Slope failure and mass transport processes along the Queen Charlotte Fault, southeastern Alaska

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Abstract: The Queen Charlotte Fault defines the Pacific–North America transform plate boundary in western Canada and southeastern Alaska for *c.* 900 km. The entire length of the fault is submerged along a continental margin dominated by Quaternary glacial processes, yet the geomorphology along the margin has never been systematically examined due to the absence of high-resolution seafloor mapping data. Hence the geological processes that influence the distribution, character and timing of mass transport events and their associated hazards remain poorly understood. Here we develop a classification of the first-order shape of the continental shelf, slope and rise to examine potential relationships between form and process dominance. We found that the margin can be split into six geomorphic groups that vary smoothly from north to south between two basic end-members. The northernmost group (west of Chichagof Island, Alaska) is characterized by concave-upwards slope profiles, gentle slope gradients (<6°) and relatively low along-strike variance, all features characteristic of sediment-dominated siliciclastic margins. Dendritic submarine canyon/channel networks and retrogressive failure complexes along relatively gentle slope gradients are observed throughout the region, suggesting that high rates of Quaternary sediment delivery and accumulation played a fundamental part in mass transport processes. Individual failures range in area from 0.02 to 70 km^2 and display scarp heights between 10 and 250 m. Transpression along the Queen Charlotte Fault increases southwards and the slope physiography is thus progressively more influenced by regional-scale tectonic deformation. The southernmost group (west of Haida Gwaii, British Columbia) defines the tectonically dominated end-member: the continental slope is characterized by steep gradients (>20°) along the flanks of broad, margin-parallel ridges and valleys. Mass transport features in the tectonically dominated areas are mostly observed along steep escarpments and the larger slides (up to 10 km^2) appear to be failures of consolidated material along the flanks of tectonic features. Overall, these observations highlight the role of first-order margin physiography on the distribution and type of submarine landslides expected to occur in particular morphological settings. The sediment-dominated end-member allows for the accumulation of under-consolidated Quaternary sediments and shows larger, more frequent slides; the rugged physiography of the tectonically dominated end-member

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leads to sediment bypass and the collapse of uplifted tectonic features. The maximum and average dimensions of slides are an order of magnitude smaller than those of slides observed along other (passive) glaciated margins. We propose that the general patterns observed in slide distribution are caused by the interplay between tectonic activity (long- and short-term) and sediment delivery. The recurrence (<100 years) of M > 7 earthquakes along the Queen Charlotte Fault may generate small, but frequent, failures of under-consolidated Quaternary sediments within the sediment-dominated regions. By contrast, the tectonically dominated regions are characterized by the bypass of Quaternary sediments to the continental rise and the less frequent collapse of steep, uplifted and consolidated sediments.

A major right-lateral transform boundary separates the North American plate and the Pacific plate for *c.* 1200 km between southeastern Alaska and western British Columbia. This boundary has been described as the northern counterpart to the better known San Andreas fault system of California. The transform boundary is split into two primary faults. The northern 300 km is defined by the transpressional Fairweather Fault, which extends southwards from Yakutat along the western front of the Fairweather Range to Icy Point (Fig. 1). The fault then steps offshore at Icy Point, bends *c.* 25° to the right (trending at *c.* 340°) and becomes the Queen Charlotte Fault (QCF). The QCF cuts southwards along the continental shelf edge and slope for *c.* 900 km to the Explorer triple junction. Because it accommodates the majority of plate motion, the narrow trace of the QCF has generated impressive tectonic geomorphology, structural geology and seismicity (Fig. 1; Plafker *et al.* 1978; Bruns & Carlson 1987; Hyndman & Hamilton 1993; Nishenko & Jacob 1990; Rohr *et al.* 2000; Doser & Lomas 2000; Wesson *et al.* 2007; Barrie *et al.* 2013; Tréhu *et al.* 2015; Walton *et al.* 2015; Brothers *et al.* 2017).

Southeastern Alaska has been a temperate glaciated margin throughout the Quaternary and has received one of the largest sediment yields of any continental margin worldwide during northern hemisphere glacial advances (Milliman & Syvitski 1992). The glacio-marine setting along the entire length of the QCF is characterized by a steep, rugged topography and high rates of glacial erosion/sedimentation (e.g. Barrie & Conway 1999). Shaking from the frequent earthquakes along the plate boundary therefore has the potential to trigger destructive submarine landslides (e.g. Hampton *et al.* 1996). An extreme example occurred in 1958 when the Fairweather Fault generated a M 7.8 earthquake (Fig. 1; Tocher 1960), which triggered a rock avalanche into Lituya Bay, generating a 534 m high tsunami wave (the highest ever documented) that killed two people (Miller 1960). Other slides documented in the region have also demonstrated the potential for the local generation of tsunamis resulting in damage to nearby infrastructure (e.g. Wieczorek *et al.* 2007; Friedenauer 2014). The plate boundary has produced seven large earthquakes since 1900 (1927 M 7.0, 1949 M 8.1, 1958 M 7.8, 1970 M 7.0, 1972 M 7.2, 2012 M 7.8 and 2013 M 7.5; Fig. 1), making this margin an opportune place to study the role of frequent seismicity in the generation of submarine slope failures (e.g. Locat & Lee 2002; Sawyer & DeVore 2015; ten Brink *et al.* 2016).

The physiography of continental margins is shaped by a complex interplay between tectonic and sedimentary processes, which often alternate between periods dominated by constructional (sediment delivery and progradation) or destructional (slope failure, canyon incision and retrogression) geomorphic processes (e.g. Ross *et al.* 1994; Galloway 1998; Pratson & Haxby 1996; Adams & Schlager 2000). Previous studies have examined the relationships between the major governing processes and the first-order, characteristic physiography of continental margins. Most of these studies were aimed at developing predictive frameworks for seascape evolution, including a better understanding of some finer scale geomorphic features, such as submarine landslides and canyons (Pratson & Haxby 1996; McAdoo *et al.* 2000; O'Grady *et al.* 2000; Pratson *et al.* 2007; Brothers *et al.* 2013; Swartz *et al.* 2015; Hill *et al.* 2017).

Although submarine (and subaerial) landslides are potential hazards in southeastern Alaska and western British Columbia, submarine mass transport processes have never been examined systematically along this 900 km long section of the plate boundary, largely due to the virtual absence of modern seafloor mapping data. The overarching goals of this paper are to use such data to investigate the role of mass transport processes in shaping the modern seafloor and to provide a first look at the high-resolution seafloor morphology along the continental margin of southeastern Alaska.

