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Coastal response to late-stage transgression and sea-level highstand

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ABSTRACT

Coastal morphologic features associated with past shoreline transgressions and sea-level highstands can provide insight into the rates and processes associated with coastal response to the modern global rise in sea level. Along the eastern and southern Brazilian coasts of South America, 6000 years of sea-level fall have preserved late-stage transgressive and sea-level highstand features 1–4 m above present mean sea level and several kilometers landward of modern shorelines. GPS with real-time kinematics data, ground-penetrating radar, stratigraphy, and radiocarbon dating within a 2–3-km-wide river-associated strandplain in central Santa Catarina (southern Brazil) uncovered a diverse set of late-stage transgressive and highstand deposits. Here, the highstand took the forms of (1) an exposed bedrock coast in areas of high wave energy and low sediment supply; (2) a 3.8-m-high transgressive barrier ridge where landward barrier migration was prohibited by the presence of shallow bedrock; and (3) a complete barrier-island complex containing a 5.2-m-high barrier ridge, wash-over deposits, a paleo-inlet, and a backbarrier lowland, formed in a protected cove with ample sediment supply from small local streams and the erosion of upland sediments. Similar signatures of the mid-Holocene highstand can be traced across all coastal Brazilian states. This study presents the first complete compilation of the diversity of these sedimentary sequences. They are broadly classified here as

exposed bedrock coasts (type A), backbarrier deposits (type B), transgressive barrier ridges (type C), and barrier-island complexes (type D), according to localized conditions of upland migration potential, wave exposure, and sediment supply. These Brazilian systems present a paradigm for understanding future coastal response to climate change and accelerated sea-level rise: the recognition of a minimum threshold sea-level-rise rate of $\sim 2 \text{ mm yr}^{-1}$ above which transgression proceeded too rapidly for the formation of these stable accretionary shoreline features demonstrates the nonlinearity of coastal response to sea-level change, and the site specificity of conditions associated with the formation of each highstand deposit type, even within a single small embayment, demonstrates the non-uniformity of that response.

INTRODUCTION

Marine transgression is defined as a condition in which shorelines translate in a landward direction. It occurs when the rate of creation of space available for potential sediment accumulation (accommodation space) outpaces sediment supply (Curry, 1964; Bokuniewicz, 2005). In its most simplified form, transgression generally results from rising relative sea level (rSL) and/or net local erosion (Curry, 1964). Recent Holocene sea-level reconstructions (e.g., Kemp et al., 2011; Engelhart et al., 2011), combined with future projections for eustatic sea-level rise (SLR; Schaeffer et al., 2012), predict that coastal zones throughout the world may be on the verge of transitioning to a phase of rapid marine transgression, driven by relative SLR (rSLR) on an order not seen since the early Holocene in most locations. A detailed understanding of the man-

ner and rates at which coastal zones can respond to this transgression and changes in the rate of rSLR is therefore of crucial importance.

Examination of coastal morphologic features associated with past shoreline transgressions can provide such insight. Unfortunately, transgressions are commonly fully erosional in nature (Kraft, 1971), thus reducing the preservation potential of their sedimentary sequences. Although some examples of complete drowned barrier sequences have been identified (e.g., Forbes et al., 1991; Hijma et al., 2012; Mellett et al., 2012), most nearshore transgressive sedimentary sequences typically have a simple morphological surface and are evidenced primarily by former lagoonal and backbarrier environments (Hoyt, 1967; Belknap and Kraft, 1985; Reinson, 1992). Thus, at least in much of the Northern Hemisphere, many of the coastal morphologic features associated with rapid post-glacial transgression were removed by continued rSLR during the latter half of the Holocene.

By contrast, the complex Southern Hemisphere Holocene sea-level history has produced wide-scale preservation of transgressive and sea-level highstand (SLH) deposits. Global eustasy dominated late Pleistocene and Holocene relative-sea-level changes in most regions of the world not directly affected by glacial isostasy. In non-glaciated regions of the Northern Hemisphere, sea level has generally risen since the late Pleistocene, rapidly at first, slowing in the early and mid-Holocene, and reaching near-modern elevations around 4000 calibrated yr B.P. (4 ka). However, influenced by inter-hemispheric redistribution of water in the world's oceans driven by glacio-hydroisostatic processes, sea level in the Southern Hemisphere and some equatorial regions reached a post-glacial sea-level maximum (highstand) at 5–7 ka and has since fallen

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1–8 m (Isla, 1989; Roy et al., 1994; Angulo and Lessa, 1997; Angulo et al., 2006). This complex history is a consequence of global hydroisostasy during the middle Holocene along previously glaciated continental margins forced by the collapse of glacial forebulges and hydroisostatic loading of continental margins (Mitrovica and Milne, 2002; Milne et al., 2005). In the presence of abundant sediment supplies, relative sea-level fall (rSLF) along the Brazilian coast of South America resulted in the formation of extensive strandplains (broad accumulations of mainland-connected parallel or semi-parallel ridges of sand separated by shallow swales; Angulo, 1999). Deposition of these strandplains seaward of SLH shorelines has resulted in excellent preservation of SLH deposits, thus providing an ideal location to investigate the nature of late-stage transgressive and highstand sedimentology.

Signatures of the mid-Holocene SLH can be traced across all coastal Brazilian states, abandoned several meters above modern sea level, and often several kilometers landward of the modern shoreline (Fig. 1; Table 1). These features have been the subject of investigation by researchers for decades, though generally as part of broader studies of the development of entire transgressive/regressive barrier-strandplain systems in individual coastal compartments; these studies are reviewed according to their geographic location by Dillenburg and Hesp (2009). Although some researchers have sought to compare Holocene coastal evolution across swaths of the Brazilian coast, these studies generally focus on a broader comparison of sites based on some commonality (e.g., fed by rivers [Dominguez et al., 1981, 1987] or fronted by strandplains [FitzGerald et al., 2007]). By contrast, we focus here on the highstand features themselves, comparing and contrasting them across the entire Brazilian coastline.

The goals of this paper are to provide new, integrated geophysical, morphological, and sedimentological signatures of the multiple forms of the mid-Holocene transgression and SLH at one such site in southern Brazil, and compare these to similar highstand deposits throughout the Brazilian coast. This latter objective is achieved by compiling the results from morphologic, sedimentologic, chronologic, and, where available, geophysical studies of Holocene coastal systems. In this manner, we use the diversity of highstand deposits to illuminate the complexities associated with coastal response to accelerated rSLR, as well as the diversity of forms resulting from SLH, and establish a paradigm for understanding threshold coastal responses to sea-level change and predicting future coastal response to ongoing and accelerated rSLR.



Figure 1. Locations of mid-Holocene highstand deposits identified along the Brazilian coast. Numbers 1–28 indicate the locations of mid-Holocene highstand transgressive deposits, and correspond to location identifiers listed in Table 1. New data are presented here for location 20 (Navegantes), located in central Santa Catarina State in southern Brazil.

REGIONAL VARIABILITY IN SOUTHERN HEMISPHERE SEA-LEVEL CHANGE DURING THE HOLOCENE

Relative sea level along the Brazilian coast of South America rose at a rate of ~ 0.15 cm yr⁻¹ during the early to mid-Holocene. It reached modern levels at 6.9–7.7 ka and continued to rise for another ~ 1000 –1500 years to a highstand at ca. 5.8–5.9 ka at an elevation of 1–4 m above modern mean sea level (m MSL) (Mitrovica and Milne, 2002; Milne et al., 2005; Angulo et al., 2006; Caldas et al., 2006a) (Fig. 2). The timing and elevation of this SLH is largely consistent across the Brazilian coast and is well matched to hydroisostatic predic-

tions (Isla, 1989; Peltier, 1998; Milne et al., 2005). Regional differences are attributed to proximity to the equator, variability in geoidal relief (Martin et al., 1985; Suguío et al., 1985; Angulo et al., 2006), tectonics along regional faults (Bezerra et al., 2003; Rossetti et al., 2008; Castro et al., 2010), or local subsidence (Rossetti, 2003; Souza-Filho et al., 2009; Angulo et al., 2012). Following the highstand, rSL fell relatively smoothly, or with gentle oscillations, to modern elevations in the last <1000 years (Angulo et al., 2006).

The only exception to these trends is presented by northeastern Brazil where records of the SLH are sparse and inconsistent, having been largely disturbed by compaction-related subsidence

TABLE 1. MID-HOLOCENE HIGHSTAND DEPOSITS IDENTIFIED ALONG THE BRAZILIAN COAST

Loc. ID	Location name	State	Latitude	Longitude	Mid-Holocene highstand sedimentologic evidence	Reported highstand age (calibrated)	Maximum elevation of deposits (m MSL)	Highstand deposit type (Fig. 10)	References
1	Marajó Island	Pará	00°12' S	49°17' W	Tidal channel, tidal flat, and tidal delta sediments	6.1–6.3 ka	N/A	Type B	Castro et al., 2010; Rossetti et al., 2008
2	Bragança Peninsula: Campo Salgado	Pará	00°56' S	46°40' W	Beach, aeolian dune, and intertidal shoal sediment; initiation of overlying mangrove vegetation	5.91 ka	+1.4 to -1.5	Type C	Behling et al., 2001; Cohen et al., 2005; Souza-Filho et al., 2006, 2009*
3	Açu River mouth	Rio Grande do Norte	5°08' S	36°39' W	Transgressive lagoon and shoreface sediments; paleo-spits, tidal inlets, and tidal delta deposits	5.98–6.14 ka (shoreface sediment); 6.92–7.12 ka (lagoon deposits)	1–2	Type D-2	Silva, 1991; Vital, 2009*
4	São Bento–Catçara do Norte strandplain	Rio Grande do Norte	5°04' S	36°03' W	Transgressive barrier; landward-dipping GPR reflectors; overwash units; transgressive lagoon	6.76–7.09 ka (lagoon deposits)	1.6 (possibly eroded)	Type D-2	Caldas et al., 2006b
5	Recife strandplain	Pernambuco	8°03' S	34°52' W	Sandstone and coral reef; paleo-lagoon deposits	5.60–6.20 ka	1.0 ± 1	Type B	Dominguez et al., 1990
6	Candeias strandplain	Pernambuco	8°11' S to 8°14' S	34°55' W to 34°57' W	Sandstone and coral reef; paleo-lagoon deposits	5.95–6.45 ka (sandstone reef); 4.91–5.37 ka, 5.60–6.06 ka, 6.01–6.05 ka, (lagoon deposits)	>0.5 (sandstone reef); >2.5 (lagoon deposits)	Type B	Dominguez et al., 1990
7	Alagoas coastal plain	Alagoas	8°53' S to 10°10' S	35°09' W to 36°8' W	Elongated marine terrace; lagoonal deposits and regressive beach ridge plain	5.20–6.50 ka (lagoon deposits)	0.1–1.5	Type D-1	Barbosa et al., 1986
8	São Francisco River coastal plain	Alagoas	10°30' S	36°30' W	Elongated marine terrace; lagoonal deposits and only regressive beach ridge plain; lagoonal deposits dated adjacent to Holocene-Pleistocene boundary	5.55–5.95 ka; 5.32–5.51 ka	4 (maximum elevation of beach ridge plain)	Type D-1 and/or D-2	Bittencourt et al., 1981; Dominguez et al., 1981*, 1983*, 1987*, 1992*
9	Sergipe strandplain	Sergipe	10°58' S	37°02' W	No direct evidence of mid-Holocene highstand; only regressive beach ridge plain and erosion of Pleistocene plain	N/A	N/A	Type C	Bittencourt et al., 1983*
10	Jequitinhonha River plain	Bahia	15°50' S	38°55' W	Lagoonal deposits underlying landward side of Holocene beach-ridge plain; erosion of Pleistocene plain; transgressive lagoonal deposits	6.10–6.30 ka, 7.00–7.90 ka (lagoon deposits)	4 (Holocene ridge)	Type D-1 and/or D-2	Bittencourt et al., 1979; Dominguez et al., 1981*, 1987*, 1992*, 2009*; Martin and Dominguez, 1994
11	Caravelas strandplain	Bahia	17°45' S	39°10' W	Lagoonal terraces; shoreface and beachface sediments of a paleo-barrier chain; Holocene terraces	5.1 ka, 6.1–6.8 ka (lagoon deposits)	~2.5 (lagoon deposits)	Type D-1	Bittencourt et al., 1979; Andrade and Dominguez, 2002; Andrade et al., 2003; Dominguez et al., 2009*; Martin et al., 1987*
12	Doce River coastal plain	Espirito Santo	19°30' S	39°45' W	Lagoonal deposits, barrier sediments, overwash deposits, and subtidal and intertidal shoreface deposits	5.1–7.6 ka (lagoon deposits)	4 (Holocene ridge)	Type D-2	Dominguez et al., 1981*, 1987*, 1992*; Dominguez and Wanless, 1991; Martin and Dominguez, 1994; Martin and Sugulo, 1992; Martin et al., 1996; Sugulo and Martin, 1981; Sugulo et al., 1982*, 1985*
13	Paraíba do Sul River coastal plain	Rio de Janeiro	21°37' S	41°01' W	Landward-most ridge in regressive strandplain; pre-highstand lagoonal deposits	N/A	4 (Holocene ridge)	Type D-1 and/or D-2	Bastos and Silva, 2000; Dias and Kjerfve, 2009*; Dominguez et al., 1981*, 1987*; Martin et al., 1984
14	Cabo São Tomé	Rio de Janeiro	22°00' S	41°00' W	Lagoonal deposits, transgressive-regressive barrier deposits	5.0–6.0 ka (lagoon deposits)	5.5 (Holocene barrier ridge)	Type D-1	Dias and Kjerfve, 2009*; Silva, 1987
15	Itaipuaçu/Maricá strandplain	Rio de Janeiro	22°58' S	42°58' W	Lagoonal deposits, transgressive-regressive barrier deposits	6.59–6.73 ka, 7.00–7.20 ka (lagoon deposits)	N/A	Type D-1	Dias and Kjerfve, 2009*; Muehe, 1984; Perrin, 1984; Turcq et al., 1986, 1999

(continued)

TABLE 1. MID-HOLOCENE HIGHSTAND DEPOSITS IDENTIFIED ALONG THE BRAZILIAN COAST (continued)

