PS Reservoir Properties of Lacustrine Carbonate Buildups from Pleistocene Lake Lahontan: Analogues for South Atlantic Reservoirs*

Laura M. DeMott[1], James D. Muirhead[1], and Christopher A. Scholz[1]

Search and Discovery Article #30585 (2018)**
Posted October 22, 2018

*Adapted from poster presentation given at 2018 AAPG Annual Convention & Exhibition, Salt Lake City, Utah, May 20-23, 2018
**Datapages © 2018 Serial rights given by author. For all other rights contact author directly. DOI:10.1306/30585DeMott2018

[1]Earth Sciences, Syracuse University, Syracuse, New York (lmdemott@syr.edu)

Abstract

The lacustrine carbonate reservoirs of the South Atlantic margin contain vast quantities of hydrocarbons, but predicting reservoir properties remains a significant challenge. Seismic-scale Late Pleistocene analogues for these reservoirs are found in carbonate buildups from paleo-Lake Lahontan, a large pluvial lake in the Basin and Range, western USA. These buildups are up to 100 m high, and consist of stacked successions of domes, pillars, and branches (< 5 m high) which exhibit meso- and microscale textural trends. Reservoir properties were examined by combining field observations, porosity and permeability measurements, and outcrop modeling. Porosity data were obtained from thin section optical porosity, and permeability measurements were made on hand samples and outcrops to create a large reservoir property dataset.

We present conceptual models of depositional "building blocks", based on observed trends in morphologies and textures, using a combination of ArcGIS, Matlab, and DecisionSpace software to model simplified reservoir properties and examine heterogeneity. We present 3D morphological models based initially on simple forms, and extended into larger stratal units. Porosity and permeability properties are stochastically incorporated into the models based on observed texture. Fluid flow through the reservoirs is modeled to examine how shape and texture affect property distribution and flow patterns. Small-scale conceptual models are applied to larger-scale, digital outcrop models constructed from imagery collected from sUAS (small unmanned aerial vehicles or drones). Reservoir property and flow simulations are applied to the larger model. We observe complex vertical and horizontal heterogeneity dependent on growth direction, texture, internal structure, overall morphology, and gross stacking patterns. The models indicate that unlike siliciclastic reservoirs, the lacustrine carbonate reservoir potential is strongly dependent upon environmental factors including water chemistry, depth, clarity, and temperature. The outcrop-based models demonstrate that stacking patterns indeed have a measure of predictability, and are useful analogues for predicting the distribution of reservoir properties and fluid pathways at the basin scale.

Reservoir Properties of Lacustrine Carbonate Buildups from Pleistocene Lake Lahontan: Analogues for South Atlantic Reservoirs

Laura M. DeMott, James D. Muirhead, and Christopher A. Scholz

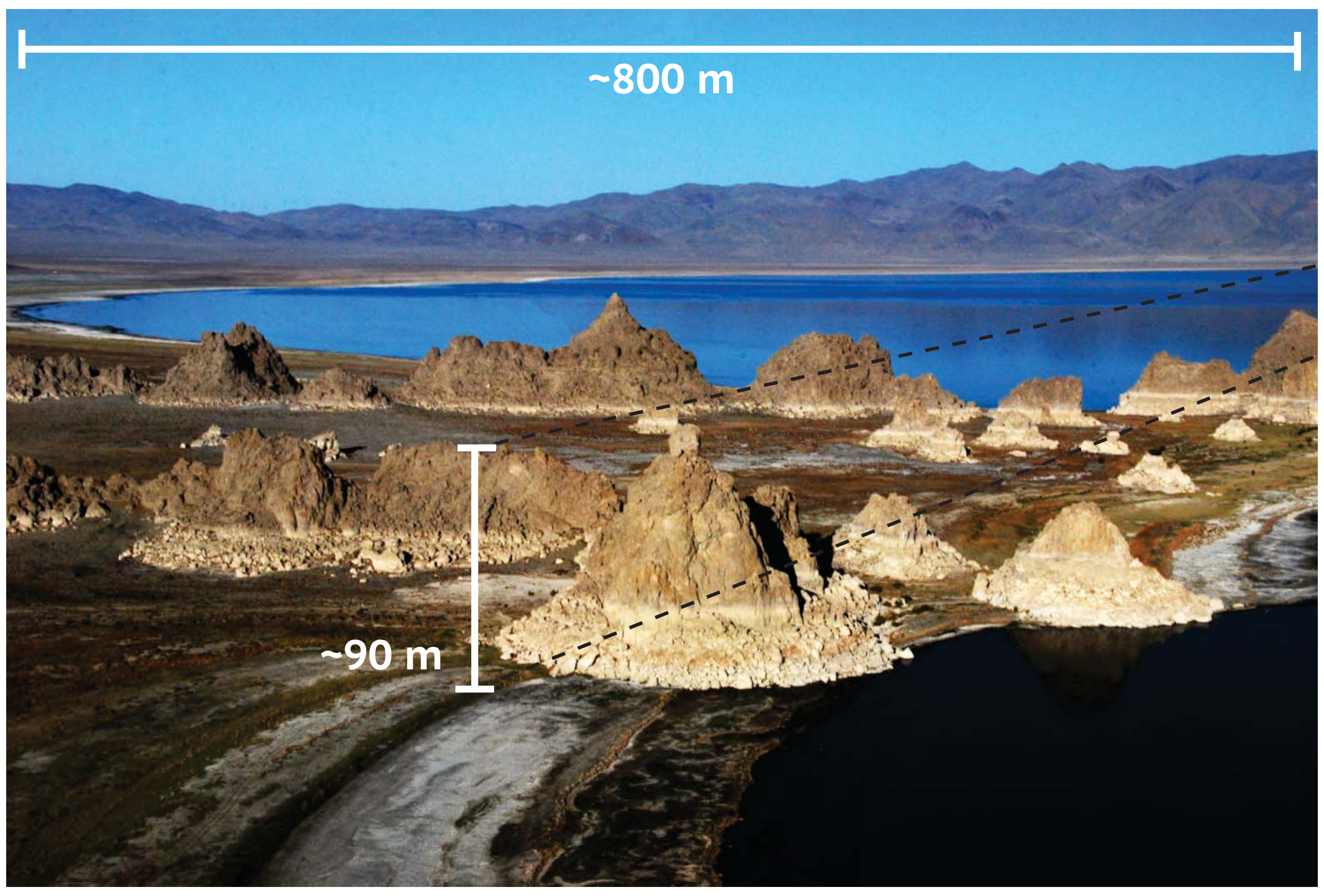
Department of Earth Sciences, Syracuse University, Syracuse, NY, USA

