Development of the Keeler Dunefield, Inyo County, California

Part 1 - Analysis of Aerial Photographs and Satellite Images

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Introduction

The Keeler Dunefield and associated sand sheets are located northeast of Owens (dry) Lake between the historic community of Swansea to the north and the community of Keeler to the south (Figs. 1 and 2). The dunefield and adjacent sand sheets are one of the last remaining sources of dust emissions in the Owens Lake area. Because they are located immediately upwind from Keeler, dust emissions resulting from strong NW winds immediately impact this community. In addition, the southeastern leading edge of the dunefield is migrating towards the settlement and may at some future time directly impact infrastructure. As defined here, the dunefield is the area of currently active dunes and does not include areas of vegetated dunes (e.g. in the area between the active dunes and Keeler).

This project component has three main goals: (1) Determine how long the currently active dunes have existed in the area northwest of Keeler; (2) Understand how the dunefield has developed over time; and (3) Understand how dunefield development relates to changes in Owens Lake in the recent historical period. These studies were undertaken in support of efforts to control dust emissions from the area of the dunefield. In this context "historical" means within the period of the record of aerial photographs, i.e. since the 1940's. This report focuses on an analysis of air photos and satellite imagery and therefore only investigates the most recent information available on the origin of the Keeler Dunes. There is a companion investigation underway that is looking at the area from a geomorphic and geologic perspective to provide information on how the units relate to one another over a longer period of time. The results of this companion investigation will be presented in a separate report.

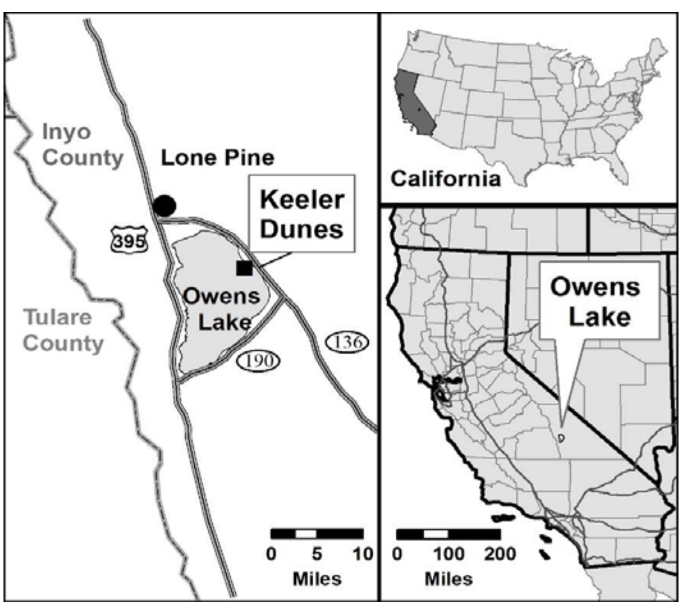

Figure 1: Location map for Keeler Dunes

Study area

The dunefield (Fig. 2) currently occupies an area of approximately 0.68 km^2 (0.26 square miles), with a further 4 km^2 (1.62 square miles) consisting of thin to discontinuous sand sheets overlying Quaternary alluvial fan deposits. Currently, the dunefield comprises two parts: (1) the northern part, which includes sand sheets on the far northwestern or trailing margin of the dunefield; together with the dunes known informally as the Horseshoe dune and the Linear dune; as well as sand sheets and nebkhas (vegetation anchored dunes) between these dune areas; (2) the southern dunes, which comprise as many as 15 crescentic dune ridges, in two main lobes - termed the south and north lobes, which are steadily migrating toward the southeast. The current volume of sand involved in the dune field is at least 527,000 m^3 based on estimates using LIDAR digital elevation data (Hydro-Bio, 2011).

The northern part of the dunefield overlies early to late-Holocene distal alluvial fan units; while the southern dunes overlie late Holocene alluvial fan deposits as well as beach ridges and lacustrine deposits associated with transgressions of Owens Lake to elevations of around 1103 m (Fig 3). Between the dunefield and the exposed bed of Owens Lake, lies an area of clays and silts associated with the Late Holocene to historic lake (units $QL4_{lp(d)}$ and $Ql3_{lp}$) This area has been extensively disturbed by historic construction, including the now-abandoned bed of the railroad, the old State Highway 136, and closer to Keeler, remnants of the Inyo Development Company salt processing facilities. In places within the dunefield there are scattered areas of thin (up to 20cm-thick) laminated silt deposits (Unit Qfl in Figure 3) that overlie horizontally laminated or cross-bedded sand of presumed aeolian origin, based on their similarity to modern wind ripple laminated sands on the upwind trailing margin of the dune field (Fig. 4b). The historic shoreline[1], at an elevation of 1096 m (3597feet) is marked by a discontinuous line of low dunes (the shoreline dunes), with a width of less than 100 m and a height of 2-3m. Areas of flood silts occur immediately behind (landward) of this dune (Fig. 4a).

[1] The usage of the term "historic shoreline" in this report refers to the shoreline formed by Owens Lake at an elevation of 3,597 feet above Mean Sea Level (MSL). This is the elevation of historic Owens Lake measured in 1872 and 1878 (Lee, 1915) prior to water diversions and water export in the Owens Valley. The term "historic shoreline" as used by the Great Basin Unified Air Pollution Control District is set at 3,600 feet above MSL for air quality regulatory purposes.

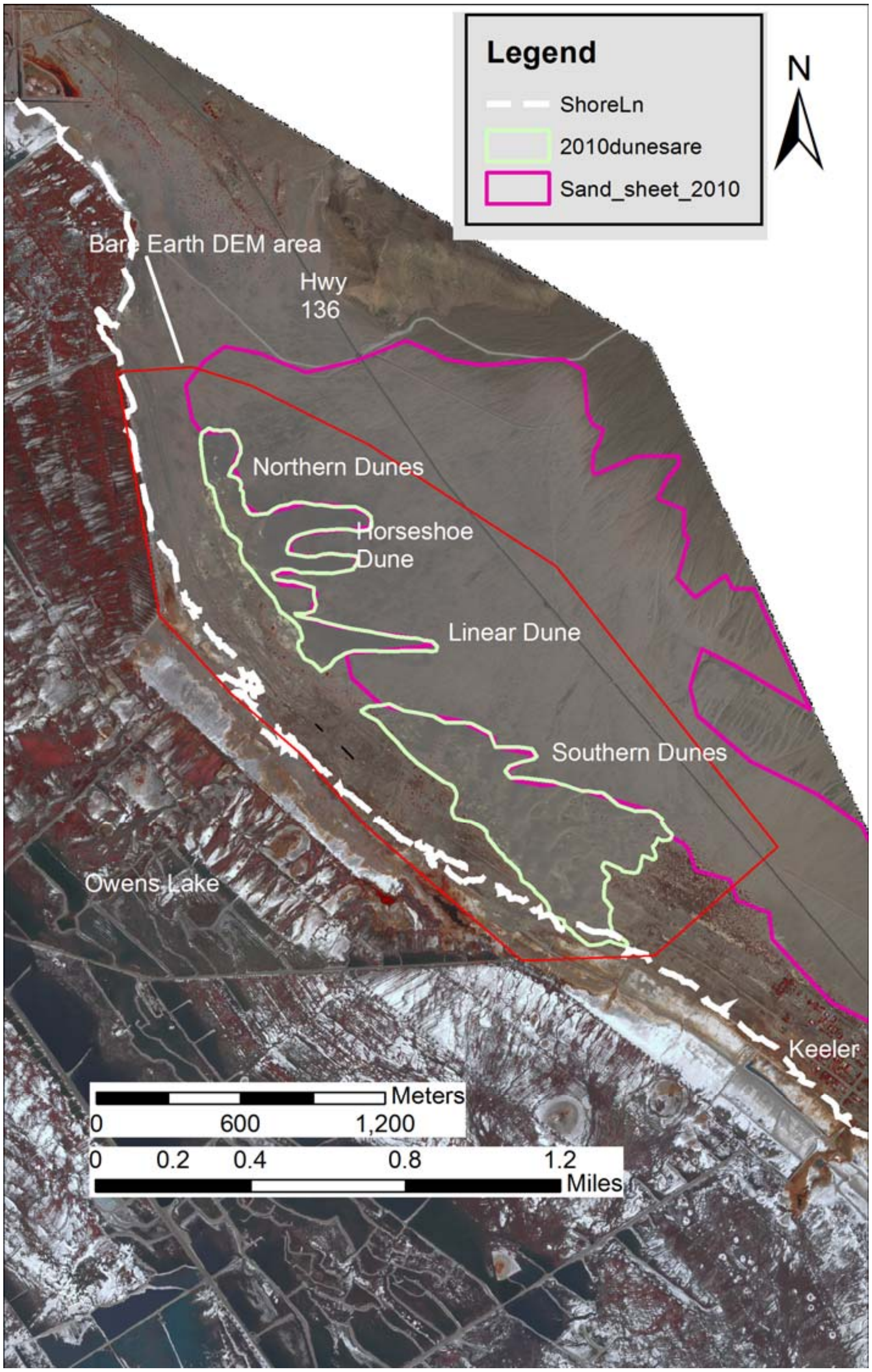

Figure 2: The Keeler Dunefield today (2010 GeoEye Image).

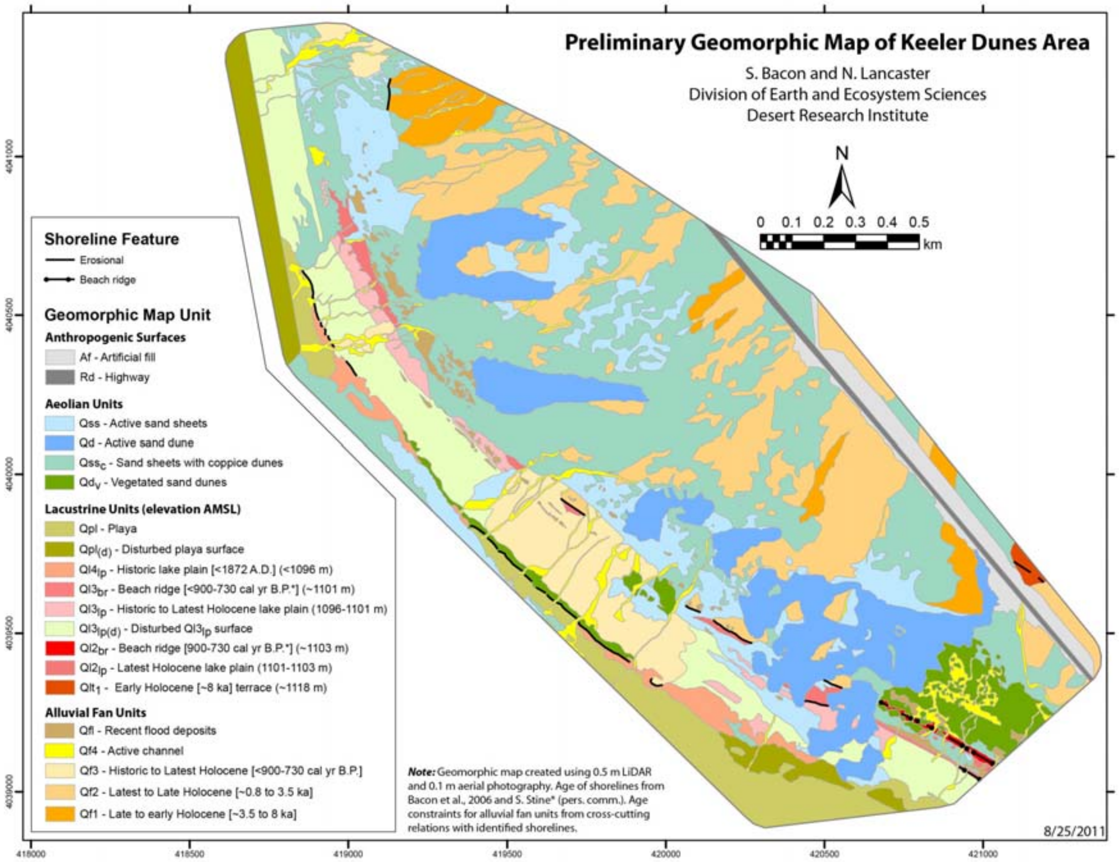

Figure 3: Preliminary geomorphic map of the Keeler Dunes area

Sand moving winds in the area are from two primary directional sectors, NW and NNW and SSE and S.   Based on the record from the A-Tower location, sand drift potential was calculated using the approach of Fryberger (1979) - see Appendix 1. , as modified to account for the use of wind speeds measured in meters per second (Fig. 5) (Bullard, 1997).   The wind regime is classified as high-energy with a total sand drift potential (DP) of 80.6 (VU) Velocity Units.   Winds from the NW-NNW sector account for 56% of the annual potential sand drift; while winds from the SSE-S sector account for 31% of annual potential sand drift. The resultant, or vector sum sand transport direction is toward 104°; with a resultant drift potential (RDP) magnitude of 25 VU; the ratio between DP and RDP is 0.38. The dune crest alignment that maximizes sand transport normal to the crest (the gross bedform normal (GBN) alignment (Rubin and Ikeda, 1990) is 74°, with a divergence angle (the angle between the two major transport directions) of 171°.   The observed dune alignments are compared to these data below. The calculated sand transport direction is similar to that measured in the dune area using Sensit and sand trap data (GBUAPCD, 2008; Kiddoo, 2010).

