Reef drowning during the last deglaciation: Evidence for catastrophic sea-level rise and ice-sheet collapse

SPECIAL REPORT

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ABSTRACT

Elevations and ages of drowned *Acropora palmata* reefs from the Caribbean-Atlantic region document three catastrophic, metre-scale sea-level–rise events during the last deglaciation. These catastrophic rises were synchronous with (1) collapse of the Laurentide and Antarctic ice sheets, (2) dramatic reorganization of ocean-atmosphere circulation, and (3) releases of huge volumes of subglacial and proglacial meltwater. This correlation suggests that release of stored meltwater periodically destabilized ice sheets, causing them to collapse and send huge fleets of icebergs into the Atlantic. Massive inputs of ice not only produced catastrophic sea-level rise, drowning reefs and destabilizing other ice sheets, but also rapidly reduced the elevation of the Laurentide ice sheet, flipping atmospheric circulation patterns and forcing warm equatorial waters into the frigid North Atlantic. Such dramatic evidence of catastrophic climate and sea-level change during deglaciation has potentially disastrous implications for the future, especially as the stability of remaining ice sheets—such as in West Antarctica—is in question.

INTRODUCTION

New evidence from Greenland ice-cores (Alley et al., 1993; Dansgaard et al., 1993; Taylor et al., 1993) and deep North Atlantic sediment cores (Bond et al., 1992; Lehman and Keigwin, 1992) demonstrates that the last glacial to interglacial transition involved sudden—and as yet unexplained—reorganization in ice-sheet, ocean, and atmosphere systems. In the Laurentide ice sheet, for example, two sudden collapse events during deglaciation released huge volumes of ice into the North Atlantic, blanketing a broad swath of the sea bed with ice-rafted sediment (Bond et al., 1992, 1993). Atmospheric circulation also changed abruptly, switching between glacial and interglacial conditions in less than a decade (Alley et al., 1993; Taylor et al., 1993). These events were accompanied by equally dramatic (~40 yr) changes in North Atlantic circulation as the strongly stratified glacial ocean was disrupted by initiation of thermohaline circulation (Lehman and Keigwin, 1992).

Besides investigating such dramatic changes, there is a need to reassess the cause of the Younger Dryas episode—a brief and possibly global return to glacial-type conditions from 12.9 to 11.7 ka (Taylor et al., 1993). (Note: Dates quoted in this paper are calendar years.) Although this episode was attributed to changes in the North Atlantic salt budget (Broecker et al., 1990), the evidence from Greenland shows that it started and ended far too rapidly and was too widespread for ocean forcing to have been the sole cause (Denton and Hendy, 1994). Any theory explaining late-glacial climate must account for the abruptness of these changes. This rules out mechanisms with slow response times, such as insolation, atmospheric CO_2 content, and whole-ocean salt budgets, and points to a triggering mechanism.

To address these problems and identify the deglacial triggering mechanism, we constrain the rate, magnitude, and timing of glacio-eustatic sea-level change from elevations and ages of drowned *Acropora palmata* reefs (herein referred to as *Acropora* reefs) in the Caribbean-Atlantic province. When these data are integrated with a coral-based sea-level curve, they show three catastrophic, metre-scale sea-level rises during deglaciation. By converting radiocarbon-dated marine and ice-sheet events to a sidereal chronology (Bard et al., 1993), we show that the timing of these catastrophic rises is coincident with ice-sheet collapse, ocean-atmosphere reorganization, and large-scale releases of meltwater.

REEF-DROWNING EVENTS

Suitability for radiometric dating (Edwards et al., 1987) and tendency to maintain themselves at sea level by rapid vertical accretion (Buddemeier and Smith, 1988) make reefs ideal for studying glacio-eustatic sea-level changes during the Quaternary. Reefs composed of the common Caribbean reef-crest coral *Acropora palmata* (Lamarck, 1816) are well suited for the task because (1) this is the only coral to form monospecific reef framework in waters less than 5 m deep and (2) it has a depth-restricted habitat range to ~10 m (Goreau, 1959; Gladfelter and Monahan, 1977), although in rare instances it has been reported as deep as 17 m (Goreau and Wells, 1967). This limited depth range means that *Acropora* reefs can track rising sea level, provided the rate of sea-level rise does not exceed the maximum reef-accretion rate of 14 mm/yr (Buddemeier and Smith, 1988). Consequently, rises that are below this threshold rate can be accurately determined by dating the elevation of *A. palmata* reef frameworks (Lighty et al., 1982).

