On The Nature of Ice Ages

By Lorraine A. Manz

Introduction

When the Pleistocene Epoch, or “Great Ice Age” ended about 11,700 years ago, marking the final demise of the great North American and Eurasian ice sheets, we might be forgiven for thinking that it also brought closure to more than 2.5 million years of unrelenting cold. But the geologic record tells a different story. From air bubbles trapped deep within the Greenland and Antarctic ice sheets; the remains of plankton in ocean sediment cores; and organic material along with ancient soil horizons and other terrestrial paleoclimatic indicators, geologists have learned that glaciation during the Pleistocene was a series of cyclic events: a regular fluctuation between long, cold (glacial) periods of ice-sheet expansion and shorter, warm interglacials when they retreated or possibly disappeared altogether. These cycles have repeated about 50 times throughout the Pleistocene at fairly regular intervals (fig. 1). At least 20 of the cold stages were severe enough to produce widespread glaciation (Ehlers and others, 2018).

Causes of ice ages

In this discussion, an ice age refers to a period of prolonged cold lasting millions to tens of millions of years that is characterized by persistent polar ice and the recurrent advance and retreat of continental ice sheets. As such, ice ages are comparatively rare in Earth’s history, with evidence in the global rock record of only five major events in the last 2.5 billion years or so, the Pleistocene being the most recent.

Compared to the Pleistocene little is known about these ancient glaciations beyond the evidence in the rock record that they occurred. Most of the theories that have been proposed to explain the causes of ice ages are based largely on what happened during the forty or so million years preceding the Pleistocene and the nature of the Pleistocene itself.

