Onshore groundwater spring carbonate mounds to lacustrine microbialites, the perplexing record of a transitional Great Salt Lake carbonate shoreline at Lakeside, Utah

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Abstract
Non-marine carbonates at Lakeside (Utah) are the depositional record of transitional shoreline palaeoenvironments around 1,285 m, as lake elevation fell from Lake Bonneville levels to low-stand Great Salt Lake levels of 1,284–1,278 m. Lakeside carbonates provide a rare example of onshore groundwater spring deposits connected to lacustrine microbialite reefs. Clotted fabrics and mineralized bacteriomorphs suggest microbial influence both in groundwater spring and littoral carbonates. Thrombolitic clotted aragonite and dendritic clotted intermediate magnesium calcite may document two distinct microbial ecosystems each with a specific mineralogy. Radiocarbon dates from interior to outer layers of a 20 cm littoral microbialite suggest several thousand years of domal growth. Climate fluctuations may be recorded in littoral deposits by the alternation of ooids (increased salinity, arid conditions) with ostracods (fresher water, humid conditions). Successive higher frequency cycles of sedimentation, exposure, microkarst and early diagenesis were cemented by vadose and phreatic very high magnesium calcite and non-stoichiometric dolomite. Several layers of littoral and beach deposits accumulated during longer lacustrine transgressive–regressive cycles. Clastic detritus and lack of known initial U and Th concentrations could explain the lack of correlation between widely scattered U-Th ages and closely grouped 14C dates. Calibrated ages from radiocarbon dating may have been increased by long residence time of groundwater in bedrock, since 87Sr/86Sr signatures do indicate possible littoral-zone mixing of lake water with groundwater from outcropping and subsurface Mississippian Great Blue Limestone. The perplexing Lakeside carbonate system is the result of interaction between microbial and chemical processes during sedimentation and early diagenesis.

KEYWORDS
groundwater springs, lacustrine shoreline carbonates, microbialites
1 | INTRODUCTION

1.1 | Context and focus of the study

Lacustrine shoreline carbonates are exposed at many localities around the Pleistocene to present-day lacustrine systems of the Great Basin, western Utah and Nevada. While very large tufa pyramids and towers, up to 100 m high developed in deeper water settings of Lake Lahontan (Benson, 2004) at locations with groundwater influx (DeMott et al., 2019), smaller metre-scale microbialite mounds formed in the shallower Great Salt Lake (Baskin, 2014; Vanden Berg, 2019; Vennin et al., 2019). They have been known since King (1878) and Gilbert (1890) and intensively studied following the pioneering work by Eardley (1938). Eardley justifiably emphasised both “stromatolites” (his term, now more broadly identified as microbialites) and ooids as significant sediment components of the lake, with probable microbial influence or mediation. Travertine is common at hot springs of the western Great Basin (Yap et al., 2018). Minor occurrences of travertine are exposed above Beck Springs at Salt Lake City, along the Warm Springs Fault, the bounding fault separating the extensive Great Basin from the Wasatch Mountains (Chiasson & Boyd, 2006; Murphy & Gwynn, 1979).

The 300 m rise and fall in elevation of the vast Lake Bonneville-Great Salt Lake system (Figure 1A) over the past 30,000 years recorded by Gilbert (1890) was laid out by Currey et al. (1984). Further research on shoreline geomorphological and depositional features, improved geochronology and calculation of isostatic response to unloading after lake-level fall has more recently allowed refinement of the chronology and hydrograph (Figure 2A; Godsey et al., 2011; Oviatt, 2014, 2019; Oviatt et al., 2015). Shoreline carbonate exposures at higher elevations were deposited along earlier and higher Provo and Bonneville shorelines (“capping tufa” and “beachrock” of Felton et al., 2006; “crusts” and “microbial deposits” of Vennin et al., 2019). Baskin (2014) developed novel sonar techniques and mapped present-day microbialite distributions even under the hypersaline lake water. Lowered lake elevations during the past decade, dropping below the historical average from the effects of climate, and the imbalance between precipitation and evaporation, have allowed the close inspection and study of Great Salt Lake littoral microbialites during exposure (Chidsey et al., 2015; Bouton et al., 2016a; Pace et al., 2016; Newell et al., 2017; Vanden Berg, 2019).

The discovery of the role of microbial activity in the formation of dolomite precursors and dolomite (Vasconcelos & McKenzie, 1997; Vasconcelos et al., 1995) was followed up at Lakeside. Pedone and Dickson (2000) examined the replacement of primary carbonate by “round-faced dolomite” in one of the larger littoral mounds at Lakeside’s Death Point but did not conclude that microbial influence was responsible for this dolomite.

The study documented here focussed on the geology of the Lakeside carbonates, backed up by limited geochemical analyses, and could provide the basis for future geomicrobiological studies. Study of the Lakeside carbonates was initiated in 2012 within the context of training and research in Petrobras linked to the exploration of pre-salt lacustrine carbonates in the Santos Basin, offshore Brazil. Popular topics discussed by the teams involved included petrographic and mineralogical evidence for the role of microbial activity in deposition of lacustrine carbonate versus chemical precipitation, and differences in facies between groundwater spring carbonates and lacustrine microbialites. These questions provided the focus of this study.

Outcrop observations were made at millimetre to 10 m scales, and were followed up by mapping, coring and sampling. Laboratory analyses were carried out at nanometre to micron and centimetre scales. Isotope geochemistry targeting bulk and point samples was carried out to provide geochronology and to refine interpretations based on stratigraphic relationships, facies associations and geobody distribution. The petrography and geochemistry of both onshore groundwater spring carbonates and lacustrine microbialites at Lakeside do indeed provide fingerprints of microbial activity associated with chemical precipitation of the carbonates.

To avoid ambiguity, given the local usage of “tufa” for all shoreline carbonates, and with regard to previous literature, the terms “groundwater spring carbonate”, “littoral microbialite” and “lacustrine microbialite” are used for the transitional shoreline carbonates at Lakeside. These features record a transitional shoreline much lower than the Provo shoreline and slightly above Great Salt Lake shorelines. Poor knowledge of water temperature during deposition precludes using either cool water “tufa” or warm to hot water “travertine” for the onshore deposits (Jones & Renaut, 2010). Evidence of microbial activity would allow “microbialite” to be used for all three carbonate types (Vennin et al., 2019) but the clear distinction between onshore, littoral and subaqueous lacustrine depositional settings at Lakeside gives preference to the use of three terms. Pentecost (2005), Jones and Renaut (2010), Capezzuoli et al. (2014) and Della Porta (2015) stand out as major sources of information among the vast literature on groundwater spring and lacustrine carbonates, and they include extensive references on the subject. The Lakeside shoreline carbonates, involving onshore groundwater spring carbonates directly connected to shallow lacustrine microbialites when the lake fell from the Provo level, provide a singular case to add to the depositional record of Great Salt Lake carbonates.

