JOURNAL OF QUATERNARY SCIENCE (2008) **23**(6-7) 503–508

Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/jqs.1225

Timing and nature of late Quaternary mountain glaciation

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Thackray, G. D., Owen, L. A. and Yi, C. 2008. Timing and nature of late Quaternary mountain glaciation. *J. Quaternary Sci.*, **Vol. 23** pp. 503–508. ISSN 0267-8179.

Received 6 June 2008; Accepted 9 June 2008

ABSTRACT: Compilations of regional- to subcontinental-scale mountain glacier chronologies from five continents, plus Hawaii, examine the temporal and spatial patterns of mountain glaciation. The compilations yield key insights into the nature of past fluctuations in temperature and precipitation in mountains and adjacent regions, and provide baseline data for examining the dynamics of glacier responses to climate change. Key insights from these compilations include the wide variability of glacier responses to fluctuations in insolation, temperature and precipitation and the regionally specific variations in climatic variables through late Quaternary time. The compilations highlight the need to improve the density and quality of geochronological data and to enhance the understanding of the links between climate and glaciation. Copyright © 2008 John Wiley & Sons, Ltd.

Journal of Quaternary Science

KEYWORDS: glaciation; mountains; climate change; geochronology; late Quaternary.

Introduction

Mountain glaciers and their deposits represent important archives of past climatic information. Mountain glaciers are highly sensitive to fluctuations in temperature and precipitation and, thus, the record of glacier growth and retreat defines those climatic variables. Data from widespread locales indicate that the timing of mountain glacier maxima and subsidiary advances varied widely, as first described on a global scale by Gillespie and Molnar (1995). That variability reflects important palaeoclimatic processes. In particular, mountain glaciation is influenced by regional, not global, climatic processes, and therefore mountain glacier fluctuations can be expected to vary strongly across the globe.

Indeed, numerous studies have demonstrated the complex variability of mountain glacier chronologies. Many mountain glacier systems, for example, reached their maximum Late Pleistocene positions around the time of the Northern Hemisphere ice sheet maximum, the global Last Glacial Maximum (LGM) centred on ca. 21 ka (e.g. numerous chapters in Ehlers and Gibbard, 2004a,b,c). Conversely, other mountain glacier systems reached their maximum Late Pleistocene positions before the ice sheet maximum, in, for example, the tropical Andes (Smith *et al.*, 2005), Tibet (Owen *et al.*, 2003, 2005), Alaska, USA (Briner *et al.*, 2005), Washington, USA (Thackray, 2001) and Mediterranean Europe (Hughes *et al.*, 2006). Other mountain glacier systems reached their maximum ice extent or near maximum extent after the 21 ka BP ice sheet maximum, at, for example, Nanga Parbat, Pakistan (Phillips *et al.*, 2000) and in parts of the northwestern United States (e.g., Licciardi *et al.*, 2001; Thackray *et al.*, 2004). Variations in precipitation delivery to glacier systems have often been cited as important influences on these 'asynchronous' fluctuations, and for some ice sheet synchronous advances as well (e.g. Shulmeister *et al.*, 2005, in New Zealand). It is thus clear from many examples that considerable variability characterises the timing of mountain glacier fluctuations around the globe, and that a variety of palaeoclimatic processes are responsible for the variability. Thus, regional patterns of mountain glacier chronologies represent a relatively untapped opportunity to enhance understanding of palaeoclimatic processes.

As part of the INQUA's Palaeoclimate Commission (PALCOMM), Project 0407 (*Timing and Nature of Mountain Glacier Advances, from 5e to YD*) was established in 2004 to examine this regional and global variability in Late Pleistocene mountain glacier fluctuations. Mountain glacier chronologies on five continents, plus Hawaii, were assessed by project members. The aim of these efforts was to review mountain glacier chronologies at the regional to continental scales, and to propose climatic interpretations for those glacier fluctuations. In so doing, the researchers have revealed temporal and spatial patterns of glaciation particular to each region of coverage. The pattern of ice fluctuations that emerges is globally complex, but potentially very meaningful in terms of our understanding of palaeoclimatic fluctuations.

