Quaternary Science Reviews 327 (2024) 108531

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Reconciling Neoglacial climates during the Late Holocene Dry Period, Great Basin, USA

Constance I. Millar [a,*], David Hurst Thomas [b]

[a] USDA Forest Service, Pacific Southwest Research Station, POB 201, Lee Vining, CA, 93541, USA
[b] American Museum of Natural History, Central Park West at 79th St., New York, NY, 10924, USA

ARTICLE INFO

Handling Editor: I Hendy

Keywords:
Neoglaciation
Late Holocene Dry Period
Great Basin
Rock glaciers
Late Holocene
Middle Archaic Archaeology

ABSTRACT

The Late Holocene Dry Period (LHDP, 3100-1800 cal yr BP) is well established as a period of extreme aridity across lowlands of the Great Basin (GB) yet little has been elaborated about high mountain conditions. Further, temperatures have not been comprehensively addressed at any elevation, although the period is often implied to have been warm. Despite a literature on the early Neoglaciation in the GB, conditions at high elevations have not been incorporated in previous treatments of the LHDP. We compile existing and new data on locations and ages for early Neoglacial advances in mountains of the GB, documenting its existence in 33 mountain ranges that extend from 36.47 °N to 44.30 °N and 110.69 °W to 121.36 °W. Dates indicate the early Neoglaciation occurred before, during, and after the LHDP; starting as early as 3800-3700 cal yr BP, with subsequent advances at 3400, 3200, 3100–3000, 2930, 2900, 2800, 2700, 2600, 2550–2640, 2400, 2240, 2200, 2150, 2100, 2000, 1955, 1880, 1700, 1600, 1500, and 1400 cal yr BP. We estimate summer temperature decreases from modern conditions that would enable rock glaciers to have advanced in the LHDP as ~1.3 °C–~4.5 °C, with no or slight increase in winter precipitation for mountain ranges with modern winter snowpacks >54 cm. Cooler summers would translate to lower evaporation and overall maintenance of wetter conditions in the uplands than modern summer conditions, supporting healthy high-elevation ecosystems. Middle Archaic GB communities significantly transformed their lifeways at the start of the LHDP, bringing entire families to summer at alpine plateaus and providing a new proxy for cool, wet uplands during this millennium. To underscore the importance of glacial conditions at high elevations in the GB, we propose that this period be referred to as the "Early Neoglaciation/ Late Holocene Dry Period."

1. Introduction

The Late Holocene Dry Period (LHDP) was a 1300-year period of extreme aridity that extended from ~3100 to ~1800 cal yr BP across much of the Great Basin (GB) of southwestern United States (Mensing et al., 2023). First formally recognized from geomorphologic (Miller et al., 2001, 2004) and vegetation (Tausch et al., 2004) evidence as the "Post-Neoglacial Drought" (2600–1600 cal yr BP), the climate interval has subsequently been defined in increasing detail using pollen and sediment data retrieved from locations across the Great Basin (Mensing et al., 2008, 2013). The latest syntheses (Mensing et al., 2023; Thomas et al., 2023) bring new vegetation data together with archaeological evidence, tree growth, submerged stump ages, lake level studies, and sedimentation rates to clarify the latitudinal and longitudinal extent, duration, intensity, and variability of expression of the LHDP. During extensive periods of a positive Southern Oscillation Index (a stable "La Niña" state) the polar front appeared to follow a more northerly storm track, producing an anomalously wet northwest and a dry southwest (relative to western North America), with a weak Aleutian low and low pressure over the West (Mensing et al., 2023). While earlier paleoenvironmental studies proposed a dipole pattern during the LHDP, with wet sites to the north and dry sites to the south (Mensing et al., 2013), the most recent work clarified the strength of the dipole, with a transition zone at ~40 °N to 42 °N. With this series of publications, the LHDP is definitively recognized as an exceptional and millennial drought of the Great Basin, with aridity during certain portions that exceeded any time in the Holocene (Mensing et al., 2023).

Given the unique character of the LHDP it is not surprising that prior studies have focused on precipitation and aridity in the Great Basin (Tausch et al., 2004; Mensing et al., 2008, 2013, 2023; Thomas et al.,

* Corresponding author.
E-mail addresses: constance.millar@usda.gov (C.I. Millar), thomasd@amnh.org (D.H. Thomas).

https://doi.org/10.1016/j.quascirev.2024.108531
Received 16 November 2023; Received in revised form 18 January 2024; Accepted 28 January 2024

2023). Despite broad geographic representation of sites across the latitudinal and longitudinal breadth of the GB that have been exploited to describe the LHDP, the pollen and sediment study locations have been almost exclusively at low-mid elevations, deriving mostly from valley basins or near-basin locations: The 12 primary sites analyzed by Mensing et al. (2008, 2013, 2023) have mean elevation of 1756 m (range 1160–2424 m; std, 362.1 m). Only three sites were located above 2400 m; excluding those, the remaining nine sites have mean elevation of 1579 m (std, 184.7 m). Geomorphic evidence from hillslope erosion during the LHDP included montane elevations, with study sites at mean elevation of 2500 m (range, 1850–3200 m; Miller et al., 2001, 2004). This focus on low-mid elevations is understandable given the nature of sites suitable for analysis, but it results in the highest elevation zones (alpine, subalpine; >3000 m) being underrepresented and little considered in prior studies. Given that the Great Basin has at least 39 ranges reaching summits over 3050 m, and many more near this (Grayson, 2011; Charlet, 2020), considerable Great Basin terrain remains unevaluated as to LHDP conditions.

Perhaps as important, whether regarding lowlands or high mountains, the role of temperature during the LHDP has been little assessed in former studies. When temperature was considered, it was most often proposed to have been warmer during the major dry phases of the LHDP (Miller et al., 2001: 85; Mensing et al., 2008: 87; Mensing et al., 2013: 276; Mensing et al., 2023: 11; an exception is Thomas et al., 2023), although some proxies implied cool conditions (Tausch et al., 2004). Mensing et al. (2023) noted that cooler temperatures appear to have coincided with the wet interval within the LHDP, from 2200 to 2000 cal yr BP, and Mensing et al. (2013: 277), briefly mentioned without discussion Late Holocene glacial advances. The result is that the role of temperature during the LHDP has been left as uncertain in prior studies, the general conclusion being that further research is necessary to determine whether temperatures were relatively cool or warm (Mensing et al., 2008: 87; Mensing et al., 2013: 277).

1.1. The Neoglaciation

The Neoglaciation (NG) is defined and widely accepted to be a widespread geo-climatic unit characterized by the rebirth and growth of alpine glaciers following their maximum shrinkage during the warm, dry Middle Holocene (Moss, 1951; Porter and Denton, 1967). Such reactivation of glaciers worldwide was first brought to attention by Matthes (1941), whose primary studies were on moraines in the Sierra Nevada, CA. By "geo-climatic unit" Porter and Denton (1967) meant that, rather than the more common convention of naming stratigraphic periods with codified age ranges, glacial advances post-Middle Holocene were time- and space-transgressive. In the broadest sense, Porter and Denton (1967) recognized the NG as extending from 5000 years ago to present (Matthes, 1941 suggested the last 4000 years), although more recent evidence indicates that some regions experienced Neoglacial advances beginning at 6.3–6.5 ka (Davis et al., 2009; Larsen et al., 2020). Generally, NG dates vary with latitude, with earlier glacial dates starting in the north and younger dates in the south. Porter and Denton (1967: 204) summarized this trend for western North America, noting that the NG started ~4000 years ago in the Gulf of Alaska, ~3500 years ago in southeastern Alaska, ~3000 years ago in southern British Columbia, Washington, and Oregon, and ~2500 years ago in California. In addition to latitudinal effects, local and regional climates strongly affected the timing, extent, and even presence/absence of a NG advance, creating variation in expression even at similar latitudes (Benedict, 1973; Munroe, 2002).

Further, within the overall extent of the NG, major clusters of glacial advances occurred at different times and in different intensities depending on region, and increasingly resolved and local information continues to accumulate for mountain regions worldwide (Porter and Denton, 1967; Davis et al., 2009; Marcott et al., 2019; Larsen et al., 2020). Some regions appear to have had more-or-less synchronous glacial stades (with local names assigned) while other regions lacked prominent stades altogether. Broadly, however, around alpine regions of the world, the glacial advances of the NG cluster into two major time intervals, the "early Neoglaciation," which extended from the regional start dates (~5000–3000 years ago) to ~1600 years ago, and the "late Neoglaciation," widely recognized as the Matthes advances, or Little Ice Age (LIA, Grove, 1988), ~700 years ago to the early 1900s CE. A ~900 year interval of no or mild/short glacial advances is commonly documented between these bookends.

1.2. The Neoglaciation in the Great Basin

Prior studies of the NG in the Great Basin have documented variability in dates and expression for this region as well; in some areas 3–4 major phases are recognized for the NG rather than two phases, the early NG and the late NG. Further, prior to work beginning in the late 1980s–1990s, glacial geologists often assumed that the NG was represented in GB mountain ranges mostly (or only) by the recent LIA interval, with minimal glacial advances earlier. This conclusion resulted from the apparent absence of lateral/terminal moraines typical of ice glacier deposits that dated older than LIA age in mountains of the GB (Burke et al., 1983, Clark and Gillespie, 1997; Konrad and Clark, 1998; Munroe, 2005; Marcott et al., 2019).

Increasing knowledge of the role of rock glaciers as glacial landforms (Barsch, 1977, 1996; Martin and Whalley, 1987; Clark et al., 1994) triggered a re-evaluation of early-NG advances in the Great Basin. Rock glaciers are tongue- or lobate-shaped masses of rock rubble, with over-steepened slopes, contain embedded ice, and have downslope movement due to pressure-induced ice creep (Giardino et al., 1987; Giardino and Vitek, 1988; Burger et al., 1999). They form as a result of both glaciogenic and periglacial conditions; a continuum between endmembers is currently recognized (Anderson et al., 2018). Rock glaciers do not routinely deposit lateral or terminal moraines and move much slower than ice glaciers as a result of their massive rock mantles. Because of the insulating effect of the mantle, ice in rock glaciers melts slower relative to ice glaciers as climates warm, and internal ice can be hundreds of years old (Müller et al., 2016); ice in temperate glaciers, by contrast, melts on decades-to-a-century timescale (Clark et al., 1996). For similar reasons, rock glaciers can occur at lower elevations than ice glaciers even during the same climatic period (Delaloye and Lambiel, 2005). Because rock glaciers do not retreat upslope as do ice glaciers when temperatures warm, their rocky mantles deflate in place as internal ice melts. Relict rock glaciers (lacking embedded ice) remain as prominent landforms on the landscape and can reactivate as climate becomes cooler and wetter, meaning that embedded ice can regrow and rock glaciers become active again. Rock glaciers have been described from parts of the Great Basin (Osborn and Bevis, 2001), especially the Sierra Nevada (Clark et al., 1994; Millar and Westfall, 2008), the Snake Range (Davis, 1988), and the Uinta Mountains, UT (Munroe, 2018). No systematic inventory or assessment was available, however, until a recent study documented the widespread distribution of rock glaciers throughout high mountains of the Great Basin, with occurrence in 34 mountain ranges across the region (Millar and Westfall, 2019).

Recognition and increased study of Great Basin rock glaciers as glacial landforms reveal that many such features initiated and advanced during the early-NG. Many advances were dated to the LHDP. Thus, especially through the elucidation of rock glaciers, the early-NG is now recognized as a period of prominent glacial advance expressed in Great Basin mountains, as throughout western North America (Davis et al., 2009). A review of this literature, with compilation of locations and ages for early-NG evidence, however, has not been undertaken, nor has new information from work in recent years been incorporated to understanding dates, temperatures, or geographic extent.

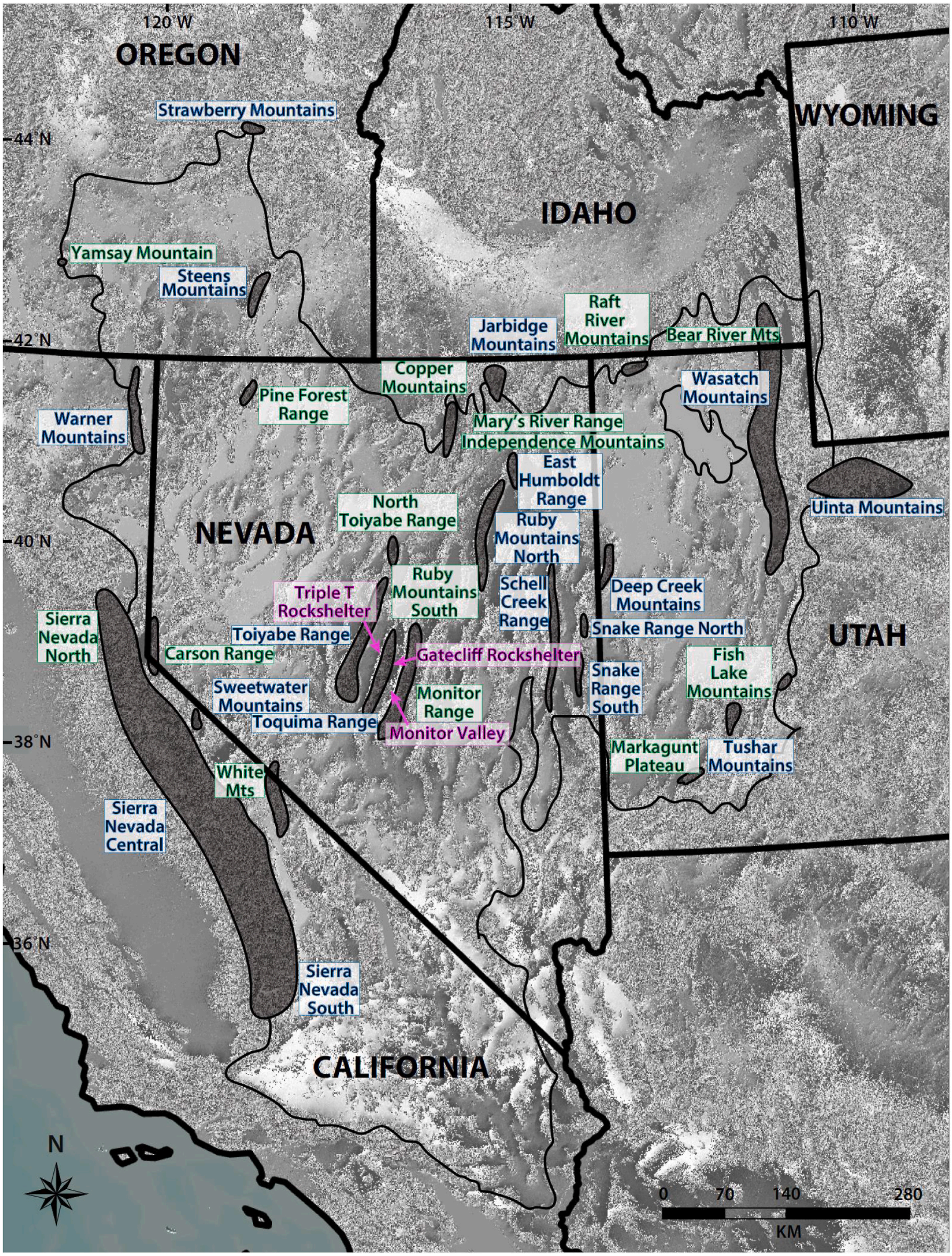

Fig. 1. Map of Great Basin mountain ranges having evidence for early Neoglaciation. Blue labels are ranges where previously published records document early Neoglacial advances (Table 1). Green labels are additional ranges evaluated to have early Neoglacial evidence from the rock glacier inventory of Millar and Westfall (2019; Table 2). All ranges labeled blue also were corroborated by the Millar and Westfall study. Magenta labels indicate archaeological locations mentioned in the text. Black outline is the boundary of the hydrographic Great Basin.

