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ORIGINAL

Seismic stratigraphy of a partially filled incised valley on a semi-arid continental shelf, Northeast Brazil

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Abstract

This study aimed to understand the key surfaces and the sedimentary filling pattern of the Coreaú incised valley (CIV) system (NE Brazil) using high-resolution seismic stratigraphy. Six key surfaces (Ss) and five seismic units (SUs) were identified. The difference in the basal reflector (S1) and the paleointerfluve (modern sea floor) was verified to be up to 40 m of incision, of which only 20 m are filled. S1 (sequence boundary—SB) was associated with the acoustic basement (Tibau Formation/Barreiras Group) and presented strong control (antecedent topography) in the incision (re-incisions in the Pleistocene lowstands) and sedimentary stacking pattern. The CIV fill showed lowstand system tract, LST (chaotic facies)–transgressive system tract, TST (horizontal layers to chaotic facies)–highstand system tract, HST (chaotic facies) from the base to top. Thin fluvial deposits above SB correspond to LST. Overlapping this system tract is the first marine flooding surface—transgressive surface. Afterwards, the largest seismic unit (lateral and vertical) with sub-parallel and parallel (onlap) seismic facies, interpreted as related to a low energy system, with shallow gas, and vertical accretion (central basin of estuary) occurred. This environment is related to the drowning of the shelf from the shelf break (a decrease in gradient). A tide ravinement surface truncated the top of SU3 and favored coastal to shallow marine deposition. The transgressive system tract (TST) is thicker in the middle (mainly) and outer sectors in the fluvial troughs (depocenter). The maximum flooding surface appears near the sea floor and favored the development above of carbonate sedimentation in the HST. These seimostratigraphic stacking patterns showed a strong influence of semi-arid climate and antecedent topography/structural inheritance. Thus, it is evident that the filling of the CIV differs from other valleys on semi-arid systems and/or influenced by paleotopography (e.g., South Africa and Texas Shelf), which demonstrates the importance of local settings. The great influence of estuarine to coastal sediments in the valley infilling is also observed in the modern Coreaú coastal plain incised valley.

Introduction

Incised valleys are important indicators of base-level changes on continental shelves during the low sea level of the Quaternary (Gomes et al. 2016; Wang et al. 2020). It produces a depositional space from fluvial erosion (mainly) and filled by fluvial, tide, and/or wave processes (Boyd et al. 2006). The valley may be completely or partially filled, containing deposits of the following transgression and highstand (Zaitlin et al. 1994), in addition to deposits which were deposited prior to the flooding (Dalrymple et al. 1992; Hanebuth and Stattegger 2004).

Boyd et al. (2006) divided the incised valley system into three segments for stratigraphic analysis, which results in lowstand erosion, transgressive deposition, and highstand progradation: segment 1 (seaward portion)—backstepping (lowstand to transgressive) fluvial and estuarine sediments, overlain by transgressive marine sediments; segment 2 (middle reach)—drowned-valley estuarine complex overlying a lowstand to transgressive succession of fluvial and estuarine sediments; and segment 3 (innermost reach)—headward of the transgressive estuarine–marine limit and extends to the landward limit of sea-level-controlled incision (only fluvial sediments). Simms et al. (2006) suggested the analysis of the proportion of fluvial versus estuarine and marine fill (overfilled and underfilled with respect to fluvial sediments)

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because the underfilled valleys follow the classic models, but overfilled valleys (without central basin or marine facies) are not pointed out in these models.

Commonly, the filling of incised valleys shows typical seismostratigraphic patterns, such as onlap and downlap terminations, vertical accretions, and truncated surfaces (Gomes et al. 2016; Aquino da Silva et al. 2016). The key surfaces are fundamental to interpretation of changes in depositional systems and their preservation. The sequence boundary (SB) marks the basal reflector and it is associated with the valley, as the transgressive surfaces are related to the flooding of the shelf and subsequent filling (Vail 1987; Catuneanu et al. 2011).

The width, depth, and filling of the incised valleys depend on the sediment supply, physiography, accommodation, and hydrodynamics (Dalrymple et al. 1992; Vital et al. 2010; Tjallingii et al. 2010; Pretorius et al. 2019). The main morphologies related to the incised valleys are terraced valleys, V- and U-shaped channels, interfluves, bedrock, flanks/wall, and overfilled and underfilled valleys (Simms et al. 2006; Cooper et al. 2012; Green et al. 2013; Dladla et al. 2019; Wang et al. 2019; Qiu et al. 2019). The bedrock morphology plays a key role in the base-level change within the incised valley, mainly determining the valleys width—confined or enlarged (Schumm 1993; Gomes et al. 2016) and neotectonic influences (Gomes et al. 2014).

The aim in this paper is to understand the seismostratigraphic patterns in a partially filled incised valley system of semi-arid climate (western equatorial Atlantic), in the context of sea-level changes, shelf drowning, bedrock morphology, and sedimentary dynamics. In addition, a comparison between this cross-shelf valley with the Coreaú coastal plain valley and other incised valleys worldwide (similar and different settings) was performed. It is emphasized that there is a lack of studies in incised valleys in this sector and consequently there is a scarcity of information about the morphosedimentary evolution since the last glacial–eustatic cycle.

Study area and regional setting

The equatorial continental shelf of Brazil represents a modern mixed siliciclastic–carbonate system developed in shallow water (< 70 m) (Vital et al. 2008) with high-energy hydrodynamic agent driven currents—winds, tides, North Brazil current (Testa and Bosence 1998).

The study area is the paleochannel systems in the inner shelf (Northeast Brazil) offshore to the Coreaú River (Camocim, Ceará) (Fig. 1). Two nomenclatures were applied: Coreaú incised valley (CIV) for the paleogeographic system of ancient valleys located between Coreaú mouth to the end of the inner shelf and Main Valley (MV) for the large incision that cuts the inner shelf. It is part of the Piauí-Camocim sub-basin (Ceará Basin) that was formed by the equatorial Atlantic margin opening during the Aptian (Peulvast et al. 2006). Barreiras Group (alluvial siliciclastics) and Tibau Formation (coarse-grained siliciclastics) are the major Cenozoic deposits that occur at shallow shelf and coast zone (Morais Neto et al. 2003). Moreover, the Precambrian basement occur in Coreaú lowermost (CPRM - Geological survey of Brazil 2003) influencing the end estuarine morphologies.

The modern sedimentary pattern on the sea floor surface is mainly represented by carbonates (red calcareous algae) but lithoclastics are important on the inner shelf (< 20 m) (Coutinho and Morais 1968; Dias et al. 2007; Morais et al. 2019). The CIV has depths up to 45 m and a sedimentary cover related to the very fine to very coarse sand with high $CaCO_3$ content (Farrapeira Neto 2013).

Northeast Brazil (NEB), because of its location at the extreme eastern side of tropical South America, is influenced by meteorological phenomena that result in peculiar climatic characteristics, unique to semi-arid areas of the world (Molion and Bernardo 2002). The interannual variability in rainfall distribution of NEB is related to changes in the large-scale atmospheric circulation configurations and the ocean–atmosphere interaction in the Pacific and Atlantic—the El Niño–Southern Oscillation and the Atlantic Dipole (Molion and Bernardo 2002).

Materials and methods

High-resolution seismic profiles of a sub-bottom profile SB216 (Edgetech) were used. The frequency range was 2–12 kHz profiling 330 km of parallel (4) and across (5) seismic lines to the CIV. The seismic profiles were spatially positioned using a global positioning system (GPS) and the ship speed was maintained at 5 knots during the seismic data survey. The dataset was saved in a JSF format (Discover software). The time-varying gain (TVG) was applied to minimize the spherical divergence effects and improve the resolution of the reflectors surfaces. The sound velocity of 1500 m/s for time-depth conversion was used (Aquino da Silva et al. 2016; Nascimento Silva et al. 2018). Bathymetric data of the Brazilian Navy (Nautical Chart and board page) were used. An isopach map was created using the Surfer 11 software.

The interpretation of seismic boundaries and units were based on the architecture, continuity, amplitude, and frequency of their key reflectors and facies (seismic stratigraphy—Vail et al. 1977; Mitchum Jr. et al. 1977). Depositional systems (seismic units) and base-level changes were correlated to understand the stacking pattern and valley evolution (Allen and Posamentier 1993; Posamentier 2001; Hanebuth and Stattegger 2004; Boyd et al. 2006; Catuneanu et al. 2011; Reijenstein et al. 2011; Green 2009; Blum et al. 2013).

