The natural range of submarine canyon-and-channel longitudinal profiles

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ABSTRACT

We differentiated 20 submarine canyon-and-channel longitudinal profiles across various types of continental margins on the basis of relative convexity or concavity, and according to their similarities to best-fitting mathematical functions. Profiles are visually differentiated into convex, slightly concave, and very concave groups, each of which generally corresponds with a continental-margin type and distinct depositional architecture. Profile groups generally reflect the competing influences of uplift and construction of depositional relief of the seafloor and its degradation by erosion related to mass wasting. Longitudinal-profile shape provides a basis for classifying deep-sea sedimentary systems, linking them to the geomorphic processes that shape continental margins.

INTRODUCTION

Submarine canyon-and-channel systems are conduits through which sediment is transported across continental margins to deep-sea basins by sediment gravity flows and other mass movements (Shepard, 1948, 1981; Menard, 1955). Processes that sculpted canyon-and-channel systems during their lifetimes are manifested in the shapes of longitudinal profiles. Longitudinal profiles of fluvial systems have been contemplated by geomorphologists since the nineteenth century (e.g., Playfair, 1802; Gilbert, 1880). Subsequent studies of fluvial profiles have highlighted the relative importance of intrinsic and extrinsic controlling variables, including water discharge, sediment supply, sediment caliber (Snow and Slingerland, 1987), and changing uplift conditions. Interactions between these variables introduce complications into the characteristic logarithmic, or concave upward, shape of terrestrial fluvial profiles (Whipple and Tucker, 1999; Schumm et al., 2000). In contrast, previous work on submarine canyon-and-channel profiles has been predominantly limited to case studies of profiles from a single type of continental margin (e.g., Goff, 2001; Estrada et al., 2005; Mitchell, 2005; Noda et al., 2008; Gerber et al., 2009). Tectonic and sedimentary influences inherent to different types of continental margins, however, have a significant impact on seascape morphology and sediment–gravity-flow erosion and deposition by controlling the gradient and stability of the seafloor, and sediment caliber and supply (Bouma et al., 1985; Normark, 1985; Stow et al., 1985; Mutti and Normark, 1987; Shanmugam and Moiola, 1988; Normark and Piper, 1991; Carvajal et al., 2009; Piper and Normark, 2009).

Bill Normark pioneered work on seafloor canyon-and-channel systems and depositional fans in 1970 with “Growth Patterns of Deep-Sea Fans” (Normark, 1970). This seminal work prompted Normark to reconcile seafloor observations and interpretations of sediment–gravity-flow processes with “ancient” buried subsurface and outcropping systems (e.g., 1982 COMFAN [COMmittee on FANs]; Bouma et al., 1985; Normark, 1985; Normark et al., 1985a; Mutti and Normark, 1987, 1991; Normark and Piper, 1991; Normark et al., 1993). These efforts produced broadly applicable models of sediment dispersal across continental margins that hold true to this day. Normark (1985) and Mutti and Normark (1987) highlighted that the characteristics of deep-water canyon-and-channel systems and depositional fans are controlled by the morphology and sediment supply characteristics of the submarine continental margin and receiving basin. Multiple continental-margin and receiving-basin scenarios and resultant deep-water seafloor and ancient stratigraphic architectures were recognized in an attempt to place a global and temporal breadth of turbidite architectures (i.e., seafloor, buried subsurface, and outcropping) within a common framework (Mutti and Normark, 1987).

Following in the footsteps of Normark and colleagues’ seminal work on seafloor features and implications for models of continental margins, this study reviews canyon-and-channel longitudinal profiles from a global range of continental margins—from the tectonically active transform and convergent margins of the Pacific to the Atlantic passive margin offshore the Americas (Fig. 1 and Table 1). We differentiated longitudinal profiles across continental slopes on the basis of (1) relative convexity or concavity from visual inspection and (2) according to their similarities to best-fitting mathematical functions. These observations and analyses provide a catalog of the breadth and general controls of the shapes of submarine sediment-delivery systems, which can be related to the depositional architecture of different continental margins.

Database and Methodology

Our submarine canyon-and-channel database includes 20 longitudinal profiles from a variety of continental margins (Figs. 1 and 2; Table 1). These canyon-and-channel systems are submarine conduits that pass from predominantly erosional, V-shaped canyons indenting the shelf and uppermost slope to U-shaped channels with overbank deposits across the lower slope and continental rise (cf. Shepard, 1948; Menard, 1955; Normark, 1970). We examined profiles of canyons and channels that are present across the modern seafloor (i.e., buried channel features are excluded) and, as such, they represent the most recent canyon-and-channel-system activity (i.e., since the last glacial cycle, <100 ka, for many systems; Lambeck and Chappell, 2001). Four canyon-and-channel profiles from the California Continental Borderland, La Jolla (14), Carlsbad (15), Oceanside (16), and Newport (17), were measured from National Oceanic and Atmospheric Administration/National Geophysical Data Center (NOAA/NGDC) and U.S. Geological Survey (USGS) multibeam bathymetry (<3 arc-second grids, 10-cm vertical resolution; Gardner and Dartnell, 2002; Dartnell et al., 2007; Divins and Metzger, 2009; Table 1). The Mississippi

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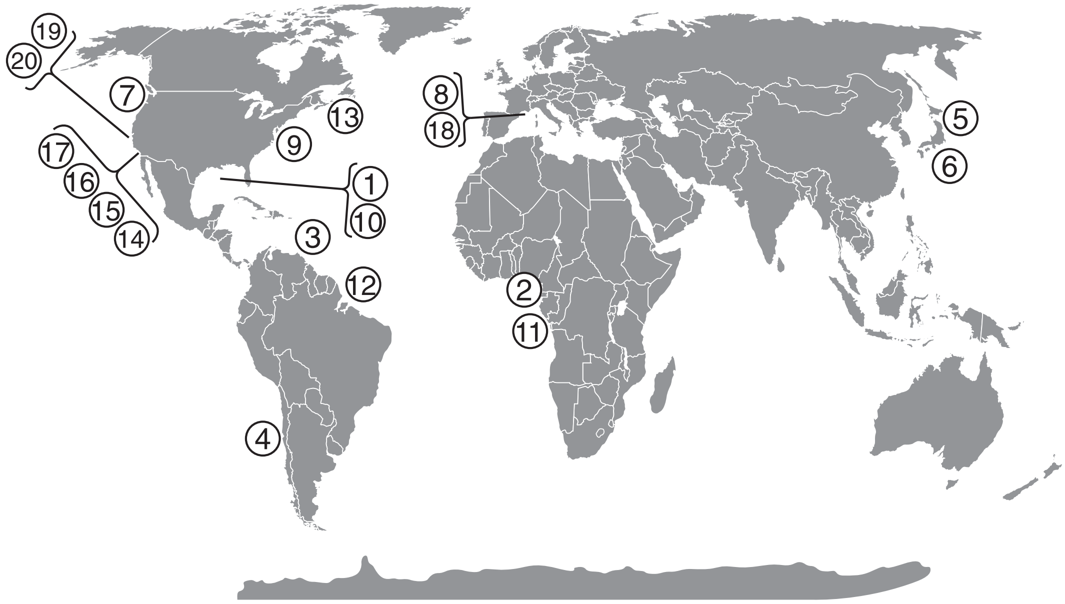


Figure 1. Location map of canyon-and-channel systems analyzed in this study. Numbers correspond to systems in Table 1 and throughout the text.

profile (10) was measured from NOAA/NGDC multibeam bathymetry (Divins and Metzger, 2009; Table 1). We chose to measure the profiles of these five canyon-and-channel systems because (1) readily available high-resolution multibeam bathymetry covers their extents from the continental shelf out to the base of slope and (2) satisfactory published profiles were not discovered during the course of our literature review. The remaining profiles were compiled from published examples to facilitate further investigation of the canyons and channels of this study (Table 1). The majority of profiles were measured by other researchers from high-resolution multibeam bathymetric data (Table 1). The exact reference for each published canyon-and-channel longitudinal profile used in this study is emboldened and italicized in Table 1. Regardless of the resolution of published longitudinal profiles, long and short profiles are compared at similar resolutions as a result of the following measurement procedure: (1) water depths and down-system lengths were measured along every bend (cf. channel length and slope measurements of Flood and Damuth, 1987); and (2) water depths and down-system lengths of the high-resolution profiles were resampled every 10 km for systems >100 km long and every 1 km for systems <100 km long. Gradient and curvature (down-system change in gradient) were also calculated.

Longitudinal-Profile Normalization

Figure 3 shows all the longitudinal profiles used in this study. These are difficult to compare to one another because of differences in canyon-and-channel lengths and depths. To rectify this problem, we have normalized longitudinal profiles in two ways: (1) on the basis of profile length from canyon head to the end of the confined portion of the system (e.g., at the channel-to-lobe transition zone of Mutti and Normark, 1987; Fig. 4); and (2) on the more objective basis of profile length from canyon head to the point where profiles reached gradients <0.25° and curvatures (i.e., down-system change in gradient) between -10^{-7} and 10^{-7}. This second method focuses on the lengths of canyon-and-channel systems across their continental slopes rather than their lengths across relatively flat basin plains (cf. Adams and Schlager, 2000) (Fig. 5).

Three problems arose when we attempted to normalize profiles across their predominantly confined segments (e.g., from canyon head to the channel-to-lobe transition): (1) not all of the profiles include the entire confined segments of their canyon-and-channel systems (i.e., many published examples and bathymetric data sets do not extend at sufficiently high resolution beyond the continental slope); (2) the exact locations of confined-to-unconfined transitions are commonly poorly defined, gradational sedimentary environments and, as a result, are subjective; and (3) even though profiles were from different continental margins, with very different tectonic and sedimentary controls on their development, they only fell into two groups of longitudinal profiles—convex upward and concave upward (Fig. 4A). Regarding problem 3, closer inspection of concave upward profiles shows that profiles from mature passive margins (e.g., Rhone [8], Zaire [11], and Amazon [12]) are only slightly concave in their proximal reaches (<0.4 of their total down-system length) relative to profiles from the margin offshore southern California, which are characterized by steeper slopes and narrower shelves (e.g., La Jolla [14], Carlsbad [15], Oceanside [16], Newport [17], and Ascension [19]) (Fig. 4B).

All 20 of the profiles used in this study were normalized across their continental slopes (Fig. 5). This normalization procedure cuts off the relatively long and flat tail of a few of the longest profiles, which extend across basin plains (e.g., Mississippi [10], Zaire [11], and Amazon [12]) (Fig. 2). This is necessary in order to compare their reaches across slopes to other systems, which do not extend as far across the basin plain and are predominantly restricted to the slope. As mentioned above, the base of slope was not measured at an arbitrary or unit length; rather, it was defined at the point where profiles reached gradients <0.25° and curvatures between -10^{-7} and 10^{-7} (cf. Adams and Schlager, 2000) (Fig. 2). Here, we include all normalized longitudinal-profile data; however, we focus on normalization across the slope in order to provide a more inclusive comparison of profiles (Fig. 5).

