The extent and chronology of Cenozoic Global Glaciation

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Abstract

The Quaternary is synonymous with extensive glaciation of Earth’s mid- and high-latitudes. Although there were local precursors, significant glaciation began in the latest Eocene (ca 35 Ma) in eastern Antarctica. It was followed by glaciation in mountain areas through the Miocene (in Alaska, Greenland, Iceland and Patagonia), later in the Pliocene (e.g. in the Bolivian Andes and possibly in Tasmania) and in the earliest Pleistocene (e.g. in the Alps, New Zealand, Iceland and Greenland). Today, evidence from both the land and the ocean floors demonstrates that the major continental glaciations, outside the polar regions, rather than occurring throughout the 2.6 Ma of the Quaternary, were markedly restricted to the last 1 Ma—800 ka or less. Marine Isotope Stage (MIS) 22 (ca 870–880 ka) included the first of the ‘major’ worldwide events with substantial ice volumes that typify the Later Pleistocene glaciations (i.e. MIS 16, 12, 10, 6, 4-2).

1. Introduction

At the congress in Berlin 1995 the INQUA Commission on Glaciation decided to form a new work group entitled ‘Extent and Chronology of Glaciations’. The idea of this ‘Work Group 5’ was to provide a comprehensive overview of the extent and chronology of glaciations during the Quaternary, particularly including digital maps, giving glacial limits, relevant key locations and type sections. The project involved the contribution of over 200 scientists working in more than 60 countries and territories throughout the world (Fig. 1). The resulting compilation represents the most complete survey of evidence of glaciations ever attempted (Ehlers and Gibbard, 2004a–c). This overview article is largely based on the results of that work group. For the purposes of this review the base of the Pleistocene Series and that of the Quaternary System are placed together at 2.6 Ma, rather than the current global standard at 1.8 Ma, following the convention adopted in Western Europe (Gibbard and van Kolfschoten, 2005).

From the mid-19th century, the Quaternary has been considered synonymous with extensive glaciation of the mid-latitudes. Although there were possibly local precursors, significant glaciation began in the Late Eocene (ca 35 Ma) in eastern Antarctica (Ingólfsson, 2004; Trapti et al., 2005). The Earth’s climate, which had been extremely warm during the Cretaceous ‘hot-house’ (Norris et al., 2002), continued to be both warm and without extreme fluctuations during the Paleogene (Jenkyns, 2003). An overall, long-term trend of cooling global climates through the Tertiary culminated in the mid-latitudes with warm temperate, alternating with cool-temperate climates in the Late Neogene. Neogene-age ice-rafted debris is found in ocean-sediment cores from the North Atlantic region, including the Barents Sea, and areas adjacent to Norway, N and SE Greenland, Iceland and northern North America, and in the Southern Ocean off-Antarctica (Mangerud et al., 1996; Chung et al., 2005; Kump, 2005).

2. The onset of glaciation

Outside Antarctica, glaciation in mountain areas apparently started by the Miocene (in Alaska, Greenland, Iceland and Patagonia), extended in the Pliocene (e.g. in the Bolivian Andes and possibly in Tasmania) and in the earliest Pleistocene (e.g. in the Alps, New Zealand, Iceland and Greenland) (Table 1). Neogene glaciations are also known from the Piedmont areas of Argentina and Chile where, like in Antarctica, substantial ice caps established...
by 14 Ma ago (Heusser, 2003). Evidence of extensive ice-rafting, an indication that glaciers had reached sea-level, is found from the earliest cold stage, the Praetiglian (2.6–2.4 Ma) and its equivalents, in both the North Atlantic and North Pacific oceans (ca Haug et al., 2005). But traces of the early glaciations are limited, and it is difficult to reconstruct a picture of the extent of those early ice sheets.