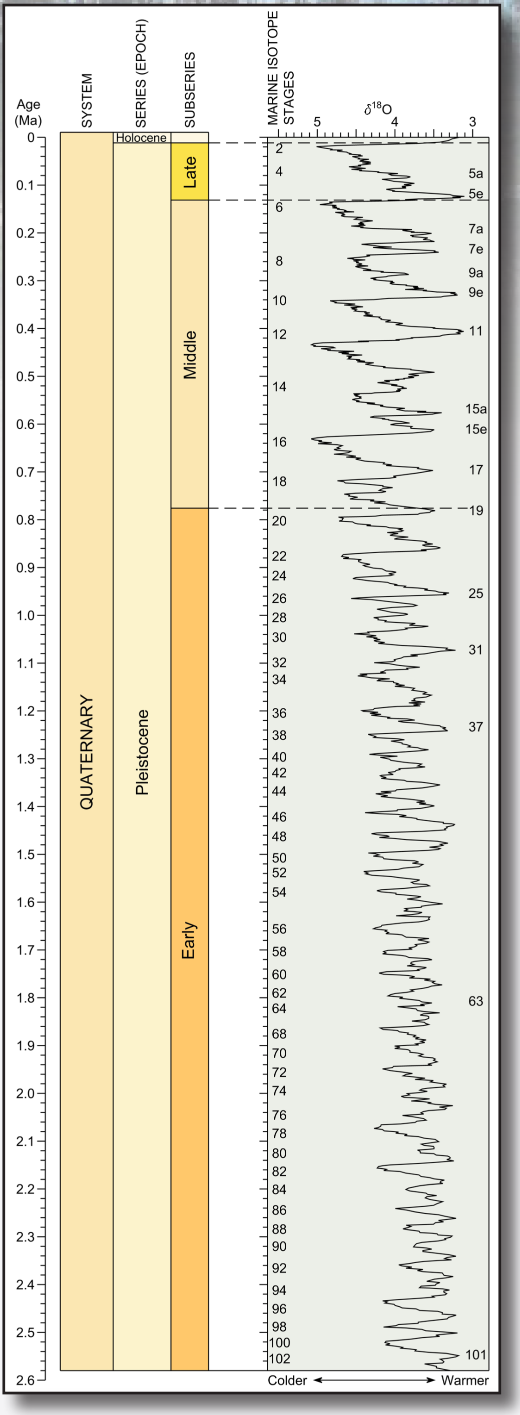

Figure 1. Quaternary glacial-interglacial cycles. The graph shows $\delta^{18}O$, a measure (in parts per thousand) of the ratio between two naturally occurring isotopes of oxygen, ^{18}O and ^{16}O, in the shells of microscopic marine organisms obtained from deep-sea sediment cores, plotted against time from the beginning of the Pleistocene, 2.58 million years ago, to the present. The $\delta^{18}O$ values serve as a proxy for ocean temperature, which is a function of climate. Quaternary time is divided into about 100 numbered “Marine Isotope Stages” (MIS) based on $\delta^{18}O$ data. Even numbers correspond to periods of cooling (high $\delta^{18}O$), odd numbers to periods of warmth (low $\delta^{18}O$). Not all of the early Pleistocene marine isotope stages were cold enough to support widespread glaciation. Modified from Cohen and Gibbard (2019).

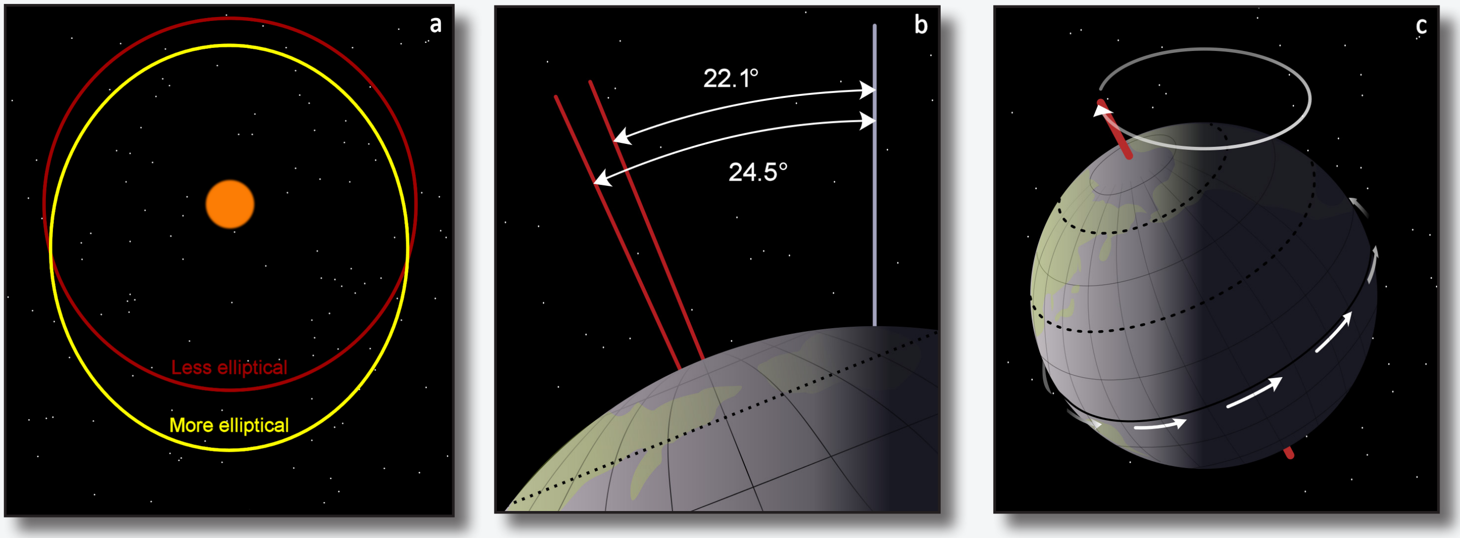

Figure 2. Milankovitch cycles are long-term variations in Earth's orbit around the sun. They play a major role in the control of global climate because they affect the amount and distribution of insolation (solar radiation) that reaches the planet's surface. The parameters concerned are eccentricity, obliquity, and precession. Eccentricity (a) refers to the shape of Earth's orbit around the sun, which changes from near-circular to elliptical with a periodicity of about 100,000 years. Because the eccentricity variations are small, their effects on Earth's climate are comparatively minor. Obliquity (b) is the tilt of Earth's rotational axis relative to its orbital plane. The angle varies between 22.1° and 24.5° over an approximately 41,000-year cycle and has a strong influence on the extremity of the seasons. The effects of obliquity are more intense at high latitudes, especially in the northern hemisphere where the widespread placement of large continental land masses in the polar and subpolar regions favor the growth of ice sheets during periods of low insolation. Earth has two precession cycles: axial (c) and orbital or apsidal (not shown). Axial precession is a gyroscopic wobble in Earth's rotational axis that completes a full circle roughly every 26,000 years. Earth's orbital path also precesses but over a much longer time span of about 112,000 years. The combined effects of these two precession cycles is a cycle with an average periodicity of approximately 23,000 years. Precession affects the relative extremities of the seasons in the northern and southern hemispheres, as well as their timing. Milankovitch cycles are clearly reflected in the Pleistocene climate record, but how they interact, and which are the dominant forces that determine the beginning and end of glaciations is a subject of vigorous scientific debate. Illustrations courtesy of NASA, CC BY 3.0.

