Giant meandering channel systems controlled by sediment supply to the deep-water Campos basin

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ABSTRACT

Large meandering submarine-channel systems are important conduits for mass transfer to continental margins; wider and deeper channels, with larger meanders, reflect larger sediment discharge. Some large meandering channel systems are known to receive voluminous sediment from the largest rivers in the world, such as the Ganges-Brahmaputra, Amazon, Indus, Mississippi, and Zaire (Congo); however, smaller rivers draining rapidly uplifting landscapes can also contribute significant terrigenous mass to continental margins. Here, we use three-dimensional seismic-reflection data from >2 km water depth in the Campos basin, offshore Brazil, to interpret the stratigraphy of a Late Cretaceous submarine-channel system within a deep-water salt-tectonic province. We mapped three regional seismic-reflection horizons, which define a sequence of at least 16 downstream-translating channel elements ~1 to >1.5 km wide with wavelengths ranging from 8 to 24 km. These are among the largest meandering channel forms and deposits in the world. Increased sediment discharge through submarine channels during the Late Cretaceous, driven by dynamic uplift along the humid and warm coast of southeastern Brazil, promoted the development of these large meandering channels. Analogous settings characterized by rapid uplift of coastal mountains and unstable, narrow shelves might promote large sediment supply to continental

margins, producing giant submarine canyon-channel-fan depositional systems and petroleum reservoirs.

INTRODUCTION

Deep-water channels are conduits through which turbidity currents transport terrigenous mass, including sediment and dissolved chemical loads, across continental margins to submarine fans (Piper and Normark, 2001). This sediment and chemical transfer shapes the seascape of continental margins, constructs a stratigraphic record of tectono-climatic environmental changes, and plays an important role in biogeochemical cycles. For example, the Bengal fan receives a large sediment load from rivers draining the rapidly uplifting Himalayas (~1 Bt/yr; Islam et al., 1999) and, as a result, it comprises wide, deep, meandering submarine channels feeding the largest accumulation of detritus on Earth (Barnes and Normark, 1985; Schwenk and Spieß, 2009; Kolla et al., 2012). Other large submarine fans, such as the Amazon, Indus, Mississippi, and Zaire (Congo), include meandering channels similar in shape and size to the Bengal. Based on insights from rivers, the morphology of such meandering submarine channels reflects their importance in mass transfer to continental margins; wider and deeper channels have larger meanders (Leopold and Wolman, 1960; Pirmez and Imran, 2003; William, 1986), reflecting larger sediment discharge (e.g., Leopold and Maddock, 1953; Konsoer et al., 2013).

Large meandering submarine-channel systems are fed voluminous sediment from some of the largest rivers in the world (Summerfield and Hulton, 1994; Milliman and Farnsworth, 2011). However, smaller rivers draining rapidly uplifting landscapes can also contribute significant terrigenous mass to continental margins (Milliman and Syvitski, 1992). For example, high-relief, tectonically active islands of the southwest Pacific Ocean, including New Zealand, Taiwan, Indonesia, Malaysia, Papua New Guinea, and the Philippines, make up only ~3% of the Earth landmass, but the short lengths and steep gradients of the rivers and the high variability of rainfall promote large fluvial sediment loads (collectively ~7 Bt/yr suspended sediment; Milliman and Farnsworth, 2011) to be routed from mountains to the ocean (Milliman and Syvitski, 1992). So, although some of the largest meandering submarine-channel systems in the world are linked to large rivers, we also expect similarly large submarine channels on the present seafloor and in ancient sedimentary successions linked to rivers draining small, tectonically active catchments (Milliman and Syvitski, 1992).

Here, we use three-dimensional (3D) seismic-reflection data from the deep-water Campos salt basin, offshore Brazil, to interpret the stratigraphic evolution of a giant Late Cretaceous submarine-channel system (Fig. 1). During the Late Cretaceous (Campanian-Maastrichtian), small rivers draining humid and warm, tectonically active coastal mountains of southeast Brazil provided voluminous sediment to the Campos-basin margin, which is characterized by rapid progradation (Bruhn and Walker, 1995; Milani et al., 2007; Fetter et al., 2009; Macgregor, 2013). These tectono-climatic conditions provide an opportunity to evaluate the hypothesis that small coastal rivers with appreciable sediment discharge can promote the development of giant meandering submarine-channel systems. Therefore, we will compare the Late Cretaceous timing of the documented voluminous sediment delivery to the Campos basin margin to the contemporaneous stratigraphic record of submarine-channel evolution in the Campos basin. We will measure the scale of meandering submarine channels (width and meander wavelength) in the Campos basin for comparison to some of the largest meandering channels on the present seafloor.

