Evidence for thermohaline-circulation reversals controlled by sea-level change in the latest Cretaceous

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ABSTRACT

Fluctuations in oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope values of benthic foraminiferal calcite from the tropical Pacific and Southern Oceans indicate rapid reversals in the dominant mode and direction of the thermohaline circulation during a 1 m.y. interval (71–70 Ma) in the Maastrichtian. At the onset of this change, benthic foraminiferal $\delta^{18}O$ values increased and were highest in low-latitude Pacific Ocean waters, whereas benthic and planktic foraminiferal $\delta^{13}C$ values decreased and benthic values were lowest in the Southern Ocean. Subsequently, benthic foraminiferal $\delta^{18}O$ values in the Indo-Pacific decreased, and benthic and planktic $\delta^{13}C$ values increased globally. These isotopic patterns suggest that cool intermediate-depth waters, derived from high-latitude regions, penetrated temporarily to the tropics. The low benthic $\delta^{13}C$ values at the Southern Ocean sites, however, suggest that these cool waters may have been derived from high northern rather than high southern latitudes. Correlation with eustatic sea-level curves suggests that sea-level change was the most likely mechanism to change the circulation and/or source(s) of intermediate-depth waters. We thus propose that oceanic circulation during the latest Cretaceous was vigorous and that competing sources of intermediate- and deep-water formation, linked to changes in climate and sea level, may have alternated in importance.

INTRODUCTION

During the early Maastrichtian (ca. 71 Ma), important changes occurred in climate, weathering, sea level, biota, and the global carbon cycle. Global climate was characterized by rapid cooling within the long-term post-Santonian refrigeration of high-latitude surface and intermediate waters (Barrera, 1994; Huber et al., 1995). The intensity of continental weathering increased, as inferred from the rate of change of the seawater $^{87}Sr/^{86}Sr$ ratio (Nelson et al., 1991; Barrera, 1994), while sea level dropped (Haq et al., 1987). Invertebrates such as rudists and inoceramid bivalves underwent extinction (Johnson and Kauffman, 1996; MacLeod and Huber, 1996), and North American angiosperms declined abruptly in diversity (Johnson, 1992). Benthic and planktic foraminiferal $\delta^{13}C$ values in the Southern Ocean decreased markedly at 71 Ma, followed by a sharp rise at 70 Ma (Barrera and Huber, 1990; Barrera, 1994).

Here we present the first evidence that a short-lived global oceanographic episode occurred in the early Maastrichtian (ca. 71 to 70 Ma), during which time thermohaline circulation was dominated by a mechanism similar to that of today: cool surface waters at high latitudes sank to form the intermediate and deep waters of the tropics. Prior and subsequent to that episode, the driving mechanism of Maastrichtian thermohaline circulation was different. Our conclusions are based on new foraminiferal $\delta^{18}O$ and $\delta^{13}C$ data from Deep Sea Drilling Program (DSDP) Sites 305, 463, and 465 in the Pacific Ocean, and published data for Ocean Drilling Program (ODP) Sites 690, 750, and 761 (Barrera and Huber, 1990; Barrera, 1994). Correlation of these sections across latitude was achieved for the first time with the aid of $^{87}Sr/^{86}Sr$ data. Paleodepths at all sites were between ~800 and 1800 m (Table 1), an interval that in the modern oceans is bathed by intermediate-water masses. Our synthesis thus yields a large-scale areal isotopic characterization of intermediate-depth waters (Fig.1).

