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FERNLEY BASIN

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INTRODUCTION

Pluvial Lake Lahontan consisted of seven sub basins that only coalesced into one lake at the very highest levels. For much of the late Pleistocene and Holocene these basins responded separately (and possibly in a unique manner) to climate change in the region. A full understanding of the history of this major Pleistocene pluvial lake can only be developed by detailed studies of the deposits and landforms of each of sub basins and by subsequent correlation between well-dated events in each basin. A reconstruction of the the lacustrine stratigraphic and lake level record of the Fernley Sink area, west, central Nevada was compiled from the area's limited lacustrine outcrops and shoreline features.

The Fernley sub basin lies between the Truckee River - Pyramid Lake basin and the much larger Carson Sink basin. Lake levels in the basin are controlled by the elevation of three sills: Darwin Pass (elevation 1238 m) which separates it from the Carson Sink; Fernley Sill (1265 m) which separates the basin from the Truckee -Pyramid Lake basin,;and an un-named sill (~ 1300 m) to the NE between the Fernley and Humbolt basins.

RESULTS

Fieldwork has involved detailed geologic mapping of late Quaternary sediments and lacustrine features combined with precise control of elevations (using an electronic distance meter and benchmarks around the basin for control) and descriptions of sediments for each of the major sedimentary units. Materials suitable for ^{14}C dating have been identified and samples of tephra have been collected to provide age-control for some of the map units.

Lake shorelines

Seven detailed shoreline profiles of the Fernley Sink, mapped from the sink's playa to the highest Lake Lahontan erosional shoreline and spaced throughout the sink, reveal a prominent shoreline at 1265 meters ($\pm$1 m) above sea level which corresponds with the elevation of the Fernley Pass Sill. The most probable explanation for this correspondence is a physical control of Lake Lahontan levels in the Fernley Sink with a corresponding western Great Basin paleoclimatic regime and lake hydrology.

In theory, rivers filled the Carson and Fernley Sinks to 1265 m where Lake Lahontan ceased to rise due to spill over the Fernley Pass Sill and into the adjoining Pyramid Lake sub-basin with subsequent spill into the adjoining Smoke Creek-Black Rock Desert sub-basin. This lake still-stand produced the

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prominent 1265 m erosional shoreline in the Fernley Sink. Only after these sub-basins of Lake Lahontan reached an elevation of the Fernley Pass Sill, could lake levels continue their previous rise.

Due to a lack of age control typical of Lake Lahontan features, the exact age of formation of the 1265 m shoreline is unknown. Also, it is not known whether the shoreline represents one or several lake still-stands. However, recent studies utilizing Pyramid Lake tufa deposits and their strontium isotope ratios have concluded that during Sehoo Lake Lahontan (oxygen isotope STAGE 2) water primarily or exclusively flowed from the Pyramid Lake sub-basin to the Fernley Sink (Benson, 1994; Benson & Peterman, 1995; Benson et al., 1995). This lake hydrology was made possible by the diversion of the Humboldt River from the Carson Sink to the Smoke Creek-Black Rock Desert. Therefore, in light of this data, it is likely that the 1265 m shoreline represents Lake Lahontan still-stands and a corresponding lake hydrology that is Eetza Lake Lahontan (oxygen isotope STAGE 6 and/or 8) in age.

We conclude that during an extended portion of the filling of Eetza Lake Lahontan, the Humboldt and Carson Rivers flowed to the Carson Sink and not the Smoke Creek-Black Rock Desert. In addition, the Walker River could have contributed waters to the Carson Sink by diversion through the Adrian Pass or by Walker Lake over-flow. These rivers filled the Carson Sink and the adjoining Fernley Sink and then spilled over the Fernley Pass Sill to finish filling the Pyramid Lake and Smoke Creek-Black Rock Desert sub-basins thereby creating an extensive lake still-stand and producing the large 1265 m erosional shoreline in the Fernley Sink. Unfortunately, only the shoreline's likely relative age is known and it remains unknown if the 1265 m still-stand was one long term event or several events.

As proposed by Benson et al. 1995, it is not necessary to invoke large-scale changes in Great Basin paleoclimates in order to produce major changes in lake hydrology like those proposed here for Eetza Lake Lahontan. Both the Humboldt River and, to a lesser extent, the Walker River have been shown to be quite capable of paleo-diversions and can greatly impact Lake Lahontan hydrology. Therefore, it's possible that a similar paleoclimatic regime was operating during both Sehoo and Eetza Lake Lahontan.