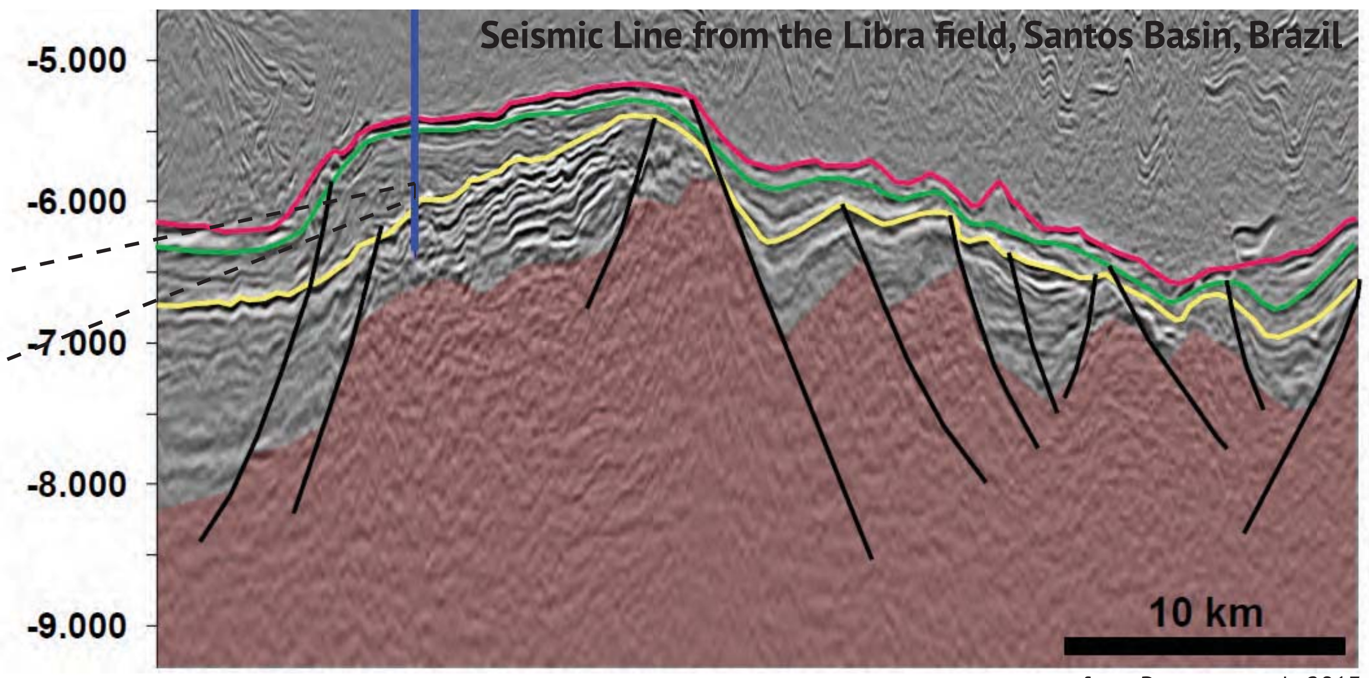
Abstract

The lacustrine carbonate reservoirs of the South Atlantic margin contain vast quantities of hydrocarbons, but predicting reservoir properties remains a significant challenge. Seismic-scale late-Pleistocene analogues for these reservoirs are found in carbonate buildups from paleo-Lake Lahontan, a large pluvial lake in the Basin and Range, western USA. These buildups are up to 100 m high, and consist of stacked successions of domes, pillars, and branches (< 5 m high) which exhibit meso- and microscale textural trends. Reservoir properties were examined by combining field observations, porosity and permeability measurements, and outcrop modeling. Porosity data were obtained from thin section optical porosity, and permeability measurements were made on hand samples and outcrops to create a large reservoir property dataset. We present conceptual models of depositional "building blocks", based on observed trends in morphologies and textures, using a combination of ArcGIS, Matlab, and DecisionSpace software to model simplified reservoir properties and examine heterogeneity. We present 3D morphological models based initially on simple forms, and extended into larger stratal units. Porosity and permeability properties are stochastically incorporated into the models based on observed texture. Fluid flow through the reservoirs is modeled to examine how shape and texture affect property distribution and flow patterns. Small-scale conceptual models are applied to larger-scale, digital outcrop models constructed from imagery collected from sUAS (small unmanned aerial vehicles or drones). Reservoir property and flow simulations are applied to the larger model. We observe complex vertical and horizontal heterogeneity dependent on growth direction, texture, internal structure, overall morphology, and gross stacking patterns. The models indicate that unlike siliciclastic reservoirs, the lacustrine carbonate reservoir potential is strongly dependent upon environmental factors including water chemistry, depth, clarity, and temperature. The outcrop-based models demonstrate that stacking patterns indeed have a measure of predictability, and are useful analogues for predicting the distribution of reservoir properties and fluid pathways at the basin scale.

