Mid-Quaternary in North America

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Contrary to the four-fold stratigraphic framework developed for Pleistocene terrestrial glacial sediments in central North America (Wisconsinan, Illinoian, Kansan, and Nebraskan; Flint, 1957), the record of global ice volume contained in the oxygen isotope (δ^{18}O) record of deep-sea sediments provides an elaborate and more complete history of glaciations (**Fig. 1**) (Hays *et al.*, 1976; Imbrie *et al.*, 1984; Ruddiman *et al.*, 1989; Mix *et al.*, 1995). The beginning of Middle Pleistocene time has been set at the last major magnetic reversal, 780 thousand years ago (ka), the transition from Matuyama Reversed Chron to the Brunhes Normal Chron (Shackleton *et al.*, 1990; Spell and McDougal, 1992; Renne *et al.*, 1994). Middle and Late Pleistocene glaciations therefore are entirely within the Brunhes Normal Chron. Soon after the Brunhes–Matuyama reversal, the global ice volume increased significantly beginning with Marine Isotope Stage (MIS) 16, based on the magnitude of the δ^{18}O isotopic excursion, which is related to the volume of water transferred from oceans to land and stored as ice. It was also at this time that the period between glacial maxima became longer, increasing from approximately 41,000 years during the Early Pleistocene to 100,000 years during the Middle and Late Pleistocene (Pisas and Moore, 1981; Ruddiman *et al.*, 1989; Imbrie *et al.*, 1993).

The volume of continental ice inferred for peak Middle Pleistocene glaciations dictates that the global extent of glaciation during these times was similar to the extent in the most recent glacial cycle. Limited stratigraphic preservation and exposure on land, however, have affected our ability to confirm the character and extent of these interpreted glacial events by mapping alone, except in places where the records of older glaciations were more extensive than younger events. Statistical simulations that follow the simple rule of 'obliterative overlap'—that is, that glaciations more extensive than prior glaciations obliterate the record of less extensive, older glaciations—determine the probability of moraine survival. Only 3 out of 10 random-size glaciations would be preserved at the surface if these very simplified rules are followed (Gibbons *et al.*, 1984). A natural corollary is that the oldest glaciation preserved is also the most areally extensive record at the surface and that progressively younger glaciations are progressively less extensive. If we apply this statistical argument to the geological record, we would expect that the mappable remnants of glaciations would represent the larger isotopic excursions of the Middle Pleistocene—that is, MIS 16, 12, and 6. The basis for the original fourfold chronology in the midcontinent may therefore simply be a result of the statistical likelihood of moraine, till, and erratic survival at the surface.

In regions such as the midcontinent of North America, where older glaciations extend beyond the Late Wisconsinan ice margin, they have been described, at least qualitatively, for more than a century. Of these, the Illinoian (MIS 6), the only pre-Wisconsinan glaciation that retains its original name, is the best documented (Williman and Frye, 1970; Hallberg, 1980a; Aber, 1999). The MIS 6 Lake Michigan lobe reached farther south than any other glaciation in southern Illinois (Williman and Frye, 1970), but farther west along the ice margin, the Illinoian ice was much less extensive than older glaciations. On the west side of the Driftless Area in Wisconsin, there are extensive areas of pre-Illinoian till at the surface; on the east side (e.g., in the Baraboo Hills of Wisconsin), the Late Wisconsinan MIS 2 ice reached as far as any older glaciation (Farrand *et al.*, 1984). In the Rockies, there is variability in ice extent, with pre-MIS 6 (pre-Bull Lake) and/or MIS 6 (Bull Lake) till extending well beyond the MIS 2 (Pinedale) moraines in some areas (e.g., in the southwestern Wind River Range) but not detectable at all in other places (Dahms, 2004; Hall, 1999).

While acknowledging the obvious limitation of the fragmentary nature of the terrestrial record of glaciations, correlation and dating of continental glacial records of possible Middle Pleistocene age remains a priority to confirm, to the extent possible, the timing, extent, and character of the glacial cycles. Recent advances toward this goal have been due, in part, to progress in magnetostratigraphy and cosmogenic exposure and burial dating methods.