Stratigarphy of lacustrine deposits

Two relatively large dissected outcrops were chosen for decriptions of the stratigraphy and sedimentolgy of the lacustrine deposits. The first outcrop (The Sand Ramp) is composed of numerous fine beds of chiefly flat lying lacustrine sands and silts and is approximately 14 m thick (fig. 2). The outcrop rests conformably atop a gravel-rich beach deposit and contains several thick gastropod shell beds which proved datable by 14C. Shells collected from near the outcrop base, center and top were examined under a scanning electron microscope and found to be free of secondary calcite. They were then dated using AMS Radiocarbon analysis and found to range in age from 13,100 to 12,800 radiocarbon years B.P. ($\pm$ 60 years) from base to top of the section (details of the AMS dates are given in Table 1).

Table 1: AMS 14C dates from Sand Ramp Section

Sample	Lab number	Age (B.P.)	1 sigma error
HSM-SR-30	Beta-85320	12,800	60
HSM-SR-10	Beta-85130	12,950	60
HSM-SR-20	Beta-85131	13,130	60

These data indicate that the outcrop was deposited over a relatively short period of time during the rapid final desication of maximum Sehoo Lake Lahontan. The outcrop ranges in elevation from ~1260 m to ~1275 m. These ages and elevations correspond well with Benson et al. 1995 Sehoo Lake Lahontan lake level curve and its corresponding paleoclimatic interpretations which are based on Pyramid Lake tufa deposit data and strontium isotope ratios.

The second Fernley Sink lacustrine outcrop is composed of massive lacustrine sands and silts, bedded gravels, and a package of finely bedded Tertiary diatomasous rock. Shell beds are relatively rare in this deposit but two were located in the coarser sediment packages that are believed to be Eetza Lake Lahontan in age due to their stratigraphic position and lithology. Both samples were examined under scanning electron microscope and both were rejected for dating as they contained large amounts of secondary calcite. This is most probably because they are Eetza Lakes Lahontan in age and were recrystallized by their immersion in Sehoo Lake Lahontan.

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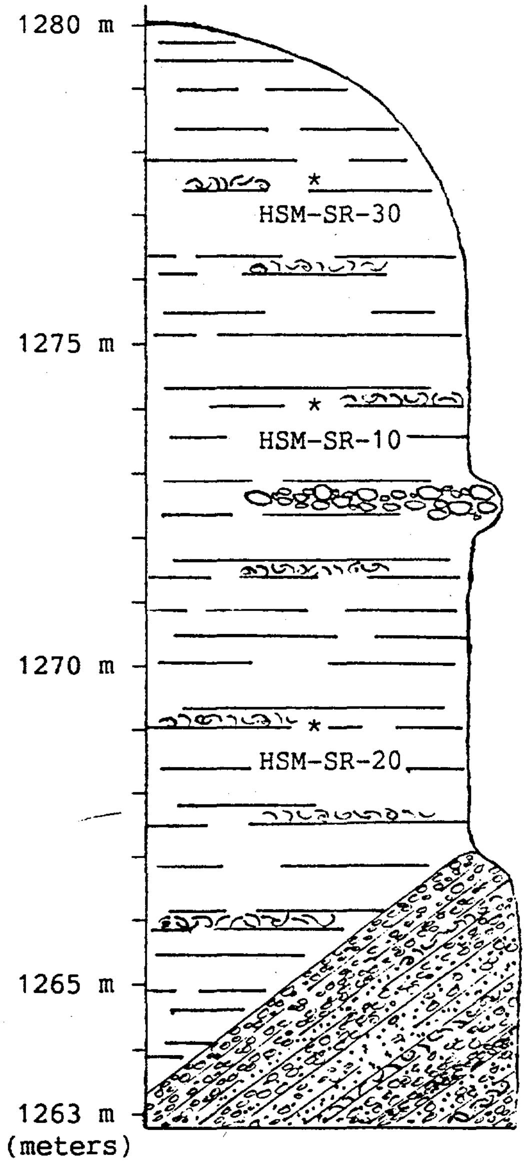
Columnar Section, "Sand-Ramp Site", Fernley Sink, Nevada

Elevation	Columnar Section	Description



<- Eroded top of section.

Bedded lacustrine coarse to very fine sands. Horizontal bedding, 3mm to 35 cm thick, and poorly to well cemented. Numerous interbedded lacustrine shells chiefly consisting of the gastropod *Vortesifex*.

Coarse gravel to boulder lag. Horizontal lag, 10 to 25 cm thick, well cemented, and consisting of sub-angular to rounded clasts.

