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Linking continental-slope failures and climate change: Testing the clathrate gun hypothesis

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ABSTRACT

It has been suggested that the release of clathrates rather than expansion of wetlands is the primary cause of the rapid increases observed in the ice-core atmospheric methane record during the Pleistocene. Because submarine sediment failures can involve as much as 5000 Gt of sediment and have the capacity to release vast quantities of methane hydrates, one of the major tests of the clathrate gun hypothesis is determining whether the periods of enhanced continental-slope failure and atmospheric methane correlate. To test the clathrate gun hypothesis, we have collated published dates for submarine sediment failures in the North Atlantic sector and correlated them with climatic change for the past 45 k.y. More than 70% by volume of continental-slope failures during the past 45 k.y. was displaced in two periods, between 15 and 13 ka and between 11 and 8 ka. Both these intervals correlate with rising sea level and peaks in the methane record during the Bølling-Ållerød and Preboreal periods. These data support the clathrate gun hypothesis for glacial-interglacial transitions. The data do not, however, support the clathrate gun hypothesis for glacial millennial-scale climate cycles, because the occurrence of sediment failures correlates with Heinrich events, i.e., lows in sea level and atmospheric methane. A secondary use of this data set is the insight into the possible cause of continental-slope failures. Glacial-period slope failures occur mainly in the low latitudes and are associated with lowering sea level. This finding suggests that reduced hydrostatic pressure and the associated destabilization of gas hydrates may be the primary cause. The Bølling-Ållerød sediment failures were predominantly low latitude, suggesting an early tropical response to deglaciation, e.g., enhanced precipitation and sediment load to the continental shelf or warming of intermediate waters. In contrast, sediment failures during the Preboreal period and the majority of the Holocene occurred in the high latitudes, suggesting either isostatic rebound-related earthquake activity or reduced hydrostatic pressure caused by isostatic rebound, causing destabilization of gas hydrates.

Keywords: clathrates, gas hydrates, continental slope failure, Heinrich events, atmospheric methane, sea level.

INTRODUCTION

Kennett et al. (2003), building on the ideas of Nisbet (1990) and Haq (1998), have suggested that destabilization of marine and continental gas hydrates is the primary control on atmospheric methane variation observed in the ice-core record during the Quaternary (Chappellaz et al., 1993; Brook et al., 1999). They called this concept the clathrate gun hypothesis to distinguish it from the more generally accepted wetland methane hypothesis, which suggests that expansion and contraction of wetlands are the primary causes of methane variability (e.g., Brook et al., 1999; Maslin and Burns, 2000). One crucial test of the clathrate gun hypothesis is determination of the temporal sequence of the continental-slope failures that are essential to the release of marine methane hydrates. This evaluation is necessary because only catastrophic sediment failures can cause sufficient explosive release of

methane hydrates to overcome consumption, oxidation, and dissolution within the sediments and the lower water column (e.g., Paull et al., 2003), and so directly affect atmospheric methane. We have produced the first temporal sequence of continental-slope failures for the past 45 k.y. This history allows us to test the clathrate gun hypothesis and to investigate the most likely causes of these failures.

COLLATION OF DATA

In this study we collated 27 dated continental-slope failure deposits in the North Atlantic sector, including the Nordic Seas and the Mediterranean Sea, for the past 45 k.y. (see Table 1; locations are shown in Fig. 1). This region was chosen for two reasons: it is the most intensively studied area with the most dated slides, and it is particularly susceptible to continental-slope failure owing to the proximity of massive Quaternary ice sheets. Dating the occurrence of slope failure remains problematic, so we have attempted to estimate the reliability of the dates for the occurrence of each deposit. We stress that the age reliability index (Table 1) is not an attempt to grade the research, but rather a measure of the difficulties encountered with dating each individual deposit.

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Figure 2 compares the number and total size of deposits in 1 k.y. intervals for the past 45 k.y. with relative global sea-level change; the interval of 1 k.y. was chosen to allow for analytical errors associated with radiocarbon dating and conversion to calendar years. Figure 2 shows that there is a strong coincidence between the occurrences of the slope failures and climatically induced changes in relative global sea level over the past 45 k.y.