The study area encompasses a region containing one of the fastest slipping strike-slip faults in the world (e.g. Brothers *et al.* 2017) and a continental margin dominated by Quaternary glacio-marine sedimentary processes. We present the first high-resolution geophysical imagery of submarine landslides ('slides') along the continental margin of southeastern Alaska and provide a preliminary, but systematic, assessment of the distribution, size and geomorphic character of these slides. We then

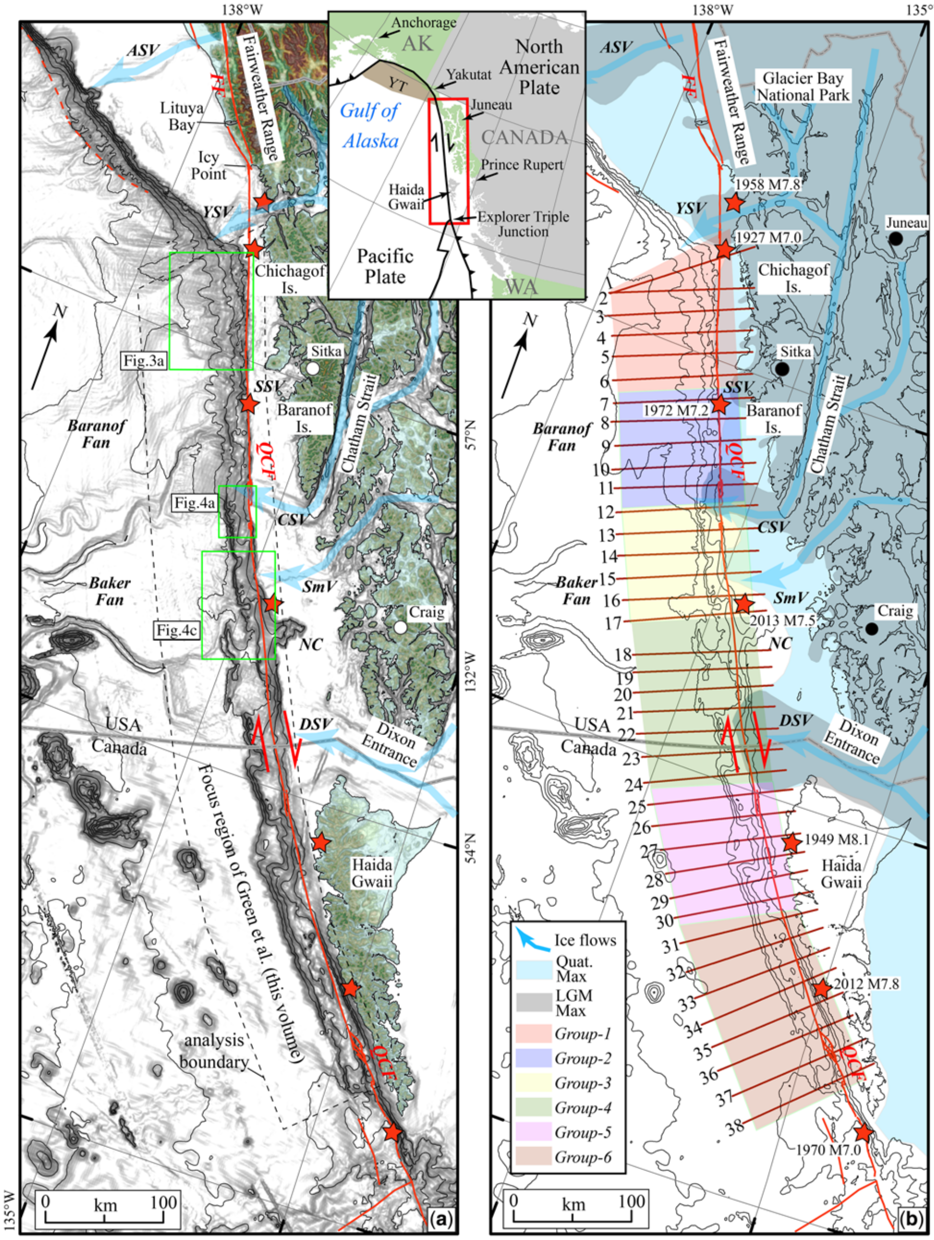

Fig. 1. (**a**) Grey-scale slope (gradient) map along the eastern Gulf of Alaska and the southeastern Alaska–western British Columbia continental margin (see red box in inset figure for regional perspective). Map frame is rotated to 340°. The plate boundary is defined by the right-lateral Queen Charlotte Fault (offshore) and Fairweather Fault (onshore), shown as red lines (Brothers *et al.* 2017). Blue arrows denote flow pathways for Quaternary glaciers that extended onto the continental shelf and scoured a series of shelf sea valleys (e.g. Alsek Sea Valley, Yakobi Sea Valley, Sitka Sea Valley, Chatham Sea Valley, Sumner Sea Valley and Dixon Entrance Sea Valley). Red stars are the epicentres of $M_w > 7$ earthquakes labelled in part (b). (**b**) Locations of topographic profiles that were extracted from the Southern Alaska Coastal Relief Model (Caldwell *et al.* 2012) and used for geomorphic classification of the margin. (Inset) Regional tectonic setting along the Pacific–North America plate boundary, including the Yakutat Terrane. ASV, Alsek Sea Valley; CSV, Chatham Sea Valley; DSV, Dixon Entrance Sea Valley; FF, Fairweather Fault; NC, Noyes Canyon; QCF, Queen Charlotte Fault; SSV, Sitka Sea Valley; SmV, Sumner Sea Valley; YSV, Yakobi Sea Valley; YT, Yakutat Terrane.

characterize the first-order variations in margin physiography between Icy Point and southern Haida Gwaii (Fig. 1) to identify patterns that may be related to the dominance of geomorphic processes (e.g. O'Grady *et al.* 2000; Brothers *et al.* 2013; Hill *et al.* 2017). Based on the results in this paper and in a companion paper by Greene *et al.* (this volume, in press), we propose that across- and along-margin sedimentary and tectonic processes vary considerably from north to south along the margin and the relative dominance of each process in a particular region appears to play a fundamental part in the spatial distribution and types of slides.

Background

Structural and tectonic setting of southeastern Alaska

The northern end of the QCF is marked by an onshore–offshore transition to the Fairweather Fault and its southern end is marked by the complex Explorer triple junction (Rohr & Furlong 1995; Rohr 2015). The QCF is slightly transpressive along much of its length, with convergence rates as high as 15–20 mm a^{-1} along the southernmost QCF due to the fault geometry, which is increasingly convergent towards the south between the Pacific and North American plates (e.g. Hyndman & Hamilton 1993; Rohr *et al.* 2000). The morphology of the deformed continental slope, often referred to as the Queen Charlotte Terrace, is highly variable and has previously been thought to be related to differing amounts and accommodation of transpression along-strike (Rohr *et al.* 2000; Tréhu *et al.* 2015).