Like the Later Neogene, the Early Pleistocene (2.6–0.8 Ma) was characterised by climatic fluctuations dominated by the 41 ka precession cycle. Only 14 of the 41 cold stages of that period currently show evidence of major glaciations. They include the Plio/Pleistocene boundary events Marine Isotope Stages (MIS) 104, 100 and 98, together with Early Pleistocene MIS 82, 78, 68, 60, 58, 54, 52, 36, 34, 30 and 26 that reach δ18O values in ocean sediments of ca 4.6–5‰. It seems that until the transition in dominant orbital cyclicity to the 100 ka cycles that began ca 1.2 Ma and was fully established by about 800 ka, that the cold periods (glacials) are regularly not cold and long enough to allow ice-sheet development on a continental scale outside the polar regions (Ehlers and Gibbard, 2004a–c). Here, MIS 22 (ca 880–870 ka) is the first of the ‘major’ cold events that reached critical δ18O values of ca 5.5‰ or above equivalent to substantial ice volumes that typify glaciations of the Later Pleistocene (i.e. MIS 16, 12, 10, 6, 4–2). Potentially therefore, it would seem likely that there were a minimum of 20 periods during which extensive glaciation could have developed during the last 2.6 Ma, with the most extensive (ca 5–6 periods) being limited to the last 900 ka (Fig. 2).

Precisely where these glaciations occurred and how far they extended is very difficult to determine, given that the remnants of early glaciations tend to be obliterated and mostly removed by later, more extensive advances. Especially in mountain regions, the preservation potential of older sequences rapidly diminishes with time and subsequent glaciation.

2.1. Southern hemisphere

In the Late Matuyama Chron (1.78–0.78 Ma) glaciation of the Southern Hemisphere would have looked very similar to the present situation (Fig. 3). The most striking feature, apart from the Antarctic Ice Sheet, would have been the Great Patagonian Glaciation of southernmost South America (Coronato et al., 2004a, b). Matuyama Chron glaciations are also known from New Zealand (Fitzsimons et al., 1996) and the Tasmanian Linda Glaciation may possibly be of Late Matuyama Chron age (Fitzsimons and Colhoun, 1991).

Throughout the last 2.6 Ma, the constant presence of orbital periodicities in the sediment record from cores off-western Antarctica confirms the relative stability of the Antarctic ice sheet (Barker et al., 1999; Hillenbrand and Ehrmann, 2001; Barker and Camerlenghi, 2002; Iorio et al., 2004). According to Iorio et al. (2004) periods of particularly intense ice rafting from the western Antarctic ice-sheet occurred at 1.07 (MIS 32–30), 2.01 (ca MIS 74), and 2.61 Ma (MIS 104) (Cowan, 2001).

2.2. North America and Greenland

During the Early Pleistocene, extensive ice sheets existed in parts of the Northern Hemisphere (Fig. 4). The figure shows the combined evidence for a Late Matuyama Chron cold stage. The North American record of glaciation (Table 2) is similar to its European counterpart, the longest sequences being restricted to Alaska and the adjacent North-West Territories of Canada. Together with Greenland and the Rocky Mountains, they preserve evidence of glaciations from the Neogene to the present (Barendregt and Duk-Rodkin, 2004). In northern Canada and Alaska, the oldest till and accompanying ice-rafted detritus in marine settings dates from the Early Miocene, with regionally widespread glaciation occurring in the Pliocene.
Table 1
Occurrence of glaciation in Europe through the Cenozoic based on numbers of observations presented in contributions to the INQUA project ‘Extent and Chronology of Quaternary Glaciations’ (Ehlers and Gibbard, 2004a)

| Stage/Age | MIS (approx) | Austria | Belgium | Bulgaria | Czechia | Denmark | Estonia | Finland | France | Germany | Greece | Iceland | Ireland | Italy | Netherlands | Norway | Poland | Portugal | Russia | Slovenia | Slovakia | Spain | Sweden | Switzerland | Ukraine | Western Europe | Northern Europe
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and regularly throughout the Pleistocene (cf. Haug et al., 2005). For North America, apart from minor mountain glaciations, four glaciation centres are known: There would have been an extensive Cordilleran Ice Sheet, a small glaciation centre in northern Alaska, and an extensive Horton Ice Cap covering the lower Mackenzie River region and Banks Island would be centred on the Horton Plateau. Whilst the Prairie Region of Canada and the USA seems to have remained ice-free, an ice sheet centred in Labrador and the eastern Hudson Bay region would have spread south across Ontario and Quebec, Canada and into the Mid-West USA in Kansas, Illinois, Indiana, Ohio and, probably, New York (Barendregt and Duk-Rodkin, 2004; Gillespie et al., 2004). It must be kept in mind that the figure drawn represents the minimum extent of glaciation. Little is known about the true ice extent in northern Canada, and if and where in Europe or northern Asia glaciers existed has so far not been determined. In the map (Fig. 4) we have drawn tentative ice sheets over Scandinavia and Svalbard.

