Late Holocene stratigraphy and chronology of Keeler Dunes area

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1. Introduction

The primary purpose of this report is to provide a geologic context for the recent and historic development of the Keeler Dunes documented in Lancaster (2012a). The report is based on (1) the mapping of the spatial extent and relative age of lacustrine, deltaic, fluvial, and aeolian landforms along the northern – northeastern margins of Owens (dry) Lake between the mouth of the Owens River and the community of Keeler (Bacon and Lancaster, 2012), (2) a site-specific geomorphic context by mapping aeolian, lacustrine, and alluvial landforms in the immediate vicinity of the dunefield with high-resolution spectral imagery and airborne laser swath mapping (ASLM) digital topographic data, and (3) stratigraphic and chronometric information from radiocarbon and luminescence dating of aeolian deposits, flood silts, and beach ridges.

2. Holocene Geomorphic and Sedimentary Units

2.1 *Lake shorelines and lacustrine deposits*

Shorelines and deposits related to former high levels of Owens Lake are recognized and mapped at 4 elevations in the northeastern margins of Owens Lake: at 1108 m (3635 feet); 1103 m (3619 feet), 1101m (3612 feet), and 1099 m (3606 feet), in addition to the historic shoreline at 1096 m (3597 feet).

The 1108 m (3635 feet) shoreline has been dated at site 4 (Fig. 2) and has OSL ages of 3620±260 and 3490± 290 years B.P. (see Appendix 1). In the area of the Keeler Dunefield, this shoreline is covered by younger alluvial fan deposits. The 1103 m shoreline is well developed as an erosional bench cut into alluvial fan and older lacustrine deposits in the vicinity of the Keeler Dunefield and as a coarse sand beach ridge between the southern limit of the dunes and Keeler. The age of the 1103 m shoreline is constrained by a single radiocarbon age from a site on the northwestern part of the lake margin (870 ± 40 BP, which calibrates to 814 ± 84 cal BP or 1136 ± 20 AD (sample 8-3-03-1, CAMS 99099) (Scott Stine personal communication August 26, 2011).

Aeolian Sands

The extent and surface expression of aeolian sand deposits in the area has been documented by geomorphic mapping (Bacon and Lancaster, 2012). They recognized five major aeolian geomorphic units (Fig 1):

(i) Active sand dunes [Qe(d)]: This unit includes accumulations of sand that currently experience active sand transport. Dune morphology includes low (2-3 m; 6-10 feet) and discontinuous dunes paralleling the historic shoreline of Owens Lake; and the linear and coalescing barchan and transverse dunes northeast of Keeler that form the present Keeler Dunefield, which overlies distal alluvial fan deposits.

(ii) Active sand sheets [Qe(ss)]: This unit include areas of highly mobile accumulations of sand less than ~4 ft (1.2 m) thick that form flat to gently undulating surfaces largely devoid

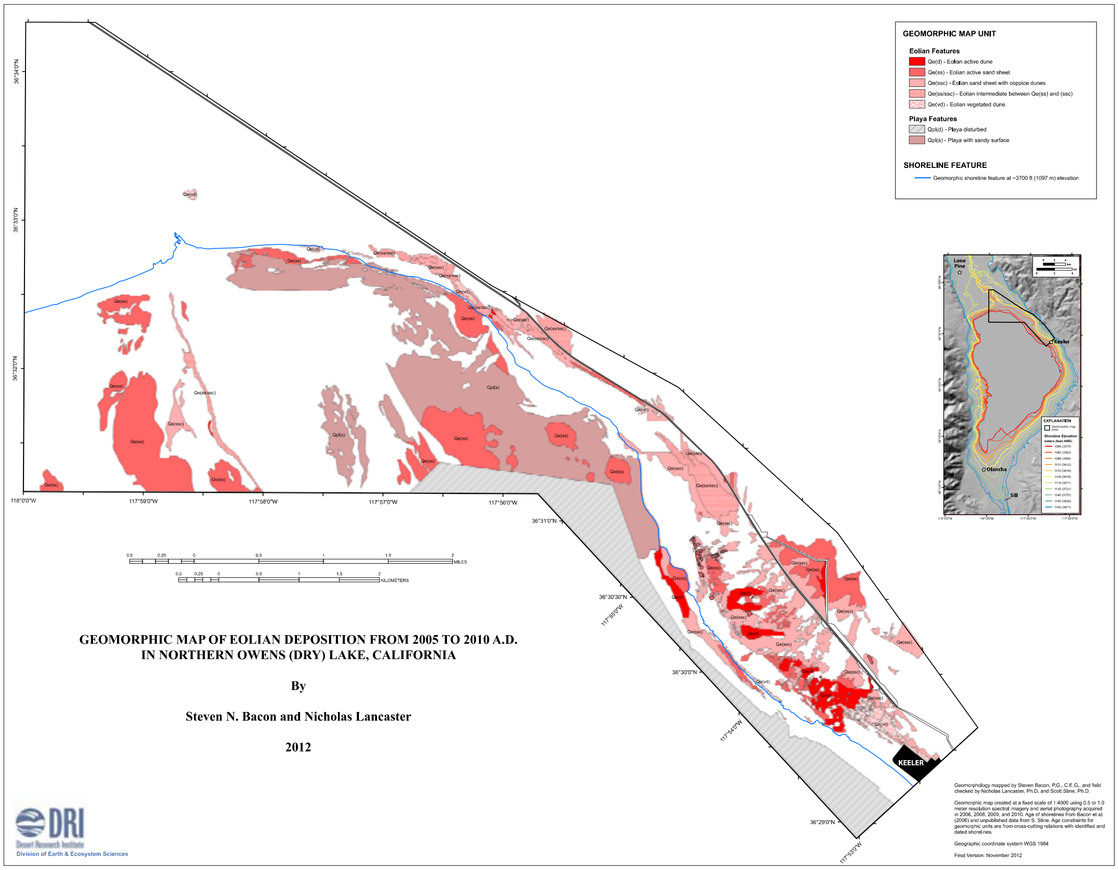

Fig.1. Aeolian sand units in the Northeastern section of Owens Lake

of vegetation. Large areas of the unit cover historical Qd7(p) delta plain surfaces and the playa floor. The unit also overlies playa margins and historical and latest Holocene shoreline features. The Qe(ss) unit is widely distributed on the distal and medial fan of Slate Canyon in the Keeler dunefield.