Analysis of new high-resolution geophysical data along the QCF (Brothers *et al.* 2017) indicates that strike-slip deformation along the northern half of the QCF, where the fault is closely aligned with plate motion (0–5° obliquity), appears to be highly localized along a single, narrow fault zone. The submarine tectonic geomorphology suggests that the QCF itself accommodates most of the relative plate motion (48–55 mm a^{-1}; Brothers *et al.* 2017), which is in agreement with indirect estimates from previous studies (e.g. Plafker *et al.* 1978; Bruns & Carlson 1987; Elliott *et al.* 2010). Because of the high slip rates along the fault, the QCF frequently ruptures in large earthquakes. The 2013 Craig (Alaska) earthquake ruptured a *c.* 150 km segment of the central QCF in a M_w 7.5 strike-slip event. This earthquake was preceded by a 2012 M_w 7.8 thrust earthquake near Haida Gwaii, thought to be related to Pacific underthrusting in response to higher convergence rates (10–20° obliquity) along the southern half of the fault system (e.g. Lay *et al.* 2013). The highly localized nature of strike-slip deformation supports the idea that variable rates of convergence due to fault orientation could lead to the significant differences in tectonic geomorphology observed within the Queen Charlotte Terrace along the QCF.

Margin sedimentary setting

The continental shelf, slope and rise of southeastern Alaska are covered by Quaternary sediments, predominantly sourced from the glacial erosion of the nearby coastal mountain ranges (Stevenson & Embley 1987; Walton *et al.* 2014). Recent sediment delivery to the shelf edge was dominated by glacial and fluvial transport during late Pleistocene and early Holocene sea-level lowstands; at one point during the Quaternary almost the entire continental shelf was covered in ice (Fig. 1b; e.g. Barrie & Conway 2002; Shugar *et al.* 2014). Broad sea valleys carved into the continental shelf during Pleistocene glacial advances acted as sediment traps and persist today (Carlson *et al.* 1982, 1996; Kaufman & Manley 2004). Sedimentary slope deposits, known as trough-mouth fans, are visible at the mouths of several sea valleys, such as Yakobi, Chatham Strait and Dixon Entrance (Fig. 1b; see Vorren & Laberg 1997; Dowdeswell *et al.* 2008; Batchelor & Dowdeswell 2013). Shelf edge marine-terminating glacial systems are capable of carrying and delivering enormous amounts of sediment to the slope (e.g. Gulick *et al.* 2015) and slope bypass processes have led to the development of deep-sea channel and thick fan systems on the abyssal Gulf of Alaska seafloor (Reece *et al.* 2011*a*; Walton *et al.* 2014).

Sediment along the margin between Haida Gwaii and the wide continental shelf formed by the Yakutat Terrane is sourced dominantly from the Coast Mountains (e.g. Plafker *et al.* 1994), with the deep-sea Baranof Fan serving as a major sediment sink until the late Pleistocene (Walton *et al.* 2014). The shelf includes the aforementioned glacially carved sea valleys as well as incised canyon systems. Slope sedimentation processes have not been studied in detail here due to a lack of high-resolution bathymetric data and because the slope is complicated by major deformation along the QCF (e.g. Tréhu *et al.* 2015), both of which make the interpretation of sedimentary processes challenging. By contrast, farther north along the seaward edge of the Yakutat Terrane (Fig. 1, inset), relatively good bathymetric data coverage from the United Nations Law of the Sea studies (e.g. Gardner *et al.* 2006) and International Ocean Drilling Program (e.g. Gulick *et al.* 2015) has allowed the more comprehensive characterization of sedimentary processes on the continental slope. The International Ocean Drilling

Program drilling results indicated extraordinarily high sedimentation rates on the wide Yakutat shelf and slope, which have been attributed to the rapidly uplifting (and eroding) St Elias Mountains (Gulick *et al.* 2015; Montelli *et al.* 2017; Sawyer *et al.* 2017). Along-strike of the margin edge, the slope geomorphology varies substantially depending on the proximity to local sediment sources, such as sea valleys, and the relative sediment flux through these pathways (Swartz *et al.* 2015; Montelli *et al.* 2017).

As a result of a general lack of, or gaps in, the high-resolution bathymetric coverage along the continental slope of southeastern Alaska, Quaternary submarine landslide deposits have not been analysed in detail, although Carlson (1978) discussed potential earthquake-induced landslide and slump deposits in the Pamplona Zone portion of the Yakutat shelf, and Sawyer *et al.* (2017) analysed sediment shear strength from IODP Expedition 341. The changing position of the slope relative to shelf edge sediment sources, particularly due to translational motion along the QCF, probably adds a tectonic feedback to margin sedimentary processes (e.g. Walton *et al.* 2014) and the possibility of earthquake-induced submarine landslides along the margin (e.g. Brothers *et al.* 2017). We postulate that along-margin variations in sediment sources, sediment delivery processes and the first-order morphology of the continental slope cause some areas to be more susceptible to slope failure, while others remain relatively stable.

Data and methodology

The morphological analyses in this study are based on compilations of bathymetric and topographic data throughout the eastern Gulf of Alaska, including shaded relief imagery derived from the 8/3 arc second SE Alaska Coastal Relief Model (Caldwell *et al.* 2012; www.ngdc.noaa.gov/mgg/coastal/), the 24 arc second Southern Alaska Coastal Relief Model (Lim *et al.* 2011; www.ngdc.noaa.gov/mgg/coastal/) and several multibeam echosounder surveys conducted throughout the region between 2005 and 2016.

Throughout the following sections we use the term 'margin' to refer to the outer continental shelf, slope and upper rise. To characterize the first-order variation in margin morphology, we examine 38 bathymetric profiles crossing the margin along transects extending for 120 km and oriented perpendicular to the general trend of the shelf-edge. Elevations along the 38 cross-margin profiles were extracted from the Southern Alaska Coastal Relief Model. The profiles are separated by *c.* 20 km between the Yakobi Sea Valley and the southern end of the Haida Gwaii islands (Fig. 1b). Elevation values were extracted every 300 m along the 120-km long transects; values were smoothed using an 11-point running average to remove spurious values in the digital elevation model. Plots of elevation and associated gradient values were shifted so that each profile was aligned to cross the QCF precisely 30 km from the start (landward end) of the line. We used the fault crossing as a baseline for comparing the profiles along the length of the margin and avoided placing the profiles across sections of the margin that may be less representative of the first-order shape (e.g. across or along large submarine canyons). We then grouped the profiles based on their similarities in shape and computed a composite (mean) profile for each grouping for visual comparison with the variance among individual profiles.

The shaded relief surface used for headwall and sidewall slide scarp identification is based on several multibeam bathymetry datasets that were digitally mosaicked and gridded at the 25 m cell size. The lower slope and upper rise (>2000 m water depths) were mapped with a Simrad EM120 (12 kHz) multibeam system (Gardner *et al.* 2006; https://ccom.unh.edu/regions/gulf-alaska), the lower and middle slope were mapped using a Simrad EM302 (30 kHz) system (cruise SKQ2016-IIT; www.rvdata.us/) and the upper slope and shelf were mapped with a variety of higher frequency systems (e.g. Brothers *et al.* 2017; Greene *et al.* 2011; www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html). Several raster derivatives were created from bathymetric elevation models to assist in the identification of the slide scarps, including the gradient, curvature, flow direction/accumulation and hill shading. The data were visually analysed at a scale of 1:20 000 and the scarps were digitized along the uppermost extent of features so that the maximum difference in depth would be captured. Metrics (length, average and maximum height, water depth range and sinuosity) were extracted for each digitized feature and used to examine the statistical patterns relating to the first-order margin morphology and substrate geology. We focused primarily on quantitative analyses for that portion of the margin within southeastern Alaska, whereas detailed descriptions of slide distribution and geomorphic character within Canadian territory are presented by Greene *et al.* (this volume, in press).

