GEOPRISMS WHITEPAPER

TITLE: Slope Failure Control on Margin Morphology at the Cape Fear Slide

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I. Summary

Retrogressive submarine slide occur occurring on all of Earth's passive margins. These repetitive back-stepping failures record long-term instability (e.g., Micallef et al., 2008). They are wide-spread, they impact margin erosion and evolution, and they are a societal risk because of their potential to generate tsunamis. Their repetitive failure cycles make them both conducive for understanding failure conditions and for testing slope stability models and establishing what influences the size and rate of failure. Ultimately, these failure processes impact the large scale form of continental margins.

Why retrogressive submarine slides occur remains controversial (e.g., Dugan and Flemings, 2000, 2002; Maslin et al., 2004). Hypotheses for their occurrence invoke external drivers such as infrequent, strong earthquakes (e.g., Kvalstad et al., 2005). Others hypothesize that hydrate dissociation driven by sea-level fall or ocean warming drives slumping (*Paull et al.* 1991; *Rothwell et al.* 1998; *Maslin et al.*, 2004; Liu and Flemings, 2009)). Conversely, other studies hypothesize that sediment strength, slope geometry, and depositional history drive retrogressive slope failure (Dugan and Flemings, 2000; Lee, 2009; Locat et al., 2009) such that external drivers including sea-level fall or earthquakes are not necessary.

We propose an interdisciplinary multi-stage field-based study of slope stability focused on integrating in situ pore pressure measurements with high-resolution 3D seismic images and 3D fluid-flow/heat-flow observations and models to constrain key factors that cause instability at a retrogressive slide. Slope failure and associated tsunamis are a recognized geohazard for the East Coast of the United States and several studies link slope failure with climate change. Many studies have relied on empirical observations and correlations to estimate causes of slope failure on continental margins. We will test these hypotheses by providing a process-oriented understanding of failure based on direct observations. This study will elucidate the geotechnics of slope failure to understand how unloading due to slope failure can lead to a characteristic timescale of regressive failure. This timescale will be influenced in-part by the geotechnical properties of the slope. We will also directly address whether steady-state or dynamic (and therefore unstable) gas-hydrate stability conditions exist at a slide, and therefore, if methane hydrates are presently contributing to instability at these sites. Our study has the potential to define slide re-occurrence time-scales, slide size, and the process of slope failure by direct measurements of in situ time-dependent variables (e.g. pore pressure, stress), and how these variables affect margin stability with time. Our study is focused on the Upper Cape Fear Slide but the approach and expected results will be broadly applicable to retrogressive submarine failures around the globe.

II. Conceptual Model for Retrogressive Slope Failure

We propose a testable hypothesis for the processes that underlie retrogressive failure systems, which we term 'Pore Pressure Rebound'. When slope failure occurs, sediments near the headwall remain relatively strong because unloading has reduced the pore pressure: this limits further failure (Figure 1). Specifically, once an initial scarp forms, the lateral stress (σ_3) is reduced in sediments near the scarp face (figure 1B, figure 1E blue-to-green dot transition). The reduction in lateral stress increases shear (q) and drives the system toward failure (red dot Figure 1e). However, since fluids in headwall sediments are also no longer being squeezed laterally, fluid pressures are also reduced (the ‘undrained poroelastic response’) immediately following failure (figure 1B, 1E).

During failure, mean stress drops and therefore pore-pressure *drops*. At this point, the in situ shear stress (green dot, Figure 2C and E) is less than the failure strength at the same mean stress (the green dot is well below the failure line). Thus the in-situ stress is less than the failure stress and the system is stable. However, over time, lateral flow occurs toward the scarp face: pore-pressure begins to rise back towards its original values (figure 2C, figure 2E between green and red dot) (Bishop and Bjerrum, 1960; L'Hereux et al., in press; Leroueil, 2001). On the p’q plot, the stress path moves horizontally (green to red dot, Figure 1e). As it does, sediments near the headwall further weaken until failure again occurs (Figure 1e). Leroueil (2001) reports time scales from 50 years to 2000 years for ~40m high cliff faces, yet similar retrogressive submarine slides may be more stable (e.g. Rodriguez and Paull, 2000).