(iii) Sand sheet with coppice dune [Qe(ssc)]: This unit include areas of active sand on flat surfaces with sparse vegetation that forms vegetated sand mounds (coppice dunes or nebkhas) with a height of usually less than ~3 ft (1 m). This unit is well developed adjacent to the Keeler dunefield.

(iv) Intermediate between sand sheet and sand sheet with coppice dune [Qe(ss/ssc)]: This unit represents areas that are transitional between active sand sheets [Qe(ss)] and sand sheets with coppice dunes [Qe(ssc)]. The unit commonly consists of areas with a range of plant mound density and size resulting in a range of topography from smooth and flat to irregular and hummocky. The unit was identified at two primary locations to the north and near Swansea. The unit north of Swansea forms a narrow band of accumulated sand that covers late Holocene shoreline features above an elevation of

~3606 ft (1099 m); however, several areas within the unit also have discontinuous and poorly preserved benches at elevations around 3597 ft (1096 m) that coincide with an 1872 A.D. lake level, representing wave-cut notches. The other location near Swansea forms a continuous and extensive band of accumulated sediment that parallels and buries shoreline features at ~3612 and 3619 ft (1101 and 1103 m). The Qe(ss/ssc) unit extends as far south as the main active channel of Slate Canyon adjacent to the northern boundary of the Keeler dunefield.

(v) Vegetated dune [Qe(vd)]: This unit represents areas that are covered by a well established and diverse plant community consisting of both coalescing plant mounds and dune ridges anchored by vegetation (*i.e.*, nebkas). Surfaces are typically irregular and hummocky having dune ridge heights up to 10 ft (3 m) that are covered by more than 50% vegetation (Figure A-12). The unit is recognized southeast of the Keeler dunefield adjacent to and parallel to the 3619 ft (1103 m) shoreline and in a relatively small area northwest of Swansea where it consists of a pair of parallel dune ridges oriented oblique to the margin of Owens playa (the Lizard Tail Dunes). In this area, the unit is associated with the Qe(ss/ssc) unit and locally covers latest Holocene shoreline features between an elevation of 3597 and 3619 ft (1096 and 1103 m).

(vi) Aeolian sands below flood silt deposits: In addition to the above mapped units, we recognize a further aeolian sand unit that is poorly and discontinuously exposed in the vicinity of the Keeler Dunefield. This unit is largely buried below discontinuous flood silt deposits (Unit Qfd) that have accumulated within depressions or behind topographic highs, such as beach ridges and sand dunes below an elevation of 3635 ft (1108 m).

Horizontal- and cross-bedded sands crop out in several locations in the vicinity of the Keeler Dunefield, where they are protected from erosion by overlying horizontally-bedded silt and silty-sand beds, interpreted to be the deposits of floods on the adjacent alluvial fans. (Qfd map unit) (Fig. 2). In some cases, the sands are inter-bedded with the flood silt deposits.

Fig 2: Flood silts (Qfd) overlying aeolian sands in the Keeler Dunefield.

The sand unit consists of beds of structureless medium-fine sands; horizontally laminated mixed coarse and medium sand; and locally medium cross-bedded sand.

The sands are typically medium-coarse and poorly to moderately sorted, and very similar in particle size and sorting to those in the modern dunes. Likewise, their composition is identical to those of the modern Keeler dunes, the Swansea dunes, and sand from the Owens River delta (Lancaster, 2012b).

The sands are interpreted as aeolian based on sedimentary structures, which are typical of aeolian sand sheets (Fryberger et al., 1979) and dunes (Hunter, 1977). The sand sheet deposits can be compared directly to modern sand sheets in the immediate area. The cross-bedded sands (Fig. 3) dip to the SSE (150°) indicating deposition by SE migrating crescentic dunes.