GEOLOGIC SETTING

The Campos basin is located along the southeastern continental margin of Brazil in the South Atlantic Ocean (Fig. 1). It is one of the most productive deep-water hydrocarbon basins in the world (Mohriak et al., 1990; Bruhn et al., 2003). The Campos basin initiated during Late Jurassic breakup of Gondwana and opening of the South Atlantic Ocean (Guardado et al., 1989) and comprises Berriasian-early Aptian continental rift deposits, overlain by middle Aptian salt (Davison, 2007; Karner and Gamboa, 2007; Winters, 2007), an early-middle Albian carbonate platform, and a late Albian to present succession of progressively deeper-water continental-margin deposits (Bruhn, 1998). The Aptian salt plays an important role in establishing the structural style of the Campos basin; deformation was initiated by early Albian eastward basin tilting and subsequent gravity spreading as progradation occurred (Demercian et al., 1993; Davison et al., 2012; Quirk et al., 2012; De Gasperi and Catuneanu, 2014). The Cretaceous-present paleoflow direction through submarine-channel systems is generally northwest-to-southeast because of the regional slope of the Brazilian continental margin. However, paleoflow direction in the Campos basin varies depending on local structural configuration and diapir orientation; Covault et al. (2019) interpreted north-to-south paleoflow for a Miocene channel system, and Ceyhan (2017) interpreted northwest-to-southeast, west-to-east, and north-to-south paleoflow for Pliocene-Pleistocene channel systems. We focused on a Late Cretaceous submarine-channel system in a structural domain generally characterized by extensional and contractional salt stocks and walls formed during west-to-east translation of surrounding minibasins across the margin (Demercian et al., 1993; Mohriak et al., 2012).

During the Late Cretaceous (Campanian-Maastrichtian), the Trindade mantle plume promoted dynamic uplift along the humid and warm coast of southeastern Brazil (Bruhn and Walker, 1995; Thompson et al., 1998; Cobbold et al., 2001; Meisling et al., 2001; Fetter et al., 2009; Quirk et al., 2013). High-relief coastal mountains were drained by small rivers, which provided sediment directly to submarine canyons, which had incised across an unstable, narrow shelf (Fetter et al., 2009). The Late Cretaceous Campos basin is characterized by rapid progradation of the margin (Guardado et al., 2000; Milani et al., 2007; Fetter et al., 2009; Macgregor, 2013) and large, coarse-grained, channelized petroleum reservoirs (e.g., Roncador Field; Rangel et al., 1998). We will compare these upstream tectono-climatic events to the contemporaneous evolution of a submarine-channel system in >2 km water depth of the Campos basin.

DATA AND METHODS

Subsurface data and interpretation

We used a Kirchhoff pre-stack depth-migrated 3D seismic-reflection volume with wavelengths of ~50-100 m (vertical resolution ~12.5-25 m) and 25 m horizontal sampling rate. The seismic-reflection volume was donated by Investigação Petrolífera Limitada (PGS). Seismic-reflection data were processed to zero phase. We used the Paradigm® SeisEarth® interpretation and visualization product suite to map three regional horizons based on line-by-line continuity and terminations of relatively high-amplitude seismic reflections. We used root mean square (RMS) amplitude maps to highlight channel systems.

Ages of seismic-reflection horizons

We focused on a Late Cretaceous submarine-channel system between two regional horizons: a basal Horizon 1 and a top Horizon 3 (Figs. 2 and 3; Supplementary Files 1 and 3). We mapped an intermediate Horizon 2 to capture the evolution of the channel system and constrain

RMS amplitude maps (Fig. 3; Supplementary File 2). We did not have well data to calibrate the seismic-reflection data; however, previous studies that overlap with our study area provide enough well-to-seismic calibration to identify and approximate the age of the key seismic-reflection horizons (Guardado et al., 1989; Fetter, 2009; Mohriak et al., 2009; Quirk et al., 2012). We interpreted a regional Upper Cretaceous, potentially Campanian (Fig. 7 of Quirk et al., 2012), horizon overlying a Santonian horizon (Fig. 15.38 of Mohriak et al., 2009). This horizon is the base of our channel system of interest (Horizon 1); it is a high-amplitude peak characterized by channel geometries and truncation of underlying reflections, which is described below in the 'Seismic Stratigraphy and Channel Morphology' section. We interpreted another regional seismic reflection to be approximately the top Cretaceous (see Figs. 8 and 9 of Fetter, 2009; Figs. 15.30, 15.38, and 15.39 of Mohriak et al., 2009; and Fig. 7 of Quirk et al., 2012). The top Cretaceous regional horizon of Guardado et al. (1989), focused on the proximal part of the margin, appears to correlate with these interpretations. This horizon is the top of our channel system (Horizon 3); it is a variable-amplitude peak that appears to be truncated by high-amplitude, channelized seismic reflections of Paleogene age. To the south and east of our study area, the top Cretaceous horizon separates more continuous, low- to moderate-amplitude reflections from an overlying interval of lower-amplitude, faulted reflections.

How do we measure the size of a submarine channel?

