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Regional Slope Stability Assessment: Challenges in Spatial and Stratigraphic Geologic and Geotechnical Data Integration

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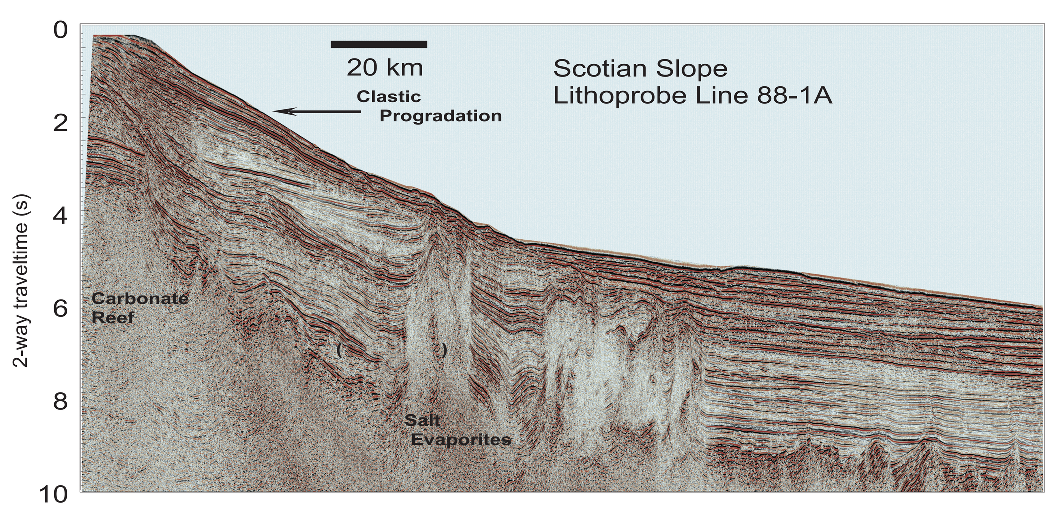
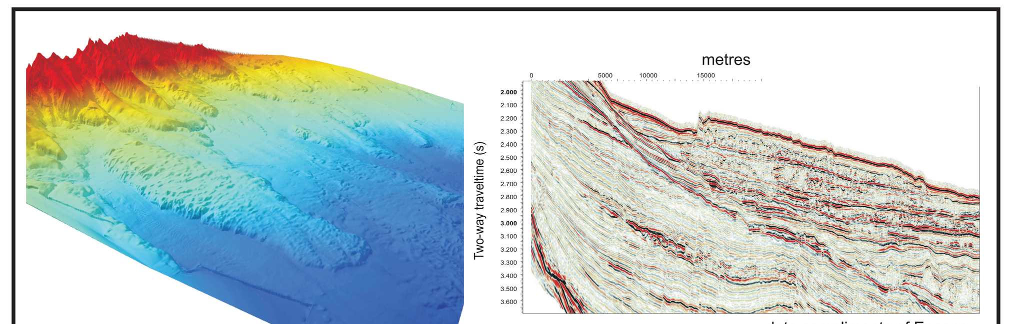
Abstract

Recent oil and gas exploration in Eastern Canada includes deep water continental slope regions. Sediment instability and risk of submarine mass failure is the most significant geohazard in this environment, as demonstrated in the rock record and even in historic times with the 1929 Grand Bank's landslide. An abundance of seismic reflection data and numerous piston cores along the Nova Scotia continental margin make it an ideal area to perform a regional slope stability assessment. Site-specific assessments typically involve slope stability analysis to predict static and dynamic critical slope failure conditions. Vertical measurements of sediment geotechnical properties used in these analyses can be reasonably extrapolated on local scales for site assessment purposes. Regional slope stability assessments, however, have the challenge of integrating geological and geotechnical conditions that vary spatially and stratigraphically. In this study, a simplified geostatistical approach was adopted to assess the effect of spatial variability of soil properties on slope stability analysis. Probabilistic and deterministic engineering assessments were performed for both non-spatially averaged and spatially averaged core sections. Results indicate that the estimated factor of safety increased by 30% when spatially averaged values were used. A slope of 10° has a 50% probability of failure under static conditions. The average slope angle for the area is between 1 and 3°. In this case, a seismic coefficient of ~12% is required to initiate instability. Given the abundance of mass transport deposits in the stratigraphic section, occasional strong earthquakes to generate these coefficients must have occurred in the past. Other contributive factors may have resulted in weakening of sediment in the stratigraphic section to lessen these critical coefficients.

