Holocene glaciation in the Americas

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Dedication: Stephen Porter (1934–2015). This review owes much to the seminal work of Stephen C. Porter, internationally renowned for his expertise in Quaternary geology and particularly Holocene neoglaciation in the Americas and beyond (Waitt et al., 2021). He authored chapters on Neoglaciation in the American Cordilleras in the first two editions of the Encyclopedia of Quaternary Science (Porter, 2013, 2007) and co-authored a recent update (Briner and Porter, 2018) upon which this current version builds. This latest version of those chapters is dedicated to his memory.

Abstract

Most glaciers on Earth are currently retreating, but detailed scrutiny of glacier response to global climate change reveals considerable regional variability. To provide context for contemporary glacier recession and regionally variable glacier response to climate change, geologists have long sought to reconstruct past glacier behavior. When compared with temperature and precipitation proxy data, and model simulations of past climate change, glacier histories can be used to quantify the sensitivity of glaciers to temperature change and, more generally, to pinpoint forcing mechanisms of glacier change. Reconstructing glacier change during the Holocene (as opposed to earlier periods in Earth history) takes particular advantage of the best-preserved evidence for past glacier change, and lends itself to bridging geological reconstructions with historical documents and satellite observations for relatively long and seamless timelines of glacier change. Below, the historical context for the study of Neoglaciation and the Little Ice Age during the Holocene is provided, some of the commonly employed dating tools are discussed and some records of glacier change from key locations in the American Cordilleras are briefly summarised. This synthesis is not comprehensive. Instead, the aim is to highlight key advances made in recent years, ending by discussing patterns of glaciation across the American Cordilleras.

Keywords

Holocene; Glacier; Little Ice Age; Neoglaciation; Moraine; Dendrochronology; Radiocarbon; Cosmogenic nuclide exposure dating; Lichenometry; Tephrochronology; American Cordillera

Key points

- Reconstructing glacier change during the Holocene takes advantage of the best preserved evidence for Quaternary glacier change.
- Holocene reconstructions bridge geological reconstructions with historical documents and satellite observations for relatively long and seamless timelines of glacier change.

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This review aims to highlight key recent advances in understanding Holocene glaciation across the American Cordilleras by:

- Providing historical context for the study of Neoglaciation and the Little Ice Age.
- Discussing some of the commonly employed dating tools for reconstructing Holocene glacier change.
- Briefly summarizing records of glacier change from key locations in the American Cordilleras.

Introduction

By the middle of the last century, glacial geologists working in the high mountains of western North America (Fig. 1) had recognized that moraines near the termini of glaciers, far up-valley from those of the last glaciation (i.e. Wisconsinan, Marine Isotope Stage 2), represented small-scale fluctuations of postglacial climate. In the 1930s and 1940s, François Matthes of the US Geological Survey published reports concerning his studies of glaciers in the Sierra Nevada of California. He proposed they had disappeared at the end of the last glaciation during a time of mild climate, but were then reborn and reached their greatest size during a period of 'Neoglaciation' after the end of the Pleistocene (Matthes, 1942, 1940, 1939). Previously, it had been widely assumed that modern glaciers were merely shrunken remnants of former large valley glaciers and ice caps, and that fresh-looking moraines beyond modern glacier termini were recessional drift bodies left behind as the remaining ice wasted away. Matthes recognized that the large coastal glaciers of Alaska and Canada and large valley glaciers on high Cascade volcanoes likely persisted throughout the mild postglacial interval, but concluded that smaller cirque and valley glaciers in the Cascades, Rocky Mountains, and Sierra Nevada disappeared as the climate warmed in postglacial time. He supported his interpretation by calling attention to a study of Owens Lake, at the eastern foot of the Sierra. Gale (1914) estimated 4000 years were required for the salt content of the lake to reach its modern concentration following the lake's desiccation during a mild mid-postglacial interval and its subsequent regeneration as the climate became cooler and wetter. Matthes postulated that the rebirth of Owens Lake and nearby Sierran glaciers were responses to the same pattern of postglacial climate change and, therefore, that modern Sierran glaciers were likely less than 4000 years old.

Recognition of a Little Ice Age

Matthes (1942) recognized two sets of young moraines fronting the Sierran glaciers (Fig. 2). Those adjacent to glaciers were unstable and typically ice-cored (now known as 'Matthes'), whereas those beyond were shorter, concentric, and relatively stable ('Recess Peak'). He surmised the former were comparable to moraines in the Alps that formed in the nineteenth century, whereas the latter were several centuries old. Matthes concluded that glacier oscillations in the last few centuries had been among the greatest during the past 4000 years of renewed glacier activity and marked the culmination of a 'Little Ice Age,' a name proposed by a 'clever journalist' (Matthes, 1940, p. 398).

In the six decades since Matthes published his Sierran studies, many additional glacial-geological investigations have clarified the sequence and chronology of Holocene glacier variations, both in the Sierra and throughout the world. The concept of a Little Ice Age is now widely accepted, and the term has been formalized. Nevertheless, its duration and detailed character remain subjects of continuing debate (Matthews and Briffa, 2005), and its noteworthiness as a glacier event in the context of the entire Neoglacial period has been questioned (Clague et al., 2009). It is widely agreed this interval was confined to the past millennium, but some place its beginning in the seventeenth century, whereas others place it as early as the thirteenth century. Furthermore, increasing evidence has shown the Little Ice Age did not always constitute the most extensive advance of the Holocene.

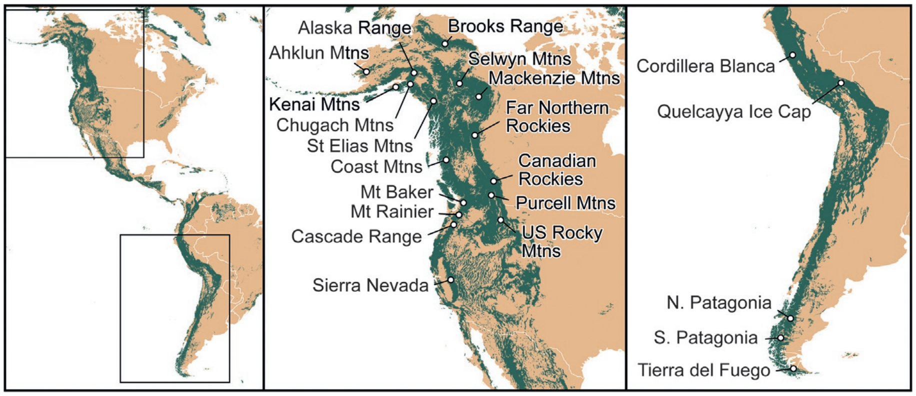

Fig. 1 Map of the American Cordillera, with key locations discussed in this review. The green shading shows the global extent of mountain ranges (Snethlage et al., 2022).

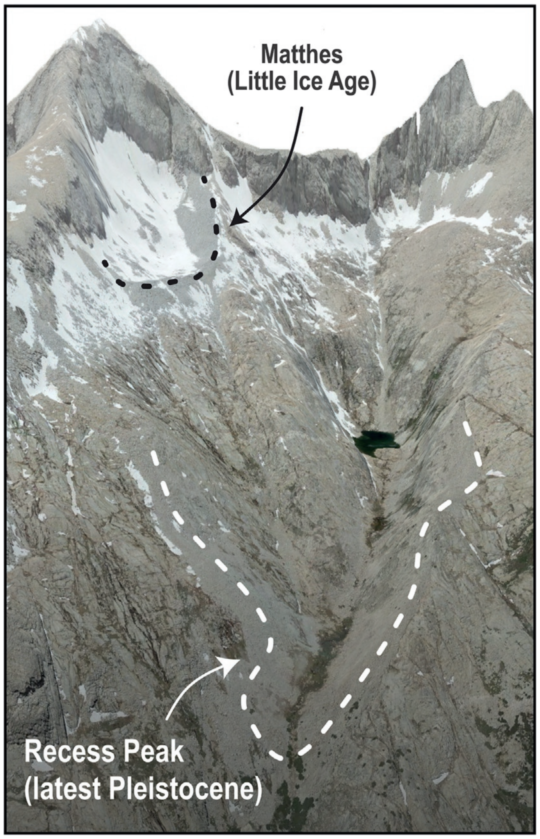

Fig. 2 Oblique view of the northeastern flank of Mount Brewer showing the two-fold moraine sequence common to many cirques in the Sierra Nevada Mountains, California. Image from Google Earth.