1. Introduction

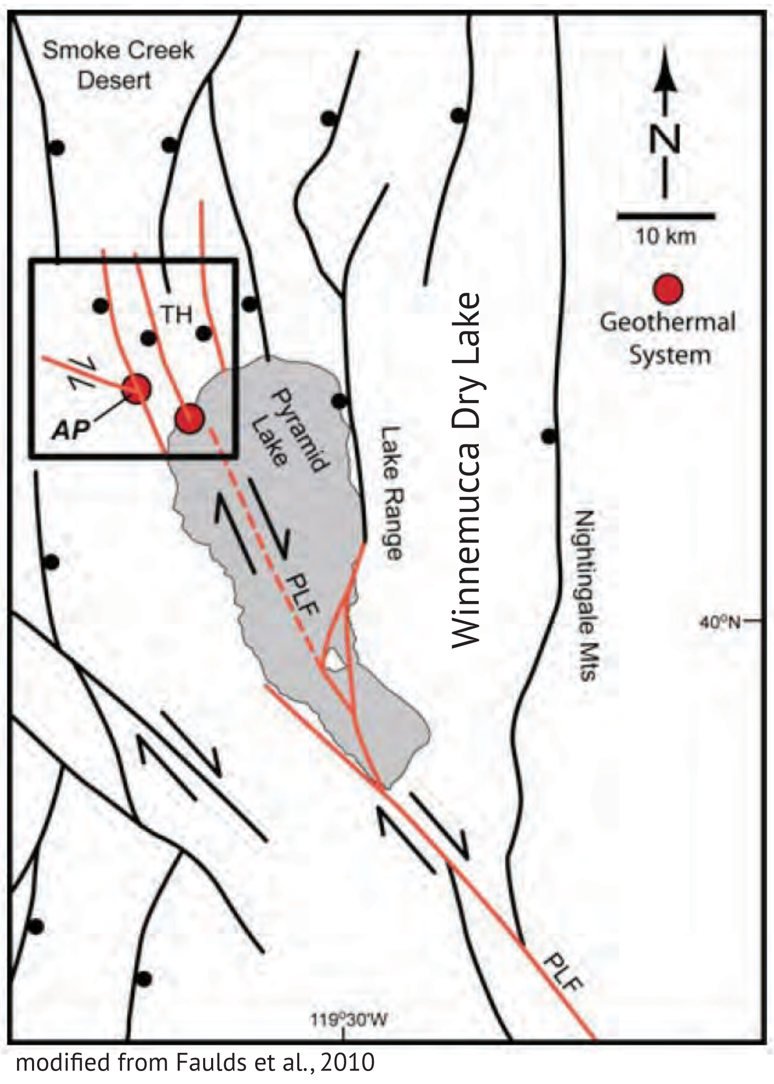
Extensive carbonate "tufas" found in the North American Great Basin rift lakes are valuable analogues for the extensive lacustrine carbonate reservoirs of ancient rift lake basins, such as those found in the Santos and Campos basins of offshore Brazil. These porous limestones are commonly associated with rift basin lake settings, and are well-known in the rift lake basins of the western United States, as well as other lake settings. However, the tufa deposits associated with Pleistocene pluvial Lake Lahontan, particularly in the Pyramid and Winnemucca subbasins, are among the few such deposits that approach the scale of Cretaceous hydrocarbon reservoirs. These tufa deposits can be up to 100 m in height, and cover thousands of square meters in area. The extensive deposits of tufa in the Great Basin, particularly those in the Pyramid and Winnemucca subbasins, are primarily thought to form where hydrothermal springs emerge into alkaline lake waters. Many of the extremely large tufa deposits in Pyramid Lake are associated with rift structures, as strike-slip and normal faults in the basin serve as the primary fluid pathways for these springs (Frary et al., 2011). To fully capture the intricacies of lacustrine carbonate stratigraphic architecture and to address the complexity of such deposits, new spatial models of lacustrine carbonate deposits are required, which are both detailed and quantitative. This poster present ongoing research developing three-dimensional digital outcrop models to address variability in tufa type and morphology across the Winnemucca Dry Lake area.





from Petersen et al., 2013

Tufa towers at the Needles Rocks area, northwest Pyramid Lake shoreline. Towers at this area are associated with hydrothermal springs, and are large enough to potentially be "seismic-scale".

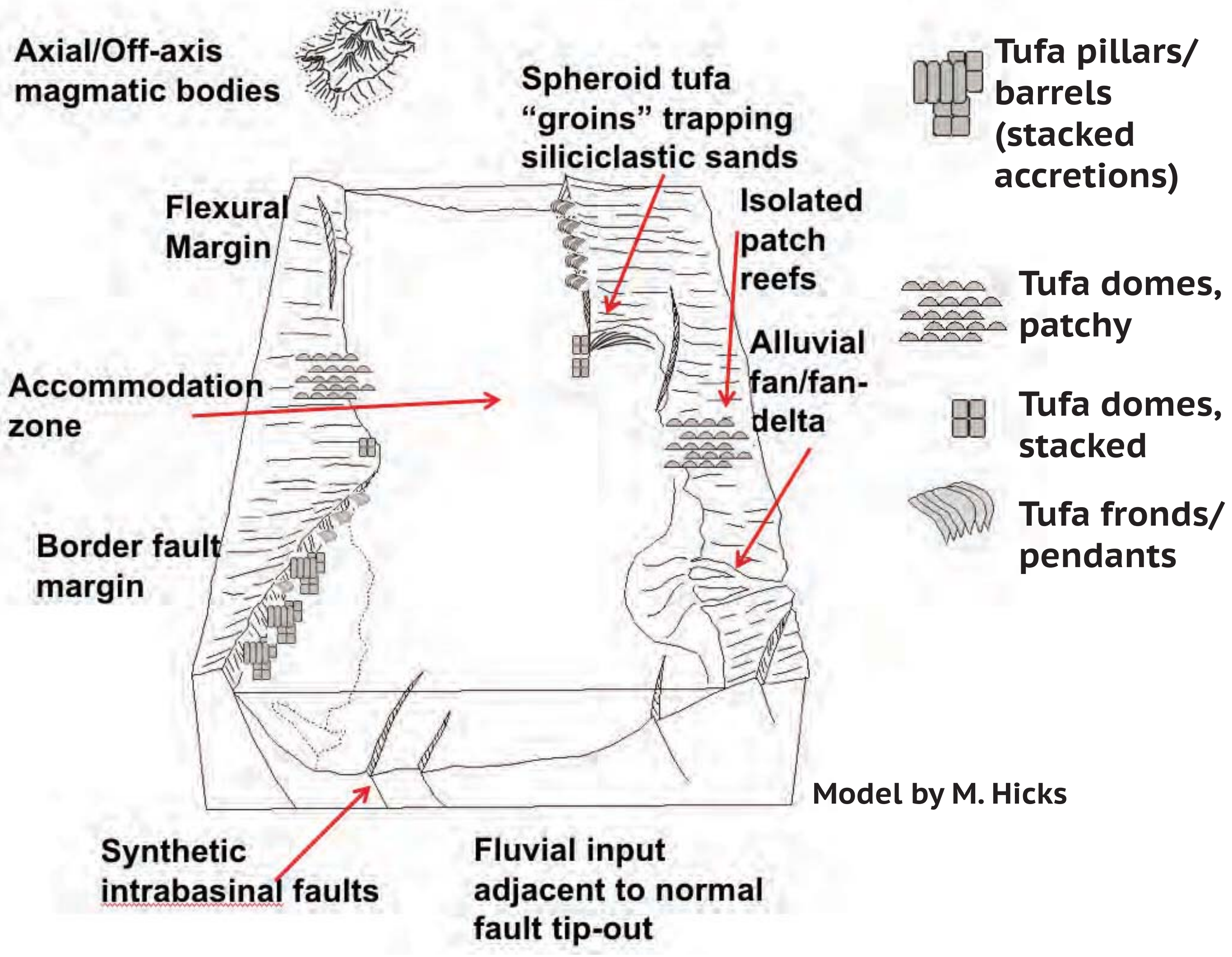


modified from Faulds et al., 2010

A generalized fault map of the area indicates the major faults in the Pyramid and Winnemucca basins. The geothermal systems indicated are known to be associated with large tufa deposits.

