Dynamic Antarctic Ice: agent for Mid-Pleistocene Transition

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In the record of Plio-Pleistocene climatic evolution the Antarctic Ice Sheet/cap is generally seen as a passive response to global change, rather than an active agent in its own right. While changes in global relief, particularly uplift of the Qinghai-Tibet Plateau, are accepted as major drivers into cold, full-glacial 100 ka cycles, the potential influence of change in the Antarctic ice cap has largely escaped attention. The southern Australian coastline, facing the Antarctic continent with some 3,000 km of unbroken fetch, is ideally placed to record changes in Southern Ocean dynamics. As the pattern of travelling cyclonic depressions that control the westerly flow across southern Australia reflects steep thermal gradients around the Antarctic margin, the winds and wave regimes impacting southern Australia can be linked to thermal conditions at the Antarctic margin. Changes in one of these systems imply correlative changes with the other. Here we argue that evidence for dramatic mid-Pleistocene change in Southern Ocean dynamics is present in a remarkable succession of stranded shorelines in the Murray Basin in south-eastern Australia, that provides a more-or-less complete record of paleoshorelines deposited over the last 6 Ma (Fig.1a).

The Murray Basin record

Situated in a relatively stable context, the Murray Basin has acted as an epeiric (epicontinental) sea controlled by the Southern Ocean for some 40 Ma. A mid-Miocene regression (12-7 Ma) was followed by an Upper Miocene transgression (6.5-6 Ma) with the maximum late Neogene marine incursion typically extending inland to heights ~60 m above present day sea level (Brown and Stephenson, 1991). Regression from Upper Miocene through Pliocene to present time has left more than 170 shore parallel strandline ridges extending from 500 km inland from the present coast near Naracoorte (Fig. 1b,c). For some 200 km inland of Naracoorte, gentle uplift on the NW-SE trending Padthaway Ridge (Fig. 1a), simultaneous with coastal retreat, has separated younger ridges and uplifted older ones (Fig. 1c). At Naracoorte, ridges dated to near the Brunhes-Matuyama boundary (780 ky) now lie at +70 metres, evidencing uplift at ~60 m/Ma (Murray-Wallace et al., 2001).

The ~6 Ma record of retreating coastlines across the Murray Basin strandplain preserves two distinctive sedimentary asociations. The older Pliocene sequence of siliceous near-shore sands of the Parilla Formation grade offshore into shallow water fossiliferous marls of the Bookpurnong Formation (Brown & Stephenson, 1991). The differential elevation between near-shore sands and offshore marls provides a measure of wave-base that rarely exceeds 40-50 m. By contrast, modern storm waves with periodicity in the 12-14 s range are characterized by a wave base in excess of 100 m depth. The younger Pleistocene sequence of shorelines is reflected in large calcarenite back-beach linear dunes of the Bridgwater Formation, and associated downwind parabolic dune fields, both of which continue to deposit along southwest facing ocean beaches to this day. The changes in shoreline facies, from the lower energy siliceous Parilla Sands to calcarenite ridges of the Bridgewater Formation, occurs in the Bordertown-Naracoorte area, and bear witness to a major change in Southern Ocean wind-wave regimes. Intriguingly, the modern interglacial regime is characterized by much higher energy circulation systems than typical of the Pliocene, and is thus more closely related to those of the Pleistocene windy world. But precisely when and how did that change come about?

The zone between Naracoorte and the present coast preserves some 8 interglacial barriers developed on the rising southern limb of the Padthaway dome with a clear reflection of 100 ka cyclicity. Inland the presence of more than 170 Parilla Sand ridges formed within the 6-2 Ma period reflects a strong 20 ka precessional signal. Between Naracoorte to Bordertown some 5 younger calcarenite ridges, with spacing intermediate between older ~20 ka strandlines and younger, more widely separated, 100 ka ridges, plausibly reflects a ~40 ka obliquity cyclicity. In the isotope curve, the sequence seawards of Naracoorte under chronological control, has been reliably correlated with isotope stages to MIS 25. Inland from Naracoorte East, correlation of younger Bridgewater Formation ridges is based on direct peak-to-peak estimates. The presence of 5 older ridges involves correlation with strong interglacial peaks immediately preceding MIS 25. This would place ages of oldest Bridgewater Formation ridges within the range MIS 43 to 47 near 1.3 to 1.4 Ma. This estimate, together with intermediate spacing between ridges, is consistent with dominant 40 ka controls in both data sets at this time (Fig. 2).