Longitudinal-Profile Groups and Curve-Fitting Functions

Normalized longitudinal profiles were grouped in two ways: (1) on the basis of relative convexity or concavity from visual inspection; and (2) according to their similarities to best-fitting mathematical functions (cf. Shepherd,

TABLE 1. CHARACTERISTICS OF CANYON-AND-CHANNEL SYSTEMS

System	(1) East Breaks	(2) Nigeria X	(3) Barbados A	(4) San Antonio	(5) Kushiro	(6) Aoga	(7) Astoria	(8) Rhone	(9) Hudson	(10) Mississippi
Longitudinal profile	Convex	Convex	Convex	Convex	Convex	Convex	Slightly concave	Slightly concave	Slightly concave	Slightly concave
Geographic context	NW Gulf of Mexico	Niger Delta, Atlantic Ocean	Venezuela, Caribbean Sea	Central Chile, Pacific Ocean	Hokkaido, Japan, Pacific Ocean	Honshu, Japan, Pacific Ocean	Washington, USA, Pacific Ocean	France, Mediterranean Sea	New Jersey, USA, Atlantic Ocean	Gulf of Mexico
Data	3D seismic-reflection data (processed bin size of 50 × 25 m)	3D seismic-reflection data	200-m-resolution DEMs with a vertical accuracy of 0.6% of depth	Hydrosweep bathymetry (better than 100-m horizontal resolution)	SeaBeam and Hydrosweep bathymetry (measured over 5 km)	1980s-vintage SeaMARC II bathymetry (measured over <10 km)	1960s-vintage bathymetry (measured over <10 km)	1980s-vintage SeaBeam and SeaMARC I bathymetry	SeaBeam bathymetry (measured over 5 km)	NOAA/NGDC bathymetry (<3 arc-second grids; 10-cm vertical resolution)
Best-fitting function	Exponential	Linear	Exponential	Linear	Linear	Linear	Linear	Linear	Linear	Linear
Margin type	Passive	Passive	Active, convergent	Active, convergent	Active, convergent	Active, convergent	Active, convergen	Mixed*	Passive	Passive
Synsedimentary deformation	Yes; gravity-driven	Yes; gravity-driven	Yes	Yes	Yes	Yes	Yes	No	No	Yes; gravity-driven
Glacial influence (>40° latitude)	No	No	No	No	Yes	No	Yes	Yes	No†	No
Normalized length across slope (km)	58	76	250	110	200	200	200	170	270	285
Fluvial sediment load ($\times 10^6$ t/yr)	16	40	N/A§	3.2 km^3/yr#	10 km^3/yr**	N/A§	15	7.4	1	400
Grain size	Mud to sand	Mud to sand	Mud to gravel	Mud to coarse-grained sand	Mud to pebbles	Presumably mud to pebbles	Mud to gravel; silt rich	Mud to fine-grained sand; silt rich	Mud to gravel; mud rich	Mud rich
References	3,4,17,***25***	17,***25***	***12***	***16***,18	***21***	***15***	2,***20***,29	2,23,***25***,29	***5***,17,26	2,29

Note: We measured five longitudinal profiles from high-resolution, multibeam bathymetric data sets that extend from the continental shelf out to the base of slope (Gardner and Dartnell, 2002; Dartnell et al., 2007; Divins and Metzger, 2009). The remaining profiles were compiled from published sources, which are highlighted in the row of references as emboldened and italicized numbers. See references list at the bottom of the table.

(*continued*)

TABLE 1. CHARACTERISTICS OF CANYON-AND-CHANNEL SYSTEMS (*continued*)

System	(11) Zaire	(12) Amazon	(13) Laurentian	(14) La Jolla	(15) Carlsbad	(16) Oceanside	(17) Newport	(18) Var	(19) Ascension	(20) Monterey
Longitudinal profile	Slightly concave	Slightly concave	Very concave	Very concave	Very concave	Very concave	Very concave	Very concave	Very concave	Slightly concave
Geographic context	West Africa, Atlantic Ocean	Brazil, Atlantic Ocean	Eastern Canada, Atlantic Ocean	Southern California, USA, Pacific Ocean	Southern California, USA, Pacific Ocean	Southern California, USA, Pacific Ocean	Southern California, USA, Pacific Ocean	France, Mediterranean Sea	Central California, USA, Pacific Ocean	Central California, USA, Pacific Ocean
Data	Simrad bathymetry (better than 100-m horizontal resolution; 10-m vertical resolution)	SeaBeam bathymetry (~100-m horizontal resolution)	1980s-vintage SeaBeam bathymetry	NOAA/NGDC/USGS bathymetry (<3 arc-second grids; 10-cm vertical resolution)	NOAA/NGDC/USGS bathymetry (<3 arc-second grids; 10-cm vertical resolution)	NOAA/NGDC/USGS bathymetry (<3 arc-second grids; 10-cm vertical resolution)	NOAA/NGDC/USGS bathymetry (<3 arc-second grids; 10-cm vertical resolution)	—	NOAA bathymetric sheet NOS 1307N-11B	Simrad bathymetry
Best-fitting function	Linear	Linear	Logarithmic	Logarithmic	Logarithmic	Logarithmic	Logarithmic	Logarithmic	Logarithmic	Linear
Margin type	Passive	Passive	Passive	Active, transform	Active, transform	Active, transform	Active, transform	Mixed*	Active, transform	Active, transform
Synsedimentary deformation	Yes; gravity-driven	No	No	Yes	Yes	Yes	Yes	Yes; Qt terrace uplift, earthquakes common	Yes	Yes
Glacial influence (>40° latitude)	No	No	Yes	No	No	No	No	Yes	No	No
Normalized length across slope (km)	370	380	360	54	25	58	81	80	84	140
Fluvial sediment load (× 10^6 t/yr)	48	1200	4	2.2 (Oceanside littoral cell)	Unknown, but likely small	0.4	0.5	1.3	Unknown, but likely small	4.8
Grain size	Mud rich	Mud to pebbles; mud rich	Mud to gravel; sand rich	Mud to gravel; sand rich	Mud to gravel; sand rich	Mud to gravel; sand rich	Mud to gravel; sand rich	Sand rich	Mud to cobbles; sand rich	Mud to cobbles; sand rich
References	***1***,29	2,9,***24***,25,29	2,17,***28***	6,10,13,22	6	6,10,14	10,14	***27***,29	8,11,***19***	2,***11***,29

*Mixed margins include settings adjacent to uplifting hinterland source areas (e.g., northwestern Mediterranean Sea). The northwestern Mediterranean Sea is a young, steep margin (post-Oligocene) with local tectonism (Savoye et al., 1993).

†Hudson Canyon head is just south of 40° N latitude.

§These canyons head on the middle continental slope, rather than the shelf edge.

#Rio Miapo discharge (not fluvial sediment load).

**Combined discharge of the Tokachi and Kushiro rivers (not fluvial sediment load).

Note: References: (1) Babonneau et al. (2002); (2) Barnes and Normark (1985); (3) Beaubouef and Friedmann (2000); (4) Booth et al. (2000); (5) Butman et al. (2006); (6) Covault et al. (2007); (7) Curray et al. (2003); (8) Fildani and Normark (2004); (9) Flood et al. (1991); (10) Graham and Bachman (1983); (11) Greene et al. (2002); (12) Huyghe et al. (2004); (13) Inman (2008); (14) Inman and Jenkins (1999); (15) Klaus and Taylor (1991); (16) Laursen and Normark (2002); (17) Milliman and Syvitski (1992); (18) Milliman et al. (1995); (19) Nagel et al. (1986); (20) Nelson (1970); (21) Noda et al. (2008); (22) Normark (1970); (23) Normark et al. (1985b); (24) Pirmez and Imran (2003); (25) Pirmez et al. (2000); (26) Pratson et al. (1994); (27) Savoye et al. (1993); (28) Skene and Piper (2006); (29) Sømme et al. (2009). DEMs—digital elevation models; NOAA/NGDC—National Oceanic and Atmospheric Administration/National Geophysical Data Center; USGS—U.S. Geological Survey.

1985; Adams and Schlager, 2000). For the visual analysis, profiles were grouped into convex-upward, slightly concave-upward, and very concave-upward categories (Fig. 5). Hereafter, convex and concave will be used for simplification.

For the curve-fitting analysis, we attempted to fit profiles to three simple functions, exponential, linear, and logarithmic, and we used coefficients of determination (r^2 values) from least-squares regression to determine which function best describes a profile (cf. Shepherd, 1985; Adams and Schlager, 2000) (Fig. 2). Exponential functions are of the general form:

$$y = ce^{bx}, \quad (1)$$

where y is water depth, x is the down-system distance, c and b are constants, and e is the base of the natural logarithm. Exponential functions indicate that profiles change basinward at an increasing rate. Linear functions are of the general form:

$$y = mx + b, \quad (2)$$

where m is the slope of the line of best fit, and b is the intersection of the line with the y axis. Logarithmic functions are of the general form:

$$y = c \ln x + b, \quad (3)$$

where c and b are constants, and ln is the natural logarithm. Logarithmic functions indicate that profiles change quickly and then level out basinward. They are the inverse of exponential functions.

Simple visual analysis did not always correspond with more objective curve fitting. For example, visual inspection of the Nigeria X (2), San Antonio (4), Kushiro (5), and Aoga (6) profiles indicates that they are convex (Fig. 5); however, they are objectively best fit, according to least-squares regression, to linear functions, and, therefore, would be classified as linear profiles by the curve-fitting method of this study (Fig. 2).

Canyon-and-Channel Longitudinal Profiles

Longitudinal profiles are presented below according to groups determined from visual inspection (Fig. 5). Information pertaining to best-fitting functions of profiles is also provided, as well as continental-margin and depositional-architecture context. Table 1 provides more information pertaining to the characteristics of canyon-and-channel systems and continental margins.

Convex Profiles

Six canyon-and-channel systems have convex profiles, which are relatively flat in their proximal reaches but are steeper in their distal reaches (East Breaks [1], Nigeria X [2], Barbados A [3], San Antonio [4], Kushiro [5], and Aoga [6]) (Fig. 6). Two of these profiles, East Breaks (1) and Barbados A (3), are best fit, according to least-squares regression, to exponential functions. The East Breaks (1) system is commonly referred to as the Brazos-Trinity system (e.g., Mallarino et al., 2006). Four profiles, Nigeria X (2), San Antonio (4), Kushiro (5), and Aoga (6), are best fit to linear functions (Fig. 2). These systems are from passive-margin slopes subjected to gravity-driven tectonic deformation that produces diapirism, growth faults, folds, and toe thrusts (e.g., the intraslope basin province of the western Gulf of Mexico for East Breaks [1] and offshore the Niger Delta continental margin for Nigeria X [2]; Damuth, 1994; Rowan et al., 2004) and tectonically active convergent margins (Barbados A [3], San Antonio [4], Kushiro [5], and Aoga [6]) (Table 1 and Fig. 6). All six of these systems were subjected to synsedimentary tectonic deformation and received relatively small volumes of sediment over the last glacial cycle relative to large submarine fan systems that were provided voluminous sediment in open ocean basins (discussed below in the Slightly Concave Profiles section) (cf. fluvial sediment-load measurements in Table 1). The development of depositional architecture on passive margins deformed by gravity-driven processes (East Breaks [1] and Nigeria X [2]) corresponds with subtle gradient changes across their diapiric and growth-faulted slopes (Pirmez et al., 2000) (Fig. 6C). Relatively fine-grained, shelf-edge, delta-fed sediment was transported through leveed channels of the small East Breaks (1) and Nigeria X (2) slope channels to pockets of intraslope accommodation, where ponded turbidite systems developed (Beaubouef and Friedmann, 2000; Booth et al., 2000; Pirmez et al., 2000). In contrast, the San Antonio (4) system offshore Chile and the Kushiro (5) and Aoga (6) systems offshore Hokkaido and Honshu, respectively, are relatively large canyon–to–erosional-channel systems that deposited relatively coarse-grained sediment in accretionary wedge-top and forearc basins, and transported sediment across the steep front of accretionary wedges that extend seaward into trenches (Klaus and Taylor, 1991; Laursen and Normark, 2002; Noda et al., 2008) (Table 1 and Fig. 6D). The Barbados A (3) system offshore Venezuela transported relatively coarse-grained sediment across the Barbados Ridge Complex (Huyghe et al., 2004) (Table 1). The system originates on a tectonically quiescent segment of the continental slope, where the gradient is flatter, which facilitated the development of levee and overbank relief. Across more distal reaches, however, the system lacks levee relief and is incised into the steeper, actively uplifting front of the Barbados Ridge Complex (Huyghe et al., 2004).