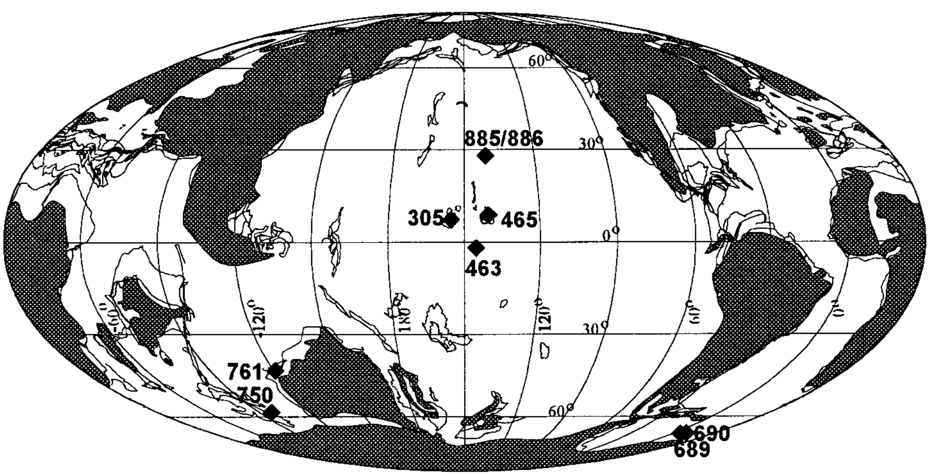

Figure 1. Paleogeography reconstruction at 70 Ma, showing location of deep-sea sites discussed in this study. Dark areas were above sea level, and areas defined by thin lines were blocks and terranes below sea level. South Atlantic and southwestern Indian Ocean waters may have been separated from southeastern Indian Ocean waters at intermediate depths by Kerguelen Plateau, Ninetyeast Ridge, India, and Madagascar.

SAMPLE MATERIAL

We analyzed monospecific benthic and shallow-dwelling planktic foraminifera; the samples were restricted to a narrow size fraction (planktic species: 200–250 µm; benthic species: 200–300 µm) to minimize biases due to vital effects (Barrera and Keller, 1994). Published isotope records for Sites 305, 463, and 465 are from samples taken at large spacing intervals and generally based on mixed taxa (Douglas and Savin, 1975; Boersma and Shackleton, 1981). Benthic and planktic foraminiferal specimens from all sites appear well preserved under the optical microscope, but show evidence of minor recrystallization of the wall structure under the scanning electron microscope. The consistency of $\delta^{18}O$ trends

TABLE 1. SAMPLE LOCALITIES USED IN THIS STUDY

Site	Latitude	Longitude	Water depth (m)	Paleodepth* (m)
305	32°13'N	157°51'E	2903	~1000
463	21°21'N	174°40'E	2525	~1000-1500
465	33°49'N	178°55'E	2161	~1200-1500
750	57°35'S	81°14'E	2041	~1000
761	16°44'S	115°32'E	2188	~ 800
690	65°10'S	01°12'E	2914	~1800

* From Thomas (1990) and unpublished data.

Data Repository item 9742 contains additional material related to this article.

