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A Characterization of Lake Abert Tufa Mounds Lake Abert, Oregon

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A Characterization of Lake Abert Tufa Mounds

Lake Abert, Oregon

by

Anthony Lynn Bartruff

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Geology

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Portland State University
2013

Abstract

A series of tufa mounds is found within the northern basin of Lake Abert, located within southeastern Oregon. The mounds have been divided into 3 main groups and 1 sub-group (A1, A2, B, and C) based upon spatial and textural considerations. Mound groups appear at two different elevations: the 1310 meter elevation (Groups A2, B, and C), and the 1318 meter elevation (Group A1). Published carbon age dating of the Lake Abert 1325 meter strandline and the 1310 meter strandline indicates that the mounds were formed during the Late Pleistocene/Early Holocene. Facies analysis and mineralogical analysis of the mounds indicates that the mounds were primarily formed subaqueously during a lake regression, supporting oxygen isotope data from previous researchers. Magnetometer data within Groups A1 and A2 suggests that the mounds are associated with a series of magnetic lows which are oriented in joint sets (NW-SE, and N-S) which match the orientation of faulting within the region. While there appears to be another early mound building episode, no direct evidence confirms this.

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CHAPTER 1.0 INTRODUCTION

Travertine and tufa deposits form under a wide range of environmental conditions by differing processes. Examples of subaerial deposits have been described as occurring in mounds and fissures at Mammoth Hot Springs in Yellowstone National Park (Fouke et al., 2000), the terraced travertines of Clinton, British Columbia (Jones and Renaut, 2007), and as fissure ridge deposits in Central Anatolia, Turkey (Atabey, 2002). Subaqueous deposits have been described as the tufa pinnacles and “tombstones” of Mono Lake (Cloud and Lajoie, 1980) and Searles Lake (Scholl, 1960).

Tufa mounds can be powerful paleoenvironmental indicators. Analysis of textures found within the subaqueous mounds of Searles Lake (Guo and Chafetz, 2012) and Pyramid Lake (Benson, 2004) record lake oscillations tied to the changing environmental conditions within the Great Basin during the Late Pleistocene. Additionally, subaqueous tufa deposits retain the isotopic signatures of their precipitating fluids. As a result, stable isotope values on tufa have been used to place constraints on lake levels in Lake Lahontan (Benson, 1994; Benson et al., 1996) and Lake Bonneville (Nelson et al., 2005). The presence of tufa mounds within a lacustrine setting offer a unique opportunity for research of the mounds themselves as well as the lake conditions they were formed in.

Tufa mounds are present along the northern shore of Lake Abert, south central Oregon. Originally investigated by Langridge and Weldon (1995), Langridge et al. (1996), and Jellinek et al. (1996) as a geothermal exploration

target, the Lake Abert tufa mounds are related to the combination of intersecting faults that were active during the late Pleistocene and Holocene and the fluctuating pluvial lake levels described by Allison (1982) within the Lake Abert Basin. While it may be generally assumed that the tufa mounds and pluvial Lake Abert water levels are genetically related, few data exist linking Lake Abert water levels to the formation of the tufa mounds. This study explores the interplay of faults, fluctuating lake levels, and the formation of Lake Abert tufa mounds.

CHAPTER 2.0 BACKGROUND

2.1 Introduction

Precipitation of carbonate in thermal environments is due to a variety of processes. Degassing, temperature change, photosynthesis, evaporation, mixing, and microbial processes have all been described as contributing to carbonate deposition (Fouke et al., 2000). Most mechanisms directly or indirectly affect the chemical relations described by Equation 2.1. As CO₂ is removed from calcium bicarbonate-type waters by degassing, and photosynthesis, the right side of Equation 2.1 is favored, resulting in precipitation of calcite.

Equation 2.1 Equation governing the precipitation of calcite.

The name “travertine” originates from the Latin word *lapis tiburtinus* or the stone of Tibur, an ancient roman city now known as Tivoli, Italy. The term travertine has come to mean all forms of non-marine carbonate precipitates formed in or near rivers, lakes, springs, and in caves (Sanders and Freidman, 1967; Fouke et al., 2000). Pedley (2009) describes travertines in three different major forms: 1) hot spring travertines which are formed on or near hydrothermal vents, 2) low temperature tufas which are normally formed under ambient temperatures and 3) speleothems which are formed as a result of CO₂ degassing within caverns.

2.2 Mounds and Faults

As summarized by Hancock et al. (1999) travertine mounds in association with active extensional fault systems can be classed into six morphological categories which are dependent on the local topographic relief, structural setting of the springs supplying fluids, and the environment of deposition i.e. subaqueous or subaerial. For reasons still poorly understood, most if not all travertine mound systems are found in association with basaltic country rock and extensional tectonics.

2.2.1 Terraced Mound Travertines

Chafetz and Folk (1984) described subaerial terraced mound accumulations as composed of small shallow pools surrounded by rims, dams, and small vertical pools with water flowing from above or spring fed. Famous examples of terraced deposits include the Minerva Spring deposit at Mammoth Hot Springs, and the terraced travertine deposits of Clinton, British Columbia. Deposition of travertine is due to exsolution of CO_2 as water flows over ridge tops (Jones and Renaut, 2007) and thermal dissipation as hot spring waters flow further from the vent (Fouke et al., 2000). Hancock et al. (1999) describe these mound types as indicative of a nearby fault trace.

2.2.2 Fissure Ridges

Fissure ridges range from 1 m to >15 m and may exceed 0.5 km in length (Pentecost, 2005). Ridges can be straight or curved in plan. Fast flow rates at the time of formation can result in ridges with aspect ratios as low as 0.1 to 0.2 (height to width). In contrast, slow flow rates can form high but narrow ridges with

aspect ratios approaching 1.0 (Hancock et al., 1999). Like mounds, hydrostatic pressure appears to influence the height of fissure ridges. Bargar (1978) estimated pressure exceeding 750 kg m^{-2} in the fissure ridges of Mammoth Hot Springs. Notable fissure ridge deposits occur in Mammoth Hot Springs, California, Soda Dam, New Mexico, and Hamman Mescoutine, Algeria (Chafetz and Folk, 1984). Atabey (2002) describes fissure tufa-travertine ridges in Central Anatolia, Turkey with length exceeding 800 m and height between 10 and 30 m.

Hancock et al. (1999) describe fissure ridges typically to be the surface expression of a line of springs situated along an extensional fissure where the bedrock is exposed at the surface. The long axes of the ridges are typically elongate and parallel to each other developing normal to the stretching direction. Figure 2.0 from Brogi and Capezzouli (2009) is a compilation of the various tectonic regimes where fissure mounds are formed.

2.2.3 Eroded Sheet Travertine

As described by Hancock et al. (1999), eroded sheet travertines are non-conglomeratic older travertines which are bedded and have been eroded. Eroded sheet travertines are primarily the remnants of older travertine mounds such as fissure ridges which have been eroded.

2.2.4 Mounds and Cones

Travertine mounds and cones can be terrestrial or subaqueous. Most terrestrial mounds are centered on a central vent and can be from <1 m to >100 m in height. While the process of mound building is still poorly understood, mounds appear to be highly dependent on water under pressure. The hydrostatic pressure needed to form the largest mounds is considerable, approaching 7 kg cm⁻² at ground level (Pentecost, 2005), and the rate of flow presumably decreases as the mound builds.

Mound profiles range from steep sided structures with slopes exceeding 50° to mounds with slopes of 1° or less. Slope and geometry appear to be driven by topography, flow rate, head, and the amount of carbonate super-saturation. A high degree of saturation leads to rapid deposition around the vent, giving a steep-sided mound while waters close to saturation will deposit at increasing distances and as a result have a lower profile (Pentecost, 2005).

Notable terrestrial mounds occur in Mammoth Hot springs of Yellowstone, and the Auburn Hot Springs of Utah. Ponder (1986) describes eleven large groupings of hundreds of mounds in the Great Artesian Basin of Australia while Melezhik and Fallick (2001) report terrestrial travertine mounds within the Pechanga Greenstone Belt of northwest Russia as old as 2.2 Ga.

The other type of mounds are those formed subaqueously, some of the most famous examples of subaqueous mounds are those of Mono Lake. Formed within the Great Basin, Mono Lake mounds are formed by fresh water springs

mixing with carbonate-rich lake waters to form pinnacle mounds and tombstones. Other widely known Great Basin examples include the mounds of Pyramid, Searles (Figure 2.1) and Washoe lakes.

Hancock et al. (1999) suggest that mounds and cones occur where fissures underlie soft sediments. A linear pattern reflects the underlying control of a fault trace.

2.2.5 Range Front Travertines

Range front travertines are deposited from springs from within the immediate footwalls of faults which locally cement talus derived from fault scarps and range fronts. Hancock et al. (1999) suggest that these are mainly older travertines due to field relationships and age dating from the Pamukkale travertines of western Turkey. Mound formation upon the footwall of a fault appears to be the defining characteristic of this style of travertine.

