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Closing of the Central American Seaway and the Ice Age: A critical review

Peter Molnar[1]

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[1] What role did the closing of the Central American Seaway play in enabling continental ice sheets to wax and wane over North America and Fennoscandia? A summary of relevant evidence presented here permits a causal relationship between them but can be interpreted to show none. The common denominator of such evidence is the approximate simultaneity of that closing with global cooling and the first major ice advance. At the resolution of paleoclimate, however, geologic evidence from Central America places only weak constraints on when interchange between Pacific and Caribbean water ceased. The strongest evidence for when North and South America became connected by a continuous land bridge, the "Great American Exchange" of vertebrates, assigns climate change the causal role, for an arid Central American climate, typical of glacial times, seems necessary for animals that inhabited savannas to pass through Panama. Paleoceanographic and geochemical studies of environments and water masses in the eastern Pacific, western Caribbean, and Atlantic in general call for continual change since ~6 Ma or earlier, if evidence concurrent with global change near 3.5–3 Ma seems more widespread than for other times. Hypothesized connections between a closed seaway and glaciation commonly call for profoundly different North Atlantic Ocean circulation, but simulations using general circulation models provide a spectrum of differences in circulation for open and closed seaways. Might much (not all) of the evidence implicating the closing of the seaway in global climate change in fact be a consequence of that change and blind to Central America's tectonic development?

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1. Introduction

[2] The recognition that ice sheets began to grow in the Northern Hemisphere at approximately the same time that the Isthmus of Panama emerged and the Central American Seaway closed has led logically to the inference that the latter somehow caused, triggered, or at least facilitated the climate change toward recurring continental ice sheets in the Northern Hemisphere. Whether argued qualitatively or buttressed by sophisticated model calculations, however, attempts to link the Ice Age to the closing of the seaway have created a myriad of conflicting opinions that range from promoting such a cause-and-effect relationship [e.g., *Burton et al.*, 1999; *Cronin*, 1988; *Frank et al.*, 1999a; *Haug and Tiedemann*, 1998; *Haug et al.*, 2001; *Keigwin*, 1978, 1982; *Lear et al.*, 2003; *Nesbitt and Young*, 1997; *Tiedemann and Mix*, 2007]; to questioning such a role [e.g., *Dowsett et al.*, 1992; *Lunt et al.*, 2007; *Mudelsee and Raymo*, 2005; *Raymo*, 1994], to hypothesizing its opposite, that closure delayed the Ice Age [*Berger and Wefer*, 1996; *Klocker et al.*, 2005]; to suggesting that a gradual emergence led to a gradual change in ocean circulation but not continental ice sheets [*Poore et al.*, 2006]. Ironically, the range of opinions does not seem to have deterred attribution of major climate change to the closing of the seaway, and discussions of the late Cenozoic cooling into recurring ice ages invariably assign some kind of role to it. Perhaps it is time to question this assignment of cause and effect and to ask a different question: To what extent do the observations linked to the closing of the seaway actually result from climate change?

[3] The evidence that constrains when the Central American landmass emerged and the seaway closed can be divided into three categories: (1) direct geologic observations of crustal thickening and of the emergence of submarine deposits in Central America; (2) the "Great American Exchange" of vertebrates from South to North America and vice versa, which requires a continuous land bridge across which those animals traveled; and (3) the development of differences in marine assemblages and their isotopic signatures in the Caribbean from those in the Pacific. Before addressing how the closing of the seaway might have affected climate and in particular how it led to the Ice Age, it makes sense to review the evidence for a late Cenozoic closing of the seaway. Thus I first discuss the geological evidence from Central America for the construction of the terrain above sea level in this region. Because of the inherent incompleteness of geologic records, the rock record from Central America cannot place a firm date on when the Central American Seaway closed, but it does strongly suggest that a deepwater passage between the Pacific Ocean and Caribbean Sea existed until at least

[1]Department of Geological Sciences, Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, Colorado, USA.

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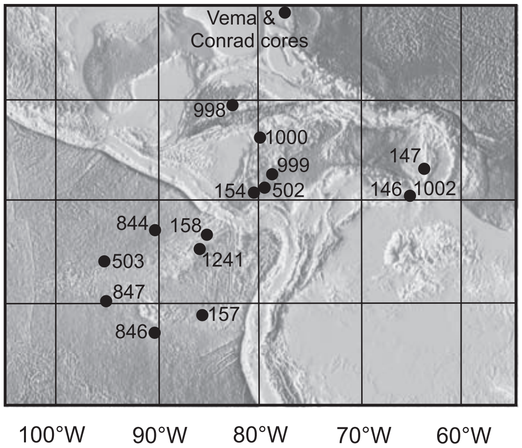

Figure 1. Map of the eastern equatorial Pacific, Central America, the Caribbean region, and northern South America showing locations of drill sites from which much of the paleoceanographic data has been obtained. Sites 849 (0°11′N, 110°31′W, 3839 m), 850 (1°18′N, 110°31′W, 3786 m), and 851 (2°46′N, 110°34′W, 3773 m) lie west of the area shown here.

~7–10 Ma. I then consider the "Great American Exchange," which places the most definitive bound on the age of when closure occurred. Next I address the paleoceanographic constraints on the evolution of the Central American Seaway. Data of three types bear on this history: (1) evolving differences in organisms living at shallow depths in the ocean, (2) the history of differences in physical properties of water masses on the two sides of the present-day isthmus, and (3) the evolution of deep water circulation that commonly is associated with the evolution of both Northern Hemisphere glaciation and the development of the Isthmus of Panama. Finally, I consider numerical calculations of ocean circulation with and without an open seaway and summarize what they seem to show.

2. Tectonic Development of Central America

[4] When North and South America are reconstructed to their positions with respect to Africa in early Mesozoic time, so that both of the South and central Atlantic oceans are closed [e.g., *Bullard et al.*, 1965; *Pindell et al.*, 1988], all of Central America, if treated as part of North America, lies within South America, where it clearly could not have been. Thus the crust that now comprises Central America either must have formed since Mesozoic time or must have lain elsewhere, in either case later to be joined to form the interconnected landmass that exists today.

[5] Crustal fragments in southern Mexico and northern Central America seemed to have been consolidated early in the (Mesozoic or older) history of Central America and during initial migration of North America away from South America. In contrast, the southern part, including parts of Nicaragua and Costa Rica and all of Panama, formed later, initially as part of a volcanic arc [e.g., *Coates and Obando*, 1996; *Coates et al.*, 1992, 2003, 2004; *Mann and Kolarsky*, 1995]. Early Cenozoic volcanic rock and the overlying marine sediment deposited in deep water are now exposed in Central America, but the construction of the volcanic arc that now forms the southern part of Central America began at ~17 Ma [e.g., *Coates et al.*, 1992, 2003, 2004]. From the presence of conglomerate, attesting to nearby subaerial erosion and from neritic organisms in the fossil record, *Coates et al.* [2003] inferred that an archipelago had emerged by ~12 Ma, with much above sea level by 6 Ma. The exchange between North and South America of a few species of mammals that are regarded as strong swimmers suggests relatively close spacing of islands by 6–9 Ma. Between 5.5 and 7.5 Ma and possibly at 9.3 ± 0.8 Ma, "raccoons and their allies" crossed to South America, and at 8.19 ± 0.16 Ma, two genera of South American sloths crossed northward [*Marshall*, 1979, 1985; *Marshall et al.*, 1982; *Webb*, 1976, 1978, 1985, 1997]. On the basis of such evidence, *Coates and Obando* [1996] showed no deep passages between the Pacific and Caribbean in paleogeographic maps for 7–6 Ma, and in their map for 3.5 Ma, they show few shallow gaps. Of course, the necessarily incomplete record for every point along the isthmus makes defining when no gap existed difficult, if not impossible.