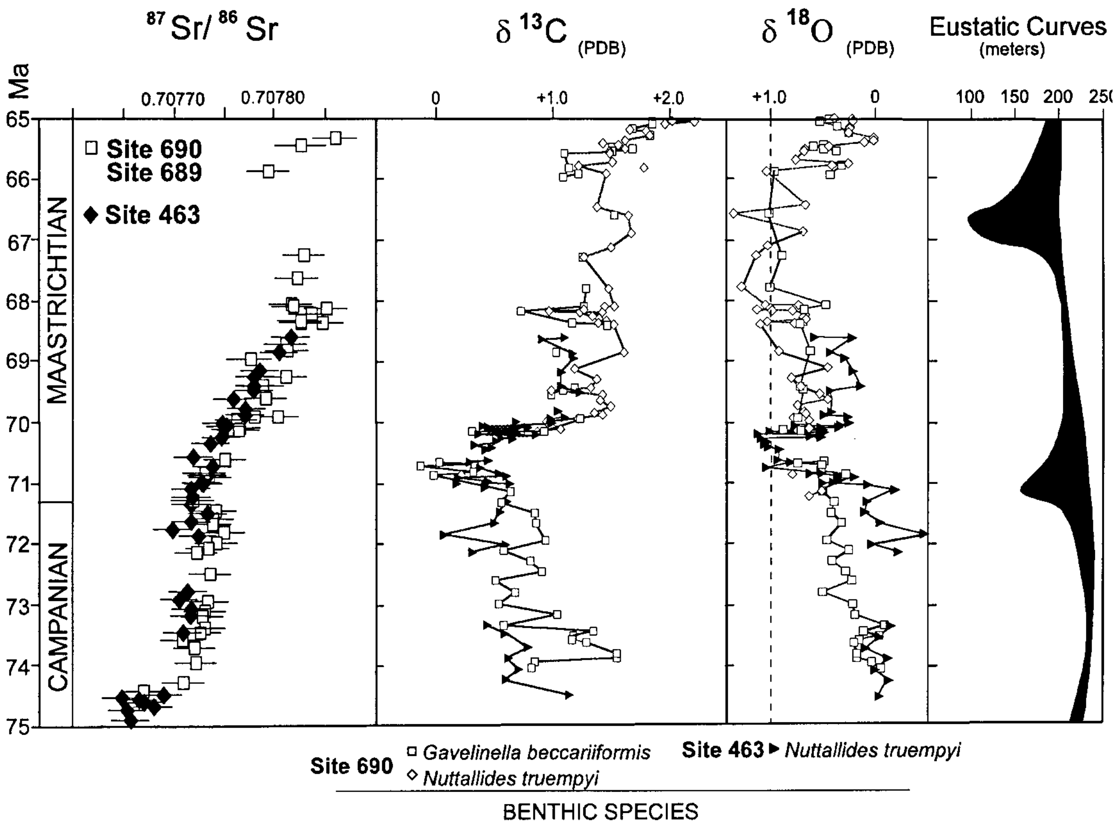

Figure 2. Strontium isotope records of planktic foraminifera and oxygen and carbon isotope records of benthic foraminifera plotted vs. sediment age at Sites 690, 689, and 463 are compared with sea-level curve of Haq et al. (1987), plotted using chronology of Cande and Kent (1995). $^{87}Sr/^{86}Sr$ ratios are normalized to NBS-987 = 0.710 235. PDB = Peedee belemnite.

among the sites (discussed below) is the main evidence that suggests that little diagenetic change of original ratios has occurred.

Time control for high-latitude Sites 690, 750, and 761 is provided by biostratigraphy and paleomagnetic-reversal stratigraphy (Barrera and Huber, 1990; Pospichal and Wise, 1990; Hamilton, 1990; Watkins, 1992; Galbrun, 1992). Numerical ages were assigned based on the magnetochronology of Cande and Kent (1995). Time control for low-latitude Sites 305, 463, and 465 is provided by biostratigraphy (Caron, 1975; Boersma, 1981; Cepek, 1981) and by comparison of their $^{87}Sr/^{86}Sr$ records with the $^{87}Sr/^{86}Sr$ data from Site 690 (Fig. 2). There appears to be a slight offset of 0.000 015 between the data at Sites 690 and 463. Linear regressions of the flat (ca. 74 to 70.5 Ma) and steep portion (ca. 70.5 to 68 Ma) of the curves define the break in slope and allow a correlation at this point to within about ±0.5 m.y. We further refined the correlation among all sites by making relatively small adjustments to improve the degree of matching of $\delta^{13}C$ records.[1] The records of Sites 305 and 465 are incomplete because of carbonate dissolution and poor recovery. The sedimentation rate at Site 463 was high, reflecting its deposition near the paleoequator (Fig. 1). The interval studied has been denoted in previous isotopic studies (Barrera, 1994; Barrera et al., 1995) as "middle Maastrichtian." However, in view of revision of the age of the Campanian-Maastrichtian boundary from 74.5 Ma to 71.3 Ma (Gradstein et al., 1994), a late Campanian to early Maastrichtian assignment, within the low-latitude planktic foraminiferal *Gansserina gansseri* Zone and the nannofossil *Lithraphiditus praequadratus* (NC21) Zone (Bralower et al., 1995), is more appropriate.

