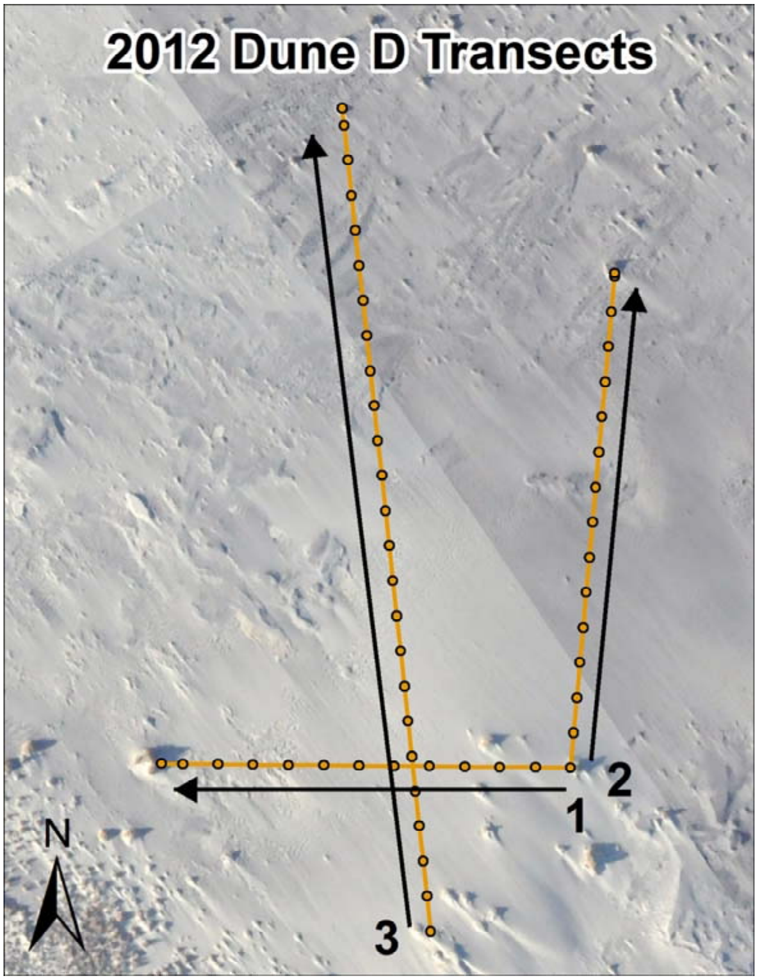


Figure 4.7-4A. Map of survey transects on Dune D. (Figure from HydroBio, 2012)

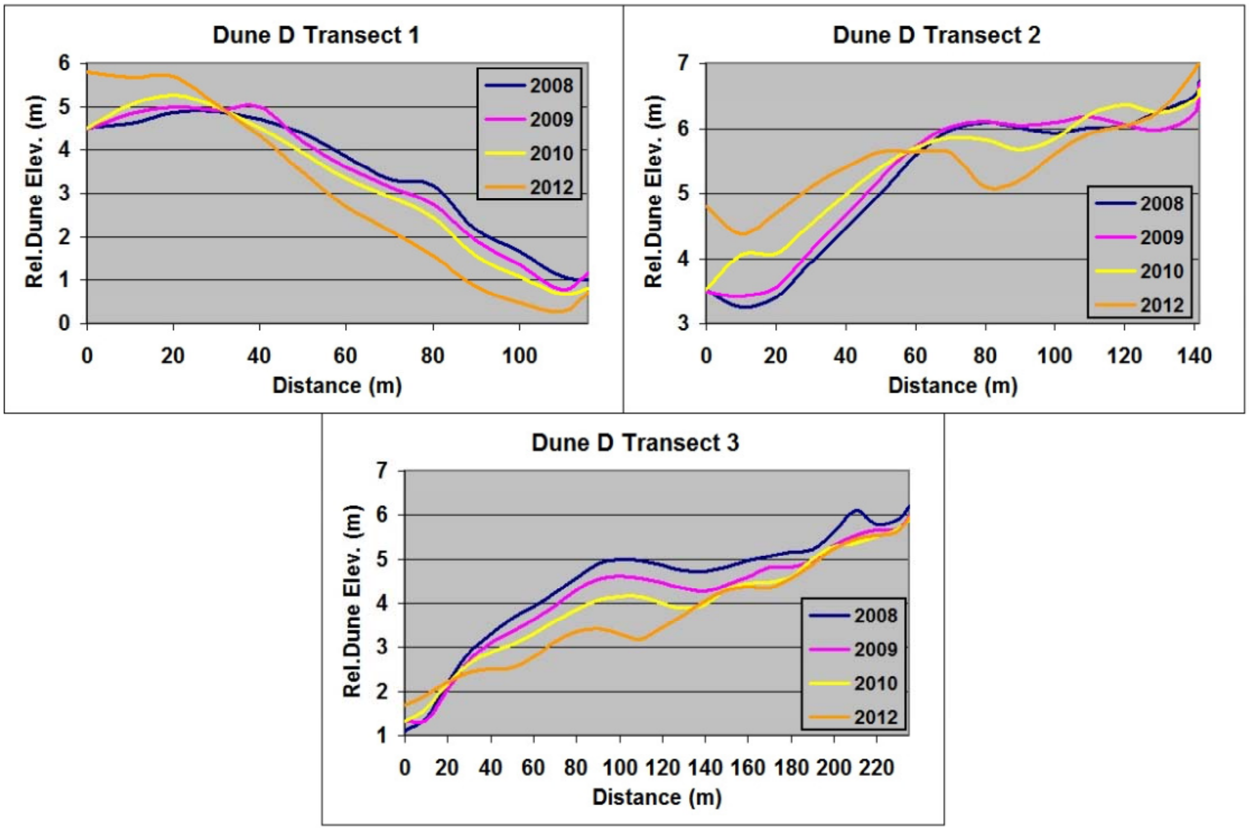


Figure 4.7-4B. Graphs of relative dune elevations along survey transects on Dune D for the 2008 – 2012 profile analysis**.** (Figure from HydroBio, 2012)

Southern Dunes - Dune E

The Dune E region is located in the southernmost portion of the Keeler Dunes in a zone with many discrete dunes feature. Dunes in this area have been moving consistently south and east for many years. Thick vegetation on the southern edge of the dune field has impeded the southeast dune movement. Sand from the dunes has encroached and buried vegetation up to several meters thick along the southern face of the dune field.

Four survey transects were established across the Dune E area (Figure 4.7-5). The Transect 1 profile shows approximately two meters of sand have deposited on this southern edge of the dune field and that the southern face of the dune has migrated 50 meters southeastward from 2008 to 2012. Transects 2 and 3 are in area between discrete crescent-shaped dunes and have less dramatic changes over the 4-year study period. Transect 4 is located in a region of a discrete crescentic dune. The southwestern edge of this transect recorded a drop in elevation resulting from passage of the dune crest to the southeast now leaving the end transect point on the sloped backside of the dune. (HydroBio, 2012)

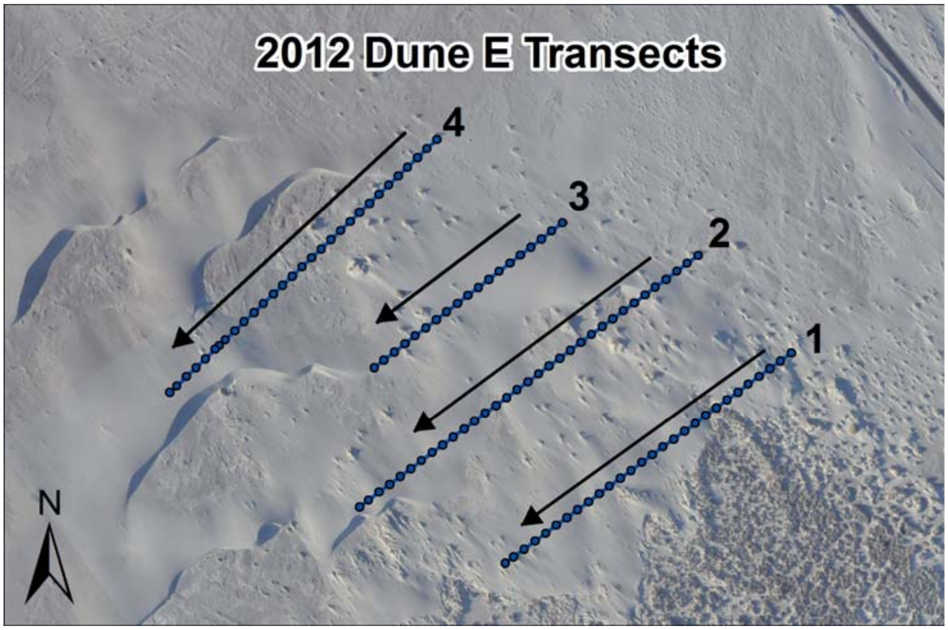


Figure 4.7-5A. Map of survey transects on Dune E. (Figure from HydroBio, 2012)

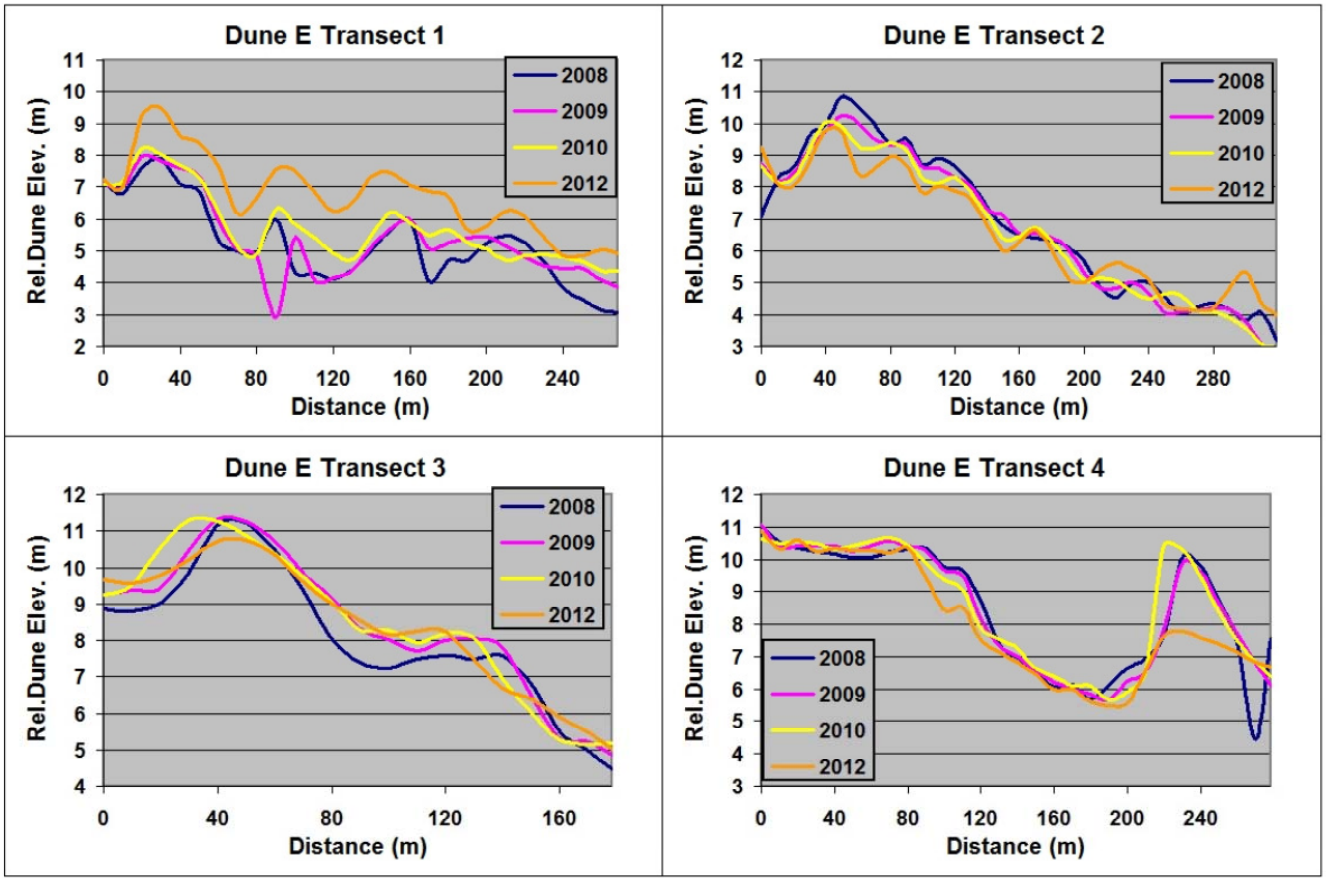


Figure 4.7-5B. Graphs of relative dune elevations along survey transects on Dune E for the 2008 – 2012 profile analysis**.** (Figure from HydroBio, 2012)

Dune Movement

As the Keeler Dunes progress to the southeast the sand that is reworked by the wind in the progression is subjected to winnowing, separation and sorting of particles by size. The action of wind in the winnowing process emits finer particles while leaving the heavier sand behind in the dunes. This is particularly evident on the Northern Dunes where there is a significant lag deposit of coarse sand and fine gravels that has developed over much of the surface.