1.3. Human dimensions

In addition to physical proxies, much can be learned about climate and ecosystem effects by studying human reactions to these events. People living in the Great Basin throughout the Holocene showed great ecological savvy and adaptability to changes in the climates of their environment (Mensing et al., 2023; Thomas et al., 2023). In this study we present new information and interpretations from anthropological studies that bear on the nature of early-NG/LHDP climates. First we briefly summarize human-climatic interactions in the GB during the Holocene.

The first Great Basin peoples (Paleoindians) lived >12,000–9000 years ago alongside Late Pleistocene and Early Holocene desert lakes and marshlands. In addition to bountiful resources directly from the lakes and adjacent wetland environments, these broad-spectrum foragers ate what their descendants would eat for millennia—bighorn sheep (*Ovis canadensis*), pronghorn (*Antilocapra americana*), occasional mule deer (*Odocoileus hemionus*), and a myriad of small birds, mammals, and plant species (Rhode and Louderback, 2007; Grayson, 2011; Madsen et al., 2015).

The Middle Holocene was a multi-millennial period of severe drought and heat, which impacted GB ecosystems and the people who lived there in multiple ways. As the Early and Middle Holocene became warmer and drier, remnant Pleistocene lakes dried up and people moved away from the playas and deltas to the mountains and upland valleys around them. The arrival of singleleaf pinyon pine (*Pinus monophylla*) in central Nevada, which was migrating north from Pleistocene refugia in the far southern GB and current Mojave Desert region as well as from putative refugia at higher latitudes (Millar and Thomas, *in press*), brought a wholly new and valuable food source. Pinyon nut procurement, alongside intensive processing and milling of other seed species, resulted in dramatic new settlement patterns (Thomas, 2024). Family groups resided in small, seasonally-occupied villages sometimes located near the valley floor and also within the lower pinyon/juniper (*Juniperus osteosperma*) zones of GB mountain ranges. At the same time, caves and rockshelters within the upper pinyon/juniper zones were occupied for the first time. These caves served as temporary summer base camps for single or a few male hunters, from which they staged bighorn sheep hunts on the alpine plateaus, returning to process meat in the caves before transport to family villages at lower elevations. Such pinyon harvesting/bighorn sheep hunting behavior became a stable pattern for millennia.

Archaeological research conducted in the 1970s in Monitor Valley (central NV, Fig. 1) revealed a puzzling hiatus in the Late Holocene sequences of two deeply stratified sites—gaps that represented absence of cultural evidence. At Gatecliff Rockshelter, a well-studied hunter base camp, 10 m of stratified sediments spanned 56 geological strata and 16 cultural horizons (Thomas, 1983). Primary stratigraphic controls derived from 47 radiocarbon dates and ranging from the Mazama tephra (~7700 cal yr BP) at the bottom to the historic period at the top showed a curious gap in human use at ~2500-2000 cal yr BP (Thomas, 1983: Table 2; Kennett et al., 2014). The stratigraphic sequence at nearby Triple T Rockshelter mirrored the Gatecliff sequence, with a 6.3-m stratigraphic profile dated by 13 ^{14}C dates spanning the last 6500 years and a cultural gap in dates ~2800-1900 cal yr BP (Thomas and Kelly, 1988: Tables 2 and 3). At the time of these studies, no known climatic or paleoenvironmental evidence provided clues for these synchronous gaps.

Subsequent "gap hunting" research (Rhode et al., 2014) generated additional higher-precision radiocarbon dates from Monitor Valley (Thomas, 2020: 586–598). This raised the total to 26 dates from Triple T Rockshelter and the 2800-2000 cal yr BP cultural gap in dates persisted. A total of 105 ^{14}C dates is now available from Gatecliff Rockshelter. High-precision Bayesian modeling of the Gatecliff sequence refined the chronostratigraphic gap to 3215-2145 cal yr BP (Kennett et al., 2014). These results correlated coarsely to the Mensing et al. (2013, 2023) determination of a multi-centennial scale dry period—the LHDP—in the central GB. Supplementary Materials S2 specifies the details of the Gatecliff Shelter chronology.

As in other studies of the LHDP, little was known about mountain climates—and GB temperatures in general—during the LHDP that might have aided archaeological interpretations for these dramatic stratigraphic gaps and they have remained an unsolved conundrum.

1.4. Goals of our study

Given the existing literature on the early Neoglaciation in the Great Basin, it is surprising that physical evidence has not been comprehensively examined in former studies of the LHDP to understand the role of temperature generally and mountain/alpine climate specifically. Here we tackle this challenge, with goals to document the extent and timing of the early-NG across the region, develop estimates of high-elevation temperature and precipitation necessary to maintain glaciers during the millennium-plus of the LHDP, and add new proxy evidence for upland conditions during this period. We first synthesize existing information on the early-NG in the Great Basin. Next, we present new evidence that extends the distribution of early-NG advances known for the region; calculate new estimates for temperature at high elevations during the interval; and describe how past behavior—evident in the archaeological record—adds useful new insights and corroboration for Neoglacial climates and environmental conditions during the LHDP. With this information, we aspire to bring attention of this prominent glacial interval into the radar of LHDP understanding.

2. Regional setting

The primary focus of the current study is the high mountains of the hydrologic Great Basin, southwestern United States. The GB region covers ~520,000 km^2 and is defined by topography where surface waters drain into interior, evaporative basins (Grayson, 2011). Extending from 33° to 44° north latitude and 111° to 122° west longitude, the GB includes parts of California, Oregon, Idaho, Utah, and most of Nevada (Fig. 1). Contained within this region are approximately 635 mountain ranges (Charlet, 2020; Grayson, 2011); many attain alpine elevations, with the highest summits extending above 4000 m (highest, Mt Whitney, CA, 4,421 m, the highest peak in the contiguous US). The area is geologically complex, with orogenies resulting from Cenozoic continental plate dynamics and extensional faulting (Dickinson, 2006; Fiero, 2009).

Most of the Great Basin is characterized by a semiarid temperate climate, with cold-wet winters, wet springs, and warm, dry summers (Grayson, 2011; Miller et al., 2019). Within this pattern, however, climates differ across the region. Temperatures vary greatly, primarily as a function of elevation, with a lapse rate ranging from −6 °C to −9 °C for every 1000 m gain in elevation. Overall, temperatures vary from −15 °C in the winter to >35 °C in the summer. In the high mountains, freezing temperatures and snowfall are possible in any month. The amount and seasonality of precipitation is strongly influenced by the juxtaposition of the eastern Pacific subtropical high and the southernwestern monsoonal circulation from the Gulf of California. The location of these zones shifts with time, but in general the southern and eastern portions of the Great Basin are more subject to monsoonal precipitation then the north and west. Overall summer precipitation typically is less than 5 % of the total annual in the northeastern Great Basin and increases to the west slopes of the Wasatch Range where summer precipitation can reach 25 %. Annual precipitation also varies by elevation, with the low valleys and basins remaining dry (<15–30 cm) while the uplands can receive amounts in excess of 65 cm, regularly in the form of winter snow.

Table 1
Locations of Great Basin sites with evidence for early Neoglacial advances. A. Locations with specific ages. B. Locations with relative-dating ages.

Map Code	Mountain Range	Location	Latitude N	Longitude W	Elev (m)	Rock Glacier; Ice Glacier; Other	Approximate ages of advances, cal yr BP, except as noted	Methods[b]	References
A. Locations dated to specify ages (11 mountain ranges)									
SS	Sierra Nevada, CA	Big Pine Crk	37.125	118.486	3061	IG, RG	<3200; 2800; 2200; 1600	SC	Bowerman and Clark (2011)
SS	Sierra Nevada, CA	The Recesses	37.407	118.792	3604	IG, RG	≫ 1740	LM, BRW	Yount et al. (1982)
CS	Sierra Nevada, CA	Mt Conness	37.975	119.317	3428	IG, RG	3400; 2600–2100; 1700; 1500	LM, RC, SC	Konrad and Clark (1998)
CS	Sierra Nevada, CA	Mt Conness	37.975	119.317	3428	IG, RG	<3300	SC	Bowerman and Clark (2011)
TU	Tushar Mountains, UT	not available	~38.423	~112.417	~3280	RG	3800–2000	RDM	Bevis (1995)
TY	Toiyabe Range, NV	Jett Creek	38.770	117.290	3080	RG	<6850 [d] and >1200	TPR	Osborn (1989)
TY	Toiyabe Range, NV	Arc Dome region	38.863	117.348	3085–3195	RG	>1200 [d]; early Neoglaciation	TPR	Piegat (1980); Osborn (1987), 1989; Davis (1988)
SK	South Snake Range, NV	Wheeler Pk, Baker Pk, and other cirques	38.990	114.300	3400	RG, Other	< ~4000 and > ~1800	RDM, GPR	Van Hoesen and Orndorff (2004), 2011; Reinemann et al., 2009
SK	South Snake Range, NV	Wheeler Pk	38.989	114.308	3395	RG	< 6850[d] and > 1200[d]	TPR	Osborn (1987) in Davis (1988); Osborn (1990); Osborn and Bevis (2001); Osborn (2004)
DC	Deep Creek Range, UT	Indian Farm Creek	39.850	113.902	3440	RG	3800–2000	BRW, RDM	Bevis (1995); Osborn and Bevis (2001); Osborn, 2004
WS	Wasatch Mountains, UT	Mt Timpanogos	40.389	111.640	3238	RG	<4000; >1200	BRW, RDM	Anderson and Anderson (1981); Davis (1988); Osborn and Bevis (2001); Osborn (2004)
NR	North Ruby Mountains, NV	Overland Lake	40.465	115.457	2881	Other	3700–2500	SC	Munroe et al. (2018)
WS	Wasatch Mountains, UT	Little Cotton-wood Cyn (multiple sites)	40.571	111.613	2972	RG, Other	3273; 3053; 2931; 2589; 2565; 2443; 2199; 1955; 1882	LM, BRW, RDM	McCoy (1977); Davis (1988); Osborn (2004)
NR	North Ruby Mountains, NV	Soldier Lakes	40.732	115.281	2774	Other	3100–3000	SC	Munroe et al. (2018)
UN	Uinta Mountains, UT	Deadhorse Lake	40.744	110.675	3385	RG, Other	3864[a]; 3090; 2955; 2864; 2727; 2636; 2545	LM	Munroe (2002)
UN	Uinta Mountains, UT	Lake Ejod	40.751	110.676	3331	Other	2900; 2150; 1400	SC	Munroe et al. (2013)
UN	Uinta Mountains, UT	Deadhorse Lake	40.744	110.675	3385	RG, Other	2250-2240; 1710–1660; 1590-1300	LM (redated from Munroe, 2002)	Munroe (2005)
UN	Uinta Mountains, UT		40.817	109.837	2868	Other	≪ 6200 [c]	SC	Carrera et al. (1985)
UN	Uinta Mountains, UT	East Fork Black's Fork	40.828	110.515	3230	RG, Other	2250-2240; 1710–1660; 1590-1300	LM	Munroe (2005)
EH	East Humboldt Range, NV	Angel Lake	41.027	115.087	2554	Other	3800–2400	SC	Munroe et al. (2018)
ST	Steens Mountains, OR	S Fk Willow Cr	42.678	118.559	2615	Other	3800–2000	RDM	Bevis (1995); Osborn (2004)
SB	Strawberry Mountains, OR	not available	44.304	118.630	~2400	RG, other	3800–2000	RDM	Bevis (1995)
B. Locations dated with relative-age methods (10 mountain ranges)									
SW	Sweetwater Range, CA	Wheeler Pk-2	38.428	119.293	3157	RG	Early Neoglaciation	RDM	Osborn and Bevis (2001)
SW	Sweetwater Range, CA	Wheeler Pk-1	38.430	119.278	3051	RG	Early Neoglaciation	RDM	Osborn and Bevis (2001)
TQ	Toquima Range, NV	Eastslope cirques	38.759 to 38.806	116.922 to 116.926	3280 to 3450	RG	Early Neoglaciatioin	RDM	Piegat (1980)
TQ	Toquima Range, NV	Moores Cyn	38.817	116.929	3128	RG	Early Neoglaciation	RDM	Piegat (1980); Osborn and Bevis (2001); Millar and Westfall (2019)
TQ	Toquima Range, NV	Anderson Creek	38.820	116.944	3140	RG	Early Neoglaciation	RDM	Piegat (1980)

(*continued on next page*)

Table 1 (*continued*)

Map Code	Mountain Range	Location	Latitude N	Longitude W	Elev (m)	Rock Glacier; Ice Glacier; Other	Approximate ages of advances, cal yr BP, except as noted	Methods[b]	References
SC	Shell Creek Range	N Fk Cleve Cr; Cleve Cr Baldy	39.265	114.640	3080	RG, other	Undifferentiated Neoglaciation; inferred early- NG	RDM	Piegat (1980)
NK	North Snake Range, NV	Mt Moriah	39.285	114.199	3200	RG	Early Neoglaciation	RDM, BRW	Osborn and Bevis (2001)
NT	North Toiyabe Range, NV	Mt Callaghan	39.715	116.946	2870	RG	Inferred early- NG	RDM	Piegat (1980)
NR	North Ruby Mountains, NV	Thomas Canyon	40.607	115.397	3195	RG	Early Neoglaciation	RDM, TPR	Wayne (1984) in Osborn and Bevis (2001)
SK	South Snake Range	Numerous locations	38.958-39.000	-114.311--114.321	3200-3397	RG	Early Neoglaciation	RDM	Van Hoesen and Orndorff (2004, 2011)
UN	Uinta Mountains, UT	Bald Mountain	40.696	110.899	3260		Early Neoglaciation	LM, RC	Barnhardt (1973)
UN	Uinta Mountains, UT	North Slope, Ostler Pk area	40.750	110.759	3286	RG	Early Neoglaciation (Ostler stade)	RDM, BRW, Other	Grogger (1975)
UN	Uinta Mountains, UT	North Slope, multiple cirques	40.778	110.473	~3475	RG	Early Neoglaciation	RDM	Richmond (1986)
UN	Uinta Mountains, UT	Burnt Fork, North Slope	40.828	110.083	3247	IG	Early Neoglaciation	RDM	Schoenfeld (1969); Davis (1988)
EH	East Humboldt Range, NV	Multiple locations, Angel Lake region	41.033	115.094	2795	RG	Early Neoglaciation	RDM, TPR	Wayne (1984) in Osborn and Bevis (2001)
WR	Warner Mountains, CA	Warren Peak	41.380	120.218	2800	RG	Matthes/LIA and possibly early-NG	RDM	Clark (1995); Millar and Westfall (2019)
JR	Jarbidge Range, NV	East slope; Cougar Pk to Jarbidge Pk	41.839	115.388	3012	RG	Early Neoglaciation	RDM	Coats (1964); Osborn and Bevis (2001)

[a] Years of lichen growth.
[b] RC, 14C; LM, lichenometry; SC, sediment core; BRW, boulder rind weathering; TPR, tephrachronology; RDM, relative dating methods; GPR, ground penetrating radar.
[c] Bog bottom date located upcanyon from Late Pleistocene moraine.
[d] Limiting dates of (younger) Mono/Inyo Craters, CA "tephra 2″ and (older) Mazama ash.

Table 2
Locations of Great Basin sites with evidence for early Neoglacial advances. A. Rock glaciers. B. Persistent ice fields. Sites selected from Millar and Westfall (2019) as likely to represent early Neoglacial features (see footnotes).