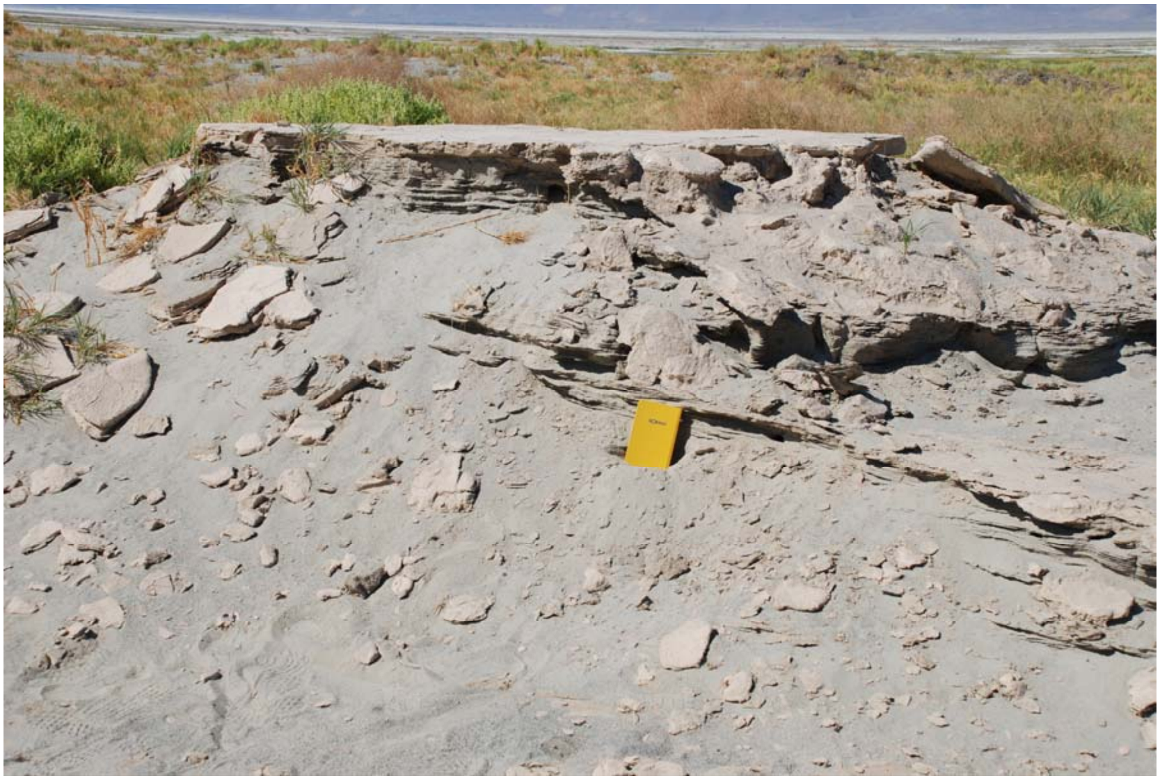

Figure 4a: Flood silts adjacent to historic shoreline

Figure 4b: Flood silts exposed by deflation at north end of Keeler dunefield.

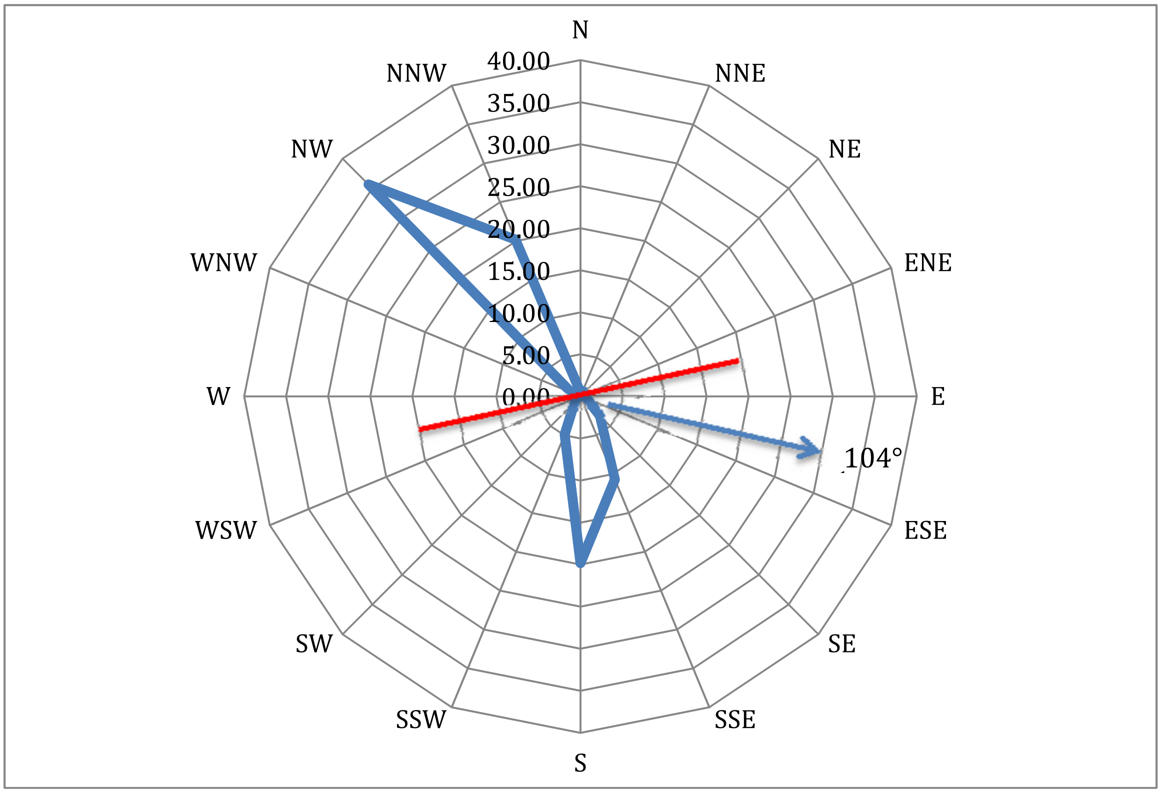

Figure 5: Sand rose for A-Tower; red bar is Gross Bedform Normal trend; blue arrow is resultant (vector sum) sand transport direction.

Methods

The primary methodology used in this study was the comparison of 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 points before incorporation in a geographic information system (GIS). Dune and sand sheet extents, and major dune ridges were then digitized from the images, and their dimensions measured using ARC-GIS. Table 1 gives the dates of the aerial photographs and satellite images used, together with an assessment of their image quality.

The varying quality and resolution of the aerial photographs used made precise identification and delineation of the dune areas difficult in some instances (Table 1). In addition, 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 below represent the best estimate given the uncertainties involved in the tracing of the dune areas.

Table 1: Aerial photographs and satellite images used in this 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
2008	Ikonos	26-Apr-08	Excellent
2010	GeoEye	3-May-10	Excellent

Results

Narrative of dunefield development as observed on image data

This section provides a description of the extent and morphology of the dune field and associated sand sheets at the times represented by the image data used. The analysis is broken into four general time periods, each of which shows similar characteristics and evolutionary patterns. The descriptions should be read in conjunction with the images in Figures 6 through 9. Copies of the individual images used in the analysis are available in Appendix 2.

It is important to bear in mind in the evaluation of the photographs and imagery is that each photo used represents an instantaneous snapshot of the area. The record used in this work consists of photographs and images from 16 individual dates spread over 66 years and is considered to provide a robust set of information for the overall developmental history of the dunes. However, there may have been significant changes in the dunefield at times between the available photos (e.g. between 1954 and 1968) and imagery that are not documented here due to the discontinuous nature of the available data set. Overall, it is felt that the general developmental trends and patterns in the Keeler Dunefield are well understood and are documented here.

Period 1: 1944-1954 (Fig 6):
The first aerial images available that cover the Keeler Dunes area date from 1944. At this time, the dunefield was restricted in extent and confined to an area of approximately 0.25 km^2 (0.10 sq miles) in the far northwestern part of the area. The dunefield at this time consisted of an area of undulating sand, with scattered

shrubs (most likely a mix of Sarcobatus, Suaeda and Atriplex), with vegetation cover similar to that of the Swansea dunes today. Small dune ridges on a trend of 100-120° can be detected. There is no evidence of any dunes elsewhere in the area, and the area now occupied by the southern part of the Keeler Dunes today consisted of scrubby vegetation, similar in appearance to that existing southeast of the dunes today. However, a sand sheet, similar in aerial photograph characteristics to that existing today, extended to the east and northeast of the dune area, covering the alluvial fans with a thin cover of sand. In addition, a continuous sand sheet existed between the dunes and the Owens River delta at this time.

There was little change from 1944 discernible on the aerial photographs for 1947 and 1954. The area of the dunefield at this time averaged 0.28 km^2 (0.11 sq miles), with an average length of 1325 m. The sand sheet area during this period averaged 1.82 km^2 (0.70 sq miles). A continuous sand sheet extended to the Owens River delta throughout the 1944 to 1954 period.

The dunes in this period were largely confined to the elevation range between 1102 and 1108 m (3615 and 3635 feet), with a prominent topographic feature between 1103 and 1108 m (3620-3635 feet). This feature is interpreted as the shorelines of a former Holocene-age high level of Owens Lake, with a calibrated radiocarbon age of 900-730 yr Before Present (B.P.) for the 1103 m shoreline (Scott Stine personal communication). The 1108 m shoreline is believed to be of mid to late Holocene age and formed after 4300 yr B.P. (Bacon et al., 2006).

<u>Period 2: 1968-1982</u> (Fig. 7):
The 1968 images are of very high quality, with excellent resolution and high contrast as a result of a low sun angle at the time of acquisition. The dunefield in 1968 occupied an area of 0.68 km^2 (0.26 sq. miles), more than twice the area in 1954, and similar to that today, as a result of the development of extensive sand sheets on the western margin of the dunes, extending to the historic shoreline and beyond onto the lake bed.

From 1968 to 1982, the dunefield consisted of an area of irregular, wind scoured dune topography with prominent scattered large Sarcobatus, Sueada, and Atriplex shrubs in the area of the core dunefield of the 1940's to early 1950's; together with a thin, but continuous, 400m-wide sand sheet extending to the southeast by as much as 1 km and covering the old State Highway. As a result, dunefield length had increased to 2179m, with an average width of 490 m. The shoreline scarp between 1103 and 1108 m was covered by small dunes, some anchored by Sarcobatus, Sueada and Atriplex bushes.

A prominent feature of the dunefield in 1968 was the existence of three 280-300 m-long linear ridges extending to the ESE on a trend of 100-120°. The two northerly ridges subsequently developed into what is known today as the Horseshoe dune, with the southern ridge developing into the dune known as the Linear dune. To the south of this are three other small linear ridges developing from the sand-covered

1103 m shoreline scarp. Interestingly, the 1968 photographs show evidence of recent flooding on the alluvial fan to the east of the dunes, with active channels cutting through the dunes at one point between the present Linear and Horseshoe dunes and flooding onto the lake bed. Active flood channels also impinged on the north end of the dunes.

The 1970 Corona image is of lower resolution, but shows that the western margin of the dunefield had contracted slightly relative to 1968, accompanied by extension of the dunefield to the southeast by as much as 175 m. Sand sheets covered much of the area between the dunefield and the historic shoreline of Owens Lake, largely covering the old alignment of State Highway 136. The linear ridges of the Horseshoe and Linear dunes observed in 1968 continued to develop slightly, with a length of 412 m, but at least 5 smaller ridges had developed in the area of the topographic break to the southeast. No dunes existed in the area occupied today by the southern dunes, but a lobe of the dunefield was extending to the south crossing the old State Highway 136 in the process. Dunefield area was 0.55 km^2 or 0.21 sq miles.

The good quality images from 1975 show a similar dunefield to that which existed in 1970, but with an extension to the south in the form of sand sheets. As a result, the dunefield area increased to back to 0.68 km^2 (0.26 sq miles).

Although the image quality is relatively poor, the aerial photograph for 1982 shows a clear extension of the dunefield to the south, with the southern lobe of this extension displaying as many as 5 identifiable dune ridges on a 070-075° trend, in addition to a migration of this part of the dunefield to the east by 100-150 m. The western margin contracted slightly, while sand sheets appeared to cover much of the area between the dunefield and the historic shoreline of Owens Lake. Dunefield area increased by 13% (to 0.62 km^2 or 0.24 sq miles) compared to 1970.

The area of sand sheets on the adjacent alluvial fans during this period averaged 4.3 km^2 (1.66 sq miles), considerably more than in the previous period. The main extension of the sand sheet area was to the east.

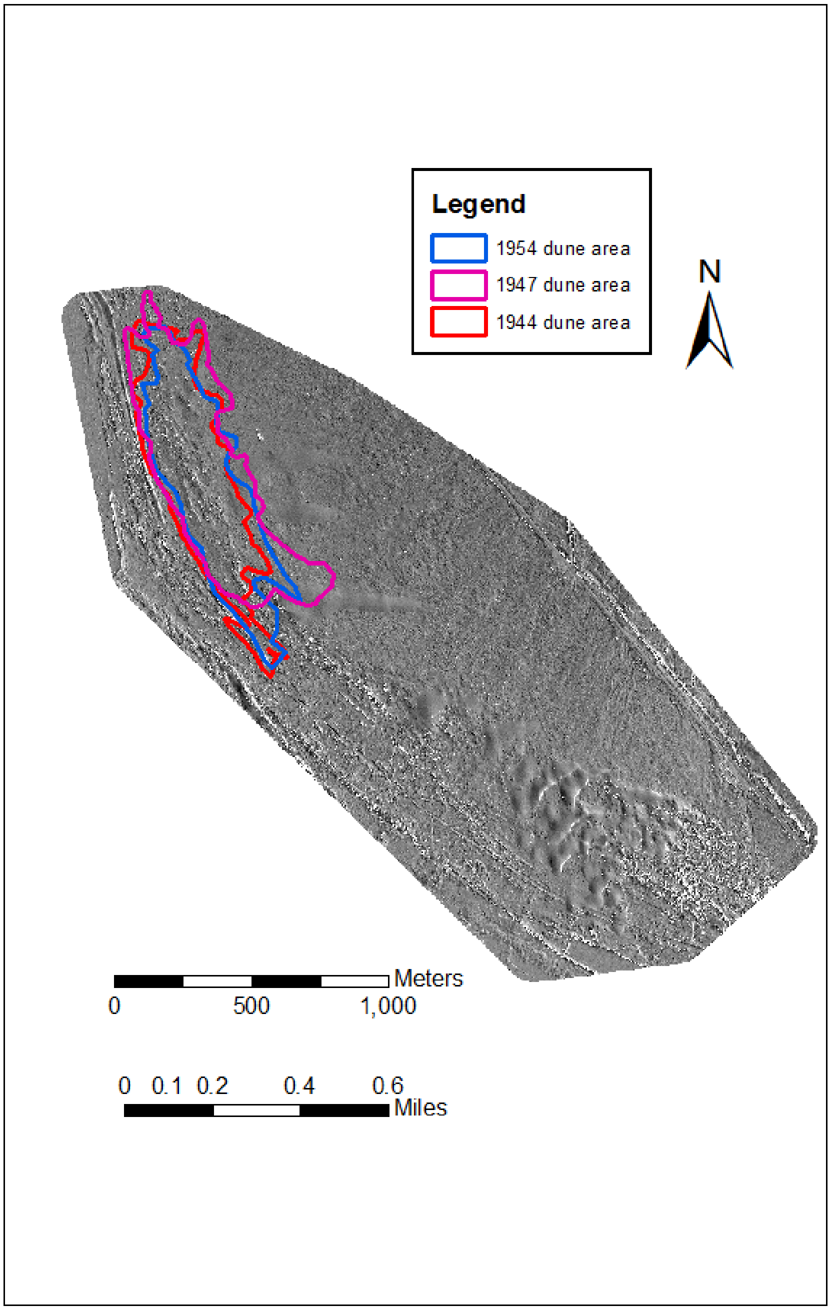

Figure 6: Period 1 - Dune areas in 1944-1954, superimposed on LIDAR DEM of 2010 dunes.

