Timing of occurrence of large submarine landslides on the Atlantic Ocean margin

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A B S T R A C T

Submarine landslides are distributed unevenly both in space and time. Spatially, they occur most commonly in fjords, active river deltas, submarine canyon-fan systems, the open continental slope and on the flanks of oceanic volcanic islands. Temporally, they are influenced by the size, location, and sedimentology of migrating depocenters, changes in seafloor pressures and temperatures, variations in seismicity and volcanic activity, and changes in groundwater flow conditions. The dominant factor influencing the timing of submarine landslide occurrence is glaciation. A review of known ages of submarine landslides along the margins of the Atlantic Ocean, augmented by a few ages from other submarine locations shows a relatively even distribution of large landslides with time from the last glacial maximum until about five thousand years after the end of glaciation. During the past 5000 yr, the frequency of occurrence is less by a factor of 1.7 to 3.5 than during or shortly after the last glacial/deglaciation period. Such an association likely exists because of the formation of thick deposits of sediment on the upper continental slope during glacial periods and increased seismicity caused by isostatic readjustment during and following deglaciation. Hydrate dissociation may play a role, as suggested previously in the literature, but the connection is unclear.

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1. Introduction: submarine landslide territories and times

1.1. Landslide territories

As noted by Hampton et al. (1996) submarine landslides commonly occur in areas with thick sedimentary deposits, sloping seafloor and high environmental stresses. These “landslide territories” are most common in five specific environments: (1) fjords, (2) active river deltas on the continental margin, (3) submarine canyon-fan systems, (4) the open continental slope, and (5) oceanic volcanic islands. Note that these “territories” exclude much of the continental shelves and deeper water basins. All five of these “territories” occur along the margins of the Atlantic Ocean, but on the east coast of the United States at present, the most common of these are submarine canyons and open slopes.

Landslides range greatly in their size from small, frequently occurring failures in very active environments such as beaches, channels and canyons to failures that are many km across but occur much more infrequently. Because of difficulties in mapping small features, most surveys of landslide deposits emphasize large failures and overlook smaller landslide deposits. In fact, McAdoo et al. (2004) speculated that some smooth seafloors, which one might expect to have experienced few failures, actually represent the passage of many sediment flows. Despite these difficulties in dealing with the full range of scales, Booth et al. (1993) surveyed almost 200 submarine landslide deposits from the US Atlantic margin and reported that somewhat more landslides occurred on the open slope than in canyons and that a much larger area is covered by open-slope landslide deposits than canyon landslide deposits (although the data set may be somewhat biased against canyon landslides because of resolution difficulties in complex canyon morphologies). Accordingly, open-slope landslides are much larger. Because the likelihood of tsunami generation varies directly with landslide size, open-continental-slope landslides clearly deserve the greatest attention in any submarine-landslide tsunami hazard evaluation. The only exception might be the partial collapse of volcanic islands, such as the Canary Islands, which could serve as a far-field tsunami source, as suggested by Ward and Day (2001), and discussed in more detail in Section 2.4.5 below.

1.2. Landslide times

There are a number of large submarine landslide deposits associated with the open continental slope off the east coast of the US with volumes in the range of several hundred km3 and areas exceeding 500 km2 (Edgers and Karlsrud, 1982; Booth et al., 1993; Maslin et al., 2004). According to landslide motion and tsunami generation models (Locat et al., 2009-this volume; Geist et al., 2009-this volume) at least some of these large landslides most likely generated significant tsunamis when they occurred. However, just as some areas of the seafloor are more prone to failure than others, the environmental conditions that cause landslides of this nature are also not uniformly distributed with geologic time. There are most likely
some time periods when the probability of failure is greater, and some periods when the probability is less. If we can evaluate when these periods occur, we can either reduce or increase our estimate of the likelihood of landslide tsunamis for the present period in geologic history.

Many temporally varying factors influence submarine slope stability. These include the following:

1. Quantities, types and rates of accumulation of sediment delivered to the margins. As the quantity of sediment delivered increases, the likelihood of formation of thick, potentially unstable sedimentary deposits also increases. The influence of sediment type is less clear (Lee and Edwards, 1986). Sandy sediment is more vulnerable to failure during cyclic loading events but fine-grained sediment, if deposited rapidly, can form weak, gassy, pore-water pressure-charged material. During glacial periods, the input of sediment to the continental margins generally increases, particularly near the edges of continental ice sheets.

2. Locations of depocenters; particularly slope vs. shelf. Thick, relatively weak sediment deposits on the continental slope clearly have a greater potential for producing open-slope failures than similar deposits on the shelf. Likewise, during glacial periods, when sea level is lowered to near the shelf break, the likelihood of deposition on the slope increases (formation of shelf-edge deltas) vs. interglacial periods when river deltas are commonly located on the shelf and sediment is stored in flooded coastal valleys and estuaries. Catastrophic drainage of glacial lakes (Uchupi et al., 2001) can also occur during glacial periods and can bring large quantities of sediment to the outer shelf and continental slope. According to Uchupi et al. (2001) such floods can trigger gravity flows on the upper slope and carry coarse debris into the deep sea.

3. Changes in seafloor pressures and temperatures, which can influence hydrate stability and the possible generation of free gas (Kayen and Lee, 1992). Changes in sea level alter hydrostatic pressures on the seafloor and can cause destabilization of gas hydrates contained within some bottom sediment. Global oceanic temperature changes and redirection of warm and cold currents can have a similar effect. When gas hydrate is destabilized, it can release free gas, increase pore-water pressure, and reduce sediment strength. Critical times in geologic history include sea-level falls during the onset of continental glaciation, the beginning and end of glacial cycles when the locations of major currents, such as the Gulf Stream, change their course and other periods of extensive environmental change.

4. Variations in seismicity related to isostatic loading or unloading of coastal and near-coastal regions by ice (or to a lesser extent by large sea level changes) (Bungum et al., 2005). The formation and melting of thick sheets of ice produce large changes in crustal stresses. Particularly in areas near the margins of ice sheets, the crust may respond to strong induced stress gradients by internal failure and the generation of earthquakes that are larger than would generally be expected for these areas. Crustal stress changes related to ice loading and sea-level changes may also play a role in the frequency of island and coastal volcanism (McGuire et al., 1997). Variations in volcanism could lead to variations in volcanic island collapses.