Neoglaciation

Holocene climate varied prior to the Little Ice Age, notable as periods of relative thermal change in Northern European pollen records (von Post, 1924). Climatic amelioration following the cool start of the Holocene resulted in a generally mild climate in European Pollen Zones V–VIII during the Early- to Mid-Holocene, named the 'Hypsithermal' by Deevey and Flint (1957) and broadly equivalent to the 'Holocene Thermal Maximum' (Kaufman et al., 2004). The Hypsithermal was followed by Mid- to Late-Holocene cooling, resulting in repeated episodes of glacier advance that culminated in the Little Ice Age. This cooler period has been given various names (e.g., 'Hypothermal', 'Katathermal', 'Medithermal', and 'Neoglaciation'). As a result of its increased use in the North American Cordillera, Porter and Denton (1967, p. 205) defined Neoglaciation as 'the climatic episode characterized by rebirth and/or growth of glaciers following maximum shrinkage during the Hypsithermal interval'. They argued maximum shrinkage probably coincided with maximum Hypsithermal warmth that—based on the evidence available—appeared to have occurred 8000–5000 years ago. Further, they called attention to pollen studies in western North America showing a regionally non-synchronous transition from Hypsithermal to post-Hypsithermal climate, implying this boundary was latitudinally time-transgressive rather than isochronous. They attempted to resolve this problem by defining Neoglaciation as a geological-climate unit (a unit that may lack isochronous boundaries) and suggested evidence of the initial Neoglacial advance in a given area might fall at any time within the past five millennia.

There is some evidence that glaciers advanced at discrete times during the Early Holocene but—in most mountain ranges—phases of glacier expansion followed a time of minimal glacial extent initiated during the Middle Holocene (8200–4200 cal year BP) and persisted through the Late Holocene (4200–0 cal year BP) (Walker et al., 2012). As such, this review mostly focuses on evidence for glacier activity following the early–middle Holocene transition at 8200 cal year BP. In some places, the Little Ice Age constituted the youngest, and sometimes only, recognised Neoglacial episode.

Establishing Neoglacial chronologies

Establishing reliable Neoglacial chronologies depends on accurate dating. In Europe and Iceland, historical data (e.g., written observations, geographic and topographic maps, paintings, sketches, lithographs, and photographs) recording the position of accessible glacier margins span hundreds of years. However, in the American Cordilleras such records seldom extend back more than a century (Porter, 1981). For many inaccessible glaciers, historical records began only in the era of aerial photography and satellite imaging. Therefore, geologists have to rely on physical, chemical and biological dating methods to develop chronologies, with varying degrees of reliability.

Radiocarbon dating commonly provides only maximum or minimum limiting ages for alpine moraines and glacial drift. However, a stacked succession of moraines may include buried soil, peat or wood that provides bracketing radiocarbon ages for successive moraines (Fig. 3). Radiocarbon chronologies can also be developed by dating organic matter in lakes and bogs lying on, behind, or beyond a moraine. The temporal variation in atmospheric radiocarbon means that for Holocene radiocarbon dates to be useful for correlation they should be calibrated using standard calibration curves (Hogg et al., 2020; Reimer et al., 2020; Stuiver et al., 1998). Radiocarbon ages in this review are expressed as calibrated ages in ^{14}C cal year BP.

Dendrochronology has been used to date Late Holocene deposits particularly effectively in northwestern North America where glaciers terminated in forested areas (Luckman et al., 2020), but increasingly also in South America (Masiokas et al., 2009). The life span of most forest trees is generally less than a millennium, so tree-ring dating based on the oldest tree is mainly applicable for dating mid- to late-Little Ice Age moraines. Minimum ages for advances have been obtained by coring the oldest trees growing on moraines. Sources of potential error include uncertainty as to whether the oldest tree has been found, the time between moraine construction and germination of the first seedlings, and the time for a seedling to grow to the height at which the tree was cored. Although these factors may lead to underestimating the age of a morainic substrate, in most cases the error range is likely no more than a decade or two. In some circumstances, the culmination of a glacier advance may be determined by coring trees at the ice margin that were tilted but not killed and noting a marked change in the pattern of ring growth resulting from tree disturbance. One additional use of dendrochronology is to apply cross-dating to glacially transported logs and sheared trees (Fig. 3). The age of outer rings of in-situ glacially sheared stumps can provide the year of death, and as such is more precise than radiocarbon dating subfossil wood (Luckman et al., 2020; Samolczyk et al., 2024). Cross-dating the outer rings on multiple glacially mobilized logs can also provide close constraints on the times of past glacier advance, although it is more challenging to build glacier time-distance histories with reworked logs than with in-place stumps (Barclay et al., 2009; Osborn et al., 2007).

Lichenometry has been a commonly applied relative method for dating moraines, such as in the Brooks, Alaska and Chugach Ranges (Begét, 1994; McKay and Kaufman, 2009; Pendleton et al., 2017) and southern Coast Mountains of North America (Koch et al., 2007a; Osborn et al., 2007), and Cordillera Blanca and Patagonian Icefields in South America (Garibotti and Villalba, 2009; Harrison et al., 2007; Rodbell, 1992; Winchester et al., 2001). Because of the slow growth rate of the ubiquitous lichen species *Rhizocarpon geographicum* at high latitudes, the method is applicable to most Neoglacial deposits (albeit with increasing and substantial uncertainty beyond the last millennium). In lower latitude mountains (e.g., the Rockies and Cascades), growth rates are more rapid, permitting high-resolution dating for the past century or two, but the effective range of lichenometry is generally placed within the Little Ice Age.

Tephrochronology has been used in dating Neoglacial moraines on and downwind from active volcanoes (e.g., in southern Alaska, the Cascade Range, and the Andes). Holocene tephra layers have been dated by means of bracketing radiocarbon dates, and their presence or absence on and/or beneath moraines permits limiting ages to be assigned to glacier advances (Fig. 3). In Mt. Rainier National Park, for example, Holocene tephras from eruptions of Mount Rainier, Mount St Helens, and Mount Mazama provide bracketing ages for Neoglacial moraines (Crandell et al., 1962; Crandell and Miller, 1974; Samolczyk et al., 2024). On Mount Baker in Washington, tephrochronology combined with dendrochronology and lichenometry has tightly constrained Neoglacial advances (Osborn et al., 2012).

