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Validation of empirical source-to-sink scaling relationships in a continental-scale system: The Gulf of Mexico basin Cenozoic record

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ABSTRACT

Empirical scaling relationships between known deepwater siliciclastic submarine fan systems and their linked drainage basins have previously been established for modern to submodern depositional systems and in a few ancient, small-scale basins. Comprehensive mapping in the subsurface Gulf of Mexico basin and geological mapping of the North American drainage network facilitates a more rigorous test of scaling relationships in a continental-size system with multiple mountain source terranes, rivers, deltas, slopes, and abyssal plain fan systems formed over 65 m.y. of geologic time. An immense database of drilled wells and high-quality industry seismic data in this prolific hydrocarbon basin provide the independent measure of deepwater fan distribution and dimensions necessary to test source-to-sink system scaling relationships.

Analysis of over 40 documented deepwater fan and apron systems in the Gulf of Mexico, ranging in age from Paleocene to Pleistocene, reveals that submarine-fan system scales vary predictably with catchment length and area. All fan system run-out lengths, as measured from shelf margin to mapped fan termination, fall in a range of 10%–50% of the drainage basin length, and most are comparable in scale to large (Mississippi River–scale) systems although some smaller fans are present (e.g., Oligocene Rio Bravo system). For larger systems such as those of the Paleocene Wilcox depositional episodes, fan run-out lengths generally fall in the range of 10%–25% of the longest river length. Submarine fan widths, mapped from both seismic reflection data and well control, appear to scale with fan run-out lengths, though with a lower correlation ($R^2 = 0.40$) probably due to uncertainty in mapping fan width in some subsalt settings. Catchment area has a high correlation ($R^2 = 0.85$) with river length, suggesting that fluvial discharge and sediment flux may be primary drivers of ancient fan size.

Validation of these first-order source-to-sink scaling relationships provides a predictive tool in frontier basins with less data. Application to less-constrained early Eocene fan systems of the southern Gulf of Mexico demonstrates the utility for exploration as well as paleogeographic reconstructions of ancient drainage systems. This approach has considerable utility in estimating dimensions of known but poorly constrained submarine fans in the subsurface or exposed in outcrop.

INTRODUCTION

Source-to-sink analysis is a broad and rapidly evolving scientific approach to paleogeographic reconstructions, but one that also has practical applications relevant to the global search for hydrocarbon resources (Sømme et al., 2009a; Walsh et al., 2016; Helland-Hansen et al., 2016). Quantification of the scales of modern and Pleistocene systems suggests linkages within and between segments of sediment-dispersal systems that terrigenous clastics follow from highland source terranes toward the basinal sinks. This makes it possible to predict the unknown geomorphological dimensions of one segment from empirical measurements of another (Sømme et al., 2009a; Bhattacharya et al., 2016). For example, deepwater depositional systems can be linked in many cases to the rivers that carry the sediment, and thus should scale with fluvial system properties (Blum and Hattier-Womack, 2009).

The possibility of linking drainage basin (catchment) characteristics with basinal deposits is intriguing for its potential utility in prediction for interpretation of Earth history, and as a predictive tool for subsurface exploration, particularly in areas where seismic reflection resolution is of poor quality, including areas of poor illumination due to thick salt canopy cover (e.g., Meyer et al., 2007). A first application of the source-to-sink approach for an ancient, deepwater subsurface system was in the hydrocarbon-bearing Maastrichtian–Danian Ormen Lange deepwater system of offshore Norway (Sømme et al., 2009b). This test of a small depositional system suggested great promise for first-order prediction of reservoir dimensions such as submarine fan length and width.

Deepwater deposits at the termini of continental fluvial systems represent valuable sedimentary archives of climate and tectonic histories along the source-to-sink continuum (Covault et al., 2010, 2011; Barnes et al., 2013; Romans et al., 2016). Identifying the dimensions and therefore the spatial distribution of submarine fans in successions in the subsurface or even in poorly mapped outcrops allows that record to be accessed and illuminated. First-order morphological parameters estimated from the scaling relationships for large source-to-sink systems like the Gulf of Mexico might further be used to extend paleogeographic reconstructions to updip areas where the sedimentary record is absent due to erosional truncation. In Namibia, for example, uplift and erosion removed large portions of the onshore record of Early Cretaceous river systems and drainage basins (Green et al., 2009), challenging efforts at sediment mass-balance estimation (Rouby et al., 2009). The approach taken here might be used to fill in the fragmentary older landscape archive in many areas, as Blum and Pecha (2014) and Snedden et al. (2016) have attempted for Cretaceous strata of the northern Gulf of Mexico.

In this paper, we apply the tenets of source-to-sink analysis and geomorphological scaling relationships, as formulated by Sømme et al. (2009a, 2009b), to a continental-scale setting, the Gulf of Mexico basin and its linked hinterland drainage network within the interior of North America. The ancient depositional sink is particularly well constrained by abundant well and seismic control (Fig. 1). Catchment reconstructions are based on those of Galloway et al. (2011) and have been since refined (Xu et al., 2016; this study). This paleogeographic mapping has been fine-tuned by recent detrital-zircon analyses (e.g., Mackey et al., 2012; Blum and Pecha, 2014; Craddock and Kylander-Clark, 2013; Wahl et al., 2016; Xu et al., 2016; Sharman et al., 2017; Blum et al., 2017). Our goals are to test and validate the source-to-sink approach in a large, well-documented system where the answers can be determined independently, so as to facilitate global application to ancient deepwater depositional systems in less well-constrained basins, and expand the use of this important approach to the deep-time sedimentary archive.

GEOLOGIC SETTING

The Gulf of Mexico basin is a small ocean basin created initially during Triassic to Jurassic rifting between the Yucatan (Mayan) microplate and North America, followed by seafloor spreading that continued into the Early Cretaceous (Salvador, 1991; Imbert and Phillippe, 2005; Hudec et al., 2013; Snedden et al., 2013, 2014). Mesozoic deposition progressed from non-marine evaporites (Louann Salt), to eolian sandstones and shallow-water carbonates, to deep-marine shales, sandstones, and carbonates before the end of the Cretaceous (Galloway, 2008). By the end of the Mesozoic, the center of the Gulf of Mexico was a deep marine basin with a prominent shelf and slope that surrounded an abyssal plain (Winker, 1982; Galloway et al., 2000; Galloway, 2008).

The Gulf of Mexico basin was also the ultimate depositional sink for large rivers that drained much of the North American continent (Galloway et al., 2011; Fig. 2). From outcrop and subsurface data, at least eight fluvio-deltaic axes can be identified as delivering sediment to the basin over the past 65 m.y. Contributing catchments for these axes evolved over four tectonostratigraphic phases from the Paleocene to the Neogene (Galloway et al., 2011; Figs. 3 and 4; Table 1), as described below.

The later stages of the Paleocene Laramide deformational event clearly drove contraction of the Cretaceous interior seaway, and as a result, a number of existing rivers extended their reach south to the Gulf of Mexico (Bhattacharya et al., 2016; Fig. 3D). Drainage reorganization was also accompanied by growth of the Laramide deformation front which increased precipitation (Sewall and Sloan, 2006; Bush et al., 2016). These longer rivers, larger catchments, and greater discharge generated the sediment load that ultimately formed the large abyssal plain fans of the Paleogene Lower and Middle Wilcox Group (Zarra, 2007). This occurred in spite of the globally high sea-level state (Miller et al., 2005; Fig. 2). In fact, the limited amplitude of high-frequency sea-level changes during this time probably reduced shelf storage and facilitated semi-continuous sediment flux from shelf-edge delta entry points onto the slope and basin (Sweet and Blum, 2011, 2016).

Retrogradation and reduction of the early Eocene Upper Wilcox fans coincides with a trend toward more arid conditions in the Western Interior (Galloway et al., 2011; Cather et al., 2008; Fan et al., 2015; Fig. 3C). It is also possible as well that exposure of deeper, more erosion-resistant crystalline rocks in the cores of Laramide-age uplifts may have reduced sediment supply to some degree. Increased accommodation associated with the growth-fault and rafted basins of the Upper Wilcox Group in south Texas may also have exacerbated the reduction of sediment supply to the submarine fans (Fiduk et al., 2004).

A volumetrically minor pulse associated with locally sourced late Eocene progradation of the Yegua Formation of Texas did interrupt this sediment supply trend (Fig. 2) but produced no known fans and only small delta-fed aprons (Galloway, 2008). The ensuing Oligocene sediment flux was substantial, particularly from newly developed Sierra Madre drainages that fed the Rio Bravo system, but only submarine aprons developed as documented by extensive basin well control (Fig. 3B; Galloway et al., 2011). Reduced erosion associated with a more arid Oligocene climate in the Western Interior (Fan et al., 2015), and small catchments connected to local uplifts (Galloway et al., 2011), may explain the paucity of submarine fans at this time.