Slightly Concave Profiles

Seven canyon-and-channel systems have slightly concave profiles (Astoria [7], Rhone [8], Hudson [9], Mississippi [10], Zaire [11], Amazon [12], and Monterey [20]) (Fig. 7). All seven are best fit to linear functions (Fig. 2). Five of these systems (Rhone [8], Mississippi [10], Zaire [11], Amazon [12], and Monterey [20]) are associated with some of the largest deep-sea fans in the world (Barnes and Normark, 1985) (Table 1 and Fig. 7). These generally mud-rich systems include enormous canyons that transition to channels with well-developed levee and overbank relief and terminate as depositional lobes in some cases greater than one thousand kilometers down-system (Fig. 7). The Monterey (20) system is exceptional in that it developed across the California transform margin, and, similar to many of the sand-rich systems of the margin, was active during the Holocene marine transgression and highstand (Paull et al., 2005; Fildani et al., 2006; Piper and Normark, 2009). One slightly concave system, Astoria (7), developed across the Cascadia tectonically active convergent margin offshore western North America (Table 1).

Figure 2 (*on following five pages*). Plots of all canyon-and-channel longitudinal profiles. Left: Lengths of entire profiles. Arrows indicate bases of continental slopes or ends of confined reaches of canyon-and-channel systems used for normalization. Bases of slopes were not measured at arbitrary or unit lengths, but were defined at the points where profiles reached gradients <0.25° and curvatures (i.e., down-system change in gradient) between -10^{-7} and 10^{-7}. Notice distal reaches of only a few profiles were cut off by this normalization procedure (i.e., Mississippi [10], Zaire [11], and Amazon [12]). Right: Normalized profiles across continental slopes with best-fitting curves and functions according to least-squares regression (red lines).

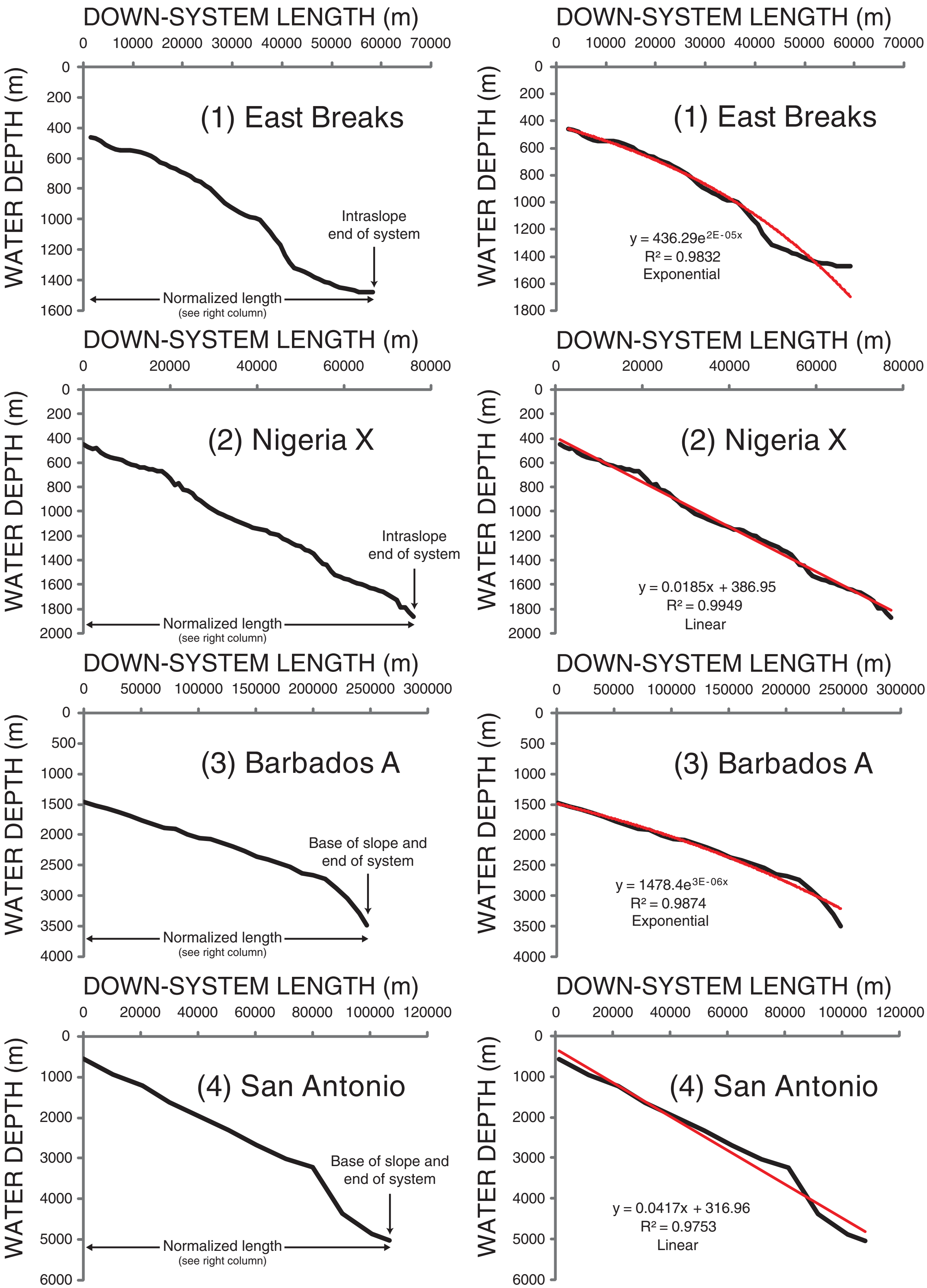
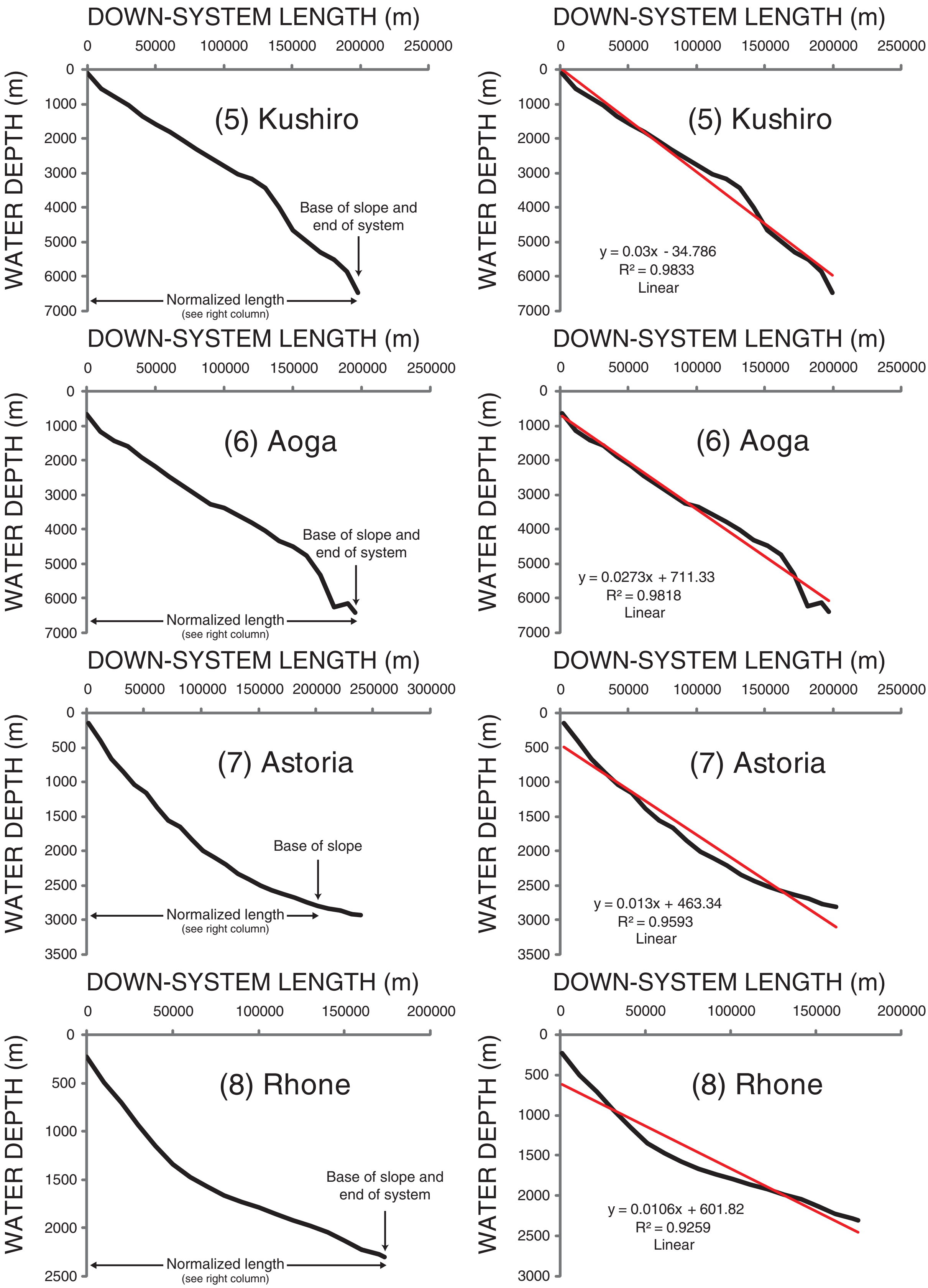

DOWN-SYSTEM LENGTH (m)
WATER DEPTH (m)
(1) East Breaks
Intraslope end of system
Normalized length (see right column)
y = 436.29e^2E-05x
R² = 0.9832
Exponential
(2) Nigeria X
Intraslope end of system
Normalized length (see right column)
y = 0.0185x + 386.95
R² = 0.9949
Linear
(3) Barbados A
Base of slope and end of system
Normalized length (see right column)
y = 1478.4e^3E-06x
R² = 0.9874
Exponential
(4) San Antonio
Base of slope and end of system
Normalized length (see right column)
y = 0.0417x + 316.96
R² = 0.9753
Linear

Figure 2.



