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Antarctic records of precession-paced insolation-driven warming during early Pleistocene Marine Isotope Stage 31

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[1] Precisely dated Antarctic continental margin and Southern Ocean geological records show that the early Pleistocene interglacial Marine Isotope Stage 31 (MIS-31) was characterized by warmer than present surface waters with reduced sea-ice and enhanced high latitude marine carbonate production. Micropaleontologic, isotopic, and paleomagnetic evidence from drill cores at 77°S (Cape Roberts Project-1) and 53°S (ODP Site 1094) indicate circumantarctic changes in sea surface temperature and water mass stratification that are in phase with high southern latitude insolation changes during MIS-31. These changes imply a significant, though as yet unquantifiable reduction in Antarctic ice volume. This study supports the hypothesis that the interhemispheric antiphased relationship of the precession cycle attenuates a potentially significant Antarctic ice volume signal in the deep sea oxygen isotope record. The implications are that Antarctic marine ice sheets may be more susceptible to warming and high insolation driven retreat than has been widely recognized. **Citation:** Scherer, R. P., S. M. Bohaty, R. B. Dunbar, O. Esper, J.-A. Flores, R. Gersonde, D. M. Harwood, A. P. Roberts, and M. Taviani (2008), Antarctic records of precession-paced insolation-driven warming during early Pleistocene Marine Isotope Stage 31, *Geophys. Res. Lett.*, *35*, L03505, doi:10.1029/2007GL032254.

1. Background and Introduction

[2] Identifying and analyzing geological records of pre-industrial Quaternary warm events becomes ever more important as analogs for modern climate change are sought. Significant climatic excursions in polar regions are of particular importance because of their potential impact on ice sheet, ice shelf and sea ice configurations. It has been argued that a key driving force behind glacier melt in polar regions, especially during late Pliocene and early Pleistocene interglacials, is either the obliquity-paced duration of the summer melt period [*Huybers*, 2006] or the precession-dominated overall intensity of high latitude summer insolation [*Raymo et al.*, 2006]. *Raymo et al.* [2006] proposed that ice sheets at both poles waxed and waned with precession forcing during this period, but that the 41 ka cycle dominates the deep sea δ^{18}O signal because the global signal of higher frequency ice growth and decay is cancelled out by the antiphased relationship of precession forcing between the poles. High latitude records of Marine Isotope Stage 31 (MIS-31) provide a test of this hypothesis.

[3] MIS-31 was characterized by some of the highest high-latitude insolation values of the last 5 million years, with a combination of high obliquity, eccentricity, and precession, with perihelion in January early in the interglacial [*Laskar et al.*, 2004]. The orbital parameters for MIS-31 forced an unusually warm and long interglacial (1.085 Ma–1.055 Ma) characterized by two Southern Hemisphere (SH) summer perihelion peaks bracketing a strong Northern Hemisphere (NH) summer perihelion peak at 1.07 Ma [*DeConto et al.*, 2007]. These parameters drove a 2–5°C model-predicted Antarctic sea surface temperature rise and WAIS collapse [*DeConto et al.*, 2007], and a ca. 20 m model-predicted eustatic sea-level rise during MIS-31 [*Raymo et al.*, 2006]. We address these hypotheses using precisely dated diatom, calcareous nannofossil, oxygen isotopic, and chronostratigraphic data from the polar water mass of the Atlantic sector of the Southern Ocean (ODP Site 1094D 53.1°S, 5.8°E, 2807 m water depth) [*Gersonde et al.*, 1999] and Cape Roberts Project Site 1 (CRP-1) from the Antarctic nearshore zone of McMurdo Sound (77.0°S, 163.8°E; 153 m water depth) [*Davey et al.*, 2001].

