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The role of deep-water sedimentary processes in shaping a continental margin: The Northwest Atlantic

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ABSTRACT

The tectonic history of a margin dictates its general shape; however, its geomorphology is generally transformed by deep-sea sedimentary processes. The objective of this study is to show the influences of turbidity currents, contour currents and sediment mass failures on the geomorphology of the deep-water northwestern Atlantic margin (NWAM) between Blake Ridge and Hudson Trough, spanning about 32° of latitude and the shelf edge to the abyssal plain. This assessment is based on new multibeam echosounder data, global bathymetric models and sub-surface geophysical information.

The deep-water NWAM is divided into four broad geomorphologic classifications based on their bathymetric shape: graded, above-grade, stepped and out-of-grade. These shapes were created as a function of the balance between sediment accumulation and removal that in turn were related to sedimentary processes and slope-accommodation. This descriptive method of classifying continental margins, while being non-interpretative, is more informative than the conventional continental shelf, slope and rise classification, and better facilitates interpretation concerning dominant sedimentary processes.

Areas of the margin dominated by turbidity currents and slope by-pass developed graded slopes. If sediments did not by-pass the slope due to accommodation then an above grade or stepped slope resulted. Geostrophic currents created sedimentary bodies of a variety of forms and positions along the NWAM. Detached drifts form linear, above-grade slopes along their crests from the shelf edge to the deep basin. Plastered drifts formed stepped slope profiles. Sediment mass failure has had a variety of consequences on the margin morphology; large mass-failures created out-of-grade profiles, whereas smaller mass failures tended to remain on the slope and formed above-grade profiles at trough-mouth fans, or nearly graded profiles, such as offshore Cape Fear.

1. Introduction

At its foundation, the geomorphology of a continental margin is the result of isostatic elevation differences between oceanic crust and adjacent continental crust, and the rift, transform or subduction processes that produce this juxtaposition. Along most margins, however, morphology is further modified and even transformed by sedimentary processes. These processes depend upon global and local forcing such as climate variation (e.g., fluctuations of glaciations, eustatic sea level, and thermohaline circulation) and quantity, style, rate and type of sediment input. Stow and Mayall (2000) in an overview of deep-water sedimentary systems, suggested that research at the level of architectural elements and their three-dimensional geometry is necessary to significantly improve models for large-scale deep-water sedimentary systems. New extensive data sets along deep-water portions of continental margins acquired of late – particularly for Law of the Sea extended continental shelf (ECS) mapping purposes – provide the data sets needed to analyze these 3D architectures. The present study utilizes data acquired along the Northwest Atlantic Margin (NWAM) within the last ~15 years to improve models for large-scale deep-water sedimentary systems and how they have produced characteristic morphologies.

Prather (2003) and Prather et al. (2017) proposed a continental margin classification system of the general shape of the margin, utilizing four categories. This study adapts their system to the modern seafloor morphology of the Northwest Atlantic continental margin. The hypothesis proposed is that rates of sediment accumulation and removal that in turn are related to sedimentary processes and slope-accommodation, have dictated the morphology of the Northwest Atlantic

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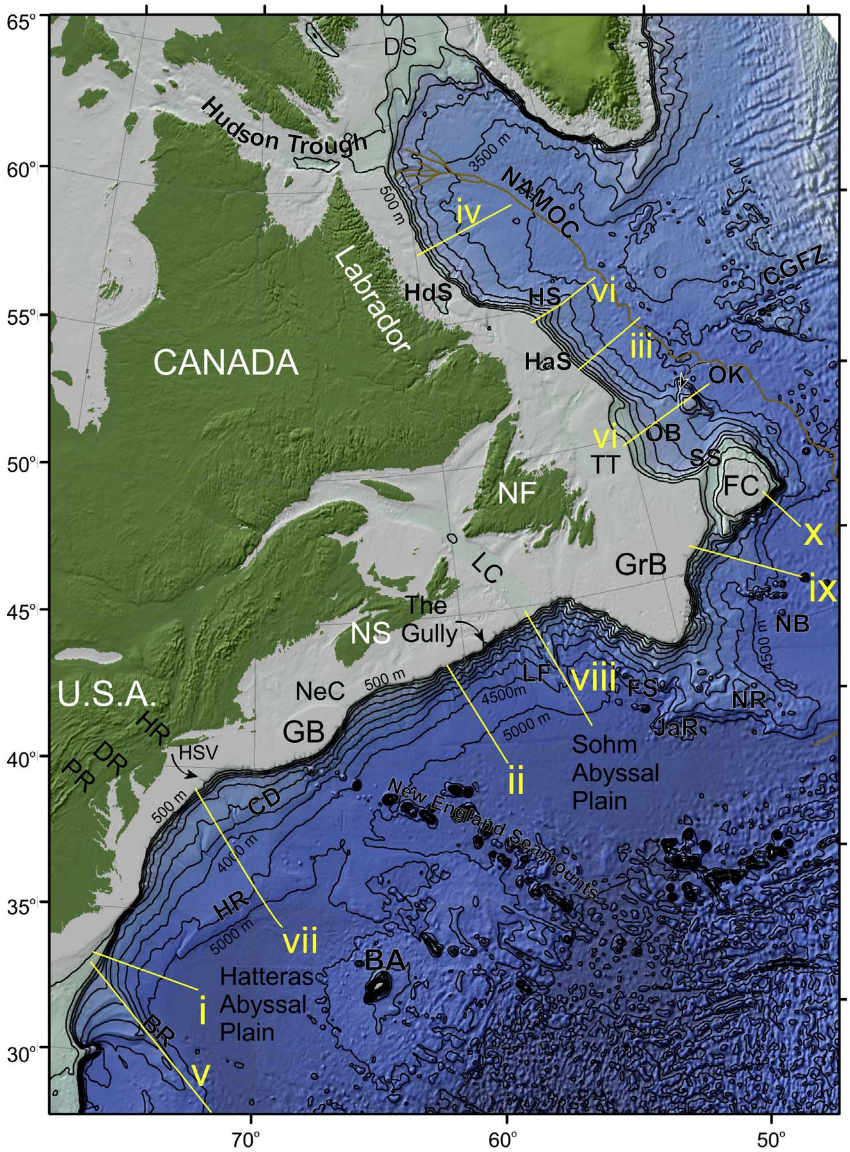

Fig. 1. Seafloor physiography of the western North Atlantic margin: (BA) Bermuda, (BR) Blake Ridge, (CD) Chesapeake Drift, (CGFZ) Charlie Gibb Fracture Zone, (DR) Delaware River, (DS) Davis Strait, (FC) Flemish Cap, (FS) Fogo Seamounts, (GB) Georges Bank, (GrB) Grand Banks of Newfoundland, (HD) Hatteras Drift, (HR) Hudson River, (HdS) Hopedale Saddle, (HS) Hamilton Spur, (HaS) Hawke Saddle, (JaR) J-Anomaly Ridge, (LC) Laurentian Channel, (LF) Laurentian Fan, (NAMOC) Northwest Atlantic Mid-Ocean Channel, (NB) Newfoundland Basin, (NeC) Northeast Channel, (NF) Newfoundland, (NR) Newfoundland Ridge, (NS) Nova Scotia, (OB) Orphan Basin, (OK) Orphan Knoll, (PR) Potomac River, (SS) Sackville Spur, (TT) Trinity Trough. The yellow lines labelled with Roman numerals indicate locations of the profiles shown in Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

continental margin (NWAM). The resulting margin morphology is one of four types: 1) graded, 2) above-grade, 3) stepped, and 4) out-of-grade. The objective of this paper is to examine the geomorphology of the NWAM to elucidate the influences of deep-water sedimentary processes in creating these morpho-types. The focus is on the predominantly siliciclastic portion of the margin between Blake Ridge in the south and Hudson Trough off the northern tip of Labrador in the north, herein referred to as the Northwest Atlantic margin (NWAM) (Fig. 1). This regional perspective of the NWAM has not been attempted since introduction of multibeam and chirp subbotttom-profiler technologies and the wealth of new data acquisition for exploration and mapping purposes.

1.1. Previous work in classifying continental margins

A number of schemes to divide continental margins into their component morphologies have been developed. Wiseman and Ovey (1953) divided the continental margin, or continental terrace in their language, as comprising a continental shelf or borderland, shelf edge, and a continental slope. The slope they defined as "*the declivity from the outer edge of the continental shelf or continental borderland into great depths*". The next significant advance in recognition of the geomorphology of the deep water portion of continental margins was by Heezen et al. (1959). They studied and published on 34 profiles from the NWAM and 23 from the margins of Europe and Africa. From these studies, they developed the well-known concept of a margin comprising a continental shelf, continental slope and continental rise. Despite limited data and despite recognition even then of the variability in shapes of the margins, they made emphatic statements that concern the division of a margin into these components and the specific gradients upon which these subdivisions are defined.

Remarkably, this concept of Heezen et al. (1959) concerning the division of a margin into component shelf, slope and rise has endured for nearly 60 years. Emery and Uchupi (1984) utilized this scheme to map these regions across the entire Atlantic Ocean. Harris et al. (2014) used the definitions of Heezen et al. (1959) in a recent description of the geomorphology of the global ocean seafloor using modern global bathymetric grids. They use the IHO (2008) definition of a slope as, "*the deepening sea floor out from the shelf edge to the upper limit of the continental rise, or the point where there is a general decrease in steepness*", and the rise as "*low gradient, evenly-spaced, slope-parallel contours extending seawards from the foot of the continental slope generally confined to areas of sediment thickness > 300 m*" (Harris et al., 2014, Table 5, p. 20).