A return to slope and deepwater deposition began in the early Miocene (Fig. 3A) during the Basin and Range structural phase, possibly associated with deep geodynamic processes (Liu, 2015). The first indications of an emerging Tennessee drainage system entering the Mississippi catchment have been revealed by new provenance work (Xu et al., 2016). However, the nascent Tennessee River was relatively small, and sediment was reworked by waves into strike-trending coastal sand bodies (Galloway, 2008).

The Middle and late Miocene paleogeographic reconstructions (Figs. 4C, 4D) highlight the expanding Tennessee River catchment. This probably reflects higher stream discharge related to the humid conditions prevailing in eastern North America (Galloway et al., 2011) as well as tectonic rejuvenation of the Appalachians (Boettcher and Milliken, 1994). Sediment supply also shows a significant increase as manifested in the eastern part of the Gulf of Mexico basin by development of large and thick abyssal plain fans, including the so-called McAVLU (for Mississippi Canyon, Atwater Valley, and Lund protraction blocks) fan that hosts large oil and gas resources (Martin et al., 2004; Combellas-Bigott and Galloway, 2006; Fulthorpe et al., 2014).

While Pliocene through Pleistocene catchment extents varied to some degree, we note an overall trend of catchment expansion, increased river lengths, and increased submarine-fan run-out lengths (Figs. 4A, 4B; Prather et al., 1998; Galloway, 2005). The Pleistocene Mississippi fan system (Fig. 4A) is among the largest Cenozoic fans, with its glacially influenced fluvial network expanding to

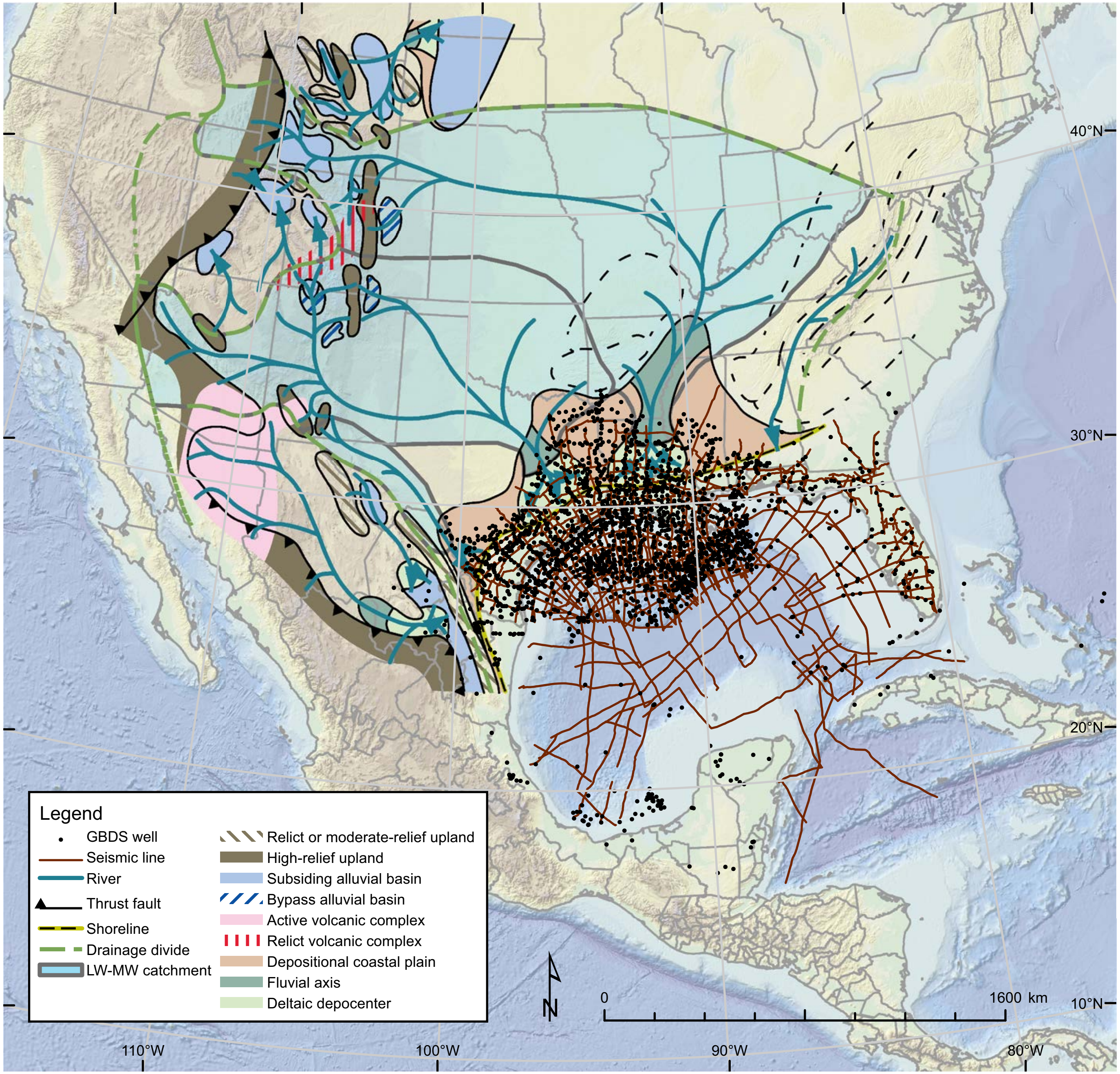


Figure 1. Locations of Gulf of Mexico wells and seismic lines used in this study, with examples of source terranes, rivers, catchments (shown as light green transparent polygons), and linked depositional systems for the Paleocene Middle Wilcox depositional episode. Background image is a present-day elevation and depth raster for the Gulf of Mexico region with an underlying shaded-relief layer to enhance visualization (derived from Smith and Sandwell, 1997). Abbreviations: GBDS—Gulf Basin Depositional Synthesis research project; MW—Mddle Wilcox depositional episode; LW—Lower Wilcox depositional episode.

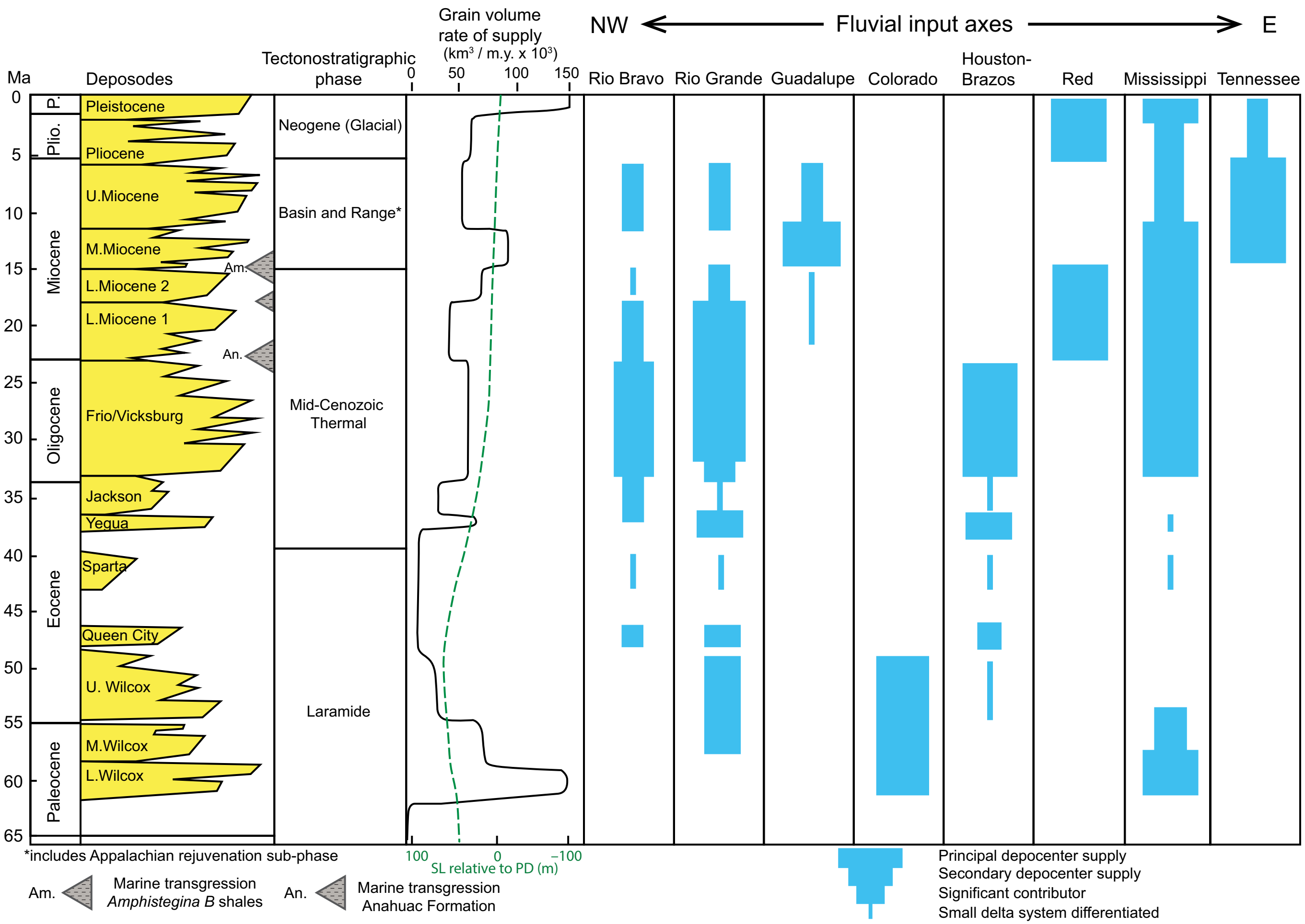
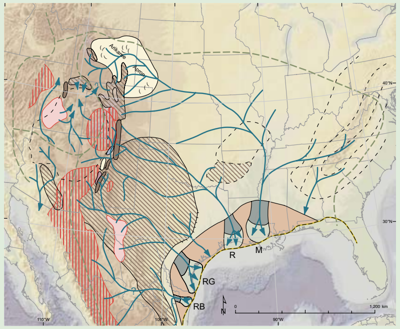


