COSMOGENIC ^{10}BE SURFACE EXPOSURE DATING AND NUMERICAL MODELING OF LATE PLEISTOCENE GLACIERS IN NORTHWESTERN NEVADA

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ABSTRACT

The Great Basin region of the southwestern United States features a rich geologic record of Pleistocene climate change. This study focuses on the glacial record in the Pine Forest and Santa Rosa Ranges in northwestern Nevada west of the Pleistocene Lake Bonneville basin. Preliminary cosmogenic exposure ages in these two ranges are consistent with observations elsewhere in the Great Basin where glacier maxima (or near maxima) and lake highstands in the northwestern Great Basin occurred at ~18–17 ka. Here, we apply numerical modeling of glaciers in both ranges to limit the range of temperature and precipitation combinations accompanying glacier maxima. Numerical model experiments simulating maximum ice extent in the Pine Forest Range and near maximum ice extent in the Santa Rosa Range yield differing results. If precipitation in the Pine Forest Range was similar to modern during a glacial maximum at 21–20 ka, then temperature depressions during this time were -9 to -8°C. If precipitation in the Santa Rosa Range was similar to modern at 18–17 ka, then temperature ranges were -6 to -5°C. Temperature-precipitation combinations for the Pine Forest Range compare favorably with results of model applications to other mountains in the northern Great Basin. To better limit precipitation in the Santa Rosa Range at 18–17 ka, glacier model results are compared with water-budget modeling results for pluvial lakes in northeastern Nevada. This comparison suggests that temperature depression at 18–17 ka was -4 to -10°C and precipitation was 1.5 to 2 times greater than modern. Overall, the chronology of glacial deposits in the northwestern Great Basin and inferred climate during the last glaciation show consistency across the northern Great Basin.

INTRODUCTION

The rich geologic record of Pleistocene climate change includes numerous locations in the Great Basin west of Pleistocene Lake Bonneville. Mountains and valleys in northern Nevada feature abundant records of Pleistocene mountain glaciers and pluvial lakes, which were likely coeval with Lake Bonneville (figure 1). The research described here focuses on (1) the relative timing of glacier maxima in the northwest Great Basin and (2) setting precise limits on temperature and precipitation based on combined results of numerical mountain glacier modeling. Here, we report new cosmogenic ^{10}Be exposure ages of moraines in the Santa Rosa and Pine Forest Ranges of northwestern Nevada, and compare new glacier modeling output to previously reported lake modeling results.

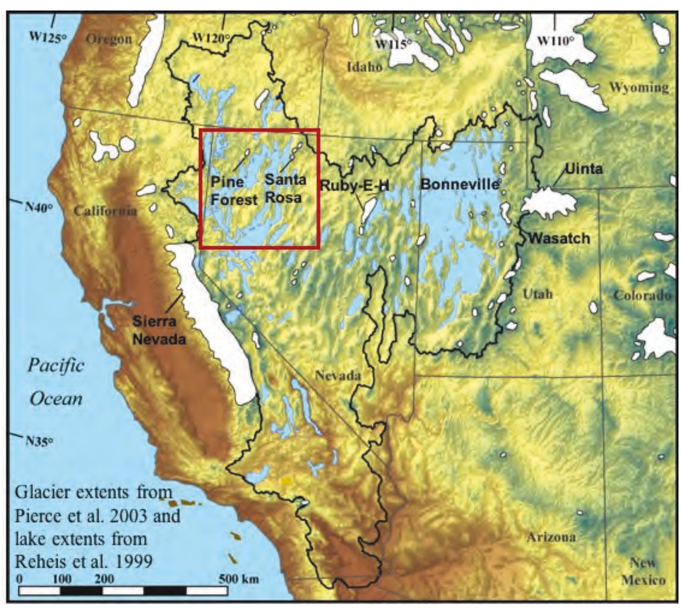

Figure 1. Shaded relief map of the Great Basin (black outline) and neighboring regions in the western United States, with extents of Great Basin lakes (blue) and mountain glacier systems (white). Glacier systems are from Pierce et al. (2003) and lake extents are from Reheis et al. (1999). Mountain glacier systems for this study are outlined in red.

There are over forty glaciated mountains in the Great Basin (Osborn and Bevis, 2001), many of which are west of the Lake Bonneville basin. Partial glacial histories of ranges in the northeastern and north-central Great Basin (Laabs and others, 2013; Laabs and Munroe, 2016) suggest that mountain glaciers were at or near their maximum extent at the time of pluvial lake highstands. The timing of the last Pleistocene glaciation in the Santa Rosa and Pine Forest Ranges is poorly known, particularly compared to the timing of pluvial lake highstands, including those of Jakes Lake and Lake Franklin. Developing the glacial record in the Santa Rosa and Pine Forest Ranges through new mapping, numerical glacier modeling, and cosmogenic ^{10}Be surface exposure dating of moraines can help reveal the temporal pattern of glaciation and accompanying changes in Pleistocene climate in northwestern Nevada. Specifically, identifying the relative timing of glacier maxima and the highstands of Jakes Lake and Lake Franklin, and then the changes in temperature and precipitation accompanying glacier and lake maxima can help to understand the drivers of climate change during the last glaciation and deglaciation (figures 2 and 3).

The Santa Rosa Range is in Humboldt County, Nevada. The highest peaks in the range are Granite Peak, 2,966 m (meters above sea level) and Santa Rosa Peak, 2,956 m. The range also includes Paradise peak of more modest elevation. There are over six glaciated valleys in the range, including those that head on the north flank of Granite Peak, the north and east flanks of Santa Rosa Peak, the north flank of Paradise Peak, and against unnamed headwalls 1.5 km south and 2.2 km south southwest of Paradise Peak respectively (Osborn and Bevis, 2001). The outermost terminal moraine in each valley was targeted for cosmogenic ^{10}Be surface exposure dating and numerical modeling. However, the moraines near Paradise Peak and Santa Rosa Peak do not yield well-defined morainal shapes, and cannot be used for numerical modeling or surface exposure dating.

The Pine Forest Range is also in Humboldt County, Nevada, just north of the Black Rock Desert near Denio, Nevada. The Pine Forest Range is of modest elevation with only a few closely spaced, relatively high summits, the highest of which is Duffer Peak at an elevation of approximately 2,865 m (Osborn and Bevis, 2001). This peak includes evidence for a minimum of three glaciers. The outermost terminal moraine in one of the glaciated valleys was targeted for cosmogenic ^{10}Be surface exposure dating and numerical modeling. Additionally, a recessional moraine farther up valley from the terminal moraine, close to Blue Lake, was also targeted for cosmogenic ^{10}Be surface exposure dating and numerical modeling.

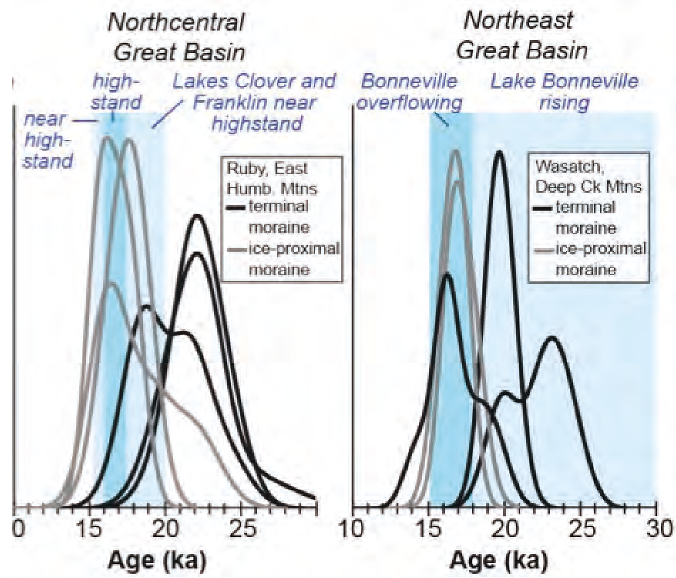

Figure 2. Relative probability plots of cosmogenic ^{10}Be exposure ages in the northcentral and northeast Great Basin. Ages are shown relative to Lakes Clover and Franklin near highstand and relative to the overflowing phase of Lake Bonneville.