This conventional view of the components of a continental margin is not particularly helpful in understanding sedimentary processes that occur in these realms, thus researchers concerned with hydrocarbon exploration have largely ignored the concept. Instead, a classification system based on overall shape of the margin has evolved. Hedberg (1970) utilized the concept of grade to classify modern continental margin physiography. He considered margins as (1) progradational, where sediment deposition advanced basinward, or (2) erosional, where the basin margin is over-steepened and sediments by-passed into a base-of-slope position. Ross et al. (1994) built on Hedberg's ideas to develop a "slope readjustment model". They suggested that out-of-grade margins form when the upper slope gradient exceeds an equilibrium grade, due to either rapid relative sea level rise, tectonic over-steepening or alternating carbonate and siliciclastic deposition. Adams and Schlager (2000) argued that continental margins fit one of three shapes that are defined mathematically: 1) linear, 2) exponential, and 3) Gaussian. They introduced the idea that the geometry of slopes gives information on the depositional environment, whereas the shape parameters offer clues to deducing sediment composition. Meckel et al. (2000) argued for three profile types (1) above-grade with ponded basins, (2) stepped, and (3) graded. They implied that these types represent end-members in a continuum of profile types based on the degree of substrate mobility and sediment flux.

It is on this concept of 'grade' that Prather (2003) and Prather et al. (2017) developed a classification system that is adapted for use in this study. In the terminology of Prather et al. (2017), there are four classifications, 1) graded, 2) out-of-grade, 3) ponded above-grade, and 4) stepped above-grade. Graded slopes have a smooth exponential decay shape, where the gradient is steepest near the shelf edge and gradually diminishes seaward. A graded slope profile represents the long-term equilibrium between depositional and erosional processes. Graded slopes involve slope by-pass and erosion as dominant sedimentary processes. Out-of-grade profiles also have a smooth concave-upward shape, but with very steep gradients near the shelf edge. The upper slope is so steep that sediment is not generally accommodated, resulting in mass-wasting and slope by-pass (Prather et al., 2017). Tectonic over-steepening may also produce out-of-grade slopes (Prather et al., 2017). Above-grade slopes generally show a linear or even convex upward shape in two-dimensional cross-section. Ponded above-grade slopes have enclosed intra-slope basins and stepped above-grade slopes exhibit subtle changes in depositional gradient resulting in a low-relief stepped or terraced topography (Prather et al., 2017).

1.2. Geologic setting

The NWAM extends from 30°N at Blake Ridge (also referred to as the Blake Outer Ridge and the Blake-Bahama Outer Ridge) in the south to 62°N at Hudson Strait in the north; a length of about 6500 km along the shelf edge (Fig. 1). The margin is predominantly siliciclastic in composition and most of it conforms to the type-section for a classic rifted 'passive' Atlantic-type margin (cf., Heezen et al., 1959). The first phase of the opening of the Central and North Atlantic was rifting of North America from Africa around 190 to 175 Ma (e.g., Klitgord and Schouten, 1986; Sibuet et al., 2012). This rifting involved the Central Atlantic spreading center and included the region offshore of the Carolinas to the southern margin of the Grand Banks (Klitgord and Schouten, 1986). Seafloor spreading progressed from south to north as Grand Banks separated from Iberia about 130 Ma. At about 92 Ma, seafloor spreading began to produce the Labrador Sea (Chian et al., 1995). Spreading here changed direction in the early Cenozoic at about 60 Ma when the modern spreading axis initiated on the east side of Greenland. Seafloor spreading in the Labrador Sea ceased by 40 Ma (Roest and Srivastava, 1989). The NWAM is deepest in the south and shoals to the north, as a function of cooling subsidence related to the age of opening.

Early in North Atlantic basin formation – particularly outboard of the northeastern U.S. and Nova Scotia - epeiric seas laid down layers of Triassic and Jurassic evaporite (Jansa and Wade, 1975). Because of their mobility, these deposits have had a continued effect on the geomorphology of this region (Shimeld, 2004; Ings and Shimeld, 2006). Jurassic carbonate deposits also impacted the architecture of the margin (Poag, 1991); the edge of Jurassic carbonate banks commonly mark the tectonic hinge line from which subsequent siliciclastic sedimentation has prograded and aggraded.

Pleistocene glaciations had the latest effect on the NWAM morphology through both proximal glacial/deglacial erosion and sedimentation and associated changes in sea level. The limit of ice during the last glacial maximum was near the southern New York border (Long Island) and near the outer edge of the continental shelf along areas to the east and north (Dyke et al., 2002; Siegel et al., 2012; Mao et al., 2015). Glaciation also affected fluvial inputs south of Long Island from meltwater discharge and low relative sea levels (e.g., Hudson Shelf Valley, Hudson Canyon) (Carey et al., 2005; Piper, 2005; Gardner et al., 2005; Thieler et al., 2007; Piper et al., 2012; Shaw et al., 2014). Eustatic sea level was ~120 m lower during the last glacial maximum (e.g., Wright et al., 2009) but fluctuated significantly during the margin's Cenozoic history (Miller et al., 2005).

Point sources of Quaternary fluvial sediment along the 6500 km length of the margin are few (e.g., Roanoke, James, Potomac/Susquehanna, Delaware, Hudson, Connecticut/Block, Saint John and St. Lawrence river systems) (Poag, 1992). The two most significant point sources are the Hudson and the St. Lawrence rivers, with modern catchment basins of 34,400 and 839,200 km^2, respectively (http://ny.water.usgs.gov/projects/hdsn/fctsht/su.html#HDR0, accessed 10/26/2016; National Atlas of Canada, 1995). Other sources of Quaternary sediment included erosion of the margin during lower sea level stands and glacier discharge during glacial epochs (Piper et al., 2012). For the Quaternary, this latter process far exceeds all other sources of sediment for the region north of Hudson River.

1.3. Oceanographic setting

Today, cold ocean water generated in the north flows south as part of the Atlantic meridional overturning circulation (Fig. 2). The Deep Western Boundary Current (DWBC) is the main component of this southward flow, known as North Atlantic Deep Water (NADW) (Sverdrup et al., 1942; Schmitz and McCartney, 1993). Labrador Sea Water (LSW) is the lightest component of NADW and is formed by winter convection in the central Labrador Sea (Lazier et al., 2002; Rhein et al., 2015). In general, LSW covers the depth range between 500 m and 2500 m. Denmark Strait Overflow Water (DSOW) is the densest component of the NADW and is found at water depths of approximately 3500–4500 m (Isachsen et al., 2007). Source water masses of DSOW are mainly formed in the Norwegian Sea by cooling of surface water

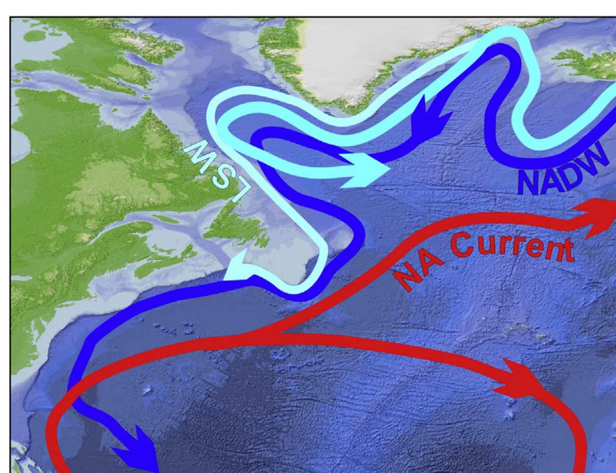

Fig. 2. Modern deep thermohaline geostrophic current patterns. (Modified from Schmitz and McCartney, 1993).

(Isachsen et al., 2007). Both of these water masses are driven westward against the continental margin by the Coriolis Force as they flow southward. The currents follow the complex configuration of the NWAM through the Labrador Sea, around the Grand Banks and southwest along the Scotian and eastern U.S. continental slope at almost all water depths (Fig. 2). Off the NWAM, the downstream portion of DSOW is the Western Boundary Undercurrent (WBUC) (Isachsen et al., 2007). Closer to the sea surface, warm water generated in the Sargasso Sea off Florida flows northward and is deflected eastward due to the Coriolis Force (Fig. 2). The resulting Gulf Stream flows offshore the U.S. and Scotian continental margins before being deflected toward Europe as the North Atlantic Current (Stommel, 1958; Worthington, 1976; Schmitz and McCartney, 1993).

Geologic records show that deep water geostrophic bottom current systems such as the WBUC have varied their flow depths and intensity over time because of changes in the large-scale Atlantic Ocean circulation patterns (Heezen et al., 1966; Ledbetter and Bassam, 1985; Boyle et al., 2017). Present current velocities in the DWBC exceed 20 cm/s (Mertens et al., 2014), but significant variability in volumes of water formation and velocities are noted even on sub-decadal scales (e.g. Rhein et al., 2015). In terms of paleoceanography, study of contourite drift deposits along this margin suggests that formation of cold polar seas and periods of eustatic lower sea level likely affected these currents at times in the past (e.g., Kaneps, 1979; Marshall et al., 2014; Friedrich et al., 2015; Boyle et al., 2017).

2. Data and methodology

2.1. Bathymetric data

The NWAM has been the focus of new bathymetry mapping in the early 21st century using the latest generation of multibeam echosounders (MBES). To date, virtually the entire northwest Atlantic margin from offshore Blake Ridge to the Laurentian Fan (Fig. 1) has now been mapped with MBES technologies from the shelf break to the 5500-m isobath (e.g., Gardner, 2004; Cartwright and Gardner, 2005; Campbell et al., 2008a, 2008b, 2008c; Calder and Gardner, 2008; Mosher and Piper, 2007; Armstrong et al., 2012; Calder, 2015; Krastel et al., 2015; Gardner et al., 2016. From the southern Grand Banks of Newfoundland to the north, multibeam coverage is sparse, with regional lines but not full coverage except along the uppermost slope of the Grand Banks and Flemish Cap (see http://www.charts.gc.ca/data-gestion/500map-eng.asp; Durán Muñoz et al., 2014). The MBES bathymetry data were used to generate digital terrain models (DTM) at spatial resolutions of 20 to 100 m/pixel (depending on water depths). For the background bathymetry and where no multibeam data exist, data were used from the Marine Geoscience Data Systems (MGDS) Global Multi-Resolution Topography (GMRT) which combines global and regional grids (Ryan et al., 2009). The global grid used in this compilation is the General Bathymetric Chart of the Oceans (GEBCO) 2014 grid at 30 arc-seconds resolution (The GEBCO_2014 Grid, version 20150318, www.gebco.net). The multi-resolution DTM was used to generate regional sun-shaded image renders, perspective views and to extract margin-wide bathymetric profiles. It was also used to generate derivative products such as slope angles.