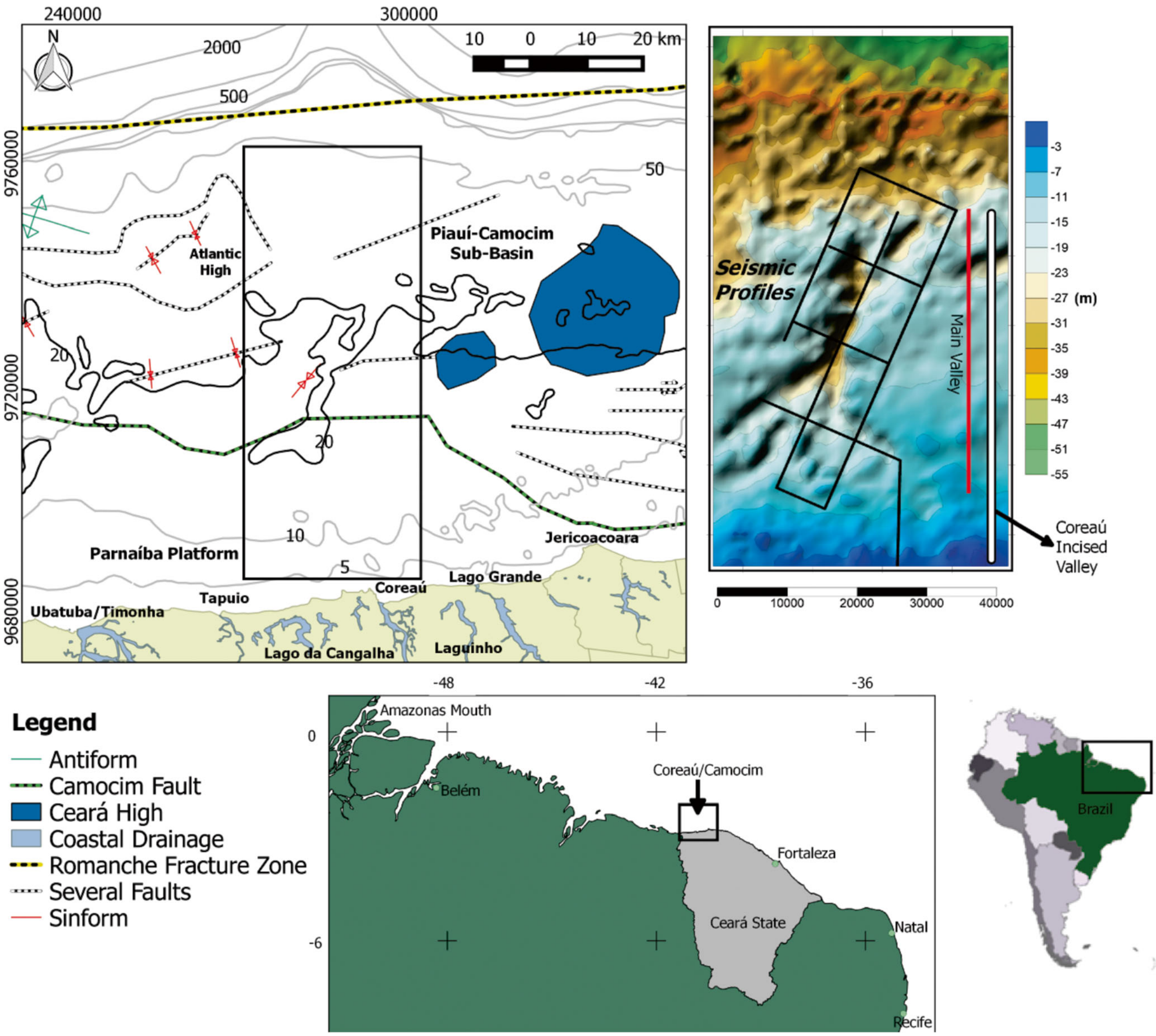


Fig. 1 Seismic line localization in the CIV and the simplified structural geology of the Piauí-Camocim Sub-basin (Brazilian equatorial margin). White solid line represents the extension of the CIV on the inner shelf. Red solid line represents the main incision of the Camocim shelf. From: Morais Neto et al. (2003); CPRM - Geological survey of Brazil 2003); Silva Filho (2004); DHN; IBGE; and PRONEX

Results

High relief bathymetry (~ 20 m) occurs between the top of the underfilled valley and upper flanks (Fig. 2b). The MV is ~ 50 km in length (Figs. 1 and 2a). Three orientation patterns (SSW-NNE, ESE-WNW, and N-S/NW-SE) were found according to the incision process (Fig. 2a).

Two types of valley shapes were found: U and V (Figs. 2a and 3). The U-shaped valley is predominant and occurs in all directions and reaches up to 5 km in width. It has the thickest fill (Fig. 2c). The V-shaped valleys are predominant in the SSW-NNE direction and narrower and smaller than those that are U-shaped. The slope of the incised valleys in the CIV is typically from 1:7.2 to 1:3.3.

Key surfaces (seismic boundaries)

Six surfaces (S) in the CIV (Fig. 4) were found. S1 is the oldest and the basal, probably related to the bedrock. Given its great lateral continuity and high amplitude, it showed high acoustic impedance. The depth of the occurrence ranged from the sea floor (shallow and middle sectors) to 20 m in the sub-bottom (resolution limit). Breaks/ruptures occur and may be indicative of a fault influence. S2 is below or alongside a parallel reflector unit (see below) and it has good lateral continuity and high amplitude. It occurs mainly

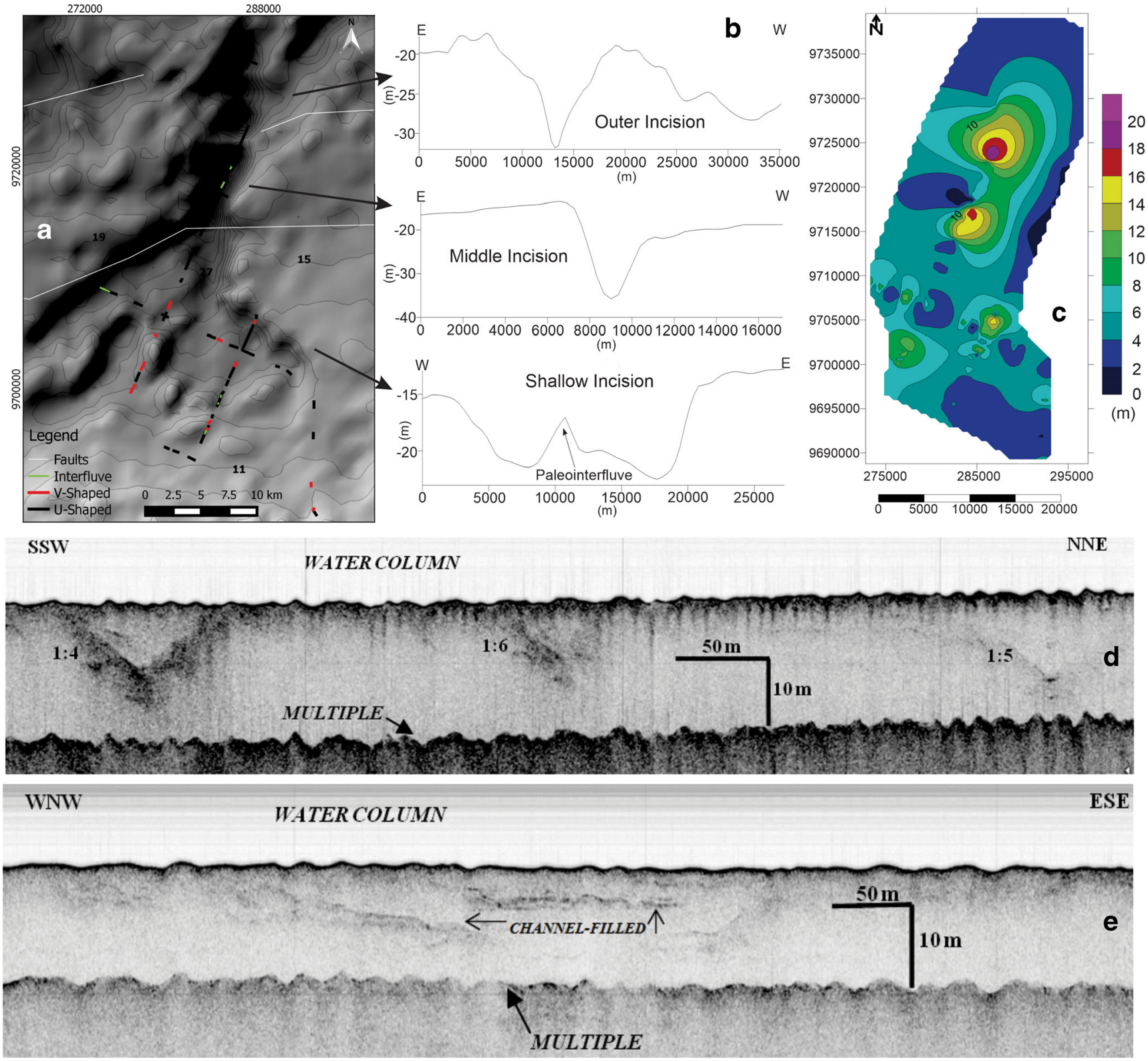
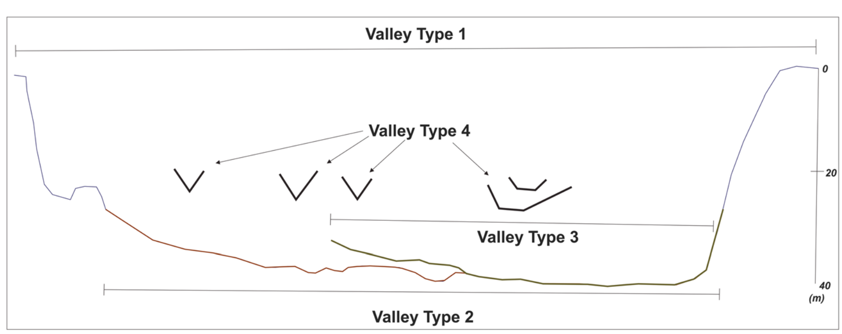