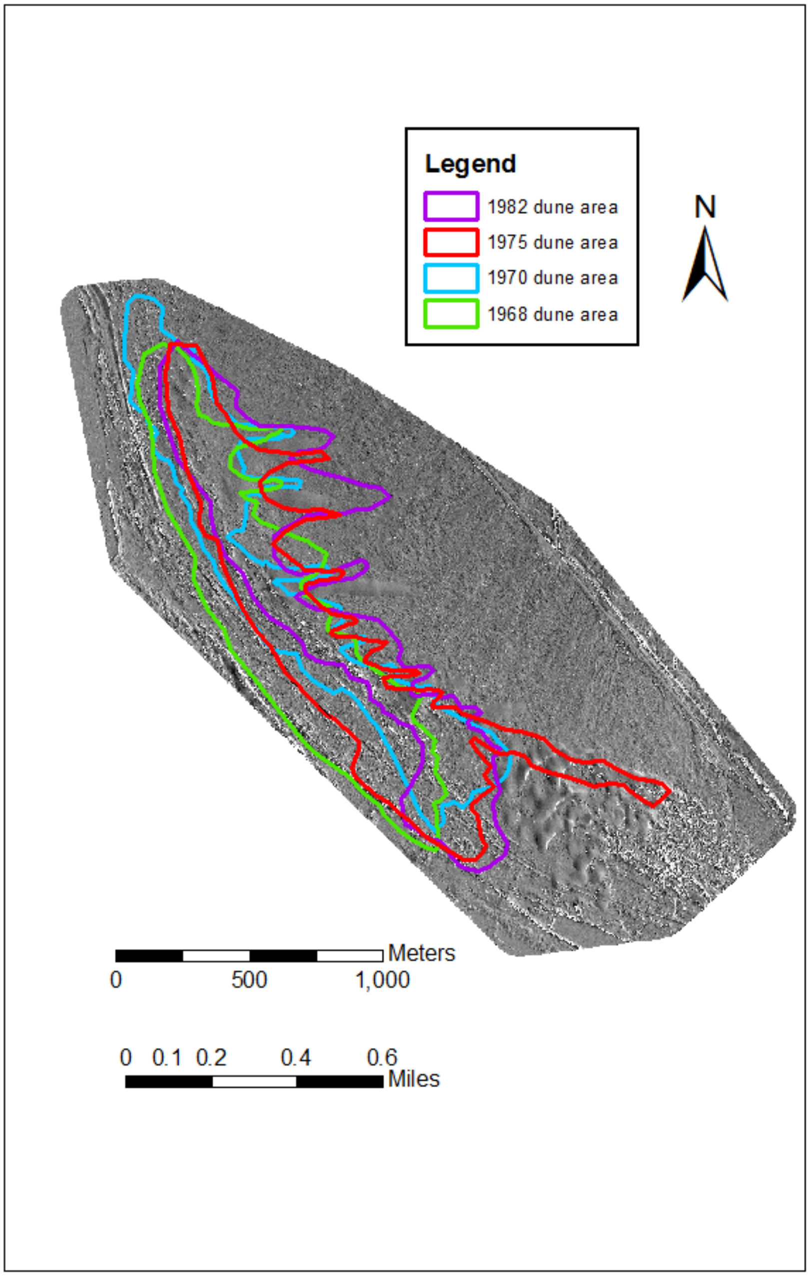

Figure 7: Period 2 - Dune areas 1968-1982

Period 3: 1986 – 2000 (Fig. 8):
In 1986, the dunefield continued to expand to the southeast, with the southern lobe extending by 124 m, while the northern lobe extended by as much as 350 m between 1982 and 1986. Significantly, the patches of flood silts deposited in and around the western margin of the dunes became clearly visible for the first time in 1986, suggesting thinning or shifting of the sand cover in these areas.

The 1993 image indicates further southeasterly expansion of the dunes, by as much as 300 m for the northern lobe and 165 m for the south lobe between 1986 and 1993. The Linear dune continued to extend to the east by 60 m, while the western margin of the dunefield was eroded. At this time, there is the first evidence for a clear split between the southern dunes, comprised of ridges oriented 070-080°, or approximately transverse to the two major wind directions in this area; and the northern dune area, with its three dune ridges extending to the east.

In 1998, the dune field appeared to have experienced significant erosion on its western margin, particularly on the upwind end of the Linear dune, so exposing more of the silt deposits. It also appeared that the Linear dune migrated laterally to the east. In the southern dunes, the overall area increased slightly, with migration of 20 – 30 m to the southeast and infilling of the area between the two lobes of this part of the dunes. Individual ridges migrated to the southeast by as much as 50 m.

In 2000, trends evident in 1998 were continued, with continued expansion of the southern dunes to the southeast, locally by as much as 50 m. Individual ridges migrated to the southeast by as much as 13 m, and a few extended slightly to the east by 20 -30 m.

In the period 1986-2000, the area and configuration of the sand sheet changed little, averaging 4.02 km^2 (1.55 sq miles).

Period 4: 2002-2010 (Fig 9):
In 2002, much of the North Sand Sheet area on the bed of Owens Lake had dust controls, and was under shallow flood irrigation. The most significant change observed in the dunefield was the erosion of the northwest margin of the dunes, with a retreat of as much as 70 m and thinning of the western margin, evidenced by exposure of silt deposits. The southeastern margin of the southern dunes extended by as much as 30 m. Individual ridges in the southern dunes migrated to the southeast by up to 25 m. In addition, the number of ridges increased by 5 (from 10 to 15).

By 2004, the main changes were again slight expansion of the southern dunes to the southeast by as much as 22 m, accompanied by migration of the dunes to the southeast by 10-20 m. The number of ridges in this area decreased, as dunes merged with each other. Thinning of the northwestern margin sand cover continued.

In 2006, erosion of the western margin was clear, with extensive thinning and exposure of silts and underlying alluvial fan deposits evident on the northwestern dune margins, so that the Horseshoe and Linear dunes now were separated by very thin sand cover. In turn, these dunes were now separated from the southern dune complex. Minor changes occurred on the southeast margins, but individual dunes in the southern dunes continued to migrate by 15 – 25 m to the southeast.

In 2008 and 2010, the trends established in prior years continued apace, with rapid migration (up to 40 m) of individual dune ridges in the southern dune complex; as well as expansion of this dune area to the southeast, by as much as 50 m in places. Thinning and erosion of the northern and western margins continued.

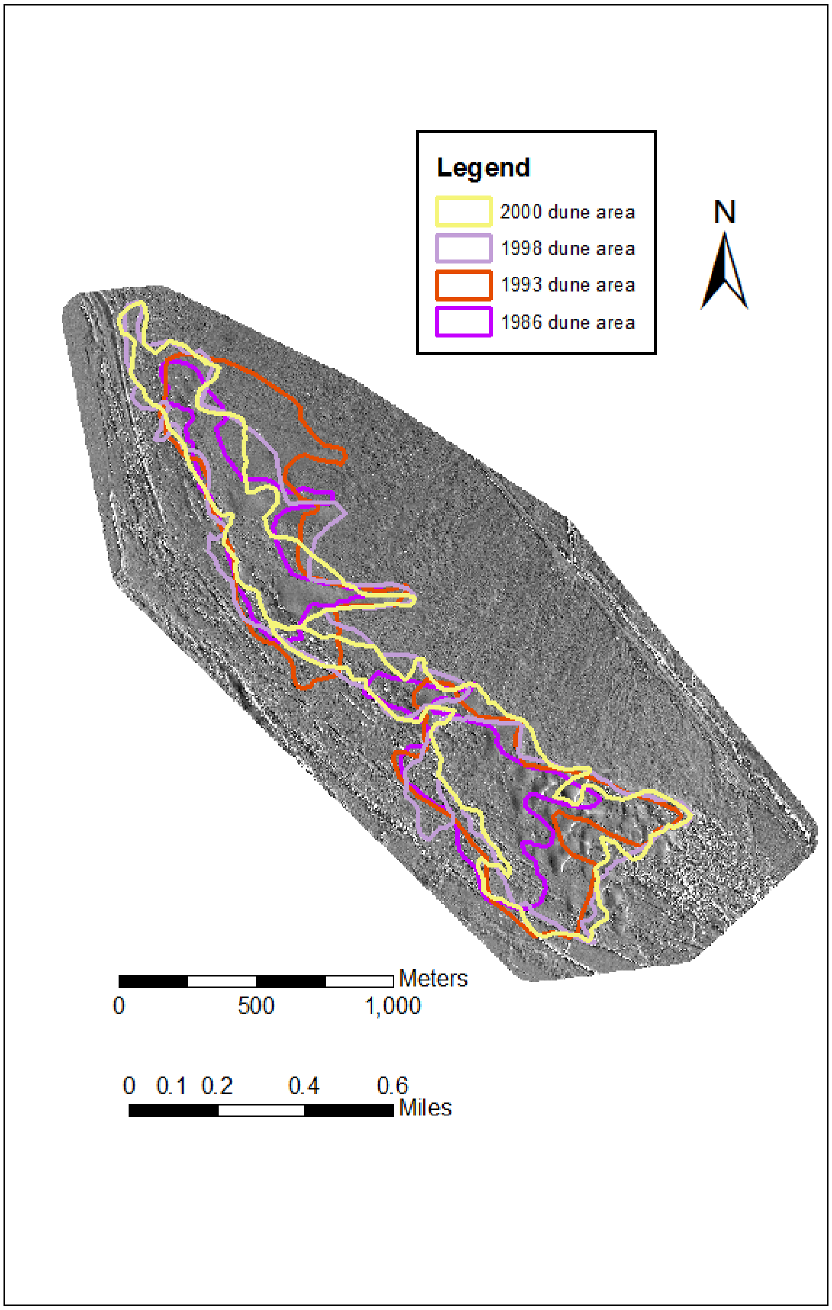

Figure 8: Period 3 - Dune areas 1986-2000.

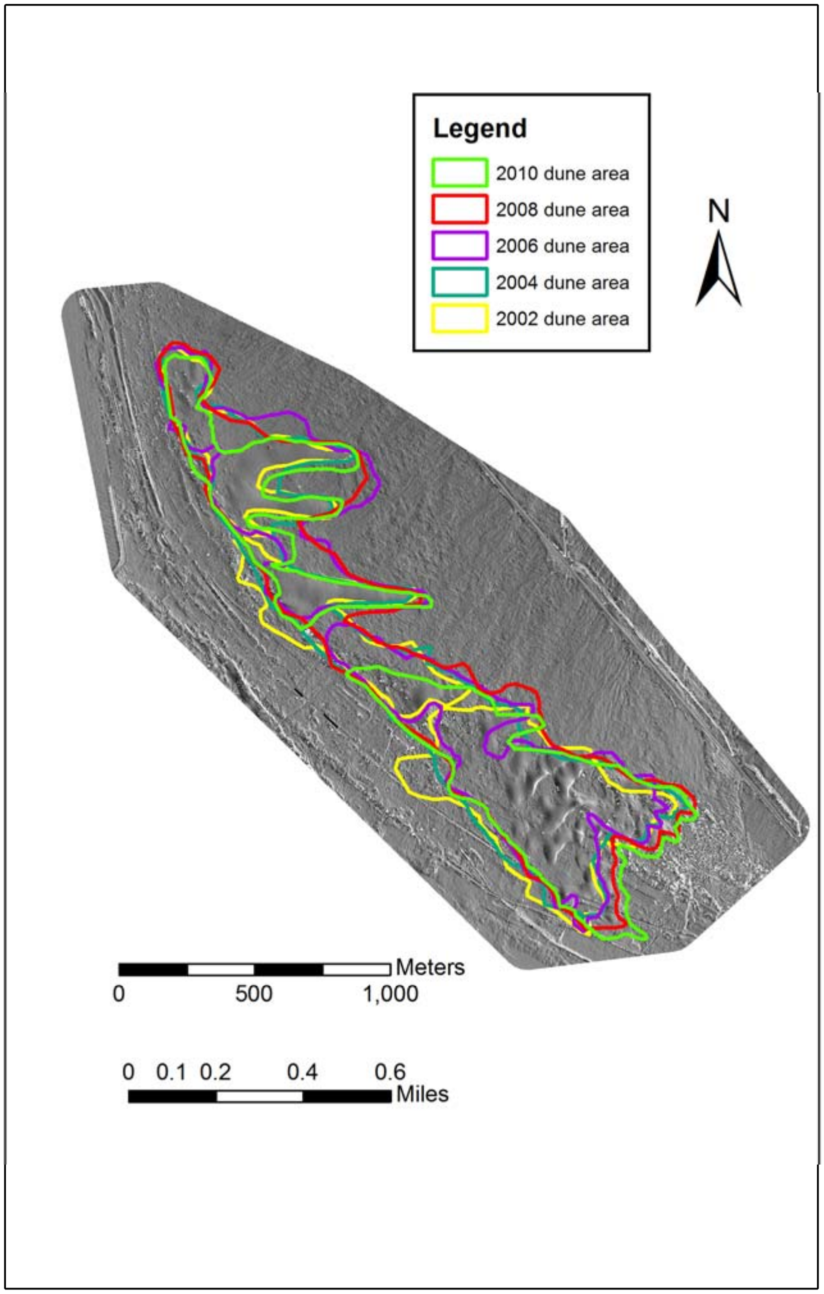

Figure 9: Period 4 - Dune areas 2002-2010

Summary of dunefield state

Based on the analysis of aerial photographs and satellite images, the following stages in the historical development of the Keeler Dunefield can be identified:

1. From 1944 or earlier until the late 1950's or early 1960's, the dunefield was small (~0.28 km^2; 0.11 square miles) and confined to an area in the far northwest of the area. Dune ridges, where identifiable, were short and small in number (4-5). Dunefield location appeared to be strongly influenced by the prominent erosional shoreline scarp developed by late Holocene highstands of Owens Lake. Dunefield and dune morphology was influenced by vegetation (Sarcobatus, Sueada, and Atriplex spp.), which acted to anchor small dune ridges. A continuous sand sheet existed between the dunefield and the Owens River delta.
2. In the late 1950's or early 1960's, the dunefield began to grow in size, and well-defined linear ridges started to extend from the core dunefield towards the east. Three of these ridges have persisted to the present day, forming the dunes known as the Horseshoe and Linear dunes.
3. From 1968 to 1982, the linear dune ridges were well developed, and increased in number (6 in 1975 to 9 in 1982). The dunefield area expanded dramatically to the east and southeast, reaching a size two times of the 1940-1950's dunefield, at 0.63 km^2 (0.24 sq miles).
4. From 1982 to 1993 the dunefield 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 be identified in the southern part of the dunefield, as sand thickness increased.
5. From 1993 through 2010, dunefield development was characterized by erosion of the northwest margin, but continued expansion and southeasterly migration of the southern crescentic dunes. As a result, the dunefield 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, resulting in widespread thinning of sand on the trailing (upwind) margin of the Keeler dunefield and exposure of alluvial fan deposits.