2.2. Seismic data

In addition to the multibeam data, new multichannel seismic reflection data were acquired in deep and ultra-deep water for extended continental shelf programs (Mosher et al., 2016; Arsenault et al., 2017). These data are of a similar resolution to industry exploration standards, with source arrays of 65 to 110 L (4000 to 6600 in^3), multichannel hydrophone arrays between six and nine kilometres in length, and frequency spectrums < 100 Hz. These new data were compiled with a significant abundance of legacy industry and academic seismic data that range anywhere from single channel and small source arrays (e.g. < 3.5 L (200 in^3)) to large multichannel surveys with arrays on the order of 110 L (6000 in^3). Frequency spectrum of these data range < 250 Hz. Most of the legacy data are publicly available through the following sites: United States Geological Survey site (https://walrus.wr.usgs.gov/NAMSS/, accessed May 31, 2017), the NOAA National Centers for Information Services data portal (https://ngdc.noaa.gov/mgg/, accessed May 31, 2017), and the Geological Survey of Canada ftp://ftp.geogratis.gc.ca/pub/nrcan_rncan/raster/marine_geoscience/Seismic_Reflection_Scanned/ (accessed May 31, 2017).

Ultra-high resolution (1–5 kHz) seismic reflection (subbottom profiler) data were acquired coincident with most of the multibeam bathymetry and lower resolution seismic reflection data and sometimes acquired independent of these other data. These data were helpful in recognizing surficial sedimentary processes and are largely available at the aforementioned web sites for download.

2.3. Slope profiles

Margin shapes were assessed by first a qualitative assessment using sun-shaded bathymetric surface renders as well as examining derivative products such as slope angle and curvature (2nd derivative) maps. Different components of the morphology were then examined in detail by producing margin-normal profiles from the shelf edge to the abyssal plain with the regional and multibeam bathymetric grids. These profiles were fitted with exponential decay curves to quantitatively assess their shapes. These curves were of the format $Y = P_0 e^{(-\alpha x)}$, where P_0 is the y intercept at $x = 0$; i.e., the position of the shelf break, and $-\alpha$ is the decay constant; x (distance) is in kilometres; and, y (depth) is in metres in which depths have been inverted to make the shelf break the maximum depth and the greatest depth is 0. This inversion was done to make the exponent a negative value to reflect decay. The exponent, correlation coefficient (R^2) and variance values were used to quantify the shape and determine the goodness of fit. Once assessed, the shapes were classified according to one of the four categories discussed below.

3. Results

3.1. Geomorphology of the Northwest Atlantic margin

The morphology of the NWAM from the shelf to the deep sea varies significantly over its length (Fig. 1). For example, the continental shelf is just 100 km wide north of Blake Ridge to > 500 km across the Grand Banks of Newfoundland. North of Georges Bank (~42°N), the shelf is incised by glacial troughs or saddles, whereas south of Georges Bank, the shelf is relatively featureless apart from a few fluvial-sourced channels such as the Hudson Shelf Valley (Fig. 1). Other channels, such as The Gully and Laurentian Channel on the Scotian margin, are dominantly glacial in origin. The shelf break ranges in water depth from 120 m along the shallow banks to > 500 m deep along the troughs and saddles.

Numerous canyons incise the shelf break, particularly off the southern segment of the NWAM, but most canyons head below the shelf break in 500 + m of water (e.g., Hesse, 1992; Wang and Hesse, 1996; Campbell et al., 2008a, 2008b; and Brothers et al., 2013). Slope gradients along this upper slope segment exceed 3°, between 200 and 2000 m water depths, for most of the margin length. Canyon and slope valleys, where they exist, tend to amalgamate downslope to form single valley systems that eventually splay out on the deep ocean floor. The adjacent deep basins range in water depths from 5500 m in Hatteras Abyssal Plain and Sohm Abyssal Plain in the south to only 4000 m in the Labrador Sea. Some deeper portions of margin are affected by structural features of the ocean crust, such as New England, Fogo and Newfoundland seamounts, but these appear to have only local influence on the margin morphology. In general, the shape of the margin from the shelf to the deep sea is sedimentary in origin and fits into one of four classifications.

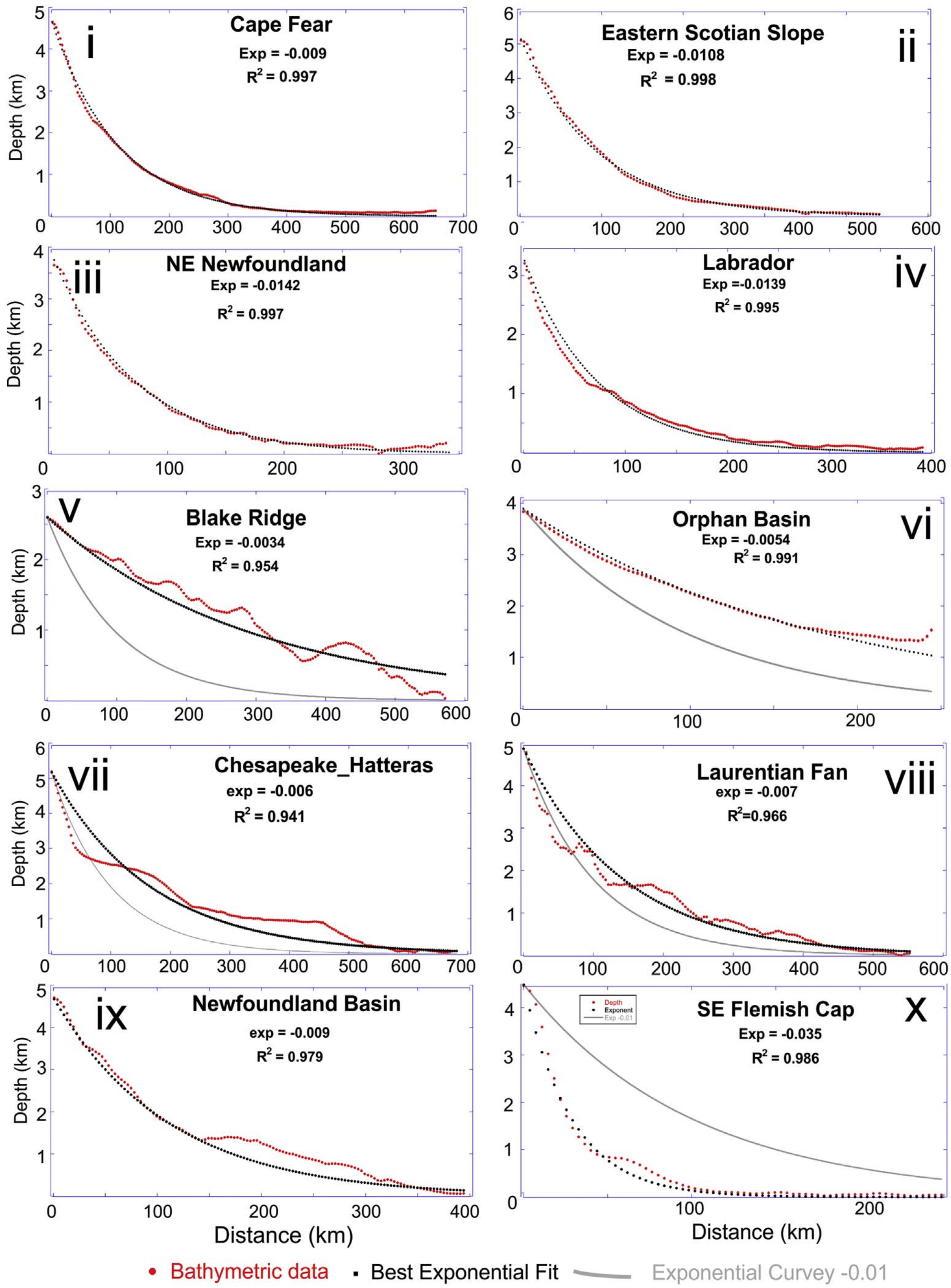

Fig. 3. Bathymetric profiles generated from global and regional grids with best-fit exponential decay curves. Profile locations are indicated on Fig. 1. Profiles extend from the shelf break to the deep ocean seafloor. Profiles i to iv are graded, profiles v and vi are above grade, profiles vii to ix are stepped and profile x represents an out-of-grade slope.

3.2. Slope classification

A series of slope-normal profiles are shown in Fig. 3. The slopes were classified according to a modified scheme of Prather et al. (2017): this shape classification scheme does not imply a genetic origin to the shape but merely describes the morphology.

1) Graded slopes exhibit an exponential decay profile giving a concave upwards appearance (e.g., Fig. 3i to iv);
2) Above-grade slopes are those where relief is positive, i.e., proud of the grade shape (e.g., Fig. 3v to vi) (linear or Gaussian in the terminology of Adams and Schlager, 2000);
3) Stepped slopes are a combination of graded and above-grade shape. They may be initially graded, but become above-grade for part of their lengths, leading to a stepped or terraced shape (e.g., Fig. 3vii to ix). There may be multiple steps in this type of slope.
4) Out-of-grade slopes have steep gradients (~10°), particularly at the shelf-edge and upper slope, that reflect their original tectonic structure; either due to erosion or minimal sedimentation (e.g., Fig. 3x).