2. Antarctic Margin Record of MIS-31

[4] CRP-1, a stratigraphic drilling program on the continental shelf near the Transantarctic Mountain front in the western Ross Sea, recovered an early Pleistocene carbonate-rich unit herein interpreted as MIS-31. CRP-1 Lithostratigraphic Unit 3.1 (LU 3.1), 31.89–33.82 m below sea floor (Figure 1), consists of variably laminated calcareous sediment with relatively abundant diatoms and calcareous planktic microfossils, including *N. pachyderma* sinistral (s.) and an unknown species of *Thoracosphaera*, a calcareous dinoflagellate [*Villa et al.*, 2005], a lithology that is in stark contrast with the dominant glacial diamictons above and below. LU 3.1 has been interpreted as a carbonate bank deposit, formed at depths >100 m [*Taviani and Claps*, 1998]. Although moderate reworking by currents is apparent, fossil assemblages are essentially *in situ* and undisturbed. Carbonate deposition was interrupted by a clay-rich interval with abundant ice rafted detritus (IRD) (Figure 1). This event is interpreted as a minor climatic reversal

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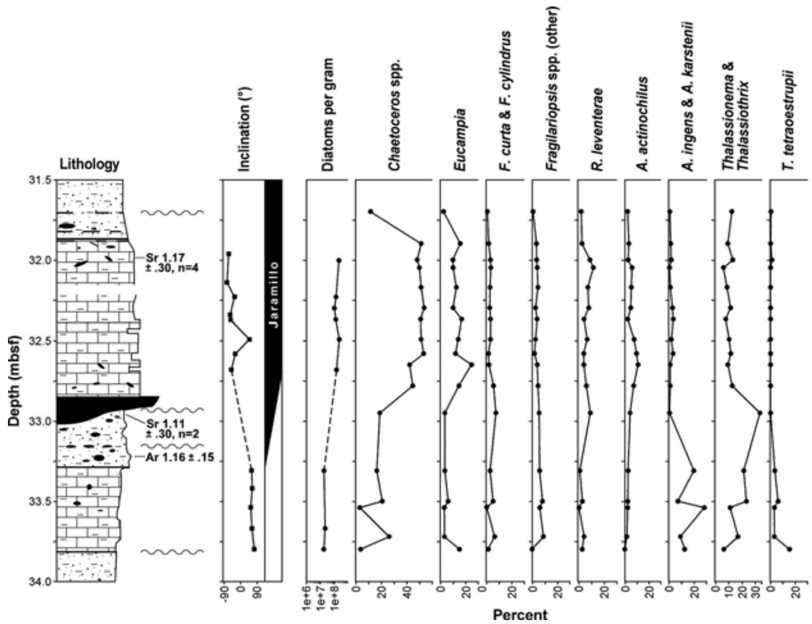

Figure 1. Lithostratigraphy, chronostratigraphy, paleomagnetic results, and relative abundance of selected diatom taxa and groups in CRP-1, LU 3.1. Diatom abundance (valves per gram dry sediment, plotted on a log scale) is relatively low below the IRD event, due to winnowing, and low during the IRD event, due to high accumulation rates of terrigenous material, but is relatively high in the upper part of LU 3.1. The stratigraphic position of the 2 $^{40}Ar/^{39}Ar$ and 6 $^{87}Sr/^{86}Sr$ samples is indicated. Specimens for $^{87}Sr/^{86}Sr$ included a bryozoan, a miliolid foraminifer, a bivalve, and an echinoid from 32.05 mbsf, and an echinoid and a bivalve from 32.97 mbsf. Precise dates for the top and bottom of the unit are not well constrained. Wavy lines indicate the positions of potential diastems. The magnetic reversal occurs within the IRD event which reflects the low insolation stadial, bracketed by insolation maxima. Note the high *Chaetoceros* abundance above the IRD, the high concentration of pelagic forms below the IRD, and the relatively low abundance of sea ice related *F. curta* and *F. cylindrus* throughout, unlike the modern southwestern Ross Sea today (Table 1).

(stadial), with local glacier advance and iceberg calving, especially on Ross Island and associated volcanic landmasses, 100 km to the south. The iceberg source is inferred from provenance analysis of ice-rafted clasts [*Talarico and Sandroni*, 1998], of which 71% are unequivocally derived from the McMurdo Volcanic Group. Included among the IRD was an allochthonous basalt clast that yielded $^{40}Ar/^{39}Ar$ plateau ages of 1.16 ± 0.15 Ma [*McIntosh*, 1998], providing a maximum age estimate for the deposit.