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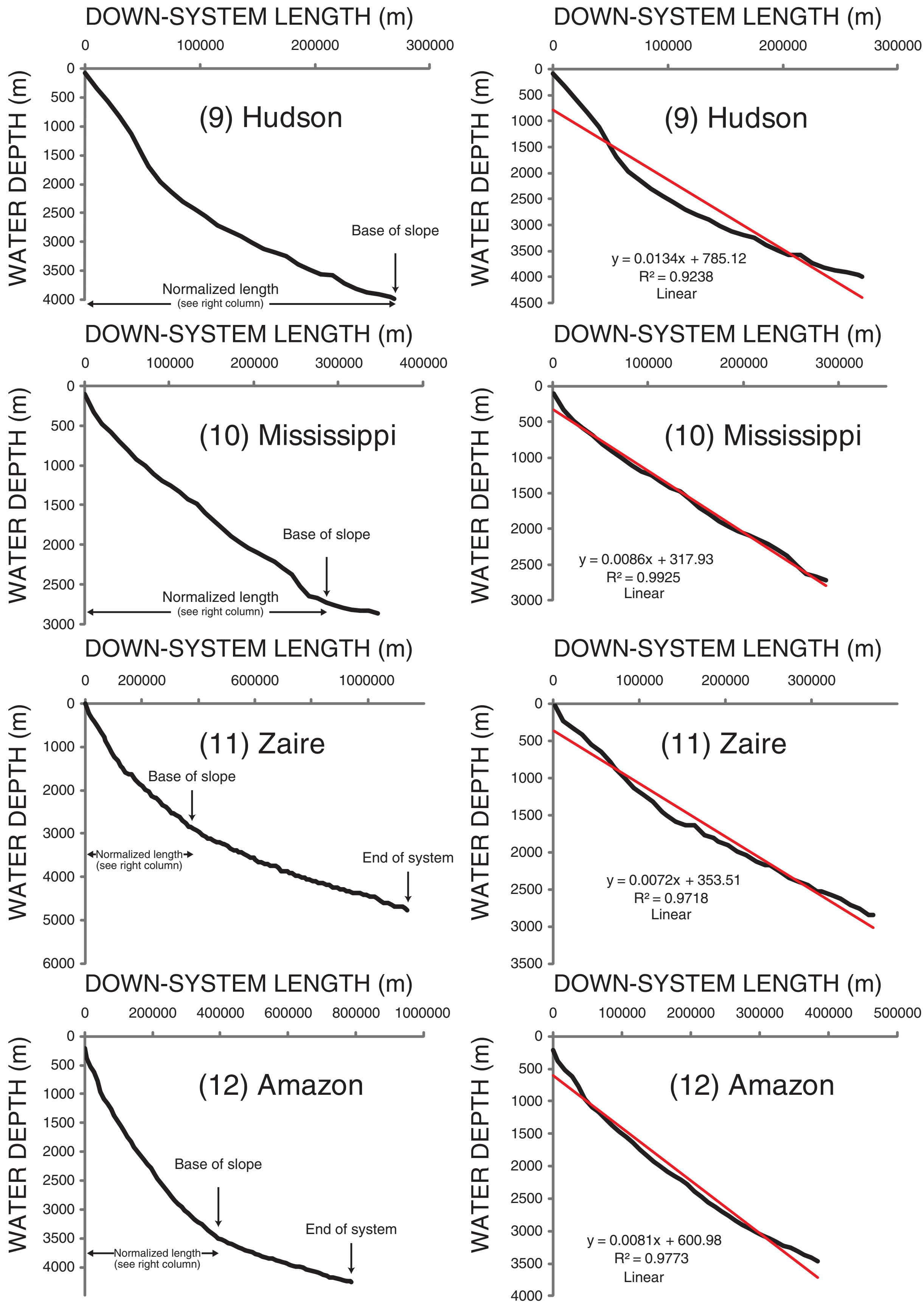

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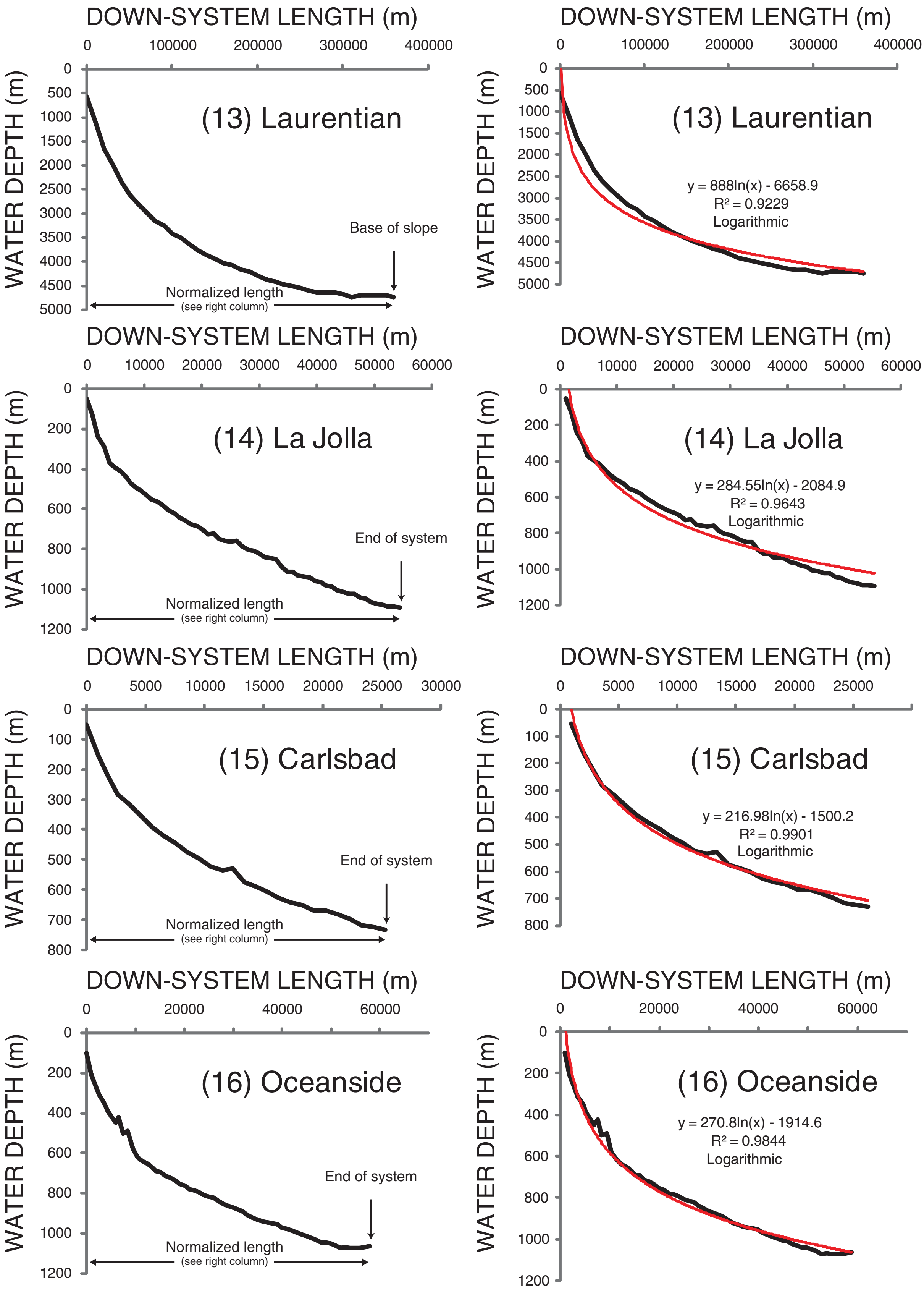

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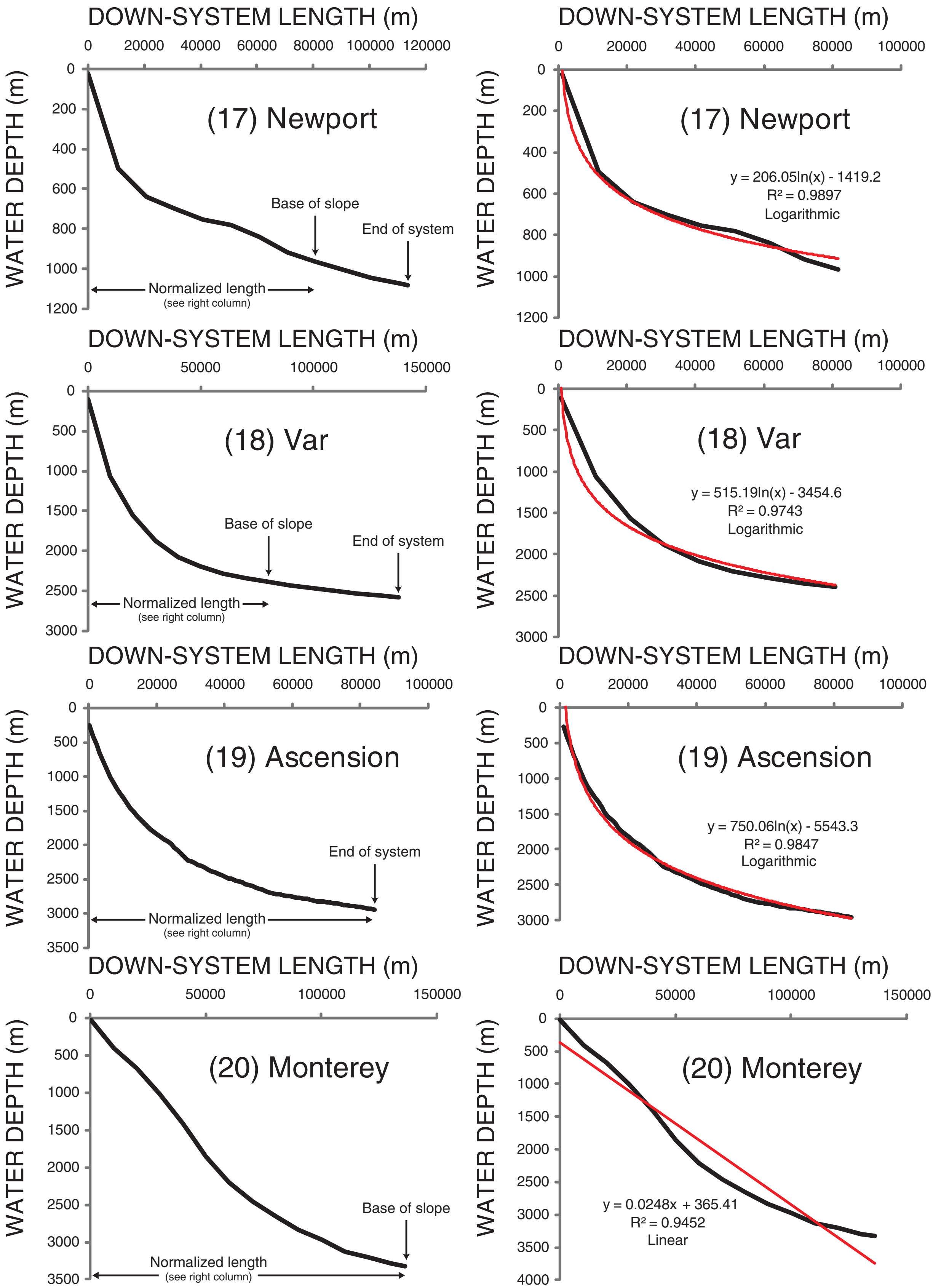

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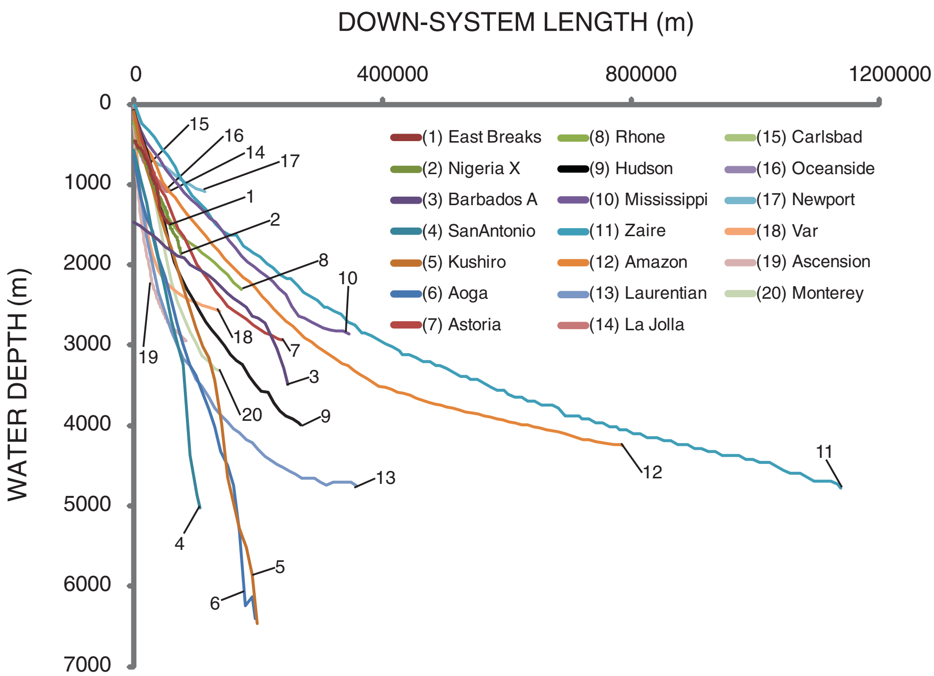

Figure 3. Canyon-and-channel longitudinal profiles.

