Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation

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The Late Cenozoic closure of the seaway between the North and South American continents is thought to have caused extensive changes in ocean circulation and Northern Hemisphere climate. But the timing and consequences of the emergence of the Isthmus of Panama, which closed the seaway, remain controversial. Here we present stable-isotope and carbonate sand-fraction records from Caribbean sediments which, when compared to Atlantic and Pacific palaeoceanographic records, indicate that the closure caused a marked reorganization of ocean circulation starting 4.6 million years ago. Shallowing of the seaway intensified the Gulf Stream and introduced warm and saline water masses to high northern latitudes. These changes strengthened deep-water formation in the Labrador Sea over the next million years—as indicated by an increased deep-water ventilation and carbonate preservation in the Caribbean Sea—and favoured early Pliocene warming of the Northern Hemisphere. The evaporative cooling of surface waters during North Atlantic Deep Water formation would have introduced moisture to the Northern Hemisphere.
Although the pronounced intensification of Northern Hemisphere glaciation between 3.1 and 2.5 million years ago substantially lagged the full development of North Atlantic Deep Water formation, we propose that the increased atmospheric moisture content was a necessary precondition for ice-sheet growth, which was then triggered by the incremental changes in the Earth’s orbital obliquity.

The gradual closing of the Isthmus of Panama lasted from 13 to 1.9 Myr ago (all originally published ages were adjusted to the new astronomically dated timescale). Most evidence for restricted water-mass exchange through the Panama strait is based on sediment records from Caribbean and Pacific Deep Sea Drilling Program (DSDP) sites 502 and 503. Significant changes in planktonic foraminiferal assemblages occur at 6.8, 4.6, 2.5 and 1.9 Myr (ref. 4). A surface-water salinity increase in the Caribbean at 4.6 Myr is indicated by δ18O values of planktonic foraminifera and implies a shoaling of the seaway to <100 m water depth. Shallow-water fossils from both sides of the Panama–Costa Rica region indicate the closure was almost complete at 3.6 Myr, but the final closure allowing land mammal exchange was achieved at 2.7 Myr, coincident with the glacial-induced sea-level drop during the main intensification of Northern Hemisphere ice-sheet growth. However, the identification of the particular step in the closure of the Panamanian gateway that acted as a critical threshold for profound changes in deep-ocean circulation and climate remained qualitative and speculative. Here we present a data set which demonstrates that the closure has affected deep ocean circulation since 4.6 Myr ago.

Today, a mixture of nutrient-enriched, low-δ13C Antarctic Intermediate Water (AAIW) and nutrient-depleted, high-δ13C Upper North Atlantic Deep Water (UNADW) and Mediterranean Overflow Water cross the Atlantic–Caribbean sills at 1,600–1,900 m (Windward Passage, Anegada–Jungfern Passage) and fill the deep Caribbean basins. During the past 2.5 Myr, the relative proportion of northern- and southern-component water masses were related to glacial–interglacial differences in the formation rate of UNADW. A weaker UNADW formation during interglacials led AAIW to extend further north and result in a less ventilated, more corrosive Caribbean deep water. Hence, the Caribbean Sea is a highly sensitive recorder of ventilation changes in the upper Atlantic if the sill depth remained constant. Tectonic evidence from the Lesser Antilles arc and Aves ridge suggests no significant vertical movements since the middle Miocene (20–15 Myr ago) when a thick crust was established; vertical movements of <100 m Myr−1 are expected, which were likely to have been closer to a few metres per Myr (ref. 11).

We report epibenthic foraminiferal δ13C and percentage sand records of the carbonate fraction from ODP Site 999 (12°44′N, 78°44′W, Colombian basin, water depth 2,828 m) for the time interval 2.0–5.3 Myr. The δ13C values of Cibicidoides wuellerstorfi are a proxy for deep-water ventilation, as δ13C of sea water is closely linked to seawater nutrient and oxygen levels, with higher δ13C values indicating lower nutrient concentrations and better ventilation. The sand content (>63 μm) of deep-sea carbonates is a sensitive indicator of changes in carbonate dissolution. The sand content (foraminifera shells) decreases as dissolution progresses. The δ18O of C. wuellerstorfi is a proxy for changes in continental ice volume and deep water temperature. The age model of Site 999 is based on δ13C stratigraphy, and was correlated to the astronomically dated δ18O records from equatorial east Pacific Site 846 (ref. 6) and equatorial east Atlantic Site 659 (ref. 15).

Oceanographic conditions that result in changes in both δ13C and sand contents are documented in Figs 1 and 2. Before 4.6 Myr, low epibenthic δ13C values and low sand contents indicate a poorly ventilated deep Caribbean and severe carbonate dissolution. In the early Pliocene, similar low δ13C values of ~0.2‰ have been
documented only at subantarctic South Atlantic Site 704 (ref. 16) (2,532 m water depth), in contrast to higher North Atlantic values of ~1‰ (for example, sites 659, 552 (ref. 17)). This suggests that the Caribbean deep water was dominated by a δ13C-depleted Southern Ocean water mass (AAIW) before 4.6 Myr. After 4.6 Myr, deep-water ventilation as well as carbonate preservation increased into the late Pliocene due to a deepening of the lysocline. This is interpreted to reflect a progressively stronger influence of less corrosive and δ13C-enriched northern component water due to an increase in UNADW formation. This increase at 4.6 Myr is paralleled by an increased formation of Lower North Atlantic Deep Water (LNADW) as indicated by records of deep-water ventilation (Fig. 1) and carbonate preservation in the equatorial east (ODP sites 639 and 665 (ref. 18)) and west Atlantic (Ceará rise depth transect, sites 925–929 (ref. 19)) below 3,000 m water depth.

