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

Mark Maslin
Matthew Owen
Simon Day
Environmental Change Research Centre, Department of Geography, University College of London, 26, Bedford Way, London WC1H 0AP, UK
David Long British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, UK

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.

LINKING CONTINENTAL-SLOPE FAILURE TO CLIMATE CHANGE

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 km^3 (Masson et al., 1998), and Amazon debris flows, totaling 3500 km^3 (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.

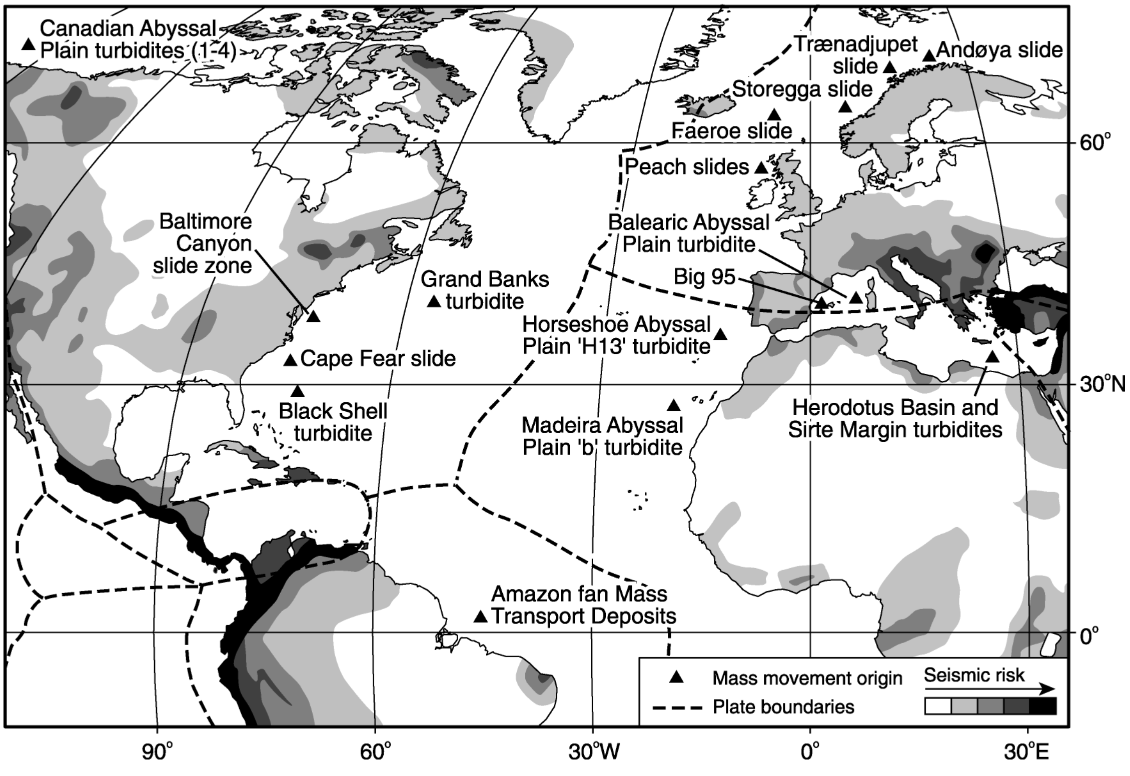

Figure 1. Location of mass-transport deposits identified in Table 1, compared with modern-day seismic risk and plate boundaries (Giardini, 1999).

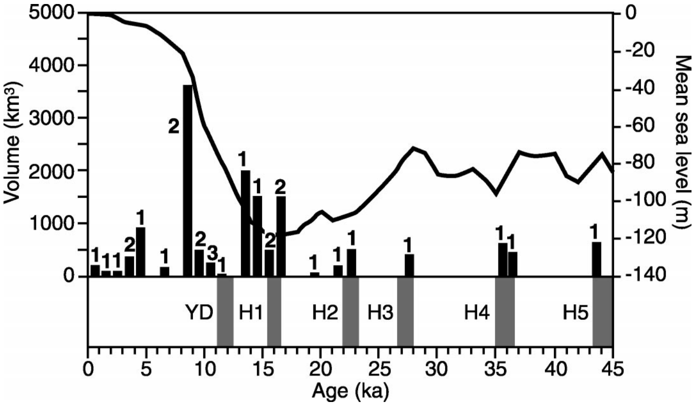

Figure 2. Total volume of mass transport or slide deposits (black bars) and number of failures (small numbers next to bars) compared with mean relative sea level (curve) for past 45 k.y. (McGuire et al., 1997). Heinrich events (H1–H5) and Younger Dryas (YD) are shown for comparison.