Radiocarbon-dated sediment records from glacially-fed lakes provide continuous records of Neoglaciation. Lake sediment archives of Holocene glacier change are now available from many sites across the American Cordilleras (Menounos et al., 2009; Stansell et al., 2023). Although time-distance information is not directly available in lake sediment records, their continuous nature

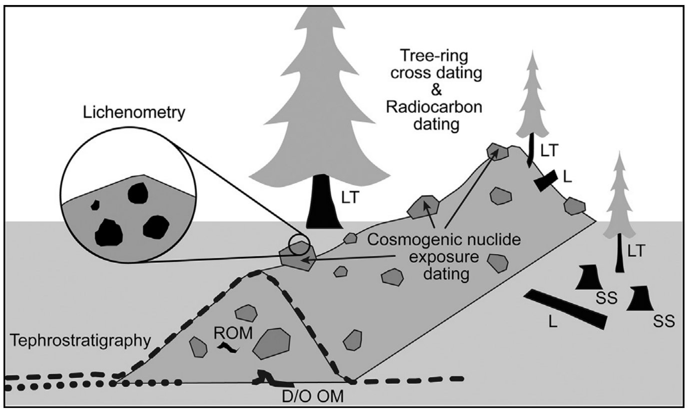

Fig. 3 Common methods used to date moraines. Targets for radiocarbon and tree-ring cross dating are labelled: LT living tree, L log, SS sheared stump, ROM reworked organic material, D/O OM deformed/overridden organic material. The dashed and dotted lines represent tephra layers.

is valuable for addressing the presence or absence of glaciers in a catchment during the Holocene and the timing of the onset of Neoglaciation. This information is otherwise often difficult to obtain because of the obliterative nature of glacier advances combined with glacier maxima achieved in the last millennium at most locations.

In-situ cosmogenic nuclides (e.g., ^{3}He, ^{10}Be, ^{14}C, ^{26}Al, and ^{36}Cl) have been widely used to obtain surface-exposure ages of alpine moraine boulders, especially those of the last glaciation (Balco, 2020; Darvill, 2013). Chronologies of Holocene deposits based on cosmogenic nuclide exposure dating are being increasingly reported. Advances in analytical capabilities and laboratory procedures allow for surfaces as young as the Late Holocene to be more routinely dated (Hawkins et al., 2023). This chronometer allows users to obtain direct ages on moraine boulders, often interpreted to represent the culmination of a glacier advance, in locations where other methods are not applicable due to the absence of appropriate materials. There are caveats to cosmogenic nuclide exposure dating. Although surface erosion and snow shielding are commonly negligible for such young surfaces, other factors can make ages too young. One such factor may be landform degradation, as late Holocene moraines can still be ice-cored, and thus still stabilizing or slowly moving downhill. An additional complication is isotopic inheritance, which yields surfaces with higher ages than their true timing of deposition. Reworked boulders or rockfall deposits are especially prone to inheritance, which can sometimes be revealed by being statistically older than other samples. Inheritance may be more common in cirque glacier systems where rockfall debris comprises a large portion of moraine boulders. In some cases, inheritance might be represented by only slightly elevated nuclide concentrations, perhaps stemming from low glacier erosion rates following exposure during the Hypsithermal. Finally, exposure dating alone often only yields the onset of glacier retreat from a period of stability, making it challenging to document glacial build-up. Recent work has used cosmogenic exposure ages in combination with radiocarbon dating of wood within moraines to provide a powerful way to document both the advance and retreat of Holocene glaciers in the southern Coast Mountains (Hawkins et al., 2021).

Several of the dating techniques above require moraines (e.g., lichenometry, cosmogenic nuclide exposure dating), and in the absence of moraines, dating methods (e.g., radiocarbon) require the intersection of glaciers and tree-line or peat-rich ecosystems. Thus, the existing record of Neoglaciation in the American Cordilleras partly reflects where various dating methods are environmentally applicable (with some techniques producing more reliable results than others). At many localities, Neoglacial moraines are absent prior to the Little Ice Age, ruling out exposure dating methods for anything but Little Ice Age moraines. High-resolution records of Neoglaciation exist in southern Alaska and western Canada due to the widespread use of dendrochronology, despite glaciers being largest during the Little Ice Age. Radiocarbon dating of glacier-overrun wood and peat has led to detailed glacier reconstructions in western Canada and certain localities in the Andes Mountains. These are some reasons why existing knowledge of Neoglaciation in the American Cordilleras is incomplete, an important consideration when making regional comparisons.

Neoglaciation in the American Cordilleras

Alaska

Glaciers cover ca. 5% of the state of Alaska today, equating to ca. 75,000 km^2 (Molnia, 2007). Numerous cirque and small valley glaciers are located in the highest sectors of the Brooks Range, Arctic Alaska and all lie above or beyond the tree-line in a landscape of herbaceous tundra vegetation. Although radiocarbon ages have been obtained for some middle to late Neoglacial moraines, the glacial chronology is based mainly on lichenometric data obtained near the margin of over 100 glaciers, mostly in the central part of the range (Fig. 4) (Calkin, 1988; Pendleton et al., 2017). A lichen growth curve controlled by radiocarbon dating back to 1300 cal year BP was extrapolated to 8000 year BP, thus spanning all of Neoglaciation. The estimated error range of the ages is $\pm$20% (i.e., $\pm$1000 years for the earliest Neoglacial time). Moraines post-dating 5000 cal year BP tend to be closely nested and often lie within less than 100 m of moraines deposited during the Little Ice Age. Adding to the lichenometry-constrained pattern of Neoglaciation are cosmogenic ^{10}Be exposure ages from seven Holocene moraines (Fig. 4) (Pendleton et al., 2017). Outermost

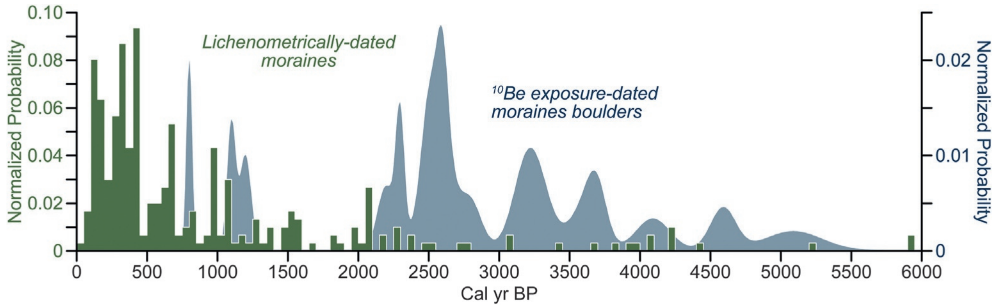

Fig. 4 Histogram of lichenometrically-dated moraines in the Brooks Range, Arctic Alaska (dark green vertical bars). Dark blue curves show the cumulative distribution of ^{10}Be ages on pre-Little Ice Age moraines. Modified from Pendleton SL, Briner JP, Kaufman DS, and Zimmerman SR (2017) Using cosmogenic ^{10}Be exposure dating and lichenometry to constrain Holocene glaciation in the central Brooks range, Alaska. *Arctic, Antarctic, and Alpine Research* 49: 115–132.

Holocene moraines date to as early as ca. 4600 cal year BP. Other pre-Little Ice Age Neoglacial moraines (ca. 3500, 2500–2000, 1600–1300 and 1100–900 cal year BP) have also been dated. Little Ice Age moraines that border nearly every glacier terminus have lichenometric ages that cluster at 600–900, 300–500, and 90 cal year BP.

Southern Alaska and the Yukon Territory are the most extensively glacierized sector of the Americas and include thousands of small to large land-terminating glaciers, as well as numerous large tidewater-calving glaciers. Here Holocene chronologies are based mainly on radiocarbon and dendrochronology of logs in glacier forefields, and in a few instances on proglacial sediment records. Away from the coastline, the onset of Neoglaciation is constrained by lake sediments to be ca. 3100 cal year BP in the Ahklun Mountains, and to 4500–4000 cal year BP in the Chugach Mountains (Levy et al., 2004; McKay and Kaufman, 2009). Neoglacial advances in the northeastern St. Elias Mountains of Yukon Territory culminated 2800, 2600, and 1230–1050 cal year BP and were followed by the most extensive advances of the Holocene during Little Ice Age (Denton and Karlén, 1977). In the Wrangell-St Elias Mountains, Alaska, glaciers advanced at 2700, 1700 and 800 cal year BP, in addition to an advance from the mid-seventeenth century through the nineteenth century (Wiles et al., 2002).

