INTRODUCTION

Submarine channels are conduits for sediment-gravity flows to deep water (Piper & Normark, 2001), delivering sediment to the largest detrital accumulations on Earth in submarine fans (Barnes & Normark, 1985). Submarine-channel deposits contain a record of deep-water sediment dispersal (Hubbard et al., 2014) and changes in upstream source areas (Romans et al., 2016) as well as form hydrocarbon reservoirs (Pettingill & Weimer, 2002) and store large amounts of organic carbon (Galy et al., 2008). Submarine channels have been known since the 1980s to exhibit planform morphologic characteristics similar to rivers (Damuth et al., 1983); however, some influential papers have stressed their unique migration style compared to their fluvial counterparts (Peakall et al., 2000; Wynn et al., 2007). This is...
important because channel migration, that is, the expansion and downstream translation of bends (i.e., ‘swing’ and ‘sweep’; Peakall et al., 2000), as well as vertical movements by aggradation and incision, set the stratigraphic architecture of channelized depositional systems (Sylvester et al., 2011; Jobe et al., 2016). For example, combined translation and expansion of river bends, with little aggradation, are thought to produce sheet-like sand bodies, whereas limited translation and significant aggradation of submarine-channel bends result in stacks of ribbon-like sand bodies (Peakall et al., 2000). Early work on the evolution of aggradational, moderate to high-sinuosity channels has suggested that downstream translation is rare or non-existent (Peakall et al., 2000). However, downstream translation has been observed since then in three-dimensional (3D) seismic-reflection datasets (Abreu et al., 2003; Posamentier, 2003; Kolla et al., 2012; Janocko et al., 2013) and sometimes attributed to allogenic changes in sediment delivery to the system (Posamentier & Kolla, 2003). Submarine channels are thought by some to maintain a relatively stable planform as they aggrade (Peakall & Sumner, 2015); however, there are published examples of meandering aggradational submarine channels (Figure 3 of Posamentier and Kolla, 2003; shows up to tens of metres of aggradation associated with downstream translation of a leveed channel offshore eastern Borneo). A quantitative analysis of exactly how much aggradational submarine channels can expand and translate is a topic for future research. Although channel migration is often discussed in terms of expansion, translation and rotation, a clear understanding of when and why channel bends expand or translate is still lacking. This is especially true for submarine channels.

Based on insights from rivers (Howard & Knutson, 1984; Smith et al., 2009; Ghinassi et al., 2016), it is proposed that downstream translation of bends might be common in settings that promote the generation of high-curvature bends, either as a result of cutoffs or other perturbations to the equilibrium planform channel pattern. Such settings include deep-water salt-tectonic provinces (Hudec & Jackson, 2007), in which rapid rates of deformation commonly create complex topography that localizes channel pathways and depocentres (Gee & Gawthorpe, 2006). Channel-sculpting sediment-gravity flows tend to follow the direction of steepest descent across a slope, and salt deformation can create topography that draws gravity flows away from the regional slope of a continental margin. The resulting sediment-dispersal system might contain complex and surprising channelized stratigraphic patterns, such as anomalous meander-loop geometries (Mendoza-Veloz, 2007). Notably, these stratigraphic patterns are a result of tectonic deformation and gravity-flow interactions with the
resultant topography, independent of any major changes in sediment delivery to the submarine-channel system.

Here, 3D seismic-reflection data from the Campos Basin, offshore Brazil, is used to characterize the structural geometry of a salt diapir and stratigraphic architecture of a submarine-channel system (Figures 1 and 2). The combined structural and stratigraphic evolution is interpreted, including meander-cutoff development adjacent to a salt diapir followed by downstream translation of a channel bend. The stratigraphic evolution is tested with a simple numerical model that has been developed based on the Howard & Knutson (1984) meandering-channel model (Sylvester & Covault, 2016). The goal of this subsurface characterization and stratigraphic modelling study is to shed light on the processes and controls of submarine-channel downstream translation, which might be common in rapidly deforming settings, like salt basins.