Coarse lacustrine beach deposit. Consists primarily of coarse rounded gravels with some sand and shell beds. Beds are 4 mm to 6 cm thick, dip from 20° to 40°, and are moderately to well cemented.

* = AMS Radiocarbon Shell Sample Locations

<u>Results of Shell Dating:</u>

Sample HSM-SR-30 = 12,800 +/- 60 yr. BP
Sample HSM-SR-10 = 12,950 +/- 60 yr. BP
Sample HSM-SR-20 = 13,130 +/- 60 yr. BP

Influence of sediment supply and climate change on Late Quaternary eolian accumulation patterns in the Mojave Desert.

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Introduction

Accumulation of aeolian deposits requires: (1) a source of sediment, (2) sufficient wind energy to transport that sediment, and (3) conditions that promote accumulation in the depositional zone. Most aeolian sand in arid regions occurs in relation to well defined regional- and local-scale sediment transport systems in which sand is moved by wind from source areas (e.g. distal fluvial deposits) via transport pathways to depositional sinks (dunefields, sand seas). Changes in climate may impact eolian sediment transport systems via changes in sediment supply and sediment mobility. Sediment supply may be affected by variations in flood magnitude and frequency, river sediment load, and lake levels that affect sediment source areas. Climatic changes impact sediment mobility via changes in the magnitude and frequency of wind capable of transporting sediment, vegetation cover, and soil moisture.

In the Mojave Desert of southern California, well-defined regional- and local-scale sand transport corridors extend from source areas in the western and central Mojave toward depositional sinks to the east and south (Zimbelman et al., 1995). Evidence indicating that eolian activity has been both more extensive and more intense than it is at present occurs throughout the region (e.g. Smith, 1967; Tchakerian, 1991) and includes: dormant vegetation-stabilized dune systems and sand sheets, relict sand ramps, and eolian sand deposits in alluvial fan sequences.

This paper documents the response of a major eolian sediment transport system in the east-central Mojave Desert: that which feeds the Kelso Dune field. This is a well-constrained system that lies in a region for which other palaeoclimatic and paleohydrologic information is available. Information from geomorphic, stratigraphic, and sedimentologic studies of aeolian deposits and landforms is combined with luminescence dating of these deposits to develop a chronology of periods of aeolian deposition. This is then compared with the proxy record of climatic change in the region to understand the conditions that favor aeolian accumulation in the region and to develop a process-response model for aeolian systems.

The Kelso aeolian sediment transport system

The Kelso aeolian sediment transport system (Fig. 1) extends for some 60 km eastwards from the fan delta of the Mojave River as it exits the Afton Canyon to the Kelso Dunes. The Mojave River is considered to be the principal source for sediment for Kelso Dunes, although local sources (e.g. the washes that drain the Granite Mountains and the Cima Dome) may also be important contributors. The Mojave River heads in the San Bernardino Mountains, a tectonically active area of granitic rocks. Following heavy winter rainfall, the Mojave River may flow through the Afton Canyon to the Mojave River sink and the adjacent east Cronese Basin or as far as Silver Lake (Enzel et al., 1992). During intervals of the late Pleistocene and early Holocene, the area of Soda Lake and Silver Lake was occupied by a shallow lake (Lake Mojave) (Brown et al., 1990). Additional eolian sand may be contributed by sand streams from the Mannix Basin to the west, which was also the site of a late Pleistocene paleolake. The area of the Mojave River sink is today characterized by gravel-size deflation lags, coppice dunes, and small climbing and falling dunes (Crucero Hills). To the east lie a series of 2 - 5 m-high active crescentic dunes and undulating sand sheets

Sand is transported east from the source zone through the Devils Playground, a 10 km-wide corridor between the Old Dad and Bristol Mountains, to the depositional sink of the Kelso dunefield. In the western part of the Devils Playground are active crescentic dunes up to 5 m high and climbing and falling dunes draped over the Devils Playground Hills north of Balch. The eastern part of the Devils Playground is, by contrast, characterized by sand sheets that are stabilized by vegetation (creosote bush, galleta grass, white bursage). A series of sand ramps mantle the Old Dad Mountains on the northeast side of the Devils Playground.

Kelso Dunes is the major depositional sink for this system. The dunefield occupies an area of 100 km^2 on the piedmont slopes of the Granite and Providence Mountains and represents a sand accumulation of approximately 1 km^3 (Lancaster, 1993; Sharp, 1966). The dune field consists of a 40 km^2 area of active dunes surrounded on their west, north, and east sides by a 60 km^2 area of low vegetation-stabilized dunes (Fig. 2). The dunes are composed of sand that is 50 - 80 % quartz, as much as 50% plagioclase and potassium feldspar, and up to 1 - 2 % granite fragments in places. Heavy minerals are dominated by amphibole and magnetite.