1.2 | Outcrop locations, local and regional geology, hydrogeology

The Lakeside carbonates are located at the northern termination of the Lakeside Mountain range on the west side of Great Salt Lake (Figure 1C,D). They are pale to white coloured
FIGURE 1  (A) Pleistocene lakes of western North America, showing the Bonneville–Great Salt Lake and Lake Lahontan systems. Red arrows show path of flood lowering Lake Bonneville to the Provo level. (B) Great Basin between the Rocky Mountains and Sierra Nevada showing Basin and Range topography. A, B from Wikipedia commons, 2020. (C) Geological map of northern Lakeside Mountains, Doelling (2003). (D) NW–SE–SSE structural cross-section (A–A’ on map) and legend for map.
discordant encrustations on Mississippian Great Blue Limestone bedrock and loose beach material (Figures 2B and 3A) as well as forming mounds and flat-lying stratified layers along the present shoreline, located (Figure 3B) between Lakeside West (41°13′3.54″N 112°54′25.65″W) and Cave Ridge south (41°11′14.12″N 112°49′6.89″W). Specific outcrop locations referred to in this study are, from north to south: Dos Equis Point (41°13′29.84″N 112°52′13.68″W; Figure 4A); Death Point (41°13′23.44″N 112°51′11.62″W; Figure 4B); Atwoods Beach (41°13′11.82″N 112°51′9.54″W; Figure 5A); Atwoods Point (41°13′10.19″N 112°51′5.13″W; Figure 5B); and Cave Ridge South (41°11′14.12″N 112°49′6.89″W; Figure 5A). Broader, 1–10 m-scale features of the carbonates at these locations are clear to see on Google Earth satellite imagery.

**FIGURE 2** (A) Chronology and hydrograph of Lake Bonneville-Great Salt Lake (Oviatt, 2019). (B) Pale to white-coloured carbonate encrustations at Atwoods Point. a: Atwoods Point, Mississippian Great Blue Limestone bedrock; b: “white band”, a thin crust of carbonate deposited along the shoreline during the 1986–1987 high stand of Great Salt Lake; c: onshore groundwater spring carbonate encrusting the bedrock; d: Monk’s head lacustrine microbialite growths in continuity with the onshore groundwater spring carbonate.

**FIGURE 3** (A) Transitional shoreline carbonates around Atwoods Point, a spur of Mississippian Great Blue Limestone (a) exposed along the historic lakeshore zone. Oblique aerial view looking NW towards Death Point (DP) located just across the causeway. The wooden log shown by a white arrow, provides a scale measuring 4.4 m. (B) Northern end of the Lakeside Mountains on the western shore of Great Salt Lake (inset) at the termination of the Union Pacific Railroad causeway. Localities mentioned in the text are as follows: (1) Lakeside west; (2) Lakeside quarries; (3) Lakeside Ridge; (4) Middle Ridge; (5) Cave Ridge South; (6) Dos Equis Point; (7) Death Point; (8) Atwoods Beach; (9) Atwoods Point. Google Earth Landsat/Copernicus satellite image 2020.

The highly detailed 1 : 24,000 geological map of the Lakeside Mountains (Figure 1C,D) by Doelling (1964, 2003) covers the outcrop area. The Lakeside Mountains, together with the Grassy Mountains and Gosute Mountains (Homestead Knoll), build a composite north trending fault-controlled range, which separates the basins of the Great Salt Lake Desert to the west from Great Salt Lake to the east. The northern Lakeside Mountains form an 8 km broad synclinal structure of Ordovician to Mississippian rocks, oriented SW to NE and cut by NNE trending faults. Normal faults determine three main ridges to the east of the Gosute Mountains, all of them exposing Mississippian Great Blue Limestone (Doelling, 1964, 2003) and ruling the coastal geomorphology of headlands and bays (Figure 3B). From west to east these major morphological features are Lakeside (Death) Ridge, Middle (Scad)
Ridge and Cave Ridge (Doelling, 1964, 2003). At broader scales the Basin and Range morphology of the Great Basin has been attributed to the Neogene rotation of listric fault blocks (Axen, 2004) during regional extension, set in the geodynamic context of the San Andreas transform system by Dickinson (2006).

The flooding of the Lakeside Mountains by Lake Bonneville for over ten thousand years, followed by the fall to historic Great Salt Lake elevations (Figure 2A) must have impacted groundwater recharge and discharge significantly, accompanying climate evolution from glacial to interglacial conditions. There are fewer groundwater systems to have played a dynamic role in the formation of the Lakeside carbonates, compared with the systems at Antelope Island (Mayo & Klauk, 2000) since there is no local river influx at Lakeside. The three main systems contributing to groundwater in the Lakeside Mountains during the transition from Lake Bonneville to Great Salt Lake are: (a) lakewater, evolving from fresh during the Bonneville rise to brackish and saline during the fall, and even to hypersaline after the fall to Holocene levels; (b) bedrock aquifers in the Lakeside syncline structure, perhaps with sufficient groundwater residence time to approach chemical equilibrium with host rocks such as the Great Blue Limestone, and (c) several higher-standing to superficial aquifers with shorter groundwater residence time. Bedrock groundwater conduits follow the fracture systems and karst in the Great Blue Limestone at Lakeside (Figures 1 and 6).

2 | METHODS AND DATA

2.1 | Field observations and analyses

The Lakeside carbonate deposits and facies were described and recorded in the field by visual observation and by hand lens, at 10 m to 1 mm scales. Coring was carried out on a large mound at Death Point (3 vertical cores and 1 horizontal core, coring tool and core diameter) and through several layers of deposits at Atwoods Beach (3 vertical cores). Cores measuring 4.5 cm in diameter were obtained using a Shaw backpack drill with a 51 mm coring bit. Core recovery was >90% from cemented rock, but much less to none from non-lithified sediment. Facies were identified and sampled on outcrop in the field and on cores. Field-based facies associations and groupings were directly linked to geomorphological units by visual observation in the field. Facies categories and geomorphological units were mapped onto high-resolution low altitude aerial photos provided by a customised quadcopter drone (phantom 3 Professional Model W323) survey, as well as on images from Google Earth.

2.2 | Laboratory observations and analyses

Initial sample preparation was carried out at: Utah Geological Survey (Salt Lake City); UNESPetro (Rio Claro, SP, Brazil); CETEM (Rio de Janeiro, RJ, Brazil); Utah State University (Logan UT); Department of Geosciences, University of Fribourg (Switzerland) and GEOSOLUTIONS TRD (Gan, France). Prior to sample preparation, facies observed in the field were grouped first under geomorphological units and then identified following Gandin and Capezzuoli (2014) and Capezzuoli et al. (2014) after combining outcrop observations with thin section petrography. Sedimentary petrography was carried out on normal and large size (7 × 5 cm) stained thin sections (alizarin red and potassium ferricyanide staining, Dickson, 1966), with polarizing optical microscopy, under cathodoluminescence microscopy with Cambridge CLmk3A stage coupled to a Nikon microscope at Fribourg University and with a CITL Cathodoluminescence...
Mk5-2 (229 mA, 11 kV) coupled to a Zeiss microscope at UNESPetro. Scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDS) was carried out at UNESPetro on polished thin section plated with carbon, for semi quantitative analyses (Zeiss EVOMA15 with a XFlash Detector Series 6110; Bruker). Freshly broken sample surfaces were coated with gold at Geosciences Department of Fribourg University and studied under an FEI XL30 Sirion FEG instrument. Micro X-ray fluorescence spectrometer analyses were carried out on thin sections at UNESPetro with an M4 Tornado from Bruker. X-ray diffraction (XRD) was made on 62 selected samples at CETEM (Bruker-AXS D4 Endeavour, using Ni-filtered CoKα, 40 kV, 40 mA) radiation, primary aperture 0.6 mm and primary and secondary 2.5° soller slits; 2θ range from 4° to 105° with 0.02° step size and 1 s acquisition time per step with LynxEye detector, and sample rotation 15 rpm; quantitative phase analysis (QPA) by fundamental parameters Rietveld method (Bruker-AXS Diffrac. TOPAS software, v.6) following Santos et al. (2017) and Neumann et al. (2018).