A common measure of a river channel is the bankfull discharge (Leopold and Wolman, 1960); channel shape and dimensions of meandering rivers are associated with bankfull flow (Wolman and Miller, 1960). As turbidity currents do not have a well-defined upper boundary, it is less obvious what can be considered as bankfull. On the seafloor, channel systems of large submarine fans commonly comprise erosional valleys oriented parallel to the steepest descent downstream, with a relatively narrow, sinuous channel form in the deepest location in the valley (i.e., the thalweg) (Fig. 4A). The depths of submarine-channel systems from thalweg to levee crest can be as many as 10-100 times larger than bankfull depth in rivers, and levee-crest widths can be 2-3 times wider than rivers (Pirmez and Imran, 2003; Konsoer et al., 2013; Shumaker et al., 2018). However, the planform characteristics of submarine channels and rivers are remarkably similar (e.g., Flood and Damuth, 1987). This suggests that the effective width and depth of turbidity currents that form submarine channels and determine the nature and dimensions of the planform are often narrower and shallower than the outer-levee-crest widths and levee-thalweg depths (Pirmez and Imran, 2003). Both the velocity and concentration maxima of turbidity currents occur near the base of the flow (Sequeiros et al., 2010; Eggenhuisen and McCaffrey, 2012). This high-velocity core is likely to be thinner and narrower than the full channel or canyon form, and it is the portion of the flow that contains most of the sediment load (Luchi et al., 2018) and actively sculpts the meandering planform of the channel (Pirmez and Imran, 2003). In the Zaire (Congo) Canyon, the largest observed turbidity currents were largely restricted to the bottom 40 m, a depth that corresponds to the part of the canyon that seems to have a characteristic width (Azpiroz-Zabala et al., 2017). These characteristic channel forms are often recognizable in the subsurface seismic-reflection data as well, especially when they are abandoned and passively filled, and therefore well preserved. The most recent channel on the proximal Bengal fan has a well-defined meandering planform with a characteristic width that is much smaller than the distance between the outer-levee crests (Fig. 4A). The latter is a measure of the channel-belt width, and has no direct relation to the characteristic discharge of the channel-shaping flows. Similar morphologies develop in forward models of submarine channel-levee systems (Figs. 4B and 4C; Sylvester et al., 2011; Sylvester and

Covault, 2016; Covault et al., 2016). The deposits within the narrow, sinuous channel form located at the bottom of the system have been called 'channel elements' (Mutti and Normark, 1987; Fildani et al., 2013; Hubbard et al., 2014), which have been interpreted to migrate and stack over time to produce larger-scale, composite channel systems (e.g., Deptuck et al., 2003; Mayall et al., 2006; Hodgson et al., 2011; McHargue et al., 2011; Sylvester et al., 2011; Covault et al., 2016; Fig. 4C).

We measured channel widths and meander half wavelengths that correspond to this characteristic channel form. Meander wavelengths were estimated through the automatic identification of inflection points along the channel centerline (see Sylvester et al., 2013; and Sylvester and Pirmez, 2017; for details). We used this approach on maps of submarine channels of the Bengal fan (Kolla et al., 2012), offshore West Africa (the Dalia channel system; Abreu et al., 2003), and the Gulf of Mexico (Joshua Channel; Posamentier, 2003; Kramer et al., 2016). We replotted data collected by Pirmez (1994) for the Amazon channel. We have also plotted width-wavelength data for rivers (Leopold and Wolman, 1960; Howard and Hemberger, 1991) and unpublished data from the Purus river in Brazil that was collected using the mapping techniques described in Sylvester et al. (2019).

SEISMIC STRATIGRAPHY AND CHANNEL MORPHOLOGY

We mapped three Late Cretaceous seismic-reflection horizons, 1-3, from base to top, within a paleotopographic low surrounded by salt diapirs (Figs. 2 and 3; Supplementary Files 1-3). Horizon 1 (Upper Cretaceous, potentially Campanian) is defined by the bases of numerous high-amplitude, discontinuous, channel-form seismic reflections. In Figure 3A, the western margins of these channel-from reflections are commonly preserved, with the eastern margins eroded, and they predominantly stack from west to east. Some of the margins of the channel forms appear to transition into lower-amplitude, continuous seismic reflections. We interpret the high-amplitude, discontinuous reflections to be coarse-grained channelized deposits and the lower amplitude, continuous seismic reflections to be finer-grained levee-overbank deposits based on seismic-facies models of deep-water depositional systems (Normark et al., 1993; Abreu et al., 2003; Deptuck et al., 2003). In Figure 3A, channel forms appear to climb and vertically stack up to horizon 2, which is an intermediate, regionally mappable horizon defined by channel forms transitioning into lower-amplitude, continuous reflections. In the central part of the study area, horizon 2 appears to truncate low-amplitude, continuous reflections; in the east, horizon 2 appears to truncate high-amplitude channel-form reflections. Horizon 3 (top Cretaceous) is the top of the seismic sequence and it appears to truncate underlying seismic reflections (Fig. 3).