A series of high-resolution multichannel seismic reflection surveys were conducted in 2016 and 2017 along the margin of southeastern Alaska (Brothers *et al.* 2017), yielding >6000 line-km of data coverage between the Yakobi Sea Valley and the international border. Surveys aboard the R/V *Medeia*, R/V *Norseman* and R/V *Ocean Starr* used variable length hydrophone streamers (between 24 and 80 channels depending on the survey) and a sparker sound source (ranging from 700 to 12 000 J), generally providing between 0.5 and 1.5 s of maximum substrate penetration (*c.* 1200 m) and 3–5 m vertical resolution of reflections. We present two representative profiles collected aboard the R/V *Norseman* in 2016 (Balster-Gee *et al.* 2017), which highlight the substrate character of the two largest slides observed on the entire margin. Stratigraphic and structural interpretations were made from these seismic profiles using the IHS Kingdom Suite software and the mapped features were imported into the ArcGIS Desktop.

Results

Margin physiography

The topographic profiles extracted from the Coastal Relief Model showed dramatic differences in the along- and across-margin morphology (e.g. width, angularity, steepness, variance) and a pattern of gradual north to south variation. The profiles are grouped into six categories based on their similarities (Fig. 2). Figures 3–5 provide high-resolution imagery of the fine-scale geomorphic features and Figure 6 is a preliminary map of the slide distribution in Groups 1–3 (see Greene *et al.* this volume, in press for detailed description of slides in Groups 4–6) and a plot of the relationship between the scarp length and scarp minimum water depth.

The first grouping (Fig. 2a) is located to the west of Chichagof Island and the northern half of Baranof Island (Fig. 1). The shelf width varies between 10 and 20 km, with the slope and rise characterized by a distinctly concave form between the shelf edge and the upper rise, and has relatively gentle gradients (<7° in the mean profile). The steepest section is along the uppermost slope (250–1000 m water depth) and then gradually decreases seawards as the slope transitions to the upper rise. The high-resolution shaded relief bathymetry throughout Group 1 contains dendritic networks of submarine canyons with heads defined by linear gullies along the upper slope and numerous scarps within canyon thalwegs, sidewalls and intercanyon ridges (Fig. 3). The canyon thalwegs also contain sequences of well-developed dynamic bedforms (i.e. sediment waves), typically located down-canyon of small scarps (Fig. 3c, d). We did not digitize the thalweg scarps as slides because they could be formed by either top-down (knick-point erosion) or bottom-up (retrogressive failure) processes (e.g. Pratson & Coakley 1996). Confluences between the upper slope canyons and gullies create higher order canyon segments over relatively short distances and each network converges into broad submarine channels as the profile gradient for Group 1 decreases to <2° along the upper rise. Forty-eight per cent of the scarps identified in the multibeam echosounder data are in Group 1; the scarp lengths range between 508 and 18 790 m, with scarp gradients between 12 and 60°. Most of the largest slides identified on the margin are located along the lower slope and upper rise of Group 1 (e.g. Fig. 3b, c); the largest slide identified (Figs 3b & 5a) has an area of 60–70 km^2 and an average scarp height of *c.* 200 m, suggesting that it evacuated >10 km^3 of material. The slide deposits and runout distances are difficult to identify except in the seismic reflection profile imagery (e.g. Fig. 5) because it appears that the slides were mostly translational and disintegrated into debris flows that are funnelled through canyons and channels. The minimum depths of the scarps in this group are between 400 and 2631 m (Fig. 6). The QCF passes through Group 1 along the shelf edge and uppermost slope at a mean water depth of *c.* 400 m; the fault appears to be a narrow, knife-edged strike-slip fault with minimal effects on the first-order shape of the margin (Fig. 3a, d).

The profiles in Group 2 (Fig. 2b) define the region from the Sitka Sea Valley to the southern end of Baranof Island and most of the slope and rise near the mouth of the Chatham Sea Valley (Fig. 1b). The QCF remains very close to the shelf edge, but the shelf width increases to between 25 and 35 km. The general shape of the mean slope profile in Group 2 is more linear than in Group 1 and displays a slight increase in steepness along the lower slope, creating a more definitive slope–rise transition in water depths between 1500 and 2000 m. The fine-scale morphology of Group 2 (submarine canyon networks and the distribution, size and character of slides) is similar to that of Group 1. Thirty-four per cent of scarps are in Group 2 and the scarp lengths range between 932 m and 20 000 km. Scarp gradients range from 14 to 82° and the minimum scarp water depths range between 554 and 2592 m.

Profiles in Group 3 are located just south of the Chatham Sea Valley and extend to Noyes Canyon, the only major shelf-indenting canyon on the entire margin (Fig. 2c). Profiles cross the QCF at a mean water depth of *c.* 750 m and the shelf is typically 60–70 km wide. The shelf edge displays a highly variable morphology and contains positive relief along the seaward extent of the Chatham Strait Sea Valley due to localized subsidence along the fault (Fig. 4a; Brothers *et al.* 2017) and what appears to be a shelf edge terminal moraine at the mouth of the Sumner Sea Valley (Fig. 4c). Group 3 marks the first evidence of a distinct separation between the geomorphic expression of the upper slope and the lower slope and the distinction becomes increasingly pronounced to the south. The separation is typically defined by a mid-slope basin or valley bounded to the west by a system of elongate, margin-