[6] Two major events in the development of Central America seemed to have played a role in the emergence of a barrier to interoceanic exchange: (1) the underthrusting of the Cocos Ridge (Figure 1) beneath Costa Rica and western Panama and (2) the collision of the Central American arc with northern South America. The underthrusting of the relatively shallow and buoyant Cocos Ridge is presumed to be responsible for the relatively high elevations and the deeply exhumed rock in Costa Rica and western Panama. Suggested dates for the initiation of this process vary from as little as 1 Ma [e.g., *Corrigan et al.*, 1990; *Lonsdale and Klitgord*, 1978], to 3.6 Ma [*Collins et al.*, 1995], to ~5 Ma [*de Boer et al.*, 1995]. The collision of the Central American volcanic arc with South America occurred earlier; thorough analyses of the records both from marine and terrestrial rocks show that collision occurred in late Miocene time [*Duque-Caro*, 1990], between 12.8 and 7.1 Ma according to *Coates et al.* [2004].

[7] As summarized here, the combination of the formation of a volcanic arc beginning at ~17 Ma and its collision with northern Colombia by ~7 Ma imply that deepwater passages connecting the Caribbean and Pacific Oceans had vanished by ~7 Ma, or perhaps a little earlier. Exchange of shallow water, however, could have continued until more recently.

3. "Great American Exchange"

[8] Although a few mammals from South America crossed into North America and vice versa before ~3 Ma, the major exchange took place beginning in a short interval now dated quite precisely at ~2.6–2.7 Ma. Where best dated, fossils were found in sedimentary rock deposited just below the horizon separating rock with magnetization normally and reversely polarized at the boundary between the Gauss and Matuyama epochs [e.g., *Marshall*, 1985; *Webb*, 1985; *Webb and Rancy*, 1996]. The virtually identical age for this transfer of large mammals with that for the onset

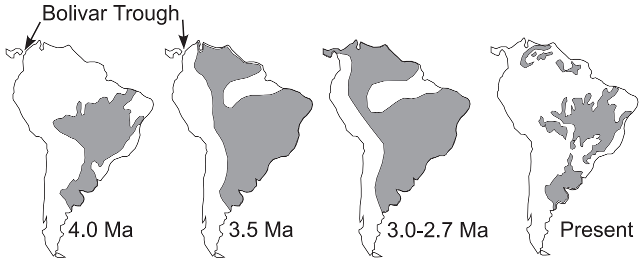

Figure 2. Maps of South America showing suggested regions of savanna-grasslands in shading. (Redrawn from maps in work by *Marshall* [1979, 1985].)

of Northern Hemisphere glaciation did not escape the attention of paleontologists; some of them called attention to the inevitable drop in sea level that must have accompanied such glaciation [e.g., *Gartner et al.*, 1987; *Marshall*, 1985; *Savin and Douglas*, 1985]. Although the large oscillations in δ^{18}O from benthic organisms thought to reflect large volumes of ice in continental ice sheets began near 1 Ma [e.g., *Zachos et al.*, 2001], *Balco et al.* [2005] showed that advances as far south as Missouri occurred at ~2.4 Ma (and indistinguishably different from 2.6 Ma). Moreover, *Naish* [1997] and [*Naish and Kamp*, 1997a, 1997b] showed that large sea level variations of tens of meters, perhaps to more than 100 m, occurred regularly on the southern coast of the North Island of New Zealand beginning at ~2.6 Ma. Thus as *Gartner et al.* [1987], *Marshall* [1985], and *Savin and Douglas* [1985] recognized, the drop in sea level due to climate change may have provided a crucial step for the great interexchange of American mammals.

[9] A drop in sea level alone and the creation of a continuous land bridge between North and South America, however, would not have sufficed to enable "interchange." Many of the animals that changed hemispheres lived in savannas, not the tropical rain forests that presently occupy much of northern South America and Central America; such animals could not traverse this region today [*Marshall*, 1985; *Marshall et al.*, 1982; *Webb*, 1976, 1978, 1985, 1997; *Webb and Rancy*, 1996]. Thus not only was a land bridge necessary for the "Great American Exchange" but so also was a climate very different from that today, one in which mammals adapted to savannas could survive. As Webb, Marshall, and their colleagues recognized [*Marshall*, 1979, 1985; *Marshall et al.*, 1982; *Webb*, 1976, 1978, 1985, 1997; *Webb and Rancy*, 1996], northern South America and Central America must have been much more arid when this exchange took place than they are today (Figure 2).

[10] Much controversy has surrounded differences between glacial and interglacial climates in South America. It appears that vegetation in most, if not all, of the Amazon Basin has changed little from glacial time to the present, and in particular the contention that this region was more of a savanna in glacial times than the present-day rain forest appears to be false [*Colinvaux and De Oliveira*, 2000; *Colinvaux et al.*, 1996, 2000; *Hooghiemstra and Van der Hammen*, 1998; *Kastner and Goñi*, 2003]. Nevertheless, differences between present-day vegetation and that during glacial times in northern South America (Guyana and Surinam [*Van der Hammen*, 1974], Venezuela [e.g., *Bradbury et al.*, 1981; *Hughen et al.*, 2004; *Lewis and Weibezahn*, 1981; *Leyden*, 1985], and Colombia [*Behling and Hooghiemstra*, 1998; *Hooghiemstra and Van der Hammen*, 1998; *Martìnez et al.*, 2003; *Van Geel and Van der Hammen*, 1973]) and in Central America (Guatemala [*Leyden et al.*, 1993], Costa Rica [*Islebe et al.*, 1995], and Panama [*Bush and Colinvaux*, 1990; *Piperno and Jones*, 2003]) suggest that in glacial periods these regions received less rainfall than today. Particularly impressive is a record of organic molecules from Site 1002 in the Cariaco Basin just offshore Venezuela (Figure 1) that allows marine and terrestrial organisms to be distinguished; *Hughen et al.* [2004] analyzed ^{13}C from terrestrial plant lipids and found that shifts in δ^{13}C correlate with the abrupt shifts from the late glacial period to the relatively warm Bølling-Ållerød period, then to the cooler Younger Dryas, and finally to the Holocene warm interval. These shifts show that C_4 plants, which thrive in seasonally dry climates typical of savannas, prevailed in the cold periods, but C_3 plants, which dominate vegetation in humid environments, characterized the warmer periods. These results emphasize a coherence of the climate change in northern Venezuela with that of cold high-latitude climates.

[11] Few would doubt that a land bridge is necessary for large mammals to cross from North to South America or vice versa, and hence the formation of the Isthmus of Panama is a prerequisite for such an exchange. In terms of cause and effect, however, that exchange follows logically from the late Cenozoic change in climate. An isthmus might have formed without a sea level fall associated with advances of ice sheets, but without climate change in the tropics, animals adapted to savannas would have stayed home [e.g., *Marshall*, 1979, 1985; *Marshall et al.*, 1982; *Webb*, 1976, 1978, 1985, 1997; *Webb and Rancy*, 1996]. Ice age conditions, not those associated with interglacial periods, seem to lead to arid conditions necessary for the "Great Exchange." Thus the concurrence of this exchange with the first ice sheet makes the exchange the result of climate change, not evidence that climate change resulted from the closure of the seaway that is so irrefutably necessary for that exchange.