Graded slopes have decay constants on the order of −0.01 and correlation coefficients in excess of 0.99 (Table 1). Above-grade slopes have smaller decay constants (less negative), and slightly lower R^2 values reflecting their more linear shape and higher frequency variability in bathymetry (i.e., more complex morphology). Stepped slopes have decay constant that may be low or high but R^2 values are significantly lower and variance higher than the graded case due to complex morphology. Out-of-grade slopes have higher decay constants (more negative) and poor correlation coefficients, reflecting their steep gradients (Table 1).

Table 1
Results of best-fit analysis of bathymetric profiles from the margin. Each profile was fitted with an exponential decay curve of the form $y = P_0e^{(-\alpha x)}$, where P_0 is the Y intercept at X = 0 (the shelf break), X is the horizontal distance and Y is depth, and α represent the decay constant, which is a negative value. R^2 is the correlation coefficient. Mean is the mean difference value between the bathymetric data and the best fit curve and var is the variance of this difference.

Profile	Graded	Profile	Above-grad	Profile	Stepped	Profile	Out-of-grade
Cape Fear	α = − 0.009 R^2 = 0.997 mean = 47 var = 1939	Blake Ridge	α = − 0.0034 R^2 = 0.954 mean = 139 var = 7699	Chesapeake drift	α = − 0.006 R^2 = 0.941 mean = 285 var = 56,770	SE Flemish Cap	α = − 0.035 R^2 = 0.986 mean = 104 var = 13,342
E Scotian Slope	α = − 0.0110 R^2 = 0.998 mean = 65 var = 3067	NE Fan	α = − 0.010 R^2 = 0.977 mean = 153 var = 15,086	Laurentian Fan	α = − 0.007 R^2 = 0.966 mean = 194 var = 37,760	NE Flemish Cap	α = − 0.016 R^2 = 0.925
Eastern Valley	α = − 0.011 R^2 = 0.993 mean = 89 var = 10,849	Central Scotian Slope	α = − 0.011 R^2 = 0.990 mean = 146 var = 16,153	NFLD Basin	α = − 0.009 R^2 = 0.979 mean = 189 var = 25,168	Makkovik	α = − 0.011 R^2 = 0.960 mean = 163 var = 56,342
NE NFLD	α = − 0.0142 R^2 = 0.997 mean = 42 var = 1451	Orphan Basin	α = − 0.0054 R^2 = 0.991 mean = 76 var = 6612				
N Labrador	α = − 0.0139 R^2 = 0.994 mean = 85 var = 3648	Hamilton Spur	α = − 0.0082 R^2 = 0.982 mean = 115 var = 10,159				

3.3. Graded slopes

Graded slopes along the Atlantic margin fit almost perfectly a mathematical exponential decay function, with decay constants on the order of − 0.01 (Table 1). Graded slopes include a narrow region of the U.S. margin that transects the Cape Fear Slide down to the Hatteras Abyssal Plain (Figs. 3i, 4), the eastern Scotian Slope to the Sohm Abyssal Plain (Figs. 3ii, 4), the Northeast Newfoundland Slope (Figs. 3iii, 4) and the northern portion of the Labrador Slope (Figs. 3iv, 4). Major channels that transect the entire slope, such as Eastern Valley of the Laurentian Fan, are also graded.

Seismic reflection data show the strong exponential decay shape of the graded-slope margin (Fig. 5). The upper and middle slope regions in each case show a seafloor that is heavily dissected by submarine canyons and valleys (Fig. 5, insets). As seismic profiles cross canyons and inter-canyon components, the seafloor appears rugose and there is little lateral internal reflection coherency. Further downslope, the canyons and valleys amalgamate, the seafloor becomes smoother and reflection coherency improves. Interbedded mass transport deposits thin in the seaward direction and there is a general and gradual thinning of the sedimentary section. Reflections become flat-lying and lateral reflection coherency improves significantly as the seismic profiles reach the abyssal plain.

3.4. Above-grade slopes

Prather et al. (2017) subdivide above-grade slopes into ponded above-grade and stepped above-grade. We consider ponded above-grade slopes as simply ‘above-grade’ as their profile shape is above the graded shape for the majority of their widths. We consider stepped above-grade as a mixed system with a portion of the slope being graded and a portion being above grade. We term these shapes simply ‘stepped’ and assign them to a separate class. Above-grade slope profiles depart from the exponential-decay shape of the graded profile, with either only a slightly concave shape, or approach linear, as shown in their smaller (less negative) decay constants as shown in Table 1 and Fig. 3v and vi. The lower correlation coefficients and higher variance values shown in Table 1 also reflect the more complex (higher variability) morphology of these margins. Above-grade slopes characterize the profile along the axis of Blake Ridge, Sackville Spur and Hamilton Spur (Fig. 4). They are also found seaward of a number of shelf-crossing troughs, such as Northeast Channel, Trinity Trough, Okak Trough and Hudson Trough (Fig. 4); although these fans are only slightly above grade.

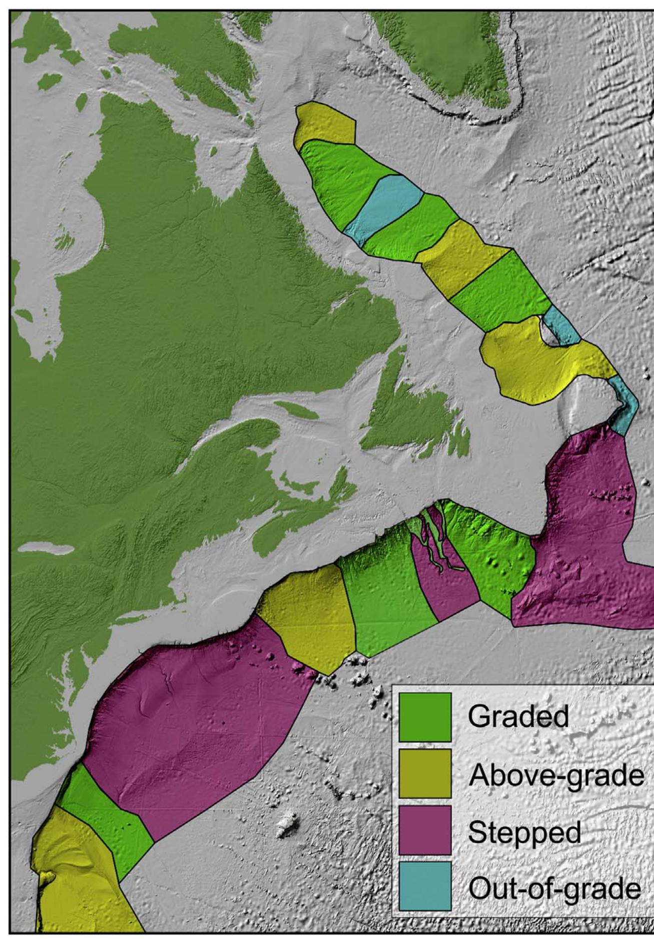

Fig. 4. Classification of segments of the NWAM according to the shape of the margin.

Figs. 6 to 8 show examples of seismic profiles from the above-grade class of margin. Fig. 6 shows structures such as salt domes and horst blocks that created slope accommodation. Accommodation is the space available for deposition to occur and it is not scale dependent (Vail,