Trends of extent of sand sheet and dunes

The growth of the Keeler Dunefield can be summarized by plotting changes in area and other parameters with time with correlation coefficients (R^2) from 0.83 to 0.90.

- Dunefield area increases with time, and is quite well described by a second-order polynomial, showing the slowing of growth in the last 20 years (Fig. 10a).
- The dunefield length has increased linearly over time (Fig. 10b).
- Within the dunefield, the number of dune ridges has increased exponentially with time (Fig. 10c).

- The total length of the ridges has likewise increased over time, in a similar fashion (Fig.10d).

These relationships seem to indicate that the dunefield has not reached an equilibrium state and continues to evolve. The rapid and extensive nature of the changes documented also indicates the relative youth of the dunefield.

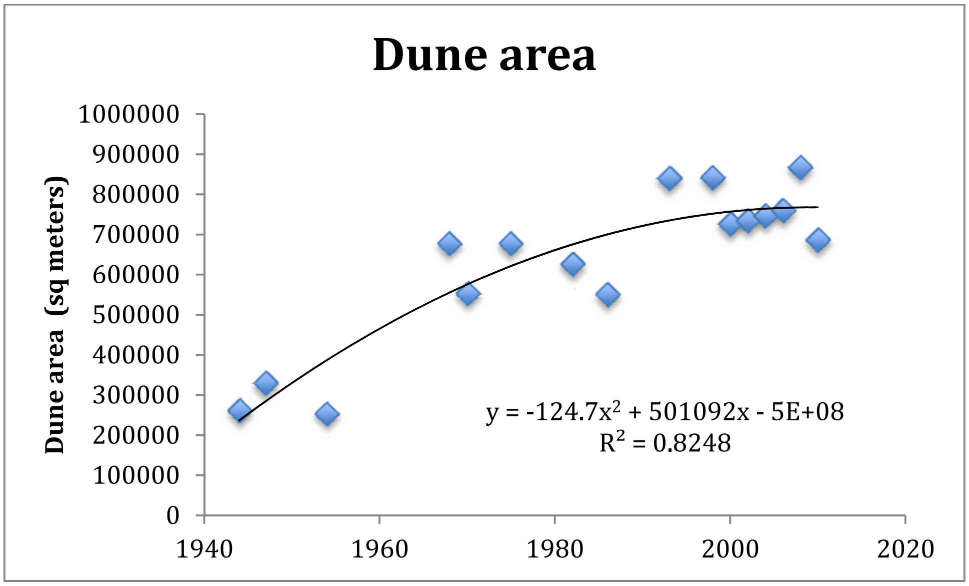

Figure 10a: Change in dunefield area with time.

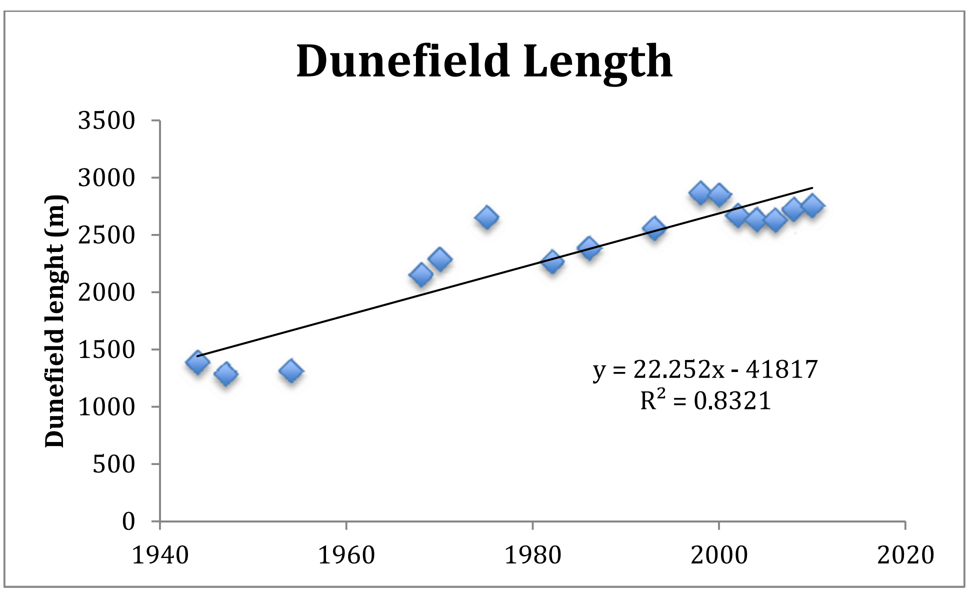

Figure 10b: Change in length of dunefield with time.

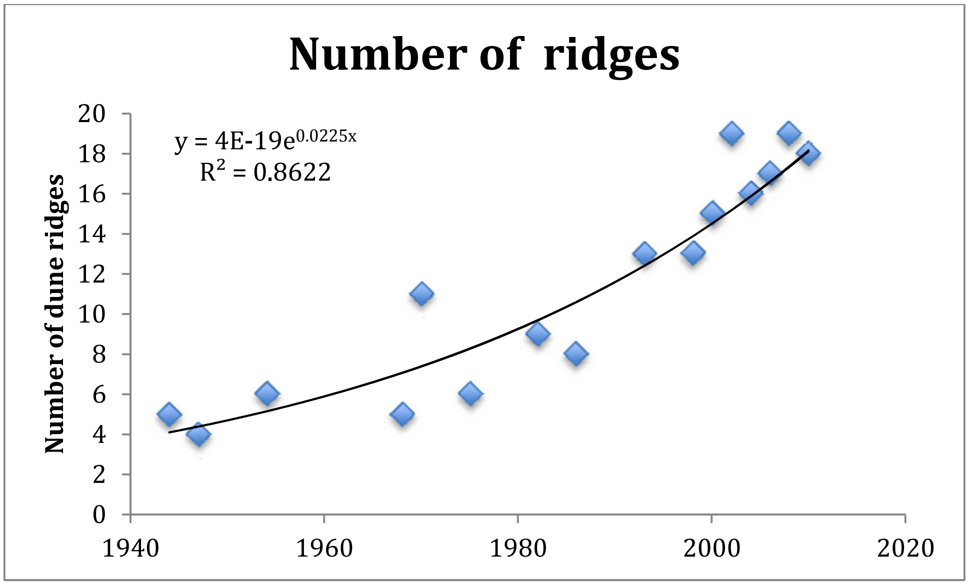

Figure 10c: Change in number of dune ridges with time.

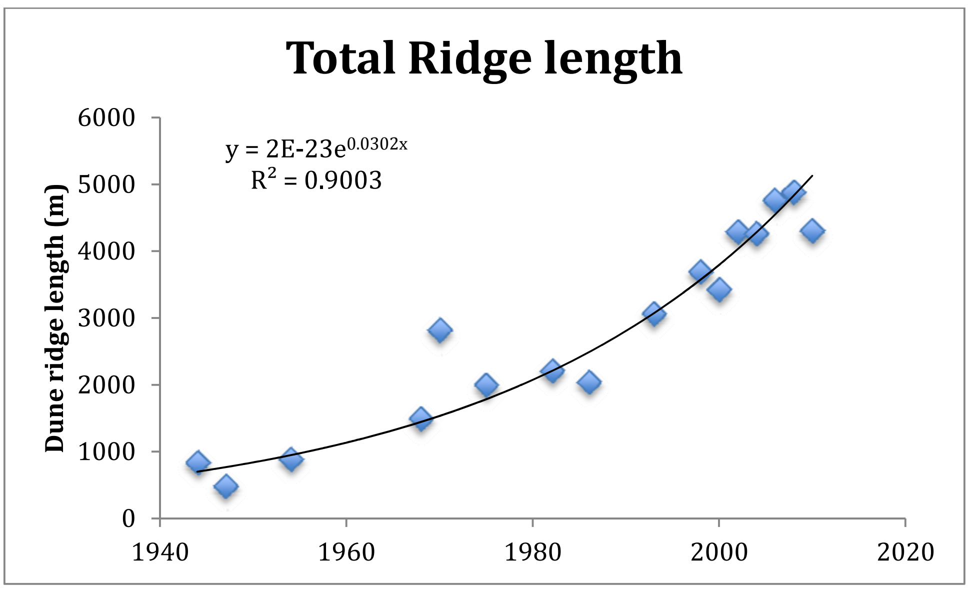

Figure 10d: Change in dune ridge length with time.

Discussion

Dunefield change over time

The Keeler Dunefield has undergone significant changes since 1944, as summarized in Fig. 11. These include an increase in the area of the dunes by a factor of 3 since 1944, and development of well defined linear and crescentic dunes. The dunefield continues to expand toward the southeast, but its upwind margins are now experiencing significant erosion.

By contrast, the adjacent Swansea Dunes appear to have experienced little change in size or morphology over the same period. They have maintained a partially vegetated state, with a morphology characterized by an undulating sand sheet with scattered vegetation anchored mounds (nebkhas) separated by open sand areas. The main changes that are detectable on the aerial photographs are related to variations in the amount and distribution of vegetation cover. It appears that there was relatively more vegetation (most likely a mix of Sarcobatus, Suaeda and Atriplex) in 1947,and 1967, compared to 1970 and 1975 as well as 1986 and 1993. The period 2002 to 2010 is characterized by a stable vegetation cover in which the distribution of vegetation seems to have changed little and some of the same plant complexes can be followed directly over the last 20 years, or more. These variations in vegetation cover and distribution are likely the result of changes in rainfall over the period of observations. The rainfall record for Independence suggests that the 1940's and 1960's were relatively wet compared to the 1950's, as well as the early 1980's and the period around 1990, which were also dry.

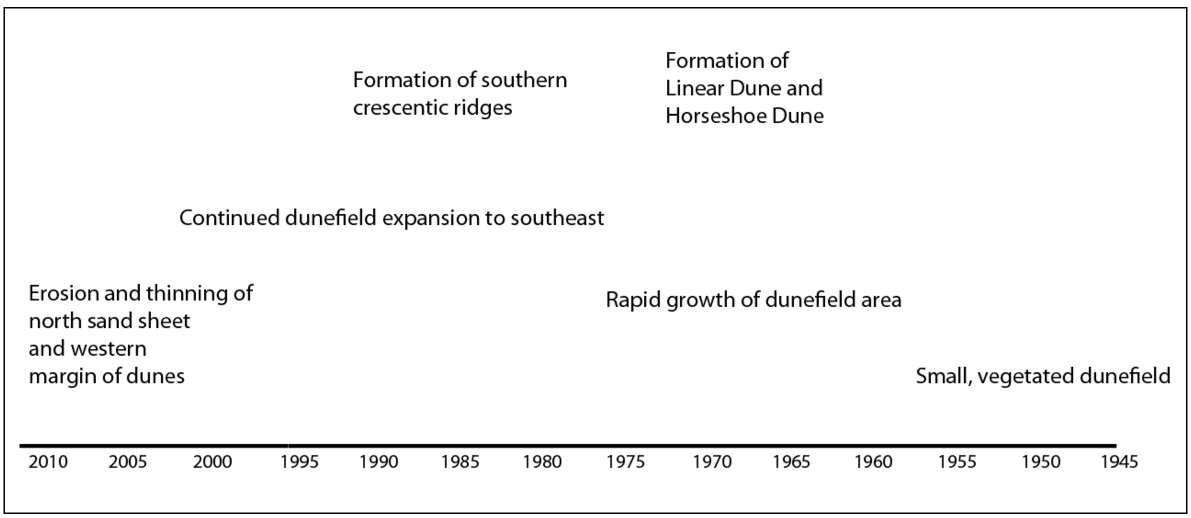

Fig. 11: Development timeline for the Keeler Dunes area

The formation and accumulation of dune fields is governed by the supply of sand-sized sediment from one or more sources; the availability of this sand for transport; and the existence of sufficient wind energy to entrain and transport this sediment (Kocurek and Lancaster, 1999). Sediment supply is defined as the emplacement of sediment that serves as a source of material for the system; sediment availability is the susceptibility of a sediment surface to entrainment of material by wind; and sediment mobility (potential transport rate, Qp). The relations between sediment supply, availability, and mobility define the state of the sand transport system and its variation through time. The overall state of the system may be described as: (1) Supply limited, in which the actual sand transport rate (Qa) is much less than the potential rate (Qp) and the system is starved of sediment; (2) Availability limited, in which Qa < Qp; and (3) Transport limited, in which the actual rate of sand transport (Qa) equals the potential rate (Qp) and the system is limited only by the capacity of the wind to move sediment from source zones.

The significant expansion of dunefield area and the number of dunes from the late 1950's to the 1990's involved addition of sand from outside the dune field. Potential sources of 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. The wind regime of the area is dominated by NW-NNW winds, which suggests the latter as a primary source of sand. The volume of additional material involved is much larger than is possible given the ephemeral nature of flow in the washes draining the Inyo Mountains. In addition, the mineral composition of the dunes is dominated by quartz; whereas sand-sized material from washes draining the Inyo Mountains is quartz-poor with mostly dolomite or volcanic lithic fragments.

NW winds have a fetch of 4-5 km across the lake bed sand sheets, so that prior to the construction of dust control measures in the North Sand Sheet area, the sand supply to the dunes was limited only by the transport capacity of the wind, in the absence of surface moisture and salt cementation that could restrict sediment availability. As noted above, this area is characterized by a high-energy wind regime, with winds above the sand transport threshold for as much as 25% of the time. Significantly, the sand transport pathway to the dunes begins in the area of one of the major distributaries of the Owens River delta (Figure 12). This area appears on the image data to regularly receive water (and sediment) from the Owens River.

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 extending from the delta to the dunes and covering the area between the shoreline of Owens Lake and the dunefield. Crossing this area is the old State Highway, which is variably covered by sand. After 1954 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 (Fig 13). 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.