Hydrothermal geyser at the Needles Rocks, Pyramid Lake.

Schematic Deposition Model of Pyramid Lake Tufas



Abstract No. 2831175

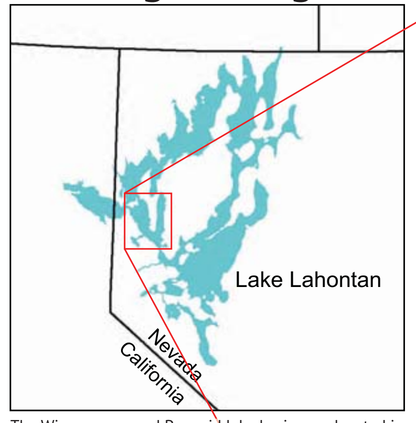
Reservoir Properties of Lacustrine Carbonate Buildups from Pleistocene Lake Lahontan: Analogues for South Atlantic Reservoirs

Laura M. DeMott, James D. Muirhead, and Christopher A. Scholz

Department of Earth Sciences, Syracuse University, Syracuse, NY, USA

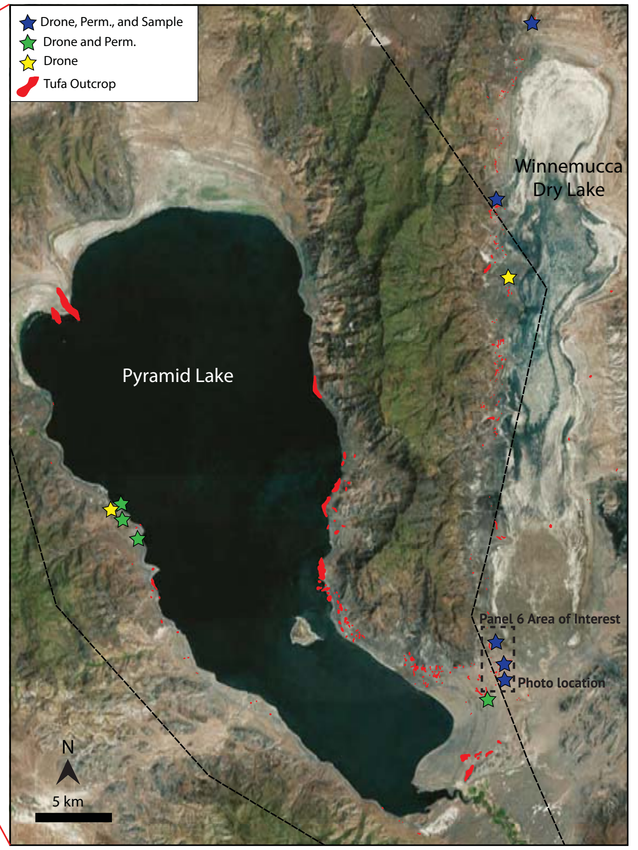
Syracuse University College of Arts & Sciences Earth Sciences

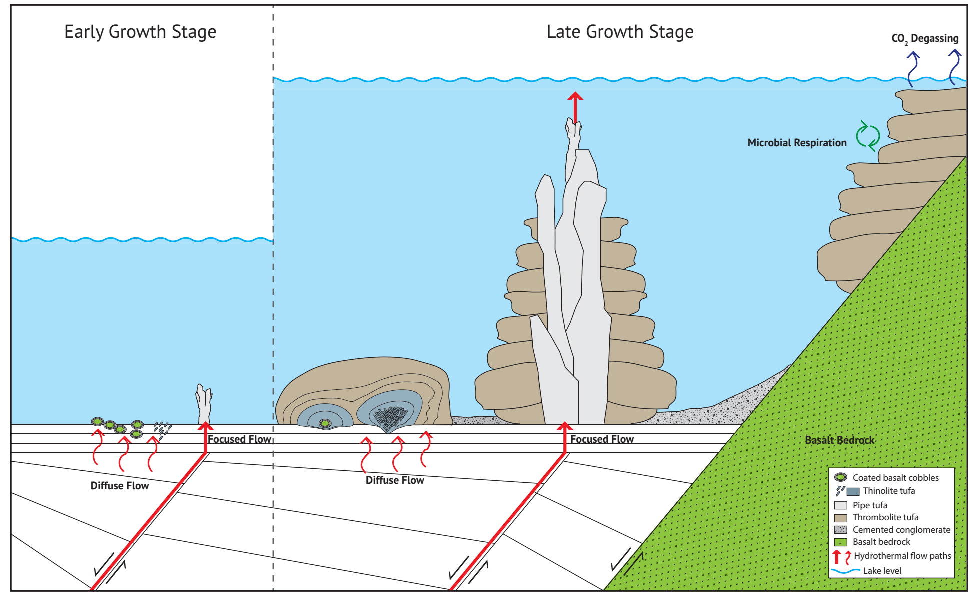
2. Geologic Background



The Winnemucca and Pyramid lake basins are located in the western Basin and Range of western Nevada. The lakes are remnants of Pleistocene pluvial Lake Lahontan. Both are half-graben rift lake basins bounded by steep border faults in the east and shallow flexural margins to the west. Winnemucca Dry Lake fills by spillover of Pyramid Lake during times of higher lake levels, and is currently dry due to agricultural diversions along the inflowing Truckee River. Both lakes have extensive deposits of lacustrine carbonate tufas exposed along the lake margins.

Aerial photo from UAV, looking north (see map)





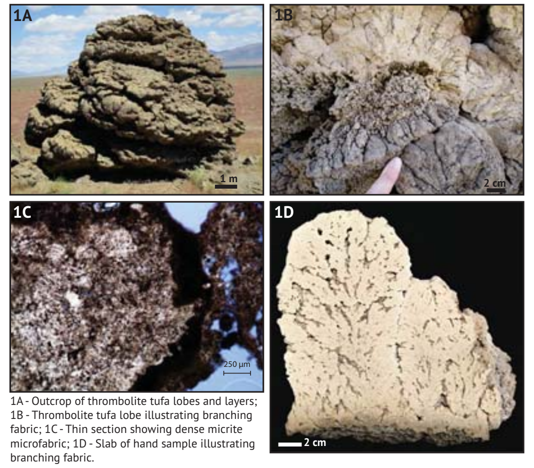
The tufas of Pyramid and Winnemucca Lakes are largely thought to have formed via thermal groundwater mixing with lake water at sites of sublacustrine springs, as well as by the influence of microbial processes. Sites of focused groundwater influx lead to formation of pipe or vent structures, similar to marine hydrothermal vents. Areas dominated by diffuse groundwater influx lead to formation of coated grains (primarily basalt cobbles) and precipitation of ikaite crystals at low water temperatures. As lake levels rise, these deposition sites develop layered mounds and towers. At high lake levels, microbial processes may dominate formation of tufa, resulting in layered thrombolitic tufas that form the outermost layers of mounds, towers, and coat bedrock.