The mineral components of the Lakeside carbonates have been determined from XRD patterns and Rietveld refinement (QPA), obtained following sample preparation by McCrone milling (to ensure homogeneous, correctly sized powders without amorphization) for the precise identification of the individual phases in complex mixtures. This was necessary to distinguish individual mineral phases given the intricate mingling of clotted fabrics together with cement crystals. Micro X-ray fluorescence spectrometer images of individual element distribution indicated the layout of elements in thin sections, and SEM-EDS analyses then linked chemical composition with crystal forms and the mineral phases identified with XRD on bulk samples.

Bulk and point sample powders prepared for isotope geochemistry were generally paired with XRD for sample composition. Analyses of O and C stable isotopes (δ18O, δ13C), radiocarbon (14C), 87Sr/86Sr ratios and U (238U, 234U) and Th (230Th, 232Th) were carried out by laboratories at: Utah State University; University of New Mexico; University of Arizona; University of California Irvine; Imperial College London; University of Heidelberg; University of Lausanne; University of Bern. Details of analytical tools and methods are given in Appendix S1.

3 | RESULTS

3.1 | Description of geomorphological and depositional features

Salient geomorphological features include coastal cliffs, rocky spits or minor promontories, mounds, pocket beaches...
and beach flats, which were draped or encrusted by carbonates along the shoreline at Lakeside. The carbonates form an outcrop strip 10 km long and up to 100 m wide.

Carbonate is found as drapes on cliff faces and as isopachous deposits in bedrock conduits, locally with geopetal infill. Cliffs at Dos Equis Point have still active groundwater conduits guided by bedrock fractures and a pre-existent karst network (Figure 7). Entrainments formed on collapse debris at the foot of the Dos Equis cliff, and built terracettes and narrow pools, as well as broad low relief mounds (Figure 8). The debris apron at the foot of the Dos Equis cliff is organised into two successive packages of boulder to sand sized debris, separated by a thin layer of 10–20 cm size mounds.

Exposed rocky spits or minor promontories of Mississippian Great Blue Limestone, progressively encrusted by carbonate as they run down towards the lake, are found at Death Point (Figures 9 and 10) Atwoods Point (Figure 11) and Cave Ridge South. Carbonate encrustations occur as drapes and cascades lining the bedrock (Figures 10 and 11) as rimmed pools, and as terracettes of different sizes (Figures 9–11). Clusters of terracettes with flat tops and curved dropwalls, reaching several metres in diameter and up to more than a metre in height, are conspicuous at Death Point (Figures 9 and 10A,C).

Mounds measuring several metres to tens of metres across, with irregular millimetre to centimetre layering, are built over bedrock protrusions or debris in the littoral zone (Figures 9 and 10). The largest mound, at Death Point (Figures 9 and 10) measuring 15 m by 30 m by 2 m high, is built over Mississippian Great Blue Limestone bedrock found by coring just 30 cm below the surface in the centre of the eroded mound top. The bedrock is the tip of the spur coming from Death Ridge (Figure 1C). Fractures lined by carbonate criss-cross the mound (Figures 9 and 10B) and terracettes are developed on the mound flanks.

Smaller 10–20 cm sized mounds (MHB on Figures 12 and 13) occur as isolated, grouped or metre-scale amalgamated growths on low-angle, flatter surfaces of grainy material re-worked from bedrock (B on Figures 12 and 13). The small mounds develop individually or as beds over flat-bedded layers of sand to gravel grade bedrock clasts, which show centimetre-scale low-angle tabular cross stratification. The beds or pavements of mounds also show a lateral facies transition into these flat-bedded, low-angle tabular cross-stratified, coarse clastics.

The upper band of carbonates exposed along the present day shore zone shows “notched”, partially eroded mounds cemented by layers of clastics (N on Figure 12 and 12B) and lobed to oval or round shaped rimmed pool features (P on Figure 12A). Pebbles and cobbles at the limit of the modern vegetation are cemented into a conglomerate as well as being encrusted by the carbonate (Figure 12A, T on 13).

The carbonate encrustations at Atwoods Point extend away from the tip of the bedrock to form broad flat-lying concentric bands. A 25 cm wide conduit (1 on Figures 14 and 15A) cuts across these bands and runs down to a patch of small mounds measuring 20 m in length (Figure 2 letter d; 2 on Figures 14 and 15B,C). Two successive fairly narrow flat-topped bands of amalgamated small mounds lying hundreds of metres farther away (3 and 4 on Figures 14 and 15E) form elongate benches measuring 3 m–10 m across by 50–100 m long.

The smaller, 10 cm to 50 cm mounds show two different morphologies, each bench being formed by only one type of mound. The distinctive shapes of the mounds suggested calling them either “monk’s head” (Figures 13, 15B,C and 16) or “monk’s tooth” (Figure 15D,E). The tonsure-like feature of individual domes explains the name “monk’s heads”. The similar sized “monk’s tooth” mounds and composite
groups of these mounds with tooth-like forms do not show this tonsure-like feature. A slabbled section of a small monk’s head mound (Figure 16, sampled at S on Figure 13) shows an irregular layering (Figure 16B). Two erosive surfaces in particular (Figure 16), an inner orange trace and outer red trace have microkarst pits and pockets filled with lacustrine sediment emplaced before the following layer. Monk’s tooth mounds have a homogenous texture with little evidence of internal layering. The irregular outer surfaces illustrated on Figure 15D,E result from later microkarst erosion during prolonged exposure with pits containing recent lake sediment and brine shrimp cysts.

3.2 Description of mineralogy and petrography

Primary lacustrine facies comprise grainstone, packstone, wackestone and bindstone fabrics. The significant mineral species from the different carbonate features are: aragonite (A; CaCO₃), intermediate Mg-calcite (IMC; 4.5 mol% MgCO₃), high Mg-calcite (20 mol% MgCO₃), very high Mg-calcite (VHMC; >40 mol% MgCO₃), and non-stoichiometric dolomite (NSD; 46-47 mol% MgCO₃). The Great Blue Limestone bedrock at Lakeside is composed of calcite (C; CaCO₃) and low Mg-calcite (LMC; <1 mol% MgCO₃).

Barite is widely distributed as a trace mineral in the carbonates, while detrital quartz and feldspars as well as authigenic Al-Mg clay minerals are common accessories. A higher content of Mn (although in trace quantities) as an activator in Mg-rich carbonates tends to give brighter orange cathodoluminescence colours for VHMC than for NSD. Lithic clasts, ranging from boulders to gravel, sand, silt and windblown dust, are mixed with the carbonates especially along the littoral zone.

The carbonate drape covering bedrock spurs (Figure 17A), coming from bedrock fracture vent outlets (Figure 17A) is
mainly composed of aragonite. This highly vuggy carbonate is a laminated to flaky flowstone in the middle of the fracture (Figures 17B,C and 18A). Thrombolitic aragonite drapes over bedrock with millimetre-thick increments, each layer is bounded by dark dense micrite (millimetres; Figure 18A,B) made of clotted aragonite. The VHMC rim cement lines vugs in a millimetre-thick dolomitized and highly leached, vuggy layer (Figure 18B, letter d). Aragonitic thrombolite comprises lumps of 20–30 μm sized clots, cemented by acicular 5–20 μm sized aragonite crystals. Prismatic aragonite crystals cementing clotted fabrics occasionally show skeletal forms when seen under high SEM magnification (Figure 18C,D). A clotted aragonitic fabric with larger acicular aragonite cement crystals (20–80 μm) is illustrated both in thin section (Figure 19A through D) and on images from freshly broken surfaces showing aragonitic micrite clots and acicular cement crystals (Figure 19E,F). Preservation of bacteriomorphs as filaments and strings of coccoids is shown in thin section on Figure 19G,H.