Loc. ID	Location name	State	Latitude	Longitude	Mid-Holocene highstand sedimentologic evidence	Reported highstand age (calibrated)	Maximum elevation of deposits (m MSL)	Highstand deposit type (Fig. 10)	References
16	Jacarepaguá coastal plain	Rio de Janeiro	23°00' S	43°20' W	Lagoon deposits, transgressive-regressive barrier deposits	5.74–6.20 ka (lagoon deposits)	N/A	Type D-2	Dias and Kjerfve, 2009*; Maia et al., 1984
17	Cananêia-Iguape coastal plain/ilha Comprida barrier system	São Paulo	24°40' S to 25°03' S	47°26' W to 47°55' W	Erosional terrace; transgressive-regressive barrier deposits; buried transgressive deposits (discovered with GPR)	5.0–6.2 ka (beach-ridge deposits)	2.6–4.1 (Holocene ridge); 3.5 (erosional terrace)	Type C	Angulo and Lessa, 1997*; Gandolfo et al., 2001; Giannini et al., 2009*; Martin and Sugulo, 1976; Martin et al., 1988; Sugulo et al., 1976
18	Paranaíba/Superaçu/Pecas/Guaratuba coastal plains	Paraná	25°12' S to 27°57' S	47°59' W to 48°35' W	Lagoon deposits; highstand beach and ridge deposits; transgressive-regressive barrier deposits; FTD deposits; paleo-estuarine deposits	4.24–4.38 ka (FTD deposits); 5.23–5.37 ka, 3.5–4 (vermitids); 4 (paleo-estuarine deposits)	5 (FTD deposits); 3.5–4 (vermitids); 4 (paleo-estuarine plain)	Type D-2	Angulo and Lessa, 1997*; Angulo et al., 2006*; 2008, 2009*; Araujo, 2001; Lessa and Angulo, 1995; Lessa et al., 1998, 2000
19	Itapoá coastal plain	Santa Catarina	26°09' S	48°35' W	Barrier-lagoon deposits; paleo-estuarine deposits; paleo-inlet deposits	5.44–5.58 ka; 6.39–6.57 ka	>2	Type D-2	de Souza et al., 2001
20	Navegantes strandplain	Santa Catarina	26°50' S	48°38' W	Barrier ridge and lagoon	6.67–6.86 ka (upland freshwater deposits)	3.5–4.5	Types A, C, D-1	This study
21	Tijucas strandplain	Santa Catarina	27°15' S	48°37' W	Lagoon, barrier ridge, overwash, inlet system	5.98–6.12 ka (overwash deposits)	4.5–5.0	Type D-2	FitzGerald et al., 2007, 2011
22	Pinheira strandplain	Santa Catarina	27°52' S	48°37' W	Bedrock scarp (strandplain abuts bedrock)	>5.6 ka	>2.5–3.0	Type A	Hein et al., 2012; Hesp et al., 2009*
23	Southern Santa Catarina coastal plain (Paulo Lopes to Jaguaruna)	Santa Catarina	28°00' S to 28°42' S	48°38' W to 49°00' W	Erosional terraces; lagoonal deposits	5–7 ka (lagoon deposits)	>2	Type B, D-2	Caruso et al., 2000; Fornari et al., 2012; Giannini, 1993; Hesp et al., 2009*; Martin et al., 1988; Sugulo et al., 1986*
24	Curumin barrier	Rio Grande do Sul	29°37' S	49°57' W	Prograded, transgressive dunefield barrier; erosional contact with Pleistocene barrier	3.3–7.2 ka (shoreface deposits)	8–10 (landward side of dunes)	Type C	Dillenburg et al., 2006; Hesp et al., 2005, 2007, 2009*
25	Tramandaí barrier	Rio Grande do Sul	30°00' S	50°08' W	Washover deposits; FTD deposits; lagoon deposits; vertically accreting barrier; transgressive dunefield deposits	5.4–7.4 ka	–4	Type D-2	Travessas et al., 2005; Hesp et al., 2007
26	Jardim do Éden barrier	Rio Grande do Sul	30°03' S	50°09' W	Lagoon and washover deposits	6.5–6.8 ka (lagoon deposits)	> 2 (lagoon deposits)	Type D-1 and/or D-2	Travessas et al., 2005
27	Cidreira barrier	Rio Grande do Sul	30°10' S	50°12' W	Lagoon and washover deposits	7.3 ka (lagoon deposits)	> 2 (lagoon deposits)	Type D-1 and/or D-2	Travessas et al., 2005
28	Central Rio Grande do Sul coastal plain	Rio Grande do Sul	30°00' S to 33°43' S	50°08' W to 53°20' W	Barriers; paleo-lagoon deposits; washover deposits	N/A	4–5	Type D-2	Dillenburg et al., 2004, 2009*; Toldo et al., 2000; Tomazelli and Villwock, 1996; Tomazelli et al., 2000, 2006; Villwock, 1984; Villwock et al., 1986

Note: Sites of sedimentologic evidence for the mid-Holocene transgression and highstand discussed in text. Location IDs refer to locations noted in Figure 1. Calibrated age of highstand deposits is either derived or calibrated from dates reported in published work. Calibrations were performed using Calib 6.0.1 (Stuiver and Reimer, 1993) with SHCal04 (McCormac et al., 2004) calibration curves for terrestrial material or Marine09 (Reimer et al., 2009) calibration curves for marine materials. A marine reservoir correction of $\Delta R = 8 \pm 17$ yrs. as defined by Angulo et al. (2005), was applied in the calibration of radiocarbon dates from all mollusk samples. All ages are calibrated, one-sigma years before present (present = A.D. 1950). Note that all locations given provide depositional evidence of the mid-Holocene highstand with the exception of Pinheira (location 22), which is discussed extensively in text. GPR—ground-penetrating radar; FTD—flood-tidal delta; m MSL—meters above modern mean sea level.

*Comparison or regional overview study; based on other original studies listed or on unpublished graduate theses.

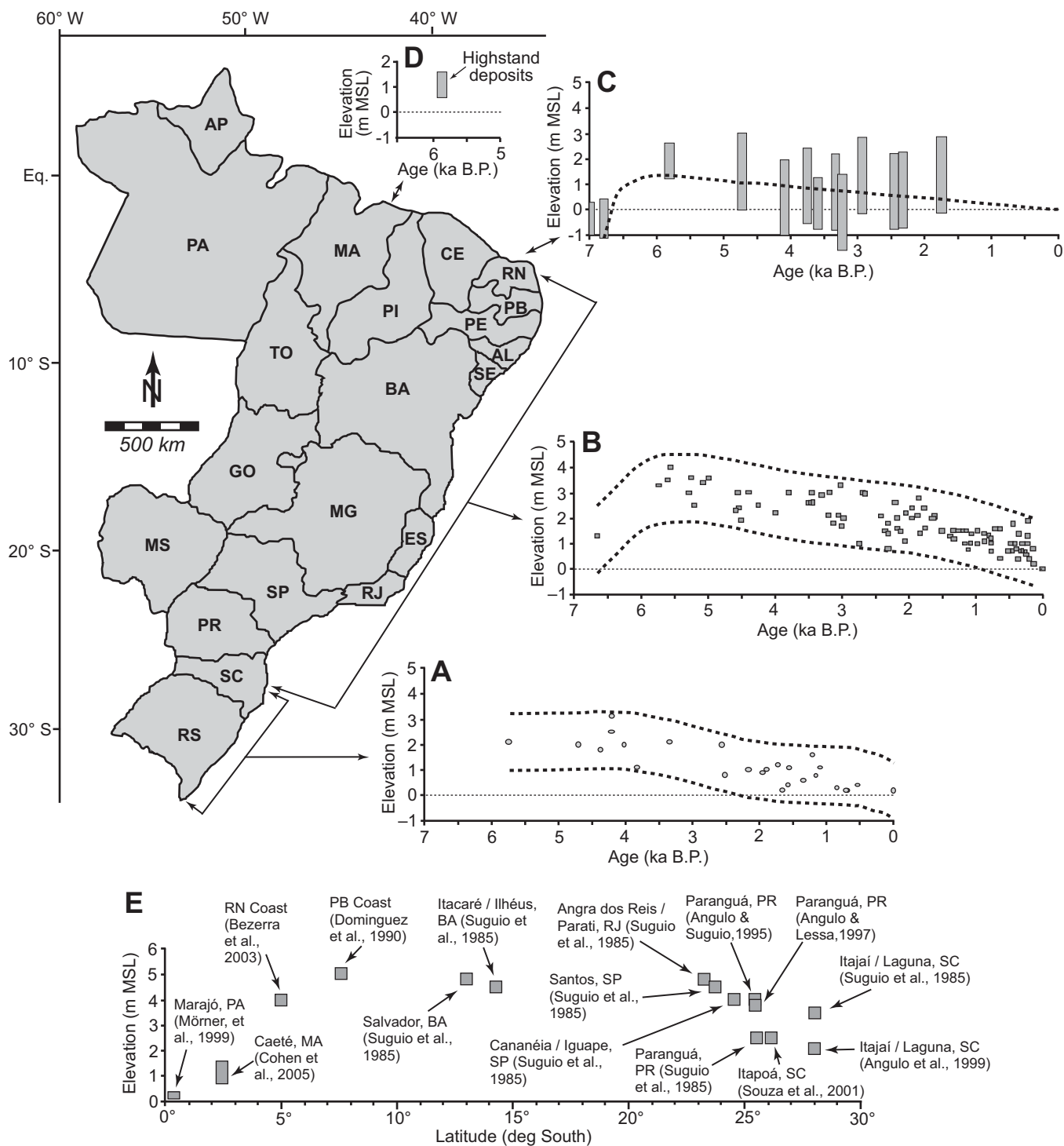


Figure 2. Brazilian sea-level curves (m MSL—meters above modern mean sea level). (A) Sea-level envelope based on vermitid radiocarbon records for the Brazilian coast south of 28° latitude (modified from Angulo et al., 2006). (B) Sea-level envelope based on vermitid radiocarbon records for the eastern Brazilian coast between central Santa Catarina and Rio Grande do Norte (modified from Angulo et al., 2006). (C) Sea-level curve for the northern Rio Grande do Norte coast based on radiocarbon dating of beachrock and lagoonal sediments (modified from Caldas et al., 2006a). (D) Elevation and age of the mid-Holocene highstand in northern Brazil (Maranhão State), where no published sea-level curves exist (Cohen et al., 2005; Souza-Filho et al., 2006, 2009). (E) Compilation of the elevation of the mid-Holocene highstand along the Brazilian coast, by latitude (modified and updated from Angulo et al., 2006). AL—Alagoas; AP—Amapá; BA—Bahia; CE—Ceará; ES—Espírito Santo; GO—Goiás; MA—Maranhão; MG—Minas Gerais; MS—Mato Grosso do Sul; PA—Pará; PB—Paraíba; PE—Pernambuco; PI—Piauí; PR—Paraná; RJ—Rio de Janeiro; RN—Rio Grande do Norte; RS—Rio Grande do Sul; SC—Santa Catarina; SE—Sergipe; SP—São Paulo; TO—Tocantins.

associated with Amazon River sediment deposition (Rossetti, 2003; Souza-Filho et al., 2009). The mere existence of a Holocene SLH north of Rio Grande do Norte remains in some doubt. Competing records from the region between Rio Grande do Norte and the mouth of the Amazon River indicate that rSL either reached and never exceeded modern elevations by 4.4–5.1 ka (Mörner et al., 1999; Irion et al., 2012), or reached only 0.6–1.5 m higher than present at ca. 5.9 ka (Cohen et al., 2005; Souza-Filho et al., 2006, 2009) (Figs. 2D, 2E).

IDENTIFICATION OF MID-HOLOCENE HIGHSTAND DEPOSITS AT NAVEGANTES, SOUTHERN BRAZIL

The Navegantes Strandplain: Coastal Geologic Setting

The Navegantes strandplain is 10–12 km long and 2–8 km wide. It is located in north-central Santa Catarina (~26°50' S, 48°38' W; Fig. 3) and is fed by the Itajaí-Açu Rivers, the largest river system draining to the Santa Catarina coast. It drains an area of $\sim 1.6 \times 10^4$ km², and has an average annual fluvial discharge of 220–230 m³ s⁻¹ and a suspended sediment yield of 0.76 Mt yr⁻¹ (ANA, 2000; Milliman and Farnsworth, 2011). This is a highly stratified river (Schettini et al., 1996) that generally only delivers sand-sized sediment to the coastal zone during floods (Ponçano and Gimenez, 1987). The modern Navegantes beach is fine-grained and dissipative, an environment suitable for strandplain formation due to constructional waves that move sand onshore. The local shoreface has a 1.5°–2.5° slope, decreasing to $\sim 0.01^\circ$ (Angulo et al., 2009) on the continental shelf.

Navegantes is located along an irregular bedrock coast, smoothed by beach ridges and dominated by large bedrock headlands, estuaries, reentrants, and bays (FitzGerald et al., 2007). This coastal segment reflects a regime of abundant sediment supply in which widely spaced promontories produce a shoreline characterized on a smaller scale by narrow barrier spits, tidal inlets, and small rivers. Navegantes is backed by the Serra do Mar coastal range that is locally exposed as fronting headlands of the Brusque Group to the south of the strandplain and the Granulítico (“granulite”) Group to the north (Horn Filho and Ferreti, 2010). Intense weathering of bedrock within the Navegantes drainage basin has produced an easily erodible saprolite that is tens of meters thick and provided abundant sediment that built the Navegantes strandplain during a period of rSLF following the mid-Holocene SLH.

Climatologically, Navegantes is located in the southern subtropics, a transitional zone between temperate and tropical environments. Although prevailing winds are from the northeast, the wind regime is dominated by the passage of moderately strong cold fronts that induce southerly winds (Nimer, 1989; Klein, 1997) and occasional cyclones (Barletta and Calliari, 2001). Intense storms are rare: only two recorded tropical cyclones have impacted this coastline in the past 100 years, Cyclone Catarina in A.D. 2004 (McTaggart-Cowan et al., 2006) and Tropical Storm Anita in 2010. Sea swells tend to be bimodal (Araújo et al., 2003) and dominated by southerly swells that result in net northerly long-shore transport (Giannini, 1993; Muehe 1998; Dillenburg et al., 2000). Local transport rates and directions are highly variable due to local wave refraction and diffraction around bedrock headlands that front many of the embayed systems that dominate much of this coast (FitzGerald et al., 2007; Siegle and Asp, 2007). This wave climate is largely reflected in the morphology of inlets and headland bay beaches (Klein, 2004; Klein and Menezes, 2001; Klein et al., 2010) and serves to protect many coastal compartments from higher-energy waves associated with the dominant swell. Tides along the Santa Catarina coast are mixed microtidal with a mean spring tide height of 0.46–1.06 m (at Imbituba and Enseada, respectively) and strongly influenced by local meteorological conditions (Trucolo, 1998).

Methods

A variety of morphologic, geophysical, sedimentologic, and geochronologic tools were employed in the identification of mid-Holocene transgressive and highstand deposits in Navegantes. Initial geomorphic surveys were carried out with orthophotographs, topographic maps, ground observations, and ~ 25 km of GPS with real-time kinematics (RTK-GPS) data collected at ~ 1 m data-point spacing along roads and walking trails. From these data, a number of sites were targeted for additional investigation; here, we focus on four of them (sites 1–4; Figs. 3, 4, 5) that are representative of three different types of mid-Holocene highstand deposits.