ISOTOPIC RESULTS

Benthic $\delta^{18}O$ values at all Indo-Pacific sites were higher by 0.5‰ to 1.0‰ between 71 and 70 Ma than during the preceding and subsequent 2 m.y. intervals (Figs. 2 and 3). The largest change observed at 71 Ma, +1.0‰ at Site 463, occurred in a stepwise manner in <0.3 m.y. The termination of the episode of high $\delta^{18}O$ values at Site 463 was characterized by high isotopic variability, with sample-to-sample fluctuations as large as 0.5‰. The $\delta^{18}O$ values at South Atlantic Site 690 at 71 Ma increased less than at the Indo-Pacific sites and did not decrease at 70 Ma.

The shallow-dwelling planktic foraminiferal $\delta^{18}O$ values at most sites gradually increase between 74 and 71 Ma (Fig. 3). Planktic $\delta^{18}O$ values increase at 71 Ma, but $\delta^{18}O$ decreases at 70 Ma are less well defined, except at the South Atlantic site. The $\delta^{13}C$ values of planktic and benthic foraminifera follow similar trends at all sites, permitting their use to fine-tune age assignments (Fig. 3). During the interval of high $\delta^{18}O$ values between 71 and 70 Ma, $\delta^{13}C$ values at all sites are sharply lower than those of both the preceding and subsequent intervals.

Interpretation of the episode between 71 and 70 Ma requires an understanding of two striking features of the data. (1) Maximum $\delta^{18}O$ values at Site 463 between 71 and 70 Ma were higher than those at any other site, but lower than those of any other site both before and after this episode. (2) The benthic $\delta^{13}C$ values in the Southern Ocean were higher than those of the equatorial Pacific between 74 and 71 Ma and subsequent to 70 Ma, but from 71 to 70 Ma, $\delta^{13}C$ values in the South Atlantic were lower than at any other site.

DISCUSSION

The $\delta^{18}O$ records of planktic and benthic foraminifera from most of the sites show a trend of increasing values, indicating cooling of surface and intermediate waters, particularly at high latitudes, from 74 to at least 68 Ma (Fig. 3). Superimposed on this long-term trend was a short-term episode at 71 Ma when intermediate waters on a large regional scale, and possibly surface waters at high southern latitudes, cooled substantially, then warmed at 70 Ma. Planktic foraminiferal $\delta^{18}O$ values in the tropics and at middle latitudes increased slightly at 71 Ma. This increase reflects a minor decline in surface-water temperature and/or in the average $\delta^{18}O$ value of seawater,

[1]GSA Data Repository item 9742, age model of the deep-sea sections and the Sr-isotopic data and method of this study, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