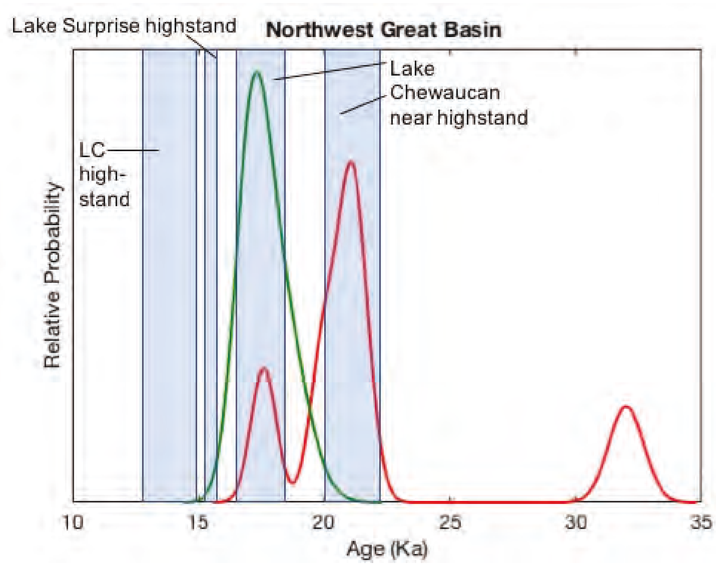

Figure 3. Relative probability plot of cosmogenic ^{10}Be exposure ages in the northwest Great Basin, including the Pine Forest and Santa Rosa Ranges. Ages are shown relative to the Lake Surprise and Lake Chewaucan near highstands.

Even though there have been many inferences of how climate changed in the northern Great Basin during and after the last glaciation, estimates of temperature and precipitation during times of glacier and lake maxima are variable. For example, recent hydrologic modeling studies of Lake Surprise and Jakes Lake in the northwest Great Basin, conclude that lake highstands in these valleys during the latter part of the last glaciation were accompanied by temperature depressions of 5–7°C from modern and precipitation 75–90% greater than modern (Ibarra and others, 2014; Barth and others, 2016), whereas other studies of glacial and lake records have concluded colder and drier climate accompanied lake highstands (e.g., Lyle and others, 2012). Speleothem stable isotopes are useful, continuous records of changes in effective moisture during the last glaciation (e.g., Lachniet and others, 2014; Oster and Kelly, 2016), but they do not by themselves distinguish changes in temperature and precipitation. Cosmogenic ^{10}Be surface exposure dating and glacier modeling can help identify how temperature and precipitation changed during the last glaciation in the northwestern Great Basin.

METHODS

This paper updates the cosmogenic chronology of glacial deposits in the Pine Forest and Santa Rosa Ranges based on newer models of *in situ* production of ^{10}Be. Seventeen samples, six samples from the Pine Forest Range and 11 samples from the Santa Rosa Range, were prepared in the Cosmogenic Nuclide Preparation Lab at NDSU following methods of Laabs and others (2013). Once the samples were loaded into their respective cathodes mixed with a niobium powder, they were then sent to PRIME Lab at Purdue University for $^{10}Be/^{9}Be$ measurement by accelerator mass spectrometer (AMS). We calculated cosmogenic ^{10}Be surface exposure ages of terminal moraines of the last glaciation and last glacial maximum using the calibrated in situ production rate for ^{10}Be determined at Promontory Point, Utah, with the LSDn production scaling model of Lifton and others (2014) as implemented in version 3.0 of the CRONUS-Earth online exposure age calculator (Balco and others, 2008; http://hess.ess.washington.edu).

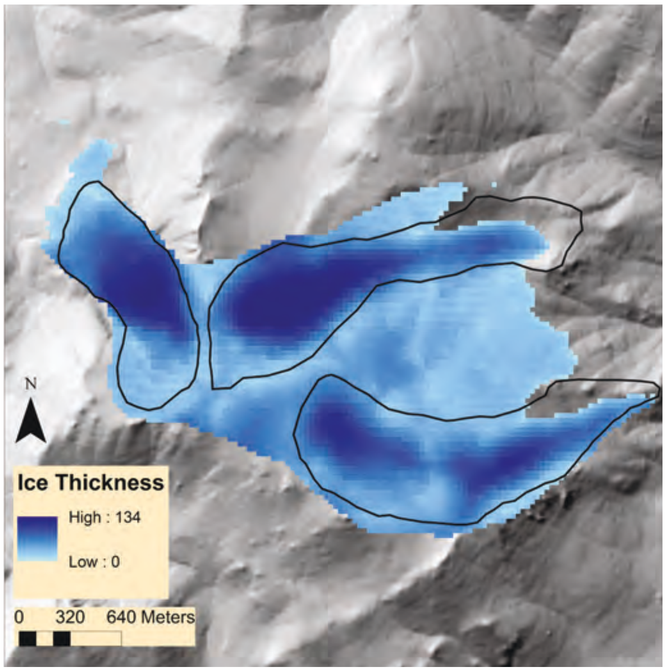

Figure 4. *The reconstructed ice extents (black line) and the modeled ice extent are shown for the Pine Forest Range, Nevada. The temperature-precipitation combination used was -9.1, 1. (https://www.usgs.gov/core-science-systems/national-geospatial-program/national-map)*

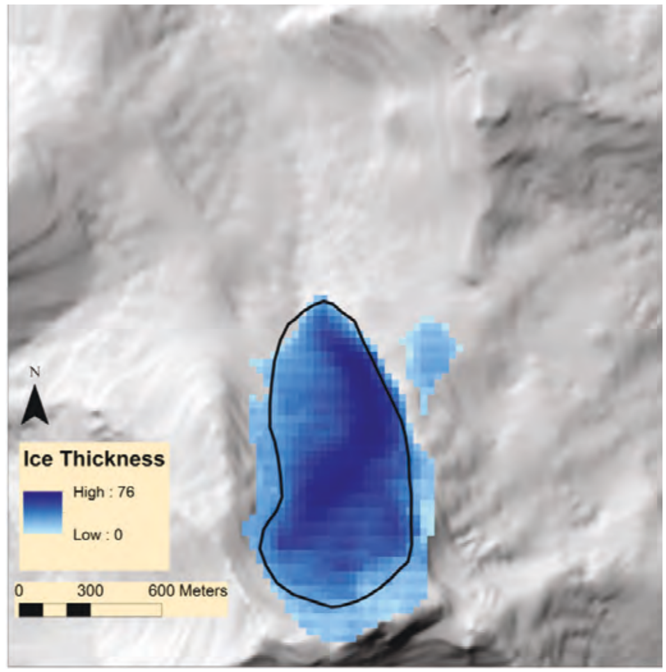

Figure 5. *The reconstructed ice extent (black line) and the modeled ice extent are shown for the Santa Rosa Range, Nevada. The temperature-precipitation combination used was -6.1, 1. (https://www.usgs.gov/core-science-systems/national-geospatial-program/national-map).*

This study also uses a forward numerical modeling approach to determine climate conditions that simulate the known maximum ice extents for the last glaciation in the Santa Rosa and Pine Forest Ranges (figures 4 and 5). The coupled energy-mass balance and ice-flow models used in this study were originally developed by Plummer and Phillips (2003), and have been used to estimate paleo-climate conditions for paleo-glaciers in various mountain glacier settings (Harrison and others, 2014; Rowan and others, 2014; Leonard and others, 2017). The modeling approach aims to match simulated ice extents produced under specific paleoclimate conditions (e.g., temperature depression from modern and precipitation) to known ice extents reconstructed from glacial deposits and landforms identified in the field (e.g., terminal and lateral moraines). The modeling approach consists of two numerical models, a mass and energy balance model and an ice-flow model. The energy-mass balance model calculates monthly snow accumulation and ablation at every cell within the model domain, a digital elevation model of a glacial valley, for the time interval of interest.

Annual mass balance depends mostly on precipitation and temperature, which are the primary inputs to the model (Plummer and Phillips, 2003). Other inputs include relative humidity, cloud cover, solar angles for the area of interest, and a digital elevation surface of the glaciated basin. Average monthly cloudiness and relative humidity are held constant at every cell and elevation within the model domain (Plummer and Phillips, 2003). The source of the inputs, including mean monthly wind speed, temperature, and precipitation, come from RAWS (remote automated weather stations). In order to get a net annual mass balance, we sum the monthly mass balance through the water year and we deviate the "modern" meteorological inputs to simulate paleo-mass balance. Sublimation and monthly snow losses due to melting are calculated from the surface-energy balance. The total is calculated only during melt season. During winter months, only the energy transfer associated with sublimation is calculated. The output is a net annual mass balance defining the areas of net accumulation and net ablation in the model domain, which is used as an input for the ice flow model.

The ice-flow model calculates the time-dependent flux of ice into or out of each cell in a grid created from a set of finite difference equations relating to flow thickness, surface slope, and bed slope (base of glacier) (Plummer and Phillips, 2003). When applying the ice-flow model to the study of geomorphic features of glaciers, we assume that major moraines represent a temporary steady-state condition. Even though the ice-flow model describes transient glacier response, we are only considering steady-state solutions. The primary variable in the model calculations is ice-free surface elevation, the behavior of which is not constant across the grid. Ice surface elevation can either increase or decrease in ice-covered portions of the grid, but can only increase or remain constant in ice-free areas (Plummer and Phillips, 2003). The output of the ice-flow model is a gridded glacier extent, which can be compared to the modeled or known ice extent. The trial-and-error method of calculating glacier mass balance based on an estimated temperature and precipitation combination and forward modeling of the glacier extent based on mass balance allows us to compare the glacier modeling results with the known ice extent. This ultimately produces a set of temperature and precipitation combinations that may have accompanied the glacier at steady state.