Figures 5A-D show ~16 high-RMS-amplitude, sinuous ribbons between horizons 1 and 3, which correspond with the high-amplitude channel forms in cross sections of Figure 3. We interpret these channel-form ribbons to record the downstream translation of a large submarine-channel system. Although the channel system appears to comprise as many as 16 individual 'channel elements' *sensu* Fildani et al. (2013), we are most confident in segments of the channel geometries mapped on horizons 1-3 (Supplementary Files 1-3), which indicate widths between ~1 to >1.5 km and half wavelengths ranging from ~4-12 km (Fig. 6, lower right, inset). Each of these channel elements appears to meander and, in aggregate, they are stacked to produce the channel system between horizons 1 and 3. Horizon 1 is the base of this large meandering channel system; horizon 2 is an intermediate horizon deposited after one of the smaller meander loops in the central-eastern part of the study area was cut off; horizon 3 is the top of this channel system, which was eroded by a younger channel system (Fig. 3).

DISCUSSION: GIANT MEANDERING SUBMARINE CHANNEL SYSTEMS

Figure 6 shows a plot of widths and meander wavelengths of some of the largest meandering channels on the seafloor and channel elements of the lower Miocene Dalia channel system, a hydrocarbon reservoir in the subsurface offshore West Africa (Abreu et al., 2003). Some of the largest rivers in the world deliver sediment to the seafloor channels, which, in turn, disperse it across some of the largest submarine fans in the world, including the Amazon and Bengal. The Dalia system received sediment from West Africa but prior to the Pliocene onset of the modern Zaire (Congo) river and submarine canyon-fan system (Ferry et al., 2005). The seafloor channels of the largest submarine fans in the world far exceed the size of the Dalia channel elements, which are similar in size to other subsurface channel systems in West Africa (e.g., McHargue et al., 2011). However, the Late Cretaceous channel elements in the Campos basin are wider and their meanders are larger than the Amazon and Bengal submarine channels and some of the largest river bends on Earth.

Although no discharge measurements are available for these systems, the channel widths we have measured are likely linked to the characteristic discharge of the channel-forming turbidity currents, just like fluvial channel dimensions are related to river discharge (Leopold and Maddock, 1953; Konsoer et al., 2013). The unusually large channel widths and meander wavelengths observed in the Campos basin suggest that turbidity currents shaping these channels had larger discharges than those responsible for building the largest submarine fans on Earth. Both the Bengal and Amazon channels are ultimately fed by large rivers with large drainage areas; however, the Campos basin received sediment from small, dynamically uplifting coastal rivers (Fetter et al., 2009). The size of channels described here attest to the extraordinary sediment discharges of the turbidity currents that shaped them. The landscape evolution modeling work of Braun et al. (2013)

suggests that, despite being characterized by low slopes, dynamic topography related to mantle plumes can result in significant pulses of erosion and sediment flux.

The idea that small rivers drain rapidly uplifting landscapes and deliver voluminous terrigenous sediment to continental margins is not new; this has been hypothesized since researchers began to compile global sediment loads from stream gauges (e.g., Milliman and Syvitski, 1992; Milliman and Farnsworth, 2011). For example, on the seafloor, offshore New Zealand, the Hikurangi channel is a large (several km wide), long (~1500 km) sinuous submarine-channel system receiving voluminous sediment from small rivers draining rapidly uplifting mountains since the late Miocene (Lewis, 1994). In the subsurface, a large (3-5 km wide, composite channel 'belt'), sinuous submarine-channel system in the Molasse foreland basin, Austria (Upper Puchkirchen Formation; De Ruig and Hubbard, 2006), developed in response to an increase in early Miocene sediment supply from the tectonically active Alps (Kuhlemann, 2007; Sharman et al., 2018). However, it is challenging to decipher the evolution of meanders in these systems and other examples; seafloor examples represent static images of a moment in time, and some subsurface studies primarily characterize the composite channel-belt fill rather than the smaller-scale, individual 'channel elements,' which are not always convincingly imaged.

Our mapping in the Late Cretaceous Campos basin provide new insights into the depositional products of increased terrigenous sediment supply to the basin margin. The Campos example is particularly impressive because it evolved in a salt-tectonic province. That is, it is impressive that the Campos example exhibits such large meander wavelengths and so much migration because it is surrounded by potentially confining salt diapirs. We speculate that the channel might meander even more, in particular, it might have expanded, or 'swung' *sensu* Peakall et al. (2000), to the north and south, if not for confinement from salt-influenced topographic highs.