Very Concave Profiles

Seven canyon-and-channel systems have very concave profiles (Laurentian [13], La Jolla [14], Carlsbad [15], Oceanside [16], Newport [17], Var [18], and Ascension [19]), which are relatively steep in their proximal reaches but are flat in their distal reaches (Fig. 8). All seven profiles are best fit to logarithmic functions (Fig. 2). Six of these systems are rich in sand and developed across the California and French Mediterranean margins. These margins are characterized by relatively steep slopes outboard of narrow shelves and nearby hinterlands from which relatively coarse-grained sediment is shed (La Jolla [14], Carlsbad [15], Oceanside [16], Newport [17], Var [18], and Ascension [19]) (Table 1 and Fig. 8). Five of these systems, La Jolla (14), Carlsbad (15), Oceanside (16), Newport (17), and Var (18), have canyons that transition to channels with modest levee and overbank relief and terminate as depositional lobes. The Ascension (19) system offshore central California also exhibits a well-developed canyon-and-channel system that does not terminate as depositional lobes; rather, it is a significant tributary to the Monterey (20) system (Normark et al., 1985c; Nagel et al., 1986; Greene et al., 2002; Fildani and Normark, 2004). The six aforementioned systems were subjected to synsedimentary tectonic deformation; however, the Laurentian (13) system developed across the Atlantic passive margin and, similar to the Astoria (7) system discussed above, was fed relatively large volumes of coarse-grained sediment during subglacial transitions (Skene and Piper, 2006; Piper et al., 2007; Piper and Normark, 2009) (Table 1). The Laurentian (13) conduit is remarkable for its straightness, 25-km width, residual buttes, flat erosional floor, and spillover channels (Piper and Normark, 2009).

Development of Longitudinal Profiles and Their Relationships to Continental Margin Types and Depositional Styles

Because we examined canyon-and-channel systems on the modern seafloor, they reflect processes and forcings that operated since the last glacial cycle (e.g., <100 ka; Lambeck and Chappell, 2001). However, effects of the more distant past—for example, millions of years of sedimentary-basin filling or uplift of an accretionary wedge—also had a profound influence on some of these recently developed sediment-delivery systems by establishing the seafloor template and morphology across which canyons and channels developed. The groups of normalized canyon-and-channel longitudinal profiles of this study generally reflect varying degrees of seafloor uplift and deformation, construction of depositional relief, and degradation of the seafloor by erosion associated with sediment gravity flows and other mass movements (Fig. 9). These influences are explained below in the context of their relative contributions to longitudinal-profile shapes in the convex, slightly concave, and very concave profile groups. There are only three canyon-and-channel systems whose longitudinal-profile shapes do not correspond well with continental-margin types or depositional architectures characteristic of other systems in their common profile group. These are the Astoria (7), Laurentian (13), and Monterey (20) systems, which are discussed below in the Exceptional Canyon-and-Channel Systems section.

Convex profiles appear to have developed as a result of the dominance of seafloor uplift and deformation (e.g., East Breaks [1], Nigeria X [2]; Barbados A [3], San Antonio [4], Kushiro [5], and Aoga [6]) (Fig. 9). Such profiles developed in passive margins affected by gravity-driven tectonics and tectonically active convergent margins. Even though the signature of seafloor uplift and deformation is apparent in the convex shape of these profiles, other factors, such as erosion by sediment gravity flows, could have impacted seafloor morphology. Contraction above detachment surfaces in both types of belts can result in a broad zone of uplift and deformation, which is manifested in the evolving wedge shape of fold-and-thrust belts (Dahlen et al., 1984; Rowan et al., 2004). This evolving wedge shape maintains an approximately convex regional profile, which is also reflected by canyon-and-channel longitudinal profiles (Fig. 9). In unstable progradational, or supply-dominated (Carvajal et al., 2009), passive-margin slope settings, gravitational instabilities can facilitate gravity-driven diapirism, growth faulting, and fold-and-thrust–related uplift and deformation (e.g., the western Gulf of Mexico for East Breaks [1] and offshore west Africa for Nigeria X [2]; Hedberg, 1970; Winker and Edwards, 1983; Rowan et al., 2004). In convergent margins, tectonic processes including basin-localized subsidence, fault-supported inner and outer margin uplift (e.g., Melnick et al., 2006; Collot et al., 2008), and construction of a frontal prism of accreted sediment (Dahlen et al., 1984; Rowan et al., 2004) can steepen the lower slope and work in concert with deep-sea canyon–and–channel-related sedimentary processes to produce the characteristic convex expression of longitudinal profiles (Ranero et al., 2006; von Huene et al., 2009). In particular, time-transgressive landward migration of the trench (e.g., Soh and Tokuyama, 2002; Noda et al., 2008), consequent margin steepening, and truncation of the submerged forearc caused by frontal subduction erosion can be fundamentally important to longitudinal profile development in convergent margins (Ranero et al., 2006; von Huene et al., 2009).

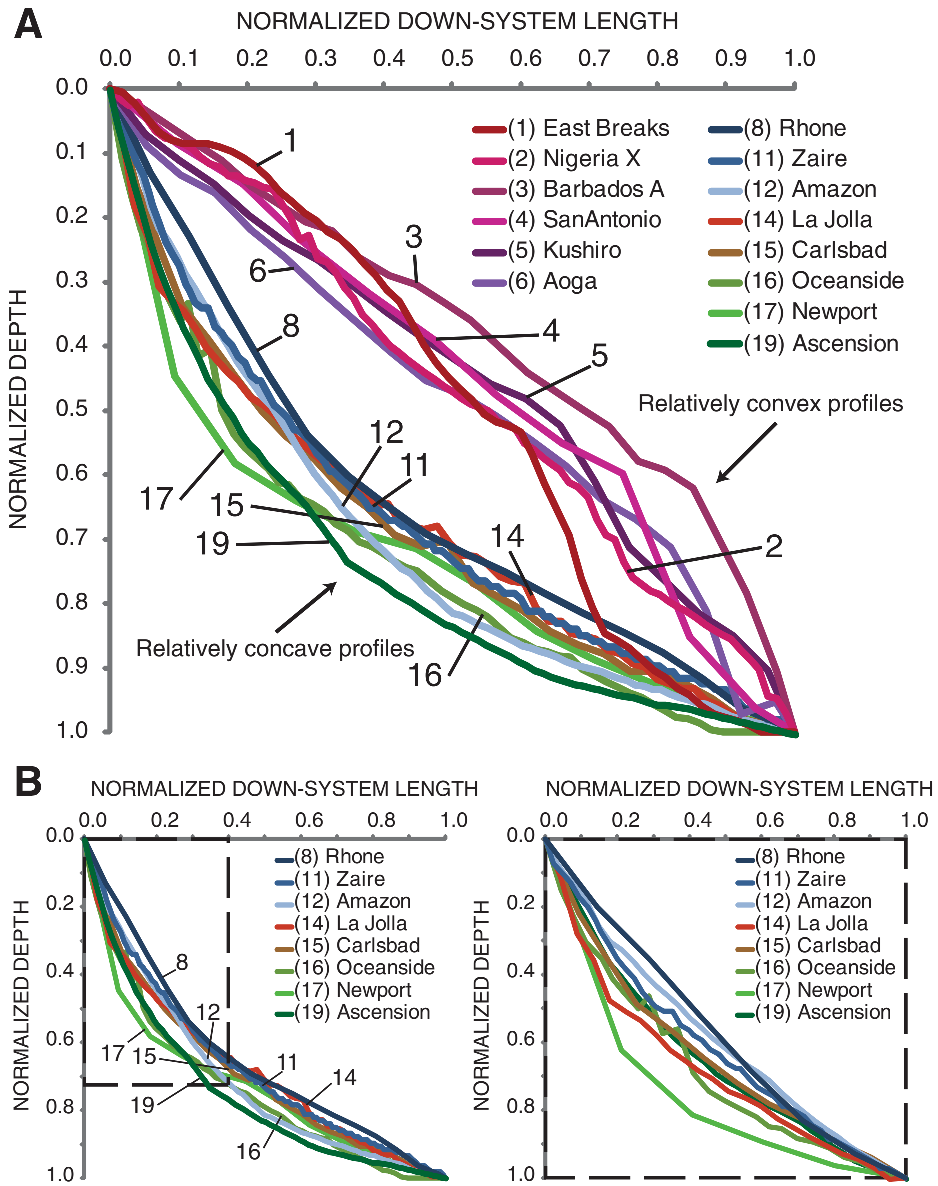

Figure 4. Canyon-and-channel longitudinal-profile normalization on the basis of profile length from canyon head to the end of the confined portion of the system (e.g., at the channel-to-lobe transition zone). (A) Only 14 profiles include the entire confined segments of their canyon-and-channel systems. (B) Closer inspection of relatively concave profiles shows that some profiles are distinctively more convex in their proximal reaches (dashed black box; <0.4 of their total down-system length) relative to other profiles.

Slightly concave profiles are commonly associated with mature passive continental margins not subjected to appreciable tectonic uplift, but gradual subsidence as a result of thermal cooling of the lithosphere (e.g., Rhone [8], Hudson [9], Mississippi [10], Zaire [11], and Amazon [12]) (Fig. 9). However, they can have pronounced relief as a result of preexisting depositional architecture. This preexisting depositional architecture is characteristic of constructional, progradational, or supply-dominated margins, which have thick sedimentary prisms composed of well-developed clinothem and fan sequences (Hedberg, 1970; Ross et al., 1994; Carvajal et al., 2009; Gerber et al., 2009; Ryan et al., 2009a). Such preexisting depositional architecture establishes a relatively convex seafloor template across which canyons and channels extend. This seafloor template facilitates the development of a distinctively less concave proximal reach of mature passive-margin longitudinal profiles relative to profiles from the immature, underfilled margin offshore southern California characterized by steeper slopes and narrower shelves (Fig. 4B). Thus, progradation of these sediment supply–dominated passive margins associated with slope clinothem and fan accretion favors the development of a relatively convex seafloor across which channels subsequently incise and create a slightly concave profile shape (cf. Carvajal et al., 2009; Gerber et al., 2009; Ryan et al., 2009a).