2.3 Subaqueous Tufa Textures

King (1878) first described the tufa dotting the remnant lakes of his Pleistocene Lake Lahontan as having a texture described as “thinolitic”. Israel

Cook Russell (1885) further defined calcareous tufa of Lake Lahontan as occurring within three different varieties: 1. Lithoid tufa: Compact and stony, light yellow to gray, contains comb-like masses resembling a massive thatch (Figure 2.2). 2. Thinolitic tufa: Primarily made of elongate crystals roughly that of a rectangular prism which is gray to brown. Crystals are 0.6 to 2.5 cm wide and 20-25 centimeters long. 3. Dendritic tufa: Calcareous rock with a dendritic or branching structure. The color is yellowish gray and weathers to rough and angular forms.

Figure 2.2 Photo from Scholl and Taft (1964) showing the relationships between dense lithoid tufa (DLT), a very fine algal mat (AM), and a porous lithoid tufa (PLT) within the inner

2.3.1 Lithoid tufa

Scholl and Taft (1964) in their in-depth study of two Mono Lake tufa mounds further delineate lithoid tufa into two separate textures defined as

dense lithoid tufa (DLT) which is typically associated with an exterior algal mat and a porous lithoid tufa (PLT) which contain tubular bodies of 7-10 microns thick and up to 200 microns in length, which they interpreted to be the calcic molds of thalli of filamentous algae (Figure 2.2). Scholl and Taft (1964) further defined a tufa texture called sparry calcite derived through solution and the reprecipitation of calcite.

2.3.2 Thinolitic Tufa

Since Russell's (1885) original description of thinolitic tufa, it is now commonly accepted that the elongate crystal structure seen in thinolitic tufa lining the current lakes of what once was Lake Lahontan is a calcareous pseudomorph of Ikaite or calcium carbonate hexahydrate ($\text{CaCO}_3 \cdot 6(\text{H}_2\text{O})$) (Pauly, 1963; Shearman, 1985). Ikaite is a metastable mineral which forms in cold ($0-25^\circ \text{C}$) water and as a result has been used as a paleoclimate marker in studies including Lake Lahontan and Mono Lake (Shearman et al. 1989), Greenland (Dahl and Buchardt, 2006) and generally as a paleothermometer in Swainson and Hammond (2001).

2.4 Geologic Features of the Abert Basin

2.4.1 Volcanism and Stratigraphic Units

As shown in Figure 2.3 the oldest geologic feature within the Abert Basin is the Coleman Hills volcanic complex abutting the north shore of the Abert basin

and immediately northwest of the upper Abert Rim fault. The Coleman Hills volcanic complex is comprised of early Miocene, large, arc-like composite volcanoes which erupted andesite and basaltic andesite with Ar^{40} – Ar^{39} age dates between 21–23 Ma. The vents are aligned along NW- and NNE-striking faults and dikes centered within the complex (Scarberry et al., 2010). Arc volcanism was predominant within Oregon during the Early Miocene (Christianson and Yeats, 1992) and the Coleman Hills complex is a remnant of this tectonic regime.

At around 16 Ma arc-volcanism transitioned to flood basalt style volcanism with the emplacement of the Steens Basalt, a large, ~450 m-thick unit (Mankinen et al., 1987; Scarberry et al., 2010) associated with the Columbia River Basalt Group. Between 16 Ma and 7.1 Ma volcanism within the northern Abert Lake basin switched to a regime similar to bi-modal volcanism within the High Lava Plains of south-central Oregon. The Sawed Horn Mountain, an eruptive center which intrudes into the northern-most extent of the lake basin is associated with this bi-modal volcanism and dates from 8.6 Ma to 7.7 Ma (Scarberry et al., 2010).

Topping the late Miocene basalt flows is the Rattlesnake tuff, a regional unit observed throughout south central Oregon (Streck and Grunder, 1995).

2.4.2 Faulting within the study area

Along the northern shoreline of Lake Abert and perpendicular to the Abert Rim fault is a set of 8-10, N30°-40°W-striking faults associated with the Northwest Basin and Range. Pezzopane and Weldon (1993) report this zone as high-angle normal faults with right oblique slip, creating a series of low relief horst and graben structures and cutting Pleistocene and Holocene deposits where the faults intersect with the Abert Rim fault scarp (Figure 2.4). This series of faults has been active since at least before or during the formation of the Abert Rim

fault and may be the reactivation of a previous fault set associated with the onset of early Miocene volcanism (Scarberry et al., 2010).

Abutting Lake Abert's eastern shore is the Abert Rim, a 48-km-long fault scarp rising, at its highest point, 760 m above the lake. The Abert Rim fault is part of the Central Oregon fault zone (Pezzopane and Weldon, 1993), a zone of active, N-NE-striking predominantly normal faults which extends in Oregon from the California border to Newberry volcano. Pezzopane and Weldon (1993) describe the Abert Rim fault as vertically displacing late Pleistocene and Holocene lacustrine, alluvial, and colluvial deposits as much as 8 m;

corresponding to an average slip rate of approximately $1/2 \text{ mm yr}^{-1}$. The beginning of the deformation causing the formation of the Abert Rim appears to have been during the onset of the late Miocene volcanism within the Sawed Horn and during the propagation and reactivation of the NNW–striking faults within the area (Scarberry et al., 2010).

2.4.3 Lake Chewaucan

Pluvial Lake Chewaucan occupied the current fault-bounded basins of Summer Lake, Lake Abert, and the lower and upper Chewaucan marshes (Figure 2.5). At its high stand, the pluvial lake covered an estimated 1243 km^2 to a maximum depth of 114 m (Allison, 1982). Allison (1982) analyzed prominent shoreline features and determined that the lake level fluctuated at least six times after attaining a high-stand elevation of 1378 m. Due to the complex geomorphology of the pluvial lake basin, variations in stand were highly dependent on local geomorphology. During the pluvial lake's high stand, a gravel delta was built into Lake Chewaucan where the Chewaucan River empties into the basin from its headwaters located on Gearheart Mountain to the southwest. Under conditions of lower lake stands, wave action spread the delta gravels into a four mile swath known as the Paisley Flat gravel plain, separating the Summer Lake basin from the Upper Chewaucan Marsh basin.

This gravel plain caused two lakes to be formed during lower lake levels. At an elevation of 1335 m, these lakes were 1) upper Summer Lake and 2) Allison's (1982) lower ZX Lake which comprise the lower and upper Chewaucan marshes and Lake Abert. Allison (1982) indicates that there was a possible difference in lake levels of as much as 15.25 m with ZX Lake overflowing into the Summer Lake basin at least once causing a dramatic and sudden decline in the ZX Lake water level. Licciardi (2001), possibly supporting this assertion, dated Lake Abert shore-zone gastropods collected at 1310 m at 11750 +/- 180 yr ¹⁴C B.P. (B.P. = before present, where present is AD 1950) and collected at 1325 m at 11930 +/- 90 ¹⁴C B.P. The overlap of these ages at different elevations is

consistent with a rapid change in lake level. Both Allison (1982) and Licciardi (2001) report evidence of beach development at 1325 m and argued for a sustained and stable lake level at this elevation. However, ZX Lake eventually overflowed at Paisley Flat and lowered the lake level to 1310 m. At an elevation of 1310 m, ZX Lake would cease to be a continuous lake with the Upper Chewaucan Marsh being dry (current elevation: 1313-1310 m), while the Lower Chewaucan Marsh would have depths between 0 and 3 m (current elevation: 1307-1310 m).

2.4.4 Modern Lake Abert

Lake Abert is a closed-basin, alkaline-saline lake lying within a half graben of the northern Basin-and-Range Province (Figure 2.6). Lake Abert is currently less than 4.9 m deep and has surface areas that fluctuates with climate between 169 km² and dry (Allison, 1982). Modern Lake Abert has a pH of 9.8, high total dissolved solids (40,800

TDS), and high Na (40%) and Cl (35%) concentrations by weight of TDS (Philips and Van Denburgh, 1971; Van Denburgh, 1975; Allison, 1982). The Chewaucan River enters Lake Abert from the south after passing through the upper and lower Chewaucan Marshes. Besides the Chewaucan River and small springs located along the lake margin, no other permanent streams or water features have been reported to feed into Lake Abert.

The primary lake chemistry is a Path I brine (Na-CO₃-CL) as defined by Eugster and Hardie (1978) and diagrammed within Figure 2.7. The primary

Figure 2.7 A Lake Brine Evolution flow chart originally produced by Eugster and Hardie (1978) and modified by Warren (2010). Lake Abert brines are characterised by high HCO₃ to Ca + Mg ratios and follows path I, typically producing halite and sodium carbonate minerals

evaporite minerals formed within this chemical regime are expected to be halite and sodium carbonates such as trona and nahcolite with trona being the stable phase at ambient (25-60° C) temperatures.

Warren (2006) reports trona is formed within a limited range of environmental conditions: 1) an under filled tectonic basin where down warping exceeds the rate of sedimentation, 2) a closed hydrographic basin where evaporation exceeds outflow, 3) evolution of solutes that lead to high $\text{Na}/(\text{Ca}+\text{Mg})$ and $(\text{HCO}_3+\text{CO}_3)/(\text{SO}_4+\text{Cl})$ ratios or alkaline waters, 4) a more or less permanent body of nutrient-rich water, 5) a warm climate favoring high productivity by microbes and algae, and 6) a high rate of bacterial sulphate reduction. Well known trona deposits include the Green River Formation, Lake Magadi, and Searles Lake.