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 km^3 (e.g., Bryn et al., 2003), and the Andøya failure, 485 km^3 (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 (Kreemer 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 water depth). Moreover, at the time of these events, all species of planktonic foraminifera across the Amazon Fan recorded a pronounced −2‰ spike in δ^{13}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.

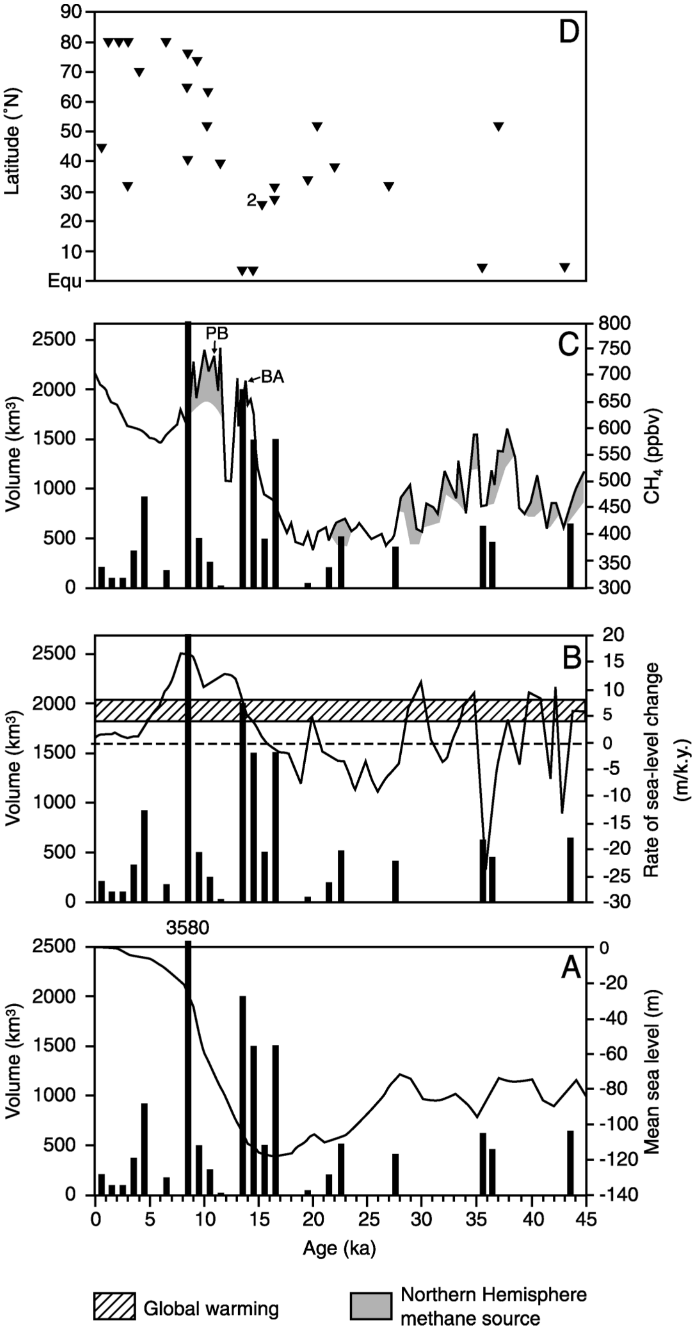

Figure 3. Total volumes of mass transport or slide deposits are compared with (A) mean sea level (McGuire et al., 1997), (B) rate of sea-level change (McGuire et al., 1997), and (C) atmospheric methane (Brook et al., 1999). Note that in B, current predicted sea-level rise over next century due to global 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.

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).

ACKNOWLEDGMENTS

Supported by Natural Environment Research Council (NERC) grants GR9/03526, NER/B/S/2001/00380, and IP/660/0900 (to Maslin). We thank the Drawing Office (University College of London), James Kennett, and the reviewers of the manuscript. Long publishes with permission of the Director of the British Geological Survey (NERC).

REFERENCES CITED

Aylsworth, J.M., Lawrence, D.E., and Guertin, J., 2000, Did two massive earthquakes in the Holocene induce widespread landsliding and near-surface deformation in part of the Ottawa Valley, Canada?: Geology, v. 28, p. 903–906.

Bouriak, S., Vanneste, M., and Saoutkine, A., 2000, Inferred gas hydrates and clay diapirs near the Storegga Slide on the southern edge of the Vøring plateau, offshore Norway: Marine Geology, v. 163, p. 125–148.

Brook, E.J., Harder, S., Severinghaus, J., and Bender, M., 1999, Atmospheric methane and millennial-scale climate change, *in* Clark, P.U., et al., eds., Mechanisms of global climate change at millennial time scales: American Geophysical Union Geophysical Monograph 112, p. 165–175.