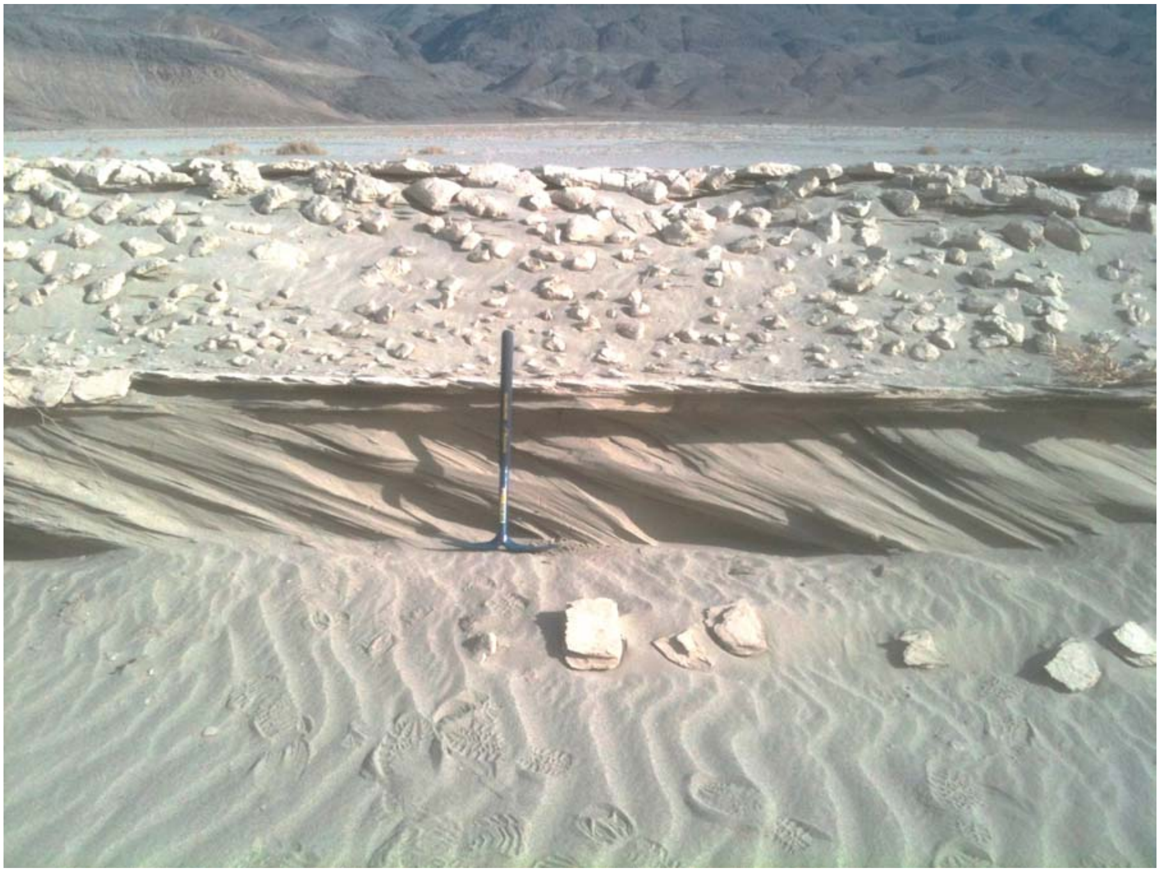

Fig. 3: Exposure of cross-bedded aeolian sand overlain by flood silt deposits

2.2. *Flood silts*

The flood silt deposits (Qfd) typically crop out in a 100 m wide swath at elevations ranging from 1102.5 to 1109.5 m, where they have been exposed by deflation of overlying sand (Fig. 2). Median elevation of the flood silts surveyed using differential GPS is 1105.9 m, with 46% of the flood silts at elevations between 1105 and 1106 m (Fig. 4). The deposits occur as a series of separated patches of silt that are either interbedded with aeolian sands or form a cap on underlying sands of aeolian origin. Contacts between the flood silts and the underlying aeolian sands are sharp and represent a clear unconformity. Their thickness varies from 10 – 50 cm, with no apparent spatial pattern of thickness, although it does appear that those towards the upper elevation range and to the north are thinner. The surface of the silts exhibits polygonal crack systems (Fig. 2), which developed as the water body dried out. Polygonal cracking is best developed on the thicker silt deposits. Some of the silt deposits have upturned edges, suggesting that they were deposited in a pre-existing dune landscape. Flood silt deposits at the upper elevational range have scattered cobble- and gravel-size clasts lying on their surface.

The flood silts are interpreted as the distal end point of floodwaters on alluvial fans that head in the Inyo Mountains. Their best expression coincides with the apex of the fan and with channels that have been active in recent years, as indicated by the aerial photographs taken in August 1968, fortuitously soon after significant surface runoff on the Keeler fan (Fig. 5). The flood silts appear to have been deposited by silt-laden water flows, which were dammed at their lower extent by small dunes. Somewhat similar deposits were described from the Mojave River terminal fan (Langford, 1989). Thicker features resulting from river flooding into dunefields have been described from the Skeleton Coast, Namibia (Stanistreet and Stollhofen, 2002; Svendsen et al., 2003).

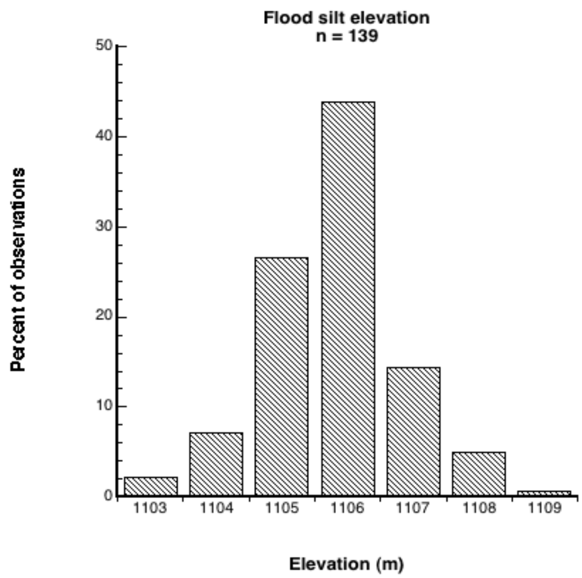

Fig. 4: Elevations of flood silt deposits mapped using differential GPS.