Ice ages cannot be attributed to any single cause, nor is there any certainty as to what those causes might be. Nevertheless, the general consensus is that ice ages are a product of the complex interplay between a number of climatic controls, some of whose effects were (or are) more profound and long lasting than others. Arguably the most important of these is plate tectonics. The configuration of Earth's continents has a profound effect on ocean and atmospheric circulation, and because these systems are the primary distributors of heat and moisture around the globe, influences climate as well. A configuration that disrupts the flow of heat to the poles favors glaciation and, if conditions are cold and persistent enough, may signal the beginning of an ice age.

Throughout geologic time the forces of plate tectonics have caused the world's great land masses to range across the surface of the globe, continually changing their positions relative to each other and to the poles. For much of the geologic past, one or both of the polar regions have been relatively free of large landmasses. Such an arrangement allows the oceans to circulate around the poles, and for ocean currents to carry warm, equatorial water to high latitudes, thereby distributing heat more uniformly across the globe. Today, the continent of Antarctica lies over the South Pole, and large regions of Europe, North America and Asia occupy high Arctic latitudes. These landmasses form very effective barriers against the delivery of heat by the oceans to the poles, and so they have grown bitterly cold. Diversion of major ocean currents in this way may also have caused global weather patterns to change, increasing precipitation in some areas, and reducing it in others.

Most geologists agree that Earth's most recent ice age began about 35 million years ago when the Antarctic continent broke away from South America and drifted towards the South Pole. The widening of the Southern Ocean and opening of the Drake Passage between Tierra del Fuego and the Antarctic Peninsula led to a profound shift in oceanic circulation that left the continent surrounded by cold circumpolar currents and isolated from the warmer waters to the north. Glaciers may have begun to form in Antarctica as early as 38 million years ago, followed by alpine glaciation at high elevations in Alaska, and in parts of Europe and South America. The widespread glaciation in the northern hemisphere that marked the beginning of the Pleistocene may have been triggered by the formation of the Panama Isthmus, which closed the seaway connecting the tropical waters of the Atlantic and Pacific oceans, necessitating a substantial alteration of ocean circulation patterns. Deprived of heat from the north Atlantic as a result, and freshened by increased precipitation across northern Eurasia, the surface waters of the Arctic Ocean began to freeze, and so another ice age began.