The project group convened a workshop entitled *Timing and Nature of Mountain Glaciation, from High Asia to the World: Exploring Aspects of Climate Change, Glaciation, and Landscape Evolution*, held in September 2006, in Xining, China, and

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the Tibetan Plateau. The workshop hosted 62 participants from eight countries, featured 31 papers in oral and poster form, and included several discussion sessions that debated the implications of glacial chronologies and glacial impacts on landscape evolution in various climatic regimes. A five-day field excursion examined several field sites across the Tibetan Plateau where new chronologies have been produced.

The project and workshop have produced two edited journal issues. The first, entitled *Mountain Glaciation and Landscape Evolution*, is a special issue of *Geomorphology*, scheduled to appear in 2008 (Owen *et al.*, 2008a). That special issue focuses on the impacts of mountain glaciation on landscape evolution. This issue of the *Journal of Quaternary Science* is the second and final one to result from the project and workshop.

The papers in this special issue take full advantage of the ongoing revolution in the dating of glacial sequences and associated landforms. Over the past ca. 15 years, methods such as cosmogenic radionuclide (CRN) surface exposure dating and optically and infrared-stimulated luminescence (OSL and IRSL) dating have come into widespread and aggressive use. Those applications have produced chronologies where none were previously possible, and have strengthened existing chronologies or expanded them to cover the entire span of the late Quaternary. Therein lies the unique contribution of this issue. Several previous efforts have compiled information on glacial extent and chronology (e.g. Gillespie *et al.*, 2003; Ehlers and Gibbard, 2004a,b,c; the Snowline Database project, Mark *et al.*, 2005). This compilation is unique in its focus on the entire late Quaternary. In approaching glacial chronologies spanning the late Quaternary, the members of Project 0407 have intended to shed light on the diversity of glacial chronologies and of climatic controls on ice fluctuations. In this paper, we summarise the key findings of Project 0407, and specifically the papers presented in this special issue.

Context

The papers presented in this issue cover mountain glacier records spanning five continents (Australasia and Antarctica excluded), plus Hawaii (Fig. 1). The geographic coverage, however, is neither uniform nor global. Rather, the coverage emphasises areas where robust new chronologies have been published and where new understanding has developed recently. As is clear in the following continental summaries, the results belie important mechanisms of mountain glacier responses to climatic fluctuations.

Asia

Three papers in this special issue address glaciation in Asia. These papers concentrate on the Himalayan–Tibetan orogen (Owen *et al.*, 2008b; Yi *et al.*, 2008), which constitutes the greatest concentration of glaciers outside the polar regions, and northeastern Russia (Stauch and Gualtieri, 2008), which has been an area of much contention.

Owen *et al.* (2008b) summarise chronologies in the Himalayan–Tibet orogen, focusing on recalculated CRN chronologies and presenting luminescence chronologies. They discern a variety of chronological patterns across the region. In the westernmost portions of the orogen, they find dominant advances ca. 75 and 20 ka, broadly correlative with Northern Hemisphere ice sheet fluctuations. In the Transhimalaya/western Tibet, monsoon-influenced Himalaya and monsoon-influenced Tibet, however, they find dominant advances during Marine Isotope Stage (MIS) 3, at ca. 45 and 30 ka, and late MIS 2, between 16 and 10 ka. They argue that this variability results largely from contrasting moisture sources and contrasting influences of global LGM cooling. The authors also discuss the myriad complications in applying these chronological methods to glacial sequences across the broad region.

The Holocene glacial chronologies from Tibet are discussed in detail in Yi *et al.* (2008). These are mainly derived from extensive radiocarbon dating. Yi *et al.* (2008) identify one early Holocene glacial episode, ca. 8.8–9.4 ka BP, and two to three substages of middle Holocene glaciation between 5.5 and 1.4 ka BP. During the Little Ice Age two to three prominent ice advances occurred, with the advances possibly occurring 200–600 a earlier in southern and eastern bordering mountain ranges than in northern bordering mountains. Glacial successions across Tibet require additional dating to discern those temporal and spatial patterns more fully and concretely, and mass balance and atmospheric circulation models may help to constrain climatic influences on the variability of glaciation across Tibet.