2 | GEOLOGIC SETTING

The Campos Basin is located in water depths >200 m along the southeastern continental margin of Brazil in the South Atlantic Ocean (Carminatti & Scarton, 1991; Bruhn et al., 2003) (Figure 1). It is separated from the adjacent Espirito Santo (to the north) and Santos (to the south) basins by northwest-southeast-oriented basement highs (Guardado et al., 2000). The Campos Basin is one of the most productive hydrocarbon-bearing basins in the world (Mohriak et al., 1990); in 2017, total daily production was 1.3 million barrels of oil and 25 million cubic metres of natural gas from a variety of reservoirs, including Cretaceous to Miocene siliciclastic turbidites (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., 1990). The basin fill comprises Berriasian-early Aptian continental rift deposits, overlain by middle Aptian salt, an early-middle Albian carbonate platform, and a late Albian to present succession of progressively deeper-water continental-margin deposits (Bruhn, 1998). The Cretaceous-present palaeoflow direction is generally northwest-to-southeast because of the regional slope of the Brazilian continental margin (Figure 1). However, palaeoflow direction in the Campos Basin varies depending on local structural configuration and orientation of topographic lows; in an MS thesis at the University of Texas at Austin, Ceyhan (2017) interpreted northwest-to-southeast, west-to-east and north-to-south palaeoflow for Pliocene-Pleistocene channel systems.

The Aptian salt plays an important role in establishing the structural style of the Campos Basin. The base of the Aptian is a detachment surface (Fetter, 2009). Below the detachment, the main structural features are horsts and grabens bounded by steep normal faults active during Early Cretaceous rifting (Chang et al., 1992). Above the detachment, salt deformation was initiated by early Albian eastward basin tilting (De Gasperi & Catuneanu, 2014). Salt deformation has resulted in structural domains including a proximal domain of east-to-west extension and extensional diapirs, an extensional to compressional intermediate, transitional domain of west-to-east translation and shortened diapirs, and a distal domain of west-to-east...
West-east seismic-reflection profiles (left) and interpreted depositional elements (right). Profiles are oriented west (left) to east (right). Profile locations are in Figure 2. Black dashed rectangles in seismic-reflection profiles (left) indicate locations of interpreted depositional elements (right). The channel system between horizons 3 and 5 is the focus of this study: cutoffs occurred at horizon 3, downstream-translating deposits are between horizons 3 and 4, and the last-active channel fill is between horizons 4 and 5. Horizons 3–6 are available to download as supplementary material (Supplementary Horizons 3–6)
contraction within a fold-and-thrust belt (Demercian et al., 1993; Mohriak et al., 2012). This paper focuses on the seismic stratigraphy of a Miocene submarine-channel system in the intermediate structural domain of the Campos Basin (Figure 1).

3  |  DATA AND METHODS

3.1  |  Subsurface data and interpretation

Amplitude and coherence (i.e., similarity between adjacent seismic traces; Bahorich and Farmer, 1995) attributes generated from a Kirchhoff pre-stack depth-migrated 3D seismic-reflection volume were used with wavelengths at the depths of interest of ~20–50 m (vertical resolution ~5–12.5 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. The Paradigm® SeisEarth® interpretation and visualization product suite was used to map six regional horizons based on line-by-line continuity and terminations of relatively high-amplitude seismic reflections (Figures 2 and 3). Root mean square (RMS) amplitude maps were used to highlight channel systems to interpret in more detail (cf. De Ruig & Hubbard, 2006) (Figure 4). A series of discontinuous, high-amplitude seismic reflections were interpreted to define channelized deposits by selecting a reflection and using a 3D propagator algorithm to cross-correlate nearest-neighbour seismic traces to within a defined confidence interval (Figure 5) (cf. Madof et al., 2009). Horizons 1 and 6 are interpreted to be base and top, respectively, of the Miocene based on Ceyhan (2017) and published seismic-stratigraphic studies and stratigraphic charts (Contreras, 2011; Contreras et al., 2010; Fetter, 2009; Winter et al., 2007).