3. Tufa Textural Classification

For the purpose of this study, we classify tufas based on texture in order to simplify classification across sample sizes (outcrop to thin section) and because the same tufa textures may occur across multiple morphologies and basin settings. Texture is also directly related to the reservoir properties examined in this study. Tufa textures are 1) Thrombolite tufa, 2) Thinolite tufa, 3) Pipe tufa, 4) Laminated/stromatolite tufa, and 5) Tufa-cemented grainstones.

1) Thrombolite Tufa

- Dense, branching mesofabric
- Clotted micrite microfabric, sometimes containing microbial filaments
- Found in all basin settings and elevations, typically on hard substrates



1A - Outcrop of thrombolite tufa lobes and layers; 1B - Thrombolite tufa lobe illustrating branching fabric; 1C - Thin section showing dense micrite microfabric; 1D - Slab of hand sample illustrating branching fabric.

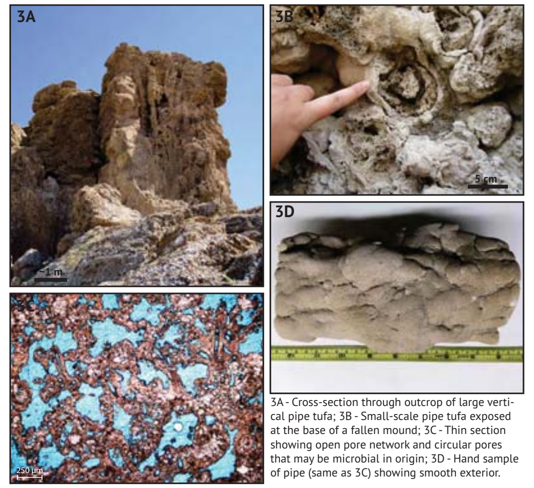
2) Thinolite Tufa

- Tetragonal, elongated crystal pseudomorphs
- Rectangular or square in cross section
- Consist of zoned calcite crystals in a boxy framework in thin section
- Found primarily at likely groundwater discharge sites
- Believed to transform from ikaite ($CaCO_3 \cdot 6H_2O$)

2A - Outcrop of thinolite tufa showing a domed, layered structure; 2B - Thinolite tufa pseudomorphs branching outward from a central node; 2C - Cross-section of a thinolite pseudomorph illustrating boxwork structure; 2D - Thin section showing zoned calcite crystals common to thinolites.

3) Pipe Tufa

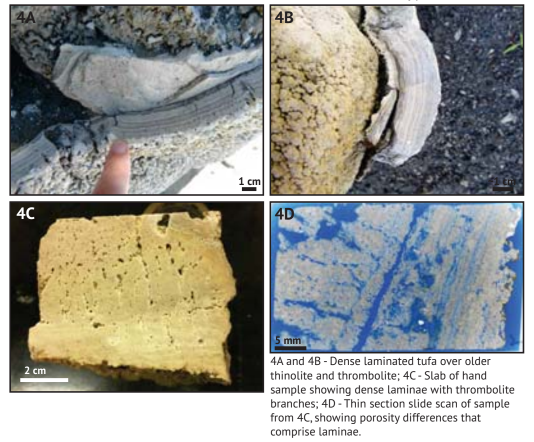
- Cylindrical or tubular columns of tufa, often with smooth outer texture and highly porous and/or crystalline inner texture
- Crystalline in thin section, with circular pores that may indicate microbial influence
- Found at sites of focused groundwater influx along faults, similar to hydrothermal vents



3A - Cross-section through outcrop of large vertical pipe tufa; 3B - Small-scale pipe tufa exposed at the base of a fallen mound; 3C - Thin section showing open pore network and circular pores that may be microbial in origin; 3D - Hand sample of pipe (same as 3C) showing smooth exterior.

4) Laminated/Stromatolite Tufa

- Dense mesofabric with laminations, sometimes occurring as small stromatolitic knobs which form the base of other layers
- Microscale laminations primarily composed of micrite with alternating degrees of porosity
- Small-scale features, less common than other tufa types



4A and 4B - Dense laminated tufa over older thinolite and thrombolite; 4C - Slab of hand sample showing dense laminae with thrombolite branches; 4D - Thin section slide scan of sample from 4C, showing porosity differences that comprise laminae.

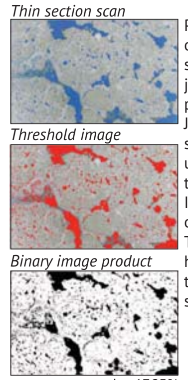
5) Cemented Grainstones

- Composed of cobbles, pebbles, coarse sand, and carbonate grains cemented with calcite
- Often encase the bases of older tufa, frequently contain large tufa cobbles
- May represent paleoshorelines or old alluvial fans

5A - Outcrop of a tufa tower with multiple layers of cemented grainstones wrapping around the base of the outcrop (horizontal and tilted layers at base of photo); 5B - A "tufa conglomerate" wrapped around the base of a large tower outcrop containing cobbles of igneous bedrock and thrombolite tufa; 5C - Thin section of a tufa-cemented grainstone containing lithic fragments, ostracod shell fragments, and coated grains, cemented with micrite.

4. Methods

Optical Porosity



Porosity was measured on blue-epoxied thin sections using the jPOR image analysis program (Grove & Jerram, 2011). Thin sections were scanned using a slide scanner, then processed with ImageJ to calculate an optical porosity value. The example shown here is from a thrombolite tufa section.