Fig. 2 Channel shape and orientation in the CIV (**a**). Transverse bathymetric profiles in three sectors of MV (shallow, middle, and outer) (**b**). Isopach map of sedimentary thickness (m) in CIV (**c**). V-shaped channels (**d**) and overlapping channels in the CIV: U-shaped channels (**e**)

between 5 and 10 m in the sub-bottom. S3 overlaps to the parallel reflectors and it marks a sharp change and truncation of the filling of the valley. It normally occurs at < 5 m in the sub-surface with good lateral continuity and a low to high amplitude. S4 always occurs at < 3 m and it has variable lateral continuity and amplitude and occasionally may

Fig. 3 Hierarchical succession of valleys in the CIV



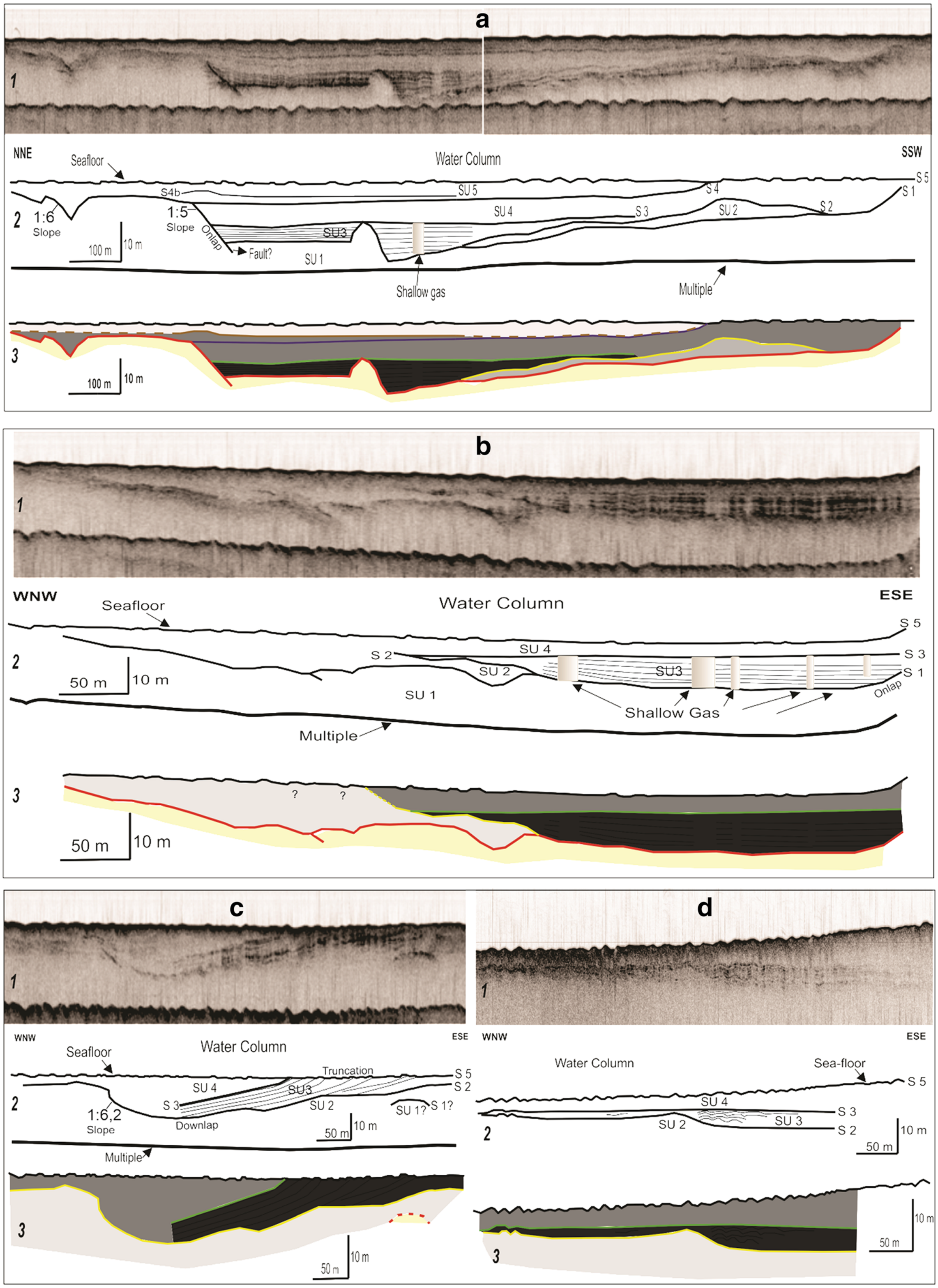


Fig. 4 Bounding surfaces and systems tracts interpretation. (1) Uninterpreted section; (2) identification of key surfaces (reflectors) and seismic units (facies); (3) seismostratigraphic interpretation. **a**, **f**, **g**, **h**, and **i** are SSW-NNE seismic profiles and **b**, **c**, **d**, and **e** are WNW-ENE seismic profiles

have a small secondary surface (S4b). S5 represents the modern sea floor. In marginal areas, the incisions in seismic data are not apparent, but using bathymetric data minor paleochannels were verified. In this sector (margins), a