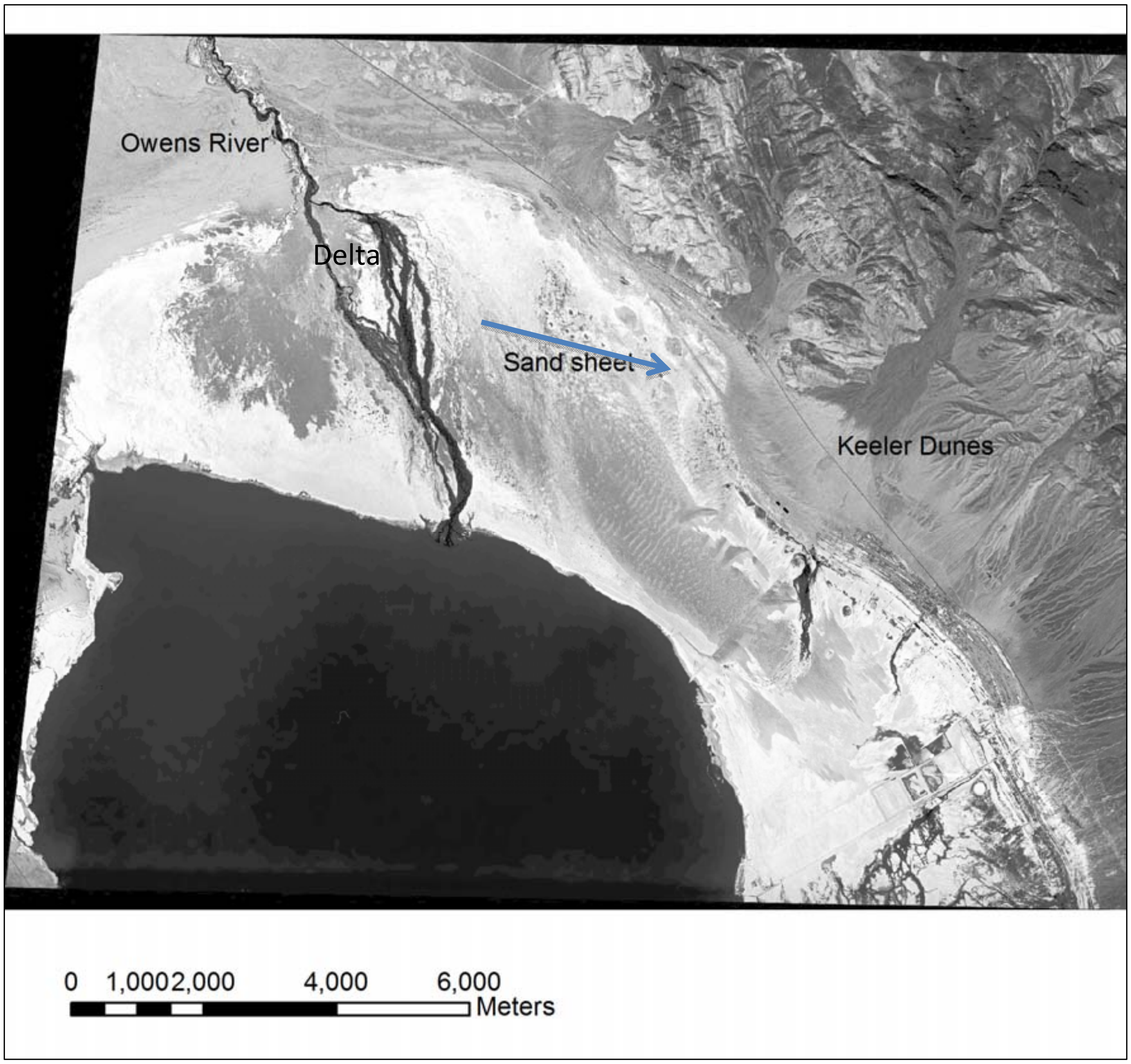

Figure 12: 1970 Corona image showing the Owens River delta and associated sand sheets; Arrow indicates resultant sand transport direction of 104° from Fryberger analysis (see Figure 5).

Aeolian sand supply from fluvial sources is typically episodic (Griffiths et al., 2002a; Griffiths et al., 2002b; Miller et al., 2010) and often correlates with major flood events. The gage record for the Owens River at the Keeler Bridge about 2 miles north of Owens Lake is shown below (Fig. 14). Major floods occurred in 1938-1939; 1969-1970; and at a much lower level, in 1982. These events likely contributed significant amounts of sand-size sediment to the delta area, in addition to water to the center of the lake (see large brine pool on 1970 image, Fig. 12). Between these years of high flow, the lake bed was relatively dry, permitting deflation of these sands and their movement to the dunes. Deflation of sand also resulted in armoring of the sand sheet areas with coarse sand and gravel as the finer material was removed, so reducing availability of sand for onward transport. The long dry interval between floods (1939-1969) gave rise to extensive movement of sand and dune construction after 1954; the shorter dry interval (1970-1982) also led to dune construction and expansion of the dune field, especially in the area of the southern dunes. Between 1982 and 2002, the main processes were the development and southeastward migration of the southern dunes, with limited input of sand, as a result of armoring of the North Sand Sheet area by coarse sand and fine gravel, until the construction of dust control measures on the North Sand Sheet in 2001. Following this, the dunefield was starved of sand and is in a state of negative sediment budget, so that erosion is occurring on the upwind margin. The continued expansion of the southern dunes towards the southeast is a result of reworking and movement of existing sand in these dunes.

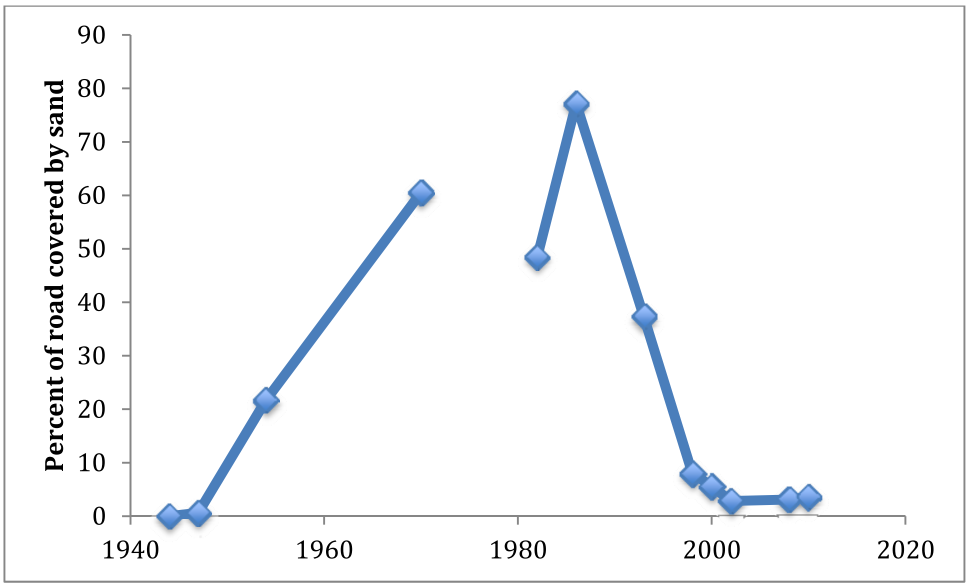

Figure 13: Percentage of the Old State Highway northwest of Keeler that was covered by sand. During the first peak (1970) the road was covered by sand sheets; second peak (1986) occurs when dunes cover road. Prior to the 1950's the road was maintained and sand cleared – so the low sand cover in the 1940's may not be representative of the sand moving across the area,

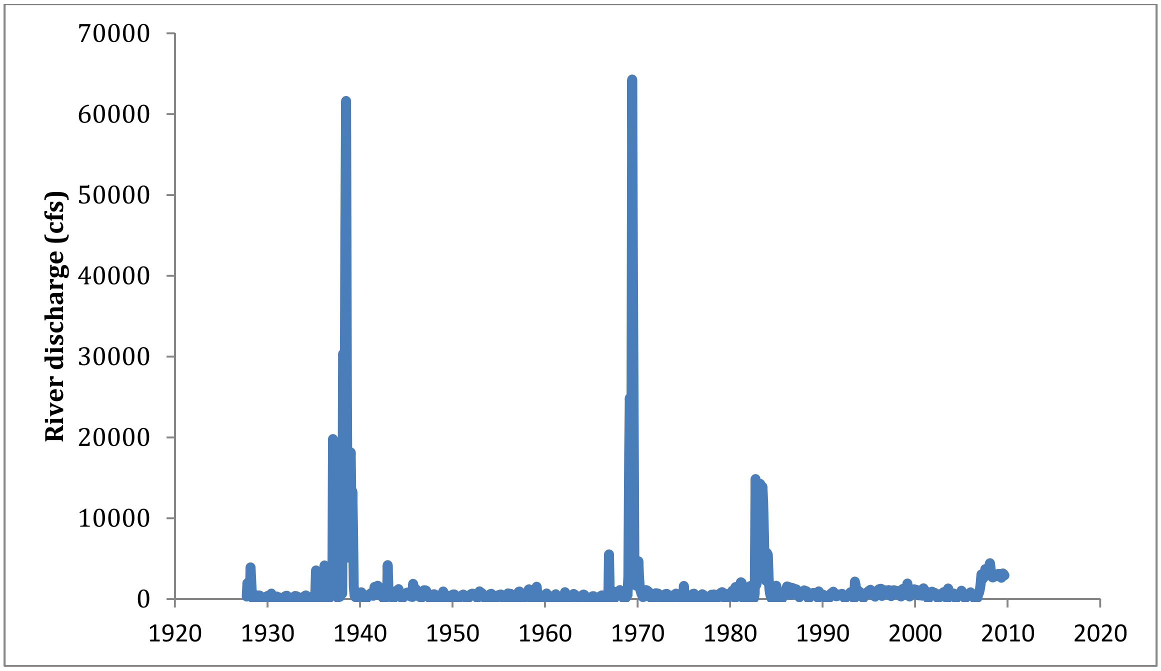

Figure 14: Discharge (in cubic feet per second, cfs) of the Owens River at the Keeler Bridge (1927-2009).

Conclusions

The Keeler Dunefield 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 dunefield is still developing and has not yet reached an equilibrium with sand supply and wind conditions.

Compared to other dunefields 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 dunefield 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 Dunefield is not a lakeshore dunefield, but a desert dunefield adjacent to a lake basin, from which its sediments are derived.

This report seeks to address the question – "Are the currently emissive Keeler Dunes the result (even partial result) of the LADWP's water-diversion actions?"

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 a 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 strongly controlled by the vegetation cover. The area of dunes was very restricted. In the late 1950's to 1960's, the Keeler dunefield 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.

Acknowledgements

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Appendix 1: Description of Fryberger method of Potential Sand Drift estimation

The quantity of potential sand transport by the wind can be assessed from wind data following the procedures developed by Fryberger (1979) – hence the name "Fryberger Method". Potential sand transport is the capacity of the wind to transport sand and is estimated using the principle that sand flux is proportional to the cube of wind speed above the threshold velocity of transport.

The Fryberger method is designed to use wind data binned by speed and direction. The Fryberger method only considers winds above a threshold velocity for sand movement and weights these winds in recognition of the fact that stronger winds are proportionately more effective in transporting sand than weaker winds, using a modified version of the Lettau sand transport equation (Lettau and Lettau, 1969). Thus:

$$q \propto V^2 (V - V_t) / 100$$

where: q is the rate of sand transport, V is the wind velocity at 10 m height and V_t is the impact threshold for transport measured at 10 m. This weighting equation is then calculated for all wind speed categories above the threshold and applied to the percentage frequency of these wind speed categories so that:

$$Q \propto V^2 (V - V_t) t$$

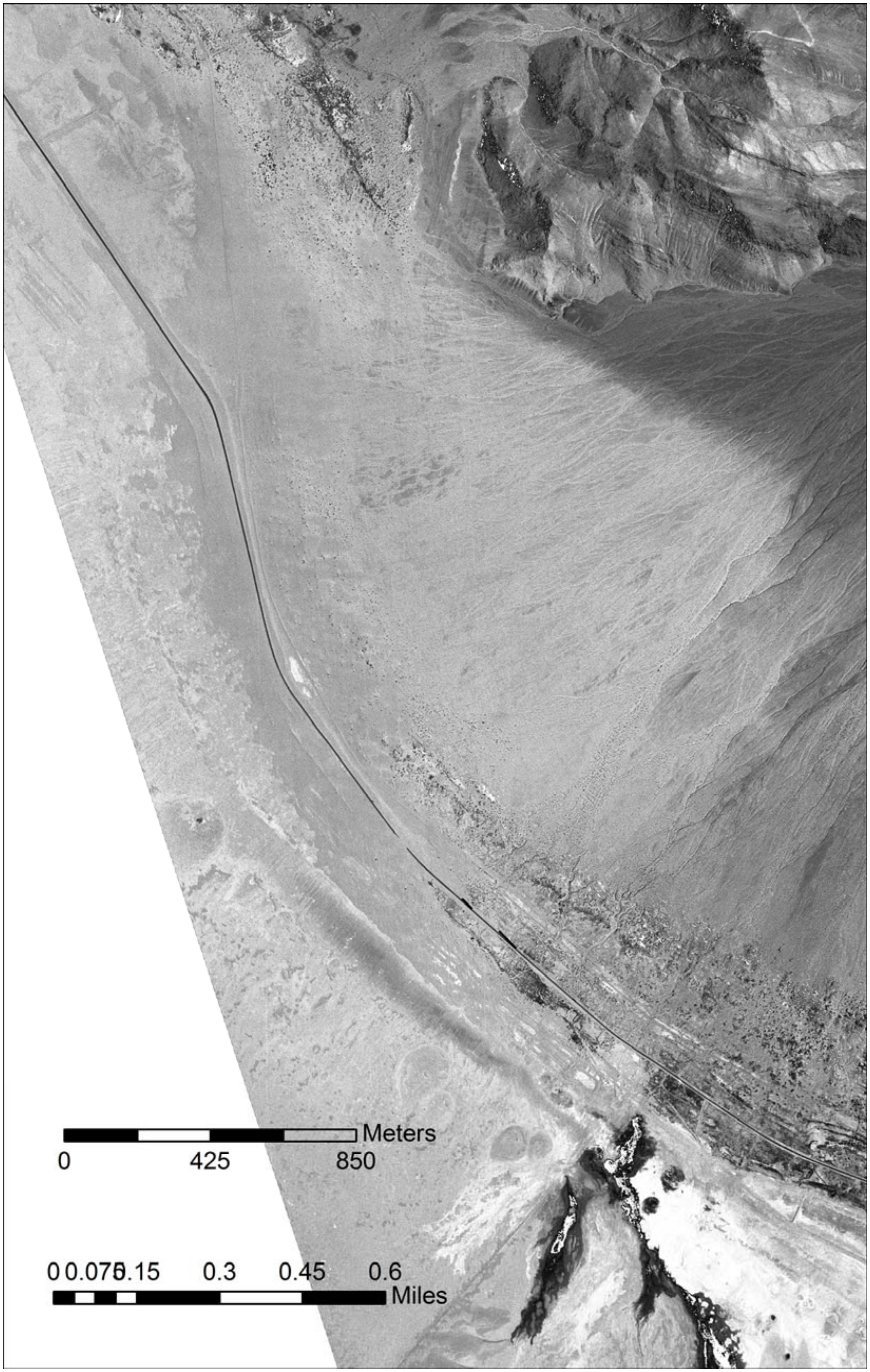
where: Q is the rate of sand drift (expressed in vector units), and t is the percentage frequency of winds in that wind speed category.
The total Q for each wind direction and the total for a station are obtained by summation to give the sand "drift potential," or DP; and the vector sum or resultant sand drift (RDP) magnitude and direction are obtained by vectoral summation. The DP is a measure of the total wind energy of a location, whereas the ratio between RDP and DP is a measure of the directional variability of the wind regime, which has been widely noted as a major control of the type of sand dune in an area (Figure 6). Full details of the methods are contained in Fryberger, 1979). The original method was based on the use of wind speeds recorded in knots. Bullard (Bullard, 1997) cautions the user and provides information on the use of the weighting factors for winds recorded in other units.