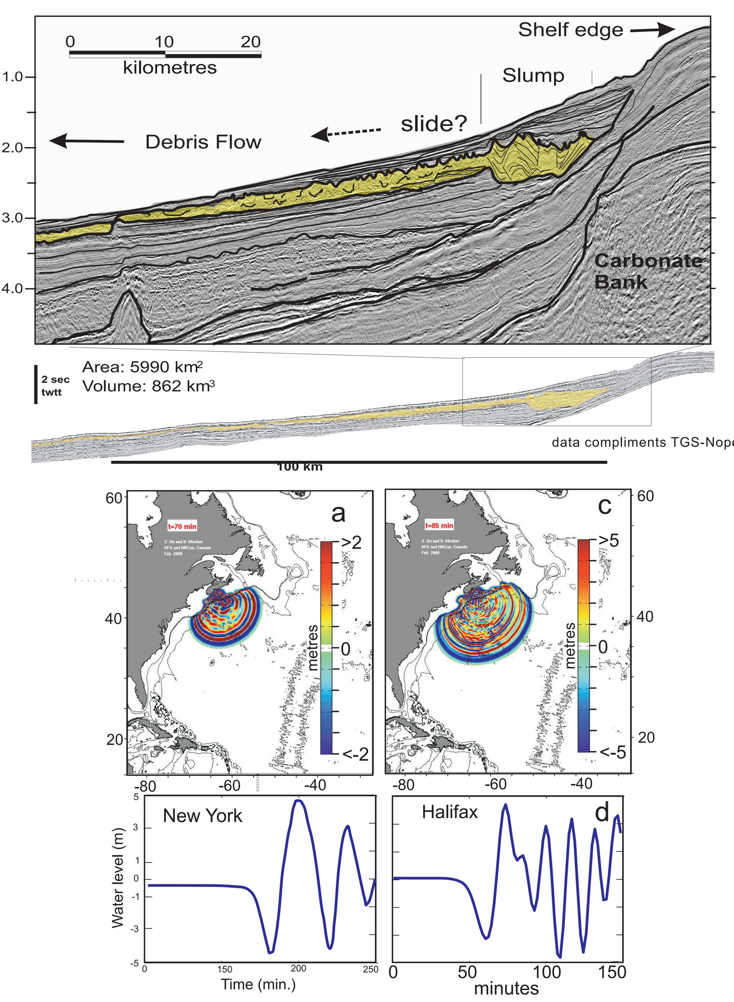


Regional Geology

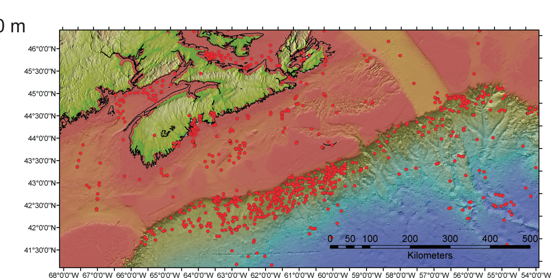
The Scotian Slope is a classic rifted, passive continental margin. A Jurassic carbonate reef complex underpins the shelf and continental edge. Jurassic and Triassic evaporites form diapirs and canopies that appear mobile even today, producing evidence on the modern seafloor. Progradation and aggradation of the margin continued through the Paleogene and Neogene, forming about an 8-12 km thick sedimentary wedge on a low angle slope in about 200 to 2500 m water depth. Periods of erosion and canyon formation interrupt the sedimentary sequence throughout. Pleistocene glaciations significantly influenced the slope, providing a phase of deep canyon incision now characterizing much of the margin. In addition, glaciomarine silts, clays and some sands cover most of the slope.