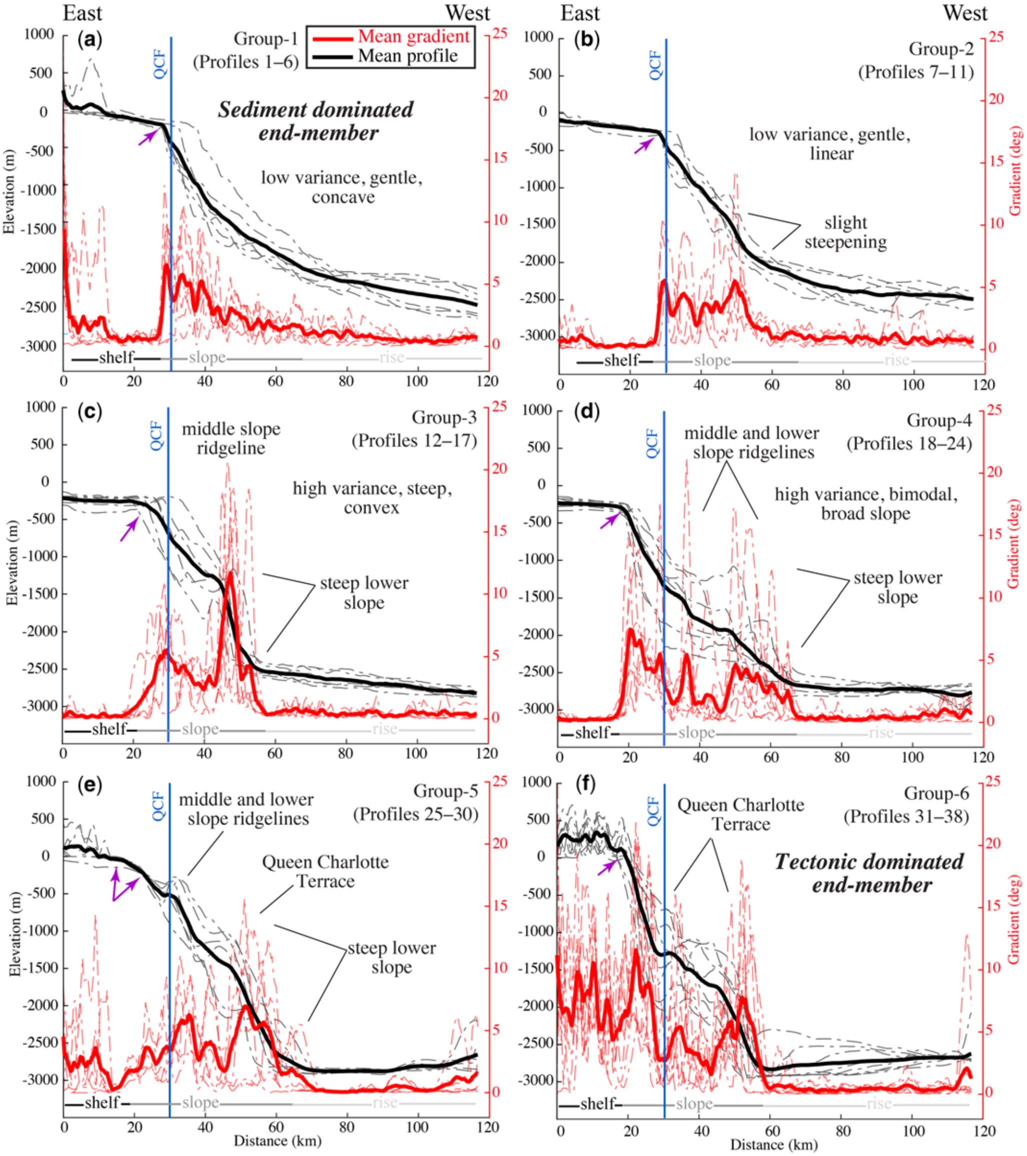

Fig. 2. Plots of bathymetric profiles (dashed black lines; see Fig. 1b for locations) based on elevation values extracted every 300 m from the Southern Alaska Coastal Relief Model (Caldwell *et al.* 2012) and then smoothed using an 11-point moving average filter; the associated along-profile gradient values are plotted as dashed red lines. Plots are aligned to cross the Queen Charlotte Fault 30 km from the start of the profile (i.e. the landward end). Profiles are grouped according to their qualitative similarities in first-order shape (see text for details) and groupings are displayed in sequential order from (**a**) north to (**f**) south; each plot includes the calculated mean, or composite, profile for each grouping (bold red and black lines). Interpreted locations of the shelf, slope and rise transitions for each grouping are shown at the base of each plot. Purple arrows denote the locations of the shelf-edge. QCF, Queen Charlotte Fault.

parallel ridgelines. In Group 3, the ridgelines display up to 500 m of relief along their landward-facing flank and up to 2100 m of very steep relief (>20° in many places) from the ridge crest to the slope–rise transition. The separation into upper and lower slope regimes appears to pose topographic boundaries and margin-parallel deflections of submarine canyons for tens of kilometres (e.g. Fig. 4c). The