Very concave profiles predominantly developed on immature, or erosional (Ryan et al., 2009a), continental margins, some of which are dominated by strike-slip deformation (e.g., La Jolla [14], Carlsbad [15], Oceanside [16], Newport [17], Var [18], and Ascension [19]) (Fig. 9). In such settings, deformation contributes to steep slopes outboard of narrow shelves (cf. erosional margins of Ryan et al., 2009a). The narrow shelves offshore California and the French Riviera and nearby hinterlands suggest that relatively coarse-grained sediment is continuously fed to canyon-and-channel systems during both high and low stands of sea level (Savoye et al., 1993; Covault et al., 2007). Gerber et al. (2009) demonstrated the influence of erosion by sediment gravity flows across steep slopes of the Catalan margin in the Mediterranean Sea on the development longitudinal-profile concavity. Because the degree of degradation is related to the cumulative shear stress imposed by a number of sediment gravity flows on the seafloor (Middleton and Southard, 1984; Leeder, 1999; Boggs, 2001), relatively coarse grain sizes, more continuous erosion by sediment gravity flows, and steep slopes inherent to these immature margins promoted more significant seafloor degradation than in other settings (cf. Gerber et al., 2009).

Exceptional Canyon-and-Channel Systems

There are a couple of exceptional canyon-and-channel systems documented in this study that exhibit more concave profiles than one might predict on the basis of their continental-margin setting: the Astoria (7) and Laurentian (13) systems (Figs. 7, 8, and 10). Both are relatively high-latitude systems and, as a result, were particularly sensitive to climatic variability associated with the latest Pleistocene-to-Holocene glacial-to-interglacial transition (Table 1 and Fig. 10). The slightly concave, rather than the expected convex, profile of the Astoria (7) system might have resulted from the margin receiving pulses of coarse-grained sediment and water from periodic catastrophic floods of the Columbia River since the Last Glacial Maximum (Nelson et al., 1970; Piper and Normark, 2009).

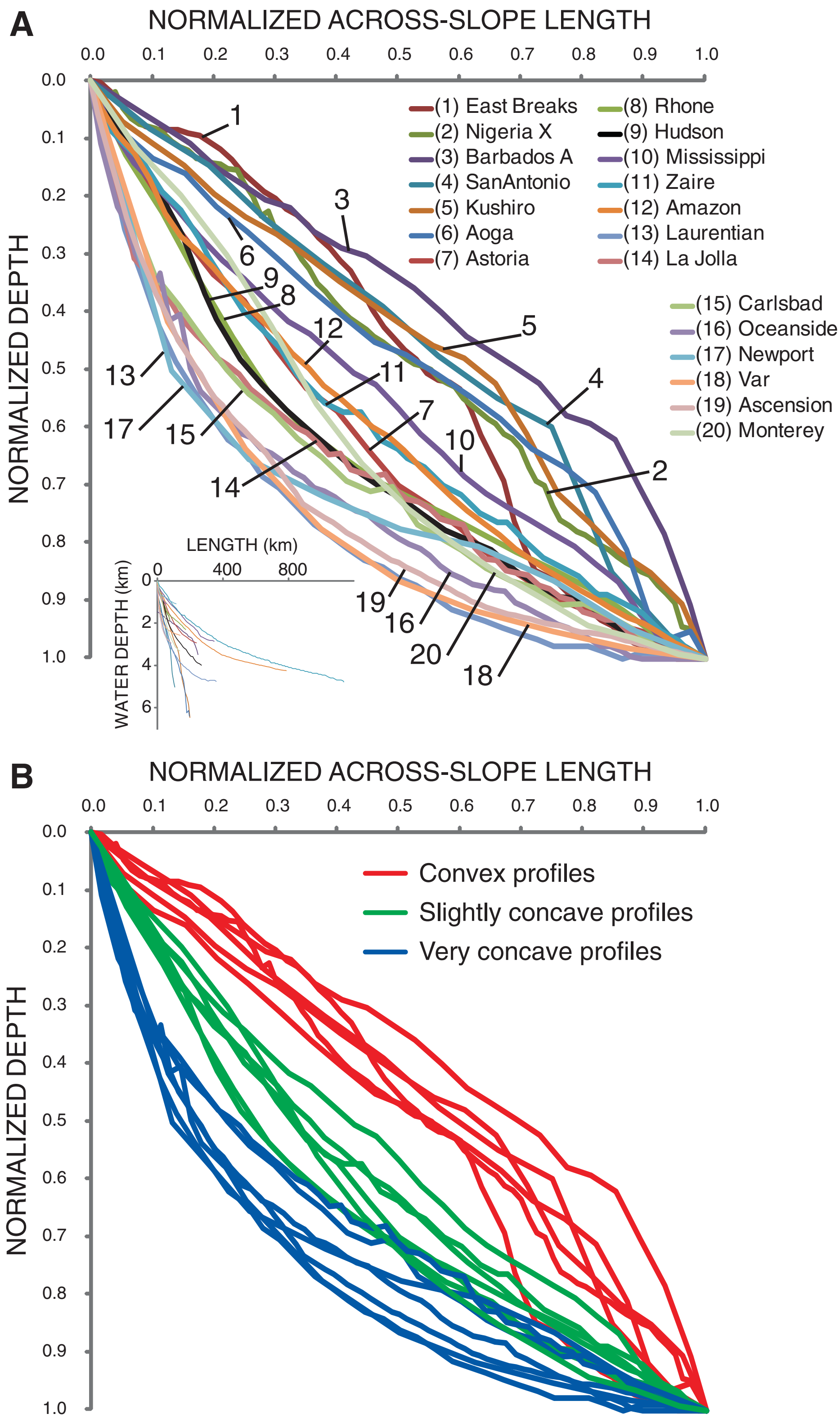

Figure 5. (A) All canyon-and-channel longitudinal profiles normalized across their continental slopes. Bases of slopes were not measured at arbitrary or unit lengths; they were defined at the points where profiles reached gradients <0.25° and curvatures between -10^{-7} and 10^{-7}. Inset: Full-length profiles from Figure 3. (B) Profile groups based on relative convexity or concavity from visual inspection.

A similar situation exists for the Laurentian (13) system, which exhibits a very concave profile, even though it developed across the Atlantic passive margin (Table 1; Figs. 8 and 10B). For both high-latitude systems, numerous sandy and coarser-grained, thick mass movements initiated during glacial-to-interglacial transitions, which promoted seafloor erosion and the development of relatively concave longitudinal profiles (Skene and Piper, 2006; Piper et al., 2007; Piper and Normark, 2009).

The Monterey (20) system is unique relative to other slightly concave profiles in that it is sand rich and developed across the California transform margin (Table 1 and Fig. 7). However, the Monterey (20) system feeds a large deep-sea fan (Fildani and Normark, 2004). Voluminous preexisting fan deposits likely fostered a relatively convex proximal segment of the Monterey (20) profile, and turbidite deposition was recently focused in the proximal reaches of the canyon (Paull et al., 2005) (Figs. 2 and 7). The distal reaches of the profile are more steeply concave, which is common in strike-slip settings. Gerber et al. (2009) related such a convex-to-concave longitudinal-profile shape across the Ebro margin in the Mediterranean Sea to sediment–gravity-flow deposition in a prograding canyon. Similarly, the Monterey (20) profile shows that the seafloor might be raised as a result of very recent localized deposition (i.e., during the Holocene, <10 ka; Lambeck and Chappell, 2001; Paull et al., 2005; Fildani et al., 2006). These observations suggest that canyons and channels are not merely conduits for sediment transport, but can be sites of deposition that might be detectable from profile analysis.

Tectonic circumstances have also been interpreted to govern Monterey (20) profile morphology (Greene et al., 2002). Monterey Bay of the central California continental margin includes two contrasting physiographic and tectonic provinces separated by the Palo Colorado–San Gregorio fault zone: (1) the eastern Salinian Block comprises metamorphic and granitic plutonic rocks; and (2) the western San Simeon Block comprises Franciscan volcanic, metamorphic, and sedimentary rocks (Mullins and Nagel, 1981; Greene et al., 2002). The Palo Colorado–San Gregorio fault zone crosses the axis of Monterey (20) Canyon at ~2000-m water depth, which approximately coincides with the inflection point between relatively convex and concave segments of the canyon-and-channel system (Paull et al., 2005) (Fig. 2). Greene et al. (2002) noted different Monterey (20) Canyon morphologies across the fault zone: the eastern Salinian Block displays steeper, V-shaped canyon cross-sectional morphology; the western San Simeon Block displays broader, U-shaped

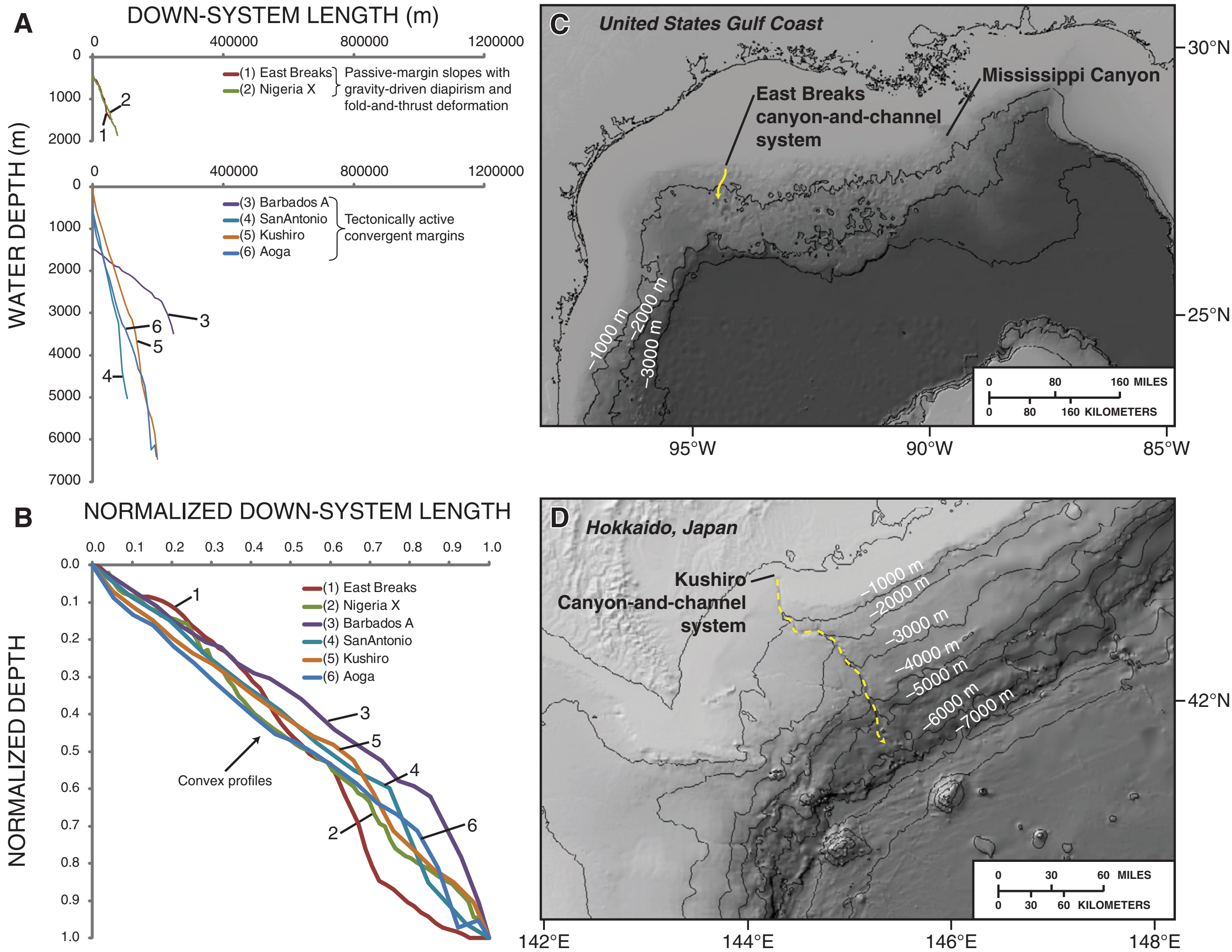

Figure 6. Convex longitudinal profiles. (A) Profiles before normalization. (B) Profiles normalized across their continental slopes. (C) Example bathymetry from the Gulf of Mexico passive margin dominated by diapirism and gravity-driven, fold-and-thrust-related tectonic deformation. Contour interval is –1000 m. East Breaks (1) system is yellow (Pirmez et al., 2000). Bathymetry from GeoMapApp, http://www.geomapapp.org (Ryan et al., 2009b). (D) Example bathymetry from the Tokachi-oki forearc basin and accretionary wedge offshore Hokkaido, Japan. Contour interval is –1000 m. Kushiro (5) system is yellow (Noda et al., 2008). Bathymetry from GeoMapApp, http://www.geomapapp.org (Ryan et al., 2009b).

morphology. Paull et al. (2005) also noted that bends in the upper Monterey (20) Canyon are oriented parallel to regional structures, presumably as a result of differential erosion along fault-generated weaknesses (Greene, 1990).