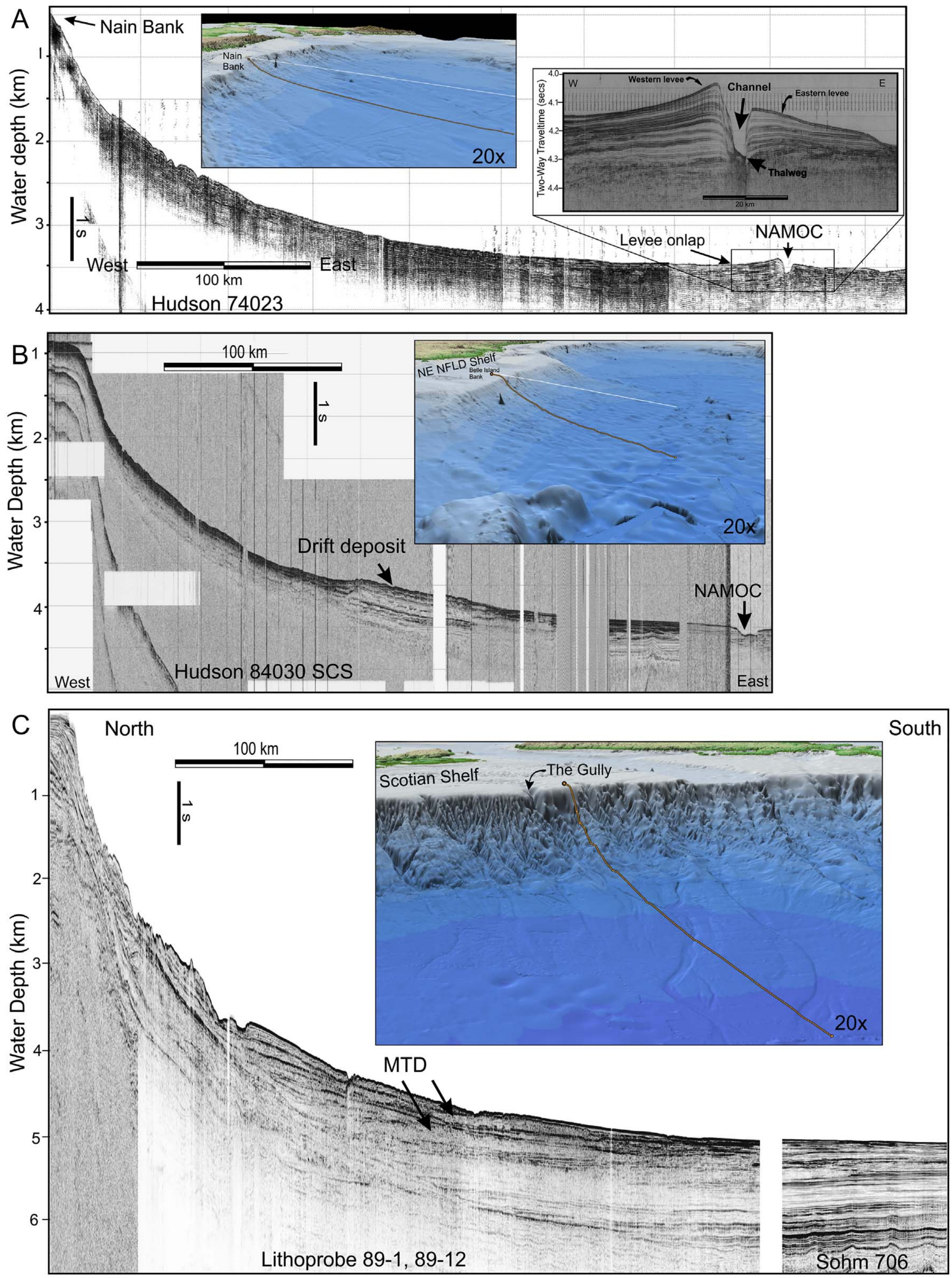

Fig. 5. Seismic profiles transecting graded slopes. A) is from the Labrador margin, B) from the Northeast Newfoundland Slope, and C) is from the eastern Scotian Slope. Horizontal and vertical scales are the same in each case for comparison purposes. Inset maps show the location of these seismic profiles with perspective views of the margin.

1987; Prather et al., 2017). Subsequent sedimentation patterns, either due to off-shelf and downslope distribution, or along-slope due to contour currents, reflect slope retention. In the case of the Scotian Slope (Fig. 6A), salt doming created slope accommodation and in the case of Orphan Basin, it is the horst blocks (Fig. 6B). The morphological effects of this retention can be seen in the inset perspective view maps, which show the distinct character of the seafloor in these regions. Fig. 7 shows a seismic profile and perspective view of the Hamilton Spur separated contourite drift. Aside from the linear profile shape of the seafloor down the axis of the separated drift, this profile shows its internal structure consisting of relatively coherent reflections that thin in the down-slope direction. These reflections are interbedded with wavy reflections representing bedforms of contourite deposits and incoherent facies of mass-failure deposits. Fig. 8 shows trough-mouth fan sedimentary

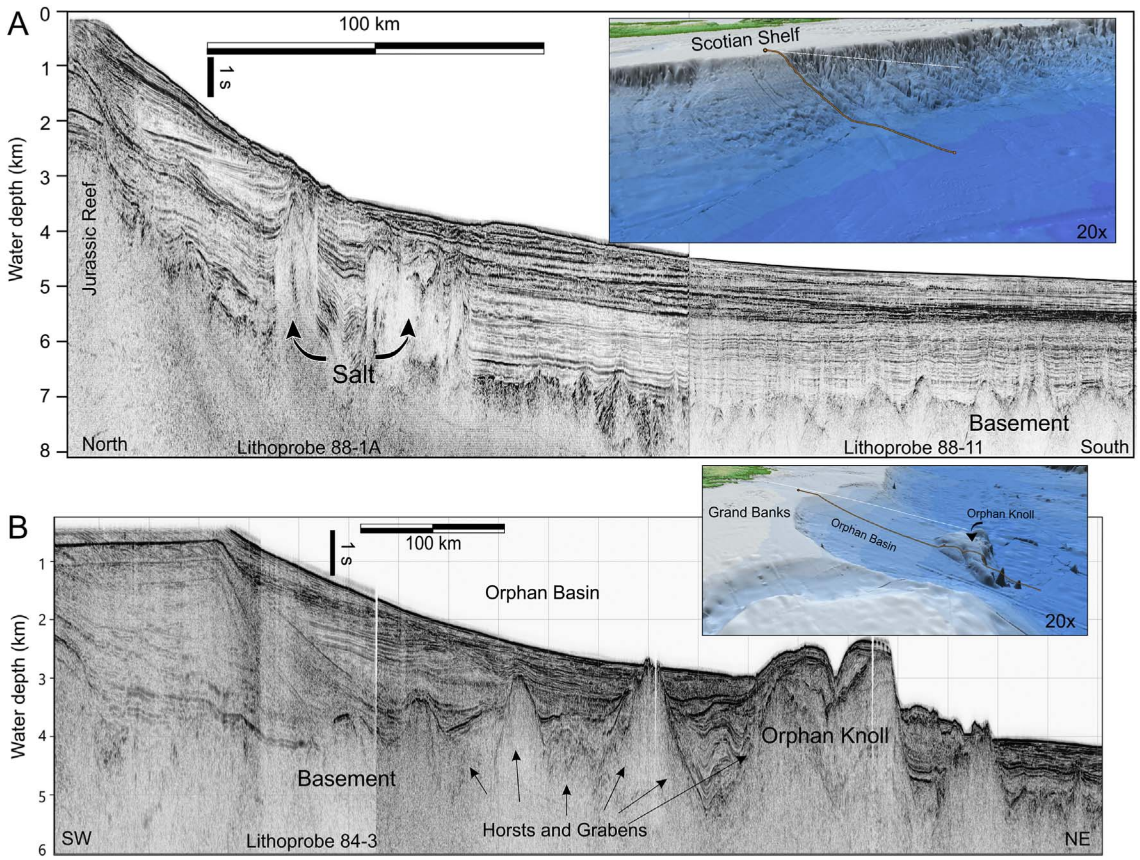

Fig. 6. Seismic profiles showing above-grade slopes due to ponded accommodation. In A), salt domes created the slope-accommodation, acting as back-stops for sediment retention on the slope. In B), it is the crustal horst blocks that created the slope-accommodation. In both cases, infill sediments are interpreted to be a mix of turbidites, contourites and MTDs. The inset maps show the location of the seismic profiles on perspective views of the margin.

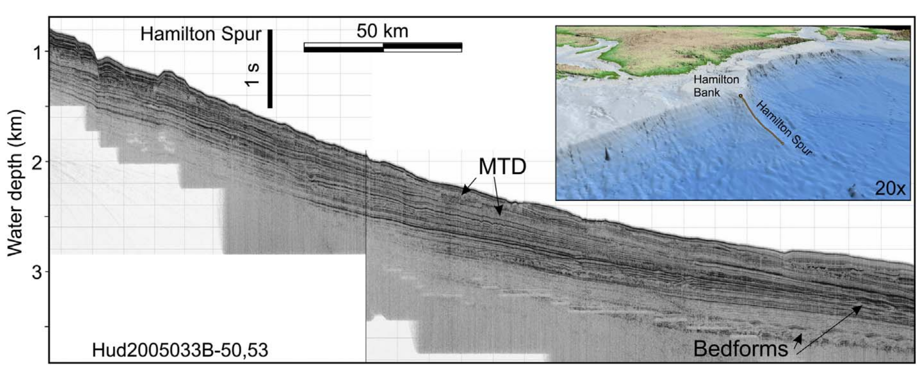

Fig. 7. Seismic profile down a portion of the ridge crest of Hamilton Spur of the Labrador margin. The inset maps show the location of the seismic profile on a perspective views of the margin.

constructions that form a near-linear profile shape. Internally, they have stacked sequences of incoherent reflections and the strike profile of Fig. 8B shows their positive bathymetric expression relative to the adjacent channelized slope.

3.5. Stepped slopes

As mentioned above, stepped slopes appear to be a mixed form, where commonly the uppermost slope portion approaches a graded shape, but the lower slope portion is above-grade. There may be significant morphological complexity to stepped slopes, as shown by best-fit exponential curves, and related R^2 and variance values (Table 1). A significant portion of the northern U.S. segment of the NWAM has a multi-stepped slope (Figs. 1, 3vii, 4). In this case, the uppermost slope approaches a graded shape while the lower slope comprises the Chesapeake Drift and Hatteras Outer Ridge (Fig. 9A; Gardner et al., 2016). A best-fit exponential decay curve has a smaller (less negative) exponent and poorer correlation coefficient than the graded case (Fig. 3vii). Comparison with a graded curve shows how the upper slope fits closely to a graded shape but the lower slope is well above-grade (Fig. 3vii). A portion of the Grand Banks margin is similarly onlapped with deposits of elongate-detached drifts (Fig. 9B). In this case, much of the slope approaches the graded shape and the drift deposits are smaller than those along the U.S. segment, thus the graded exponential decay curve is a reasonable fit, albeit with a lower correlation coefficient than the fully graded case (Fig. 3ix). The Laurentian Fan also demonstrates a complex multi-staged slope profile (Fig. 3viii) with a smaller (less negative) best fit decay exponent than the graded case, although the upper slope portion fits a graded curve.