Deep-sea drilling into submarine canyon-fan systems has focused on some of the largest sediment-routing systems in the world (e.g., Deep-Sea Drilling Project Leg 96 of Mississippi Fan, Ocean Drilling Program Leg 155 of Amazon Fan, International Ocean Discovery Program Expedition 354 of Bengal Fans; Bouma et al., 1986; Flood et al., 1995; France-Lanord et al., 2016), with some exceptions (e.g., Ocean Drilling Program Leg 167 of the California margin, International Ocean Discovery Program Expedition 308 of the Brazos-Trinity deep-water depositional system; Piper and Normark, 2001; Pirmez et al., 2012). However, smaller rivers draining rapidly uplifting landscapes can also deliver significant sediment loads to continental margins, promote increased sediment discharge, and form large meandering submarine-channel systems, such as the Late Cretaceous Campos basin fill. These channel systems can disperse terrigenous mass across large areas of continental margins and promote the formation of thick depositional successions recording signals of upstream tectono-climatic perturbations (e.g., Romans et al., 2016). Studies of these types of deep-water systems linked to small, mountainous rivers can potentially improve understanding of Earth history and the depositional response of continental margins to environmental perturbations.

The idea that sediment supply, and not simply drainage area, is the key control on the scale of submarine-channel meanders is useful in predicting large channels in the subsurface of basin margins. For example, in frontier, petroliferous sedimentary basins, thermochronology data can provide clues to the uplift of coastal mountains, which promotes sediment generation and supply to offshore basin-margin canyon-channel-fan systems. Based on our study in the Campos basin, these are the ingredients for the generation of large meandering submarine-channel systems. As a case in point, in the western Gulf of Mexico, a currently active exploration target, Cenozoic uplift of the North American Cordillera, and accelerated uplift of southern Mexico during the late

Miocene (Witt et al., 2012; Molina-Garza et al., 2015), promoted the development of the long run-out Veracruz submarine canyon-channel-fan system (Hessler et al., 2018). The presence of this deep-water depositional system was only recently predicted based on provenance analysis of deep-sea drilling (Hessler et al., 2018) coupled with knowledge of the rapid uplift of the sediment source area in southern Mexico. However, subsequent seismic-reflection interpretations in the western Gulf of Mexico revealed meandering submarine-channel systems similar in scale to the Late Cretaceous of the Campos basin (Winter et al., 2017; Clark et al., 2019). Keeping in mind the primary result of our study, that increased sediment supply from small rivers draining uplifting coastal mountain catchments can result in giant meandering submarine-channel systems, knowledge of the sediment source area can be used to predict the scale of meandering submarine-channel systems in a frontier basin.

CONCLUSIONS

Some of the largest meandering submarine channels in the world developed in the Campos basin during the Late Cretaceous as a result of increased sediment supply from small, but rapidly uplifting, coastal mountain rivers. Increased sediment discharge promoted the development of these giant meandering submarine channels. The idea that small, mountainous rivers can deliver large sediment discharge to continental margins is not new (Milliman and Syvitski, 1992); we show some of the first detailed imagery and interpretations of the resultant deep-water stratigraphy. Continental margins linked to small, mountainous rivers can contain thick and near-complete accumulations of stratigraphic information of Earth history; moreover, explorers of natural resources might expect to find giant submarine-channel systems in these settings.

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FIGURE CAPTIONS

Figure 1. Study area in the deep-water Campos Basin. Gray polygon indicates location of seismic-reflection volume and maps in Figures 3 and 5. Modified from Peres (1993).

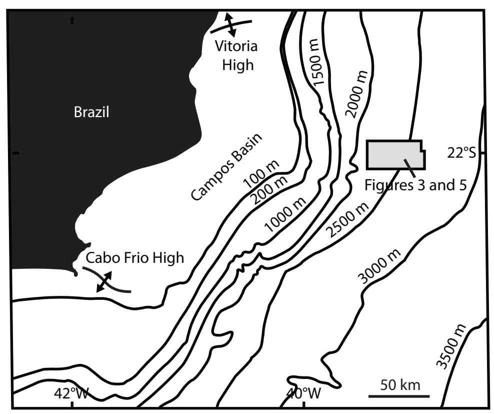
Figure 2. Structure maps of horizons bounding the Late Cretaceous channel system in the Campos basin. Black lines indicate locations of cross sections in Figure 3.

Figure 3. Cross sections of the Campos basin channel system between horizons 1 and 3. Black dashed rectangles in seismic-reflection profiles A-A’ and B-B’ indicate locations of depositional elements in line-drawing interpretations. In cross section A-A’, overlying Horizon 3, discontinuous, high-amplitude seismic reflections are Cenozoic channel deposits, including the Miocene channel system of Covault et al. (2019).

Figure 4. Concept of bankfull depth of a meandering channel system as a basis for measuring channel geometry. (A) Seafloor of the Bengal channel. Note the relatively narrow, sinuous channel form in the deepest location in the valley (i.e., the thalweg). Modified from Kolla et al. (2012). Map (B) and cross-section (C) views of a forward model of a submarine channel-levee system from Sylvester and Covault (2016) and Covault et al. (2016).