Methods of Grouping Longitudinal Profiles

We employed two methods in order to group longitudinal profiles: (1) visual inspection and categorization on the basis of relative convexity or concavity; and (2) more objective categorization on the basis of best-fitting mathematical functions (cf. Shepherd, 1985; Adams and Schlager, 2000). Profiles that were grouped based on visual inspection generally correspond with continental-margin type and depositional architecture, with a few exceptions. More objective curve-fitting methods do an adequate job of differentiating the most convex and concave profiles; however, there is more ambiguity associated with differentiating between less convex and slightly concave profiles (Fig. 2). For example, visual inspection of the Nigeria X (2), San Antonio (4), Kushiro (5), and Aoga (6) profiles indicates that they are convex (Fig. 5); however, they are objectively best fit to linear functions and, therefore, are linear profiles along with the Rhone (8), Hudson (9), Mississippi (10), Zaire (11), and Amazon (12) profiles (Fig. 2). The Nigeria X (2), San Antonio (4), Kushiro (5), and Aoga (6) systems developed in the Niger Delta passive margin affected by gravity-driven tectonics and tectonically active convergent margins, and contributed to distinctively different depositional architectures relative to the Rhone (8), Hudson (9), Mississippi (10), Zaire (11), and Amazon (12) systems.

More objective numerical methods, however, have been shown to adequately differentiate submarine geomorphic features. Adams and Schlager (2000) grouped 19 passive continental-

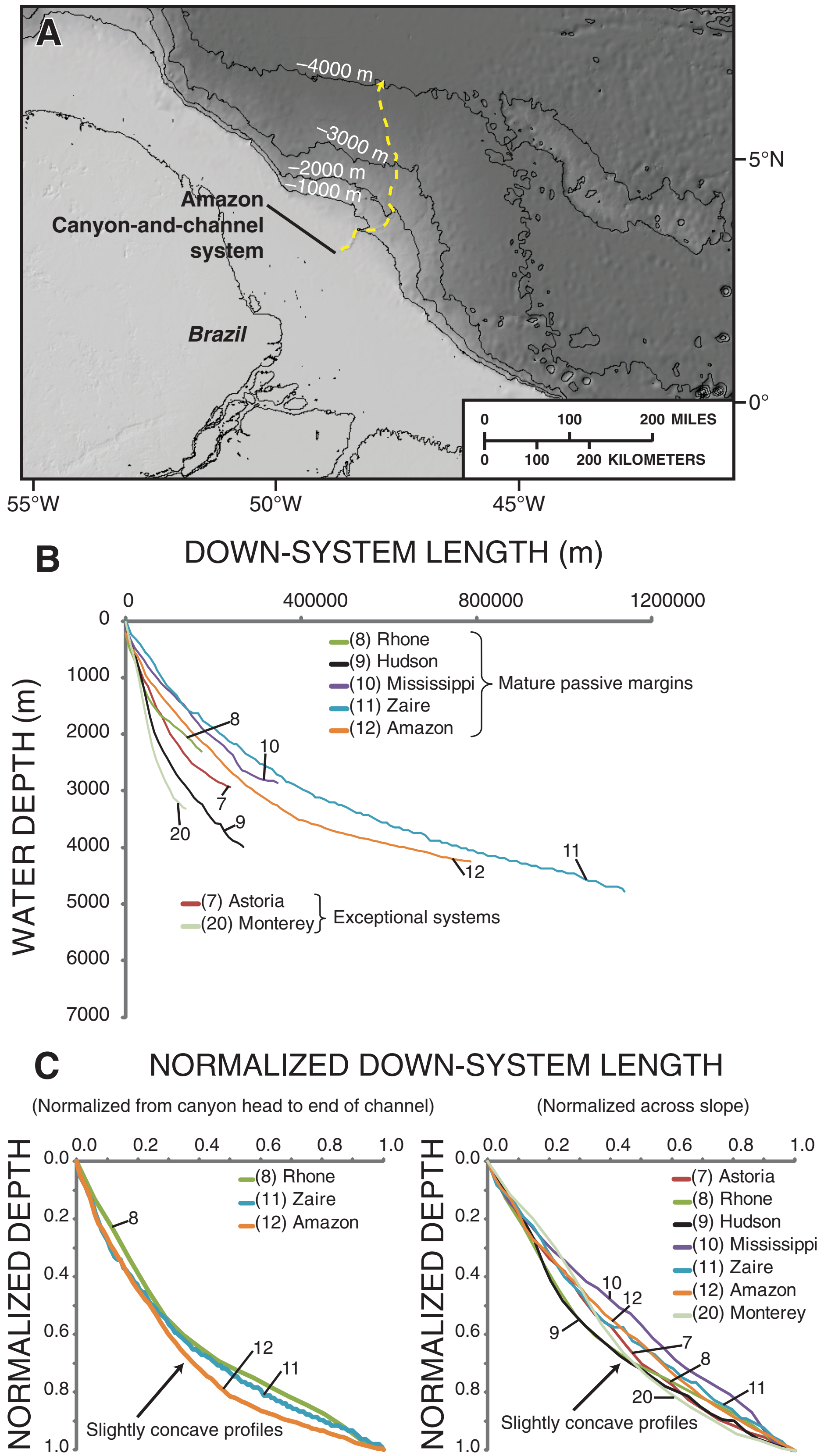

Figure 7. Slightly concave longitudinal profiles. (A) Example bathymetry from the Amazon deep-sea fan (GeoMapApp, http://www.geomapapp.org; Ryan et al., 2009b). Contour interval is –1000 m. Amazon (12) system is yellow (Pirmez and Imran, 2003). (B) Profiles before normalization. (C) Left: Profiles normalized from canyon heads to ends of channels. Right: Profiles normalized across their continental slopes.

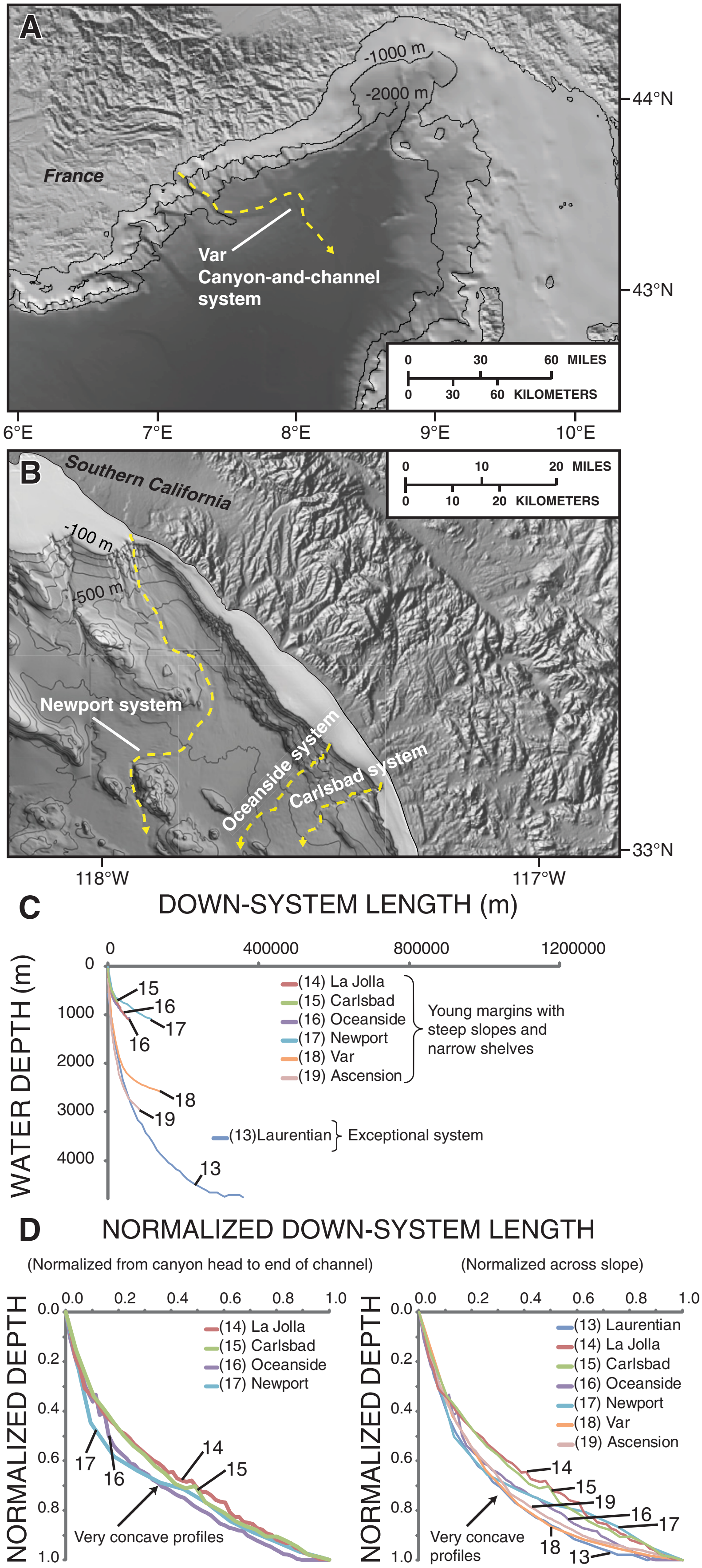

Figure 8. Very concave longitudinal profiles. (A) Example bathymetry from the Mediterranean Sea (GeoMapApp, http://www.geomapapp.org; Ryan et al., 2009b). Contour interval is –1000 m. Var (18) system is yellow (Savoye et al., 1993). Notice proximity to Alpine sediment source area, narrow shelf, and steep slope. (B) Example bathymetry from offshore southern California (Gardner and Dartnell, 2002; Divins and Metzger, 2009). Contour interval is –100 m. Carlsbad (15), Oceanside (16), and Newport (17) systems are yellow (Graham and Bachman, 1983; Covault et al., 2007; Covault et al., 2010). (C) Profiles before normalization. (D) Left: Profiles normalized from canyon heads to ends of channels. Right: Profiles normalized across their continental slopes.