Stauch and Gualtieri (2008) describe glaciation in northeastern Russia, focusing on five relatively robust chronologies. In the eastern portion of this region, ice advances correlate broadly with Northern Hemisphere ice sheet chronologies and with other proxies in the circum-North Atlantic region. In the western portion of the region, however, the latest ice advance is dated to ca. 55 ka, and no global LGM-correlative advance has been identified. Two additional advances occurred early in the last glacial cycle. Generally, the eastern areas lack evidence of those earlier advances, except on the Chukotka Peninsula. Stauch and Gualtieri (2008) attribute these chronological contrasts to contrasting moisture sources. The eastern region received moisture directly from the North Pacific Ocean. Conversely, drier conditions prevailed in the more continental western region, which receives moisture from Atlantic sources.

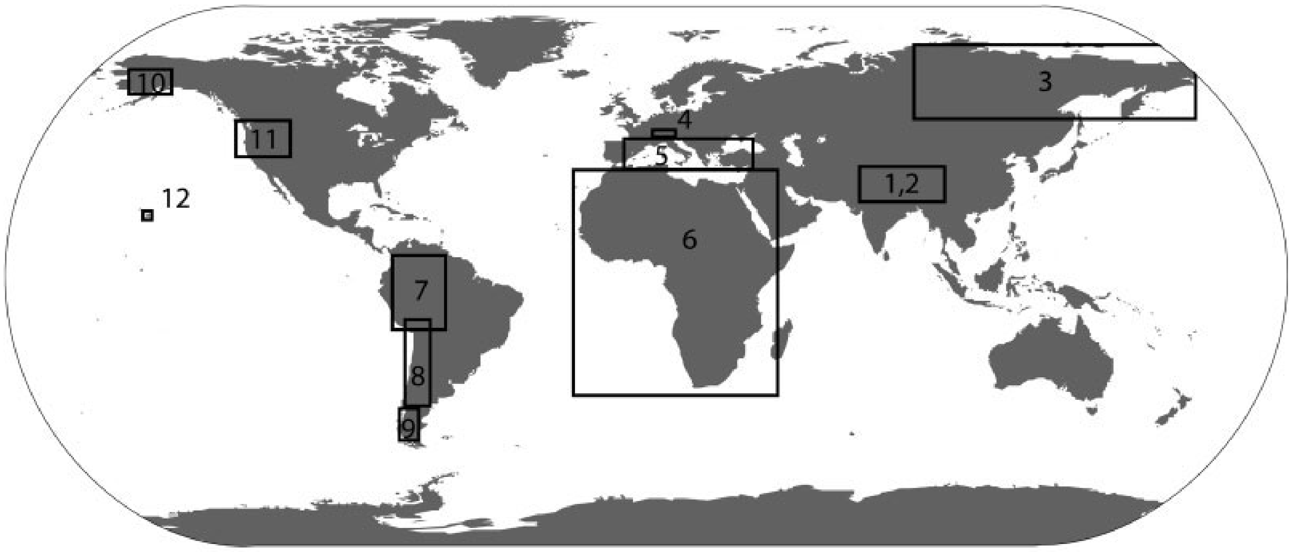
Europe

This special issue illustrates the nature of mountain glaciation in Europe by considering studies from the Alps and from several mountain ranges around the Mediterranean, including the Cantabrian, Pyrenees, Pindus and Apennine ranges. The Alps provide robust chronologies for mid-latitude glaciation, while the locales around the Mediterranean provide a low-latitude assessment of glaciation and an east–west gradient.

The Late Pleistocene chronologies from the northern foreland of the European Alps are reviewed by Ivy-Ochs *et al.* (2008). Luminescence ages define early advances beyond the mountain front at ca. 100 and 70 ka, but the most extensive ice cover developed between 30 and 18 ka, broadly synchronous with the global LGM. Ice retreated rapidly from those maximum positions, with 80% of ice volume lost by 18 ka, and readvanced during two Lateglacial stades.