Figure 4.7-6 illustrates movement of barchan dunes on the southern edge of the dune field (near Dune E transects). These dunes have been moving an average of about 10 m (33 ft) a year (Figure 4.7-6) over the last ten year period extending from 2002 to 2012. The movement of dunes is highest in the south and much lower in the north. Over the 2002 to 2012 time period, the Dune B (Northern Dune), Dune C (Linear Dune), and Dune D have moved approximately 30, 50, and 85 meters (98, 164, 279 ft), respectively as compared to the 100 m (328 ft) movement for the southern dunes (HydroBio, 2012). In all four cases examined, the overall movement direction was consistently to the southeast.

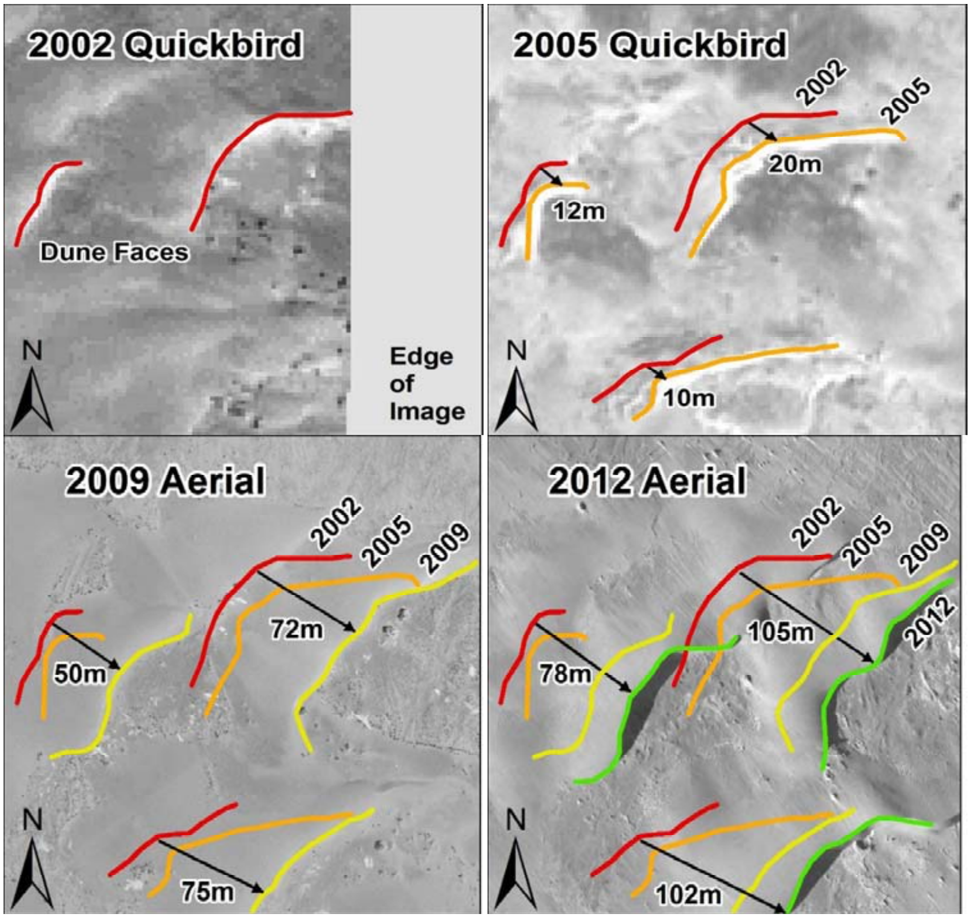


Figure 4.7-6. Quickbird satellite imagery showing the movement of dunes in a portion of the southern Keeler Dunes from 2002 to 2012. The dune faces are marked with a colored line for each year. (from HydroBio, 2012)

Vegetation cover within the dunes has been severely reduced due to dune movement. This is particularly evident in the southern portion of the dunes where dense stands of shrubs have been destroyed by migration of dunes. Shrubs are the main type of permanent vegetation found within the Keeler dune field. The age of the shrubs may vary from a few years for small, rapidly growing species such as Parry's saltbush, to many decades and perhaps centuries for greasewood. Movement of dunes during the past decade have largely covered and then exposed locations where shrubs previously grew. This is particularly evident in a comparison of the current conditions to the air photos from the 1940's. Although shrub species such as greasewood are associated with many stable vegetated dune fields (for example the shore of Mono Lake) the rapid pace of dune movement near Keeler overwhelms shrub growth capability. Hence, shrubs that may be multiple decades old have succumbed to the sand movement during only a decade of sand movement. (HydroBio, 2012)

SECTION 5.0 SUMMARY OF DISTRICT RESEARCH

The District has pursued many different lines of investigation and research in order to understand the origin and development of the landscape and terrain in the area where the Keeler Dunes are located. This effort has taken considerable time and effort by the District and its consultants. The purpose of the work is to provide information to address the question concerning the timing and nature of the Keeler Dunes formation: specifically if the dunes are natural in origin or due to anthropogenic causes.

This work was done in good faith and not with a predisposed result. One of the unexpected results of the work was learning about and gaining an appreciation for the rich cultural history of the area. While the community of Keeler and the surrounding area might currently appear to be a small and desolate place, it has had an amazingly dynamic history over the past 150 years. This fascinating modern history started with the discovery of silver in the Inyo Mountains and the development of the Cerro Gordo mining district and included the use of steam-boats on Owens Lake, the construction and operation of the narrow gauge railroad, the development of salt mining on Owens Lake and in Saline Valley, the desiccation of modern Owens Lake and, most recently, implementation of dust control projects on the bed of Owens Lake. All of these historic activities left an imprint on the landscape that is distinguishable today.

Prior to the historic record, the Native American cultural resources in the area attest to a rich and diverse pre-historic past. In order to protect and preserve the pre-historic cultural resources in the area, the pertinent knowledge of these resources and their relationship to the development landscape are not presented here. The District respects the sensitivity of the Native American community to dissemination of this information and will keep all information received confidential, to the extent possible. However, the District requests that information on these resources that bear on the timing and development of the landscape of the area be made available to the District so that it can be evaluated along with the data and information presented in this report.

Some of the most compelling information collected as part of work on this project is the collection of historic photographs, both ground-based as well as aerial. Based on a thorough search of available photo collections it is apparent that the landscape in the current location of the Keeler Dunes has changed considerably since 1900 and is nearly as dynamic as the community of Keeler itself. The maps and analyses provided in Section 4.2 (Attachment B) and Section 4.7 (Attachment G) of dune extent since 1944 and sand flux since 2000, respectively, provide persuasive evidence of the dynamic nature of the landscape and the progression and growth of the dunes and associated aeolian sand deposits.

To many, the view across the landscape of the Keeler Dunes and northern portions of the Owens Lake shorelands is barren and boring with their attention generally turned to the surrounding rugged mountains. However, viewed through the eyes of experienced geomorphologists and geologists, the subtle variations in this terrain can be broken into a dynamic array of geomorphic units that tell a fascinating and unique story on the Quaternary history of the area. That history includes the development of multiple shorelines from ancient Owens Lake, phases of alluvial fan development and erosion, formation of deltaic and fluvial deposits associated with the Owens River-Owens Delta system and of the formation of aeolian dunes and sand sheet deposits. The relationships discovered in the delineation and study of these geomorphic units indicates that the current active Keeler Dunes are one of the youngest geologic features in the area and that they formed after 1872 to 1894. Figure 5-1 shows the relationship of the current active and emissive Keeler Dunes deposit along with the general location of the old dunes that are associated with the Late Holocene shoreline features. Notice the difference in character between the two. The current Keeler Dune sand deposit sits on top of and buries portions of the former dune system while the Late Holocene dunes appear to be limited in extent such that they are sub-parallel with the mapped shorelines with ages of hundreds to thousands of years ago.

In summary, the Keeler Dunes are a recent element of the landscape and were formed in historic times since the recent desiccation of modern Owens Lake. They are formed from material that was transported across and from the exposed lake bed onto the base of the Keeler alluvial fan. Wind and sand flux data indicate that the prevailing transportation direction was from the northwest from the Owens River delta and the North Sand Sheet. Based on information from the earliest aerial photos, it appears that the northern portion of the Keeler Dunes began forming prior to 1944 as sands were deposited across the northwestern portion of the alluvial fan. As sands continued to migrate from the lake bed onto the Keeler Fan, the aeolian deposit changed character from an open sand sheet without distinct dune forms to the development of first, the well-known “Horseshoe” and “Linear” dunes in the 1960’s, and then, the crescentic dunes in the southern dune complex in the 1980’s. Currently, there is significant erosion and thinning of the edge of the Keeler Dunes on the northern and western portions of the deposit attributed to stabilization of the adjacent lake bed due to dust control implementation since 2001. However, even as the Keeler Dunes are eroding on the north and west, the mobile aeolian sands continue to follow the prevailing transportation pattern and are spreading and moving to the southeast toward the community of Keeler.

Based on the work conducted by Great Basin staff and consultants, there is little doubt the emissive Keeler dunes are a recent phenomenon caused by the water-diversion desiccation of Owens Lake.

