The Mid-Pleistocene Enigma

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Variations in Earth's orbit affect incoming solar radiation and have guided past glacial-interglacial oscillations. These rhythmic changes in insolation are known as Milankovitch cycles. Approximately 900,000 years ago, Earth's climate pacemaker skipped a beat and switched from the 41,000-year obliquity (Earth's axial tilt) pacing of the early Pleistocene to ~100,000-year eccentricity (circularity of Earth's orbit around the sun) pacing of the late Pleistocene. This glacial-interglacial shift, the Mid-Pleistocene Transition (MPT), remains one of the most enduring mysteries of the Quaternary and in the field of paleoceanography. Recent reconstructions of atmospheric and oceanic processes and studies of the dynamic linkages between them have paved the way for a more detailed mechanistic understanding through this climatic transition and of Earth's climate system at large.

Advances in geochemical techniques applied to ocean sediment cores recovered by scientific ocean drilling enable the reconstruction of higher resolution paleoclimatic records of atmospheric CO_2, ocean remineralized carbon content, ocean circulation change, and ice volume. We now understand that the characteristic timescales of glacial-interglacial variability are primarily linked to dynamical processes modulated by the ocean and its interaction with ice sheets—in particular, we understand much more about the Southern Ocean's role in moderating Earth's climate and its characteristic beats.

The MPT occurred in at least two steps (Figures 1 and 2). The first was the "900 kyr event," around Marine Isotope Stage (MIS) 22, when the quasi-eccentricity signal emerged. The second was MIS 16 when the transition was complete. The first step had the largest impact on ocean carbon cycling and (likely) atmospheric carbon. The early Pleistocene had symmetrical ice age cycles and a glacial-to-interglacial atmospheric CO_2 of ~240–285 µatm (Yan et al., 2019, and references within). Between MIS 22 and MIS 16, there were weak interglacial and increasingly severe glacial periods. At MIS 16, the strong glacial periods of the Late Pleistocene emerged, and after MIS 12, glacial-to-interglacial atmospheric CO_2 ranged from ~200 µatm to 280 µatm.

The role of CO_2 as a driving mechanism for the MPT is debated, largely due to the absence of a continuous high-resolution record over the transition. Within the next few years, ice drilling in Antarctica may yield some of the world's oldest ice, with the potential of recovering a continuous record of ancient atmospheric composition back to 1.5 million years ago (Dahl-Jensen, 2018). Nevertheless, existing high-resolution atmospheric CO_2 snapshots before, during, and after the MPT suggest that a combination of ocean and ice sheet dynamics control atmospheric CO_2 cycles (e.g., Chalk et al., 2017).

Ocean dynamics played an increasingly important role in sequestering carbon in the deep ocean over the MPT, particularly during the glacial intervals. Neodymium isotopes, which are used as a water mass tracer, show that intermediate- to deep-ocean circulation reorganized between MIS 25 and MIS 21 (Pena and Goldstein, 2014). Prior to the MPT, deep water formed in the polar north extended toward southern subpolar latitudes during glacial and interglacial periods. During the 900 kyr event, southern-sourced deep water flooded the Atlantic, and the spatial extent of southern-sourced deep water remained extensive during subsequent glacial intervals. This southern-sourced deep water is carbon-rich and has low carbonate ion values (e.g., more acidic, higher carbon content water; Farmer et al., 2019, and references within) and increased the deep ocean carbon reservoir.

In addition to changing the geometry of major water masses, enhanced biological production changed the carbon content of the water subducting into the ocean's interior from the Southern Ocean, effectively sequestering more carbon in the global deep ocean. During the early stages of the MPT, the amount of iron-bearing dust supplied to the Southern Ocean began to increase (Figure 1), particularly during ice ages (Martínez-Garcia et al., 2011). This iron fertilized the Southern Ocean, increasing biological productivity and biological pump efficiency and contributing to the draw down CO_2 (Chalk et al., 2017).