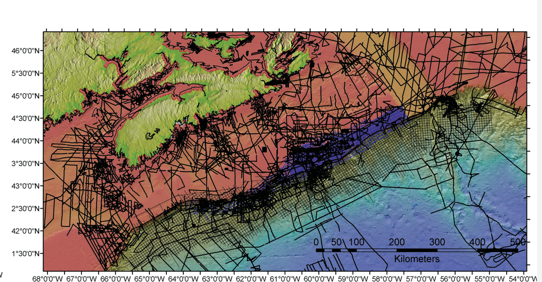


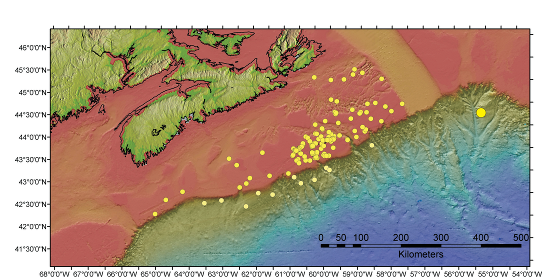
A rendering of the seafloor from a 3D seismic volume shows a mass transport deposit, probably mid-Pleistocene in age. A seismic profile through this block shows a stacked sequence of MTDs, indicating that slope failure is a geologically common process in this environment.

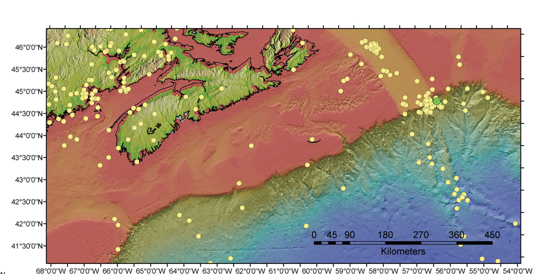


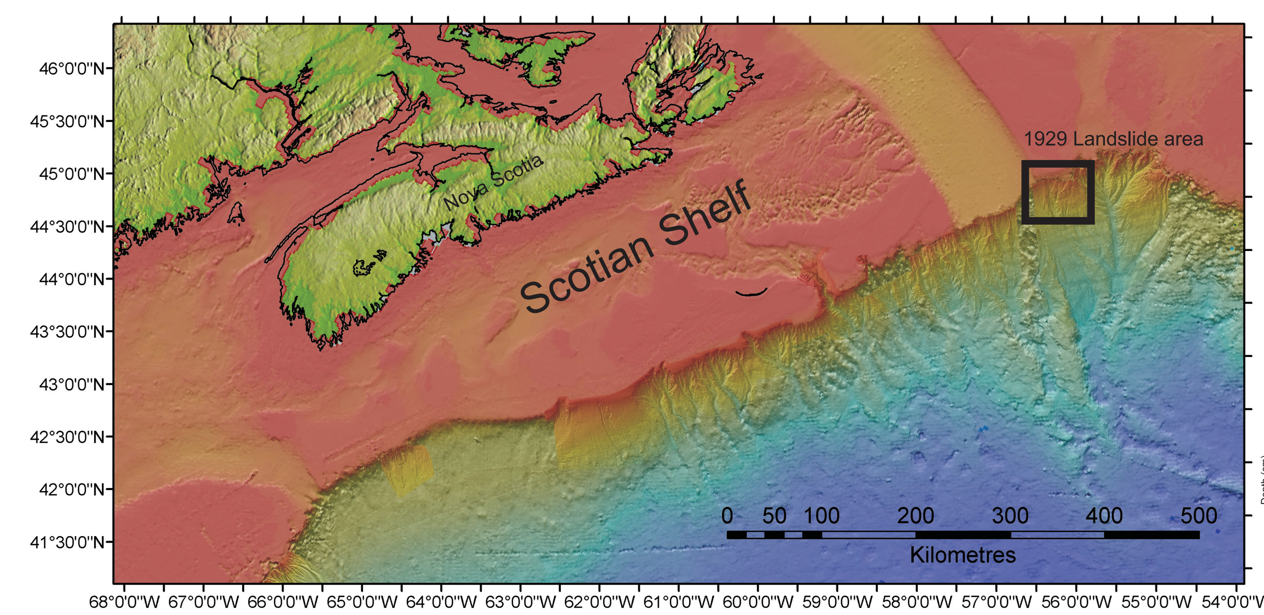
A large MTD was mapped from the central Scotian Slope. A tsunami modeled from this failure impacts Halifax after 75 minutes and New York in about 200 minutes.



