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Potential for large-scale submarine slope failure and tsunami generation along the U.S. mid-Atlantic coast

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Notes

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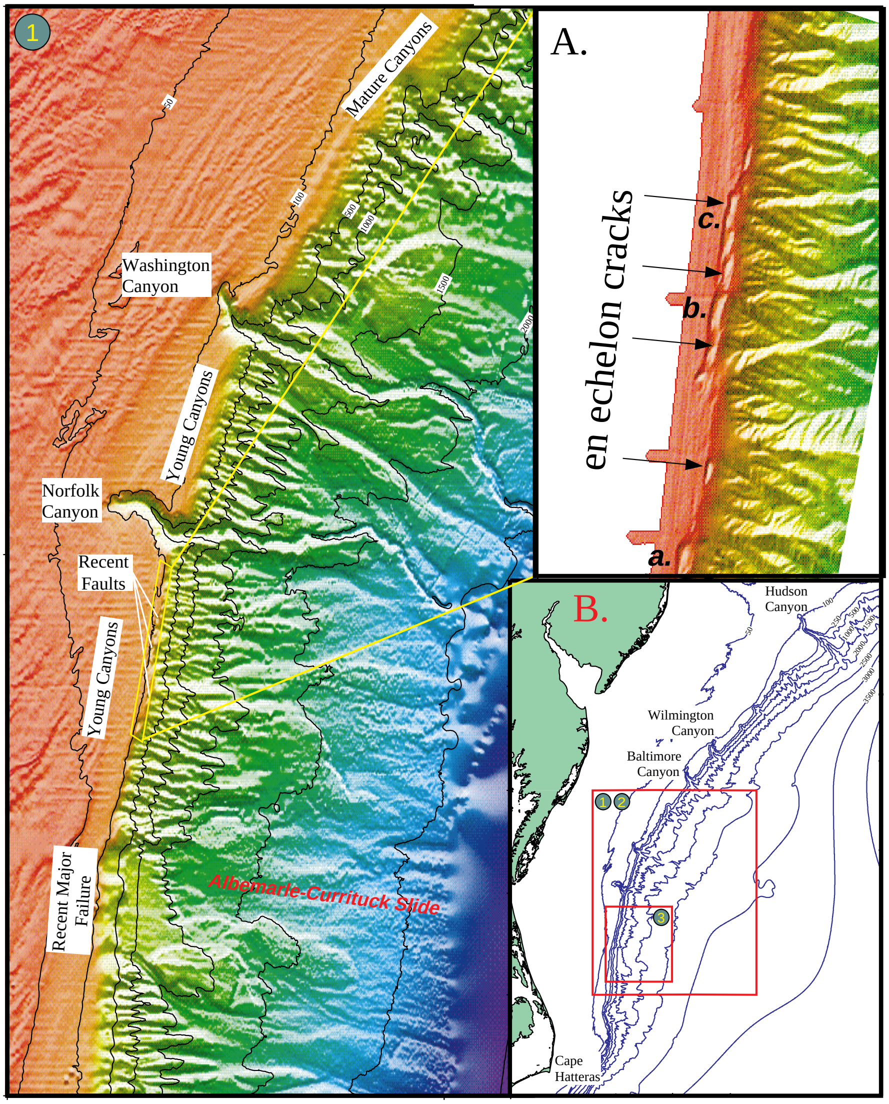
ABSTRACT

The outer continental shelf off southern Virginia and North Carolina might be in the initial stages of large-scale slope failure. A system of en echelon cracks, resembling small-offset normal faults, has been discovered along the outer shelf edge. Swath bathymetric data indicate that about 50 m of down-to-the-east (basinward) normal slip has occurred on these features. From a societal perspective, we need to evaluate the degree of tsunami hazard that might be posed by a major submarine landslide, such as the nearby late Pleistocene Albemarle-Currituck slide, if it nucleated on the newly discovered crack system. Toward this goal, a tsunami scenario is constructed for the nearby coastal zone based on the estimated volume and nature of the potential slide. Although a maximum tsunami height of a few to several meters is predicted, the actual extent of flooding would depend on the tidal state at the time of tsunami arrival as well as the details of the hinterland topography. The Virginia–North Carolina coastline and lower Chesapeake Bay would be most at risk, being nearby, low lying, and in a direction opposite to potential slide motion.