What has not been previously recognized, however, is that sea-level rates that exceed the accretion threshold can be quantitatively constrained from framework changes in an *Acropora* reef as it drowns. Sea level rising faster than 14 mm/yr will displace *A. palmata* from its (monospecific) framework range (0–5 m) into its remaining habitat range (5–10 m), where a mixed framework with other corals develops (Goreau, 1959). During the final stage of drowning, the reef surface passes out of the *A. palmata* habitat range, and the mixed framework is replaced by deeper-water corals. Because the residence time of the reef surface in the habitat range is controlled by the rate of sea-level rise, there is an inverse relation between the thickness of mixed framework developed during drowning and the rate of sea-level rise (Fig. 1). Where mixed framework is >2

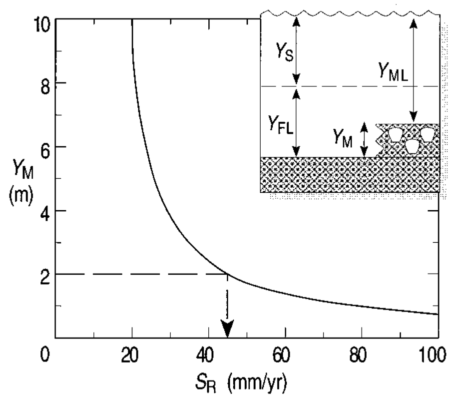

Figure 1. Relation between thickness of mixed-coral framework (Y_M) developed during reef drowning and rate of sea-level rise (S_R). This is given by $S_R = 1/t\ (Y_{ML} + Y_M - Y_{FL})$ derived from inset diagram, where t is time taken for accretion of Y_M during drowning, Y_{FL} is framework depth limit for *Acropora palmata*, Y_{ML} is depth limit for mixed *A. palmata*–other-coral framework, and Y_S is sea-level rise during accretion of Y_M. Note that t is obtained from Y_M by assuming reef-accretion rate of 13 mm/yr—the maximum accretion rate of *Acropora* reefs during the last deglaciation (from Bard et al., 1990). Dashed arrow shows rate of sea-level rise required to form 2 m of mixed framework—a thickness that could be easily distinguished in core.

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m thick, the rate of sea-level rise must be >14 mm/yr—the maximum *Acropora* reef accretion rate—but <45 mm/yr. At higher rates, the residence time of the reef surface in the habitat range is insufficient for a significant thickness of mixed framework to develop. Hence, mixed frameworks <2 m thick indicate sea level rising at >45 mm/yr (Fig. 1).

To use this mixed-framework and rise-rate relation, the possibility of framework changes induced by autogenic processes—such as progradation—must be eliminated. Progradation can clearly be ruled out if reef-framework changes in the drowned *Acropora* reef are accompanied by reef back stepping—i.e., the establishment of *A. palmata* growth further upslope following drowning. Thus, we argue that abrupt framework changes accompanied by back stepping in *Acropora* reefs indicate a sea-level rise of >45 mm/yr.

Using this approach, we have constrained rapid rates of sea-level rise during deglaciation from drowned *Acropora* reefs (Fig. 2). Depths of the drowned reefs are grouped at ~80, 50, and 15 m below present sea level. Although fewer data exist of the 80 and 50 m groups, drilling on the Barbados shelf (Fairbanks, 1989) shows them to be composed of thick, back-stepping sequences of *A. palmata* framework overlain abruptly by 10–15 m of deeper-water coral framework. Depths of the deep reefs on Barbados correspond to deep reefs in other areas (Fig. 2), pointing to a common drowning history. This is especially clear for the 15 m *Acropora* reef group, which drowned simultaneously at ~7.6 ka and back stepped at least 5 m instantaneously (e.g., compare the drowning date of Florida reefs with establishment of Panamanian reefs in Fig. 2).