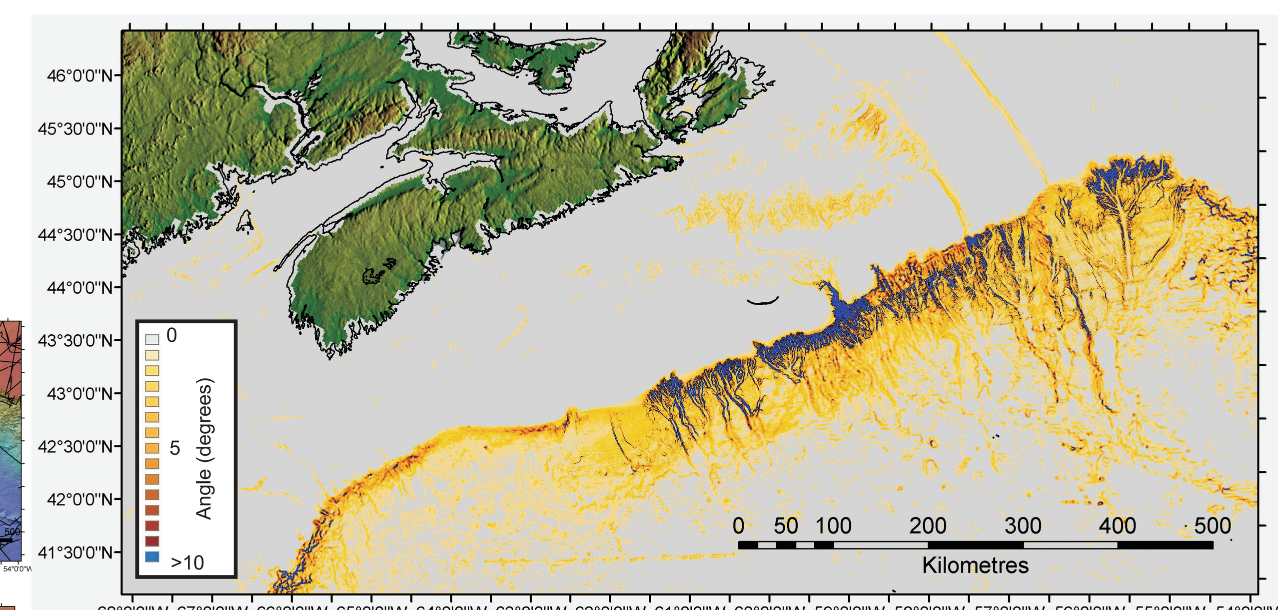




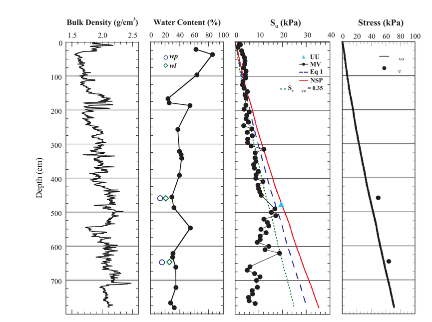


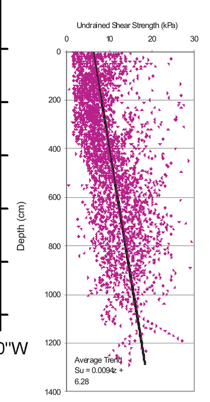


Seafloor bathymetry showing deep canyon incisions over much of the continental slope off Nova Scotia. Multibeam data, where available, are overlain on a regional bathymetric grid.