Evidence indicating that aeolian activity has been both more extensive and more intense than it is at present occurs throughout the Kelso aeolian sediment transport system (Fig. 3). There are vegetation-stabilized dunes and sand sheets at Kelso dunefield and in the eastern Devils Playground. Sand ramps on the flanks of the Cronese, Kelso, Cowhole, Bristol, and Old Dad Mountains represent sites of long-continued aeolian accumulation (Lancaster and Tchakerian, in press). Many sand ramps are capped by a mantle of gravel to boulder colluvium and in some cases a well developed caliche palaeosol, and have subsequently been trenched by ephemeral streams. In addition, aeolian sand occurs in alluvial fan sequences east of Kelso dunes (Clarke, 1994; McDonald and McFadden, 1994) . Other evidence for past aeolian activity includes aeolian sand mantles on beach ridges at Silver Lake (Wells and McFadden, 1987) and ventifacts covered by desert varnish (Dorn et al., 1989).

Methodology

Three main areas were studied to determine the history and characteristics of aeolian accumulation in the region: (1) the Cronese Basin, representing conditions adjacent to the source zone; (2) the Devils Playground (the transport corridor), and (3) Kelso Dunes and adjacent areas (the sediment sink). At each location, geomorphic and stratigraphic relations between aeolian units were determined. These served to locate sample sites for luminescence dating.

Luminescence Dating

The single aliquot IRSL method (Duller and Wintle, 1991) was applied to 180-212 µm potassium-rich feldspar separates from sands at the three main study areas. The sample preparation and measurement were carried out under subdued, orange lighting. The sands were sieved to obtain the 180-212 µm fraction, which was the modal grain size in the majority of samples. This fraction was washed in 0.003M HCl to remove carbonates and 30% H_2O_2 to remove organics. The potassium-rich feldspar fraction was separated from this sand by settling in sodium polytungstate solution at a specific gravity of 2.62 to separate the quartz-rich fraction from the lighter feldspars, then re-settling with a gravity of 2.58. The fraction which floated at 2.58 (potassium-rich feldspar) was then washed and dried before being deposited on aluminum discs using silicon oil. For luminescence measurement, 6-18 aluminum discs containing about 15 mg of separate were used in equivalent dose (ED) determination, where IRSL age = ED/Dose rate. Good agreement has been shown between calibrated radiocarbon dates and IRSL dates on dune sand bracketing the Mazama Ash at Skull Creek Dunes, Oregon (Clarke, 1994) indicating that the single aliquot additive dose IRSL method appears to work well on sands of Holocene age.

IRSL measurements were carried out in an automated Risø TL-OSL Reader System with a detection system consisting of an EMI 9635QA photomultiplier tube and a combination of Schott BG-39 and Corning 7-59 glass filters, with the addition of a neutral density filter (nd 1.0) used for the older, and thus brighter, East Cronese Basin samples. Stimulation was achieved using a 0.5 second 'short shine' from an array of 31 infra-red diodes emitting at a wavelength of 88080 nm. Single aliquots were exposed to beta radiation from a $^{90}Sr/^{90}Y$ source within the Risø Reader with a strength of 1.50Gymin^{-1}.

Results

The Cronese Basin

The Cronese Basins (Fig. 4) are located downstream of the Afton Canyon, north of the Mojave River Wash. Floodwaters reach the East Cronese Basin directly from the Mojave River and a narrow spillway connects the East Cronese Basin to the West Cronese Basin. Water flows between the two basins once the lake level in the East Cronese Basin has reached a minimum elevation of two meters (Brown, 1989). During the Late Pleistocene, the West Cronese Basin may have drained into the East Cronese Basin, which then drained over a bedrock sill into the Soda Lake basin. During the Holocene, a drainage reversal occurred between the East Cronese and Soda Lake basins because of aggradation of sediment in the Mojave River fan delta and the East Cronese Basin (Meek, 1990). Shorelines occur at elevations of 340, 334.5, 332.9 - 331 m, 330.2 - 326.8 m.

Aeolian deposits in the Cronese Basins consist of climbing and falling dunes, sand ramps, and low dunefields (Fig. 5). Their stratigraphy is summarized in Fig. 6. The source of sand is believed to be the adjacent Cronese Lake basins, but the volume of eolian sands in the area may indicate an additional source in the paleolake Mannix basin to the west. The most prominent of the dunes is the Cat Dune, a falling dune that fills a ravine between elevations of 370 and 670 m on the east side of the Cronese Mountains (Evans, 1961). The dune is indurated and its surface is covered by a thin angular gravel talus. At the base of the main dune is a smaller talus-covered falling dune informally named the "Kitten Dune". Extensive sand ramps mantle the western slopes of the Cronese Mountains, where there are also a series of low dune ridges.

