Earth-Science Reviews 135 (2014) 83–102

Contents lists available at ScienceDirect

Earth-Science Reviews

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

# A global synthesis of the marine and terrestrial evidence for glaciation during the Pliocene Epoch

Stijn De Schepper [a,*], Philip L. Gibbard [b], Ulrich Salzmann [c], Jürgen Ehlers [d]

[a] Department of Earth Science, University of Bergen, PO Box 7803, N-5020 Bergen, Norway
[b] Philip L. Gibbard, Cambridge Quaternary, Department of Geography, University of Cambridge, Cambridge CB2 3EN, England, United Kingdom
[c] Ulrich Salzmann, Department of Geography, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, NE1 8ST England, United Kingdom
[d] Jürgen Ehlers, Hellberg 2a, 21514 Witzeeze, Germany

ARTICLE INFO

*Article history:*
Received 11 January 2014
Accepted 8 April 2014
Available online 18 April 2014

*Keywords:*
Pliocene
Northern Hemisphere
Southern Hemisphere
Ice sheet
Climate
Global compilation

ABSTRACT

The Pliocene climate is globally warm and characterised by high atmospheric carbon dioxide concentrations, yet the terrestrial and marine scientific communities have gathered considerable evidence for substantial glaciation events in both the Northern and Southern Hemisphere prior to the Quaternary. Evidence on land is fragmentary, but marine records of glaciation present a more complete history of Pliocene glaciation. Here we present a global compilation of the terrestrial and marine glacial evidence for the Pliocene and demonstrate four glaciation events that can be identified in the Southern and/or Northern Hemisphere prior to the latest Pliocene intensification of Northern Hemisphere glaciation. There are two globally recognisable glacial events in the early Pliocene (*c.* 4.9–4.8 Ma and *c.* 4.0 Ma), one event around the early/late Pliocene transition (*c.* 3.6 Ma), and one event during Marine Isotope Stage M2 (*c.* 3.3 Ma). Long-term climate cooling, decreasing carbon dioxide concentrations in the atmosphere and high climate sensitivity in the Pliocene probably facilitated each glaciation event, however the mechanisms behind the early Pliocene glacial events are unclear. The global glaciation at *c.* 3.3 Ma may be caused by changes in ocean gateways, whereas the decline in carbon dioxide concentrations is important for the latest Pliocene intensification of Northern Hemisphere glaciation.



**Contents**



* Corresponding author at: Current address: Uni Research Climate, Allégaten 55, N-5007 Bergen and Bjerknes Centre for Climate Research, Bergen, Norway. Tel.: +47 55 58 3826.
*E-mail addresses:* stijn.deschepper@geo.uib.no (S. De Schepper), plg1@cam.ac.uk (P.L. Gibbard), ulrich.salzmann@northumbria.ac.uk (U. Salzmann), jehlersqua@aol.com (J. Ehlers).

http://dx.doi.org/10.1016/j.earscirev.2014.04.003
0012-8252/

## 1. Introduction

The Pliocene Series or Epoch (5.33–2.58 Ma) is divided into two stages, the Zanclean (or early Pliocene Subepoch) with a base at 5.33 Ma (van Couvering et al., 2004), and the Piacenzian (or late Pliocene Subepoch), which begins at 3.60 Ma (Castradori et al., 1998). Since 2009, the end of the Pliocene has been defined by the base of the Pleistocene Series (Quaternary System) and the Gelasian Stage, which is dated at 2.58 Ma. This replaced the previous base of the Pleistocene, which was placed at 1.81 Ma, and caused the transfer of the Gelasian Stage (2.58–1.81 Ma) from the Pliocene into the early Pleistocene Subepoch (Gibbard et al., 2010).