Distinct breaks between the *A. palmata* reef-framework (Fig. 2) demonstrate that these reefs drowned and back stepped to upslope positions three times during deglaciation. Not only did the rate of sea-level rise exceed accretion rates during these drowning events, but the magnitude of the rise was also sufficient to remove *A. palmata* from its 5 m framework range, thereby preventing reef recovery. Furthermore, the abrupt transition from monospecific *A. palmata* framework to other-coral framework documented in cores from Barbados and St. Croix (Fig. 2) indicates that sea-level rise events also displaced *A. palmata* from its habitat range before significant accretion of a mixed framework could occur, implying that the rise rate was >45 mm/yr (Fig. 1). Such drowning events must have been truly catastrophic, involving—to our knowledge—the fastest rates of glacio-eustatic sea-level rise yet reported.

When these catastrophic rise events (or CREs) are integrated with the corrected Caribbean sea-level curve (Fig. 3), the stepped nature of sea-level rise during deglaciation becomes clear. The first two *Acropora* reef-drowning events confirm and further constrain previously identified rapid rises (Fairbanks, 1989), and the third identifies a new rise event. Each step in the curve starts with a CRE with a rise-rate of >45 mm/yr and concludes with a slower rise rate of <15 mm/yr. By using established coral dates (Bard et al., 1990; Fairbanks, 1989; Lighty et al., 1982) and gaps between *A. palmata* framework, the timing and magnitude of each CRE can be constrained (Fig. 3): CRE 1 started at 14.2 (± 0.1) ka and had a magnitude of 13.5 (± 2.5) m; CRE 2 started at 11.5 (± 0.1) ka and had a magnitude of 7.5 (± 2.5) m; and CRE 3 started at 7.6 (± 0.1) ka and had a magnitude of 6.5 (± 2.5) m. The exact duration of the CREs is unknown but, given that the minimum rate of sea-level rise was >45 mm/yr, the duration of the 14.2 ka event must have been <290 (± 50) yr, the 11.5 ka event was <160 (± 50) yr, and the 7.6 ka event was <140 (± 50) yr.

SEA-LEVEL–ICE-SHEET LINK

Catastrophic steps in sea level recorded by drowned *Acropora* reefs demonstrate that oceans were inundated by massive volumes of meltwater and/or icebergs at least three times during deglaciation. Smoother steplike rises in the deglacial sea-level record have been identified, but were attributed to large increases in seasonal meltwater discharge (Fairbanks, 1989). Although melting rates varied during deglaciation, it is unlikely that this alone could account for the magnitude of CREs. This assertion is supported by widely dispersed layers of ice-rafted detritus in cores of deep North Atlantic sediment (Heinrich, 1988; Bond et al.,

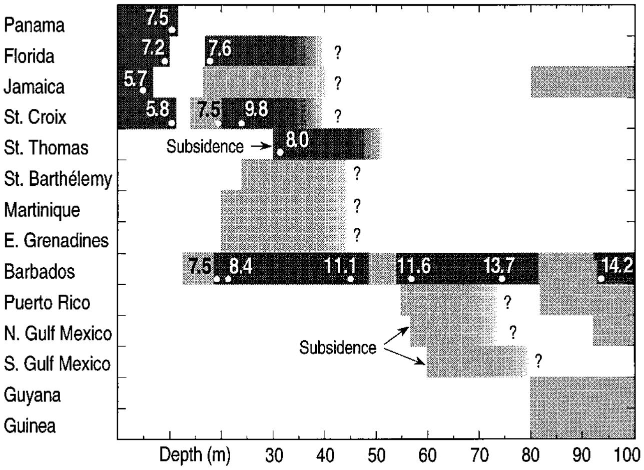

Figure 2. Depth below sea level, age (calendar ka), and framework character of drowned reefs in Caribbean-Atlantic province (Blanchon and Jones, 1994). Dark shading indicates *Acropora palmata* framework; light shading indicates other-coral and unknown framework. Ages are corrected ^{14}C or U/Th dates. Barbados reef positions corrected for tectonic uplift of 0.34 m/ka (Fairbanks, 1989) on basis of U/Th chronology (Bard et al., 1990). Note that reestablishment following drowning of 15 m group was not synchronous because (1) there was local lack of substrate (e.g., rise did not fully drown local sea cliffs) or (2) lowest date does not reflect true date of reestablishment.