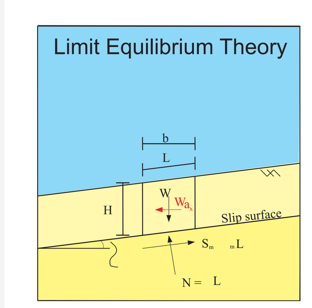


Slope angle map showing the regional gradient on the continental slope is only 1 to 3 degrees. Steepest areas are along canyon walls but these are in highly consolidated material. Escarpments in unconsolidated material are a higher risk, as are areas of unfailed sediment accumulations. The steeper uppermost slope is also of higher risk for instability in areas of unconsolidated material.





Although there are over 550 cores available from the Scotian margin, it represents a sample density of only 3.9 cores per 1000 km². 54 cores with a full suite of physical property measurements were analysed for this study. Mini-vane shear strength was typically measured at 10 cm intervals. providing a normal consolidation profile as seen to the left. Advanced geomechanical testing included consolidation and triaxial shear measurement. The shear strength profile is overlain with a normal consolidation curve of 0.35 and predictive curves of calculated shear strength from triaxial measurements. The stress plot is calculated from overburden pressure and compared with consolidation results.



INFINITE SLOPE STABILITY ANALYSIS

The infinite slope method (right) uses force equilibrium theory to evaluate both the resisting and driving forces on an assumed sliding surface. For simplicity of analysis, the end and side restraining conditions of the sliding mass are ignored. The Factor of Safety (FS) for a potential failure plane is the resistance to shear divided by the driving force (the mass under the influence of gravity), defined as

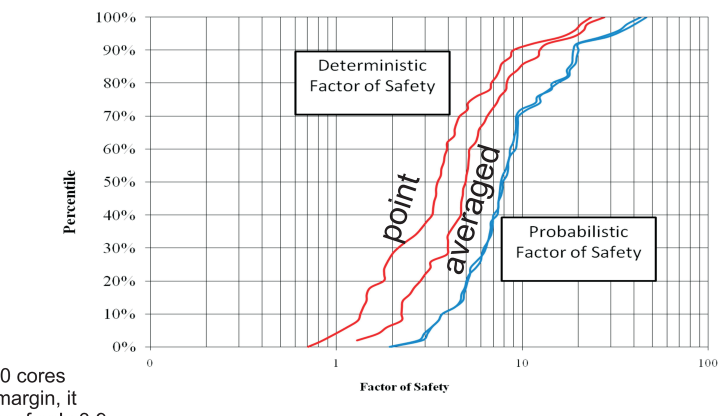
$$FS = \frac{Su}{{}_b H \sin \quad \cos}$$

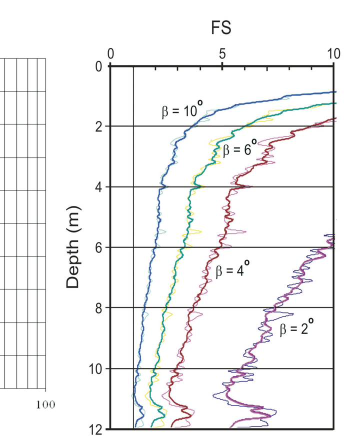
Where S_u is the undrained shear strength of the soil, is the slope inclination and $_b$ is the buoyant unit weight of the soil above the potential failure plane and H is the vertical distance from the potential failure plane to the surface. $_b$ = W/(H*b), where W is the weight of the slab.