Correlation of Glaciated Landscapes

Where Middle Pleistocene deposits outcrop, these landscapes have been separated from younger landscapes on the basis of soil development, depth of leaching, and degradation of glacial landforms (e.g., Cincinnati, Ohio) (Szabo and Chanda, 2004). Middle Pleistocene landscapes may also be eroded by wind and thereby display a faceted stone 'lag' or may be buried by loess or sand, especially where located near the Late Wisconsinan ice margin. These weathering and erosion horizons, where preserved, make the task of recognizing these older landscapes easier.

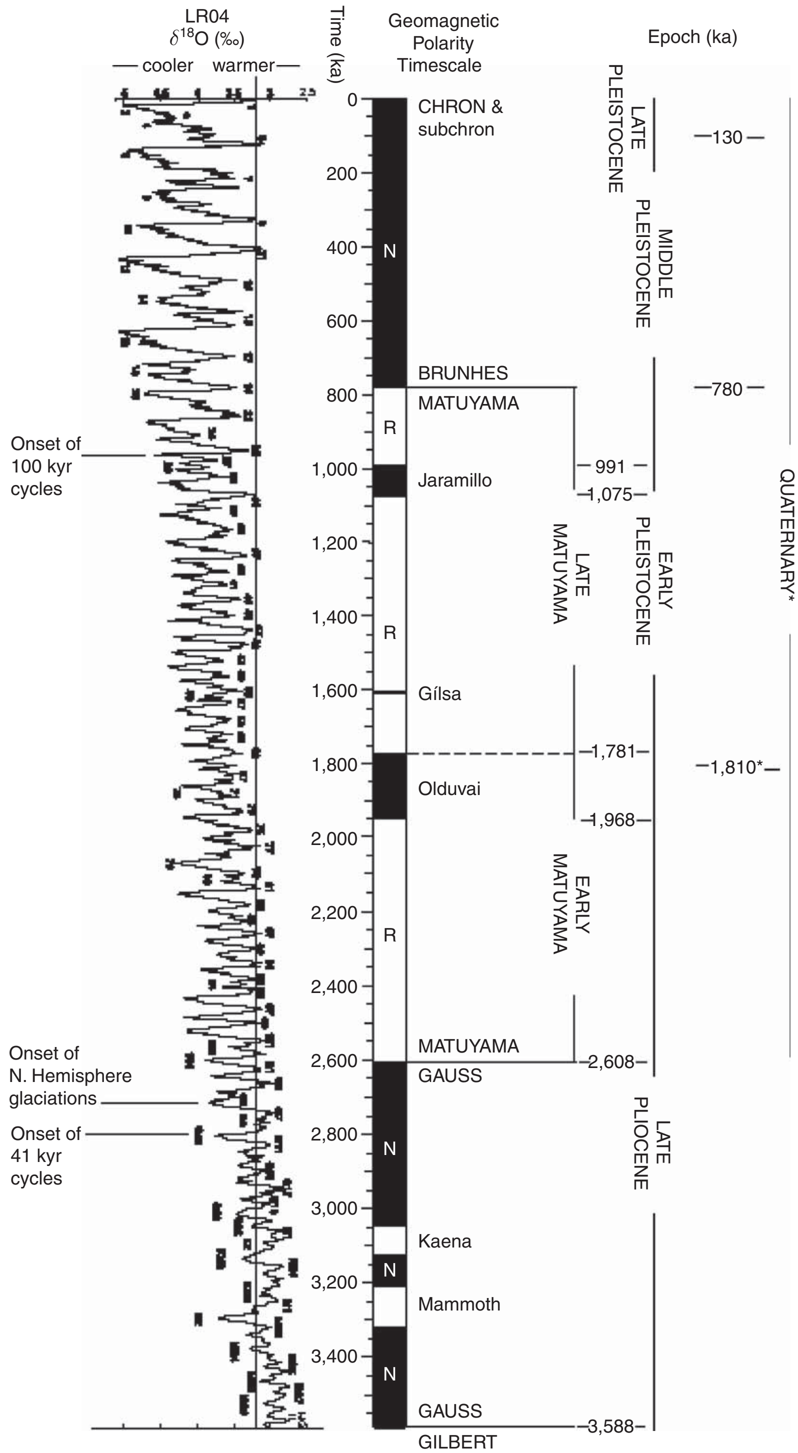

Figure 1 Geomagnetic polarity timescale for LR04 benthic and $\delta^{18}O$ paleotemperature profile. Black (white) areas represent normal (reversed) polarity. Marine Isotope Stages (MIS) are labeled on LR04 (even numbers represent glacials and odd numbers interglacials). MIS scheme follows Ruddiman *et al.* (1989) and Raymo *et al.* (1989) from the present to MIS 104 and Shackleton *et al.* (1995) in the Gauss Chron. Arrow marks Holocene mean $\delta^{18}O$. *Gradstein *et al.* (2004) and Pillans and Naish (2004). From Lisiecki LE and Raymo ME (2005) A Pliocene–Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. *Paleoceanography*. Reproduced with permission.