Ground-penetrating radar (GPR) profiles were collected along shore-parallel and shore-normal transects at each of the target sites using a digital Geophysical Survey Systems, Inc. (GSSI) SIR-2000 GPR with a 200 MHz monostatic antenna (see van Heteren et al. [1998] and Jol and Bristow [2003] for technical aspects of the use of GPR in coastal settings) with a two-way-travel-time (TWTT) range of 150–250 ns. This system penetrated 4–8 m deep, depending on signal

attenuation caused by fine-grained sediment (Figs. 6, 7, 8). Data were post-processed (site-specific data filtering, variable-velocity migration, gain control) and time-depth converted using a combination of Radan (GSSI) and Rad-Explorer (MALÅ Geoscience) software packages. Profiles were topographically corrected using RTK-GPS elevation data points collected along the profile lines at 5 m intervals. Descriptive terminology of radar-reflection geometry is derived from Neal (2004).

Approximately 8250 high-resolution RTK-GPS data points were collected at site 4 (Fig. 5) at 1 m point spacing along 35 parallel north-south transects spaced at <10 m plus east-west and switchback tie lines along and across a topographically high linear ridge. These data were acquired using a Trimble R6 GPS unit (datum: SAD69) and analyzed in a geographic information systems (GIS) framework to create a digital elevation model for a ~ 0.25 km² region (Fig. 5B).

A suite of fourteen 2–4-m-deep hand-auger cores, sixteen 4–6-m-deep vibracores, and two 8–10-m-deep wash borings provided detailed stratigraphy used to verify lithologic units inferred from GPR reflection profiles (locations shown on maps in Figs. 3, 4 and 5; core logs shown on GPR radargrams in Figs. 6, 7, 8; detailed vibracore logs for sample cores at site 4 provided in Fig. 9). The wash-bore cores used a combination of liquid wash and percussion direct push that provided for 45 cm of continuous recovery every meter. Sections of continuous core were described and photographed in the field. At least one sample was collected within each described sedimentologic unit (2–20 cm sampling intervals). Auger cores were logged and sampled in the field. Vibracores were opened, logged, and sampled at the Laboratory for Geological Oceanography at the Universidade do Vale do Itajaí (UNIVALI).

Selected sediment samples were prepared and analyzed using combined wet/dry sieve (0.5 phi [ϕ] intervals) techniques to determine particle-size characteristics (Folk and Ward, 1957). Two samples of organic-rich, micaceous sandy mud (samples NVV07-S1, NVV08-S1; Table 2) and one sample of freshwater peat (sample NVV09-S1; Table 2) were selected for radiocarbon analysis. No other in situ organic matter or shell debris was recovered in any other sediment cores. Radiocarbon analysis was performed at the National Ocean Sciences Accelerator Mass Spectrometry Facility at Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA. Terrestrial samples were calibrated using Calib 6.0.1 (Stuiver and Reimer, 1993) with SHcal04 (McCormac et al., 2004) calibration curves (Table 2). Marine samples

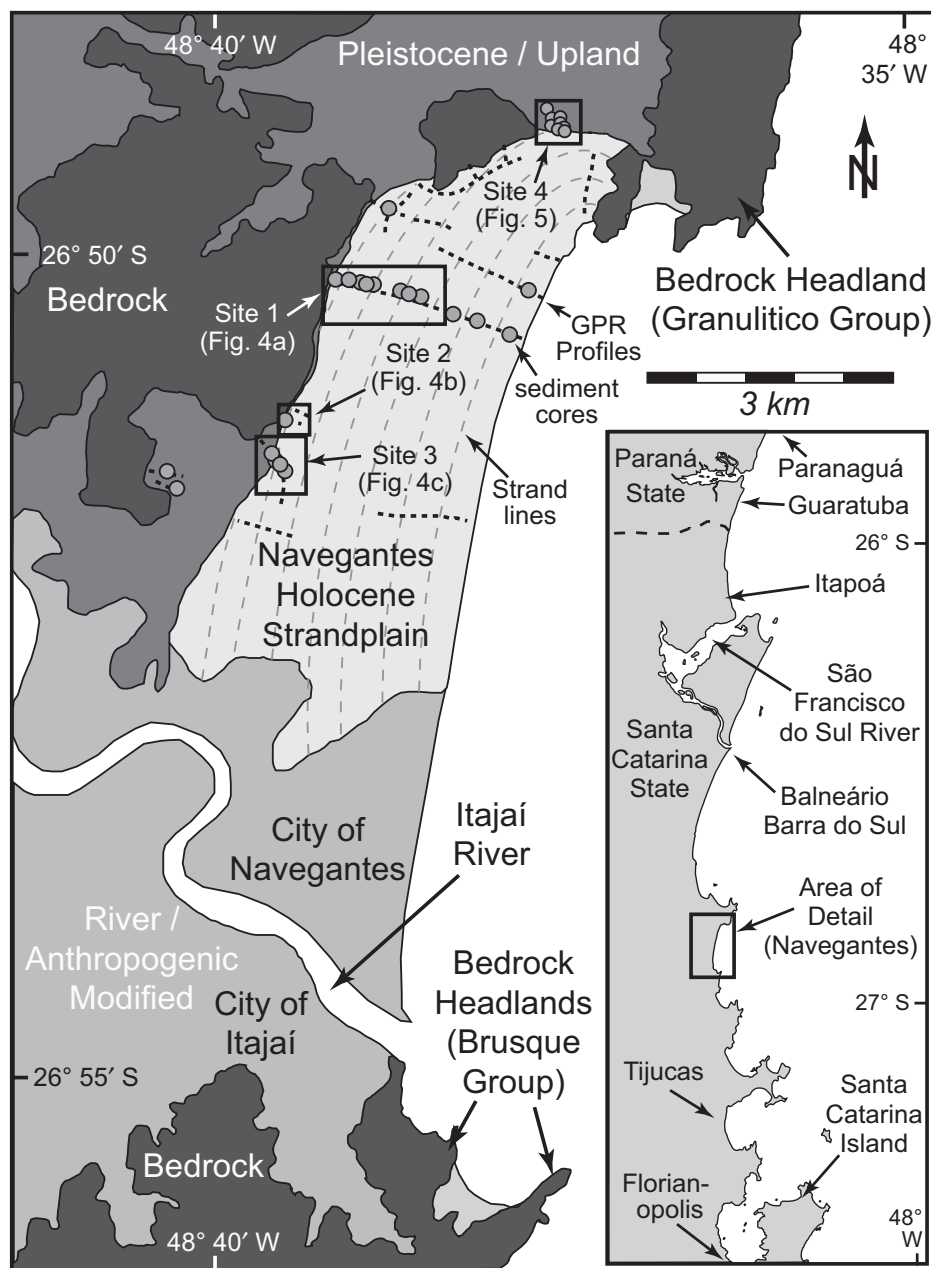


Figure 3. Overview map of Navegantes. Locations of the four sites investigated in detail for evidence of depositional mid-Holocene highstand features are shown. Note the fronting headlands that provide protection from dominant southeasterly swell and isolation from the northerly longshore transport regime. Dashed black lines are locations of ground-penetrating radar (GPR) profiles collected throughout the Navegantes strandplain. Gray dashed lines represent strand lines of the strandplain. Gray circles show locations of sediment cores. Inset: Regional overview of northern Santa Catarina and southern Paraná States, showing the location of Navegantes with respect to several other sites discussed in text.

(mollusks) were calibrated using Marine09 (Reimer et al., 2009), and a marine reservoir correction of 8 ± 17 yr, as defined by Angulo et al. (2005), was applied. All dates presented in text are calibrated, two-sigma years B.P. (present = A.D. 1950).

Results and Interpretation of Units

The natural landscape at Navegantes has undergone significant anthropogenic disturbance (farming, deforestation, road building, sand mining, and development). This has flat-

tened the topography and removed most sub-aerial evidence of the mid-Holocene SLH. However, the highstand features have been mapped in different forms in several locations throughout Navegantes (sites 1–4; Figs. 3–5). These locations share many common radar-reflection morphologies and sedimentological characteristics that allow for the identification of several common, laterally discontinuous units.

Unit I: Pleistocene Upland

The basal unit I is found in the topographically high, landward-most sections of profiles. It is sub-horizontal to gently ($\sim 0.8^\circ$) seaward dipping and dominated by laminated muddy sand with variable organic content, common rip-up clasts, blue-green silty clay, and thin beds and/or laminae of coarser sediment (granules to pebbles). It has a sharp upper contact (e.g., Fig. 9A) and contains weak, horizontal to sub-horizontal internal GPR reflections. This unit contains no coastal or marine signatures and is thus interpreted as Pleistocene upland deposits. Iron staining and coatings are signs of oxidation and prolonged subaerial exposure. Radiocarbon analysis of two organic-rich muddy layers within this unit (samples NVV07-S1 and NVV08-S1; sample locations shown in Figs. 9A, 9C) confirms a pre-Holocene age of this unit (Table 2). The high amounts of bioturbation, bedded sands, organic matter, clay, and angular gravel reflect discontinuous upland deposition, possibly from overland flow or the flooding of local streams. In many areas, this unit provides the substrate upon which Holocene transgressive, SLH, and regressive deposits have formed.

No Pleistocene upland deposits were observed in central Navegantes (sites 1–3). Here, units III or V (described below) extend to bedrock outcrops that mark the landward boundary of the Navegantes plain. In these locations the shoreline abutted, or was immediately adjacent to, bedrock at the SLH. Although it is likely that this unit still forms the basal surface seaward of these bedrock outcrops, radar profiles and sediment cores did not penetrate through overlying units.

Unit II: Lagoon/Freshwater Peat

Unit II is found only in one location in Navegantes: underlying the topographic ridge at site 4. Here, this unit, cored in vibracore NVV09, is a 15-cm-thick, highly organic-rich freshwater peat or paleosol located at 2.8 m MSL. It has an erosional upper contact with unit III. A fragment of peat from within this section was dated to 6764 ± 98 cal yr B.P. (Table 2), ~ 1000 years prior to the mid-Holocene SLH in this region (5.8 ka; Angulo et al., 2006). It is therefore concluded that this unit represents a backbarrier

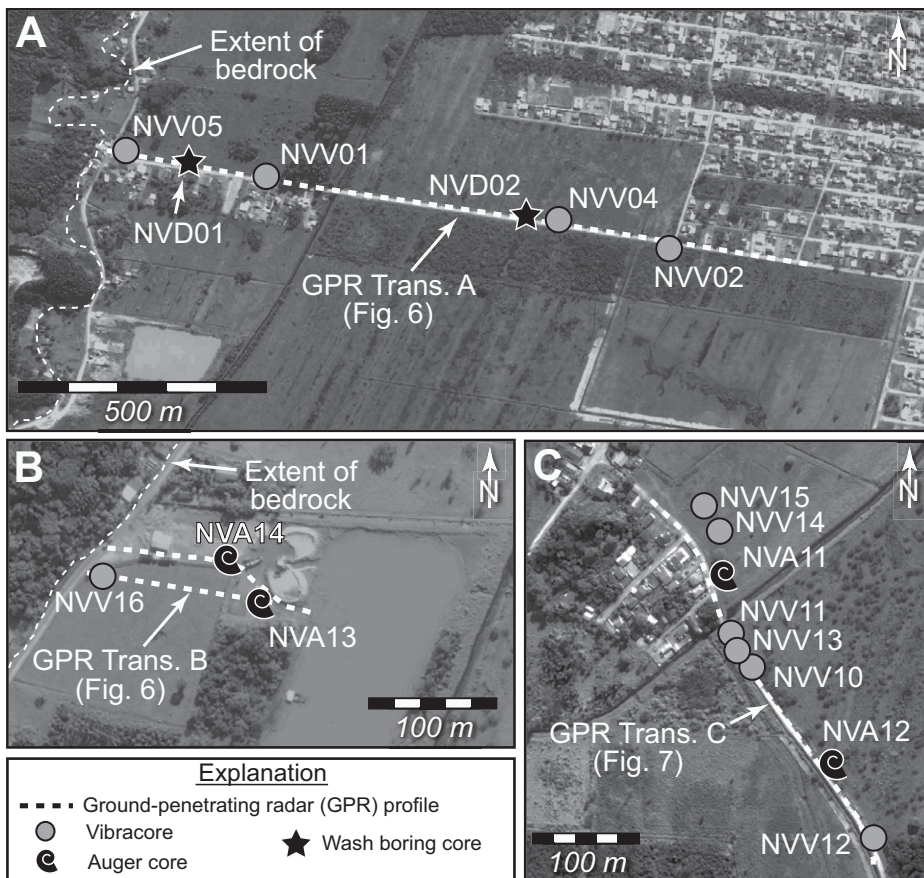


Figure 4. Data collection at sites 1–3 at Navegantes. Locations of ground-penetrating radar (GPR) profiles, auger cores (prefix NVA), vibracores (NVV), and wash borings (NVD). See Figure 3 for location. Trans.—transect. (A) Site 1. (B) Site 2. (C) Site 3.

peat, unconformably deposited onto the older, eroded upland during the latest stages of transgression and SLH. Notably, this unit is absent from all but one profile. This trend may reflect the overall dearth of muddy sediment within the Navegantes plain (cf. FitzGerald et al., 2007), or a rate of marine transgression too rapid for the formation of fronting barriers that would have produced a quiet backbarrier environment in which a lagoon or marsh could form. The 6.7 ka age of this unit provides an oldest possible time for the emplacement of overlying unit III.

Unit III: Highstand Ridge and Bar

At site 3 in central Navegantes, unit III is fully buried, likely due to anthropogenic disturbance and road construction that resulted in topographic smoothing. A bar-like feature with horizontal to sub-horizontal internal reflections is visible in GPR radargrams (transect C; Fig. 7). It is 100 m wide in an east-west (seaward-landward) direction and contains landward-dipping internal reflections on its landward side and a strong, horizontal basal reflection. The top of

this feature is 20–30 cm higher than the adjacent seaward-dipping reflection sets of unit V. Its crest is ~3.5 m MSL and it is ~4.5–5 m thick. A sediment core through this unit reveals a bedded, fine (median grain size: 2.41 ϕ) to medium-fine sand with variable concentrations of mica.

At site 4, unit III is identified subaerially as a disjointed, linear, 400-m-long, east-west-trending, topographically high ridge (Fig. 5B). It is ~1 m higher than surrounding topography, cresting at 5.2 m MSL. GPR profiles (transects D and E; Fig. 8) reveal that this unit is generally thin (1–3 m), 25–30 m wide, and characterized by concave-down reflections that dip in both landward and seaward directions. This unit reaches a maximum elevation of 4.5 m MSL and is capped with an additional ~70 cm of unit VI, accounting for the remainder of the ridge elevation. Profiles collected in a shore-parallel orientation along this ridge contain monotonous, horizontal reflections, indicating that ridge-perpendicular profiles reflect the true reflection morphologies. This unit is up to 3 m thick along

transect E (Fig. 8) and dominated by horizontal to seaward-dipping reflections. At this location, the sediment composing unit III is generally coarser than at site 3. It is dominated by moderately well-sorted, quartz-dominated, medium-coarse sand with abundant heavy minerals (primarily ilmenite and magnetite). Cores NVV06 (Fig. 9B) and NVV09, both of which penetrate this unit, reveal 10–20-cm-thick normal- and reverse-grading sequences. The uppermost sections of this unit contain modern roots and are topped by a 10-cm-thick modern soil forming in medium to fine sand.