The Pliocene Epoch spans a critical period in Earth's history during which global climate underwent a profound transition from relatively warm climates to the substantially cooler climates of the Pleistocene. The early Pliocene is considered to have had a globally warm climate (Ravelo et al., 2007; Brierley et al., 2009; Larivière et al., 2012), but is considerably less investigated than the mid-Piacenzian Warm Period (previously mid-Pliocene Warm Period, 3.29–2.97 Ma), which has been the focus of the Pliocene Research, Interpretation and Synoptic Mapping (PRISM) initiative (e.g. Dowsett et al., 2010) and the Pliocene Model Intercomparison Project (PlioMIP) (e.g. Haywood et al., 2013). Suggestions that the mid-Piacenzian Warm Period could serve as a true direct analogue for a globally warmed future have been questioned (Sarnthein et al., 2009; Haywood et al., 2011), but it nevertheless provides an ideal time interval to understand the climatic processes of a warm, high carbon dioxide world. In particular, the similarity of the late Pliocene palaeogeography to that of today, the occurrence of fossil assemblages similar to modern assemblages, and the well-preserved terrestrial and marine geological records, mean that, although problems remain, a relatively good insight into the ocean conditions and biosphere during a warm global late Pliocene climate can be assembled (Dowsett et al., 2012; Salzmann et al., 2013). Even within this globally warm Pliocene world, short-lived, episodic glaciation events and accompanying sea-level fluctuations have been recorded in benthic isotope records as well as sequence boundaries before the end-Pliocene climate deterioration. Such glacial events and sea-level fluctuations are rare in the Zanclean, but become progressively more common since 3.6 Ma (Lisiecki and Raymo, 2005; Miller et al., 2005, 2012). The global climate deteriorated severely only in the latest Pliocene, which led to the onset of widespread Northern Hemisphere glaciation at *c.* 2.75 Ma.

In this review, we compile both the terrestrial and marine evidence of glaciation during the entire Pliocene Epoch and present a global comparison of Arctic and Antarctic Pliocene (episodic) glaciation. Firstly, we aim to bridge the gap between the terrestrial and marine communities investigating Pliocene climate. Although there is ample evidence of episodic Pliocene glaciation in the marine and terrestrial realm, they have never been compared directly to identify synchrony or diachrony between the terrestrial and marine records. Secondly, by comparing all Pliocene records of glaciation on a global scale, we aim to identify the timing of Arctic and Antarctic ice sheet expansion. We also provide potential links between the glaciation events to large-scale, long- and short-term changes in oceanography and global climate. Finally, by comparing the Pliocene record with that from the Pleistocene, we attempt to reconstruct the World immediately before the impact of major Northern Hemisphere glaciation and present an assessment of how the Northern Hemisphere glaciations were initiated.

## 2. Pliocene global climate—characteristics

The chronology of the Pliocene Epoch has been finely tuned by orbital tuning or astrostratigraphy based upon marine oxygen isotope sequences (Shackleton et al., 1990; Hilgen, 1991; Tiedemann et al., 1994; Shackleton and Crowhurst, 1995; Shackleton et al., 1995). These approaches were further improved in the most recent Neogene timescales, where could be relied on more accurate numerical astronomical solutions, high-resolution studies of uplifted land-sections and more complete ocean drill records (Lourens et al., 2005; Hilgen et al., 2012). A highly detailed global benthic foraminifer oxygen isotope stack, of comparable resolution to those for the Pleistocene, has also been presented for the Pliocene demonstrating that the climate system during the period was controlled mainly by the *c.* 40 ka obliquity periodicity (Lisiecki and Raymo, 2005). Because the global stack, supported by a palaeomagnetic reversal chronology, provides a global standard for detailed chronostratigraphical division, key events in the Pliocene global climate history can be identified.

The evidence for climate oscillations through the Pliocene is seen in geological sequences throughout the world. They include ice-volume records from oxygen isotope successions, the occurrence of glacio-marine sediments or IRD (=-ice rafted debris/detritus), the variation of a range of geochemical or palynological proxies in marine and terrestrial sediment sequences (e.g. Willis et al., 1999; Knies et al., 2009;