5. Changes in groundwater flow conditions within the continental slope and shelf (Dugan and Flemings, 2000). Some sediment beds within continental margins can become pressurized for a variety of reasons, including flow from higher elevations, tectonic activity, direct loading by ice and gas reservoirs. Pressure gradients in these beds induce groundwater flow, commonly from the continents into the offshore. Sea-level changes during the waxing and waning of ice sheets alter these conditions and rates of flow. This in turn alters the pore water pressure regime within the slope and can, under some conditions, contribute to slope failure.

Although all of the above conditions can occur on a small scale, because of local effects (e.g., river course changes, tectonic activity, opening and closing of straits, etc.), the dominant factor that can influence the times of occurrence of significant submarine landslides is glaciation. Pleistocene glacial and interglacial cycles include several phases (see Fig. 1 for a conceptual diagram of these effects) that can cause or impede the development of large submarine landslides:

1. Initiation of glaciation. With the onset of a glacial cycle, large, thick ice sheets form over high latitude continental areas. The resulting impoundment of water causes sea level to fall worldwide in the range of 100 m, and the fronts of the ice sheets advance toward the coast. The ice erodes large quantities of geologic material, and meltwater from the front of the ice sheets increases in flow rate and sediment concentration. Deposits of rapidly accumulating sediment form near the shelf break, and these increase in thickness with time. With sea level lowered, a result is the development of more extensive and potentially more unstable shelf-edge deltas, even in areas far removed from continental ice sheets. Shifting the weight of
large amounts of water from the ocean to land changes crustal stresses and can create an environment of increased seismicity, particularly near the edges of the ice sheets where the stress gradients are highest.

Most of these effects increase the likelihood of submarine slope failure. Lowering sea level decreases seafloor pressure and this can lead to gas-hydrate dissociation and the development of high excess pore-water pressures in some places. The resulting decreased shear strength can lead to failure. Increased seismicity can load continental slope sediment bodies and also potentially cause them to fail (Lee and Edwards, 1986). The development of thick sediment bodies near the shelf break, including shelf-edge deltas, can also increase the risk of failure. However, this last process extends throughout a glacial cycle, and the slope stability progressively decreases as the cycle continues. Groundwater flow conditions can change. The head difference between groundwater levels in near coastal highlands and the ocean is increased, owing to sea-level fall. In the absence of other changes, this can reduce stability.

(2) Full glaciation. After the ice sheets have reached their maximum extent, seismicity at the margins may begin to decline and the tendency toward hydrate dissociation will be reduced. Both of these factors will, in themselves, lead to reduced slope instability. However, rapidly deposited sediment bodies will continue to form on the slope, and as they become thicker, the tendency towards excess pore-water pressure development will actually increase. Likewise, enhanced groundwater flow and resulting elevated pore-water pressures may also continue. The net effect of all of these factors is unclear. Almost certainly the likelihood of slope instability is greater during full glaciation than during interglacial times although it may well be less than during the transition period between interglacials and glacialcs.

(3) Transition from glacial to interglacial time. As continental ice sheets melt and sea levels rise, increased seismicity near the margins of areas that were heavily glaciated will begin to occur as a result of isostatic readjustment. Shelf-edge deltas will be near their maximum extent and may have pore-water pressures that are near their greatest values owing to long periods of rapid deposition during the glacial period. Major current systems such as the Gulf Stream may readjust, bringing warmer water to areas like northern Europe and possibly altering the stability of gas hydrates (Sultan et al., 2004b). This effect is countered by larger sea floor pressures produced by greater water depths on the slope. Groundwater flow may be slowed owing to higher sea levels, and new deposition will tend to occur more commonly on the shelf than on the slope. The net effect of these changes is complex, although some aspects of the response can be modeled (Sultan et al., 2004a,b). From an empirical point of view, as illustrated below, the geologic record shows many large submarine landslides occurring in the Early Holocene.

(4) Interglacial time. After sea level has risen, seismicity near the margins of the former ice sheets will slowly decline. Unstable shelf edge deltas formed during the glacial period will either already have failed or will become gradually less likely to fail. Enhanced stability occurs because of a lack of new sediment and the dissipation of excess pore-water pressures produced during rapid deposition. Conditions of hydrate stability will become less variable and elevated pore-water pressures related to groundwater flow will decline. The period well after the end of a glacial cycle is most likely one in which the likelihood of submarine slope failure is lowest, except on deltas of large rivers that have prograded across the shelf, e.g., the Mississippi River Delta.

2. Field data

2.1. Techniques

The data base of reliable ages of submarine landslides is limited. To properly date a landslide, one generally must have a sample of sediment from immediately above either the landslide debris itself or the surface along which sediment has been completely removed (landslide scar). Datable materials (e.g., calcareous microfossils, mollusks) from within the sediment above the slide are separated and dated using a variety of techniques, among which radiocarbon methods are most popular (e.g., Normark et al., 2004). For very recent (last 100 yr) landslides, measurements of short-half-life radiotopes such as 210Pb or 137Cs can be used (Lee et al., 2007). Dating landslide debris itself is not as reliable because the sediment that failed may be relatively old. Likewise the sediment preserved below the failure may have been eroded and may also have a date that is greater than that of the failure. Another technique that has been used is to observe acoustic reflectors in seismic-reflection profiles across the front of a landslide extending into unfailed areas. If identified reflectors can be dated within a nearby boring (e.g., an ODP hole), then the age of the critical reflector associated with the top of the landslide deposit can be taken as the age of the slide (e.g., Fisher et al., 2005). Another common but less reliable dating method is to determine the thickness of post-landslide sediment above a landslide scar or landslide debris, estimate a representative sediment accumulation rate, and convert the sediment thickness into time (e.g., Prior et al., 1986).