Hughes and Woodward's (2008) study of the Mediterranean region demonstrates that Late Pleistocene glacial maxima several thousand years prior to the global LGM. Other chronologies, based primarily on ^{10}Be dating of moraine boulder exposure ages from the Pyrenees and Kaçkar mountains, however, suggest a close correlation of local mountain glacier maxima with the global LGM. Hughes and Woodward (2008) suggest the early local mountain glacier

DOI: 10.1002/jqs



1. Owen *et al*, 2008b
2. Yi *et al*., 2008
3. Stauch and Gualtieri, 2008
4. Ivy-Ochs *et al*., 2008
5. Hughes and Woodward, 2008
6. Mark and Osmaston, 2008
7. Smith *et al*., 2008
8. Zech *et al*., 2008
9. Kaplan *et al*., 2008
10. Briner and Kaufman, 2008
11. Thackray, 2008
12. Pigati *et al*, 2008

Figure 1 Map of location of studies included in this special issue and discussed in the text. Bounding boxes are approximate only

maximum is consistent with long palaeoecological records from the region, with the rapid ice build-up characteristic of the small mountain glaciers, and with models of southward diverted cyclonic tracks. They further infer that the global LGM-correlative chronologies are problematic because the global LGM was very dry in the region, and extreme temperature depression would have been required to drive glacier growth at that time. Interestingly, the contrasting chronological results in some ranges (e.g., the Pyrenees) reflect different dating methods. Those conflicting results require resolution if the true glacial and palaeoclimatic patterns are to be revealed.

Clearly, much remains to be learned concerning European mountain glaciation. Contrasting chronological patterns in the Alpine and Mediterranean ranges likely reveal important palaeoclimatic contrasts, and only with further chronological, palaeoecological and ice modelling studies will those patterns be fully revealed. The remaining questions suggest that European glacial sequences should provide fruitful research opportunities for many years to come.

Africa

Mountain glacier chronologies from ten major mountains and ranges in Africa are reviewed by Mark and Osmaston (2008). The chronological record of African glaciation remains quite limited, but patterns are emerging with new chronologies. Radiocarbon dates document a widespread synchronous advance around the global LGM. An extensive ^{36}Cl exposure age dataset from Mt Kilimanjaro and Mt Kenya define the ages of glaciation more clearly. Landforms from the earliest documented glaciation yielded ages of between 355 and 74 ka. The maximum Late Pleistocene glaciation is dated to 17–20 ka, while a statistically indistinguishable, less extensive ice advance is dated to 15.8–16.3 ka. At Mt Kenya, the oldest deposit, a till, is dated by palaeomagnetic methods to >740 ka. ^{36}Cl exposure dates define the ages of two moraine successions to the Middle Pleistocene. Unfortunately, results for suspected global LGM moraines are equivocal, ranging from 28 to 10 ka, but without any distinct age cluster(s).

South America

Glacial chronologies for South America are reviewed for the length of the Andes from the tropics to the Straits of Magellan. Smith *et al*. (2008) concentrates on the glacial chronologies from the tropical Andes of Ecuador, Peru and Bolivia. They discern both regional and local variability in the temporal and spatial patterns of glaciation. In Peru, surface exposure dating indicates an early local LGM (ca. 30 ka) in some areas and a Lateglacial local maximum elsewhere. In Bolivia, timing of maximum advances varies between leeward and windward valleys. In Ecuador, radiocarbon chronologies define the ages of glaciation, but the timing of the local LGM and Lateglacial advances are controversial. Smith *et al*. (2008) suggest that the strong variability results from changes in Atlantic and Pacific moisture sources, the El Niño–Southern Oscillation and insolation.

Mountain glacial chronologies between 15° and 40° S are examined by Zech *et al*. (2008). They recalculate numerous Andean CRN exposure ages and address the temporal patterns of glaciation. Contrasting chronological patterns are identified in four regions. In the tropical Andes the recalculated ages reveal timing of dominant Late Pleistocene advances ca. 25–22 ka, ca. 15 ka and ca. 13–11 ka. Zech *et al*. (2008) correlate those advances with temperature minima. Glaciers reached maximum or near maximum extent during the Lateglacial, synchronous with major lake highstands between the tropical

Andes and as far south as 30° S. Between 30° and 40° S, glaciers reached maximum extent well before the global LGM, ca. 35 ka, which Zech *et al.* (2008) attribute to a northerly shift of the westerly belt, followed by drier conditions and moisture-limited glaciers at the time of the global LGM. Finally, Zech *et al.* (2008) conclude that glaciers receive ample moisture at all times and reached maximum extent during the global LGM south of 40° S. Zech *et al.* (2008) discuss uncertainties in cosmogenic exposure age calculations, and note that the apparent patterns require much additional research.