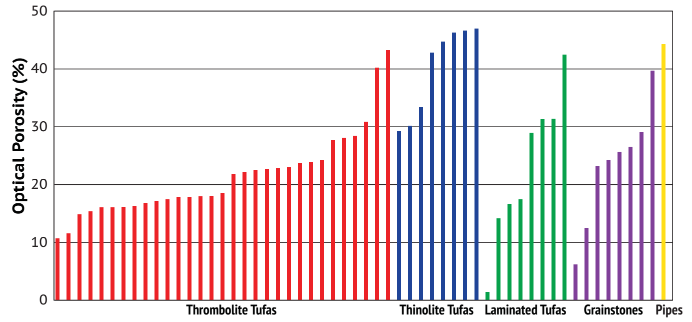
Permeability

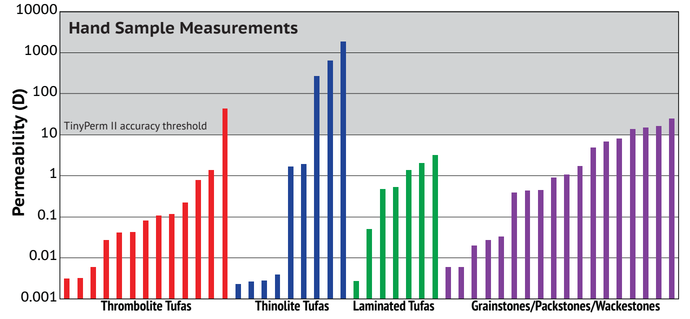
Permeability was measured on both hand samples and outcrops using an NER TinyPerm II air permeameter. Outcrop measurements were taken with care to avoid fractures in the rock.

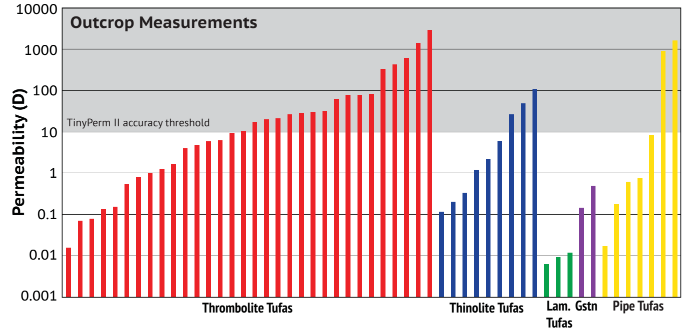
UAV-Sourced Photogrammetry

Eleven outcrops in the Winnemucca and Pyramid lake basins were photographed using a DJI Inspire 1 Pro equipped with a ZenMuse X5 M3/4 camera. Flight acquisition parameters varied by site, depending on outcrop type. Structure-from-Motion models were built from imagery using Agisoft Photoscan.

5. Porosity and Permeability of Tufa Outcrops







Porosity

- Mean porosity of all tufa types is 25% (n = 56)
- Thinolite tufas have the highest overall mean porosity (36%)
- Laminated tufas have the widest range of values (1.5 to 42%)
- Mean values of porosity for thrombolites, laminated tufas, and grainstones are all ~23%
- Pipe tufas are underrepresented in the data set, but the single value is shown (44%) for completeness

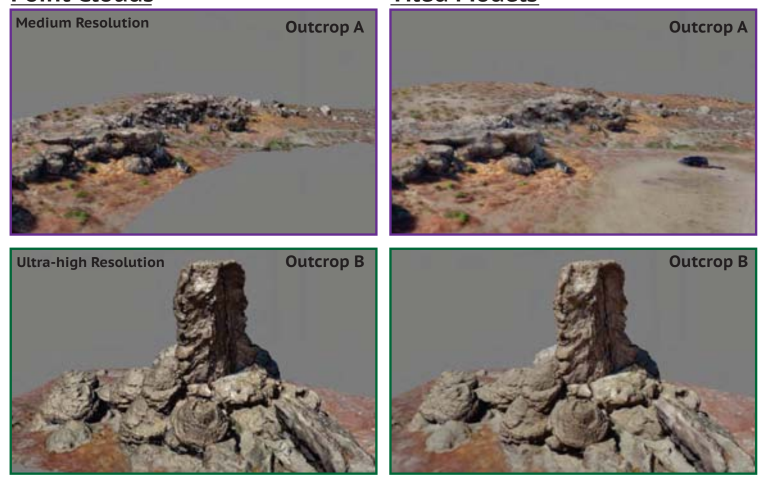
Permeability

- Hand sample and outcrop data sets were separated due to the accuracy of the TinyPerm II
- Due to the wide range of values, the median is considered a more applicable value for reporting
- The median of all hand samples is 450 mD (n = 47)
- Thinolite tufas have the highest median *k* value (1.6 D) for hand samples (n = 9)
- Thrombolite tufas have the lowest median *k* value (80 mD) for hand samples (n = 13)
- The median of all outcrop samples is 5.8 D (n = 53)
- Thrombolites have the highest median *k* values (14 D) for outcrops (n = 35)
- Laminated tufas have the lowest median *k* values (10 mD) for outcrops (n = 3)
- The large difference between outcrop and hand sample median and maximum values is attributed to fracture permeability present only in outcrops

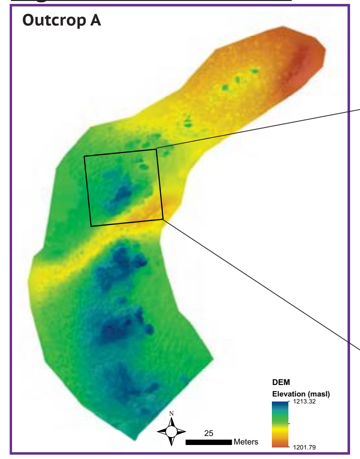
6. Outcrop Models

UAV-sourced photos were used to create 3D models, digital elevation models, and orthomosaics of tufa outcrops. Two examples are shown below, with different resolution data sets (see panel 1 for location). Outcrop A is a low-relief outcrop containing mounds composed of thinolite interiors and thrombolite exteriors (diffuse influx scenario). Models were created using a medium resolution setting. Outcrop B is a high-relief system with a large pipe tufa tower surround by thrombolite coatings and smaller thrombolite mounds (focused influx scenario). This model was created using an ultra-high resolution setting.