Unit III is interpreted as the mid-Holocene highstand shoreline. At site 3, this feature is a supratidal barrier bar that was either mainland-attached or possibly separated from upland bedrock by a shallow bedrock-bottomed lagoon; however, no evidence of such a lagoon was uncovered. By contrast, at site 4, the unit III is a low-profile (~1-m-high) barrier ridge. The relatively coarse and heavy mineral-rich nature and landward- and seaward-dipping internal reflections are all suggestive of landward migration and barrier overwash at the leading edge of the transgression.

Unit IV: Upland Aeolian Sand

Unit IV is observed only along the landward 180 m of GPR transect C, where it unconformably overlies shallow (1–4 m deep) bedrock (site 3; Fig. 7). It is composed of a 1–3-m-thick sequence of very fine to medium, very well-sorted sand with rare, thin, heavy-mineral laminations. GPR penetration in this region is poor due to overlying fine-grained sediment, but visible internal reflections are chaotic in nature. This unit is interpreted as upland aeolian dunes deposited behind the barrier ridge that was pinned to the seaward edge of the shallow bedrock during the late stages of transgression.

Unit V: Strandplain

Unit V is observed as a 3–6-m-thick sequence of strong, seaward-dipping (0.5° – 5°) reflections observed in the seaward sections of all GPR profiles at all sites. It is interpreted as the progradational strandplain sequence formed by the forced regression following the highstand. At sites 1 and 2, where the landward sides of GPR transects A and B are immediately adjacent to subaerial bedrock outcrops, the landward-most sections of internal reflections within this unit are generally nearly planar and dip seaward at shallower (0.5° – 1.5°) angles. These become steeper (2° – 3°) and more planar-tangential to sigmoid-oblique in a seaward direction. Shore-parallel GPR profiles contain only horizontal to very slightly ($<0.5^{\circ}$) inclined reflections, indi-

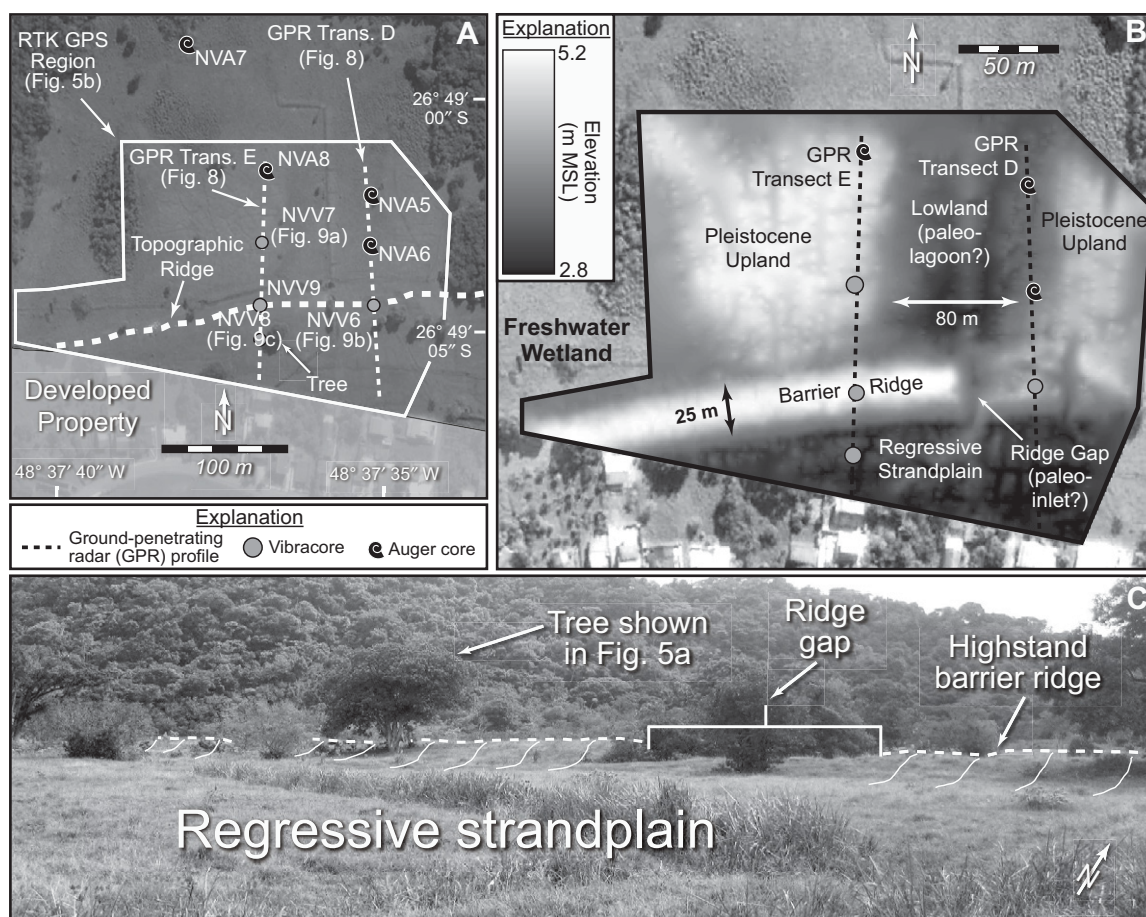


Figure 5. Data collection at site 4 at Navegantes. (A) Locations of ground-penetrating radar (GPR) profiles, auger cores (prefix NVA), and vibracores (NVV). See Figure 3 for location. Topographic ridge is shown as a thick dashed line. Solid-line polygon shows the region of the digital elevation model (DEM) shown in B. Trans.—transect. RTK-GPS—global positioning system with real-time kinematics. (B) Grayscale DEM of barrier-ridge topography at site 4. Topographic data are derived from interpolation of ~8250 RTK-GPS data points, collected at ~1 m point spacing along 35 parallel north-south transects spaced at <10 m plus east-west and switchback tie lines along and across the barrier ridge. Data are corrected to modern mean sea level (datum: SAD69). Note the linear morphology of the 25-m-wide, 400-m-long segmented barrier ridge and 80-m-wide lowland immediately landward of the ridge. The barrier ridge marks the landward extent of the mid-Holocene transgression and the landward-most ridge in the regressive strandplain that built in a seaward (south-southeast) direction. The ridge has been truncated on the western side by anthropogenic disturbance. m MSL—meters above modern mean sea level. (C) Perspective ground photo of the mid-Holocene highstand ridge at site 4. Note the tree shown in the photo and indicated in A.

cating that true dips of internal reflections are in a shore-normal direction. GPR profiles across the strandplain reveal that it extends laterally to the modern shoreface as repetitive, seaward-dipping strata. Sandy ridges are occasionally interrupted by muddy swales, 10–30 m in width and <1.5 m thick. These sedimentologic and clinoform patterns are identical to those previously interpreted as shoreface accretion units in Navegantes (FitzGerald et al., 2007). Previous studies at Navegantes have demonstrated that this unit extends laterally to the modern shoreface and is dominated by repetitive, seaward-dipping (angle of ~1.5°–2.5°) strata that are

occasionally truncated by more steeply dipping clinoforms interpreted as high-energy event markers (Buynevich et al., 2006; FitzGerald et al., 2007; Buynevich et al., 2011). The planar-tangential to sigmoid-oblique clinoform sets likely reflect deposition in the shallow shoreface (basal, near-horizontal sections of reflections), foreshore (high-angle intermediate sections of reflections), and the uppermost upper beach and foredune sections. Similar units are described in detail in Hein et al. (2012) for the nearby (115 km south) Pinheira strandplain (location [loc.] 22, Fig. 1). Otvos (2000), Hesp et al. (2005), and Hesp (2006) provide detailed

descriptions of such strandplains (also called “strand plains” or “beach-ridge plains”).

Sediments from the bottom of a single wash boring that penetrated this unit (NVD01; Fig. 6) were coarse grained and semi-rounded, possibly fluvial in origin. Similar deposits underlying the Tijucas strandplain (loc. 21) were interpreted as fluvial sediments deposited by the Tijucas River during lower stands of rSL (FitzGerald et al., 2011). Although current data do not provide confirmatory proof, a fluvial origin for these basal sediments would indicate that the strandplain built directly on top of an eroded Pleistocene surface.

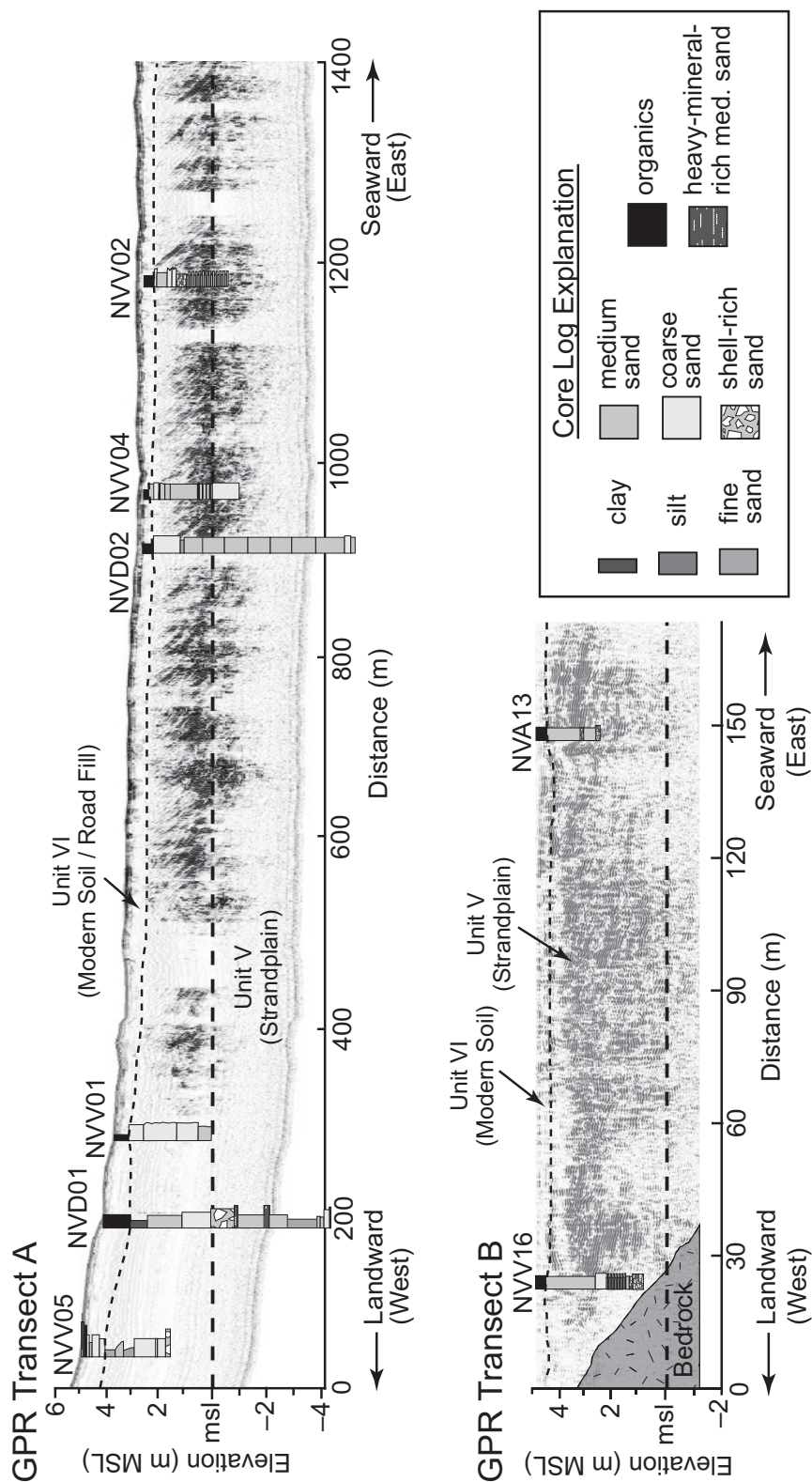


Figure 6. Ground-penetrating radar (GPR) transects A and B. GPR transect A was collected at site 1, and GPR transect B collected at site 2 (see Figs. 3 and 4 for locations). Graphic core logs from auger cores (prefix NVA), vibracores (NVV), and wash borings (NVD) are shown. msl—modern mean sea level; m MSL—meters above modern mean sea level.

Unit VI: Soil/Road Fill

All sites at Navegantes are capped with 0.2–1.0 m of unit VI, interpreted as road fill and/or modern soil and freshwater peat. Organic-rich sections are dominated by laminated, muddy, fine to medium sand to muddy silty sand in a generally fining-upward sequence that has increasing root abundance and mottling toward the top. This is overlain by laminated, bioturbated, organic-rich mud. Internal radar reflections are weak and chaotic, likely reflecting the high degree of bioturbation and/or anthropogenic and modern disturbance. The contact between unit VI and underlying units is generally gradual and transitional, with roots often extending from unit VI into underlying units; this is particularly common at sites 2 and 4. This section of GPR transect A (site 1) attained little penetration due to the predominance of fine sediment near the surface that attenuates radar energy.

CHARACTERIZATION OF TRANSGRESSIVE AND HIGHSTAND DEPOSITS

Diverse Characteristics of the Mid-Holocene Highstand at Navegantes

The contrasting forms of mid-Holocene highstand deposits at Navegantes can be largely attributed to differences in sediment supply and the ability of coastal sediments to be transported in a landward direction during the latest stages of transgression. This latter factor, defined here as the *upland migration potential* (UMP), is a function of both the slope and erodibility of the upland surface onto which the shoreline is migrating (the submergence-controlled shoreline; Oertel et al., 1992). The ability of coastal waves and tides to rework any available sand-sized sediment into highstand shoreline features is strongly dependent upon the availability of space along the transgressive shoreline into which sediment can be deposited (i.e., upland accommodation space) (Posamentier et al., 1988; Van Wagoner et al., 1990). For example, lateral migration of a bedrock-dominated shoreline will be primarily determined by the slope of the resistant substrate. By contrast, an upland composed of unconsolidated sediments, regardless of the slope, will provide a substrate that is easily erodible by coastal processes (waves, tides). Erosion of this surface will reduce the upland slope, thus providing additional accommodation space for the deposition of transgressive deposits, and a local source of sediments for these deposits. The diverse transgressive and SLH deposits at Navegantes are considered here in terms of the UMP at each site and the availability of sediment to form highstand features.