2.5 Previous work on Lake Abert tufa mounds

Located on the north end of Lake Abert and within the North Lake Abert and Sawed Horn quadrangles are tufa mounds and ridges that have been reported by Jellinek et al. (1996) to be limited to an elevation of 1310 m. The mounds were thought to mark the intersection of northeast and northwest-striking fault zones (Langridge et al., 1995). The mounds were described by Jellinek et al. (1996) as oblate- to mushroom-shaped, 1-3 m high, constructed of weakly bedded to massive, spongy and porous carbonate material overlying Quaternary alluvium and the late Miocene Rattlesnake Tuff.

While the terms “travertine” and “tufa” appear to be well defined according to Pedley (2009) the term travertine is used by Langridge and Weldon (1995), Langridge et al. (1996), and Jellinek et al. (1996) to describe solid relatively dense calcium carbonate veins and outcrops associated with the Abert tufa mounds. Jellinek et al. (1996) reported carbon and oxygen isotope ratios for travertine from the study area (Table 1.0). The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values indicate enrichment in the heavy isotope of each element. Jellinek et al. (1996) indicated that the $\delta^{18}\text{O}$ values for Lake Abert tufa mounds were too heavy to obtain geologically reasonable temperatures via equilibrium isotope thermometry; implying that significant evaporation was taking place during tufa precipitation.

Sample	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
IMLA-7	24.9	1.8
COGBUT-1	24	1.4
IMLA-8	24.8	1.3
IMLA-1b	28.9	4.5
MJLA-5	24.8	1.5
Table 1.0 showing heavy Oxygen and Carbon Isotopes of Lake Abert tufa from Jellinek et. al. (1996)		

CHAPTER 3.0 METHODS

3.1 Field Studies

Field investigations were performed on the Lake Abert tufa mounds during mid-summer 2009, early winter 2009, and fall 2010. During these investigations, the mounds were mapped and interpreted using field methods as outlined by Compton (1962). Spatial coordinates were determined with a Trimble Geoexplorer 3 and a Garmin 76 Global Positioning System (GPS) receiver. A total of 60 field specimens were collected and analyzed for textural patterns.

3.2 X-Ray Diffraction

Three samples, two tufa samples and a sample of inferred evaporite found layered within a mound, were collected and crushed using a mortar and pestle and then sieved through a 230 μm sieve. After the initial X-ray run on the evaporite sample, successive runs followed treatment with de-ionized water to dissolve evaporite minerals to determine the presence of other insoluble minerals within the sample. Water was carefully decanted and the material was rinsed again to eliminate residue and an x-ray run was performed. In order to further identify non-carbonate minerals 1 M acetic acid was used to dissolve calcium carbonate. The sample was carefully rinsed and decanted three times and an x-ray run was performed. Diffractograms obtained following various treatments are presented in Appendix C.

All samples were analyzed using a Phillips PW 3040 X-ray Diffractometer located in the Reka Gabor Clay Mineralogy Lab. Two theta scan conditions for

the diffractometer were set from 0 to 60 degrees set on step scan. Mineral phases were identified using the Phillips proprietary analytical software, aided by online references such as www.Webmineral.com.

3.3 Magnetometer Survey

A magnetometer survey was performed during the fall of 2010. The survey was performed with a Geometrics 858 cesium vapor magnetometer in simple survey mode and at 1 data acquisition per second for a total of 10,868 data points. The raw magnetic data and the paths used to collect the data are included within Appendix A.

Survey lines were chosen to maximize the clarity of relationships between possible faults and mound groups. Line endpoints were surveyed with a GPS receiver and profile lines were performed at a constant pace during measurements. Measurements were collected over a cumulative total distance of 8.9 kilometers.

CHAPTER 4.0 RESULTS

4.1 Introduction

The tufa mounds of Lake Abert can be separated into three groups according to spatial and morphological conditions. The characteristics of the three groupings of tufa mounds are presented along with interpretations of lake conditions and the influence of faulting for each group. Prior to this section (4.6), the general location, faulting and facies relations observed in the Lake Abert tufa mounds are presented.

4.2 Location of Tufa Mounds

Figure 4.0 is a Google Earth image of the general locations of the three main tufa mound groups within the north Lake Abert basin. Comprising the northernmost extent of observed tufa mounds, Group A mounds are approximately 50 mounds subdivided into Group A1 and Group A2 on the basis

of morphology, elevation and spatial relationships.

The Group B mound is a large single reef-like mound based on the topographic transition from the southeast flank of Sawed Horn Mountain and the lake basin. The Group C mounds are a series of three mound groups striking N-S parallel to the Abert Rim.

4.3 Magnetometer Survey

The Group A tufa mounds are located in a faulted area between two N60°W –striking faults that cut the olivine basalts (ToB) of the Sawed Horn and an older 8.8 Ma basaltic andesine (Tba). In the field, these faults are identified by topographic breaks and abrupt termination of outcrops of the olivine

basalt and basaltic andesite. Because of the prominence of the Group A mounds and the surface expression of these faults, this area was selected for a magnetic survey to better delineate the relations between faulting and mound distribution.

Figure 4.1 is a map showing the magnetic intensity of a portion of the field area covering Groups A1 and A2. Intensities are measured in nanoTeslas and the contour interval is 50 nanoTeslas. The light grey shading denotes outcropping of the Steens Basalt. Basalt outcrops in the area are associated with higher magnetic intensities when compared to intensities within the north playa shown on the intensity map. Both tufa Groups A1 and A2 are centered on a magnetic low. Using magnetic intensities as a guide, the Steens Basalt is associated with higher intensities within the sub-surface.

Assuming that lower magnetic intensities reflect the effects of a fractured shear zone while higher magnetic intensities reflect more competent rock (i.e. the Steens Basalt), the magnetic intensity map appears to show several subsurface tendencies:

1. The Group A1 and A2 tufa mounds generally correlate with magnetic lows and there appears to be a general magnetic low trending NE through the survey area and terminating against a previously mapped NW-striking fault (Pezzopane and Weldon, 1993). Orthogonal to the NE-trending low is a magnetic low coming from

the northwest edge of the survey and terminating generally within the surface expression of the Group A1 mounds. The general trends of the magnetic lows conform to previously reported strikes of faults within the area (Pezzopane and Weldon, 1993; Jellinek et al., 1996; Scarberry et al., 2010). With this in mind, inferred subsurface faults are dashed within Figure 4.1.

2. Mounds that do not match with magnetic lows are generally immediately adjacent to the surface expressions of previously mapped faults by Jellinek et al.

(1996) and Scarberry et al. (2010) and are on the footwall of the fault. Mounds immediately adjacent to the surface expressions of faults imply that the angle of the fault in these areas is nearly vertical in order for conduit pathways to proceed through a presumed fracture zone.

4.3.1 Section Summary

The northern edge of the Lake Abert basin exists within the intersection of two regional fault systems, an N-NW-striking, high-angle style of faulting comparable to the Brothers Fault Zone located immediately to the northeast and an N-NE-striking structural regime associated with the normal faulting of the northern Basin and Range (Lawrence, 1976; Scarberry et al., 2010). Within the magnetic survey area, all previously mapped faults are indicated as N-NW striking which matches the topographic expression produced by outcrops of the Steens Basalt. The magnetic intensity data indicate magnetic lows corresponding to additional subsurface fracture zones running N-NE and N-NW; Group A mounds correspond to either subsurface magnetic lows or within the fault trace of previously mapped N-NW-striking faults.

4.4 Facies Relationships

Hand samples from the tufa mounds were examined to determine common textures and textural associations. These textures and textural associations were related to facies identified in research literature on tufa

mounds and travertine deposits. In this section, the textures observed in the Lake Abert tufa mounds are compared to textures described in research literature.

Textures within the mounds of Lake Abert are similar to the dense lithoid tufa (DLT) and porous lithoid tufa (PLT) textures described in Mono Lake by Scholl and Taft (1964). Guo and Chafetz (2012) in their detailed study of lithologic characteristics of the Searles Lake tufa further define four styles of major mound deposition, 1) an innermost highly porous mound facies called Porous 1 and an outermost Porous 2 facies, followed by 2) a nodular facies, 3) a columnar facies, and 4) a laminated facies all of which reflect response to a change in environmental conditions.

The Searles Lake Tufa Pinnacles have experienced a relatively longer continuous period of mound building than Lake Abert tufa mounds resulting in textures and facies which are much more distinct and mature than those of the Lake Abert mounds. The nodular, columnar, and laminated facies are described as major styles of mound development by Guo and Chafetz (2012). Within the Lake Abert mounds, the laminated and columnar facies are minor components; the nodular facies is non-existent as a facies style.

The travertine style facies is a facies style closely resembling Scholl and Tafts (1964) original sparry calcite texture. This texture has also been described as “travertine” within the Abert tufa mounds by Langridge and Weldon (1995), Langridge et al. (1996), and Jellinek et al. (1996).

Using Guo and Chafetz (2012) and Scholl and Taft (1964) as a guide to textural interpretations and facies, the following facies styles within the Lake Abert Mounds are summarized here and examined in depth later within the chapter.

1. A Porous 1 facies described by Guo and Chafetz (2012), as representing a deep water phase (> 1 meter). The Porous 1 facies within the Lake Abert mounds is characterized by an extremely porous texture only found in fresh outcrop. The Porous 1 facies is interpreted to be a representation of primary unaltered texture relative to the initial precipitation of carbonate.