Hance (2003) presented an extensive review of documented seafloor slope failures. This review listed 534 failures that have been described in the literature and included a tabulation of the location, size and reported age of many of the failures. The number of failures discussed below is not nearly as large as that given by Hance (2003). However, the dates given here are interpreted as being the most reliable and, accordingly, most suitable for drawing conclusions regarding temporal variation in the occurrence of submarine slope instability.

2.2. Canadian margin

One area where a relatively large number of landslides have been dated is southeast Canada (Piper et al., 2003). For this area, the investigators have estimated the ages of 23 failures extending back to about 125,000 yr before present, although most (20) are younger than 50,000 yr. The methodology used for determining the chronology of piston cores taken in the vicinity of the failures included radiocarbon dating of mollusks or foraminifera, comparison of oxygen-isotope profiles with accepted oxygen-isotope stage data, and the observation of indicators of Heinrich events in the cores (Piper and Skene, 1998). Heinrich layers are periodic beds of detrital carbonate transported by ice rafting and proglacial plumes that come from the vicinity of Hudson Strait. They were clearly laid down during glacial times and their mechanism for development is likely related to oscillations in the Laurentide ice sheet. Canadian scientists are well acquainted with the events and their ages, and their presence can be used as a chronologic indicator. With dated cores, the investigators could date landslides directly, follow acoustic reflectors from coring sites into the zones of failure or use a dated stratigraphy to recognize a set of key reflectors that could be used regionally to date landslide features. On the basis of these various dating techniques, Piper et al. (2003) developed a graph showing the distribution of failures vs. time and general location (Fig. 2). The graph shows only two dated failures in the last 10,000 yr, one of them being the Grand Banks earthquake event of 1929. These failures occurred under post-glacial conditions. In contrast the graph shows 14 dated failures for the preceding 20,000 yr (30,000 to 10,000 yr before present). This period generally corresponds to glacial conditions. Fewer events are identified for times before 30,000 yr.
described by Bunn and McGregor (1980). Prior et al. (1986) described the volume of the outer, later slide is greater than 46 km$^3$. Locat et al. (2009-this volume) were covered with a fairly thick sediment drape that clearly postdates the event. The drape is 5–9 m thick over a deeper trough part of the feature and 4–6 m thick over the shallower and steeper headwall. Deposition rates are likely about 5 cm/ky for the Holocene and about 20 cm/ky for the Late Pleistocene. According to Prior et al. (1986), these rough numbers indicate that the age of the Currituck Slide is between 25 and 50 ky. Such values would clearly indicate a period of glaciation and lowered sea level. Prior et al. (1986) suggest that the landslide may have been associated with a shelf-edge delta created by the ancestral James and Roanoke Rivers, which would have deposited sediment rapidly on the upper slope during periods of sea-level lowering.

### 2.3.1. Currituck slide

Prior et al. (1986) and the Cape Fear slide (Popenoe et al., 1993; Paull et al., 1996; Paull et al., 1996; Rodriguez and Paull, 2000; Hornbach et al., 2007) in subsequent years. Gravity and piston core samples taken from within the landslide source area show a 1- to 2-m-thick surface layer of brown clay overlying sediment with a fabric suggestive of mass–movement deposits (inclined beds, small convolutions and clasts within a finer matrix and a relatively large proportion of sand). Embley (1980) and Popenoe et al. (1993) reported $^{14}$C dates from the base of the younger brown clay in two cores; these were about 21 and 12 ky, respectively. Paull et al. (1996) obtained sediment ages from 9 cores that pass through the sole of the slide within 50 km of the headwall; these consistently yielded ages of 9 to 14.5 ka at locations 5 to 50 cm above the unconformity. Directly below the unconformity, the ages are all greater than 29 ka. Finally, a recent ODP boring (Site 991) sampled the sole of the landslide and recovered 2.09 m of post slide material above a distinct contact (Rodriguez and Paull, 2000). Five $^{14}$C dates above the contact show a uniform rate of sedimentation (27 cm/ky) above the hiatus. Below the hiatus the age of sediment is about 27 ky yr (Rodriguez and Paull, 2000). Accordingly, numerous radiocarbon dates show that the landslide occurred between 8 and 14.5 yr ago. The one older age (about 21 ky) reported by Embley (1980) most likely has been affected by contamination by material below the unconformity. The age of the material below the unconformity (i.e., age of slip surface) is in the range of 20 ky to greater than 29 ky.

The results above show that the Cape Fear slide occurred near the transition between the last major glacial cycle and the present interglacial. The Cape Fear slide is clearly younger than the Currituck slide as suggested by these radiocarbon dates and the significantly less post-failure drape on top of the failed material (1–2 m vs. 4–9 m). The Cape Fear slide is also younger than the Cape Lookout Slide to the north as indicated by GLORIA records that show the Cape Fear Slide cutting across it (Booth et al., 1993).

At least one of the causes for the Cape Fear slide is salt tectonics and diapirism (Cashman and Popenoe, 1985). A salt body was deposited during the period of rifting that marked the birth of the North Atlantic. Subsequent loading by sediment from the North American continent caused the salt to mobilize and move seaward (Popenoe et al., 1993). This mobility caused the development of salt diapirs and the formation of normal faults (Cashman and Popenoe, 1985; Popenoe et al., 1993, Hornbach et al., 2007). Recent high-resolution multibeam and chirp surveys show that a single massive normal fault, related to salt intrusion, intersects the main Cape Fear headwall. These data suggest that slide failure initiated along this fault (Hornbach et al., 2007). If salt tectonics and normal faulting are the basic cause of the slide, then temporally varying environmental conditions (e.g., glacial and sea level cycles) might have played a smaller role than they did along the Canadian Atlantic margin or at the location of the Currituck slide.