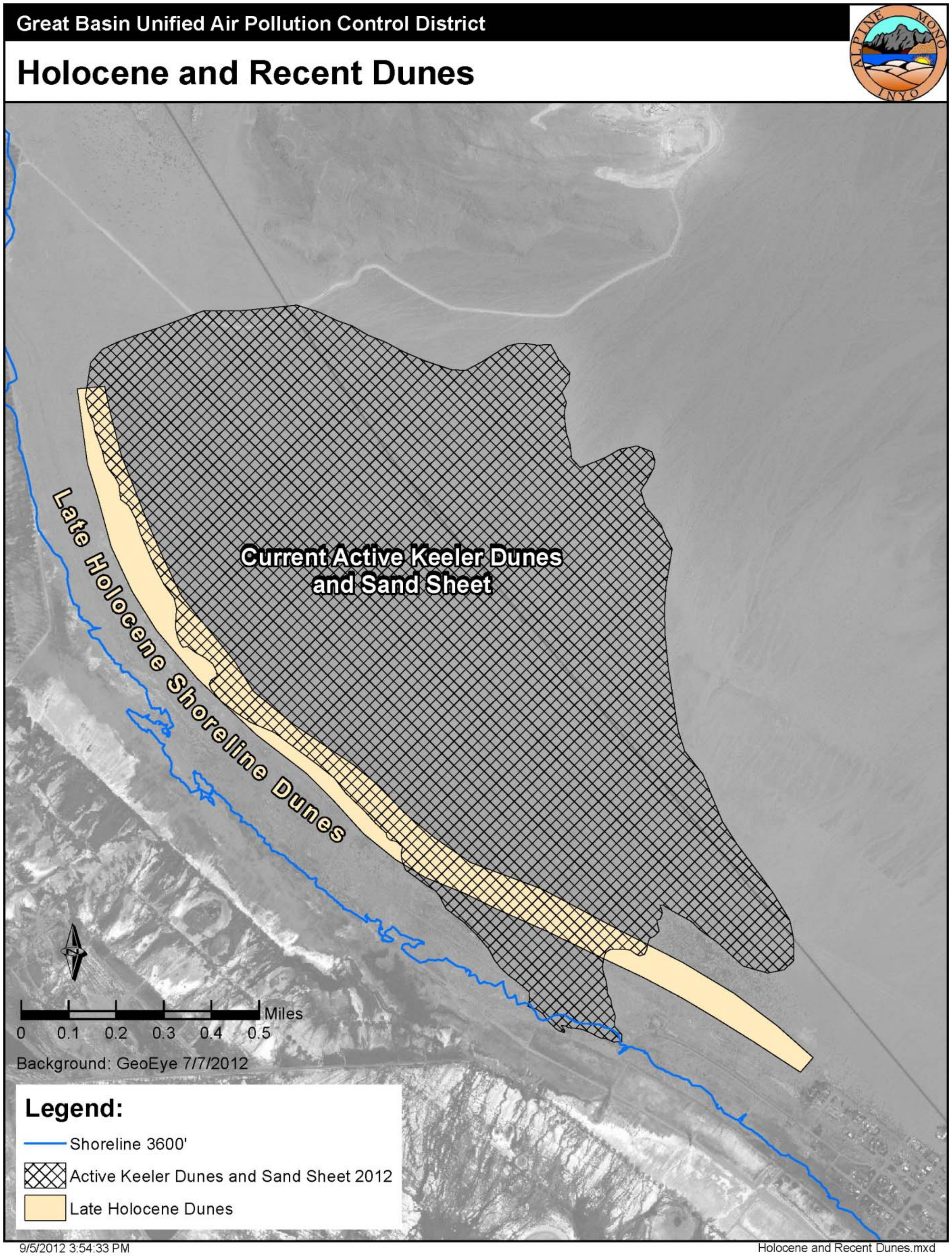


Figure 5-1: Map showing the extent of the active Keeler Dunes and sand sheet deposit (from July 2012) with the general extent of older dune features associated with Late Holocene shorelines.

SECTION 6.0 REFERENCES

Agrarian, 2001. Final Report, Shallow Un-Confined Re-Circulated Flooding (SURF) Project, Owens Lake, California, Report prepared by Agrarian Research and Management Company, Ltd for the Great Basin Unified Air Pollution Control District, May 2001.

Antinao, J.L., E. Huenupi, S. Baker, A. Lewis, G. Berger. 2012, Luminescence Dating of Aeolian Deposits, Keeler, Owens Valley, California. Report by DEES Desert Research Institute for Nick Lancaster. August 30, 2012. 18 pages.

Bacon, S. N., R.M. Burke, S.K. Pezzopane, and A.S. Jayko, 2006. Last Glacial Maximum and Holocene Lake Levels of Owens Lake, Eastern California, USA. *Quaternary Science Reviews* 25: 1264–1,282.

Bacon, S. N. and N. Lancaster, 2012. Geomorphic Mapping of the Keeler Dunefield and Surrounding Areas, Draft Report prepared by the Desert Research Institute for the Great Basin Unified Air Pollution Control District. August 2012.

Bacon, S.N., and Pezzopane, S.K., 2007. A 25,000-year record of earthquakes on the Owens Valley fault near Lone Pine, California: Implications for recurrence intervals, slip rates, and segmentation models. Geological Society of America Bulletin 119/7, 823-847.

Beanland, S., and Clark, M.M., 1994. The Owens Valley fault zone, eastern California, and surface rupture associated with the 1872 earthquake. U.S. Geological Survey Bulletin 1982, 29 p.

Benson, L., Burdett, J., Lund, S., Kashgarian, M., Mensing, S., 1997. Nearly synchronous climate change in the Northern Hemisphere during the last glacial termination. Nature 388, 263–265.

California State Route 136. California Highways website, accessed August 3, 2012. (http://www.cahighways.org/129-136.html#136)

Elliott, D.G, 1904. Catalogue of Mammals Collected by E. Heller in Southern California. Field Columbian Museum, publication 91, vol III, no, 16., Chicago, March 1904.

Ferrell, M.H., 1982. *Southern Pacific Narrow Gauge.* Pacific Fast Mail, 1st edition, 272 pages.

Gale, H.S., 1915. Salines in the Owens, Searles, and Panamint basins, southeastern California. US Geological Survey Bulletin 580, 281–323.

GBUAPCD, 2003. Great Basin Unified Air Pollution Control District, Owens Valley PM_{10} Planning Area Demonstration of Attainment State Implementation Plan - 2003 Revision, GBUAPCD, Bishop, California, November 13, 2003.

GBUAPCD, 2008. Great Basin Unified Air Pollution Control District, 2008 Owens Valley PM_{10} Planning Area Demonstration of Attainment State Implementation Plan, GBUAPCD, Bishop, California, January 28, 2008.

Grimm, 2012. Ground-Based Photo Analysis: Comparison of Historical and Recent Views in the Keeler Dunes Vicinity. Report prepared by Great Basin Unified Air Pollution Control District, Bishop, CA, November, 2012.

HydroBio ARS, 2009. Preliminary Assessment of Dune Movement, and Factors Influencing Air Quality and Potential Mitigation near Keeler, California. Report prepared for the Great Basin Unified Air Pollution Control District by HydroBio ARS, Santa Fe, New Mexico. April 16, 2009.

HydroBio ARS, 2010. 2009 Assessment of Dune Movement near Keeler, California. Report prepared for the Great Basin Unified Air Pollution Control District by HydroBio ARS, Santa Fe, New Mexico. April 16, 2010.

HydroBio ARS, 2012. 2012 Assessment of Dune Movement near Keeler, California. Report prepared for the Great Basin Unified Air Pollution Control District by HydroBio ARS, Santa Fe, New Mexico. April 13, 2012.

Jayko, A.S. and Bacon, S.N. (2008). Late Quaternary MIS 6-8 shoreline features of pluvial Owens Lake, Owens Valley, eastern California, in Reheis, M.C., Hershler, R., and Miller, D.M., eds., Late Cenozoic Drainage History of the Southwestern Great Basin and Lower Colorado River Region: Geologic and Biotic Perspectives: Geological Society of America Special Paper 439, pp. 185-206.

Klett, M. 2010. Three methods of presenting repeat photography. In: *Repeat Photography: Methods and Applications in the Natural Sciences.* Published by Island Press, 337 pages.

Knopf, A., 1914. Mineral Resources of the Inyo and White Mountains. USGS Bulletin 540.

Knopf, A., 1918. A Geological Reconnaissance of the Inyo Range and the Eastern Slope of the Southern Sierra Nevada, California. USGS Professional Paper, 110.

Lancaster, N.L., 2012a. Development of the Keeler Dunefield, Inyo County, California, Part 1 – Analysis of Aerial Photographs and Satellite Images. Report to the Great Basin Unified Air Pollution Control District, March 2012.

Lancaster, N.L, S. Baker and N. Pepe, 2012. Keeler Dunes, Mineralogical Analyses to Determine Sand Source(s). Report prepared for the Great Basin Unified Air Pollution Control District by the Desert Research Institute. November 9, 2012. 8 pages.

Lancaster, N. and S.N. Bacon. 2012a. Late Holocene Stratigraphy and Chronology of Keeler Dunes Area. Preliminary Draft Report prepared by Desert Research Institute for Great Basin Unified Air Pollution Control District. November, 2012.

Lancaster, N. and S.N. Bacon. 2012b. Potential Sources of Sand for the Keeler Dunes. Report prepared by Desert Research Institute for Great Basin Unified Air Pollution Control District. November, 2012.

Lancaster, N.L. and Holder, G.M., 2012. Decadal-scale evolution of a small dune field: Keeler Dunes, California 1944-2010. Geomorphology, in press http://dx.doi.org/10.1016/j.geomorph.2012.10.017

Lee, C.H., 1915. Report on the hydrology of Owens Lake Basin and the natural soda industry as effected by the Los Angeles Aqueduct Diversion. Hydraulic Engineer, Los Angeles, CA.

Li, H., Bischoff, J.L., Ku, T., Lund, S.P., Stott, L.D., 2000. Climate variability in east-central California during the past 1000 years reflected by high-resolution geochemical and isotopic records from Owens Lake sediments. Quaternary Research 54, 187–197.

Mettam, B., 2009. Email message from Brad Mettam of CalTrans to Ted Schade of GBUAPCD on State Hwy 136 realignment. August 6, 2009.

Mihevc, T.M., Cochran, G.F., and Hall, M., 1997. Simulation of Owens Lake Water Levels. Report prepared by Water Resources Center, Desert Research Institute for the Great Basin Unified Air Pollution Control District. Dated June 1997, Publication No. 41155, 71pp.

Morris, J.D., 2010. *Southern Pacific's Slim Princess in the Sunset, 1940-1960.* Published by Southern Pacific Technical Society, 339 pages.

Myrick, D.F., 1962. Railroads of Nevada and Eastern California, Volume I: The Northern Roads. University of Nevada Press, Reno, Nevada.

Myrick, D.F., 2007. Railroads of Nevada and Eastern California, Volume III: More on the Northern Roads. University of Nevada Press, Reno, Nevada.

Ono, D., G. Holder, C. Howard, and M. Slates. 2012. Study of the Surface Change in the Northeast Portion of Owens Lake Due to Wind Erosion. Revised report prepared by the Great Basin Unified Air Pollution Control District, November 2012.

Orme, A.R., and Orme, A.J., 2008. Late Pleistocene shorelines of Owens Lake, California, and their hydroclimatic and tectonic implications. In: M.C. Reheis, R. Hershler, and D.M. Miller (editors), Late Cenozoic Drainage History of the Southwestern Great Basin and Lower Colorado River Region: Geologic and Biotic Perspectives. Geological Society of America, Special Paper 439, 207-225.

Rhodes, E., 2012. Results of OSL Dates from Keeler Dunes, prepared for the Desert Research Institute for the Great Basin Unified Air Pollution Control District, November 2012.

Sapphos, 2011, Memorandum for the Record, Historical Research of Keeler Dunes, by Leslie Heumann and Marlise Fratinardo to Great Basin Unified Air Pollution Control District. November 11, 2011.

Smith, G.I., Street-Perrott, F.A., 1983. Pluvial lakes of the western United States. (H. E. Jr. Wright, ed.), *in* Late-Quaternary environments of the United States vol. 1, S.C. Porter, (ed.), Minneapolis, University of Minnesota Press, pp. 190-212.

Smith, G.I., Bischoff, J.L., 1997. Core OL-92 from Owens Lake: project rationale, geologic setting, drilling procedures, and summary. In: Smith, G.I., Bischoff, J.L., (Eds.), An 800,000-year Paleoclimatic Record from Core OL-92, Owens Lake, Southeast California. Geological Society of America Special Paper 317, pp. 1–8.

Stine, 2012. Von Schmidt's Cadastral Survey of the Owens Lake Shorelands: Clues to the Presence/Absence of Sand Dunes in 1856. Report prepared for the Great Basin Unified Air Pollution Control District. August 2012.

Stone, P., Dunen, G.C., Conrad, J.E., Swanson, B.J., Stevens, C.H., and Valin, Z.C, 2004. Geologic Map of the Cerro Gordo Peak 7.5' Quadrangle, Inyo County, California. Pamphlet to accompany Scientific Investigations Map 2851. US Geological Survey, Reston, VA. http://pubs.usgs.gov/sim/2004/2851/

Turner, G., 1974. *Slim Rails Through the Sand, The Saga of the Carson and Colorado – Southern Pacific Narrow-Gauge Railroad Through the Desert*. 4th edition, published by Trans-Anglo Books, Corona Del Mar, CA, 103 pages.

U.S. Census, results accessed from http://censusviewer.com/city/CA/Keeler on August 1, 2012.

Web, R. H., D. E. Boyer, and R. M. Turner, eds., 2010, Repeat Photography: Methods and Applications in the Natural Sciences: Washington, D.C., Island Press, 337 p.