However, these landscapes may have also been eroded by hillslope processes, especially those that allowed the movement of the active layer on low slopes when permafrost was present. This makes the task of recognizing them more difficult because of the removal of well-developed soils, as on the 'Iowan Erosion Surface' (Ruhe, 1969).

In mountain glacier systems, boulder weathering, pitting, grussification, and degradation of moraine form are commonly used as relative dating methods and have been supported by $^{36}Cl/^{10}Be$ exposure ages, for example, for the Bull Lake moraines in the Rockies, dated as being >130 to 95 ka (Dahms, 2004). In California, the Mono Basin glaciation was originally assigned to the Middle Pleistocene based on these relative dating methods and has been confirmed as being MIS 6 based on ^{36}Cl exposure dates of 80–60 ka (Gillespie and Zehfuss, 2004). Alaska has a particularly well-preserved Middle Pleistocene record owing to the limited extent of Wisconsinan ice. Glacial units were qualitatively dated by relative weathering, paleosol formation, and tectonic evolution and further bracketed in time by magnetic chronology of underlying sediment and overlying basalts and amino-acid racemization dates on underlying shells (Hamilton, 2001; Manley *et al*., 2001). There are exceptions, however, where surfaces that were assumed to belong to 'early' glaciations because of their relative weathering and discontinuous preservation are actually younger than expected. One such landscape, represented by scattered granitoid erratics southwest of the Missouri River in North Dakota, was tentatively revised as being early Late Wisconsinan in age, between 27.8 and 28.8 ka, based on ^{36}Cl exposure dating (Manz, 2005). Similarly, on Baffin Island, young erratics indicated that heavily weathered upland surfaces had been overrun by latest Pleistocene ice that was cold-based (Marsella *et al*., 2000; Bierman *et al*., 1999).

In the Midwest, particularly in Iowa and Missouri, the pre-Illinoian tills have good continuity in the subsurface and are distinct enough lithologically to correlate over broad areas (Rovey and Kean, 1996; Hallberg, 1980a,b). However, this is not the case everywhere with pre-Illinoian units at the surface. If the till sheets are discontinuous, it can be difficult to extend the exposed units into the subsurface, especially if tills of different age are lithologically similar and lack identifiable horizons. For example, pre-Illinoian deposits exposed in a limited area at the surface in New Jersey have not been correlated to subsurface units anywhere in New England (Stone *et al*., 2002). In some places, it is even difficult to distinguish Pleistocene units from remnants of pre-Pleistocene units in the subsurface (e.g., Nova Scotia) (Stea, 2004).

In some areas, there are no older ice margins on land that extend beyond the Late Wisconsinan margin (e.g., Maine; Borns *et al*., 2004) or they extend for only a short distance (e.g., Pennsylvania (Braun, 2004) and Montana (Fullerton *et al*., 2004)). Additionally, in many places outside the midwestern United States, subglacial erosion during the last glaciation has removed all but a few patches of glacial sediment attributed to glaciations prior to MIS 2 (e.g., New York (Cadwell and Muller, 2004) and Nova Scotia (Stea, 2004)). This appears to be more commonly reported in the east, where crystalline substrates produced sandy tills that are more easily reworked during subsequent glaciations.

In areas where thick glacial sequences are preserved (e.g., South Dakota, Minnesota, Michigan, Iowa, and Missouri), the till is derived from fine-grained sedimentary rocks (Soller, 2004) and therefore more cohesive and resistant to erosion. However, the lack of subsurface information away from natural exposures even in the areas where thick sequences are preserved makes distinguishing the remnants of older glaciations very difficult. Most geological surveys have simply lumped similar glacial units or 'counted down from the top,' attributing units in the same stratigraphic position to the same glaciation. For example, in New Hampshire, units older than Wisconsinan glaciation in the subsurface have traditionally been treated as a single older unit of Illinoian age (Koteff and Pessl, 1985). In Minnesota, tills in the subsurface that are presumed to be pre-Late Wisconsinan have only recently been distinguished and correlated regionally, mainly on the basis of details in texture and lithology rather than on dated horizons (Meyer, 1997, 2005). In exposures or cores, the distinctions are problematic if soil profiles are truncated or if the time between glaciations did not allow recognizable weathering profiles to develop.