RESULTS AND DISCUSSION

Six cosmogenic ^{10}Be exposure ages from a terminal moraine in the Pine Forest Range range from 19.9 ka to 21.2 ka, coinciding with the latter part of the Last Glacial Maximum (21–17 ka). A single exposure age of 17.6 ± 0.5 ka on a younger moraine up valley of the terminal moraine suggests a later advance or pause in ice retreat, although additional cosmogenic exposure ages are needed to obtain an accurate numeric age of this moraine. Eleven Cosmogenic ^{10}Be surface exposure ages from a moraine in the Santa Rosa Range range from 16.8 ka to 18.7 ka. These ages provide the chronological framework for interpreting results of glacier modeling experiments in the two mountain ranges.

The glacier modeling outputs for both the Santa Rosa and Pine Forest Ranges show that modeled glacier shapes closely match the small, simple shapes that characterize the known ice extents (figures 4 and 5). The Santa Rosa numerical modeling results include a broad range of temperature and precipitation combinations that could have accompanied glacier maxima in the two mountain ranges. For example, if precipitation in the Pine Forest Range was similar to modern at the time of the local glacial maximum (~21–20 ka), then temperature depressions during the last glaciation were -9 to -8°C. If precipitation in the Santa Rosa Range was similar to modern during the later glacial maximum at ~18–17 ka, then the temperature ranges were -6 to -5°C.

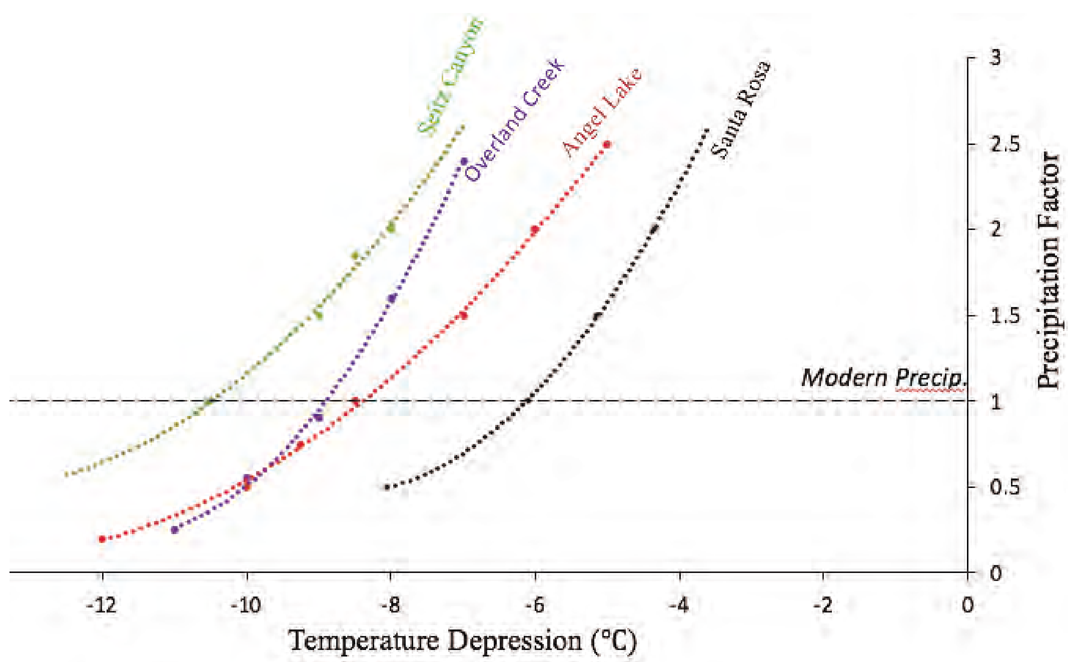

Figure 6A. Temperature-Precipitation combinations yielded from glacier modeling results west of Pleistocene Lake Bonneville. The precipitation factor is a multiplier and the precipitation factor of 1 is equal to modern precipitation.

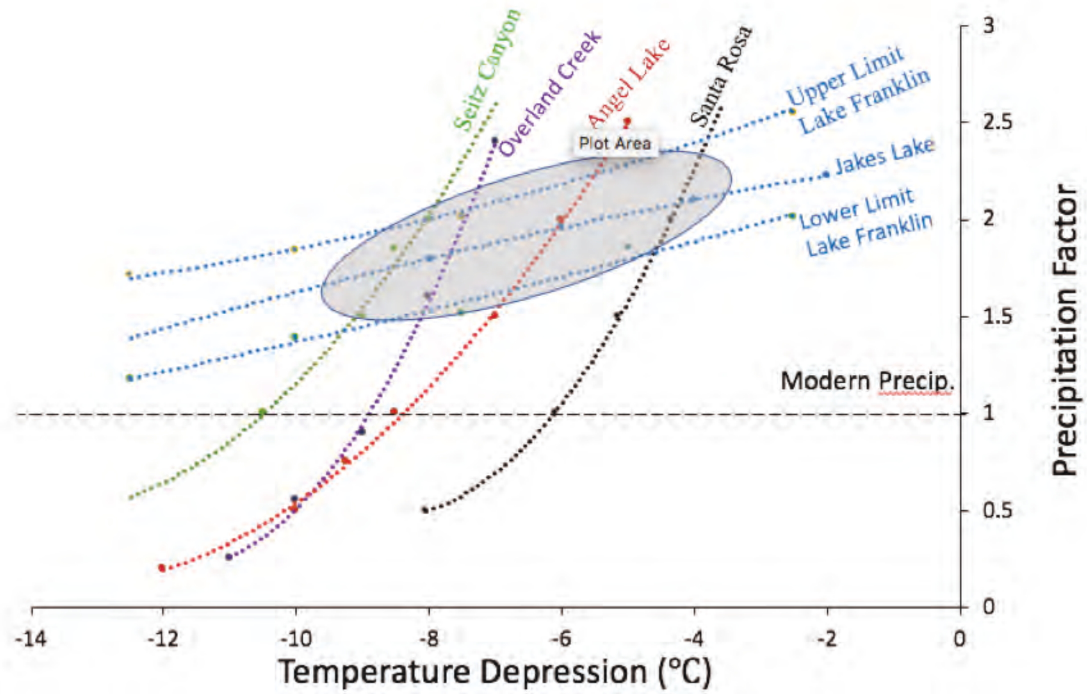

Figure 6B. *Temperature-Precipitation combinations yielded both from glacier and lake modeling results west of Pleistocene Lake Bonneville. The precipitation factor is a multiplier and the precipitation factor of 1 is equal to modern precipitation.*

It is difficult to obtain a unique temperature and precipitation value when only looking at the glacier modeling results (figure 6A). We compare modeling results reported here with others from the northern Great Basin, and with results of water-budget modeling studies of pluvial lakes to identify a unique temperature and precipitation combination for a given time interval (figure 6B). Glacier modeling results are available for the eastern Ruby Mountains (Overland Creek valley; Reimers and others, 2016) and the western Ruby Mountains (Seitz and Hennen Canyons; Truong and others, 2014) as well as the Angel Lake valley in the East Humboldt Mountains (Bradley and Laabs, 2015), providing additional limits on possible temperature and precipitation combinations for the time interval 18–17 ka. Lake-water-budget modeling results, which also provide limits on temperature-precipitation combinations for 18–17 ka, are available from Jakes Lake (Barth and others, 2016) and Lake Franklin (Ferragut and others, 2017). When comparing the Santa Rosa modeling results against other glacier modeling results, including Seitz Canyon, Overland Creek, and Angel Lake, we see that all the lines defining possible temperature-precipitation combinations run nearly parallel to one another (figure 6A). This suggests that glacier modeling results alone do not provide a unique temperature-precipitation combination for 18–17 ka. However, comparing glacier-modeling results with lake-modeling results of Barth and others (2016) and Ferragut and others (2017) reveals intersecting trajectories of possible temperature-precipitation combinations, which yield a more unique estimate of temperature and precipitation at 18–17 ka in the northern Great Basin (figure 6B). For this comparison, we include the upper and lower limits of inferred temperature and precipitation combinations for the modeling of Lake Franklin (Ferragut and others, 2017), and one range of estimates for temperature-precipitation combinations accompanying the highstand of Jakes Lake (Barth and others, 2016). For glacier and lake maxima at 18–17 ka, modeling results suggest temperature depressions from -4 to -10°C and precipitation change from 1.5 to 2 times modern. This range of temperature depressions compares favorably to clumped isotope records from Lake Chewaucan (Hudson and others, 2017), a pluvial lake that expanded in a valley just north of the Santa Rosa Range. Importantly, the combined results indicate greater-than-modern precipitation during the interval 18–17 ka, the time when most lakes of the northern Great Basin expanded (Munroe and Laabs, 2013) and the early part of Heinrich Stadial 1 (Hemming, 2004).