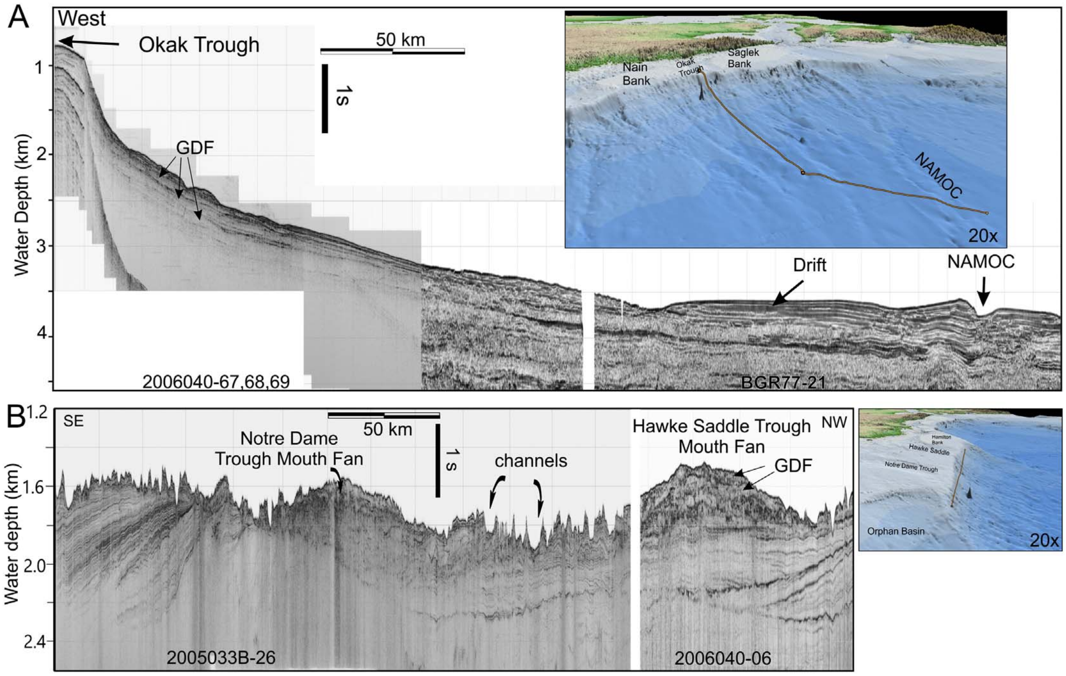

Fig. 8. Above grade slopes generated by trough-mouth fans. A) dip seismic profile extending from Okak Trough of the Labrador margin, and B) strike profile along the Northeast Newfoundland slope showing a mounded expression of the trough-mouth fans seaward of Hawke Saddle and Notre Dame Trough. GDF is Glaciogenic Debris Flow. The inset maps show the location of the seismic profiles on perspective views of the margin.

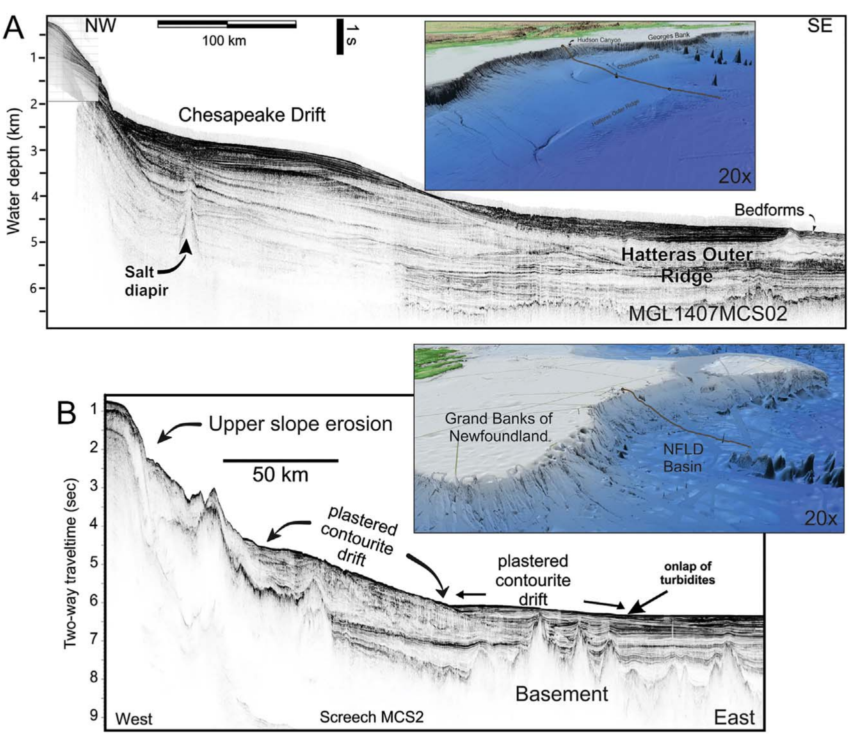

Fig. 9. Stepped slopes: A) seismic profile across the U.S. continental margin, crossing the Chesapeake and Hatteras drift deposits that form a stepped slope profile (Arsenault et al., 2017); B) seismic profile across the eastern Grand Banks margin into Newfoundland Basin, showing stacked plastered contourite drift deposits that form a stepped slope (see Welford et al., 2010a, 2010b for details on the seismic profiles). The inset maps show the location of the seismic profiles in perspective view.

3.6. Out-of-grade slopes

Out-of-grade profiles are those in which the steepness of the slope exceeds the graded case. An example of an out-of-grade slope along the NWAM is the eastern region of Flemish Cap (Fig. 10A). Upper slope angles exceed 10° in places along this segment of the margin. The inset bathymetric profile shown in Fig. 10A shows an exponential-decay fit with a large exponent (− 0.035) (Table 1). At Flemish Cap, there is a slight stepped appearance at the lowest slope because of a low gradient sedimentary wedge at the base of the slope (Fig. 10A); but most of the slope is high gradient and almost barren of sediment and none of the profile approaches a graded exponential shape.

A profile seaward of the Makkovik Bank/Hopedale Saddle of the Labrador Sea has a steep initial gradient and lower gradient lower slope (Fig. 3x). In this case, the upper slope is out-of-grade while the lower slope fits a graded shape. A seismic section (Fig. 10B) shows the upper slope stratigraphy contains truncated shelf-edge off-lapping reflections. Offlap was related to shelf-margin progradation. The truncation of

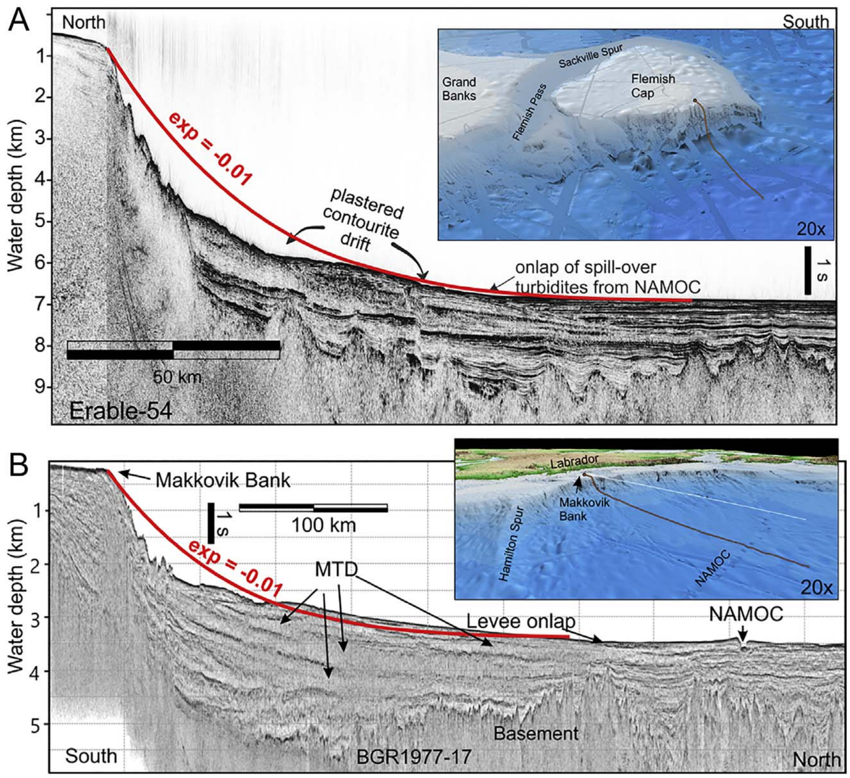

Fig. 10. Out-of-grade slopes as shown by, A) a seismic profile from the southeastern Flemish Cap margin (Welford et al., 2010a, 2010b), and B) a seismic profile crossing the Makkovik-Hopedale failure complex (Deptuck et al., 2007). The red curve in each case is an exponential decay curve with a decay constant of − 0.01 that represents the graded case, to show for comparison and to emphasize the over-steepened upper slope. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reflections was presumably caused intense erosion or mass failure. The lower slope consists of stacked sequences of incoherent reflections interpreted as mass failure deposits of giant submarine landslides (Fig. 10B) (Deptuck et al., 2007).

4. Discussion

The NWAM is classified according to the shape of its margin from the shelf break to the deep ocean floor (Fig. 4). Each of the four margin-shape classes, 1) graded, 2) above grade, 3) stepped, and 4) out-of-grade, is examined in the context of determining the sedimentary process responsible for its development. Principal deep-sea sedimentary processes along the NWAM are a consequence of turbidity currents, sediment mass failures and geostrophic contour-parallel currents (e.g., Embley, 1980; Carter and Schafer, 1983; Hesse, 1989; Piper, 1991; Poag, 1992; Wold, 1994; Galloway, 1998; Hesse et al., 1999; Evans and Hall, 2008; Twichell et al., 2009). Hemipelagic and pelagic processes have been minor contributors to the total Quaternary and even the Cenozoic sediment budget along the NWAM (e.g., Mosher et al., 2004; Carey et al., 2005; Piper, 2005; Chaytor et al., 2015). These processes are, therefore, not significant factors in determining the shape of the NWAM and will not be considered further. The relative importance of each process, the interaction of these processes, the rate and style of sediment supply and slope-accommodation have all combined to produce the specific evidentiary geomorphologies that have led to assignment of each margin segment to one of the four morphologic types.