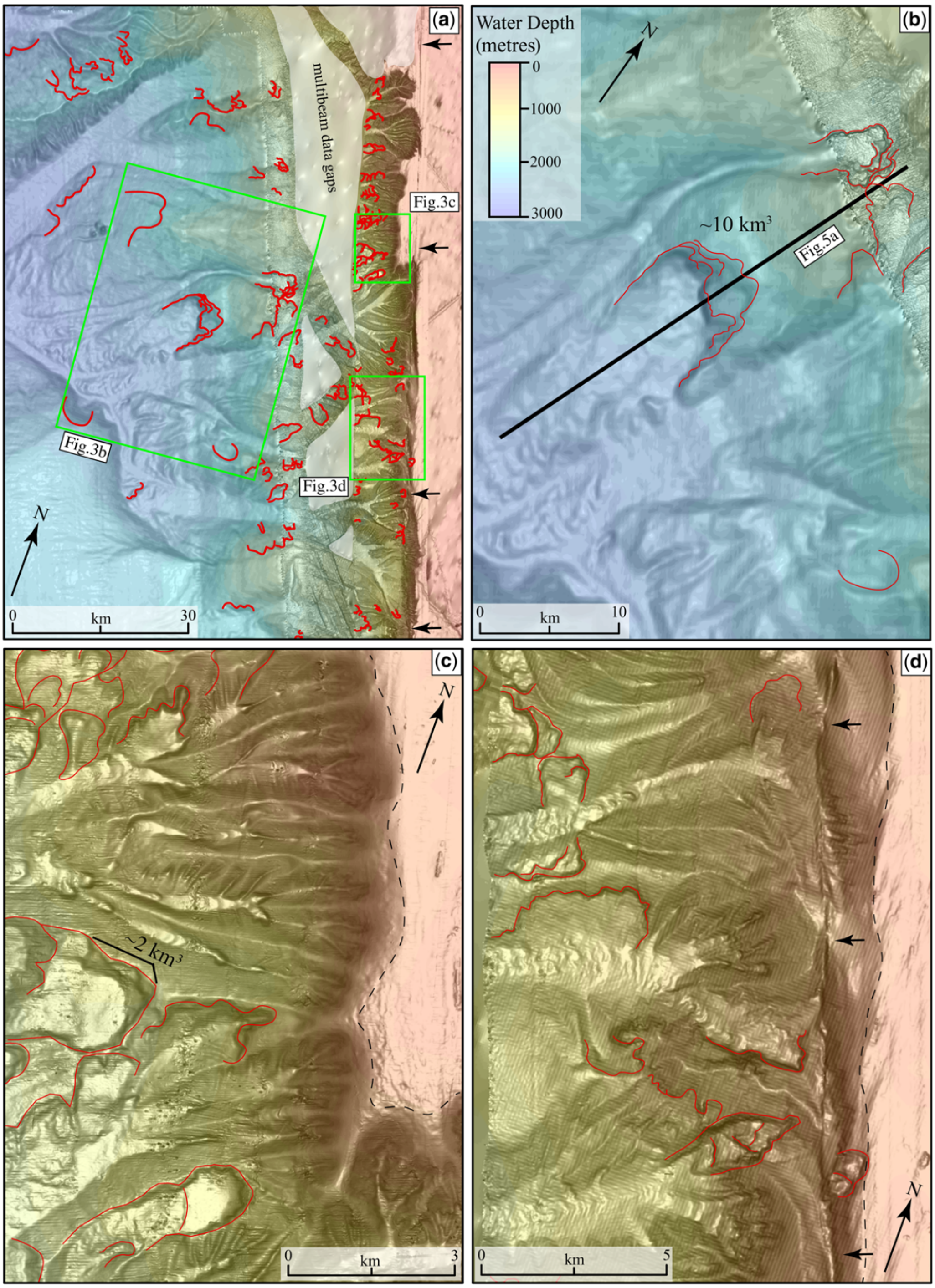

Fig. 3. Select examples of morphologies related to mass transport that are characteristic of Group 1. Red lines are scarps that were digitized for morphometric analyses. The slide in part (b) is the largest slide identified along the entire margin; the black line is the location of the seismic reflection profile in Fig. 5a. Black arrows denote the location of the Queen Charlotte Fault trace; the dashed line defines the approximate location of the shelf edge.

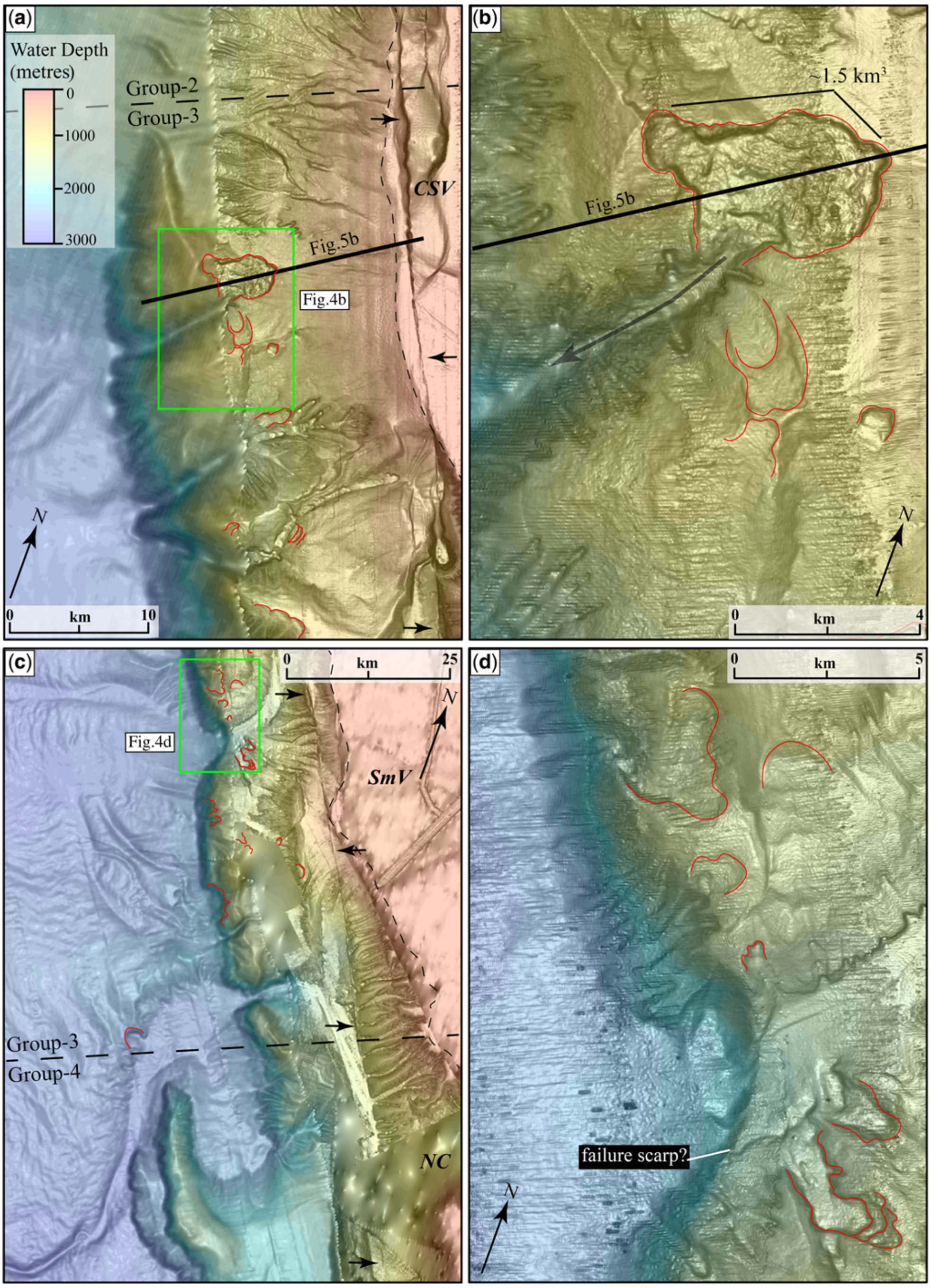

Fig. 4. Select examples of mass transport related morphologies characteristic of Groups 3 and 4. The slide enlarged in part (**b**) is the second largest slide identified along the entire margin, which evacuated into an adjacent submarine canyon in the direction of the black arrow (black line is the location of the seismic reflection profile in Fig. 5b). The dashed lack line in part (**c**) denotes the approximate location of the shelf-edge. Part (**d**) illustrates some of the challenges in the identification of slide scarps and potential to mis-classify morphological features as slides that may be related to knick-point erosion by sediment flows. NC, Noyes Canyon; SmV, Sumner Sea Valley. Small black arrows in (**a**) and (**c**) mark the trace of the Queen Charlotte Fault.

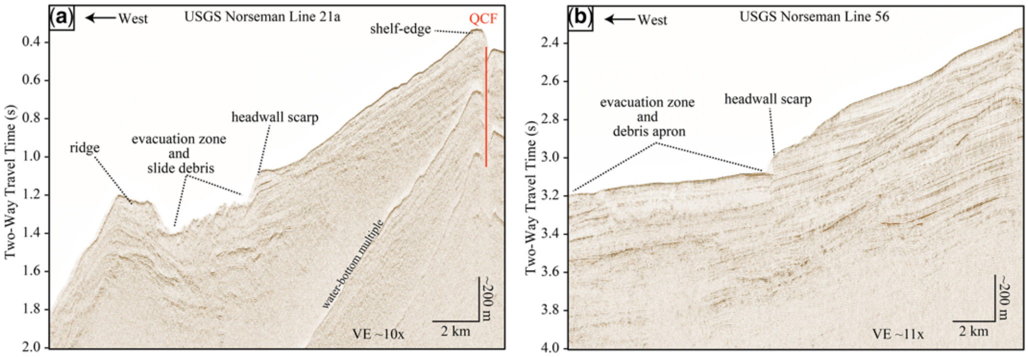

Fig. 5. Select seismic reflection profiles across the two largest slides along the margin within (**a**) Group 1 and (**b**) Group 3. Both slide deposits appear within stratified Quaternary depocentres. QCF, Queen Charlotte Fault.