Bryn, P., Solheim, A., Berg, K., Lien, R., Forsberg, C.F., Haflidason, H., Ottesen, D., and Rise, L., 2003, The Storegga complex; repeated large scale sliding in response to climatic cyclicity, *in* Locat, J., and Mienert, J., eds., Submarine mass movements and their consequences: Advances in natural and technological hazards research series: Dordrecht, Kluwer Academic Publishers, p. 215–222.

Chappell, J.A., Omura, T., Esat, M., McCulloch, J., Pandolfi, Y., Ota, B., and Pillans, B., 1996, Reconciliation of late Quaternary sea level derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records: Earth and Planetary Science Letters, v. 141, p. 227–236.

Chappellaz, J.A., Fung, Y., and Thompson, A.M., 1993, The atmospheric CH_4 increase since the Last Glacial Maximum: Tellus, ser. B, v. 45, p. 228–241.

Dällenbach, A., Bunier, T., Fluckiger, J., Stauffer, B., Chappellaz, J., and Raynaud, D., 2000, Changes in the atmosphere CH_4 gradient between Greenland and Antarctica during the last glacial and the transition to the Holocene: Geophysical Research Letters, v. 27, p. 1005–1008.

Elmore, R.D., Pilkey, O.H., Cleary, W.J., and Curran, H.A., 1979, Black Shell turbidite, Hatteras Abyssal Plain, western Atlantic Ocean: Geological Society of America Bulletin, v. 90, p. 1165–1176.

Embley, R.W., and Jacobi, R.D., 1986, Mass wasting in the western North Atlantic, *in* Vogt, P.R., and Tucholke, B.E., eds., The western North Atlantic region: Boulder, Colorado, Geological Society of America, Geology of North America, v. M, p. 479–490.

Evans, D., King, E.L., Kenyon, N.H., Brett, C., and Wallis, D., 1996, Evidence for long term instability in the Storegga Slide region off western Norway: Marine Geology, v. 130, p. 281–292.

Giardini, D., 1999, The Global Seismic Hazard Assessment Program (GSHAP)—1992/1999: Annali di Geofisica, v. 42, p. 957–974.

Grantz, A., Phillips, R.L., Mullen, M.W., Starratt, S.W., Jones, G.A., Naidu, A.S., and Finney, B.P., 1996, Character, paleoenvironment, rate of accumulation, and evidence for seismic triggering of Holocene turbidites, Canada abyssal plain, Arctic Ocean: Marine Geology, v. 133, p. 51–73.

Haq, B.U., 1998, Natural gas hydrates: Searching the long-term climatic and slope stability records, *in* Henriet, J.P., and Mienert, J., eds., Gas hydrates: Relevance to world margin stability and climate change: Geological Society [London] Special Publication 137, p. 303–318.

Holmes, R., Long, D., and Dodd, L.R., 1998, Large-scale debrites and submarine landslides on the Barra Fan west of Britain, *in* Stoker, M.S., et al., eds., Geological processes on continental margins: Sedimentation, mass-wasting, and stability: Geological Society [London] Special Publication 129, p. 67–79.

Jansen, E., Befring, S., Bugge, T., Eidvin, T., Holtedahl, H., and Sejrup, H.P., 1987, Large submarine slides on the Norwegian continental margin: Sediments, transport and timing: Marine Geology, v. 78, p. 77–107.

Kennett, J., Cannariato, K.G., Hendy, I.L., and Behl, R.J., 2003, Methane hydrates in Quaternary climate change: The clathrate gun hypothesis: Washington, D.C., American Geophysical Union, 216 p.

Kreemer, C., and Holt, W.E., 2000, What caused the March 25, 1998 Antarctic plate earthquake?: Inferences from regional stress and strain rate fields: Geophysical Research Letters, v. 27, p. 2297–2300.

Kuntz, P.C., Austin, W., and Jones, E.J.W., 2001, Millennial-scale depositional cycles related to British Ice Sheet variability and North Atlantic paleocirculation since 45 kyr BP, Barra Fan, U.K., margin: Paleoceanography, v. 16, p. 53–64.

Laberg, J.S., and Vorren, T.O., 2000, Holocene megaslides on the North-Norway continental margin: GeoScience2000, Abstract volume, p. 14.

Laberg, J.S., Vorren, T.O., Dowdeswell, J.A., Kenyon, N.H., and Taylor, J., 2000, The Andøya Slide and the Andøya Canyon, north-eastern Norwegian-Greenland Sea: Marine Geology, v. 162, p. 259–275.

Lastras, G., Canals, M., Hughes-Clarke, J.E., Moreno, A., De Batist, M., Masson, D.G., and Cochonat, P., 2002, Sea-floor imagery of the BIG'95 debris flow, Western Mediterranean: Geology, v. 30, p. 871–874.