Midland Valley’s Move® software was used to apply 2D restoration to the cross-section profile A of Figure 3. For the restored sections, a regional topographic slope of 0.18° was assumed, which is parallel to the modern slope in the study area. Deflections to this regional slope were interpreted based on the positions of channel systems, which were assumed to follow topographic lows. All bedding was restored to the topographic surface using flexural slip because salt-diapir uplift was interpreted to be a result of regional shortening (see below). Sediment was not decompacted because the primary concern in the restorations was the evolution of surface topography. Therefore, unit thicknesses are incorrect, but the interplay between salt deformation and topography has been captured.

3.2  |  Numerical model of planform channel evolution

A simple kinematic meandering model that is based on Howard and Knutson (1984), using a formulation that is equivalent to the approach of Ikeda et al. (1981) (Sun et al., 1996), is used to better understand the migration patterns of submarine channels (i.e., expansion and translation). A key aspect of this model is that migration rate is a function of the weighted sum of upstream curvatures. To compute the migration rate, the upstream curvatures are converted to a ‘nominal’ migration rate, defined as follows:

\[ R_0 = \frac{k_i W}{R} \]  

where \( R_0 \) is the nominal migration rate, \( k_i \) is a migration rate constant, \( W \) is channel width and \( R \) is radius of curvature. Then, the actual migration rate \( R_1 \) can be estimated using:

\[ R_1(s) = \Omega R_0(s) + \Gamma \int_0^\infty R_0(s - \xi)G(\xi)d\xi \int_0^\infty G(\xi)d\xi^{-1} \]

2.5, and \( G(\xi) \) is an exponential weighting function:

\[ G(\xi) = e^{-\alpha \xi} \]

The weighting decreases exponentially with distance from the point of interest and the exponent \( \alpha \) is a function of channel depth \( D \) and the friction factor \( C_f \)

\[ \alpha = 2k D/C_f \]

where \( k \) is a constant that takes the value of 1.0 (Howard & Knutson, 1984). In the original formulation of the model, in an attempt to mimic the observations of Hickin and Nanson (1975), curvatures higher than a critical value result in a lower migration rate (Howard and Knutson, 1984). However, new data from modern rivers suggest that migration rate increases with higher curvatures if the phase lag between curvature and migration rate is considered (Furbish, 1988; Sylvester et al., 2019); therefore, for all curvature values, a simple linear relationship between curvature and nominal migration rate is used (Equation 1).

Although more physics-based models of submarine channel evolution have been developed (Das et al., 2004), they do not capture the long-term evolution of channel migration. The Howard and Knutson (1984) model has been previously used in modelling both subaerial and submarine meander development (Finnegan & Dietrich, 2011; Limaye & Lamb, 2014; Sylvester & Covault, 2016). While the model used here only captures the large-scale kinematics of meandering and does not reproduce phenomena like compound meander development and upstream influence of curvature, it captures well the translation and expansion of meander bends and it provides a simple framework with a small number of parameters to explore the origins of the bends observed in the Campos Basin.
4 | RESULTS

4.1 | Subsurface characterization

Six horizons were mapped across a ~12 × 18 km area of the intermediate, transitional structural domain of the Campos Basin, in water depths between ~2,100 and 2,500 m (Figure 1). The seismic character is described from the base of the subsurface section (horizon 1) to the top (horizon 6) (Figures 2 and 3). The detailed seismic-stratigraphic architecture between horizons 1 and 3 is not interpreted; these horizons were mapped for the purposes of the structural restoration presented below (Figure 7). Horizons 3–6 are available to download as supplementary material (Supplementary Horizons 3–6).