4.1. Graded slopes

The idealized graded profile represents the long-term equilibrium between depositional and erosional processes on a continental slope (Prather, 2003). Profiles grade to a submarine base-level, which is the deepest point reached by sediment gravity flows in the basin (Pirmez et al., 2000). Bypass characterizes the upper parts of graded slope profiles and unconfined deposition dominates the toe-of-slope and basin floor regions (Prather, 2003). In the cases examined along the NWAM, the graded profiles fit exceptionally well to an exponential decay curve, with a decay constant variable of − 0.01 (Table 1).

Canyon and channel incisions result from multipoint-source systems in which turbidity currents cut into the seafloor. During glaciations, a shelf-edge ice margin shed sediment and cold dense water directly to the slope (Myers and Piper, 1988; Hesse, 1989; Wang and Hesse, 1996; Hesse et al., 1999; Piper, 2005; Roger et al., 2013; Shaw et al., 2014). The same effects may be a result of lower sea levels and subaerial exposure of the shelf, particularly along segments that were not glaciated to the shelf edge (e.g., Carey et al., 2005; Brothers et al., 2013; Miller et al., 2014). All three turbidity-current initiation mechanisms (transformation of failed sediment, hyperpycnal flow from rivers or ice margins, and resuspension of sediment near the shelf edge by oceanographic processes) described by Piper and Normark (2009) are likely at play along these margins.

The canyons and channels along the NWAM were conduits for turbidity currents and debris flows that transported material from the outer shelf and upper slope to the deep sea (Hesse, 1989; Piper and Ingram, 2003; Piper, 2005), facilitating slope by-pass. Between canyons and channels, sediment deposition principally resulted from either channel overspill, plume fallout and unconfined turbidites or contour currents (Myers and Piper, 1988; Hesse, 1989; Hesse et al., 1997; Piper, 2005; Piper et al., 2012). Canyons and channels generally amalgamate down slope to become single systems before they reach the abyssal plain. Multibeam and seismic data show unconfined deposition dominates the toe-of-slope and basin floor regions (e.g., Piper and Ingram, 2003).

The extreme case of channel amalgamation occurs in the Labrador Sea, with the formation of the Northwest Atlantic Mid-Ocean Channel (NAMOC); a 3000 km-long turbidity-current channel formed by convergence of many channels of the northern Labrador Slope and Hudson Trough (Figs. 1 and 5A, B). In this case, overflow of suspended sediment within turbidity flows was deflected westward due to the Coriolis force (Chough and Hesse, 1976; Klaucke et al., 1998). This phenomenon is evidenced in the high western levees of the channel, as seen in Fig. 5A inset. The importance of these levee deposits is that they onlap the adjacent NWAM, through the Labrador Sea and around the Grand Banks margin, so that sediments derived from the slope and adjacent shelf are distinguished from those derived from the deep sea channel.

The upslope component of graded slopes is created by slope by-pass processes while the downslope component generally becomes more depositional toward the basin. Although turbidity current processes may dominate, evidence of other deep water processes can be seen. In Fig. 5B, for example, a plastered drift deposit is notable on the lower part of the margin, leading to a section that is slightly above grade.

4.2. Above-grade slopes

Above grade slopes require sediment retention on the slope to create the positive morphology. This retention is due either to creation of accommodation space through generation of intra-slope basins, or type and style of sediment supply such as certain types of contourite drift formation or sedimentary fan construction.

4.2.1. Intra-slope basins

A fundamental mechanism that can produce an above-grade profile is slope sediment retention due to accommodation (Prather, 2003). Salt mobility, such as occurred along the U.S. and Scotian segments of the margin, created intra-slope basins that allowed sediment ponding (e.g., Fig. 6A) and construction of a slightly above-grade profile shape. In the case of Orphan Basin, it is not a mobile substrate but rather crustal extension that produced horst blocks (Chian et al., 2001), including Orphan Knoll, and it was these features that created accommodation that was subsequently infilled (Fig. 6B). Sediment delivery mechanisms to these basins were mixed because the sedimentary sequences comprise turbidites, contourites and MTDs (Tripsanas and Piper, 2008; Li et al., 2012; Campbell et al., 2015; Campbell and Mosher, 2016).

4.2.2. Detached drifts

Above-grade slopes in the form of linear bathymetric profiles from the shelf edge to the deep basin characterize segments of the margin that host large, elongate-mounded detached drift deposits (Faugères et al., 1999), such as Blake Ridge (Mountain and Tucholke, 1985), Hamilton Spur (Goss, 2006) and Sackville Spur (Kennard et al., 1990) (Figs. 1 and 7). In these cases, sediment is retained on the slope not because of formation of an intraslope basin or specific slope-accommodation, but because of the contourite sedimentation process and rate of sediment delivery relative to sediment removal.

Detached drifts occur along the NWAM at structural perturbations, i.e., bends in the strike of the margin. As the WBUC and the LSW flowed south and were forced against the margin by the Coriolis force, they entrained sediment already in suspension, such as turbidity current plumes (e.g., Hesse et al., 1997). Bends in the margin morphology caused flow detachment and sediment in suspension was deposited (Rebesco et al., 2014). The position and style of the drifts that formed were controlled by the seafloor morphology (e.g., the presence and steepness of a slope) and by the depth and velocity of the water masses (see e.g., Hernández-Molina et al., 2008; Rebesco et al., 2014), and by up-current sediment supply (Hesse et al., 1997; Amblas et al., 2006). In the case of detached drifts, there is seaward and down-current progradation of the sedimentary body that produces an above-grade profile along the crest of the drift. Occasional sediment mass failure is part of the progradational process, so MTDs form part of the stratigraphy, as seen in Fig. 7 and shown by Laberg and Camerlenghi (2008), Cameron et al. (2014) and Hawken (2017).

4.2.3. Trough-mouth fans

Near-linear above-grade bathymetric profiles are often found seaward of shelf-crossing troughs along the NWAM (Figs. 1, 4 and 8). These above-grade slopes are over trough-mouth fans (cf., Vorren et al., 1989 and Vorren and Laberg, 1997). In these cases, the profile shapes appear unrelated to available slope-accommodation and are more related to the specific sedimentary process and sediment type that built the fans. Trough-mouth fans include stacked sequences of glaciogenic debris flows (Vorren, 2003; Ó Cofaigh et al., 2003). The glacial troughs are interpreted to have hosted fast-flowing ice streams during glacial periods. These ice streams rapidly shed large quantities of sediment at the shelf edge and this sediment moved downslope as glaciogenic debris flows (e.g., Tripsanas and Piper, 2008). The grain sizes of these debris flows are highly mixed because of their glacial origins and resulting deposits have distinctive acoustic characteristics that include highly transparent and potentially thick, steep but rounded lateral and terminal edges (see Laberg and Vorren, 1995 and Tripsanas and Piper, 2008). Mounded deposit shapes suggest thixotropic non-Newtonian flow behavior. It is these distinctive sediment properties and the rapid and unique style of sediment delivery that distinguish these fans from conventional siliciclastic fans at the mouths of large rivers. High sedimentation rates and sediment flow properties ensured that deposits remained on the slope, thus sediment retention outpaced sediment removal and led to the above-grade profile shape.

Along the NWAM, trough-mouth fans seaward of Trinity Trough, Notre Dame Trough, Hawke Saddle, Okak Trough and Karlsefini Trough have above-grade bathymetric profiles. Northeast Channel of the SW Scotian margin, the southernmost glacial trough, was subjected to higher meltwater discharge and likely hyperpycnal flows (Piper et al., 2017). As a result, Northeast Fan seaward of the channel has an exponential shape but with a low correlation coefficient and high variance (Table 1).

4.3. Stepped slopes

Stepped slopes exhibit changes in gradient resulting in a stepped or terraced topography. According to Prather et al. (2017), stepped slopes develop where sediment flux is high relative to rates of intraslope basin subsidence. Steps may also be generated with syndepositional tectonics (faults and folds). In context of the NWAM, stepped slopes are principally sedimentary in origin and not specifically related to basin subsidence or accommodation. In this sense, sediment flux could have outpaced sediment removal and basin subsidence. Stepped slopes along the NWAM usually exhibit a mix of graded and above-grade components; the uppermost slope fits closely to a graded slope profile but the mid to lower slope portion are above grade. The best example of such a stepped slope along the NWAM involves much of the U.S. segment (Figs. 1, 3vii, 4).

The upper slope of the U.S. segment of the NWAM, from the shelf break to about the 2500 m isobath, is characterized by numerous canyons (> 200) and mass failure scars (Twichell et al., 2009; Chaytor et al., 2009; Brothers et al., 2013; Hill et al., 2017). This dominantly erosional segment of the margin has a graded profile shape (Fig. 3vii). However, the remaining deep-water portion of the margin is dominated by two contourite drifts; the relict Chesapeake Drift and the still-active Hatteras Outer Ridge (drift) (Figs. 1 and 9A; Tucholke and Laine, 1982; McCave and Tucholke, 1986; Sweeney et al., 2012; Gardner et al., 2016). These drifts now play a fundamental role in controlling downslope sediment transport and depositional processes due to low gradients on their landward sides (Gardner et al., 2016).