Keywords: slope failure, tsunami, submarine canyons, continental margin morphology.



SUBMARINE LANDSLIDES AND MARGIN MORPHOLOGY

Coastal regions face increasing threats from a variety of natural hazards as their populations grow and urban areas expand. Development of an improved understanding and forecasting of these hazards must be considered a priority in order to mitigate future threats. Media coverage and storm tracking has increased public awareness of the damage to coastal communities caused by severe storms. Tsunamis resulting from offshore earthquakes, landslides, and volcanic activity are equally destructive but rarer events. As a result, public awareness of tsunamis is limited and our capability to forecast when or where they will strike is still underdeveloped (Synolakis et al., 1997; Kawatat et al., 1999). Marine geologists have long appreciated the importance of submarine landslides in the development of continental margin seascapes (Booth et al., 1993; Evans et al., 1996; Embley and Jacoby, 1986), but until recently little attention has been given to the potential hazards that large submarine slides pose to coastal communities in terms of associated tsunamis (Synolakis et al., 1997). The devastating tsunami that struck northern Papua New Guinea in July 1998, killing about 2000, brought the problem of tsunami hazards triggered by seafloor deformation into sharp focus (Kawatat et al., 1999; Tappin et al., 1999). It is often difficult to differentiate tsunamis generated by landslides from those generated by earthquakes on the basis of teleseismic records (Hasegawa and Kanamori, 1987; Julian et al., 1998). Tsunamis are commonly much larger than predicted from earthquake magnitude, suggesting that landslides play an important role in tsunami generation (Tappin et al., 1999). Most researchers agree on the need for more and better bathymetric surveys to find evidence for past landsliding, and to identify areas of seafloor susceptible to future slope failure (Synolakis et al., 1997).

In this paper we draw attention to a system of en echelon cracks recently discovered along a 40-km-long section of the outer continental shelf

Figure 1. System of en echelon cracks, resembling small offset normal faults, recently discovered off Virginia and North Carolina between Norfolk Canyon and Albemarle-Currituck submarine slide using NOAA gridded bathymetry. Inset A shows enlargement of en echelon cracks and inset B shows location map.

off southern Virginia and North Carolina. These features are located in water depths of 100–200 m between the Norfolk Canyon and the Albemarle-Currituck submarine slide (Figs. 1 and 2). The asymmetric shape of the features in vertical cross section suggests that about 50 m of down-to-the-east normal slip of the continental shelf edge has already occurred on a failure surface subparallel to the upper continental slope (Fig. 3). This asymmetry is best explained by the existence of a normal fault with collapse and rollover of the hanging wall into the fault trace. There are two reasons for studying these features. First, knowledge about these incipient submarine landslides will lead to a better understanding of how cycles of large-scale slope failure, canyon cutting, and sedimentation interact to create the observed margin morphology. Second, it is important to understand the hazard implications of these features. Any future submarine landslides nucleating on this en echelon crack system might trigger a tsunami that poses a danger to populations along the adjacent coast.

The swath data illustrate how large submarine slides and canyon systems shape the morphology of the U.S. Atlantic continental margin (Figs. 1–3). We recognize two different categories of slope failure: (1) smaller scale failures that either form canyons, or occur within and are channeled by existing canyon systems, regardless whether the mode of failure was progressive (top down), or retrogressive (bottom up); and (2) larger scale, catastrophic failures like the Albemarle-Currituck slide (Figs. 1–3) that undermine large areas of canyons and effectively erase preexisting canyon morphology. Because work on land has shown that landslide size cumulative frequency statistics follow power-law or fractal distributions (e.g., Hovius et al., 1997), we expect the canyon systems to be steady-state features because they are conduits for many small-scale events, and the large-scale landslides to be temporally infrequent, and spatially isolated events. When these infrequent large-scale slope failures occur, they effectively reset or smooth the continental slope by undermining and removing canyon systems, which are forced to regenerate over time following the landslide event. Evidence for this is shown by the small canyons that are starting to regenerate within the Albemarle-Currituck slide scar at depths of ~1500 m (Figs. 1 and 3).