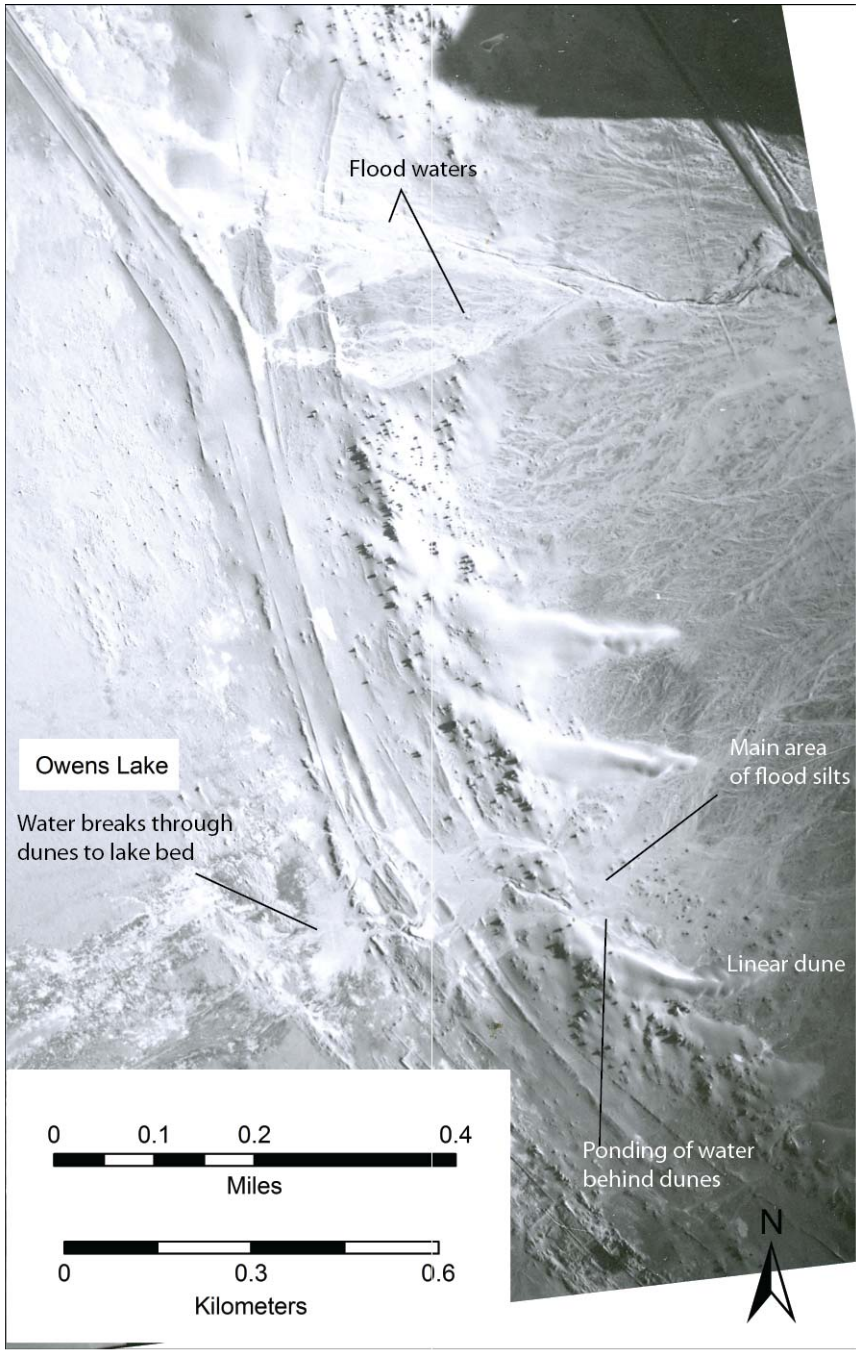

Fig. 5. Aerial photograph taken in August 1968, showing recent flooding on the Keeler Fan and ponding of floodwaters against the dunes that existed at this time.

3. Stratigraphy of Aeolian and Flood Silt Deposits

3.1 *Linear dune site*

The stratigraphy and chronology of aeolian sand and flood silt deposits is best expressed in the area immediately west of the current trailing margin of the dune known informally as the linear dune (Fig. 6). In this area, there are extensive outcrops of flood silts, as well as inter-bedded aeolian sands.

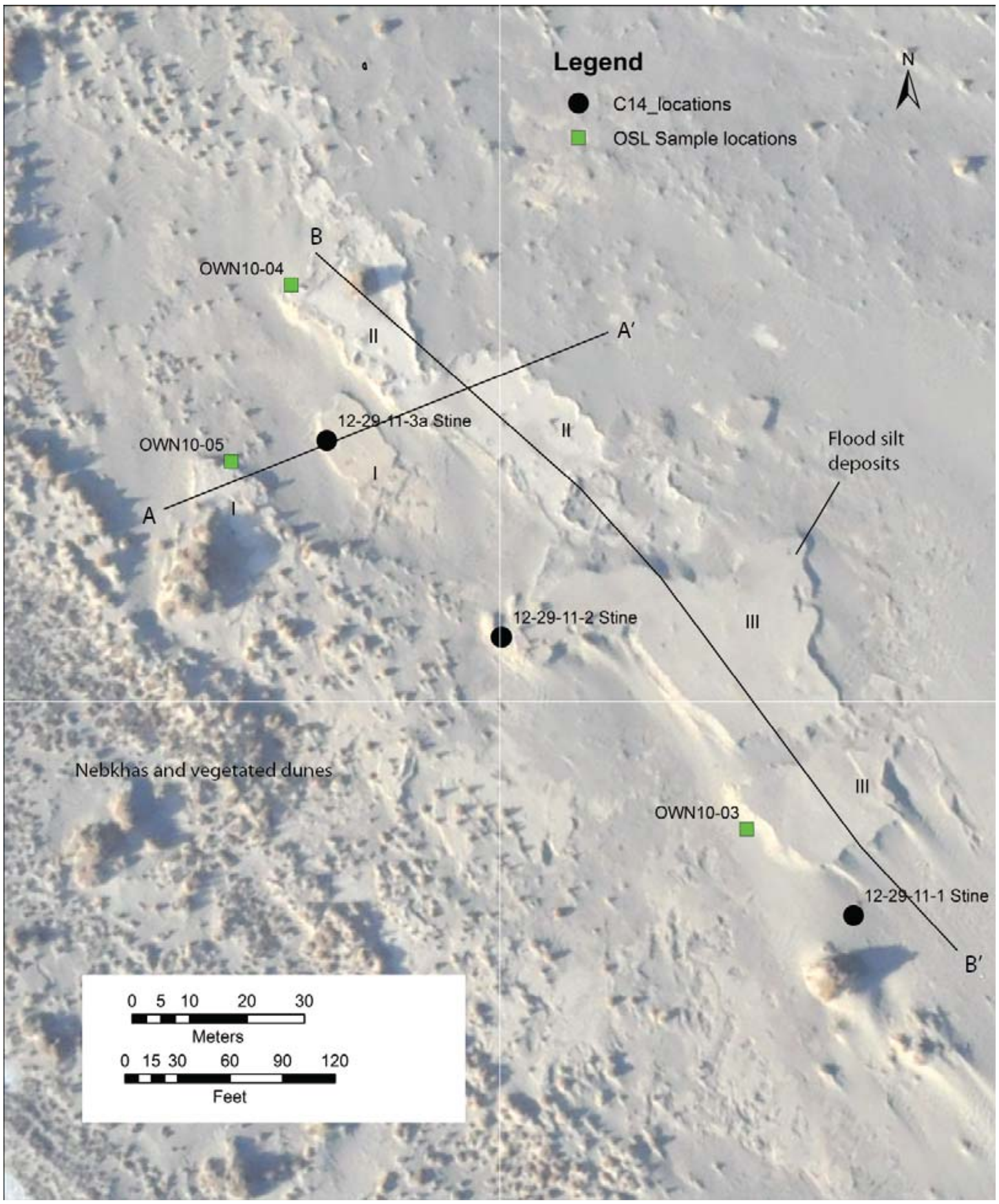

Fig. 6: The Linear Dune site, showing location of OSL and radiocarbon dates and cross-sections (Fig. 7).

Flood silts occur at three primary elevations in this area – at 1104, 1105, and 1106 m (3622, 3626, and 3629 feet), which are designed units I – III from lower to upper. Of these, the ~ 1105 and 1106 m elevation silts (units II and III) are the most extensive and form a prominent 2m-high bench that extends for 170 m from NW to SE (Figs. 6 and 7). The flood silts at lower elevations are more patchy and thinner (<10 cm thick).

It appears that there are two primary aeolian units, the upper unit that is capped by flood silt III is a medium fine moderately well-sorted sand that displays cross-bedding; and a lower horizontally bedded unit underlying flood silt II. Sands below flood silt I are poorly exposed, but appear to be structureless.