abrupt slope–rise transition also characterizes the morphology of the remaining groups to the south. Although the number of distinctive scarps identified in Group 3 (only 31) is significantly less than in Groups 1 and 2, the steep, rugged and highly variable seafloor contains subtle, but widespread, evidence for mass transport activity, particularly along the (very) steep flanks of ridges and along submarine canyon sidewalls (e.g. short, rugged scarps, rills, gullies and topples). The second largest slide identified along the margin is located within an intraslope basin to the west of the Chatham Sea Valley (Figs 4b & 5b). The scarp encloses the failure zone on all sides except at its outlet through a canyon that incises the steep flank of the lower slope; there is no identifiable deposit along the upper rise. Group 3 contains 11% of the total number of scarps (31 of 275), with lengths between 981 and 15 815 m and gradients between 12 and 61°. The minimum water depth of the scarps ranges between 753 and 2870 m (Fig. 6).

Group 4 extends from Noyes Canyon to the northern tip of Haida Gwaii and includes the Dixon Entrance Sea Valley, one of the major sediment routing pathways during the Quaternary. Like Group 3, the shelf throughout this region is broad (60–70 km). The variability and complexity of the slope morphology increases substantially in Group 4 (Fig. 2d). The margin-parallel ridgelines observed in Group 3 are more pronounced in Group 4, are conjugate to the QCF, and appear to be associated with rugged, steep relief along the middle and lower slope. The ridgelines create a series of elongate, margin-parallel bathymetric boundaries that have step-like discontinuities every 50–100 km. The gullies and small canyons that emanate from the shelf edge and down the upper slope appear to converge into higher order channels that are deflected in a margin-parallel direction along the flanks of the ridges. Channels cross the lower slope and debouche onto the upper rise at bathymetric gaps between the ridges. The QCF is located farther seaward in this region (700–2200 m water depths) than in Groups 1–3 and appears to separate the upper slope from the ridgelines that define the morphology of the middle and lower slope. The steepest gradients are located along the seaward-facing flank of the lower slope or along the flanks of margin-parallel ridges. Evidence of submarine slides west of Dixon Entrance are described in Greene *et al.* (this volume, in press).

Groups 5 and 6 are both located to the west of Haida Gwaii and display a very narrow shelf (<10 km), with the Queen Charlotte Terrace dominating the middle and lower slope morphology. These groupings do not include any shelf sea valleys or other major Quaternary sediment delivery pathways from the continental mainland (Fig. 1b). The profiles in Group 5 show a more rounded shelf edge and a series of across-margin bathymetric steps (Fig. 2e). Profiles cross the QCF higher on the slope (300–900 m) relative to Groups 4 and 6. The margin appears to have a convex shape on average and the profile variation is less than that of Group 4. Group 6 spans the southern half of Haida Gwaii and shows the greatest total relief (3000 m) over the shortest distance (40 km; Fig. 2f). The shoreline and shelf edge are nearly coincident along several stretches of the margin. There are broad margin-parallel valleys that separate the upper slope from ridgelines that characterize the Queen Charlotte Terrace and lead to significant along-strike variation. The QCF is located in water depths between 600 and 2200 m. The largest slides identified in Groups 5 and 6 appear to be preferentially located along the western flank of the Queen Charlotte Terrace, where the gradients are >15° (Greene *et al.* this volume, in press, their figs 2–4). The deposits, ranging in size from 0.56 to 10.2 km^2, appear to be slumps and block glides of relatively cohesive material that

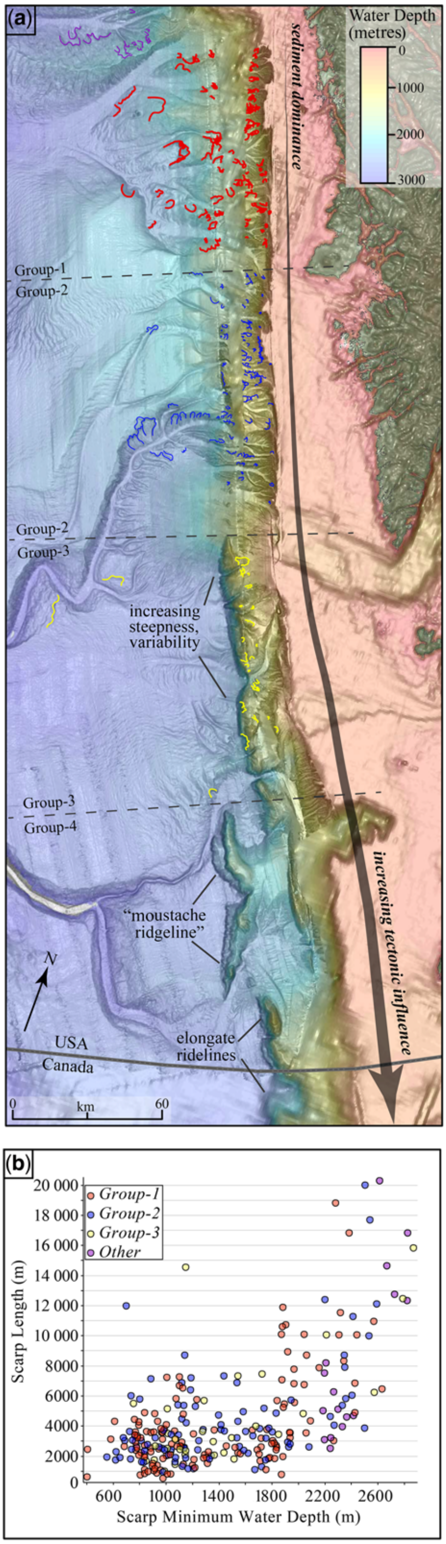

Fig. 6. (**a**) Map summarizing scarp distribution along the southeastern Alaska margin and the relationship between scarp length and water depth (**b**).

is scattered along the base of the slope below the slide zones. Similar to Groups 3 and 4, the steep, rugged and highly variable bathymetry to the west of Haida Gwaii contains few large slides, but shows widespread evidence for mass transport activity, particularly along the steep flanks of ridges and along submarine canyon sidewalls.

Discussion

Along- and across-margin variations in slope physiography had fundamental roles in the distribution of Quaternary sediment accumulation, slope failures and the development of sediment bypass zones. For example, the average gradient of continental slopes (*c.* 4°) lies near the threshold angle above which turbidity currents will erode the seafloor and below which they will deposit their sediment load (Pratson *et al.* 2007).