Figure 2. Northern Gulf of Mexico stratigraphy, tectonostratigraphic phases, and supply of important rivers (modified from Galloway, 2008), and grain volume rate of supply (black solid line) compared to the global sea-level (SL) curve (green dashed line) of Miller et al. (2005) (PD—Present day). Time scale is from Luterbacher et al. (2004). Plio.—Pliocene; P.—Pleistocene; U.—Upper; M.—Middle; L.—Lower.

encompass a large portion of North American drainage (Bentley et al., 2016). Recent published detrital-zircon U-Pb and (U-Th)/He double-dating analyses from the Late Pleistocene Mississippi fan indicate expanded drainage network but also the important role of high-discharge meltwater and glacial-lake outbursts during ice retreat in North America (Fildani et al., 2016). The newly exposed Colorado Plateau also contributed sediment (Roberts et al., 2012).

Paleogeographic maps (Galloway et al., 2011) suggest that many of these North American catchments feeding the Gulf of Mexico basin were quite significant in terms of their area and length (Figs. 3 and 4; Supplemental Figs. S1–S8[1]). It is also no coincidence that a series of large abyssal-plain submarine fans are active targets of oil and gas industry drilling over the past 20 yr (e.g., Zarra, 2007; Meyer et al., 2007), and will remain so into the near future. Forty or more deepwater systems, including highly organized submarine fans and less-organized aprons (defined further below), have been penetrated by wells and their extent further defined by two- and three-dimensional (2-D and 3-D) seismic reflection data (Fulthorpe et al., 2014). Exploring potential linkages



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[1] Supplemental Files. Figures S1–S8: Cenozoic drainage basin maps with captions and references. Table S1: Source-to-sink measurements. Please visit http://doi.org/10.1130/GES01452.S1 or the full-text article on www.gsapubs.org to view the Supplemental Files.

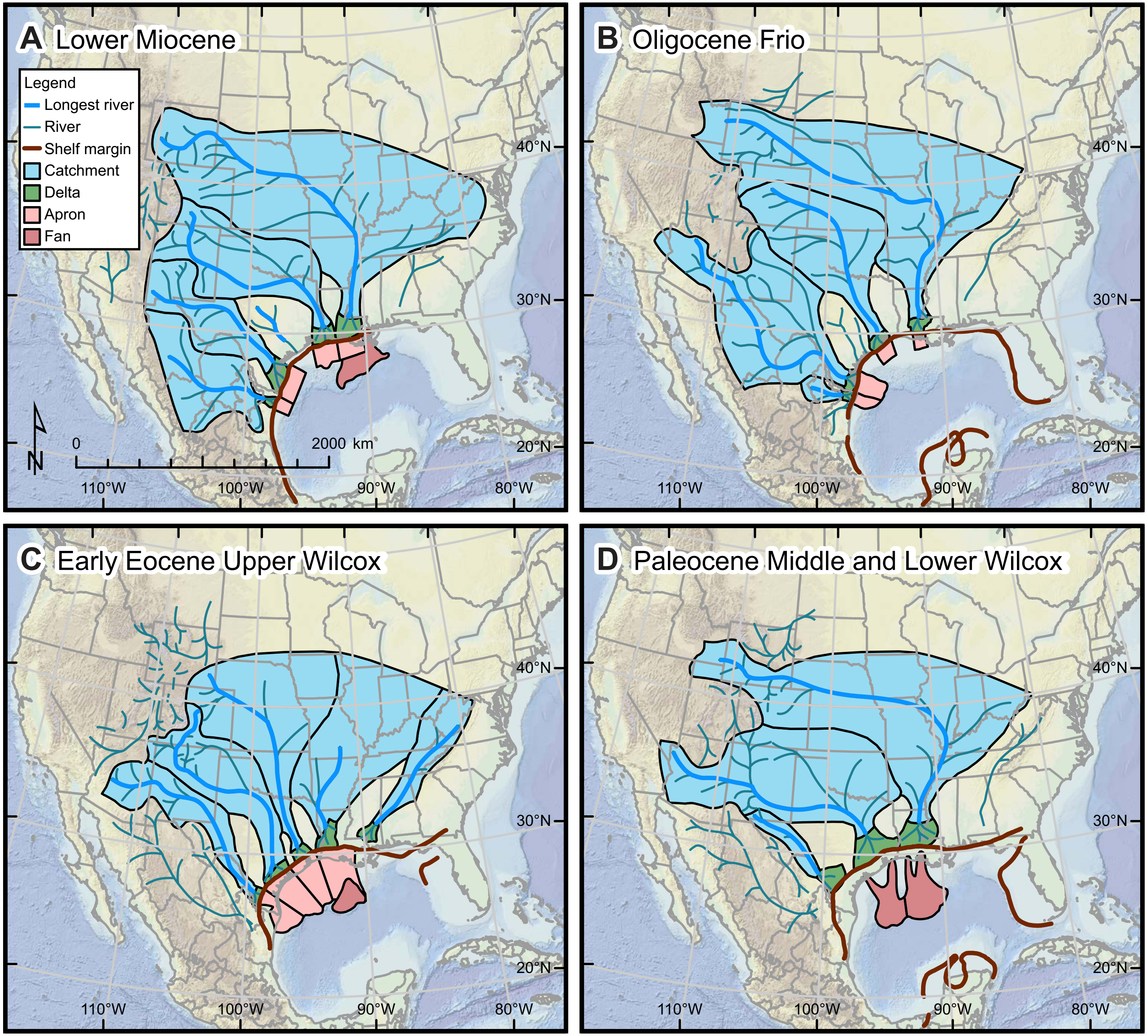

Figure 3. Selected interpreted Paleogene and Early Neogene catchments and linked depositional systems, Gulf of Mexico. (A) Lower Miocene depositional episode. (B) Oligocene Frio depositional episode. (C) Early Eocene Upper Wilcox depositional episode. (D) Paleocene Middle and Lower Wilcox depositional episode(s). Interpreted longest river in each catchment is shown as a dark blue line. Shore zones and wave-dominated deltas are not shown, as these were not used in empirical scaling evaluations. Catchments are revised from maps of Galloway et al. (2011) based on new published work, including detrital zircon provenance and geochronology. Detailed major source terrane and drainage reconstructions are available as Supplemental Figures 1–4 (footnote 1).