4. Paleoceanographic Evidence for the Closing of the Central American Seaway

[12] As noted above, one may separate paleoceanographic evidence and arguments that have been used to date the closing into three separate categories: (1) the evolution of different taxa on the two sides of the isthmus, which presumably arose from the isolation of those in one ocean from those in the other; (2) the history of water masses on the two sides of the isthmus and the association of differences with restricted flow and/or mixing of them; and (3) inferred changes in large-scale deepwater circulation that are presumed to have occurred when the Central American Seaway closed, and specifically, changes in the production of North Atlantic Deep Water, which various authors have associated with differences in meridional overturning circu-

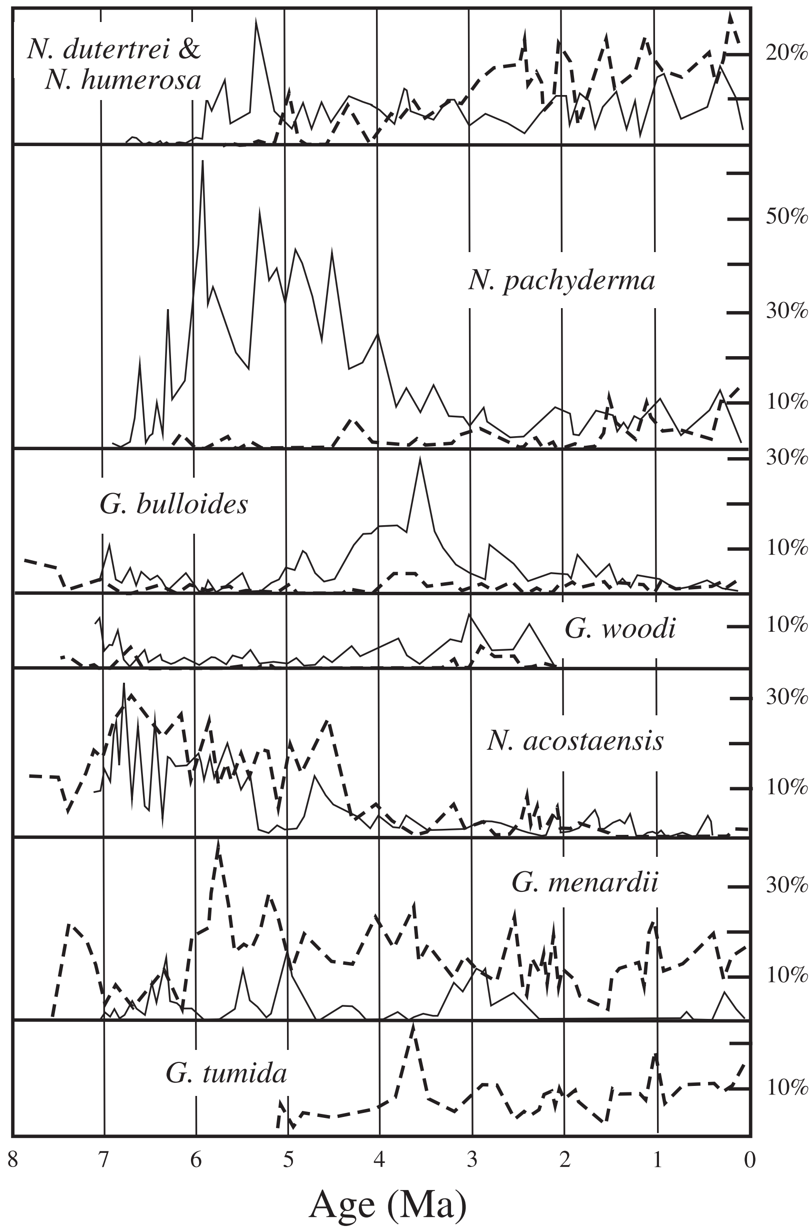

Figure 3. Percentages of various planktonic foraminifera versus age in cores from the Caribbean (Site 502A, solid) and Pacific (Site 503A, dashed). (Redrawn from plots of *Keller et al.* [1989].)

lation. I treat them separately, but as will be clear, doing so will require some repetition.

4.1. Evolution of Shallow Water–Dwelling Animals on the Atlantic and Pacific Sides of Central America

[13] The suggested connection between the closing of the Central American Seaway and the Ice Age rests on their temporal correlation. The work of *Kaneps* [1970] seems to have figured importantly in modern views. *Berggren and Hollister* [1974, p. 159] noted that Kaneps had associated the presence of *Globorotalia miocenica* in the Atlantic and its absence in the Pacific and the interruption of the evolution of the genus *Pulleniatina* in the Atlantic with the emergence of Panama [*Kaneps*, 1979]. Kaneps had relied on samples from piston cores taken by the R/V *Vema* and R/V *Conrad* near Florida (Figure 1). *Saito* [1976] extended this view using a comparison of records from cores in the Atlantic, Indian, and Pacific oceans not near Central America. *Saito* [1976] reported that between 6.5 and 3.5 Ma, most *Pulleniatina* in all oceans coiled sinistrally, but after 3.5 Ma the coiling pattern in the Atlantic became largely dextral and different from that in the Pacific and Indian oceans. Building on *Kaneps*' [1979] work and *Saito*'s [1976] observations but using Sites (147, 148, 154, 157, and 158) (Figure 1) closer to Panama, *Keigwin* [1978] suggested that closure might have been more recent, 3.1 Ma. Gaps in records of these various taxa, however, render the arguments for timing of closure less than defin-

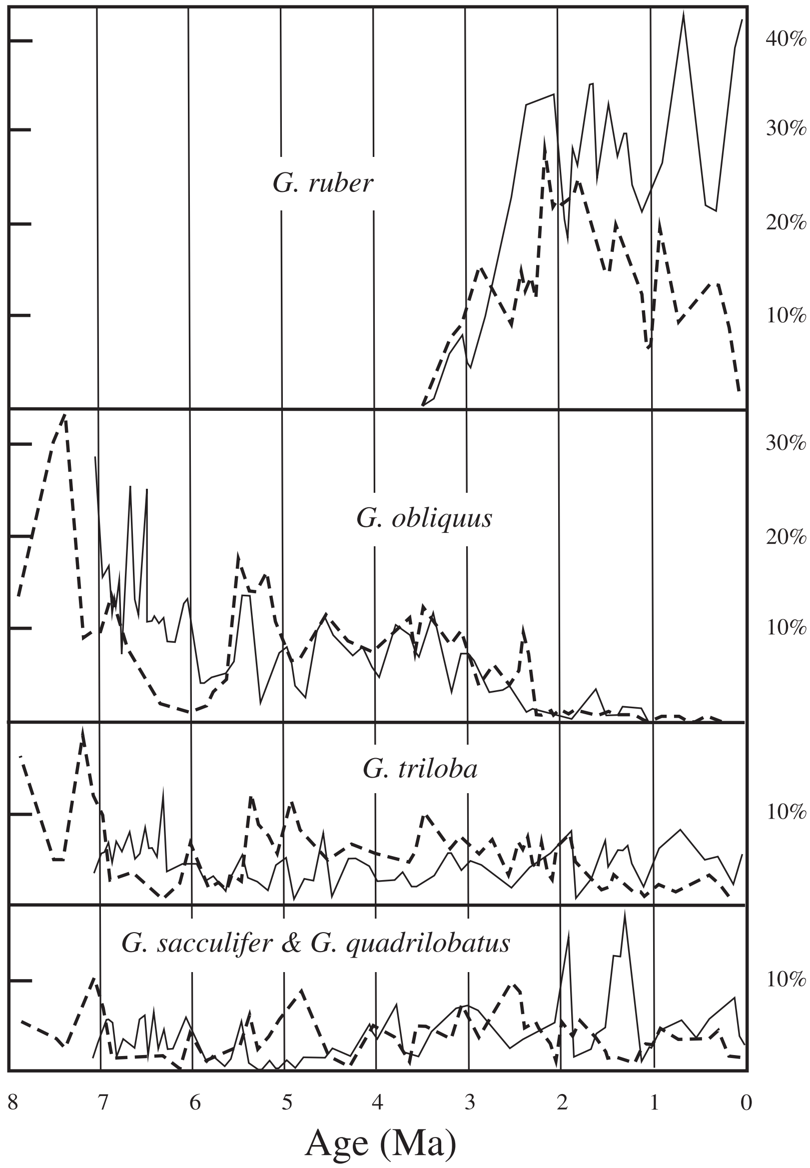

Figure 4. Percentages of various surface-dwelling organisms versus age in cores from the Caribbean (Site 502A, solid) and Pacific (Site 503A, dashed). (Redrawn from plots of *Keller et al.* [1989].)

itive. For instance, both *Saito* [1976] and *Keigwin* [1978] show no evidence of *Pulleniatina* at all in the Atlantic between 3.5 and ~2.3 Ma.

[14] Benthic organisms on opposite sides of Central America seem to have diverged earlier than ~3 Ma. Both *Collins et al.* [1996a] and *Keller et al.* [1989] inferred that marked divergence had occurred by ~6 Ma (Figure 3). Based in part on these data, *Coates et al.* [2004] inferred that a barrier to deep water had formed by 7 Ma.