Wikepedia, 2012. California State Route 136, accessed August 3, 2012. (http://en.wikipedia.org/wiki/California_State_Route_136)

SECTION 7.0 KEELER DUNES PROJECT TEAM

(Listed alphabetically by last name)

Name	Affiliation
Mr. Steven Bacon, CEG, PG	Desert Research Institute, Associate Research Geomorphologist (see attached Curriculum Vitae)
Mr. Clarus Backes, MA, PRA	Sapphos Environmental INC, Archeological Resources Manager
Dr. Dave Barz	HydroBio ARS, Remote Sensing Scientist
Mr. Nik Barbieri	Great Basin Unified Air Pollution Control District, Director of Technical Services
Ms. Marie Campbell	Sapphos Environmental INC., President
Dr. Tiffany Clark, RPA	Sapphos Environmental INC., Senior Cultural Resources Coordinator
Dr. Jack Gillies	Desert Research Institute, Research Professor
Dr. Grace McCarley Holder, PG	Great Basin Unified Air Pollution Control District. Playa Geologist
Mr. Chris Howard	Great Basin Unified Air Pollution Control District, Research and Systems Analyst II
Ms. Sondra Grimm	Great Basin Unified Air Pollution Control District, Technical Services Technician
Dr. David Groeneveld	HydroBio ARS, Remote Sensing Scientist
Ms. Donna Grotzinger	Sapphos Environmental INC., Environmental Compliance Specialist
Mr. Phill Kiddoo	Great Basin Unified Air Pollution Control District, Senior Research and Systems Analyst
Dr. Nicholas Lancaster	Desert Research Institute, Research Professor (see attached Curriculum Vitae)
Mr. Duane Ono	Great Basin Unified Air Pollution Control District, Deputy Air Pollution Control Officer

Mr. Ted Schade, PE	Great Basin Unified Air Pollution Control District, Air Pollution Control Officer
Mr. Mike Slates	Great Basin Unified Air Pollution Control District, Research and Systems Analyst II
Dr. Scott Stine	Geomorphologist, Paleoclimatologist, California State University, East Bay, Professor Emeritus of Geography and Environmental Studies (see attached Curriculum Vitae)

SECTION 7.0 CURRICULA VITAE

Dr. Nicholas Lancaster	Research Professor, Desert Research Institute
Mr. Steven Bacon	Associate Research Geomorphologist, Desert Research Institute
Dr. Scott Stine	Professor Emeritus of Geography and Environmental Studies

Nicholas Lancaster Tel: 775-673-7304
Research Professor
Desert Research Institute email: nick@dri.edu
2215 Raggio Parkway
Reno, NV 89512

Education

Ph.D, 1977, University of Cambridge, Geography
M.A., 1975, University of Cambridge, Geography
B.A. *(College Exhibitioner and Scholar)*, 1971, University of Cambridge, Geography

Professional Interests

Nicholas Lancaster is a geomorphologist with over 30 years of research on sand dune dynamics and Quaternary Geology in desert regions. He has conducted research in deserts in Africa (Namib, Kalahari, northern and western Sahara), Arabia, Antarctica, the western United States (Mojave and Sonoran Deserts), and (via remote sensing) Mars. His current research focuses on: (1) Global and regional patterns of aeolian accumulation; (2) Application of remote sensing to aeolian processes and paleoenvironments in arid regions; (3) Impacts of climatic change on deserts; and (5) Use of GPR and OSL dating to determine dune development. Dr Lancaster serves on the Editorial Boards of the international journals *Geomorphology*, *Earth Surface Processes and Landforms*, *Quaternary Research*, and *Sedimentology*. His work has been recognized by the award of the Dandini Medal of Science from DRI in 1994, a Distinguished Career Award from the Geomorphology Speciality Group of the Association of American Geographers in 1997, the Farouk El-Baz Award for Desert Research from the Quaternary Geology and Geomorphology Division of the Geological Society of America in 2001, and the Nevada System of Higher Education Regents' Researcher Award in 2007.

Recent Professional Experience

2005-2008	Senior Director, Center for Arid Lands Environmental Management (CALEM), Desert Research Institute
2003-2005	Program Coordinator, Earth Surface Dynamics Program, US Geological Survey
2002-	Distinguished Visiting Research Associate, School of Geography, University of Oxford.
1999-2003	Adjunct Professor, Department of Geography, University of Guelph, Guelph, Ontario, Canada.
1994-present,	Research Professor, Desert Research Institute, Division of Earth and Ecosystem Sciences, University of Nevada System, Reno, Nevada

Recent Projects

2008-present	Keeler Dunes, California. Studies of recent history and origins of Keeler dunes using aerial photographs and satellite images for Great Basin Unified Air Pollution Control District. Project PI for DRI. GIS mapping of dune field since 1944 using aerial photographs and satellite images; sediment analyses

2010-present	Oceano Dunes SVRA: Field studies of sand movement and dust emission reduction pilot projects. Project co-PI for DRI — assisted in set up of field projects and analyzed sand transport and wind data.
2008-present	NSF EPSCoR – Nevada Infrastructure for Climate Change Science, Education, and Outreach -National Science Foundation Cooperative Agreement EPS-0814372. Co-PI with shared responsibility for management of $5million/year project.
2007-present	PI, INQUA Project 0704, Sand seas and dune fields of the world: a digital Quaternary atlas: Project Leader and coordinator.
2008-2011	Ash Meadows NWR. Studies of age and origins of dunes using field survey, sediment analysis and geochemistry, and dating. Project PI for DRI; conducted fieldwork (geomorphology, stratigraphy, sediment sampling) and analyzed results of sediment analyses and geochemistry.
2010-2011	PI - British Petroleum – Pipelines and dune mobility. Survey of information on dune dynamics and recommendations for future studies of sand transport around natural gas pipelines.
2007-2011	Co-PI NASA ESPCoR Planetary Surfaces; Co-PI with shared responsibility for management of project.
2008-2010	Co-I, Israel Bi-national Science Foundation – Negev Dunes (with Haim Tsoar and Dan Muhs). Field studies of dunes
2006-2010	Principal Investigator, Visualization of sand dune and sand sea development, DOD/STTC. Computer visualization of GPR data
2006-2008	Principal Investigator, Fringe toed lizard habitat study, Coachella Valley, CA, USGS Denver. Remote Sensing Studies of aeolian deposits in Coachella Valley
2003-2008	Co-Principal Investigator (with Michael Ramsey, University of Pittsburgh) Eolian processes in arid regions, NASA Earth Sciences Division. Remote sening studies of dunes and dust sources, including Soda Lake, CA, and Gran Desierto, Mexico

Publications

A total of over 120 journal articles and book chapters, 3 books, numerous abstracts.

Recent publications (last 5 years)

Lancaster, N. and McCarley-Holder, G., 2012, Decadal-scale evolution of a small dune field: Keeler Dunes, California 1944-2010, *Geomorphology*, doi:10.1016/j.geomorph.2012.10.017

Lancaster, N. and Shannon A. Mahan, 2012, Holocene dune formation at Ash Meadows National Wildlife Area, Nevada, *Quaternary Research*, 78, 266-274, doi:10.1016/j.yqres.2012.05.012

Gillies, J.A. and Lancaster, N., 2012, Large roughness element effects on sand transport, Oceano Dunes, California, *Earth Surface Processes and Landforms*, doi:10.1002/esp.3317

Scheidt, S., Lancaster, N., Ramsey, M., 2011, Eolian dynamics and sediment mixing in the Gran Desierto, Mexico determined from thermal infrared spectroscopy and remote sensing data, *Geological Society of America Bulletin*, 123; 1628–1644; doi: 10.1130/B30338.1.

Lancaster, N., 2011, Dune Dynamics and Morphology, in Thomas, A.S.G. (editor), *Arid Zone*

Geomorphology, Wiley-Blackwell, 487-516.

Lancaster, N., Nickling, W.G., Gillies, J.A., 2010, Sand transport by wind on complex surfaces: field studies in the McMurdo Dry Valleys, Antarctica, *Journal of Geophysical Research, Earth Surface*, 115, F03027, doi:10.1029/2009JF001408.

Gillies, J.A., Nickling, W.G., King, J., Lancaster, N., 2010, Modeling Aeolian Sediment Transport Thresholds on Physically Rough Martian Surfaces: A Shear Stress Partitioning Approach, Geomorphology, 121,15-21. doi:10.1016/j.geomorph.2009.02.016.

Scheidt, S., Ramsey, M., Lancaster, N., 2010, Determining soil moisture and sediment availability at White Sands Dune Field, NM from apparent thermal inertia data, *Journal of Geophysical Research, Earth Surface*, 115, F02019, doi:10.1029/2009JF001378.

Lancaster, N., 2009, Aeolian features and processes, *in* Young, R.S., and Norby, L., *Geological Monitoring*, Boulder, Colorado, Geological Society of America, 1–26, doi: 10.1130/2009.monitoring(01).

Lancaster, N., 2009, Deserts, In: Spencer, T.S., Slaymaker, O., Embleton-Hamann, C., *Geomorphology and Global Environmental Change*, Cambridge University Press, 276-296.

Lancaster, N., 2009, Dune morphology and dynamics, In: Parsons, A.J. and Abrahams, A.D (eds.) *Geomorphology of Desert Environments*, 2nd edition, 557-595.

Katra, I. Scheidt, S., Lancaster, N., 2009, Changes in eolian active sand in the northern Coachella Valley, California, *Geomorphology*, 105, 3-4, 277-290.

Lancaster, N., 2008, Desert dune dynamics and development: insights from luminescence dating, *Boreas*, 37, 559–573. 10.1111/j.1502-3885.2008.00055.

Lancaster, N., and B. Marticorena, 2008, Introduction to special section on Aeolian Processes: *Field Observations and Modeling*, Journal of Geophysical Research (Earth Surface), *113, F02S00,doi:10.1029/2008JF001056.*

Breton, C., Lancaster, N., Nickling, W.G, 2008, Magnitude and frequency of grain flows on a desert sand dune, *Geomorphology*, 95, 518-523.

Katra, I. and Lancaster, N., 2008, Surface-sediment dynamics in a dust source from spaceborne multispectral thermal infrared data, *Remote Sensing of Environment*, doi:10.1016/j.rse.2008.03.016.

Scheidt, S., Ramsey, M., Lancaster, N., 2008, Radiometric normalization and image mosaic generation of ASTER thermal infrared data: An application to extensive sand sheets and dune fields, *Remote Sensing of Environment*, 112, 920-933, doi:10.1016/j.rse.2007.06.020.

Bristow, C.S., Duller, G.A.T., Lancaster, N., 2007, Age and dynamics of linear dunes in the Namib Desert, *Geology*, 35, 6, 555-558.

Lancaster, N., 2007, Low latitude dune fields, in Elias, S.A. (editor), *Encyclopedia of Quaternary Science*, Elsevier, 626-642.

BIOGRAPHICAL SKETCH

Steven N. Bacon
Desert Research Institute
Division of Earth and Ecosystem Sciences
2215 Raggio Parkway
Reno, NV 89512

Phone: (775) 673-7473
Fax: (775) 673-7485
Email: Steven.Bacon@dri.edu

License

California Certified Engineering Geologist (C.E.G.), No. 2559
California Professional Geologist (P.G.), No. 8581

Education

M.S.	2003	Humboldt State University	Environmental Systems, Geology
B.S.	1996	Humboldt State University	Geology

Research Interest and Experience

- Application of basic and applied research in Quaternary geology, geomorphology, and engineering geology related to terrain characterization, landscape evolution, paleoclimate studies, and geologic hazards;
- Geotechnical applications to characterize soil and site conditions;
- Applied tectonic geomorphology and paleoseismic research for seismic hazard assessments;
- Landslide investigations for geologic hazards and land management; and
- Research field areas and/or areas of interest include the western United States and Alaska, Israel, Egypt as well as southwest Asia.