### 2.3.2. Cape Fear slide

The Cape Fear slide is the largest submarine slope failure off the east coast of North America, having a volume that is likely in excess of 200 km$^3$. The failure deposits were discovered in the late 1970s (Embley, 1980) and have been studied extensively (Popenoe et al., 1993; Schmuck and Paull, 1993; Paull et al., 1996; Rodriguez and Paull, 2000; Hornbach et al., 2007) in subsequent years. Gravity and piston core samples taken from within the landslide source area show a 1- to 2-m-thick surface layer of brown clay overlying sediment with a fabric suggestive of mass–movement deposits (inclined beds, small convolutions and clasts within a finer matrix and a relatively large proportion of sand). Embley (1980) and Popenoe et al. (1993) reported $^{14}$C dates from the base of the younger brown clay in two cores; these were about 21 and 12 ky, respectively. Paull et al. (1996) obtained sediment ages from 9 cores that pass through the sole of the slide within 50 km of the headwall; these consistently yielded ages of 9 to 14.5 ka at locations 5 to 50 cm above the unconformity. Directly below the unconformity, the ages are all greater than 29 ka. Finally, a recent ODP boring (Site 991) sampled the sole of the landslide and recovered 2.09 m of post slide material above a distinct contact (Rodriguez and Paull, 2000). Five $^{14}$C dates above the contact show a uniform rate of sedimentation (27 cm/ky) above the hiatus. Below the hiatus the age of sediment is about 27 ky yr (Rodriguez and Paull, 2000). Accordingly, numerous radiocarbon dates show that the landslide occurred between 8 and 14.5 yr ago. The one older age (about 21 ky) reported by Embley (1980) most likely has been affected by contamination by material below the unconformity. The age of the material below the unconformity (i.e., age of slip surface) is in the range of 20 ky to greater than 29 ky.

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Investigators have also observed indicators of gas hydrates (e.g., bottom simulating reflectors, BSRs) and gas accumulations below the hydrate seal. These factors could induce excess pore-water pressures and possibly trigger failure (Popenoe et al., 1993; Schmuck and Paull, 1993). If so, environmental conditions related to glacial stages could conceivably play a role because hydrate stability is known to be influenced by sea-level stands and bottom-water temperatures (Carpenter, 1981). However, the most likely period for hydrate-destabilization-induced failure is during sea-level falls (Kayen and Lee, 1992) and the Cape Fear slide apparently occurred during a period of sea-level rise.

2.3.3. Mid-Atlantic slope

The mid-Atlantic slope between roughly the entrance to Chesapeake Bay and Hudson Canyon has been studied intensively for the locations and mechanics of submarine landslides (Embley and Jacobi, 1977; McGregor and Bennett, 1977; McGregor, 1977; Malahoff et al., 1980; Cardinell et al., 1982; Robb et al., 1982). This is mainly because the area was a focus for possible Outer Continental Shelf (OCS) energy resource development in the late 1970s and early 1980s prior to moratoria on offshore drilling in the area passed in the 1980s. Submarine landslides played a major role in assessing whether or not lease sale areas were safe for development. According to W. Menard, USGS Director at the time (Folger and Hathaway, 1986), “because of the uncertainty of whether or not there were large submarine landslides or scars that might be reactivated off the area (Baltimore Canyon Trough), we were unable to tell the Bureau of Land Management that it was safe to go ahead and develop.... Some of the most promising tracts, as far as the oil companies were concerned, were simply eliminated because we didn’t know whether it was safe to develop them.”

The Mid-Atlantic slope is complex with many small to medium canyons incising the slope and, in some cases, the shelf break. Distributed among the canyons and extending out onto the continental rise are a number of mapped submarine landslide deposits, some of them quite large. For example, Embley and Jacobi (1977) report a slide on the slope and rise off Maryland with a scar and deposit area of about 2000 km². GLORIA imagery shows an almost continuous series of landslides all along the mid-Atlantic margin (Booth et al., 1993). Surprisingly, given the importance of this area and the number of investigations that have been conducted, few reliable landslide ages are available. Embley and Jacobi (1986) note that the existing data set of more than 40 cores suggests that all of the mass-wasting events with initial water depths shallower than 3000 m are of

Fig. 3. Locations of east coast submarine landslides discussed in the text (after Twichell et al., 2009-this issue). Deposit thicknesses shown for several of the large landslides.
Wisconsin or Early Holocene age. Embley (1980) presents several of these landslide ages that are consistent with the observations of Embley and Jacobi (1986). Four cores taken between Baltimore and Norfolk Canyons sampled homogeneous brownish–gray silty clay without primary structures overlying distinct clasts, suggestive of failure deposits, below 80–120 cm. Radiocarbon dates for the bases of the homogeneous clay layer, presumed to be post-landslide sediment, were 5500, 7285, 10,080 and 6680 yr before present. These ages correspond to the Early Holocene, a period during or shortly after the latest sea-level rise following the last glacial cycle. No dates more recent than 5000 yr ago are reported although the data base is clearly incomplete.

2.3.4. New England slope

The continental slope south and southeast of New England is an area of extensive mass wasting processes (O’Leary, 1986, 1993; Booth et al., 1993). GLORIA imagery shows generally greater backscatter for this part of the US margin, likely indicating the presence of more coarse grained material introduced by landslides, and much of the margin has been mapped as landslide terrain (Embley and Jacobi, 1986; Booth et al., 1993; O’Leary, 1993). Since this is the part of the US Atlantic margin that bounds the region of major continental glaciation, there likely is a connection between glacial processes and the prevalence of submarine landslides, much as there is farther to the north in Canada (Piper et al., 2003). However, the marine community has gathered scant information regarding the ages of the failures. Embley (1980) notes that cores from a landslide area southeast of Long Island, first discussed by Uchupi (1967), all contain an apparently undisturbed hemipelagic section overlying mass–flow units, indicating that failure did not occur in the very recent past. One published age for landslide deposits south of New England, in the area identified by O’Leary (1993) as the Southeast New England Landslide Complex, is given by Embley (1982) as 23,440 yr old. Such an age is near the last glacial maximum, further supporting the premise that slope failure processes were most active south of New England during glacial times. The lack of an extensive data base prevents us from drawing any definite conclusions.