A. Rock Glaciers [a]

Mountain Range	Latitude, Southernmost	Longitude, Southernmost	Latitude, Northernmost	Longitude, Northernmost	Elev (m)	Number of Features
Sierra Nevada South	36.469562	−118.217279	37.317458	−118.640500	3557	161
Sierra Nevada Central	37.312094	−118.698343	38.523198	−119.788082	3347	229
White Mountains	37.588383	−118.211513	37.860643	−118.332268	3579	19
Markagunt Plateau	37.685081	−112.828753	37.711215	−112.795773	3199	3
Tushar Mountains	38.37617	−112.360952	38.466331	−112.402100	3333	9
Sweetwater Mountains	38.428085	−119.291875	38.468981	−119.309992	3150	8
Fish Lake Mountains	38.576975	−111.717315	38.720996	−111.649661	3211	19
Toiyabe Range	38.759211	−117.304254	39.249029	−117.118974	3107	26
Monitor Range	38.790776	−116.583945	38.796716	−116.581318	3178	3
Toquima Range	38.800982	−116.914957	38.822022	−116.945889	3210	17
Carson Range	38.849979	−119.901284	39.323658	−119.930189	2855	10
Sierra Nevada North	38.903751	−120.123000	38.907752	−120.121322	2724	2
Snake Range South	38.940439	−114.295801	39.029358	−114.318917	3283	20
Schell Creek Range	39.258116	−114.639687	39.429407	−114.606275	3115	15
Snake Range North	39.286028	−114.200456	39.301743	−114.184152	3112	3
North Toiyabe Range	39.715598	−116.944192			2886	1
Deep Creek Mountains	39.779028	−113.958488	39.850787	−113.897611	3176	7
Ruby Mountains South	40.220566	−115.528658	40.430933	−115.471063	3010	9
Wasatch Mountains	40.256075	−111.540282	40.657877	−111.746801	3120	37
Ruby Mountains North	40.456127	−115.459051	40.678941	−115.371887	3054	16
Uinta Mountains	40.648677	−111.050195	40.818139	−110.946351	3204	29
East Humboldt Range	40.899613	−115.107180	41.039408	−115.098375	2937	10
Warner Mountains	41.307609	−120.194765	41.39014	−120.223692	2718	9
Independence Mountains	41.50297	−116.017257			2716	1
Pine Forest Range	41.676849	−118.713640	41.677026	−118.716440	2561	2
Marys River Range	41.763657	−115.358318			2936	1
Copper Mountains	41.792728	−115.517583			2818	1
Jarbidge Mountains	41.796102	−115.367646	41.858014	−115.389473	2968	18
Raft River Mountains	41.916071	−113.358613			2832	1
Bear River Mountains	42.143482	−111.573476			2610	1
Steens Mountains	42.6333	−118.620714	42.728164	−118.577532	2660	9
Yamsay Mountain	42.931953	−121.361305			2422	1
Strawberry Mountains	44.28665	−118.663133	44.297689	−118.672513	2295	2
Overall, 33 ranges					**mean, 3288**	**699**

B.Persistent Ice Fields [b]

Mountain Range	**Latitude, Northernmost**	**Longitude, Northernmost**	**Latitude, Southernmost**	**Longitude, Southernmost**	**Elev (m)**	**Number of Features**
Sierra Nevada South	36.482293	−118.247806	37.299598	−118.652765	3795	81
Sierra Nevada Central	37.308055	−118.698053	38.1605	−119.442771	3615	98
White Mountains	37.781191	−118.33827	37.781191	−118.33827	4044	2
Tushar Mountains	38.352779	−112.354519			3570	1
Sweetwater Mountains	38.418627	−119.285374	38.454043	−119.305327	3361	2
South Snake Range	38.878126	−114.288627	38.986079	−114.308837	3491	2
Schell Creek Range	39.42223	−114.607384			3451	1
Wasatch	40.255754	−111.540878	40.542142	−111.66601	3235	8
Ruby Mountains	40.477485	−115.467712	40.769359	−115.262960	3186	18
East Humboldt Range	40.896535	−115.112481	41.015407	−115.101435	3104	9
Warner Mountains	41.387565	−120.223336	41.629841	−120.277832	2564	2
Jarbidge Range	41.761719	−115.358713	41.848115	−115.390582	3049	10
Steens Mountains	42.667565	−118.564734			2854	1
Overall, 13 ranges					**mean, 3541**	**235**

[a] Features are a subset of the Millar and Westfall (2019) inventory selected to be only those on northerly and east-northeasterly aspects (NW, N, NE, to E), and above the following latitude- and longitude dependent elevations: Sierra Nevada South, 3000 m; Sierra Nevada Central, 2950 m; Sierra Nevada North, 2600 m; Toiyabe/Toquima, 2800 m; Snake Range, 3000 m; Schell Creek Range/Deep Cr Ranges, 2800 m; Wasatch Mountains, 2900 m; Uinta Mountains, 2800 m; Ruby Mountains, 2770 m; East Humboldt Range, 2500, Warner Mountains, 2600 m; Warner Mountains, 2600 m; Steens Mountains, 2500 m; Strawberry Mountains, 2200 m. Ranges not assigned specific elevation limits were given thresholds of the nearest range.

[b] Features are a subset of the Millar and Westfall (2019) inventory selected to be ice fields only on northern aspects.

3. Methods

3.1. Extent, timing, and climate conditions of the early Neoglaciation in the Great Basin; existing evidence

To document the distribution and dates of known early-NG conditions in the Great Basin, we searched the literature for studies describing Neoglacial evidence (ice glaciers, rock glaciers, periglacial activity) during the period known as the early-NG (~4000-1600 years ago). A range of common methods has been used in prior studies that return ages of varying accuracy and resolution. We considered studies that use isotopic analysis (e.g., ^{14}C and ^{10}Be) to be the gold standard for dating moraines and rock-glacial till, recognizing that they, too, have limitations, including that the source of material for dating can affect the reliability of dating glacial advances. Material from lake-sediment cores has high accuracy when correlated with glacial-signal sediments.

Table 3

Temperature and precipitation data for three high-elevation ranges in the Great Basin. Site locations with periods of record for time series data on mean annual air temperature (MAAT); summer temperature (June–September); elevation-adjusted summer temperature to highest elevation site of the range; winter precipitation (December–March); winter precipitation adjusted to highest elevation site of the range and adjusted for snow redistribution; temperature and precipitation differences necessary for ice glacier (per Leonard, 1989) and rock glacier initiation (see text and Supplemental Materials S1). Data from Coop Weather Stations (WRCC, 2023) and SNOTEL Stations (NRCS, 2023).

Mountain Range	Location	Latitude	Longitude	Elev	Period of Record	Modern Climate Means					Difference Modern to Neoglacial, Ice Glacier Growth[c]		Difference Modern to Neoglacial, Rock Glacier Growth[d]	
		°N	°W	(m)		MAAT (°C)[a]	Summer Temperature (°C)[a]	Winter Precipitation, Station Elev (cm)	Winter Precipitation, Elev-Adjusted (cm)	Winter Precipitation, Adjusted for Elev and Snow Redistribution (cm)[b]	Summer Temperature Decrease (°C)	Winter Precipitation Increase (cm)	Summer Temperature Decrease (°C)	Winter Precipitation Increase (cm)
White Mountains, CA	Upper Cotton-wood Basin	37.551	118.207	3574	2007–2022	0.2	9.2				5.6		0.2–3.2	
	Barcroft WMRC COOP	37.583	118.237	3792	2007–2022			2	2	7		88		55
Toquima Range, NV	South Fork Pine Creek	38.777	116.931	3436	2012–2022	1.1	10.3				4.5		1.3–4.3	
	Big Cr SUM SNOTEL, Toiyabe Range	39.293	117.119	2647	1991–2020			42	76 [e]	258		84		0
Snake Range, NV	Mt Wheeler	39.001	114.322	3407	2010–2022	0.1	10.5				4.5		1.5–4.5	
	Wheeler Peak SNOTEL	39.010	114.310	3066	2010–2022			54	79 [f]	269		101		0

[a] Temperature data from thermochrons at locations of modern relict rock glaciers.

[b] Winter precipitation adjusted to account for snowfall redistribution, using a factor of 3.4 (midpoint of 2.5–4.2) times the elevation-adjusted values, following Munroe, 2008.

[c] Differences based on modern summer temperature and winter precipitation values (adjusted to elevation) relative to boundary values from Leonard (1989) and Fig. 3. Differences calculated based on midpoint values of temperature and precipitation from Fig. 3; boundary extremes are also shown on Fig. 3 for no change in temperature or no change in precipitation.

[d] Summer temperatures estimated as the depression from the modern site value to 6–9 °C, estimated as mean values for rock glacier initiation and growth. Winter precipitation estimated as the additional amount from elevation-adjusted values and snow-redistributed adjusted values needed to achieve 62 cm (mean of 54–70 cm, see text).

[e] Winter precipitation adjusted to higher elevation South Fork Pine Creek rock glacier site using regression curve from Bowerman and Clark (2011), pg 1075 to estimate snowall proportional to the station elevation.

[f] Winter precipitation adjusted to higher elevation Mt Wheeler rock glacier site using regression curve from Bowerman and Clark (2011), pg 1075 to estimate snowfall proportional to the station elevation.

Vegetation deriving from within glacial and rock glacier till has also been used to successfully date Holocene advances. Unfortunately, isotope methods have been applied in only a few locations in the GB.

Relative dating methods also provide useful age ranges from the studies we compiled for GB glacial advances. Several well-characterized and dated tephras are known from the greater Great Basin region (and beyond, e.g., Mt. Mazama, OR), and their presence or absence within moraines or rock glacial mantles provides useful age envelopes. Lichenometry and boulder-rind dating rely on increase in size of lichens or weathering rinds, respectively. The width of these is understood to indicate time since deposition of the boulders, presumably dating the advance. For highest accuracy, these methods require calibration to local conditions, i.e., climate, aspect, substrate type, and species (for lichens). Region-specific growth-rate equations have been developed in a few GB situations to determine ages from lichens or weathering rinds; sometimes equations from nearby regions outside the GB were used with caveats about their applicability.

Traditional field-based relative-dating approaches rely on comparing glacial morphologies and locations/positions from locations with known ages to those with unknown ages. For example, Late Pleistocene glaciers produced long and high lateral and terminal moraines, often extending many kilometers down valleys of GB mountain ranges. LIA moraines, by contrast, occur higher in elevation and have shorter moraines, extending at Great Basin locations usually <2 km from cirque headwalls (Clark et al., 1994; Clark, 1995). Knowing the relative positions of moraines in a cirque allows an estimate of relative age. Local variation, including topography, aspect, elevation, shading, and substrate, can distort these relationships in any canyon.

Temperature and precipitation for Neoglacial advances were estimated in prior studies through several methods. For ice glaciers, one approach was to compare conditions at the modern equilibrium line altitude (ELA) with those at the projected historic ELA, using local lapse-rate estimates to generate temperatures and precipitation differences (e.g., Munroe, 2002; Bowerman and Clark, 2011). Much less is known about climate conditions necessary for growth of rock glaciers. Rock glaciers tend to develop under drier conditions than for ice glaciers, and initiation and maintenance require less winter precipitation than for ice glaciers (Müller et al., 2016; Anderson et al., 2018). In estimating precipitation needs for rock glaciers to grow, Munroe (2002) evaluated the important role of local redistribution of snow in small alpine cirques.

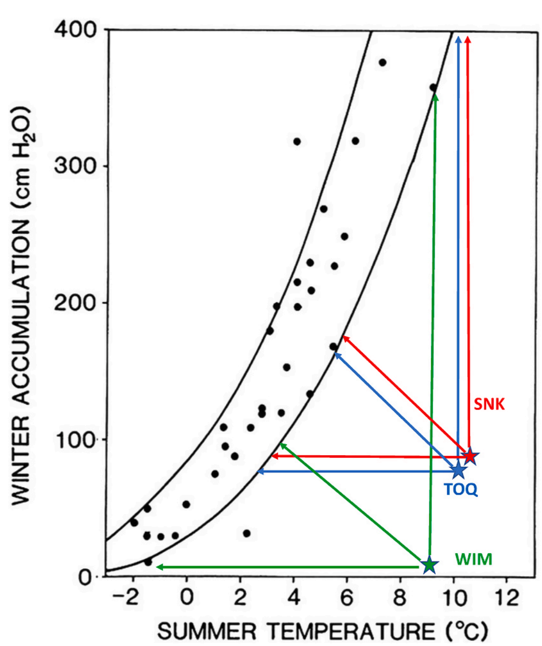

Fig. 2. Summer temperatures and winter precipitation values estimated by Leonard (1989) to sustain ice glaciers, based on 32 glaciers worldwide. Superimposed in color are estimated differences from modern in these metrics needed to initiate ice glaciers in three Great Basin mountain ranges. Green, White Mountains (WIM), CA; blue, Toquima Range (TOQ), NV; red, Snake Range (SNK), NV. Horizontal and vertical arrows indicate boundary conditions where no change in winter precipitation and no change in summer temperature, respectively, would be needed. Diagonal arrows indicate a midpoint of differences in the two indicators. Base figure modified from Leonard (1989).

The insulating nature of rock-glacier mantles and the location of the ablation line at the top of the rocky mantle mean that thermal relations for rock glaciers differ from those for ice glaciers (Müller et al., 2016; Anderson et al., 2018). Further, the open rocky matrix of the mantle supports internal ventilation partially decoupled from external conditions (Morard et al., 2010). Clark (1995) modeled geophysical and geomorphic factors that affect insolation and insulation in rock glaciers, and calculated that average summer (June to September) air temperature of ~5.9 °C above Sierra Nevada rock glacier mantles with ~70 cm winter precipitation at ~3500 m would sustain active modern landforms.

In addition to temperature estimates from physical data (glaciers, rock glaciers), biotic proxies provide insight into late Holocene climates. These include evidence from past terrestrial vegetation and aquatic faunal diversity, from which climate envelopes are inferred. While diverse studies of these proxies are cited as evidence for Late Holocene climate intervals, we are cautious about interpretations for some of the indicators, and we were conservative in the studies we selected. For instance, treeline fluctuations, including those of bristlecone pine (*Pinus longaeva*) and foxtail pine (*P. balfouriana*) in GB mountains, are classically cited as evidence for warm versus cold Holocene periods (e.g., LaMarche, 1973; Lloyd and Graumlich, 1997). Increasingly, however, treeline fluctuations are understood to be complexly related to climate, and care is needed in interpreting trends (Körner and Paulsen, 2004; Harsch et al., 2009; Millar et al., 2018a, 2020). Similarly, tree ring-width patterns over time are routinely interpreted for temperature and/or precipitation significance. For most species these also are complexly related to climatic factors. For instance, tree growth can switch from temperature-sensitive to precipitation-sensitive (even within one's tree's lifetime) depending on the climate period (e.g., bristlecone pines at upper treeline, Salzer et al., 2009, 2014; Tran et al., 2017), and different combinations of precipitation and temperature can yield similar ring-widths, as when cold temperatures rather than dry conditions produce narrow ring widths (e.g., LaMarche and Stockton, 1974; Graumlich, 1993). Patterns of vegetation diversity or indicator species (presence/absence/ %) from pollen studies-core are also used to assess paleo-temperature and paleo-precipitation with high confidence, as in their application in the Great Basin LHDP studies (Mensing et al., 2008, 2013, 2023). We included evidence from studies where reliable indicator species were present and alternated over time (as in the LHDP studies) for their climate inferences.

3.2. Extending the locations for early Neoglacial conditions in Great Basin mountains during the LHDP; new evaluations

In addition to compiling existing literature on early-NG advances, we add new locations and climate data derived from a GB-wide inventory on rock glaciers. We also developed new evidence from archaeological records of human behavior during the LHDP in the central GB relevant to mountain climates during the interval.