2.3. Africa

The early glacial record in Africa may be restricted to the mountains of East Africa (Mount Kilimanjaro, Mount Kenya). On the latter, glaciations began at ca 2.0 Ma (ca MIS 68), whilst a second glaciation is recorded before the Brunhes/Matuyama magnetic reversal (Mahaney, 2004). There is evidence for probably three glaciations of the Atlas mountains, but their age remains equivocal at present (Hughes et al., 2004).
Fig. 3. Extent of Matuyana Chron glaciation in the Southern Hemisphere (based on Ehlers and Gibbard, 2004a–c).

Fig. 4. Extent of Matuyana Chron glaciation in the Northern Hemisphere (based on Ehlers and Gibbard, 2004a–c).
2.4. Eurasia

Evidence of glaciation is widespread across Europe and West Siberia throughout the Quaternary and indeed the Neogene (Table 1). However, before the Middle Pleistocene glaciation appears to be represented only by ice-rafter clasts, outside the mountain or high-latitude regions (e.g. in the Netherlands, lowland Germany, European Russia and the British Isles) (Mangerud et al., 1996). In this context, the Dutch ‘Hattem Beds’ of Menapian age (1.2–1 Ma; ca MIS 36-34) are of particular significance in that they indicate substantial glaciation of the Baltic region late in the Early Pleistocene (Ehlers, 1996). On Iceland glaciation began in the Miocene (Geirsdóttir, 2004), occurred regularly through the Pliocene and onwards to the present-day (cf Greenland, below, Table 2). Likewise, in Norway, its adjacent offshore and the neighbouring Barents Sea, glaciations are recorded from the Early Miocene, Early Pliocene, Plio/Pleistocene and periodically throughout the remaining period (Mangerud et al., 1996). The absence of evidence from the early Middle Pleistocene probably represents removal of evidence by later glaciation rather than an interruption of the glacial history.

In Italy, particularly in the northern mountains, glaciation is identified possibly from the Plio/Pleistocene onwards, but becomes established in the Dolomites by MIS 22 (Muttoni et al., 2003). Comparable evidence is also found from north of the European Alps in Switzerland and southern Germany. However, in many cases truly glaciogenic deposits are scarce, and in the absence of long, continuous sequences, dating is often problematic. Elsterian deposits may be present in Greece, where the currently best-dated glacial sequence of the Mediterranean region is found (Hughes et al., 2006a, b). Further to the west, in the Pyrenees, the oldest glaciation currently identified is thought to be of early Middle Pleistocene (Cromerian Complex) age (Calvet, 2004).

2.5. Asia

Glaciations of Tibet and Tianshu are not recorded before the Middle Pleistocene.

2.6. Southern hemisphere

Glaciation in the Southern Hemisphere has always been limited by the lack of available landmass. Whilst Antarctica was already glaciated from early in the Tertiary, only southernmost South America reached far enough polewards to allow extensive glaciations (Fig. 5). Whilst in

Table 2
Occurrence of glaciation in North America through the Cenozoic based on numbers of observations presented in contributions to the INQUA project ‘Extent and Chronology of Quaternary Glaciations’ (Ehlers and Gibbard, 2004b)
southern Chile in the Pleistocene glacial maximum the ice sheet extended to the shelf edge, only major glacier tongues seem to have reached the Atlantic Ocean. Both easternmost Tierra del Fuego and the Falkland Islands are supposed to have remained largely unglaciated (Clapperton, 1993). In New Zealand and on Tasmania glaciers formed, the New Zealand glaciers covering about one-third of the South Island (Suggate, 1990).