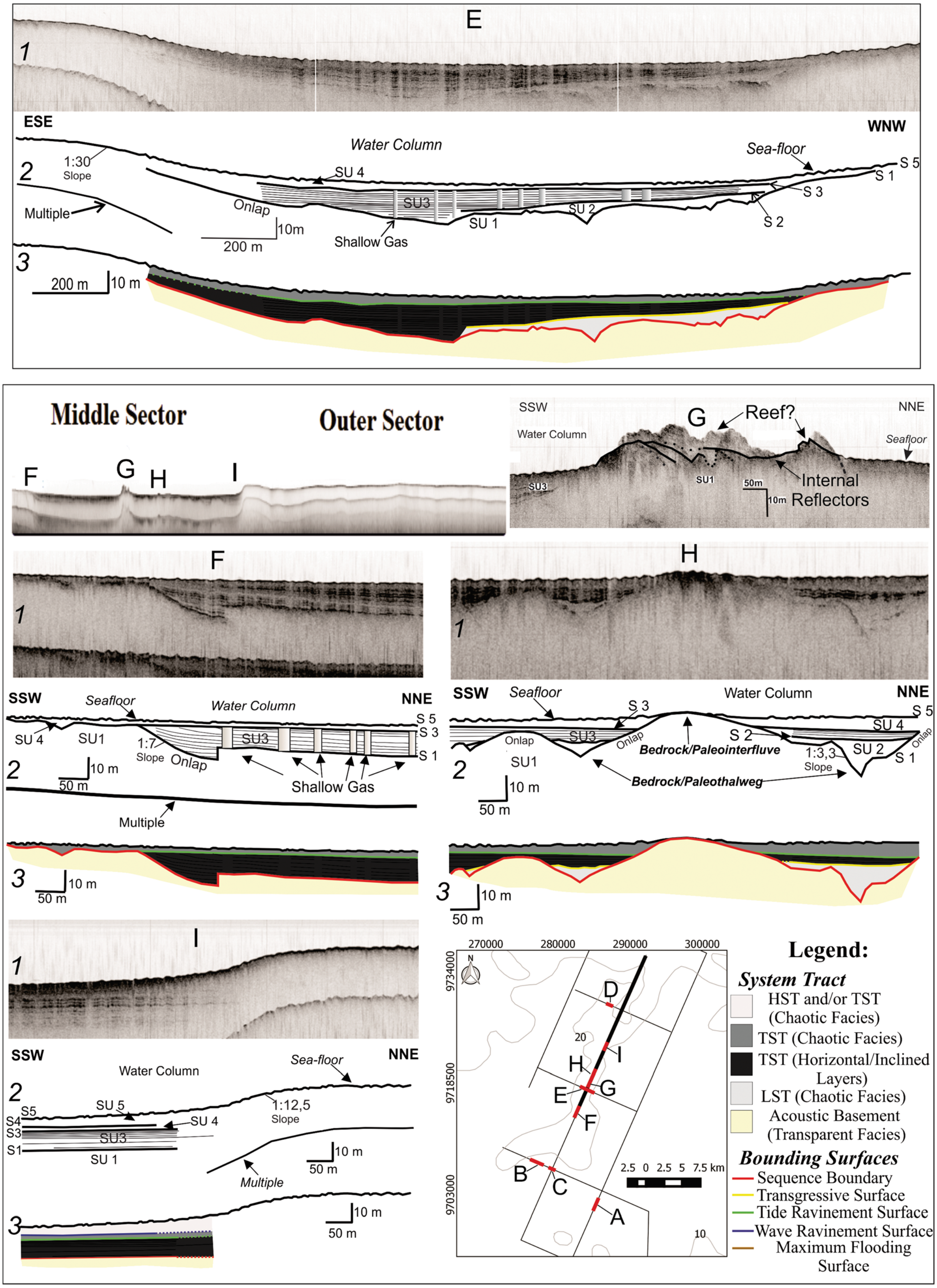


Fig. 4 (continued).

reflector 2–8 m below the modern sea floor was observed. In the shallow and middle sectors, the more basal and frequent reflector surface is S1. Nevertheless, in the outer sector, S2 is more basal due to seismic resolution (Fig. 4).

The isopach map shows sedimentary fills, always considering the most basal reflector—S1 (Fig. 2c). However, because of the seismic resolution limit and penetration, the more basal reflector may be other surfaces at any sites, such as S2.

Thus, most of the mapping, mainly in the MV, is represented by sedimentary packages and the bedrock depth. The greatest packages (depocenters) occur in the middle and outer sectors of the CIV (fluvial trough). The shallow sector has the largest number of fill cores. The thickness ranges from 0 m (rocky outcrop) to ~ 21 m (12 m—mean). The interfluves interrupt and control the sedimentation style. Rocky outcrops on the sea floor and can be up to 500 m in width. In the middle sector, a rock style similar to a reef was identified.

Four hierarchical successions of valleys in the CIV (Fig. 3) were verified. The first is represented by MV, which possesses S1 at its base. The second is represented by the first basal valley that was filled during the late Pleistocene/early Holocene. Its base may be S1 or S2. Valley 3 is above or adjacent to valley 2 and it may possibly be related to the autogenic process changes in the CIV. Valley 4 is related to the V-shaped channels (mainly), which occur at the upper seismic sections, and it may be associated with tidal inlets or fluvial channels (Fig. 2d). In this valley type superimposed channels (U-shaped) (Fig. 2e) were verified. Valley 1 is *bedrock*, valley 2 is of mixed nature (bedrock and alluvial), and the other valleys have unconsolidated substrates. These valleys did not necessarily simultaneously occur in a same seismic section or inside of the MV. The width of the channels ranges from 100 m to 4.7 km (800 m—mean) with the greatest width in the middle and shallow sectors. The width/thickness (*w*/*t*) ratio ranged from 390 to 11 with a mean of 112.

Seismic units (SUs)

SU1 is the first and ancient sedimentary system below S1. It shows transparent facies (low amplitude) and occurs at the limit of the seismic resolution and/or because of the presence of a rocky unit. SU2 is overlain by S1 and underlain by S2. It possesses a laterally confined shape in the middle and shallow sectors because of the valley shape and large area of the external sector. It is characterized by chaotic facies. SU3 is the largest seismic unit (laterally and vertically) and overlaps S2 and underlies S3 (truncated). It shows sub-parallel/parallel (high amplitude and continuous) to inclined facies. It presents onlap and downlap (secondarily) terminations (Fig. 4). The vertical accretion is linked to the onlap terminations (S1 and S2) and parallel facies. The lateral migration of channels/point bars is suggested by the inclined reflectors and downlap (S1) and interior progradational configuration. It appears on the modern sea floor at some sites. SU4 is overlain by S3 and underlain by S4 (or S4b). It shows low- to high-amplitude facies (transparent to chaotic). SU5 is above S4b (or S4) and below S5; it presents chaotic facies (high to low amplitude).

SU3 is thicker in the middle sector (15–20 m), with horizontal to sub-horizontal reflectors of vertical accretion patterns. A succession of sharp reflectors (high amplitude) interleaved to white facies (chaotic) is found. In this unit, shallow gas was present interrupting the continuity of the reflectors.

Seismostratigraphic interpretation

Seismic stratigraphic interpretation is summarized in Table 1 and Figs. 4 and 5. The six surfaces and five units (seismic facies) identified in Fig. 4 are related to the six sequence stratigraphic surfaces and three systems tracts in response to base-level changes, respectively. The system tracts did not wholly fill in the MV.

The S1 is a sequence boundary (SB) and represent the base (unconformity) of the MV. Below this surface occurs the acoustic basement (SU1). The stacking pattern above SB represents the partially filled of CIV. The lowstand system tract (LST)—SU2—occurring overlapped the SB and underlying the transgressive surface (TS)—S2. The transgressive system tract (TST)—SU3 and SU4—appear between TS or SB (below) and marine flooding surface (MFS)—S4b—or seafloor—S5 (above). Onlap, truncation, and downlap terminations occur in the parallel to inclined facies (SU3), being that the change between this layer and the chaotic facies above (SU4) is characterized by a tide ravinement surface (TRS)—S3. The wave ravinement surface (WRS)—S4—occurs inside upper TST (chaotic facies). The highstand system tract (HST)—SU5—occurs above MFS and below sea floor.

This stacking pattern in response to flooding shelf during MIS1 shows fluvial deposits in the base (LST), estuarine to shallow water deposits (TST), and the shelf sedimentation on the top (HST).