[5] LU 3.1 has been dated using multiple chronostratigraphic methods in addition to the $^{40}Ar/^{39}Ar$ (maximum) age, including $^{87}Sr/^{86}Sr$ ratios from six unrecrystallized calcareous shells from two levels (Figure 1). $^{87}Sr/^{86}Sr$ age estimates from above and below a large ice-rafted boulder reflect statistically identical ages, interpreted as 1.11 ± 0.45 Ma [*Lavelle*, 1998] (Figure 1). Diatom biostratigraphy indicates the *Thalassiosira elliptipora* acme [*Bohaty et al.*, 1998], near the base of Subzone C of the *Actinocyclus ingens* Partial Range Zone of the Southern Ocean diatom biochronology of *Zielinski and Gersonde* [2002], 1.13 to 0.78 Ma. New paleomagnetic investigation of LU 3.1 was performed on 13 samples from fine-grained calcareous muds. All paleomagnetic samples were subjected to stepwise alternating field demagnetization at peak fields of 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 80, and 100 mT, and all were found to have stable magnetizations. Paleomagnetic results include identification of a reversed to normal polarity transition in this interval, which is assigned to the base of the Jaramillo event (C1r. $1n_{base}$), 1.072 Ma [*Horng et al.*, 2002] (Figure 1), which coincides with the global MIS-31 $\delta^{18}O$ peak and the NH insolation maximum. We rule out the Bruhnes/Matuyama boundary for this transition based on the aforementioned chronologic criteria, and the coincidence with strong interglacial conditions, which would not be expected for the B/M boundary during MIS-19. Given this chronology, LU 3.1 can be confidently correlated with any stratigraphic record that includes C1r.$1n_{base}$ and/or an oxygen isotope record that includes MIS-31. The C1r.$1n_{base}$ magnetic reversal in LU 3.1 coincides with the IRD event (Figure 1), which confirms that this minor climatic reversal is coincident with the SH insolation minimum at 1.07 Ma. Because precise age control of LU 3.1 is internally based on this single point, it is not possible to accurately constrain accumulation rates for the entire unit, but the *in situ* nature of the deposit and the low sediment accumulation rates on modern Antarctic carbonate banks [*Taviani and Claps*, 1998] suggest that Unit 3.1 reflects deposition spanning at least several millennia on each side of the IRD event. However, several minor stratigraphic breaks, especially at the base of the unit, suggest that the entirety of MIS-31 is not preserved.

[6] Diatom analysis of LU 3.1 is based on quantitative counts (>300 valves) on 18 samples, with absolute abundance estimates on 10 samples (Figure 1), plus qualitative assessment of an additional 37 samples, including smear slides. MIS-31 sediments from CRP-1 include planktic paleontological tracers indicative of warmer than present

Table 1. Mean Total Relative Abundance of Selected Diatoms From LU 3.1 and Holocene Samples From McMurdo Sound (HMS)[a]

Diatoms	CRP-1, %	HMS, %
Actinocyclus spp.	8.5	0.4
Chaetoceros (cells and spores)	41.4	1.1
Eucampia antarctica var. *recta*	11.1	2.5
% terminal valves	0.25	43.0[b]
% intercalary valves	99.75	57.0[b]
Fragilariopsis curta	3.5	59
Fragilariopsis spp. (other)	4.4	15.1
Rouxia spp.	5.7	0
Thalassionema + *Thalassiothrix*	13.9	0
Thalassiosira spp.	4.5	14
Other taxa	7	8.1

[a]From *Leventer* [1988].
[b]New data based on analysis of 5 core top samples from McMurdo Sound.

conditions. Today, this area is characterized by 2 to 3 m of multiannual fast ice, which provided a stable platform for the drilling system [*Davey et al.*, 2001], and average summer water temperatures of $-1.6°$ to $-2.1°$. Modern sediments in this area are characterized by abundant diatoms that reflect the pervasive sea ice. The modern diatom assemblage of the McMurdo Sound area is strongly dominated by *Fragilariopsis curta* and other sea ice indicators, exceeding 90% in many samples, and a paucity of *Chaetoceros* spp. (subgenus *Hyalochaete*) [*Leventer*, 1988; *Leventer and Dunbar*, 1988], which sharply contrasts with the diatom assemblage from LU 3.1 (Table 1).