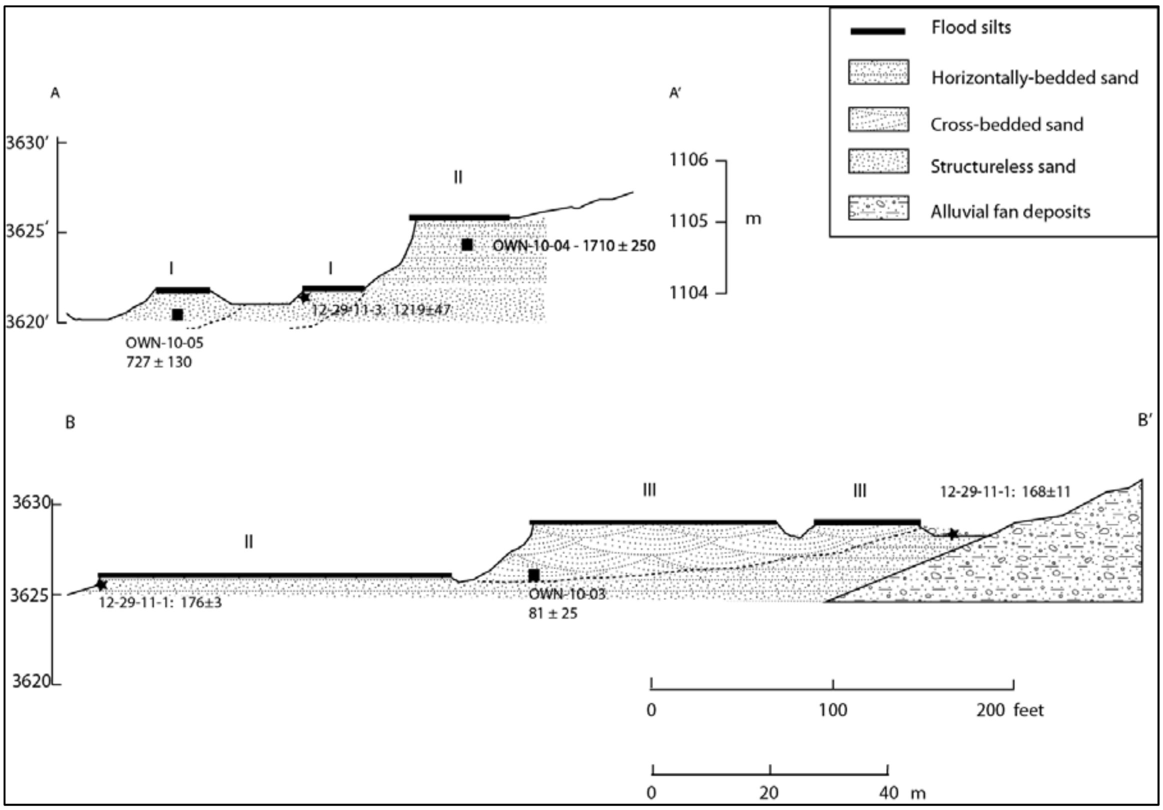

Fig. 7: Topographic and geologic cross-sections of the linear dune site for area shown in Figure 5. For location of profiles see Figure 5. Profile based on 0.5 m LiDAR topographic data, augmented by differential GPS surveys..

4. Chronology of aeolian and flood silt deposits

In addition to geomorphic and stratigraphic relationships between units, chronometric ages were determined using OSL (optically stimulated luminescence) and radiocarbon methods. The location of the OSL samples is shown on Figs 8 and 9; with radiocarbon samples on Figs. 9. Details of the OSL procedures are provided in Appendices 1 and 2; with the radiocarbon calibration procedures documented in Appendix 3.

