The relative influence of precession and obliquity on Late Pliocene (3.3-2.4 Ma) polar ice sheet dynamics and global sea-level change

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Abstract

The origin and timing of the ice ages is one of Earth Science's enduring mysteries[1,2]. Since the development of the $\delta^{18}O$ proxy for global ice volume, the growth and decay of polar ice sheets has been shown to fluctuate in concert with long-term changes in Earth's orbital geometry[3]. However, the causal link between the two has yet to be satisfactorily explained, a situation compounded by complications in converting $\delta^{18}O$ into ice volume[2].

For much of the Pliocene eustatic sea level, as reconstructed from $\delta^{18}O$, varied with an obliquity period of ~41 kyrs, yet the intensity of insolation over polar ice sheets is dominated by a ~20 kyr precession periodicity. Two leading explanations for this apparent conundrum have been proposed[4-6]. In one, polar ice sheets expand and contract in phase with the globally synchronous obliquity cycle[5], when the melt threshold of the polar ice sheets is <~300 w/m^2. Under this condition the melt season is longer and influenced by mean annual insolation, rather than the intensity of peak summer insolation, which is controlled by precession. In the other hypothesis, precession determines the magnitude of the high latitude summer melt season and is out of phase between the hemispheres[4], so the effect of ice growth in one hemisphere on sea level may be largely cancelled by melting in the other, and the residual 41 kyr response common to both poles dominates the globally integrated $\delta^{18}O$ ice volume proxy.

A key interval of Earth history for testing these hypotheses is the Late Pliocene (~3.4-2.4 Ma). This period contains intervals of strongly contrasting orbital geometry. It also contains a well-constrained paleomagnetic reversal stratigraphy that removes the need to date sediments by reference to orbitally-tuned $\delta^{18}O$ curves. Lastly, geological evidence from drill cores proximal to glacial-period polar ice sheets provides some evidence of the extent of ice, and its variability, in these regions during the Late Pliocene[e.g.7,8].

We have reconstructed the timing of glacial-interglacial global sea level fluctuations independently of $\delta^{18}O$ from a shallow marine sedimentary succession in Whanganui Basin, New Zealand[9], and from compositional cyclicity measured by x-ray fluorescence (XRF) in a deep ocean sediment core from ODP Site 1124, adjacent to the eastern continental margin of New Zealand. We suggest changes in the supply of land-derived sediment to Site 1124 also reflects orbitally-paced sea level, via its influence on source-to-sink terrestrial sediment delivery. Both records have been correlated cycle-by-cycle within a high-resolution chronostratigraphic framework constrained by a magnetic reversal stratigraphy and a tephra occurring within the Kaena Subchron (3.04-3.11 Ma) that has been geochemically characterised on the basis of its unique major and trace element geochemistry[9].

Based on our initial results, we find precession-duration sea level variability between ~3.2 - 2.9 Ma and obliquity-duration cycles dominating both records between 2.9 and 2.4 Ma. Proximal records of East Antarctic Ice Sheet (EAIS) variability, as evinced from ice-rafted debris[7], show eccentricity/precession pacing dominates ice sheet advance and retreat between 3.3-2.4 Ma.

The most parsimonious explanation of our data is that southern high latitude insolation regulated a dynamic EAIS driving precession-paced, global sea level variability from ~3.2-2.9 Ma, in the absence of a significant Northern Hemisphere (NH) ice sheet. Subsequent, large amplitude, obliquity-dominated sea level cycles in the global $\delta^{18}O$ record, and New Zealand sea level records, are consistent with the rapid growth of a large NH ice sheet with a relatively minor contribution from EAIS. The NH ice sheet was likely dominated by the influence of obliquity on mean annual insolation because of its lower latitude ablation margins and lower melt threshold.

Keywords: Pliocene, insolation, Milankovitch, ice sheets

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