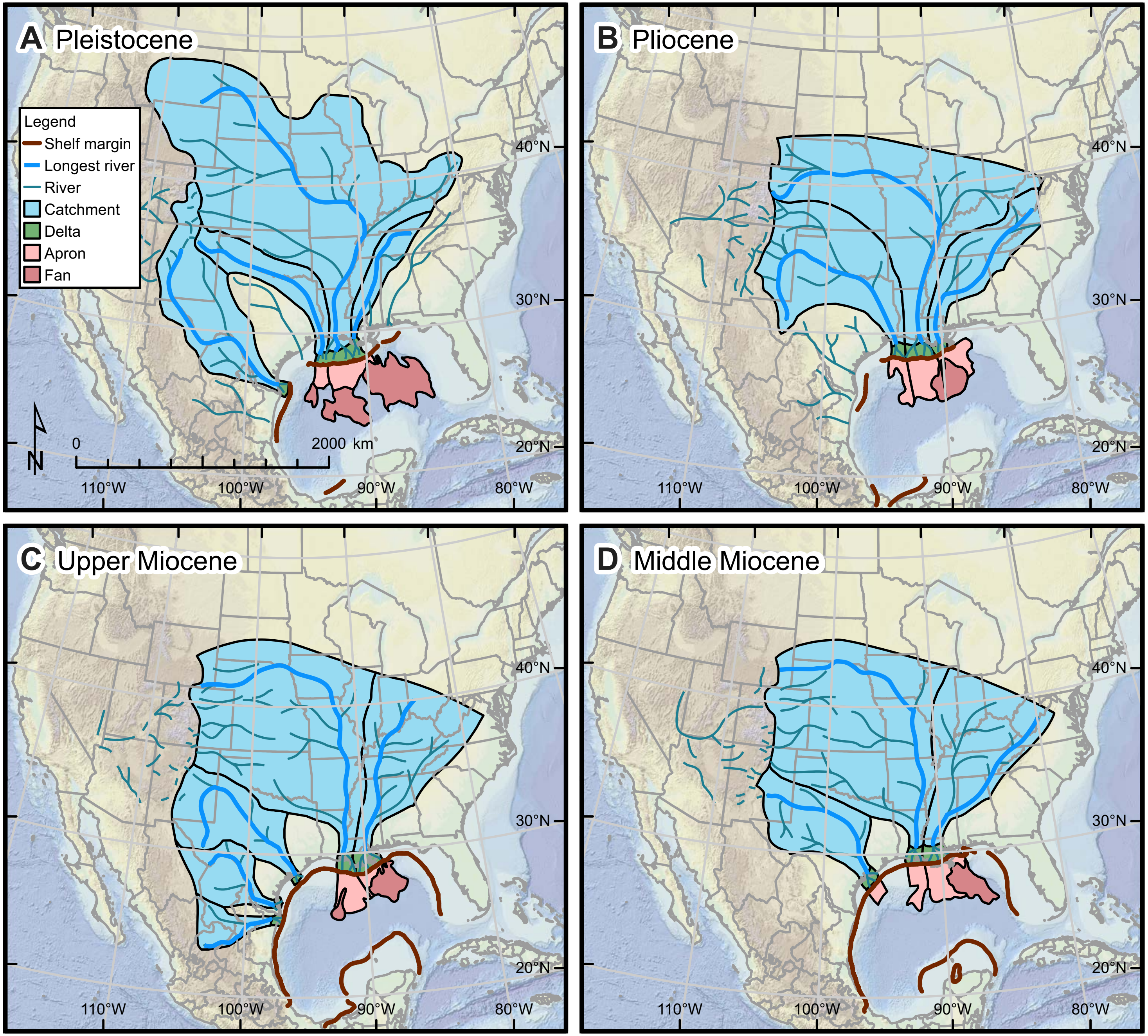

Figure 4. Selected interpreted Neogene and Quaternary catchments and linked depositional systems, Gulf of Mexico. (A) Pleistocene. (B) Pliocene. (C) Upper Miocene. (D) Middle Miocene. Interpreted longest river in each catchment is shown as a dark blue line. Shore zones and wave-dominated deltas are not shown, as these were not used in empirical scaling evaluations. Catchments are revised from maps of Galloway et al. (2011) based on new published work, including detrital zircon provenance and geochronology. Detailed major source terrane and drainage reconstructions are available as Supplemental Figures 5–8 (footnote 1).

TABLE 1. TECTONOSTRATIGRAPHIC PHASES, RELEVANT STRATIGRAPHIC UNITS, AND PALEO-RIVER SYSTEMS MEASURED, GULF OF MEXICO

Tectonostratigraphic phase*	Relevant stratigraphic units*	Paleo–river systems measured here†
Neogene (glacial)	Pleistocene, Pleistocene Ang B, Pliocene *Globoquadrina altispira*§, Pliocene	Mississippi, Tennessee, Red River
Basin and Range	Upper Miocene, Middle Miocene, Lower Miocene	Mississippi, Tennessee, Rio Bravo, Guadalupe, Rio Grande
Mid-Cenozoic thermal	Oligocene Frio	Rio Grande, Rio Bravo
Laramide	Lower Wilcox, Middle Wilcox, Upper Wilcox	Mississippi, Calvert, Holly Springs, Houston

*From Galloway (2008).
†From Galloway et al. (2011).
§Pliocene *Globoquadrina altispira* biostratigraphic marker.
Note: Pleistocene Ang B—Pleistocene *Angulogerina* "B".

through analysis of empirical source-to-sink scaling relationships, as originally suggested by Sømme et al. (2009a), is therefore of considerable interest from both a scientific and an economic perspective.

DATASET

Testing source-to-sink empirical scaling relationships requires access to a robust database of dimensional information. The Gulf of Mexico basin (Fig. 1) has been the site of active drilling since the 1950s, and thus a wide variety of high-quality data are available (Galloway et al., 1998). Our offshore database largely consists of released well information available from the Bureau of Ocean Energy Management (BOEM); well logs used in this study can be accessed at their Web site (https://www.data.boem.gov/Main/Well.aspx). Comparable seismic data can also be ordered for a nominal fee at the BOEM portal (https://www.data.boem.gov/Main/Seismic.aspx). Seismic data shot by The University of Texas Institute for Geophysics in Mexico and adjacent areas of the U.S. are available for download at the Academic Seismic Portal (http://www-udc.ig.utexas.edu/sdc/). Biostratigraphic data that constrain the well log and local seismic reflection correlations can be accessed at the BOEM portal (https://www.data.boem.gov/Main/Paleo.aspx).

Key source-to-sink features were digitized, geospatially located, and stored in a geographic information system (ArcGIS), with accuracy in the range of ±10 m in most cases (Galloway et al., 1998). Dimensional information was collected using various ArcGIS measurement tools for feature length, area, and perimeter. Major paleogeographic features, including paleo-shelf margins, local depocenters, depositional system outlines, mapped submarine canyons, and continental-margin embayments are compiled from various published sources (e.g., Winker, 1982; Cantú-Chapa, 2001; Fiduk et al., 2004; Combellas-Bigott and Galloway, 2006).

Our paleogeographic and sand-body thickness maps are updated on a regular basis, with continuing release of U.S. oil and gas industry well logs about two years after drilling or immediately upon license relinquishment. Selected maps are published on a regular basis for evaluation and testing by others (e.g., Galloway et al., 2011; Fulthorpe et al., 2014; Snedden et al., 2012, 2016). Catchment and paleogeographic maps pertinent to this study are included in Figures S1–S8 [footnote 1]).

METHODS

To investigate source-to-sink scaling relationships in ancient deepwater depositional systems of the Gulf of Mexico, we applied a workflow of subsurface correlation and mapping, deposystem classification, and ArcGIS analyses to the data set described in the previous section. We then used statistical analyses to search for relationships between measured subsurface system segment scales and paleo-catchment parameters including fluvial system segment scales and paleoclimate records supplied from published literature.

Subsurface Gulf of Mexico

Our depositional classification system for the Gulf of Mexico recognizes a large diversity of deepwater morphological and sedimentological types, including channel complexes, mass-transport complexes, submarine aprons, and abyssal plain fans. Depositional system and facies terminology is adapted from Galloway and Hobday (1996) and Galloway (2008). In particular, the distinction between a submarine apron and fan is important to consider. Submarine fans, as we define these, are large paleogeographic features with generally high sand content (in some cases approaching 90% sand; see Meyer et al., 2007), significant thickness, and commonly mounded external form in less-confined, basin-floor settings. These features usually include multiple stacked, well-organized channel complex networks. Isopach mapping from well control and seismic reflection mapping often indicate a point source, an apex usually (but not always) in proximity to a well-defined delta and river input location. It should be noted that our subsurface-focused methodology largely defines the minimum fan run-out length, as the muddy fringes may extend some distance past sand-prone areas.

Submarine aprons, as we define them, appear to be more poorly organized channel and lobe systems, commonly with low net sand content and limited thickness (except in the core of a laterally discontinuous deepwater channel system). Paleogeographic maps suggest that aprons are usually line sourced on a regional basis rather than point sourced, and are typically linked with updip shore zones, in contrast to fluvial-dominated deltas and their connected rivers (Reading and Richards, 1994; Galloway, 1998).

Key morphological parameters considered here are listed in Table 2. Supplemental Table S1 (footnote 1) lists specific measurements by time interval and river system. These are comparable to a number of the parameters of modern and submodern global source-to-sink systems compiled by Sømme et al. (2009a). The larger number of data points in this study reflects the longer time span of sampling, early Cenozoic to Pleistocene, versus the modern and Quaternary data of Sømme et al. (2009a). The parameters we measure from rivers, shore zones, deltas, shelves, and submarine fans are typical of this high-accommodation setting, where Cenozoic rivers fed prominent deltas and robust submarine fans (Figs. 3 and 4).