Bypass, erosion and deposition along continental slopes by sediment flows, particularly along glaciated margins due to high sediment fluxes, are fundamental to the geomorphic development of the margin (e.g. submarine canyon incision, submarine fan growth and the redistribution of mass). Where sediment flows bypass, erode and deposit sediment is highly dependent on the steepness of the slope (e.g. Ross *et al.* 1994; Pirmez *et al.* 1998; Gerber *et al.* 2008; Prather *et al.* 2017). Ross *et al.* (1994) defined graded margins as margins having across-margin stratigraphic profiles that approach a state of equilibrium between competing processes, such as sediment supply, basin subsidence/uplift and margin physiography. Changes to margin physiography (e.g. by rapid tectonic deformation) can lead to retrogressive failure and the bypass of areas that become too steep. This often leads to sediment aggradation at the base of the over-steepened section in an attempt to return to a graded margin. Analyses of depth-gradient profiles can be used to identify graded and out-of-grade geomorphic end-members based on the downslope fluctuations in steepness and the spatial variations in Quaternary sediment accumulation. Previous studies have suggested that sediment bypass starts to occur when the downslope gradient reaches 3–5° and erosion occurs when the gradient is >5° (e.g. Gerber *et al.* 2008). We apply these concepts to interpret in greater detail the geomorphic classification of the southeastern Alaska and western British Columbia margin.

The geomorphic groupings that we defined here (Figs 1b & 2) show that shape of the continental slope changes gradually from north to south, with the degree of variation and geomorphic complexity increasing towards the south. The variation appears to roughly track the gradually increasing degree of convergence and transpressional deformation along the QCF. We identify two geomorphic end-members on either end of the QCF with a continuum of changing morphological groupings in between. Group 1 represents the sediment-dominated end-member. Despite the fact that the QCF has a high slip-rate throughout the region, Group 1 closely resembles the shape commonly found along passive siliciclastic margins (e.g. O'Grady *et al.* 2000; Brothers *et al.* 2013). We did not observe the steep, high-relief physiography typically associated with antecedent tectonic episodes. Instead, the mean profile appears to be approaching that of a graded system (Ross *et al.* 1994) in which sediment delivery to the shelf edge is in equilibrium with sediment accumulation along the lower slope/upper rise. We propose that in the Group 1 region, the relatively high sediment flux from glacial outwash during sea-level lowstands was able to overprint or bury the majority of the fine-scale tectonic geomorphology associated with the trace of the QCF. Because the mean profile (Fig. 2a) shows relatively gentle gradients, Quaternary sediments have been able to accumulate along the slope and upper rise, forming broad depocentres of potentially unstable (i.e. under-consolidated) material (e.g. Sawyer *et al.* 2017). We infer that the greater density and size of scarps observed in Groups 1 and 2 is due to the combined effects of a high sediment flux, a low degree of convergence along the QCF and gentle slope physiography. The failures observed along the sediment-dominated margin appear to have been predominantly translational (Varnes 1958) and less cohesive than the slides observed along the flank of the Queen Charlotte Terrace (see Greene *et al.* this volume, in press), indicating further that failures occurred mostly within under-consolidated Quaternary depocentres.

The slide scarps on the upper rise (water depths >2000 m) are, on average, two to three times longer than the scarps on the slope/shelf area (Fig. 6b), in part because the slides on the upper slope are restricted by the dimensions of the short-wavelength canyon/channel morphology. We observed hundreds of short (<500 m) semi-circular scarps within canyon thalwegs, along sidewalls and near the heads of gullies. Although these smaller scarps were not digitized for statistical analysis, they appear to have played a fundamental part in the mass transport processes most active along the entire margin, particularly in the development of submarine canyons. The scarps observed in and around submarine canyons may have had a genetic relationship with the sediment waves that are observed along most of the canyon thalwegs (e.g. Pratson & Coakley 1996). Within the sediment-dominated regions, there was a greater potential for sediment accumulation and the subsequent development of retrogressive failure complexes (bottom-up geomorphic process) that, in turn, may have generated sediment flows and associated sedimentary bedforms farther down the canyon (top-down processes). This would have been especially true where canyons and gullies were sinuous and the down-canyon transport of sediment was damned in meanders, later to be displaced and to move further down-canyon (Greene *et al.* 2002).

Moving southwards, we infer that the role of antecedent (probably pre-Quaternary) physiography, whether strictly related to tectonics or to some other process, exerts an increasing influence on the distribution of Quaternary depocentres. The most pronounced change in the slope morphology occurs near the mouth of the Chatham Sea Valley and continues to increase in variability all the way to the southern tip of Haida Gwaii. The shapes of Groups 3–6 and the character of the fine-scale geomorphology suggest that the upper and lower slopes can be split into separate morphological regimes. We propose that Quaternary sedimentary processes had a significant influence on the shape of the shelf edge and upper slope, whereas the lower slope was controlled by tectonic deformation, sediment bypass and erosion. Within Groups 5 and 6, the tectonically dominated end-members, sediment delivery from the shelf appears to have been routed around the tectonically generated topographic barriers and tended to bypass the slope. In addition, Haida Gwaii appears to have formed a glacial shadow, or blackade to the continental ice sheet, during the last glacial advance, thus preventing significant late Pleistocene and Holocene glacial sediment supply to the continental shelf and slope in this area (Greene *et al.* this volume, in press).

As noted, the character of the mass transport morphologies and types of individual slides observed also changes along the margin. The larger failures along steep, tectonically controlled sections of the margin appear to have involved block falls and slumps of older, more consolidated material. Although the number of distinctive scarps identified in Groups 3–6 is significantly less than in Groups 1 and 2, the steep, rugged and highly variable seafloor in these areas displays pervasive evidence for mass transport activity, particularly along the (very) steep flanks of ridges and along submarine canyon sidewalls (gravitational collapse of steep, structurally controlled features). Perhaps due to the relatively limited sediment accumulation in these areas (i.e. sediment either bypasses or fails before significant depocentres can develop), the mass transport processes left behind subtle geomorphic signatures that are difficult to resolve.

Conclusions

Along- and across-margin variations in slope physiography played fundamental parts in the distribution of Quaternary sediment accumulation, slope failures and the development of sediment bypass zones along the QCF system. New high-resolution marine geophysical data along the southeastern Alaska and western British Columbia continental margin provide the first detailed view of the types of mass-wasting features present along the margin, as well as an opportunity for a systematic examination of their underlying causes. Our results suggest that classification of the broad-scale shape of the shelf, slope and rise can be used to develop a predictive framework that splits the margin according to process dominance. We identified six basic groupings that define a morphological continuum from north to south, bounded by two basic end-members: (1) regions of the margin dominated by sedimentary processes and (2) regions dominated by tectonic deformation. The sediment-dominated physiography of the northern margin (Yakobi Sea Valley southwards to Chatham Sea Valley) is characterized by larger and more frequent translational slides that involved the failure of under-consolidated Quaternary depocentres. By contrast, the tectonically dominated section of the southern margin (west of Haida Gwaii) is characterized by fewer translational slides and more slumps and topples along the steep flanks of uplifted structures.

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