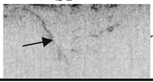
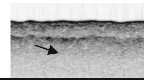
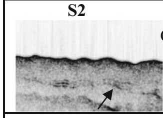
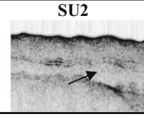
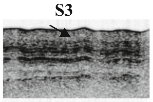
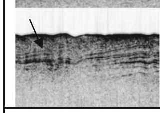
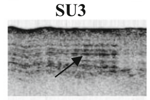
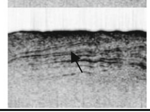
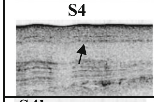
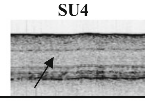
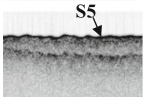
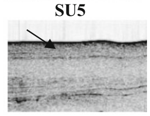
Discussion

Acoustic basement, structural inheritance, and sequence boundary

The high topographic amplitude (~ 40 m) between S1 (SB) and the modern sea floor (upper flank) suggests that a long time exposure to the incision action during the brief Last Glacial Maximum (LGM) (29–14 ka) may not explain the entire MV. Thus, the genesis of MV (valley 1) that runs for ~ 50 km across the inner shelf may be related to several Pleistocene lowstands (Fig. 5). Moreover, valleys 2, 3, and 4 originated and were preserved inside sedimentary packages formed between the MIS2 and MIS1 (Fig. 3). The CIV origin may be associated with the unconformity of the Pliocene that separates alluvial sediments of the Barreiras Group and the Tibau Formation (Morais Neto et al. 2003).

Structural inheritance and neotectonics are important factors in the knowledge of the CIV system, mainly because the direction of the MV coincides with orientation of the

Table 1 Seismic stratigraphy and paleogeographic interpretations

Key-Reflectors	Boundary	Surfaces	Base of Stacking Pattern	Seismic Units	Seismic Facies	Bounding Surfaces	Paleogeographic Environment	Sea Level
S1 	Erosive Truncation	Sequence Boundary	Lowstand	SU1 	Transparent	S1 (above)	Tibau Formation and/or Barreiras Group	Regressive
S2 	Concordant and Downlap	Transgressive Surface	Lowstand	SU2 	Chaotic	S1 (below) and S2 (above)	Fluvial (channel-belt or overbank)	Regressive to Transgressive (early)
S3  	Onlap Downlap and Truncation	Tide Ravinement Surface	Transgressive	SU3  	Sub-Parallel to Parallel Prograding	S2 (below) and S3 (above)	Estuarine	Transgressive
S4 	Concordant	Wave Ravinement Surface	Transgressive	SU4 	Chaotic	S3 (below) and S4 (above)	Coastal to Shallow Marine	Transgressive
S4b  S5 	Concordant	Maximum Flooding Surface Sea-Floor	Highstand	SU5 	Chaotic	S4 or S4b (below) and S5 (above)	Shallow Marine	Highstand

Precambrian trend (NE-SW) and there are some indicators of faults in S1. Pre-existing topography played a key role in the incision process control (valley formation and paleointerfluves preservation), which is easily viewed in the rocky outcrops and high bathymetric features of the MV (Figs. 2 and 4). These inherited topographies controlled filling during the sea-level rise, mainly in the depocenters (Figs. 2 and 4). Along the equatorial shelf of NE Brazil, Gomes et al. (2016) noted that the geometry of the Assu valley was a result of Cenozoic fault reactivation and lithological control.

Thus, the CIV is an important paleogeographic morphology that justifies the high frequency base-level changes and structural inheritance. Several factors provide the great development of the MV at the inner shelf—the Parnaíba platform (shallow basement), paleotopography, structural control by faults, re-incision, and a point source system/river confluences (merging of Coreaú, Tapuio, Seco, Cangalha, and Timonha/Ubatuba rivers). The CIV probably functioned similarly to the paleochannels of the Sunda shelf (Hanebuth and Stattegger 2004) with several minor tributaries feeding the central system (MV, Fig. 6). In the Texas shelf, some incised valleys (e.g., Nueces) do not occur on the outer shelf, because of an increase in sediment supply, a reduction in stream flow and/or the antecedent topography; furthermore, they can cut in the same location through repeated eustatic cycles (Simms et al. 2006). This repeated re-incision was also recorded in Lake St Lucia (South Africa), where two regionally sequence boundaries are developed (Dladla et al. 2019).

After MIS 5e (~ 120 ka), sea level fell and an unconformity was created on the exposed surface during the regression, representing a surface of sedimentary bypass (Posamentier and Allen 1999). During this period (the initial phase of glaciation), the incision process started and probably was not as strong in the CIV, because sea level did not fall below the shelf break (low gradient). Incision intensified during MIS 4 (~ 70 ka), but only during MIS 2 (LGM) were the main incised patterns formed in CIV (Fig. 5). During this time, S1 was created (re-incised) when sea level fell overtaking the shelf break (60–70 m) and the gradient increased. The base level dropped to around − 120 m, favoring incision in the middle (40 m deep) and outer sectors (fluvial trough). S1 may be related to the Barreiras Group and/or Tibau Formation (acoustic basement). They interdigitate in the shallower shelf and they lie atop crystalline basement along the coast; seaward the Barreiras tends to disappear and only the Tibau occurs (Morais Neto et al. 2003).

Lowstand system tract

The first seismic facies (depositional unit) above the basal surface (S1) is SU2. It is related to fluvial deposits (channel belts or overbank) as a terrace. Its depositional genesis possibly occurred between the LGM and the early of MIS1; because of the semi-arid climate in NE Brazil (interannual irregularity), sedimentation pulses during strong rainfall may have occurred. NE Brazil shows dry pre-LGM and LGM periods

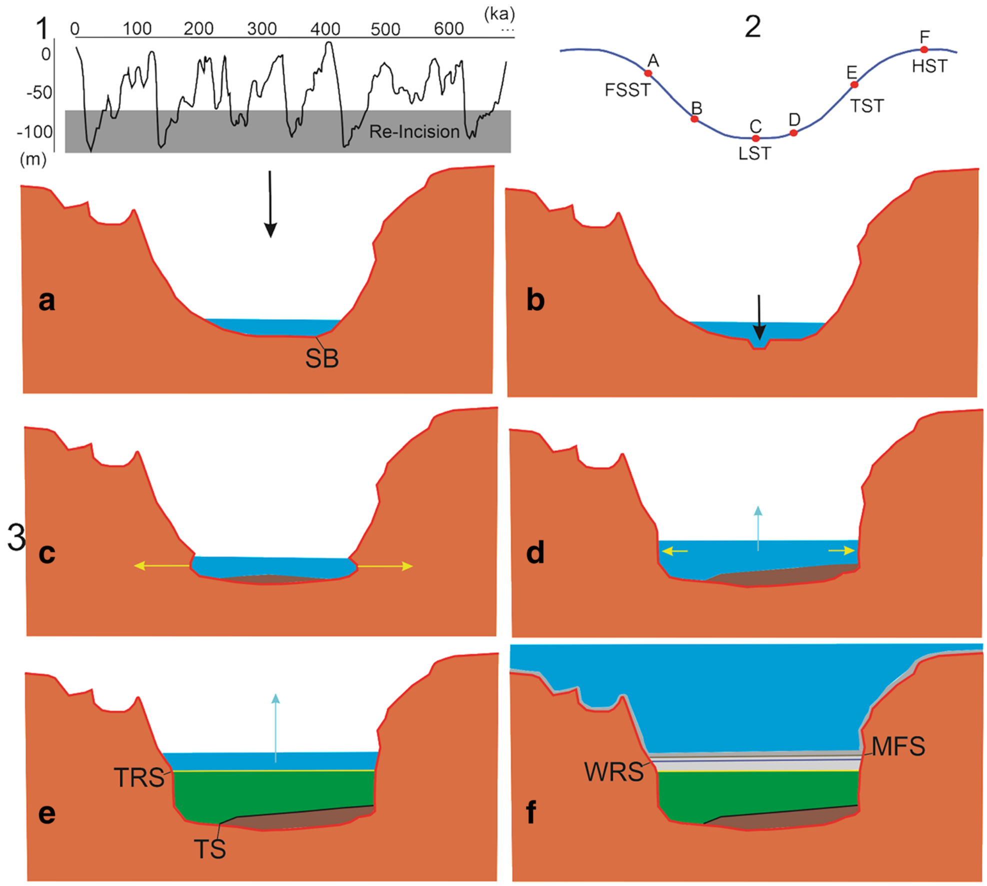


Fig. 5 Re-incision process on the inner shelf during the lowstands of Pleistocene (1, modified from Spratt and Lisiecki 2016). Relative sea-level curve for the incision and infilling of the CIV (2, modified from Catuneanu et al. 2011). Cut-fill evolution of the MV during the last glacial-interglacial cycle (3). **a** and **b** show the sea-level drop and incision and bypass may occur; **c** presents widening valley during the maximum low sea-level; **d** shows the development of LST during early sea-level rise; **e** beginning the flooding of MV and creation of TS, development of estuarine environment and the TRS with the continuation of sea-level rise (TST); **f** coastal to shallow marine deposition above WRS (TST) and afterward the development of HST related to the whole marine/shelf deposition above MFS (MV drowned). Black line is incision, yellow line is widening valley, and blue line is sea-level rise

(caatinga vegetation), but during the late glacial the environment was wetter (mountains, floodplains, and gallery forests). During this interval (pre-LGM to end-LGM) four humid periods occurred as follows: 40,000, 33,000, 24,000, and 15,500–11,800 ka (Behling et al. 2000). Thus, humid conditions are associated with terrigenous sedimentation pulses (Arz et al. 1998). SU2 represents a thin LST in the CIV and may present characteristics of braided patterns. Otherwise, Qiu et al. (2019) found thick fluvial seismic facies in South Yellow Sea related to retrogressive aggradation because of early stage of transgression.