The two scales of slope failure proposed here predict that the morphology of the resulting debris deposits downslope from the failure scarp should also vary as a function of failure mode. Funneled, coalescing slide deposits like the Baltimore-Accomac slide (Figs. 1 and 2) reflect failures that form canyons or occur within canyon systems, and their downslope morphology is affected by the evolving and/or preexisting canyon relief. In

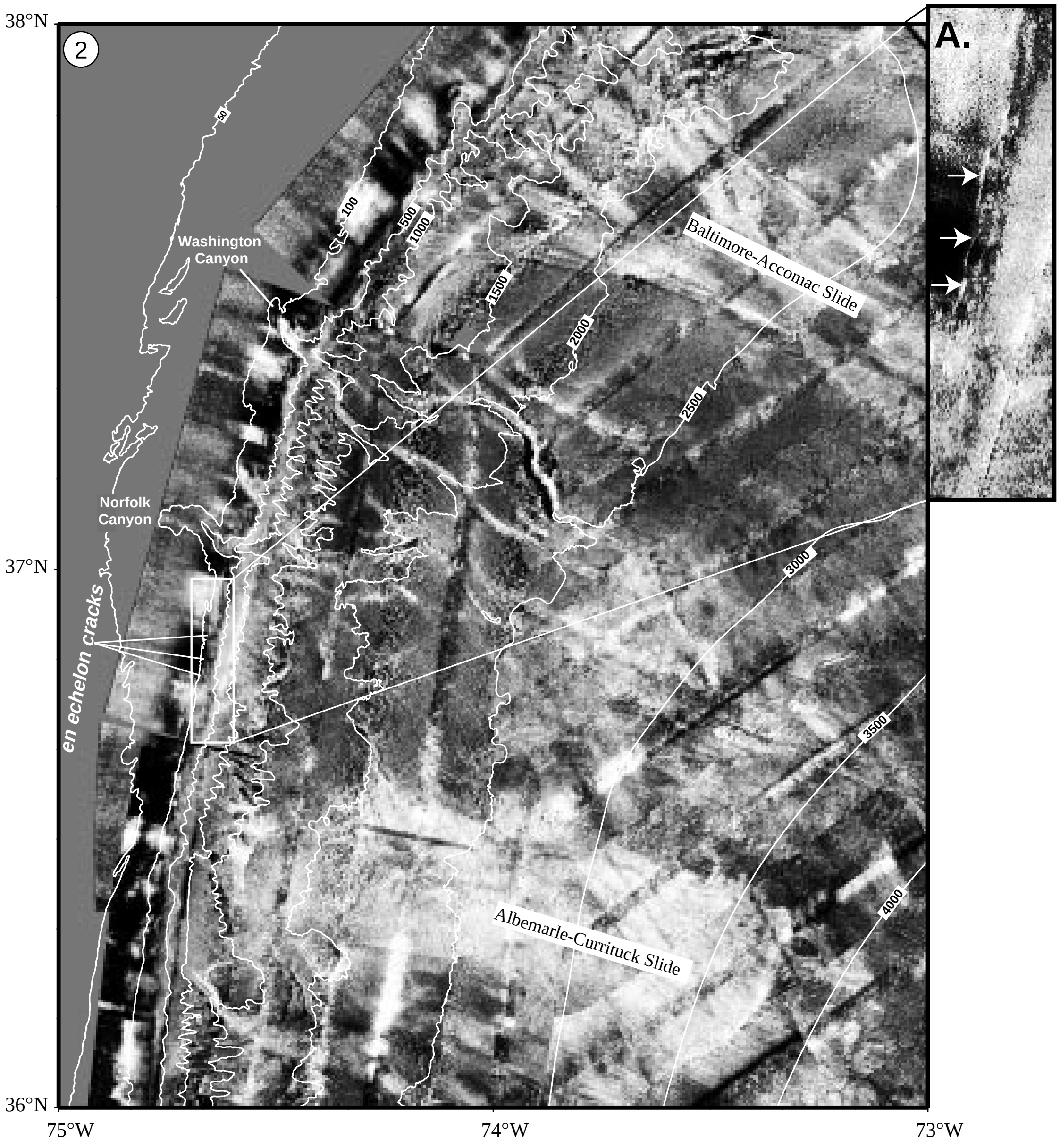


Figure 2. GLORIA sidescan imagery collected by U.S. Geological Survey (EEZ-SCAN 87 Scientific Staff, 1991). Slide deposits appear to vary as function of failure mode and produce (1) funneled, coalescing slide deposits (e.g., Baltimore-Accomac slide) and (2) large blocky slide deposits (e.g., Albemarle-Currituck slide). Contours from Figure 1 are coregistered on GLORIA sidescan. Inset A shows enlargement of en echelon cracks.

the GLORIA sidescan data (Fig. 2), mass-wasting debris deposits can be recognized because of their generally brighter backscatter compared to seafloor covered by hemipelagic finer grained sediments (Schlee and Robb, 1991). Debris channeled in and by canyon systems tends to show as narrow ribbons of bright backscatter, as for the Norfolk and Washington Canyons and the coalescing deposits associated with the Baltimore-Accomac slide (Fig. 2). Conversely, large sheet-like areas of bright backscatter are associated with the blocky debris fields of large slope failures like the Albemarle-Currituck slide that undermine several canyon systems.

Prior et al. (1986) proposed that the Albemarle-Currituck slide is actually a slide complex comprising two main slides, one within another, produced by retrogressive slope failure in the late Pleistocene. Assuming that the upper 100 m of sediments failed, estimates from GLORIA and bathymetric data (Schlee and Robb, 1991) place the total volume of sediment released by the Albemarle-Currituck slide at about 150 km^3 (Figs. 1 and 2). This value is consistent with a previous estimate of 128 km^3 from deep-tow data (Prior et al., 1986). For comparison, the volume of turbidites deposited from the 1929 Grand Banks slide is about 185 km^3, based on sidescan, seismic, and coring data (Piper and Aksu, 1987).

