Neptune Field Studies, December, 2014

Eolian Depositional History
Clive Disposal Site

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Contents

1.0 Utah Field Work Energy Solutions Clive Site

1.1 December 15 to December 17, 2014

The following goals were identified for field studies at the Clive site:

1. Evaluate the modern geological and depositional setting of the Clive site.
    a. Potential for current and future eolian deposition.
2. Assess the stratigraphy of Holocene and Pleistocene lake sedimentation of Lake Bonneville and post-lake depositional processes within the Clive site.
    a. Evaluate the stratigraphic section described by Oviatt in 1985 (cited in Neptune, 2014) focusing on the presence or absence of eolian deposits in the upper part of the stratigraphic section.
    b. If eolian deposits are present, describe the eolian sediments and processes affecting the sediments; measure variations in thickness of the deposits across the site.
    c. If possible, provide sufficient replicate measurements of thickness variations of eolian deposits at multiple sites to enhance the information used in the Deep Time appendix of the Neptune report (Neptune 2014; mean, standard deviation, standard error of the mean; all used to estimate the future eolian deposition rate).
3. Assess the stratigraphic position and origin of lake gravels described in the consultant report provided to the Utah Department of Environmental Quality (*Review of Deep Time Supplemental Analysis White paper;* referred to as the SC&A White Paper in the remainder of this report).
4. Develop a conceptual model of present and future eolian depositional processes at the Clive site.
5. Respond to observations and questions in the SC&A White Paper.

2.0 Summary of Field Activities with Annotated Photographs

2.1 December 15, 2014: Reconnaissance Field Studies in the Region of the Clive Disposal Site

2.1.1 Location: quarry exposures in the southeast edge of the Grayback Hills north of Highway 80 (12-15-1 on Figure 1).

2.1.1.1 Observations:

1. Quarrying activity provides exposures of coarse gravels of volcanic conglomerate with clasts derived from local volcanic bedrock exposed at the Grayback Hills. These volcanic rocks are a distinctive lithology in the vicinity of the Clive site and crop out only within the Grayback Hills.
2. The coarse gravel deposits underlie basal laminated marl and massive marl of the main Lake Bonneville stage. The marls were deposited over and drape elongate bar/spit topography formed by the gravel deposits. Note: the term “Lake Bonneville marl” is used in this report to include the composite sedimentary sequence of lake deposits and includes transgressive-phase laminated marl, deep-water massive marl, the Bonneville flood bed, Provo marl (post-flood bed deposits) and post-Provo regressive phase marl. These stratigraphic units are described in subsequent text and figures within the report.

3. The volcanic gravels are transgressive-phase Lake Bonneville deposits and are inferred to have been deposited by high energy, longshore drift (south flowing) paralleling the north-south elongate margins of the Grayback Hills.

2.1.2 Location: dirt road paralleling the railroad tracks approximately 3 kilometers northwest of the northwest edge of the Clive disposal site (12-15-2 on Figure 1).

2.1.2.1 Observations:

1. Undisturbed modern vegetated surfaces in the general vicinity of the Clive site preserve multiple sets of surface vegetation stripes. These are sub-parallel to crescentic shaped composite features formed by interacting processes of surface erosion, deposition and vegetation development. They are elongate generally perpendicular to the low-gradient west sloping modern surface in the Clive vicinity. Ives (1942) referred to these features as "desert ripples;" other terms are "tiger bush" Wakelin-King (1999). We prefer not to use "desert ripples." While modern eolian silt is incorporated into the vegetation stripes, the silt is not redistributed by eolian processes during formation of the stripes.
2. The vegetation stripes are observed on Google Earth images throughout the region (Figure 2) and are preserved on undisturbed surfaces within the Clive disposal site.
3. Field examination of the vegetation stripes show that they are marked by cm-scale stepped topography, higher on the east (up-gradient side) and lower on the west side (Figures 3 and 4). The higher (east) slopes are eroded with sparse vegetation; the smoothed surfaces on the west (lower slope) form by deposition of fine-grained silt and clay (Figures 3 and 4). Higher density vegetation bands tend to form on the downslope parts of the ridge form from increased infiltration (Figure 3).
4. These features are inferred to form on low-gradient, stable surfaces from the combination of west-directed episodic sheet-wash runoff, differential erosion and deposition, and development of vegetation bands in downslope areas of enhanced infiltration.
5. The preserved vegetation stripes require long-term stability of modern surfaces promoting preservation of small-scale features formed by differential erosion and deposition. The long-term stability of the modern depositional surface in the region is additionally supported by the presence and preservation of fine-grained eolian silt and the extensive soil modification of the silt observed in deposits at the Clive site.