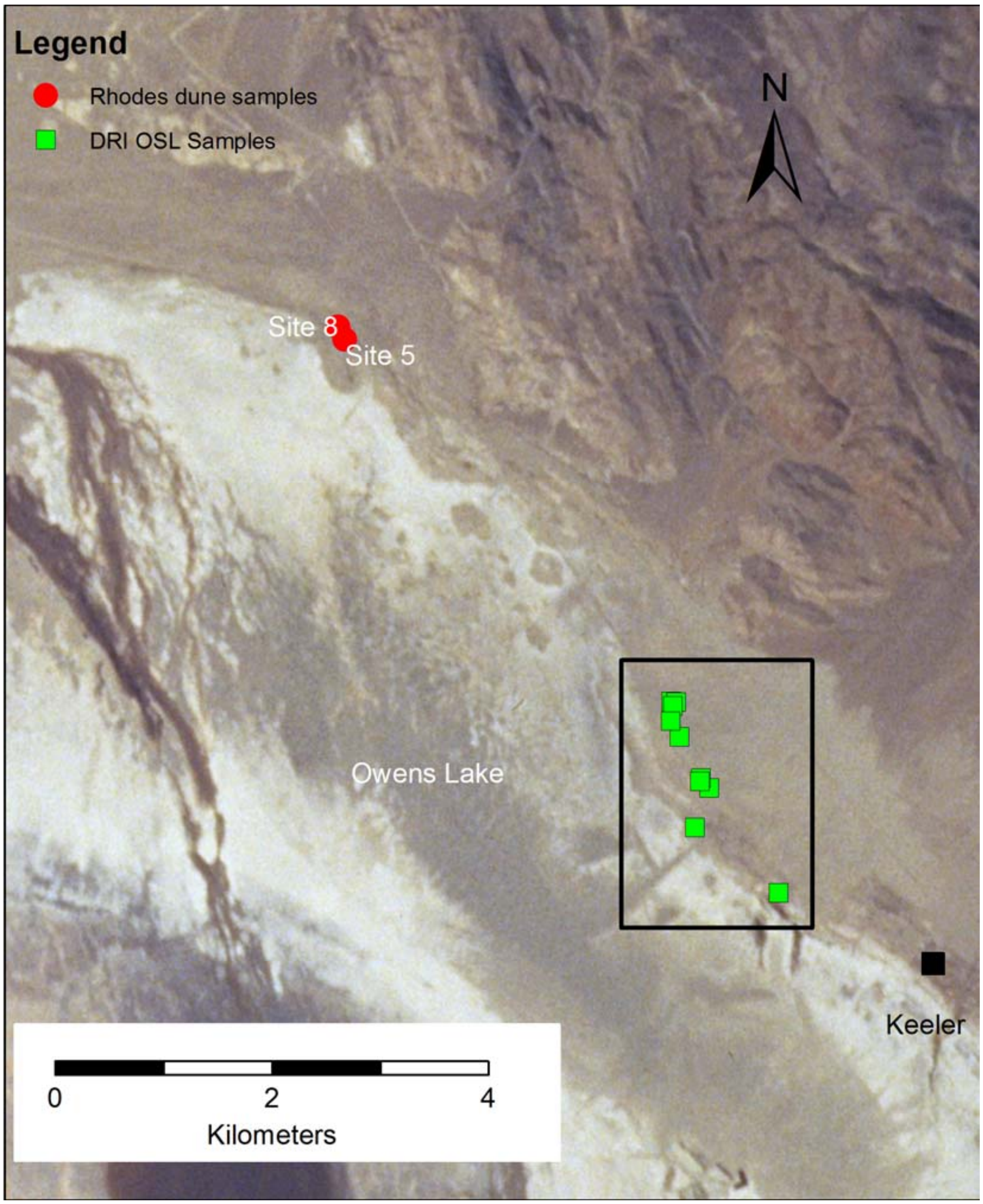

Fig. 8. Location of sampled sites – box indicates area of Fig. 9.

4.1 Linear dune site

Chronology for these units is provided by 7 OSL ages (Table 1) and 3 radiocarbon dates (Table 2). The radiocarbon ages are from charcoal embedded in or immediately below the flood silt, and were collected by Scott Stine. The OSL ages were determined on aeolian sands below each of the main silt units. Sample location information is given in Table 1 and 2 and Figures 8 and 9.

Table 1: OSL samples on Aeolian Sands from Keeler Dunes area

Sample	**Northing**	**Easting**	**Elevation (m)**	**Age (before 2011)**	**Error (1 sigma)**	**Calendar Years (AD)**
OWN10-02	4039913.40	419251.92	1096	35.1	4.2	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	730	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

Note the years before present (B.P.) are years before 2011

Table 2: Radiocarbon samples from Keeler Dunes area

Sample	Northing	Easting	Elevation (m)	RC age	RC Error	Calibrated Age (BP)	Calendar age (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
12-29-11-3	4040346.78	419313.62	1102.937	1255	35	1219±47	731

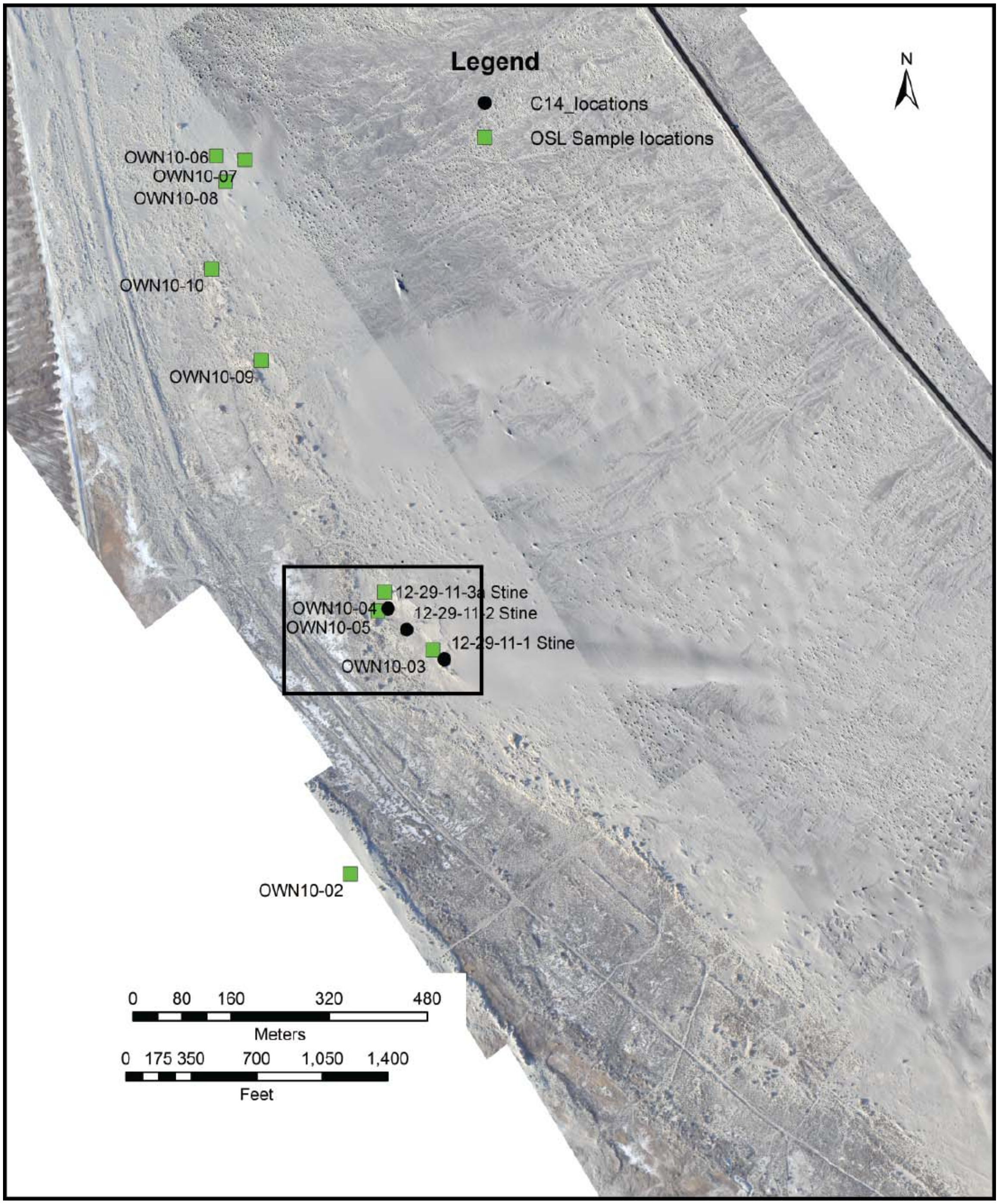

Fig. 9. Location of all radiocarbon and OSL samples collected in the area of the Keeler Dunes. Box indicates location of Fig. 5.