CONCLUSIONS

Overall, the cosmogenic chronology of a terminal moraine in the Pine Forest Range displays some coincidence with the latter parts of the Last Glacial Maximum. On the other hand, the cosmogenic chronology of a moraine in the Santa Rosa Range provides the chronological framework for interpreting results of glacier modeling experiments in the two mountain ranges. Additionally, cosmogenic ^{10}Be surface exposure ages from both the Santa Rosa and Pine Forest Ranges have ages that overlap with high lake phases of the nearby Lake Franklin and Lake Chewaucan (Munroe and Laabs, 2013; Hudson and others, 2017).

Temperature depression for Last Glacial Maximum conditions of -4 to -10°C with 2 to 1.5 times modern precipitation is consistent with estimates from western North America derived from terrestrial pollen (Worona and Whitlock, 1995), and from global climate, hydrologic, and glacial modeling studies (Birkel and others, 2012; Ibarra and others, 2014; Barth and others, 2016). Continued consideration of glacier and lake chronologies for the last glaciation along with refined modeling experiments will help to narrow estimates of temperature and precipitation across the northern Great Basin. For future work, our primary focus will be refining glacier modeling experiments summarized here and water-budget modeling of pluvial lakes of the northern Great Basin. There will also be additional cosmogenic ^{10}Be surface exposure dating of the Santa Rosa and Pine Forest Ranges.

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Numerical Modeling of Late Pleistocene Glaciers and Lakes West of Lake Bonneville, Implications for Regional Climate Change

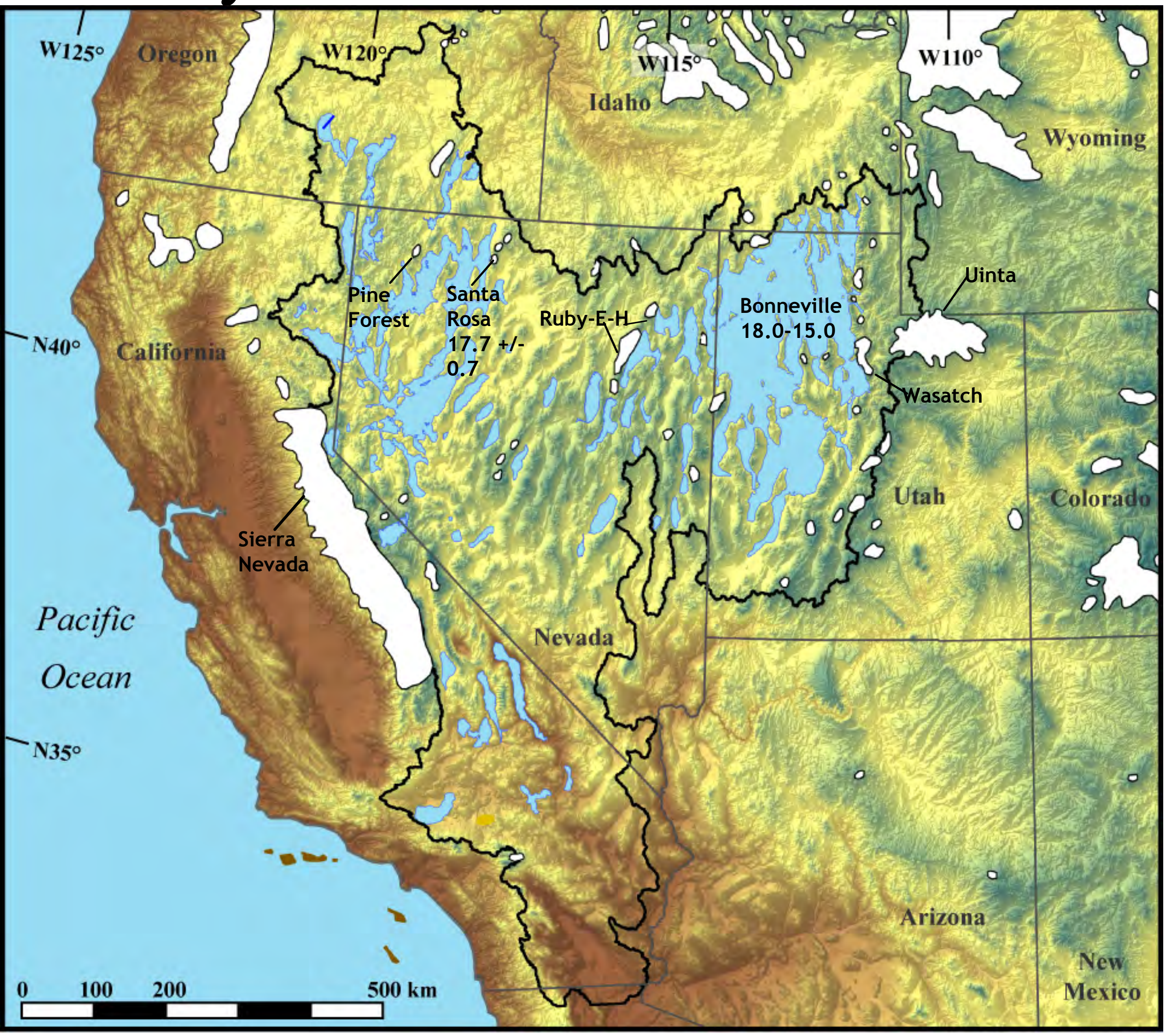
By Kaitlyn Fleming

North Dakota State University

Outline

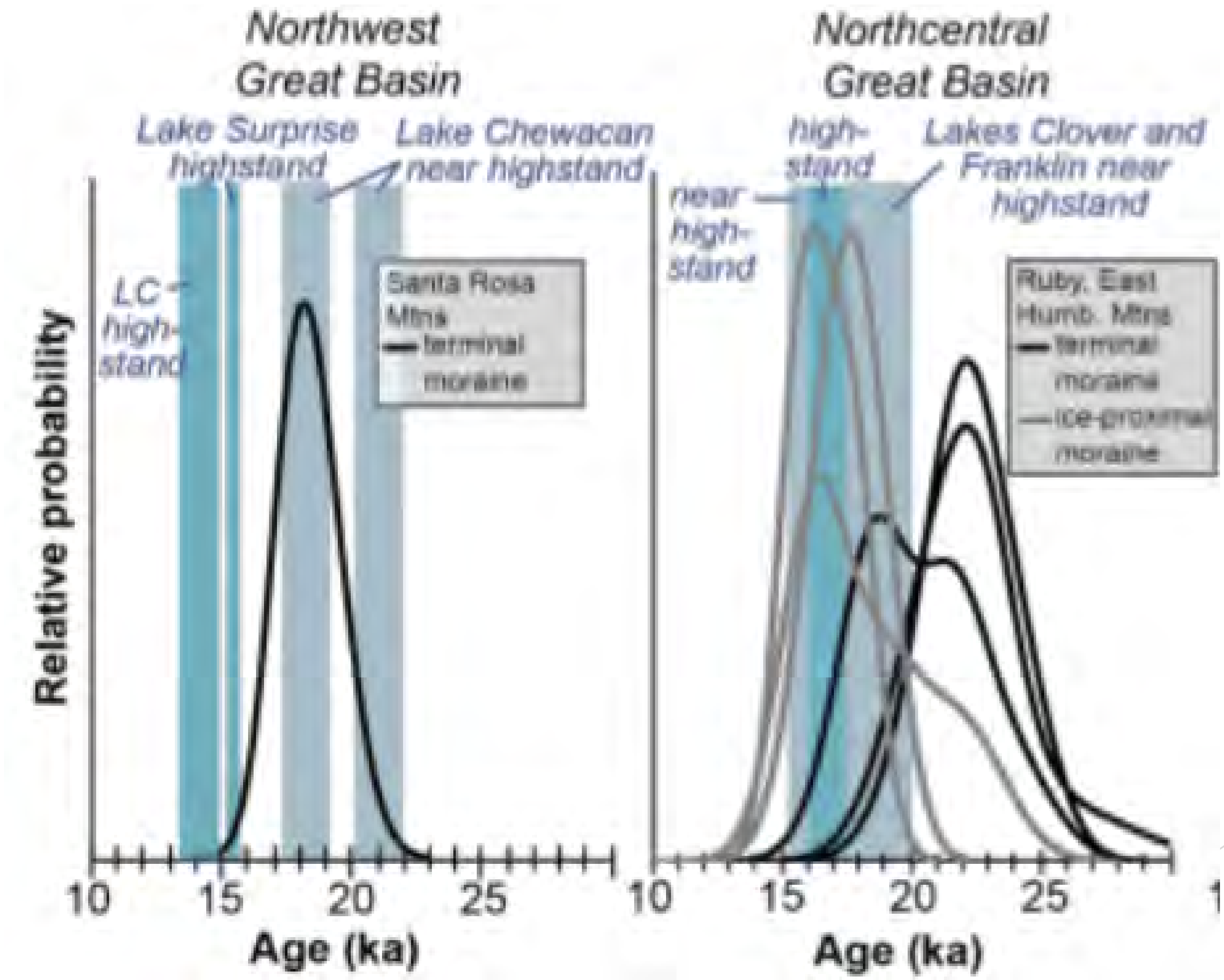
- Study area- Pleistocene glaciers and lakes west of Lake Bonneville
- Research objectives- paleoclimate in the northwest Great Basin
- Glacier modeling
- Inferences of Late Pleistocene climate