Transgressive system tract

In the MV, the marine flooding was favored by the paleotopography (low relief—channels), as viewed predominantly near the ~ 25-m isobath (Fig. 6c). The paleodrainage system of the paleo-Coreaú watershed reveals the fluvial confluence of the MV on the inner shelf (Fig. 6d).

According to the Lambeck et al. (2014) sea-level curve (Fig. 6a), the major phase of deglaciation occurred between approximately 16, 5, and 7 ka BP, with a 12-m ka^{-1} rising rate that corresponds to a sea-level rise of ~ 120 m. In this interval, the main period (after Younger Dryas cold period) occurred in ~ 11.4–8.2 ka BP (near-uniform rise) with a rate of ~ 15 m ka^{-1}. During this interval, lasting about ~ 3.2 ka BP, the Ceará shelf (Fig. 6b) was drowned (starting after MWP1B), and the S2 (first surface associated with the drowning of the CIV—TS), S3 (TRS), S4 (WRS), SU3, and SU4 were formed. The estuarine deposition (SU3—vertical aggradation) with a thickness of up to ~ 20 m occurred in a short time interval (between ~ 11 and ~ 8.5 ka BP) when the sea level was at outer-middle shelf. This stacking pattern occurs because the rate of the increase in accommodation space and the rate of sediment supply are balanced (Green 2009). The aggradation rates were possibly the highest during the early Holocene, similar to as well as those recorded in the Rhine-Meuse delta (Netherland) (Törnqvist 1993; Gouw 2007).

The SU3 stacking pattern of large spatial distribution presented a depositional style with horizontal layers associated with the low energy system. This SU was associated with an estuarine environment, as noted in incised valleys of the Gulf of Thailand (Reijenstein et al. 2011) and the New Jersey Shelf, USA (Nordfjord et al. 2006). However, fluvial geneses were proposed for similar units at the Parnaíba Incised Valley, NE Brazil (Aquino da Silva et al. 2016) and at the Adriatic Sea, Italy (Ronchi et al. 2018).

Vertical accretion (onlap—central basin) and lateral accretion (downlap—point bar/channel migration) depositional units in a stratigraphic trap such as incised valleys are

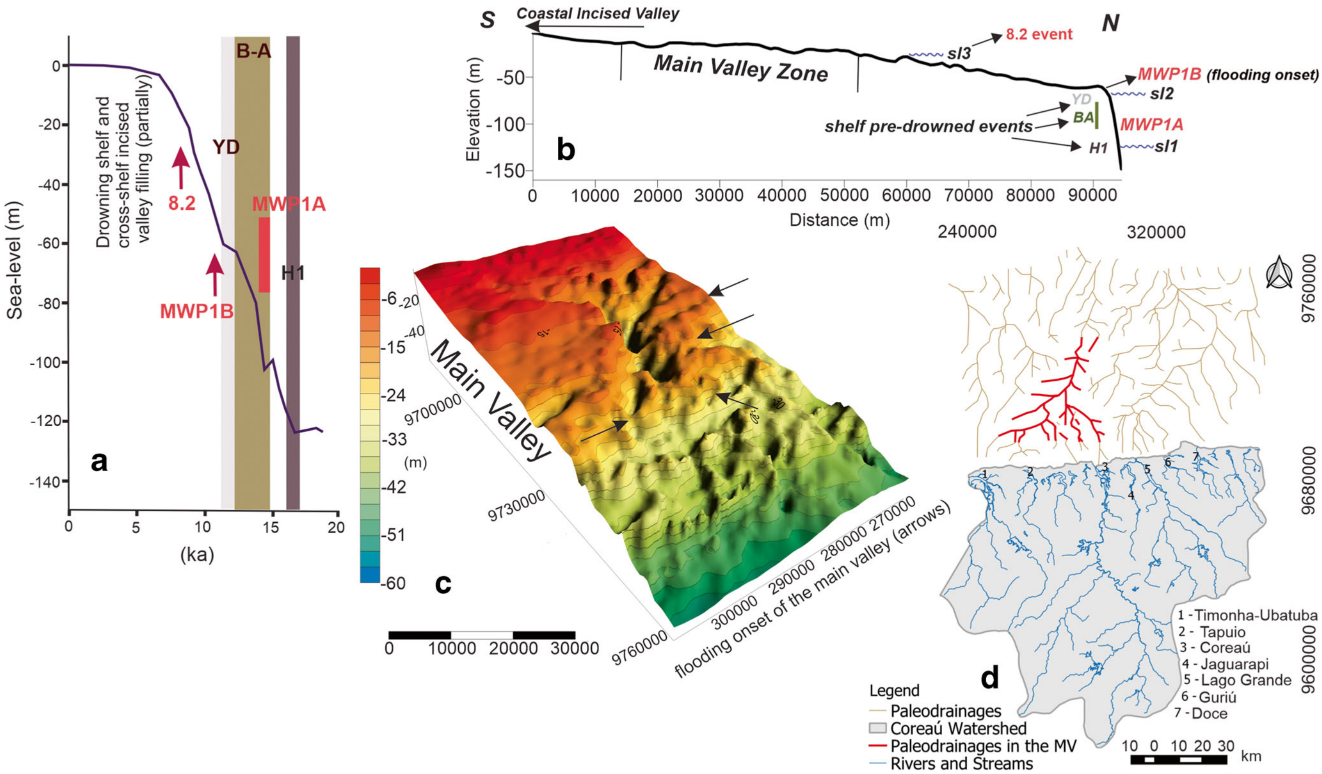


Fig. 6 Sea-level curve (Lambeck et al. 2014) with the main global events and local response (**a** MWP, meltwater pulses; B-A, Bølling-Allerød; YD, Younger Dryas; H, Heinrich). Bathymetric cross-shelf profile and association with global events (**b** sl, sea level). Digital model bathymetry of the Coreaú shelf with highlight to the incision areas and flooding onset process (**c**). Correlation of the continental watershed with the paleodrainage framework (**d**, modified from Silva Filho 2004; CPRM - Geological survey of Brazil 2003)

commonly associated with estuarine environments. Seismic termination onlap on the valley wall and confined, laterally continuous reflections and high amplitude are typical of muddy estuarine facies of the transgressive initial phase (Reijenstein et al. 2011). The estuarine genesis is similar to the Allen and Posamentier (1993) approach to the Gironde valley, France, wherein the estuarine transgressive sediments end onlap in the lowstand fluvial deposits (SU2), and the transgressive surface merges with the sequence boundary (S1) on the valley walls.

The alternation of high-amplitude and continuity reflectors to thin chaotic facies may be related to a sedimentation pattern, wherein the estuarine muds contain isolated sand lenses and ripple laminae (Allen and Posamentier 1993). Thomas et al. (1987) used the term inclined heterolithic stratification for the fine and coarse alternation with probable tide influence related to the distributary estuarine channels.

Seismic termination downlap may represent a lateral migration of a coastal barrier or point bar. The lateral channel migration found in the CIV is similar to examples in the lower Coreaú. Thus, it could be large sand spit on the estuarine mouth in a mixed depositional coast (dominated by tides and waves such as in Chaumillon et al. (2010) or a point bar such as in Aquino da Silva et al. (2016)). Vital et al. (2010) found oblique features in the Apodi-Mossoró incised valley, and they were interpreted as a Holocene relative sea-level rise product, accompanied by coastline progradation, similar to inclined reflectors (downlap) at the CIV. The channel lateral migrations correlate to periods of relatively stable sea level (Tjallingii et al. 2010).