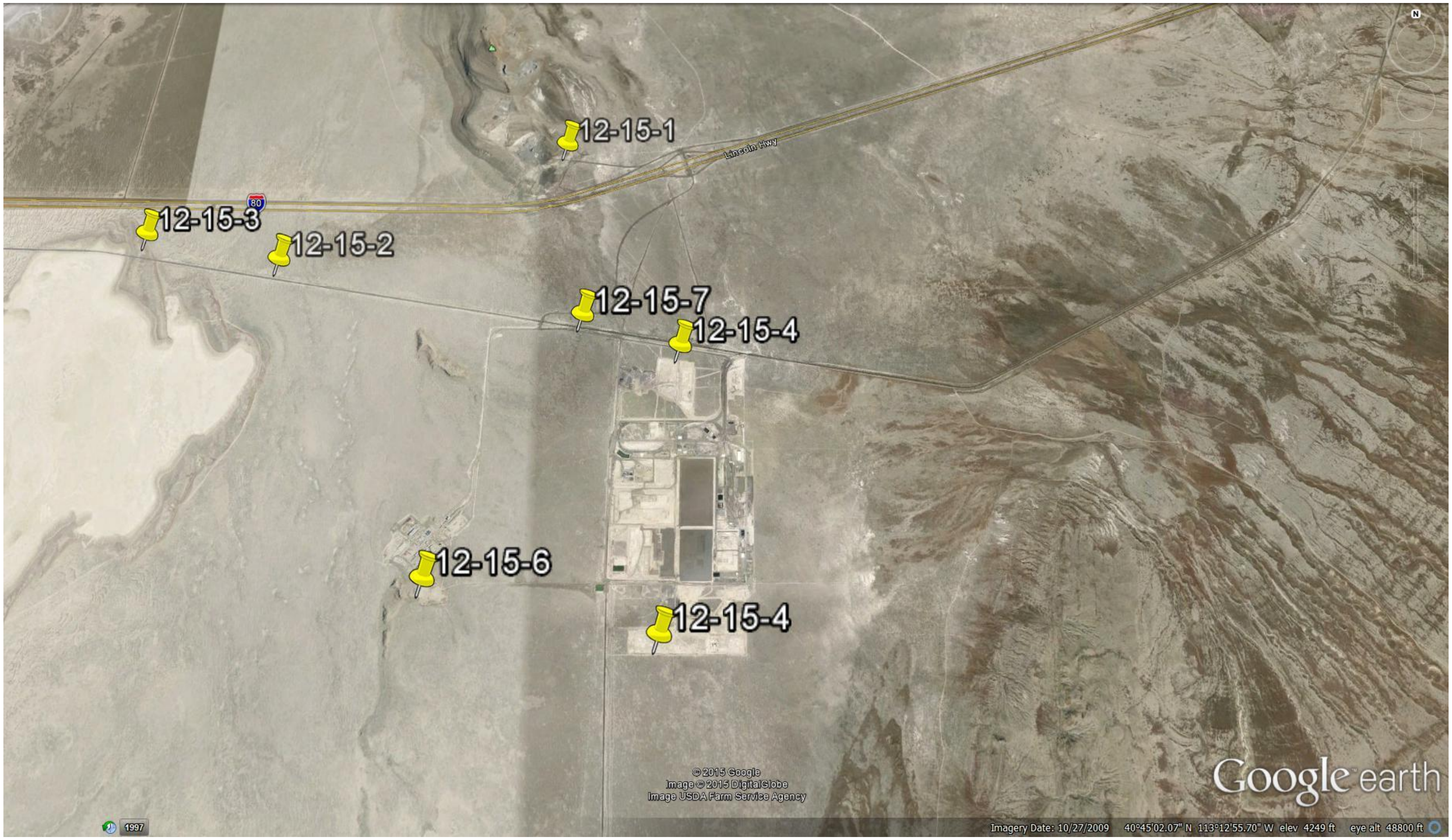

Figure 1 Google earth image (January, 2014) with the locations of field sites used to study the local stratigraphy, and the eolian depositional processes in the vicinity of the Clive disposal site.

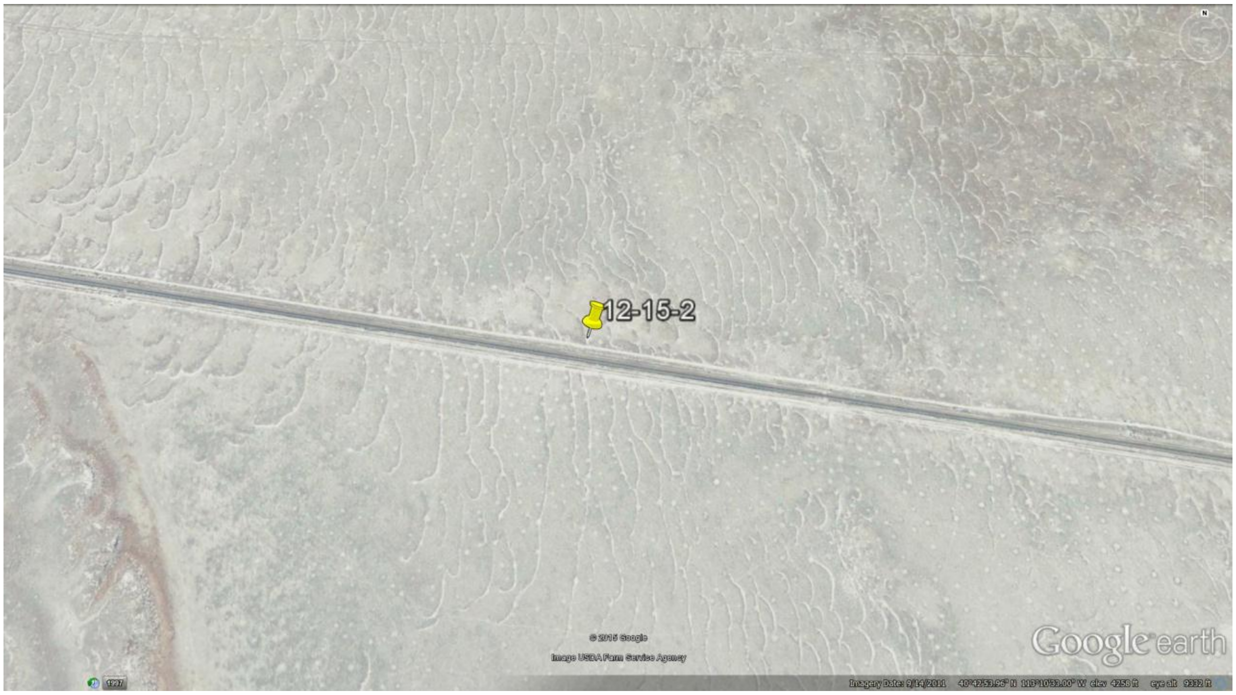

Figure 2. Google Earth image (January 2015) of sub-parallel to crescentic vegetation stripes developed on the stable low-gradient surface in the eastern Lake Bonneville area west of the Clive site (see also Ives, 1946).

Figure 3 Along-strike, north view of a vegetation stripe developed on the modern surface northwest of the Clive site. Vegetation concentrations tend to form on the lower (western) side from increased downslope infiltration.

Figure 4. View to the east across the topographically higher part of a vegetation stripe showing enhanced erosion, surface lag deposits and sparse vegetation.

2.1.3 Location: dirt road paralleling the railroad tracks six kilometers northwest of the northwest edge of the Clive disposal site (12-15-3 on Figure 1).

2.1.3.1 Observations:

1. Gypsum-dominated sands form elongate dunes paralleling the eastern edges of wet playa lake margins west of the Clive site.
2. The areas of maximum sand deposition are present where shallow groundwater provides a continuous supply of moisture (wet playas) allowing formation of surface evaporate minerals (predominantly gypsum) that are mobilized and transported by prevailing winds (for example, Reheis, 2006; Szynkiewicz et al., 2010). Active dune deposits fringing wet playa lakes are located 4.5 km west of the west margin of the Clive site.
3. There are also multiple sub-parallel sets of partially buried ridges east of the wet playa margins (Figure 5; ridges as close as 3.25 km from the west margin of the Clive site). There are multiple alternative explanations for these ridges (Note: the ridges were not evaluated in these studies). These include: 1) Secondary dune forms developed east of the wet playa margins, 2) paleodunes formed at former wet playa margins during periods of higher water table elevations, and 3) buried bedrock ridges or constructional sedimentary deposits formed during the transgressive phase of Lake Bonneville.

Figure 5. Google earth image (January, 2015) of gypsum sand dunes developed along the eastern fringes of wet playa surfaces 4.5 kilometers west of the Clive site. Note also the sets of secondary ridges east of the active dune fringes (see text for alternative explanations of these ridges).

2.1.4 Location: Fill-material quarries within the Clive disposal site (Pits 29 and 5; locations 12-15-4 and 12-15-5 on Figure 1).