During the last glacial period, between 45 ka and 16 ka, there are nine dated slope failures that correlate with Heinrich events (Fig. 2). These slope failures occur in the middle to low latitudes (Fig. 3A) and correlate with drops in sea level (Chappell et al., 1996). This correlation suggests that the most likely explanation for slope failures during the last glacial period is lowering sea level leading to reduced hydrostatic pressure and thus destabilized gas hydrate deposits (e.g., Haq, 1998; Maslin et al., 1998; Rothwell et al., 1998; Kennett et al., 2003).

Of the volume of displaced sediment represented in the entire data set, 70% was produced during two short periods, 15–13 ka and 8–11 ka (Fig. 3). The first of these periods occurred during the Bølling-Ållerød. It involves four major submarine slides and correlates with the first increase in sea level associated with deglaciation. This 2000 yr peak includes the Canary Island debris flows, totaling 400 km³ (Masson et al., 1998), and Amazon debris flows, totaling 3500 km³ (Maslin et al., 1998). All these failures occurred in the low latitudes, suggesting a rapid response to the onset of deglaciation at these latitudes. Relevant climate changes that occurred in this period include (1) increased deep- and intermediate-water temperature that may have caused gas hydrate destabilization, as suggested for the Cape Fear slide (Popenoe et al., 1991) and for the Santa Barbara Basin (Kennett et al., 2003), and (2) an increased continental wetness that may have produced increased sediment deposition (Maslin et al., 1998). In addition, shifting of the depocenters from the Amazon Fan onto the continental

TABLE 1. OCCURRENCE AND DISTRIBUTION OF MASS-TRANSPORT DEPOSITS IN THE NORTH ATLANTIC REGION FOR THE PAST 45 k.y.

Name	Location	Type	Age* (yr B.P.)	Age rel. index†	Volume (km ³)	Reference
Grand Banks	Sohm Abyssal Plain	turbidite	70	1	185	Piper and Asku (1987)
Canadian Abyssal Plain (CAP) turbidite 1	Canadian Abyssal Plain	turbidite	1300	4	80	Grantz et al. (1996)
CAP turbidite 2	Canadian Abyssal Plain	turbidite	2400	4	80	Grantz et al. (1996)
CAP turbidite 3a	Canadian Abyssal Plain	turbidite	3100	4	240	Grantz et al. (1996)
Sirte margin	Southeast Mediterranean	turbidite	3500	1	165	Rebesco et al. (2000)
Trænadjupet	Norwegian margin	slide	4100	3	900	Laberg and Vorren (2000)
CAP turbidite 3b	Canadian Abyssal Plain	turbidite	6000	3	160	Grantz et al. (1996)
Storegga	Norwegian margin	submarine slide	8150	1	3500	Jansen et al. (1987), Evans et al. (1996), Bouriak et al. (2000), Bryn et al. (2003)
Baltimore Canyon	U.S. East Coast margin	slide complex	8000–9000?	5	200	Embley and Jacobi (1986)
CAP turbidite 4	Canadian Abyssal Plain	turbidite	8200	4	80	Grantz et al. (1996)
Andøya	Norwegian margin	slide	9000	5	485	Laberg et al. (2000)
Faeroe slide	Northeast Faeroe margin	slide	10,300	4	135	Van Weering et al. (1998)
Peach slide, event 4	Barra Fan, Scottish margin	debris flow	10,500	4	135	Holmes et al. (1998), Kuntz et al. (2001)
BIG'95	Western Mediterranean	debris flow	11,500	4	26	Lastras et al. (2002)
Western debris flow	Amazon Fan	debris flow	13,000	1	2000	Maslin et al. (1998)
Eastern debris flow	Amazon Fan	debris flow	14,500	3	1500	Maslin et al. (1998)
Madeira b turbidite	Madeira Abyssal Plain	turbidite	15,000	2	125	Weaver and Rothwell (1987)
Canary debris flow	Canary Island margin	debris flow	15,000	2	400	Masson et al. (1998)
Black Shell turbidite	Hatteras Abyssal Plain	turbidite	16,900	4	180	Elmore et al. (1979)
Cape Fear slide	Blake Ridge	slide	16,800	3	1400	Popenoe et al. (1991)
H ₁₃ turbidite	Horseshoe Abyssal Plain	turbidite	17,700	4	33	Lebreiro et al. (1997)
Peach slide, event 3	Barra Fan, Scottish margin	debris flow	21,000	4	199	Holmes et al. (1998), Kuntz et al. (2001)
Balearic Abyssal Plain	West Mediterranean	turbidite	22,000	1	500	Rothwell et al. (1998)
Herodotus Basin	Southeast Mediterranean	turbidite	27,125	2	400	Reeder et al. (2000)
Deep eastern MTD	Amazon Fan	debris flow	35,000	2	610	Maslin et al. (1998)
Peach slide, event 2	Barra Fan, Scottish margin	debris flow	36,500	4	673	Holmes et al. (1998), Kuntz et al. (2001)
Deep western MTD (unit R)	Amazon Fan	debris flow	43,500	2	630	Maslin et al. (1998)