GPR Transect C

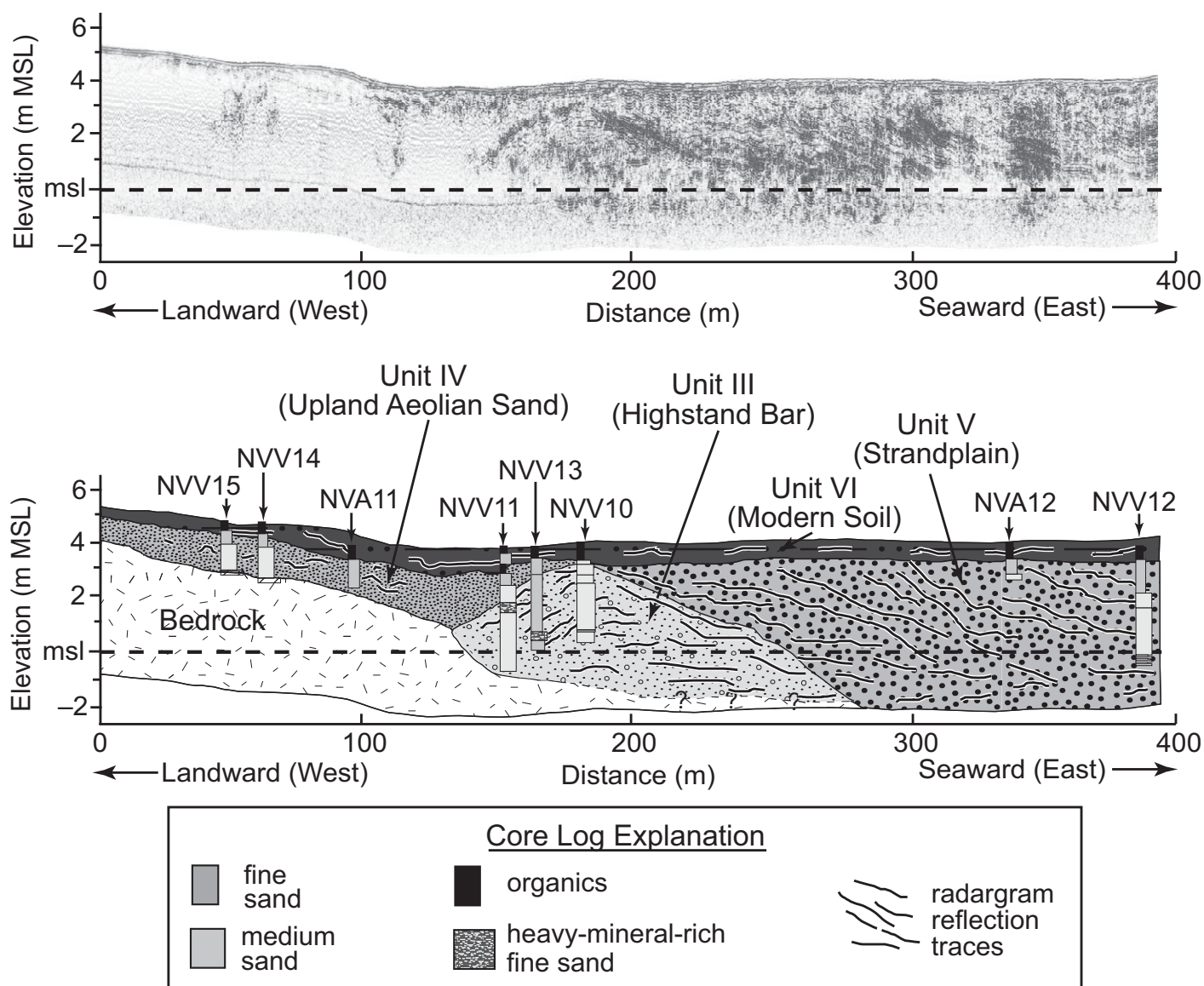


Figure 7. Ground-penetrating radar (GPR) transect C. Shown are the processed GPR radargram (top) and interpretation (bottom) across the barrier ridge in central Navegantes (site 3; see Figs. 3 and 4 for location). Profile was collected along a road, accounting for smoothing of topography. Graphic core logs from auger cores (prefix NVA) and vibracores (NVV) are shown. msl—modern mean sea level; m MSL—meters above modern mean sea level.

Exposed Bedrock Highstand Coast (Sites 1 and 2)

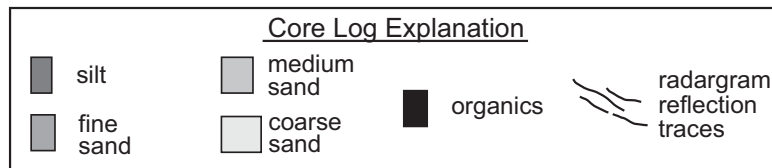
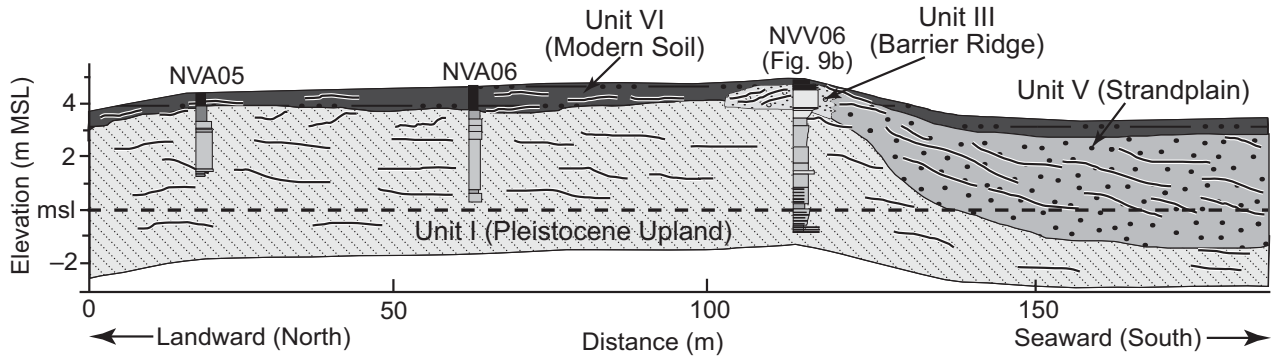
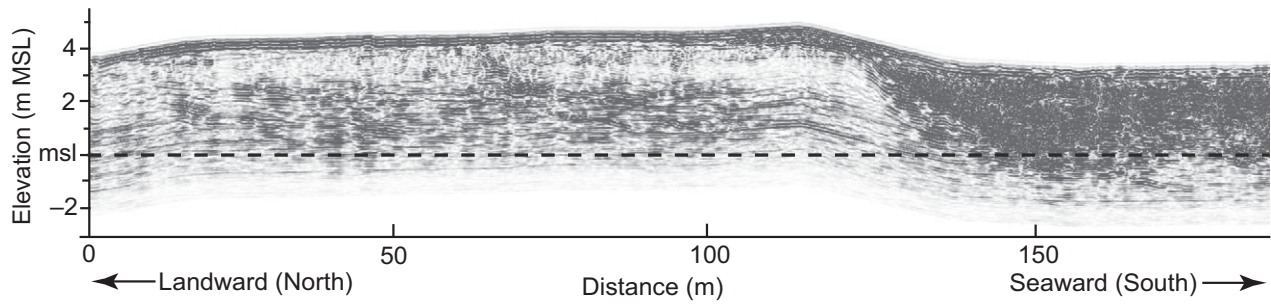
The simplest form of the mid-Holocene SLH at Navegantes was an exposed bedrock coast. Such a case is evident at sites 1 and 2 (GPR transects A and B; Fig. 6), where the regressive strandplain (unit V) abuts subaerial bedrock. The bedrock face at site 1 is nearly vertical and extends to the landward (western) end of the GPR transect (Fig. 4A), either continuing to dip steeply seaward, or shallowing

at a depth below the maximum penetration of GPR and core NVV05. Subaerial bedrock adjacent to site 2 (Fig. 4B) dips seaward at a lower angle (~45°) and can be observed extending under the strandplain (Fig. 6). Here, the strandplain unit clearly overlies bedrock, indicating that, at SLH, waves in this region crashed along a bedrock headland, while fine and medium sand was deposited in the shallow nearshore zone as the basal sections of the regressive strandplain.

Bedrock-Pinned Highstand Barrier Bar (Site 3)

In contrast to sites 1 and 2, clear subaerial, constructional sedimentological signatures of the mid-Holocene SLH exist elsewhere in Navegantes. In these locations, UMP was greater due to lower bedrock slopes or the presence of more expansive, easily erodible upland deposits. At site 3 (Fig. 4C), a buried, 100-m-wide, 5-m-thick, shore-parallel bar is pinned on its landward side to a shallow (-1 to 1 m MSL)

GPR Transect D



GPR Transect E

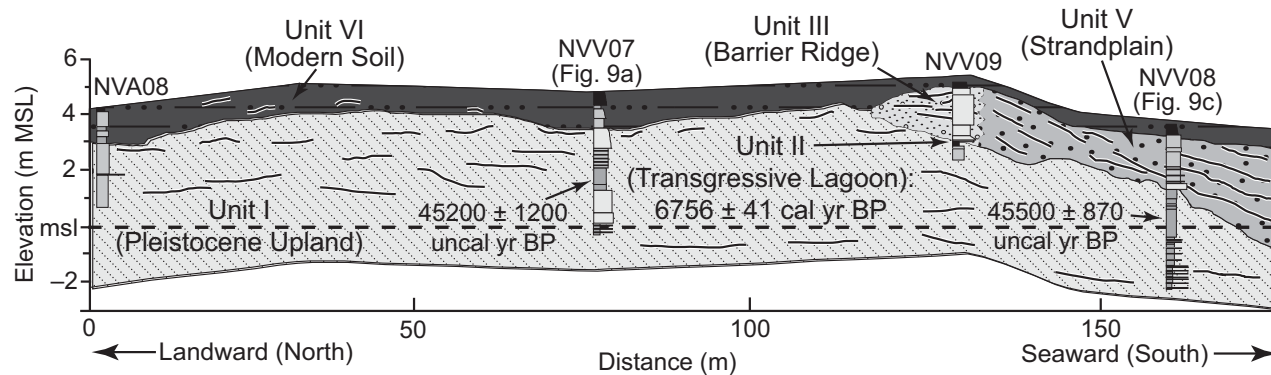
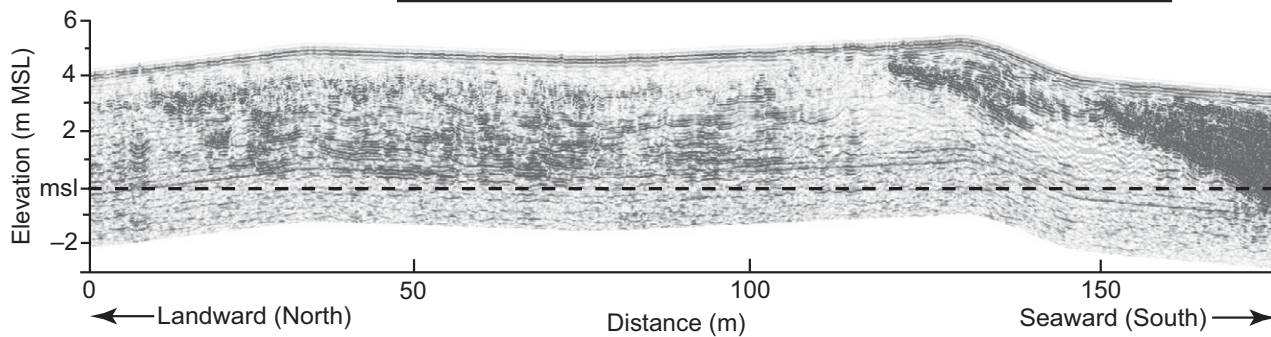


Figure 8. Ground-penetrating radar (GPR) transects D and E. Shown are the processed GPR parallel radargrams (top) and interpretations (bottom) across the northern Navegantes barrier ridge (site 4; see Figs. 3 and 5 for locations). Graphic core logs from auger cores (prefix NVA) and vibracores (NVV) and calibrated radiocarbon dates are shown. msl—modern mean sea level; m MSL—meters above modern mean sea level; yr B.P.—years before present; cal/uncal—calibrated/uncalibrated.

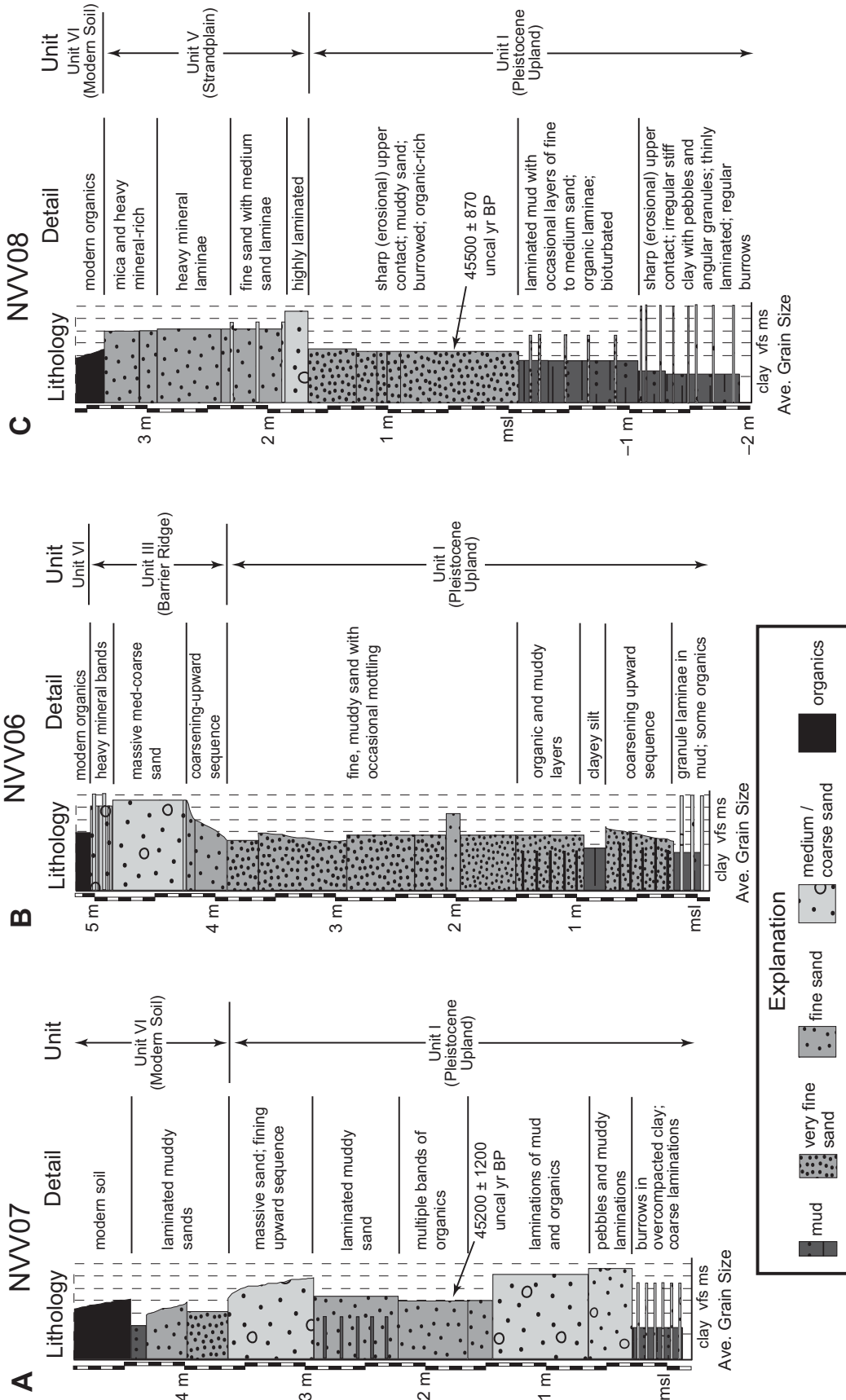


Figure 9. Detailed graphic core logs from three vibracores indicated in Figure 8. Note generally coarsening-upward sequences in cores NVV06 and NVV08 and sharp erosional contacts between strandplain and barrier sequences and underlying lagoonal material. msl—modern mean sea level; uncal yr BP—uncalibrated years before present; Ave.—average; vfs—very fine sand; ms—medium sand.