In the Kenai Mountains and other ranges that border the Gulf of Alaska, pre-Little Ice Age advances are dated to between 3300 and 2900 cal year BP, around 2000 cal year BP and between approximately 1550 and 1300 cal year BP; this latter advance is referred to as the 'First Millennium AD' advance (Barclay et al., 2009; Calkin et al., 2001; Wiles et al., 1999). This advance, although less extensive than subsequent advances during the last millennium, has been recorded throughout southern Alaska and the Coast Mountains of British Columbia (Reyes et al., 2006). Land-terminating glaciers experienced major periods of expansion during the Little Ice Age in the middle 13th, early 15th, middle 17th, and last half of the 19th centuries.

By contrast, large calving tidewater glaciers in this region experience advance/retreat cycles that differ from glacier to glacier: some glaciers advanced while others retreated or were stable. Nevertheless, on the scale of millennia, a gross correspondence can be seen among phases of expansion, which may last nearly 1000 years, and intervals of rapid retreat (Fig. 5) (Barclay et al., 2009; Calkin et al., 2001). The record of calving glacier activity has mainly been reconstructed from wood- and peat-bearing deposits exposed by ice recession. Rooted tree stumps sheared off by advancing ice have been used to develop tree-ring chronologies that help assess the rate of glacier advance and time of glacier maxima. Around the Gulf of Alaska, episodes of calving glacier expansion seem to have occurred throughout the Holocene. The most extensive advance of calving glaciers coincided with the Little Ice Age, although previous advances achieved similar extents (Fig. 5). Several very large glacier systems (e.g., Hubbard, Icy Bay, Glacier bay) retreated significantly (10s to 100 km) by the twentieth century. Columbia Glacier is the most recent of the major calving glaciers to begin retreating and its terminus is now receding rapidly up-fjord; its dramatic retreat follows a relatively stable front since an advance dating to ca. 1000 cal year BP (Carlson et al., 2017).

Coast, Rocky, Mackenzie and Selwyn Mountains of western Canada

Glacial reconstructions provide most information about pre-Little Ice Age Holocene glaciation in the North American Cordillera. Middle Holocene advances between ca. 6900–5600 cal ka BP are dated from glacially overridden tree stumps in growth position at Garibaldi Park, southern Coast Mountains (Fig. 6) (Koch et al., 2007a, b; Ryder and Thomson, 1986). Evidence for advances during

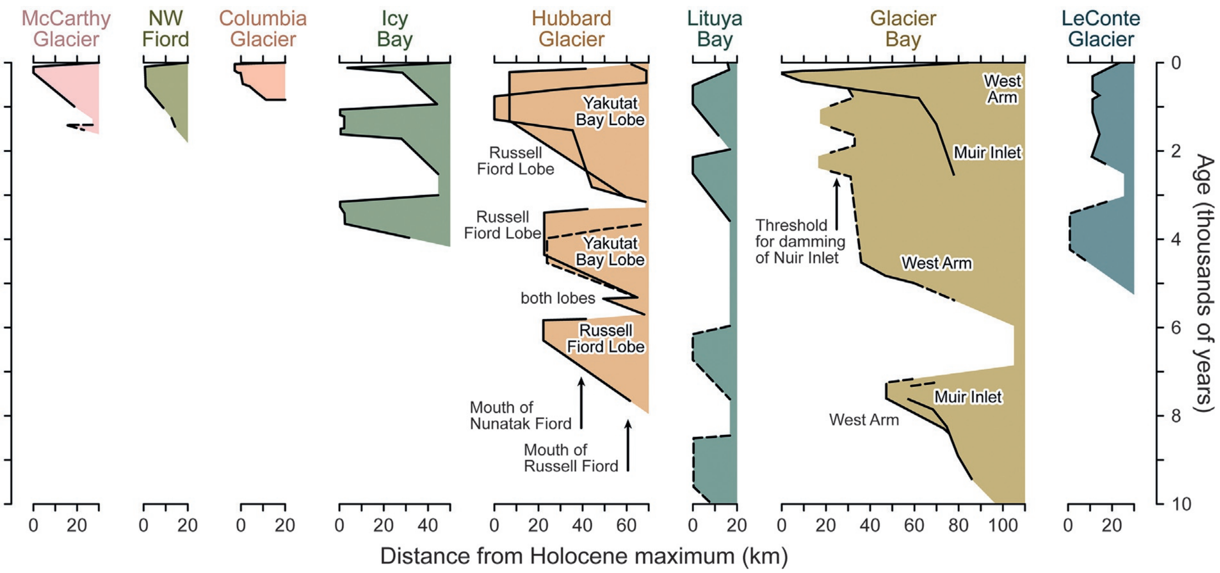

Fig. 5 Holocene records of marine glaciers in southern Alaska. *Modified from* Barclay DJ, Wiles GC, and Calkin PE (2009) Holocene glacier fluctuations in Alaska. *Quaternary Science Reviews* 28: 2034–2048 *with Columbia Glacier history added from* Carlson AE, Kilmer Z, Ziegler LB, Stoner JS, Wiles GC, Starr K, Walczak MH, Colgan W, Reyes AV, Leydet DJ, and Hatfield RG (2017) Recent retreat of Columbia Glacier, Alaska: Millennial context. *Geology* 45: 547–550.

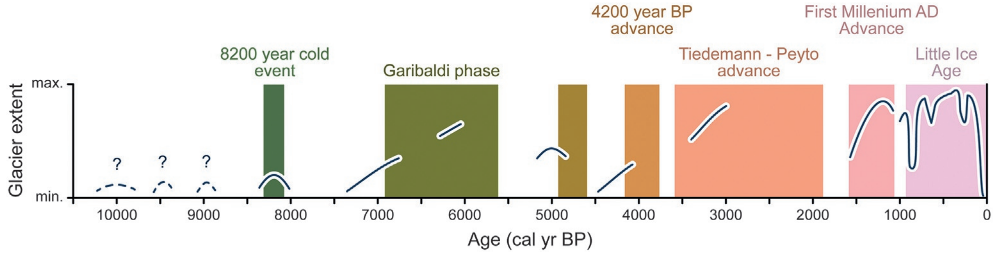

Fig. 6 The glacial record in western Canada. Modified from Clague JJ, Menounos B, Osborn G, Luckman BH and Koch J (2009) Nomenclature and resolution in Holocene glacial chronologies. *Quaternary Science Reviews* 28: 2231–2238.

this 'Garibaldi Phase' based on radiocarbon-dated wood and proglacial lake sediments are derived from additional sites in the Coast and Rocky Mountains (Menounos et al., 2009), as well as limited evidence from glacial forelands for advances of Castle Creek Glacier in the Cariboo Mountains at ca. 9000–8600 and 5600–5500 cal year BP (Maurer et al., 2012). The absence of moraines dating to the Middle Holocene implies these early advances were less extensive than later ones.