3.2.1. Evidence from rock glaciers and persistent ice fields

Recognizing that for many Great Basin mountain ranges early-NG advances were expressed as rock glaciers, we sought to expand the list of mountain ranges that may have experienced early-NG conditions by drawing on the recent GB-wide assessment of rock glaciers (Millar and Westfall, 2019). In that study, 842 features were mapped from 36 mountain ranges (including major subdivisions of the largest range) as well as 237 persistent icefields from 14 ranges. Following the rationale of studies summarized above, we reviewed the rock glacier inventory of Millar and Westfall (2019) for evidence of potential early-NG features throughout the Great Basin. To do this, we recognized that 1) early-NG climates were estimated to have been less extreme than the LIA, with potentially lower precipitation (otherwise ice glaciers would form); 2) early-NG (as well as LIA) rock glaciers are higher in cirques relative to Pleistocene moraines and extend $< \sim 1.0$ km from headwalls; 3) several ages of rock glaciers often overlap, with younger (LIA) rocky mantles highest in cirques, "fresher" in appearance of the rocky mantle, with oversteepened fronts, and overriding older (early-NG) mantles; and 4) many higher/younger rock glaciers are evaluated to be still active and may have re-activated during the LIA; these we considered to have potentially initiated or re-activated in the early-NG.

To calibrate the new set of Great Basin rock glaciers and related periglacial features by these characteristics, we reviewed the list of rock glaciers in Millar and Westfall (2019) and evaluated them as follows: We deleted all features located on warm modern aspects, that is, west, southwest, south, and southeast locations. We did this to eliminate features that might require more severe (cold/wet) climates than occurred during the Late Holocene and are more likely to be Late Pleistocene in age. For the same reason, we deleted features below elevations dated as early-NG by locations in Table 1. To do this, we estimated a mean lower elevation limit by latitude of the mountain ranges from Table 1 (i.e., higher in the south and lower in the north). We considered the resulting list to be of putative early-NG age.

Using the same logic we evaluated the persistent icefields inventoried from Millar and Westfall (2019) and developed a subset that we propose are of early-NG ages. Except for the Sierra Nevada, persistent ice fields (including ice glaciers) had not previously been inventoried in the Great Basin, and only a few features had been described. We propose the filtered list of persistent ice fields to also indicate potential early-NG features for reasons of their cold locations (very high-elevation cirque headwalls, >99 % north aspect, narrow cirques with severe shading) that would have allowed for Late Holocene initiation, and cold enough to have been initiated in the early-NG.

In addition to mapping new locations, we sought to estimate temperatures and precipitation necessary to initiate active rock glaciers, and compare these to temperature differences needed for early-NG rock glaciers. While understanding of climate controls on ice glaciers—their processes of formation, increase and melt, and responses to changing climates—is extensive and sophisticated, this is not the case for rock glaciers. While studies have been done that improved understanding (e.g., Müller et al., 2016; Anderson et al., 2018), the state of knowledge for rock glacier lags far behind that for ice glaciers. We recognize, accordingly, that our estimates presented below are crude, limited by knowledge constraints.

For three GB ranges (White Mountains, CA, Toquima Range, NV, and Snake Range, NV), we estimated temperature and precipitation and assumed these to be analog values for early-NG cirque conditions. First we compiled average climate values for modern active rock glaciers and considered these as proxies for conditions necessary to initiate rock glaciers in the early-NG. Warm-season temperatures we used included Clark's (1995) estimate of 5.9 °C for Sierra Nevada active rock glaciers; thermochron (mini-temperature sensors) measurements at five active Sierra Nevada rock glaciers of 6.7 °C (Millar et al., 2013); and PRISM-estimated (Daly et al., 1994) values for active rock glaciers inventoried in the Sierra Nevada of 8.1 °C (Millar and Westfall, 2008) and throughout the Great Basin of 8.2 °C (Millar and Westfall, 2019). Taken together, the mean warm-season temperature for rock glacier initiation is 6.9 °C (range ~5.9–9.0 °C). We then sought to evaluate the difference between modern conditions and conditions necessary to initiate rock glaciers (analog for early-NG), choosing three GB ranges as case examples, the White Mountains, Toquima Range, and Snake Range. High-elevation thermochron data at rock glacier locations we have been recording for 10–15 years (2007/2012 to 2022) provided values on modern temperatures at relict rock glaciers. Locations and methods are given in Millar et al. (2018b); temperature observations continued past 2016, as described in that study, at the same sites and intervals through 2022. We recognize these as highly simplified estimates in that they do not include topographic effects of solar shading on temperature as well as other unknowns.

Similarly, we estimated the difference in winter precipitation between modern and early-NG for rock glacier initiation for the same three mountain ranges, using Clark's (1995) estimate of 70 cm (Sierra Nevada), Millar and Westfall's (2008) estimate of 65 cm (Sierra Nevada), and Millar and Westfall's (2019) estimate of 54 cm (GB-wide). Together these give a mean of 63 cm (range ~54–70 cm). We further followed Munroe (2002) for estimating redistribution of snow in cirques (4–8 times greater than mean winter snowfall). To estimate the difference between modern conditions in the White Mountains, Toquima Range, and Snake Range and early-NG conditions, we used SNOTEL-observed values (NRCS, 2023) in the three ranges, adjusted to rock-glacier elevations following Bowerman and Clark (2011), as modern values. We calculated the difference between these values and average values for active rock glaciers to estimate differences between contemporary and early-NG conditions.

In addition to summer temperature and winter precipitation parameters, annual temperature thresholds for maintaining permafrost (including ice embedded in rock glaciers) have been developed at locations worldwide. In alpine zones, discontinuous permafrost generally requires mean annual air temperature (MAAT) < 0 °C (Péwé, 1983); sporadic permafrost can develop under certain environmental conditions, such as caves and talus, where MAAT is warmer (Harris, 1981, 1986; Gude et al., 2003). For GB conditions, Munroe (2018) estimated MAAT of <0 °C for 395 rock glaciers in the Uinta Mountains; Millar and Westfall (2008) estimated MAAT of 0.9 °C for 184 active rock glaciers in the Sierra Nevada; Millar et al. (2013) recorded MAAT of five active Sierra Nevada rock glaciers as 1.8 °C; Millar et al. (2014) recorded MAAT for four high-elevation periglacial talus fields in the Sierra Nevada as 2.0 °C; and Millar and Westfall (2019) calculated PRISM values of MAAT for 219 active rock glaciers across the GB of 1.1 °C. Taking these estimates together, we consider a MAAT range of < 0–2.0 °C as necessary for maintaining ice in GB rock glaciers and consider this as another analog for early-NG cirque conditions. To assess whether modern MAATs are adequate to sustain active rock glaciers in the White Mountains, Toquima Range and Snake Range, we compared our modern thermochron observations measured over 10–15 years (2007/2012 to 2022) to the MAAT range for GB rock glaciers above.

Finally we estimated differences in temperature and precipitation that would be required for ice glaciers to grow in the early-NG. We followed the approach of Bowerman and Clark (2011) with Leonard's (1989) winter precipitation/summer temperature curves based on a sample of ice glaciers worldwide (Fig. 2). Boundary conditions were developed for a range of winter precipitation and summer temperature values. We compared modern temperature and precipitation means at rock glacier locations in the White Mountains, Toquima Range, and Snake Range to Leonard's (1989) curves, and assessed whether the differences required to initiate ice glaciers were feasible during the early-NG.

3.2.2. *Evidence from the archaeological record*

John Rick's seminal paper entitled "Dates as Data" introduced the core assumption that "[a]ll things equal, more occupation produced more carbon dates" (Rick, 1987: 56). The past two decades have witnessed an exceptional increase of archaeological studies that transcend the simple notion of ^{14}C as a dating tool and build instead upon this pioneering core assumption ("more people = more sites = more dates"). Doing so assumes that, given a sufficiently large series of anthropogenic radiocarbon dates, the changing frequency of dates through time should encode highs and lows in past human activity. Further, by extension, they should reflect changes in human population densities by indirectly tracking energy extracted as fuel, food, clothing, housing, and so forth

(Freeman et al., 2018; Crema and Bevan, 2021; Kelly et al., 2022). In turn, employing summed probability densities (SPDs) as a proxy of ancient demography has potential for assessing the role of human population dynamics relative to climatic change, the rise and fall of cultural phases, timing of migration events, and the spread of farming (Riede, 2009; Peros et al., 2010; Johnson and Brook, 2011; Shennan et al., 2013; Kelly et al., 2013; Crema et al., 2016; Zahid et al., 2016; Crema, 2022).

With these objectives and assumptions in mind, Thomas et al. (2023) generated a filtered database of 4727 Great Basin radiocarbon dates from archaeological contexts; this was part of a larger effort (Kelly et al., 2022) documenting a database of more than 100,000 archaeological, geological, and paleontological radiocarbon samples from the lower 48 states. Demographic trends were estimated by comparing the SPD from the pooled Great Basin sample (N = 4727) against the exponential null model derived from 1000 Monte Carlo simulations, using methods detailed by Crema and Bevan (2021). Because radiocarbon dating can today provide results accurate to a human lifespan, Thomas (2020, 2023) relied heavily on ^{14}C dating to document human responses to abrupt climate changes in the Great Basin. These methods are employed here to help interpret human responses to early-NG climates during the LHDP.

4. Results

4.1. Locations and dates of early-Neoglacial advances in the Great Basin

In this section we summarize locations and dates compiled from existing literature as well as new evidence. We summarize these by mountain range from south to north in the Great Basin.

4.1.1. Locations with quantitative ages

First we consider evidence based on studies that gave quantitative dates for glacial advances of the early-NG, albeit with varying degrees of precision (Fig. 1; Table 1A). Twelve mountain ranges that span the longitudinal extent and a large portion of the latitudinal extent of the central GB are included. The best dated NG advances in the Great Basin derive from the central and southern Sierra Nevada, CA, the Ruby Mountains and East Humboldt Range, NV, and the Uinta Mountains, UT (Fig. 1; Table 1A); in this section we also include studies that have determined minimum and/or maximum ages.

Studies by glacial geologist Douglas Clark and his colleagues frame the dates for the early-NG of the Sierra Nevada, at the western edge of the Great Basin. From lichenometry and ^{14}C-dated sediment cores retrieved from tarns below Mt Powell, Mt Mendel, and Mt Conness ice/rock glaciers, Konrad and Clark (1998) concluded that the onset of the Neoglaciation occurred ~3800–3400 cal yr BP. Their firmest limiting date for the first NG advance was 3400 cal yr BP (pg. 282). Sediment core evidence from Mt Conness documented subsequent glacial advances at 2600–2100 cal yr BP, and lichenometry on the Mt Mendel rock glacier suggested more recent glacial advances ~1700 and 1500 years ago.

More intensive examination of sediment cores below the Mt Conness ice/rock glacier subsequently led Bowerman and Clark (2011) to conclude that Late Holocene glaciation initiated shortly after 3300 cal yr BP. They also extracted sediment cores from tarns below the North Palisade ice/rock glacier in Big Pine Creek, Sierra Nevada (Table 1), which yielded dates for onset of the NG at ~3200 cal yr BP, followed by a distinct glacial maximum at 2800 cal yr BP, and subsequent advances at ~2200 cal yr BP and ~1600 cal yr BP.

Studies on rock and ice glaciers in cirques of The Recesses, Mono Creek (Table 1A), Sierra Nevada, further corroborated early-NG advances. Yount et al. (1982) used lichenometric, boulder-weathering, and soil data, supported by limiting radiocarbon ages, to document early and middle NG advances. A single radiocarbon age of 1740 cal yr BP was related to a middle NG feature, whereas older rock glaciers appeared to represent the early-NG but no radiocarbon dates were retrieved from these.

In the far southeastern Great Basin, the Tushar Mountains have Holocene glacial features. Bevis (1995) estimated two drift unit ages for the Neoglaciation. The older unit ("III"), which we interpret as early-NG, he estimated from boulder weathering data to be 2000–3800 years old.

Many small rock glaciers occur in the cirques on the north and east slopes of the Toiyabe Range near Arc Dome, central NV. These occur near the headwalls of the cirques, extending less than 0.5 km (Piegat, 1980; Osborn, 1989). Through relative position and characteristics of the mantles and vegetation these features were assigned to the youngest group of glacial evidence in the range; Piegat differentiated several ages of Neoglaciation from these. Concluding further that LIA advances were not expressed in the Toiyabe Range, Osborn (1989) estimated dates by tephra, which gave ages older than 1200 cal yr BP and likely younger than 6850 cal yr BP, suggesting that these features were early-NG (Osborn, 1987, 1989; Davis, 1988).

The large Wheeler Peak rock glacier (0.9 km long) in the South Snake Range, NV, is considered to be the only active glacier in the state. It retains an associated ice field on its headwall, an upper rocky portion analyzed by GPR to be ice-cored and active (Van Hoesen and Orndorff, 2011), and extensive down-canyon rocky mantles that appear progressively older. Osborn (1987) detected Mono Craters "Tephra 2" (~1200 cal yr BP) on the surfaces of the lower portion, and considered this part to be early-NG. Moraines adjacent to the rock glacier were evaluated through tephra dating by Osborn (1990) to be > 1200 and <6850 cal yr BP. Additional evidence for cool high-elevation climates in the South Snake Range is supported by biotic proxy data of aquatic chironomids in Stella Lake (3170 m). Reinemann et al. (2009) reconstructed temperatures for the past ~7000 years and document a cold early Neoglacial, starting ~4000 cal yr BP and warming after ~1800 cal yr BP.

The Deep Creek Range, UT, has extensive Late Glacial and some Holocene glacial evidence. Of the latter, Bevis (1995) recognized two ages, including one likely early-NG. This drift unit ("III") he estimated from boulder weathering data to be 2000–3800 years old.

In the central and eastern Great Basin, studies by Jeffrey Munroe and his colleagues provide well-dated evidence for early-NG advances in several high mountain ranges. Munroe et al. (2018) retrieved sediment cores from high-elevation Overland Lake and Soldier Lake in the northern Ruby Mountains, NV, and from Angel Lake in the East Humboldt Range, NV. Physical proxies from these cores (C:N ratio, organic matter, coarse clasts) indicated a cold, wet phase collectively in these lakes from ~5800 to ~3800 cal yr BP; the subsequent two millennia (through the LHDP) show high variability in these indicators. Individually, cold and wet intervals occurred ~3100–3000 cal yr BP at Soldier Lake, ~3700–2500 cal yr BP at Overland Lake, and ~3800–2400 cal yr BP at Angel Lake.

Davis (1988) considered the onset of the early-NG in the Wasatch Range, UT, at ~4000 years old. This derived from comparative cirque elevations of glacial features, and age-relative morphological characteristics of rock glacier and other till in Little Cottonwood Canyon (McCoy, 1977; Madsen and Currey, 1979) and the Mt Timpanogos basin (Anderson and Anderson, 1981). The 0.5 km rock glacier under Mt Timpanogos, often referred to as the only glacier in Utah (the ice headwall has now melted) appears to have at least two ages of rock glacier growth (Anderson and Anderson, 1981). Using boulder rind weathering and inferences from morphological characteristics of the rock glacier mantles, they aligned the uppermost region of the rock glacier, still active, with the LIA interval, and the lower 200–500 m of the rock glacier as early-NG. Relative dating and association of small and relict rock glaciers from tephra dated ~1200 cal yr BP lead Wayne (1984, in Osborn and Bevis, 2001) to speculate, as in the reasoning for young Toiyabe Range glacial features, these could be early-NG, a conclusion corroborated by Osborn and Bevis (2001).