TRIGGERING MECHANISMS

Many processes have been suggested as triggers for submarine slope failures along continental margins. For example, during sea-level lowstands, ground waters may discharge on the continental slope and gas hydrate decomposition may occur in slope sediments (Kvenvolden, 1993). We propose that secular warming of bottom water during interglacials caused by competition and deflection of water masses could also cause gas hydrate decomposition and consequent slope failure. During glacial periods, intensified North Atlantic Intermediate Water (Boyle and Keigwin, 1987) could deflect the warmer Gulf Stream seaward away from the U.S. continental slope. As the production of North Atlantic Intermediate Water diminishes during interglacials (Boyle and Keigwin, 1987), the Gulf Stream would return to its present position. Because of their extreme sensitivity to temperature (Kvenvolden, 1993), gas hydrates in the upper several meters sub-seafloor could melt over the 18 k.y. time interval since the last glacial maximum as a result of changing bottom-water temperatures. One implication of such a triggering mechanism is that the upper part of continental slopes, where gas hydrate should occur at extremely shallow depths (Booth et al., 1993; Kvenvolden, 1993), might undergo slope failure with increasing frequency over time—a possible link between recent climate change and submarine slope failure. In summary, the scale and architecture of slope failures and resulting debris deposits are governed by the location and type of triggering mechanism. Debris chutes and canyons reflect small-scale failure triggered along the slope, whereas the large failures (e.g., Albemarle-Currituck) that indent the shelf edge appear to be triggered by processes that affect, weaken, and undermine the lower slope.