2.1.4.1 Observations:

1. Discussions with personnel at the Clive site established that the quarry exposures at the Old Rollover Facility described by Oviatt in 1985 no longer exist (cited in Neptune 2014, in the *Deep Time Supplemental Analysis for the Clive DU PA*, and in the SC&A White paper).
2. New quarry sites are needed that meet two criteria:
   a. Expose the sequence of Lake Bonneville sedimentary deposits, and
   b. Preserve the modern depositional surface and sedimentary (eolian) deposits directly beneath this surface.
3. Two quarry sites were identified that meet these criteria. These sites include Pit 29 and Pit 5, located respectively, at the north and south edges of the Clive site.
4. The two quarry sites were briefly examined and eolian silts were identified at both sites immediately below the modern vegetated surface.

2.1.5 Location: Quarry site located 2.1 km west of the southwest edge of the Clive site (12-15-6 on Figure 1).

2.1.5.1 Observations:

1. Coarse gravel deposits overlie local bedrock exposures and underlie the Lake Bonneville sedimentary deposits 2 km west of the Clive site.
2. These gravels are stratigraphically equivalent to the gravels described at the southeast end of the Grayback Hills (Location 12-15-1 on Figure 1).

2.1.6 Location: One-half km west of the northwest edge of the Clive site, north and south of Deseret Well road (12-15-7 on Figure 1).

2.1.6.1 Observations:

1. Road-cut exposures (south side of road) and surface exposures north and south of the road are upheld by low ridges of volcanic conglomerate and coarse sands overlain by eolian sand and silt that drape the ridges and form eroded and vegetated dune forms (Figure 1; Figure 5).
2. The ridges are upheld by north-south elongate spits and barrier bars of lake sediments that are laterally equivalent to the coarse volcanic conglomerate observed at the Grayback Hills; they are assumed to be stratigraphically beneath the transgressive Lake Bonneville deposits (this stratigraphic position was subsequently confirmed in road-cut exposures along Highway 10).
3. The subdued ridge topography upheld by gravel and sand deposits of transgressive-phase Lake Bonneville gravel deposits near and north of location 12-15-7 (Figure 1) may have been miss-identified in previous studies as shorelines of Lake Gilbert (Currey, 1982).
4. These dune deposits confirm the past operation of eolian processes including saltation/bedload deposition within 0.5 km of the Clive site.

2.1.7 Location: Knolls Special Recreation Management Area, south of Highway 80

2.1.7.1 Observations:

1. Active gypsum sand dunes located approximately 13.5 km west of the Clive site.
2. Dunes are formed of sand and silt particles of gypsum crystals, ooids, and siliciclastic material (Eardley, 1938; 1962).
3. These sand deposits with local dune-forms are associated with wet playa areas along much of the eastern edge of the Great Salt Lake Desert both south and north of Highway 80 (Eardley, 1962) with the current largest and most active dune field located about 20 km southwest of the Clive site (Jewell and Nicoll, 2011).
4. The Clive site is within a region of significant eolian activity. The expected primary mode of eolian deposition at the Clive site is deposition of fine-grained silt from suspension fallout during episodic wind storms. Exceptionally strong surface winds could potentially transport sand-sized material by saltation; fine-grained sand associated with surface dunes was identified in surficial deposits as close as 0.5 km of the boundaries of the Clive site.

Figure 6. Eolian sand-mantling transgressive-phase Lake Bonneville volcanic conglomerate and sand deposits 0.5 km west of the Clive site. The low ridges in the foreground and background are upheld by sand and silt deposits draped over the pre-existing topographic features.

Figure 7. Gypsum sand accumulations 14 km west of the Clive site at the Knolls Special Recreation Management Area

3.0 December 16, 2014: Documentation of the Stratigraphy and Thickness Measurements of the Upper Eolian Section at Pit 29, and Pit 5 at the Clive Disposal Site

The stratigraphy of the Lake Bonneville sedimentary deposits at the Clive site includes, in addition to a Lake Bonneville sequence of deposits, pre-and post-Lake Bonneville lacustrine sediments, and interbedded subaerial soil and eolian deposits. These deposits were examined in a series of 9 excavated sections at Pit 29 (5 measured sections) and Pit 5 (4 measured sections) at the Clive site. The locations of the studied trenches are shown on Figure 8. Construction equipment was used to cut fresh exposures in quarry walls at Pit 29; one excavation trench in the northwest quarry wall of Pit 29 (Pit 29-5) was expanded to expose the pre-Bonneville stratigraphic section. The quarry walls in Pit 5 were cleaned by hand using picks and shovels to freshly expose the upper part of the Lake Bonneville stratigraphic section.

The primary purpose for measurement of stratigraphic sections in the quarry walls is to document the nature, thickness, and thickness variations of eolian sediments at the upper part of the sedimentary section across the Clive site.

Figure 8. Locations of measured sections of eolian silt at the Clive Disposal Site.

3.1 Pit 29

The near-surface sedimentary sequence was examined in five freshly excavated exposures in the north-central and west-central walls of Pit 29 (Figures 9 and 10). The quarry walls expose 3-4 meters of lake sediments and eolian deposits. Stratigraphic units in a representative excavation trench are shown in Figure 11.

The focus of our field studies was on identification and measurement of the thickness of eolian silt at the top of the stratigraphic section (Figure 11). These deposits are composed of fine-grained silt reddened by secondary processes of soil formation with internal platy structure from clay-soil formation. The degree of soil development in the eolian silt is gradational through the deposits indicating soil formation contemporaneous with eolian deposition; well-developed soil horizons are not superimposed on the upper part of the eolian section. This requires long-term maintenance of stable surfaces to allow continuing operation of soil-forming processes and relatively low depositional rates of eolian sediments. The predominance of fine-grained silt in the eolian deposits is consistent with deposition by suspension fall-out; conspicuous layers of cross-bedded sand associated with saltation deposition are not observed in the deposits.

Figure 9. Google earth image (Jan 2015) of trench locations in Pit 29.

Figure 10. Excavation sites in the northeast part of Pit 29. The irregular upper deposits (above the dashed white line) are spoil piles from the quarry construction.