4.1.1 *Radiocarbon ages*

Sample 12-29-11-1 Stine (= CAMS 156482). Charcoal from below the highest of the three fine-grained flood deposits (Unit III) gave a radiocarbon age of 190 ±30 yrs. BP.

There are two fairly strong calibration probabilities on this sample: 168 ±20 cal BP, and 278 ±9 cal BP. This can be pinned down a little more closely because the lab ran a replicate on this sample (replicate = CAMS 156487), with a result of 205 ±30 yrs. BP. Calibration on the replicate shows strong tendencies at 168 ±18 cal BP, and at 283 ±13 cal BP. Taken together (sample and replicate) the two likely calibration possibilities are 168 ±18 cal BP, and 278 ±8 cal BP. As will be pointed out in regard to the next sample (12-29-11-2 Stine), the younger of the two calibration possibilities is the favored one.

Sample 12-29-11-2 Stine (= CAMS 156527). Charcoal embedded in the underside of the middle of the three flood deposits (unit II) provided a radiocarbon age of 140 ±40 BP.

This date is difficult to calibrate, and it septuplicates on the calibration curve, with no statistically clear favorite among the seven. But because this sample lies stratigraphically below Sample 12-29-11-1 (and must therefore be older than Sample 12-29-11-1), the only compatible solution is that 12-29-11-1 calibrates to 168 ±18 cal BP (the younger of the two possibilities), and 12-29-11-2 calibrates to one of these three possibilities: 176 ±3 cal BP, 206 ±22 cal BP, or 262 ±11 cal BP.

Sample 12-29-11-3a Stine (= CAMS 156483). Charcoal from the sediments immediately underlying the lowest of the three flood deposits(Unit I) gave a radiocarbon age of 1255 ±35 yrs. BP. This calibrates cleanly to 1219 ±47 cal BP.

4.1.2 *OSL ages*

OSL ages for the Keeler dune area were determined by the late Glenn Berger and José-Luis Antinao at the DRI luminescence laboratory. Measurement of the paleodose was performed using the SAR (Single aliquot regenertative) OSL procedure (Murray and Wintle, 2000), using the single grain approach (Duller, 2004). The dose rate was determined using ICP-MS to determine the content of potassium and thick-source alpha counting to determine the uranium and thorium contributions. Full details of the luminescence procedures are contained in Antinao et al (2012). The years B.P. given below are before 2011.

Sample OWN-10-02 was from a depth of 1.0 m in sand below flood silts deposited behind the historic shoreline dune and provided an age of 35.1±4.2 B.P (1976), indicating deposition in the period 1972-1980

Sample OWN-10-03 is from a depth of 1.25 m in cross-bedded aeolian sand below flood silt III and provided an age of 81±25 B.P.

Sample OWN-10-04 is from a depth of 0.73 m below the horizontally bedded aeolian unit below flood silt II and provided an age of 1710±250 B.P.

Sample OWN-10-05 is from a depth of 0.50 m in the structureless sand below flood silt I and provided an age of 727±130 B.P.

Sample OWN-10-06 is from a depth of 0.90 m in sand below a mesa of flood silts exposed by deflation in the sand sheet area at the north of the Keeler Dunefield and provided an age of 40±20 yr B.P (1971)., indicating deposition of sands in the period 1960-1980, i.e. during the time of maximum expansion of the Keeler Dunefield (Lancaster, 2012a). The flood silts overlying this sand now form an erosional residual about 1.2 m high, providing an indication of the amount of erosion that has taken place in this area since about 1980.

Sample OWN-10-09 is from a depth of 0.43 m below a flood silt deposit and provided an age of 172± 72 B.P.

Sample OWN-10-10 is from a depth of 0.67 m below a flood silt deposit and provided an age of 423± 45 B.P.

4.2 Lizard Tail dunes

Two sites were sampled for OSL dating in the western part of the dunes west of Swansea, in the vegetated dunes of unit Qe(vd) (Fig.) adjacent to the Lizard Tail meteorological station (Figs 8 and 10). Site 5 was located on the southern, lake proximal ridge, which is approximately 2 m high; whereas site 8 was located on the northern ridge away from the lake, which reaches a height of 4 – 5 m (Fig.10). 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 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, 2 samples were processed. 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. This age likely reflects that of the distal alluvial fan materials that underlie the dunes, rather than the basal age of the dune. At Site 8, 4 samples were processed, at depths of 0.87, 2.0, 3.0, and 3.74 m. Ages range between 400 ± 30 and 820±30 B.P. It appears that two periods of accumulation occurred at this site: 400-420 B.P. and 710-820 B.P., reflecting more rapid accumulation in the younger of these periods (Fig. 11).

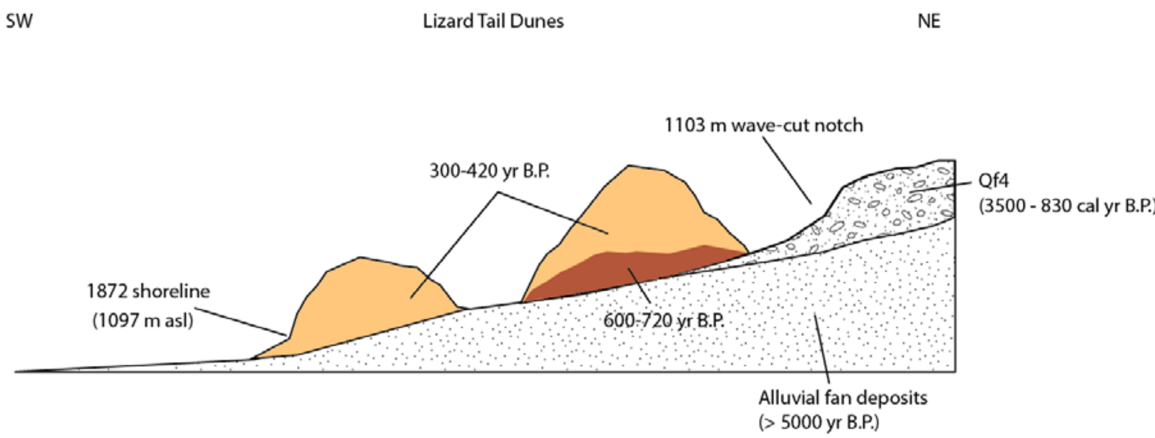

Fig. 10. Schematic cross section of the Lizard Tail dunes area.