Professional Experience

2011-present	**Associate Research Geomorphologist**: Desert Research Institute, Division of Earth and Ecosystem Sciences, Reno, NV
2007-2011	**Assistant Research Geomorphologist**: Desert Research Institute, Division of Earth and Ecosystem Sciences, Reno, NV
2005-2007	**Staff Geomorphologist**: Desert Research Institute, Division of Earth and Ecosystem Sciences, Reno, NV
2004-2005	**Research Geologist**: U.S. Geological Survey, Bishop, CA
2003-2005	**Senior Staff Geologist**: Piedmont GeoSciences, Inc., Reno, NV
1998-2003	**Staff Engineering Geologist**: Busch Geotechnical Consultants, Arcata, CA
2000	**Field Assistant**: William Lettis & Associates, Inc., Walnut Creek, CA
2000	**Field Research Assistant**: Humboldt State University & University of Washington
1999-2000	**Field Research Assistant:** New Zealand Institute of Geological & Nuclear Sciences, Lower Hutt, New Zealand
1998-1999	**Field Geologist**: ENGEO Incorporated, San Ramon, CA
1997	**Geologist**: U.S. Geological Survey / Ground Deformation Program, Hawaiian Volcano Observatory
1998; 1999; 1996-1997	**Geologist**: U.S. Geological Survey / Earthquake Hazards Team, Mammoth Lakes, CA

Peer-reviewed Publications (first authored)

Bacon, S.N., and McDonald, E.V. (Accepted). Regional distribution of salt-rich dust across southwest Asia based predictive soil-geomorphic mapping techniques, *in* Harmon, R.S., and McDonald, E.V., eds., Reviews in Engineering Geology Volume XX: *Military Geoscience in the 21st Century*. Geological Society of America, Denver, CO.

Bacon, S.N., McDonald, E.V., Dalldorf, G.K., Lucas, W., and Nikolich, G. (Accepted). Recommendations for the development of a dust-suppressant test operations procedure (TOP) for U.S. Army materiel testing, *in* Harmon, R.S., and McDonald, E.V., eds., Reviews in Engineering Geology Volume XX: *Military Geoscience in the 21st Century*. Geological Society of America, Denver, CO.

Bacon, S.N., McDonald, E.V., Amit, R., Enzel, Y., and Crouvi, O. (2011). Total suspended particulate matter emissions at high friction velocities from desert landforms, *Journal of Geophysical Research*, 116, F03019.

Bacon, S.N., McDonald, E.V., Caldwell, T.G., and Dalldorf, G.K. (2010). Timing and distribution of alluvial fan sedimentation in response to strengthening of late Holocene ENSO variability in the Sonoran Desert, southwestern Arizona, USA. *Quaternary Research* 73, 425-438.

Bacon, S.N., McDonald, E.V., Dalldorf, G.K., Baker, S.E., Sabol Jr., D.E., Minor, T.B., Bassett, S.D., MacCabe, S.R., Bullard, T.F. (2010). Chapter 32 **-** Predictive soil maps based on geomorphic mapping, remote sensing, and soil databases in the desert southwest, *in* Boeettinger, J., Howell, D., Moore, A., Hartemink, A., Kienast-Brown, S., eds., Digital soil mapping: bridging research, production, and environmental application, Springer, Netherlands, pp. 409-419.

Bacon, S.N., McDonald, E.V., Baker, S.E., Caldwell, T.G., and Stullenbarger, G. (2008). Desert terrain characterization of landforms and surface materials within vehicle test courses at U.S. Army Yuma Proving Ground, USA. *Journal of Terramechanics* 45, 167-183.

Bacon, S.N., and Pezzopane, S.K. (2007). A 25,000-year record of earthquakes on the Owens Valley fault near Lone Pine, California: Implications for recurrence intervals, slip rates, and segmentation models. *Geological Society of America Bulletin*, **119/7,** 823-847.

Bacon, S.N., Burke, R.M., Pezzopane, S.K., and Jayko, A.S. (2006). Last glacial maximum and Holocene lake levels of Owens Lake, eastern California, USA. *Quaternary Science Reviews*. **25/11-12,** 1264-1282.

Bacon, S.N., Jayko, A.S., and McGeehin, J.P. (2005). Holocene and latest Pleistocene oblique dextral faulting on the southern Inyo Mountains fault, Owens Lake basin, California. *Bulletin Seismological Society of America*. **95,** 2472-2485.

Bacon, S.N., Chinn, T.C., Van Dissen, R.J., Tillinghast, S.F., Goldstein, H.L., and Burke, R.M. (2001). Paleo-equilibrium line altitude estimates from late Quaternary glacial features in the Inland Kaikoura Range, South Island, New Zealand. *New Zealand Journal of Geology and Geophysics*. **44,** 55-67.

Peer-reviewed Publications (coauthored)

Bullard, T.F., **Bacon, S.N.**, Canonne, P., Smith, J.N., Queen, C.R., Ruehlen, L., Ormond, J. (2011). Geology, geomorphology and the vertical dimension of the World War II battlefield, *in* Häusler, H. and Mang, R., eds., International Handbook Military Geography Volume 2: Arbeitsgemeinschaft Truppendienst, Ministry of Defence and Sports, Vienna, pp. 99-106.

Caldwell, T.G., McDonald, E.V., **Bacon, S.N.**, and Stullenbarger, G. (2008). The performance and sustainability of vehicle dust courses for military testing. *Journal of Terramechanics* 45, 213-221.

Jayko, A.S. and **Bacon, S.N.** (2008). Late Quaternary MIS 6-8 shoreline features of pluvial Owens Lake, Owens Valley, eastern California, *in* Reheis, M.C., Hershler, R., and Miller, D.M., eds., Late Cenozoic Drainage History of the Southwestern Great Basin and Lower Colorado River Region: Geologic and Biotic Perspectives: Geological Society of America Special Paper 439, pp. 185-206.

Slemmons, D.B., Vittori, E., Jayko, A.S., Carver, G.A., and **Bacon, S.N.** (2008). Quaternary fault and lineament map of Owens Valley, Inyo County, eastern California. Geological Society of America Map and Chart 96, 25 p.

Other Publications

Van Dissen, R. J., R. M. Burke, P. J. Tonkin, **S. Bacon**, R. Bowers, H. Goldstein, J. Redwine, D. Sutherland, and S. Tillinghast (2005). Kekerengu Fault assessment of late Quaternary slip rate using alluvial terrace and soil stratigraphy. *Geological Society of New Zealand miscellaneous publication 119B*, p. 100-108.

Bacon, S., Burke, B., Pezzopane, S., and Jayko, A. (2005). Geologic and geomorphic record of late Pleistocene and Holocene lake levels of Owens Lake, eastern California. *In* "Geologic and biotic perspectives on the late Cenozoic drainage history of the southwestern Great Basin and lower Colorado River region: Conference abstracts" (M.C. Reheis, Ed.), pp. 15-16. *U.S. Geological Survey Open-File Report 2005-1404*. http://pubs.usgs.gov/of/2005/1404/pdf/OFR-2005-1404.pdf

Bacon, S.N., Pezzopane, S.K., and Burke, R.M. (2003). NEHRP Final Technical Report: Paleoseismology on the Owens Valley fault and latest Quaternary stratigraphy in Owens Valley near Lone Pine, eastern California, 42 p. http://erpweb.er.usgs.gov/reports/abstract/2002/ni/02hqgr0003.pdf

Abstracts (first authored)

Bacon, S.N., McDonald, E.V., Sweeney, M.R., Amit, R., Enzel, Y., and Crouvi, O. (2011). Emission of PM_{10} and total suspended particulate matter from desert landforms across the southwestern U.S. and Israel: Implications for near-surface and atmospheric dust loading models: *XXIII Inqua-Congress, Abstract with Programs,* July 21-27, 2011, Bern, Switzerland, ID 3015.

Bacon, S.N., McDonald, E.V., and Green, H.L. (2011). Development of geomorphic-based dust source emissions data in support of forecasting dust storm activity in southwest Asia: *9th International Conference on Military Geosciences, Abstracts with Programs,* June 19-24, 2011, Las Vegas, Nevada, p 18.

Bacon, S.N., McDonald, E.V., Caldwell, T.G., and Dalldorf, G.K. (2009). Alluvial fan response to strengthening of late Holocene ENSO variability in the Sonoran Desert, southwest Arizona: *Geological Society of America Annual Meeting, Abstracts with Programs,* v. 41, n. 7, p. 647.

Bacon, S.N., McDonald, E.V., Dalldorf, G.K., Baker, S.E., Sabol Jr., D.E., Minor, T.B., Bassett, S.D., MacCabe, S.R., Bullard, T.F. (2009). Predictive terrain hazard maps for military operations in the desert based on geomorphic mapping, remote sensing, and soil databases: *8th International Conference on Military Geosciences, Abstracts with Programs,* June 15-19, 2009, Vienna, Austria, p 14.

Bacon, S.N., McDonald, E.V., Dalldorf, G.K., Baker, S.E., Sabol Jr., D.E., Minor, T.B., Bassett, S.D., MacCabe, S.R., Bullard, T.F. (2008). An expert based system to predict soil attributes using geomorphic mapping, remote sensing, and soil databases in the desert southwest USA: *European Geological Union,* EGU2008-A-10709; SSS25-1FR5P-0669, Abstract XY0669.

Bacon, S.N., McDonald, E.V., Dalldorf, G.K., and Caldwell, T.G. (2007). Late Holocene soil stratigraphy and geochronology of alluvial sedimentation in the Sonoran Desert, Arizona, *EOS Trans., AGU,* 88 (52), Fall Meet. Suppl., Abstract H53C-1390.

Bacon, S.N., McDonald, E.V., Baker, S.E., Caldwell, T.G., and Stullenbarger, G. (2007). Desert terrain characterization of landforms and surface cover within vehicle test courses at U.S. Army Yuma Proving Ground, USA: *Proceedings of the Joint North American, Asia-Pacific ISTVS Conference and Annual Meeting of Japanese Society for Terramechanics,* Fairbanks, Alaska, USA, June 23-26, 2007, Session 41 Terrain Impacts, talk and short paper.

Bacon, S.N., McDonald, E.V., and Bassett, S.D. (2007). Catalogue of analogs: Identifying terrain similarities between the World's deserts and the US Army Desert/Hot Weather test site, Yuma Proving Ground (YPG), southwestern Arizona: *7th International Conference on Military Geology and Geography,* June 18-21, Quebec, Canada, Session 4 Spatial Analysis, abstract and talk, p. 8.

Bacon, S.N., and Jayko, A.S. (2004). Holocene and latest Pleistocene surface ruptures on the southern Inyo Mountains Fault, southern Owens Valley, *Basin and Range Seismic Hazard Summit, II, Reno, NV, May 2004.*

Bacon, S.N., and Jayko, A.S. (2004). Holocene(?) and latest Pleistocene surface ruptures on the southern Inyo Mountains Fault, southern Owens Valley, Eastern California shear zone: *Geological Society of America, Abstracts with Programs*. **36,** 16.

Bacon, S.N., Bayasgalan, A., Gillespie, A., and Burke, R.M. (2003). Paleoseismic displacement measurements from landforms subjected to periglacial processes: Observations along the Jarai Gol fault near the Tamyn Am Hills, Darhad Depression, northern Mongolia. *XVI Inqua Congress, Abstract with Programs*. 103.

Bacon, S.N., Pezzopane, S.K., and Burke, R.M. (2002). Paleoseismology on the Owens Valley fault and Holocene stratigraphy of pluvial Owens Lake near Lone Pine, eastern California: *Geological Society of America, Abstract with Programs.* **34,** 6.

Bacon, S.N., Pezzopane, S.K., and Burke, R.M. (2002). Stratigraphic evidence for only one Holocene paleoearthquake since ca. 12 ka on the Owens Valley fault, near Lone Pine, eastern California: *Geological Society of America, Abstract with Programs.* **33,** 4.

Bacon, S.N., and Burke, R.M. (2000). Preliminary Paleoseismic Investigations on the Owens Valley Fault Zone and Latest Quaternary Stratigraphy in Owens Valley near Lone Pine, eastern California. *American Geophysical Union, 2000 Fall Meeting, Program and Abstract.* **81,** 48.

Bacon, S.N., Chinn, T.C., Van Dissen, R.J., Goldstein, H.L., Tillinghast, S.F., and Burke, R.M. (2000). Late Pleistocene Equilibrium Altitude Estimates from Glacial Features in the Inland Kaikoura Range, New Zealand (Abstract). 9th Australian and New Zealand Geomorphological Group Conference.