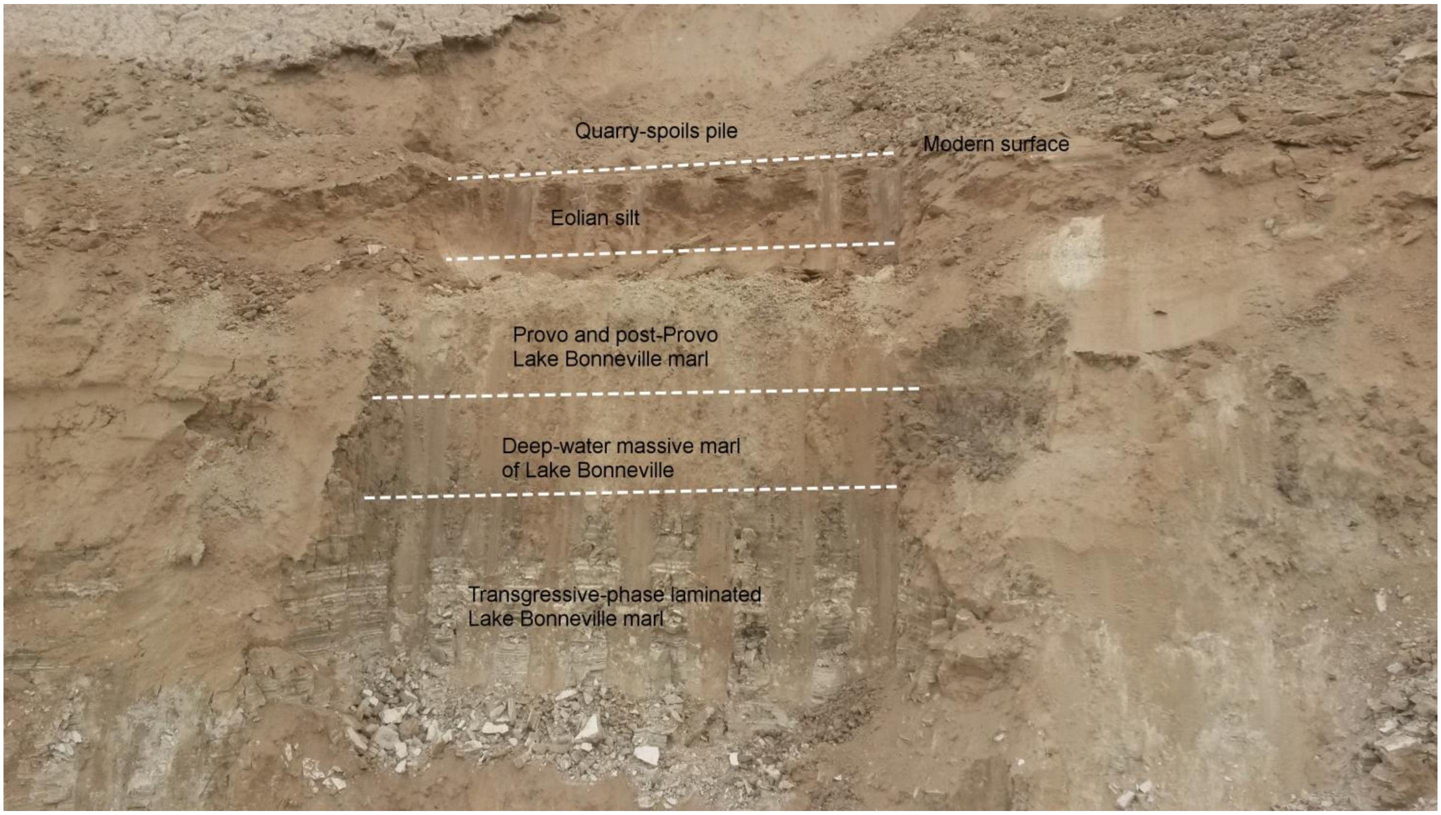

Figure 11. Lake Bonneville sedimentary deposits and eolian silt in trench Clive 29-3.

The basal contact for the eolian deposits is not an abrupt geologic contact — it is a gradational contact that cannot be precisely identified in the field. For these studies, the field-identified contact is located stratigraphically at the first appearance of significant quantities of silt in the sedimentary deposits. This contact coincides with a transitional color change between a light-red silt/marl mix and an underlying white transgressive marl (Figure 12; the approximate middle of the pick handle). Upward in the section (Figure 12), the eolian interval transitions to a laminated silt with no marl constituents (dark red-interval at the top of the pick handle).

There are two permissible alternative interpretations of the basal contact of the eolian silt. The field-based, first alternative places the base of the eolian sediments at the transition to the light-red silt/marl mix. As Lake Bonneville regressed below the elevation of the Clive site, there would have been a long period of surface exposure of the regressive marl (white deposits at the base of the pick in Figure 12). The gradational deposits at the field contact interface may have formed from a combination of episodic deposition of eolian silt that become intermixed by surface-sheet wash with the underlying white marl exposed at the dry lake surface. These reworked deposits would be equivalent to the modern sheet-wash reworking of surface deposits associated with the described vegetation stripes. Eventually, there was sufficient eolian deposition to isolate the lake muds/marl from surface reworking and subsequent deposition was entirely silt and reworked silt (transition to the dark red silt at the top of the pick handle of Figure 12).

Figure 12. Upper soil-modified eolian silt in Clive 29-3. Basal contact of the silt is approximately located at the middle of the pick handle. It is a gradational contact between eolian silt intermixed with regressive Lake Bonneville marl (bottom of the pick handle).

The white marl, the light red silt/marl mix, and the dark-red eolian silt were all subsequently altered/overprinted by continuing soil-forming processes that has partially obscured the sedimentary features and contract relations of the deposits.

The second alternative was developed after completion of laboratory studies of samples collected from Pit 5 (excavation Clive 5-5a; see section 3.2). Ostracodes and ostracode fragments were found as high as 20 cm above the base of the light-red interval identified in Figure 12. Ostracodes are delicate fossils, so their presence, even as fragments, indicates that soil-forming processes have not completely disrupted the parent material (marl in this case). In addition to oxidation, which has reddened the marl, fine (eolian) silt has probably been translocated from higher in the profile into the spaces between the fragments of weathered marl in the light red interval. Under this interpretation, the basal contact of the eolian silt would be placed at the bottom of the dark red silt (top of the pick handle in Figure 12) where pure eolian silt is present and there is no weathered marl.

The advantages of alternative one are first, the light red-white contact can be consistently identified in the field, and second, the first appearance of silt in the sedimentary sequence is used to estimate the thickness of the eolian blanket. The disadvantage of alternative one is that the silt in the light-red interval could be the result of soil-forming processes rather than direct eolian deposition (more-extensive field and laboratory work would be required to resolve this question). Alternative one gives ***maximum*** estimates of the thickness of the eolian silt. The advantage of alternative two is that the dark-red silt contact marks the point where deposition of eolian silt overwhelmed the soil-forming effects and thus may provide a more physically realistic location of the start of significant eolian deposition. The disadvantage of this interpretation is that it is difficult to identify the dark-red/light-red contact in the field – this contact was not recognized until completion of the ostracode studies and careful examination of photographs after completion of field work. The second alternative ignores the translocated silt in the light-red interval and gives ***minimum*** thickness estimates for the eolian silt.

The implications of the two alternative approaches for identifying the basal contact for the eolian silt and estimating eolian depositional rates at the Clive site are discussed in Section 5.0.

The uppermost contact of the eolian silt is the modern vegetated surface and it is mostly covered in Pit 29 by spoil materials from quarrying activity (Figure 10). This surface was identified in the trench excavations by a combination of leveling and projecting the undisturbed upper surface into the quarry face, by identifying buried modern vegetation, and/or by excavating the spoil pile to locate the contact between unconsolidated spoil deposits and the partially indurated, soil-modified upper surface. Uncertainty is assigned to the location of the upper contact (see Table 1).