Study Area: Santa Rosa and Pine Forest Ranges



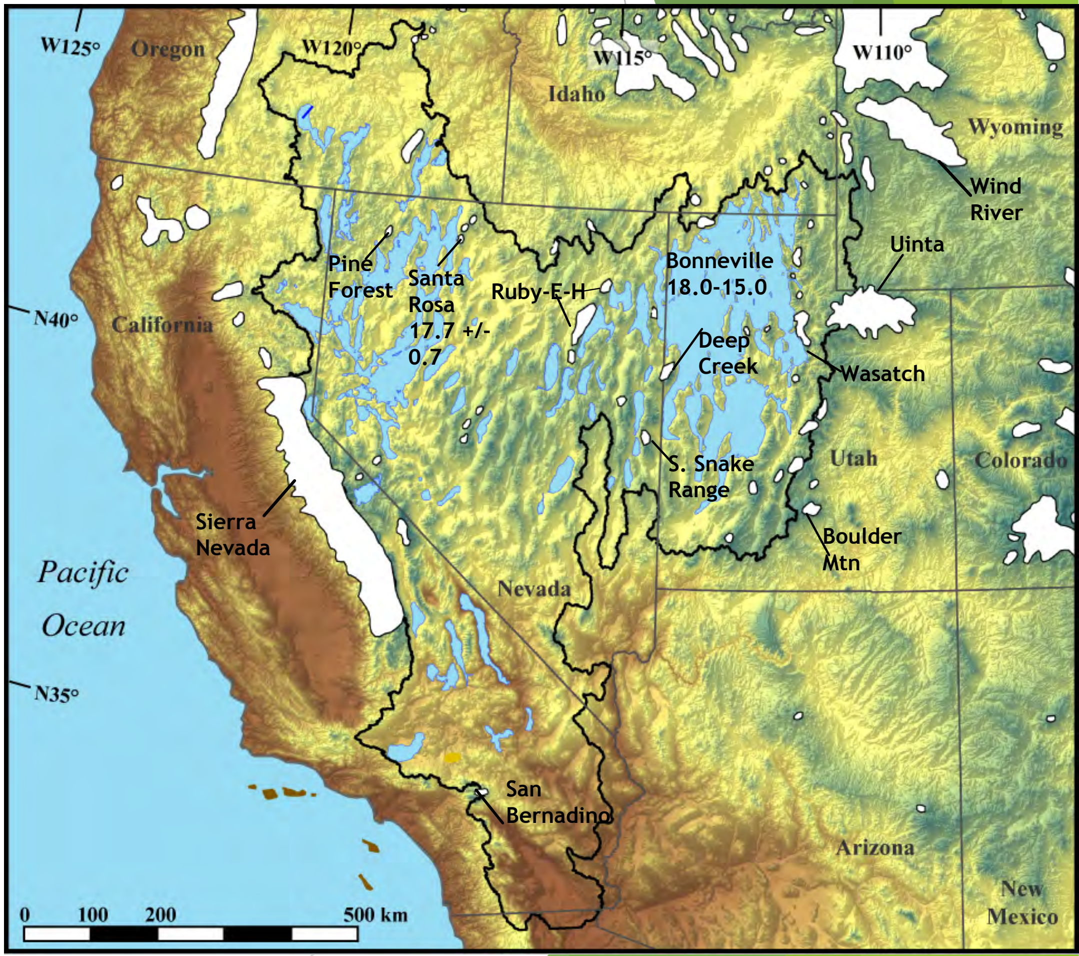
- Forty glaciated mountains in the Great Basin (Osborn and Bevis, 2001).
- Glacial histories of ranges between the Sierra Nevada and the Wasatch Mountains are partly developed (Laabs and Munroe, 2016)
- Santa Rosa and Pine Forest Ranges

Relative Timing of Moraine Deposition and Lake Highstands

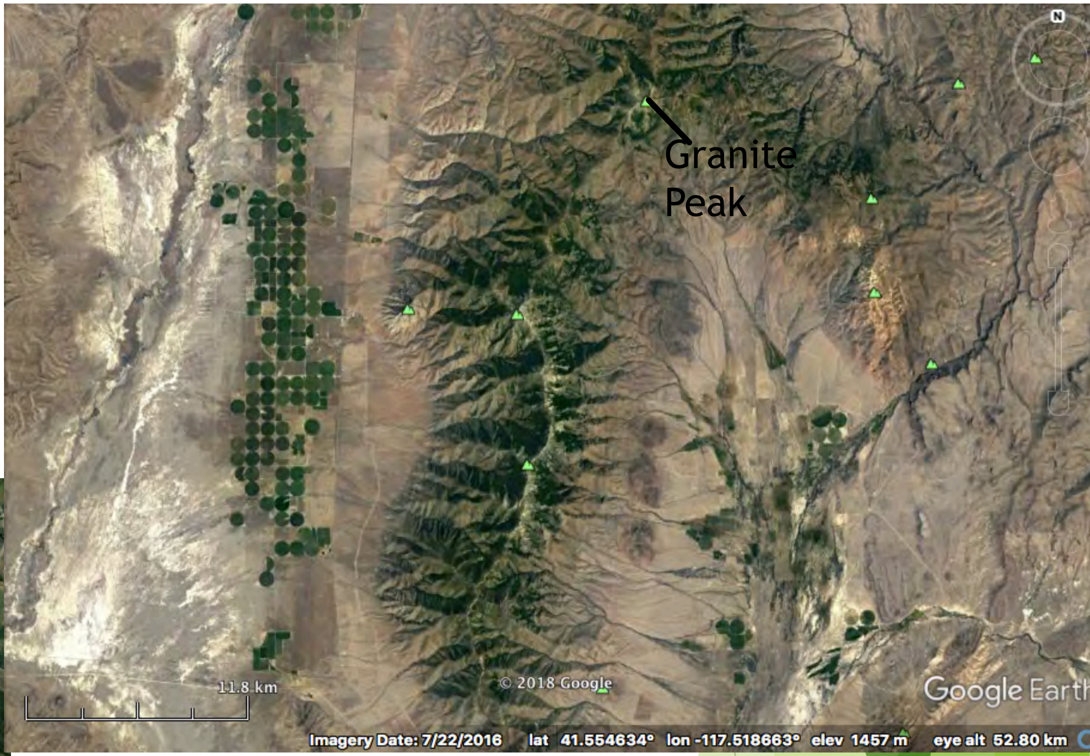


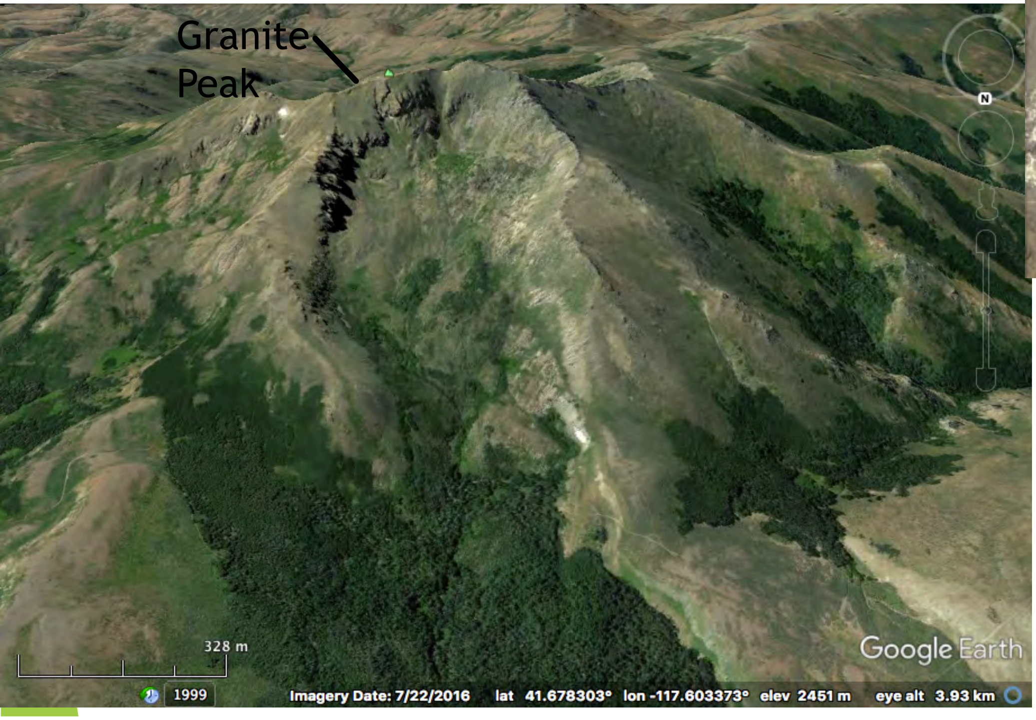
Research Objectives

- Determine the relative timing of glacier maxima and lake highstands in the northwest Great Basin
- Set precise limits on temperature and precipitation based on modeling glaciers and lakes