3. Pleistocene Glacial Maximum

During the Pleistocene Glacial Maximum, extensive ice sheets covered major parts of North America and Europe (Fig. 6). In both continents they reached south beyond 40° N, in Europe only leaving an ice-free corridor of a mere 200 km between the Nordic and the Alpine piedmont glaciers. The Eurasian ice sheet extended eastwards beyond 110° E. It covered the northern part of the West Siberian Lowlands, blocking all northward-directed drainage and adding a vast meltwater input to the Black Sea/Mediterranean Sea system (Lambeck et al., 2006). Extensive shelf areas were glaciated, including the northeastern Canadian Arctic, all around Greenland, all around Iceland and the shelf seas of the Barents Sea and Kara Sea (Svendsen et al., 2004a, b). The North Sea and Irish Sea were fully glaciated (Clark et al., 2004). With the exception of the Yukon Territory, Canada, was largely ice-covered (Duk-Rodkin, 1999). Only in Alaska, as well as in eastern Siberia, major areas seem to have remained ice-free (Brigham-Grette et al., 2003; Gualtieri et al., 2005).

Also, mountain glaciations reached a considerable size, e.g. in the Apennines (Italy) (Federici, 1980). Glaciation of the high mountains and the Tibetan Plateau in central Asia seems to have not extended far beyond that of the Last Glacial Maximum (LGM). Glaciation in MIS 12 seems to have been the most extensive. In Tainshu an older glaciation (?MIS 16) may also have occurred. Subsequent events took place during MIS 8 and 6. The map shows the Chinese (minimum) version (Li Binyuan et al., 1991). When assessing this map, it must be taken into account that age control on the glacial maximum position is poor, and that not all parts of the ice sheets reached their maximum positions simultaneously. For instance, the Dniepr Lobe and the Don Lobe in Eastern Europe (Fig. 6) are of a different age (Astakhov, 2004). Whilst the Don Lobe formed in the early Middle Pleistocene Donian Stage (MIS 16), the Dniepr Lobe originated in the Saalian (MIS 6).

4. Last Glacial Maximum

The term LGM is widely accepted as referring to the maximum global ice volume during the last glacial cycle.
corresponding with the trough in the marine isotope record centred on ca 18 14C ka BP (Martinson et al., 1987) and the associated global eustatic sea level low also dated to 18 14C ka BP (Yokoyama et al., 2000). It has also been assigned chronozone status (23–19 or 24–18 ka cal BP dependent on the dating applied) by Mix et al. (2001) who consider the event should be centred on the calibrated date at 21 ka cal BP. (i.e. LGM sensu stricto) However, since the last maximum glaciation after MIS 5 occurred in some areas much earlier than in others, the term LGM should be used with care.

During the LGM, the extent of the glaciation of the Southern Hemisphere differed very little from the Pleistocene glacial maximum (Fig. 7). Glaciers in Antarctica still reached to the shelf edge, and on New Zealand, Tasmania and in South America the glacier tongues were only slightly smaller than during earlier events (Andersen et al., 1999; Coronato et al., 2004a, b). In mainland Australia, local mountain glaciation occurred (Barrows et al., 2001, 2002). It seems that the LGM in the Southern Hemisphere began earlier than in the Northern Hemisphere, probably around 27 ka (Suggate and Almond, 2005). The high mountains of East Africa were glaciated (Osmaston, 2004). There is no unequivocal evidence of glaciation in South Africa, although minor glaciers have been postulated by various authors (Borchert and Sänger, 1981; Hall, 1994). However, it has to be kept in mind that South Africa is located relatively close to the equator to the North. Were it in the Northern Hemisphere, Cape Town would be situated at the same latitude as Atlanta, Georgia, USA or, if placed relative to the European ice sheet it would be south of Tunis.

During the LGM, ice in many parts of the Northern Hemisphere reached an extent very similar to the Quaternary glacial maximum (Fig. 8). In North America, the differences are very small. Again, most parts of Canada were ice-covered, including the shelf areas (Dyke, 2004). The same can be said of Greenland (Funder et al., 2004; Weidick et al., 2004).