The mountain glacier chronologies for southern South America, around 45° S, are reviewed by Kaplan *et al.* (2008). They show that glacial chronologies varied across the southern Andes. On the western flank of the Andes glaciers were more extensive during MIS 4 than during MIS 2, with the reversed pattern on the eastern flank. They note a general pattern of major glaciation in phase with the global LGM, but with possible regionally contrasting glacier responses to millennial-scale events between 17 and 10 ka. They note that the apparent variability may be due either to real climate/glacial variability, or to methodological uncertainties, mainly in dating methods.

Notably, all these reviews overlap somewhat in their regional coverage, and do not agree in all cases with respect to timing of glacial maxima or controls on glaciation. As discussed in detail by Zech *et al.* (2008), CRN production rate scaling schemes vary significantly, particularly for low-latitude, high-elevation sites. For these and other reasons, uncertainties remain in the application of cosmogenic exposure methods to the dating of glacial sequences. Furthermore, as in many parts of the globe, relative influences of temperature and precipitation on glacial chronologies remain open to debate. Clearly, resolution of cosmogenic exposure age issues and of glacier–climate linkages are keys to improved understanding of Late Pleistocene palaeoclimatic patterns.

North America

Temporal and spatial patterns of glaciation in western North America are described by Briner and Kaufman (2008) and Thackray (2008).

Briner and Kaufman (2008) review key glacier chronologies from northern Alaska (Brooks Range), central Alaska (Alaska Range), and south-west Alaska (Ahklun Mountains). Cosmogenic exposure ages indicate maximum Late Pleistocene ice extent during MIS 4 or 3. Briner and Kaufman (2008) attribute limited ice extent during MIS 2, and recession from terminal positions ca. 27–25 ka in northern Alaska and ca. 22–19 ka in southern Alaska, to reduced precipitation. The reduced precipitation resulted from exposure of the Bering–Chukchi shelf during the MIS 2 sea-level lowstand. A Younger Dryas-synchronous readvance is indicated by 12–11 ka exposure ages in two ranges of central and southwestern Alaska.

Thackray (2008) reviews mountain glaciation variability and glacial chronologies on a transect from the northwestern to western interior United States. In the coastal Olympic Mountains, he shows that maximum ice extent was reached during MIS 4 and MIS 3, with ice extent during the global LGM significantly diminished by drier regional climates. Similarly, ice extent on the eastern flank of the Cascade Mountains was greater during MIS 5, 4 and 3 than during MIS 2. The timing of those earlier advances, however, varies between the two regions, occurring during insolation maxima in the Olympic Mountains and during insolation minima in the Cascade Mountains just 250 km east of the coastline. Farther inland, maximum Late Pleistocene ice extent occurred during MIS 2, but with variable timing. In some ranges maximum ice extent was reached at the time of the global LGM, while maximum or near-maximum ice extent in those and other areas was reached 15–18 ka. Thackray (2008), Licciardi *et al.* (2001) and other workers attribute the detailed patterns of timing to the drying effects of an ice sheet anticyclone apparent in general circulation models, to variations in westerly atmospheric flow and to local precipitation effects of pluvial Lake Bonneville. Clearly, additional dating and modelling efforts will be required to constrain and understand those patterns more fully.