Horizon 1 is the base of a section of seismic reflections including a high-amplitude package confined within large-scale concave-up surfaces defined by reflection terminations (Figures 2 and 3). Reflections are more continuous and lower amplitude outside the concave-up surfaces (Figure 3). An RMS-amplitude extraction between horizons 1 and 2 shows a north-south-oriented channel pattern, which is continuous across a salt diapir (Figure 4A). Seismic reflections are truncated against the western side of the diapir (Figure 3). The package of high-amplitude seismic reflections between horizons 1 and 2 is interpreted as channel deposits. The trend of the channel system is oriented directly over the salt diapir (Figure 4A); therefore, the channel system likely initiated while there was no positive relief over the salt diapir (Figure 6B). Overlying this channel system, seismic reflections onlap horizon 2 and are truncated by horizon 3 (Figure 3).

Horizon 3 defines a ~2 km wide and straight, north-south-oriented erosional surface (Figure 2). In the northeast of the study area, the erosional surface is truncated by the salt diapir, and includes an arcuate scour to the west of the diapir (Figure 2). High-amplitude, discontinuous seismic reflections are confined by the erosional surface (see RMS-amplitude extraction between horizons 3 and 5; Figure 4B), with a thin section of more continuous reflections outside of it (Figure 3). Horizon 3 is interpreted as defining the base of another channel system. Horizons 4 and 5 define the base and top, respectively, of a relatively narrow (<1 km) channel form (Figures 2 and 3). This channel form is the last-active channel of the system. Overlying horizon 5 is a section of low-to-moderate amplitude, chaotic seismic reflections that are interpreted to be mass-transport deposits (Figure 3). These deposits are emplaced from northwest to southeast (Figures 2 and 3). The channel system appears to shutdown with the emplacement of mass-transport deposits overlying horizon 5. Horizon 6 locally truncates horizons 3, 4 and 5 (Figures 2 and 3) and forms the base of a sequence of Pliocene–Pleistocene channel and mass-transport deposits, which were studied by Ceyhan (2017). The channel system between horizons 3 and 5 exhibits the characteristics of meander cutoff and downstream translation in a topographic low adjacent to a salt diapir and is the main focus of this study (Figures 5 and 6A). Below, more detailed interpretations are provided of the seismic-stratigraphic architecture of this channel system.

A coherence attribute map between horizons 3 and 5 shows a pair of channel-bend cutoffs in a syncline adjacent to the northeastern diapir (Figure 5). These cutoffs are truncated by the last-active channel defined by horizons 4 and 5,
FIGURE 5  Detailed seismic-stratigraphic interpretation of channel system between horizons 3–5. (Above) Uninterpreted (left) and interpreted (right) coherence maps. Solid black lines in interpreted (right) coherence map indicate locations of seismic-reflection profiles below. (Below) Interpreted seismic-reflection profile b–b’ shows a depositional-dip view of north-to-south dipping, downstream-translating and high-amplitude seismic reflections. Profile c–c’ shows a depositional-strike view of the channel system.
which exhibits a pair of ~90° bends as it crosses the diapir (Figure 5). This last-active channel is approximately straight as it descends to the south, where it exhibits another pair of sharp bends. Upstream from these bends, low coherence values define arcuate shapes, which are parallel to the concave (outer) bend of the last channel (Figure 5). These arcuate shapes are defined by north-to-south dipping, downstream-translating and high-amplitude seismic reflections in cross-section (Figure 5B). To summarize, the cutoffs occurred at horizon 3, the downstream-translating deposits are between horizons 3 and 4, and the last-active channel fill is between horizons 4 and 5 (Figures 2 and 3). This stratigraphic architecture suggests a channel evolution beginning with the development of highly sinuous meanders in a syncline adjacent to salt, followed by cutoff and the generation of a high-curvature perturbation, which resulted in multiple bends that translated ~10 km downstream from north to south. Remnant channel deposits with concave bends, parallel to the outer bend of the last channel, developed in the wake of this downstream translation. Two questions remain. First, is this channel evolution feasible? Interpreting the seismic-stratigraphic architecture and evolution of the channel system between horizons 3 and 5 is a hypothesis that can be tested with a simple forward model of meandering-channel evolution (Sylvester and Covault, 2016). Second, if the seismic-stratigraphic evolution is confirmed by numerical modelling, what is the role of structural deformation in promoting these processes in tectonically active salt basins? Some of the key channelized stratigraphic patterns in the study area are associated with the northeastern diapir; to understand the growth of this diapir and the resultant topography, a 2D structural restoration is applied to the cross-section profile A of Figure 3.