The east wall of the northwest Pit 29 quarry exposes lenses of coarse volcanic conglomerate (Figures 13 and 14). These conglomerates underlie the laminated marl deposits of Lake Bonneville and are distal facies of the transgressive volcanic conglomerates described at multiple locations (clast source surface exposures of volcanic rocks at the Grayback Hills), identified deposits of transgressive early Lake Bonneville at locations 12-15-1, 12-15-6, and 12-15-7 on Figure 1). These exposures demonstrate that longshore drift during the early phases of development of Lake Bonneville deposited local lenses of volcanic conglomerate at the Clive site. These volcanic conglomerates are correlated with the gravel beds described in Attachment A of the August 13, 2014 memorandum to Helge Gabert from Loren Morton (see photos 1 through 4 in Attachment A of the memorandum). Note: As a result of continuing quarry activity, the gravel deposits described in the August 13, 2014 memorandum are no longer exposed.

Figure 13. View looking south from trench Clive 29-5 along the east wall of the northwest Pit 29 quarry. The dashed line marks the contact between the laminated marl of Lake Bonneville and underlying transgressive sands with lenses of volcanic conglomerate.

Figure 14. Gully exposure of lens of volcanic conglomerate shown in Figure 13. The dashed line is the base of the laminated marl of Lake Bonneville. The gravel lens is approximately 1 meter thick.

3.2 Pit 5

The location of excavation sites used to establish the thickness of eolian silt in Pit 5 are shown on Figure 15.The same stratigraphic units described in Pit 29 are present in Pit 5 but the depth of excavation of the quarry bottom is shallower than Pit 29. The contact relations for the upper eolian silt are similar to Pit 29; the bottom contact is a gradational contact marked by the color change from light red, silt/marl deposits to white marl denoted on Figure 11. The top contact is covered by freshly cut spoil deposits; the top of the silt was identified by the induration contrast between the soil-modified silts and the spoil deposits, and the presence of surface vegetation.

Figure 15. Location of excavation sites in Pit 5 at the south end of the Clive disposal site.

4.0 December 17, 2014. Measurement of the Eolian Sediments in Surface Soil Pits

Two soil pits were dug by hand on respectively, the east central and west central boundary of the Clive site (Figure 8). These excavations were started in undisturbed vegetated surface deposits and extended downward to the base of the eolian silt (Figure 16). The base of the eolian silt in these pits was identified by the color change between the light red silt/marl mix and underlying white marl consistent with the described excavations Pit 29 and Pit 5. The surface soil pits were dug for two reasons: First, to examine the thickness of eolian silt at sites that reduce the uncertainty in identification of the upper surface, and second, to extend the geographic extent of sites with measured eolian silt at the Clive site.

Figure 16. Measurement of the eolian silt thickness in excavation Clive hand-dug-1.

5.0 Summary of the Field Measurements of the Upper Eolian Section at the Clive Site

The field measurements of the thickness of eolian silt are presented in Table 1. Eleven measurements were completed during the field studies; one measurement site, Clive 5-5a, was not included because the upper part of the eolian section was removed during quarry construction (Pit 5). These field measurements are supplemented with 21 measurements obtained at mixed waste test pit locations as part of a clay resource assessment for the Clive site (Table 2). These test pits systematically identified and measured the depth of a contact between red brown clay and tan clay that is consistent with the field identification of the base of eolian silt from our studies.

The eolian thickness identified in the field studies of the Clive site range from 55 cm (Clive 5-1 and Clive hand-dug-2) to 110 cm (Clive 29-5; Table 1). The thickness of eolian silt measured in the soil test pits from Table 2 range from 46 cm to 122 cm.

Table 1 Thickness Measurements from Field Studies of Eolian Silt, Clive Disposal Site

NEPTUNE FIELD STUDIES DECEMBER 2014

Site	GPS Cord	GPS Cord	Silt Thick	Base1	Top2	Date
	UTM E	UTM N	(cm)	(± cm)	(± cm)	
Clive 29-1	321354	4508262	90.0	3.0	10.0	12/16/14
Clive 29-2	321390	4508256	80.0	3.0	10.0	12/16/14
Clive 29-3	321423	4508248	80.0	3.0	10.0	12/16/14
Clive 29-4	321502	4508236	60.0	3.0	10.0	12/16/14
Clive 29-5	321239	4508283	110.0	3.0	10.0	12/16/14
Clive 5-1	320813	4504729	55.0	3.0	10.0	12/16/14
Clive 5-2	320869	4504730	70.0	3.0	10.0	12/16/14
Clive 5-3	320914	4504731	60.0	3.0	10.0	12/16/14
Clive 5-4	321041	4504732	70.0	3.0	10.0	12/16/14
Clive Hand-Dug-1	322093	4507482	70.0	3.0	2.0	12/17/14
Clilve hand-Dug-2	320445	4507035	55.0	3.0	2.0	12/17/14
		Mean	**72.7**	cm		
		STD	**16.6**	cm		

Footnotes

1. Estimated uncertainty in replicate identifications of basal contact. Alternative interpretations of the basal contact of eolian silt could reduce measured thickness by 20 cm (see text).
2. Estimated uncertainty in replicate identifications of the vegetated surface; soil pit measuremei were made starting from the surface and uncertainty estimate is based on the thickness of the vesicular Av soil zone.

Table 2. Thickness measurements from soil test pits for eolian silt, Clive Disposal Site

CLAY RESOURCE ASSESSMENT TEST PITS1				
Site	**Location**	**Location**	**Silt Thick**	**Date**
	North	East	(rounded to nearest 15 cm)	
S29_TP1	15,771.58	15,215.56	61.0	1/5/05
S29_TP2	16,339.57	15,160.68	122.0	1/5/05
S29_TP3	17,045.80	15,243.46	91.0	1/6/05
S29_TP4	16,835.53	14,244.06	61.0	1/6/05
S29_TP5	18,215.03	14,276.67	61.0	1/6/05
S29_TP6	17,689.84	14,288.91	76.0	1/6/05
BC_TP1	14,667.22	12,500.42	61.0	1/10/05
BC_TP2	14,116.10	12,109.52	61.0	1/10/05
BC_TP3	14,657.03	11,751.68	61.0	1/10/05
BC_TP4	13,849.52	11,795.49	46.0	1/10/05
BC_TP5	14,657.19	11,083.02	76.0	1/10/05
BC_TP6	13,888.00	11,083.09	76.0	1/10/05
BC_TP7	14,657.19	10,432.01	76.0	1/10/05
BC_TP8	13,887.81	10,431.93	76.0	1/10/05
MW_TP1	14,911.18	15,593.46	46.0	1/14/05
MW_TP2	14,101.00	15,592.31	91.0	1/14/05
MW_TP3	13,253.19	15,592.55	91.0	1/5/05
MW_TP4	12,393.45	15,592.58	46.0	1/4/05
MW_TP5	14,911.40	15,076.48	76.0	1/14/05
MW_TP6	14,100.84	15,076.76	76.0	1/14/05
MW_TP7	13,253.29	15,076.48	61.0	1/14/05
	Mean		**71.0**	cm
	STD		**18.1**	cm
	Mean (all measuremen		**71.6**	cm
	STD (all measurements		**17.4**	cm
Footnotes	1. Interpreted data from clay test pits; base of eolian deposits inferred to be at contact between red brown clay and tan clay; uncertainty assumed to less than the roundoff (± 15 cm) 2. Data combined from Table 1 and Table 2			