A first ventilation maximum in the Caribbean Sea as well as in the deep Atlantic was reached at 3.6 Myr, when Caribbean δ13C values approached those from North Atlantic component water (Site 659, Fig. 1). This mechanism supplied additional heat and moisture to the Northern Hemisphere and may have contributed to the mid-Pliocene warmth. Since 3.6 Myr, both sites 999 and 659 show similar δ13C minima and reflect the increased strength of northern component water masses. During cooler periods, δ13C minima at Site 659 are more pronounced than those from Caribbean Site 999 and reflect vertical fluctuations of the LNADW-AABW mixing zone (AABW, Antarctic Bottom Water). Thus, even though LNADW may have been in the ‘reduced’ mode during harsh climate episodes, the Caribbean was still relatively nutrient-poor compared to the deep Atlantic (Site 659) because of increased formation of UNADW. This suggests that the familiar dipole in the Pleistocene ocean circulation10,20 has been operating at least since 3.6 Myr ago.

The comparison between the Caribbean and Pacific sand-fraction records of sites 999 and 846 demonstrates a substantial change in ocean carbonate preservation at 4.6 Myr (Fig. 2). Before 4.6 Myr, vigorous carbonate dissolution characterized both the Caribbean and the Pacific. Beginning at 4.6 Myr, the increasing thermohaline circulation amplified the inter-basin fractionation between the Atlantic and Pacific, which is reflected in a strong increase in Caribbean and Atlantic19 carbonate preservation and a remaining strong carbonate dissolution in the Pacific. This sedimentary response to changes in ocean circulation before and after isthmus formation has been predicted by ocean model studies21.

Our data provide a precise picture of the final phase of NADW intensification that had been developing during the mid-Miocene22. In response to the gradual emergence of the Central American seaway, we observe an enhanced thermohaline overturn since 4.6 Myr that reached a first maximum at 3.6 Myr. This was amplified by an increased salt transport to the North Atlantic and the initiation or intensification of UNADW formation in the Labrador Sea, as predicted by recent results23 from global circulation model simulations. In support of this interpretation, we note that results from the Labrador Sea (ODP Leg 105) indicate increased bottom-water currents and drift sedimentation since ~4.5 Myr (ref. 24).

The closure of the Panamanian seaway has always been an attractive candidate for the ultimate cause of the Pliocene intensification of the Northern Hemisphere glaciation2. The pronounced ice-sheet growth in Eurasia, Greenland and North America is marked by a progressive 18O-enrichment in benthic foraminifera δ18O records between 3.1 and 2.5 Myr (Fig. 3) and by the massive appearance of ice-rafted debris in northern high-latitude oceans since 2.7 Myr (ref. 25). The intensification of Northern Hemisphere glaciation finalizes the Cenozoic cooling trend, which started in the late Eocene and is marked by first indications of ice sheets in Antarctica 36 Myr ago26. This long-term cooling is considered to be a direct response to permanent removal of atmospheric CO2 through enhanced silicate weathering27 and/or enhanced burial of organic carbon28 resulting from tectonically uplifted areas such as the Himalayas and American West. This long-term cooling brought the climate system of the Earth to a state critical for ice-sheet build-up in the Northern Hemisphere. This has been the case since ~10–5 Myr ago, when the first, and minor, occurrence of ice-rafted debris in the Arctic and North Atlantic indicates the first attempts of the climate system to start a glaciation29. However, until 2.7 Myr ago, the climate system failed to amplify and continue a large Northern Hemisphere glaciation.

To initiate and continue the build-up of the prominent Laurentide and Scandinavian ice sheets, three factors are needed to act together. First, general cooling must have reached a critical threshold to allow precipitation to fall as snow rather than rain. Second, moisture needs to be introduced to high northern latitudes. Our results suggest that moisture was provided by an increased thermohaline circulation and Gulf Stream flow since 4.6 Myr, well before the intensification of Northern Hemisphere glaciation. Third, astronomical theory requires that the summer in northern high latitudes must be cold enough to prevent winter snow from melting30. High-amplitude fluctuations in the Earth’s obliquity (low tilt angle) triggered cold summers in the Northern Hemisphere, and prepared the way for strengthening of the glacial–interglacial 41-kyr cycles during late Pliocene and early Pleistocene15,30. However, a pronounced long-term minimum in obliquity amplitude fluctuations occurred between 4.5 and 3.1 Myr (ref. 31). The δ18O records of sites 659 (ref. 15), 846 (ref. 6) and 999 show that during this unfavourable orbital configuration there may have been several failed attempts of the climate system to start the glaciation, for example during 4.1–3.9 Myr and 3.5–3.3 Myr. We therefore suggest that the progressive increase in obliquity amplitudes between 3.1 and 2.5 Myr was the final trigger for amplification and continuation of the long-term expansion of Northern Hemisphere ice sheets after the necessary preconditions were met 4.6–3.6 Myr ago by formation of the Isthmus of Panama. These incremental changes in obliquity31, coupled with changes in the background state of the ocean, suggest a threshold value for ice-sheet growth, which should be testable with climate models.

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