[15] With reference to surface dwellers, *Keller et al.* [1989] reported a growing abundance of *G. triloba* in the Pacific between 5.4 and 2.4 Ma, but otherwise that most taxa seem to have thrived with comparable ability in both oceans (Figure 4). They argued that the first major, permanent change began at 2.4 Ma (but now closer to 2.6 Ma with revised timescales). Specifically, *Globigerinoides* species, especially *G. ruber*, became dominant in the Caribbean and declined in the eastern equatorial Pacific (Figure 4). Perhaps more impressive than the divergence of *G. ruber* since 2.4 Ma, however, is the abrupt onset of it in both oceans near 3.5 Ma. When viewed all together (Figures 3 and 4), different taxa in pelagic environments across the future isthmus seemed to have evolved independently without a sudden event like that of the "Great American Exchange" discussed above.

[16] Studies addressing changes in diversity of mollusks and other organisms living in littoral environments on the two sides of Central America also suggest gradual, not abrupt, change. Common to many of these studies, and especially those employing DNA dating [*T. Collins*, 1996; *Knowlton et al.*, 1993], is the inference that both diversification and evolution were occurring quite rapidly in late

Miocene time, at ~6 Ma, before most suggested dates for the closure of the seaway [e.g., *L. S. Collins*, 1996; *Collins et al.*, 1996a]. *Kirby and Jackson* [2004, p. 1027] did allow for an association of the extinction of fast-growing oyster *C. cahobasensis* between 4.7 and 4.2 Ma in Central America with a closing of the Central American Seaway. If a single date younger than ~6 Ma recurs more commonly among these studies than any other, however, it would be ~3.5 Ma. Thus although uncertainties in many of these dates surely reach 0.5 Ma, reported changes definitely seem to have preceded the first major advance of ice in the Northern Hemisphere at ~2.6–2.7 Ma [*Allmon et al.*, 1993, 1996; *Budd et al.*, 1996; *Coates et al.*, 1992; *Collins et al.*, 1996b; *Jackson et al.*, 1993, 1996]. For instance, *Allmon et al.* [1993] reported that about 70% of the Pliocene mollusks in the western Atlantic have become extinct since ~3.5 Ma, although high origination rates have sustained the diversity. Later, *Allmon et al.* [1996] specifically noted that extinction in Virginia was rapid between 3.5 and 3.0 Ma before North American ice sheets developed. Similarly, *Budd et al.* [1996] reported that that 75% of coral species in the Caribbean went extinct between 4 and 1 Ma, if again origination maintained diversity. They emphasized that this turnover occurred largely before 3 Ma and maybe before 3.5 Ma [*Budd et al.*, 1996, p. 194]. Perhaps the most definitive study is that of *Coates et al.* [1992], who dated stratigraphic sections on both sides of Central America. They showed that many species of mollusks found on the Pacific side since 3.6–3.5 Ma (50 species between 3.6–3.5 and 1.7–1.5 Ma, 87 at ~1.7–1.5 Ma, and 130 since 1.7–1.5 Ma) cannot be found in Atlantic sedimentary sequences. This result argues for separation by 3.5 Ma, but as their sedimentary sections on the Pacific side begin at 3.6 Ma, isolation of some of these mollusks could have occurred earlier.

[17] Taken together, these various observations make a strong case for evolving environments from ~6 to 3.5 Ma (and perhaps to ~2.5 Ma), and although several authors use their own observations to argue for an age for closure of the seaway at ~3.5 Ma, others do not. Moreover, because the period between ~4–3.5 and ~2.7–2.5 Ma was one of changing climate throughout the Earth, rapid evolution in Central America need not imply changing local tectonic conditions but might instead have resulted from changing global climate.

4.2. Changes in Physical Properties of Shallow Water Across Central America

[18] Physical properties of water in the present-day Caribbean Sea and Pacific Ocean across Central America differ in a number of ways, with the Caribbean being the more saline and somewhat warmer, and the Pacific undergoing the larger seasonal changes. Many attempts have been made to determine when these differences were established with the assumption that those differences developed when the seaway was blocked.

[19] *Keller et al.* [1989] considered the continued increase and growing dominance of *G. ruber*, a "high salinity tolerant species," in the Caribbean (Figure 4) since ~3.5 Ma as an indication of increasing salinity. Correspondingly, the decrease of *G. ruber* in the Pacific since ~2.2 Ma suggests decreasing salinity there. (This date of 2.2 Ma would now be assigned 2.3–2.4 Ma, but their data would also allow an uncertainty of ~0.5 Ma in such an assigned age.)

[20] The value of $\delta^{18}O$ in organisms is sensitive to both the temperature at which organisms calcify and the concentration of ^{18}O in the water, which varies both with local salinity, and as seawater globally is converted into glacier ice. Most organisms retain more ^{18}O in colder than warmer water, but because evaporation preferentially removes ^{16}O from regions where evaporation exceeds precipitation, saline water tends to be richer in ^{18}O than fresher water. Accordingly, microorganisms in relatively saline water yield more positive values of $\delta^{18}O$ than those where water is fresher.

[21] Studies of both planktonic foraminifera and mollusks show changing values of $\delta^{18}O$ on both sides of the seaway but with different amounts or trends. By comparing measurements from Sites 851 (at 110°W) and 999 (Figure 1), *Haug et al.* [2001] showed that values of $\delta^{18}O$ in the eastern Pacific Ocean and Caribbean Sea began to diverge near 4.7 Ma, which they attributed to an increasing difference in salinity between the two oceans. They stated that the modern salinity difference of ~1.5‰ was established at 4.2 Ma, a change also noted by *Keller et al.* [1989] from Sites 502 and 503 and by *Steph et al.* [2006a] from Sites 851, 999, 1000, and 1241 (Figure 1). From a large set of measurements from Site 1241, *Groeneveld et al.* [2006] suggested that the freshening in the eastern equatorial Pacific began at 3.7 Ma. These results refine a pattern inferred by *Keigwin* [1982] (discussed further below), whose study has been one of the bulwarks in the argument that the Central American Seaway closed at ~3.5 Ma.

[22] Using fossil and modern mollusk shells from both sides of Central America, *Teranes et al.* [1996] measured peak-to-peak differences in $\delta^{18}O$ in order to infer ranges of temperature or salinity of water in which they lived (Figure 5). At present, the Pacific shows large seasonal differences in temperature and salinity; $\delta^{18}O$ varies during the year because upwelling events bring cold water to the surface. By contrast, $\delta^{18}O$ varies little in the continually warm Caribbean, where the warmer seasons are also associated with high evaporation and high salinity. The effects of warmth and high evaporation on $\delta^{18}O$ cancel to some extent. Values of $\delta^{18}O$ dating from ~9 and from ~6 Ma, when water in the Pacific and Caribbean apparently was free to mix, show more variation (~1‰) than those in the Caribbean today but less than those from present-day mollusks in the Pacific (Figure 5). Near 3.5 (±~1) Ma, values of $\delta^{18}O$ from the Caribbean side decreased toward values somewhat less than +1‰, indicating somewhat less variability than before, and those from the Pacific, if with scatter, increased toward values of ~+2‰ consistent with increased variability, again as observed today. The timing of the shift toward present-day conditions near 3.5 Ma, however, is not precisely defined (Figure 5).