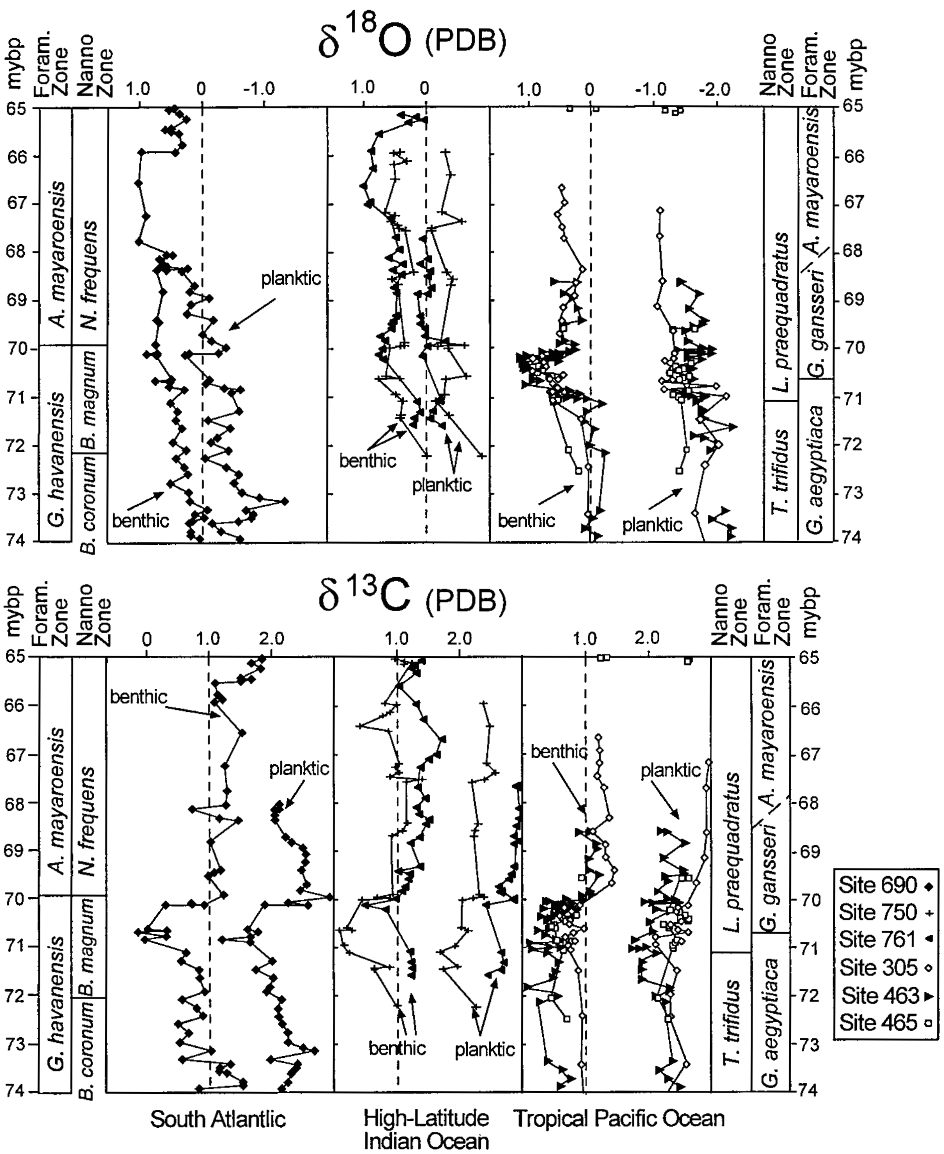

Figure 3. Correlation of oxygen and carbon isotope records of Sites 690, 750, 761, 465, 463, and 305 vs. sediment age, showing planktic foraminiferal and nannofossil zonations for southern high-latitude (Barrera and Huber, 1990; Pospichal and Wise, 1990; Watkins, 1992) and tropical Pacific sites (Caron, 1975; Boersma, 1981; Cepek, 1981). Analyses are of benthic species *Gavelinella beccariiformis* for Sites 690, 750, and 761, and *Nuttallides truempyi* for Sites 305, 465, and 463; and planktic species *Archeoglobigerina australis* for Sites 690 and 750, *Rugoglobigerina* sp. for Site 761, and *Pseudoguembelina costulata* and *Psg. excolata* for Sites 305, 463, and 465.

such as might be caused by an increase in continental ice volume.