2. The Porous 2 facies (DLT of Scholl and Taft, 1964) which is ubiquitous within all mounds of Lake Abert and is typically found within the tops and sides of mounds forms a pseudo-crust around the Porous 1 facies. The Porous 2 facies reflects a deep water phase transitioning to dry lake conditions. The contact between the Porous 1 facies and the Porous 2 facies grades from highly porous texture to minimal porosity towards the exposed exterior of the mound.

3. The columnar facies is specific to the Abert Tufa mounds, typically underlying the Porous 1 and Porous 2 style facies. The columnar facies is typically associated with large void spaces at or near ground level.

4. As the name implies, the laminar facies is a series of thin (< 1 mm) carbonate laminates of alternating light and dark layers. Typically overlying all other facies, the laminar facies is considered to mark the transition from an intermittent deep water phase to a dry lake phase.

5. The travertine facies within the Lake Abert Mounds is usually found within the lower portion of the mound along and below the basal contact of the surrounding topography and the mound. The travertine facies does not retain its original texture and is a relatively dense rock and is considered to be either the eroded remnants of a previous mound building event or a calcic vein associated with the initial stages of formation of the mound.

4.4.1 Porous 1 Facies

The primary textures of the Porous 1 facies series are the remains of calcified thalli of filamentous blue green cyanobacteria (Figure 4.2) which

closely resemble the description of Scholl's and Taft's (1964) PLT at Mono Lake.

The Porous 1 facies typically surrounds and/or overlies columnar chimneys which are interpreted by Scholl and Taft (1964) to be the calcified remains of underwater springs resulting in a cyanobacteria “halo” surrounding the chimneys. Where observed in fresh cross section the Porous 1 facies is typically a highly porous cyanobacteria-rich matrix perforated with numerous small to large conduits/voids above the central chimney(s). The conduit/voids within this facies are typically a mixture of open voids partially filled with a mixture of secondary crystallization crusts such as nodular calcite formed from thin

laminates (Figure 4.3), extremely delicate and thin calcite blades (Figure 4.11), and sub-horizontal calcic rafts. A detailed description of calcic rafts and calcite blading is provided further within this text. Like the Searles Lake mounds described within Guo and Chafetz (2012), the Porous 1 facies is interpreted to be a reflection of relatively deep water conditions formed at least 1 meter beneath the air-water interface.

Figure 4.3 showing nodular or botryoidal calcite textures on an algal matrix typically observed within the Porous 1 Facies.

4.4.2 Porous 2 Facies

The Porous 2 (weathered) facies can be found within a majority of the Lake Abert tufa mounds. Described as DLT by Scholl and Taft (1964), the Porous 2 facies is characterized by a relatively dense, resistant brown tufa typically exhibiting a remnant filamentous cyanobacteria texture which has been filled with microcrystalline calcite matrix. The texture is due to dissolution and reprecipitation. Without exception, the Porous 2 facies is found within outcrop on the exterior of all mounds which have been exposed to the modern environment (Figure 4.4).

In many of the larger mounds over-hanging draping features are commonly seen. These features mark the transition of the elevation of the air-water interface via cyanobacteria growth from deep water environments to dry lake conditions. The Porous 2 facies within the Abert tufa mounds are interpreted to be an intermediate stage weathering feature associated with the change from deep water to dry conditions.

4.4.3 Columnar Facies

The columnar facies at Lake Abert is similar to that described by Guo and Chafetz (2012) as the columnar facies within Searles Lake, “limestone cylinders” within the Miocene lacustrine algal reefs as described by Straccia et al. (1990), and physically similar to the marine carbonate chimneys of the Lost City Hydrothermal Field (Ludwig et al., 2006). Straccia et al. (1990) describe hollow central tubes surrounded by a calcareous cyanobacteria digitate zone enveloped by an exterior thick dense laminated limestone. Guo and Chafetz (2012) describe the columnar facies as being typically within the middle of the mounds and radiating outwards from the center (Figure 4.5 A, B, C, and D). Within cross section the columns are filled with micro stromatolites cemented with aragonite needles. Within the mounds of Lake Abert, the columnar facies is sporadically found both in Group A1 mounds and the most spectacularly within the Group B mound. Where observed in outcrop in Group B the columnar facies exhibits small

10-12 cm-high chimneys underlying Porous 1 facies within a central void.

Other local outcrops within Group A1 exhibit less well-defined crowded columns. These features are interpreted to be the remnants of vents that conveyed fault-derived fluids to the upper algal Porous 1 and 2 facies. Due to its position within the center of mounds observed in cross-section this facies style is interpreted to be older than the Porous 2 and laminar facies and older to concurrent with the Porous 1 facies.

4.4.4 Laminar Facies

The laminar facies is noted by Guo and Chafetz (2012) as being a fine-grained calcareous, 0.5 cm- to 4 cm-thick laminate crust covering specific sections of Searles Lake tufa mounds. The laminar facies is described as alternating wavy light-colored laminae of 10-100 μm thick and dark-colored laminae of 10-200 μm draping over mounds in fine crusts. Guo and Chafetz (2012) interpret these features as being the remnants of spring flow from lake-bottom vents which seeped through the mounds and flowed as small sheets down the exterior, analogous to flow stone in caves and seen in cones at Mammoth Hot Springs. Figure 4.6 is a comparison of laminar facies as described by Guo and Chafetz (2012) compared to a specimen collected from Lake Abert

tufa mound Group A2. Guo and Chafetz (2012) describe this facies style

as marking the transition to dry lake conditions as the lake water level dropped below the elevation of the mounds.

Within the Lake Abert tufa mounds, the laminar facies is found locally within the Group A2 mounds and primarily within smaller (<1 m height) escarpments within the Group A1 mounds. Since this facies style is found encrusting the porous travertine, columnar, Porous 1, Porous 2, and nodular facies it is interpreted to be the youngest of the tufa facies seen within Lake Abert

tufa mounds and like in Searles Lake, marks the secession of lake waters at the mounds elevation.

4.4.5 Travertine Facies

Where observed in outcrop this texture type is on the basal portion of mounds where it forms a low lying microcrystalline matrix in rounded lake gravels (Figure 4.7A) as well as angular talus near the Abert Rim Fault within road cuts (Figure 4.7B). Originally described at Lake Abert as travertine by Jellinek et al. (1996) this texture type is hard dense microcrystalline grey to grey-white rock weathering to grey brown. While most definitions of travertine are described as being formed in association with subaerial environments such as subaerial fissure style mounds and cones and associated higher temperatures (Chafetz and Folk, 1984; Pedley, 1990; Pedley, 2009), no such traditional subaerial morphologies exist within Lake Abert tufa mounds.

It is possible that the travertine texture seen at the base of some Lake Abert tufa mounds are the remnants of deposits of an older sub-aqueous mound-building event which have been eroded and the primary texture subsequently destroyed by dissolution and re-crystallization. This facies style is interpreted to be older than the overlying deposits of the subaqueous mounds stratigraphically above.

4.4.6 Section Summary

Figure 4.8 summarizes facies environment of deposition and the temporal relationships to each other. In general the relative facies porosity increases with deep water conditions and decreases with non-aqueous phase environments.

Facies	Environment of Deposition				Porosity
	Pre-Deposition	Deep Water	Intermittant Phase	Dry Lake Conditions (current)	
Porous 1	██████████	██████████	██████████	██████████	High
Porous 2	██████████	██████████	██████████	██████████	Intermediate
Columnar	██████████	██████████	██████████	██████████	High
Laminar	██████████	██████████	██████████	██████████	Low
Travertine	██████████	██████████	██████████	██████████	Low

Figure 4.8 showing the environment of deposition in the Abert tufa mounds.

Assuming a linear time path, the Porous 1 facies is indicative of a primary mound building event occurring contemporaneously with the “venting” pre-existing columnar facies. Both the Porous 2 and laminar facies occur during later stages related to weathering and the switch to a dry lake environment.

4.5 Detail of Mound Groups

Section 4.4 established the facies and facies associations identified in the Lake Abert tufa mounds in relation to research literature. The facies, facies associations, and environmental interpretations that were presented in section 4.4 are examined in relation to the details of the tufa mound groups in this section. From this examination, the context of the mounds and the conditions of mound formation are linked to the evolution of Lake Chewaucan.

Although the majority of the Lake Abert tufa mounds appear to have formed subaqueously, the Hancock et al. (1999) travertine mound classification is used here even though Hancock et al. (1999) generally described subaerial mounds. While the environment of deposition may vary from the environments to which the Hancock et al. (1999) classification was applied, the structural settings do not. Therefore the classification system may provide insights to the mound styles of the Abert tufa. It is with this in mind that the Hancock et al. (1999) classification is included here. The term tufa shall be used in this text to describe a porous textured calcium carbonate deposit whereas travertine will be used to describe relatively hard dense material with little or no remnant texture.

The Lake Abert tufa mounds are classified in four groups based on spatial proximity and, to a lesser extent, morphology. Each group will be described as to facies, morphology, elevation, and structural setting. Table (4.1) summarizes these characteristics for all groupings.