Dating Tools

Dating tools that have been used to confirm or refute suggested Middle Pleistocene ages include amino-acid racemization, optically stimulated luminescence of sediment formerly exposed to light (e.g., loess); uranium–thorium dating of shells where they are incorporated or of calcrete soils that cap glacial units; radionuclide dating of volcanic ashes or lava where they intercalate glacial deposits; magnetostratigraphy and cosmogenic isotope dating. The latter two techniques rely less on fortunate occurrences of datable material and are being more widely applied.

Magnetostratigraphy can place normally magnetized sediment of the Middle Pleistocene within the Brunhes Normal Chron (Barendregt and Duk-Rodkin, 2004) and is especially useful if transition from the Matuyama Reversed Chron is captured in a sequence because it marks an unique event in time. In Pennsylvania, large proglacial lakes record the transition from Matuyama to Brunhes (Braun, 2004). In Missouri, the Early Pleistocene, reversed Moberly Formation is distinguished from three overlying normally magnetized Middle Pleistocene units of the McCredie Formation (Rovey and Keen, 1996; Colgan, 1999). The same sequence is present in Iowa; the reversed Alburnett Formation is overlain by three normal tills of the Wolf Creek Formation (Baker and Stewart, 1984; Rovey *et al.*, 2002). Findings from northeastern Kansas and northwestern Missouri (Aber, 1991) restricted the 'classical Kansas' till (now Independence Formation) to the age range ~600 to 700 ka based on the normal polarity of the till and a dated volcanic ash. The Independence Formation is therefore related to MIS 16 (or possibly 18), the most extensive glaciation with a record preserved on land in the central United States. Also for the midcontinent, Roy *et al.* (2004a,b) presented magnetostratigraphical data together with dated units that are constrained by three volcanic ashes (0.6, 1.2, and 2.0 Ma) derived from eruptions of the Yellowstone Caldera present in the sections (Boellstorff, 1978; Izett, 1981). They presented a summary map of the limit of Early and Middle Pleistocene ice in eastern North America, in which a large fraction of the glacial deposits are now assigned to the Middle Pleistocene (**Fig. 2**) (Roy *et al.*, 2004a,b). The southernmost border of the eastern portion of the ice sheet extends from northeastern Kansas through Missouri, southern Illinois, the southern tip of Indiana, the northern part of Kentucky, includes all of Ohio, crosses the middle of West Virginia, and includes all of New York and the northern part of New Jersey.

A great deal of paleomagnetic work has been conducted in northwestern North America. An isolated and uncorrelated section in southwestern Saskatchewan includes till that is interpreted as being Middle Pleistocene in age based on magnetic polarity. This interpretation is strengthened by the age of an underlying tephra and an underlying assemblage of mammal fossils (Barendregt *et al.*, 1991). In Montana and Alberta, paleomagnetism was used to decide between two age estimates for the Kennedy Drift, composed of tills and paleosols. The inferred rates of soil development placed the paleosols within the Middle Pleistocene (younger than 800 ka) or in the Pliocene (>2,600 ka). Paleomagnetism demonstrated the presence of six glacial and six interglacial episodes that span that time, beginning in the Gauss Normal Chron and continuing through the Matuyama Reversed Chron and ending during the Brunhes Normal Chron (Cioppa *et al.*, 1995). In the Pacific Northwest, a Middle Pleistocene flood deposit is recognized by its normal polarity and capping calcrete soil with a 200 to >400 ka Th/U date, whereas earlier flood deposits in the sequence had a reversed polarity (Bjornstad *et al.*, 2001). On Banks Island in the Canadian Arctic Archipelago, the strata exposed in the Nelson River Bluffs and nearby outcrops span the Pleistocene. They record the Brunhes–Matuyama boundary within an interglacial deposit and preserve the deposits of an unnamed Middle Pleistocene