*The age before present is in calendar years, and any radiocarbon dates have been converted by using Calib 4 (Stuiver and Reimer, 1993).

†The age reliability index is a broad qualitative estimate of the reliability of the age provided for each mass-transport deposit (MTD). We stress that this is not an attempt to grade the research, but rather that it is a measure of the difficulties encountered with dating each individual deposit. The age reliability index is ranked as follows: 1 = excellent, 2 = good, 3 = average, 4 = below average, and 5 = poor. For example, an "excellent" (1) indicates reliable and reproduced radiocarbon dates at least above and below the deposit and in some cases within the deposit. In contrast, a "poor" (5) indicates either no radiocarbon dates and that ages were inferred by correlation to adjacent dated sediment cores or that there has been significant erosion of sediments underlying the MTD.

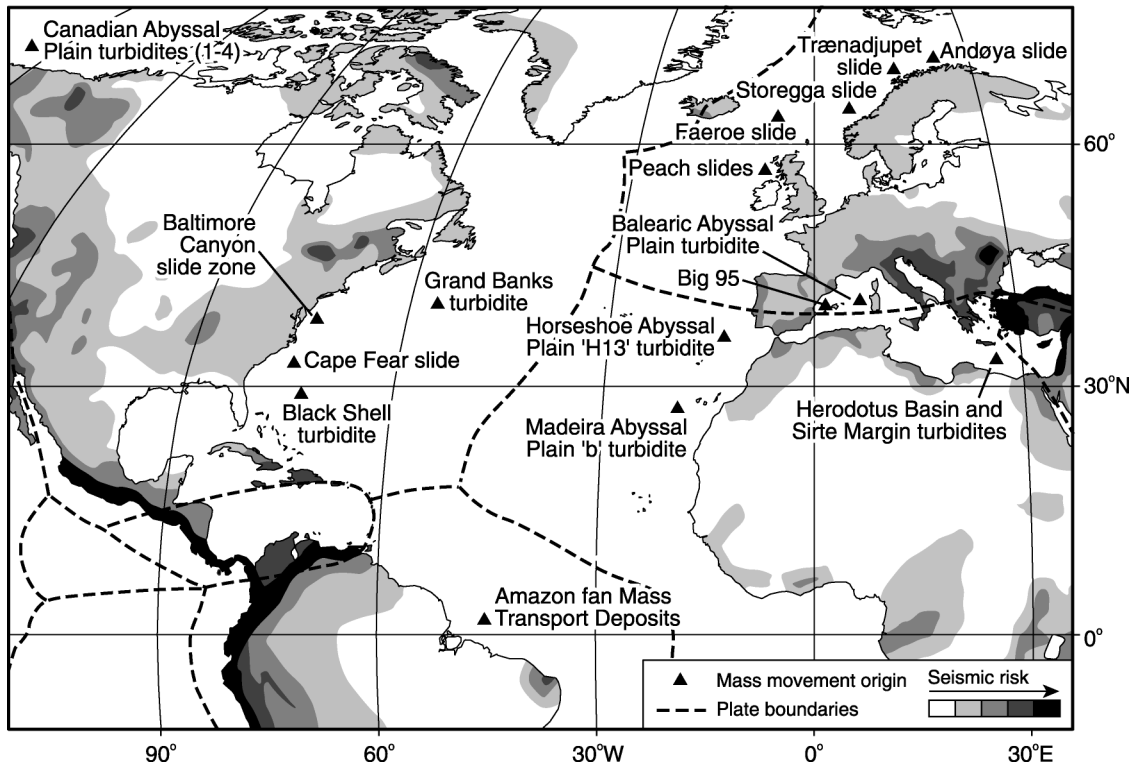


Figure 1. Location of mass-transport deposits identified in Table 1, compared with modern-day seismic risk and plate boundaries (Giardini, 1999).