Bacon, S.N., Van Dissen, R.J., Goldstein, H.L., Tillinghast, S.F., and Burke, R.M. (2000). Late Pleistocene Equilibrium Altitude Estimates from Glacial Features in the Inland Kaikoura Range, New Zealand. *Geological Society of America, Abstract with Programs.* **32,** 7.

Bacon, S.N., Balzer, V., Batton, C., and Gere, T.M. (1996). Quaternary Volcanic and Glacial Stratigraphy in the central High Cascades, outside Sisters, Oregon. *Geological Society of America, Abstracts with Programs.* **28,** 5.

Abstracts (coauthored)

Caldwell, T., McDonald, E., Bacon, S., Young, M., and Lin, H. (2012). Hydropedology and ecosystem response on an arid soil chronosequence: *2nd International Conference on Hydropedology, Abstract with Programs,* July 22-27, Leipzig, Germany.

McAlpine, J.D., Koracin, D., **Bacon, S.**, and McDonald, E. (2012). Development of an operational predictive tool for visibility degradation and brownout caused by rotorcraft dust entrainment: *Weather Impacts Decision Aids (WIDA) Workshop, Abstract with Programs*, March 13-15, Reno, Nevada.

McDonald, E.V., Spears, L., Fleming, S.D., and **Bacon, S.N.** (2012). Developing science-based testing – characterizing the physical environment with enough detail to support test procedures: *28th Annual National Test & Evaluation Conference, Abstract with Programs,* March 12-15, 2012, Hilton Head, South Carolina, #13755.

McDonald, E.V., **Bacon, S.N.**, Schumer, R., Jenkins, S., and Caldwell, T. (2011). The question of the origin of cleared circles as cultural resource features: weary humans or energetic rodents?: *9th International Conference on Military Geosciences, Abstracts with Programs,* June 19-24, 2011, Las Vegas, Nevada, p 80.

Caldwell, T., McDonald, E., **Bacon, S.**, Schumer, R., and Bullard, T. (2011). Cleared circles: Anthropogenic or Biogenic? Use of non-invasive geophysical techniques to determine origin, *The Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Abstracts with Program,* April 10-14, 2011.

McDonald, E.V., **Bacon, S.N.** (2010). Rapid measurement of dust emission from semi-arid to hyperarid landforms: Implications for assessing impacts of global climate change on wind erosion and dust emission. *International Dryland Development Commission (IDDC), Tenth International Conference on Development of Drylands, Cairo, Egypt, Abstracts with Program*, December 12-15, 2010**.**

Caldwell, T.G., Sweeney, M., **Bacon, S.N.**, and McDonald, E., (2009). Hydraulic gradient and dust emissivity along a playa to distal fan transect, *EOS Trans., AGU*, 90 (52), Fall Meet. Suppl., Abstract EP24A-05.

Bullard, T.F., Canonne, P., **Bacon, S.**, Queen, C.R., Ormond, J. (2009). Geology, geomorphology, and the vertical dimension of the battlefield: First ever surrender of major ground force unit to an air force – Chateauroux Region, France, August – September 1944: *8th International Conference on Military Geosciences, Abstracts with Programs*, June 15-19, 2009, Vienna, Austria, p 28.

McDonald, E.V., **Bacon, S.N.**, Dalldorf, G.K., Bullard, T.F., Minor, T.B. (2009). Integrated desert terrain forecasting for military operations: Geologic basis for rapid predictive mapping of soils and terrain features: 8th *International Conference on Military Geosciences, Abstracts with Programs*, June 15-19, 2009, Vienna, Austria, p 92.

Dalldorf, G.K., Caldwell, T.C., **Bacon, S.N.,** Young, M.H., Miller, J.J., McDonald, E.V. (2009). Rapid characterization of runoff potential on arid alluvial fans using terrain prediction and geomorphic mapping. American Association of Geographers annual meeting, Las Vegas, Nevada, Session 5603, March 26, 2009.

Dalldorf, G.K., **Bacon, S.N.,** McDonald, E.V., Baker, S.E., Sabol Jr., D.E., Minor, T.B., Bassett, S.D., MacCabe, S.R., Bullard, T.B. (2008). Predictive soil maps based on geomorphic mapping, remote sensing, and soil databases in the desert southwest: 3rd *Global Workshop on Digital Soil Mapping*, Paper in Session 6, 10 p.

Caldwell, T.G., McDonald E.V., Young, M., **Bacon, S.N.**, Marion, G.M. (2008). Numerical simulations of salt accumulation in a hyper-arid soil chronosequence in the Sonoran Desert: *Geological Society of America Joint Annual Meeting, Abstracts with Programs*, 335-9.

Berli, M., Caldwell, T., **Bacon, S.**, McDonald, E. (2008). Trafficability of fine-textured arid soils – a model evaluation: *Geological Society of America Joint Annual Meeting, Abstracts with Programs*, 58-6.

Dalldorf, G.K., McDonald, E.V., **Bacon, S.N.**, Nikolich, G. (2008). Testing and evaluation of a synthetic polymer for dust suppression in military applications: *Geological Society of America Joint Annual Meeting, Abstracts with Programs*, 135-14.

McDonald, E.V., and Bassett, S.D., **Bacon, S.N.**, Minor, T.B., and Bullard, T.B. (2007). Integrated terrain forecasting for military operations: Predicting the location of critical soil conditions using geomorphic image analysis: 7th *International Conference on Military Geology and Geography*, June 18-21, Quebec, Canada, Session 9 Soil and Technology, abstract and talk, p. 22.

Caldwell, T.G., McDonald, E.V., and **Bacon, S.N.** (2007). Vehicle dust courses and military testing at the U.S. Army's Yuma Proving Ground: *Proceedings of the Joint North American, Asia-Pacific ISTVS Conference and Annual Meeting of Japanese Society for Terramechanics*, Fairbanks, Alaska, USA, June 23-26, Session 41 Terrain Impacts, poster and short paper.

Caldwell, T.G., McDonald, E.V., Young, M.H., Hamerlynck, E.P., and **Bacon, S.N.** (2006). Ecohydrology of an arid soil chronosequence in the Sonoran Desert, Yuma Proving Ground, USA, *EOS Trans., AGU*, 87 (52), Fall Meet. Suppl., Abstract H13A-1355.

McDonald, E.V., Bassett, S.D., **Bacon, S.N.**, Minor, T.B., Bullard, T.F. (2006). Integrated desert terrain forecasting for military operations: 25th Army Science Conference, November 27-30, Orlando, FL, Session O Environmental and Engineering Geosciences; OP-14, poster & short paper, 6 p.

Awards

U.S. Geological Survey (USGS) / National Association of Geology Teachers (NAGT) 1996 internship. *http://www.nagt.org/nagt/programs/usgs_field.html*

Affiliations

Geological Society of America
American Geophysical Union
Association of Environmental and Engineering Geologists

Discipline/profession Services

2010 nominee for the panel of the Geological Society of America, Quaternary Geology and Geomorphology Division.

Peer-Review Services

- Reviewer, 2012, *Journal of Mountain Science*
- Reviewer, 2012, *U.S. Geological Survey, 7.5-Minute Quadrangle Surficial Geological Map*
- Reviewer, 2012, *Quaternary Research*
- Reviewer, 2012, *Geological Society of America Bulletin*
- Reviewer, 2012, *Geology*
- Reviewer, 2012, *Bulletin of the Seismological Society of America*
- Reviewer, 2010, *Lithosphere*
- Reviewer, 2009, *Quaternary Research*
- Reviewer, 2008, *Sedimentary Geology*
- Reviewer, 2007, *Geophysical Research Letters*
- Reviewer, 2007, *Quaternary Research*
- Reviewer, 2007, *Journal of Arid Lands Management*
- Reviewer, 2006, *Geological Society of America Special Paper*
- Reviewer, 2006, *Journal of South American Earth Sciences*
- Reviewer, 2005, *Quaternary Science Reviews*

CURRICULUM VITAE

NAME Scott William Stine

HOME ADDRESS P.O. Box 816
Point Reyes Station, California 94956

HOME WIRES Phone: 415-663-8406; e: scott.stine@sbcglobal.net

DATE OF BIRTH July 30, 1950

POSITION Professor Emeritus
Department of Geography and Environmental Studies
California State University, East Bay
Hayward, California 94542
(510) 885-3193
scott.stine@csueastbay.edu

EDUCATION

B.A. (Honors) in Physical Geography, June, 1975
  University of California, Berkeley
M.A. in Physical Geography, June, 1980
  University of California, Berkeley (as a U.C. Regent's Fellow)
Ph.D. in Physical Geography, July, 1987
  University of California, Berkeley
Post-Doctoral Fellow, 1987 - 1989
  Lamont-Doherty Earth Observatory of Columbia University, N.Y.

EXPERTISE Fluvial, glacial, and lacustrine geomorphology; paleoclimatology; Quaternary stratigraphy; hydrographically closed lakes; biogeography; historic landscape reconstruction; stream and lake restoration; exploration and discovery in Intermontane North America.

SPECIAL APPOINTMENTS/AWARDS/GRANTS (selection)

Fellow, California Academy of Sciences (elected 1992)
Named "Outstanding Professor of the Year," 2004-5, by California State University, East Bay
Adjunct Research Scientist, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, 1990-present (intermittent)
Grant from the Comer Science and Education Foundation ($300,000) to investigate past droughts of western North America
Grants (four) from the National Science Foundation to study the hydrographically closed lakes of Patagonia
Grant from Argentina's Agencia de Promocion Cientifica y Tecnologica to work with Argentine archeologists on lakes in southern Patagonia
Grant from the State of California for a "critical elevations assessment" of Mono Lake
Grant from the United States Geological Survey for paleoclimatic research in the Mono Basin
Award for Excellence, American Association for the Advancement of Science, 65th Annual Meeting

PUBLICATIONS--Refereed Journals, Books, Maps, and Book Chapters (selection)

A Way Across The Mountain: The 1833 Trans-Sierran Route of Joseph Walker and Zenas Leonard. Book manuscript complete, in press.

The effects of recent uplift and volcanism on deposition in Mono Lake, California, from seismic-reflection (CHIRP) profiles (with S.M. Colman--lead author--and others). Journal of Geophysical Research (2012--in press).

Chronostratigraphy and Lake-Level Changes of Laguna Cari-Laufquén, Río Negro, Argentina (with Alyson Cartwright--lead author--and others). Quaternary Research v. 76 (3), pp. 430-440 (2011)

Eruption Chronology and Petrologic Reconstruction of the Holocene-aged Eruption of Red Cones, Southern Inyo Chain, California (with B.L. Browne--lead author--and others). Geological Society of America Bulletin v. 122, pp. 1401-1422 (2010).

Economic Consequences of Optimized Water Management for a Prolonged, Severe Drought in California (with Julien Harou--lead author--and others). Water Resources Research v. 46, W05522, 12 pp. (2010).

Field Excursion (invited) for the 16th Congress of the International Quaternary Association, "Pliocene to Holocene Lakes in the Western Great Basin: New Perspectives on Paleoclimate, Landscape Dynamics, Tectonics, and Paleodistribution of Aquatic Species" (2003).

Holocene paleoclimates of southern Patagonia: Limnological and environmental history of Lago Cardiel, Argentina (with Vera Markgraf--lead author, and others). The Holocene, v.13(4), pp. 581-591 (2003).

Influence of the Pacific decadal oscillation on the climate of the Sierra Nevada, California and Nevada (with Larry Benson--lead author, and others). Quaternary Research v. 59, pp. 151-159 (2003).

Drainage reversals in the Mono Basin during the late Pliocene and Pleistocene (with Marith Reheis--lead author, and Andrei M. Sarna-Wojcicki). Geological Society of America Bulletin v. 114, pp. 991-1006 (2002).

Digital Bathymetric model of Mono Lake, California (with Christian Raumann--lead author, and others). United States Geological Survey Field Studies Map MF-2393, 10 pp + map (2002).

Full- and Late-Glacial Lake Records along the PEP-1 Transect: Their Role in developing Inter-Hemispheric Paleoclimate Interactions (with J.P. Bradbury--lead author, M. Grosjean, and Florence Sylvestre). Pp. 265-291 *in,* V. Markgraf (ed.), *Pole-Equator-Pole: Inter-Hemispheric Correlations of Late Quaternary Climate in the Americas.* Academic Press (2001).