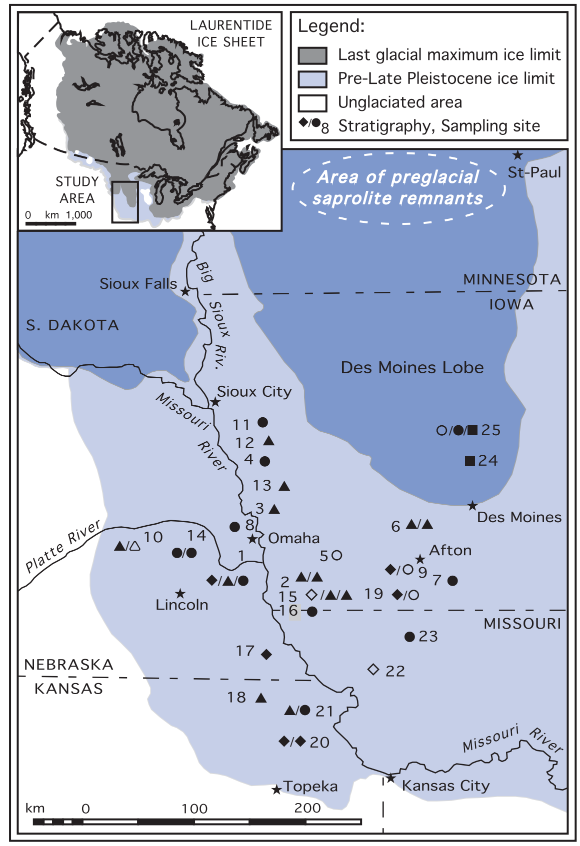

Figure 2 Location of the stratigraphic sections investigated in relation to the maximum ice limit of late Cenozoic glaciations. Symbols correspond to the till stratigraphy exposed at each site: solid diamonds, Late Pliocene R2 tills (~2.7–1.3 Myr); solid circles, Middle Pleistocene N tills (~0.8–0.25 Myr); solid squares, late Pleistocene LGM tills (~17 kyr). Age constraints are provided by three volcanic ashes and the Brunhes–Matuyama magnetic reversal. Current chronological methods do not allow the dating of individual ice advances, and each till group represents multiple ice advances. Open symbols correspond to till units with uncertain magnetic polarity but of lithological composition similar to their corresponding till group category. Volcanic ash localities: sites 4, 8, 9, and 10. From Roy M, Clark PU, Raisbeck GM, and Yiou F (2004b) Geochemical constraints on the regolith hypothesis for the Middle Pleistocene transition. *Earth and Planetary Science Letters* 227: 281–296. Reproduced with permission.

glaciation (<780 ka), unnamed interglacials (one or more) between 780 and 130 ka, and the previously recognized Middle Pleistocene (Illinoian) Thomsen glaciation (>130 ka). The latter is constrained by the inferred Sangamonian age of the capping paleosol (Barendregt *et al.*, 1998). A long sequence in the Mackenzie Mountains in the Northwest Territories begins in the late Tertiary (Gauss-normal); has two reversed tills (Matuyama) and, as its upper units, three normal tills (Brunhes); and is further constrained by means of ^{36}Cl dating of exposed boulders and multiple paleosols (Duk-Rodkin *et al.*, 1996; Duk-Rodkin *et al.*, 2004).

The collective results of the magnetostratigraphic work in the west have been interpreted to support a reconstruction of paleo-ice centers and the number of Middle Pleistocene glaciations related to these proposed centers: Cordilleran Ice Sheet, three glaciations; the Horton Ice Cap/Keewatin Ice Sheet, three glaciations. These ice centers are proposed in areas near the Late Pleistocene, Laurentide ice centers but were apparently less extensive (**Fig. 3**) (Barendregt and Irving, 1998; Barendregt and Duk-Rodkin, 2004).

Figure 3 Proposed distribution and timing of Brunhes/Middle Pleistocene ice sheets in northwest North America. Montane glaciations for northern and northwestern Alaska are not included. From Barendregt RW and Duk-Rodkin A (2004) Chronology and extent of Late Cenozoic ice sheets in North America: A magnetostratigraphic assessment. In Ehlers J and Gibbard PL (eds.) *Quaternary Glaciations—Extent and Chronology, Part II: North America*, pp. 1–7. Amsterdam: Elsevier.