TSUNAMI GENERATION AND HAZARD

Extremely large landslides are a feature of mid-ocean volcanic islands like the Hawaiian Islands (Moore et al., 1989; Normark et al., 1993) and the Canary Islands (Watts and Masson, 1995). Passive continental margins are also sites of slope instability and major landslides (Embley and Jacobi, 1986). If a large submarine landslide were to occur on a margin adjacent to a populated coastal area, it could be catastrophic because of tsunami generation. Only 71 yr ago, a tsunami from the landslide associated with the magnitude 7.2 Grand Banks earthquake of 1929 left 51 dead along the south coast of Newfoundland (NOAA, 1999). Tsunami wave heights recorded from the Grand Banks earthquake and landslide varied from an estimated 4–12 m for southern Newfoundland, north of the epicenter, to less than 1 m along the Nova Scotia coast to the west (e.g., Murty and Wigen, 1976).

Tsunamis generated by landslides have been modeled using hydrodynamic shallow-water equations (Harbitz, 1992; Henry and Murty, 1992). The wave structure for relatively slow seafloor motions like submarine slides is strongly dependent on the time-displacement history of the movement. In particular, large wave-height, short-period tsunamis result from landslides that accelerate rapidly to a high maximum velocity. A sudden but small-volume landslide can therefore generate a tsunami that is more dangerous than a tsunami from a relatively larger but slower slide. The succession of trans-Atlantic cable breaks on the lower slope and rise during the 1929 Grand Banks event (Heezen and Ewing,