On the Medieval Climatic Anomaly. Current Anthropology v. 41 (4), pp. 627-628 (2000)

A Medieval Climatic Anomaly in the Americas. Pp. 43-67 *in,* Arie Issar and Neville Brown (eds.), *Water, Environment, and Society in Times of Climatic Change,* Kluwer Academic (1998).

Climate of the Sierra Nevada, 1650-1850. Chapter 2 (pp 25-30) *in, Sierra Nevada Ecosystem Project,* Final Report to Congress, v. 2: Assessments and Scientific Basis for Management Options (1996).

Quaternary Geologic Map of the Mt. Whitney 4° X 8° Quadrangle. Quaternary Geologic Map of the United States. United States Geological Survey (co-authored with Clyde Wahrhaftig) (1995).

Extreme and persistent drought in California and Patagonia during Medieval time. Nature v. 369, pp 546-549 (1994).

Ikaite precipitation at Mono Lake, California (with James Bischoff--lead author). Geochimica et Cosmochimica ACTA v. 57, pp 3855-3865 (1993).

Quaternary Geologic Map of the San Francisco 4° X 6° Quadrangle, United States. United States Geological Survey Map I-1420 (NJ-10) (1993).

Geomorphic, geographic, and hydrographic basis for resolving the Mono Lake controversy. Environmental Geology and Water Science v. 17, pp 67-83 (1991).

Past Climate at Mono Lake, California. Nature v. 345 (6274), p. 391 (1990).

Late Holocene fluctuations of Mono Lake, eastern California. Palaeogeography, Palaeoclimatology, Palaeoecology v. 78, pp 333-381 (1990).

A record from Lake Cardiel of climate change in southern South America (lead author, with Mary Stine). Nature v. 345 (6277), pp 705-708 (1990).

PUBLICATIONS (cont.)

Chronology of expansion and contraction of four Great Basin lake systems during the past 35,000 years. With L. Bensen (lead author) and others. Palaeogeography, Palaeoclimatology, Palaeoecology v. 78, pp 241-286 (1990).

The radiocarbon budget for Mono Lake. With W. Broecker (lead author) and others. Earth and Planetary Science Letters v. 88 (1), pp 16-26 (1988).

Mono Lake's radiocarbon budget: An unsolved enigma. With W. Broecker (lead author). EOS, June 7, 1988, p. 633.

Holocene paleoclimatology and tephrochronology east and west of the central Sierran crest (editor and contributor). Field trip guidebook for Friends of the Pleistocene, Pacific Cell, October, 1984, 107 pp.

Late Holocene fluctuations of Mono Lake: Tephrochronology and ages of the islands. Pp 79-83 *in,* Western Geological Excursions (v. 2) 1984 meetings, Geol. Soc. of America.

Geology and hydrology of the Mono Basin. Pp 11-16 *in, Proceedings of the UCLA Public Policy Symposium on "Mono Lake: Beyond the Public Trust* (1984).

Destruction of riparian habitat due to water diversions in the Mono Basin, California (lead author, with P. Vorster and D. Gaines). Pp 528-533 *in,* R. Warner and K.M. Hendrix (eds.), California Riparian Systems, Univ. California Press (1984).

Reinterpretation of the 1857 surface elevation of Mono Lake, California. Water Resources Center, University of California, Report No. 52, 41 pp (1981).

PUBLISHED ABSTRACTS

Late Holocene volcanism in and adjacent to Mono Lake, California (abstract). Annual Meeting of the Geological Society of America, Minneapolis (2011).

CHIRP Seismic-Reflection Profiles from Mono Lake: The Effect of Volcanic Eruptions on Lacustrine Stratigraphy (abstract, with Steven Colman--lead author--and others). Annual Meeting of the Geological Society of America, Minneapolis (2011).

Holocene Sedimentation Patterns and Volcanic History from BINGO Expedition Sediment Core, Mono Lake, California, USA (abstract, with Susan Zimmerman--lead author--and others). Annual Meeting of the Geological Society of America, Minneapolis (2011).

History of Late Holocene Tufa Deposition at Mono Lake, California (abstract). American Geophysical Union Fall Meeting, San Francisco (2009).

Radiocarbon constraints on fossil thinolite tufa formation in the Mono Basin, CA, USA (abstract, with S.L. LeRoy--lead author--and others). American Geophysical Union Fall Meeting, San Francisco (2009).

Rare earth element and uranium-thorium variations in tufa deposits from the Mono Basin, CA (abstract, with E.S. Wilcox--lead author--and others). American Geophysical Union Fall Meeting, San Francisco (2009).

Springs and Seeps as Possible Aquatic Refugia During the Droughts Of Medieval Time (lead author, with Tom Brown and Tom Guilderson). 27th Biennial Groundwater Conference - 18th Groundwater Resources Association Annual Meeting and Conference, Sacramento (2009).

Increasing Evidence for the Medieval Drought-Deluge-Drought Sequence in the Western U.S. Joint Meeting of The Geological Society of America, Soil Science Society of America, American Society of Agronomy, Crop Science Society of America, Gulf Coast Association of Geological Societies with the Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists, Houston (2008).

Late Holocene Environmental Flux and Human Adaptive Responses at Owens Lake (abstract). Great Basin Anthropological Conference, "From Highstand to Desiccation: Lacustrine Adaptations in the Western Great Basin," Sparks, Nevada, October 2004.

Reconstruction of Great Basin and Patagonian Lakes Using Geomorphic and Stratigraphic Evidence from Deltas (abstract). Amer. Geophysical Union Annual Meeting, San Francisco, December, 1998.

Abrupt and Synchronous Climate Shifts Across the Americas During Little Ice Age and Medieval Times (abstract). International Conference on Inter-Hemispheric Correlations of Paleoclimate (sponsored by the National Science Foundation and the International Geosphere and Biosphere Program). Merida, Venezuela, March 16-20, 1998.

PUBLISHED ABSTRACTS (cont.)

Seeking Our Climatic Past: A View Beyond the Greenhouse (abstract). Invited presentation to the Conference on Drylands Environments, Desert Research Institute, University of Nevada at Reno, June 10-11, 1997.

Scientific Background to the Mono Lake Controversy (abstract). Invited presentation to the Conference on The Public Trust Doctrine, sponsored by the Boalt Hall School of Law and the Ecology Law Quarterly. University of California, Berkeley, February 22, 1997.

A Medieval Climatic Anomaly Across the Americas (abstract). Invited presentation to the International Conference on Water, Environment and Society in Times of Changing Climate. Ben-Gurion University of the Negev, Beer Sheva, Israel, July 7-12, 1996.

Drought off the Pacific (abstract). Plenary Address to the 13th Annual Pacific Climate Workshop of Scripps Institute and the U.S. Geological Survey, Asilomar, April 15, 1996.

Estimating the severity of Medieval drought and its impact on human populations (abstract). Invited presentation to the Society for American Archeology, New Orleans, April 14, 1996.

Droughts and Deluges in Late Holocene California: The Record From Lake Fluctuations and Drowned Stumps (abstract). EOS (1994).

Paleoclimatic evidence of extended extreme drought in California (abstract). Seventy-fifth Annual Meeting of the Pacific Division, American Association for the Advancement of Science, June 19-24, 1994.

Drought During Medieval Time in the Sierra Nevada and the Western Great Basin (abstract). Invited paper to the United States Geological Survey Workshop on Paleoclimatic Studies in the Northern Great Basin, May 16-19, 1993.

Extreme Drought During Medieval Time, and its Possible Influence on Human Populations of California. Plenary Address to the Plenary Session of the Society of California Archeologists, April, 1993.

The "Medieval Warm Epoch": Its sign, severity, timing, and duration in western North America and southern South America (abstract). Medieval Warm Period Workshop, University of Arizona, November 6-8, 1991.

Geomorphic evolution of Gilbert-type deltas in widely fluctuating lakes (abstract). Conference on Sedimentary and Paleolimnological Records of Saline Lakes, Saskatoon, Saskatchewan, August 13-16, 1991.

Drought in western North America and southern South America, AD 750 to 1400: Evidence from lakes and marshes (abstract). Fifth International Symposium on Inland Saline Lakes, Lake Titicaca, Bolivia, March,1991.

Holocene abrasion platforms at Mono Lake, California (abstract). Annual Meeting of the Southern California Academy of Sciences (1989).

Tufa formation at Mono Lake, California: Some misconceptions (abstract). Annual Meeting of the Southern California Academy of Sciences (1989).

Late Holocene lake fluctuations and island volcanism at Mono Lake, California (abstract) Proceedings of the 65th Annual Meeting of the American Association for the Advancement of Science, Pacific Division (1984).

Most recent eruption of the Mono Craters, eastern California (abstract). With K. Sieh (lead author) and S. Wood. EOS, v. 64, p. 889 (1983).

PUBLISHED SCIENCE PHOTOGRAPHS ***(exclusive of Stine articles)***

"Twentieth Century [Glacial] Retreat," *in,* "1000 Years of Climate Change." Science v. 288, pp. 1353-55 (May 26, 2000).

"West Walker River, Mono County, California," *in,* "Endless Summers", Cal Academy's Pacific Discovery, Spring, 1995.

"Stumps of "the graveyard, West Walker River, Mono County, California," *in,* "Stumps Tell a Tale of Long, Severe Drought", National Geographic, April, 1995.

"Stumps of the West Walker River, Mono County, California," *in,* "Severe Ancient Droughts: A Warning to California", New York Times (Science Times), July 19, 1994.

"Graveyard of pine stumps along the West Walker River, testament to ancient droughts," *in,* "Drowned Trees Record Dry Spells", Nature, v. 369, p. 518, June 16, 1994.

"Mono Lake from Dechambeau Creek, Mono County Park." *The California Water Atlas* (p. 108), William Kahrl, ed. State of California (1978).

KEYNOTE AND PLENARY ADDRESSES RELATED TO ENDORHEIC LAKES

It's About Time: The Past 1800 years of Landscape Evolution in the Mono Basin. Keynote Address to the Mono Basin Chautauqua, Lee Vining, California, June 17, 2005.

A Widening Perimeter of Medieval Drought in Western North America. Keynote Address to the Society for California Archeology, Sacramento, March 21, 2005.

Past Changes in Earth's Climate: Evidence and Environmental Consequences. Keynote Address to the Schools and Colleges for Advancing the Teaching of Science: The California Science Project. California State University, Sacramento, Nov. 6, 1996

Prehistoric Drought in Southern California's Artificial Catchment. Keynote Address to the Southern California Environment and History Conference, "Southern California Before 1900: Landscape, Ecology, Climate", Northridge, Sept. 20-22, 1996

Drought off the Pacific. Plenary Address to the 13th Annual Pacific Climate Workshop of Scripps Institute and the U.S. Geological Survey, Asilomar, April 15, 1996

"Delta." Keynote Address to the American Fisheries Society, Ventura, California, March 29, 1996

Droughts and the future of California's Water Supply. Keynote Address to the Ecological Interagency Program on the Sacramento-San Joaquin River Estuary, Asilomar, March 1995

Extreme Drought During Medieval Time, and its Possible Influence on Human Populations of California. Plenary Address to the Plenary Session of the Society of California Archeologists, Asilomar, California, April, 1993

TECHNICAL REPORTS

Environmental History of Late Holocene Owens Lake, California. Pp. 419-446 *in*, Brian F. Byrd and Micah Hale (eds.), Lacustrine Lifestyles Along Owens Lake: NRHP Evaluation of 15 Prehistoric Sites for the Olancha/Cartago Four-Lane Project, U.S. Route 395, Inyo County, California (2003).

Restoration of Degraded Riparian, Wetland, and Deltaic Environments on Mill Creek, Mono County, California. Report to Ducks Unlimited, Hornocker Wildlife Research, and the United States Forest Service. 23 pp (1995).

Historic and Future Waterfowl Habitat at Mono Lake, California. Report to the California State Attorney General's Office, the California State Lands Commission, and the California Department of Parks and Recreation. 61 pp (1995).