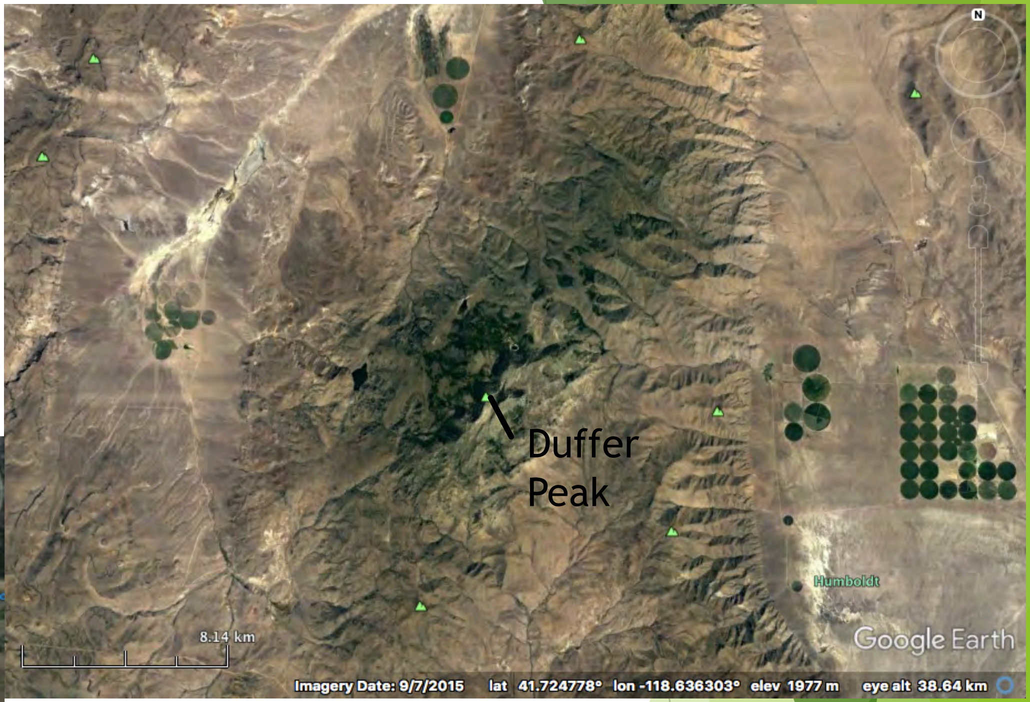


Santa Rosa Range

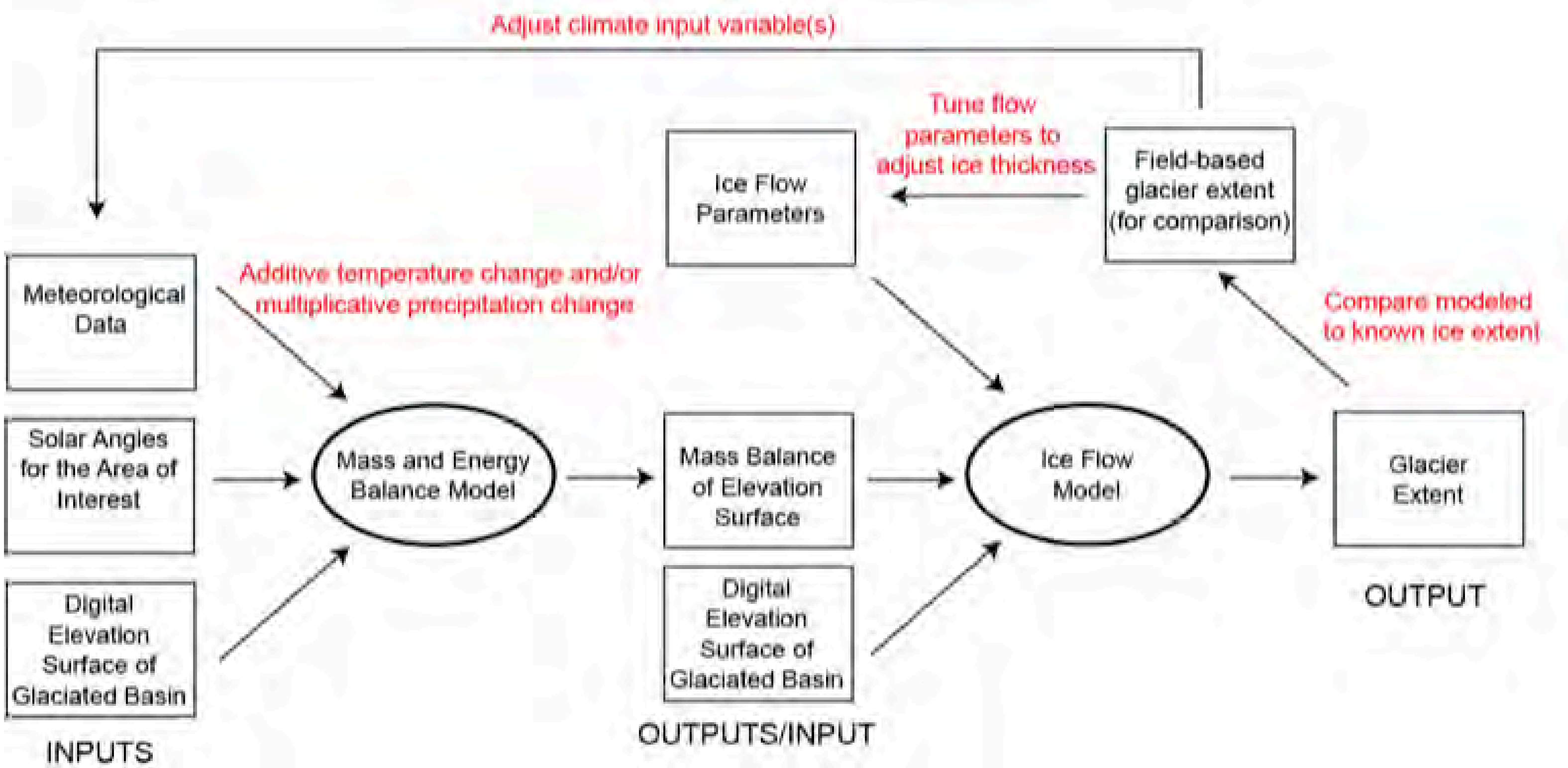




Pine Forest Range

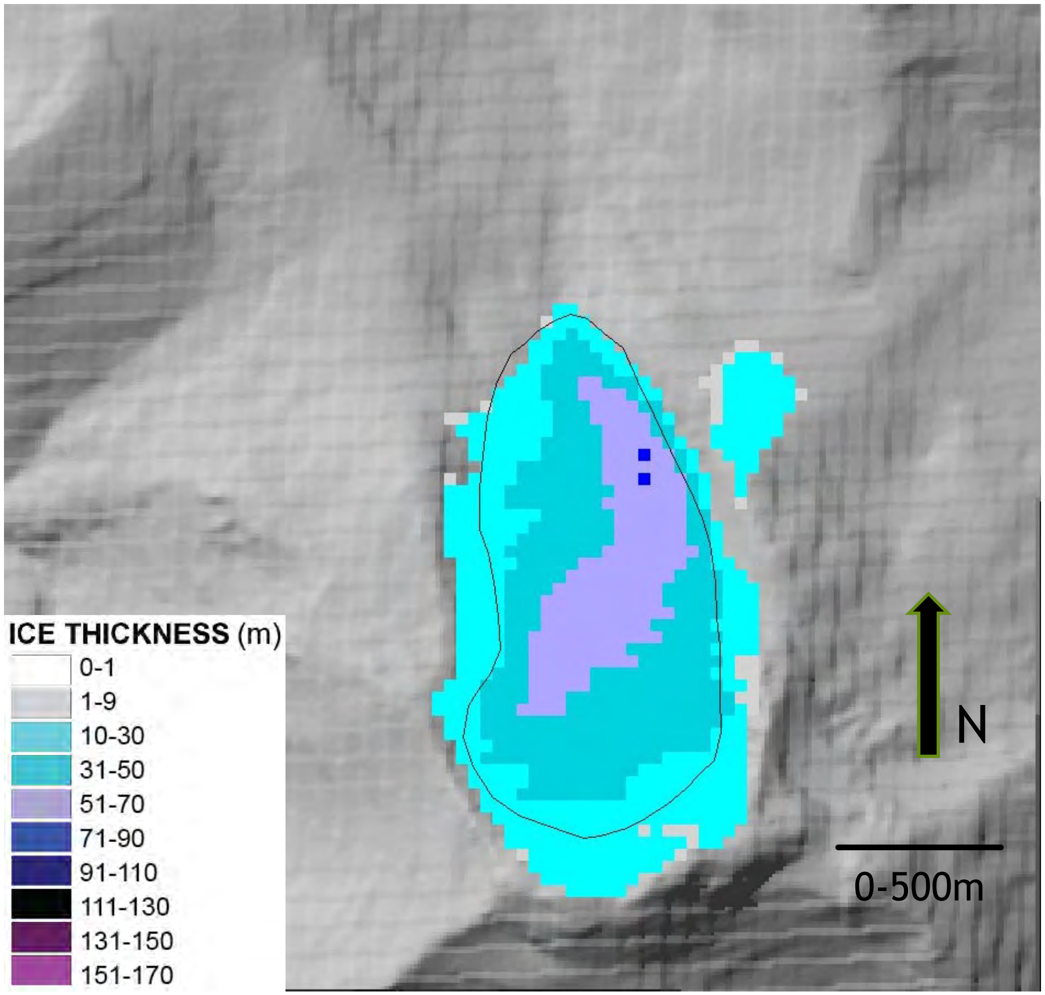


Glacier Modeling Procedure



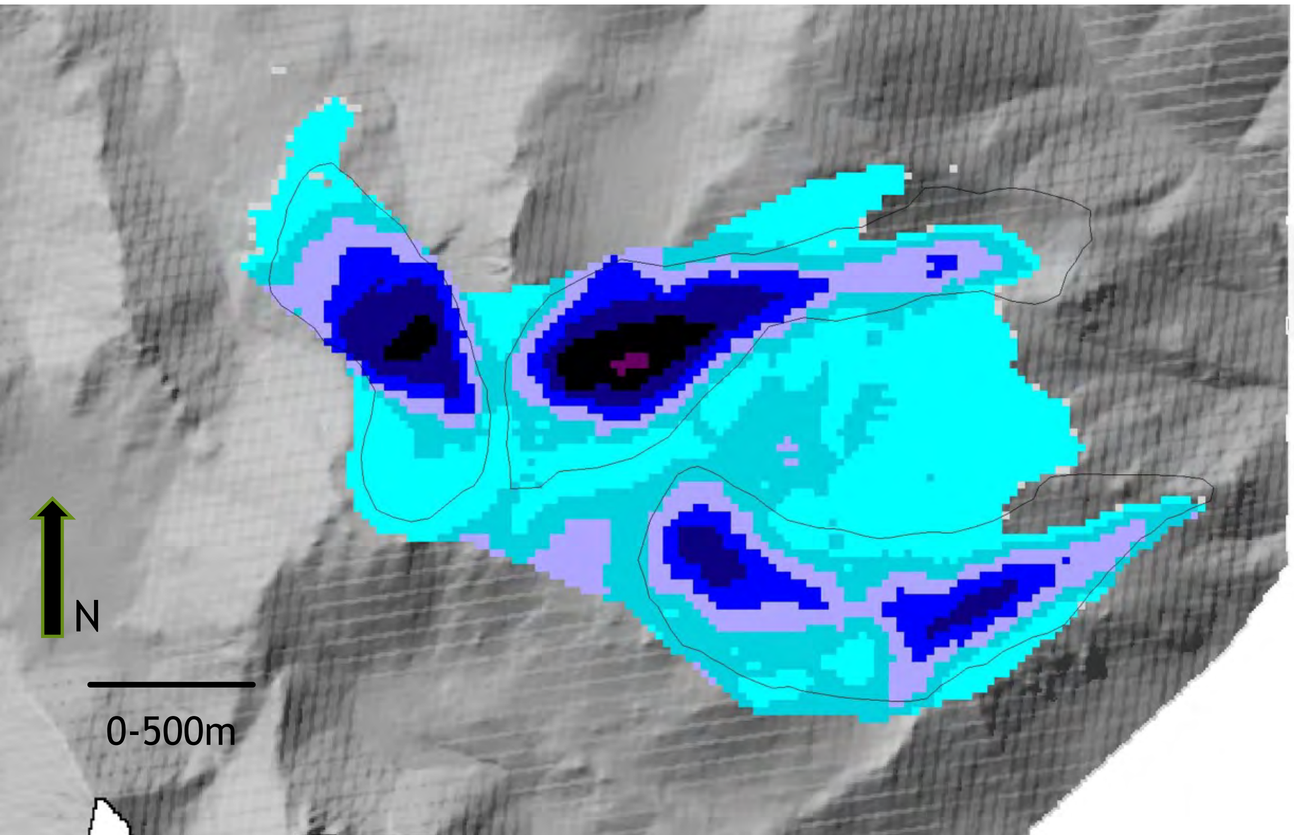
Plummer and Phillips, 2003