TABLE 2. NAVEGANTES RADIOCARBON DATES

Core/sample ID	Latitude	Longitude	Lab ID	Dated material	Elevation (m MSL)	Reported age (yr B.P.)	Calibrated 1 σ age (yr B.P.)	Probability	Calibrated 2 σ age (yr B.P.)	Probability
NVV07-S1	-26.8174	-48.6262	OS-72238	Micaceous sandy mud	1.7	45,200 \pm 1200	Old: outside calibration curves			
NVV08-S1	-26.8171	-48.6262	OS-72239	Micaceous sandy mud	0.4	45,500 \pm 870	Old: outside calibration curves			
NVV09-S1	-26.8181	-48.6263	OS-72240	Muddy freshwater peat	2.8	5990 \pm 35	6756 \pm 41	0.805	6764 \pm 98	0.980
							6691 \pm 14	0.195	6875 \pm 6	0.020

Calibration of radiocarbon age from freshwater peat sampled from cores collected at site 4 in Navegantes, Santa Catarina (see Figs. 3, 5, and 8 for locations). m MSL—meters above modern mean sea level; yr B.P.—years before present (present = A.D. 1950).

bedrock platform. This feature is interpreted as a highstand barrier bar that formed on a bedrock platform that may have been denuded of sediment in association with the late stages of marine transgression when sea level reached \sim 1 m MSL (ca. 7.5–8 ka; Fig. 2B). Horizontal to sub-horizontal internal reflections in the central part of this bar (Fig. 7) are interpreted as resulting from vertical accretion during the late transgression and SLH. Landward-dipping reflections on the landward side of the bar are interpreted as washovers, likely deposited at the mid-Holocene SLH when the barrier reached a maximum elevation of \sim 3.5 m MSL. Several strong radar reflections along the seaward side of this bar likely mark the highstand foreshore and shoreface. This clinoform package merges seamlessly into the regressive strandplain sequence to the east, marking the transition from the SLH to regression forced by falling rSL and strandplain progradation.

Highstand Barrier Ridge (Site 4)

The SLH at Navegantes site 4 is marked by a linear barrier ridge oriented perpendicular to the modern coastline. It is located in a small, protected embayment along the lower-energy northern edge of the plain (Fig. 3). This orientation resulted from waves refracting and diffracting around the fronting headland, such that incoming wave approach was from the south, constructing a swash-aligned, east-west-trending ridge. This ridge reaches a maximum elevation of 4.5 m MSL and is emplaced directly on the Pleistocene surface (unit I). This surface was ravined during the transgression, leaving an erosional contact between unit I and units III/V (Fig. 8).

Evidence at this site indicates only minor anthropogenic disturbance; thus, the disjointed nature of the ridge and the complex topography on its landward side (Fig. 5) are indicative of a more complex system than a single highstand barrier ridge such as that identified at site 3. The 10-m-long break in the linear ridge is backed by a broad, 80-m-wide lowland that is \sim 1.5–2 m lower than the surrounding topography. These features are interpreted as a paleo-inlet and paleo-lagoon, respectively. The seaward side of this ridge closely approximates

that of the bar at site 3: seaward-dipping clinoforms of the ridge merge seamlessly with the regressive strandplain sequence and denote the transition from the SLH to forced regression and progradation.

Diverse Late-Stage Transgressive and Highstand Deposits in Brazil

The rSL trends experienced at Navegantes were hemispheric in nature and produced a SLH within a range of a few hundred years and a few vertical meters along the entire Brazilian coast (Fig. 2). The highstand deposits at Navegantes are representative of several of the common forms of features deposited by this SLH throughout Brazil (Table 1). Here, we seek to place these features into the context of other mid-Holocene transgressive and highstand deposits found along this coast, and present a conceptual model for categorizing these deposits (Fig. 10). Due to the challenges that accompany the derivation of paleo-sea level from constructional deposits and regional geologic and tectonic controls on sea-level variability (e.g., in Rio Grande do Norte; Bezerra et al., 1998, 2003), the compilation presented here is not intended for use in regional rSL reconstructions, but rather to investigate the commonality and variability of coastal deposits associated with late-stage transgression and SLH.

Exposed Bedrock Coasts (Type A Highstand)

The exposed bedrock coast-type highstand seen at sites 1 and 2 in Navegantes is associated with locations where bedrock protruded to the SLH shoreline, thus producing a fully erosional section of coastline (Fig. 10, type A). Such exposed bedrock coasts are common features throughout the southeastern and eastern Brazilian coasts, which are dominated by rugged, high-relief Precambrian and Cambrian shield bedrock headlands interspersed with coastal outcrops of Mesozoic and Tertiary sedimentary formations (Bizzi et al., 2001; Dominguez, 2009). Examples include Pinheira (Santa Catarina) and sections of the Rio Grande do Sul coast. These exposed bedrock coasts lack any subaerial depositional features associated with the mid-Holocene highstand.

Constructional Highstand Deposits (Type B, C, and D Highstands)

Following local geologic and bathymetric controls, the depositional landforms and sedimentological signatures of the middle Holocene highstand may be located anywhere from within tens of meters of the modern coastline to $>$ 10 km inland. Pleistocene uplands and earlier coastal deposits were widely eroded during the late stages of the transgression. The nature of the constructional highstand features deposited upon these erosional surfaces take diverse forms, ranging from barrier bars and ridges similar to that seen in Navegantes, to reef deposits. The following discussion is limited only to unconsolidated, depositional sequences; accretionary carbonate structures are omitted. These depositional sedimentary features fall along a continuum that can be broadly classified in the following manner (Fig. 10):

Backbarrier deposits (type B highstand).

Paleo-backbarrier (lagoon, estuarine) deposits (Table 1, type B) above modern MSL are the most common form of depositional sedimentologic evidence of the early to mid-Holocene transgression and SLH in Brazil. Due to rapid burial under regressive barrier-strandplain systems following the SLH, these deposits maintain the highest preservation potential of all transgressive-highstand deposits. They are found throughout the Brazilian coast and are located anywhere from approximately modern MSL to $>$ 4 m MSL (Table 1). They can be $>$ 10 m thick and extend seaward of the modern coastline. Their upland extent marks the highstand mainland shoreline. Deposition of these lagoonal deposits requires protection from open-water conditions, often in the form of fronting barriers or headlands. However, paleo-lagoonal deposits are found in isolation along the entire Brazilian coast (Table 1). Examples include Marajó Island (Pará), Recife (Pernambuco), Candeias (Pernambuco), and the southern Santa Catarina coast.

Transgressive barrier ridge-bar system (type C highstand).

In their simplest form along the Brazilian coastline, transgressive and highstand barriers are preserved as the landward-most beach ridges in regressive Holocene strandplain sequences (Table 1, type C). In these cases,

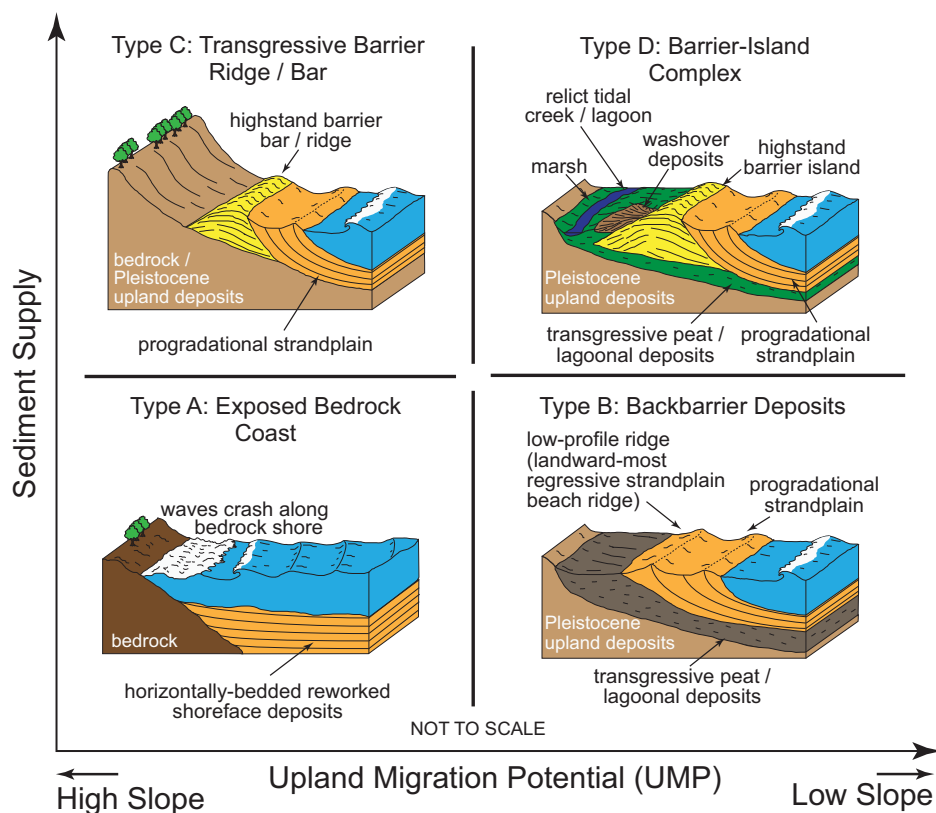


Figure 10. Conceptual model for highstand deposits. Shown is a generalized classification scheme for mid-Holocene highstand deposits preserved and identified along the Brazilian coastline. Drawings represent the morphologies of coastal systems ~100 years after the mid-Holocene highstand, following the initiation of relative sea-level fall, forced regression, and shoreline progradation. These deposits fall along a continuum but can be broadly classified according to the availability of sediment and upland migration potential (UMP) during their formation. Four general categories are defined as those sites lacking any depositional evidence of the mid-Holocene highstand (exposed bedrock coast; type A), and those sites containing: backbarrier paleo-lagoon and paleo-estuarine deposits (type B); transgressive bar systems (type C); and complete highstand barrier complexes (type D). Type D deposits are subdivided into welded transgressive-regressive barriers with backbarrier deposits (type D-1) and complete transgressive-barrier sequences (type D-2).

transgressive and regressive deposits seamlessly merge and no distinct, isolated highstand barrier exists. These are often found in conjunction with erosional upland terrestrial deposits or Pleistocene coastal deposits. Paleo-lagoon sediments are minor or lacking in these settings. Examples include site 3 at Navegantes, Bragança Peninsula (Pará), Sergipe Plain (Sergipe), Cananéia-Iguape (São Paulo), and Curumin (Rio Grande do Sul).

Barrier-island complexes (type D highstand). Complete barrier-island sequences commonly contain some combination of shoreface and beachface deposits, sub- and inter-tidal backbarrier deposits (flood-tidal deltas, tidal flats, etc.), washovers, and, in the best-preserved circumstances, transgressive barriers themselves. These transgressive barrier depos-

its mark the landward extent of the shoreline and often merge seamlessly with the regressive barriers or strandplains on their seaward sides. These can be subdivided into two types: (1) welded transgressive-regressive barriers with backbarrier deposits (type D-1) as exemplified by site 4 in Navegantes (GPR transect E, Fig. 8), and (2) complete transgressive-barrier sequences (type D-2). The latter type is commonly associated with storm washover deposits, backbarrier lagoons/marshes, flood-tidal delta sequences, and/or tidal inlets. Such highstand barrier complexes are found along much of the Brazilian coast (Table 1). For example, a complete transgressive-highstand paleo-barrier was identified fronting a 300-m-wide paleo-lagoon in the São Bento-Caiçara do Norte strandplain (loc. 4, Fig. 1; Caldas et al., 2006b). Here, trans-

gressive lagoonal deposits are continuous under the highstand barrier and the entire regressive strandplain sequence. The paleo-barrier overlies organic-rich sandy, muddy tidal flat sediments and is backed by medium to coarse washover sands that dip landward at 6° – 10° . These features are broadly similar to those identified at Navegantes site 4. Likewise, FitzGerald et al. (2007) identified a similar sequence along the landward boundary of the Tijucas strandplain (loc. 21) in which a barrier ridge at ~4 m MSL overlies a tidal channel facies, fronts a nearly 300-m-wide backbarrier lagoon, and, similar to Navegantes, merges on its seaward side with a ~6-km-wide river-associated regressive strandplain. A 75-m-long washover into the backbarrier lagoon was dated to ca. 5.9 ka (FitzGerald et al., 2011). Finally, transgressive barrier deposits are best exemplified by the multi-phase transgressive-regressive barrier-strandplains of the central Rio Grande do Sul coast (Villwock, 1984; Villwock et al., 1986). The seaward-most barrier dates to the mid-Holocene highstand and is located 4–5 m MSL. It is underlain by lagoonal deposits, backed by paleo-lagoon and washover sequences, and fronted by a welded regressive strandplain (Villwock et al., 1986; Martin et al., 1988; Dillenburg et al., 2004, 2009).

Intermediate Highstand Deposit Types

The four late-stage transgressive-highstand deposit types described herein are end-members along a continuum of deposit types. This conceptual model is designed to provide a broad contextual outline for the consideration of the forcings responsible for the formation of the diverse sedimentological features associated with the mid-Holocene SLH in Brazil. It is expected that individual highstand features will commonly possess characteristics of more than one type. For example, the morphological characteristics at site 4 in Navegantes would classify it as a highstand barrier ridge; however, the thin wetland deposits (unit II) observed along GPR transect E (Fig. 8) and the possible paleo-inlet/paleo-lagoon observed in the morphological record (Fig. 5B) are indicative of a barrier-island complex (type D). This intermediate member reflects the moderate erodibility of the upland deposits at this site, as well as the recognized uncertainty associated with reconstructing the nature, extent, and complexity of imperfectly preserved, 6000-year-old geomorphic features. Care must therefore be taken when assigning a set of features to any highstand-deposit type presented here.