Appendix 2: Aerial Photographs and Satellite Images of Keeler Dunes 1944-2010

This appendix contains aerial photographs and satellite images from 1944 to 2010 that were used for dune mapping and derivation of changes in dune extent and morphology. Refer to Table 1 for further details.

1944

1944



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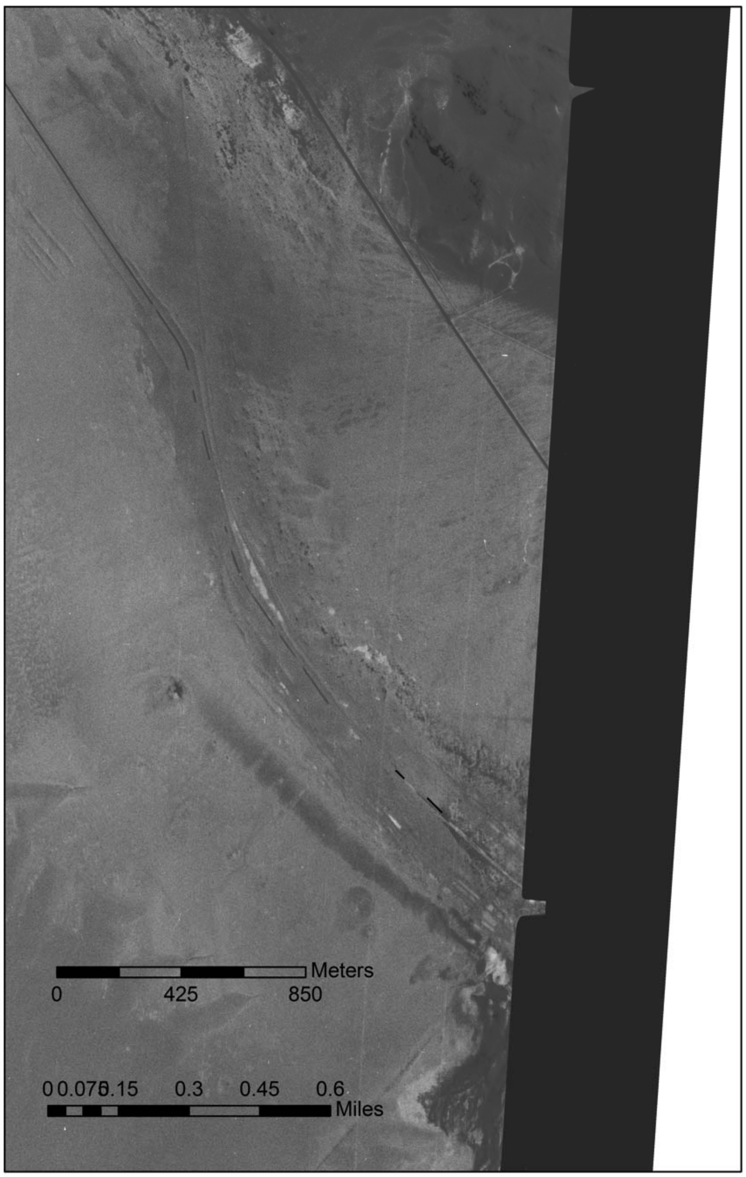
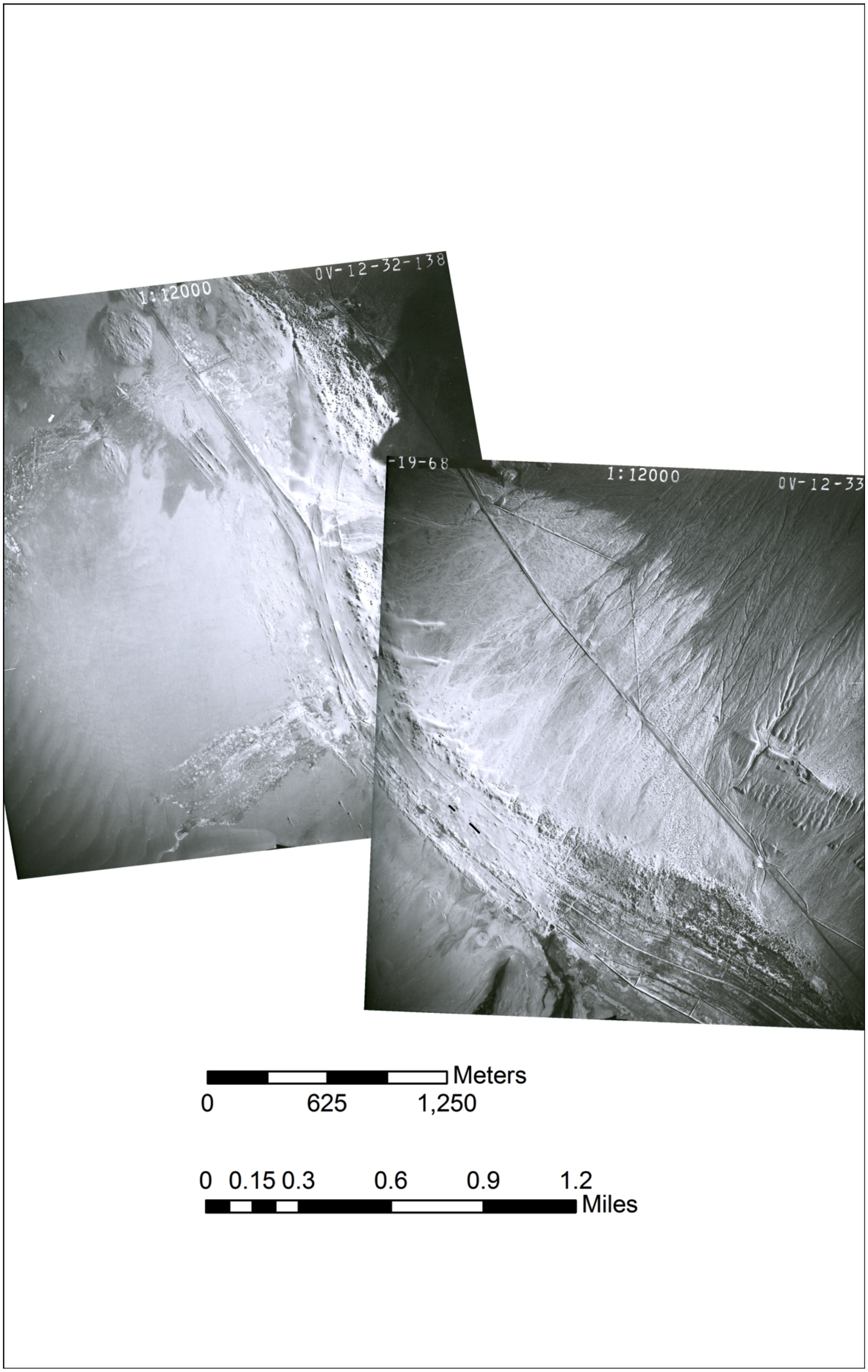


1954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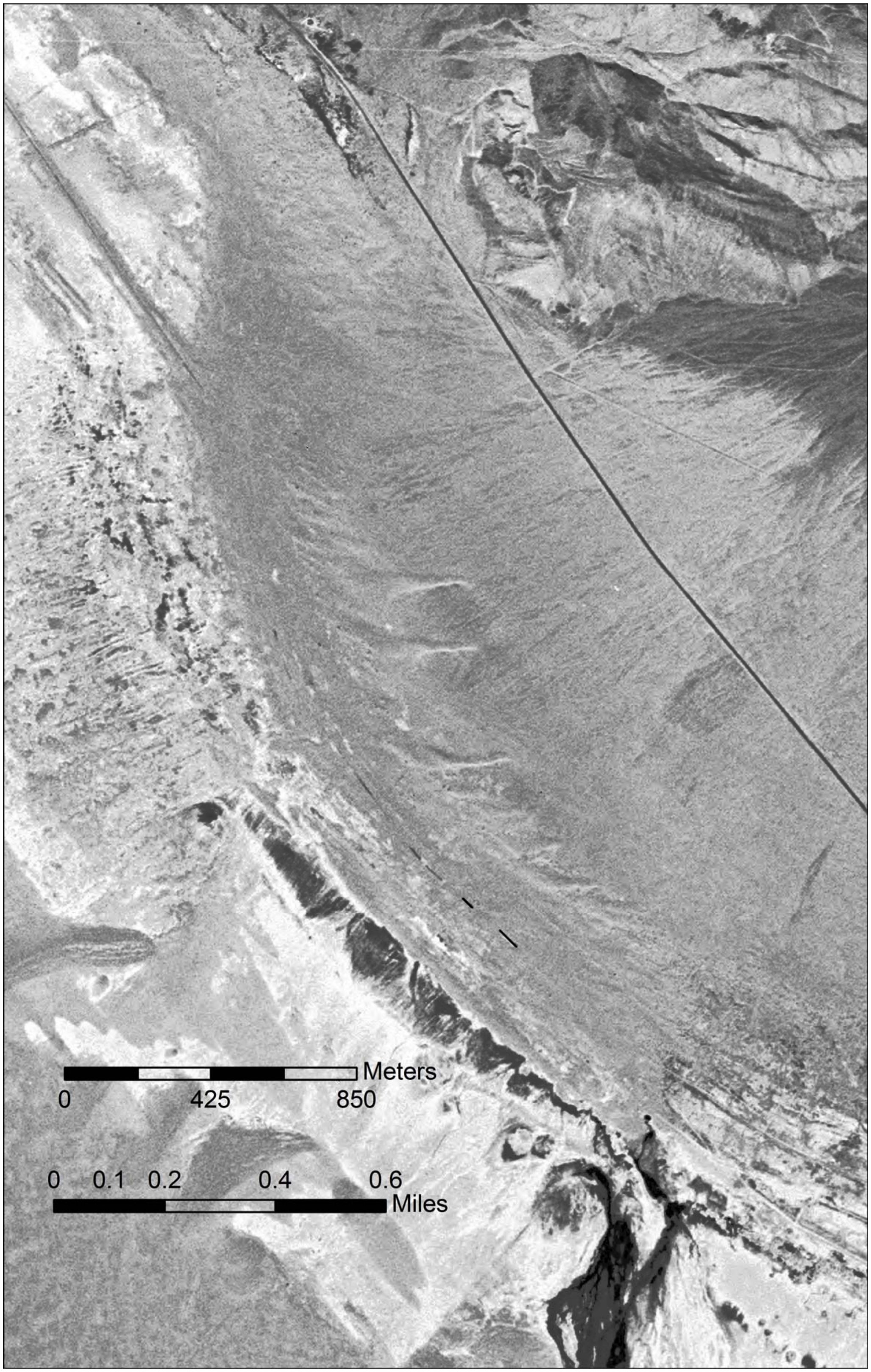
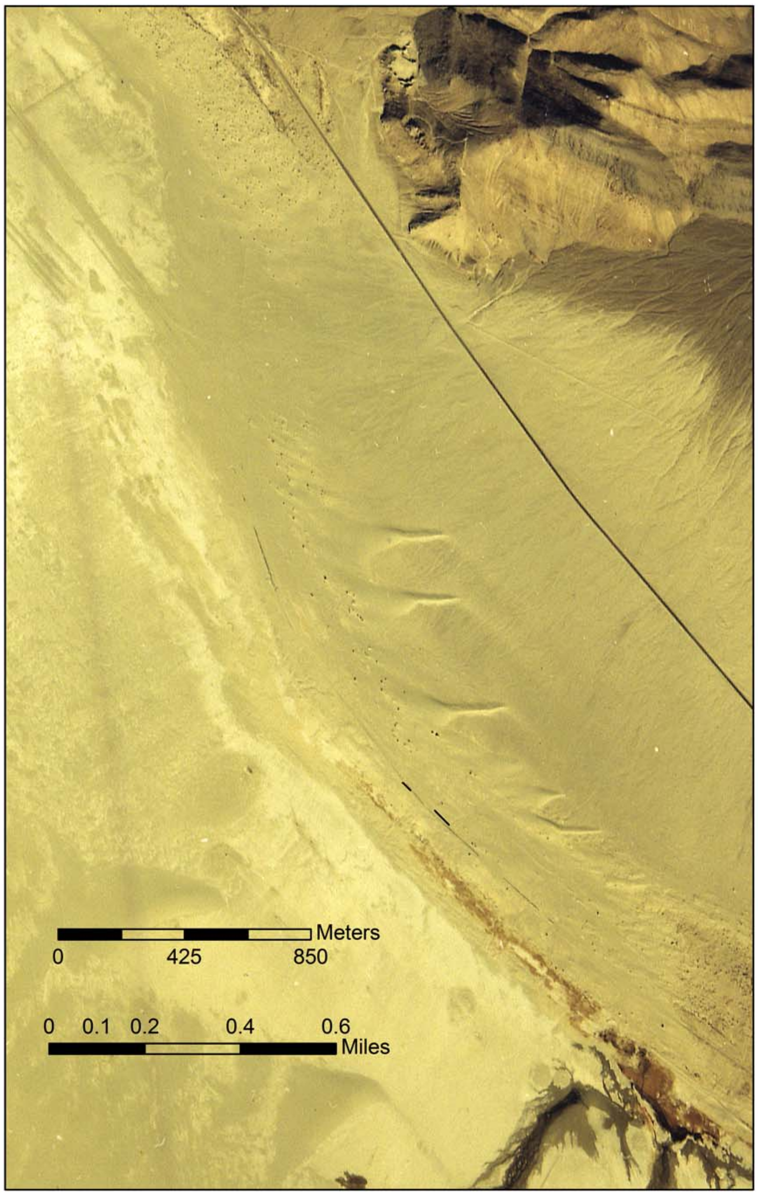
0V-12-32-138
-19-68
1:12000
0V-12-33
Meters
0
625
1,250
0
0.15
0.3
0.6
0.9
1.2
Miles