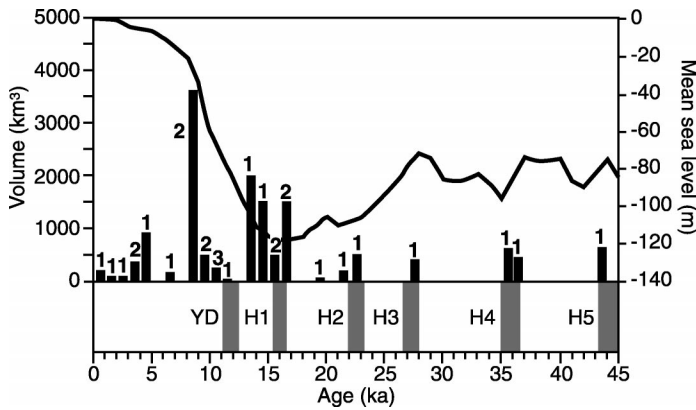


Figure 2. Total volume of mass transport or slide deposits (black bars) and number of failures (small numbers next to bars) compared with mean relative sea level (curve) for past 45 k.y. (McGuire et al., 1997). Heinrich events (H1–H5) and Younger Dryas (YD) are shown for comparison.

shelf has been suggested as a possible cause of the Amazon Fan debris flows (Maslin et al., 1998).

The second of these periods of frequent slope failures occurred during the Preboreal period. It includes seven recorded slope failures and coincides with the maximum rate of sea-level rise that has occurred in the past 45 k.y., to 15 m/k.y. (Fig. 3C). The largest events in this period are the Storegga slide, 3500 km³ (e.g., Bryn et al., 2003), and the Andøya failure, 485 km³ (Laberg et al., 2000). Most of the slope failures during the Preboreal and Holocene are in the high latitudes, suggesting a direct link to isostatic rebound caused by the retreat of the Laurentian and Fennoscandian Ice Sheets. Isostatic rebound has two major influences on slope stability. (1) Extensive isostatic rebound produces a shallowing of the continental shelf that reduces hydrostatic pressure and may cause gas hydrates in the sediment to destabilize, which in turn would cause the continental slope to fail. (2) Isostatic rebound also produces significant related seismicity, and earthquakes are known to cause submarine slope failures (Morner, 1991). For example, Holocene landslides on land have also been linked to major earthquakes in continental-shield areas previously covered by thick ice sheets (Aylsworth et al., 2000). The correlation between Holocene high-latitude continental-slope failures and regions of elevated intraplate seismic hazard (Giardini, 1999) is notable (Fig. 1). This correlation implies that the largest threat to continental-slope stability in the possible greenhouse future is melting of the ice-sheet margins and the resultant isostatic rebound. There is evidence that these processes are occurring in Antarctica (Kremer and Holt, 2000) and Greenland (e.g., Thomas, 2001).

TESTING THE CLATHRATE GUN HYPOTHESIS

Kennett et al. (2003) suggested that the enhanced levels of atmospheric methane during Dansgaard-Oeschger interstadials were due to the release of large quantities of methane hydrates. The temporal sequence of large continental-slope failures in this study does not support the clathrate gun hypothesis because the slides occur during stadial periods. This does not, however, rule out the possible influence of intermediate water temperature on the stability of gas hydrate deposits (Kennett et al., 2003).

Timing of large continental-slope failures supports the clathrate gun hypothesis as envisaged by Kennett et al. (2003) for deglaciation. For example, during the Bølling-Ållerød period, coinciding with a rise of >200 ppbv in atmospheric methane, two massive slides occurred on the Amazon Fan, both roughly the size of Jamaica. Maslin et al. (1998) has shown that these slides originated within water depths at which gas hydrates are most susceptible to disassociation (200–600 m