Glacier Modeling Results: Santa Rosa Range

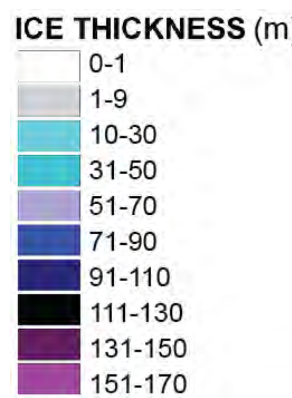


- Modeled glacier shape closely matches the known ice extent
- Temperature: -6.1
- Precipitation: 1

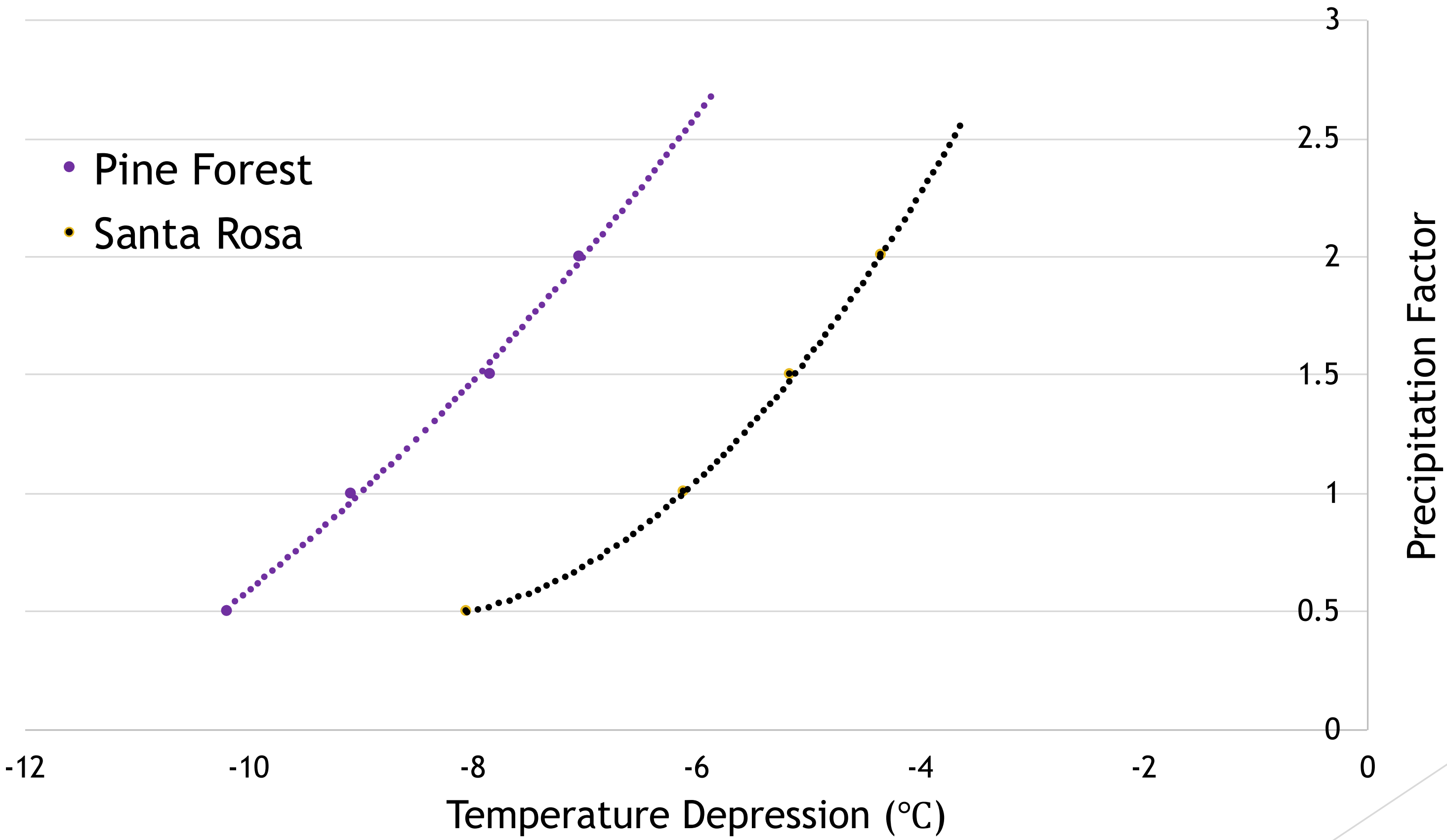
Glacier Modeling Results: Pine Forest Range