Closer to the vents, these thrombolite fabrics also have layers or zones rich in fine bubbles (0.2–0.4 mm; Figure 20A through D). Bubbles may remain empty, commonly having been preserved by a very thin carbonate crust or lining. Alternatively, some may enclose aragonitic clots or micrite (Figure 20D), or be partially or totally filled with aragonitic cements. The relationships between clots, bubbles and cements show that they formed more or less together since some bubbles act as nuclei for radiating clusters of acicular aragonite crystals (Figure 20D). Both larger (>1 mm) and much smaller (0.005 mm) bubbles are also found in lacustrine sediment (Figure 20E) but these are not associated with the aragonitic cements.

The outermost terracettes on the flanks of the large mounds at Death Point (Pedone & Dickson, 2000) and at Cave Ridge South show a peculiar shrubby non-crystalline dendritic thrombolite that coats the last dropwalls of the large, >1 m high terracettes (Figures 9 and 21). The shrubby dendritic thrombolite is composed of IMC (with an average of 4.4 mol% CaCO₃). The dropwall at Death Point comprises an earlier (inner) clotted aragonitic and a later (outer) IMC layer (Figure 21C,D), with: (a) an aragonite fabric; (b) an aragonitic ooid-rich layer; (c) a dendritic IMC layer; and (d) an ostracode-rich layer. The ooids of the inner layer (Figure 22A,B) are mostly superficial ooids cemented with
acicular aragonite, and cemented with round-faced VHMC when located in small cavities. They lack both the radial fabrics and layers of clay minerals that are common in Great Salt Lake ooids like those found in recent microkarst sediments at Lakeside (Figure 22C through H). A more recent ooid with radial aragonitic fabric and concentric clay mineral fabric is detailed in Figure 22 (F through H).

The two Mg-rich carbonates VHMC and NSD (>40 mol% MgCO₃; Appendix S2) are commonly found in association, replacing aragonite but with varying proportions. Round-faced crystals (Pedone & Dickson, 2000) that coat or replace aragonite clots and cements (Figure 23) are mostly composed of VHMC, whereas NSD tends to form the fine equigranular crystals pervasively replacing lacustrine carbonate sediment (Figure 23A,B). Isopachous Mg-carbonate rim cements, commonly formed by round-faced crystals, occur in flat-beded layers of arenites and conglomerates with centimetre-scale low-angle tabular cross stratification (Figure 23A,C,D,G). Corroded, pervasively dolomitized sediment (Figure 23A,B) is found encrusted by leached, vuggy and partially dolomitized aragonitic fabric with VHMC rim cements around vugs and grains (Figure 23A through D,G). Pendant VHMC vadose cements formed at the roof of microkarst cavities (Figure 22E,F).

4 GEOCHEMISTRY AND GEOCHRONOLOGY

Geochemical and geochronological results are listed in Appendices S3 and S4. This part of the study is limited in scope but specifically targets the onshore groundwater spring carbonates and microbialites in order to support or to eliminate various interpretations and conclusions from the outcrop and laboratory results. Isotope geochemistry focussed on the search for groundwater and lake water.
fingerprints, on geochronology, and on palaeo-groundwater temperature. Groundwater and transitional lake water fingerprinting was attempted by using $^{87}\text{Sr}/^{86}\text{Sr}$ ratios as well as $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values referenced to Vienna-Pee Dee Belemnite (PDB). Both $^{14}\text{C}$ and U-Th dating were carried out for geochronology.

Values of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ cluster by mineralogy and by categories of depositional features (Appendix S5). 1 Mg-rich carbonates: $\delta^{18}\text{O}$: $-3.00$ to $-0.98\%e$ and $\delta^{13}\text{C}$: $1.18$ to $2.05\%e$ PDB; 2 IMC carbonates: $\delta^{18}\text{O}$: $-4.23$ to $-3.61\%e$ and $\delta^{13}\text{C}$: $3.76$ to $4.18\%e$; 3 aragonitic carbonates: $\delta^{18}\text{O}$: $-5.25$ to $-4.4\%e$ and $\delta^{13}\text{C}$: $3.67$ to $4.55\%e$; 4 mixed mineralogy: $\delta^{18}\text{O}$: $-5.60$ to $-3.5\%e$ and $\delta^{13}\text{C}$: $2.1$ to $4.41\%e$; 5 Bedrock fracture calcite: $\delta^{18}\text{O}$: $-15.44$ to $-15.95\%e$ and $\delta^{13}\text{C}$: $-5.54$ to $-5.79\%e$.

$\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotopes in four successive incremental units show trends mostly with increasingly heavy values of $\delta^{18}\text{O}$ from core to top of a small mound (see Figure 14 and Appendix S5).

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Appendix S6) show clusters by mineralogy and by categories of depositional features as well as by location. Cluster numbers and groups for $^{87}\text{Sr}/^{86}\text{Sr}$ ratios on Appendix S6 are: Mg-rich carbonates 1:0.714087; 1a: 0.712814; 1b: 0.714048; IMC carbonate 2: from 0.71186 to 0.712238; Aragonite 3: from 0.713070 to 0.713314; aragonite 3a: 0.714006. Lettered clusters on Appendix S6 are: (A) mixed mineralogy (0.713547-0.713776); (B) Great Blue Limestone reference sample from Lakeside quarry (0.711908); (C) reference values for lakewater (0.71469) and modern ooids are from Stansbury Island (0.71469) and modern ooids are from Stansbury Island (0.71508) and Bridger Bay (0.71522). 5, calcite from a bedrock fracture has a value of 0.710785. Empty circles in clusters 2 and C are data provided by Vicki Pedone.

The U-Th corrected ages show a broad scatter from 16.703 ka ± 0.023 to 235.245 ka ± 2.177. A second sample taken from the same point on a small microbialite mound gave U-Th corrected ages of 17.446 ka ± 0.024 and 73.774 ka ± 1.086. Non-calibrated radiocarbon ages for the IMC terracette dropwalls, together with aragonitic mounds, are grouped between 12.4 ka and 14.747 ka ± 0.050. Aragonite groundwater spring carbonate gave a non-calibrated radiocarbon age of 17.4 ka ± 0.060, and calcite or aragonite for fracture fills of 29.4 ka ± 0.24 and 35.33 ka ± 0.47.
**5 | INTERPRETATION**

**5.1 | Interpretation of depositional features**

Coastal geomorphology along the transitional shoreline between Lakeside and Cave Ridge during deposition of the Lakeside carbonates was similar to that of the pre-causeway configuration. Modern shoreline and beach features of the Great Salt Lake described by Atwood and Mabey (2000), Murchison and Mulvey (2000), Atwood (2006, 2009) include debris lines, gravel ridges and beaches, erosional steps, notches and vegetation lines. With these features for comparison, the interpretations of depositional environments for the transitional shoreline carbonates is fairly straightforward.