1968

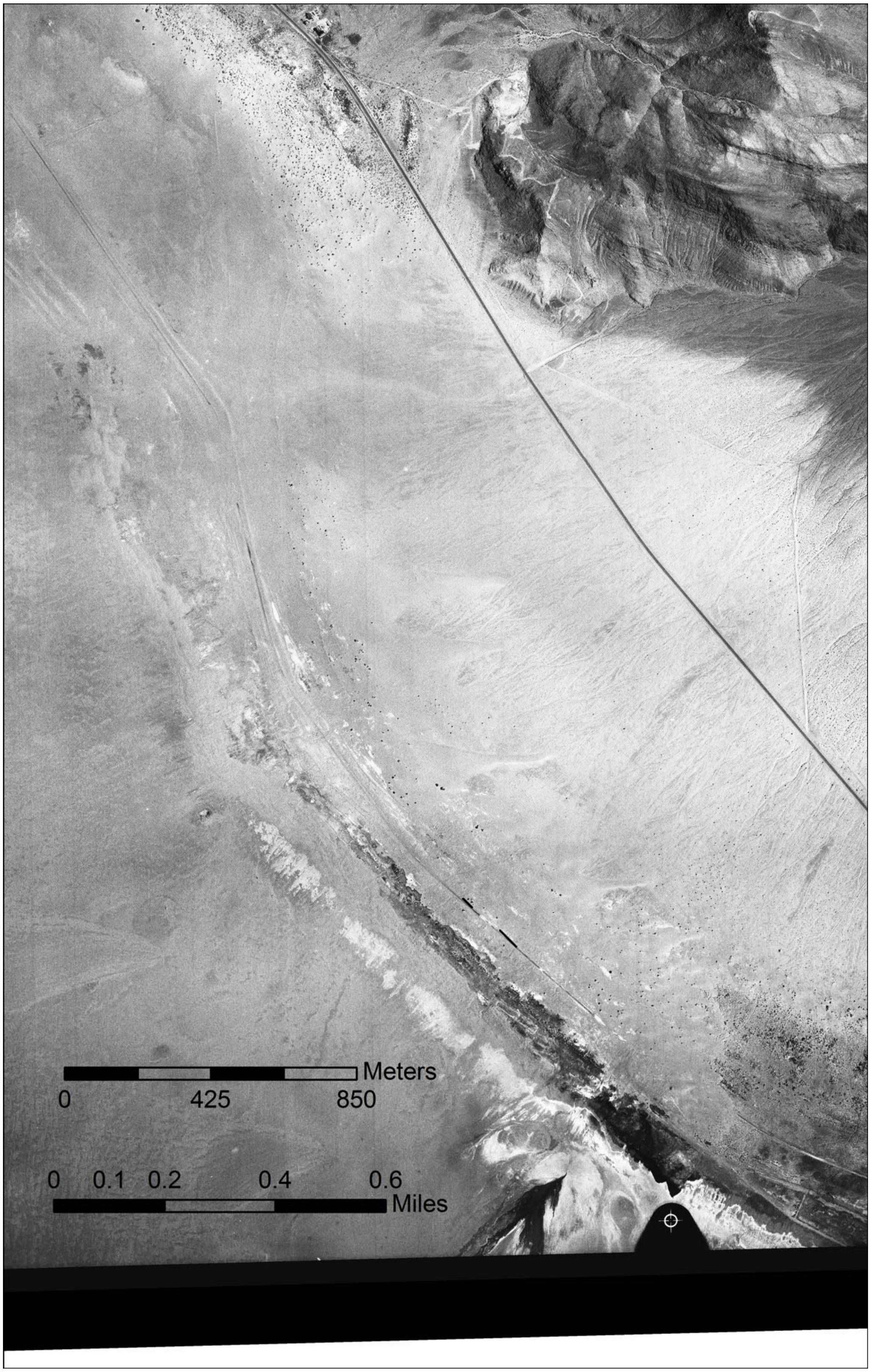


1970

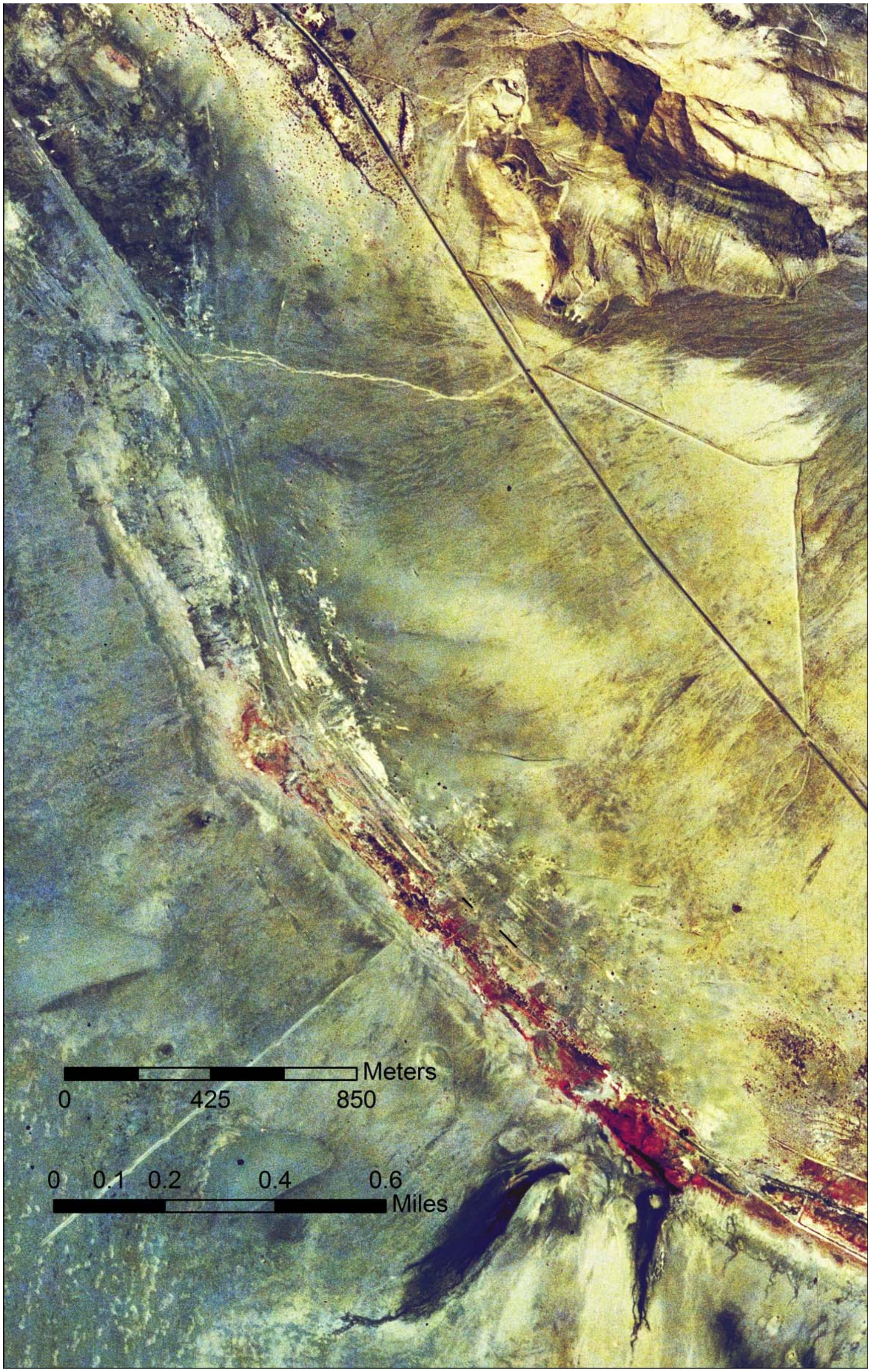


1975

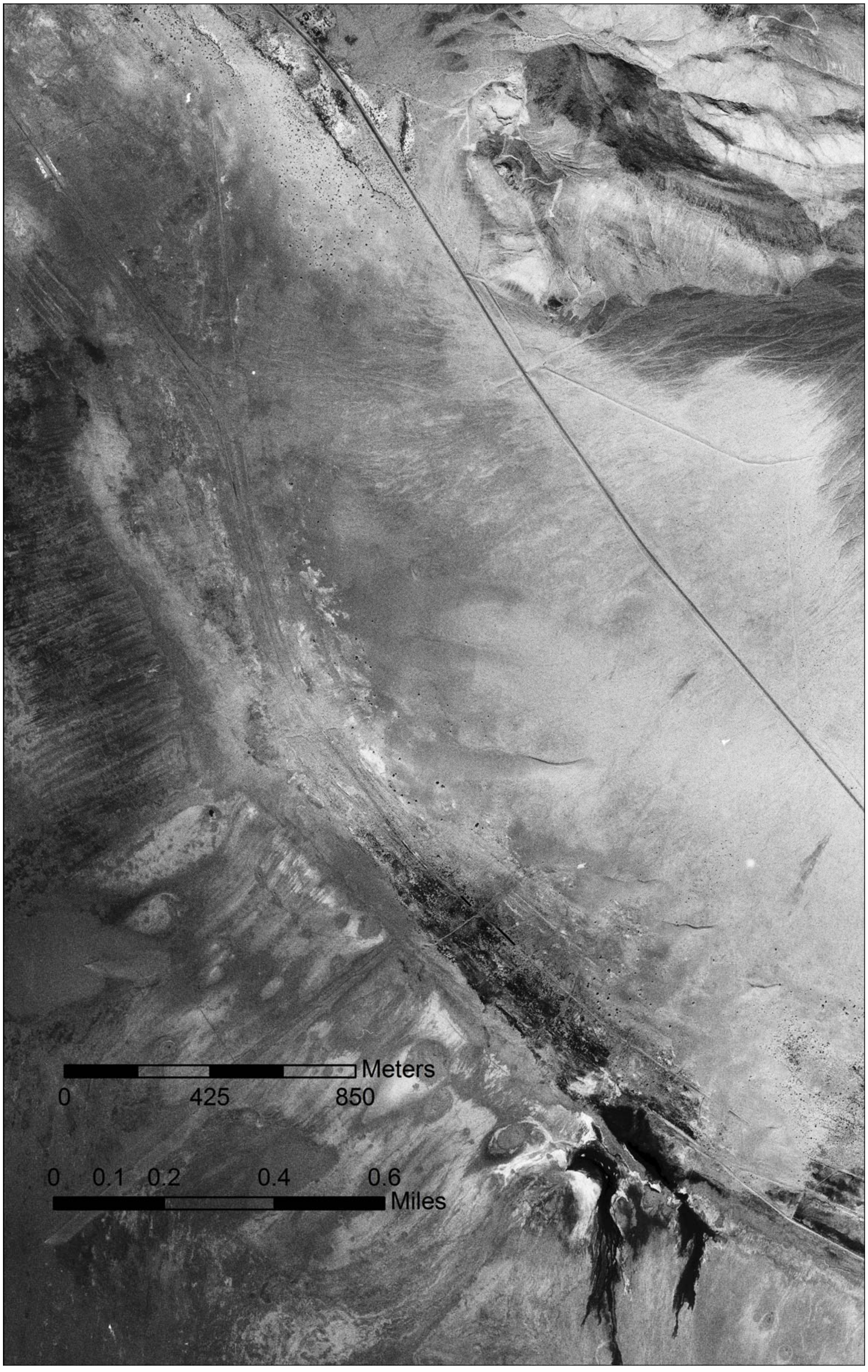
1982



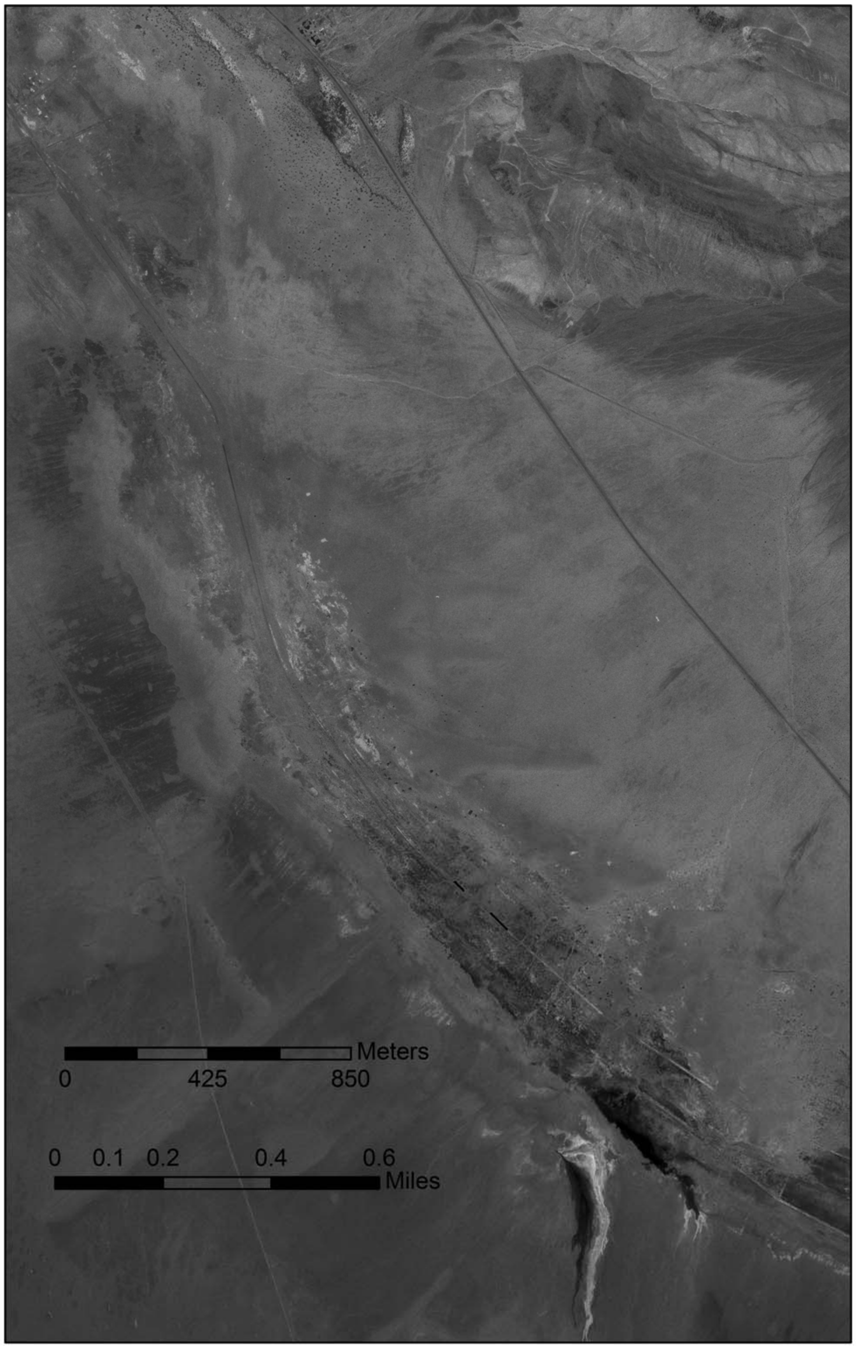
1982



1986



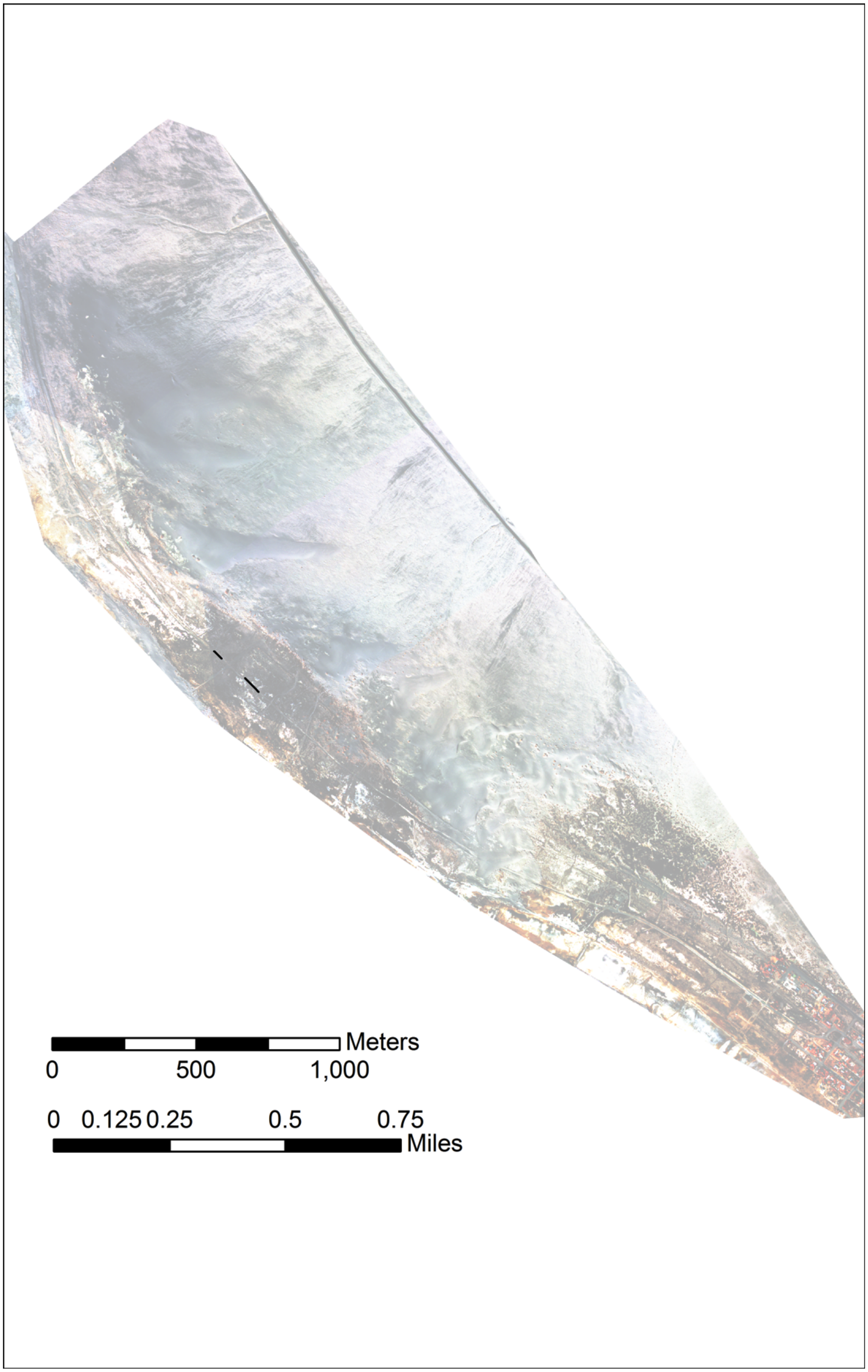