In Europe, however, the situation was different. New evidence suggests that the North Sea was not fully glaciated during the Weichselian glacial maximum (Sejrup et al., 1994; Carr, 2004). An ice sheet covered the Barents Sea and extended well into the Kara Sea but hardly touched the Russian mainland (Svendsen et al., 1999; Svendsen et al., 2004a, b). The ice sheet was much smaller than during the Quaternary glacial maximum. It seems that the northwards drainage of the Ob and Yenisei rivers was not impeded (Lambeck et al., 2006). In glaciated mountain areas outside of the major ice sheets, such as in Italy and Greece, the maximum Middle Pleistocene glaciations were much bigger than the local last glacial maxima (Giraudi, 2004; Woodward et al., 2004). This is because a change in
Fig. 7. Extent of the LGM on the Southern Hemisphere (based on Ehlers and Gibbard, 2004a–c).

Fig. 8. Extent of the LGM on the Northern Hemisphere (based on Ehlers and Gibbard, 2004a–c).
equilibrium line altitude (ELA) in areas characterised by only mountain glaciation has a much bigger impact on glacier size than in areas where ice covered the lowlands during multiple glaciations.

There were major ice sheets or mountain glacier systems in the Siberian mountains further to the east. Because of the lack of detailed investigations so far in most cases it is not possible to differentiate between the extent of the LGM and earlier glaciations (Glushkova, 2001; Zamoruyev, 2004). Also, the age and extent of the glaciers in Iran and the mountain ranges and high plateaux further to the east, and especially the extent of glaciation on the Tibetan Plateau, are still matters of debate (Owen et al., 2003; Klinge and Lehmkuhl, 2004; Kuhle, 2004; Lehmkuhl and Owen, 2005; Abramowski et al., 2006). In contrast, the small mountain glaciers of Japan are well mapped and dated and, in contrast to the adjoining Asian mainland, the maximum ice advance of the last glaciation occurred in MIS 4 (Sawagaki et al., 2004). The same date for the maximum extent is found in New Zealand (Suggate, 1990; Preusser et al., 2005).

5. Modern glaciations

As a consequence of topography and latitude, modern glaciation of the Southern Hemisphere is largely restricted to Antarctica (Pudsey et al., 2006), the land surface of which is still almost completely ice-covered (Fig. 9). In South America, minor ice caps remain in Patagonia and on Tierra del Fuego, and there are numerous mountain glaciers in the Andes. In New Zealand there are only small mountain glaciers left on the South Island. Africa and Australia, including Tasmania, are ice-free today. Some of the Subantarctic Islands are still extensively glaciated (Hall, 1990). These include the islands of South Georgia, Kerguelen, Heard and Bouvet. Marion Island has a small area (2–3 km²) of permanent snow and ice. The Îles Crozet are ice-free, so are Prince-Edward, Macquarie, Campbell and the Auckland Islands (south of New Zealand).

In the Northern Hemisphere, recent glaciation is very limited compared to that during the Pleistocene (Fig. 10). Of the large LGM ice sheets only the Greenland ice cap has survived (Funder and Hansen, 1996). Even that has shrunk considerably, from the shelf edge to its present ‘inland ice’ position, with unglaciated margins that are locally over 150 km wide in the SW and in the NE. In contrast to Greenland, Iceland has only a few ice caps and mountain glaciers at present (Björnsson, 1979). There are mountain glaciers in the Rocky Mountains, especially in Alaska and Canada, and major ice caps in the northeastern Canadian Arctic, especially on the large islands of the Canadian

Fig. 9. Extent of the recent glaciation in the Southern Hemisphere (based on Ehlers and Gibbard, 2004a–c).
Arctic Archipelago, west of Greenland, on Ellesmere, Devon, Bylot and Baffin Islands (Dowdeswell et al., 1997).

Europe is ice-free, except a few mountain glaciers in Scandinavia and in the European Alps. Small glaciers are found in the Pyrenees (Pallàs et al., in press) and also the Italian Appenines (Giraudi, 2005), although they are subject to rapid retreat. Only 100 years ago, southern Europe was home to many glaciers in other areas as well, such as the Dinaric Alps, Picos de Europa and even the Sierra Nevada (Hughes et al., in press). Mainland Russia and Siberia are ice-free. The only major glaciers and ice caps left are found on the Subarctic Islands of Svalbard (Spitsbergen), Franz-Josef-Land, Novaya Zemlya (especially the North Island) and Severnaya Zemlya.