2.4. European and North African margins

The European and North African margins (Fig. 4) have been studied extensively for submarine landslides. This results in part from the many active marine science institutions in the countries bordering the North Atlantic in Europe, the presence of the largest gas field in Norway in the source region of the largest landslide in the North Atlantic and a general interest on the part of the European Union in funding submarine landslide research. The EU-funded COSTA (continental slope stability) Project (Mienert, 2004) extended from 2000 to 2004 and involved a large group of scientists from many countries (including Norway, UK, Belgium, France, Spain, Portugal, Italy and Canada).

Within the COSTA Project, a review was made contrasting the characteristics of submarine landslides in the western and eastern North Atlantic (Huhnerbach and Masson 2004). The reviewers found that submarine landslides are more abundant in the western North Atlantic (off Canada and the US) than in the eastern North Atlantic (off Europe) and that, with the exception of a few huge failure complexes, the slides in the west are generally smaller than those in the east. A majority of slides on both sides of the Atlantic seem to originate in water depths between 1000 and 1300 m.

Weaver et al. (2000) reviewed sedimentation processes along the European and North African margins and prepared a map that summarizes the distribution of landslides. The authors noted that sedimentary environments can be divided into three general sections: a glaciated margin north of 56° N (southern tip of Norway), a “glacially-influenced” margin from 26° N to 56° N, and a non-glaciated margin south of 26° N. Large-scale mass movements are a prominent feature along the glaciated margins of Norway and the Faeroe Islands and some of these are known to have occurred in the Holocene (following the last glacial period). However, a major causal factor for the Holocene failures may have been high sedimentation rates occurring during the glacial period. The intermediate or “glacially influenced” margin has surprisingly few instances of mass movements but is rather cut by a large number of canyons, which funnel sediment to the deep sea by means of turbidity currents. South of 26° N (North Africa) upwelling produces elevated sediment accumulation rates and the area is subject to infrequent but large-scale debris flows.

Canals et al. (2004) reviewed the dating work that has been done on the North Atlantic landslides studied by the COSTA project. These include (from north to south) Traenadjupet, Finneidfjord, Storegga, Afen and Canary (Fig. 4). The first four of these are in the section that Weaver et al. (2000) terms a glaciated margin west of Norway, and the Canary slide is in a clearly non-glaciated margin off North Africa.

2.4.1. Traenadjupet slide

The Traenadjupet slide occurred off northern Norway, extends from the shelf break to more than 3000 m water depth, and has a scar and deposit area of about 14,000 km² (Laberg and Vorren, 2000). Failure was initiated either at the present headwall or retrogressed landward from a deeper site. Apparently, a combination of events led to the slope failure. Sedimentation rates were high within the failure zone during the glacial maxima. Such high sedimentation could have led to high pore-water and gas pressures, which would have produced relatively low shear strength. Although smaller slides were likely initiated during the glacial maxima through sediment loading, the
main Traenadjupet slide was probably caused by seismicity related to postglacial coastal uplift (Laberg and Vorren, 2000).

Two gravity cores from the Traenadjupet slide scar show post-slide sediment overlying what is apparently the slide basal plane. Radiocarbon dating of the post-slide sediment (Laberg et al., 2002) shows that the slide likely occurred about 4000 yr ago, after significant glaciation in Norway had stopped but during a time when post-glacial isostatic readjustment could have led to increased seismicity.

Deposits from an older slide, the Nyk slide (Lindberg et al., 2004) occur south of the Traenadjupet slide and have a mapable area of 2200 km², although parts of the slide are buried by subsequent debris flows, and parts of the slide were removed by the Traenadjupet slide. The slide has been dated at greater than 16.3 ka BP, which is synchronous with fluctuations of a major ice sheet near the shelf edge. Lindberg et al. (2004) suggest that the slide was triggered by loading and unloading of the ice front.

### 2.4.2. Storegga slide

The Storegga slide occurred off the coast of Norway and has a headwall that is about 310 km wide and a runout of over 800 km. Accordingly, with a volume of between 2500 and 3500 km³ (Bryn et al., 2005), the Storegga slide is one of the world’s largest submarine landslides. The Ormen Lange gas field, the largest in Norway, lies in the scar left by the slide and this coincidence has led to what has certainly been the most extensive submarine-landslide investigation ever conducted. The Storegga slide was a component of the COSTA project (Mienert, 2004; Hafldason et al., 2004) and was also the center of a major industry-supported thrust that is summarized in a special publication of the journal Marine and Petroleum Geology (Solheim et al., 2005), containing 26 individual papers.

Dating the Storegga slide has involved the analysis of 89 cores from within a number of identified slide lobes within the larger slide deposit (Hafldason et al., 2005). In all, about 80 dates were obtained, most of them allowing the determination of the age of the base of post-slide sediment. Although more than 60 individual lobes were identified, the dating results show that all of the main lobes represent slide phases that took place within a very short time interval. Indeed most of the lobes evidently intermingled into each other during the failure phase. The lobes become progressively smaller upslope, showing that the Storegga slide has the classic character of a retrogressive slide process. The dating results show that all of the retrogressive phases of the main slide event are clustered within an age interval from 6400 ¹⁴C to 7800 ¹⁴C yr BP. The average of all the dates is 7240 ¹⁴C yr BP with a standard deviation of 239 yr. A few younger lobes were dated with ages that clustered around 5000 and between 2000 to 3000 ¹⁴C yr BP. However, these events were very small in comparison with the main event, having volumes less than 0.1% of the total volume of the slide debris. The general conclusion of the dating study (Hafldason et al., 2005) is that the main Storegga slide is one retrogressive event dated at 7250 ± 250 ¹⁴C yr BP or about 8100 ± 250 cal. yr BP. A few minor events have occurred more recently along the northern escarpment and are dated at 5000 ¹⁴C yr BP and 2500–3000 ¹⁴C yr BP (5700 and 2200–2800 cal. yr BP).