Facies classification	Group A1	Group A2	Group B	Group C
Porous 1	Yes, typically within recently exposed rock faces	Not exposed, present locally.	Yes, large interior portion of mound exposed.	Not observed
Porous 2	Present in all mounds	Present in all mounds	Within top and laterally distal ends	Observed as float
columnar	Present locally	Not observed	Yes large exposure	Not observed
laminar	Locally, typically associated with lower elevation exposures (<1311 meters)	Found sporadically within the group	Not observed	Not observed
travertine	Underlies most mounds within group.	Found within low (<50cm) exposures	Not observed	Yes, found within roadcuts and surface.
Hancock Classification	Mound/Cones 1 Range Front	Mounds/cones	Range Front	Range Front Sheet Travertine
Elevation Range	1310-1318 Meters	1308-1309	1304-1311	1304-1310
Table 4.1 Summarizing facies distribution within the Abert mounds				

4.5.1 Group A mounds

Group A is the northernmost collection of mounds within the Lake Abert basin (Figure 4.9). Comprised of a large central complex of prominent mounds and several smaller spatially associated mound groups, Group A is the largest and most diverse grouping. Group A is subdivided into 2 sub-groups on the basis

of spatial location and morphology: Group A1 and Group A2. The spatial locations of the Group A mounds is included within Appendix B.

Group A1

Group A1 (Figure 4.10) includes a series of large (4-10 m), normally elongate, high-relief (2-3 m) tufa ridges that overlie a low, reef-like, travertine platform. This platform dips to the northwest and extends from 1310 meters in elevation in the south to 1318 meters in the north. All mounds within Group A1 have relatively flat tops of Porous 2 facies which locally overhangs steep sides by as much as 1 m. The steep overhanging sides are typical of the larger mounds

within the group; these mounds appear to have been either undercut by erosional processes post formation or were formed during mound epigenesis (Figure 4.10). Group A1 mounds conform to the Mound/Cone classification as defined by Hancock (1999). Several mounds have suffered structural collapse revealing relatively fresh mound faces and cross-sections. One such mound has been labeled as mound A1.4 (Figure 4.11). Tufa mound A1.4 is an elongate mound with long axis striking N20W. The southern face of the mound has broken off revealing a mound cross section striking N60W.

Mound A1.4

Mound A1.4 is positioned upon a large travertine facies platform which in hand sample exhibits a hard, dense, relatively massive/non-porous, cream to gray crystalline texture.

The core of mound A1.4 contains Porous 1 cyanobacteria tufa intermittently infused by a network of elongate sub-vertical conduits and random void spaces. The sub-vertical conduits are typically 3-4 cm in diameter and no more than 12 cm in length. Conduits found within the center of the mound exhibit a delicate calcite blading formed perpendicular to the presumed direction of fluid flow (Figure 4.12). This calcite blading (or platy calcite) has been associated with higher fluid temperatures ($>75^{\circ}\text{C}$) and elevated levels of carbon dioxide degassing in the fluid (Jones and Renaut, 2007).

The calcite blading is only found within the centermost interior portions of the mound and above the columnar facies. The void spaces average 10-16 cm in length while having heights no larger than 8 centimeters. Botryoidal/nodular calcite consisting of small round nodules 2-3 mm in diameter typically line the walls of the void spaces and are interpreted to be the result of calcite dissolution and secondary crystallization due to fluid flow. Void spaces on the distal ends of the center portion of the mound are filled with ubiquitously horizontal, flat, 1-2 mm calcic forms and are interpreted to be calcified lake mud known as calcic rafts (see section 4.62 on formation of calcic rafts) which were trapped within

void spaces as the lake water level dropped.

The top 25 centimeters of mound A1.4 is a harder less porous form of algal tufa (Porous 2) partially exhibiting the remnant algal texture filled with a

sparry crystalline calcite. The texture is due to calcite dissolution and reprecipitation from the original genesis of the mounds to current conditions.

Tufa Mound A1.6

Figure 4.13B is a photo showing the external features of tufa mound A1.6. Ellipsoid in map view with a dished top, the southern (lake facing) side of the mound is a monolithic block of travertine facies calcite capped by a distinct separate layer of Porous 2 tufa draping over the mound on the lake-ward side of the mound. A portion of the eastern side of the mound has broken off revealing a large, resistant block of sparry calcite in sharp contact with a 5 cm-thick layer of evaporite. An XRD analysis was performed upon the evaporite layer (Figure 4.14; Appendix C), revealing the presence of trona, calcium carbonate, halite and minor amounts of thenardite, feldspars and clays. Diffractograms for tufa and evaporite samples are included within Appendix C.

The evaporite-bearing layer is topped by a section of mound with larger void spaces and columnar facies grading to Porous 1 algal tufa underlying a resistant Porous 2 tufa layer (Figure 4.13C). Partial chimneys lying on top of the trona layer suggest a continuation of fluid seeps feeding algae and a small sub-aerial spring seep at the top of the mound (Figure 4.13A).

Figure 4.13A Photo from the top of mound 6 looking south. Abert Rim shown in the background, Abert Lake within the upper right hand corner.

Figure 4.13B Photo of the top of mound 6 looking north showing relatively flat top

Figure 4.13C Photo of interior of mound 6 showing sparry calcite in sharp contact with a layer of trona grading to Porous 1 facies.

- Traavertine facies
 - Porous 1 Facies
 - Porous 2 Facies
 - Trona Layer
- Mound 6 Location

Group A2

Concentrated at a constant elevation of 1308 meters, the southern group of mounds, Group A2, (Figure 4.9) is located less than 100 meters southeast of the northern group (Group A1) and form a line of mounds striking N60W. The average height of the Group A2 mounds is one meter; the flanks are more gently sloped when compared to the flanks of the Group A1 group. Figure 4.15 is a photo showing the typical mound style. Textures appear to mirror the basal layer of the mounds of Group A1: typically microcrystalline and exhibiting lower porosity. Like the Group A1 mounds, the Group A2 mounds are classified under Hancock (1999) as mounds and cones.

Both colloform and botryoidal forms of calcite can be found locally amongst the tufa. In general, exterior calcic textures within the Group A2 mounds appear to exhibit more weathering and re-crystallization than the Group A1 mounds. Due to their smaller size and structurally stable morphologies the interior textural and structural components of Group A2 mounds largely remain a

mystery. A hand sample of the mounds reveals the calcified thalli of filamentous cyanobacteria topped by what appears to be multiple calcified successions of algal mats. Since the mound was formed at a lower elevation, presumably lake waters would still have been available to support cyanobacteria unlike portions of the larger and higher Group A1 mounds immediately to the north.

Figure 4.15 Typical mound style of the A2 Group

4.5.2 Group B mound

The group B mound is the tallest and longest tufa mound found within the Lake Abert basin. The mound strikes N30E for 250 m before bending 90 degrees to strike N60W for another 100 meters. The mound is located at the southeastern flank of the Sawed Horn Mountain (Figure 4.16 inset). At its highest point of 1312 meters the mound towers over the adjacent dry lake bed to the southeast (1304 m). Like the largest mounds within Group A1 the mound has undergone significant structural collapse as evidenced by the debris apron surrounding the mound (Figure 4.16).

The collapse has revealed a relatively hard Porous 2 facies tufa within the top 100 centimeters and on the sides at approximately 12 centimeters (Figure 4.17).

The center portion of the mound is dominated by a large void space situated at approximately 1307 meters in elevation which has been cut in half revealing shrubby carbonate chimneys that merge into overlying Porous 1 and Porous 2 facies of tufa. Much like the conduits seen within the Group A1 tufa, the now calcified shrubby columns mark the placement of fluids seeping from the ground.

Surrounding the columns and within the center void are large (20 cm x 15 cm) sub-horizontal calcic rafts which are remnants of carbonate crusts. These

Figure 4.17 Showing collapse features of the Groups B mound.

structures are formed in stagnant waters such as evaporative pools within caves (Baker and Frostick, 1951; Black, 1953; White, 1976; Folk et al., 1985; Jones, 1989) and quiet stagnant fluvial environments (Taylor et al., 2004).

As water becomes supersaturated with respect to calcium carbonate usually due to either evaporation or CO₂ degassing, a carbonate film develops upon the air-water interface, and the nucleation of CaCO₃ continues until the crust increases in mass and sinks to the bottom of the pond, pool, or lagoon. Figure 4.18 shows the debris pile after several cycles of rafting which occurred within the large center void space of the mound. The material on top of the rafts appears to be thalli-bearing detritus from the top and sides of the void emplaced after and during the deposition of the rafts.

Figure 4.18 showing interior columnar facies and calcic rafting within the group B mound.

Due to the calcic rafting, the interior columnar facies, and the Porous 1 facies found throughout the interior of the mound, the Group B mound was formed entirely within a subaqueous environment. The Group B mound is classified as range front according to the Hancock (1999) classification.

4.5.3 Group C mounds

The Group C mounds (Figure 4.19) are a series of tufa exposures formed along north-south striking faults that branch from the base of the Abert Rim fault. The mounds are all at the 1303-1310 meter elevation level and are typically very low relief. Road cuts bisecting the mounds reveal conglomerate of talus from the nearby Abert Rim within a matrix of dense travertine. The mounds are highly weathered but are distinguished by their yellow white color against the black red backdrop of the black-red talus of the Steens Basalt from the Abert Rim fault. Parts of the mounds exhibit a remnant Porous 1 algal texture in small localized areas and occasional float littering the surrounding area. Liccardi (2001) reports imbricated pebbles at the 1310 meter shoreline further south consistent with wind-driven northward long shore drift along the eastern shore of the lake. This long-shore drift probably resulted in increased erosion of the relatively delicate tufa within Group C contributing to the current condition of outcrops within Group

C.