The carbonates tend to be concentrated close to where minor fault-bound bedrock ridges met the transitional shoreline, suggesting that the fault network was a major conduit for groundwater entering from above the lake and precipitating the carbonates. Groundwater entered the lake at the bedrock points (precipitating carbonate), but then the localised Ca-rich lake water was pushed into the bays, where microbes mediated carbonate precipitation. But the carbonates also occur on beaches in embayments between promontories. There the carbonate apron covering the beach (and maybe some carbonate precipitation of the beach gravels) was fed by linear rather than point-source onshore groundwater resurgence, at the upper limit of the palaeobeach (Figure 12).

The lack of any late fault offset or deformation along the palaeoshoreline from Lakeside to Cave Ridge (established by mapping) indicates that no local structural activity such as tilting or recent fault movement took place during or after deposition of the carbonate system.

Pipes and fractures in bedrock cliffs and spurs were identified as possible groundwater conduits or vents (Figure 7). These are partly or completely filled by carbonate facies similar to the bedrock drapes (Figure 8). Groundwater flowing from these sources deposited or built typical onshore groundwater spring cascades on bedrock walls, with smaller pools, mounds and larger terracettes (Figure 9).

Some shoreline carbonate features (gravel ridges and beaches, erosional notches on mounds) are found preserved in the transitional shoreline deposits at Lakeside by encrustation.
and cementation (Figure 12). Sedimentary structures that are common features of beach deposits are found at Atwoods Beach. Laterally extensive thin beds of low-angle cross-stratified grainy material were caused by wave swash and backwash, whereas scattered pebbles or thin gravel layers were left by storms as stringers in finer material. These features formed close to the transitional lake level and designate a palaeoshoreline or shorelines around 1,285 m (Figure 12).

The carbonates at Lakeside cemented beach and sand flat deposits (Atwoods Beach; Figure 12) and encrusted even coarser boulder beaches to the south of Atwoods Point and a storm ridge at Atwoods Beach. However, these features are not entirely similar in setting, petrography and mineralogy to the beachrock along the Bonneville, Provo and Stansbury shorelines described by Felton et al. (2006) and Vennin et al. (2019).

Erosion of the upper part of individual monk’s head mounds on the lake margin, during ephemeral exposure, left an outer ring standing proud and the bald tops of adjacent domes were levelled to a flat or gently lakeward sloping platform. The centimetre-scale layering in these littoral microbialites shows increments of growth alternating with microkarst erosion (Figure 16). The similar sized “monk’s tooth” mounds and composite groups of these mounds with tooth-like forms do not show this tonsure-like feature, showing only post-growth microkarst features. The lack of indications of exposure during growth suggests a slightly deeper, permanently flooded lacustrine as opposed to littoral depositional environment.

The distribution of the different carbonates at Lakeside, from onshore groundwater spring carbonates across the shoreline with littoral microbialites to lacustrine microbialites provides a clear picture with regard to the onshore–offshore depositional profile summarised on Figure 24. The subaerial cascades, terracettes, and pools are physically linked with lacustrine microbialite deposits (reefs) to form a succession of facies from land to lake within a single depositional system. Cascades, streams, films and pools
of groundwater deposited the variety of onshore carbonate features described. Shoreline environments with littoral microbialites were characterised by the repeated flooding and exposure of the monk's head mounds, by the association with sedimentary features such as erosional notches, and by sedimentary structures typical of beaches and swash zones such as low-angle tabular sets of cross bedding. More permanent lacustrine environments are recorded by wave-rippled sediment with ooids but with no evidence of shorter-term exposure. Water depths of the lacustrine deposits described here were shallow, above wave-base but with no precise indication of bathymetry. The larger metre-scale microbialite mounds, lying hundreds of metres farther out in the lake (and that were exposed along the 2016 low-stand margin), have not been included among the transitional shoreline carbonates studied at Lakeside. These mounds are covered by microbial-algal growth when submerged at the present time (Vanden Berg, 2019), but they may result from much older carbonate growth. Although these larger mounds fit readily into a zonation linked with successively deeper environments at Lakeside there is no indication of them belonging to the same generation as the other transitional shoreline carbonates.

The lateral continuity and the stratigraphic succession of the layers of clastics, mounds and encrustations were documented by coring on Atwoods Beach (Figures 13 and 25). Several beach and littoral units are superimposed in stratigraphic order. Each unit measures decimetres in thickness, and is part of a transgressive-regressive (T-R) cycle that was confirmed by the coring (Figure 25). The stratigraphy of the debris apron at Dos Equis Point (Figure 8) with two phases of cliff collapse debris separated by a layer of monk's head littoral microbialite can be a similar, longer-term cycle of lake-level fall and rise.

The longer term variations in lake level, at the scale of several metres, probably took place over a period of thousands of years since the growth of an individual monk's head mound, just one bed of the stratigraphic succession, may have taken

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**Figure 13** Microbialite domes coalesce to form a biostrome or pavement (MHB) on Atwoods Beach. Low-angle cross-stratified beach deposits (B) and onshore groundwater spring carbonate pools (T) overlie the pavement. S=Location of sample described on Figure 14.
some 2,000 years according to radiocarbon ages (Figure 16). Newell et al. (2017) document a similar rate of growth for a small microbialite mound at Antelope Island. This frequently exposed littoral microbialite records flooding alternating with exposure at a higher frequency within the longer term T-R cycle. The surfaces traced in the monk's head mound follow discontinuities with changes in carbonate cement or growth fabric and amounts of clastic detritus. These changes suggest four successive growth increments (white arrows on Figure 16B) over a period of 2,000 years. The non-calibrated radiocarbon ages of spot locations (Figure 16C) are discussed below in the section on geochemistry.

5.2 | Interpretation of mineralogy and petrography

The mineralogy of the carbonates at Lakeside is tightly linked both to petrography and to geomorphological units. Aragonite and Ca-rich sources are clearly linked to the onshore groundwater, whereas Mg-rich minerals, restricted to the lacustrine and littoral zones, are linked to lakewater.

Prismatic aragonite crystals that cement clotted fabrics and occasionally show skeletal forms (Figure 18C,D) suggest highly alkaline groundwater (Jones & Renaut, 1996, 2010). Precipitation of aragonite as opposed to calcite is taken as an indication of warmer water, >40–45°C (discussion in Jones & Renaut, 2010). Larger 20–80 μm acicular aragonite cement crystals (Figure 19) may result either from further overgrowth of smaller crystals or from neomorphism (de Boever et al., 2017b). As the groundwater bubbled out of vents an initial matrix must have supported the clots and gas bubbles to keep them spaced out in their respective positions before some cementation occurred. Acicular aragonite cements have replaced this matrix, which was probably microbial EPS (extracellular polymeric substance, which has not been preserved) as suggested by the preservation of bacteriomorphs as filaments and strings of coccoids (Figure 19G,H). Degassing of CO₂ from vented groundwater may have produced the finer bubbles, but the much larger category of 2 mm sized bubbles
in aragonitic micrite (Figure 20) was probably O₂ from microbial photosynthesis (Bozak et al., 2010).

In contrast, VHMC and NSD with a high Mg content were formed as very early diagenetic products in the lacustrine and littoral zones, mostly during ephemeral exposure of the shoreline deposits. Synsedimentary or very early diagenetic vadose and phreatic cements of round-faced VHMC (Figure 23) indicate that the exposure of lacustrine and littoral features occurred after cycles of microbialite growth. The pervasive dolomitization by NSD is also shown to have been early from the encrustation of previously dolomitized sediment by renewed growth and deposition of clotted aragonite fabrics (Figure 23A through D). Cements of VHMC round-faced crystal lined vugs in this later clotted aragonite during a subsequent exposure cycle. Soil glaebules and different generations of clastic grains and ooids were observed in microkarst pockets in the littoral carbonates, where several generations of superimposed microkarst have been observed. Round-faced crystals and micron-size spherules of VHMC calcite occur as the last (perhaps even recent) phase deposited in open vugs of littoral carbonates up to several metres above the palaeoshoreline.