Following the early Neoglacial further glacier advances occurred during the Tiedemann Advance, originally described in the southern Coast Mountains (Ryder and Thomson, 1986), and Peyto Advance, described in the Rockies (Luckman et al., 2020, 1993), between 3500 and 1900 cal year BP (Fig. 6). Further evidence for glacier advances during this interval has been derived from additional radiocarbon-dated fossil wood and proglacial lake sediments (Menounos et al., 2009). Radiocarbon-dated fossil wood has also revealed episodes of glacier advance between the Garibaldi Phase and the Tiedemann-Peyto Advance, occurring at ca. 4900 and ca. 4200 cal year BP (Luckman et al., 2020; Maurer et al., 2012; Menounos et al., 2009). Evidence for advances from 4400 to 3000 cal year BP and 2300–1800 cal year BP has been found at Bugaboo Glacier in the Purcell Mountains (Osborn and Luckman, 1988). Recent work has refined the chronology of Gilbert Glacier in the Coast Mountains using a combination of radiocarbon-dating of subfossil wood from lateral moraine sediments and cosmogenic nuclide dating of moraine boulders (Hawkins et al., 2021). This tandem dating approach constrains four glacier advances to ca. 2000–1800, 1500–1300, 900–800 and 400–100 cal year BP, adding to evidence from radiocarbon dating that many glaciers in western Canada were at or close to their Little Ice Age extents within the last ~2000 years (Hawkins et al., 2021; Luckman et al., 2020; Maurer et al., 2012; Menounos et al., 2009; Reyes et al., 2006). The Little Ice Age glacier expansion began shortly before 900 cal year BP and culminated in the eighteenth or nineteenth century when most glacier termini reached their maximum Neoglacial limits (Hawkins et al., 2021; Luckman et al., 2020; Osborn and Luckman, 1988; Ryder and Thomson, 1986).

Holocene glacial chronologies outside the Coast and Rocky Mountains have generally been lacking, but recent cosmogenic ^{10}Be dating in the Mackenzie and Selwyn Mountains of Yukon and Northwest Territories has constrained the maximum extent of cirque and valley glaciers to the late Little Ice Age in the seventeenth to nineteenth centuries (Hawkins et al., 2023). Additional exposure ages from erratic boulders slightly distal to the Little Ice Age moraines date to the Early Holocene at 11,600–10,900 cal year BP, suggesting the glaciers may have been no more extensive by this time (Hawkins et al., 2023).

Cascade Range

Many of the hundreds of glaciers in the Cascade Range terminate in vegetated terrain where radiocarbon dating of buried wood and soils, lichenometry and tree-ring dating are feasible methods for dating Neoglacial deposits. Tephrochronology and cosmogenic nuclide dating are also applicable, and in a few cases historical data extend back to the middle to late nineteenth century. Most Neoglacial Cascade moraines date to the sixteenth, nineteenth and twentieth centuries, and mark the most extensive position during Neoglaciation. However, recent cosmogenic nuclide dating suggests some moraines previously ascribed to the Neoglacial may have been created by glaciers advancing prior to the Holocene. For example, the outer of two moraines in the Enchantment Lakes Basin in the Central Cascades was deposited at ca. 10,800 cal year BP (Marcott et al., 2019), with the inner thought to have been deposited during the Little Ice Age, sometime after 450 cal year BP (Waitt et al., 1982).

An early Neoglacial advance (5400–5600 cal year BP) has been dated using in situ glacier-sheared trees exposed by ongoing retreat of the South Cascade Glacier, in the North Cascade Range in Washington State (Daniel Miller, 1969). More recent radiocarbon dating of stumps in this glacier's forefield date to 5900–5300 cal year BP (Osborn et al., 2012). No moraines of this advance have been identified beyond Little Ice Age moraines, implying Middle Holocene advances were less extensive than those of recent centuries.

Tephra layers broadly bracket earlier Neoglacial moraines at Mt. Rainier, Washington between 3400 and 2200 cal year BP, and 2200 and 450 cal year BP (Crandell and Miller, 1964). Elsewhere on Mount Rainier, at Nisqually Glacier, a 3400-year-old tephra is found immediately adjacent to the outermost Little Ice Age moraine marking the most extensive Neoglacial advance (ca. 1825 CE). Investigations of lateral moraine till stratigraphy at three Mount Rainier glaciers led to 11 radiocarbon-dated wood fragments indicating an advance of at least two of the glaciers at ca. 1700 cal year BP, potentially part of the First Millennium AD advance described elsewhere (Barclay et al., 2009; Samolczyk et al., 2024, 2010). Other advances occurred within the Little Ice Age.

Glaciers on Mount Baker, in the North Cascades in Washington, were most extensive during the mid-1800s, but stratigraphic evidence combined with radiocarbon dating of buried wood and tephrochronology reveal the onset of Neoglaciation at ca. 6000 cal year BP, followed by advances at ca. 2200, 1600, 900 and 400 cal year BP (Osborn et al., 2012). An investigation of the central Cascades in Oregon State detailed a few moraines beyond Little Ice Age moraines bracketed by tephra between 7600 and ca. 2000 cal year BP (Marcott et al., 2009).

US Rocky Mountains

Chronologies of Holocene glaciation in the US Rocky Mountains have typically been lacking (Davis, 1988). Early studies hypothesized pre-Little Ice Age moraines in many locations dated to the Middle or Late Holocene, but lake sediment coring and cosmogenic nuclide dating has since shown many of these moraines date to the latest Pleistocene and earliest Holocene (Davis, 1988; Marcott et al., 2019). For example, the inner Triple Lakes moraine in the Colorado Front Range was deposited at ca. 9100 year BP and a moraine near Bigfoot Lake in the Wind River Range at ca. 9600 year BP (Marcott et al., 2019). Following this phase, glaciers retreated up-valley and many may have melted completely prior to the onset of Neoglaciation.

Reliable records of pre-Little Ice Age Neoglacial moraines have proven elusive, and dendrochronological approaches used in western Canada are not applicable in the US Rockies where only small extant glaciers are present above the tree-line. Relative dating techniques and lichenometry applied to rock glaciers may support pre-Little Ice Age Neoglacial activity (Davis, 1988), but drawing conclusions about absolute timing is tenuous. Thus, Marcott et al. (2019) concluded Little Ice Age glaciers across the region may have been the most extensive since the Early Holocene.

Recently, cosmogenic ^{10}Be dating of high-elevation Little Glacier Lake moraines in the Beartooth Mountains, Wyoming revealed the glacier (possibly a rock glacier) slightly exceeded its Little Ice Age extent at ca. 2300–1100 cal year BP, with continued glacier fluctuations thereafter until ca. 700 cal year BP and glaciation up-valley until ca. 400–100 year BP (Barth et al., 2022). These findings support proglacial lake sediment records such as in Glacier National Park, where phases of glacier expansion have been interpreted at ca. 6000, 3700, 2300 and 1500 cal year BP, followed by fluctuations since ca. 700 cal year BP (Munroe et al., 2012). A similar pattern is seen further south, in the Teton Range, where continuous lake sediments dated with radiocarbon and tephra suggest Teton glacier persisted through the Early Holocene as a small debris-covered or rock glacier (Larsen et al., 2020). The glacier then advanced from ca. 6300 cal year BP and again between ca. 3900 and 2800 cal year BP before reaching its maximum during the Little Ice Age at ca. 700–100 cal year BP (Larsen et al., 2020). These phases of glaciation overlap in timing with glacier expansions in western Canada.

Sierra Nevada

The Sierra Nevada might be considered the ‘classic’ area of Neoglaciation and the Little Ice Age, but its geological record of Holocene glaciation remains sparse and poorly dated (Clark and Gillespie, 1997). The known moraine record is mainly confined to the Little Ice Age, although sediment cores from Conness Lakes down-valley from cirque moraines suggest Neoglaciation may have begun by 3200 cal year BP (Konrad and Clark, 1998), remarkably close to Matthes’ (1942) original estimate. Little Ice Age moraines are often referred to as ‘Matthes-age moraines’ and date to the past 700 years based on lichenometry, radiocarbon dating, and tephrochronology. Lichen ages of 970 and 1100 cal year BP for moraines in the east-central Sierra were reported more than three decades ago, but have not been confirmed or replicated elsewhere in the range. More recent efforts to learn about Neoglaciation in the range use rock-flour records from multiple lakes down-valley of Palisade Glacier (Bowerman and Clark, 2011). Increases in rock flour beginning ca. 3200 cal year BP indicate initial glacier growth, followed by spikes in rock flour at ca. 2200, 1600, 700 and 250–170 cal year BP. It is difficult to know whether the growth of Palisade Glacier marks the onset of Neoglaciation in the Sierra Nevada more broadly, or if ca. 3200 cal year BP is when a lowering snowline intersected this particular cirque basin.