In SU3 shallow gas cutting, the plan-parallel depositional style was evident. The presence of gas in shallow seismic studies is commonly noted in incised valley fill (Garcia-Gil et al. 2002; Gomes et al. 2016), estuarine environments (Frazão and Vital 2007), lagoon and lake environments (Klein et al. 2016; Weschenfelder et al. 2016), and continental shelves (Vardar and Alpar 2016). Gas accumulation occurs in Quaternary fine sedimentary deposits, which possess a strong relation with the paleotopography—incised valley systems (Weschenfelder et al. 2016). Weschenfelder et al. (2016) noted that the major gas concentrations occur in the central portions of estuarine basins within the incised valleys, presenting an association with the onlapping seismic reflector. This relationship between gas-topography-seismic reflector occurs in the CIV.

The rapid vertical accretion ceased due to the ravinements (S3 and S4) during the drowning of CIV (after the 8.2 event) (Figs. 5 and 6). This time interval is plausible because

Rodrigues (2014) found the onset estuarine system and mangrove ecosystem of the Coreaú incised valley on the coastal plain in approximately 8190 years BP and 7585 years BP, respectively (Fig. 7). This period coincides with the 8.2-ka BP cooling event in Greenland and North Atlantic.

It was evident at some sites that the TRS and WRS passes laterally from the valley to the margin, which then merges with the SB (S1)-mixed surface (Cattaneo and Steel 2003; Hanebuth and Stattegger 2004; Catuneanu et al. 2011; Ximenes Neto et al. 2018). SU4 overlaps TRS and is related to the transitional sediments reworked by erosion and shallow marine sediments. Barrier/inlet deposits may occur overlying the TRS (Boyd et al. 2006).

Different orientations, *w*/*t* ratios, and peculiar features (point bars) in the CIV are indicative of meandering drainage patterns (SU3), as are found in the modern semi-arid estuaries of the Jaguaribe, Acaraú, Timonha/Ubatuba, and Coreaú (Ceará State—NEB).

Reef morphology interpreted in an outcrop of the middle sector of the MV shows a similar pattern as found by Gomes

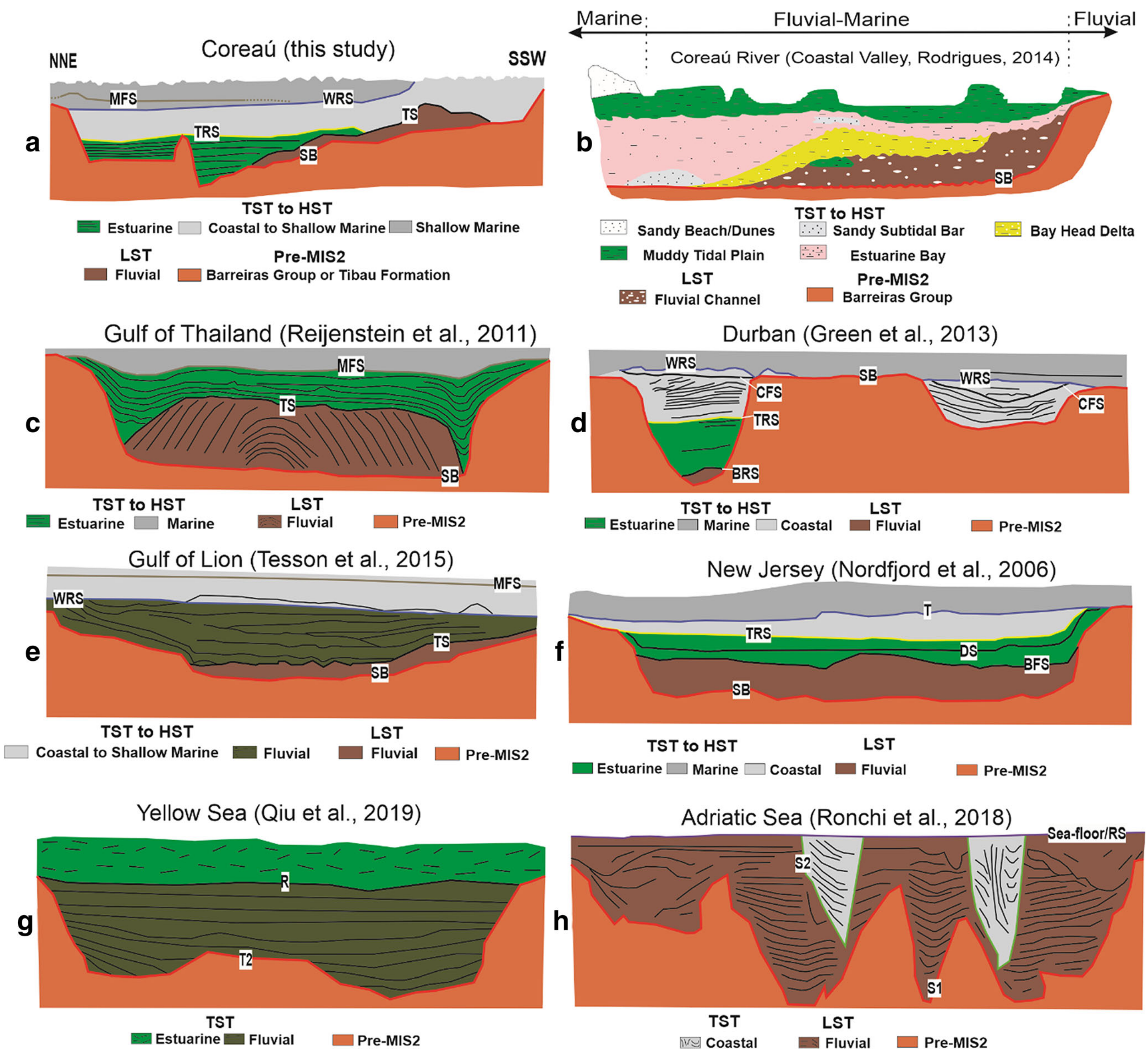


Fig. 7 Seismostratigraphic (bounding surfaces, system tracts) comparison between valley infilling of some cases of the worldwide (**a** and **c**–**h**), besides the sedimentary systems of the Coreaú coastal incised valley (**b** modified of Rodrigues 2014). Cross-shelf valley: **a** Coreaú (this work); **c** Gulf of Thailand (Reijenstein et al. 2011); **d** Durban, South Africa (Green et al. 2013); **e** Gulf of Lion, France (Tesson et al. 2015); **f** New Jersey, USA (Nordfjord et al. 2006); **g** Yellow Sea, China (Qiu et al. 2019); **h** Adriatic Sea, Italy (Ronchi et al. 2018). Legend: WRS, wave ravinement surface; TRS, tidal ravinement surface; SB, sequence boundary; TS, transgressive surface; MFS, maximum flooding surface; CFS, catastrophic flood surface; BFS, bay flooding surface; DS, depositional surface; S1, surface 1 (similar to SB); S2, surface 2 (may be a TRS); T2, surface t2 (similar to SB); R, surface r (may be a TS); T, transgressive ravinement surface (similar to WRS)

et al. (2016) and Nascimento Silva et al. (2018) in the Assu incised valley in the Potiguar Basin (semi-arid environment). This reef may be formed during the valley drowned in MIS1 overlain to prior bedrock (acoustic basement) (Fig. 4).

Highstand system tract

SU5 shows minor spatial distribution and it is possibly related to marine sediments (mainly near the sea floor). S4b may be a MFS, which Aquino da Silva et al. (2016) termed the regional surface. It marks the start of the HST, during which only marine sediments were deposited—mainly carbonates (in addition to the relict sediment being reworked). However, similar to SU5, it shows a minor spatial distribution; thus, S4b may only be a WRS and not necessarily the MFS. Nevertheless, in this work, the S4b was treated how MFS because this bounding surface commonly is well verified only from retrogradation to progradation changing identification (this process occurs in the sea floor, in which Farrapeira Neto (2013) found carbonatic fine sediments related to the HST).

Rodrigues (2014) pointed out that from 4 ka BP, the seaward mangrove progradation occurred due to sea-level fall and stillstand in the Coreaú coastal incised valley (Fig. 7). In the Late Holocene, the top of CIV filling shows modern deposition of bioclastic sediments (mainly calcareous algae) (Coutinho and Morais 1968; Farrapeira Neto 2013).