The investigators of the Storegga slide have developed a good understanding of how it occurred (Bryn et al., 2005). First, it was not the first megaslide to occur at this location (Evans et al., 2005). Rather, similar slides have occurred periodically with intervals of approximately 100 ky since the onset of continental shelf glaciation about 500 ky ago. The repeated sliding seems to be a response to climatic variability, and the seismic stratigraphy indicates that sliding occurs at the end of a period of glaciation or soon after the glaciation. Destabilization prior to the slide is related to rapid loading from glacial deposits with generation of excess pore pressure and development of relatively low shear strength in underlying clays. The slide was likely triggered by a strong earthquake and initiated in an area downslope from the present head scar. The failure then developed into a retrogressive slide and the head propagated shoreward. The earthquake, in turn, was likely related to glacio-isostatic rebounding following the deglaciation of Scandinavia. Bryn et al. (2005) claim that a new ice age with infilling of glacial sediment on top of marine clays in the slide scar will be needed to create a new unstable situation at the site of the Storegga slide.

The Storegga slide clearly produced a tsunami, the deposits of which have been observed around the Norwegian Sea and North Sea and along the northeast coast of England (Bondvik et al., 2005). The deposits are found on shore elevations of up to 10–12 m in Norway, 3–6 m in northeast Scotland and above 20 m on the Shetland Islands above the estimated sea level at the time of failure. A model of a tsunami resulting from a retrogressive slide that descends at 25–30 m/s is in good agreement with the observed deposits (Ward, 2001; Bondvik et al., 2005).

### 2.4.3. Slides off the British Isles

A series of relatively large landslides has been surveyed off the north and northwest coasts of the British Isles. Several large slides are found on the slopes of the Norwegian Basin northeast of the Faeroe Islands. One of the most recent failures has been dated from one box core at 9850 ± 140 yr BP (van Weering et al., 1998). Farther south, the Afen slide, located about 100 km northwest of the Shetland Islands, is relatively small (area of scar and deposit ~ 40 km², volume ~ 0.2 km³) but has been studied extensively (Wilson et al., 2004) as part of the COSTA project. One dated core shows that it occurred more recently than 5800 yr BP. On the Barra Fan, in Rockall Trough, west of Scotland and northwest of Ireland, the Peach slide (Holmes et al., 1998) has had multiple failure events extending back to the mid-Miocene. The most recent event is thought to have occurred after the last glacial cycle. An age of 10,500 yr is given by Maslin et al. (2004). In the same general area, failures have been mapped on the east side of Rockall Bank and these appear to have ages in the range of 15,000–16,000 (Flood et al., 1979). In general, and with the exception of the small Afen slide, the failures on slopes to the north and northwest of the British Isles appear to have occurred either shortly after the last period of glaciation or during it.

### 2.4.4. Southern Europe

The section of the continental margin between the British Isles and West Africa is dominated by submarine canyons and deep sea fans. The fans are likely accumulations of turbidites, mass flow deposits that originate in many cases in slope failures in the upper parts of submarine canyons. A study of the Horseshoe fan off Portugal (Lebreiro et al., 1997) shows that significantly more turbidites are deposited during glacial periods than during interglacial. Lebreiro et al. (1997) estimate that there were about 2.7 times as many turbidity currents during glacial periods than during inter-glacials.

### 2.4.5. West Africa

A surprisingly large number of mass-wasting deposits are found in the area off West Africa and surrounding the Canary Islands (Fig. 4. Uregeles et al., 1997, 1999; Krastel et al., 2001; Masson et al., 2002). The landslides appear to have two distinctly different origins (Gee et al., 1999). The first type consists of pelagic sediment deposited off the coast of northwest Africa. This sediment results from highly productive surface waters that produce large quantities of biologic material deposited fairly rapidly on the slope. This biogenic sediment is augmented by dust blown off the Sahara Desert. The second type of landslide consists of volcanlastic debris derived from collapses of parts of the Canary Islands. Both types of failure have long runouts and can involve large quantities of sediment. Volcanic collapse occurring on La Palma Island has been suggested as a potential source of a huge tsunami that could strike the coasts of the Americas with waves in the range of 3–8 m (Ward and Day, 2001). Recent analyses of such a collapse (Gisler et al., 2006) show that high amplitude waves could be
produced that would be dangerous to the Canary Islands themselves and the shores of Morocco, Spain and Portugal. However, waves striking the coast of Florida would likely not exceed 77 cm.

Many studies have been conducted to date Saharan and Canary Island landslide deposits (e.g., Krastel et al., 2001). According to Gee et al. (1999), an event about 60,000 yr ago initially involved a failure of the pelagic sediment off Africa. The resulting pelagic debris flow proceeded downslope into deeper water areas and ultimately loaded and destabilized volcaniclastic material, most likely a previously deposited set of turbidites or debris avalanches derived from the Canary Islands. The combined flow continued for a distance of 400 km. More common are Canary Island debris avalanches (Urgel et al., 1997, 1999). The most recent significant event likely occurred off the island of El Hierro about 15 ka ago (Masson, 1996, Carracedo et al., 1999) and probably involved the failure of a subaqueous lava platform. A much older (~130 ka) failure caused a collapse that removed a substantial subaerial part of the island as well (Carracedo et al., 1999). Major debris avalanches related to partial island collapses appear to be correlated with turbidity-current deposits in the Madeira Abyssal Plain. If so, there have been seven major landslides in the Canary Islands in the last 750 ka, yielding a recurrence interval of about 100 ka. Canals et al. (2004) suggested a slightly shorter recurrence interval of 75 ka. There may be a correlation between eruptions of island volcanoes and sea level (McGuire et al., 1997), and this could lead to a possible temporal effect on volcanic island collapses. Also, Saharan debris flows might be slightly more common during glacial periods and sea-level lowstands because of the greater sediment production in Africa.