Northern and Central Andes

Moraines relating to the Little Ice Age are ubiquitous throughout the Northern and Central Andean Mountains (Rodbell et al., 2009). Robust evidence for earlier Neoglacial moraines is only found in a few localities. In Cordillera Blanca, northern Peru, radiocarbon ages from ice-pushed peat beyond the Little Ice Age glacier limit constrain an advance to ca. 1500 cal year BP (Rodbell, 1992; Röthlisberger, 1987), consistent with a nearby lacustrine record showing maximum glacier sediment flux at this time (Rodbell et al., 2008). Elsewhere in Peru, cosmogenic ^{10}Be dating shows moraines date to the Little Ice Age period, with no evidence for pre-Little Ice Age Neoglacial moraines (Licciardi et al., 2009; Stansell et al., 2015). Based on proglacial lake sediment analysis, Stansell et al. (2014) suggest glaciers were only active in the Venezuelan Andes during the Little Ice Age.

There have been many studies on the Holocene history of the Quelccaya Ice Cap, Peru. A ^{10}Be dating study concluded Little Ice Age moraines delimit the most extensive advance of the ice cap in the Holocene (Stroup et al., 2014). However, there are clastic sediment flux records (Rodbell et al., 2008), and radiocarbon ages on ice-killed vegetation in growth position (Buffen et al., 2009) and on ice-pushed peat (Mark et al., 2002) suggesting the Quelccaya Ice Cap grew to near its Little Ice Age extent at ca. 5100 cal year BP.

In Bolivia, cosmogenic nuclide dating on moraines showed they were deposited in the early Holocene (ca. 10,000 cal year BP) and Little Ice Age (ca. 420 cal year BP), with one pre-Little Ice Age moraine dating to ca. 1200 cal year BP (Jomelli et al., 2022, 2011). The absence of Mid-Holocene moraines implies glaciers retreated between the Early Holocene and Little Ice Age.

Southern Andes

Holocene glaciation in the Southern Andes is recorded by moraines dated by radiocarbon analysis of in situ or glacier-transported trees in nested moraine sequences, and of basal peat in bogs on moraines or in meltwater channels. Tree-ring chronologies have been developed for some Little Ice Age moraine sequences. For many glaciers, radiocarbon dating provides only minimum limiting constraints on earlier phases of Neoglaciation, and the common assumption is that these ages are closely limiting (Aniya, 2013; Hall et al., 2019). Some ages provide only broad age brackets (e.g. sometime within a 1500-year interval, or sometime after 3300 years ago), making close age assignment and reliable correlations across the Southern Andes and between the Northern and Southern Hemispheres challenging. Furthermore, moraines deposited by tidewater- or lake-calving glaciers may be out of phase with the regional pattern. Recent cosmogenic nuclide dating has helped refine the timing of Holocene glacier advances across the Southern Andes (Kaplan et al., 2016; Reynhout et al., 2019).

Mercer (1968) first suggested Holocene glaciers in Patagonia may have been more extensive prior to the Little Ice Age. Heusser (1960) and Mercer (1982, 1976, 1970) then pioneered research into the timing of Neoglaciation in the southern Andes, largely around the Patagonian Ice Fields. Developing their initial three-fold pattern of Neoglaciation, Aniya (2013) used further radiocarbon ages to constrain glacier deposits to five key phases at 4500–4000, 3600–3300, 2700–2000, 1600–900 cal year BP, and from the 17th to 19th centuries. Evidence from multiple locations now points to multiple phases of Holocene glaciation in the Southern Andes, but with apparent variability in timing and extent.

Mid-Holocene ages for glacial moraines in the Southern Andes have emerged from a number of studies. Espizua (2005) interpreted minimum radiocarbon ages to suggest a glacier advance through the Rio Valenzuela valley at the far northern reaches of Patagonia at ca. 5900 cal year BP. For the North Patagonian Icefield, Douglass et al. (2005) dated the Fachinal moraines using ^{10}Be and ^{36}Cl to ca. 8000 and ca. 6000 cal year BP. Subsequent production rate and scaling updates (Kaplan et al., 2011) increase these ages further and Rodbell et al. (2009) could not rule out pre-Holocene ages for the Fachinal moraines given wide age distributions and possible nuclide inheritance. Harrison et al. (2012) later used optically-stimulated luminescence dating at San Rafael Glacier to reveal a phase of glaciation greater in extent than the Little Ice Age at ca. 7700 and 5700 cal year BP. Cosmogenic nuclide dating permitted more direct dating of moraines in the Southern Andes, with Kaplan et al. (2016) demonstrating glaciers extending from the South Patagonian Icefield were most extensive between ca. 6100 and 4500 cal year BP.

Several studies around the North and South Patagonian Icefields have highlighted patterns of nested moraines indicating decreasing glacial extent through the Holocene (Kaplan et al., 2016), in contrast to the Northern Hemisphere (Davis et al., 2009). ^{10}Be exposure dating at Río Tranquilo Glacier, Monte San Lorenzo—between the Icefields—shows the glacier approached its Holocene maximum position between ca. 9860 and 6730 cal year BP then produced a series of less extensive advances at ca. 5750, 4290, 3490 and 1140 cal year BP, culminating in the Little Ice Age (Sagredo et al., 2021). Likewise, nested moraine sequences at Glacier Torre in the South Patagonian Icefield were dated with ^{10}Be exposure ages to ca. 9700, 6900, 6100, 4500 cal year BP (Fig. 7) (Reynhout et al., 2019). Further south, Strelin et al. (2014) combined radiocarbon and ^{10}Be dating to provide relatively tight constraints on a sequence of Neoglacial moraines (Fig. 8). An early glacier phase smaller in extent relative to later phases occurred at ca. 7700–7200 cal year BP. This was followed by the deposition of three moraines, representing sequentially shorter glaciers, but all beyond the Little Ice Age limit, at 6000–5000, 2500–2000 and 1500–1000 cal year BP. Slightly up-valley are Little Ice Age moraines dating to ca. 700, >400 and < 300 cal year BP. In Torres del Paine, Zapata, Pingo and Tyndall Glaciers advanced at ca. 3200 cal year BP before later advances during the Little Ice Age (García et al., 2020).

The pattern in northern Patagonia of progressively less-extensive Holocene glacier advances that exceed the Little Ice Age extent does not appear to be replicated by glaciers in the southernmost Andes (Reynhout et al., 2021). Strelin et al. (2008) used radiocarbon dating in Tierra del Fuego to document pre-Little Ice Age advances at ca. 3400 and 1200–700 cal year BP, but confirmed

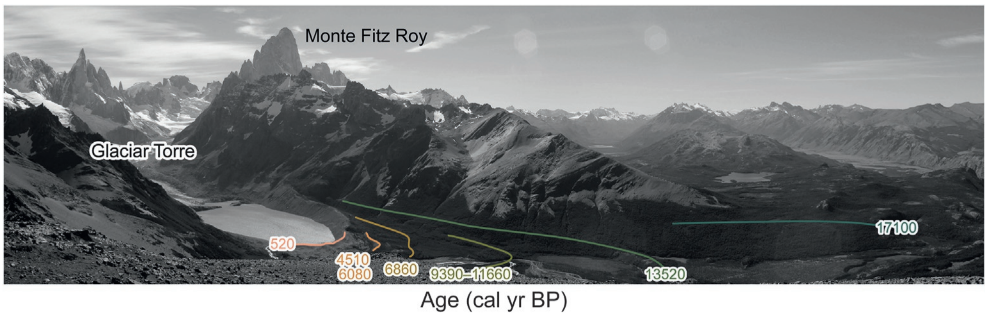

Fig. 7 Holocene history of Glaciar Torre, Argentina. Lines trace moraine ridges, with summary ages of numerous ^{10}Be ages. Moraine M4 has two age populations at 4510 and 6080 cal year BP (Reynhout et al., 2019).