Cenozoic Catchments

Two important catchment dimensions, longest river length and catchment area, are based on our Cenozoic catchment reconstructions. These paleocatchment reconstructions (Figs. 3 and 4) are updates to maps previously published by Galloway et al. (2011) and Xu et al. (2016) that include detailed compilations of published subsurface and outcrop information (see also Figs. S1–S8 [footnote 1]). Our maps honor published compositional data (Bart, 1975; Condon, 2005; Cather et al., 2012) and in many places tie back to preserved alluvial records in western catchments (e.g., Lillegraven and Ostresh, 1988; McMillan et al., 2006; Davis et al., 2009; Lawton, 2008). Reconstruction of catchments largely hinges upon documented basement uplift patterns and history (e.g., Dickinson et al., 1988; Chapin et al., 2014). For example, late Paleocene drainage networks depicted in Figure 1 are compiled from over 30 papers published on source terrane elements, including catchments, interior basin structure, igneous features and provinces, and fluvial transport systems. The interpreted drainage systems represent our best interpretation of such data, with paleocurrent data from outcrops where available (e.g., Hamlin, 1988; Flores, 2003) linked to probable source terranes and tectonic elements. General paleoclimate data were derived from the website http://www.scotese.com/climate.htm. Recent provenance analysis using detrital zircons, which to a great degree is also a test of method, has largely supported the catchment interpretations for the Paleocene–Eocene Wilcox, Oligocene, and Lower Miocene intervals (Mackey et al., 2012; Craddock and Kylander-Clark, 2013; Blum and Pecha, 2014; Xu et al., 2016; Bush et al., 2016). Channel-belt scaling, an empirical approach to drainage basin estimation, also confirms the Lower Miocene catchment reconstructions (Xu et al., 2017).

The utility of zircon provenance information in defining catchment boundaries is illustrated as an example in Figure 1. Earlier papers (e.g., Duk-Rodkin and Hughes, 1994) suggested that the Paleocene drainage divide between southerly flowing and northerly flowing rivers was probably located along the present-day U.S.-Canada border. The nearly complete absence of Penokean–Trans-Hudson (1800–2000 Ma) Superior-Wyoming province detrital zircons (>2500 Ma) in Wilcox sandstone outcrops as documented in Blum and Pecha (2014) suggests that the Paleocene catchment boundary must have been ~600 km farther south. Modern Mississippi River samples do contain zircons from these source terranes (Blum et al., 2017), suggesting northern expansion of the catchment over time.

The interpretations of catchments and river locations are obviously an interpretation from compiled information as described above. For future testing of these paleo-catchment models, we provide larger-scale drainage reconstruction maps in Figures S1–S8 (footnote 1), with a listing of the key papers that form the basis for these interpretations.

Uncertainty

Accurately measuring catchments, river channel lengths, and submarine fans in ancient systems is inherently more difficult than for modern systems. Drainage basin reconstructions, as described above, represent a compilation of numerous published studies, including those employing advanced approaches like detrital zircon provenance and geochronology from outcrop samples. Obviously, areas such as the central and southern continental interior lowlands, Mississippi River valley, and southeastern Appalachians where there is little preserved sedimentary record have greater uncertainty. However, we fully expect modifications of these interpreted catchments due to new data

TABLE 2. COMPARISON OF MORPHOLOGICAL PARAMETER SAMPLE SIZES, GULF OF MEXICO DEPOSITIONAL SYSTEMS

Morphological dimension	Sample size, this study	Sample size, Sømme et al. (2009a)
Catchment area	63	26
Length of longest river	64	26
Backwater length	35	Not measured
Delta length	59	Not measured
Delta area	59	Not measured
Shelf length	62	Not measured
Fan length*	50	27
Fan width	51	27

*Fan length (distance from base of slope to fan termination) of Sømme et al. (2009a) compared to fan run-out length (distance from shelf margin to sandy fan termination) measured here.

and offer our reconstructions as shown in Figures S1–S8 (footnote 1) as testable hypotheses for future studies.

For estimation of longest river lengths, we focused on the prominent trunk river systems that are linked to the basinal sinks. The areal extent of Cenozoic catchments was previously interpreted by Galloway et al. (2011) and Xu et al. (2016) and further refined here to permit measurements along the average centerline of these catchment areas (e.g., Figs. 3 and 4). Some deviation would be expected where rivers are highly sinuous, but first-order relationships should still be apparent (Sømme et al., 2009a). The uncertainty around delineation of drainage divides between catchments naturally increases with geologic age, but as discussed below, generally does not materially impact measurement of longest river length within a catchment.

As a test of sensitivity, river length for the Lower Wilcox paleo-Mississippi system was varied within the interpreted catchment, to derive a range of alternative minimum and maximum longest river lengths. None of these yielded a difference of more than 15% from the longest river length that is roughly the centerline of the Mississippi catchment. As an example illustrated in Figure 5, a minimum length of 2240 km (data point 10 of Fig. 5) was generated versus the centerline measured length of 2750 km (data point 9 of Fig. 5), a difference of 15%. Changing the longest river length by ±15% changed the predicted fan length by only ±2%. As Sømme et al. (2009a) suggested, such first-order relationships are not substantially impacted by the greater uncertainty when reconstructing ancient fluvial systems.

Submarine fan length as defined by Sømme et al. (2009a) is the distance from the toe of the continental slope to the submarine fan termination. For ancient systems like the Gulf of Mexico Cenozoic system, the toe of slope is difficult to consistently identify and define due to post-depositional tectonic rotation and presence of mass-transport complexes that obscure the change in the slope. A far easier boundary to recognize is the shelf margin, identifiable as a clinoform topset-foreset break, with corresponding change in slope, change in facies types, initiation of major growth faults, and/or position of the most landward slope minibasins in the salt canopy (Edwards, 1981; Winker, 1982). We measure the distance from the shelf margin to the termination of the submarine fans and refer to this as the "fan run-out" length. This would include the distance from the channel terminus to fan terminus (in contrast to the channel run-out length measured by Covault et al. [2012], which is measured to the end of the channel-lobe transition). Direct comparison to the Sømme et al. (2009a) database is made by simply adding their interpreted slope length to the fan length.

The uncertainty of locating submarine fan terminations in the deepwater Gulf of Mexico is a direct function of the well and seismic database, which is quite robust for every Cenozoic time interval investigated (Fig. 1). Naturally, such a database reflects a focus on the sandy fan terminations, while for some intervals, a muddy fringe may continue some distance beyond the dominantly sandy areas. Sand-rich, high-density turbidity flows that dominate many submarine fans are sensitive to bottom topography such as

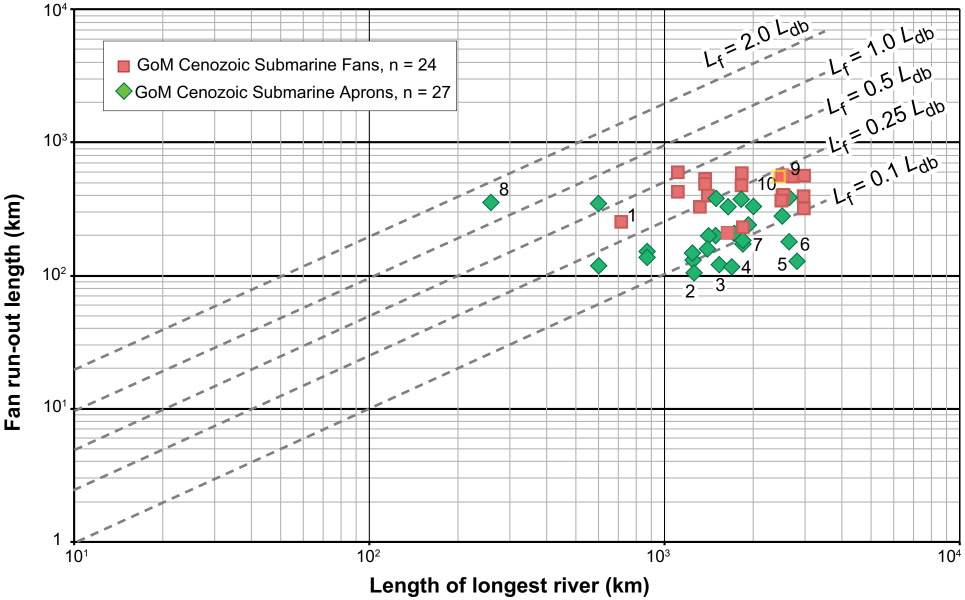

Figure 5. Longest river length versus fan run-out length (defined as slope length + fan length) for all Gulf of Mexico (GoM) Cenozoic deepwater systems including fans (red squares) and aprons (green diamonds). Indicated deepwater system points (refer to Fig. 2 for deposode names): 1—Upper Wilcox Mississippi fan; 2—Lower Miocene 1 Rio Grande apron; 3—Oligocene Frio Houston-Brazos apron; 4—Yegua Cockfield-Jackson apron; 5—Oligocene Frio Mississippi apron; 6—Lower Miocene 1 Mississippi apron; 7—Lower Miocene 1 Red River apron; 8—Oligocene Rio Bravo north apron; 9—Lower Wilcox Mississippi system measured at centerline of catchment; 10—Lower Wilcox Mississippi system plotted at minimum possible river length as a test of sensitivity, discussed in the text. Abbreviations used: L_f—fan run-out length; L_{db}—drainage basin (catchment) length.

salt structures, which are common in the Gulf of Mexico Cenozoic section. Sand-rich, high-density turbidity flows tend to terminate abruptly, in contrast to dilute, low-density turbidity flows that are less sensitive to bottom topography (Bakke et al., 2013). We acknowledge that, from this perspective, Gulf of Mexico submarine fan measurements are a minimum length and width, due to a rugose bottom topography that influenced sandy fan terminations and a database focused on sand-prone systems. However, the Gulf of Mexico fan lengths and widths fall in a similar range as those in the data set of Sømme et al. (2009a), which includes modern systems with relatively smooth or even basin floors, and notable muddy fan fringes (e.g., Amazon Fan; Lopez, 2001).