Sediments of the Cat Dune consist of medium to fine moderately- to well-sorted eolian sand with an admixture of grus and angular gravel to cobble-sized talus derived from adjacent hill slopes. In the lower units, the talus clasts are slightly to moderately weathered and have caliche rinds on their lower faces. Talus in the upper part of the section is angular and unweathered. A loose gravel- to small boulder-sized talus covers the indurated surface of the dune. The composition of the Cat Dune sediments is very similar to those of Unit Qe2 of Brown, (1989), which forms a mantle at the eastern base of the Cronese Mountains. An IRSL age of 23,370 ± 5, 480 yr. was obtained from the base of the Cat Dune. Aeolian sand from unit Qe2 gave IRSL ages of 23,350 ± 1,400 to 18,850 ± 1,250 yr. (Clarke et al., in press).

The Kitten Dune is comprised of 3 main units. Unit A consists of moderately well sorted medium sand with 5% highly weathered grus and weak caliche development. Unit B has a matrix of moderately well sorted eolian sand of a similar composition to Unit A and up to 10% grus in which 5 to 20 cm boulders of highly weathered granite are embedded. There is moderate development of caliche rinds on all faces of the boulders. A sharp boundary separates the upper 3.5 m of the section (Unit C), which consists of massive to friable well sorted red brown medium eolian sand with 5 - 10 % granule-sized grus. This sand ramp is capped by a moderately developed pavement of angular, weakly varnished cobbles and small boulders. IRSL ages for the Kitten Dune are 17,010 ± 970 for unit A and 8,220 ± 970 yr. for unit C.

Aeolian deposits in the West Cronese Basin comprise yardangs, dune ridges, and sand ramps (Fig. 7). The sand ramps mantle the west and northwest facing slopes of the Cronese

Mountains. Those on the southern part of the range are heavily dissected. All ramps are covered by cobble- to boulder sized angular talus. The northern sand ramps (WCS) consist of three stratigraphic units. At the base of the exposed section, Unit A consists of well-indurated massive structureless to very weakly horizontally laminated red-brown sand with a caliche cemented zone in upper 10-20 cm (abundant rhizoliths in places). The upper surface of this unit is in erosional contact with the overlying units and is covered in many places by an angular cobble to 40 cm boulder colluvium. Unit B consists of up to 8 m of horizontally bedded and laminated coarse to medium buff sand. There is slight reddening (? paleosol), and abundant white caliche along laminae at the top of this unit. Unit A is composed of 2 m of friable, slightly indurated pale brown structureless sand with a thin cover of angular gravel-sized colluvium. Lapping onto the exposed surfaces of this ramp are three crescentic dune ridges (Unit D) that are composed of slightly indurated, friable, very well laminated pale brown medium and coarse sand with beds dipping at ± 10° to 120 - 130°.

Infra-red stimulated luminescence ages for the WCS sand ramp range from 1,470 ± 190 yr. to 2,230 ± 190 yr. for unit C and 5.44 ± 740 to 6,780 ± 920 yr. for unit B. Dune ridge 1 (nearest the playa) formed between 755 ± 100 and 390 ± 80 yr. The base of dune ridge 2 is 2,000 ± 115 yr. old (approximately equivalent to unit C), whereas the upper part has an age of 200 ± 25 yr. The laminated sands of dune ridge 3 are 155 + 50 to 215 ± 40 yr. old.

The southern sand ramp (A) consists of a 7 m thickness of massive, friable reddish brown to buff medium sand with common grus and concentrations of angular cobble to boulder clasts at depths of 2 m and 6 m. At 2 m depth is a weak paleosol. IRSL ages range from 1,680 ± 220 yr. at 1.5 m depth to 5,620 ± 760 yr. at 3.1 m.

Adjacent to this ramp are falling dunes (B, C) that are comprised of up to 8 m of pale brown sand with a modal grain size of 1.5 to 2.25 phi, cut by a 0.5 to 1 m gravel-filled channel. IRSL ages for these aeolian units are 1,600 ± 220 yr. for the sand above the channel and 11,810 ± 1,590 and 12,270 ± 1,650 yr. for the lower units.