Retrogression will be controlled by four factors: (1) the magnitude of pore pressure drawdown due to unloading; (2) the coefficient of consolidation of the material which determines the rate of pore-pressure rebound; (3) the initial pressure conditions; (4) the failure properties of the material. Our research will lead us to (1) an understanding of the time scale of pore pressure equilibration (thus the timing of recurrent failure) (2) the current pore-pressure values at slide headwalls and (3) from this, if slides are near failure. Furthermore, by dating slide failure events, we can test whether pore-pressure rebound times generally match observed failure times, and from this, recognize if a link between pore-pressure rebound and slope failure exists.

To test whether pore-pressure rebound controls slope failure at retrogressive submarine slides, we must know (1) soil properties (e.g. undrained strength, porosity, permeability, friction angle), (2) sediment/slide geometry and thickness (to estimate overburden, pore-pressure, and stability near the headwall and extend sediment properties in space), and (3) the frequency of sliding, which we need to compare estimated pore-pressure rebound times with actual slope failure recurrence. To determine the timing of failure events across the slide, we will use C14 radiometric dating at the site in conjunction with seismic stratigraphy. To determine slide geometry and sediment/slide dip, we will use reflection seismology. To constrain soil properties, we will obtain and analyze long cores across the pre failure, failure, and post-failure surface, and interpolate these properties in two- and three-dimensions using seismic images.

III Study Area: The Upper Cape Fear Slide (CFS)

The Cape Fear Slide (CFS), perhaps the largest slide complex on the U.S. Atlantic margin, is located ~200 km southeast of Cape Fear, North Carolina, just seaward of the Carolina trough (Figures 2 and 3). Initial studies (Cashman and Popenoe, 1985) suggested the CFS may consist of only a few large slides. However, more recent multibeam studies have identified at least five (but likely many more) moderately sized (all >1 km^2) slide events [(Hornbach et al., 2007; Paull et al., 1996; Popenoe et al., 1993; Rodriguez and Paull, 2000; Schmuck and Paull, 1993)].

The upper headwall of the CFS has a crown-shaped morphology, is ~10 km long and ~20 m high (figures 2, 3). It is likely one of the youngest slides in the complex; old single-channel seismic lines indicate no other up-slope debris obscures the scarp and associated features (Carpenter, 1981). As the most landward component of a retrogressive slide, it also represents an area where future failure will likely occur.

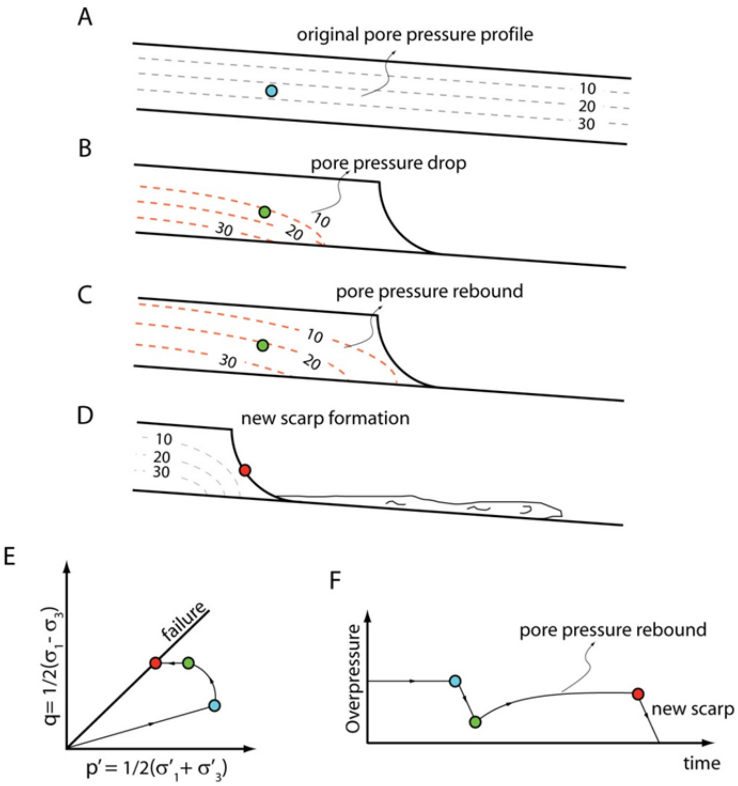

Figure 1. *Conceptual model for retrogressive failure.* ***A*** *Sediment is initially buried from seafloor to pre-failure depth.* ***B.*** *An initial slope failure unloads the lateral stress behind scarp. This increases shear stress but decreases pore pressure, keeping the slope stable in the short-term.* ***C****. Lateral flow causes pore pressures to rise gradually, which decreases effective stress over time and triggers subsequent scarp formation (****D****).* ***E.*** *Effective stress path plot illustrating the evolution of retrogressive failure.* ***F.*** *Overpressure vs. time showing pore pressure drop, rebound, and drop to failure.*