Farther east, on the north slope of the Uinta Mountains, UT, Munroe (2002) studied ages of rock glacial and ground moraines in the Dead

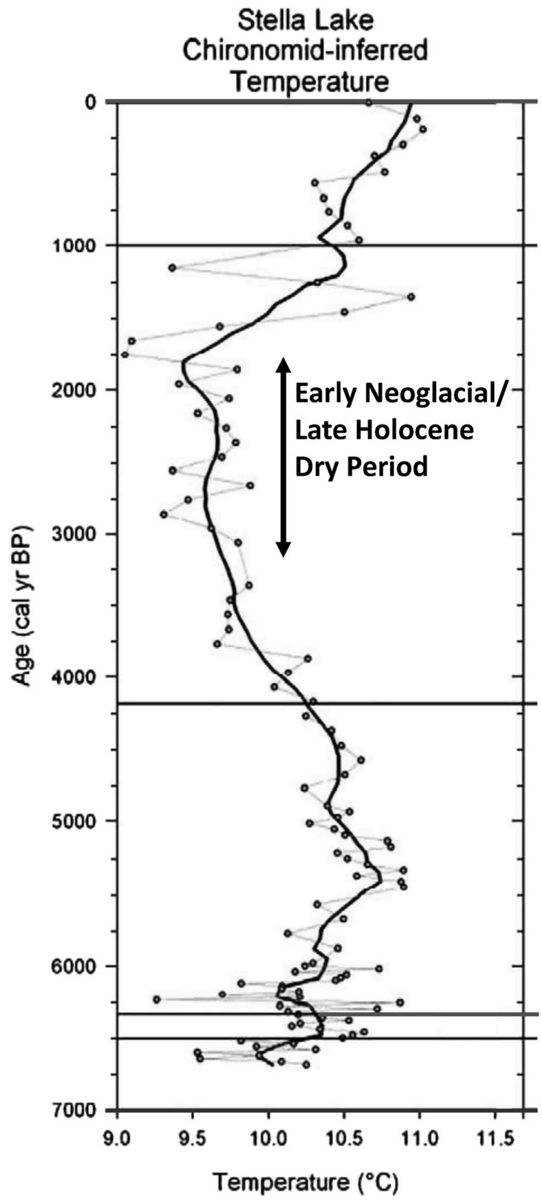

Fig. 3. Reconstructed July air temperatures from temperature-sensitive chironomid species diversities retrieved from a sediment core taken in Stella Lake (3170 m), South Snake Range. Modified from Reinemann et al., (2009).

Horse Lake cirque using lichenometry. In that lichen growth curves had not been calculated for the northern Uinta Mountains, Munroe used two equations from the Colorado Front Range and one from the Wind River Range, the latter of which he concluded was likely the best for conditions at Deadhorse Lake cirque. Based on that curve, lichen sizes on the glacial till returned ages of 2545-, 2636-, 2727-, 2864-, 2955-, 3090-, and 3864 years. In subsequent reanalysis of the lichens, and using different growth equations, Munroe (2005) estimated dates from lichens clustering at 1300–1590 years, 1660–1710 years, and 2240–2250 years old. Sediment cores taken from Ejod Lake near Deadhorse Lake returned dates of peak periglacial activity as 2900-, 2150-, and 1400 years old (Munroe et al., 2013). Munroe (2002, 2005) noted the surprising lack of LIA glacial activity in the Uinta Mountains, an especially unusual situation in that the LIA was the largest pulse in the past 4000 years in adjacent Great Basin and Rocky Mountains.

The splendidly glaciated gorges of the Steens Range, northern Great Basin (OR), were mapped and their ages assessed by Bevis (1995). Clear evidence of Pleistocene glaciation abounds in the form of long U-shaped canyons and moraines (Osborn and Bevis, 2001). Some small rock glacier and periglacial features at high elevations are interpreted by Bevis (1995) and Osborn (2004) to date to the early-NG. One drift unit ("III") identified in the range and found widely in Great Basin mountains, Bevis (1995) estimated from boulder-weathering data of rock glaciers to be 2000–3800 years old.

The Strawberry Mountains are the farthest north mountain range in the Great Basin to have been glaciated (Osborn and Bevis, 2001). Bevis (1995) recognized Pleistocene glacial evidence and two ages of Neoglaciation, including a likely early-NG rock glacial advance. This drift unit ("III") he estimated from boulder-weathering data to be within 2000 and 3800 years old.

4.1.2. Locations based on relative dating

Next we consider evidence from studies based on relative dating methods for glacial advances of the early-NG (Fig. 1; Table 1B). These assignments included eleven mountain ranges, four of which were the same as the specifically dated group (Table1A). Combining the two groups amounts to 19 mountain ranges.

The Sweetwater Mountains are a small spur range of the Sierra Nevada in northern Mono County, CA, in the far western Great Basin. Two prominent rock glaciers lie in north-aspect canyons of Wheeler Peak. From morphology of their mantles and vegetation growth on the surfaces, Osborn and Bevis (2001) considered these to be inactive at present but likely active during the Neoglaciation.

Similar evidence for Holocene glaciation exists in the Toquima Range, NV. Piegat (1980) mapped and estimated ages for Neoglacial till in eleven canyons of the range. He described several ages, including early Neoglaciation, of rock glacier till high in cirques, including of east-facing South Summit Fork of Pine Creek, South and North Forks Pine Creek, Bucks Canyon, and north-facing Anderson Creek and Moores Canyon (several of these canyons bifurcate to produce multiple cirques). Osborn and Bevis (2001) corroborated rock glacier and periglacial till to be of Neoglacial age. In particular, they called out one tongue-shaped, steep sided, rock glacier inset in north-aspect Moores Canyon cirque, where otherwise long (3 km) Pleistocene moraines are obvious. Piegat (1980) mapped this as an active rock glacier, suggestive of LIA age. Despite its young appearance, however, Osborn and Bevis (2001) consider that it may have been Late Pleistocene likely re-activated in the early Neoglaciation.

The Schell Creek Range of east-central Nevada is heavily glaciated, with abundant evidence of Pleistocene advances. Neoglaciation has been little studied in the range, but Piegat (1980) noted Neoglacial till in cirques of the southern part of the range. He did not differentiate ages, but from eroded surfaces, these appear to be pre-LIA, i.e., early-NG.

In the North Snake Range, NV, Osborn and Bevis (2001) considered the rock glacier under a cliff off the northwest side of Mt Moriah as potentially early Neoglacial.

The North Toiyabe Range, NV, is considerably disjunct from the main uplands of the range, and only one region rises to glaciated uplands, at Mt Callaghan. Piegat (1980) mapped rock glaciers that appear to be Neoglacial and pre-LIA, presumably NG.

An apparently still active rock glacier in Thomas Canyon of the North Ruby Mountains was noted as potentially early Neoglacial age (Wayne, 1984; Osborn and Bevis, 2001).

In addition to the tephra-dated Mt Wheeler rock glacier, Van Hoesen and Orndorff (2004, 2011)Van Hoesen and Orndorff (2004, 2011) mapped other rock glaciers, protalus ramparts, and periglacial features in the South Snake Range, which they speculated could be of Neoglacial age. By relative position and morphology they described active recent features (presumably LIA) and older features immediately down-canyon yet far above Pleistocene features, suggesting an early-NG age.

Several studies used relative dating methods to assign early-NG ages in the northern Uinta Range, UT. In the Burnt Rock Lake cirques, Schoenfeld (1969) gave two NG ages to high-cirque rock glaciers. The youngest group he considered to be still active and of LIA age and the

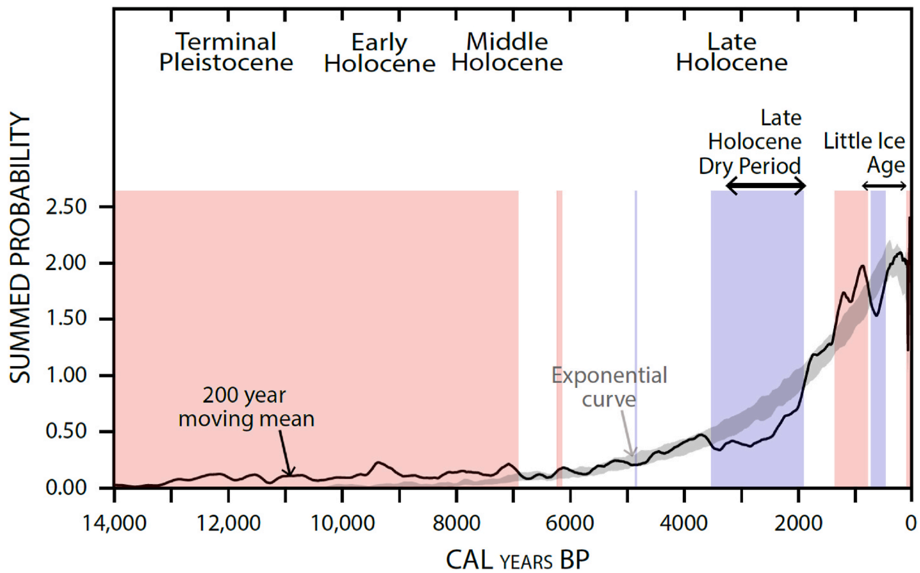

Fig. 4. The pooled summed probability distribution from the Basin-wide database of $N = 4727$ ^{14}C dates expressed as a 200 year moving mean (dark line) and contrasted with 95 % confidence interval from the null exponential model. Statistically significant positive deviations from the null model are highlighted in pink, and significant negative deviations are highlighted in blue (after Thomas, 2024: Fig. 13.2).

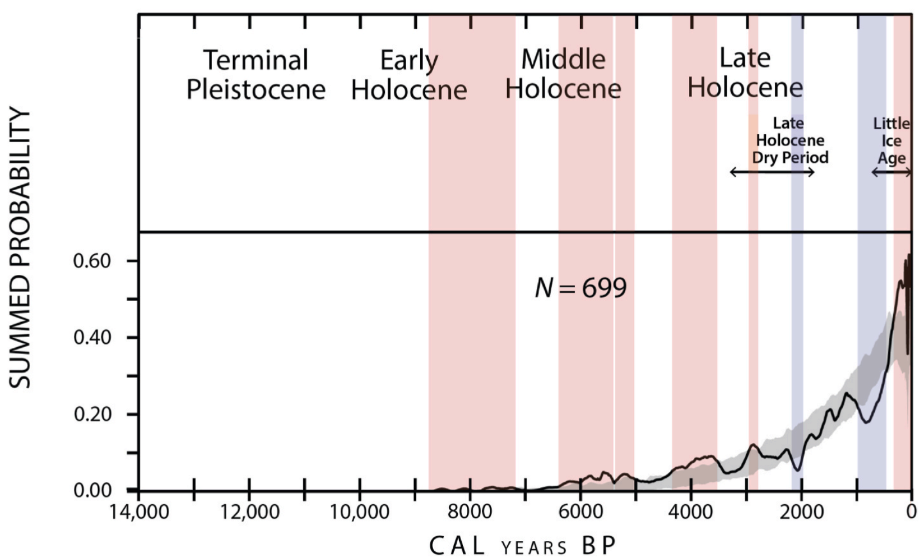

Fig. 5. Summed probability distribution for $N = 699$ radiocarbon dates from Central Great Basin (after Thomas, 2024: Fig. 13.3C). Statistical conventions as in Fig. 4.

older he assigned to an early-NG phase. Similar determination of early-NG age was made by Bradley (in Richmond (1986) for rock glaciers in cirques of the Uinta Mountains north slope; Grogger (1975) made similar age determinations for rock glaciers in the Ostler Peak cirques of the north slope.

Multiple cirques along the high northeast slope of the East Humboldt Range, NV, centered around Angel Lake, are noted as possibly early Neoglacial (Wayne, 1984; Osborn and Bevis, 2001).

The Warner Mountains of northeast California, like the Sierra Nevada to their south, form the hydrologic divide of the Great Basin along most of their crest. Pleistocene-eroded canyons and moraines are evident along the east side and a prominent rock glacier under Warren Peak in the south Warner Mountains may still be active (Clark, 1995). This led Clark to assume it was LIA age, but may also have been active in the early-NG.

Surprisingly few studies have analyzed the extensively glaciated cirques of the Jarbidge Range or adjacent Copper or Independence Mountains in northeast Nevada. In mapping the geology of the region, Coats (1964) described moraines in many canyons, and assigned them to Late Pleistocene ages. He also mapped rock glaciers, particularly along the east slope, high in headwalls of deep cirques and far above the Pleistocene moraines. Portions of fresher appearing mantles at higher elevations appear to have overrun mantles of older-appearing debris. Coats also noted interstitial ice in one of these rock glaciers, and glacial meltwater ("milky discoloration characteristic of streams draining active glaciers," page M20) in a pond below another. In summarizing Coat's work, Osborn and Bevis (2001) concluded a "Neoglacial age for these [rock glaciers] cannot be ruled out."

4.1.3. Locations based on new evidence from rock glaciers and ice fields

Based on the criteria described for selection from the Millar and Westfall (2019) GB inventory, we propose 699 rock glaciers from 33 mountain ranges of the Great Basin (mean elevation, 3288 m) and 235 persistent ice fields from 13 ranges (mean elevation, 3541 m; Tables 2A

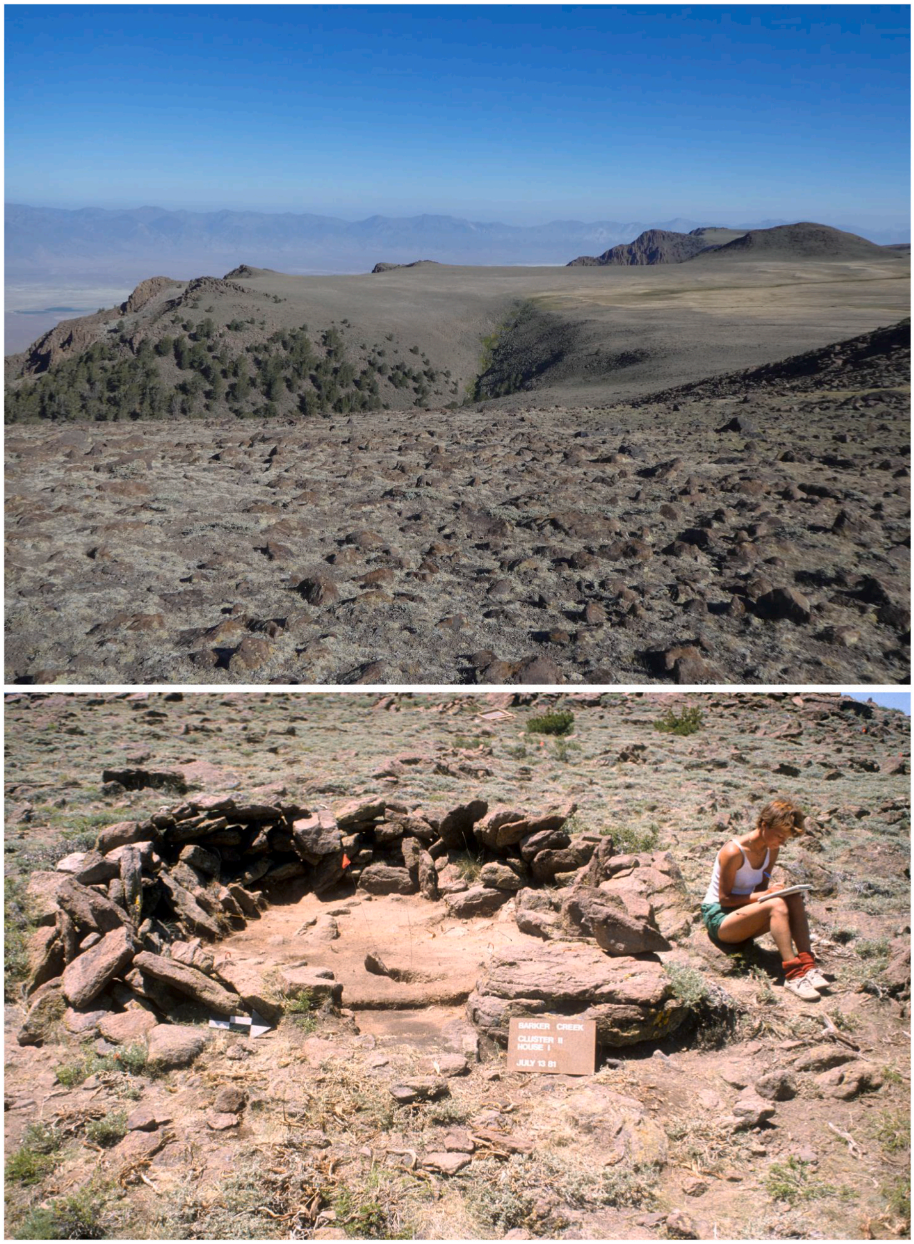

Fig. 6. Alta Toquima Village (ATV). The summer village residence site for Central Mountains Archaic people during the LHDP lies at 3350 m on the alpine plateau of Mt Jefferson, Toquima Range, NV. **A.** View north along the summit plateau; **B**. One of 31 foundations for summer residences at ATV during archaeological excavations.

and 2B, Fig. 1; Supplemental Tables S1 and S2) as having been active in the early-NG. The ranges with ice fields comprise a subset of ranges with rock glaciers. The new rock glacier list adds 14 ranges beyond those from studies in Table 1. All ranges from the earlier studies (Table 1) were also found in the new rock glacier list. Considering all evidence, the distribution of early-NG sites extends from 36.469562 °N to 44.297689 °N latitude and from 110.68644 °W to 121.361305 °W longitude.