Due to the current condition of the mounds it is impossible to say with certainty that the mounds were formed within a subaqueous or subaerial environment. The presence of Porous 1 facies in float and localized areas implies some history of subaqueous development. The Group C mounds are classified as range front and sheet travertine under the Hancock (1999) classification.

4.5.4 The “New Mound”

Most of the mounds that have been examined so far consist of mounds that are grouped according to spatial and textural relationships. The “New Mound” is neither part of the previously discussed mound groups nor within the immediate vicinity of the study area. Measuring approximately one meter in height and 1.5 meters in diameter, the New Mound is located on the eastern shore of Lake Abert (Figure 4.20) and is located 14 km south of the Group A1 tufa group. The preliminary analysis of textures in hand sample reveal a friable partially lithified calcium carbonate matrix inundated with rhizoliths tentatively identified as the pupa of *Ephydra hians*. The mound was examined in late summer 2010 during a seasonal lake low stand, at an elevation of around 1298 meters. A preliminary quantitative SEM study of hand samples was performed by Kurt Schimdt (2010 Portland State University; Appendix D) revealing that the mound was predominantly calcium carbonate with elevated phosphorous levels. Backscattered Electron imaging (BSE) photos reveal that the formation of new tufa begins as growth shrubs which in cross-section resemble the laminar facies.

Due to its delicate slightly consolidated nature and lack of weathering, this mound is interpreted to have formed recently.

Figure 4.20 Photo of the “New Mound” seen on the eastern shore of Lake Abert inset is a location map courtesy of Google Earth.

4.5.5 Section Summary

The textures and structures of the Group A mounds inform about lake conditions during and after the formation of the mounds. Using Hancock’s (1999) terminology for travertine mounds, the Group A1 mounds are a group of relatively large (>1 meter) mounds and cones. The Group A1 mounds are larger and more complex than the Group A2 mounds. The interior portions exhibit structures and textures which are indicative of the primary fluids feeding the mounds. The columnar facies is found locally amongst the mounds where the interior has been

exposed. Bladed calcite is found in conduits within mounds that probably shielded the hotter primary fluids from the cooler lake waters.

The Group A1 mounds are built upon a large low travertine facies platform which may have been part of an earlier mound building phase. Tufa mound A1.6 is a large composite mound where the basal portion appears to have been part of an earlier formed, eroded mound. This configuration suggests periods of mound building with intervening periods of desiccation and erosion within the group. The presence of an evaporite layer in sharp contact with the lower travertine facies of the platform and grading upward to the Porous 1 facies of the upper part of the mound supports the idea of a hiatus between the formation of the tufa now represented by the travertine facies and the Porous 1 facies.

As a whole, Group A1 is similar to the terrestrial fissure mound style as described by Hancock (1999) implying a tensional structural regime at the time of formation. The general strike of Group A1 is N-S indicating N-S compression and E-W extension.

Group A1 is almost entirely above the 1310 meter lake level and extends up to the 1318 meter lake level. Since there is little or no evidence of laminar facies within Group A1 it appears that the larger mounds of Group A1 were formed entirely subaqueously requiring a lake stand of at least 1318 in order to form the mounds.

Group A2 is elongate and strikes generally N60W. The different strike and elongate nature of Group A2 is the surface representation of a high angle to nearly vertical fault 50 meters to the south of the Group A1 structure.

Group A2 exhibits laminar facies and is at or below the 1310 meter lake level. The stabilized lake level of 1310 meters documented by Allison (1982) and dated to 11750 +/- 180 yr ¹⁴C B.P. by Liccardi (2001), implies that Group A2 was formed during this time. Seasonal wet-dry lake oscillations at the 1310-meter level explain the formation of the laminar facies within Group A2 mounds.

These field, textural, and spatial relations suggest the travertine platform for Group A1 formed during an earlier mound building event. Fluctuation in lake level stopped subaqueous growth of the mound and allowed partial erosion before lake level increased and deposition of the mounds that overlie the platform. The evaporite layer at the contact between the travertine platform and overlying mounds records this fluctuation in lake level. However, the facies in mounds above the evaporite layer accumulated while lake levels were high. Group A1 is older than Group A2. Group A1 formed before the overtopping of the divide between ZX Lake and Summer Lake which allowed lake levels to fall to 1310 m. Group A2 formed after the lake level fell.

The Group B mound is a large composite mound which formed on the southeastern flank of the Sawed Horn volcano. The N30E and N60W branches of the mound suggest fluid flow along both orientations during deposition of the mound. The Group B mound appears to have been formed along a fault set (NW

and NNE) which appears to reflect the two main orientations of faulting within the northern Lake Abert basin (section 2.4). The mound has the Porous 1, Porous 2, and the columnar facies, but lacks the travertine and laminar facies. The lack of the laminar facies implies that the mound was subaqueous throughout its history and did not occur contemporaneously with the lowering of lake levels.

The Group C mounds are a collection of highly eroded mounds that occur between the elevation of 1316 meters and 1304 meters along the northeast shoreline of Lake Abert and are bisected by U.S. Highway 395. The Group C mounds exhibit travertine facies in place, but some Porous 2 facies amongst tufa float. It is unclear whether the relatively weathered condition of the mounds is due to the impact of talus from mass wasting from the Abert Rim scarp, wave action from the lake, or an older age than mounds to the west. The Group C mounds are located on a series of north-south striking faults which terminate at the nearby Abert Rim fault scarp.

A relatively recent mound is present along the eastern shoreline of Lake Abert and 14 km south of Group A1. The mound is relatively small and texture in hand sample reveals a loosely consolidated calcium carbonate matrix interspersed with the tentatively identified calcified pupa of *Ephydra hians*. The presence of a relatively recent tufa mound implies that the fluids forming the mounds still discharge today.

CHAPTER 5.0 DISCUSSION

5.1 Introduction

The following disseminates the apparent causal relationship between the mounds, the faults on which they appear to overlie, and the early Holocene - late Pleistocene lake levels of Lake Chewaucan. The section has been divided into five sections:

1. **Mounds and Faults:** This section explores the relationship of the mounds to regional fault patterns and magnetometer data suggesting that the formation of the mounds is intrinsically linked to the presence of faults below them.
2. **Lake Levels:** This section examines the timing of lake levels at elevations critical to the formation of mounds located at 1310 meters and 1318, and attempts to constrain the age of the mounds by carbon age dating of lake levels available in the literature.
3. **Mounds and the Lake:** This section delves into facies analysis and mineralogical associations of the mounds. The presence of trona and features such as calcite rafts are examined in context to what the lake conditions were during the formation of the mounds.
4. **Evidence of mounds older than 12000 ka:** The character of the A1.6 mound and other sporadic mounds throughout the study area suggest that an earlier mound building event may have occurred. This section

explores this idea and suggests that the mounds may have been formed during an earlier lake oscillation recorded within the literature.

5. A conceptual model for the formation of Lake Abert Tufa mounds: A conceptual model is presented attempting to explain the formation of the mounds in context of the evidence presented. A cartoon is included at the end of the section.

5.2 Mounds and Faults

It is clear that the formation of the Abert tufa mounds are intricately linked to faults along the Central Oregon Fault Zone as described by Pezzopane and Weldon (1993), due to proximity of all mounds groups studied to nearby fault traces and the matching orientations of the mound groups (NNE-NW).

It is tempting to link the formation of the mounds to movement of faults within the study area; however there is no direct evidence to suggest that the mounds formed directly as a response to movement and may have just formed along previously dilated pathways. Interestingly, Weldon et al. (2009) discovered evidence of a major earthquake cluster ($M \sim 7$) between 7 and 13 ka within the Summer Lake Basin during the period when Lake Chewaucan went from 1325 meters in elevation to its current low stand and corresponding to the general time of formation of the Lake Abert tufa mounds. Weldon et al. (2009) hypothesized that the drying of Pleistocene Lakes significantly affected the recurrence interval of earthquakes within the area.

Magnetometer data imply that faulting has occurred directly below both Group A1 and Group A2 tufa, both groups B and C physically overlie fault traces; clearly the Abert tufa mounds are associated with faulting within the Abert fault zone. The presence of fluids migrating thru faults feeding the mounds implies that faults involved were either active or dilated during mound formation creating preferential pathways within the individual fracture zones. In addition, mound formation within relatively discrete individual zone and not as part of a large scale event of all faults under north Lake Abert suggests that mound formation occurred only within those faults which were dilated enough to allow fluids to the surface.

The history of faulting during the Pleistocene and Holocene on the faults of the Lake Abert system is open to debate. Pezzopane and Weldon (1993) reported 4- to 5-m fault scarps cutting debris flow deposits that bury the 1310 m shoreline on the Abert Rim fault along the western flank of Abert Rim. They also reported preliminary results from the analysis of the high stand shoreline (1378 m shoreline of Allison, 1980) of pluvial Lake Chewaucan. The elevation difference for this shoreline along the base of Abert Rim and other parts of the basin is as much as 14 m.