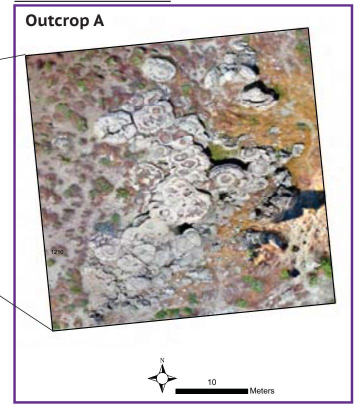
Point Clouds / Tiled Models



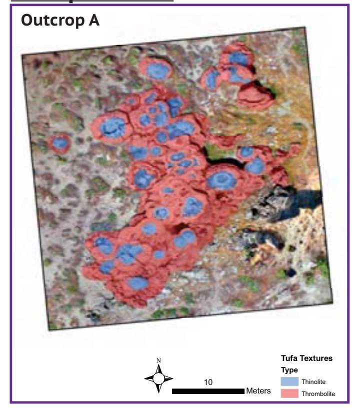
Digital Elevation Models

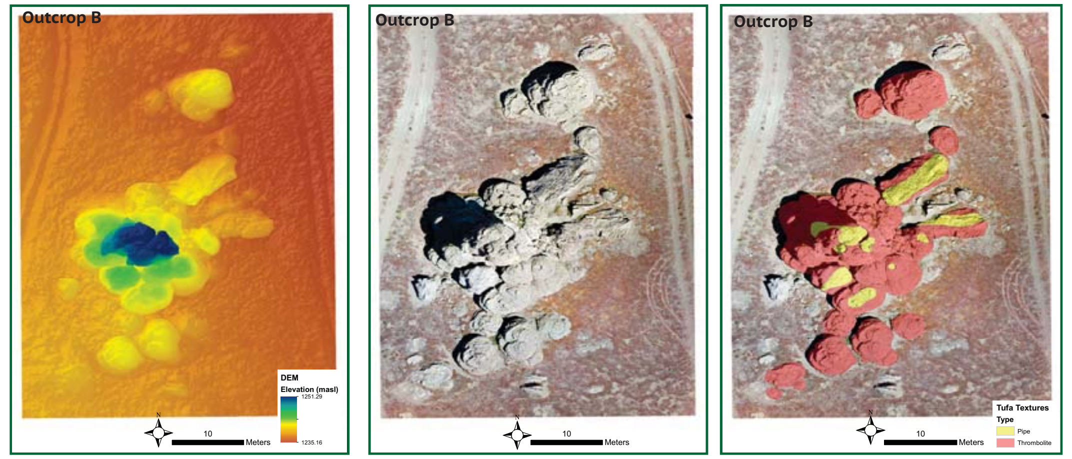


Orthomosaics



Interpretation





Reservoir Properties of Lacustrine Carbonate Buildups from Pleistocene Lake Lahontan: Analogues for South Atlantic Reservoirs

Laura M. DeMott, James D. Muirhead, and Christopher A. Scholz

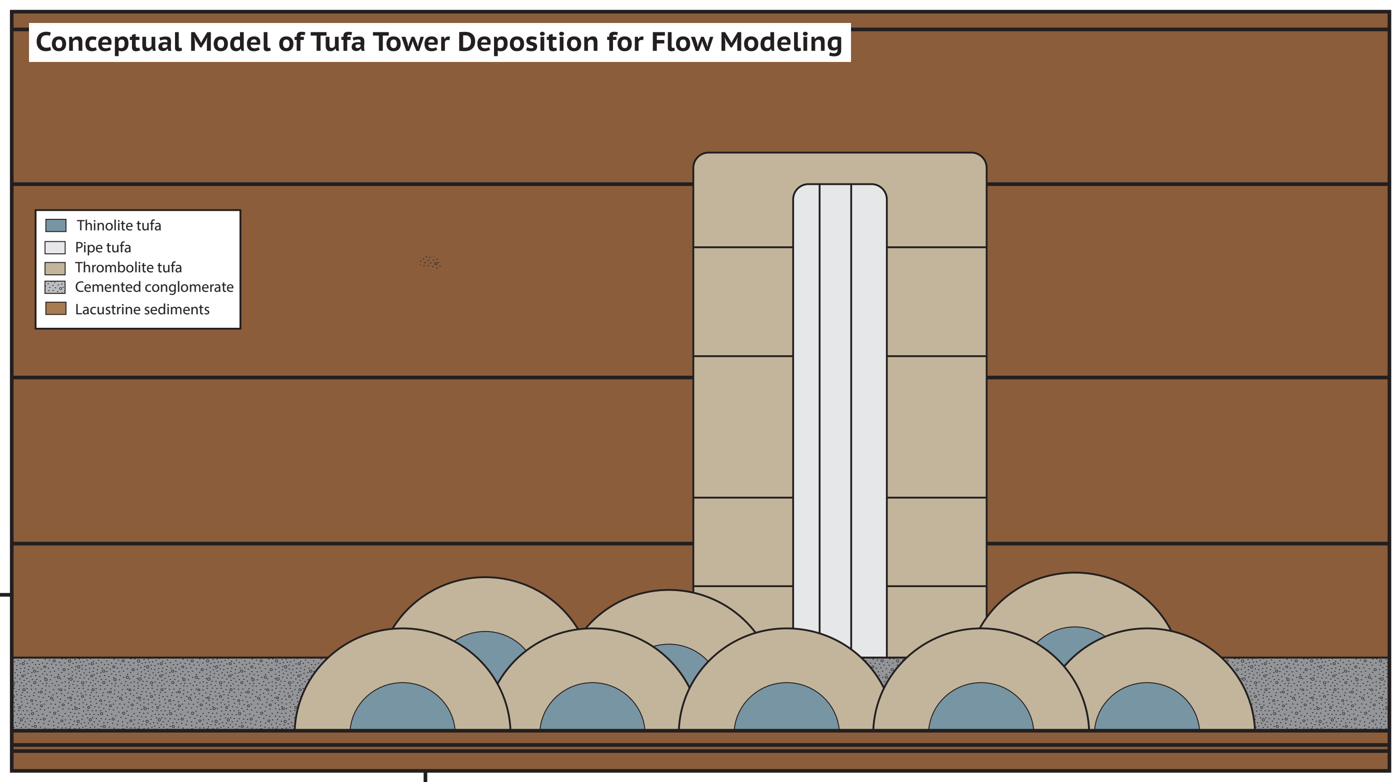
Department of Earth Sciences, Syracuse University, Syracuse, NY, USA