The yardangs occur at the northwest tip of the Cronese Mountains. They are approximately 1 m high with long axes oriented SW-NE and are formed in horizontally-stratified coarse yellow-red aeolian sands lying on a colluvial gravel surface. An IRSL age for the yardang material is 250 ± 75 yr., while a radiocarbon date (Beta-84635) from charcoal exposed at the base of the yardangs gave an calibrated age of 1425 AD.

A record of aeolian accumulation from Hanks Mountain Sand ramp, located southeast of Baker, CA is indicative of conditions in the Soda Lake - Silver Lake source area. This ramp comprises 1 m of medium to fine sand with a 2 m- thick calrete-cemented and colluvium unit and a possible paleosol, underlain by medium sand. Sand from the upper part of this ramp has IRSL ages of 19,740 ± 2,660 yr. to 20,220 ± 2,730, whereas sand from below the calcrete and colluvium has an IRSL age of 30,630 ± 4,130 yr.

The Devils Playground

Aeolian deposits in the Devils Playground comprise active crescentic dunes and falling dunes to the west and vegetation-stabilized sand sheets and sand ramps to the east (Fig. 8). Active dunes consist of pale brown to buff moderately well-sorted medium sand. The sand sheets typically consist of 1.5 to 2 m (locally as much as 4 m) of grey brown fine sand that overlies fine gravel to granules that is partially cemented by a powdery caliche. Sand ramps mantle the Old Dad Mountains on the northeast side of the valley as well as the northwest parts of the Bristol Mountains on the southern side. Their stratigraphy is summarized in Fig. 9. The studied sand ramp in the Old Dad Mountains is a falling ramp on the northeast slopes of the mountain. The upper part of the ramp consists of friable medium to fine moderately well to well-sorted sand with a cover of boulder- to cobble-sized talus. At a depth of 1 m is a layer of 15 - 20 cm clasts which are underlain by a zone of massive red-brown sand that contains abundant grus. The lower part of the ramp is exposed in a stream section and consists of three main units. From the base, these comprise 1.5 m of pale brown sand with sparse grus (I) capped by a very weakly-developed paleosol, 2 m of mixed fluvial sands, gravel channels and stringers (II), capped by a well-developed argillic and in places calcic paleosol, and 2 m of fine red-brown sands with rare coarse sand grus (III). IRSL ages for the upper Old Dad Mountains ramp are 8,190 ± 730 yr. for the base of the exposed section in the upper part of the ramp, 2,600 ± 340 to 3,000 ± 240 yr., for the upper aeolian sand unit in the lower ramp (unit III) and 11,050 ± 880 yr. for the basal unit (I).

The sand ramp at Balch is a composite of aeolian and fluvial deposits. The upper part of the ramp consists of 5 m of grey brown sand, 8 m of fluvial sand with gravel stringers and 1 - 1.5 m deep gravel-filled channels and 2 m of fine grey brown aeolian sand, capped by a well-developed caliche palaeosol. IRSL ages for the aeolian sand units are 15,150 ± 2,040 yr. for the upper unit and 15,570 ± 2,100 yr. for the lower. The topgraphically lower, but stratigraphically higher, part of the ramp is comprised of 4 m of fine grey brown sand that contains varying amounts of grus. It overlies a angular granitic gravel unit and is also capped by a angular gravel stratum. The upper part of this ramp has an IRSL age of 2,060 ± 280 yr.

Kelso Dunes

The "core" of the Kelso dune field consists of 3 large WSW-ENE trending complex linear ridges up to 160 m high and 1900-2000 m apart. On the west and northwest sides of the core of the dune field lie degraded, vegetated straight-crested and barchanoid crescentic ridges up to 15 m high and linear dunes up to 5 m high . The eastern section of the dune field consists of a

1 - 5 m thickness of sand formed into of five smaller areas of dunes, each cut by washes and separated from the "core" area by Cottonwood Wash, which is incised into eolian and fluvial deposits by as much as 20 m. To the north is a smaller version of the main area of active dunes that consists of three linear ridges up to 50 m high with superimposed 2-4 m high crescentic dunes. Areas of low, partially active, linear and crescentic ridges, as well as extensive areas of sand sheets occur on the northeast and southern edges of this part the dune field. East of Winston Wash are areas of vegetated and degraded crescentic ridges with a height of 8 - 10 m.

A characteristic feature of Kelso Dunes is the juxtaposition of areas of dunes of distinctly different morphological type, size and spacing and alignment. A total of 14 dune units can be identified on aerial photographs of the dunefield. Geomorphic and sedimentary relations between the morphological units indicate that they are superimposed on one another, and the dune field represents in part a stacked or shingled sequence of dunes of different generations. The dune field appears to have developed by the coalescence of a series of smaller genetically-independent dune fields, each of which represents an episode of sediment input or reworking of existing dunes.