RESULTS AND INTERPRETATIONS

Our analysis reveals important relationships between source-to-sink segments of the Gulf of Mexico basin, particularly for river and submarine fan dimensions (Figs. 5–8). A key scaling relationship is between submarine fan run-out length and catchment length. As mentioned, we use a proxy for catchment length by measuring the longest interpreted paleo-river in a catchment. There is a close relationship between river channel length and catchment area (Schumm and Winkley, 1994; Sømme et al., 2009a; Blum and Hattier-Womack, 2009). Because long rivers drain large catchment areas, average fluvial discharge tends to be high and sediment transport toward submarine fan depositional sinks is enhanced (Miall, 2014; Syvitski and Milliman, 2007; Covault et al., 2012). This pattern appears to hold true in both icehouse to greenhouse worlds (Anderson et al., 2004), both of which characterized portions of the Cenozoic Era.

We consider first a larger population that yields some expected scatter due to inclusion of submarine aprons. Exclusion of these line-sourced depositional bodies greatly reduces the observed dispersion but still provides a data set ($n = 24$) comparable in size to that of Sømme et al. (2009a; $n = 18–27$, depending on parameter; see Table 2).

Fan Run-Out Length versus Catchment Length

The majority of the Gulf of Mexico Cenozoic river catchments are large, covering nearly one-half of the U.S. and smaller portions of Mexico. Catchments draining the western U.S. dominate the Paleogene alluvial record (Figs. 3B–3D). Eastern terranes become increasingly important in the Neogene (Figs. 3A, 4), with rejuvenation of the Appalachians (Boettcher and Milliken, 1994), and climatic conditions favoring greater discharge, until the expansion of the Mississippi catchment in the Plio-Pleistocene (Bentley et al., 2016). Longest river lengths for both Paleogene and Neogene catchments plot toward the large-river (>1000 km) end of the length spectrum (Fig. 5), comparable with continental catchment scales (Sømme et al., 2009a).

Cenozoic deepwater systems are also large, with most fan run-out lengths exceeding 100 km. The aggregate larger population of submarine fans generally have run-out lengths concentrated in the range of 0.1–0.5 times the longest interpreted river length (Fig. 5), consistent with the scaling relationship identified by Sømme et al. (2009a). This includes depositional bodies of all scales within our database, including at least one (of the Upper Miocene Rio Bravo) that has been reinterpreted as a deepwater current-modified sand body (Snedden et al., 2012).

However, a significant number of deepwater bodies, all of which are classified as submarine aprons, fall outside of that range (points 2–7 of Fig. 5). By contrast, the contemporaneous systems in the paleo-Mississippi and paleo–Houston-Brazos drainage networks yield much smaller aprons. These and other outliers for the Lower Miocene and a few other units may indicate some uncertainty in defining sand-body dimensions in these poorly organized, deepwater systems (e.g., point 8 of Fig. 5). Two of the aprons are of Oligocene age (points 3 and 5), where South Texas low-angle detachment faulting created high sediment accommodation in marginal-marine growth-fault basins (Galloway, 2008), possibly reducing sediment transfer to lower slope and abyssal plain depocenters.

Exclusion of submarine aprons and current-modified submarine fans produces a tighter clustering within the general domain of fan run-out length (0.1–0.5 times drainage basin length) (Fig. 5). Virtually all large submarine fans are linked to river lengths of the continental scale (±1000 km). One outlier value is the Upper Wilcox of the paleo-Mississippi drainage system (point 1 of Fig. 5). In this case, both catchment size and fan size are reduced compared to earlier Paleocene Wilcox systems, suggesting updip drainage reorganization and growth-fault and raft-enhanced accommodation near the basin margin (Fiduk et al., 2004; Galloway et al., 2011). Overall, the Upper Wilcox basinal data shows a distinct reduction in submarine fan size and backstepping of the locus of sedimentation from abyssal plain to an upper slope position (McDonnell et al., 2008).

Catchment area and longest river length were independently measured for the major Cenozoic systems. Catchment geometries vary from narrow to broad, even within a single stratigraphic interval (e.g., Upper Wilcox in Fig. 3C). This variation in river length and catchment area is apparent in the dispersion around the best-fit line. However, the strong overall correlation between Gulf of Mexico catchment area and longest river length ($R^2 = 0.85$) is comparable to that of the modern systems as analyzed by Sømme et al. (2009a; $R^2 = 0.99$), which supports use of this approach for large ancient systems.

Plotting of Cenozoic Gulf of Mexico data against those of submodern systems studied by Sømme et al. (2009a) reveals that for catchment area, longest river length, and fan run-out length, our data are in the range of the larger global systems (Figs. 6 and 7). Gulf of Mexico Cenozoic fan widths are greater than or equal to those of all but seven of the Sømme et al. (2009a) measured submodern examples (Fig. 8). This clearly reflects both the continental scale and the longevity of many of the Gulf of Mexico drainage systems we analyzed.

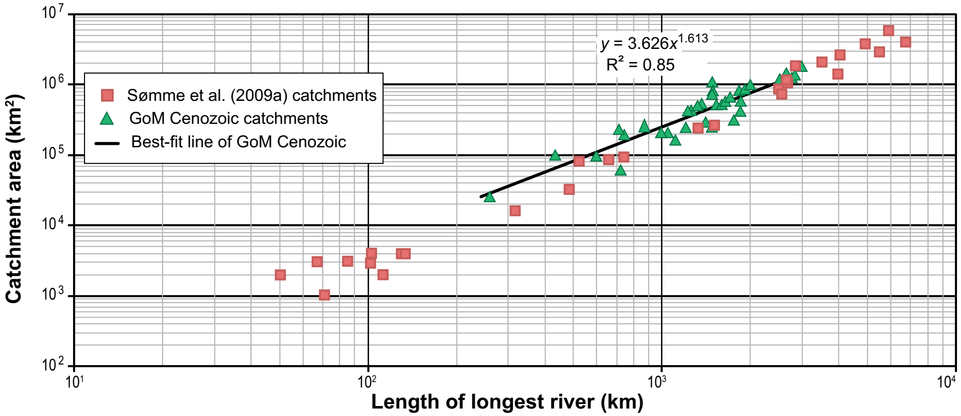

Figure 6. Catchment area versus longest river length for Gulf of Mexico (GoM) Cenozoic deepwater systems (green triangles) plotted against data of Sømme et al. (2009a) (red squares).

As discussed above, well-developed Cenozoic submarine fans have not been documented in some portions of the Gulf of Mexico Cenozoic record, such as the Oligocene and late Eocene. Lack of fans in these time frames may be due to basin-margin enhanced accommodation effects such as growth faulting and rafting as mentioned. Reduced precipitation in western catchments may also have played a role for the Oligocene (Fan et al., 2015). Thus, one shortcoming to our approach is that is does not uniquely predict submarine fan occurrence. But once submarine fan presence has been discerned by other analyses (e.g., seismic interpretation, well penetrations), it has considerable utility in estimating fan length and width from reconstructed catchment dimensions.