[7] Abundant planktic diatoms in LU 3.1 reflect high diatom productivity in an open water setting, with little or no summer sea ice. The dominant diatom group includes resting spores and vegetative cells of *Chaetoceros* spp. (Figure 1 and Table 1), which are representative of a highly productive shallow mixed layer maintained under stable, relatively warm and low salinity conditions, similar to parts of the modern northern Antarctic Peninsula [*Leventer et al.*, 2002]. *Chaetoceros* is less dominant below the IRD event, but because grain size is generally coarser in this interval, with indications of bottom current winnowing [*Taviani and Claps*, 1998], this observation may reflect reduced accumulation of the very small *Chaetoceros* frustules. Also present are taxa that are generally rare in the modern Ross Sea, and are characteristic of pelagic waters of the Southern Ocean (e.g., *Thalassionema nitzschioides sensu latu* (*sen. l.*) and *Thalassiothrix antarctica*), as well as extinct taxa believed to be pelagic, based on their distribution in Southern Ocean cores (e.g., *Actinocyclus ingens*, *Actinocyclus karstenii*, and *Thalassiosira tetraoestrupii sen. l.*) (Figure 1 and Table 1).

[8] The ratio of terminal to intercalary valves of *Eucampia antarctica* winter forms provides an estimate of water temperature and sea ice extent on the Antarctic continental shelf, with short chains reflecting very cold water [*Whitehead et al.*, 2005; *Kaczmarska et al.*, 1993], as evident in Holocene sediments of McMurdo Sound, where terminal valves constitute >40% of the *Eucampia* population, based on ratio counts from 5 surface sediment samples from southern McMurdo Sound (Table 1). These counts augment the work of *Leventer* [1988], which did not include such assessment. Our counts from CRP-1 included terminal/intercalary ratios on all samples, discounting broken or obscured specimens. In LU 3.1, *Eucampia antarctica* var. *recta* consists of >99% intercalary valves (Table 1), indicating very long chains, thus reflecting production in open water and an absence of sea ice well into the transitional seasons; conditions suggesting annual average temperatures above 3°C [*Kaczmarska et al.*, 1993].

[9] Despite the proximity of the drill site to the coastline, sea ice related diatoms, especially *Fragilariopsis curta,* are uncommon in LU 3.1, averaging 2.2% of the diatom assemblage, including a maximum of 7.3% in association with the IRD event (Table 1). *F. curta* thrives in sea ice brine pockets through the winter and blooms in the water column following seasonal ice thinning or break-out. The low concentration of these forms further suggests that surface waters were sufficiently warm to significantly delay winter sea ice formation. Ice-associated holoplanktic *Fragilariopsis* taxa characteristic of the modern Ross Sea, including *F. obliquecostata* and *F. sublinearis*, are also present in much lower proportions than in modern southwestern Ross Sea sediments (Table 1). The relative scarcity of sea ice related diatoms, the abundance of long-chain *Eucampia* populations, and the common occurrence of pelagic diatoms indicate water temperatures ca. 3–5°C warmer than today's sub-zero summer temperatures, with sea ice free conditions throughout most of the growing season.

[10] Diatom data from LU 3.1 are corroborated by new drill core evidence from beneath the Ross Ice Shelf in the southern McMurdo Sound area. The ANDRILL (Antarctic Geologic Drilling) Core AND-1B recovered a diatomite unit dated as MIS-31 that provides additional evidence of warmer than present conditions during MIS-31, with independent evidence of retreat of the Ross Ice Shelf [*Naish et al.*, 2008].

3. Southern Ocean Record of MIS-31

[11] Significant oceanographic changes during MIS-31 are recorded at ODP Site 1094D, located at 53°S in the South Atlantic, approximately two degrees of latitude south of the present Antarctic Polar Front [*Gersonde et al.*, 1999]. MIS-31 sediments at Site 1094D are identified by high resolution paleomagnetic and oxygen isotopic data. MIS-31 is characterized by a foraminifer-nannofossil-diatom ooze containing up to 30% nannofossils; the highest abundance of biogenic carbonate in the entire drill core. To assess surface water conditions during MIS-31, we analyzed Core 1094D-12H in high resolution for diatom (75 samples) and calcareous nannofossil (142 samples) assemblages and abundance, and oxygen and carbon isotopes (180 samples) from the planktic foraminifer *N. pachyderma* (s.) from the >150 μm fraction.