[23] These results point to increased salinity in the Caribbean since ~3.5 Ma and decreased salinity in the Pacific during the same period. The extent to which these changes

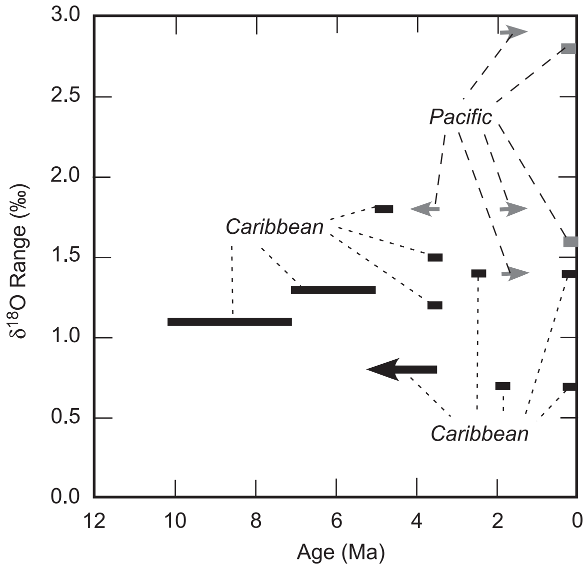

Figure 5. Ranges in δ^{18}O values from fossil and modern mollusk shells taken from the Pacific (gray) and Caribbean (black) sides of as a function of age [*Teranes et al.*, 1996]. Ranges in values sample seasonal differences and therefore provide a measure of seasonal variability in temperature and/or salinity. Bars or lines give age ranges, and where arrows are used, *Teranes et al.* [1996] gave no upper or lower bound on the age. Note the separation between Pacific and Caribbean samples since ~3.5 (±1) Ma, but clearly the date is not tightly resolved.

reflect the closing of the Central American Seaway, however, seems less certain (at least to me). Suppose instead that the main process responsible for a fresher eastern Pacific were simply a change from a permanent El Niño–like state before 3–5 Ma to the modern El Niño–Southern Oscillation (ENSO) state characterized by a relatively cool, cloud-covered eastern Pacific interrupted by occasional El Niño events [e.g., *Dekens et al.*, 2007; *Fedorov et al.*, 2006; *Huybers and Molnar*, 2007; *Lawrence et al.*, 2006; *Molnar and Cane*, 2002, 2007; *Philander and Fedorov*, 2003; *Ravelo et al.*, 2004, 2006; *Wara et al.*, 2005], though see *Groeneveld et al.* [2006], *Rickaby and Halloran* [2005], and *Steph et al.* [2006b] for contrary views. (This begs the question of what processes led to that change from a permanent El Niño–like state to the modern ENSO state, but most hypotheses for this change do not implicate a closing of the Central America Seaway [e.g., *Cane and Molnar*, 2001; *Dayem et al.*, 2007; *Fedorov et al.*, 2006; *Philander and Fedorov*, 2003].)

[24] Modern El Niño conditions in the Caribbean are characterized by a sequence of two different phenomena. First, easterly winds become stronger as the high-pressure center over the eastern Pacific weakens and as the North Atlantic high-pressure system shifts southward and strengthens. With the strengthening of the North Atlantic high, stronger winds cool the Caribbean Sea surface by evaporation and reduce rainfall [*Giannini et al.*, 2000]. Moreover, the enhanced easterlies appear to transport more moisture westward from the Atlantic to the Pacific during El Niño events than during normal times [*Schmittner et al.*, 2000]. Evaporation minus precipitation is greater than normal in the Atlantic and less in the eastern Pacific during El Niño events, as the atmosphere transports the excess evaporation to the region of greater precipitation. Thus at first glance, the shift toward more saline, and perhaps cooler water, in the Caribbean during El Niño does not agree with the proposed shift from a permanent El Niño state before ~3–5 Ma to the present day; paleoceanographic data suggest instead an increase in Caribbean salinity since 3–5 Ma [e.g., *Haug et al.*, 2001; *Keigwin*, 1982; *Keller et al.*, 1989]. During the spring immediately following the mature phase of El Niño, however, rainfall in the Caribbean tends to be unusually high [*Giannini et al.*, 2000]. The intense warming that occurs during the typical El Niño period facilitates atmospheric convection. Thus if the early Pliocene Caribbean Sea surface resembled this second phase of El Niño anomalies, it would be consistent with a shift from a permanent El Niño state. In any case, it is difficult to predict how a permanent El Niño–like sea surface temperature (SST) distribution in the Pacific would affect Caribbean SSTs or precipitation.

[25] In the eastern equatorial Pacific, in addition to the characteristically warm SSTs and the deep thermocline during El Niño events, salinity tends to increase at depths between the mixed layer and the pycnocline (which lies near the 20°C isotherm) [*Johnson et al.*, 2000]. Surface salinity, however, tends to be low during El Niño events because of the heavier than normal rain [*Johnson et al.*, 2002]. Thus on the Pacific side, a shift from a permanent El Niño–like state, characterized by less variability than today (and smaller peak-to-peak differences in δ^{18}O in mollusks [*Teranes et al.*, 1996]), to the present-day ENSO system is consistent with observed trends in δ^{18}O.

[26] In summary, the paleoceanographic results from the Caribbean offer strong support neither for a major role of the closing of the Central American Seaway nor for a pre–Ice Age permanent El Niño condition. They could, however, be forced to fit either.

4.3. History of North Atlantic Deep Water Production and Meridional Overturning Circulation

[27] Many arguments that associate the closing of the Central American Seaway with major climate change link them through a change in the strength of North Atlantic Deep Water production and therefore of meridional overturning (or thermohaline) circulation [e.g., *Berger et al.*, 1993; *Berggren and Hollister*, 1974; *Haug and Tiedemann*, 1998; *Schneider and Schmittner*, 2006]. North Atlantic Deep Water forms when sufficiently saline water releases heat to the atmosphere, cools, and sinks (but not without some process to sustain a compensating upwelling elsewhere [e.g., *Munk and Wunsch*, 1998]). This North Atlantic Deep Water then flows southward through the Atlantic as a western boundary current in the North Atlantic that mixes with water in the adjacent gyre and/or that sank elsewhere. Flowing over and again mixing with colder, denser water that forms in the Weddell Sea, it eventually passes into the Indian and Pacific oceans. Thus flow in the deep Atlantic

depends intricately on how both salinity and temperature affect the density of surface water before it sinks, and tracers of that deep water depend crucially on mixing along its path (as well as on other processes operating elsewhere to assure a compensating, sustained upwelling somewhere). In various versions, the formation of Northern Hemisphere ice sheets is thought to result either from a stronger meridional overturning circulation that transports warm water poleward, which increases transport of moisture from ocean to land, or from a decrease in that circulation and, therefore in northward heat flux that enables the adjacent continents to cool. The closing of the Central American Seaway is presumed to affect the strength of this circulation largely through its effect on salinity in the Caribbean Sea, which influences the salinity of the Gulf Stream and North Atlantic.

[28] Several tracers have been used to quantify the production of North Atlantic Deep Water and the strength of the meridional overturning circulation. Inferences differ not only when the different tracers or methods are used but also when the same method is applied to different sediment cores or sites. I review such evidence, but at the outset let me state a caveat. Studies designed to examine what constraints paleoceanographic measurements can put on fluxes of water masses suggest that such data can map changes in the presence and relative amounts, or "standing crop," of water masses; but by lacking a "clock," they apply, at most, weak constraints on fluxes of water, and hence on the strength of the meridional overturning circulation [e.g., *Huybers et al.*, 2007; *Legrand and Wunsch*, 1995]. Most paleoceanographic studies that employ tracers of water masses rely on box models, and most deduce changes in the balance of fluxes of water masses, such as increased or decreased North Atlantic Deep Water (NADW) compared with other fluxes. As *Legrand and Wunsch* [1995] point out, such deductions are unique only if just two water masses, two boxes in box models, are involved. Because tracer observations can be influenced by other, unmonitored sources or sinks, the assumption of only two water masses may rule out very different changes in fluxes that would be permitted by a less restrictive assumption. I try to be faithful to what others have written, but readers should be aware that the words used below may differ somewhat from the implications of what is written above in this paragraph.

[29] Perhaps the most widely used approach exploits the logic of the meridional overturning circulation as a "conveyer belt" whose deeper branch accumulates and dissolves organic material descending from overlying surface water. Microorganisms preferentially fractionate ^{12}C to make organic molecules. Thus as such organisms sink into the deeper water and dissolve, they reduce the isotopic ratio $\delta^{13}C$ in the deep water, and values of $\delta^{13}C$ in benthic organisms decrease with distance from the North Atlantic to reach a minimum in the North Pacific. Changes in $\delta^{13}C$ over time have been used to infer changes in the strength of the meridional overturning circulation.