Other Scaling Relationships Considered

A number of other empirical scaling relationships were evaluated for the Cenozoic source-to-sink segments, with mixed results. Sømme et al. (2009a) noted a strong, positive correlation ($R^2 = 0.88$) between submarine fan width and run-out length (red squares in Fig. 8). The Cenozoic data considered here (green triangles of Fig. 8) yield a weaker but still strongly positive correlation ($R^2 = 0.4$) between fan width and run-out length. This lower correlation coefficient for our data may reflect some uncertainty in delineating fan width due to the laterally extensive salt canopy, as mentioned earlier in the paper. The tight cluster of Cenozoic points falls nearly within a single order of magni-

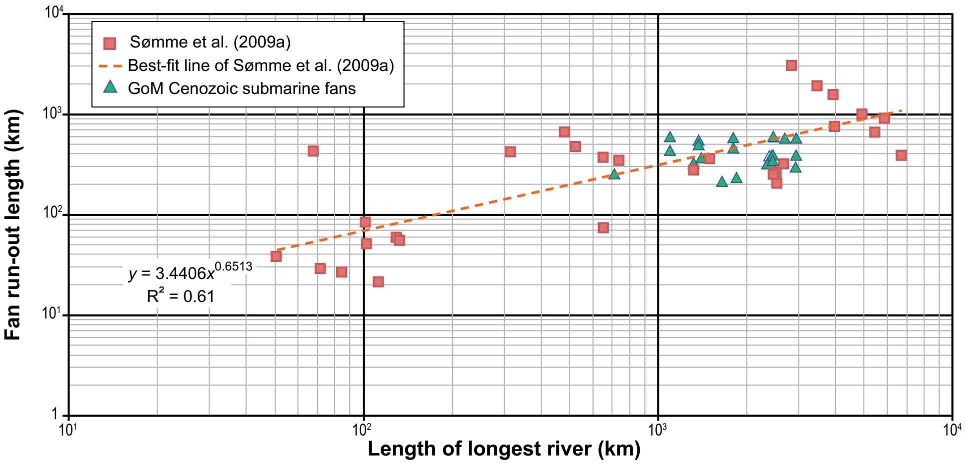

Figure 7. Longest river length versus fan run-out length (defined as slope length + fan length) for Gulf of Mexico (GoM) submarine fans only (excluding aprons, as defined in text), plotted against data and best fit line of Sømme et al. (2009a).

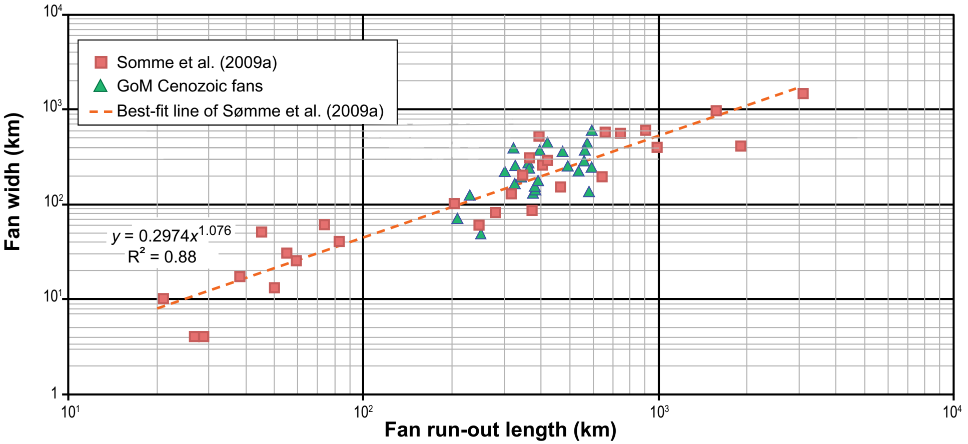

Figure 8. Submarine fan width versus fan run-out length for Gulf of Mexico (GoM) submarine fans (excluding aprons, as defined in text), plotted against data and best-fit line of Sømme et al. (2009a).

tude, versus the three-orders-of-magnitude spread for the submodern data of Sømme et al. (2009a).

Other empirical relationships like fan run-out length versus delta length and fan width versus delta width show generally low correlation coefficients. This implies that, for Cenozoic fan systems considered, processes like shelf storage and local failure events (e.g., margin collapse) may intervene between the delta and submarine fan (e.g., Covault and Fildani, 2014). This and the earlier-noted strong relationship between river length and submarine fan run-out length suggest logically that when submarine fans are present, the larger catchment exerts a greater influence on the scale of the submarine fan than the local delta sediment repository.

APPLICATION TO A LESS WELL-CONSTRAINED SOURCE-TO-SINK SYSTEM

The overall pattern of Gulf of Mexico fan evolution clearly reflects numerous factors including reorganization of drainage through the Cenozoic. The interpreted temporal trends in catchment area and longest river lengths mirror changes in fan run-out length and width (Figs. 3, 4). This is in spite of the fact that contemporaneous coastal zones are known to accommodate substantial thicknesses of deltaic sediments (Galloway, 2008), suggesting that local shoreline accommodation is overwhelmed by the high fluvial sediment flux from the source terranes. These covariations exist over a long time frame (65 m.y.), extend across multiple tectonic and climatic phases, and seem to persist through frequent changes in global sea level (Fig. 2). These relationships support the application of this approach to a less well-constrained source-to-sink system of the Gulf of Mexico basin: the Eocene Upper Wilcox of the southern Gulf of Mexico (Mexico).

Galloway et al. (2000; see also McDonnell et al., 2008) posited the location of two Upper Wilcox submarine fan systems in eastern Mexico, based on the published location of two prominent paleo–canyon systems, the Bejuco and Chicontepec (Fig. 9), as well as seismic data acquired by The University of Texas Institute of Geophysics in Mexico before 1980. These canyons are thought to have formed by submarine erosion (Cantú-Chapa, 2001; Cossey, 2007), although alternative views have been suggested (Rosenfeld and Pindell, 2003). Map extent of the submarine fans was initially based on seismic reflection character from the 1970s-vintage 2-D seismic reflection data. Precise delineation of the fans and characterization of reservoir properties has been impeded by structural complexity as well as restricted access to newer Mexico seismic reflection and well data, even after recent opening of Mexico to international exploration. However, available regional studies support the hypothesized fan locations by confirmation of basin entry points through the Bejuco and Chicontepec paleocanyons (see synthesis in de la Rocha, 2016).

Publication of new updip outcrop data in the area, including detrital zircon provenance information (Lawton et al., 2015), allows evaluation of the hypothesized fan dimensions using empirical scaling relationships described earlier (Fig. 9). Most workers agree that by the early Eocene (during Upper Wilcox deposition), tectonic deformation reached its present position and sediment routing to areas east of the Sierra Madre foreland was underway (Lawton et al., 2009; Rodriguez, 2013). Three drainage systems are suggested to have transported siliciclastics from the interior of Mexico (Guerrero terrane) into a foreland basin east of the Sierra Madre Oriental thrust front. Detrital zircons of Pan-African (Gondwana) affinity from coeval strata indicate separation of these catchment areas from systems of the La Popa Basin (Fig. 9), where Laurentian grains are more common and Pan-African zircons are largely absent (Lawton et al., 2015). It is likely that sediment bypassed basement-cored highs