[12] Abundant and diverse calcareous nannofossils at this latitude indicate a southward shift or deterioration of the Polar Front. Such southward expansion of warmer surface waters is also apparent in ODP Site 1090, located within the present Subantarctic Zone [*Becquey and Gersonde*, 2002]. At Site 1094D, the increase of SH insolation, which culminated at about 1.08 Ma, coincides with a sharp shift from glacial to interglacial conditions, documented by the sudden reduction of cold water and sea ice related diatom species such as *F. curta*, *E. antarctica*, and *Rouxia leven-*

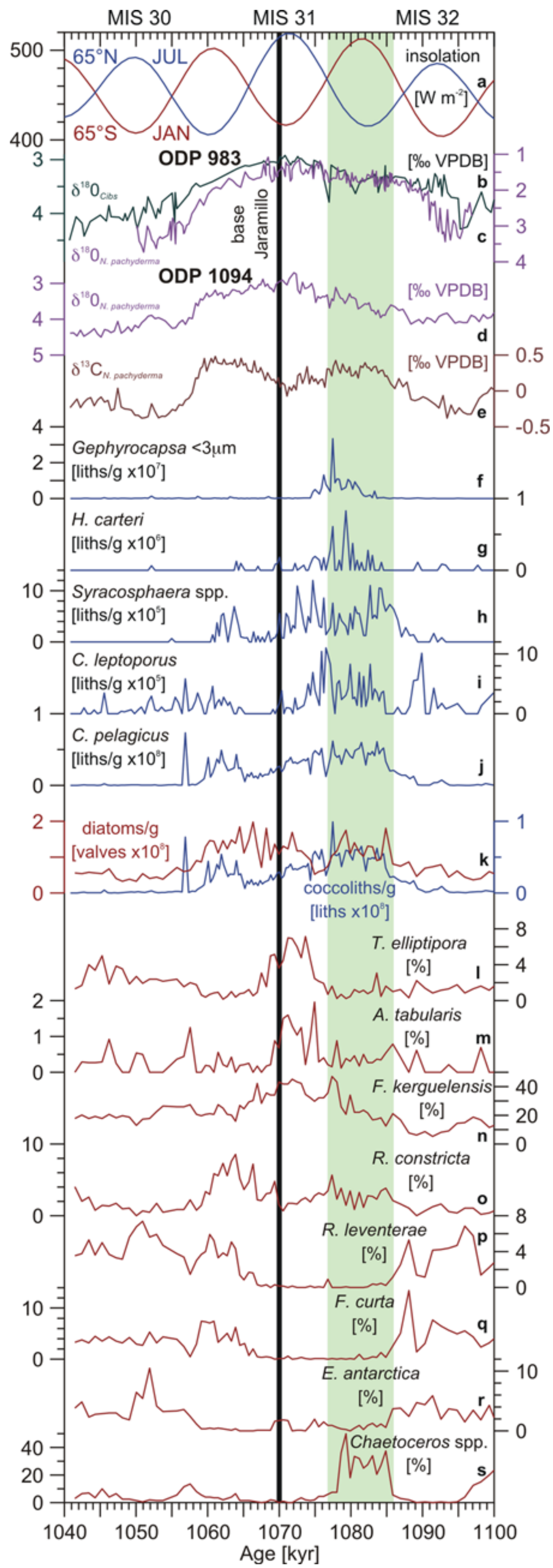

Figure 2. (a) Marine Isotope Stages 32-30 as defined by Northern and Southern hemisphere summer insolation (65°) [*Laskar et al.*, 2004], (b) benthic and (c) planktic isotope records from the North Atlantic ODP Site 983 [*Channell and Kleiven*, 2000], and stratigraphic and paleoceanographic data from the Southern Ocean ODP Site 1094, including (d)–(e) stable isotope measurements, (f)–(k) calcareous nannofossil, and (l)–(s) diatom relative and absolute abundance. The stratigraphic age assignment was based on graphic correlation [*Paillard et al.*, 1996] of the planktic isotope record from ODP Site 1094 with the benthic and planktic isotope records from Site 983. The lower boundary of the Jaramillo geomagnetic Subchronozone (age 1.07 Ma, black line) as recorded from ODP Site 983 and ODP Site 1094 [*Channell and Kleiven*, 2000] has been used for numerical dating and correlation. The reversal is re-allocated to a depth of 128.55–129.3 mcd in Site 1094, according to J. E. T Channell (personal communication, 2006). The green bar marks the southern summer insolation maximum (1.08 Ma) [*Laskar et al.*, 2004], which coincides with a distinct warming of the surface waters.