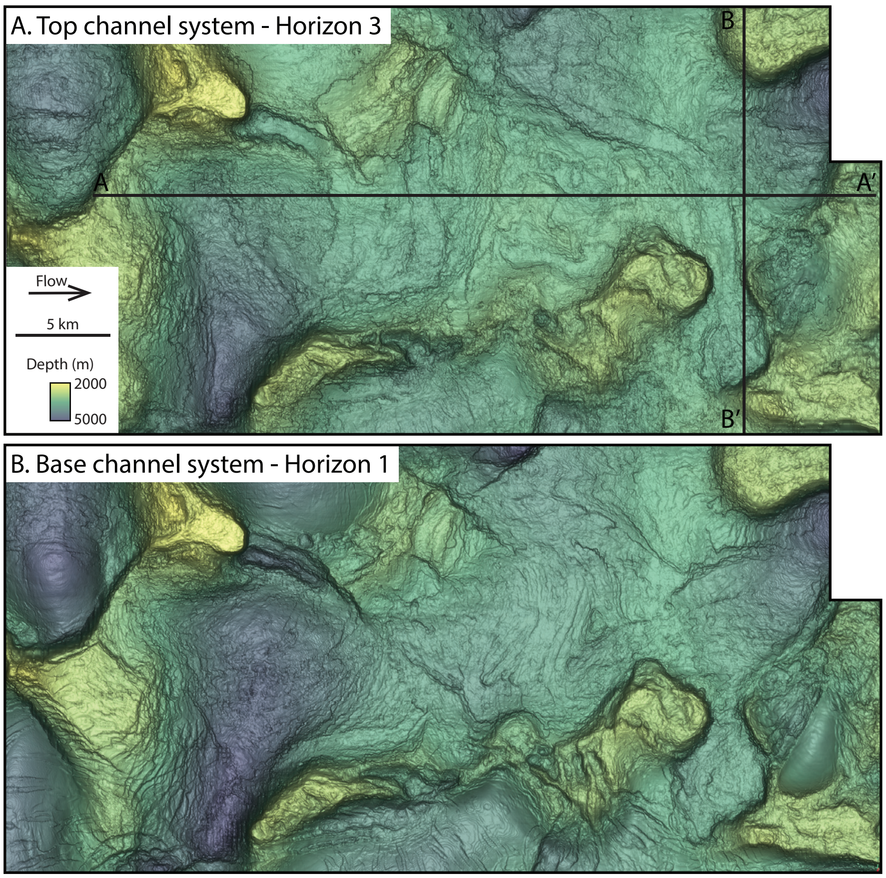
Figure 5. (A) RMS amplitude map between horizons 1 and 2. (B) Interpretation of channel forms. (C) RMS amplitude map between horizons 2 and 3. (D) Interpretation of last channel form in the system.

Figure 6. Submarine and fluvial channel wavelength vs. width. See ‘How do we measure the size of a submarine channel?’ for methods of measurement (Sylvester et al., 2013; Sylvester and Pirmez, 2017). Black boxes indicate measurements of channels in the Campos basin. Lower right, inset: Campos channel bends we felt most confident in measuring in the seismic-reflection data.



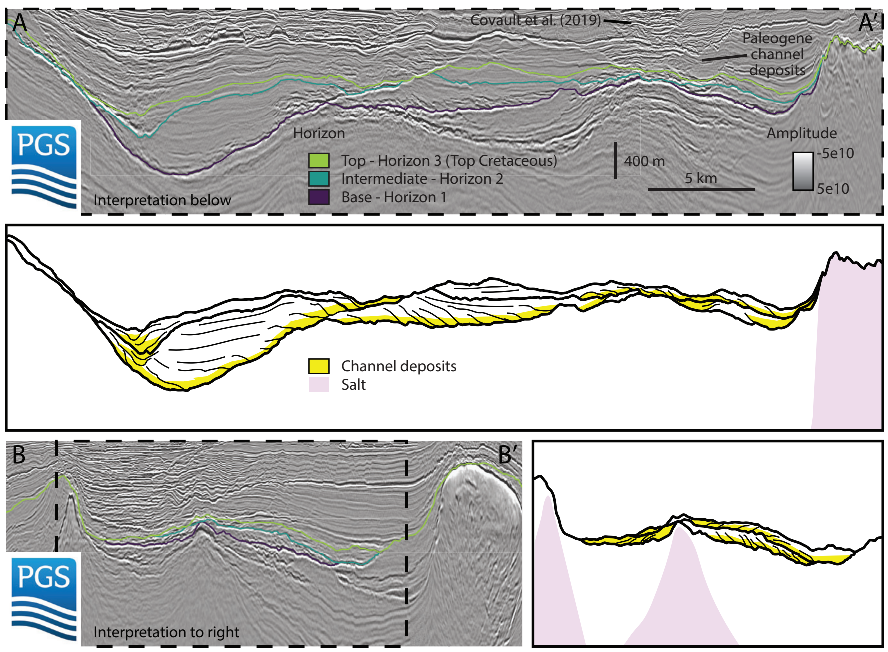
Vitoria
High
Brazil
Campos Basin
100 m
200 m
1000 m
1500 m
2000 m
2500 m
3000 m
3500 m
22°S
Figures 3 and 5
Cabo Frio High
42°W
40°W
50 km

Figure 1.