5.1 Data Set Used for Assessing Future Eolian Depositional Rates

Multiple alternatives were evaluated for selecting the data set and parameters used for estimating eolian depositional rates. The depositional rate at the Clive site is not expected to be a steady state rate (see Section 6.0); deposition is assumed to be variable dependent on: transgressive and regressive changes in the elevation of the Great Salt Lake; the elevation of the local ground water table; local changes in supply of eolian material; temporal variations in wind directions and wind velocity; and, variations in burial, preservation, and modification of eolian silt by soil processes. The following assumptions were made in assessing these factors:

1. There is insufficient information to evaluate future variations in all parameters affecting eolian depositional rates.
2. The preserved record of eolian deposition at the Clive site integrates variations in eolian parameters and processes of deposition and burial over thousands of years. This integrated record is assumed to provide the most consistent information for forecasting eolian depositional rates over tens of thousands of years.
3. The depositional rate is estimated by dividing the eolian thickness by the age (duration) of the deposits. The uncertainty in the age of the eolian deposits is included in the estimation of depositional rates.
4. There is not an established method for estimating future eolian depositional rates and any estimations will be uncertain. These issues are addressed by fully describing and contrasting alternative approaches used to estimate eolian depositional rates and treating the uncertain depositional rate as a probability distribution.

The following alternatives were evaluated for estimating future eolian depositional rates:

1. The age of the eolian deposits tied to the two options described in Section 3.1.
2. The data set from Table 1 (field measurements from this study).
3. The data set from Table 1 modified by the minimum thickness alternative for the basal contact of the eolian silt (Section 3.1).
4. The combined data sets from Table 1 and Table 2 (clay resource assessment test pits)

5.1.1 Age of the Eolian Deposits

The summary paper by Oviatt (2015) provides the most recent compilation and interpretation of radiocarbon ages for the chronology of Lake Bonneville. Based on information summarized in Figure 2 of Oviatt (2015) and supported by the supplemental radiocarbon data referenced in the paper, the preferred estimate for the age of the final regression of Lake Bonneville below the altitude of the Clive site is about 13,500 yrs B.P. (Clive elevation 1304 m). A reasonable lower bound on the youngest or minimum age for this event is 13,300 years B.P based on radiocarbon ages determined from organic material collected in post-Bonneville wetland deposits (Oviatt, 2015). The reasonable oldest or maximum age of lake regression at the Clive site is constrained by the age of the Provo shoreline and reliable radiocarbon ages for sites above the altitude of the Clive site and below the Provo shoreline. This reasonable maximum age is estimated to be about 14,500 yrs B.P.

With regression of Lake Bonneville below the Clive site, the lake bottom/marl deposits would have been exposed at the land surface initiating drying conditions, oxidation and modification of the marl deposits by processes of soil-formation with sporadic deposition of eolian silt/sand. Episodic surface processes would have reworked the soil-amended marl and eolian silt forming the light-red marl/silt deposits observed at the base of the described eolian silt deposits (see Section 3.1 and Figure 12; the ***maximum*** eolian thickness alternative).

Minor eolian silt deposition would have begun at Clive as soon as Lake Bonneville regressed below this altitude, but the rate of silt deposition is inferred to have been low until the mudflats west of Knolls (the primary source of the eolian source material) dried out sufficiently to allow mobilization in prevailing winds. There is evidence from Dugway, south of Clive that groundwater discharge created extensive wetland systems on what are now mudflats as late as about 10,000 yrs B.P. (Oviatt, et al., 2003). Therefore, by inference, the age of the increase in the rate of eolian silt deposition at Clive marked by the basal contact of the dark-red silt is estimated at about 10,000 yrs B.P (see Section 3.1 and Figure 12; the ***minimum*** eolian thickness alternative). This age is consistent with estimations of the length of time required to develop the oxidation and soil modifications observed in the upper part of the regressive marl sediments of Lake Bonneville.

5.1.2 Maximum thickness alternative for the Table 1 Data Set

The mean estimated depositional rate using the data from Table 1 is 5.4 x 10^{-3} cm/yr (mean thickness of 72.7 ± 16.6 cm and a mean age of 13,500 years B.P.). The advantages of using these data are the consistency in field-based measurements at 11 sites and the description of uncertainty for the location of the upper and lower contacts for all sites. The disadvantage of this approach is that field measurements may overestimate the thickness of eolian silt, but for a different time frame.

5.1.3 Minimum Thickness Alternative for the Table 1 Data Set

The data for this alternative was developed by subtracting 20 cm from the eolian thickness measurements for each of the sites in Table 1, which corresponds roughly to the depth of the mixed eolian and ostracodes layer. The mean estimated depositional rate using this data set is 5.3 x 10^{-3} cm/yr (mean thickness of 52.7 ± 16.6 cm and a mean age of 10,000 years B.P). The advantages of this approach is it incorporates the ostracode data at Pit 5-5 and does not overestimate the thickness of eolian site; the disadvantages are the ostracode data is available for only one site, it is uncertain whether the 20 cm subtraction should be applied systematically to all sites, and the age of the dark red silt deposit is less well constrained than the age for the final regression of Lake Bonneville.

5.1.4 Combined Data Sets from Tables 1 and 2

The mean estimated depositional rate using the data from the combined Tables 1 and 2 is 5.3 x10^{-3} cm/yr (mean thickness of 71.6 ± 17.4 cm/yr and a mean age of 13,500 years B.P. The advantages of using this approach are it expands the number of measurements (32 total measurements) and the geographic extent of data coverage for the Clive site. The disadvantages of using the soil resource assessment test pit data is the techniques used to identify and measure the stratigraphic contacts, and the uncertainty of the measured contacts are not documented.

5.1.5 Summary and Recommendations for Eolian Thickness Data

The chronology data and uncertainty in chronology data are about the same for all approaches to eolian thickness measurements. The standard deviation of all three data sets is also about the same. The estimated mean depositional rates are virtually identical for the three data approaches. For simplicity in estimating an uncertain parameter and consistency in measurement methodology, the Table 1 data set is used to develop the probability distribution for the eolian depositional rate. This approach relies on the most well defined measurement data, and the most well defined age data/information. If the distributions are to be used in a model that reflects deposition rates into the long-term future, then the average depositional rate is of primary interest, which is affected by the number of data points available. Using only the data from Table 1 (and not also from Table 2) limits the number of data points, and hence maintains greater uncertainty in the average deposition rate.