The mid-Pleistocene transition

The onset of Bridgewater facies in the 1.3-1.4 Ma time range poses significant questions for the mid-Pleistocene 100 ka transition (MPT). The appearance of distinctive calcarenite facies involving an abrupt increase in wave-base with associated shelf abrasion reflects a significant increase in controlling Southern Ocean wind and wave regimes. With Australia's coastal climate so closely tied to high latitude thermal gradients, any major change in controlling Southern Ocean pressure systems points to a change in those controlling regimes; changes that almost certainly involved dynamics of the Antarctic ice cap.

The following interpretation of events is proffered: oscillating patterns on a progressively falling Murray Basin sea level with equivalent isotope reflection defines progressive but oscillatory Pliocene growth of Antarctic ice under warmer and presumably, wetter conditions than prevail today. After sea level stabilized near present interglacial levels by 2.5 Ma, northern hemisphere ice controlled major changes; Antarctica remained relatively stable in terms of total ice volume. The subsequent transition to a base frozen ice sheet, with development of a sea ice girdle, leaves virtually no signature in the eustatic record, but enhances surrounding thermal gradients and leads to changes Southern Ocean dynamics. The increased coastal energy reflected in the transition from Parilla to Bridgewater thereby points directly to amplified cooling in the circum-Antarctic region.

Significantly this change precedes the MPT by some 300-400 ka. Once established such amplified cooling offers two effects. Firstly, it strengthens the control of ~41 ka obliquity signal by effectively dampening weaker precessional effects. Secondly, by acting in a new role as a global thermostat, the now super-cold ice cap becomes capable also of damping the power of obliquity insolation to return to full interglacial levels. This process would effectively favour development of 100 ka cycles, a process anticipated by Ruddiman's (2003) hypothesis for the explanation of the MPT.

The Murray Basin evidence points directly to the role of a highly dynamic ice cap controlling elements of both sea level and climatic evolution, not only in this region of the Southern Ocean, but with implications of wider global significance. Far from a simple passive response to global change, it suggests that the Antarctic ice cap has played a much more active role than previously recognized. Improved understanding of that role presents new challenges in modeling predictions of future greenhouse responses.

References

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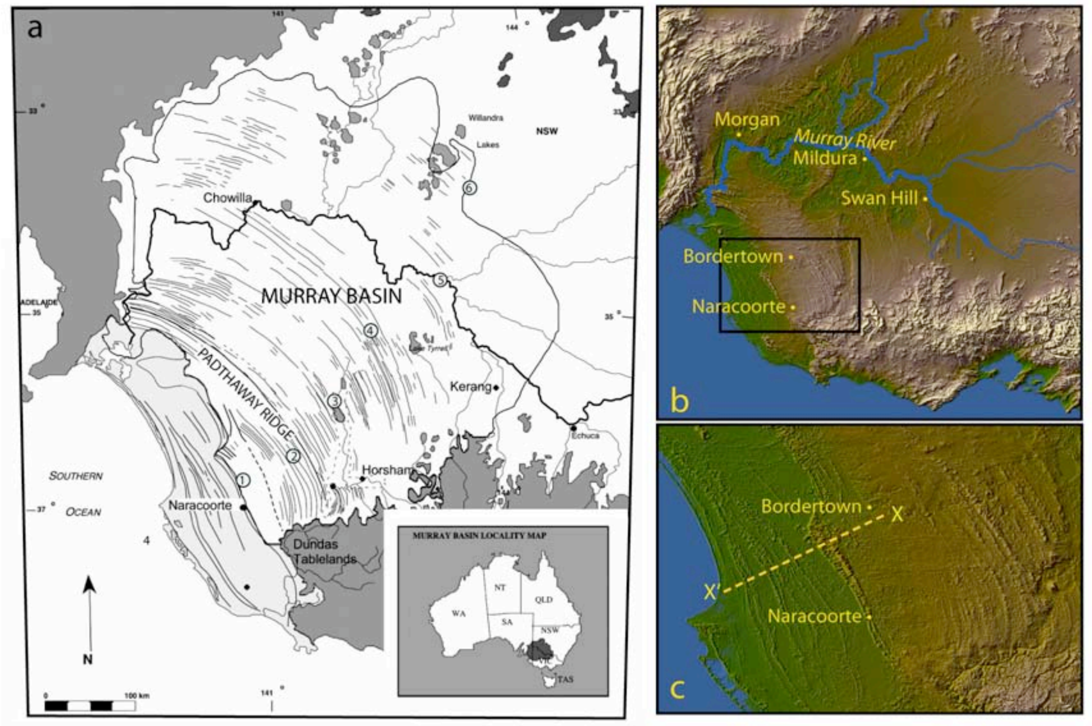