The Mg-rich carbonates were not found above the littoral zone at Lakeside. Dolomitization is more developed in the lacustrine carbonates, while VHMC is most abundant in littoral deposits. Magnesium-rich minerals in Lakeside carbonates decrease above the littoral zone going away from the lake, indicating that the main source of Mg for VHMC and NSD was the lake water. In contrast an IMC bushy dendritic fabric carbonate, similar to the outer terracette dropwalls, was found in a large fracture higher up on the bedrock spur at Atwoods Point (1,295 m; well away from the transitional lake shoreline). This bushy dendritic fabric is free of VHMC or NSD. So the change in mineralogy from aragonite to IMC (with characteristically fairly low Mg content) on the outer terracettes at Death Point and Cave Ridge South was perhaps not governed by the Mg source in lake water. It is assumed that the abrupt change from aragonite to IMC would register a significant change in temperature or composition of groundwater, as opposed to an effect of Mg/Ca ratio from any degree of mixing with lake water (Jones & Renaut, 2010). Isotopic signatures do potentially show a link to Great Blue Limestone bedrock (see next section).
Ooids from Great Salt Lake (McGuire, 2014; Paradis, 2019) have attracted attention since Eardley (1938), but the ooids in the tall Lakeside dropwall show interesting differences with modern ones. Lack of radial fabric, lack of layers of clay minerals, intense micritization and predominant superficial ooids are shown on Figure 22, with a recent ooid from lake sediment in a microkarst pocket for comparison. Ooids are associated with higher salinity lake water such as in modern Great Salt Lake, whereas ostracods thrived in the less saline brackish to fresh water of Lake Bonneville or other high stands (Oviatt, 2017).

5.3 | Interpretation of geochemistry and geochronology

Most carbonates at Lakeside have δ¹⁸O and δ¹³C values that are fairly typical for Great Salt Lake carbonates (Appendix S5) in the range expected for closed lake systems (Talbot, 1990) and in the field of equilibrium of aragonite with modern lake water (Newell et al., 2017). Categories such as onshore groundwater spring carbonates, microbialites and the dropwalls of large mounds, already linked to specific mineralogy, show separate clusters of values. Samples mainly composed of Mg-rich carbonates (VHMC, NSD) compared with those of aragonite and IMC calcite have higher δ¹⁸O values, in the range of −1 to −3‰ (VPDB) and lower δ¹³C values in the range of 1 to 2‰ (VPDB). These values, although for different minerals, are in the range expected for calcite precipitating from modern lake water isotopic values (Newell et al., 2017). In general, the results from this study support the conclusion that lake water was the main source of Mg for the Mg-rich carbonates at Lakeside. A groundwater spring carbonate pool sample from Atwoods Point (mostly VHMC, some NSD) stands out from other Mg-rich carbonates with the highest δ¹⁸O values, possibly indicating
an effect of stronger evaporation. The monk’s head sample from Atwoods Beach (Appendix S5 C, D) shows how the values for $\delta^{18}O$ and $\delta^{13}C$ record four successive increments of growth, separated by microkarst or hiatal surfaces (Figure 16). Samples with mixed as opposed to a predominant mineralogy show a broader scatter of results. The calcite cement sampled deeper in a bedrock fracture below the Death Point mound (cluster 5 on Appendix S5 A) shows significantly different values. Strontium isotope ratios for this sample are also significantly different from the $^{87}\text{Sr}/^{86}\text{Sr}$ for the Lakeside carbonates (Appendix S6, Figure 26). The results for this anomalous sample, with values suggesting meteoric groundwater, provide a check on the Lakeside carbonate geochemical results, which comprise well-defined clusters.

Strontium isotope ratios of aragonitic bedrock drapes and an onshore groundwater spring pool on the beach, as well as of aragonitic shoreline and lacustrine microbialites show narrow ranges of values lying between those of Great Blue Limestone bedrock and of Great Salt Lake water (Appendix S6, Figure 26). In clear contrast, IMC dendritic terracette outer dropwalls of the large Death Point mound have lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. The IMC dropwall values and the dendritic IMC of the fracture higher above Atwoods Point are similar to the Great Blue Limestone from the adjacent quarry. Carbonates in other fractures are dominated by A, C, LMC, and in some cases show high proportions of VHMC or NSD. Strontium isotope ratios for Lakeside carbonates lying close to 1,285 m (except from one bedrock fracture) are in the range of the ratios recorded from carbonates at Bonneville to Gilbert elevations (Hart et al., 2004, their figure 8). The cluster of values of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for IMC dendritic dropwalls is similar to the Great Blue Limestone, which is the bedrock supporting the carbonate system (Figure 26). Groundwater feeding the IMC outer dropwalls at this late stage was probably in equilibrium with the bedrock and could have given a reservoir effect on $^{14}C$ ages.
Two feeder conduits in the cliff face at Dos Equis, a feeder vent in a bedrock fracture at Death Point and a fracture cutting the mound at Death Point, grouped together under “fractures”, show $^{87}\text{Sr}/^{86}\text{Sr}$ results ranging between the lower values of Great Blue Limestone bedrock and those grouped under microbialites (Appendix S6). The microbialites in turn show higher ratios, closer to the average GSL water. Together with the values for the IMC terracette dropwall, these data suggest that groundwater with long residence time in bedrock aquifers may have contributed fingerprints to geochemical signatures in the Lakeside carbonates.

The $^{238}\text{U}/^{235}\text{Th}$ ages show an extremely wide range (Appendix S3 and S4) with no relationship either to groupings of facies and depositional environment, to $^{14}\text{C}$ ages of the same samples, or to values of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Furthermore, two spot samples from the same point in a monk’s head microbialite gave corrected U-Th ages of 17.4 ka and 73.8 ka. This major discrepancy suggests pollution of carbonate samples by fine wind-blown and bedrock clastics, as thin sections and XRD have shown ubiquitous detrital components and dust, comprising feldspar and plagioclase as well as quartz and carbonates (Figure 16). Clearly, the $^{238}\text{U}/^{235}\text{Th}$ dating procedure is hampered for Lakeside carbonates by this detrital pollution as well as by the lack of constraints on the initial U and Th values (Placzek et al., 2006).

The $^{14}\text{C}$ radiocarbon dates are more coherent with the geomorphological and geological features than the U-Th results. The youngest features of the Lakeside transitional shoreline, IMC calcite dropwalls at Death Point and Cave Ridge South, give the following cluster of non-calibrated radiocarbon dates (Appendix S1 and S3): 12.5 ka and 12.5 ka (Currey in Pedone & Dickson, 2000); 12.4 ka and 13.8 ka (data provided by V. Pedone); 12.9 ka and 12.4 ka (Godsey et al., 2005); 14.2 ka (this study). Non-calibrated radiocarbon dates from littoral microbialites and groundwater spring carbonates range from about 12 ka in a lacustrine monk’s tooth microbialite (Figure 14, sample XRD 18 in Appendix S3) and 14.8–12.7 ka from interior to external...
layers of a monk's head microbialite (Figures 13, 16 and LS16 01 A,B,C in Appendix S3) at Atwoods Beach. This clustering of dates gives confidence in the results, but it is perplexing because when calibrated for lake water they fall into an age bracket of 14,000–16,000 cal yr BP or more, and lake elevation at that time was at least 150 m higher than the 1,285 m of the transitional shoreline at Lakeside.