Hawaii

Hawaii provides one of the most interesting locations to examine mountain glaciation. It is essentially a palaeoclimatic lightning rod, sampling climate in the equatorial Pacific ocean. New ^{36}Cl chronologies from Mauna Kea, Hawaii, are assessed by Pigati *et al.* (2008). They document the development of two summit ice caps, of similar extent, during MIS 2, with glaciers retreating from terminal positions ca. 23 and 13 ka. The climatic factors influencing the two ice cap expansions, however, appear to be quite different. Using subtropical Pacific palaeotemperature proxies and glacier mass balance models, they suggest that the earlier ice cap formed during a wet and cold period, while the later ice cap formed during a warmer but yet wetter period. The warmer but wetter, later period of ice cap development appears to have been characterised by persistent La Niña-like conditions. Thus, it is clear that these tropical island ice caps can be influenced by cooling or by increased moisture, in turn driven by a variety of climatic influences.

Conclusions

Mountain glaciers respond in complex fashion to combinations of temperature, precipitation, ice dynamics and bed conditions (see discussion, for example, in Owen *et al.*, 2008). Thus, detailed inferences of palaeoclimate from studies of extent and chronology can be fraught with pitfalls. The chronologies presented in these papers, however, reveal clear patterns of glacial chronology and extent spanning the Late Pleistocene, and the inferences at the broad temporal and spatial scales of study are insightful and robust.

The chronologies described herein demonstrate strong variability in mountain glacier chronologies across the globe. While chronologies in several areas demonstrate synchrony with Northern Hemisphere ice sheet fluctuations, with maximum ice extent at the time of the global LGM (19–23 cal. ka BP at chronozone level 1, or 18–24 cal. ka BP, at chronozone level 2 after Mix *et al.*, 2001), that pattern appears to be the exception rather than the rule. Many ice systems reached maximum extent either before or after the ice sheet maximum, and demonstrate ice fluctuations spanning much of Late Pleistocene time.

While the studies presented in this special issue cover a wide variety of geographic and climatic settings there are several dominant themes:

1. Glacial systems have highly variable chronologies, especially when viewed across the entire late Quaternary.

2. The late Quaternary pattern of glacial advances at any location depends upon the actual climatic fluctuations at that location and the mass balance characteristics of the glaciers.
3. Insolation variations are the primary driver of glacial fluctuations, but are linked to ice volume in multiple ways. To some degree, thinking in the field still points to cooling during the global LGM as a dominant driver of glacier fluctuations. Certainly that is true in some areas, but not in all areas. Insolation also influences the Asian monsoon, which strongly influences Himalayan–Tibetan glacial systems, and westerly flow strength, which appears important in some mid-latitude mountain ranges.
4. Despite vast improvements in our ability to date glacial sequences, much improvement is still needed. Zech *et al.* (2008) and Owen *et al.* (2008b), for example, provide discussions on scaling factors and their influence on CRN dating and interpretation for chronologies in the Andes and Himalayan–Tibetan orogen. Significant programmes in geochronology are underway that will help resolve many of the dating issues, for example, the US National Science Foundation's Cosmic-Ray Produced Nuclide Systematics on Earth Project (CRONUS). CRONUS is making headway on that issue and others, but cosmogenic chronologies will likely maintain substantial uncertainties (e.g. Balco *et al.*, 2008).
5. The chronologies summarised herein show many climatic events, especially where the global LGM-correlative advance was diminished in extent. Examples include Tibet, western central Asia, South America, and portions of the northwestern United States.
6. Mountain glaciers are widely useful indicators of palaeoclimatic fluctuations. Their rapid response to climate change and widespread distribution make them ideal probes of past climates.
7. Understanding of mountain glaciers and palaeoclimate will be improved through further refinement of dating methods and their applications, and through improved understanding of linkages between insolation, spatially heterogeneous climatic responses, ice dynamics and glacial sedimentation processes.

In summary, although general statements can be made regarding the timing and extent of mountain glaciation, much more intensive study is needed on local and regional scales to elucidate the nature of mountain glaciation. Significant geographic gaps exist in robust global glacial chronologies, particularly in many of the mountain ranges in South America, Africa, Asia and Australasia.

Acknowledgements This paper is an outgrowth of discussions at a workshop on mountain glaciation that was held in Tibet during September 2006, sponsored by the US National Science Foundation (grant numbers OISE-0536909 and EAR-0640378), Natural Science Foundation of China, and the International Quaternary Union. We thank the participants in that workshop and the authors of the papers in this special issue for their insightful contributions.

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