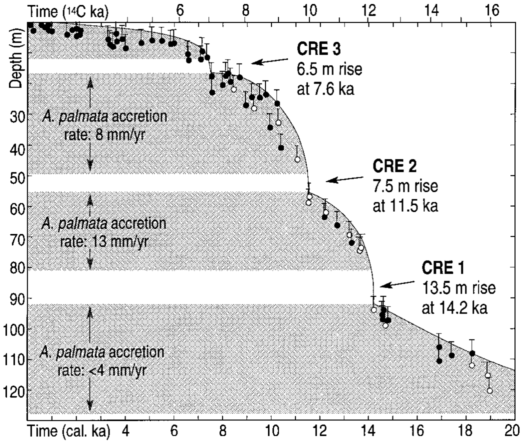

Figure 3. Caribbean deglacial sea-level curve showing positions of drowned *Acropora palmata* reef framework (light shading). Curve is extended after Lighty et al. (1982) and incorporates data from Bard et al. (1990) and Fairbanks (1990). Curve must lie on or above all data points because corals grow below sea level. Circles show positions of U/Th-dated *A. palmata* (white) and corrected ^{14}C-dated (black) *A. palmata*; error bars represent 5 m range of sea level due to framework range of *A. palmata* and age error (1σ). Gaps between *A. palmata* framework enable magnitude of sea-level rise events with rates >45 mm/yr to be quantified by using ½(2*h* + 5) where *h* is height (m) between successive frameworks and 5 is framework depth range (m) for *A. palmata*.