4.2. *Temperature and precipitation estimates for Early-NG conditions*

4.2.1 Existing Evidence—Several of the glacial studies that provided the best estimates for dates of the onset and duration of the early-NG in the Great Basin (Table 1A) also assessed climate conditions necessary to initiate glacial growth during the Neoglaciation. In the Palisades Basin of the North Fork Big Pine Creek, southern Sierra Nevada, CA, Bowerman and Clark (2011) estimated that only small differences from modern in mean summer temperature (June–September) and mean winter precipitation (November–March) were needed to grow ice glaciers during the LIA (i.e., to move modern ELAs to LIA ELAs). They calculated decreases in mean summer temperature from modern (4–5 °C, 3500 m) of 0.2–2.0 °C and increases in winter precipitation from modern (~70 cm, 3500 m) of 3–26 cm as necessary for glacial initiation.

On the far eastern side of the Great Basin, Munroe (2002) also calculated differences from modern conditions in climatic variables necessary to initiate small cirque ice glaciers in the Uinta Mountains, UT. Starting with equations for sensitivity of ELA, he estimated a decrease of mean summer temperature of 3.2 °C–5.3 °C if precipitation remained unchanged, or an increase of winter snow accumulation of 100 cm–167 cm snow water equivalent if summer temperatures remained unchanged. Munroe considered these to be endmember conditions, and that changes in both precipitation and temperature were more likely.

Adding snow redistribution from wind into cirques into the equations (e.g., Clark et al., 1994; Munroe, 2002), which can amount to four to eight times the actual winter snowfall, Munroe concluded that a relatively modest increase in winter precipitation of 40 cm (slightly more than twice the modern value) and depression of mean summer temperature of 0.5 °C–2.0 °C would be adequate for growth of LIA size ice glaciers. Farther east in the Uinta Mountains, Munroe (2003) used repeat photography to estimate change in ELAs relative to modern and to determine that summer temperatures were depressed by 1 °C in the late 1800s, and concluded this was adequate to grow small cirque ice glaciers there. These values correspond remarkably well to Bowerman and Clark's (2011) estimates, suggesting that consistent boundary conditions exist across the climate zones of the Great Basin.

Although relatively few studies of biological proxies are available for high-elevation sites (>2800 m) in the Great Basin for the early Late Holocene, most of those available confirm cold periods for the time interval of the early-NG. Caveats regarding methods considered, these include foxtail pine treeline shifts in the southern Sierra Nevada (Scuderi, 1987); ring-width time series in bristlecone pine in the White Mountains (LaMarche, 1974); establishment of limber pine populations on currently too warm (south/west/east) aspects in the Wassuk Range (Millar et al., 2018a); and patterns of cold-hardy plant indicator species in the alpine zone of the high central Sierra Nevada (Anderson, 1990). These studies corroborate cold conditions starting ~3300-3000 cal yr BP and continuing at least to 2000 cal yr BP. In particular, Anderson (1990; 485) inferred "cooler conditions occurred from about 3000 to 2500 cal yr BP," and (1990: 486) that "January precipitation remain [ed] nearly at modern levels." He further inferred (1990: 486) that "the decrease in evaporation associated with declining July temperatures must have been enough to result in greater effective precipitation for the higher-altitude site."

Calibration of biotic proxy species, such as aquatic chironomids and diatoms, with modern air temperatures enables their use for estimating paleoclimatic conditions. Reinemann et al. (2009) extracted a ~7000 year sediment core from Stella Lake (3170 m) in the South Snake Range, eastern NV, and analyzed temperature-dependent chironomid diversities (Fig. 3). From these they developed a smoothed July air temperature curve for the duration of the core, characterizing a warm middle Holocene followed by a cold Neoglaciation. The decline in mean July temperature after the middle Holocene warmth began ~4000 cal yr BP. July mean air temperatures remained stably cold at ~9.6 °C, which was ~1.5 °C colder than older or younger intervals, from ~3100 cal yr BP until ~1800 cal yr BP, paralleling the duration of the LHDP. Unsmoothed mean temperatures had greatest declines and lowest temperatures at ~2800 cal yr BP, ~2650 cal yr BP, and ~1900 cal yr BP. After the early-NG, temperatures warmed again. Modern mean July air temperature was ~10.5 °C, as estimated from their chironomid reconstruction whereas Reinemann et al. (2009) report weather station summer (June, July, August) temperatures at "high elevations" as 13.5 °C. Thus the temperature depression from modern to early-NG was ~1 °C–4 °C.

4.2.1. *Temperature and precipitation estimates for early-NG conditions; new evidence*

In Table 3 we present modern air temperature data for high-elevation cirque locations in the White Mountains, Toquima Range, and South Snake Range and modern winter precipitation data. Based on these means and ranges for permafrost development and rock glacier initiation, we estimated conditions that would be needed to support rock glaciers in these ranges during the early-NG.

From MAATs calculated for modern conditions (Table 3), we conclude that all three mountain ranges have current and most likely had early-NG MAATs adequate to sustain persistent ice (embedded in rock glaciers, permafrost in talus).

Using the values estimated for rock glacier initiation, we calculate depressions of summer temperatures and increases in winter precipitation, respectively, from modern as 0.2–3.2 °C and 55–60 cm for the White Mountains; 1.3–4.3 °C with no to slight increase in precipitation for the Toquima Range; and 1.5–4.5 °C with no to slight increase in precipitation for the South Snake Range. Only the White Mountains seem marginal for growth of rock glaciers, given the exceedingly low current modern winter precipitation and the large differences in winter precipitation required. The other ranges appear to have sufficient or near sufficient winter precipitation at present to sustain rock glaciers, especially considering wind redistribution of snow into cirques (Table 3), although depression in mean summer temperatures is implicated. Thus, with LHDP winter precipitation similar to or slightly greater than modern conditions, summer temperature depressions noted above appear to be adequate to initiate rock glaciers. Any increases in winter precipitation would require less temperature depression.

Considering the role of ice glacier growth in these three ranges during the early-NG, we compared existing conditions with those described by Leonard (1989; Fig. 2, Table 3). The White Mountains would require (at a mid-point for both indicators) depression of ~6 °C in summer and ~88 cm increase in winter precipitation; the Toiyabe Range and Snake Range cirques would require ~4.5 °C temperature depression with ~84–100 cm increase in precipitation. These differences seem too large to be reasonable for Late Holocene conditions, and thus we corroborate earlier studies that concluded ice glaciers were likely lacking at these locations in the early-NG.

4.3. *Evidence from the archaeological record for early Neoglaciation climates during the LHDP*

4.3.1. *Evidence from exponential population growth trends*

For the past 12,000 years, human population growth in the Great Basin appears to have grown exponentially with two notable exceptions during late Holocene megadroughts—the LHDP and the Medieval Climatic Anomaly (Robinson and Thomas, 2023). Fig. 4 demonstrates the demographic trends from the comparison of the summed probability distributions from the pooled Great Basin sample against the exponential null model derived from 1000 Monte Carlo simulations. The black line plots the 200-year moving mean for the pooled sample of individual ^{14}C dates and the broad gray band represents the 95 % confidence envelope projected for the exponential null model (Robinson, 2023). Statistically significant positive deviations (the "peaks") are highlighted by the pink bands and statistically significant negative deviations (the "troughs") are plotted in blue.

Following millennia of exponential growth, Fig. 4 shows a demographic trough dropping below the exponential envelope at 3497 cal yr BP and continuing throughout the entire early-NG/LHDP (ending 1883 cal yr BP). During this interval, virtually every major Great Basin site south of 40° N latitude was abandoned—including Gatecliff Shelter, Danger Cave, Bonneville Estates, Lovelock Cave, Hidden Cave, the Falcon Hill caves, Gypsum Cave, Firebrand Cave, Newberry Cave, and large parts of the northern Mojave Desert (Thomas, 2024: chap 9; Thomas et al., 2023, Fig. 1). Fig. 5 shows the LHDP demographic impact in the central Great Basin, defined by significant peaks at 4153–4142 and 3965-3657 cal yr BP, followed by a steep drop in ^{14}C evidence and a statistically significant trough at 2152-1948 cal yr BP, the rising again to a significant peak at 1608-1085 cal yr BP.

This massive population decrease in the central Great Basin corresponds to portions of the LHDP. The latitudinal climate dipole further defined by these LHDP studies, of dry conditions south of a transition zone ~42°–40° N latitude and wet conditions north of that zone, is relevant to the archaeological record. The central Great Basin straddles the 42°–40° dipole and continues southward into the drought zone, with statistically significant peaks exceeding exponential expectations and troughs extending below. Before the LHDP, bighorn hunters occupied caves and rockshelters throughout the pinyon-juniper woodlands that functioned as base camps for high-elevation bighorn sheep hunting (Gatecliff Shelter, Triple T Shelter, and at least seven others, Thomas, 2024). Extensive upland central Great Basin bighorn sheep hunting is evidenced by hundreds of open-air hunting features as well.

This all fell apart shortly after 3100 cal yr BP, when the highest-ranking lowland habitats south of 40° N latitude rapidly became degraded by drought, while landscapes north of ~42° N latitude persisted largely unchanged or even improving somewhat. Some central Great Basin foragers moved northward to those still mesic places despite the absence of high-valued pinyon pine north of the Humboldt River; these formerly marginal northern habitats now ranked higher than those in the now-arid south. Bighorn hunting declined at Gatecliff Shelter from 3000 to 3760 cal yr BP, and the site was abandoned by ~3365-3315 cal yr BP. This marked the end of the logistic bighorn sheep hunting era, highlighted by the distinctive LHDP hiatus documented at almost every locality within the central Great Basin, including Triple T Shelter, the other caves and rockshelters in Monitor Valley, Ruby Cave, and the lower Goshute Valley (Thomas, 2024). These sites are reflected in the statistically significant trough at 2152-1948 cal yr BP of Fig. 5, with corresponding exponential growth persisting north of the ENSO dipole.

Despite the megadrought, the LHDP failed to trigger a total abandonment of the central GB mid-latitudes (Thomas et al., 2023). Some resilient communities adapted in place (and perhaps some newcomers arrived), pioneering a shift to mostly residential-mobility strategies involving numerous short-term, water-tethered extended family encampments. Coincident to the abandonment of Gatecliff Shelter and the other hunting base caves, some central Great Basin communities refused to abandon the homelands of their ancestors by finding new ways to survive the outset of the LHDP.

Just a few kilometers from then-abandoned Gatecliff Shelter, Indigenous Monitor Valley populations pioneered ways to mitigate the impacts of lowland drought-degraded landscapes by heading to uplands in summertime, where they established Alta Toquima Village (ATV), the earliest alpine residential site then-recorded in North America (Thomas, 2020). Perched at 3350 m on the summit plateau of the Toquima Range (Fig. 6), ATV documents a dramatically new human behavioral pattern. Rather than hunters who for millennia used the uplands to hunt bighorn, entire whole families moved upslope to live on the alpine plateau of Mt Jefferson. The 31 domestic structures at ATV were occupied ~2500–2200 cal yr BP, with the earliest dates correlating with the occupational hiatus downhill at Gatecliff Shelter and spanning the range of that abandonment; Supplementary Materials S2 details the interrelationships between the Gatecliff Shelter and Alta Toquima seqeuences. Simultaneously, a number of additional upland localities were occupied during LHDP aridity (including Dirty Shame Rockshelter, James Creek Rockshelter, Battle Mountain Pasture, the Little Boulder Basin, and upland Goshute Valley), reflecting new, intense adaptations that persisted in the arid latitudes during the Late Holocene Dry Period (Thomas, 2024; Thomas et al., 2023: Fig. 1).

4.3.2. *The pivotal role of the early Neoglaciation*

Unexpected upland/alpine residential occupations during the LHDP raise an archaeological conundrum: In times of extreme drought, how did residents at remote places like 3360 m Alta Toquima get sufficient water and adequate food in the summertime? If high elevations were severely arid, like lowlands described for the LHDP, would not the upland springs and vegetation in the uplands similarly desiccate? Especially if temperatures were warm (as often been described for the LHDP) we expect that evaporative stress would degrade alpine vegetation, habitat, melt snow patches by summer, and desiccate springs. Such conditions occurred in GB mountains during the hot, dry Medieval Climate Anomaly (MCA, Stine, 1994; Mensing et al., 2008; Graumlich, 1993; Scuderi, 1993), and also in modern times at alpine locations including the high Toquima Range, Toiyabe Range, and White Mountains plateaus, where snow patches disappear and springs are dry by early-midsummer, even in many wet-winter years (Supplementary Materials S1). If MCA and modern conditions were (inappropriately) considered to be analogs for the LHDP—and these would be milder considering their short durations relative to the LHDP—then living conditions in alpine central GB would have been untenable.

We argue that the evidence of Neoglaciation detailed in this paper provides the mechanisms necessary to explain the remarkable human responses to the LHDP, and in the process, offers new proxies for cool-moist conditions at high elevations during the LHDP. We hypothesize that early-NG conditions at high elevations from at least 3400 to 1700 cal yr BP—rather than characterized by desiccated springs and degraded vegetation/habitats—had cooler alpine temperatures that supported adequate soil moisture to enable lush plant growth in plateau wetlands. Cool temperatures would have dampened evaporative stress even for vegetation on rocky substrates. Active rock-glaciers would produce persistent springs at their fringe springs, further supporting wetland habitat (Thomas et al., 2023). Current evidence shows that ongoing neoglaciation (even during extreme lowland drought) created ample habitat for the small alpine mammals and alpine plants that fed the alpine villagers and generated adequate surface water for drinking in alpine zones. These cooler summer temperatures (Millar, 2020) would have been within living and foraging tolerances of native Americans.

We think that, rather than fleeing northward to wetter lowland territory during the LHDP, some resilient Indigenous foragers found that seasonal migration to the uplands could sustain their families during the LHDP. Families summered at alpine Alta Toquima and other high locations almost exclusively during the driest parts of LHDP. They moved back downhill to repurpose sites like Gatecliff Shelter during the mesic two centuries of the LHDP when the lowlands became sufficiently re-watered to support patches of seeds and geophytes (Thomas, 2020, pp 871–898), and then returned to high elevations when extreme aridity resumed (2000–1800 cal yr BP).

Crafting alpine summer residential sites at ATV and elsewhere provides dramatic examples of survivance, a concept that implies more than mere survival in the face of challenge, and, instead, active, intentional adaptation based on knowledge and creativity (Vizenor, 1998; Riris and de Souza, 2021). Survivance strategies played out during central Great Basin LHDP times, when resilient foraging communities downsized, intensified their provisioning strategies, and moved upslope in summers. These behavioral changes provide new proxies documenting cool-wet early-Neoglacial upland conditions during extreme lowland drought.

5. Synthesis and conclusions

Reviewing evidence for the early Neoglaciation, we conclude that high elevations across the latitudinal and longitudinal extent of the central to northern Great Basin experienced multiple glacial advances, mostly in the form of rock glaciers, before, during, and after the Late Holocene Dry Period. These appear to have started as early as 3800-3700 cal yr BP, with early-NG dates estimated for high mountain ranges across the longitudinal and latitudinal extent of the “cold” Great Basin (e.g., excluding Mojave Desert regions and mountains) at ~3400, 3200, 3100–3000, 2930, 2900, 2800, 2700, 2600, 2550–2640, 2400, 2240, 2200, 2150, 2100, 2000, 1955, 1880, 1700, 1600, 1500, and 1400 cal yr BP.