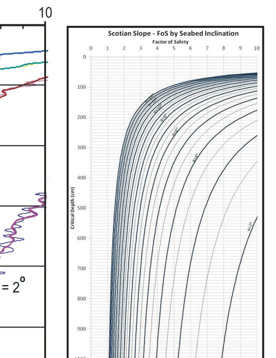
Spatial (depth) Averaging

Discretely measured point observations, i.e. $S_u(z)$ are variable and extreme low strength values will yield conservative estimates of slope instability. The strength of the slope likely involves an average of $S_u(z)$ values over the failure surface, and not just the minimum value observed in the sample. Two methods of assessing spatial correlations were used: variance reduction and variogram modeling. The two methods indicated an averaging length of 0.7 to 0.95 m is acceptable.

Slope Stability Analysis

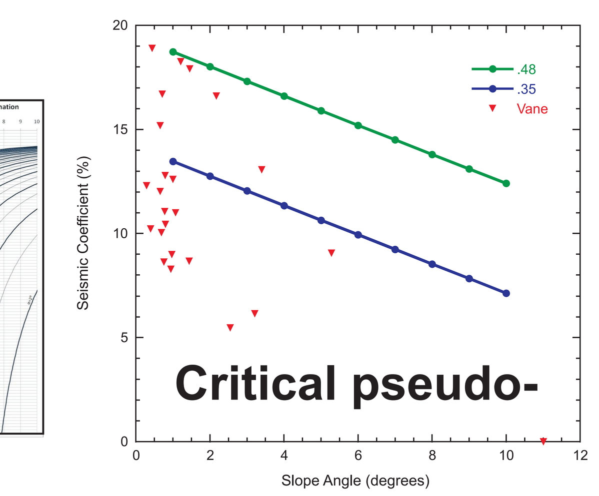






The infinite slope method was used to estimate factor of safety values. A deterministic model was applied to both the point and spatially averaged core sections. The results indicate the calculated factor of safety increased on average by 30% for the study area when data are averaged over the correlation depth.

A probabilistic analysis was performed using a Taylor series with depth below seabed, *z*, and slope inclination , as non-random variables and undrained shear strength, S_u, and unit weight $_b$ as random variables. The analysis was also applied to both the point and spatially averaged core data in order to assess the FS for each core. It was found that there is little difference in the estimated value for FS between the averaged data set and the point estimates using probability theory. An effective stress analysis was performed for limited data using probability theory. The analysis indicates that for static conditions, the region is inherently stable. It suggests a critical seabed inclination of approximately 10°. As one can see from the slope angle map to the left, regions of >10° are small in area and mostly confined to steep slopes of canyon walls, where these analyses do not apply.



Failure Conditions: The plot above shows the critical pseudo-static ground acceleration to initiate slope instability versus slope angle. Values were obtained from miniature vane shear strength data and consolidated isotropic undrained (CIU) triaxial tests. The average $S_u/\ '_v$ value from the miniature vane shear strength data is 0.35 while the CIU $Su/\ '_v$ value is 0.48. The minimum earthquake coefficient calculated for each core site was also included. This analysis suggests that on slopes of 3–6°, a seismic coefficient of >10% is required to cause failure in most of the sediment. A plot on the far left shows the historic seismicity for the Scotian Slope, indicating earthquakes are rare.

Conclusions

Even the most conservative geotechnical estimates show that the Scotian Slope is stable under static conditions.

Slopes in excess of 10° have a 50% likelihood of failure under static conditions according to probabilistic models.

Under dynamic conditions, seismic coefficients in excess of 10% are required to initiate failure, given soil strength measurements and typical slope angles.

Evidence of geologically common mass transport deposits in stratigraphic sections of the margin suggests that seismicity is common enough to produce these deposits or that there other trigger mechanisms. In all likelihood, there are other contributive factors to weaken soil conditions and lower the threshold for failure, but seismicity remains the most probable initiating factor.

In spite of this fact, historic earthquakes suggest seismicity is presently rare on the Scotian margin and the likelihood of exceeding critical ground accelerations is low, although the 1929 Grand Banks earthquake at M7.2 certainly demonstrates that the possibility still exists.

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