Navegantes is unique in that multiple highstand-deposit types have seldom been found at the same location. However, it is expected that future high-resolution studies will further docu-

ment the complexity of highstand deposits at a number of sites described here. Likewise, the compilation presented here, though geographically diverse, likely presents only a superficial insight into the variety of highstand shoreline deposits preserved along the Brazilian coast. Undoubtedly, future mapping and study will add significant details to the framework understanding of highstand deposits as well as help quantify the drivers of transgressive and highstand coastal evolution.

CONTROLS ON COASTAL RESPONSE TO LATE-STAGE TRANSGRESSION AND SEA-LEVEL HIGHSTAND

The evolution of depositional sedimentary systems is controlled by the relative rates of sediment delivery and creation of accommodation space (Posamentier et al., 1988; Van Wagoner et al., 1990). In coastal settings, the latter is in turn a function of rSL changes and antecedent topography (Wolinsky and Murray, 2009; Moore et al., 2010). Given the similar history of Holocene rSL change across the eastern and southern Brazilian coasts, the substantial morphologic, sedimentologic, and stratigraphic diversity observed in SLH deposits can be attributed solely to differences in UMP and sediment supply (Fig. 10), both functions of the local coastal oceanographic processes responsible for erosion, reworking, and deposition of sediment. Variable contributions of sediment supply and UMP will result in different transgressive response rates and highstand sedimentary architectures (Fig. 10).

It is possible that spatial variability in the strength of coastal oceanographic processes (e.g., wave climate, storminess) responsible for the erosion, reworking, and deposition of sediments may have had a secondary effect on the development of late-stage transgressive and SLH deposits along the Brazilian coast. For example, a period of stronger wave climate would likely have caused more enhanced erosion along open sections of coast than along semi-enclosed embayments (e.g., Navegantes) which are buffered from such variability by fronting headlands (see Hein et al. [2013] for complete discussion). Likewise, if all other variables are held constant, a more intense wave climate could force a coastal compartment toward more erosional conditions, either providing additional sediment for the construction of transgressive-SLH deposits, or pinning the shoreline to resistant bedrock. Little is known about the regional variability in coastal oceanographic processes during the middle to late Holocene. Likewise, in contrast to the records of coastal response to such changes documented in some late Holo-

cene regressive strandplains (e.g., Dominguez et al., 1992), the site-specific nature of coastal responses to these changes during the transgression and SLH is unknown. Both questions warrant further research. As such, this discussion assumes that temporal changes in coastal oceanographic processes were either regional in nature, of small enough magnitude to be masked by larger-scale changes in regional rSL, or overprinted by the intrinsic local differences in UMP and sediment supply along the coast.

Although the roles of accommodation space and sediment supply in coastal response to rSL change are not unique (cf. Curry, 1964), the identification of multiple signatures of SLH within one small embayment (Navegantes) is novel. It demonstrates the need to characterize potential climate-change impacts at a local scale and emphasizes the importance of interdependent drivers in coastal response to climate change: one driver (sea-level change, sediment supply, UMP) alone did not dictate sedimentological response at Navegantes or any other site along the eastern and southern Brazilian coast. Rather, local controls dominate sedimentologic and geomorphic response to rSLR. Here, we consider each of these controls independently for insights that allow us to further develop our predictive ability for coastal response to the ongoing acceleration in rSLR.

Control of Sea-Level Changes

The dominant control on Holocene coastal evolution along much of the Brazilian coast was a set of rSL changes that were nearly uniform in rate and direction. The only exceptions are north of Rio Grande do Norte, in regions proximal to the mouth of the Amazon, where the mid-Holocene SLH was either less pronounced (only 0.6–1.5 m MSL; Cohen et al., 2005; Souza-Filho et al., 2006, 2009) or non-existent, because of broad subsidence induced by the large sediment supply from the Amazon River that likely overwhelms the signature of meter-scale rSL variability. Various predictive (Peltier, 1998; Milne et al., 2005) and data-based (Martin et al., 1979; Suguío et al., 1985; Angulo and Lessa, 1997; Angulo et al., 2006; Caldas et al., 2006a) rSL curves for the eastern and southern Brazilian coast all document a SLH that lasted anywhere from 100 to 800 years between 5 and 6 ka. Associated highstand features have been documented along the coast to have formed between 4 and 7 ka.

The shoreline transgression at Navegantes was fully erosional in nature: an erosional contact is commonly observed between Pleistocene upland sediments and overlying highstand deposits (Fig. 8). A likely fluvial origin and

Pleistocene age of sediments underlying the strandplain fronting highstand deposits indicates that the strandplain was built directly on top of a Pleistocene surface. Thus, the transgression in Navegantes removed any evidence of the existence of transgressive barriers landward of the highstand shoreline.

By contrast, buried backbarrier lagoonal deposits (type B highstand deposits) dated to ca. 7–8 ka and extending anywhere from the highstand shoreline to seaward of the modern shoreline have been identified along many other parts of the Brazilian coast. For example, Bittencourt et al. (1979), Andrade and Dominguez (2005), and Andrade et al. (2003) identified a series of lagoonal terraces and shoreface and beachface sediments from a paleo-barrier chain welded to the landward side of the Caravelas strandplain in Bahia (loc. 11, Fig. 1). The earliest lagoonal deposits in this sequence are dated to 7.7 ka, indicating that a barrier had formed offshore of the highstand barrier from partial erosion and reworking of the Pleistocene strandplain during the latest stages of transgression, when rSL was still 6.5 m below present (Andrade et al., 2003). Lagoonal deposits here reach ~2.5 m MSL. At Itaipuaçu-Maricá along the Rio de Janeiro coast (loc. 15), lagoonal deposits were dated to 6.6–7.1 ka and are fronted by extensive transgressive-regressive barrier deposits (Turcq et al., 1999). Likewise, Dominguez et al. (1981, 1987) identified lagoon-associated transgressive barriers welded to regressive river-associated strandplains along the east-southeast Brazilian coast: based on studies at the coastal systems at the mouths of the Paraíba do Sul (loc. 13), São Francisco (loc. 8), and Jequitinhonha (loc. 10) Rivers, they proposed the formation of extensive barrier-island systems at the mid-Holocene SLH based on evidence of transgressive erosion of Pleistocene coastal deposits and the presence of Holocene backbarrier lagoonal deposits. The latter deposits are interpreted as evidence that these barriers pre-date the SLH, having formed during the transgression and migrated landward. Further south, at the Jequitinhonha River plain, Bahia (loc. 10), late transgressive and highstand lagoonal deposits underlying the landward side of a Holocene beach-ridge plain were dated to 6.2 ka, 6.3 ka, and between 7.0 and 7.9 ka (Bittencourt et al., 1979; Suguío et al., 1985; Martin and Dominguez, 1994). Lastly, the mid-Holocene SLH is marked by the 4-m-high landward-most ridge in the regressive Paraíba do Sul River coastal plain in Rio de Janeiro (loc. 13; Dominguez et al., 1981, 1987, 1992; Martin et al., 1984; Bastos and Silva, 2000). The earliest dates from lagoonal deposits at this site are reported as ca. 7.4 ka (Martin et al., 1996).

Together, these data confirm the presence of fronting barriers along much of the Brazilian coast ~2000–3000 years prior to SLH. Given the ca. 7.5 ka “MSL-crossing time” (the time at which rising rSL during the early Holocene crossed modern MSL) for this coast (Milne et al., 2005; Angulo et al., 2006), rSLR rates for this period are calculated to be on the order of 2–2.5 mm yr⁻¹, nearly 1 mm yr⁻¹ greater than global rates of SLR during the 20th century (1.7 mm yr⁻¹; Church and White, 2006). These barriers were free from development or shoreline stabilization and migrated landward. They were eventually pinned at their highstand locations, primarily in response to a decrease in the rate of rSLR. This occurred by 5.5–6.0 ka, a time when the rate of rSLR had decelerated to <1.5–2.0 mm yr⁻¹.

This scenario suggests a threshold rSLR rate for barrier migration along the Brazilian coast. Here, the threshold below which rSLR had to decelerate for a landward-migrating barrier system to stabilize, and eventually begin to build vertically and prograde, was ~2 mm yr⁻¹, all other factors (sediment supply, UMP, etc.) equal. This is well in line with previous estimates of rates to which rSLR decelerated during periods of barrier formation and stabilization leading to the modern highstand along the East and Gulf Coasts of the U.S. (e.g., Timmons et al., 2010; Hein et al., 2012; Wallace and Anderson, 2013).

Control of Sediment Supply

At any given location, the existence and nature (size, type) of the highstand shoreline features are directly related to the volume of sediment available. At the broadest scale, the sediment provided to construct these features was derived from local rivers, the shallow shelf, and the reworking of earlier terrestrial and coastal deposits eroded during transgression. For example, the river-associated strandplains at Açú, Doce, Paranaguá, and Tijucas (locs. 3, 12, 18, and 21, respectively) all received ample locally sourced sediment and contain evidence of type D-2 highstand barrier sequences. However, only more limited barrier complexes have been identified at plains fronting the São Francisco, Paraíba do Sul, and Jequitinhonha rivers (locs. 8, 10, and 13, respectively). The presence of lagoonal deposits and ridges (type D-1 deposits) at each of these sites indicates that this is likely due to either post-SLH erosion or an error of omission resulting from incomplete investigation. By contrast, several river-distal sites (i.e., Jacarepaguá coastal plain [loc. 16], Itapoá coastal plain [loc. 19], Rio Grande do Sul coast [locs. 25–28]) share this complex highstand morphology and were likely fed from shallow-

shelf sediment sources; indeed, the importance of nearshore sediment sources to post-Holocene highstand infilling of embayments along the Brazil coast has been well recorded (Dominguez et al., 1987; Tomazelli et al., 1998; Lessa et al., 2000; Dillenburg et al., 2004; Martinho et al., 2008; Hein et al., 2013). Thus, given the potential diversity of sediment sources, no strict correlation exists between the proximity of major fluvial systems and highstand deposit types.

Investigations at Navegantes revealed the importance of local geological and oceanographic controls on sediment supply within even small coastal compartments. Here, sediment is derived dominantly from the largest river in Santa Catarina State and is reworked by waves and tides within a headland-fronted coastal embayment. The continuous (alongshore) and sedimentologically homogeneous strandlines that mark paleo-shorelines across the strandplain are indicative of the short time necessary for waves to distribute fluvial sediment within the embayment. However, at SLH, this same rapid alongshore sediment redistribution would result in a dearth of sediment proximal to bedrock headlands that receive the highest wave energy (e.g., at type A sites 1 and 2). The steeply sloped bedrock headlands at such locations would have focused wave energy and enhanced transport. By contrast, shoaling waves propagating across the shallow bedrock platform at site 3 (type C) would have diminishing energy, thereby allowing for sediment deposition prior to rSLF. Likewise, sediment reworked along the shoreline from the Itajaí River was easily deposited in the low-energy environment of site 4 (type D-1). In this manner, sediment supply, modified by the regional wave and tidal regime, exerts a first-order control on the highly localized nature of constructional features associated with transgression and SLH.

Control of Upland Migration Potential (UMP)

The effects of variable UMP on highstand shoreline development are well recorded within the Navegantes strandplain and largely dictate the boundaries between depositional-sequence types A and B, and between C and D. Three central Navegantes sites (1–3) all face the coastal ocean and received direct wave energy, resulting in effective erosion of upland deposits during transgression.

Upland regions were eroded to bedrock along coastal stretches receiving the highest wave energy, allowing for the development of exposed bedrock coasts at sites 1 and 2 at Navegantes, and the deposition of SLH sediment pinned to shallow bedrock at site 3. Fur-

thermore, high wave energy in the exposed regions of the Navegantes embayment also likely reworked and possibly eroded sediment in the central embayment, deepening the profile seaward of the highstand, which provided significant accommodation space (≥8 m of depth) for strandplain development following SLH. By contrast, the bedrock headlands at site 4 provided a protected embayment and low wave energy, prohibiting deep erosion of the muddy substrate. This low-energy environment also produced a backbarrier freshwater marsh along the submergence-controlled mainland shoreline. At SLH, a barrier ridge developed at the head of a 900-m-wide pocket beach, backed by a broad, gently seaward-sloping upland plain and possibly a small tidal lagoon. Furthermore, the development of this ridge as an erosion/deposition-controlled outer (barrier) shoreline (Oertel et al., 1992) would have provided additional protection from incoming waves, lessening erosion along the mainland shoreline, and reducing sediment supply from in situ erosion of upland deposits. Hence, despite a relatively flat upland plain, the combination of low wave energy and resistant substrate reduced the erosive capacity of the transgression, limited UMP, and prevented the formation of a complete transgressive barrier island.

The rate of rSLR maintains a first-order control on UMP. However, given the regional extent of early to mid-Holocene rSLR along most of the Brazilian coast, the variability in UMP can be directly related to the antecedent topography and the wave energy available for upland erosion. Each of these drivers is modified by local and regional geologic, oceanographic, and climatic controls such as tectonics, shelf width, coastal configuration, substrate type, slope, local subsidence, and climate changes (Curry, 1964; Collier et al., 1990; Wolinsky and Murray, 2009; Moore et al., 2010). Moreover, climatic conditions, oceanographic conditions, and sediment supply rates and directions all vary significantly along the Brazilian coast (Dominguez, 2009). Antecedent topography is affected by the proximity and slope of resistant bedrock, the erodibility and slope of unconsolidated upland deposits, and the presence of incised valleys, among other local factors. Locally, wave energy is controlled by such regionally diverse attributes as inner shelf bathymetry, shoreline orientation, and the presence of headlands that reduce exposure to open-ocean conditions (FitzGerald et al., 2007).

A rugged, high-relief landscape produces a narrow coastal plain and regular bedrock headlands in much of southeastern and eastern Brazil. Here, exposed bedrock shorelines (type A) dominate. Other highstand-deposit types are

largely limited to reentrants (e.g., Navegantes [loc. 20] and Tijucas [loc. 21]) and/or proximal to rivers (e.g., São Francisco [loc. 8], Jequitinhonha [loc. 10], Doce [loc. 12], Paranaguá [loc. 18], among others). In such locations, the sediment supply is abundant because of easily erodible medium- to coarse-grained Pleistocene upland fluvial and floodplain deposits. However, exceptions do exist: for example, with the exception of Paraíba do Sul (loc. 13), highstand deposits along the Rio de Janeiro coast have been recognized in bedrock-dominated and river-distal locations. Here, Holocene barriers were emplaced upon eroded Pleistocene barriers and regressive plains and, although representing near-complete barrier sequences, are relatively thin, and remain as active barriers today.