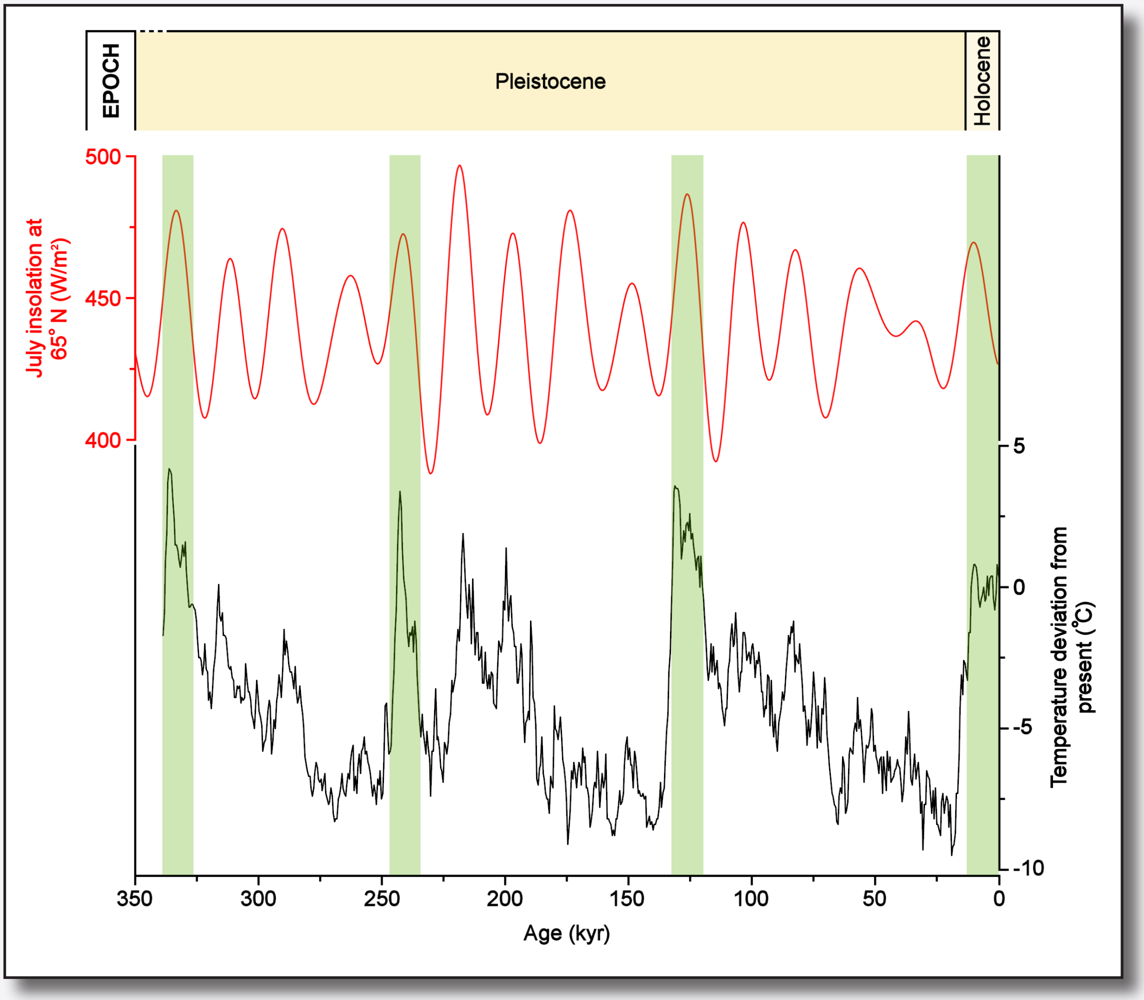

Figure 3. July insolation at 65° N (Berger and Loutre, 1991) and glacial-interglacial cycles for the last 350,000 years based on data from the Dome Fuji ice core, Antarctica (Kawamura and others, 2007). Within each approximately 100,000-year cycle, relatively brief interglacials (10,000-30,000 years), denoted by green bands, are followed by 70,000-90,000 years of slow cooling before ending abruptly with the onset of the next interglacial. Note that the Holocene is an interglacial, meaning that geologically, we are still living in an ice age.

Long-term global climate change is also associated with tectonic uplift and mountain building (Nance and Murphy, 2013), and the last 40-odd million years have been particularly active in this respect. Regions of high elevation affect atmospheric circulation and so change rainfall and temperature patterns. Moreover, the steep terrains, high rates of precipitation, and large areas of exposed rock characteristic of mountain environments accelerate the processes of weathering and erosion, which impact the release and sequestration of atmospheric CO_2. Carbon dioxide is present in rainwater as carbonic acid (H_2CO_3), which reacts with silicate minerals in rocks to produce bicarbonate (HCO_3^-) and other dissolved species. These are washed into rivers and carried to the ocean where the bicarbonate combines with calcium (as Ca^{2+}) to form calcium carbonate (limestone). In this way, CO_2 is drawn out of the atmosphere and the higher the rates of weathering and erosion, the more is removed. And because CO_2 is a greenhouse gas, diminished atmospheric levels mean colder climates. The cooling that initiated the last ice age has been attributed, at least partially, to the uplift of the Tibetan Plateau and the Himalayas, and the Intermontane Plateau region of the western U.S. (Raymo and others, 1988; Ruddiman and Kutzbach, 1989).