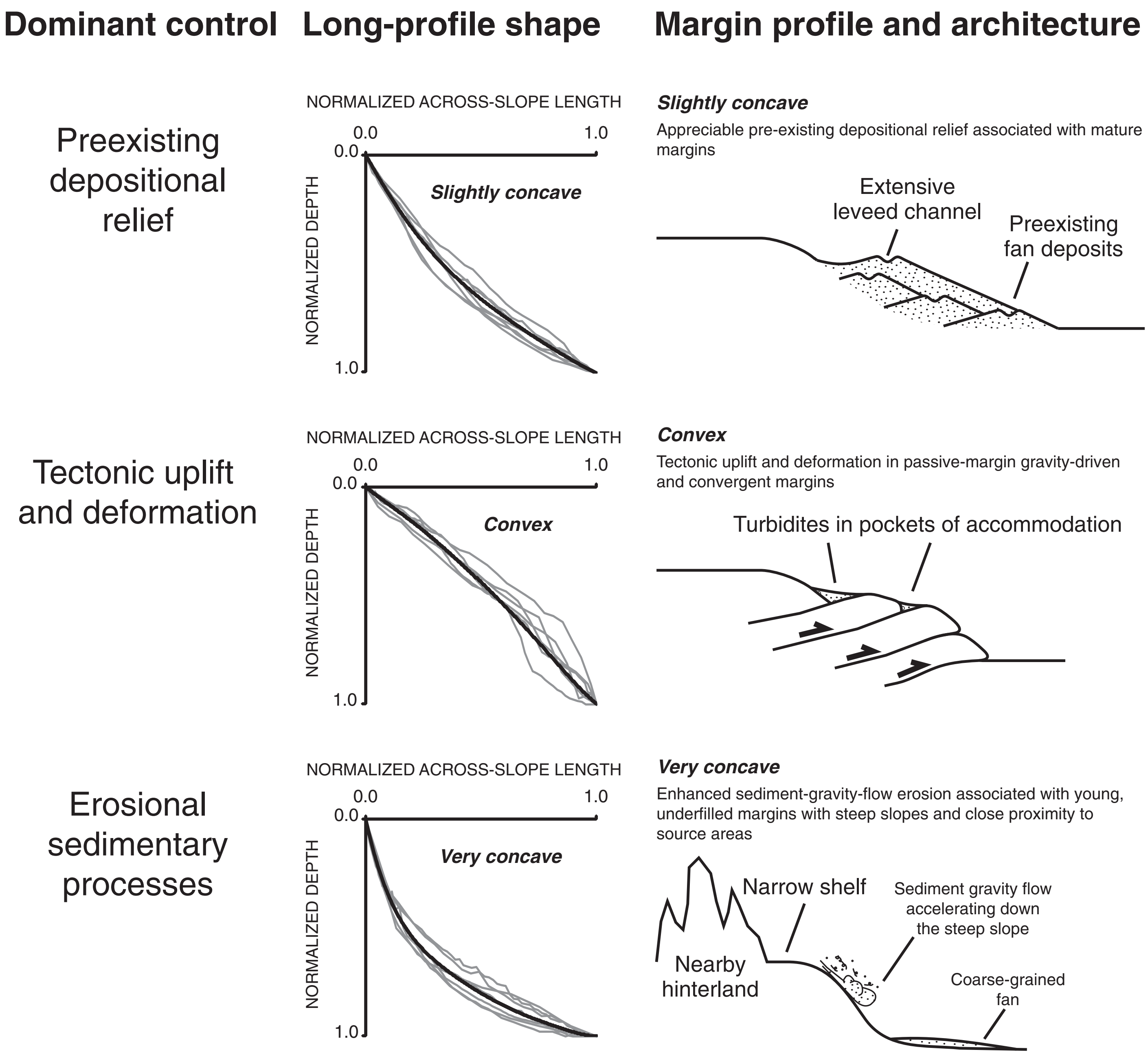

Figure 9. Summary chart of controls on longitudinal-profile shape: preexisting depositional relief, tectonic uplift and deformation, and erosional sedimentary processes. Although profiles reflect varying degrees of controlling factors, and exceptional profiles exist, profile groups are located adjacent to dominant controls and general continental-margin types with characteristic depositional architectures. Average profiles for each group are represented by bold black lines.

margin profiles on the basis of three functions: linear, exponential, and Gaussian distribution. Linear functions describe unstable margins that are interpreted by Adams and Schlager (2000) to rest at the angle of repose. Exponential functions represent the exponential decay of sediment transport capacity or competence with increasing distance across a margin (Adams and Schlager, 2000). The majority of margins follow a Gaussian curve as a result of perturbing extrinsic processes at the shelf edge (e.g., wave-reworking processes and shelf-edge instabilities; Adams and Schlager, 2000). Quantitative characteristics of margins are effective at predicting depositional architecture and sediment caliber (Adams and Schlager, 2000). Why were objective curve-fitting methods of entire-margin profiles more effective at creating meaningful and predictive groups relative to similar methods applied to canyon-and-channel longitudinal profiles of this study? Adams and Schlager (2000) only examined passive continental margins in order to avoid tectonic influences on primary depositional setting (Pratson and Haxby, 1996). If we were to exclude canyons and channels of tectonically active continental margins from our analysis, profiles would be

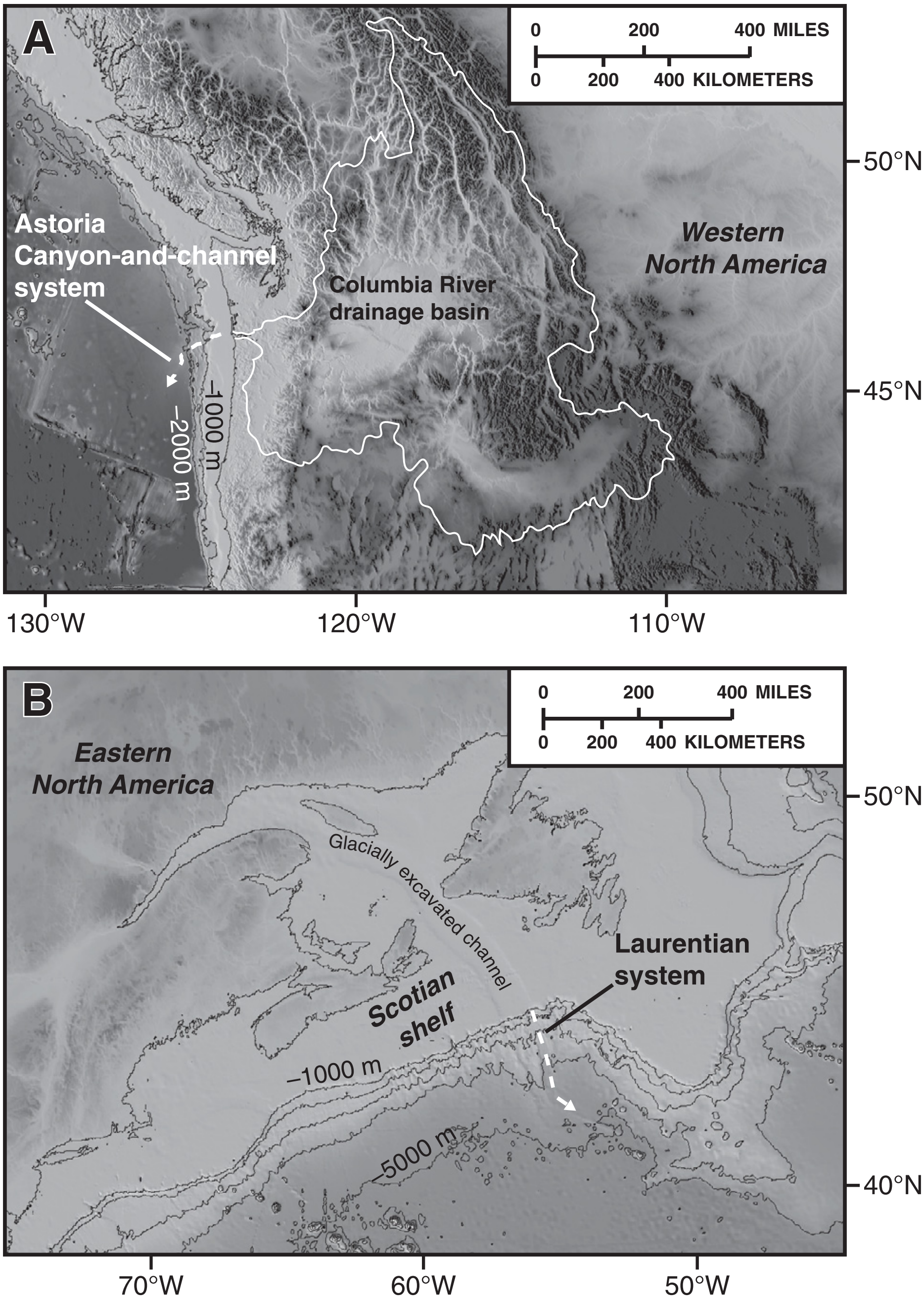

Figure 10. High-latitude continental margins conducive to the development of exceptionally concave canyon-and-channel longitudinal profiles. (A) Western North America topography and offshore Cascadia margin bathymetry from GeoMapApp, http://www.geomapapp.org (Ryan et al., 2009b). Contour interval is –1000 m. Columbia River drainage basin is outlined in white. Astoria (7) system is a dashed white line offshore (Nelson et al, 1970). (B) Scotian margin bathymetry offshore eastern North America from GeoMapApp, http://www.geomapapp.org (Ryan et al., 2009b). Contour interval is –1000 m. Notice the prominent glacially excavated channel leading to the Laurentian (13) system (dashed white line; Skene and Piper, 2006).

neatly differentiated into two groups: (1) linear profiles across mature margins with large depositional fans (e.g., Rhone [8], Hudson [9], Mississippi [10], Zaire [11], and Amazon [12]); and (2) logarithmic profiles across settings dominated by erosional sedimentary processes (e.g., Laurentian [13] and Var [18]).

Visual inspection of longitudinal profiles, therefore, is relatively useful in differentiating profiles into groups with some predictive capability of continental-margin type and depositional architecture; however, exceptional longitudinal profiles dominated by erosional sedimentary processes (e.g., Astoria [7] and Laurentian [13]) show the shortcomings of simple visual inspection, and highlight the need for more rigorous and objective numerical methods for differentiating profiles. Gerber et al. (2009) developed a morphodynamic model that predicts submarine canyon-and-channel longitudinal profiles affected by continental-margin progradation and the downslope evolution of turbidity currents. Such a model is an important step toward assessing the relative contributions of forcings to longitudinal-profile character, including preexisting depositional relief, margin evolution, and erosional sedimentary processes. Subsequent modeling efforts should focus on balancing those effects with tectonic uplift and deformation (cf. Fig. 9). Such models can be used in order to more precisely and meaningfully differentiate profiles and test some of the interpretations of this study, which were developed from more empirical observations and quantification of profiles.

CONCLUSIONS

Canyon-and-channel systems on the modern seafloor, and their characteristic longitudinal profiles, reflect processes and forcings that operated approximately since the last glacial cycle, for example, sediment–gravity-flow erosion (Fig. 9). However, effects of the more distant past can also have a profound influence on more recent sediment-delivery systems by establishing the seafloor template across which canyons and channels develop (Fig. 9). Longitudinal profile groups generally correspond with continental-margin types and depositional architectures, with a few exceptions. Furthermore, our assessment of methods of grouping profiles indicates that empirical observations of profiles are an effective means of constructing groups that have some predictive capability of continental-margin type and depositional architecture. However, exceptional longitudinal profiles dominated by erosional sedimentary processes highlight the need for more rigorous and objective numerical methods for differentiating profiles and assessing controls on their development. Results of this study provide a new catalog of the breadth and general controls of the shapes of submarine sediment-delivery systems, which can be related to the depositional architecture of different continental margins.

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