The rim of an onshore groundwater spring carbonate pool on the upper beach at Atwoods Beach gives an uncalibrated radiocarbon date of about 17.4 ka. But this feature (with well-developed bubble fabric showing strong degassing and proximity to a groundwater vent) lies at the closing stage of a T-R cycle starting with the littoral microbialites (confirmed by core, see Outcrop Geology) that give dates from 14.8 ka to 12.7 ka. This discrepancy between the stratigraphically older microbialites at the transitional lakeshore (about 14.8–12.8 ka) and the stratigraphically younger onshore groundwater spring carbonate on the upper beach (17.4 ka) provides a possible estimate of more than 5,000 years for a groundwater reservoir effect that would have been more pronounced higher up on the beach, close to a vent. The groundwater reservoir effect would have decreased in the littoral microbialites at the foot of the beach with greater dilution from lake water.

**FIGURE 19** Onshore groundwater spring carbonate fabrics. (A and B) Thin section photomicrograph (PPL, Plane Polarized Light) of aragonite clotted fabric and acicular cement. (C) Thin section (PPL) with clots (1) and acicular cement (2). (D) SEM BSD images of lightly etched thin section; clots (1) and acicular cement (2). (E and F) SEM images of freshly broken surface showing aragonitic micrite clots and acicular cement crystals. (G and H) Bacteriomorphs in micrite, onshore groundwater spring carbonate. Chains of coccoid bacteriomorphs in micrite (white arrows).
Clumped isotope analyses for groundwater temperatures require further work to be confirmed. Preliminary runs did provide indications of cool (<10°C) to moderately warm temperatures (<30°C) for microbialites and groundwater spring carbonates from the Lakeside carbonates. But these results are too equivocal to be given in detail.

6 | DISCUSSION

The record from the Lakeside transitional lake shoreline may well register variations in lake water salinity and in microbial communities linked to discharge of different ground waters mixing with lake water, with fluctuations of lake level under climate control as the level approached current elevations. Groundwater temperature may have been warm to hot, suggested by the evidence mentioned above.

Apart from a study on the dolomitization of the Lakeside mound at Death Point (Pedone & Dickson, 2000), radiocarbon ages from the Death Point mound (Godsey et al., 2005; Pedone & Dickson, 2000) and radiocarbon ages from a monk’s head microbialite from Atwoods Beach (Newell et al., 2017), the Lakeside carbonates have attracted limited attention. The carbonates at Lakeside do have some similarities with other Bonneville-Great Salt Lake microbialites, but more generally they stand in contrast
to most of the shoreline and lacustrine deposits previously described (Bouton et al., 2016a, 2016b; Chidsey et al., 2015; Felton et al., 2006; Newell et al., 2017; Pace et al., 2016; Vanden Berg, 2019; Vennin et al., 2019). Farther afield, the lacustrine bioturbs, spring mounds and marginal carbonates described from the Ries Impact Crater in Germany (Arp, 1995; Pache et al., 2001) show many similar morphological and petrographic features with the Lakeside carbonates.

A transitional shoreline at Lakeside, dating after the fall from Provo to historic levels as suggested here is not anomalous, particularly if the radiocarbon ages at Lakeside have been increased significantly by an ageing effect from much older groundwater dating from the Bonneville lake, with long residence time in bedrock. The elevation of the transitional shoreline may have been related to the threshold between Great Salt Lake and the Desert to the west. This passage lies close to the altitude of the transitional shoreline beach carbonates at Lakeside, and the passage was used when lake water was evacuated into the West Desert to limit the flooding of the causeway in 1987. The elevation of the transitional shoreline beaches may have been constrained by this threshold.

The subaerial geomorphological features at Lakeside, as well as the clotted aragonite fabrics of groundwater spring carbonates and microbialite with 20–40 μm acicular aragonite cement crystals, are closer to fabrics and features known from hot water springs (De Boever et al., 2017a; Fouke, 2011; Fouke et al., 2000) than to those of the modern Great Salt Lake microbialites described by Pace et al. (2016). Fabrics from lithified microbialites at Bridger Bay, similar to the Lakeside clotted aragonite, are commented and illustrated by Hart et al. (2004), Della Porta (2015), Pace et al. (2016) and Vanden Berg (2019). No subaerial groundwater spring carbonate features (e.g. pools, terracettes), nor fabrics similar to the late stage shrubby dendritic IMC have been reported previously from the Bonneville-Great Salt Lake system.
However, highly similar shrubby IMC has been observed during this study along the Warm Springs fault at Beck Springs (Salt Lake City). Warm water springs there have stimulated research for geothermal energy (GHC, 2004), but no such geothermal anomalies have been reported anywhere close to Lakeside.

“Ancient laminated and cauliflower structures” from Antelope Island are described and dated to 10,600 cal yr bp or more by Bouton et al. (2016a). These may correspond with the “monk’s tooth” lacustrine microbialites at Lakeside. Bouton et al. (2016b) describe microbialite encrustations on a 1,280 m-level boulder beach at Buffalo Point on Antelope Island (their Figure 2D), with a lobe shaped debris flow conglomerate running farther into the lake. The encrustations on the quartzite boulders there may be similar to encrustations on a Lakeside boulder beach south of Atwoods Point. Bouton et al. (2016b) consider the conglomerate to have formed sometime between 21 and 12 ka. The debris flow, triggered perhaps by the sudden fall from Bonneville to Provo level at 15 ka (Bouton et al., 2016b) is located next to an active fault and was probably related to an earthquake. But the 5,800 yr ages attributed to the Buffalo Point microbialites are much younger than any age indications at Lakeside. These are probably equivalent to the 1 m-scale microbialite mounds far from the shore at Lakeside (Figure 24).

Newell et al. (2017) describe a densely laminated lacustrine microbialite from Antelope Island with growth from interior to rim dated by 14C organic carbon from about 10,500 to 7,600 cal yr bp. This microbialite is somewhat similar to “monk’s head” microbialites from the transitional shoreline at Lakeside. The freestanding metre-scale microbialites, domes and rings commonly described in the lake today (Bouton et al., 2016a; Eardley, 1938; Vanden Berg, 2019) are also abundant at Lakeside, but at much lower elevations, closer to the modern day shoreline about 600 m east of the Lakeside study area. Although they may belong in part to the depositional record of the transitional shoreline carbonates they have not been included in this study.

Several major issues remain unresolved at Lakeside: (a) the precise age(s) of one or perhaps several events building
the system, either spread over a few thousand years or set apart by longer periods of time; (b) the fingerprinting of groundwater from one or possibly several cool or warmer bedrock aquifers; (c) the relative importance of microbial activity compared to physicochemical controls from Ca and CO₂ rich groundwater.
The emplacement of a shoreline at 1,282–1,285 m, similar in elevation but earlier than Holocene Great Salt Lake, needs to fit within the limits imposed by the established rise and fall in the Lake Bonneville-Great Salt Lake lacustrine system (Figure 2A; Godsey et al., 2005; Oviatt, 2019). Credible geochronology dating is crucial to pinpoint whether the shoreline deposits record only one or several depositional events occurring early (e.g. during the rise to Stansbury and Bonneville elevations) or later (during the fall from Provo to Great Salt Lake). The U-Th age results on the Lakeside carbonates are consistently confusing and have not yet given satisfactory results. Placzek et al., (2006) suggested strategies for U-Th dating of palaeolake carbonates, together with an assessment of possible sources of uncertainty or error in results. The Lakeside carbonates suffer from all of the drawbacks mentioned: fractions of fine siliciclastic and carbonate detritus; synsedimentary weathering and pedogenesis; diagenetic alteration and cementation; unknown initial U concentration and unknown unsupported Th in both groundwater and lake water; and unknown initial $^{230}$Th/$^{232}$Th ratios.