Tectonic processes operate over long timescales, so although they may explain the climatic downturn that culminated with the last ice age, they cannot account for its cycles of cold and warmth, which are orders of magnitude shorter by comparison. The prevalent theory is that, governed by regular, predictable changes in Earth's orbit around the sun (Milankovitch cycles) (fig. 2), glacial-interglacial cycles are a response to variations in the amount of insolation (solar radiation) that reaches the planet's surface. Earth's orbit around the sun is elliptical (eccentric) and it changes periodically, sometimes putting the planet a little closer to, sometimes a little farther away from, the sun. The tilt of Earth's axis of rotation also changes over time, and as it turns it wobbles, or precesses, slightly on this axis. All these movements occur in regular, predictable cycles of about 100,000, 41,000 and 23,000 years respectively, and each cycle affects insolation in some way. Interglacials tend to occur when insolation is at a maximum during the Northern Hemisphere summer. Most of the early Pleistocene was characterized by relatively short-lived glaciations that followed the 41,000-year obliquity cycle, but for reasons that have yet to be fully explained, by about 800,000 years ago, this had lengthened to a precession-dominated cycle of about 100,000 years (fig. 3).

Although longer and colder than their precursors, these cycles were punctuated by several warming events coincident with insolation maxima. The onset of interglacials, which mark the end (or beginning) of each 100,000-year cycle occur every fourth or fifth high. The transition from glacial to interglacial conditions and back again is asymmetric, following a generally downward-trending sawtooth pattern alternating between abrupt temperature rises at the beginning of interglacials and the gradual descent, interrupted by brief periods of warmth, into the deep cold of the next glaciation (fig. 3). The timing of this sequence of peaks and troughs matches an eccentricity- and obliquity-modified 23,000-year precessional Milankovitch cycle very well, but what of its progressively diminishing amplitude and the rapidity (a few thousand years) of the change from a full glacial to a full interglacial climate? Evidence suggests that the culprit is the moderating effect of windblown dust on the high albedo (solar reflectivity) of ice sheets (Ellis and Palmer, 2016).

Glacial stages are subdivided into stades and interstades: alternating periods of relative cold and warmth lasting a few hundred to several thousand years, during which glaciers expand (stades) and temporarily retreat (interstades). Some of these events were global in extent, whereas others were more regional; some appear to have been cyclic, others not. Many came and went with astonishing swiftness – seesawing between warmth and cold by as much as 10°C (18°F) in the space of a few years or decades (Alley, 2000). The influence of Milankovitch cycles on such rapid temperature swings is probably incidental. Most stadial-interstadial oscillations are thought to be driven by ice sheet dynamics and their effects on ocean and atmospheric circulation (Li and Born, 2019; Science Direct, 2020).

Glacial North Dakota

We may never know how many times North Dakota was glaciated. The early Pleistocene 41,000-year glacial-interglacial cycles may not have been long or cold enough for glaciers to extend so far south. Erosion and more recent glaciations have left little to no trace of the earliest events and have quite possibly erased some of the later ones from the stratigraphic record as well. Even so, within the sequence of glacial sediments that blanket roughly two-thirds of the state, are clear indications of three, possibly more, major, and several minor glaciations. Most were deposited between about 29,000 and 11,700 years ago during the last major southward expansion of the Laurentide Ice Sheet, or Late Wisconsinan glaciation (≈ MIS 2; fig. 4). These deposits form a thick cover across almost all of North Dakota east and north of the Missouri River and are the reason for the area's wide, rolling landscapes. The surface landforms include a number of end moraines that define the outer margins of multiple glacial advances.