[30] Although controversies remain, differences in $\delta^{13}C$ in organisms deposited during glacial and interglacial periods imply that during glacial periods, North Atlantic Deep Water was more restricted to the North Atlantic than during interglacial periods and, by extension, that the meridional overturning circulation was weak during cold periods [e.g., *Boyle*, 1995, 1997; *Boyle and Keigwin*, 1987; *Donnelly et al.*, 2005; *Raymo et al.*, 1989, 1992]. From analyses of both sea surface temperatures using alkenones and deep water nutrient availability using ratios of Cd/Ca benthic organisms, *Rühlemann et al.* [1999] inferred a slowing of this circulation during brief cold periods associated with Heinrich Event H1 16,900–15,400 years ago and with the Younger Dryas.

[31] Analyses of $\delta^{13}C$ for periods spanning much of Neogene time call for widespread North Atlantic Deep Water and strong meridional overturning circulation since at least 7 Ma [*Wright et al.*, 1991] and in most studies since 10 Ma or earlier [*Poore et al.*, 2006; *Woodruff and Savin*, 1989; *Wright*, 1998; *Wright and Miller*, 1993, 1996], although the different studies of $\delta^{13}C$ in benthic organisms report different detailed histories of NADW production and meridional overturning circulation. Using ratios of Mg/Ca in benthic foraminifera, *Lear et al.* [2003] inferred a history of proto–North Atlantic Deep Water that varied in both strength and temperature during the past 12 Ma. (They associated warming of this water (by $\sim$1°C) and increased salinity between 6 and 5 Ma with decreasing flow of surface water through the Central American Seaway.) There seems little doubt that meridional overturning circulation occurred well before ice sheets began forming in the Northern Hemisphere.

[32] From the association of weaker North Atlantic Deep Water production during glacial than interglacial periods, one might expect stronger meridional overturning circulation before $\sim$3 Ma, before continental ice sheets began to accumulate in Canada and Fennoscandia; indeed, most analyses of $\delta^{13}C$ do suggest higher interoceanic differences in $\delta^{13}C$ consistent with stronger circulation before that time [e.g., *Poore et al.*, 2006; *Ravelo and Andreasen*, 2000; *Raymo*, 1994; *Raymo et al.*, 1996; *Wright and Miller*, 1996]. The most prominent exception to this pattern, however, arises with differences in $\delta^{13}C$ across the Isthmus of Panama; *Keigwin* [1982] showed that this difference, between measurements from Sites 502 and 503 (Figure 1), increased at $\sim$6 Ma and again at $\sim$3 Ma to reach the current difference of 1‰. He associated the shift at $\sim$3 Ma with closing of the seaway and a strengthening of North Atlantic Deep Water production.

[33] Following *Keigwin*'s [1982] logic, *Haug and Tiedemann* [1998] reported a shift at Site 999 (Figure 1) in the Caribbean toward higher values of $\delta^{13}C$ between $\sim$4.6 and 3.6 Ma, from which they too inferred a strengthening of meridional overturning circulation that brought water with high $\delta^{13}C$ values to the region. Thus like *Keigwin* [1982] they inferred a strengthening of this circulation as ice age times approached, not a weakening. Moreover, they buttressed this inference by demonstrating an increase at $\sim$4.6 Ma in sand content at Site 999 (particles with sizes bigger than 63 μm) of deep-sea carbonate sediment, which are less sensitive to deepwater dissolution than smaller particles. *Bickert et al.* [2004] extended this record to show that small sizes characterized the period from 8.5 to 5.3 Ma. *Haug and Tiedemann* [1998] and *Bickert et al.* [2004]

interpreted the increase in sand fraction as the result of intrusion of less corrosive water from the North Atlantic than the more corrosive Southern Ocean water and hence a strengthening of the meridional overturning circulation beginning near 4.6 Ma.

[34] Because this inference of a strengthening of North Atlantic Deep Water production conflicts with other observations suggesting the opposite, a weakening, I suspect that there may be another explanation for *Keigwin*'s [1982] and *Haug and Tiedemann*'s [1998] data, such as a shift in the depths occupied by North Atlantic Deep Water and Southern Ocean water masses. Site 999 used by *Haug and Tiedemann* [1998] lies at a depth of only 2,828 m and well below the present-day sill at 1540–1800 m separating the Caribbean from the Atlantic [*Bickert et al.*, 2004] but above depths where colder, heavier water could pond.

[35] Work on benthic organisms in the western Caribbean Sea also suggests variability in deepwater masses within the Caribbean. From assemblages of benthic microfossils from Site 502 (Figure 1), *McDougall* [1996] inferred several changes during the past 7 Ma in both the Caribbean and the Pacific. She reported that before 6.7 Ma, Antarctic Bottom Water (AABW) was present in both areas. From the fossil assemblages, she inferred that since ~6.7 Ma deep water in both regions warmed, and she suggested that the warmer water was North Atlantic Deep Water in the Caribbean and Pacific Deep Water (PDW) in the Pacific. She also inferred that at ~5.6 Ma, both deep and intermediate depth waters became isolated from those on the other side of the isthmus, and she suggested that at ~3.4 Ma, the Caribbean became flooded with cold AABW until 2 Ma. She inferred that changing depths of the sill separating the Caribbean from the Atlantic and changing sea levels played a much more important role in deep water masses in the Caribbean than the growing barrier between it and the Pacific. Although *McDougall*'s [1996] results do not disprove *Haug and Tiedemman*'s [1998] inference that meridional overturning circulation strengthened between 4.6 and 3.6 Ma, they open the possibility that the history of North Atlantic Deep Water in the Caribbean is neither as monotonically simple as Haug and Tiedemann suggested nor related to the closing of the Central American Seaway.

[36] Finally, using principal component analysis of fossil assemblages from five Ocean Drilling Program cores, Sites 998 and 999 in the Caribbean and Sites 844, 846, and 850 in the Pacific (Figure 1), *Kameo and Sato* [2000] sought similarities and differences as a function of time. Plotting the first two principal components versus one another for different periods of time, they showed evolving populations in the region. By associating different populations with different water masses, they then inferred a history of water masses in the region. They deduced that "An important event occurred in the late Pliocene (Interval VIII, 3.65–2.76 Ma)," and they reported that "closure of the Isthmus was completed by 2.76 Ma" [*Kameo and Sato*, 2000, p. 215]. Although their plots of principal components show changes over time, I confess to be unable to see a major change near 2.76 Ma; differences between plots for other adjacent time intervals appear to me to be comparably large.

[37] A second approach to estimating variations in the strength of the meridional overturning circulation exploits isotopic differences in ferromanganese crusts that accumulate on the ocean floor. Because of differences in isotopic ratios on land, water masses that form near different continents can in some cases be fingerprinted with isotopes [e.g., *Frank*, 2002]. The short residence times of some elements, like lead (~50 years in the Atlantic [*Frank*, 2002]), make them less suitable for such fingerprinting than other elements that can be transported large distances before being precipitated from the water column. Accordingly, ferromanganese crusts from the Pacific and Indian oceans show little evidence for change that might be ascribed to changes in meridional overturning circulation at, for instance, 3–4 Ma [e.g., *Abouchami et al.*, 1997; *Christensen et al.*, 1997; *Frank*, 2002; *Frank et al.*, 1999a; *O'Nions et al.*, 1998]. Those from the Atlantic, however, have been used to address variations in NADW. With a residence time of 600–2000 years [*Frank*, 2002], neodymium has been the most widely exploited tracer.

[38] A second problem, independent of mixing of water masses, hinders the use of radiogenic isotopes as tracers and neodymium in particular; large differences in sources of isotopes surrounding the North Atlantic may have contributed to inferences attributed to changes in deep circulation. Many sources of neodymium in the North Atlantic are indistinguishable from those in the Southern Ocean; only Labrador seawater makes NADW distinctive [e.g., *Burton et al.*, 1997; *von Blanckenburg and Nägler*, 2001]. Accelerated erosion by glacial processes of ancient rock with large negative values of $\varepsilon_{\mathrm{Nd}}$, however, may have enhanced the contribution of Labrador seawater $\varepsilon_{\mathrm{Nd}}$, when continental glaciers began to grow near 3 Ma. *Burton et al.* [1999] noted specifically that either increased erosion, as might be expected from increased glaciation, and transport of sediment to the North Atlantic or accelerated deepwater formation could explain the changes in their earlier records [*Burton et al.*, 1997]. Although some studies using neodymium isotopes from ferromanganese crusts in the North Atlantic suggested that near 3–4 Ma (Figure 6), the production of North Atlantic Deep Water increased, if it did not form then for the first time [e.g., *Abouchami et al.*, 1999; *Burton et al.*, 1997, 1999; *Frank et al.*, 1999a; *Ling et al.*, 1997] (or perhaps more recently near 1.8 Ma [*Reynolds et al.*, 1999]), in a subsequent reassessment, *von Blanckenburg and Nägler* [2001] inferred little change in the strength of meridional overturning circulation during this period.