4.2  |  Structural restoration

Based on the observation that the channel system passed directly over the salt diapir (Figure 4A), it is possible to conclude that the diapir had little or no positive relief between deposition of horizons 1 and 2 (Figure 6B). Deposits between horizons 2 and 5, however, thin dramatically onto the diapir. Furthermore, horizon 5 incises the diapir roof. These observations suggest that renewed uplift of the diapir started after horizon 2. What could have caused this? A mild shortening event beginning at horizon 2 time is proposed; the unit between horizons 1 and 2 is nearly isopachous on the east side of the diapir, and it is then uplifted, onlapped and truncated (see profile A of Figure 3). Uplift of an isopachous roof is a diagnostic feature of diapir shortening (Vendeville & Nilsen, 1995).

Section restoration is constructed using this contractional interpretation (Figure 7). A slight topographic low is suggested above the diapir, possibly as a result of salt dissolution, prior to the onset of shortening. This topographic low focused a channel system over the diapir crest (see ‘horizon 2 – pre shortening’ of Figure 7). Mild shortening arched and uplifted the diapir crest. Uplift above and adjacent to the diapir created a syncline to the west of the diapir, at the intersection of the east-dipping regional slope and the west-dipping flank of the diapir uplift (see ‘horizon 2 – post shortening’ of Figure 7). The supradiapir channel system shifted to this syncline, where it cut the meander loops at horizon 3 (see ‘horizon 3’ structure map of Figure 2). These meanders are at the base of the channel-bend cutoffs between horizons 3 and 5. Shortening continued to the present based on folding of younger units and erosion of the modern sea floor (Figure 7). Total shortening in the restoration is only 85 m; however, even this modest shortening was sufficient to change sea floor topography and shift channel-system location.
Most numerical models of meandering are initialized with a straight centreline that has random noise added throughout its entire length (Limaye & Lamb, 2014; Sun et al., 1996). Although both expansion and translation are common in these models, long stretches of deposits showing downstream translation are rarely preserved, as their upstream side gets rapidly eroded by the upstream meanders. The seismic-reflection data show highly sinuous channel cutoffs in a syncline adjacent to a salt diapir, which transition downstream to a straighter channel with a few bends downstream of the structure (Figure 5). In general, for simple geometric reasons, cutoff events result in small but high-curvature bends (Camporeale et al., 2008). Therefore, an initial condition has been used here with a single perturbation of relatively high curvature that affects an otherwise straight channel (Figures 8, 9 and Supplementary Animations 1, 2). It is tempting to think that for a given channel size, the amount of translation and expansion would be the same. However, the duration and length of translation are affected by channel depth $D$ and friction factor $C_f$ through the exponent $\alpha$ (Equation 4).

In general, a smaller value of $\alpha$ results in longer downstream translation (Figure 8 and Supplementary Animation 1). To generate translation similar to that observed in the Campos Basin example, a relatively small width-to-depth ratio and a small friction factor were applied. Values of $W = 300\,\text{m}$, $D = 30\,\text{m}$ and $C_f = 0.01275$ result in a reasonable match to the channel system in the Campos Basin (Figure 9 and Supplementary Animation 2). The width of the last-active channel in the Campos Basin ranges from $\sim 600\,\text{m}$ at the levee crest to $\sim 300\,\text{m}$ in the thalweg (Figures 2 and 3). The $W$ and $D$ values in the numerical model employed are likely to be representative of the lower, higher density part of the channel-sculpting sediment-gravity flows, which probably drive the evolution of the planform pattern and the width-to-wavelength scaling (cf. Pirmez & Imran, 2003). Of course, larger values of $D$ give the same result if $C_f$ is increased by the same amount (Equation 4). The initial bend migrates downstream, leaving behind deposits; at the same time, two or three additional bends develop further downstream, in a wave-like fashion (Figure 9 and Supplementary Animation 2). These bends are strongly translational in nature and leave behind significant translation-related deposits similar in scale to the channel deposits in the Campos Basin. However, the preservation potential of these deposits is variable: as bends gradually switch from translation to expansion, the translation-related units of the downstream bends tend to be eroded, and only the downstream migration of the first couple of bends is preserved (e.g., see model with $\alpha = 0.0015$ of Figure 8 and Supplementary Animation 1). The Campos Basin example described here is likely a relatively short-lived feature that has developed from a low-sinuosity, newly established channel with a single perturbation and was abandoned before meander expansion took over from translation. Indeed, the channel system is shutdown following the emplacement of the mass-transport complex above horizon 5.