Morphological and infilling patterns of partially filled incised valleys

Incised valleys may be overfilled or underfilled (partially filled); their deposition control is related to topography, structural inheritance/tectonics, sediment supply, valley size, rates of sea-level rise, and oceanographic processes (Zaitlin et al. 1994; Simms et al. 2006; Green et al. 2013; Gomes et al. 2014; Wang et al. 2019; Pretorius et al. 2019). Green (2009) pointed out that the underfilling of older topographic features can notably influence the preservation of incised valleys and their ensuing fills on narrow continental shelves.

Simms et al. (2006) reported several underfilled incised valleys at the Gulf of Mexico—such as Nueces, Lavaca, Baffin Bay, and Trinity—wherein the topography had a low influence (similar gradients as those for overfilled incised valleys). Anderson et al. (2004) pointed out that the size of the drainage basin and climatic setting of the Gulf of Mexico are the main factors influencing the control of supplied sediment. The Nueces and Lavaca incised valleys are located in semi-arid environments. Some underfilled incised valleys may not connect to the shelf margin and generally follow the model summarized by Zaitlin et al. (1994). In addition, they tend to incise in the same location through several eustatic cycles (Simms et al. 2006). These aspects (Zaitlin's model and incision in the same site) of the semi-arid underfilled valleys present similarities to the Coreaú incised valley. However, in CIV, the ancient topography plays a key role in the filling valley.

Partially filled incised valleys associated with the Patos Lagoon (southern South America) have been reported (Bortolin et al. 2018), wherein the inherited topography had major control of the interfluves and creation of spits. Their infill showed a basal fluvial unit and a central estuarine mud unit, forming a similar pattern to the Coreaú incised valley (base and mid-infill).

Crockett et al. (2008) pointed out that only partially filled valleys present at deep up to 20–50 m in the relief occur in front of the Fly River (Gulf of Papua). This is attributed to three mechanisms: strong currents, avulsion, and burial of sediments followed by erosion (Harris 1994). In the Coreaú incised valley, a similarly large incision has been verified (up to ~ 40 m), wherein the partial filling is mainly due to low sediment supply (predominantly semi-arid environment) and the rapid Holocene transgression.

Green et al. (2013) observed stacked compound valleys with central basin deposits in the earliest fills of the Durban continental shelf. They reported underfilled valleys as a result of low gradient and limited sediment supply. The central basin estuarine, mouth, and fluvial point bar deposits presented onlap and low to moderate amplitude reflectors (Fig. 7d). In the Coreaú incised valley, the onlap terminations and the parallel to sub-parallel reflectors were the main settings of seismic facies related to the estuarine depositional system.

On the east coast of Australia, a partially filled incised valley was formed by the last eustatic sea-level change. It is being filled by shelf dunes, indicating that the valley has been an effective sediment trap till the present (Payenberg et al. 2006). In the margins of the Coreaú incised valley (between 10 and 20 m) siliciclastic to bioclastic ripples have been verified (Ximenes Neto 2018).

At the equatorial Atlantic, semi-arid shelf underfilled incised valleys such as Açu and Apodi-Mossoró are observed (Vital et al. 2010; Nascimento Silva et al. 2018). They show the influence of structural inheritance and reef association (Gomes et al. 2014; Gomes et al. 2020). These valleys, as well as the Coreaú incised valley, present a nitid framework influenced by the faults of the equatorial Brazilian margin (Açu and Apodi-Mossoró = Potiguar Basin; Coreaú = Ceará Basin) and semi-arid climate.

Seismostratigraphic comparisons of cross-shelf valleys during the Late Quaternary

Figure 7 shows the seismostratigraphy (bounding surfaces, system tracts) of valley infilling of some worldwide examples to enable comparison with the Coreaú incised valley. From this analysis, it is evident that the main surfaces and the stacking pattern present variations in the system tract framework because of local factors, such as drainage basin (area, physiography, and geology), sediment supply, paleotopography, and hydrodynamic. However, in general, the sequence boundaries limit the base of the valleys, and the filling is marked by presence of ravinement surfaces.

Wang et al. (2020) compared coastal plain and cross-shelf valleys (passive and active margins) to verify the stratigraphic organization. They observed a higher proportion of fluvial deposits and a lower proportion of central basin estuarine deposits (thicker central basin estuarine deposits) on active margins. This suggests a control in the stratigraphic architecture exerted by the tectonic setting, notably basin physiography, sediment supply (rates and mode), and nature of sediment load.

Analysis of the CIV revealed three patterns: 1, thinner lowstand deposits (SU2); 2, thicker estuarine deposits/central basin (SU3); and 3, coastal/mouth to open shelf sediments (SU4 and SU5) that were thinner in the fluvial trough (main depocenters—middle sector) and thicker in the shallower areas (shallow sector) (Figs. 4 and 7). Coreaú Valleys (cross-shelf and coastal plain) present up to ~ 20 m of thick transitional to shallow marine deposits (estuarine to carbonatic shelf).

This pattern of CIV differs of the incised valley fills of Yellow Sea (Qiu et al. 2019) and Adriatic Sea (Ronchi et al. 2018) due to the broad presence of fluvial deposits because of the high sediment supply (Fig. 7g, h). Otherwise, the incised valley filled of Durban (Green et al. 2013) and New Jersey (Nordfjord et al. 2006) show similar setting to the CIV because the great presence of TST and/or HST, related to the estuarine to shelf sediments (Fig. 7d, f). Although the Gulf of Thailand (Reijenstein et al. 2011) is similar to the CIV because the presence of LST-TST-HST pattern, the LST related to the fluvial deposits is thicker, probably due to the high sediment supply (Fig. 7c).

The seismic facies (architecture and terminations of reflectors) found in different settings of incised valley fill may present similar patterns but refer to distinct environments. This can be seen in Fig. 7, where the horizontal to sub-horizontal reflectors (sometimes with onlap terminations) can inspire variable interpretations: estuary (a CIV and c Gulf of Thailand); river (e Gulf of Lion, g Yellow Sea, and h Adriatic Sea) and coastal (d Durban). These demonstrate the important role of understanding local settings. Durban and CIV show similar patterns of system tracts (LST-TST-HST) in semi-arid systems; however, the seismic facies settings (terminations of reflectors and seismic units) are distinct (Fig. 7a, d).

Conclusion

The CIV system shows structural inheritance, bedrock/paleotopography, regional climate, and eustatic control in its morphology and sedimentary filling pattern. CIV geomorphic system created during the lowstand period (re-incisions in the Pleistocene) encompassed a great watershed composed of the Coreaú, Tapuio, and Timonha/Ubatuba rivers and coastal lakes (paleochannels).

Structural inheritance (Precambrian and post-breakup of Pangea) and neotectonics (Cenozoic reactivations) played key roles in the geomorphic formation of the CIV. This relation has been verified by MV orientation (a similar trend to the continental tectonic style/NE-SW) and relief breaks (S1). The paleotopography played a key role in the sedimentary filling during flooding shelf, mainly in the fluvial trough (chief depocenters).

The basal reflector (S1) was heavily remodeled when the sea level dropped (~ 120 m) after the shelf break (60–70 m) because of the increase in the topographic gradient. The valley's sedimentary stacking pattern starts with deposition above S1 (as a terrace along the valley margins—type 2) of the fluvial deposits (channel or floodplain) related to the LST. The drowning of the Camocim shelf and increase in the sedimentary accommodation space (gradient decrease) favored deposition above S1 and S2 of the TST. The first unit was related to the low energy deposits with onlap terminations on the valley walls, vertical accretion, and shallow gas (estuarine system). The tide ravinement surface (S3) truncated these deposits and initiated the drowning of the MV with superimposed coastal and marine deposition. Afterwards, the MFS favored the beginning of HST, which related to the modern carbonate sedimentation.

Seimostratigraphic stacking pattern of the CIV shows a nitid influence of semi-arid climate because thinner LST and thicker TST related to the drowned shelf and deposition favored by the antecedent topography. Thus, it is evident that the seimostratigraphic stacking patterns of the CIV differs from other valleys on semi-arid systems and/or influenced by paleotopography (e.g., South Africa and Texas shelf), which demonstrates the importance of local settings.

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