5.1.6 Probability Distributions for the Depth and Age of Eolian Depostion

Two distributions are developed from which depiction rate modeling can be performed assuming the eolian deposition rate has been in steady-state since the regression of Lake Bonneville, and will continue in steady-state in the future until conditions at the site change (e.g., natural climate change). These distributions represent the depth of eolian deposition since Lake Bonneville regressed past the elevation of Clive, and the age at which regression past the Clive elevation occurred.

5.1.6.1 Probability Distribution for the Depth of Eolian Depostion

The summary statistics provide the information needed to develop a distribution of average eolian depostion rate since the regression of Lake Bonneville past the elevation of Clive. The mean is 72.7 cm, and the standard deviation is 16.6 cm. There are 11 data points, and the data are reasonably symmetric about the mean. Consequently, a normal distribution is assumed with the following parameters:

Mean eolian deposition thickness = 72.7 cm

Standard error of the eolian deposition thickness = 16.6 / 11^0.5 = 5.0 cm

Consequently, the distribution is normal with a mean of 72.7 cm and a reasonable simulation range of approximately 57.5 – 87.5 cm (+/- 3 standard errors).

5.1.6.2 Probability Distribution for the Age of Eolian Depostion

Information for the age of the eolian deposition comes from various studies that are summarized in Oviatt (2015). A distribution was developed based on the available information in Oviatt (2015) and on expert elicitation of Oviatt. The following information/data were considered most relevant during the elicitation:

1. Samples Beta-141593 and Beta-131590 were of organic materials from wetland sediments at Fish Spring Flat and Dugway Proving Ground. They should be considered the oldest reliable post-Bonneville ages at their altitudes (about 1310 m)
2. The wood age for the sample from Roy (W-1824), even though that analysis is quite old (1967), is probably reasonable. That places the older age limit for the regression at 1314 m at less than ~14500 (note the elevation of Clive is considered to be 1304 m).
3. Lake Bonneville probably evaporated very quickly, except for short episodes of wet weather during the approximately 2000 yrs of lake-level drop to what is now the Great Salt Lake.
4. Lake Bonneville was dropping fast during the regressive phase, and although specific evidence does not exist, the rate of regression probably changed through time. It was a closed-basin lake, with no known river diversions or other complications to the water balance at that time, so weather and climate were the dominant controls on lake level. Because weather and climate change constantly, the regression rate would have changed constantly, and the radiocarbon dating method does not give precise-enough results to allow us to know what those rate changes were. Consequently, uncertainty should be brought into the age estimate.

5. The regression past Clive was probably about 13500 yr B.P. The uncertainty on this would be minus a century or two, and plus maybe as much as 1000 yr (based on the remaining data presented in Oviatt 2015).

Based on this information a Beta distribution was fit to approximate elicited quantiles. The following inputs were used:

- Absolute minimum possible age – 13,000 yrs
- Reasonable minimum age – 13,300 yrs
- Most likely age – 13,500 yrs
- Reasonable maximum age – 14,500 yrs
- Absolute maximum possible age – 15,000 yrs

After considering possible quantiles for the middle three terms, a Beta distribution fit was agreed upon with the following parameters and quantiles:

- Minimum – 13,000 years
- Maximum – 15,000 years
- Alpha (shape 1 parameter) – 3.318
- Beta (shape 2 parameter) – 7.498
- Quantiles:
  - 2.5% – 13,174 yrs
  - 10% – 13,284 yrs
  - 20% – 13,378 yrs
  - 50% –13,592 yrs
  - 80% – 13,846 yrs
  - 90% – 13,988 yrs
  - 97.5% – 14,207 yrs

A histogram of the Beta distribution is provided in Figure 17.