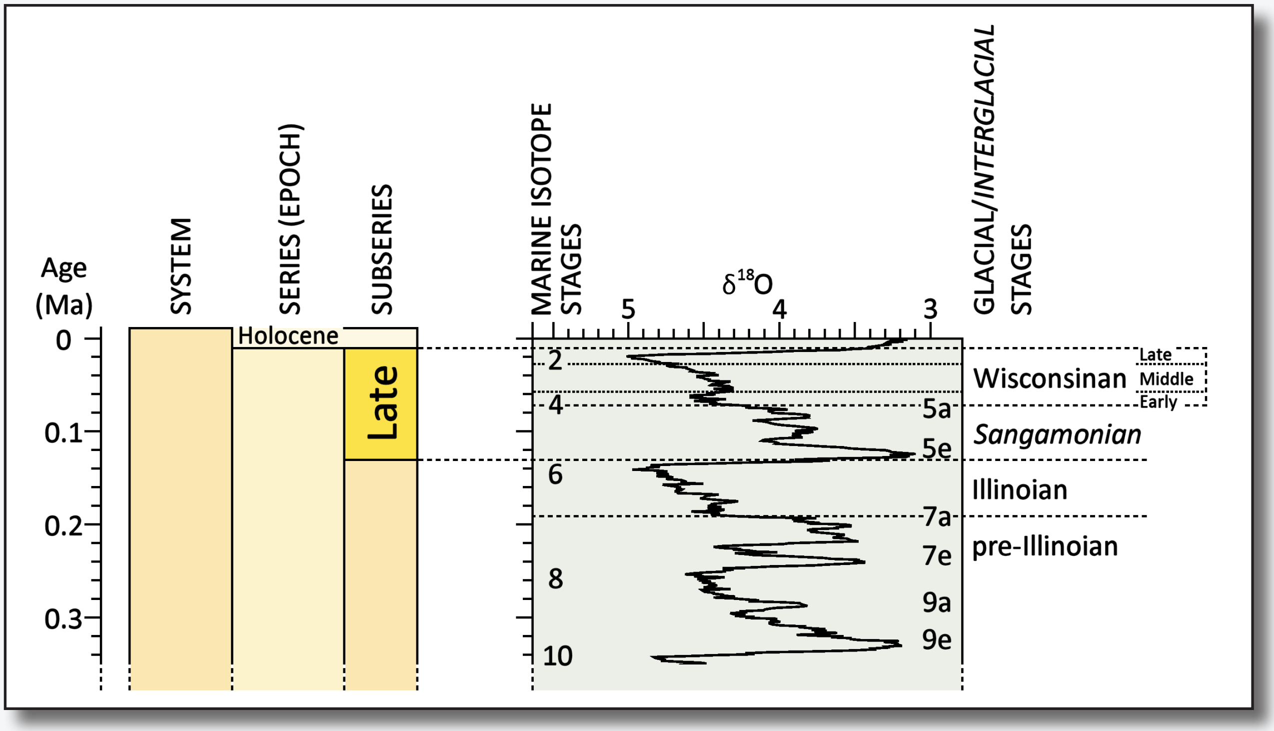

Figure 4. Expanded view of the upper part of figure 1 showing named North American glacial and interglacial stages. The pre-Illinoian stage incorporates all stages of the early and middle Pleistocene older than, and including, MIS 7. Modified from Cohen and Gibbard (2019).

Southwest of the Missouri River are glacial sediments that appear to be much older. They are thin, patchy, and heavily eroded – all signs of prolonged aerial exposure – and are thought to be Early Wisconsinan (≈ MIS 4; fig. 4) or Illinoian (≈ MIS 6; fig. 4) in age.

In the Red River Valley, the glacial stratigraphy tells a similar story but with the added advantage that it has been the subject of a great deal of study in both North Dakota and Minnesota (Harris and others, 2020). Here, geologists have recognized 22 till units representing 16 discrete glacial advances. Eight are known or inferred to have taken place during the Late Wisconsinan glaciation. Of the remaining eight, one may be anything from Late Wisconsinan to pre-Illinoian in age, whereas the deeply weathered surface of the youngest of the seven underlying units strongly suggests they are all pre-Illinoian and were probably deposited sometime between about 190,000 and 780,000 years ago. The base of the second-youngest of these units contains an abundance of beautifully preserved wood fragments, some quite large (fig. 5) and other organic debris – another indication of a warm interval long enough to allow trees and other plants and animals to flourish, for a while at least, until the glaciers came again.

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Figure 5. Wood fragments weathering out of the Gervais Formation, a pre-Illinoian till unit that outcrops in several places along the Red Lake River in northwestern Minnesota and a at handful of sites in southeastern North Dakota. These ancient pieces of wood are probably at least 200,000 years old. Photos by K.L. Harris and L.A. Manz.