A. Top channel system - Horizon 3
B
A
A'
B'
Flow
5 km
Depth (m)
2000
5000
B. Base channel system - Horizon 1

Figure 2.



A
A'
Covault et al. (2019)
Paleogene channel deposits
Horizon
Top - Horizon 3 (Top Cretaceous)
Intermediate - Horizon 2
Base - Horizon 1
400 m
5 km
Amplitude
-5e10
5e10
PGS
Interpretation below
Channel deposits
Salt
B
B'
PGS
Interpretation to right

Figure 3.

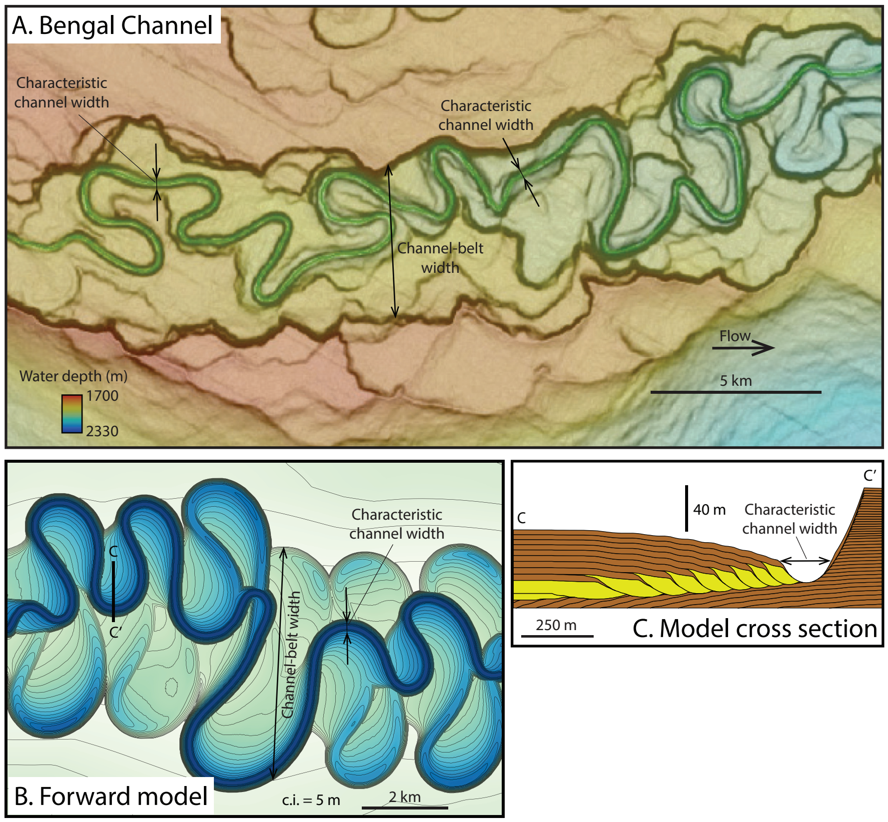

A. Bengal Channel
Characteristic channel width
Characteristic channel width
Channel-belt width
Flow
5 km
Water depth (m)
1700
2330
B. Forward model
C
C′
Characteristic channel width
Channel-belt width
c.i. = 5 m
2 km
C
C′
40 m
Characteristic channel width
250 m
C. Model cross section

Figure 4.