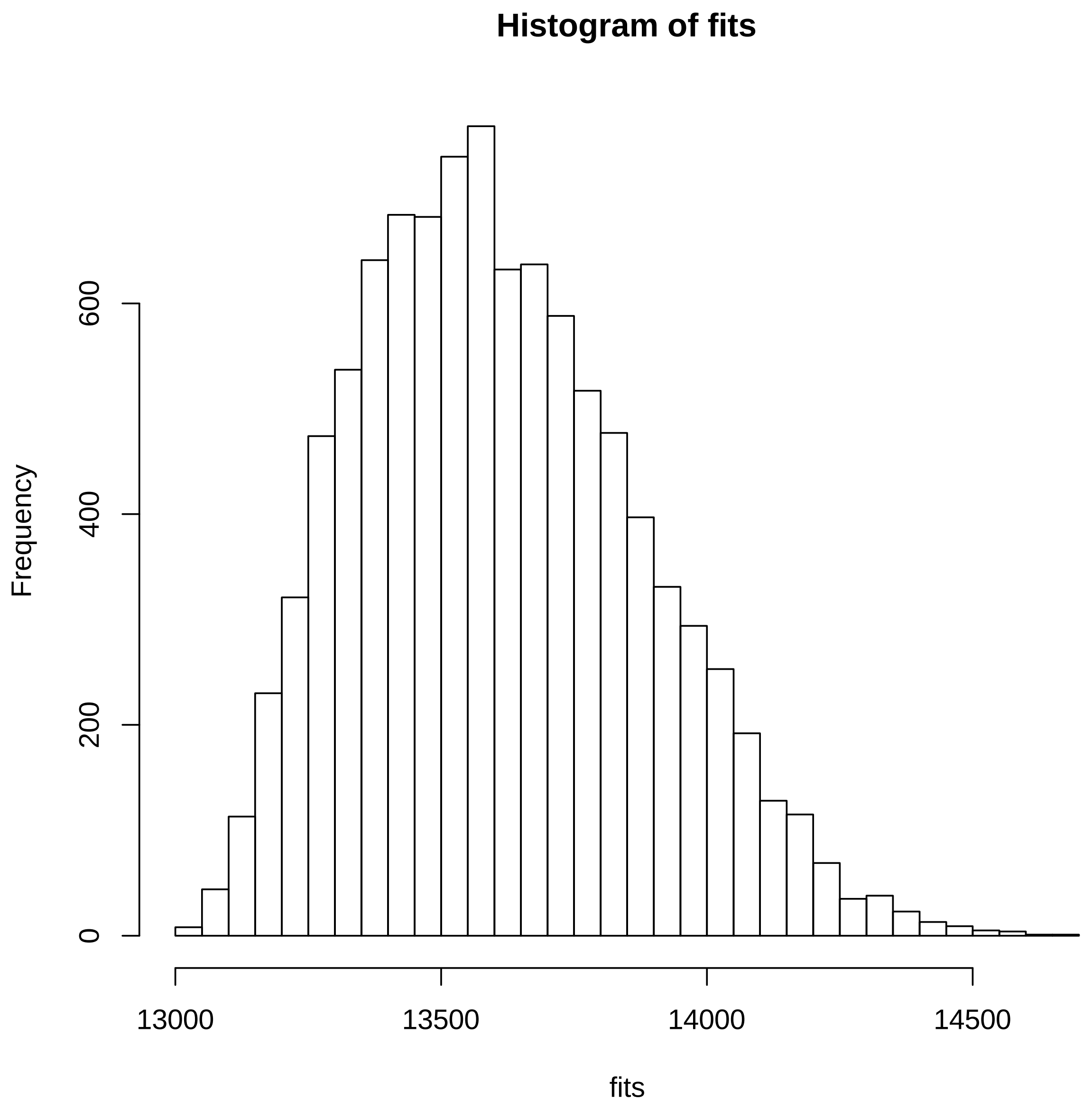

Figure 17. Histogram of the simulated Beta distribution for Age of Lake Bonneville Regression past the Elevation of Clive

6.0 Conceptual Model of Current and Future Eolian Deposition at the Clive Site

Reconnaissance field studies in the Clive region and detailed studies of eolian silt at the Clive site demonstrate that the site is an area of past, current and expected future eolian deposition. The integrated accumulation rate of silt is low (long-term mean depositional rate of approximately 5 x 10^{-3} cm/yr; see section 5.0). The modern primary mode of eolian deposition is accumulation of fine-grained silt from suspension fallout during wind storms. Saltation deposition of sand may be possible at the Clive site during high energy wind storms; fine-grained sand in dune forms was observed within 0.5 km of the west edge of the Clive site. However, significant accumulations of sand were not observed in the silt deposits at the site.

Eolian deposits are reworked by surficial processes, primarily sheet-wash run-off during episodic rain storms. However both the magnitude and depth of reworking is limited by the extremely low gradient modern surfaces near the Clive site (estimated slope 0.00167 from topographic data). This is demonstrated by the widespread preservation of delicate vegetation stripes throughout the Clive region (see Figures 2-4).

The more important processes affecting modern eolian deposits are sediment modifications from soil-forming processes. The effects of soil formation were observed at the field scale throughout the eolian section and extend downward into the underlying Lake Bonneville marl. Buried soils were also observed in the eolian and lake sediments below the Lake Bonneville sequence at excavation Clive 29-5. These observations are consistent with a long-history of eolian deposition on stable surfaces that promote and preserve processes of soil formation. The modern setting allowing contemporaneous operation of processes of eolian deposition and soil formation has persisted at the Clive site since the regression of Lake Bonneville below the Clive elevation (approximately 13,500 years B.P.). Our observations of soils in eolian silt at the Clive are based on field studies. Enhanced documentation of processes of soil formation in the eolian silt would require more detailed field and laboratory studies by soil specialists.

The sources of eolian silt at the Clive site are local reworking of surface deposits, and continued generation of eolian source material at the wet playa areas west and southwest of the site. Current eolian depositional rates at the site are low and may be lower than the long-term mean depositional rates. Minor fluctuations in eolian depositional rates are expected to occur with variations in the water table elevation and elevation of the capillary fringe above the water table west of the Clive site.

The lateral persistence and uniformity in thickness of eolian silt at the Clive site (55 to 110 cm in excavated trenches and soil pits) are consistent with the low-gradient depositional surface (former lake bottom) and long-term continuing eolian deposition. Significant future changes in depositional rates are not expected without changes in the elevation of the Great Salt Lake associated with interpluvial climate variations or a future return to glacial maximum conditions. For either of these conditions, the following changes are expected to occur at the Clive site:

1. Increased water table elevation and eastward expansion of the location of wet playa areas toward the Clive site. These conditions are expected to increase the rate of supply of eolian source material and eolian deposition at the site.
2. As lake levels rise, dune fields similar to the observed fields at the Knolls would be expected to migrate eastward toward the Clive site. The exact patterns of migration are uncertain and would depend on the scale and rate of lake rise, and the distribution of future wet playa areas associated with higher ground-water levels. In general, a significant lake rise should result in

a significant increase in the eolian deposition rate and an increase in the ratio of saltation/suspension deposition at the Clive site. Deposition of saltation sands would, however, be expected to be transitory and may or may not be preserved in surface deposits at the Clive site.

3. As rising lake levels approach the Clive elevation, dune development similar to the fringe dunes observed at location 12-15-3 (Figure 1) would be expected to occur at the Clive site. Eolian deposition at the site would be high with local sand accumulations exceeding 1 m.
4. When lake waters reach the Clive elevation, wave action would be expected to efficiently rework eolian deposits at the site and intermix eolian sand and silt with shoreline sands/oolitic sands including possible local accumulations of gravels from longshore drift. These deposits would be expected to be distributed across a wide area in the vicinity of the Clive site.
5. The duration of the operation of wave action is expected to be significant. The low-surface gradient in the area will promote maintained periods of surface-wave action. The duration of wave activity will also depend on the rate of rise of the lake level and the extent of transgressive and regressive lake activity at the elevation of the Clive site.

7.0 Applications to the SC&A White Paper

- Field studies confirm that eolian processes with associated deposition of sand and silt has been and will continue to occur in the regional setting of the Clive site (sources of eolian material, evidence of eolian deposits at and near the Clive site).
- Deposits of soil-modified eolian silt formed primarily by suspension fallout directly overlie the Lake Bonneville sedimentary deposits and are directly beneath the modern surface throughout the Clive site. The observations and are consistent with the reinterpreted 70 cm-thick upper eolian section described in the 1985 observations by Oviatt (cited in Neptune, 2014).
- Depositional rates of eolian silt are low (mean integrated rate of about 5×10^{-3} cm/yr; see section 5.0) and are expected to remain low until future lakes return near the elevation of the Clive site.
- A near-continuous record of eolian deposition and soil formation is preserved at the Clive site above the post-Provo regressive phase of Lake Bonneville.
- There are now sufficient measurements of the thickness of eolian sediments to allow estimation of future eolian depositional rates from the stratigraphic record at the site. These measurements have been made at 4 separate locations (11 measurements) in the Clive site and are consistent with stratigraphic data from test pits constructed at 21 sites.
- Detailed studies of shorelines associated with the Gilbert episode (Oviatt 2014) were not conducted in this study. However, field observations northwest of the Clive site show features that in past studies (Currey,1982) were inferred to be Gilbert shorelines are instead depositional forms associated with processes of shoreline drift during the transgressive-phase of Lake Bonneville.
- Gravel deposits in the north east part of Pit 29 described in the Attachment A of the SC&A White Paper are no longer accessible for detailed study. However observations at multiple locations in the Clive site and the Clive vicinity are consistent with assignment of these gravels to the transgressive phase of the sedimentary deposits of Lake Bonneville.

8.0 References

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