2.5. Amazon Fan

Seismic reflection profiles through the Amazon fan show at least four major mass-transport deposits (Piper et al., 1997). Deep-sea drilling has shown that all of the deposits date from the Late Pleistocene. Each deposit extends over an area on the order of 10^4 km^2 and is 50–100 m thick. According to Piper et al. (1997), the failures initiated in upper-fan levee sediment and occurred because the sediment was underconsolidated due to rapid deposition during marine lowstand, as well as the presence of shallow gas and gas hydrates. The exact timing of the failures is not completely clear (Piper et al., 1997; Maslin and Mikkelsen, 1997; Maslin et al., 1998), but the two most recent deposits appear to date between the time of peak glaciation and the Early Holocene. Maslin et al. (1998) suggest the failures occurred at about the same time, with ages of 14–17 ka. The two more deeply buried and older failures date to about the periods of 35 ka and 42–45 ka. These times predate the last glacial maximum but still correspond to sea levels much lower than today’s. Maslin et al. (1998, 2004) suggest that the ages of these Amazon fan (and other North Atlantic) failures are associated with short periods (few thousand years) of relatively lower sea level and that these low sea levels produced hydrate dissociation. Although such a mechanism is possible, the accuracy of dating landslide deposits does not seem to be high enough to confirm a strong correlation.

2.6. Other large failures worldwide

Probably most of the world’s large submarine landslides that have been dated are located in the North Atlantic. However, a few examples of dated large landslides are noted in other areas. The BIG95 slide, whose deposits cover an area of about 2000 km^2 in the Mediterranean Sea off the east coast of Spain, has been dated at about 11.4 ka (Canals et al., 2004; Lastras et al., 2004). Off Southern California, the Goleta slide covers about 100 km^2 and contains three surface lobes, two of which have been dated at 8 and 10 ka (Fisher et al., 2003). Older failure deposits lie below one of the lobes and have been dated at 75, 130, and 164 ka, indicating a recurrence interval of failure of about 50 ka for this lobe (Lee et al., 2004). The Palos Verdes debris avalanche, off Los Angeles (Bohannon and Gardner, 2004; Normark et al., 2004) has a deposit with an area of about 50 km^2. The most recent major failure of the Palos Verdes debris avalanche has been dated at 7.5 ka (Normark et al., 2004), but seismic-reflection profiles indicate that numerous failures have occurred at the location of this failure zone in the past. The Sur submarine slide off central California (Normark and Gutmacher, 1988) has an area (scar and deposit) of more than 1000 km^2. The slide has not been dated directly, but by observing the thickness of post-failure deposits in piston cores along with sediment accumulation rates obtained from a core taken 50 km away, Normark and Gutmacher (1988) estimated that the latest phase of the slide occurred 1.5 to 6 ka. The Hawaiian Islands are surrounded by very large landslide deposits that resulted from partial collapses of the islands (Moore et al., 1989). One of the youngest, the Arika 2 slide (Lipman et al., 1988; Normark et al., 1993; McMurtry and Herrero-Bervera, 2003) has an age of around 120 ka. Possible tsunami deposits on the island of Lanai, at a maximum elevation of 326 m above sea level (Moore and Moore, 1984), have been attributed to the Arika 2 slide (Lipman et al., 2008), and the two largest failures (Nuuanu and Wai’alu) have ages between 1 and 2 Ma (Moore et al., 1989).

2.7. Historic landslide tsunamis

Several tsunamis from the last 100 yr are known to have been caused by submarine landslides. These include the 1929 Grand Banks event, the 1964 Alaskan earthquake, which caused major submarine landslides and tsunamis in many places including Seward and Valdez (Lee et al., 2006), the 1970 aseismic submarine-landslide at Nice, France (Seed et al., 1986), the 1975 landslide in Kitimat, British Columbia (Prior et al., 1982), the 1975 Kalapana event in Hawaii (Goff et al., 2006), and the 1998 earthquake-related Papua-New Guinea landslide tsunami which killed approximately 2000 people (Tappin et al., 2003). A large landslide that might have caused an anomalously large tsunami following the 1946 Aleutian earthquake has been suspected (Fryer et al., 2004), but a definitive deposit has yet to be found and the source of the tsunami remains controversial (Fryer and Tryon, 2006; Okal and Hebért, 2007). In general, a fairly large number of tsunamiogenic submarine-landslide deposits have been found at locations where tsunamis have been observed, corresponding to one century of historic time. Most likely few, if any, of these landslide deposits would have been discovered by routine surveys if the occurrence of the tsunami had not focused the attention of researchers on specific locations. Accordingly, one must be wary of the completeness of any list of submarine-landslide dates such as that presented in this paper. Many times more tsunamiogenic-submarine landslides likely have not been mapped or dated. On the other hand, all mapped landslide deposits do not necessarily correspond to tsunami generation at the time of occurrence. The landslides could have moved slowly or as a series of smaller pluses. Conclusions regarding timing and significance of past events need to be tempered with the knowledge that the available data are very limited and incomplete.

3. Modeling

Hutton and Syvitski (2004) report on numerical modeling of the role of sediment failure in the development of continental margins. The authors use the SedFlux model (Syvitski and Hutton, 2001) to simulate the lithologic character of basin stratigraphy through the use of a series of process-based event modules to distribute sediment through surface or subsurface plumes, ocean storm events, slope failures, turbidity currents or debris flows. The model can change accommodation space (space available for sediment deposition) as a result of subsidence, tectonics or compaction. The model produces distributions of grain size, bulk density, porosity and permeability.
Hutton and Syvitski (2004) applied the model to a representative 2-D continental margin and allowed the margin to develop over a period of one million years, incorporating many glacial and sea level cycles. The authors related the modeled sedimentologic properties to geotechnical properties and used the results to predict how earthquake-loading influenced slope stability of the margin as a function of time over this large time span. The model simulates many of the factors thought to be important in continental margin stability and allows an additional check on the role of glacial cycles in affecting margin stability. The results show a strong association between slope stability and sea-level stand. Although failures were modeled to occur at any sea-level position, depending on the prior depositional history, many more (by a factor of 3) occur during periods of falling or low sea level than during comparable periods of rising or high sea level. The largest number of failures was modeled to occur during falling sea level. The model showed that most of the failures are located on the upper continental slope in 500±250 m water depth. The model also showed that most of the failures have a thickness less than 10 m although some can exceed 30 m. The thickness of sediment failure increases during periods of rising or high sea level.