Estimates of the age of Kelso Dunes have varied widely between "several thousand years and possibly 10,000-20,000 [years]" (Sharp, 1966) to "very likely greater than 100,000 years, and quite possibly more than a million years" (Yeend et al., 1984, Smith, 1984). Because the Kelso dune field overlies, and in some cases intercalates with, alluvial fan deposits derived from the Granite and Providence Mountains, it is possible to use the ages of these alluvial fans (Wells et al., 1990) to constrain the age of the dunes. It appears that the western part of the dune field rests on fans of Early or possibly Middle Pleistocene age. Late Pleistocene fan units underlie the southern margins of this part of the dune field. A well-developed paleosol is developed on eolian sand that lies on the Granite Mountains piedmont alluvial fans south of the main dunefield. This soil appears similar to those developed on sand ramps elsewhere in the region with an age of more than 20,000 yr.

Dunes east of Cottonwood Wash appear to be much younger and mostly lie on fan surfaces of Holocene and latest Pleistocene age (Clarke, 1994; McDonald and McFadden, 1994). Unit Qe1 of McDonald and McFadden (1994) consists of thin discontinuous sand sheets that overlie alluvial fan unit Qf4 which is of Late Pleistocene age. Eolian Unit Qe2 includes much of the eastern part of the dunefield (geomorphic units I through V) and overlies fan unit Qf5 (early Holocene to latest Pleistocene). In turn, Qe2 is truncated by the late Holocene Qf6 unit.

Several key dune geomorphic units were selected for luminescence dating (Wintle et al., 1994). These included the core of active dunes (unit VI), vegetation stabilized dunes and sand sheets on the eastern margin of the dunefield (Unit II), vegetation-stabilized crescentic ridges on the northern margin of the dunefield (units IX and XII), and vegetated crescentic ridges on the southwest side of the dunes (Unit XIV). The dunes were sampled by augering to depths of 5 to 8 m. As luminescence dating provides an estimate of the time since the grains were buried, the results from dune areas that are subject to multiple periods of remobilization record the last time the sand was active. If the whole dune was reworked, it is impossible to determine when it was originally formed. The ages reported below are therefore minimum ages for the dunes.

Luminescence dates from Unit II indicate that it accumulated between 10,410 ± 890 and 3,500 ± 220 years ago. Unit VI was apparently in place by 4115 ± 335 yr. The crescentic dunes of unit XIV were formed around 1,500 yr. and dunes on the north side of the dunefield were formed, or reworked, between 800 and 400 yr.. ago. The oldest sands known are those which were deposited as sand sheets on alluvial fan surfaces as much as 5 km southeast of the present dune margins between 16,830 ± 1465 and 17,300 ± 1935 yr. ago (Clarke, 1994). The pattern of luminescence ages indicates that there is a exponential increase in the age of dune and sand sheet units from northwest to southeast, supporting the hypothesis that the dune field accumulated by stacking or shingling of successive generations of eolian units on the piedmont of the Providence and Granite Mountains.

Discussion

Periods of aeolian accumulation and dune activity

Geomorphic and stratigraphic relations, together with the IRSL ages obtained from different aeolian units enable several periods of Late Pleistocene and Holocene aeolian deposition and/or dune remobilisation to be identified. The timing and duration of these events varies between different parts of the Kelso aeolian sediment transport system (Fig. 8).

The earliest period of accumulation identified (Phase I) spans the time from 30,000 yr. (or earlier) to 15 - 17,000 yr. and comprises the Cat Dune complex, the upper part of the sand ramp at Balch, and the oldest sand sheets in the eastern part of Kelso Dunes, as well as Hanks Mountain sand ramp. The next major period of aeolian accumulation (Phase II) started around 13,000 yr. and extended to 4,000 yr. Phase II accumulation can be sub-divided into parts: Phase IIa extends from 13,000 to 8,000 yr. and comprises the bulk of the accumulation in sand ramps at the West Cronese Basin, Balch, the Old Dad Mountains; Phase IIb continues to 4,000 yr. in the Old Dad Mountains, West Cronese, and at Kelso Dunes. Phase III of aeolian accumulation is only found at West Cronese and Kelso, and spans the period from 2,000 to 1,500 yr. Likewise, Phases IV and V are restricted to these localities and span the intervals 350 - 800 yr. and 150 - 250 yr., respectively. Regional studies involving luminescence dating of periods of aeolian accumulation in sand ramps elsewhere in the Mojave (Rendell, in press) also identify two major periods of aeolian activity: 20,000 - to 30,000 and 15,000 to 7,000 yr.