Figure 1: a) Extent of Upper Miocene marine invasion in the Murray Basin, southeastern Australia. Multiple strandline ridges represent legacy of Plio-Pleistocene marine regression falling from near 60 m to present sea level. The Padthaway Ridge controlled early Pleistocene levels on a rising platform with successive interglacial levels separated laterally on uplifted platform (modified from Kotsonis, 1999). Numbers 1 to 6 represent estimated position of coastline 1-6 Ma. b) Shaded relief image of the Murray Basin derived from the Shuttle Radar (SRTM) 3 arcsecond topographic data. The green to brown colour transition defines the 60 m contour and corresponds to the former extent of a Plio-Pleistocene lake (Lake Bungunnia) formed by tectonic depression following retreat of the sea. c) Detail of the area of transition between inland Parilla siliceous strandlines and the calcarenite beach ridges of Mid-Pleistocene age near Naracoorte. For detail, see Fig. 2.

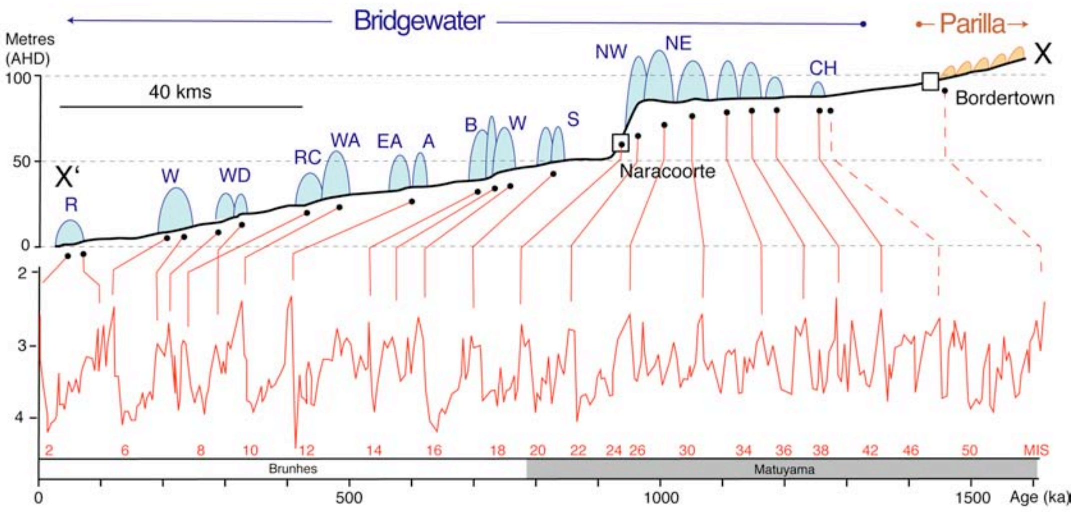

Figure 2: Correlation of the strandline-coastal ridge system (along profile line X'-X in Fig 1c from near Kingston via Naracoorte to Bordertown) with marine isotopic interglacial peaks based on the chronology of Tian et al., 2002. Ridge sequence and isotope correlation, Naracoorte to coast from Murray-Wallace et al., 2001. The age of the oldest Bridgewater ridge is tentatively correlated with isotope stages 43 or 47, dated to near 1.3- 1.4 million years ago. Beach-ridge names: (CH) Cannonball Hill, (NE) Naracoorte East, (NW) Naracoorte West, (S) Stewart, (W) Woolumbool, (B) Baker, (A) Ardune, (EA) East Avenue, (WA) West Avenue, (RC) Reedy Creek, (WD) West Diary, (W) Woakwine, (R) Robe (Murray-Wallace et al., 2001).