Table 3: OSL ages from Lizard Tail Dunes

Sample Number	Northing	Easting	Depth (m)	Age	1 sigma error	Calendar years (AD)
KD-12-08	4044423	416019	0.75	300	20	1712
KD-12-10	4044423	416019	2.00	5000	210	
KD-12-12	4044542	415959	0.87	400	30	1612
KD-12-14	4044542	415959	2.00	420	30	1592
KD-12-16	4044542	415959	3.00	710	40	1302
KD-12-17	4044542	415959	3.75	620	30	1192

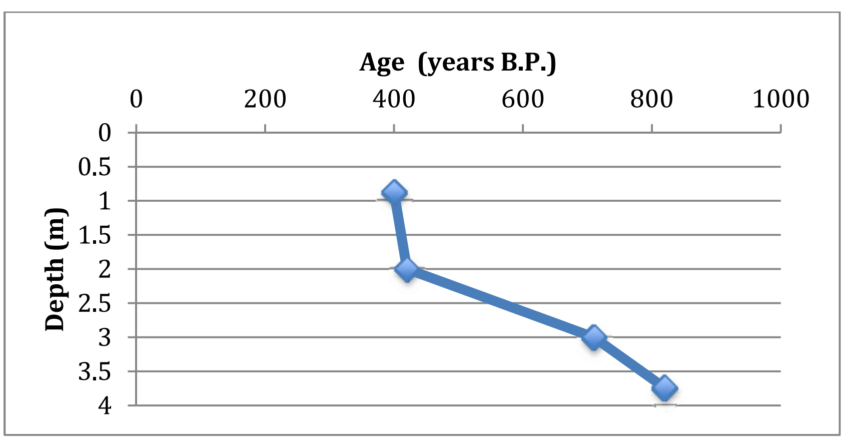

Fig. 11. Age-depth profile for dune sand accumulation at site 8 (Lizard Tail dunes).

5. Discussion

These studies provides evidence for episodic 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 stratigraphic order (oldest on top) relative to other deposits. This often occurs in alluvial settings 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 (e.g., Pain and Ollier, 1995). 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. 8). The radiocarbon ages, despite calibration issues with the younger two samples, fall in stratigraphic order and provide good age 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). Recent dated sand deposits span the range from around 80 to 35 years ago (1931-1976).

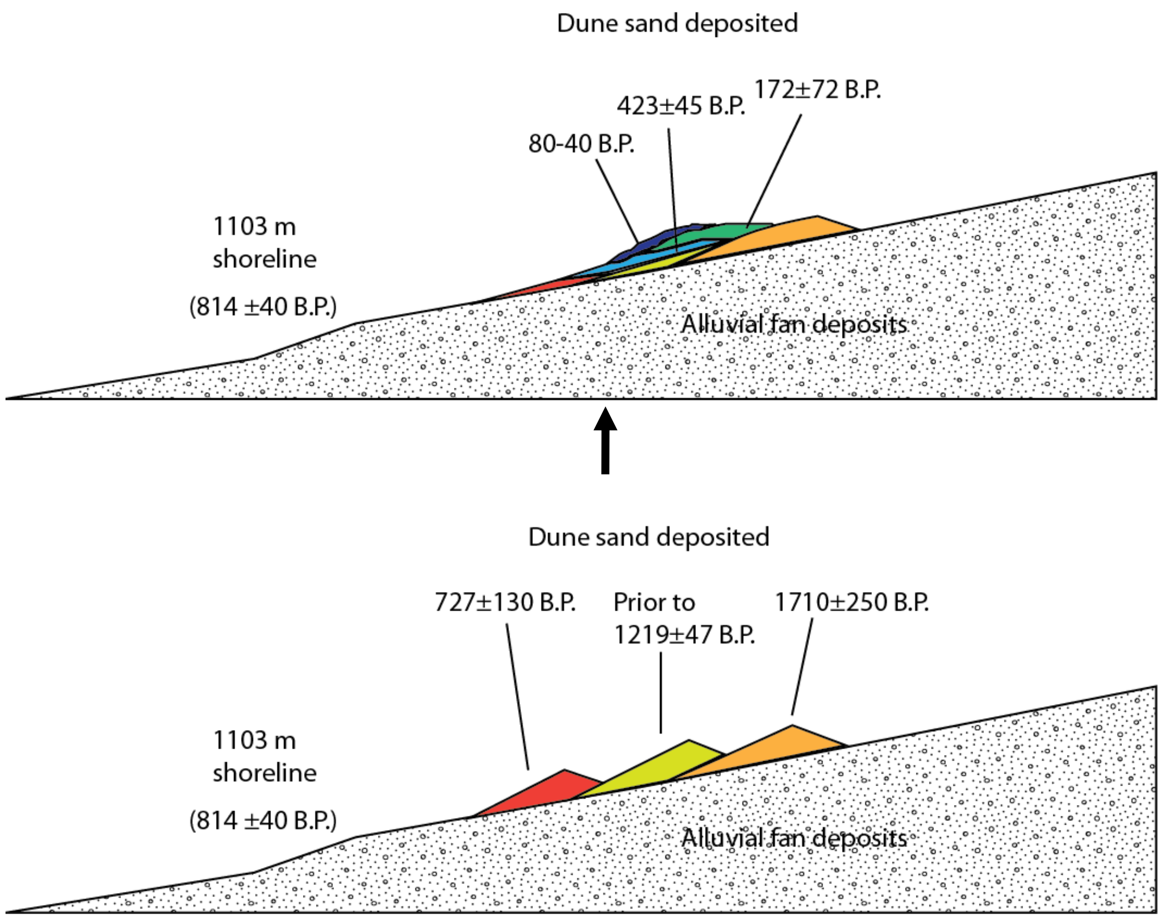

Fig 8: Schematic illustration of aeolian sand deposition on the Keeler Fan

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, or during the latter part of 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 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.

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 extensive aeolian sand accumulation in the area around 300-450 and 600-730 yr B.P (1563-1712 and 1282-1412AD). The older of these periods immediately follows the 1103 m lake highstand that occurred at around 814 yr B.P. (1136 AD), and likely was the result of the lowering of the lake level and exposure of lake plain sediments at this time.

Conclusions

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