6. Conclusions

Examination of the frequency of glaciation through the Cenozoic (Fig. 11) indicates that glaciation in the Southern Hemisphere, having been established first, principally in Antarctica (and southern South America), occurred continually from the early Neogene to the present day. By contrast, Northern Hemisphere glaciation, although initially somewhat restricted, grew markedly at the Plio/ Pleistocene boundary, increasing again in frequency in the latest Early Pleistocene and reaching a maximum in the Middle–Late Pleistocene. Whilst this pattern is not unexpected, potentially a result of the relative distribution of land and land-locked seas on the earth’s surface, the striking increase in ice sheets through the Quaternary clearly emphasises that worldwide glaciation is in effect a northern-hemispheric phenomenon. Examination of the evidence accumulated in the INQUA project ‘Extent and Chronology of Quaternary Glaciations’ (Ehlers and Gibbard, 2004a–c: Fig. 1), supported by other published sources, demonstrates the current state of knowledge.

6. Some major uncertainties remain and will have to be resolved by later research. They include:

(1) *LGM definition.* The term LGM refers to the maximum global ice volume during the last glacial cycle at ca 18
Fig. 11. Distribution of major and minor glaciations through Quaternary time. Extracted from Global Correlation Table by Gibbard and van Kolfschoten, (2005); Gibbard et al., (2005). Please note that the base of the Pleistocene according to the latest definition should be at 2.6 Ma.

Table 3
Occurrence of glaciation in the rest of the World through the Cenozoic based on numbers of observations presented in contributions to the INQUA project ‘Extent and Chronology of Quaternary Glaciations’ (Ehlers and Gibbard, 2004c)

<table>
<thead>
<tr>
<th>Stage/Age</th>
<th>MIS (approx)</th>
<th>Antarctica &amp; Southern Ocean</th>
<th>Argentina</th>
<th>Patagonia</th>
<th>Bolivia</th>
<th>Chile</th>
<th>China - Tibet</th>
<th>China - Taiwan</th>
<th>Colombia</th>
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<th>Equador</th>
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14C ka BP or 21 ka cal BP (Martinson et al., 1987; Mix et al., 2001). However, since the last maximum glaciation after MIS 5 occurred in some areas much earlier than in others, this term must be used with care (cf above).

(2) LGM ice sheet extent between Norway and Britain. It is stated that the North Sea was not glaciated during the LGM. As a matter of fact, there is evidence to suggest that the Scandinavian Ice Sheet was merging with an ice sheet over the British Isles during the glacial maximum (Carr, 2004, Carr et al., 2006). However, this did not occur during the LGM (21 ka). As mentioned above, in the North Sea the maximum glaciations seem to have occurred a few thousand years prior to the LGM.

(3) LGM glaciations in Russia. The LGM reconstruction shows an extensive ice cap on the Putorana Plateau during the LGM (and over other mountain areas as well). Judged from the available evidence it seems quite possible that the glaciers on this mountain plateau were much smaller during the LGM and that the ice caps shown on Fig. 8 are significantly older (see discussion in Svendsen et al., 2004a, b).

(4) Pleistocene glacial maximum. It seems likely that the glacier coverage may have been even more extensive over parts of the Arctic, especially over Arctic Canada and adjacent shelves than shown on the map. Recent findings from the shelf areas in the Arctic Ocean seem to suggest that thick marine ice shelves grew into the central Arctic Ocean during some of the large glaciations (Svendsen et al., 2004a, b; Mangerud et al., 2004). If correct, the ice sheets/caps must have been somewhat larger than shown here. Considering the large differences (between the LGM and Pleistocene maximum) in other parts of Eurasia, it also seems strange that some of the glaciers during the Pleistocene maximum in eastern Russia had nearly the same size as during the LGM. Probably there were more extensive glaciers in these areas prior to the LGM (Svendsen, pers. commun.).

(5) Glaciation of Tibet. The extent of Pleistocene glaciation on the Tibetan Plateau is still not well known. There is also evidence to suggest that the glaciers in Tibet were significantly larger during some of the older (Saalian?) glaciations as compared to the LGM.

(6) Differences between North America and Eurasia. It is interesting to note that the glacial maximum in Canada and the USA was not much more extensive than during the LGM. This is a striking difference between Eurasia and the North American continent. The reasons for this difference are still unknown.

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