The triggers for these alterations in Southern Ocean circulation and biological dynamics remain unknown. A Southern Hemisphere insolation minimum around the 900 kyr event points toward an Antarctic trigger, which allowed sea ice to expand. It has been hypothesized that Antarctica's ice sheets transformed from terrestrial-based to marine-based at this time (Raymo et al., 2006), though there is little physical evidence to support this. These changes altered the freshwater balance of the Southern Ocean, strengthened watercolumn stratification, and contributed to sequestration of carbon into the ocean's interior (Hasenfratz et al., 2019).

Deciphering when, where, and how much ice volume growth occurred over the MPT from benthic $\delta^{18}O$ records is difficult. An individual record reflects both the regional signal from where deep waters are formed (temperature and evaporation and precipitation processes that imprint on the $\delta^{18}O$ of seawater), its water mass circulation history, and the global signal of both temperature and ice volume. What was revolutionary about the original Lisiecki and Raymo (2005; recently updated by Ahn et al., 2017) "LR04 stack" was that these regional imprints were largely "averaged out" to create a global picture of temperature and ice volume over the last few million years (Figure 1). The question of *where* ice volume increased can only be inferred even in a benthic stack.

Isolating the $\delta^{18}O$ of seawater is crucial for reconstructing changes in global ice volume over the MPT, and by coupling the $\delta^{18}O$ (temperature and $\delta^{18}O$ of seawater) and the magnesium-to-calcium ratio (temperature) of benthic foraminifera, the $\delta^{18}O$ of seawater can be teased apart. Although early interpretations from individual sediment cores were complicated by changes in ocean circulation, a recent stack of $\delta^{18}O$ of seawater that includes North Atlantic, South Pacific and North Pacific sites aims to construct a global picture of ice volume change (Ford and Raymo, 2020). This MPT $\delta^{18}O$ of seawater shows that ice volume grew during both MIS 22 and MIS 16 (Figure 1), though we don't know the precise location of this ice. Given the Southern Hemisphere insolation minimum during the 900 kyr event, ice volume growth likely occurred in Antarctica during MIS 22 and consequently increased the sensitivity to the 100 kyr cycle through hemispheric phase locking (Raymo and Huybers, 2008). Ice volume growth during MIS 16 likely had Northern Hemisphere origins, possibly related to Laurentian regolith removal and ice sheet stability (Clark and Pollard, 1998), and this growth completed the transition.

The MPT is a prime example of a gradual climate transition whereby small, additive changes in Earth's internal climate dynamics can force a large response, and the transition occurs with relatively minor changes to average CO_2 levels (less than 20 years at current rates of anthropogenic emissions) and with no apparent changes to the structure of orbital parameters that have governed much of Cenozoic climate change. Studying how exactly these changes were triggered and how they interact with one another is going to be crucial as we enter the next phase of human-caused climate change.

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Figure 1: A selection of records across the Mid-Pleistocene Transition: (a) Benthic oxygen isotope stack (Lisiecki and Raymo, 2004). (b) Ice volume as a proxy for sea level, derived from $\delta^{18}O$ of seawater from benthic foraminifera (Ford and Raymo 2020). The light blue is the 1 sigma error envelope from a Monte Carlo simulation. (c) Atmospheric CO_2 reconstructions, where the black line is the Antarctic ice core record. The colored records are from marine sediment reconstructions (Chalk et al., 2017 and references within). Error bars are 2 sigma error. (d) carbonate ion records (Farmer et al., 2019. and references within), (e) Southern Hemisphere iron dust (Martínez-Garcia et al., 2011). Marine Isotope Stages (MIS) discussed in text are annotated and yellow bar highlights the 900 kyr Event.

Figure 2: Schematic of biological productivity, carbon storage, ocean circulation, sea ice, and ice volume changes over the Mid-Pleistocene Transition derived from data displaying in Figure 1. SCW is southern component water, which is carbon-rich. NCW is northern component water. The 900 kyr Event represents a large reorganization of Southern Hemisphere processes. SCW and NCW are derived from Nd records.