[39] Measurements of other isotopes from ferromanganese crusts in the North Atlantic support this assignment of isotopic change to increased, locally derived terrigenous matter into the Labrador Sea [e.g., *von Blanckenburg and Nägler*, 2001], not a strengthening of the NADW production. *Zhu et al.* [1997] reported a gradual increase in the iron isotopic ratio ε^{57}Fe in the North Atlantic between 6 and 2 Ma and then a more rapid increase at a couple of sites in the North Atlantic, not the sharp change that others had measured for neodymium isotopes near 3–4 Ma. *Zhu et al.* [1997] attributed the change in Nd isotopes to a change in source, not in ocean circulation. Indeed, when more than

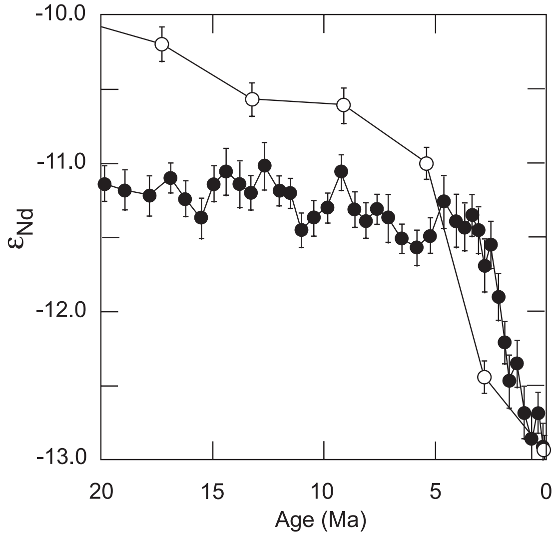

Figure 6. Plots of ε_{Nd} from two ferromanganese crusts in the North Atlantic as a function of age. Open symbols show data of *O'Nions et al.* [1998], and closed symbols show data of *Burton et al.* [1999]. Note the marked change near 3 to 5 Ma, which some attribute to a change in North Atlantic ocean circulation and others to a change in the source Nd, associated with increased glacial erosion since ~3 Ma.

one isotopic system is considered from the same ferromanganese crust, changes in different isotopic ratios commonly are not synchronous [e.g., *Frank*, 2002; *Frank et al.*, 1999b]. In a comprehensive summary, *Frank* [2002] argued for a major change in neodymium isotopes in the North Atlantic near 3 Ma (Figure 6), but he did not emphasize a role for a changing deep circulation. In addition, the residence time of beryllium in the ocean is only ~200–250 years, making its transport in North Atlantic Deep Water as far as the Pacific unlikely but sensitive to changes in the flux of deep water near sources of it. Accordingly, *von Blanckenburg and O'Nions* [1999] used measurements of $^{10}Be/^{9}Be$ in ferromanganese crusts at different distances from the North Atlantic to infer little change in the strength of meridional overturning circulation during this period.

[40] In contrast to these other studies, *Frank et al.* [2002] exploited the change in ε_{Nd} (and in lead isotopes) from ferromanganese crusts in the North Atlantic beginning near ~3 Ma, presumed by others to reflect a changing source of Nd, together with the absence of a change in crusts from the Southern Ocean, to infer a decrease in the intensity of NADW production. They argued that because Nd transported by NADW affects the concentration of ε_{Nd} in the Southern Ocean today, the growing difference in ε_{Nd} between crusts in North Atlantic and Southern Ocean implies a marked weakening of NADW, not an insensitivity of the Southern Ocean to Nd carried by NADW. Roughly synchronous changes in ε_{Nd} in cores from the North and South Atlantic on glacial-interglacial timescales support their assumption that NADW affects the Nd budget of the Southern Ocean [*Piotrowski et al.*, 2004, 2005].

[41] More recently, *Thomas and Via* [2007] exploited Nd isotopes from the southeastern South Atlantic to suggest that North Atlantic Deep Water production gradually strengthened from 23 to 11 Ma, and then between 10.6 and 7.3 Ma, it became much more widespread. They relied on a depth transect (of three sites at different depths on the Walvis Ridge) in the southeastern South Atlantic. All three sites show the same gradual decrease in ε_{Nd} until 10.6 Ma, when the deepest site recorded much more negative values than the shallower sites did. They interpreted that drop in ε_{Nd} to signal a greater fraction of deep water from the North Atlantic. Their data did not sample the past 3 million years well enough to detect or exclude a change since ~3 Ma.

[42] In summary, the inferences that have been drawn from $\delta^{13}C$, both from measurements at a single site and from differences among widely distributed sites, and from other isotopes (ε_{Nd} in particular but also $\varepsilon^{57}Fe$ and $^{10}Be/^{9}Be$) offer evidence that has been taken as consistent with virtually all possibilities: a strengthening [e.g., *Abouchami et al.*, 1999; *Bickert et al.*, 2004; *Burton et al.*, 1997, 1999; *Frank et al.*, 1999a; *Haug and Tiedemann*, 1998; *Ling et al.*, 1997], a weakening [e.g., *Frank et al.*, 2002; *Ravelo and Andreasen*, 2000; *Raymo*, 1994; *Raymo et al.*, 1996; *Wright and Miller*, 1996], or no evidence for any change [*von Blanckenburg and Nägler*, 2001] in North Atlantic Deep Water production and meridional overturning circulation, when global climate shifted to include continental ice sheets, or whenever the Central American Seaway closed. Some studies seem to favor a strengthening of North Atlantic Deep Water formation before 3–4 Ma, perhaps near 10 Ma or even earlier. Moreover, hypothesized stimuli for changes in fluxes include not just a closing of the Central American Seaway (often used more as a deus ex machina than as a cog in a logical wheel), but also the depth of the sill formed by the Greenland-Scotland Ridge in the North Atlantic [e.g., *Poore et al.*, 2006; *Wright*, 1998; *Wright and Miller*, 1996] or varying strength of Antarctic Bottom Water. Insofar as the closing of the Central American Seaway is concerned, applications of both stable and radiogenic isotopes to quantify fluxes, if not just volumes, of various deep water masses seem to leave that seaway's role open.

5. Modeling: Suggested Impacts of the Closing of the Seaway

[43] As noted above, hypothesized impacts of the closing of an open Central American Seaway on ocean circulation and on climate in general span the range from triggering or "causing" an ice age climate to retarding an inexorable trend in that direction. The approximate correlation in time of the closing of Central American Seaway and the onset of Northern Hemisphere ice sheets led logically to inquiries of what effects the closing would have on ocean circulation. Again the spectrum of responses denies us, at least at present, a definitive statement of how an open seaway would affect ocean circulation.

[44] In what appears to be the first application of an ocean global circulation model (GCM) to this question, *Maier-Reimer et al.* [1990] found that opening the Isthmus of Panama, with no other change, caused their calculated thermohaline circulation to collapse, a result similar to what

several others obtained subsequently with GCM runs [e.g., *Klocker et al.*, 2005; *Mikolajewicz and Crowley*, 1997; *Mikolajewicz et al.*, 1993; *Murdock et al.*, 1997; *Prange and Schulz*, 2004; *Schneider and Schmittner*, 2006]. With further calculations employing a spectrum of amounts of flow across the seaway, however, *Mikolajewicz and Crowley* [1997] did find that with a narrowly open seaway, a weak thermohaline circulation could exist.