Licciardi (2001) found the 1310 m shoreline to be continuous throughout the basin implying little or no movement on faults since the early Holocene. Licciardi (2001) states that there was little or no movement at least since the early Holocene or that any movement along the Abert Rim was restricted to the

footwall of the fault above the shoreline: in direct conflict with Pezzopane and Weldon (1993) who reported fault scarps offsetting as much as 4 meters of Holocene colluvium overlying the 1310 meter lake shoreline.

5.3 Lake levels

Textures in the Lake Abert tufa mounds are consistent with formation in “deep” (>1 m) subaqueous to slightly above the air/water interface. The Group A1 and Group B mounds lack textural facies that are consistent with subaerial growth. However, Group A2 and probably Group C contain textural facies consistent with shallow water to subaerial growth.

The textural evidence is consistent with tufa formation during various stage conditions of pluvial Lake Chewaucan. Although the high stand shoreline reported by Allison (1982) is at 1378 m, the shoreline of importance for the timing of tufa formation is the 1310 m shoreline that developed after overtopping of the gravel bar between the ZX Lake and Paisley Flat. The overtopping and subsequent erosion allowed the lake level in ZX Lake which included Lake Abert to fall from 1325 m to 1310 m. Licciardi (2001) reports a mean radiocarbon date of 11750 ± 180 ^{14}C yr B.P. for three gastropod shells along the 1310-m eastern shoreline of Lake Abert in sediments that imply a regressive sequence. The 1310 m elevation is also the elevation of the narrows separating the lower Chewaucan Marsh from the Upper Chewaucan Marsh which consists of a broad flat plain sloping from 1313 meters in the north to 1310 meters in the south. Any seasonal

transgressions of water would have been limited in elevation due to the upper Chewaucan Marsh acting as an overflow reservoir for the lower Lake Abert and Upper Chewaucan Marsh resulting in a stabilizing effect of lake depth at the 1310 meter elevation.

Jellinek et al. (1996) reported the elevation of the mounds at around 1310 meters. The Group A2, Group B, and Group C mounds conform to this description. However, the Group A1 mound was formed at an elevation range from 1310 meters to around 1318 meters. The Group A1 mounds were probably formed between the drawdown of the 1325 meter strandline dating from 11930 $\pm$ 90 C¹⁴ B.P. to the 1310 meter strandline at 11750 $\pm$ 180 C¹⁴ B.P. (Figure 5.0).

5.4 Mounds and the Lake

Textural and spatial evidence indicates the Group B mound formed at a lower elevation, on the edge of a topographic high, and in a deeper water column. However, all mounds associated with the 1310 m level exhibit the same characteristics: sub-meter height, highly weathered, and evidence of extensive dissolution and recrystallization. These characteristics suggest prolonged exposure to water and seasonal transgressions and regressions. The laminar facies style within the Group A2 mounds is particularly supportive of transgressive-regressive seasonal cycles before the area entered into dry-lake conditions.

The Group A1 mounds, however, are located at elevations higher than the 1310 m shoreline. With the exception of one highly weathered large mound located to the east of Group A1 all mounds with an elevation higher than 1310 m overlie a low (1-2 m), gently sloping, hard carbonate platform rising above the northern lake bed. The platform was formed before the larger mounds on top, judging from its highly weathered character and stratigraphic position.

The mounds that overlie the travertine platform exhibit subaqueous textures implying that the lake level was at least as high as the mounds during their formation. The presence of the highly porous Porous 1 facies requires at least very limited contact with the weathering effects of water after its formation. The rafting features within the void spaces which were presumably in hydraulic contact with the lake water are indicators of the lake level as the waters of Abert

receded. The relatively pristine character of the Porous 1 facies within the Group A1 mounds combined with the secondary carbonate rafts imply that the formation of at least part of the mounds probably occurred during a relatively rapid lake regression. These inferred relations may account for the heavy oxygen and carbon isotope values reported by Jellinek et al. (1996) (Table 1.0) for Lake Abert tufa and interpreted to be partially due to tufa formation during highly evaporative conditions.

Highly evaporative conditions are also indicated by the mineralogy determined by XRD for the evaporite layer in mound A1.6. The mineral assemblage included calcite, aragonite, trona, and halite. This mound formed when lake levels were above the 1318 meter strandline.

Calcium carbonate minerals included calcite and aragonite. The presence of carbonates, calcite and aragonite, as shown within the diffractogram is not particularly surprising considering that sample T6A3 was collected between two tufa layers. Because the sample was exposed to water treatment after the original diffractogram was taken, it is impossible to say whether unstable hydrous minerals such as gaylussite ($\text{CaNa}_2(\text{CO}_3)_2 \cdot 5(\text{H}_2\text{O})$) existed within the sample and then were converted over to CaCO_3 .

Trona is associated with evaporative waters that have high concentrations of HCO_3^- , Cl^- , Na^+ and low $\text{Ca}^{2+}/\text{CO}_3^{2-}$ ratio (Eugster and Hardie, 1978). The traditional model for trona deposition has been formation in closed drainage basins developed in volcanic rocks. Hydrolysis of the volcanic rock provides CO_2 ,

whereas the closed basin concentrates the Na^+ cations (Jones, 1966). However, as pointed out by Earman et al. (2005) the formation of trona is a rare occurrence when compared to the amount of closed basin lakes that are dominated by volcanic inputs within the western United States. Lake Abert is one of only four lakes within the western United States that have the present day potential to precipitate trona (Smoot and Lowenstein, 1991).

According to Earman et al. (2005) the occurrence of major trona deposits either 1) overlie oil shales such as the Green River Formation where the decomposition of organisms associated with oil shales supply an injection of excess CO_2 to the saline deposits above them; or 2) are found in areas of crustal thinning and volcanism such as found near Mono Lake where crustal thinning and associated hydrothermal activity would similarly contribute magmatic CO_2 to the evaporative waters forming trona within the lake.

The presence of trona within the evaporite sample confirms published reports of trona being present (Banfield et al., 1991) within Lake Abert sediments. Curiously, all spatial references to trona formation are associated with highly Na^+ and Cl^- concentrated brines at the water table usually in the subsurface. Sample T6A3 was found approximately 2.5 meters above current ground surface between two tufa layers. Due to the position of the trona and the subaqueous character of the mound texture, water levels had to be at least as high as the mound during the formation of trona.

Like trona, the presence of halite within the sample is indicative of highly evaporative conditions and corresponds to the Na-CO₃-Cl types of brine attributed to Abert Lake by Eugster (1980). Once again, ephemeral ponding could create the conditions for halite precipitation while the lake was under high stand conditions.

Within evaporitic brine, the formation of calcium carbonate is always favored and will precipitate first as long as there is enough CO₂ and Ca²⁺ available. Sodium carbonate forms only if the Ca²⁺ has been depleted and there is adequate supply of CO₂ (Eugster, 1980). The presence of trona requires that the Ca²⁺ cation was temporarily depleted during the formation of the evaporitic layer within tufa mound 6. The presence of calcium carbonate (tufa) overlying the evaporite (trona/halite) layer implies that the source of the Ca²⁺ cation was temporarily halted during formation of trona and started again with the formation of tufa above the trona layer. Since the evaporitic brine of Lake Abert is Ca²⁺ and Mg²⁺ poor (Figure 2.7) and an alkaline lake by definition provides a rich source of CO₂, the formation of tufa within Lake Abert is driven by the source of Ca²⁺ and H₂O which is provided by springs emanating from faults.

While ikaite has not been observed within the Lake Abert mounds it has been observed within other analogous Basin-and-Range tufa- producing pluvial lakes (Shearman et al. 1989). Due to the temperature conditions of the formation of ikaite, the lack of thinolite textures within the Abert Basin may infer important

environmental conditions or temporal relations during the formation of Lake Abert Tufa.

5.5 Evidence of mounds older than 12000 ka

Mound A1.6 is a large travertine facies carbonate block mound overlying a stratigraphically older carbonate ramp and sharply contacting the underlying Porous 1 facies and a trona layer. The evaporate layer implies a hiatus between the formation of the underlying sparry calcite block and the overlying Porous 1 texture (Figure 4.14). The larger, heavily weathered mounds found sporadically throughout the Group A1 basin indicate differential age for some mounds and elevation range within the same group. None of these mounds exhibit the typical character of sub-aerial mounds as detailed by Chafetz and Folk (1984) and appear to be formed subaqueously. These mounds may have been formed during one of the older 13-14 ka wet-dry oscillations as detailed within (Liccardi, 2001) and Benson (1999) using $\delta^{18}\text{O}$ proxy data for the Owens Lake Basin.

Although the formation of the tufa mounds occurred while pluvial Lake Chewaucan existed, the conditions that allowed tufa mounds to form, i.e. discharge of water of appropriate composition apparently did not persist after lake levels receded to their modern condition. There appears to be no evidence of purely subaerial depositional conditions. The small, apparently active mound located 14 km south of the Group A1 mounds and along the east shore of Lake

Abert suggest modern discharge of fluid of appropriate composition for mound formation is occurring.

5.6 Conceptual Model for the Formation of the Abert Tufa Mounds

In order for a conceptual model of Abert tufa mounds the following conditions need to be accounted for:

1. A system that introduces calcium carbonates in the lake environment.
2. A system where calcite rafts and bladed calcite could form.
3. Lake conditions that could produce trona.