terae, and by the increase in calcareous nannofossil deposition. This is followed by nannofossil and diatom evidence interpreted as reflecting lower salinity surface waters during the time of maximum SH insolation (Figure 2). Surface water freshening and a stable mixed layer is suggested by the high concentrations of *Chaetoceros* spp. and by the occurrence of the calcareous nannofossils *Helicosphaera carteri* and *Syracosphaera* spp. The ecology of these coccolithophorids at these latitudes is not well documented, however, upper Pleistocene deposits in the Mediterranean show significantly increased abundances of these taxa during Heinrich events, reflecting meltwater influxes to the ocean, due to both melting icebergs in the North Atlantic and increased surficial runoff to the Mediterranean [*Colmenero-Hidalgo et al.*, 2004; *Sierro et al.*, 2005]. At Site 1094D, these nannofossils and *Chaetoceros* spp. abundance are interpreted as indicating surface water freshening and stratification related to a significant influx of glacial meltwater. Very low IRD through this interval is likely due to high biogenic input and IRD loss at the more southerly polar front. Reduced storminess would also stabilize the warm, relatively fresh upper water layer, further enhancing *Chaetoceros* [*Leventer et al.*, 2002] and calcareous nannofossil production. Despite diminished SH insolation prior to the Jaramillo event, ice-free conditions and warmer surface waters persisted, as evidenced by the near absence of *F. curta* and the increased abundance of *Azpeitia tabularis*. Full glacial conditions returned with strongly waning SH insolation after 1.06 Ma, as expressed by increased abundance of *F. curta* and *R. leventerae* (Figure 2).

4. Implications Regarding Insolation and MIS-31 Warming

[13] Together, the Antarctic (CRP-1) and Southern Ocean (ODP Site 1094D) records, which are precisely dated and correlated to MIS-31, demonstrate significant climatic events that are in phase with precession-driven high-latitude insolation changes (Figure 2) during an obliquity-paced early Pleistocene cycle, prior to onset of the Mid-Pleisto-

cene Transition [*Raymo et al.*, 2006]. Direct effects of these changes on the ice sheets are uncertain, though significant impacts of sea surface and air temperature warming on the stability of glaciers and ice shelves has been observed. The sensitivity of Antarctic ice shelves to surface warming was dramatically demonstrated in 2002 by the melt-induced collapse of the Larsen-B Ice Shelf [*Scambos et al.*, 2003], which was unprecedented over at least the last 10,000 years [*Domack et al.*, 2005], and by the subsequent surging and rapid thinning of feeder glaciers [*Rignot et al.*, 2004]. It is reasonable to suggest that circum-Antarctic warming of the magnitude and duration reported here for MIS-31 may have led to ice shelf collapse [*Scambos et al.*, 2003; *Williams et al.*, 2002], and subsequent loss of marine based ice sheets [*Scherer*, 2003; *Raymo et al.*, 2006; *DeConto et al.*, 2007].

[14] We suggest that during MIS-31 marginal Antarctic melting, driven by direct and indirect responses to insolation forcing, led the NH ice sheet melt. This implies that the initial Antarctic ice shelf and marine ice sheet response preceded the subsequent MIS-31 sea level maximum, which would have peaked following ice sheet retreat associated with the NH thermal maximum. Although we do not reject the importance of obliquity in the broader context [*Huybers*, 2006], Antarctic and Southern Ocean data and their interpretations with respect to ice sheet responses to insolation forcing during MIS-31 strongly support the hypothesis of *Raymo et al.* [2006] and, in turn, further suggest Antarctic ice sheet sensitivity to climatic warming.

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