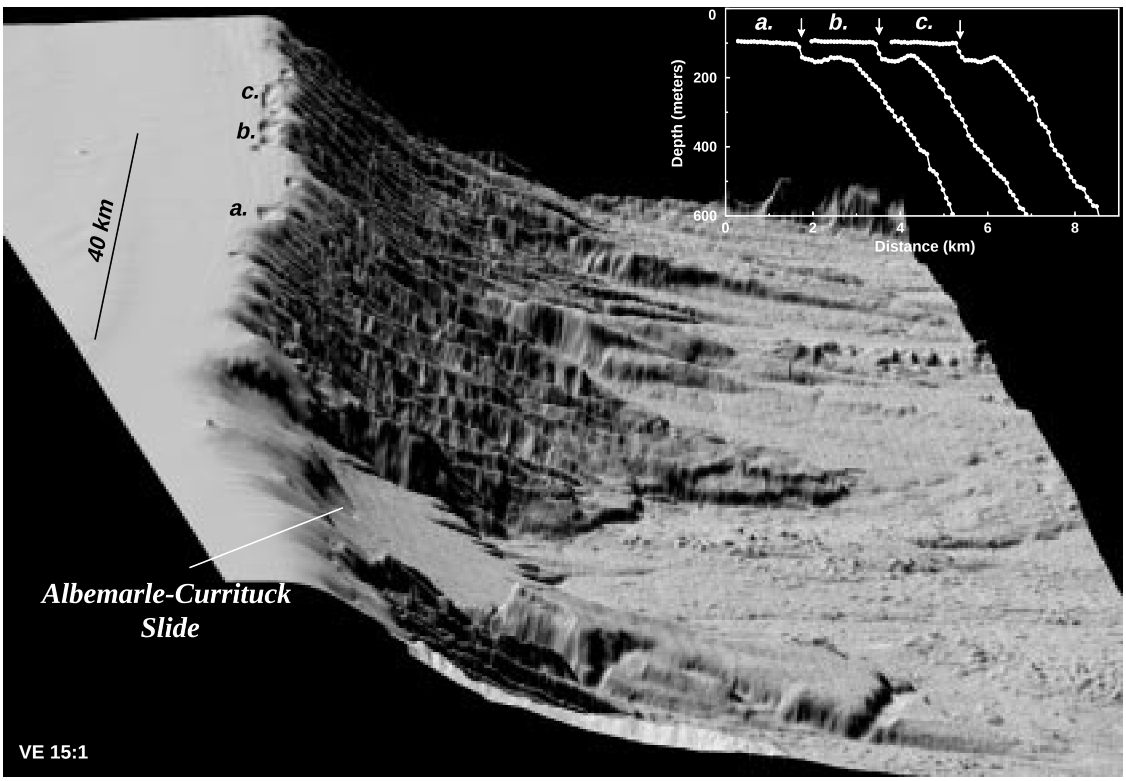


Figure 3. Three-dimensional perspective of continental margin off southern Virginia and North Carolina looking in direction aligned with shelf edge. Shading imitates illumination of seafloor by artificial sun in northwest. Upper Currituck failure surface is smooth area in foreground, and en echelon crack system is seen farther north on outermost shelf. Inset shows three representative bathymetric profiles over cracks, and their locations are noted on perspective image. Location of perspective image is shown in Figure 1.

1952) has been used to constrain maximum slide velocity in the models (Harbitz, 1992). The azimuthal variation in tsunami wave height is related to the direction of slope failure. The largest wave heights occur in the direction of slope failure (downdip direction) and opposite to slide motion (updip direction). The marked difference in tsunami wave heights following the Grand Banks slide recorded to the north in Newfoundland, which is directly updip, and in Nova Scotia to the west is partly explained in this way. Tsunami wave heights might be enhanced by local topographic effects, causing resonance phenomena, as well as from interference and focusing of the incident waves in bays and estuaries along the coastline (Harbitz, 1992). Tsunami runup heights calculated for the ca. 7.2 ka Storegga II slide on the Norwegian margin (Harbitz, 1992) are in good agreement with the runups inferred from the height of dated tsunami deposits mapped along the coasts of eastern Scotland (Dawson et al., 1988), northern Iceland (Hansom and Briggs, 1991), and western Norway (Bondevik et al., 1987).

From a societal perspective we would like to know the tsunami hazard that a slide the size of the Albemarle-Currituck slide (Figs. 1–3) would pose if it nucleated on the newly discovered en echelon crack system. The bathymetric profiles in Figure 3 suggest that future submarine landslides nucleating on the system of en echelon cracks would involve a layer of sediment 100–200 m thick. We construct a tsunami scenario for the nearby coastal zone based on the following assumptions: (1) the future slide will be the same size as the late Pleistocene Albemarle-Currituck slide (volume ~150 km^3), (2) it will generate a tsunami with the same characteristics as the tsunami spawned by the 1929 Grand Banks slide (volume of ~185 km^3), and (3) the other tsunami properties captured in the models (e.g., Harbitz, 1992) apply to the future slide. Within about half an hour after the slope failure, the shoreline would undergo a precursory drawdown in the sea surface of a few meters owing to the back propagation of wave energy in the direction opposite to slide motion. Several minutes to an hour after the drawdown a positive sea-surface displacement would occur, reaching a maximum height of a few to several meters above normal. The extent of flooding would depend on the tidal state at the time the positive part of the tsunami wave arrived as well as the hinterland topography.

The size of the tsunami wave in this scenario is equivalent to the height of the storm surge associated with a category 3 or 4 hurricane, using the Saffir-Simpson hurricane scale. Nevertheless, the nature of the potential hazard is quite different. Each year, there is a small but finite probability of a large hurricane striking the mid-Atlantic coast. A large submarine landslide, however, is a rare event on human time scales. Despite the fact that we know the location of the potential slide very well, we do not yet know if and when slope failure is likely to occur. Given the risk to the coastal community, it seems wise to invest effort to determine whether the en echelon cracks along the Virginia–North Carolina continental shelf edge are fossil features or are active and likely to produce a potentially disastrous, large submarine slide in the near future.

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