Lebreiro, S.M., McCave, I.N., and Weaver, P.P.E., 1997, Late Quaternary turbidite emplacement on the Horseshoe abyssal plain (Iberian margin): Journal of Sedimentary Research, v. 67, p. 856–870.

Maslin, M.A., and Burns, S.J., 2000, Reconstruction of the Amazon Basin effective moisture availability over the last 14,000 yr: Science, v. 290, p. 2285–2287.

Maslin, M.A., and Thomas, E., 2003, Balancing the deglacial global carbon budget: The hydrate factor: Quaternary Science Reviews, v. 22, p. 1729–1736.

Maslin, M.A., Burns, S., Erlenkeuser, H., and Hohnemann, C., 1997, Stable isotope records from ODP Sites 932 and 933, *in* Ocean Drilling Program Leg 155, Scientific results, Volume 155: College Station, Texas, Ocean Drilling Program, p. 305–318.

Maslin, M.A., Mikkelsen, N., Vilela, C., and Haq, B., 1998, Sea-level– and gas-hydrate–controlled catastrophic sediment failures of the Amazon Fan: Geology, v. 26, p. 1107–1110.

Masson, D.G., Canals, M., Alonso, B., Urgeles, R., and Huhnerbach, V., 1998, The Canary debris flow: Source area morphology and failure mechanisms: Sedimentology, v. 45, p. 411–432.

McGuire, W.J., Howarth, R.J., Firth, C.R., Solow, A.R., Pullen, A.D., Saunders, S.J., Stewart, I.S., and Vita-Finzi, C., 1997, Correlation between rate of sea level change and frequency of explosive volcanism in the Mediterranean: Nature, v. 389, p. 473–476.

Morner, N.A., 1991, Intense earthquakes and seismotectonics as a function of glacial isostasy: Tectonophysics, v. 117, p. 139–153.

Nisbet, E.G., 1990, The end of the ice age: Canadian Journal of Earth Sciences, v. 27, p. 148–157.

Paull, C.K., Brewer, P.G., Ussler, W., III, Peltzer, E.T., Rehder, G., and Clague, D., 2003, An experiment demonstrating that marine slumping is a mechanism to transfer methane from seafloor gas-hydrate deposits into the upper ocean and atmosphere: Geo-Marine Letters, v. 22, p. 198–203, DOI 10.1007/s00367-002-0113-y.

Piper, D.J.W., and Asku, A.E., 1987, The source and origin of the 1929 Grand Banks turbidity current inferred from sediment budgets: Geo-Marine Letters, v. 7, p. 177–182.

Popenoe, P., Schmuck, E.A., and Dillon, W.P., 1991, The Cape Fear landslide: Slope failure associated with salt diapirism and gas hydrate decomposition: U.S. Geological Survey Bulletin 2002, p. 40–53.

Rebesco, M.A., Cita, M.B., and Hieke, W., 2000, Deep-water tsunami-induced Holocene megaturbidite in the eastern Mediterranean: GeoScience2000, Abstract volume, p. 18.

Reeder, M.S., Rothwell, R.G., and Stow, D.A.V., 2000, Influence of sea level and basin physiography on emplacement of the late Pleistocene Herodotus Basin megaturbidite, southeast Mediterranean Sea: Marine and Petroleum Geology, v. 17, p. 199–218.

Rothwell, R.G., Thomson, J., and Kähler, G., 1998, Low-sea-level emplacement of a very large late Pleistocene ''megaturbidite'' in the Western Mediterranean Sea: Nature, v. 392, p. 377–380.

Stuiver, M., and Reimer, P.J., 1993, Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program: Radiocarbon, v. 35, p. 215–230.

Thomas, R.H., 2001, Remote sensing reveals shrinking Greenland Ice Sheet: Eos (Transactions, American Geophysical Union), v. 82, p. 369–373.

Van Weering, T.C.E., Nielsen, T., Kenyon, N.H., Akentieva, K., and Kuijupers, A.H., 1998, Large submarine slides on the northeast Faeroe continental margin, *in* Stoker, M.S., et al., eds., Geological processes on continental margins: Sedimentation, mass-wasting, and stability: Geological Society [London] Special Publication 129, p. 5–17.

Weaver, P.P.E., and Rothwell, R.G., 1987, Sedimentation on the Madeira abyssal plain over the last 300,000 years, *in* Weaver, P.P.E., and Thompson, J., eds., Geology and geochemistry of abyssal plains: Geological Society [London] Special Publication 31, p. 71–86.

Manuscript received 8 May 2003
Revised manuscript received 19 September 2003
Manuscript accepted 22 September 2003

Printed in USA