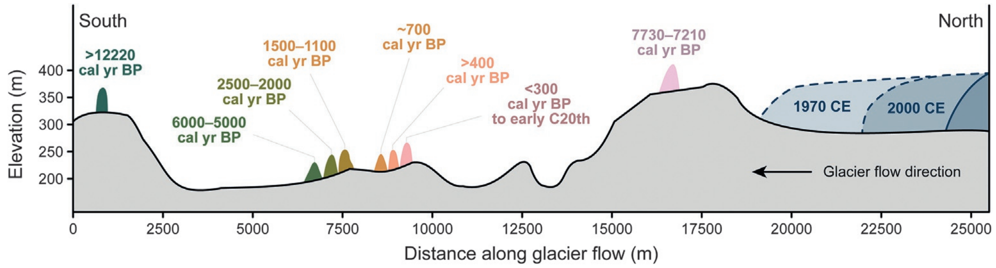

Fig. 8 A record of Holocene glaciation from the southern Patagonia Icefield. Modified from Strelin JA, Kaplan MR, Vandergoes MJ, Denton GH and Schaefer JM (2014) Holocene glacier history of the Lago Argentino basin, Southern Patagonian Icefield. *Quaternary Science Reviews* 101: 124–145.

the most extensive Neoglacial moraines belonged to the Little Ice Age. Likewise, Menounos et al. (2020) used radiocarbon dating of organic material to date the lateral moraine stratigraphy of Stoppani Glacier to ca. 3800–3600, at 3200–2800, 2300–2100 cal year BP, implying glacier thickening through time but all within the Little Ice Age extent. An exception to the overall pattern is in Cordón Martial, where Menounos et al. (2013) found some evidence for a slightly more extensive advance at ca. 7500–5200 cal year BP than the eventual Little Ice Age limit.

Moraines relating to the Little Ice Age are found across the Southern Andes within the range 900–100 cal year BP, with the most extensive advances typically occurring between the 16th and 19th centuries (e.g. Masiokas et al., 2009; Rodbell et al., 2009). It is likely glaciers retreated significantly during the Medieval Climate Anomaly (ca. 1200–1000 cal year BP) before readvancing during the Little Ice Age (Lüning et al., 2022). Analysis of glacier Equilibrium Line Altitudes for several alpine glaciers suggests temperatures were ~0.6–1.0 °C cooler and/or precipitation was ~0.22–0.52 mm year^{-1} greater in order to sustain Little Ice Age glacier advances (Sagredo et al., 2017).

For some glaciers in the southernmost Andes, the Little Ice Age advance was the most prominent in the Holocene (Menounos et al., 2020; Reynhout et al., 2021). Farther north, Little Ice Age moraines represent the final major advance during gradual retreat through the Holocene (Reynhout et al., 2019) and the Little Ice Age may be represented by more than one glacier advance in some places, such as Universidad Glacier, which advanced at least twice to similar extents during the 13–16th centuries and the mid-19th century (Fernández-Navarro et al., 2023). Typically, glacier advances during the Little Ice Age have not been exceeded since (Davies et al., 2020).

Onset of neoglaciation

Because Neoglaciation is defined as the first phase of glacier growth following the Holocene minimum extent, the onset of Neoglaciation is expected to be spatially non-uniform. In addition, in mountainous areas not currently glaciated, a later onset for Neoglaciation may be due to the simple fact that regional snowlines did not lower across cirque floors until cooling had already progressed. Finally, the patchy geologic record leads to an incomplete record of Holocene glaciation, further complicating interpretations of the onset of Neoglaciation.

In some parts of the American Cordilleras, moraines date to the latest Pleistocene and/or Early Holocene, including the Andes (Douglass et al., 2005; Jomelli et al., 2022, 2011; Reynhout et al., 2019; Sagredo et al., 2021) and US Cascade and Rocky Mountains (Marcott et al., 2019). According to the definition of Neoglaciation, glacier phases that generally date between ca. 7000 and ca. 6000 cal year BP mark the onset of Neoglaciation. These occur in both North America (Garibaldi phase in western Canada) and at various localities in South American. In general, this glacier phase was less extensive than subsequent advances. However, recent work has demonstrated that nested moraines in parts of Patagonia become less extensive from the Early Holocene until the Little Ice Age (Reynhout et al., 2019; Sagredo et al., 2021), similar to some glacial records in New Zealand (Dowling et al., 2021; Kaplan et al., 2013; Putnam et al., 2012) and the Antarctic Peninsula (Kaplan et al., 2020) and seemingly in contrast to North America (Menounos et al., 2009) and southernmost South America (Menounos et al., 2020; Reynhout et al., 2021).

Temporal pattern of glacier variations

Studies from across the American Cordilleras identify glacier phases following the Mid-Holocene, beginning ca. 5000 cal year BP. Glacier advances between ca. 5000 and ca. 4000 cal year BP may delimit the most widespread occurrence of Neoglacial activity throughout the Americas as a whole. Following this interval, there is then evidence for glacier advances in almost every subsequent millennium. Given the fragmentary nature of the geologic record (most glacier advances in this time period were within Little Ice Age glacier extents), it is difficult to pinpoint discrete intervals of glacier advance and common time periods between glacier advances. Between 4000 and 2000 cal year BP, almost all mountain ranges contain evidence for advancing glaciers.

There is increasing evidence for glacier advances in the last 2000 years. It is difficult to know if this reflects a more complete record of glaciation, or if glaciers were nearer their eventual Little Ice Age extents, or both. Prominent among pre-Little Ice Age advances in this interval is the First Millennium AD advance, where glaciers in coastal Canada and Alaska experienced widespread, coherent advances ca. 1700–1300 cal year BP (Koch et al., 2007b; Reyes et al., 2006). This interval may be equivalent with the Dark Ages cool-climate period in Europe. Glacier advances during this interval are also prevalent throughout the Andes Mountains. Moraines dating throughout the last millennium have been broadly assigned to the Little Ice Age cool period. In some localities, glacier advances date to the early portion of the last millennium, making it difficult to know whether or not to assign the advances to Little Ice Age cooling or not: testament to the challenge of attributing glacier advances to a specific climate interval and, conversely, defining a climate interval based on the glacier record. Most glacier advances in the last millennium culminated within the well-accepted definition of the Little Ice Age.

In only a few places in the Northern Cordillera do Middle or Late Holocene moraines appear to exist beyond the Little Ice Age extent of glaciers, including at Mount Rainier (Crandell and Miller, 1964), Oregon (Marcott et al., 2009), parts of the US Rocky Mountains (Marcott et al., 2019), and the Brooks Range (Pendleton et al., 2017). In the Brooks Range, cold, slow-moving cirque glaciers produced nested and superposed moraines that occasionally include early Neoglacial deposits. This limited older moraine record in the Brooks Range may in part be due to younger glacier advances being re-directed by older, bulky moraines, and not exclusively resulting from climate forcing of more extensive pre-Little Ice Age glaciation (Fig. 9). In the Southern Cordillera, the existence of pre-Little Ice Age moraines appears to be more common, particularly in the Southern Andes Mountains. One example is glaciers draining the Southern Patagonian Icefield, where Strelin et al. (2014) dated several pre-Little Ice Age moraines to 6000–5000, 2500–2000 and 1500–1000 cal year BP (Fig. 8). This pattern of pre-Little Ice Age moraines has since been extended elsewhere (Reynhout et al., 2019; Sagredo et al., 2021) mirroring glacier change in New Zealand (e.g. Putnam et al., 2012).