Other refinements in the dating of Middle Pleistocene glaciations have been the result of the application of cosmogenic exposure dating. Exposed, striated quartzite lying beyond the Late Wisconsinan glacial limit in southwestern Minnesota revealed a complex burial history that indicated the striations were between 640 and 740 ka (MIS 16) (Bierman *et al.*, 1999). Stratigraphic interpretations do not have this region affected by glaciation after this time. In some places, outcrops that have been glaciated during Wisconsinan time preserve an inherited comsogenic nuclide abundance that is more a signature of limited Late Wisconsinan erosion, owing perhaps to cold-based glaciation, than the true exposure age of the rock (Baffin Island (Bierman *et al.*, 1999), Wisconsin (Colgan *et al.*, 2002), Puget Lowland, Washington (Briner and Swanson, 1998), and Arctic Canada (Briner *et al.*, 2003)).

The use of the disequilibrium of two radioactive, cosmogenic nuclides that have decayed since the burial of previously exposed sediment can constrain the age of that surface (Balco *et al.*, 2005). In southwestern Minnesota and eastern South Dakota, the minimum limiting age for tills previously known only as pre-Wisconsinan was determined to be >500 ka (Balco *et al.*, 2005b). A core in eastern Nebraska revealed that the Loveland Loess (135–150 ka) (Foreman and Pierson, 2002) overlay an unnamed loess with a best fit burial age of MIS 14–16. This loess overlaid the youngest till in eastern Nebraska (Balco *et al.*, 2005a,b), most likely of MIS 16. In general, paleosols with long exposure periods produced the best burial ages, and this technique is therefore more effective in the southern tier of states, where the time between glaciations was longer (Balco *et al.*, 2005c).

See also: **Glaciations**: Overview; Late Quaternary in North America.

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Mid-Quaternary in the Southern Hemisphere

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Introduction

Geological and geomorphological surveys demonstrate that the ice-covered land in the Southern Hemisphere would have been more extensive than at present and also than that of the Last Glacial Maximum (LGM). Several glaciations occurred during Middle Pleistocene times, through the period (MIS) 6 to 22–26. Alternatively, they began from the Brunhes-Matuyama Chron boundary and/or the top of the Jaramillo subchron, in the global paleomagnetic scale, and the beginning of the Last Interglacial stage (ca. MIS 5e).

Current geomorphological and geological investigations have been focused on the search for appropriate datable materials contained within the glacially-related deposits, in order to link these terrestrial units with the global oceanic sedimentary record. Different dating techniques have been being used for this purpose. Cosmogenic isotope exposure dating techniques provide absolute ages from glacial boulders within morainic belts. However, K-Ar and ^{40}Ar-^{39}Ar radiometric dating has yielded absolute ages of lavas interbedded with till, which provide constraining limiting ages for glacier expansion. Fission-track dating on tephras, magnetic polarity of lava flows and sedimentary sequences, and the presence of weathering profiles and soils, are other methods used to obtain relative dates for the estimation of the age of these ancient glacial events. Information available for these older glaciations is increasing thanks to the application of these dating techniques, which extend far beyond the limits of the radiocarbon method,. The latter is useful only to establish the chronology of the LGM and part of the preceding interstadial (Middle Wisconsin and Weichselian Substage; MIS 3).

The orbital-scale forces that reduced solar energy at the Earth's surface in the Northern Hemisphere during the Middle Pleistocene also affected the southern half of the globe. One of the current hypotheses currently being evaluated is whether the eccentricity of the Earth's orbit was the dominant factor driving global climatic change in both hemispheres. Other climate-forcing elements are tectonics, ocean circulation, and sea-level changes, although local and regional conditions may also have played significant roles in influencing the record of global climate. South of latitude 40 °S, oceanic conditions strongly influenced Southern Hemisphere climate, increasing moisture content to the westerlies and to the polar air-mass flow. The interaction between the ocean and the atmosphere at low rates of insolation, resulting from astronomic forces, must be considered as one of the singularities of the Southern Hemisphere in comparison to the northern, more continental hemisphere. This could be one of the main reasons why such powerful glacial events developed during the Middle Pleistocene in areas such as South America, New Zealand, Tasmania and also, on the highest tropical mountains of Africa, where variations in the paleo-monsoonal activity must be also considered.

The evidence for old glaciations summarized here demonstrates that the climates were cold and moist enough to sustain mountain ice sheets of various sizes in the Southern Hemisphere, beyond Antarctica, although the synchronicity with the larger Northern