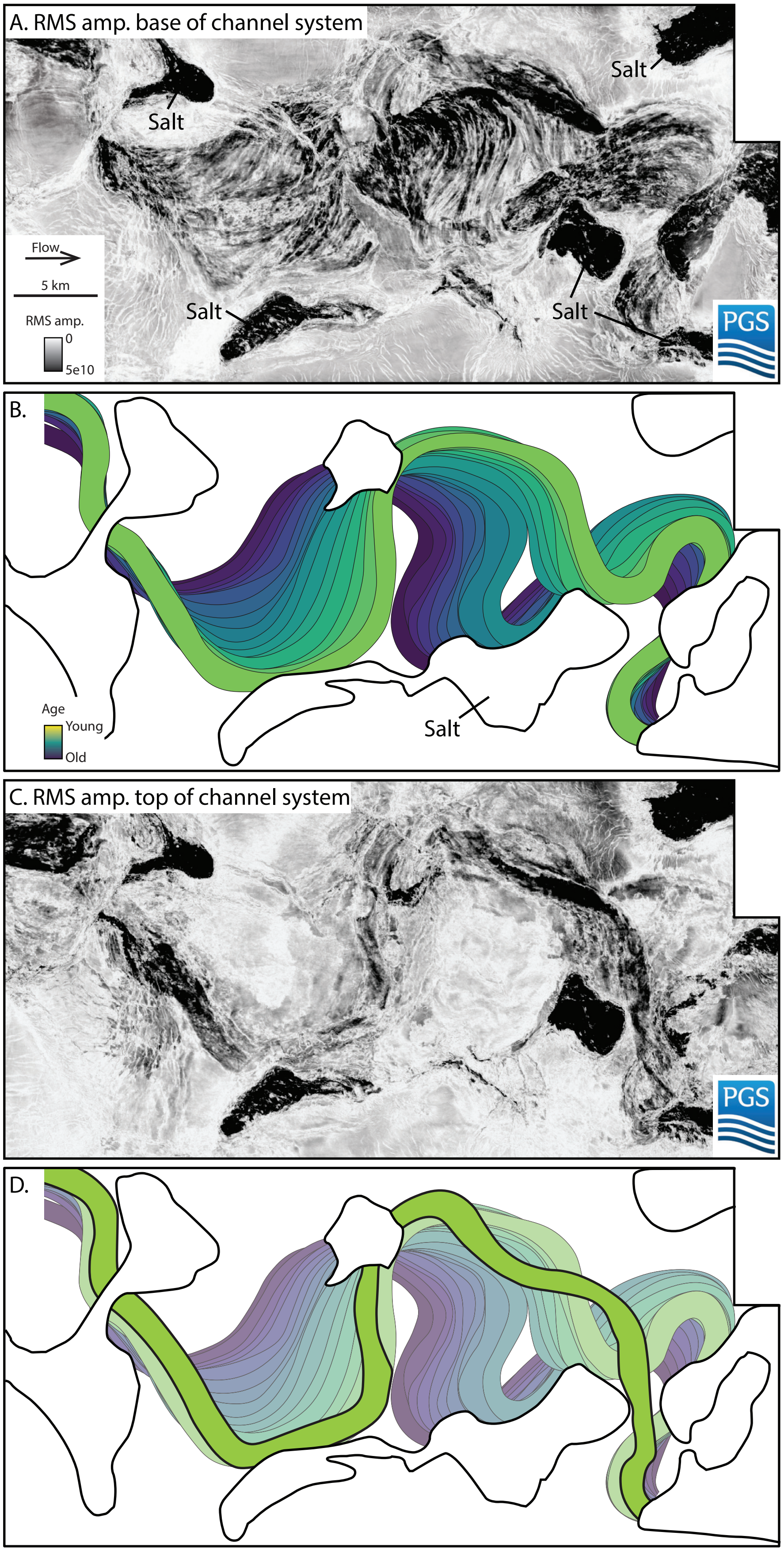

A. RMS amp. base of channel system
Salt
Salt
Flow
5 km
RMS amp.
0
5e10
Salt
Salt
PGS
B.
Age
Young
Old
Salt
C. RMS amp. top of channel system
PGS
D.

Figure 5.

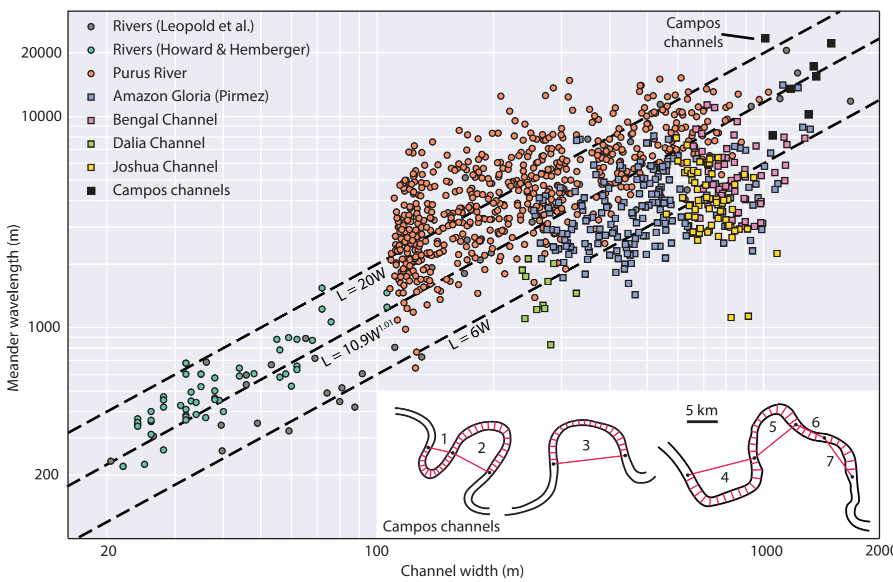

Rivers (Leopold et al.)
Rivers (Howard & Hemberger)
Purus River
Amazon Gloria (Pirmez)
Bengal Channel
Dalia Channel
Joshua Channel
Campos channels
Campos channels
L = 20W
L = 10.9W^1.01
L = 6W
5 km
1
2
3
4
5
6
7
Campos channels
20000
10000
1000
200
20
100
1000
2000
Meander wavelength (m)
Channel width (m)

Figure 6.