We estimated temperature and precipitation for rock glacier initiation and compared these to potential conditions during the early-NG conditions, recognizing the limited state of knowledge about climate controls on rock glaciers and acknowledging that our estimates are crude. Temperatures differences from modern conditions for rock glaciers to have advanced in the early-NG range from ~1.3 °C to ~4.5 °C decrease in summer temperatures, with no or slight increase needed in winter precipitation for ranges with modern winter snowpacks >54 cm. Cool summers would translate to lower evaporation and overall maintenance of wetter conditions in high elevations than modern hot-summer conditions.

From this we propose that although the LHDP was a millennium of extreme aridity in low-elevation basins of the GB south of a 40 °N—42 °N latitude climate-transition zone (Mensing et al., 2023)—the most severe megadrought of the past 6000 years—high elevations in the GB conditions were considerably cooler than modern throughout the latitudinal and longitudinal extent of the central to northern GB, and effectively wetter. A latitudinal climate dipole at high elevations is not supported in that evidence for the early-NG extends throughout and north of the transition zone. It is likely that low elevations during the LHDP were also cool, although we have no evidence for this.

While it might seem surprising that uplands could be cool and wet enough to grow glaciers while lowlands were extremely dry, there is some evidence pointing to these conditions. Such climate-elevation contrasts have been observed in the Great Basin for other prehistoric periods, as during the early Holocene (Wigand and Rhode, 2001) and Medieval Climate Anomaly (Millar et al., 2006). More recently, atmospheric conditions have been documented and modeled that support contemporary wet uplands while lowlands are in severe drought (Strachan, 2016; Lundquist et al., 2019). Those, however, depend on mechanisms that provide increased summer, not winter, moisture (e.g., monsoon, increased convection). The extreme and extended aridity of the LHDP has been convincingly explained via ENSO processes (Mensing et al., 2013, 2023), in particular, the existence of an overall stable La Niña state. Strong La Niña ocean conditions are generally associated with dry and warm terrestrial conditions in the American Southwest, but weaker La Niña phases can also bring unusually cold and wet winters to the California/central Great Basin region (Guirguis et al., 2015). An extended La Niña state does not, however, readily explain cooler/wetter uplands while lowlands are extremely arid.

The most convincing evidence for these conditions—glacial in the mountains and arid in the lowlands—comes from work by glacial geologist Fred Phillips and his student working in the southern Sierra Nevada, CA. Plummer (2002) developed water-balance models to explain precipitation–temperature relationships between glacier growth in the uplands and water relations—using Owens Lake level as a proxy—in the lowlands. Conditions under which glaciers could grow during periods of low precipitation required cooler temperatures overall. From their model, temperature depressions in the range of ~1°C–4°C would allow glaciers to grow even with decreased precipitation (Plummer and Phillips, 2003), matching our estimates for the early-NG/LHDP.

Growth of rock glaciers in GB mountains due to cooler summers and none-to-slight increases in winter precipitation would have sustained mountain ecosystems in healthy conditions. Drainage from ice-embedded rock glaciers does not lead to significant downstream flow; instead, water from these features is retained in the uplands as abundant glacier-fringed springs (Millar et al., 2013), explaining lack of water in the lowlands. Abundant springs around rock glaciers promote mesic-adapted flora, which in turn provide favorable habitat for small and large upland mammals. More broadly, cool summer temperatures in the uplands reduce evaporation, enhance soil moisture, and lower transpiration stress and water needs by plants. Thus, conditions at alpine elevations could have supported diverse and healthy vegetative growth, distributed springs, and persistent snow patches, even while lowland streams and lakes desiccated and vegetation diminished as a result of extreme drought. These were conditions exploited by Indigenous Nevadans as they sought to escape degraded conditions of their winter lowland residential sites. Settlements such as alpine Alta Toquima Village, occupied during the most intense centuries of the LHDP, further corroborate evidence for cool, moist conditions in high mountains during periods of extreme lowland aridity.

We began this evaluation by observing that the series of detailed investigations documenting the duration and extent of the LHDP had not directly evaluated climates at high GB elevations or temperatures generally in the GB. We hope here to demonstrate that high elevations experienced rock-glacial advances, with concomitant summer-cooler conditions relative to modern, during much of the LHDP. To accurately describe climatic conditions and avoid the implication that the Neoglacial period ended at the start of the LHDP, we urge the name of this millennial interval be modified to "Early Neoglaciation/Late Holocene Dry Period."

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Constance I. Millar: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **David Hurst Thomas:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank Drs. Chrissy Howell (USDA), Greg Stock (USDI National Park Service), Fred Phillips (New Mexico Tech), Dave Rhode (Desert Research Institute), and Robert Westfall (USFS emeritus) for reviewing early versions of the manuscript or pieces of it, and Erick Robinson, Diana Rosenthal-Roberson, Kayla Younkin (American Museum of Natural History) for rendering the illustrations. Robert Westfall also generously provided updated calculations on thermochron data from Millar team's installations. The manuscript was improved by reviews from two anonymous journal reviewers.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2024.108531.

References

Anderson, R.S., 1990. Holocene forest development and paleoclimates within the central Sierra Nevada, California. J. Ecol. 470–489.
Anderson, L.W., Anderson, D.S., 1981. Weathering rinds on quartzarenite clasts as a relative-age indicator and the glacial chronology of Mount Timpanogos, Wasatch Range, Utah. Arct. Alp. Res. 13 (1), 25–31.
Anderson, R.S., Anderson, L.S., Armstrong, W.H., Rossi, M.W., Crump, S.E., 2018. Glaciation of alpine valleys: the glacier–debris-covered glacier–rock glacier continuum. Geomorphology 311, 127–142.
Barnhardt, M.L., 1973. *Late Quaternary Geomorphology of the Bald Mountain Area: Uinta Mountains*. Utah (Doctoral dissertation, Department of Geography, University of Utah.
Barsch, D., 1977. Nature and importance of mass-wasting by rock glaciers in alpine permafrost environments. Earth Surf. Process. 2 (2-3), 231–245.
Barsch, D., 1996. Rockglaciers: Indicators for the Present and Former Geoecology in High Mountain Environments, vol. 16. Springer Science & Business Media.
Benedict, J.B., 1973. Chronology of cirque glaciation, Colorado front range. Quat. Res. 3 (4), 584–599.
Bevis, K.A., 1995. Reconstruction of late Pleistocene paleoclimatic characteristics in the Great Basin and adjacent areas. Department of Geology, Oregon State University, p. 278. PhD Dissertation.
Bowerman, N.D., Clark, D.H., 2011. Holocene glaciation of the central Sierra Nevada, California. Quat. Sci. Rev. 30 (9–10), 1067–1108.
Burger, K.C., Degenhardt Jr., J.J., Giardino, J.R., 1999. Engineering geomorphology of rock glaciers. Geomorphology 31 (1–4), 93–132.
Burke, R.M., Birkeland, P.W., Wright, H.E., 1983. Holocene glaciation in the mountain ranges of the western United States. Late-Quaternary Environments of the United States 2, 3–11.
Carrera, P.E., Short, S.K., Shroba, R.R., 1985. A pollen study of Holocene peat and lake sediments, Leidy Peak area, Uinta Mountains, Utah. Geology Studies 32 (1), 1–7.

Charlet, D.A., 2020. Nevada Mountains: Landforms, Trees, and Vegetation. University of Utah Press.
Clark, D.H., 1995. Extent, Timing, and Climatic Significance of Latest Pleistocene and Holocene Glaciation in the Sierra Nevada. PhD Dissertation, Department of Geology. Washington Univ., Seattle, WA. *California* (No. DOE/OR/00033-T709).
Clark, D.H., Gillespie, A.R., 1997. Timing and significance of late-glacial and Holocene cirque glaciation in the Sierra Nevada, California. Quat. Int. 38, 21–38.
Clark, D.H., Clark, M.M., Gillespie, A.R., 1994. Debris-covered glaciers in the Sierra Nevada, California, and their implications for snowline reconstructions. Quat. Res. 41 (2), 139–153.
Clark, D.H., Steig, E.J., Potter Jr., N., Updike, A., Fitzpatrick, J., Clark, G.M., 1996. Old ice in rock glaciers may provide long-term climate records. Eos, Transactions American Geophysical Union 77 (23), 217–222.
Coats, R.R., 1964. Geology of the Jarbidge quadrangle, Nevada-Idaho. In: Contributions to General Geology Geological Survey Bulletin, vol. 1141. m US Government Printing Office, Washington, D.C.
Crema, E.R., 2022. Statistical inference of prehistoric demography from frequency distributions of radiocarbon dates: a review and a guide for the perplexed. J. Archaeol. Method Theor. https://doi.org/10.1007/s10816-022-09559-5.
Crema, E.R., Bevan, A., 2021. Inference from large sets of radiocarbon dates: software and methods. Radiocarbon 63 (1), 23–39.
Crema, E.R., Habu, J., Kobayashi, K., Madella, M., 2016. Summed probability distribution of ^{14}C dates suggests regional divergences in the population dynamics of the Jomon Period in eastern Japan. PLoS One. https://doi.org/10.1371/journal.pone.0154809.April.29, 2016.
Davis, P.T., 1988. Holocene glacier fluctuations in the American Cordillera. Quat. Sci. Rev. 7 (2), 129–157.
Davis, P.T., Menounos, B., Osborn, G., 2009. Holocene and latest Pleistocene alpine glacier fluctuations: a global perspective. Quat. Sci. Rev. 28 (21–22), 2021–2033.
Daly, C., Neilson, R.P., Phillips, D.L., 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. J. Appl. Meteorol. Climatol. 33 (2), 140–158.
Delaloye, R., Lambiel, C., 2005. Evidence of winter ascending air circulation throughout talus slopes and rock glaciers situated in the lower belt of alpine discontinuous permafrost (Swiss Alps). Norsk Geografisk Tidsskrift-Norwegian Journal of Geography 59 (2), 194–203.
Dickinson, W.R., 2006. Geotectonic evolution of the Great Basin. Geosphere 2 (7), 353–368.
Fiero, B., 2009. Geology of the Great Basin. University of Nevada Press.
Freeman, J., Byers, D.A., Robinson, E., Kelly, R.L., 2018. Culture process and the interpretation of radiocarbon data. Radiocarbon 60, 453–467.
Giardino, J.R., Vitek, J.D., 1988. The significance of rock glaciers in the glacial-periglacial landscape continuum. J. Quat. Sci. 3 (1), 97–103.
Giardino, J.R., Shroder, J.F., Vitek, J.D. (Eds.), 1987. Rock Glaciers. Allen & Unwin, London, p. 355.
Graumlich, L.J., 1993. A 1000-year record of temperature and precipitation in the Sierra Nevada. Quat. Res. 39 (2), 249–255.
Grayson, D., 2011. The Great Basin: a Natural Prehistory. Univ of California Press.
Grogger, P.K., 1975. Neoglaciation of the northern slope of the high Uintas primitive area, Utah. Great Plains Rocky Mountains Geogr. J.; U.S.A. 4, 37–43, 1975.
Grove, J.M., 1988. The Little Ice Age. Methuen, New York, p. 498.
Gude, M., Dietrich, S., Mäusbacher, R., Hauck, C., Molenda, R., Ruzicka, V., Zacharda, M., 2003. Probable occurrence of sporadic permafrost in non-alpine scree slopes in central Europe. Proceedings 8th International Conference on Permafrost 1, 331–336. Zürich.
Guirguis, K., Gershunov, A., Cayan, D.R., 2015. Interannual variability in associations between seasonal climate, weather, and extremes: wintertime temperature over the Southwestern United States. Environ. Res. Lett. 10 (12), 124023.
Harris, S.A., 1981. Climatic relationships of permafrost zones in areas of low winter snow-cover. Arctic 64–70.
Harris, S.A., 1986. Permafrost Distribution, Zonation and Stability along the Eastern Ranges of the Cordillera of North America. Arctic, pp. 29–38.
Harsch, M.A., Hulme, P.E., McGlone, M.S., Duncan, R.P., 2009. Are treelines advancing? A global meta-analysis of treeline response to climate warming. Ecol. Lett. 12 (10), 1040–1049.
Johnson, C.N., Brook, B.W., 2011. Reconstructing the dynamics of ancient human populations from radiocarbon dates: 10 000 years of population growth in Australia. Proc. Biol. Sci. 278 (1725), 3748–3754.
Kelly, R.L., Surovell, T.A., Shuman, B.N., Smith, G.M., 2013. A continuous climatic impact on Holocene human population in the Rocky Mountains. Proc. Natl. Acad. Sci. USA 110 (2), 443–447.
Kelly, R.L., Mackie, M.E., Robinson, E., Meyer, J., Berry, M., Boulanger, M., Codding, B. F., Freeman, J., Garland, C.J., Gingerich, J., Hard, R., 2022. A new radiocarbon database for the lower 48 states. Am. Antiq. 87 (3), 581–590.
Kennett, D.J., Culleton, B.J., Dexter, J., Mensing, S.A., Thomas, D.H., 2014. High-precision AMS 14C chronology for Gatecliff Shelter, Nevada. J. Archaeol. Sci. 52, 621–632.
Körner, C., Paulsen, J., 2004. A world-wide study of high altitude treeline temperatures. J. Biogeogr. 31 (5), 713–732.
Konrad, S.K., Clark, D.H., 1998. Evidence for an early neoglacial glacier advance from rock glaciers and lake sediments in the Sierra Nevada, California, USA. Arct. Alp. Res. 30 (3), 272–284.
LaMarche, V.C., 1973. Holocene climatic variations inferred from treeline fluctuations in the White Mountains, California. Quat. Res. 3 (4), 632–660.
LaMarche Jr., V.C., 1974. Paleoclimatic Inferences from Long Tree-Ring Records: Intersite comparison shows climatic anomalies that may be linked to features of the general circulation. Science 183 (4129), 1043–1048.
LaMarche Jr., V.C., Stockton, C.W., 1974. Chronologies from temperature-sensitive bristlecone pines at upper treeline in Western United States. Tree-Ring Bull. 34, 21–45.
Larsen, D.J., Crump, S.E., Blumm, A., 2020. Alpine glacier resilience and Neoglacial fluctuations linked to Holocene snowfall trends in the western United States. Sci. Adv. 6 (47), 7661 eabc.
Leonard, E.M., 1989. Climatic change in the Colorado Rocky Mountains: estimates based on modern climate at late Pleistocene equilibrium lines. Arct. Alp. Res. 21 (3), 245–255.
Lloyd, A.H., Graumlich, L.J., 1997. Holocene dynamics of treeline forests in the Sierra Nevada. Ecology 78 (4), 1199–1210.
Lundquist, J.D., Kapnick, S.B., Wrzesien, M., Rasmussen, K.L., Hinkelman, L.M., Dozier, J., Pavelsky, T., Durand, M.T., 2019. Could increased summer rains save mountain ecosystems as snow disappears? AGU Fall Meeting Abstracts 2019, 4. GC44B.
Madsen, D.B., Currey, D.R., 1979. Late quaternary glacial and vegetation changes, little Cottonwood canyon area, Wasatch mountains, Utah. Quat. Res. 12 (2), 254–270.
Madsen, D.B., Schmitt, D.N., Page, D. (Eds.), 2015. The Paleoarchaic Occupation of the Old River Bed Delta. University of Utah Press, Salt Lake City.
Marcott, S.A., Clark, P.U., Shakun, J.D., Brook, E.J., Davis, P.T., Caffee, M.W., 2019. 10Be age constraints on latest Pleistocene and Holocene cirque glaciation across the western United States. npj Climate and Atmospheric Science 2 (1), 1–7.
Martin, H., Whalley, W.B., 1987. Rock glaciers: part 1: rock glacier morphology: classification and distribution. Prog. Phys. Geogr. 11 (2), 260–282.
Matthes, F.E., 1941. Rebirth of the Glaciers of the Sierra Nevada during Late Post-pleistocene Time, vol. 2030. Geological Society of America Bulletin, p. 52.
McCoy, W.D., 1977. *A reinterpretation of certain aspects of the late Quaternary glacial history of Little Cottonwood Canyon, Wasatch Mountains, Utah* (MA thesis). Department of Geography, University of Utah.
Mensing, S., Smith, J., Norman, K.B., Allan, M., 2008. Extended drought in the Great Basin of western North America in the last two millennia reconstructed from pollen records. Quat. Int. 188 (1), 79–89.
Mensing, S.A., Sharpe, S.E., Tunno, I., Sada, D.W., Thomas, J.M., Starratt, S., Smith, J., 2013. The Late Holocene Dry Period: multiproxy evidence for an extended drought between 2800 and 1850 cal yr BP across the central Great Basin, USA. Quat. Sci. Rev. 78, 266–282.
Mensing, S., Wang, W., Rhode, D., Kennett, D.J., Csank, A., Thomas, D.H., Briem, C., Harper, T.K., Culleton, B.J., George, R.J., Southon, J., 2023. Temporal and geographic extent of the late Holocene dry period in the central Great Basin, USA. Quat. Sci. Rev. 300, 107900.
Millar, C.I., 2020. Reconstruction of forest and alpine environments over three millennia in the high Toquima range. Alpine archaeology of Alta Toquima and the Mt. Jefferson Tablelands (Nevada) Part 1. In: Anthropological Papers of the American Museum of Natural History. David Hurst Thomas, pp. 373–388 (Chapter 10) in.
Millar, C.I. and Thomas, D.H.T.. Historical biogeography of singleleaf piñon in the Great Basin. Chapter 3 in D.H.T. Thomas, Shoshonean Ethnogenesis and the Numic Spreadings. American Museum of Natural History, Anthropological Series..
Millar, C.I., Westfall, R.D., 2008. Rock glaciers and related periglacial landforms in the Sierra Nevada, CA, USA; inventory, distribution and climatic relationships. Quat. Int. 188 (1), 90–104.
Millar, C.I., Westfall, R.D., 2019. Geographic, hydrological, and climatic significance of rock glaciers in the Great Basin, USA. Arctic Antarct. Alpine Res. 51 (1), 232–249.
Millar, C.I., Westfall, R.D., Delany, D.L., 2013. Thermal and hydrologic attributes of rock glaciers and periglacial talus landforms: Sierra Nevada, California, USA. Quat. Int. 310, 169–180.
Millar, C.I., Westfall, D., R, Delany, D.L., 2014. Thermal regimes and snowpack relations of periglacial talus slopes, Sierra Nevada, California, USA. Arctic Antarct. Alpine Res. 46 (2), 483–504.
Millar, C.I., Delany, D.L., Westfall, R.D., 2020. From treeline to species line: thermal patterns and growth relationships across the krummholz zone of whitebark pine, Sierra Nevada. California, USA. Arctic, Antarctic, and Alpine Research 52 (1), 390–407.
Millar, C.I., King, J.C., Westfall, R.D., Alden, H.A., Delany, D.L., 2006. Late Holocene forest dynamics, volcanism, and climate change at Whitewing mountain and san Joaquin ridge, Mono county, Sierra Nevada, CA, USA. Quat. Res. 66 (2), 273–287.
Millar, C.I., Charlet, D.A., Delany, D.L., King, J.C., Westfall, R.D., 2018a. Shifts of demography and growth in limber pine forests of the Great Basin, USA, across 4000 yr of climate variability. Quat. Res. 91 (2), 691–704.
Millar, C.I., Charlet, D.A., Westfall, R.D., King, J.C., Delany, D.L., Flint, A.L., Flint, L.E., 2018b. Do low-elevation ravines provide climate refugia for subalpine limber pine (*Pinus flexilis*) in the Great Basin, USA? Can. J. For. Res. 48 (6), 663–671.
Miller, J.R., House, K., Germanoski, D., Tausch, R.J., Chambers, J.C., 2004. Fluvial geomorphic responses to Holocene climate change. In: Jeanne, C., Chambers and Jerry R, Miller (Eds.), Great Basin Riparian Ecosystems: Ecology, Management, and Restoration, Society for Ecological Restoration International. Tucson. Island Press, Washington, pp. 49–87.
Miller, R., Chambers, J.C., Evers, L., Williams, C.J., Snyder, K.A., Roundy, B.A., Pierson, F.B., 2019. *The ecology, history, ecohydrology, and management of pinyon and juniper woodlands in the Great Basin and Northern Colorado Plateau of the western United States*. United States Department of Agriculture, Forest Service, Rocky Mountain Research, Station.