With these three conditions in mind, the following is a conceptual model for the formation of the Lake Abert tufa mounds. Figure 5.1 is a cartoon illustrating conceptual mound formation:

1. Mounds formed where warm $\text{Ca}^{2+} + \text{HCO}_3^-$ -rich water discharged from dilated segments of the regional fault system and mixed with Na^+ rich lake water. Cyanobacteria present in the lake in the area of discharge and CO_2 degassing became encrusted in carbonate minerals as the mound accumulates.
2. Carbonate precipitation occurs as a result of CO_2 degassing, cooling, and mixing with lake waters. Pipes and conduits carried water onward thru the interior of the mound creating bladed calcites within conduits

and isolating interior portions of the accumulating mound producing open spaces similar to mini caverns. As water levels declined carbonate rafts formed at the air-water interface, periodically sank and accumulated along with fragments of the calcium carbonate encrusted cyanobacteria surrounding the evolving cavern walls and ceiling.

3. Episodic/seasonal variations in lake levels allowed partial isolation of pools from the lake and possibly during a time of low discharge from the vents (Ca^{2+} starved) allowing evaporite minerals such as sodium carbonate (Trona) to accumulate. Perennial vent fluctuations and lake level rise allowed the shift in conditions to calcium carbonate precipitation.

Figure 5.1a Fluids begin seeping from faults

Figure 5.1b Calcium carbonate begins to precipitate in the form of small chimneys. A zone of diffusion begins to develop over the chimneys as spring fluids mix with the lake water.
At the air-water interface an algal mat develops above the site. Calcification of the mat occurs simultaneously. Porous 1 and columnar facies begin to develop.

Figure 5.1c Chimney growth advances; the algal mat thickens as the water level starts to drop.

5.1d Water level continues to drop, fluids flow through preferential pathways and conduits within the mound, resulting in bladed and botryoidal calcite crystals. Mound features exposed to the arial environment begin to weather resulting in the Porous 2 facies. Laminar facies develops were fluids reach the exterior of the exposed mound.

5.1e As the water level continues to drop the water within the mound becomes superaturated in respect to calcium. Calcic rafts develop at the air water interface and drop as they develop mass. Porous 1 and columnar facies experience little to no growth. Porous 2 facies is dominant with episodic fluid discharges forming the laminar facies.

5.1f Mound is now dry, all exposed mound features undergo weathering (Porous 2 facies).

6.0 Conclusions

1. Mounds were formed where active faults were underlying the lake during a time of higher lake levels than today. Magnetometer data and field relationships confirm the relation between mounds and faults.
2. Due to its subaqueous textures the formation of the Group A1 mounds is intrinsically linked to the lake levels during formation. Carbon dating by Liccardi (2001) indicates that the lake drew down from 1325 meters at 11930 $\pm$ 90 C¹⁴ B.P. to the 1310 meter strandline at 11750 $\pm$ 180 C¹⁴ B.P.; requiring that the Group A1 mounds were formed between a time period of not more than 450 years. Because of the relatively intact nature of the 1310 meter strandline displacement on the faults forming the Group A2, Group B, and Group C Abert tufa mounds were restricted to the time immediately before or during the formation of the 1310 meter strandline which has been dated at 11750 $\pm$ 180 C¹⁴ B.P. These dates are statistically indistinguishable, suggesting a relatively short time passed.
3. Facies analysis suggests that after Group A1, Group A2 and Group B were formed, evaporative conditions persisted. Analysis of oxygen isotopes in Abert tufa mounds by Jellinek et al. (1996) confirms that the mounds were formed in an evaporating environment.

4. Evidence of earlier mound building events exists solely in the travertine facies style block mounds and the composite nature of tufa A1.6. While there may have been an earlier tufa mound building event, its timing and original extent are not resolved.

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Appendices

Appendix A Magnetometer Data

Magnetic survey pathways: black lines are pathway locations, raw magnetic data are included with cd inset.

Appendix B Group A1 and A2 Locations

descrip	Strike	waypoint			UTMS		PIC#	Height
Tufa 1	N40E	18	10	T	733421	4736791	726-729	11
Tufa 1a	N40E	19	10	T	733414	4736770	731-734	11
Tufa 2	N45E	20	10	T	733510	4737032	735-737	5
Tufa 3	?	21	10	T	731961	4737403	738-741	7'6"
Tufa 4	N20W	22	10	T	732105	4737415	742-755	8
Tufa 5	N20W	23	10	T	732131	4737444	756-757	3
Tufa 6	N50W	25	10	T	732136	4737467	760-761	12
Tufa 7	N20W	26	10	T	732174	4737457	762-770	8
Tufa 8	N35W	29	10	T	732146	4737535	774-775	9
Tufa 9	N5W	24	10	T	732138	4737444	758-759	3
Tufa 10	N35W	27	10	T	732146	4737484	771-773	4
Tufa 11		30	10	T	732099	4737543	776-778	
Tufa 12		31	10	T	732102	4737540		3
Tufa 13		32	10	T	732102	4737578	779-783	
Tufa 14	N5E	33	10	T	732103	4737580	785-788	
		34	10	T	732115	4737613		
		35	10	T	732140	4737690		
	N5W	36	10	T	732088	4737701		
Tufa 15	N	37	10	T	732197	4737706	789-793	7
		39	10	T	732186	4737741		
Tufa 16	N15W	40	10	T	732247	4737498	794-795	7
Tufa 17	N30E	41	10	T	732190	4737484	796-798	
Tufa 18	N5W	42	10	T	732191	4737482	799-800	
Tufa 19	N65W	43	10	T	732182	4737413	801-803	2
Tufa 20	N45W	44	10	T	732190	4737379	804-806	2
Tufa 21	N5E	45	10	T	732208	4737364	807-808	3
Tufa 22	N15W	46	10	T	732217	4737354	809-810	2
Tufa 23	N15E	47	10	T	732468	4737378	811-813	4
Tufa 24		48	10	T	732499	4737414	814	
Tufa 25	S80E	49	10	T	732510	4737404	815-817	2
Tufa 26		50	10	T	732510	4737398	818-819	2
		51	10	T	732535	4737393		3
Tufa 27	a	52	10	T	732554	4737369	820-823	
	b	53	10	T	732560	4737369		
	c	54	10	T	732562	4737368		
Tufa 28		55	10	T	732576	4737352	826	5
Tufa 29		56	10	T	732583	4737361	827	2
Tufa 30	S80E	57	10	T	732590	4737352	828	5
Tufa 31	S75E	58	10	T	732596	4737349	829	4
Tufa 32	S80E	59	10	T	732596	4737338	830-831	5
Tufa 33		60	10	T	732607	4737342	832	1
Tufa 34	N25E	61	10	T	731707	4737645	836-837	3'6"
Tufa 35	N15W	63	10	T	732053	4737486	845-846	5
Tufa 36	N10W	64	10	T	732716	4737457	847-848	12
Tufa 37	N35E	65	10	T	732675	4737339	852	3
Tufa 38	N35E	66	10	T	732673	4737329	853	3
Tufa 39	N35E	67	10	T	732666	4737329	854-855	3
Tufa 40		69	10	T	732780	4737294	859-860	1
Tufa 41			10	T	733031	4737053	861	5
Tufa 42			10	T	733001	4737081	862	1
Tufa 43	N75E	71	10	T	733223	4737051	863	4' 6"
Tufa 44	N70W	72	10	T	731317	4736710	864	3' 6"
Tufa 45	N70W	73	10	T	731304	4736714	865	5
Tufa 46		74	10	T	731292	4736724	866	1
Possible tufa					730761	4723078		
roadside 1					734551	4734081		
roadside 2					735787	4734081		

Appendix C XRD Data

Edited diffractogram of evaporite sample.

Edited diffractogram of evaporite sample after being washed with deionized H₂O.

Edited diffractogram of evaporite sample after acid and H₂O wash.

Unedited diffractogram of a Group A2 sample, major constituents calcite and clay tentatively identified as palygorskite.

Unedited diffractogram of a bladed calcite sample containing calcite, aragonite, and possible palygorskite.

Appendix D New Mound SEM Photos

Courtesy of Kurt Schmidt, Department of Geology, Portland State University

Hand sample cross section, with EDX analysis areas labeled with area. Dime for size reference.

BSE-T image of area A, showing growth shruvs. Figure 6B , BSE-C image of the slice section highlighting the perpendicular growth from the nucleation sites.

BSE-T image of area B, white arrows highlight unconstrained crystal growth inside the Rhizoloth rim (black arrow).

Oxford INCA plot of a 60 second active EDS scan of area A. The phosphorus peak is the main element which exceeds average concentrations for carbonates.

BSE-C image of area B, note square burn marks left by 60 second active scan. Figure B Oxford INCA plot for the upper scan on figure A.

Appendix E Photo Micrographs of Tufa Textures

Photomicrographs of bladed calcite crystals pencil lead is .7 mm

Left is photomicrograph of algal remains right is botryoidal calcite

Appendix F Raw Magnetic Data

Appendix F Is included as a supplemental file in .pdf format. Data includes 10867 data points including magnetic intensity, location, and time of acquisition.