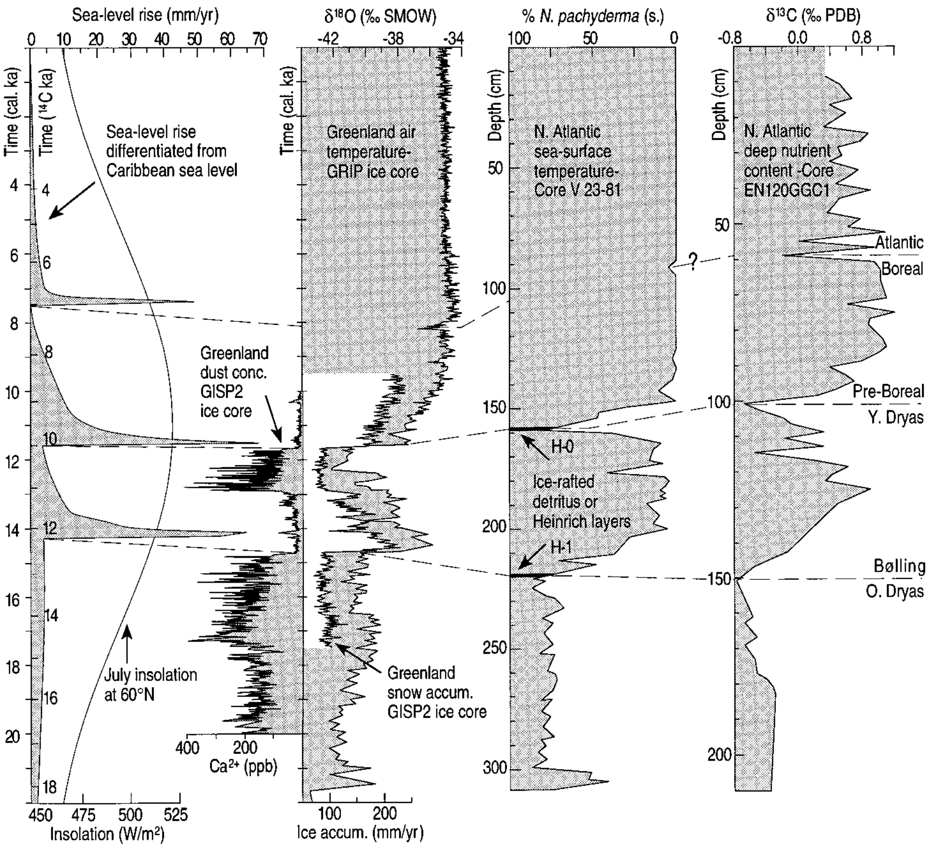

Figure 4. Rate of sea-level rise, differentiated from curve in Figure 3, correlated with Northern Hemisphere insolation and ocean-atmosphere changes during last deglaciation. Ice-core records of dust (Mayewski et al., 1993), snow (Alley et al., 1993), and temperature (Dansgaard et al., 1993) are dated by layer counting with an estimated accuracy of 3%. With these errors considered, CREs in sea-level record are synchronous with atmospheric-reorganization events recorded in ice cores. Note how Heinrich layers immediately precede oceanic reorganization events that correlate with CREs and atmospheric reorganizations.

1992). These Heinrich (H) layers, as they are called, record the massive discharge of icebergs into the North Atlantic resulting from the collapse of the Laurentide ice sheet (Bond et al., 1992), which, according to some estimates, may have taken place in <100 yr (Broecker et al., 1992). Such rapid purges of ice into the North Atlantic would cause CREs that drowned the fast-growing *Acropora* reefs in the Caribbean.

To link ice-sheet collapse and CREs, we matched deglacial ocean-volume changes, recorded by the Caribbean sea-level curve, with patterns of climatic and oceanic change recorded in ice and deep-ocean cores (Fig. 4). This matching shows that episodes of ice-sheet collapse, marked by H-1 and H-0 layers in core V23-81 (Bond et al., 1993), correlate closely with CREs 1 and 2 and with reorganization of the ocean-atmosphere system. A survey of ^{14}C dates for H-1, however, shows that calendar ages range from 14.5 ka (Broecker et al., 1992) to 16.9 ka (Bond et al., 1992; Andrews et al., 1994). For an event that is considered to be almost instantaneous (Bond et al., 1992), such poor resolution indicates that dates are affected by bioturbation, and this is confirmed by numerous date reversals in the best dated cores (e.g., DSOP 609 in Bond et al., 1992). Nevertheless, the youngest date in the H-1 age range correlates with CRE 1.

More reliable temporal evidence of ice-sheet collapse has been identified from dated terrestrial and submerged diamictons on the north shore of the Hudson Strait (Miller and Kaufman, 1990; Kaufman et al., 1993). These, together with ice-direction and source indicators, show that a major ice stream from the Labrador dome (the single largest center of the Laurentide ice sheet) underwent surge-and-retreat events consistent with collapse at ~14 and 11.5 ka—dates that match closely with CREs 1 and 2.

Although ice-sheet collapse provides a compelling explanation for CREs 1 and 2, a link between CRE 3 at 7.6 ka and Northern Hemisphere ice-sheet instability is improbable because of the small volume of ice remaining at that time. Corrected ^{14}C dates on marine cores from the shelves adjacent to the Antarctic ice sheet, however, show that significant changes in marine-ice extent took place between 7 and 8 ka (Herron and Anderson, 1990; Domack et al., 1991). Thus, Antarctic ice-sheet instability could account for CRE 3.

ICE-SHEET–OCEAN-ATMOSPHERE LINK

The correlation between CREs and ocean-atmosphere reorganization (Fig. 4) implies that ice-sheet collapse had a significant impact on climate. This is best illustrated by covariant trends in ice-sheet and ocean records. Abrupt changes occurred in all records at ~14.5 ka (Fig. 4): glacial air masses over Greenland were suddenly (<10 yr) replaced by warmer, moister, and less dusty conditions (Alley et al., 1993; Dansgaard et al., 1993; Mayewski et al., 1993), the sea-ice–covered North Atlantic was invaded by warm-water masses (Koç et al., 1993; Lehman and Keigwin, 1992), and deep waters overturned in response to North Atlantic deep-water formation (Charles and Fairbanks, 1992). Although temperature and snow-accumulation trends show gradual deterioration (Dansgaard et al., 1993; Alley et al., 1993), these conditions persisted until the next major reorganization at 12.9 ka—the onset of the Younger Dryas—when ocean-atmosphere circulation abruptly reverted to former glacial-type patterns (Lehman and Keigwin, 1992; Taylor et al., 1993). Finally, at ~11.5 ka, the Younger Dryas was terminated by an abrupt (<3 yr) reorganization in ocean-atmosphere circulation that heralded the start of present interglacial conditions (Alley et al., 1993; Koç et al., 1993).