**FIGURE 7** Structural restoration. Early is at the bottom; present configuration is at the top. The channel system between horizons 3 and 5 is the focus of this study. See text for explanation.

**4.3 | Numerical model of planform channel evolution**

Most numerical models of meandering are initialized with a straight centreline that has random noise added throughout its entire length (Limaye & Lamb, 2014; Sun et al., 1996). Although both expansion and translation are common in these models, long stretches of deposits showing downstream translation are rarely preserved, as their upstream side gets rapidly eroded by the upstream meanders. The seismic-reflection data show highly sinuous channel cutoffs in a syncline adjacent to a salt diapir, which transition downstream to a straighter channel with a few bends downstream of the structure (Figure 5). In general, for simple geometric reasons, cutoff events result in small but high-curvature bends (Camporeale et al., 2008). Therefore, an initial condition has been used here with a single perturbation of relatively high curvature that affects an otherwise straight channel (Figures 8, 9 and Supplementary Animations 1, 2). It is tempting to think that for a given channel size, the amount of translation and expansion would be the same. However, the duration and length of translation are affected by channel depth $D$ and friction factor $C_f$ through the exponent $\alpha$ (Equation 4).

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**5 | DISCUSSION**

The numerical model results are similar to the seismic-reflection example from the Campos Basin: upstream meander cutoffs result in a high-curvature perturbation that initiates
additional bends downstream, and all bends leave downstream-translating channel deposits in their wake (Figures 5 and 9). The geomorphologic and stratigraphic expression of these deposits is reminiscent of fluvial counter-point bars (Figure 9C). Furthermore, similar to a fluvial channel system, the Campos Basin submarine-channel system does not appear to have aggraded much as it translated downstream (Figure 5B). Fluvial counter-point bars form where long-term deposition takes place on a concave bank; the corresponding deposits are usually finer grained than those of the point bar (Smith et al., 2009). In submarine channels, flume-tank experiments have shown how flow separation can result in finer-grained deposition along concave banks (Straub et al., 2008); these processes might be common in nature as

**FIGURE 8** Forward models of channel evolution based on different values of $a$ (Equation 4). From bottom to top, decreasing $a$ (increasing $D$, decreasing $C_f$) results in progressively larger meander size and more translation of a high-curvature perturbation. See Supplementary Animation 1
well. Qualitatively, counter-point bars have been linked to downstream translation and confinement; although there is evidence that confinement is not always necessary. Sharp and small cutoff-related bends in rivers often result in significant translation and are likely locations of counter-point bar formation (Figure 9C).

The integrated seismic-stratigraphic interpretation and numerical modelling presented here suggests that translation might be common in settings that promote (1) meander cutoffs and the generation of high-curvature bends and (2) repeated local re-establishment of relatively straight channels. The former can happen in salt-tectonic provinces, in which deformation can draw channel pathways into low topography (Gee & Gawthorpe, 2006; Oluboyo et al., 2014). The latter can happen when a large mass-transport event erases the existing channel topography, either through erosion or burial, and sets the stage for a new channel with low sinuosity. These conditions are satisfied by continental margins affected by salt tectonics, such as the area of this study in the Campos Basin. Here, a syncline adjacent to a salt diapir appears to have localized sinuous meander loops, which were cutoff as they expanded into the syncline. Other examples of downstream translation of submarine-channel bends have been linked to major changes in flow regime and type of sediment load (Posamentier & Kolla, 2003). However, it is proposed that allogenic changes in sediment delivery to the system are not necessary to produce these deposits (see also Das et al., 2004) and downstream translation might be common in rapidly deforming settings, like salt basins, that promote localized subsidence, meander cutoffs, and rapidly translating, high-curvature bends.