Waterfowl Habitat Restoration in the Mono Basin: A Preliminary Examination of Constraints and Possibilities. Report to the California State Attorney General's Office, the California State Lands Commission, and the California Department of Parks and Recreation. 7 pp (1995).

Late Holocene Fluctuations of Owens Lake, Inyo County, California. Report to Far Western Anthropological Group Inc., Davis, California. 19 pp (Nov. 1994).

Restoration Conceptual Plan: Concepts and Principles Guiding the Restoration of Rush and Lee Vining Creeks, Mono County, California. Report to the Mono Basin Restoration Technical Committee for the El Dorado County Superior Court. 12 pp (Sept. 1994).

Feasibility of Rejuvenating the West-Side Springs of the Rush Creek Bottomlands, Mono County, California. Report to Trihey and Associates for the Rush and Lee Vining Creeks Restoration Technical Committee. 12 pp (July 1994).

Feasibility of Rewatering Abandoned Channels of the Rush Creek Bottomlands, Mono County, California. Report to Trihey and Associates for the Rush and Lee Vining Creeks Restoration Technical Committee. 71 pp (June 1994).

Historic and Modern Distribution of Lake-Fringing Wetlands, Mono Lake, California. Technical Report to the California State Water Resources Control Board and Jones and Stokes Associates, Sacramento. 50 pp + maps and appendices (October, 1992).

Past and Present Geomorphic, Hydrologic, and Vegetative Conditions on Rush Creek, Mono County, California. Technical Report to Trihey and Associates, Walnut Creek, California. 13 pp + appendices (Sept. 1992).

Lake-Fluctuation-Induced Changes in the Size and Configuration of the Mono Islands, California. Technical Report to the California State Water Resources Control Board and Jones and Stokes Associates, Sacramento. 22 pp + maps and append. (May 1992).

TECHNICAL REPORTS (cont.)

Past and Future Toppling of Tufa Towers and Sand Tufa at Mono Lake, California. Technical Report to the California State Water Resources Control Board and Jones and Stokes Associates, Sacramento. 20 pp + maps and appendices (April, 1992).

Past and Present Geomorphic, Hydrologic, and Vegetative Conditions on Lee Vining Creek, Mono County, California. Technical Report to Trihey and Associates, Walnut Creek, California. 13 pp + appendices (Jan. 1992).

Distribution of Substrate Types at Mono Lake, California. Technical Report to the California State Water Resources Control Board and Jones and Stokes Associates, Sacramento. 18 pp + maps and appendices (Jan. 1992).

Parker Creek at the Parker Plug: Ancient and modern geomorphic history, and recommendations for restoration. Technical Report to Northwest Biological Consultants, Ashland, Oregon. 11 pp + maps and appendices (Nov. 1991).

Extent of Riparian Vegetation on Streams Tributary to Mono Lake, 1930-1940: An assessment of the streamside woodlands and wetlands and the environmental conditions that supported them. Technical Report to the California State Water Resources Control Board and Jones and Stokes Associates, Sacramento. 73 pp + appendices (May 1991).

Geomorphology and stratigraphy of the Gabbott Reach of Highland Canyon, Alpine County, California. Technical Report to Ann Peak and Associates, Sacramento. 25 pp + maps and appendices (March 1987).

Geomorphic and geohydrographic aspects of the Mono Lake controversy. Report to the California State Legislature and the Community Organization and Research Institute, University of California, Santa Barbara, 135 pp + 11 maps (Jan. 1987).

Historic and future trends in the growth, shrinkage, and peninsularization of islands and islets, Mono Lake, California. Technical Report to Hubbs/Sea World Research Institute, San Diego, California. 30 pp + maps and appendices (Nov. 1984).

EXPERT WITNESS/TESTIMONY

State’s Expert Witness before the Bi-State Board of Governors of the Tahoe Regional Planning Agency, for the California State Attorney General’s Office, on the matter of the proposed South Shore Estates Development, Tahoe City, California, September, 1999

State’s Expert Witness before Judge Diane Wayne for the California Department of Fish and Game, on the matter of development in Big Tujunga Wash, Los Angeles County, California, July, 1999

State’s Expert Witness before Judge E.C. Reed, U.S District Court, District of Nevada, for the California State Attorney General’s Office, on the matter of Tahoe-Sierra Preservation Council (Plaintiffs) v. Tahoe Regional Planning Agency, December, 1998

State’s Expert Witness for the California State Attorney General’s Office, the California State Lands Commission, and the Natural Heritage Institute, to the California State Water Resources Control Board, on the matter of the restoration of fish and wildlife habitat in the Mono Basin, May, 1997

State's Expert Witness in Mono Water Rights Relicensing Hearings before the California State Water Resources Control Board, 1993-1997

State's Expert Witness in Newhall Land and Farming Company v. California Department of Fish and Game, Case No. 122863, Valencia, California, 1994

State's Expert Witness in Mono Water Rights Cases Alpine No. 566, Mono No. 8092 and Mono No. 8608, Superior Court of the State of California for the County of El Dorado, Department No. 3 (Judge Terrance Finney), 1990-1993

State's Expert Witness in State of California v. Nickel, Superior Court of the State of California for the County of Kern, 1991-1992

State's Expert Witness before Judge Lawrence Karlton, United States District Court, Eastern District of California, in Federal Civil Case U.S. v. State of Cal., 1983-1985

Testimony submitted to the House Public Lands and National Parks Subcommittee regarding the creation of a Mono Basin National Monument, March, 1983

Historic and Prehistoric context of the Recent and Ongoing Salinity Increase at Mono Lake. Testimony presented to California State Assembly Committee on Water, Parks, and Wildlife, November, 1981

EXPERT WITNESS/TESTIMONY (cont.)

The Scientific Value of Mono Lake's Tufa Structures. Testimony presented to the California State Senate Committee on Natural Resources, May, 1981

SERVICE TO BOARDS OF DIRECTORS, COMMITTEES, AND COUNCILS

Member, Board of Directors, Sierra Nature Notes (Yosemite Association), 2000-2005

Member, Board of Directors, California State Water Resources Archives, 2002-2005

Member, Science Advisory Committee, Center for Ecological Health Research, University of California, Davis (U.S.E.P.A.), 1998-2002

Primary organizer of conference on "Alien Species of the San Francisco Bay-Estuary System: Problems and Prospects", for the California Academy of Sciences, February 1997 (~200 participants)

Member, Mono Basin Science Council, 1998-2001

Member, Fellows' Steering Committee, California Academy of Sciences, 1994-98

Member, Science Council, California Academy of Sciences, 1994-98

Member, El Dorado County Superior Court-Mandated Planning Team for the Restoration of Rush and Lee Vining Creeks (1993-95)

SERVICE TO EDITORIAL BOARDS AND FUNDING ORGANIZATIONS

Member, Editorial Board, Sierra Nature Notes (Yosemite Association), 2000-2005

Member, Editorial Board, Geology , 1995-98

Member, Editorial Board, International Journal of Salt Lake Research, 1992-96

Referee for the following journals (~50 papers, total):

- Palynology (American Association of Stratigraphic Palynologists)
- Quaternary Research
- Geology
- Boreas
- Holocene
- Quaternary Science Reviews
- Geological Society of America Bulletin

Grant Reviewer for the following organizations (~18 grants total):

- National Science Foundation
- National Geographic

WORK FEATURED/HIGHLIGHTED IN:

- Appearance in the PBS *Nova* documentary "Elements," 2012.
- *The Great Ocean Conveyer*. Book by W. Broecker, 2010. Princeton University Press, Princeton, N.J.
- "The Climate Race." Radio feature by Public Radio International's *Marketplace*, broadcast October 28, 2009.
- *Fixing Climate*. Book by W. Broecker and R. Kunzig, 2008. Hill and Wang, N.Y.
- *The Great Warming*. Book by B. Fagen, 2008. Bloomsbury Press, N.Y.
- "The Drying of the West," National Geographic, February, 2008
- *Thin Ice*. Book by Mark Bowen, 2005. Henry Holt and Company, N.Y.
- "Why the West is Burning," by Madeleine Nash, Time Magazine, August 16, 2004.
- "Environmental Imperatives Reconsidered," by T. Jones and others, Current Anthropology, April, 1999.
- *The Ecology of Fear: Los Angeles and the Imagination of Disaster*. Book by Mike Davis, Henry Holt and Co., 1998.
- The Battle for Mono Lake. Documentary Film by Steven Fischer (underwritten by Public Broadcasting System affiliate KTEH), 1997.
- The Desert Speaks. Documentary Film by T. Kleespie (underwritten by Public Broadcasting System affiliate KUAT), 1997.
- *Storm over Mono: The Mono Lake Battle and the California Water Future*. Book by John Hart, University of California Press, 1996.

WORK FEATURED/HIGHLIGHTED IN (cont.):

- Interviewed by the British Broadcasting Company's "World Service" (Jane Taylor, Interviewer), broadcast October 13, 1996.
- "When the Rivers Ran Dry," Los Angeles Weekly, September 20, 1996.
- "Great Plains or Great Desert? The Sea of Dunes Lies in Wait," New York Times *(Science Times)*, May 28, 1996
- "California Social Climbers: Low Water Prompts High Status," Science *(Research News)*, 10 May, 1996
- U.S. News and World Report, June, 1995
- "Endless Summers," California Academy of Science's Pacific Discovery, Spring, 1995
- "The Mono Lake Water War," Earth Magazine, October, 1995
- "Stumps Tell a Tale of Long, Severe Drought," National Geographic, April, 1995
- "How Scientists Saved Mono Lake," San Francisco Examiner, October 9, 1994
- "California's Climate Poised on a Knife Edge," New Scientist, June 25, 1994
- "Severe Ancient Droughts: A Warning to California," New York Times *(Science Times)*, July 19, 1994
- "California Seen at Risk for 'Extreme and Persistent' Drought," Global Environmental Change Report *(Focus Report)*, v. VI, June 24, 1994
- "Drowned Trees Record Dry Spells," Nature *News and Views* v. 369, p. 518, June 16, 1994
- "'Epic Droughts' in Past Suggest Harsh Future in State," Sacramento Bee, June 16, 1994
- "Ancient Trees Reflect Century-Long Droughts," Los Angeles Times, June 16, 1994
- "Study Suggests 'Epic' Medieval Droughts in Sierra," Associated Press, June 16, 1994

CONSULTANCIES

Consultant to the California State Attorney General's Office, 1984-present. (Projects include assessments of historical environmental conditions, assessments of environmental change, assessments of vegetation/geomorphology interaction, assessments of watershed erosion and marsh loss.)

Consultant to the California Department of Fish and Game 1992-1999. (Projects included rewatering and restoration of Owens River; opposition to golf course construction in Big Tujunga Wash.)

Consultant to the Natural Heritage Institute, 1994-2000. (Projects include stream restorations.)

Consultant to the National Audubon Society and the Mono Lake Committee, 1990-2000. (Projects related to the Mono Lake controversy.)

Consultant to Northwest Biological Consultants, Ashland, Oregon, 1991-1996. (Projects included reconstruction of historical conditions, and stream restoration.)

Consultant to Trihey and Associates, Walnut Creek, California 1990-1996. (Projects included reconstruction of historical conditions, fishery restoration, and assessments of stream erosion and sedimentation.)

Consultant to Jones and Stokes, Associates, Sacramento 1990-1994. (Projects included historical riparian and marshland reconstructions, assessment of littoral erosion, geological and geomorphological mapping, and hydrological reconstructions.)

Consultant to Far Western Anthropological Group Inc., Davis, California, 1992-1994. (Project involved reconstruction of the Late Holocene fluctuations of Owens Lake.)

Consultant to the Mono County District Attorney's Office and Dickson and Ross, Attorneys, 1992. (Project involved rewatering and restoration of Owens River.)

Consultant to the California State Legislature, 1985-1987. (Project involved a "critical elevations assessment" for Mono Lake, California.)

Consultant to Ann Peak and Associates, Archeological Contractors, Sacramento,1986-1987. (Project involved stratigraphic logging of archeological research excavations.)

Consultant to Hubbs-Sea World Research Institute, San Diego, 1984. (Project involved geomorphic and historic assessment of Mono Lake's islands and islets.)