On the basis of the coincident timing of CREs, we propose that this covariant pattern of dramatic ocean-atmosphere reorganization resulted from atmospheric threshold changes induced by a rapid decrease in the elevation (collapse) of the Laurentide ice sheet. In this view, the first collapse event—marked by CRE 1 at 14.2 ka—lowered the ice-sheet surface sufficiently to change tropospheric boundary conditions, weakening the ridge in the upper westerlies over the ice sheet and causing the split polar-front jet stream to unite and rapidly retreat northward (COHMAP, 1988). This retreat facilitated the expansion of subtropical air masses and westerly winds; this, in turn, caused retreat of North Atlantic sea ice and allowed the warm western-boundary current to flow unrestricted into the northeast Atlantic, reactivating deep-water formation. In addition to abrupt circum-Atlantic warming, this rapid influx of subtropical water caused a dramatic increase in evaporation rates and delivered large amounts of moisture to Laurentide margins. Snow accumulation rates doubled (Alley et al., 1993), and over the next few thousand years, the ice sheet began to regain lost elevation, aided to some extent by glacio-isostatic recovery. By 12.9 ka it had regained sufficient height to split and divert the polar-front jet stream once more, causing an arm to shift southward. By restricting the subtropical air masses and westerly winds, this shift in the jet stream caused sea-ice formation, which effectively blocked the transport of warm water into the North Atlantic and plunged the global climate back into glacial mode during the Younger Dryas. The second ice-sheet collapse event—marked by CRE-2 at 11.5 ka—had the same effect as the first, switching the cold Younger Dryas ocean-atmosphere system back into warm interglacial mode, but this time, melting induced by peak insolation—and perhaps reduced glacio-isostatic uplift—offset the increase in snow accumulation, and the Laurentide ice sheet was never able to recover.

A key point in this explanation is the expansion of subtropical air masses and the activation of thermohaline circulation by North Atlantic sea-ice retreat. Thermohaline activation was previously attributed to an over-balanced North Atlantic salt budget related to a gradual increase in salinity during glacial conditions (Broecker et al., 1990; Lehman and Keigwin, 1992). Carbon and oxygen isotope records from the Greenland, Iceland, and Norwegian seas show that these sensitive areas of North Atlantic deep-water formation were dominated by low-salinity waters during glacial conditions, therefore throwing doubt on this mechanism (Veum et al., 1992). Our suggestion—that thermohaline activation resulted from air-mass expansion during atmospheric reorganization—finds support from evidence of rapid and synchronous climate change at ~14 and 11.5 ka in tropical African lake systems (Street-Perrott and Perrott, 1990) and Younger Dryas advance of mountain glaciers in New Zealand (Denton and Hendy, 1994). Such parallel and synchronous trends from distant areas of the globe suggest that atmospheric circulation flipped between glacial and interglacial modes, regulating deglaciation by switching the North Atlantic thermohaline heat pump on and off.

TRIGGERING ICE-SHEET COLLAPSE

Although ice-sheet collapse accounts for CREs and ocean-atmosphere reorganization, a fundamental problem remains: What initially triggered ice-sheet collapse? MacAyeal (1993) proposed that collapse was related to the onset of warm-based conditions in a previously cold-based ice sheet and, by estimating accumulation rates and geothermal flux, he calculated a collapse-recurrence interval of ~7 ka. Although this mechanism might explain collapse during the last glaciation, with 7 to 14 ka between events (Bond et al., 1993), it cannot account for events <3 ka apart during deglaciation. Furthermore, if internal processes forced collapse and triggered deglaciation, it is difficult to explain why previous collapse events did not have the same effect. In short, deglaciation must have been triggered by an external mechanism that affected ice-sheet stability.