With respect to the architecture of continental margins, submarine-channel systems commonly include a complex stacking of erosional remnants of sandstone-dominated channel fills (Deptuck et al., 2003, 2007; Hodgson et al., 2011; McHargue et al., 2011; Sylvester et al., 2011; Covault et al., 2016), especially during their early evolution when cutoffs are more common (Sylvester & Covault, 2016). This architecture is reminiscent of the sand bodies produced by the combined translation and expansion of rivers, although aggradation is often, but not always, significantly higher in submarine channels (Peakall et al., 2000; Sylvester et al., 2011; Jobe et al., 2016). Further work is needed to evaluate whether (1) downstream translation is more or less common in submarine channels than in rivers and (2) submarine ‘counter-point bars’ are relatively fine-grained, like in flume-tank experiments (Straub et al., 2008) and in rivers (Smith et al., 2009). The results of this study and previously published seismic images suggest that long-term and long-distance translation is an important component of submarine-channel evolution, and, similar to rivers, it is primarily driven by the downstream shift of the location of maximum migration relative to the bend apex (Furbish, 1988; Sylvester et al., 2019). This phase lag is well-known from models of river meandering (Johannesson and Parker, 1989; Seminara, 2006), has implications for the orientation of secondary flow at the bend apex (Ezz & Imran, 2014), and is the result of the influence of upstream curvatures on the local migration rate. In the model used here, this influence and the resulting translation are stronger when the channel is deep and the friction factor is low (e.g., a smaller value of $\phi$; Figure 8 and Supplementary Animation.
1); therefore, a possible explanation for the excessive translation observed in the Campos Basin and elsewhere is that submarine channels on the continental slope tend to be overall deeper (Konsoer et al., 2013) and might be smoother than their fluvial counterparts. The downstream shift in the location of deposition and erosion relative to the bend apex in submarine channels has been illustrated, without much discussion, by Abreu et al. (2003; their fig. 27). The potential importance of this downstream shift, and the resulting similarities with fluvial counter-point bars, has been recognized in several studies (Das et al., 2004; Straub et al., 2008; Amos et al., 2010; Ezz & Imran, 2014; Peakall & Sumner, 2015). This study suggests that the long-term consequence of this phenomenon is the significant downstream translation of short and high-curvature bends.

6 | CONCLUSIONS

The combined structural and seismic-stratigraphic evolution of a Miocene salt diapir and submarine-channel system in the tectonically active Campos salt basin has been characterized. Structural restoration shows diapir shortening created a syncline to the west of the diapir, which localized a channel-system depocentre comprising meander cutoffs (Figure 7). A simple forward model of meandering-channel evolution was used to show that these upstream meander cutoffs resulted in a high-curvature perturbation that initiated additional bends downstream, and all bends left downstream-translating channel deposits in their wake (Figure 9 and Supplementary Animation 2). These deposits are reminiscent of fluvial counter-point bars, which might commonly develop during the early evolution of relatively deep, smooth-floored submarine-channel systems, and, in general, after the formation of high-curvature perturbations. Moreover, it has been shown that downstream translation can develop without allogenic changes in sediment delivery to the system and without any confinement. Early work on submarine-channel evolution has suggested that downstream translation is rare; it is, however, apparently a common migration process in submarine-channel systems in salt basins and other tectonically active settings with complex topography, which might promote the development of cutoffs and other perturbations.

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CONFLICT OF INTEREST

We have no conflict of interest to declare.

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Additional supporting information may be found online in the Supporting Information section at the end of the article.

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