Hatteras Outer Ridge lies in 4000 to 5500 m water depth northeast of Blake Ridge and forms a distinctive deposit from about 33°30′N to ~37°N (Fig. 1). North of Hatteras Outer Ridge, the morphological expression of the buried Chesapeake Drift shows it to lie between 2500 and 4000 m water depth, and extend from the southwestern edge of George's Bank to offshore Cape Hatteras. Both deposits are plastered elongate mounded drifts (cf., Faugères et al., 1999) that were formed by the WBUC as it swept along the margin. The drifts perhaps formed as a result of flow perturbations caused by the New England Seamount Chain and/or Georges Bank that forms a promontory that deflected flow. The morphological consequence of these two large contourite deposits is a two-stepped above-grade bathymetric profile that is

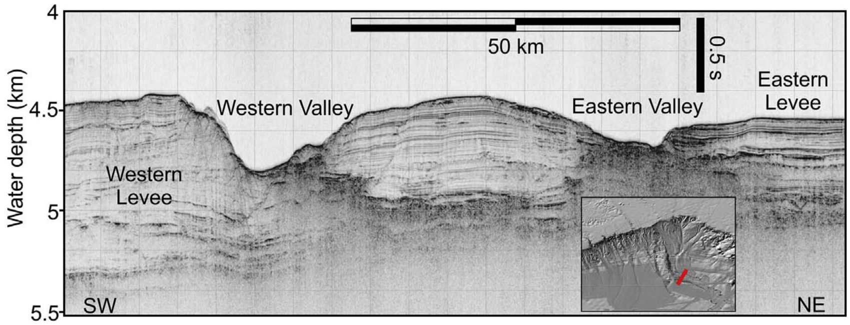

Fig. 11. Seismic profile (from Krastel et al., 2015) across the lower portion of the Laurentian Fan showing the two principle channels (Eastern Valley and Western Valley) and thick (> 800 m) levees that comprise the fan and create the stepped slope profile.

apparent over an area of about 230,000 km^2 (Figs. 1, 3vii and 9A).

Similar multi-stepped slopes, although less pronounced, are noted off of much of the eastern Grand Banks margin. These steps too were generated by multiple plastered drift deposits (Fig. 9B) that now form a portion of the continental slope in this region (Carter and Schafer, 1983; Boyle et al., 2017).

Laurentian Fan demonstrates a stepped bathymetric profile shape. In the case, the high gradient upper slope (> 6°) resulted from erosion by occasional large volume proglacial flows that maintained their width and erosional capacity from the ice margin to below the 4000 m isobaths (Shor et al., 1990; Skene and Piper, 2006; Piper et al., 2007, 2012). Probably a few tens of such flows have occurred since the initiation of shelf-crossing glaciation at 0.5 Ma (Piper et al., 2012). The flows maintained a graded shape to the main channels, such as Eastern Valley (Table 1), but channel overspill of such high volumes of sediment produced a thick accumulations on the lower slope (Fig. 11). The thick levee deposits that constitute Laurentian Fan resulted in the above-grade shape of the lower slope that covers about 60,000 km^2 in surface expression (Figs. 1, 11).

4.4. Out-of-grade slopes

Out-of-grade slopes are those that have little sediment cover, either due to non-deposition or intense erosion, such that sediment removal drastically outpaced sediment delivery (c.f., structural slopes of Helland-Hansen et al., 2012). In general, the consequence is that the slope has higher gradients than the graded case (Fig. 3x), at least for the upper slope portion. Only a few regions along the NWAM are recognized as this morphological type, such as Eastern Flemish Cap and seaward of Makkovik Bank/Hopedale Saddle (Figs. 1, 4, 10). Flemish Cap is isolated from terrestrial or shelf sources of sediment, so the principal tectonic structure remains (Fig. 10A; Welford et al., 2010a, 2010b). Seaward of Makkovik Bank and Hopedale Saddle, along the Labrador margin, a steep out-of-grade slope was created by successive mass failures along the margin. These failures moved material from the upper slope and shelf-edge to the lower slope (Fig. 10B). Deptuck et al. (2007) termed this concentration of MTDs the Hopedale-Makkovik failure complex and determined that they constitute > 85,000 km^2 in area. These failures produced a high gradient (> 3°) upper slope that is out-of-grade (i.e. steeper than graded) and a lower gradient (< 1°) platform at the base of slope that is close to the exponential shape expected for a graded margin (Fig. 10B). The seaward flank of Orphan Knoll is the only other region of the NWAM categorized as out-of-grade.

5. Conclusions

The conventional categorization of a continental margin into shelf, slope and rise is not particularly useful for knowing its geomorphology nor for understanding the sedimentary processes that formed it. Even trying to separate a slope from its rise is artificial as there is usually a continuum of shapes and processes that formed them. In this study, the NWAM, where the concept of slope and rise was developed (Heezen et al., 1959), is classified not on these historical categories but on the overall shape of the margin: graded, above-grade, stepped and out-of-grade. These shapes were defined by the margin's geologic history and are related to rates of sediment accumulation and removal that are in turn related to sedimentary processes and slope-accommodation. The principal deep-sea sedimentary processes along the NWAM are deposition from turbidity currents, sediment mass failures and geostrophic currents. These processes and their potential effect on the continuum of geomorphologies are conceptualized in Fig. 12.

5.1. Turbidity currents

Turbidity currents tend to be erosive or at least non-depositional on the continental slope, as long as the seafloor gradient supports accelerating density flow. As a result, areas of the margin that were dominated by turbidity currents, (as evidenced by numerous canyons, channels and valleys) are characterized by erosion and slope by-pass and development of graded slopes (Prather, 2003). Where dominant, therefore, this process resides at one apex of the quaternary diagram of Fig. 12, with an associated graded slope morphology. Examples of such end member terrains include the northern Labrador margin, the NE Newfoundland slope and Eastern Valley of the Laurentian Fan.

If turbidity currents decelerated on the slope, due to accommodation for example, then their deposits were retained; usually resulting in above-grade or stepped slopes. Orphan Basin is an example of an above-grade slope created in this way. At the Laurentian Fan, deposition of sediment along levees and depositional lobes was great enough that it raised the base-level of the slope and generated a stepped slope profile.

5.2. Geostrophic currents

As cold deep water-masses flowed southward and were driven westward by the Coriolis Force, they interacted with the seafloor along the continental margin. Along route, these geostrophic currents variably charged and discharged their sediment load depending upon availability of sediment, the intensity of the flow and the morphology of the margin (Nowell et al., 1985; Tucholke et al., 1985; Hollister, 1993; Rebesco et al., 2014). Deposition from these currents created sedimentary bodies of a variety of forms and positions along the NWAM. Detached drifts form linear, above grade slopes from the shelf edge to the deep basin (e.g., Hamilton Spur, Blake Ridge). This process and resulting morphology, therefore lie at an apex of the quaternary diagram of Fig. 12. Plastered drifts form sedimentary bodies against the continental slope, producing stepped slope profiles (e.g., Chesapeake and Hatteras drifts) and this morphology forms another apex of Fig. 12.

5.3. Mass failure

Sediment mass-failure had a variety of consequences on the NWAM morphology. A large mass-failure (or numerous failures at the same location), such as the Makkovik-Hopedale Failure Complex, created an out-of-grade slope profile. This morphology forms the fourth corner of

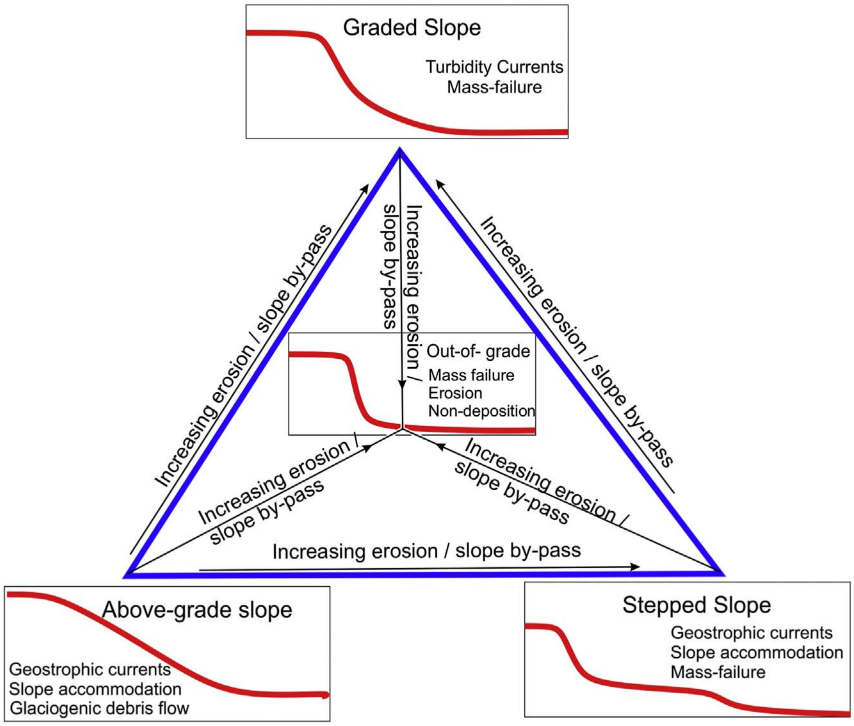

Fig. 12. Quaternary diagram showing the continuum of morphotypes of the four classes used in this study, and including the responsible sedimentary processes.

the quaternary diagram (Fig. 12). Severe erosion or non-deposition has had the same effect, such as along the margin of Flemish Cap. Sediment mass failure may be responsible for other morphologies, depending on the scale, style and sediment composition of the failure mass. Smaller mass failures tended to remain on the slope, so in total (i.e., many of them are stratigraphically related) created high gradient upslope regions and low gradient lower slopes. The resulting morphology may approximate a graded shape, such as in the Cape Fear region. In cases outboard of trough-mouth fans, high rates of sediment input directly to the slope as glaciogenic debris flows tended to remain on the slope and resulted in above-grade profiles. Mass failures, therefore, may play a role in each category of the quaternary diagram.

The descriptive method of classifying continental margins as graded, above-grade, stepped and out-of-grade slopes separates the NWAM into various components that reflects the role of dominant sedimentary processes and slope accommodation at the same time as being non-interpretative. In this way, it is a sound approach for understanding the sedimentary processes that form a continental margin, at least along the NWAM, and superior to simply categorizing the continental slope and continental rise when there is a continuum of deep sea sedimentary processes that create these morphologies.

Acknowledgements

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