[45] There seem to be two reasons for the calculated weak (or nonexistent) thermohaline circulation with an open seaway. First, common to most GCM runs is the assumption that present-day salinities in the eastern Pacific and Caribbean, which differ from one another by ∼1.5‰, applied to pre–Ice Age time. Thus if the fresher water of the eastern Pacific mixed with the saline Caribbean water, the lowered salinity and resulting lowered density of water in the northward branch of the meridional overturning circulation might prevent it from sinking when cooled. Second, by assuming present-day winds, including the strong easterlies of the Walker Circulation, these GCM runs induce a strong east-west pressure gradient across the equatorial Pacific Ocean that in turn forces Pacific water at the latitude of Central America into the Atlantic, not to flow in the opposite direction.

[46] Of course, differences in assumptions, including boundary conditions, make ocean GCM runs differ from those of *Maier-Reimer et al.* [1990] and *Mikolajewicz and Crowley* [1997]. For instance, *Murdock et al.* [1997] allowed for some adjustment of the winds to a modified temperature distribution, but the difference appears to be small, and in their calculation, 15.7 Sv of water pass from the Pacific into the Atlantic. The run that differs most from that of *Maier-Reimer et al.* [1990] seems to be that of *Nisancioglu et al.* [2003], who found little reduction in thermohaline circulation with an open Central American Seaway. They too used present-day wind stress fields, and they too calculated that surface water from the Pacific should enter the Atlantic. They also initialized calculations with present-day salinity fields, but their run yielded a smaller reduction in North Atlantic salinity than that of *Maier-Reimer et al.* [1990] and others; hence cooling in the North Atlantic enabled surface water to sink. The most important difference between their run and others, however, seems to be their closing of the Bering Straits as it surely was in most of the Miocene, but not Pliocene, Epoch [*Marincovich*, 2000; *Marincovich and Gladenkov*, 1999, 2001]. At present, relatively fresh water from the North Pacific passes through the Bering Strait into the Atlantic and reduces the salinity of North Atlantic surface water. Thus by denying the Atlantic a source of fresh water from the North Pacific in their calculation, but which other studies had included, the lowered salinity of Atlantic water due to the intrusion of Pacific water through the Central American Seaway did not prevent it from sinking when cooled.

[47] Allowance for both different effects of wind stress and different salinity distributions opens new possibilities for circulation through the Central American Seaway. In simple model runs forced solely by winds, *Nof and Van Gorder* [2003] calculated that Atlantic water should flow into the Pacific, opposite to that in the GCM runs cited above. *Nof and Van Gorder* [2003] assumed a level of no motion at 1500–2000 m. For a barotropic state with surface and deep water following the same paths, however, *Omta and Dijkstra* [2003] calculated that for an open Central American Seaway but closed Tethys (through the present-day Mediterranean to the Indian Ocean) and forced by winds deemed appropriate for early Cenozoic time, Pacific water should flow into the Atlantic.

[48] Similarly, in some coupled atmosphere-ocean GCM runs, surface flow through the Central American Seaway is westward, not eastward [e.g., *Motoi et al.*, 2005; *von der Heydt and Dijkstra*, 2005, 2006]. With a closed Tethys Seaway between Africa and Europe, however, the net flux through a deep Central American Seaway is eastward, because of stronger deeper currents [*von der Heydt and Dijkstra*, 2005, 2006]. Moreover, in these coupled model runs, resulting salinity differences between the Pacific and Atlantic are not great. The studies by *von der Heydt and Dijkstra* [2005, 2006], which focused on a period of geologic time more than 10 Ma before the Isthmus of Panama formed, did not address thermohaline circulation. That of *Motoi et al.* [2005], however, specifically addressed how an open Central American Seaway would affect the thermohaline circulation. In their run with an open seaway, a westward flux of saline water from the Atlantic to the Pacific enabled thermohaline circulation to develop in the North Pacific. *Motoi et al.* [2005] also calculated a reduced northward flux of saline water in the North Atlantic and no thermohaline circulation there, which differs from paleoceanographic inferences [e.g., *Poore et al.*, 2006; *Woodruff and Savin*, 1989; *Wright and Miller*, 1996].

[49] In another coupled atmosphere-ocean GCM run, *Lunt et al.* [2007] found a weaker meridional overturning circulation in the Atlantic with an open seaway, like that for purely oceanic GCM runs that used energy balance atmospheric models and prescribed winds. *Lunt et al.* [2007] focused on the effect of Panama on the growth of ice in the Northern Hemisphere, and they reported that closed seaway led to greater transport of moisture from ocean to land and to greater precipitation on Greenland and North America, but they concluded "that although the closure of the Panama Seaway may have slightly enhanced or advanced the onset of [Northern Hemisphere glaciation], it was not a major forcing mechanism." *Lunt et al.* [2007] extended calculations by *Haywood et al.* [2007], who failed to replicate the small east-west temperature gradient across the tropical Pacific shown by paleoceanographic inferences of early Pliocene SSTs. For me, at least, this failure casts doubt on the assumptions used in these model runs.

6. Discussion and Conclusions

[50] As have others whom I cited in section 5, I challenge the assumption, if not deduction, that the closing of the Central American Seaway was necessary for the climate change leading to the waxing and waning of ice sheets on Northern Hemisphere. First, defining when the seaway closed is difficult, if not impossible, until 2.7–2.6 Ma, when the "Great American Exchange" of vertebrates between North and South America occurred. Yet, for that exchange,

the argument that the closing of the seaway was crucial for climate change seems backward; climate change, if not from lowered sea level [e.g., *Gartner et al.*, 1987; *Marshall*, 1985; *Savin and Douglas*, 1985], almost surely from the aridification of Central America, enabled savannah-dwelling vertebrates to pass through a region that now is inhospitable to them [*Marshall*, 1979, 1985; *Marshall et al.*, 1982; *Webb*, 1976, 1978, 1985, 1997; *Webb and Rancy*, 1996].

[51] Much paleoclimatic evidence now shows that cooling in many places began before 2.7 Ma [e.g., *Dekens et al.*, 2007; *Groeneveld et al.*, 2006; *Lawrence et al.*, 2006; *Marlow et al.*, 2000; *Mudelsee and Raymo*, 2005; *Wara et al.*, 2005]. Correspondingly, many inferences of when the Caribbean and eastern tropical Pacific emergence became sensitive to an obstructed seaway point to the period 1–2 Ma before 2.7 Ma [e.g., *Groeneveld et al.*, 2006; *Haug and Tiedemann*, 1998; *Keigwin*, 1978, 1982; *Keller et al.*, 1989; *Steph et al.*, 2006a, 2006b]. Although all such paleoclimatic evidence can be construed to reflect a consequence of the closing of the seaway, none seems to require that closure for its explanation. It may prove that no other sensible explanation can be offered to explain these data, but the present appears to be too early to draw that conclusion.

[52] Many pairs of runs using general circulation models of the oceans and coupled in different ways to the atmosphere call for a major difference in meridional overturning circulation that depends on whether the Central American Seaway is open or not. Most, however, specify present-day winds and begin with the large sea surface difference in salinity between the eastern Pacific Ocean and the Caribbean Sea for both runs, when other processes might have allowed, if not required, very different wind fields and similar values of salinity across the seaway at 5–3 Ma. Some, but not all, runs with a fully coupled atmosphere, indeed, show ocean circulations with an open seaway that differ significantly from those with imposed wind fields and salinity distributions. Perhaps coupled general circulation models of the atmosphere and oceans can be exploited to define the role of an open Central American Seaway in climate change, but the disagreements among the various model runs suggest that that state has not been reached.

[53] Lest it not be obvious to casual readers, let me state that the closing of the Central America Seaway seems to be no more than a bit player in global climate change. Quite likely it is a red herring.

[54] **Acknowledgments.** This paper grew out of a graduate seminar on climate and tectonics specifically focused on gateways. I appreciate the encouragement and perspectives of participants Sean Bryan, Jill Haynie, Rachelle Richmond, and Marcia Wyatt. I thank Peter Huybers, Ellen Martin, and an anonymous reviewer for unusually prompt constructive criticism and Huybers and Martin for continued advice.

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P. Molnar, Department of Geological Sciences, Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, CO 80309-0399, USA. (molnar@colorado.edu)