Miller, J.R., Germanoski, D., Waltman, K., Tausch, R.J., Chambers, J., 2001. Influence of late Holocene hillslope processes and landforms on modern channel dynamics in upland watersheds of central Nevada. Geomorphology 38, 373–391.
Morard, S., Delaloye, R., Lambiel, C., 2010. Pluriannual thermal behaviour of low elevation cold talus slopes in western Switzerland. Geograph. Helv. 65, 124–134.
Moss, J.H., 1951. Glaciation in the Wind River mountains and its relation to early man in the eden valley, Wyoming. Early Man in the Eden Valley 9–92.
Müller, J., Vieli, A., Gärtner-Roer, I., 2016. Rock glaciers on the run–understanding rock glacier landform evolution and recent changes from numerical flow modeling. Cryosphere 10 (6), 2865–2886.
Munroe, J.S., 2002. Timing of postglacial cirque reoccupation in the northern Uinta Mountains, northeastern Utah, USA. Arctic Antarct. Alpine Res. 34 (1), 38–48.
Munroe, J.S., 2003. Estimates of little ice age climate inferred through historical rephotography, northern Uinta mountains, USA. Arctic Antarct. Alpine Res. 35 (4), 489–498.
Munroe, J.S., 2005. Glacial geology of the northern Uinta mountains. In: Dehler, C.M., Pederson, J.L., Sprinkel, D.A., Kowallis, B.J. (Eds.), Uinta Mountain Geology, vol. 33. Utah Geological Association Publication, pp. 215–234.
Munroe, J.S., 2018. Distribution, evidence for internal ice, and possible hydrologic significance of rock glaciers in the Uinta Mountains, Utah, USA. Quat. Res. 90 (1), 50–65.
Munroe, J.S., Klem, C.M., Bigl, M.F., 2013. A lacustrine sedimentary record of Holocene periglacial activity from the Uinta Mountains, Utah, USA. Quat. Res. 79 (2), 101–109.
Munroe, J.S., Bigl, M.F., Silverman, A.E., Laabs, B.J., 2018. Records of late quaternary environmental change from high-elevation lakes in the Ruby mountains and East Humboldt range, Nevada. In: From Saline to Freshwater: the Diversity of Western Lakes in Space and Time. Geological Society of America Special Paper, p. 536.
NRCS (Natural Resources Conservation Services), 2023. USDA national water and climate Service. In: SNOTEL Weather Data Extracted December 2022.
Osborn, G., 1987. Late quaternary tephra and glacial deposits in the Toiyabe range, Nevada. Abstr. Progr. Geol. Soc. Am. 19 (7), 796.
Osborn, G., 1989. Glacial deposits and tephra in the Toiyabe range, Nevada, USA. Arct. Alp. Res. 21 (3), 256–267.
Osborn, G., 1990. The Wheeler Peak cirque and glacier/rock glacier. In: 1990. A Report Prepared for the Great Basin Natural History Association, p. 58.
Osborn, G., Bevis, K., 2001. Glaciation in the Great Basin of the western United States. Quat. Sci. Rev. 20 (13), 1377–1410.
Osborn, G., 2004. Great Basin of the western United States. Dev. Quat. Sci. 2, 63–67. Elsevier.
Peros, M.C., Munoz, S.E., Gajewski, K., Viau, A.E., 2010. Prehistoric demography of North America inferred from radiocarbon data. J. Archaeol. Sci. 37 (3), 656–664.
Péwé, T.L., 1983. Alpine permafrost in the contiguous United States: a review. Arct. Alp. Res. 15 (2), 145–156.
Piegat, J.J., 1980. Glacial Geology of Central Nevada. Unpublished M.S. Thesis, Purdue University.
Plummer, M.A., 2002. Paleoclimatic conditions during the last deglaciation inferred from combined analysis of pluvial and glacial records. PhD dissertation. Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro.
Plummer, M.A., Phillips, F.M., 2003. A 2-D numerical model of snow/ice energy balance and ice flow for paleoclimatic interpretation of glacial geomorphic features. Quat. Sci. Rev. 22 (14), 1389–1406.
Porter, S.C., Denton, G.H., 1967. Chronology of neoglaciation in the North American cordillera. Am. J. Sci. 265 (3), 177–210.
Reinemann, S.A., Porinchu, D.F., Bloom, A.M., Mark, B.G., Box, J.E., 2009. A multi-proxy paleolimnological reconstruction of Holocene climate conditions in the Great Basin, United States. Quat. Res. 72, 347–358.
Rhode, D., Louderback, L.A., 2007. Dietary plant use in the Bonneville basin during the terminal pleistocene–early Holocene transition. In: Graf, K.E., Schmitt, D.N. (Eds.), Paleoindian or Paleoarchaic? Great Basin Human Ecology at the Pleistocene/ Holocene Transition: 231–247. University of Utah Press, Salt Lake City.
Rhode, D., Brantingham, P.J., Perreault, C., Madsen, D.B., 2014. Mind the gaps: testing for hiatuses in regional radiocarbon date sequences. J. Archaeol. Sci. 52, 567–577.
Richmond, G.M., 1986. Stratigraphy and correlation of glacial deposits of the rocky mountains, the Colorado plateau and the ranges of the Great Basin. Quat. Sci. Rev. 5, 99–127.
Rick, J.W., 1987. Dates as data: an examination of the Peruvian preceramic radiocarbon record. Am. Antiq. 52 (1), 55–73.
Riede, F., 2009. Climate and demography in early prehistory: using calibrated 14C dates as population proxies. Hum. Biol. 81 (3), 309–337.
Riris, P., de Souza, J.G., 2021. Formal tests for resistance-resilience in archaeological time series. Frontiers in Ecology and Evolution 9, 40629.
Robinson, E., 2023. Radiocarbon time and human paleodemography in the Intermountain West. In: *Defining the Central Mountains Archaic: Natural and Cultural Great Basin Biographies.* Anthropological Papers of the American Museum of Natural History No. TK. American Museum of Natural History, New York.
Robinson, E., Thomas, D.H., 2023. Intermountain demography. In: *Defining the Central Mountains Archaic: Natural and Cultural Great Basin Biographies.* Anthropological Papers of the American Museum of Natural History No. TK. American Museum of Natural History, New York.
Salzer, M.W., Hughes, M.K., Bunn, A.G., Kipfmueller, K.F., 2009. Recent unprecedented tree-ring growth in bristlecone pine at the highest elevations and possible causes. Proc. Natl. Acad. Sci. USA 106 (48), 20348–20353.
Salzer, M.W., Bunn, A.G., Graham, N.E., Hughes, M.K., 2014. Five millennia of paleotemperature from tree-rings in the Great Basin, USA. Clim. Dynam. 42 (5), 1517–1526.
Schoenfeld, M.J., 1969. Quaternary geology of the Burnt Fork area, Uinta mountains, summit County, Utah. University of Wyoming. Unpublished thesis. Department of Geology, University of Wyoming.
Scuderi, L.A., 1987. Late-Holocene upper timberline variation in the southern Sierra Nevada. Nature 325 (6101), 242–244.
Scuderi, L.A., 1993. A 2000-year tree ring record of annual temperatures in the Sierra Nevada mountains. Science 259 (5100), 1433–1436.
Shennan, S., Downey, S.S., Timpson, A., Edenborough, K., Colledge, S., Kerig, T., Manning, K., Thomas, M.G., 2013. Regional population collapse followed initial agriculture booms in mid-Holocene Europe. Nat. Commun. 4 (1), 2486.
Strachan, S., 2016. Precipitation and conifer response in semiarid mountains: a case from the 2012–15 drought in the Great Basin, USA. Dev. Earth Surf. Process 21, 193–238. Elsevier.
Stine, S., 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. Nature 369 (6481), 546–549.
Tausch, R.J., Nowak, C.L., Mensing, S.A., Chambers, J.C., 2004. Climate change and associated vegetation dynamics during the Holocene: the paleoecological record. In: Great Basin Riparian Ecosystems: Ecology, Management and Restoration. Island Press, Covelo, CA, pp. 24–48.
Thomas, D.H., 1983. The archaeology of Monitor Valley: 2. Gatecliff shelter. In: Anthropological Papers of the American Museum of Natural History, vol. 59. American Museum of Natural History, New York, p. 1. http://digitallibrary.amnh.org/handle/2246/267.
Thomas, D.H., 2020. Alpine archaeology of Alta Toquima and the Mt. Jefferson tablelands (Nevada). In: Anthropological Papers of the American Museum of Natural History No. 104. American Museum of Natural History, New York. https://doi.org/10.5531/sp.anth.0104.
Thomas, D.H., 2024. Defining the central mountains archaic: natural and cultural Great Basin biographies. In: Anthropological Papers of the American Museum of Natural History. American Museum of Natural History, New York (in press).
Thomas, D.H., Kelly, R.L., 1988. The archaeology of Triple T shelter (Ny345). In: Thomas, D.H. (Ed.), The Archaeology of Monitor Valley: 3. Survey and Additional Excavations, Anthropological Papers of the American Museum of Natural History, vol. 66, pp. 240–271, 2. http://hdl.handle.net/2246/266.
Thomas, D.H., Rhode, D., Millar, C.I., Kennett, D.J., Harper, D.K., Mensing, S., 2023. Great Basin survivance (USA): challenges and windfalls of the neoglaciation/late Holocene Dry Period (3100–1800 cal yr BP). Am. Antiq. 88, 402–418.
Tran, T.J., Bruening, J.M., Bunn, A.G., Salzer, M.W., Weiss, S.B., 2017. Cluster analysis and topoclimate modeling to examine bristlecone pine tree-ring growth signals in the Great Basin, USA. Environ. Res. Lett. 12 (1), 014007.
Van Hoesen, J.G., Orndorff, R.L., 2004. A comparative SEM study on the micromorphology of glacial and nonglacial clasts with varying age and lithology. Can. J. Earth Sci. 41 (9), 1123–1139.
Van Hoesen, J.G., Orndorff, R.L., 2011. The morphology and spatial distribution of late quaternary periglacial landforms, Snake Range, Nevada: a GIS-based approach to prioritizing field sites. J. Ariz.-Nev. Acad. Sci. 43 (1), 48–60.
Vizenor, G., 1998. Fugitive Poses: Native American Indian Scenes of Absence and Presence. University of Nebraska Press, Lincoln. Lincoln.
Wayne, W.J., 1984. Glacial chronology of the Ruby mountains-East Humboldt range, Nevada. Quat. Res. 21 (3), 286–303.
Wigand, P., Rhode, D., 2001. Great Basin vegetation and late quaternary aquatic history. Great Basin Aquatic System History. Smithsonian Contributions to Earth Sciences 33.
WRCC (Western Regional Climate Center), 2023. Historical Data. https://wrcc.dri.edu/. (Accessed 2 January 2023).
Yount, J.C., Birkeland, P.W., Burke, R.M., 1982. Holocene Glaciation, Mono Creek, Central Sierra Nevada, California, vol. 14. Abstracts with programs – Geological Society of America, p. 246.
Zahid, H.J., Robinson, E., Kelly, R.L., 2016. Agriculture, population growth, and statistical analysis of the radiocarbon record. Proc. Natl. Acad. Sci. USA 113 (4), 931–935.