TABLE 1. MELTWATER MEGAFLOODS DURING DEGLACIATION

Megaflood (Ref.*)	Calendar age† (ka)	Discharge (km^{3}x10^4)	Eustatic rise (mm)
Livingstone Lake (1)	~14-15§	8.4	230
Baltic Ice Lake (2)	12.1	2.9	~100
Lake Agassiz (3)	11.4	2.3	70
Lake Agassiz (4)	11.5	2.9	~100
Lake Agassiz-Ojibway (5)	8.0	7.5-15	200-420

*1—Shaw (1989), 2—Bjorck and Digerfeldt (1986), 3—Broecker et al. (1989), 4—Smith and Fisher (1993), 5—Hillaire-Marcel et al. (1981).

†Calculated from ^{14}C dates (Bard et al., 1993).

§Products of the Livingstone Lake megaflood (see Rains et al., 1993) extend to position of last glacial maximum, limiting their timing to onset of deglaciation. Estimates of discharge and eustatic rise are from Shaw (1989) and Dawson (1992).

Atmospheric cooling has been proposed as a cause of ice-sheet instability (Bond et al., 1992), but no simple relation between climate change and ice-sheet response exists (Oerlemans, 1993). The only other viable mechanisms for destabilizing ice sheets over a relatively short time are either delayed glacio-isostatic subsidence along the ice-sheet grounding line or rapid sea-level rise (Hughes, 1987).

We propose that ice-sheet instability during the last deglaciation was triggered by the catastrophic release of meltwater megafloods from glacial and proglacial reservoirs. Such megafloods were released close to the times of ice-sheet collapse and CREs (Table 1). For instance, a large meltwater reservoir associated with the Laurentide ice sheet was catastrophically released sometime after the ice sheet reached its maximum extent during early deglaciation (Shaw, 1989). The volume of water discharged produced regional-scale fields of drumlins, giant flutings, and extensive tracts of scoured bedrock (see Rains et al., 1993). Furthermore, faunally derived records of meltwater influx into the Gulf of Mexico—an expected megaflood outflow site—demonstrate an exceptionally large meltwater spike at ~14 ka (Broecker et al., 1989) that may have diluted a 1112 m water column in the gulf (Aharon, 1992). Such large amounts of meltwater could potentially destabilize ice sheets grounded below sea level.

Although the link between gradual meltwater input, sea-level rise, and ice-sheet collapse has been suggested (Denton and Hughes, 1983) it is considered ineffective because of compensation by glacio-isostatic rebound (Lingle and Clark, 1985). The rapid influx of meltwater megafloods at times coincident with ice-sheet collapse and CREs is a more effective mechanism for triggering ice-sheet instability. It also provides the link between deglaciation mechanisms and insolation—a forcing function acknowledged to be a major player in the glacial-interglacial cycle (Hays et al., 1976).

DEGLACIATION MECHANISMS

By identifying CREs from drowned *Acropora* reefs, we provide a critical piece of evidence that links insolation, large meltwater influxes, ice-sheet collapse, and ocean-atmosphere reorganization. From these links, we conclude that Northern Hemisphere summer-insolation maxima forced deglaciation because greater land area in mid-latitudes allowed more extensive ice sheets. Stronger insolation over these latitudes generated large volumes of meltwater that, when catastrophically released, provided a trigger for subsequent interactions among ice sheets, oceans, and atmosphere. These interactions were dramatic. Collapse of one ice sheet affected them all (Denton et al., 1986), producing CREs that drowned reefs and other coastal features (Blanchon and Jones, 1994). Collapse also abruptly switched atmospheric circulation patterns from glacial to interglacial modes and consequently initiated changes in oceanic circulation that activated the Atlantic thermohaline heat pump—the mechanism ultimately responsible for Northern Hemisphere warming.

More important, we show that ice-sheet collapse and CREs were an integral part of deglaciation. Given that two large ice sheets over Greenland and Antarctica still exist, there is further potential for collapse. Indeed, if global atmospheric and surface-ocean warming continues at its present rate (Intergovernmental Panel on Climate Change, 1992), collapse of the West Antarctic ice sheet is a distinct possibility (Bindschadler, 1990). Consequently, despite the prediction of gradual sea-level rise by the IPCC (1992), the potential for future catastrophic sea-level rise also exists—especially now that catastrophic rises have been recognized from the recent past.

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