The similar isotopic trends from 74 to 68 Ma, but the different absolute δ^{18}O values at each of the Indo-Pacific sites, suggest that the intermediate water bathing each of the sites was generated by sinking of surface waters at a restricted number of locations, each of which was affected by relatively similar (thus possibly global) climatic change (Figs. 2 and 3). In the central Pacific Ocean before 71 and after 70 Ma, δ^{18}O values suggest that intermediate waters at the deeper-water Site 463 were warmer than those at the nearby shallower-water Sites 305 and 465. To maintain a stable density stratification, intermediate waters at Site 463 must have also had higher salinity than those at Sites 305 and 465. In the 71 to 70 Ma interval, δ^{18}O values at Site 463 indicate cooler waters than those at Sites 305 and 465; i.e., a water temperature vs. depth relationship similar to that observed there today. Thus, the benthic foraminiferal δ^{18}O increase in the Indo-Pacific basin at this time could reflect a short-term influx of cool waters from a high-latitude source. In contrast, the lower benthic δ^{18}O values before 71 Ma and after 70 Ma may reflect mixing of Indo-Pacific intermediate waters with warm salty waters, possibly originating from lower-latitude regions (e.g., eastern Tethys and/or Atlantic Ocean), and/or a decreased flux of high-latitude cool waters (MacLeod and Huber, 1996). Short-term occurrence of such cooler, oxygenated waters may have been at least the partial cause of the extinction of organisms adapted to warm, low-oxygen waters such as inoceramids. The source(s) and total vertical extent of the cool water mass invading the Indo-Pacific basin in the 71–70 Ma interval cannot be determined on the basis of foraminiferal stable isotope data. Sediments in contact with deep and bottom waters at the time are noncalcareous because of the shallow calcite compensation depth (Van Andel, 1975). However, evidence from accumulation rates of distal hydrothermal precipitates at North Pacific ODP Sites 885 and 886 (Fig. 1) at paleodepths below 5000 m suggests a temporary change in bottom-current flow at ca. 70 Ma and possibly a southwardly flow of bottom waters from the North Pacific (Dickens and Owen, 1995).

Benthic foraminiferal δ^{13}C data support the hypothesis that oceanic circulation changed at ca. 71–70 Ma. Modern deep waters distant from their source have lower δ^{13}C values than younger waters (Kroopnick, 1980). During the 71–70 Ma interval, benthic foraminiferal δ^{13}C values at polar Sites 690 and 750 became lower than at Pacific Site 463 (Figs. 2 and 3), which could mean that southern high-latitude waters were more distant from their source than low-latitude Pacific waters and, possibly, that the cooler waters were derived from high northern, rather than southern latitudes. An important caveat is that, by analogy to the modern ocean, waters at intermediate depth may have been too shallow to record δ^{13}C water-mass aging effects (Kroopnick, 1980). Moreover, flow of Indo-Pacific intermediate waters into the South Atlantic basin may have been restricted by topography (Fig.1).

The 71–70 Ma change in oceanic circulation would have resulted from a short-term process, which affected the volume and/or density of the dominant source waters. Barrera (1994) used magnetostratigraphic data to suggest that the foraminiferal positive δ^{18}O and negative δ^{13}C excursions in the Southern Ocean were coeval with a eustatic sea-level drop (Haq et al., 1987), and that fluctuations in δ^{13}C values could have resulted from the erosion and storage of organic carbon with sea-level change. The correlation between sites as proposed here supports the tentative link between changes in eustatic sea level and δ^{13}C values: planktic and benthic foraminiferal values at all sites show similar fluctuations (Figs. 2 and 3).

CONCLUSIONS

Thermohaline circulation in the Indo-Pacific Basin before 71 Ma and after 70 Ma may have been dominated by the flow of warm-water plumes with relative high salinity. Intermediate and deep waters generated by this process would have been cool, because the bulk of the water composing these water masses and entrained by the warm saline plumes would have been generated in high-latitude areas. At about 71 Ma, regression may have reduced low- and middle-latitude areas of warm-saline water formation, which may have caused weakening or termination of warm-saline plume formation. Intensification of high-latitude cooling at 71 Ma would have also contributed to the dominance of a high-latitude source of intermediate and deep waters. Thermohaline circulation at this time would have been more similar to today's, although there were probably no restricted frozen seas, as at present, for the rapid generation of salty and cold water masses. At about 70 Ma, the numerous high-frequency ^{18}O oscillations during the termination of the episode of high δ^{18}O values at Site 463 (Fig. 2) may indicate the instability of the thermohaline system, possibly resulting from changes in the size of the warm saline water reservoir and gateway as well as the volume of the warm saline plume(s) during a time of rising sea level.

Our data thus indicate that during overall warm periods of Earth history such as the latest Cretaceous, deep-sea circulation was not sluggish and invariant, but was characterized by relatively rapid changes, possibly because density differences between different water masses were relatively small.

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