1993



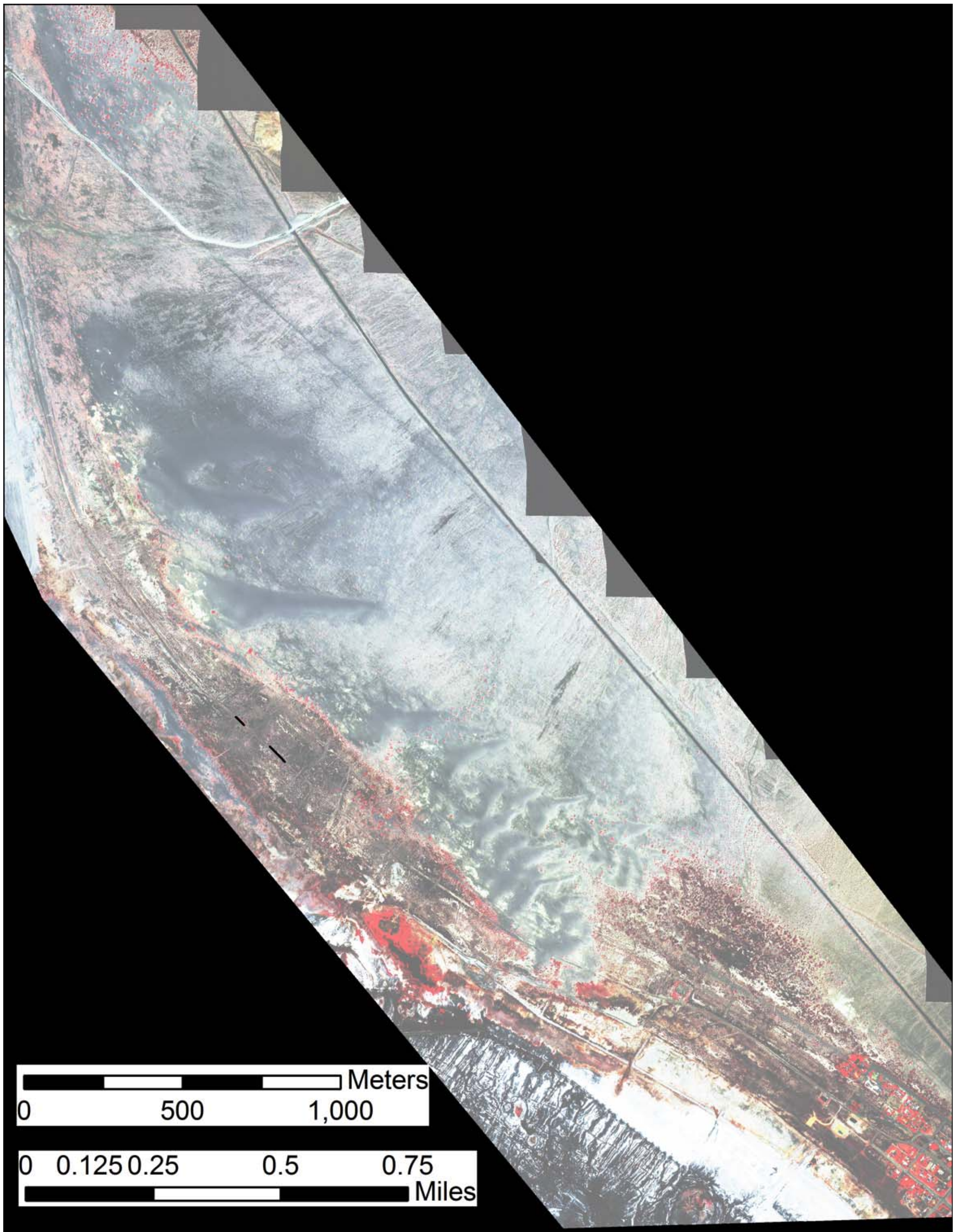
1998

2000

2002



2004



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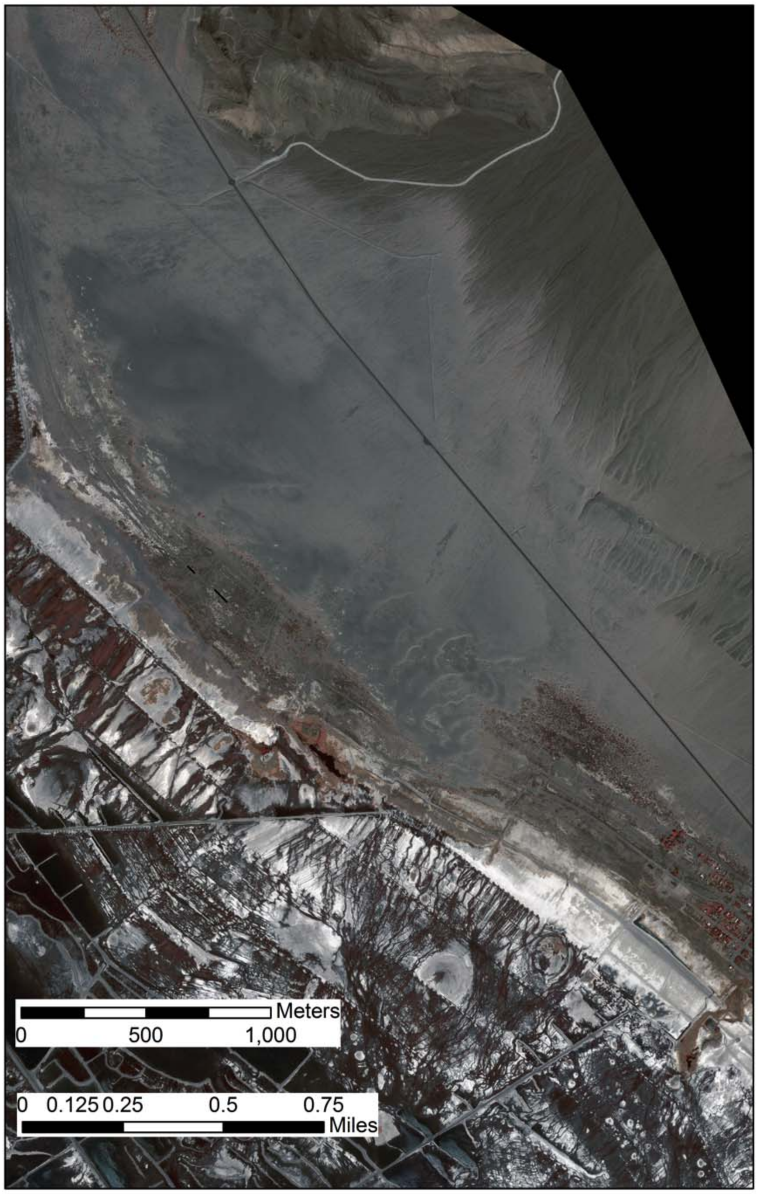
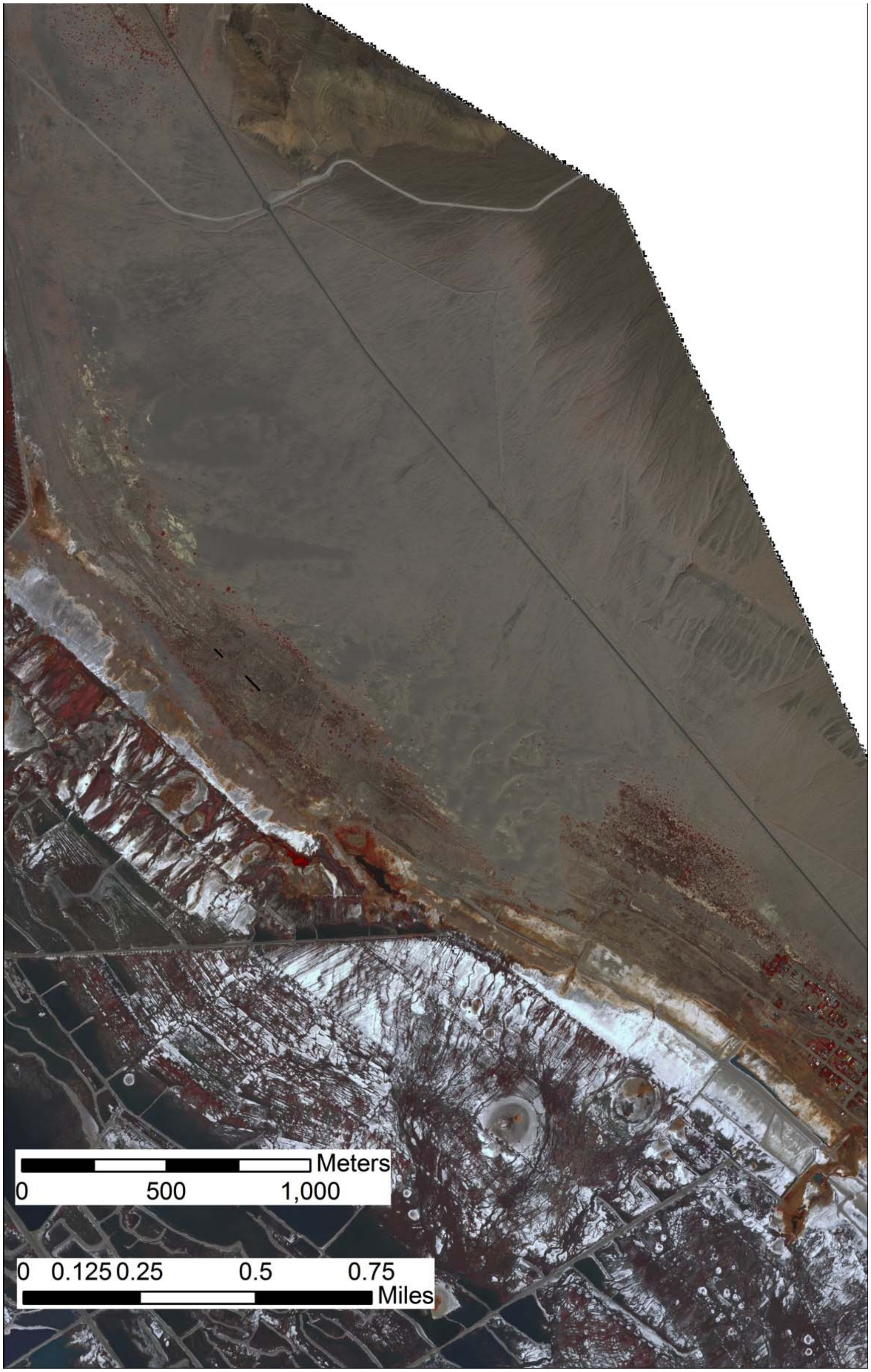


2008



2010