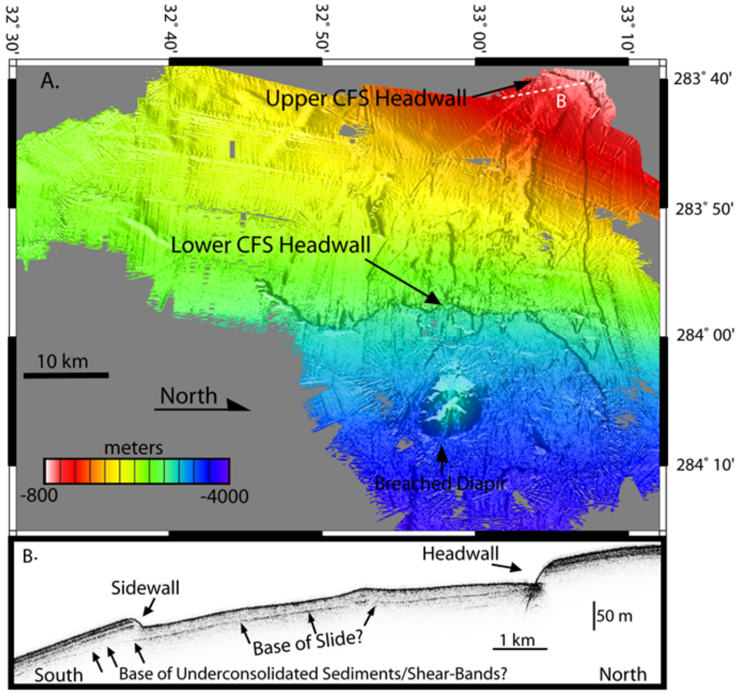

Figure 2.(**A**) Multibeam data collected at the Cape Fear slide complex during reconnaissance work on 2003 NOAA Ocean Exploration cruise (adapted from Hornbach (2007). (**B**) Single chirp seismic line collected across the headwall of Upper CFS. A continuous, variable amplitude reflector tracks across the section and may represent both the base of overpressure and base of the slide. No sediments onlap the sidewall or headwall, suggesting recent failure.

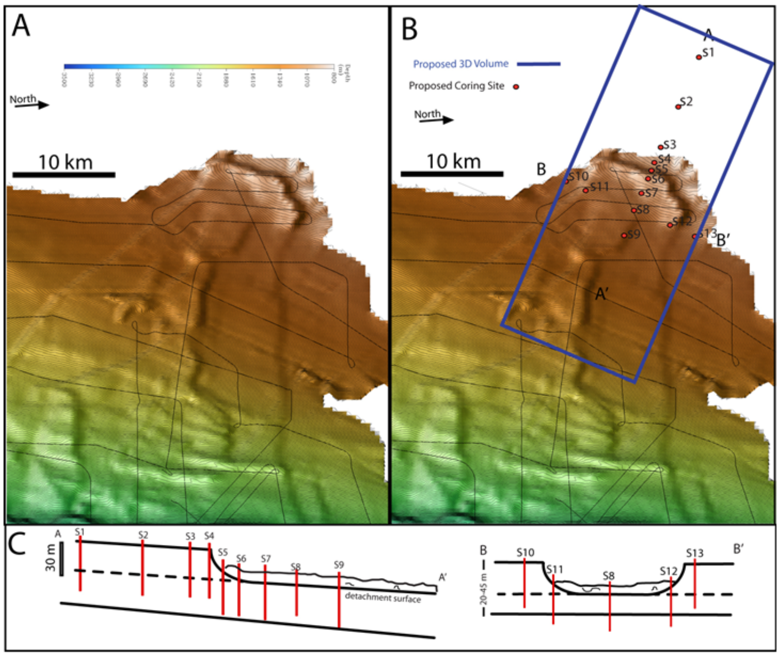

FIGURE 3(***A***) *Basemap (same orientation as Figure 1) showing the multibeam data obtained in 2003 on the R/V Atlantis. Chirp lines are shown as thin black lines.* (***B***) *Proposed coring and seismic lines at the Upper headwall.* (***C***) *idealized 2D cross section of seismic data with core site locations in red. Chirp images and previous coring results near this area indicate long cores should penetrate below the proposed detachment surface.*

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