In contrast, the tight grouping of radiocarbon ages from littoral and lacustrine features at Lakeside suggests greater reliability. Uncalibrated ages ranging from 14.7 ka to 12 ka indicate that the lacustrine and littoral microbialites record a single depositional system, rather than a superposition of two systems at different times.

The mixing of lake water with onshore groundwater, bringing chemical fingerprints after long residence time in bedrock aquifers, would affect both the radiocarbon ages and the Sr isotope ratios to varying degrees. The Sr isotope ratios in onshore groundwater spring carbonates and microbialites at Lakeside spread between values of Lake Bonneville carbonates, Mississippian Great Blue Limestone and of Great Salt Lake (Figure 26). The values for the dropwalls, and the fracture fill at Upper Atwoods, all cluster at the same value as the Great Blue Limestone, close to the range of those for Lake Bonneville carbonates.

The Great Blue Limestone bedrock with abundant chert at Lakeside contains calcite and quartz, as well as 5% dolomite. Stueber et al. (1993) have discussed the effect on groundwater Sr isotope ratios from long residence in a Mississippian bedrock aquifer, and Banner and Hanson (1990) discuss the equilibration of trace elements and their isotopic compositions in subsurface fluids dolomitizing Mississippian limestones during diageneis. The abundant VHMC and dolomitization in littoral and lacustrine carbonates at Lakeside is clearly linked more to lake water than to groundwater as the source of Mg. Although lake water might also be the source of Mg for the IMC of the terracette dropwalls on the big mounds, the fracture IMC at Upper Atwoods with similar geochemical signatures stood far from the lake at that time. This indicates that groundwater was the source of the Mg in IMC mineralogy. The $^{87}$Sr/$^{86}$Sr ratios of the IMC from terracette outer dropwalls and the fracture above Atwoods Point suggest a Great Blue Limestone bedrock aquifer source for the groundwater. An alternative could be that Lake Bonneville water stored in a Lakeside Mountain aquifer was the source of the groundwater. The resurgence of groundwater from one or several specific aquifers at that time would provide a solution to solve the riddle linking limited Mg in IMC, “old” radiocarbon ages, and a microbial ecosystem with a conspicuous shrubby microbial fabric, previously absent in these carbonates.

Tangible evidence for a radiocarbon reservoir effect of more than 5,000 years from groundwater is provided by the radiometric ages and the stratigraphic position of groundwater spring carbonate over littoral microbialites on the upper
FIGURE 25  Cores of sediment and correlation between lithological units at Atwoods Beach. (A) Inset showing position of cores and map on vertical aerial photograph. (B) Sketch of geomorphological features at Atwoods Beach (see Figures 5A, 12 and 13) with core locations. (C) Cores and core slabs (slab portions outlined in yellow on core). The littoral microbialite pavement extends landward below Beach 4 at least as far as core 5, confirming the geomorphological features to be lithostratigraphic units.
Atwoods Beach. Residence times of 5–10 ka would not be exceptional when compared with other geothermal groundwater systems (Cook, 2020; Sonney, 2010) if the groundwater circulated from tens of kilometres away in the Lakeside Mountains syncline. The groundwater sources of the carbonates were clearly rich in Ca, while CO₂ degassing close to groundwater vents (shown by the abundance of bubble fabrics there) may have increased carbonate supersaturation (Jones & Renaut, 2010). Difficulties with preliminary clumped isotope analyses may perhaps be due to excessive alkalinity. All the same, aragonite is generally more common than calcite at springs with temperatures above 40–45°C (Folk, 1994; Jones & Renaut, 1996, 2010) and sometimes with acicular and skeletal crystal habits as found at Lakeside. But cooler temperatures of the IMC terracette dropwalls away from vents may have governed the change in mineralogy to IMC (Pentecost, 2005) rather than either rates of CO₂ degassing (Folk, 1994; Kitano, 1963), the Mg/Ca ratio (Pentecost, 2005), or the concentration of organic matter or biofilms (Folk, 1994; Kitano & Hood, 1965; Pentecost, 2005). Two different microbial fabrics characterise the aragonitic and IMC deposits. The same intimate association of clotted thrombolitic fabric and radiating acicular cement forms both in onshore groundwater spring carbonates on bedrock spurs and in pools on beaches, as well as in the

**FIGURE 26** The ⁸⁷Sr/⁸⁶Sr values at 1,285 m compared with values for other Bonneville-GSL shoreline carbonates. Other values from Hart et al. (2004), illustration adapted from their figure 8. Ranges of values for Bonneville, Provo, Stansbury and Gilbert shoreline elevations measured in carbonates (blue lines); range of values for Great Salt Lake from water samples (green line). Values for transitional shoreline carbonates cluster for terracette dropwalls (blue) with the same value as for Great Blue Limestone at Lakeside quarry, values for onshore groundwater spring carbonate (turquoise) are higher, and values for microbialites (violet) are closer to values for Great Salt Lake. Terracette dropwall and onshore groundwater spring carbonate values are in the same range as Gilbert shoreline values from Hart et al. (2004). The terracette dropwall samples are stratigraphically younger (relative chronology 3) than the microbialites and onshore groundwater spring carbonates (relative chronology 1–2). The progressive positive deviation of ⁸⁷Sr/⁸⁶Sr values for onshore spring groundwater and littoral microbialites may result from mixing of more or less long-residence time groundwater with lakewater at the transitional shoreline elevation (1,285 m). Note that the Great Blue Limestone values lie between Bonneville shoreline and Gilbert shoreline values given by Hart et al. (2004)
littoral microbialite of monk’s head mounds. A change in microbial assemblage, with the development of a shrubby non-crystalline dendritic fabric in a cooler environment, may have accompanied the change in mineralogy from argonite to IMC as groundwater from a different reservoir aquifer and with a different temperature flowed over the last, outer terracette dropwalls.

7 | CONCLUSION

The carbonate depositional system of the transitional shorelines between 1,280 m and 1,285 m at Lakeside, Great Salt Lake, Utah, is clearly documented by geomorphology, outcrop geology, sedimentology, relative chronology, petrography and mineralogy. This points to a Lakeside carbonate system with groundwater depositing carbonate at and close to onshore springs, and with onshore groundwater streaming down to mix with lake water, building microbialites on the shore and sustaining microbial reefs nearby in the shallow lake. Dolomitization resulted from early but secondary diagenetic processes rather than from primary organomineralization.

Despite these straightforward geomorphological/geological observations, the geochemical results are perplexing when dating the depositional system, and in characterising possible different groundwater types. Unresolved questions concern the specific age(s) of the deposits, the temperature of the onshore groundwater springs, and the roles of microbes as opposed to physicochemical processes in carbonate deposition. The novelty in the carbonate system at Lakeside lies in the addition of onshore groundwater spring deposits to the lacustrine system, and the preservation of the physical continuity linking the onshore groundwater spring carbonates with littoral and lacustrine microbialites.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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