7. Implications and Future Work

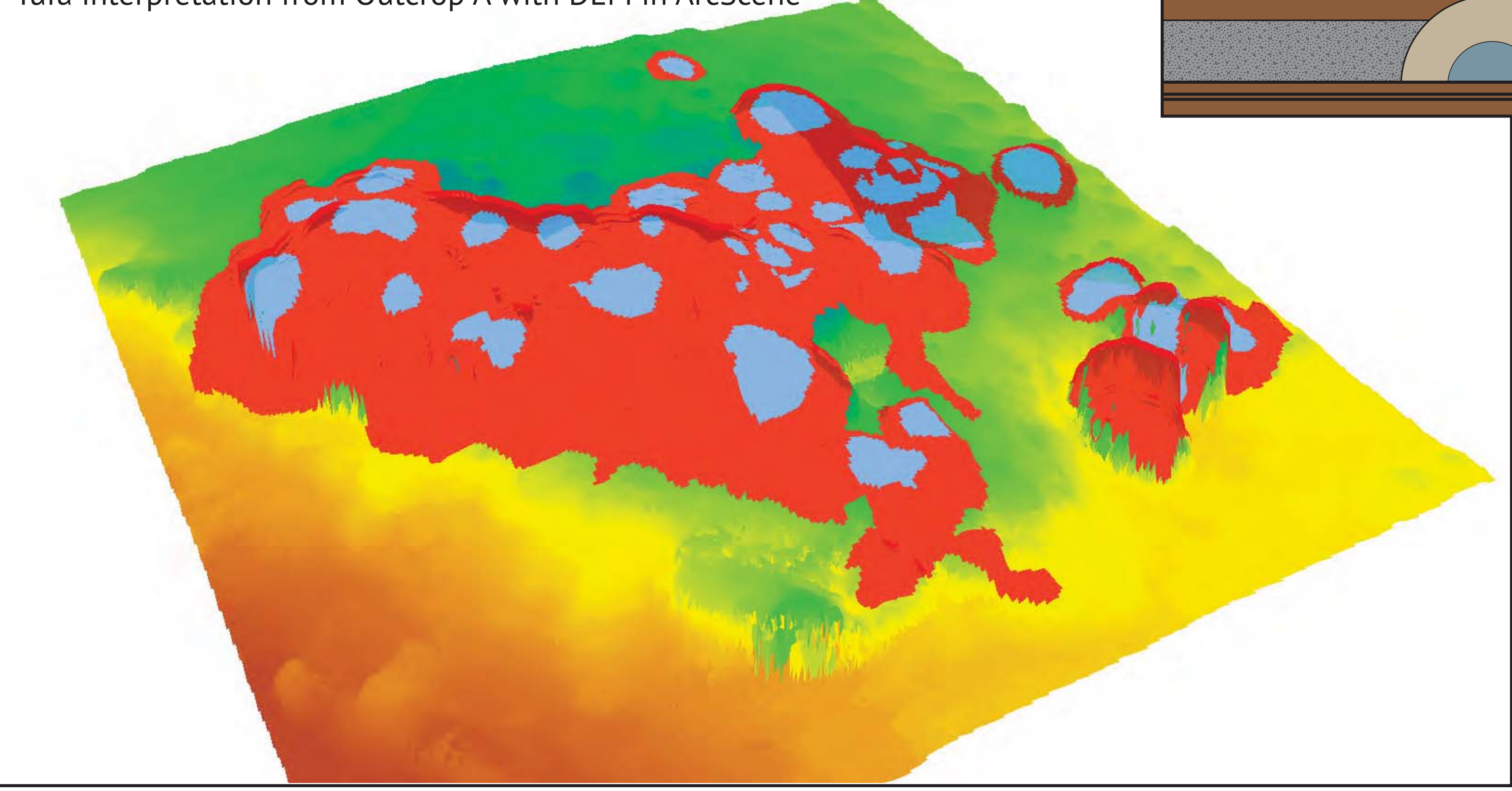
The current results demonstrate that:

- Tufa textural and morphological patterns are present across both basins
- While the mean porosity is similar across tufa textures, the range of values is distinct to each textural type
- Permeability is highly variable with respect to tufa texture, and indicates that some tufa types may be significant barriers to flow (laminated/stromatolite tufas)
- 3D models have provided insight into the depositional trends across the basin and the relationship to subsurface geology

Conceptual Model of Tufa Tower Deposition for Flow Modeling



Tufa interpretation from Outcrop A with DEM in ArcScene



Future work on tufa reservoir architecture includes:

- Increasing the sample size for porosity and permeability measurements
- Transfer of 3D digital outcrop models into geomodeling software such as Petrel, Move, or Skua-GOCAD
- Development of 3D flow models
    - Conceptual models using generalized tufa morphologies and textures
    - True earth models using inputs derived from the digital outcrop models

References

Benson, L. (1994) Carbonate deposition, Pyramid Lake Subbasin, Nevada: 1. Sequence of formation and elevational distribution of carbonate deposits (Tufas). *Palaeogeography, Palaeoclimatology, Palaeoecology,* 109, 55-87.

Faulds, J., Coolbaugh, M., Bouchot, V., Moeck, I., and Oğuz, K. (2010) Characterizing structural controls of geothermal reservoirs in the Great Basin, USA, and Western Turkey: Developing successful exploration strategies in extended terranes. International Geothermal Association. World Geothermal Congress 2010, Apr. 2010, France. 11 p.

Frary, R.N., Louie, J.N., Stephenson, W.J., Odum, J.K., Kell, A., Eisses, A., Kent, G.M., Driscoll, N.W., Karlin, R., Baskin, R.L., Pullammanappallil, S., and Liberty, L.M. (2011) Recent faulting in western Nevada revealed by multi-scale seismic reflection: *SEG Technical Program Expanded Abstracts,* 30, 1373-1377, doi: 10.1190/1.3627458.

Grove, C., and Jerram, D.A. (2011) jPOR: An ImageJ macro to quantify total optical porosity from blue-stained thin sections. *Computers and Geosciences,* 37, 1850-1859.

Petersen, E., M. Abelha, and L. Pedrosa, 2013, Brasil Pré-Sal-1: Libra – avaliação geológica e diretrizes ambientais: ANP, 17/09/2013, 90 p.

Russell, I.C. (1885) Geological history of Lake Lahontan, a Quaternary lake of northwestern Nevada. *U.S. Geol. Surv. Monogr.*, 94, 287 p.

Acknowledgements

The authors would like to thank Jacqueline Corbett for field assistance and drone piloting, Peter Cattaneo for computing assistance, Lachlan Wright and Nick Zaremba for valuable discussion, and the EMPOWER program at Syracuse University for support throughout this research.

This material is based upon work supported by the National Science Foundation under Grant No. DGE-1449617. Additional funding for this work was provided by Syracuse University through the John J. Prucha Field Research Fund, the College of Arts and Sciences Graduate Student Summer Fellowship, alumnus James Thomson, and the Central New York Association of Professional Geologists Grant for Earth Science Student Research.

Syracuse University
College of Arts & Sciences
Earth Sciences

SYRACUSE UNIVERSITY EMPOWER