In terms of climate forcing of glacier pulses, several mechanisms have been proposed. Millennial-scale forcing from summer insolation is thought to drive the broad pattern of net glacier growth or recession on the Holocene timescale, and is discussed further below. On centennial timescales, solar and volcanic forcing have been proposed to control changes in glacier length (Denton and Karlén, 1973; Porter, 1981), but making these correlations requires a level of precision in glacier chronologies that is the exception rather than the rule (cf. Miller et al., 2012; Wiles et al., 2002). A synthesis of Holocene glaciation concluded that attributing glacier length changes to solar and volcanic forcing remains somewhat ambiguous, and further research on mechanisms relating solar and volcanic perturbations to glacier length changes is needed (Solomina et al., 2015).

Hemispheric contrasts in relative glacier extent?

The pattern of relative glacier extent during the Holocene may relate to hemispheric contrasts in insolation (incident solar radiation) forcing (Solomina et al., 2015). In the southern Andes, summer insolation (and perhaps summer temperature) was lowest in the Early Holocene when some glaciers reached maximum extents, but became progressively higher approaching the Little Ice Age when glaciers were smaller (Fig. 10). In contrast, Northern Hemisphere insolation was initially high during the Early Holocene and decreased towards the Little Ice Age. The maximum Neoglacial ice extent in the Northern Hemisphere would therefore be predicted to occur during the Little Ice Age.

According to this orbital hypothesis, valley glaciers in the Southern Hemisphere reached their greatest extent during the early Neoglacial, with successive subsequent limits diminishing in extent. In the Northern Hemisphere, Little Ice Age moraines would represent the most extensive advances. Is this orbital hypothesis supported by glacier reconstructions? It appears pre-Little Ice Age moraines are indeed more often preserved in the southern Andes, whereas in the northern Andes and throughout the northern Cordillera, pre-Little Ice Age moraines are less common. However, there are clear exceptions (e.g., valleys in the southern Andes where Little Ice Age moraines mark the maximum Neoglacial extent; valleys in the northern Cordillera where pre-Little Ice Age

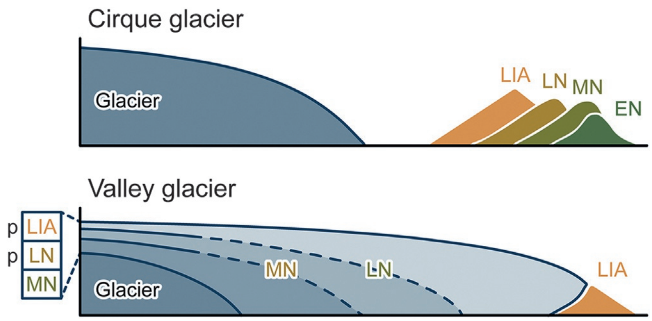

Fig. 9 Moraine records of cirque and valley glaciers. (Top) Neoglacial moraine succession of a small cirque glacier in which the oldest moraine (EN, Early Neoglaciation) has acted as a barrier to the glacier during later advances. Advancing ice may run up against older moraine barriers, developing a stacked sequence, and may override them, burying the older deposits (MN: Middle Neoglaciation; LN: Late Neoglaciation; LIA: Little Ice Age). (Bottom) Successively more extensive advances of a valley glacier override earlier moraines (dashed lines) along the valley floor, with the Little Ice Age advance being the greatest of Neoglaciation. Evidence of earlier advances is preserved in lateral-moraine stratigraphy in which buried soils (p), sometimes tree log- and stump-bearing, separate deposits of successive advances.

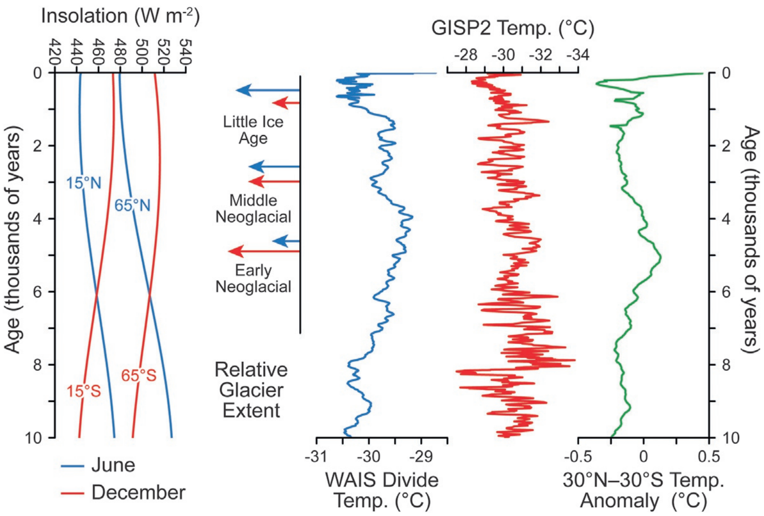

Fig. 10 Relative extents of Neoglacial moraines in the North (blue) and South (red) American cordilleras compared with summer insolation received at different latitudes. Also shown are key paleotemperature records from the Northern Hemisphere GISP2 record (Kobashi et al., 2017), Southern Hemisphere WAIS Divide record (Cuffey et al., 2016), and mid-latitude reconstruction (Marcott et al., 2013).

moraines exist). It is difficult to know whether these exceptions mean the orbital forcing hypothesis is not supported, or if they relate to noise within the natural system (e.g. differing glacier response time, moraine or topographic funneling, etc.)

To further investigate the orbital forcing hypothesis, representative Holocene temperature reconstructions can be plotted from GISP2 in Greenland (Kobashi et al., 2017) and the West Antarctic Ice Sheet (WAIS) Divide site (Cuffey et al., 2016), which arguably represent the high latitudes in both hemispheres (Fig. 10). The result does not yield a simple opposite temperature history indicative of pure insolation forcing. Including temperature compilations from lower latitudes, such as the composite reconstructions from Marcott et al. (2013), shows a Late Holocene cooling in the Southern Hemisphere compared with earlier millennia, beginning 4000–3000 cal year BP. This exercise reveals the Little Ice Age as the coldest period within Neoglaciation, although the WAIS Divide record and the 30°S–30°N band from Marcott et al. (2013) display equally low temperatures prior to ca. 7000–8000 cal year BP. That Early Holocene temperatures were as low as the Little Ice Age in these temperature reconstructions is consistent with the preservation of Early Holocene moraines in parts of South America (e.g., Licciardi et al., 2009; Jomelli et al., 2011, 2017; Strelin et al., 2014), not to mention a similar moraine pattern in New Zealand (Putnam et al., 2012). Recent attempts to establish a more detailed picture of Holocene temperatures across the globe also highlight potential differences in Early Holocene temperatures between the Northern and Southern Hemispheres, but simultaneously the challenges involved in statistically modelling regional temperatures (Bader et al., 2020; Kaufman et al., 2020).

Conclusion

This review summarizes current understanding of patterns of glaciation through the Holocene across the American Cordilleras. Recent work has shown that the onset of Neoglaciation may have been more variable than previously thought. The record of pre-Little Ice Age glaciation in North America remains patchy, but some studies have demonstrated more extensive moraines dating to the Mid-Holocene despite most glaciers reaching their Holocene maxima during the Little Ice Age. In contrast, multiple records in the Southern Andes show decreasing glacial extent through the Holocene and towards the Little Ice Age, although southernmost glaciers appear to have been most extensive during the Little Ice Age. The forcing factors behind these complex patterns of glacial change require further attention, particularly understanding hemispheric differences. Combined with the nuanced picture of Holocene glaciation outlined in this review and challenges in establishing robust neoglacial chronologies, it is clear that a full understanding of the nature and forcing of Holocene glaciation across the American Cordilleras is yet to be achieved.

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