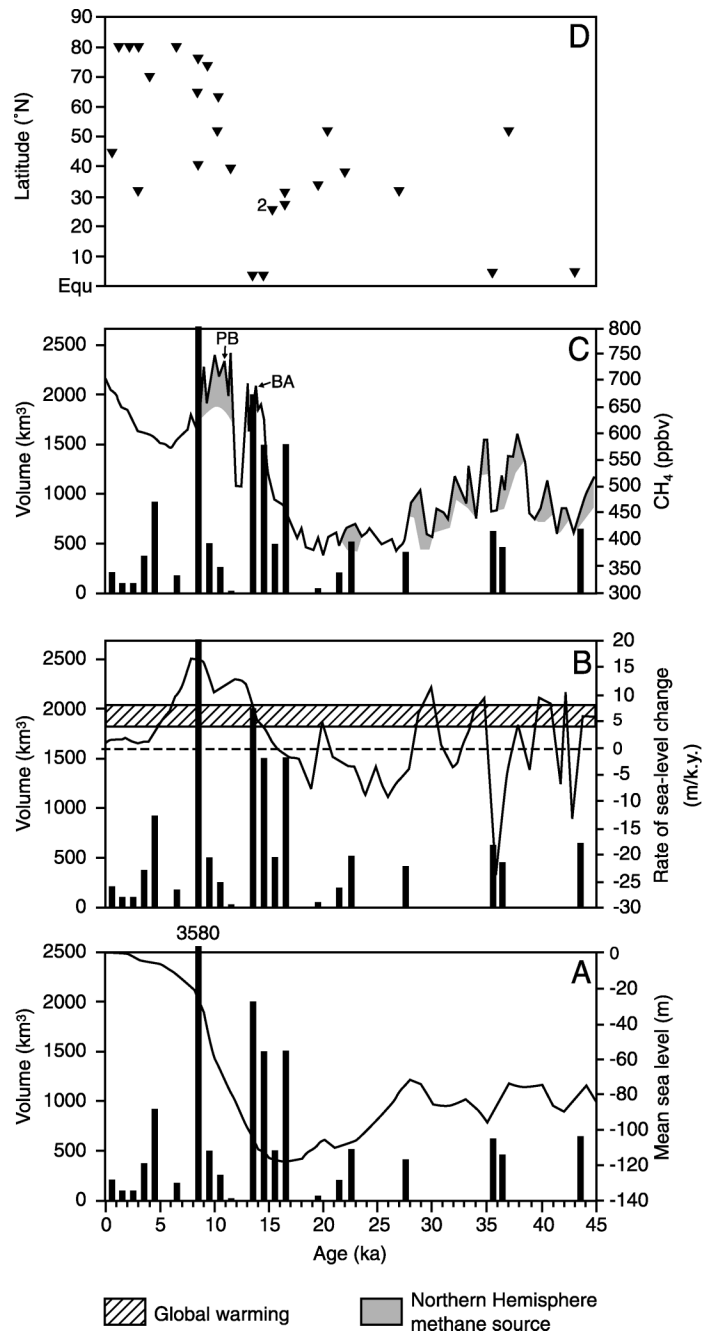


Figure 3. Total volumes of mass transport or slide deposits are compared with (A) mean sea level (McGuire et al., 1997), (B) rate of sea-level change (McGuire et al., 1997), and (C) atmospheric methane (Brook et al., 1999). Note that in B, current predicted sea-level rise over next century due to global warming has been plotted for comparison. Note that in C, shaded region indicates distinct Northern Hemisphere methane source (Dällenbach et al., 2000). Plot of latitude of each slide deposit (D) shows marked change from predominantly low-latitude occurrences prior to ca. 14 ka to high-latitude occurrences after 11 ka. BA—Bølling-Ållerød; PB—Preboreal.

water depth). Moreover, at the time of these events, all species of planktonic foraminifera across the Amazon Fan recorded a pronounced –2‰ spike in $\delta^{13}\text{C}$ values (Maslin et al., 1997), supporting the view of a massive coeval release of methane hydrates, which are very depleted in ^{13}C . Depending on the assumed quantity of pore space occupied, each one of these slides has the capacity to release 5–20 Gt of methane.

The evidence for the coincidence of slides with elevated methane levels during the Preboreal period is even better, because seven slides occurred within this period, including the massive Storegga slide. The suggestion that there was a significant release of methane due to continental-slope failures in the North Atlantic sector during the Bølling-Ållerød and Preboreal is also supported by the strong Northern Hemisphere influence on the Inter-Polar methane gradient (Dällenbach et al., 2000), shown in Figure 3. Further support comes from global carbon isotope budgeting, which suggests that at least 30% of the rise in atmospheric methane during the deglaciation can be attributed to methane hydrates (Maslin and Thomas, 2003).

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