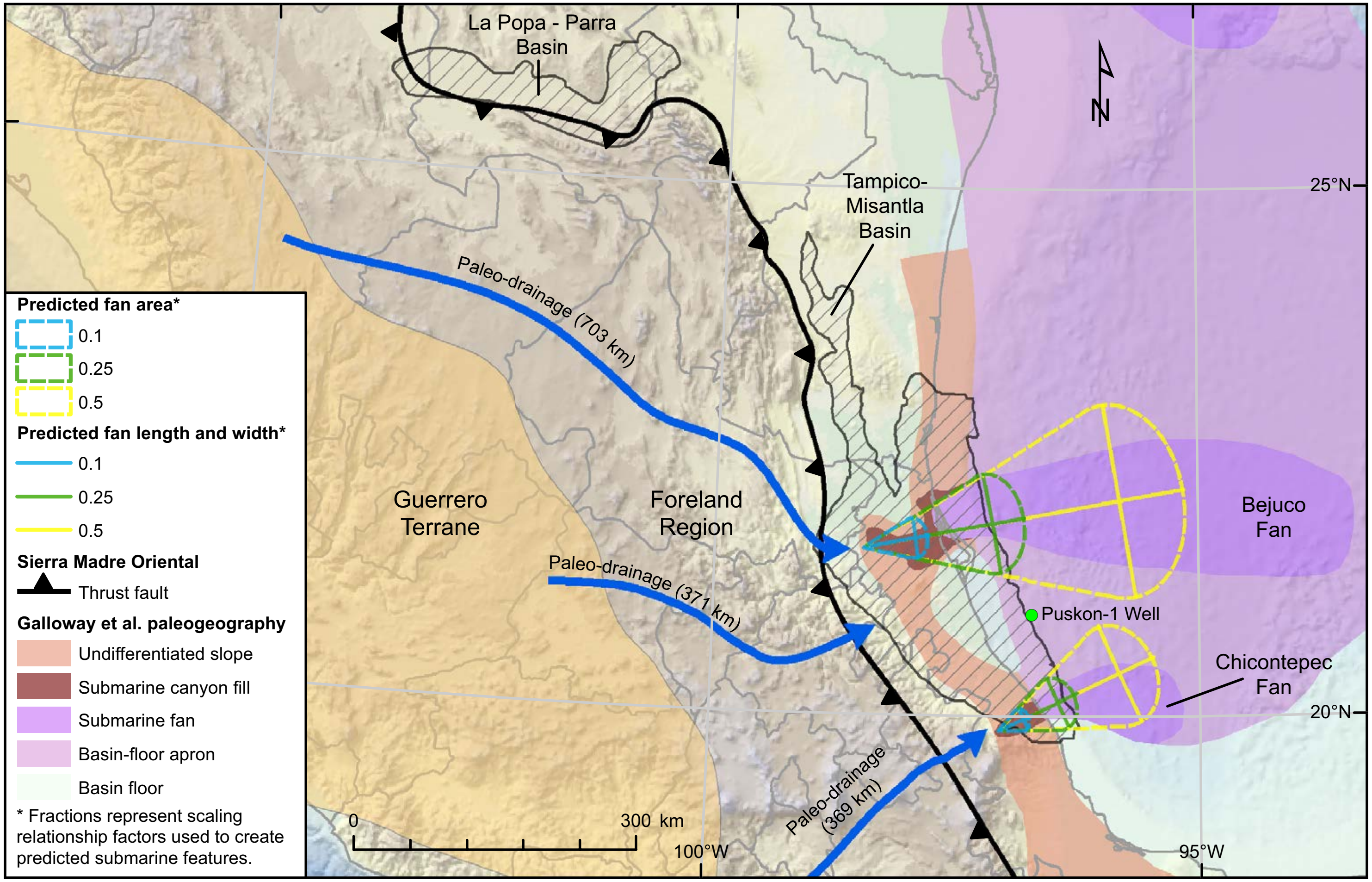

Figure 9. Comparison of predicted and interpreted Eocene Upper Wilcox submarine fans of Mexico (southern Gulf of Mexico) using scaling relationships between longest river length, fan length, and fan width. Predicted fans with lengths of 0.5, 0.25, and 0.1 times the longest river length are color coded and compared to the interpreted extents of Galloway et al., 2000). Lengths of river systems derived from Lawton et al. (2015).

of the Tampico-Misantla area at two entry points, the Bejuco canyon (Cantú-Chapa, 2001) and the Chicontepec canyon (Cossey, 2007), and was deposited in the two fan systems as suggested by Galloway et al. (2000).

An estimate of the fan run-out length was prepared at 0.5, 0.25, and 0.1 times the interpreted longest river length of the three systems of Lawton et al. (2015; Table 3). Use of 0.5 times the catchment (drainage basin) length for estimating submarine fan run-out length in these cases is justified based on: (1) proximity of the Sierra Madre deformation front; and (2) reconstructions suggesting a relatively short source-to-sink distance (Lawton et al., 2009; de la Rocha, 2016). Such a drainage-basin profile resembles what Helland-Hansen et al. (2016) called a "steep, short, and deep" system. In such higher-gradient transects, a greater percentage of the sediment load is delivered to the basin than for larger source-to-sink systems, all other factors considered (Milliman and Syvitski, 1992).

The Bejuco fan, which was apparently sourced by the largest of these three drainage systems, is predicted to have greater length and width than the

TABLE 3. PREDICTED SUBMARINE FAN DIMENSIONS USING SOURCE-TO-SINK WORKFLOW, EARLY EOCENE (UPPER WILCOX) OF WESTERN MEXICO OFFSHORE AREA, GULF OF MEXICO

Drainage system	Interpreted river length[1] (km)	Interpreted fan length, Galloway et al. (2011) (km)	Predicted fan length at 0.5 × river length (km)	Predicted fan length at 0.25 × river length (km)	Predicted fan length at 0.1 × river length (km)	Interpreted fan width, Galloway et al. (2011) (km)	Predicted fan width at 0.5 × interpreted river length[3] (km)	Predicted fan width at 0.25 × interpreted river length[3] (km)	Predicted fan width at 0.1 × interpreted river length[3] (km)
Bejuco system	703	279	351.5	175.75	70.3	140	201.7	103.1	42.4
Chicontepec system	369	282	184.5	92.25	36.9	111	108.0	55.2	22.7
Alternative Chicontepec system[2]	371	282	185.5	92.75	37.1	111	108.6	55.5	22.9

[1] From Lawton et al. (2015).

[2] Alternative Chicontepec system represents second of two potential river systems connected to the Chicontepec canyon, as discussed in the text.

[3] Follows Sømme et al. (2009a) empirical scaling approach, as discussed in the text.

Chicontepec fan (Fig. 9). The earlier-interpreted Bejuco fan outline, interpreted from older seismic data and proximity to the canyon by Galloway et al. (2000), exceeds 0.5 times the longest river length, suggesting the need for revision of maps based upon older seismic data.

The Chicontepec fan is a more complicated case, as: (1) there is some disagreement regarding the age of the canyon; and (2) there are two potential catchments that might have routed sediment to the foreland trough connected to the Chicontepec canyon. The Chicontepec canyon was initially identified by Busch and Govela (1978), dismissed by Cantú-Chapa (2001), and revived as an important element by Cossey (2007), who described seismic reflection, well log, and core data confirming the presence of a long-lived canyon system. High-resolution biostratigraphic data made available to Cossey (2007) by the Pemex Company suggest a complex canyon formation and filling history. A key unconformity is related to canyon development during the Ypresian and Lutetian stages and overlaps with the Upper Wilcox and overlying Queen City equivalent sections of the northern Gulf of Mexico. However, several other unconformities were noted in the Chicontepec operational area, extending canyon formation as far back as the early Paleocene, equivalent to the time of the Lower Wilcox.

The presence of two potential river systems feeding the Chicontepec canyon does, to some degree, complicate use of empirical scaling relationships, but it is likely that the middle paleo–drainage system (371-km-long stream in Fig. 9) provided sediment to the foreland basin while the southern river, being closer to the basin entry point, probably is linked with the submarine fan interpreted by Galloway et al. (2000). In any case, interpreted run-out lengths of the two systems are similar, and thus the scaling dimensions that result are virtually the same (Table 3).

The estimated submarine fan dimensions (fan-run out length and fan width) at 0.5 times the reconstructed paleo-river length roughly match the earlier-interpreted map area of the Chicontepec fan (Galloway et al., 2000; Fig. 9). The proximity of the tectonic front and interpreted small drainage network are reasons supporting the 0.5 fractional prediction, as used by Somme et al. (2009a) in similar examples. The nearby Puskon-1 well, located between the two fans (Fig. 9), penetrated the coeval Upper Wilcox (Eocene) interval (Rigzone, 2012; Lawton et al., 2015), but borehole logs from this well are not presently publicly available and thus represent a future calibration point for these predictions.

We expect that, with continued international exploration in Mexico and increased access to proprietary seismic data, the geometry of these two Upper Wilcox fans will be better resolved in the future. Certainly our predictions should be considered as testable hypotheses for future work. However, exploration is in the early stages here, and utility of these predictions ahead of drilling is considerable, given the high costs and long time frames involved. In addition, should new well penetrations suggest substantially larger submarine fan dimensions, we will have learned something important about the size of the updip catchments, and thus improvement of tectonic and paleogeographic reconstructions will certainly result from this effort.

CONCLUSIONS

The Gulf of Mexico basin is a rich and robust sedimentary archive that facilitates validation of first-order morphological relationships between and within segments of a source-to-sink system. It is also a continental-scale system, with most paleo-river lengths approaching or exceeding 1000 km, and therefore complements the initial application of Sømme et al.'s (2009b) scaling relationships to the much smaller Ormen Lange system of Norway (Sømme et al., 2009b).

Investigation of empirically derived source-to-sink scaling relationships from over 40 Cenozoic deepwater systems and their linked source areas shows a strong covariance between measured submarine fan size and up-system catchment area and longest river length. Submarine fan run-out lengths (defined as the distance from the coeval shelf margin to sand-prone fan termination) fall in the range of 10%–50% of the longest river length, with larger systems generally in the range of 10%–25% of the longest river length. Fan width also scales proportionally with fan length, though a lower positive correlation coefficient ($R^2 = 0.4$) is noted due to challenges in delineating fan width for some subsalt systems. Catchment area has a high correlation ($R^2 = 0.85$)

with longest river length, pointing to discharge and sediment flux as primary drivers of fan size.

The first-order relationships first identified by Sømme et al. (2009a) are clearly validated with this robust Gulf of Mexico subsurface information. These relationships are applicable over the 65 m.y. Cenozoic time interval because tectonic events within the hinterland source terrane result in changes to catchment area and relief, which in turn impacts sediment supply volume to the depositional basin. This long-term tectonic signal may be modulated by local factors, but ultimately propagates through the sediment routing system and becomes encoded in depositional systems over long time scales in terms of extents and scales of basin-floor fans.

Our work supports continued investigation and refinement of scaling relationships between and within source-to-sink segments. Further refinement will enhance applications to areas or systems that are less well constrained than northern Gulf of Mexico Cenozoic depositional systems; our application to the southern Gulf of Mexico Upper Wilcox interval supports this view. Global deep-time archives of continental processes that are embedded in ancient outcrops of submarine fans will be more readily accessed through this approach. Continued validation of this source-to-sink scaling methodology, primarily through deepwater drilling calibration but also detrital zircon–based catchment reconstructions, will support future application to exploration of data-poor frontier areas as well as unlocking the fragmentary record of ancient submarine systems in outcrop sections.

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