Correlations with other proxy paleoclimatic data sets

Information on past hydrologic and sediment supply conditions affecting the Kelso aeolian sediment transport system is provided largely by the record of fluctuations in paleolake Mojave, which occupied the principal sediment source area at two main intervals during the late Pleistocene and Holocene. The timing of high stands of Pluvial Lake Mojave is based upon radiocarbon-dated shell and tufa from Silver and Soda Lake beach ridges (Brown, 1989; Brown et al., 1990; Ore and Warren, 1971), and organic carbon from sediment cores taken from the Silver Lake playa (Brown et al., 1990). These dates have been expressed as calibrated ages here in order to compare them with the IRSL ages presented above. The calibrated ages were obtained from the data given in Brown et al. (1990) using Mazaud *et al.* (1991) for radiocarbon ages in excess of 18,360 yr. BP and Bard *et al.* (1993) and the CALIB v3.0 program of Stuiver and Reimer (1993) for radiocarbon ages younger than 18,360 yr. BP.

The radiocarbon-dated evidence suggests an intermittent lake lasting from 24,500 to 9,700 ka with two persistent high stands from 20,900 to 19,600 yr.(Lake Mojave I) and 16,500 to 13,400 yr.(Lake Mojave II), with final desiccation at 9,700 yr.

In addition, Pluvial Lake Mannix is believed to have had three high stands during the Late Pleistocene: 33,500 to 30,500 yr., 23,500 to 20,800 and 17,600 to 16,500 yr.(Meek, 1990). The final stage of Lake Manix ended with the incision of the Afton Canyon around 16,500 yr., causing the draining of the lake, and the subsequent formation of Lake Mojave II in the Silver and Soda Lake Basins downstream (Brown et al., 1990; Meek, 1989).

Phase I of aeolian accumulation in the Kelso system therefore both predates and in some cases postdates the period of Lake Mojave I, whereas Phase II postdates Lake Mojave II. Phase IIa is directly associated with the desiccation phase of Lake Mojave II. Close inspection of the IRSL-dated record suggests that the Cat Dune and Hanks Mountain ramps are coeval with the Intermittent Lake I of Brown et al. (1990), whereas the Balch upper sand ramp and Kelso sand sheets are associated with Intermittent Lake II of Brown et al. (1990). They also lie downwind of a source area in Lake Mojave I, which probably supplied their sediments.

The Holocene record of aeolian accumulation and dune reactivation and stabilization can be compared to multiple proxy paleoclimate data sets. Phase IIb accumulation appears to be associated with a period of dry climates 6,800 - 5,060 yr. ago (Spaulding, 1991). This period of aeolian accumulation was brought to an end with stabilization of dunes at Kelso and elsewhere in the region after 4,000 yr. B.P. as a result of cooler and wetter regional climates that resulted in increased vegetation cover. The period 4,000 - 3,000 yr. ago appears to have been cooler and wetter in many parts of the southwestern U.S.A. with lowering of the woodland - desert scrub boundary (Spaulding, 1985; Spaulding et al., 1994), increased groundwater recharge in southern Nevada, and shallow lakes in Death Valley, Searles Lake, and the Silver Lake Basin (Enzel et al., 1992). The latter was probably fed by increased winter rainfall in the San Bernardino Mountains (Enzel et al., 1989). Renewed aeolian accumulation in Phases III - V was probably a response to renewed aridity. Limited paleobotanical and dendroclimatological evidence from southern California suggest that relatively dry conditions persisted at around 1450 yr. B.P. (Spaulding et al., 1994), and from 850 to 450 yr. B.P. (Fritts and Gordon, 1982). A radiocarbon-dated beach ridge with an age of 390 ± 90 yr. B.P. indicates that a permanent lake again developed in the Silver Lake basin at this time as a result of cooler and wetter conditions and increased rainfall coeval with the Little Ice Age in Europe (Enzel et al., 1992), giving rise to renewed stabilization of dunes at Kelso and elsewhere in the region and terminating Phase IV accumulation. Radiocarbon dated shells and charcoal from the Cronese Basins suggest human occupation and lacustrine conditions 390 ± 140, 560 + 110 and 570 ± 150 yr. ago (Drover, 1979). Eolian accumulation 150 - 250 years ago in the West Cronese Basin (Phase V) may therefore reflect deflation of sediment deposited by shallow water bodies in these wetter periods.

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