4. Findings and conclusions

Table 1 summarizes the ages of submarine landslides reviewed in this paper (including failures in both the Atlantic Ocean and elsewhere but excluding those from the last 100 yr), and these results are plotted in Fig. 5 along with sea level data to provide a measure of the degree of glaciation. Also provided in the table is a brief description of the bases used for making age estimates. As can be seen, many different age estimate strategies have been applied, and the reliability of the estimates varies greatly. Conclusions drawn from these results must be considered as tentative. If these ages are binned in groups of 5000 yr for the last 20,000 yr (using the mean age for landslides that show a range of possible ages), we find the following: two slides in the last 5000 yr; five from 5 to 9.9 ka, four from 10 to 14.9, and five from 15 to 19.9. Using 10,000 yr ago as a crude approximation for the end of the last glacial cycle and 20,000 yr ago as a crude approximation for the last glacial peak, these results imply that the occurrence of large landslides was roughly evenly distributed with time from the last glacial maximum until about five thousand years after the end of glaciation. In the past 5000 yr the occurrence of submarine landslides has been less frequent. Note that the last 100 yr were excluded because landslide-tsunamis are now directly observed and these observations lead us to conduct surveys and find landslides. Some, perhaps most, of the very recent tsunamigenic landslides would not have been seen if we had not known where to look. However, for the end of the last glacial cycle and 20,000 yr ago as a crude approximation for the last glacial peak, these results imply that the occurrence of large landslides was roughly evenly distributed with time from the last glacial maximum until about five thousand years after the end of glaciation. In the past 5000 yr the occurrence of submarine landslides has been less frequent. Note that the last 100 yr were excluded because landslide-tsunamis are now directly observed and these observations lead us to conduct surveys and find landslides. Some, perhaps most, of the very recent tsunamigenic landslides would not have been seen if we had not known where to look. However,
possibly the Grand Banks event, which laid down a 1-m-thick turbidite over large parts of the Sohm Abyssal Plain (Heezen et al., 1954), would still have been observed even if observers had not been available to experience the earthquake, tsunami, and cable breaks. If so, then we can increase the apparent number of large landslides of the last 5000 yr from two to three. We could then conclude that ratio of landslide occurrence during and shortly after glacial cycles to landslide occurrence well into an interglacial period is about 5:3.

These observations regarding increased occurrence of submarine slope failures during and shortly after periods of glaciation are supported by other data. For example, as discussed above, Piper et al. (2003) show that glacial periods produce about 3.5 times as many submarine landslides on the Canadian margin as do non-glacial periods. Likewise, Lebreiro et al. (1997) estimate that there were about 2.7 times as many turbidity currents during glacial periods off the coast of central Europe. Although at least part of the reason for reduced turbidity current activity during interglacial periods is that some canyon heads become stranded at the shelfbreak, an association is still likely between turbidity-current deposits on deep-sea fans and abyssal plains and submarine-slope failures on the slope and within canyons. In summary, all these field results appear to indicate an increase in the frequency of large landslides by about a factor of 1.7 to 3.5 during and shortly after glacial periods, relative to times well after glaciation.

Model results (Hutton and Syvitski, 2004) support the idea that significantly more submarine landslides occur during falling or lowered sea level than during rising or high sea level. The model, in fact, suggests that occurrences are 3 to 5 times more likely under falling or lowered conditions, with the greatest number corresponding to the time when sea level is falling. A plausible explanation for field observations that many more landslides occur during and shortly after glacial periods is that during glacial periods and the associated lowstands of sea level, thick deposits of sediment form readily on the upper continental slope, often in shelf-edge deltas. When glacialization ends, seismicity is increased near previously glaciated areas, serving as a trigger for causing these thick slope deposits to fail. Even in regions that were not glaciated, relatively thick, potentially weak deposits may have been preferentially deposited on the upper slope. These deposits might be more susceptible to failure during glacial cycles or shortly thereafter than similar slopes at times farther into an interglacial cycle (after most of the potentially unstable slopes have failed, probably during large earthquakes).

The role of hydrate dissociation in the initiation of submarine landslides has been discussed extensively in the literature (e.g., Kayen and Lee, 1992; Paull et al., 1996; Maslin et al., 2004), but there are few definitive studies that show that this process indeed caused a landslide. One problem is that most of the landslides reported are from the last 20,000 yr, which is a period of mostly stable or rising sea level, a time when significant hydrate dissociation might not be expected. Also, the relatively poor accuracy of landslide dates makes it difficult to associate failure events with relatively short periods of sea level fall (Maslin et al., 2004). Large landslides such as the Storegga slide were at one point thought of as possibly having been caused by hydrate dissociation but more recent studies appear to show that hydrates were not a major factor in causing failure (Bryn et al., 2005).

Clearly, not all tsunamigenic landslides involve failures of sediment deposits that were emplaced on the slope during lowstands or were failures triggered by isostatic-rebound related seismicity. Collapses of volcanic islands and other mechanisms for steepening slopes, such as the salt tectonics associated with the Cape Fear slide and some failures in the Gulf of Mexico, may be less influenced by glacial stands, although even for these cases, crustal stress changes associated with sea level change may play a role (McGuire et al., 1997). Likewise, as evidenced by the Grand Banks event, there is a continuing possibility of slope failures in previously glaciated areas that are initiated through the residual effects of the last ice age. Such failures could possibly occur off the southern margin of New England where we know many submarine landslides have occurred in the past but where we have little knowledge of their chronology.

In summary, a risk of tsunamigenic submarine landslides exists off the east coast of the US. and likely elsewhere along the margin of the Atlantic Ocean. However, the probability of occurrence is less during the present interglacial period, perhaps by a factor of 1.7 to 3.5, than it was during the last glacial period. Also, the probability is likely decreasing with time. Most likely areas where future tsunamigenic landslides could occur include volcanic islands (which are possibly too distant to have a significant impact on the eastern US.), within salt tectonics areas such as near the head of the Cape Fear slide, and off previously glaciated margins such as southern New England.

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