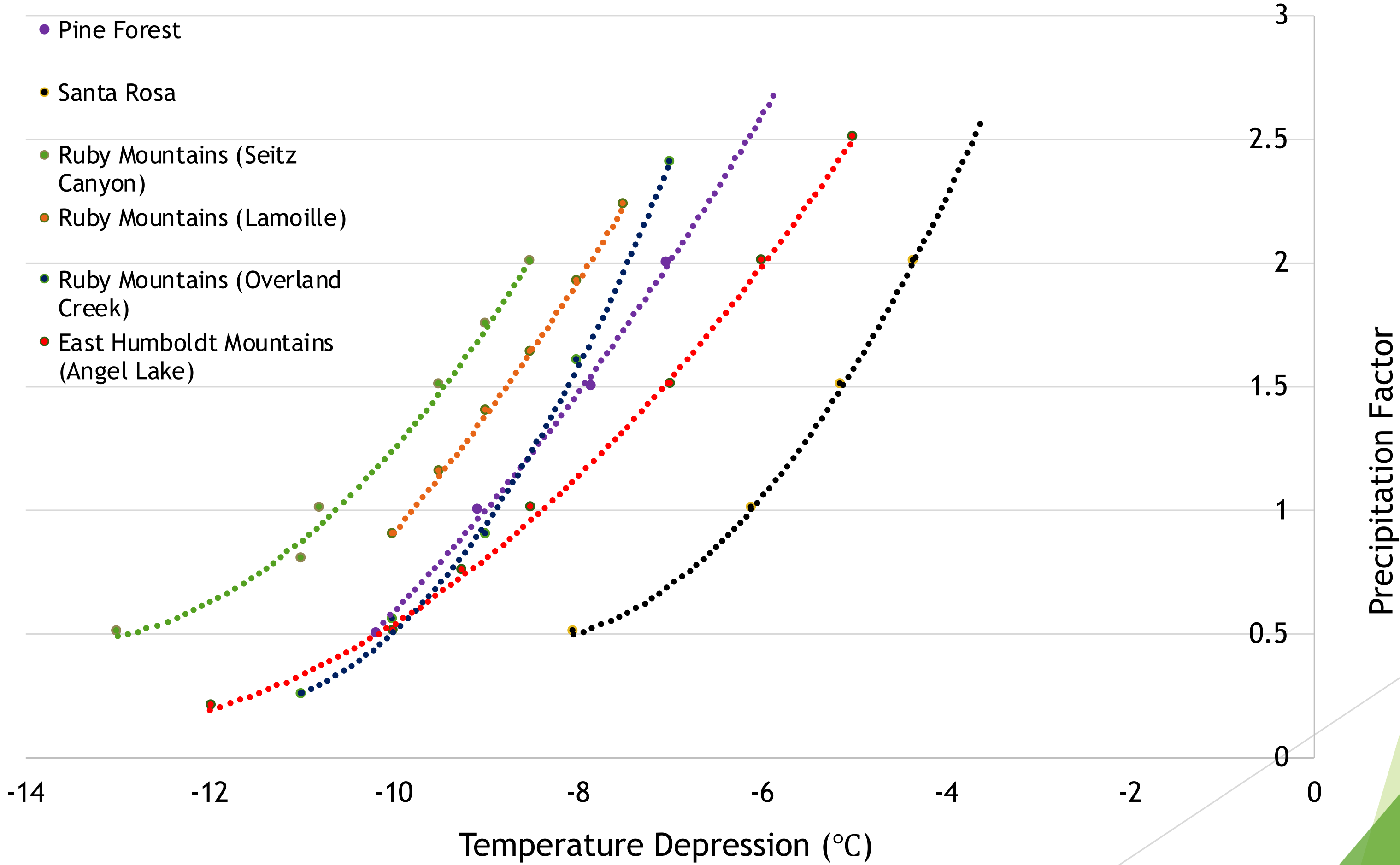
- Temperature: -10.2
- Precipitation: 1



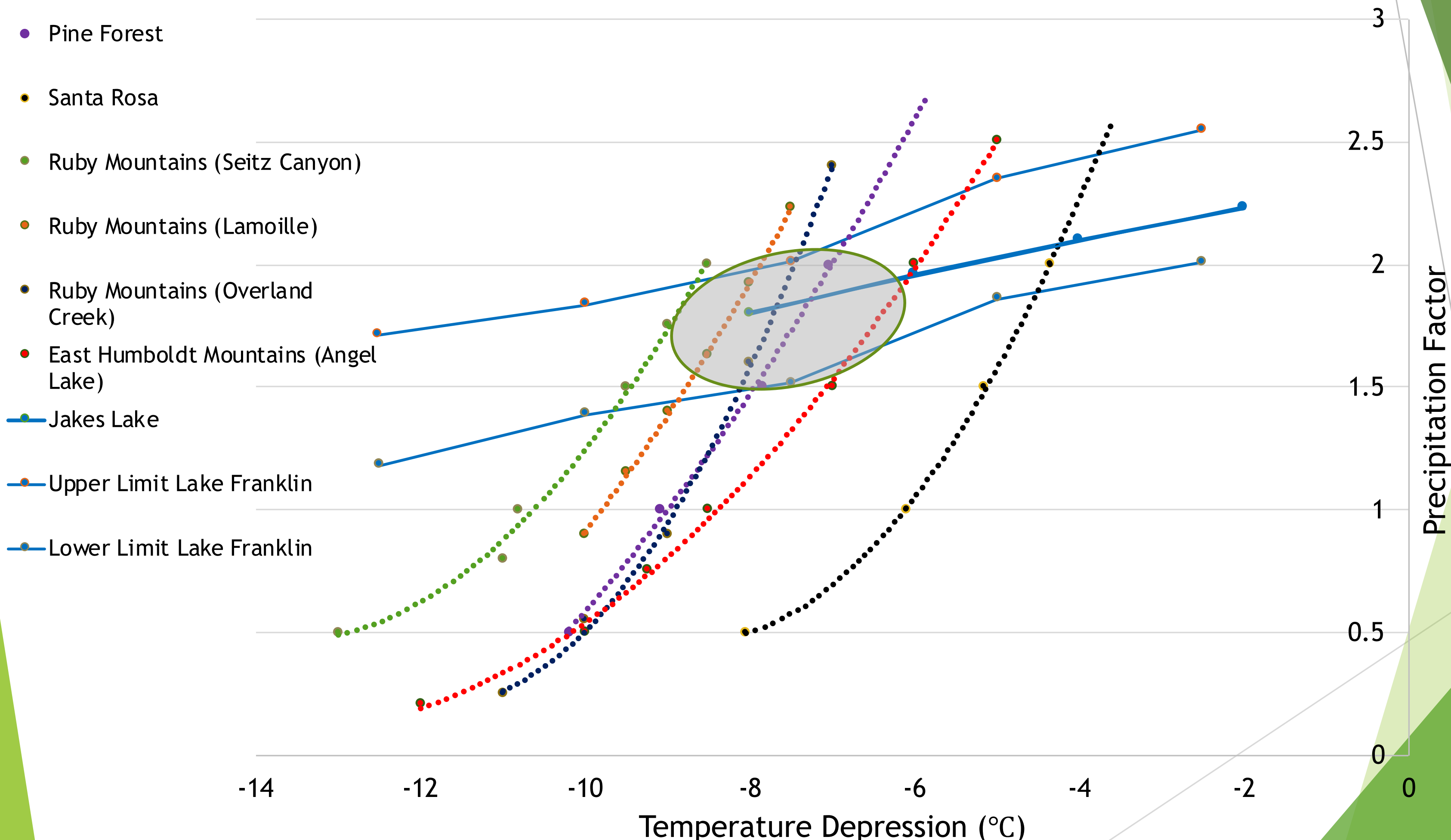
Pine Forest and Santa Rosa Glacial Model Results



More Glacier Model Results From West of Lake Bonneville



Comparison of Glacial and Lake Model Results



Conclusions

- Glacier modeling experiments yield a broad range of possible temperature and precipitation combinations for the northern Great Basin
- Combining glacier and lake modeling results yield temperature and precipitation combinations from -7 to -9
- Results of numerical model experiments that simulate Last Glacial Maximum (LGM) and Lateglacial ice extents include a range of temperature and precipitation combinations accompanying glacier maxima in the northwestern Great Basin
- Chronology of glacial deposits and inferred climate during the last glaciation show consistency across the northern Great Basin
  - Suggests that precipitation in the region was similar to modern

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