COASTAL RESPONSE TO MODERN ACCELERATED SEA-LEVEL RISE: INSIGHTS FROM THE MID-HOLOCENE IN BRAZIL

Global rates of SLR for the 20th century (a period of relative coastal stability) were ~ 1.7 mm yr⁻¹ (Church and White, 2006). These are nearly an order of magnitude lower than rates predicted for A.D. 2100 under current CO₂-emissions scenarios (Rahmstorf, 2007; Schaefer et al., 2012). Coastal response to this acceleration will be driven by interactions between barriers, tidal inlets, and backbarrier environments such as marshes, tidal flats, and open-water lagoons (FitzGerald et al., 2008). This study demonstrates both the nonlinearity and non-uniformity of this response. For example, transgressive and highstand barriers along the Brazilian coast were not able to stabilize prior to rSLR deceleration to < 2 mm yr⁻¹. This value is consistent with estimates for threshold rSLR rates for backbarrier marsh accretion rates (2–5 mm yr⁻¹; Argow and FitzGerald, 2006; Titus et al., 2009; Jennings et al., 1993). Future rSLR acceleration beyond this possible threshold value may result in the destabilization of backbarrier environments, resulting in a return to rapidly transgressing systems (FitzGerald et al., 2008).

However, coastal response to climate change will not be strictly limited to transgression induced by accelerated rSLR. Rather, it will be strongly influenced by coincident regional changes in storminess, meteorological and oceanographic conditions, and changes in the rate and nature of sediment delivered to the coastal zone (FitzGerald et al., 2008). The complexity of transgressive and highstand deposits along the Brazilian coast, despite a broadly similar history of rSL changes, dem-

onstrates that these responses will be location specific. Moreover, the three contrasting forms of highstand deposits within the 12-km-long Navegantes embayment exemplify the highly localized nature of coastal response to rSLR. Here, a combination of factors (UMP, sediment supply, oceanographic conditions, structural controls, shoreline orientation) dictated sedimentological and geomorphic response. This finding contrasts with the prevailing paradigm that climate change uniformly impacts 10- to 100-km-long sections of coast. Thus, this variability demonstrates the necessity to characterize individual coastal compartments at high resolution, considering the local controls that can dominate sedimentologic and geomorphic response to a changing climate.

CONCLUSIONS

The 9200-km-long coastline of Brazil accounts for nearly 60% of the entire eastern (Atlantic and Caribbean) coast of South America. The Holocene evolution of the Brazilian coast has been largely controlled by an abundant supply of sediment and rSL changes. Relative SLR during the early Holocene flooded Pleistocene uplands and ancient (ca. 120 ka) regressive shoreline deposits. These older deposits were eroded by wave action and the resulting sediments were driven landward by the transgressing shoreline. Stable to slowly retrograding barriers first formed along much of the eastern and southern Brazilian coasts at ca. 6.0 ka when rSLR slowed to ~ 2 mm yr⁻¹, an apparent threshold rate above which stable barrier-backbarrier systems could not stabilize and build. The formation of these barriers, in turn, served to protect the mainland shoreline from wave energy, thereby minimizing upland erosion and allowing the stabilization of barriers along highstand shorelines. Associated SLH deposits range in height from 0 to > 5 m MSL and date between ca. 4 and 7 ka. Broad strandplains were deposited in front of these highstand shorelines during a period of rSLF during the late Holocene, thereby preserving late-stage transgressive and highstand deposits several kilometers landward of the modern shoreline along nearly the entire Brazilian coast.

The nature of coastal erosion/deposition patterns associated with late-stage transgression and SLH is dictated by a number of factors, including the rate of rSL change, local and regional sediment supplies, and the ability of coastal deposits to migrate laterally landward (upland migration potential, or UMP). These factors are each, in turn, affected by local controls such as oceanographic conditions, storminess, structural geologic controls

(tectonics, shelf width, coastal configuration, shoreline orientation), upland slope, and erodibility of upland deposits. The resulting highstand deposits can be broadly categorized into three types differentiated by the availability of sediment and UMP for the section of coast upon which they formed: backbarrier deposits (type B), transgressive barrier ridges (type C), and barrier-island complexes (type D). The latter is subdivided into welded transgressive-regressive barriers with backbarrier deposits (type D-1) and complete transgressive-barrier sequences (type D-2). A fourth highstand type, exposed bedrock coasts (type A), are found only along sections of the coast where landward migration was prohibited (for example, by steep, resistant outcrops) and sediment supply rates were too low to allow for vertical aggradation to keep pace with rSLR. Such sites contain no deposits associated with the transgression or SLH. The presence of three of these highstand types (A, C, and D-1) within a single embayment in central Santa Catarina State emphasizes the weakness of studies that only consider climate-change impacts along broad sections of coast or in only one or two settings. Furthermore, it highlights the complex nature of coastal response to rSLR and the importance of interrelated controls (sea-level change, sediment supply, UMP), acting at a very local scale, on coastal response to regional and global climate change.

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REFERENCES CITED

- ANA (Agência Nacional de Águas), 2000, Estado de Santa Catarina: Brasília-DF, Brazil, Agência Nacional de Águas, <http://hidroweb.ana.gov.br/cd3/sc.doc> (accessed 18 October 2010).
- Andrade, A.C.S., and Dominguez, J.M.L., 2005, Holocene barrier island-lagoon system at Caravelas strandplain, Bahia, Brazil: *Journal of Coastal Research*, Special Issue 42, p. 164–173.
- Andrade, A.C.S., Dominguez, J.M.L., Martin, L., and Bittencourt, C.S.P., 2003, Quaternary evolution of the Caravelas strandplain, southern Bahia State, Brazil: *Anais da Academia Brasileira de Ciências*, v. 75, p. 357–382, doi:10.1590/S0001-37652003000300008.
- Angulo, R.J., 1999, Morphological characterization of the tidal deltas on the coast of the state of Paraná: *Anais da Academia Brasileira de Ciências*, v. 71, p. 935–959.
- Angulo, R.J., and Lessa, G.C., 1997, The Brazilian sea level curves: A critical review with emphasis on the curves from Paranaguá and Cananea regions: *Marine Geology*, v. 140, p. 141–166, doi:10.1016/S0025-3227(97)00015-7.
- Angulo, R.J., and Suguio, K., 1995, Re-evaluation of the Holocene sea-level maxima for the State of Paraná, Brazil: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 113, p. 385–393, doi:10.1016/0031-0182(95)00055-Q.
- Angulo, R.J., Giannini, P.C.F., Suguio, K., and Pessenda, L.C.R., 1999, Relative sea-level changes in the last 5500 years in southern Brazil (Laguna-Imbituba region, Santa Catarina State) based on vermetid ¹⁴C ages: *Marine Geology*, v. 159, p. 323–339, doi:10.1016/S0025-3227(98)00204-7.
- Angulo, R.J., Souza, M.C., Reimer, P., and Sasoka, S.K., 2005, Reservoir effect of the southern and southeastern Brazilian coast: *Radiocarbon*, v. 47, p. 67–73.
- Angulo, R.J., Lessa, G.C., and de Souza, M.C., 2006, A critical review of mid- to late-Holocene sea-level fluctuations on the eastern Brazilian coastline: *Quaternary Science Reviews*, v. 25, p. 486–506, doi:10.1016/j.quascirev.2005.03.008.
- Angulo, R.J., de Souza, M.C., Assine, M.L., Pessenda, L.C.R., and Disaró, S.T., 2008, Chronostratigraphy and radiocarbon age inversion in the Holocene regressive barrier of Paraná, southern Brazil: *Marine Geology*, v. 252, p. 111–119, doi:10.1016/j.margeo.2008.03.006.
- Angulo, R.J., Lessa, G.C., and de Souza, M.C., 2009, The Holocene barrier systems of Paranaguá and northern Santa Catarina coasts, southern Brazil, in Dillenburg, S., and Hesp, P., eds., *Geology and Geomorphology of Holocene Coastal Barriers of Brazil*: Berlin, Springer, p. 2–44.
- Angulo, R.J., de Souza, M.C., Fernandes, L.A., and Disaró, S.T., 2012, Quaternary sea-level changes and aeolianites in the Fernando de Noronha archipelago, northeastern Brazil: *Quaternary International*, v. 305, p. 15–30, doi:10.1016/j.quaint.2012.12.029.
- Araújo, A.G.M., 2001, Dinâmica sedimentar e evolução paleogeográfica do saco do limoeiro na Ilha do Mel, e sua relação com o canal de acesso ao Porto de Paranaguá [M.S. thesis]: Curitiba, Brazil, Universidade Federal do Paraná, 75 p.
- Araújo, A.G.M., Neves, W.A., and Pilo, L.B., 2003, Eventos de seca no Holoceno e suas implicações no povoamento pré-histórico do Brasil Central, in *Anais do IX Congresso da Associação Brasileira de Estudos do Quaternário*, Recife: Pernambuco, Brazil, Associação Brasileira de Estudos do Quaternário (ABEQUA), CD-ROM.
- Argow, B., and FitzGerald, D.M., 2006, Processes on northern salt marshes: Evaluating the impact of in-situ peat compaction due to ice loading, Wells, ME: *Estuarine, Coastal and Shelf Science*, v. 69, p. 360–369, doi:10.1016/j.ecss.2006.05.006.
- Barbosa, L.M., Bittencourt, A.C.S.P., Dominguez, J.M.L., and Martin, L., 1986, The Quaternary coastal deposits of the state of Alagoas: Influence of the relative sea-level changes, in Rabassa, J., ed., *Quaternary of South America and Antarctic Peninsula*: Rotterdam, A.A. Balkema, p. 269–290.
- Barletta, R.C., and Calliari, L.J., 2001, Determinação da intensidade das tempestades que atuam no litoral do Rio Grande do Sul, Brasil: *Pesquisas em Geociências*, v. 28, no. 2, p. 117–124.
- Bastos, A.C., and Silva, C.G., 2000, Caracterização morfodinâmica do litoral Norte-Fluminense, RJ, Brasil: *Brazilian Journal of Oceanography*, v. 48, no. 1, p. 41–60, doi:10.1590/S1413-7739200000100004.
- Behling, H., Cohen, M.C.L., and Lara, R.J., 2001, Studies on Holocene mangrove ecosystem dynamics of the Bragança Peninsula in northeastern Pará, Brazil: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 167, p. 225–242, doi:10.1016/S0031-0182(00)00239-X.
- Belknap, D.F., and Kraft, J.C., 1985, Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems: *Marine Geology*, v. 63, p. 235–262, doi:10.1016/0025-3227(85)90085-4.
- Bezerra, F.H.R., Lima-Filho, F.P., Amaral, R.F., Caldas, L.H.O., and Costa-Neto, L.X., 1998, Holocene coastal tectonics in NE Brazil, in Stewart, I.S., and Vita-Finzi, C., eds., *Coastal Tectonics*: Geological Society of London Special Publication 146, p. 279–293.
- Bezerra, F.H.R., Barreto, A.M.F., and Suguio, K., 2003, Holocene sea level history on the Rio Grande do Norte State coast, Brazil: *Marine Geology*, v. 196, p. 73–89, doi:10.1016/S0025-3227(03)00044-6.
- Bittencourt, A.C.S.P., Martin, L., Vilas-Boas, G.S., and Flexor, J.M., 1979, The marine Quaternary formations of the coast of the state of Bahia (Brazil), in Suguio, K., Fairchild, T., Martin, L., and Flexor, J.M., eds., *Proceedings of the 1978 International Symposium on Coastal Evolution in the Quaternary*: São Paulo, Brazil, Instituto Astronômico e Geofísico, p. 232–253.
- Bittencourt, A.C.S.P., Dominguez, J.M.L., Martin, L., and Ferrreira, Y.A., 1981, Dados preliminares sobre a evolução do delta do rio São Francisco (SE/AL) durante o Quaternário: Influência das variações do nível do mar, in *Atas do IV Simpósio do Quaternário no Brasil*, Rio de Janeiro: Rio de Janeiro, Brazil, Sociedade Brasileira de Geologia, p. 49–68.
- Bittencourt, A.C.S.P., Martin, L., and Dominguez, J.M.L., 1983, Evolução paleogeográfica quaternária da costa do Estado de Sergipe e costa sul do Estado de Alagoas: *Revista Brasileira de Geociências*, v. 13, p. 93–97.
- Bizzi, L.A., Schobbenhaus, C., Gonçalves, J.H., Baars, F.J., Delgado, I.M., Abram, M.B., Neto, R.L., de Matos, G.M.M., and Santos, J.O.S., 2001, Geologia, tectônica e recursos minerais do Brasil: Sistema de Informações Geográficas-SIG e mapas na escala: Brasília, CPRM, scale 1:2,500,000, 4 CD-ROMs.
- Bokuniewicz, H., 2005, Ingression, regression, and transgression, in Schwartz, M.L., ed., *Encyclopedia of Coastal Science*: Dordrecht, The Netherlands, Springer, p. 64–65.
- Buynevich, I.V., Cleary, W.J., FitzGerald, D.M., Klein, A.H.F., Asp, N.E., Hein, C., Veiga, F.A., and Petermann, R.M., 2006, Modern and ancient erosion indicators on a high energy coast: Camboriú Peninsula and Navegantes Plain, SC, Brazil: *International Geological Correlation Programme 495 Abstracts with Programs*, Balneário Camboriú, Brazil, p. 28–31.
- Buynevich, I.V., Klein, A.H.F., FitzGerald, D.M., Cleary, W.J., Hein, C., Veiga, F., Angulo, R.J., Asp, N.E., and Petermann, R.M., 2011, Geological legacy of storm erosion along a high-energy indented coastline: Northern Santa Catarina, Brazil: *Journal of Coastal Research*, Special Issue 64, v. 1840–1844.
- Caldas, L.H.O., Statteger, K., and Vital, H., 2006a, Holocene sea-level history: Evidence from coastal sediments of the Rio Grande do Norte coast, NE Brazil: *Marine Geology*, v. 228, p. 39–53, doi:10.1016/j.margeo.2005.12.008.
- Caldas, L.H.O., Statteger, K., and Vital, H., 2006b, Geometry and evolution of Holocene transgressive and regressive barriers on the semi-arid coast of NE Brazil: *Geo-Marine Letters*, v. 26, p. 249–263, doi:10.1007/s00367-006-0034-2.
- Caruso, F., Jr., Suguio, K., and Nakamura, T., 2000, The Quaternary geological history of the Santa Catarina southeastern region (Brazil): *Anais da Academia Brasileira de Ciências*, v. 72, no. 2, p. 257–270, doi:10.1590/S0001-3765200000200011.
- Castro, D.F., Rossetti, D.F., and Pessenda, L.C.R., 2010, Facies, $\delta^{13}C$, $\delta^{15}N$ and C/N analyses in a late Quaternary compound estuarine fill, northern Brazil and relation to sea level: *Marine Geology*, v. 274, p. 135–150, doi:10.1016/j.margeo.2010.03.011.
- Church, J.A., and White, N.J., 2006, A 20th century acceleration in global sea-level rise: *Geophysical Research Letters*, v. 33, L01602, doi:10.1029/2005GL024826.
- Cohen, M.C.L., Souza Filho, P.W.M., Lara, R.J., Behling, H., and Angulo, R.J., 2005, A model of Holocene mangrove development and relative sea-level changes on the Bragança Peninsula (northern Brazil): *Wetlands Ecology and Management*, v. 13, p. 433–443, doi:10.1007/s11273-004-0413-2.
- Collier, R.E.L., Leeder, M.R., and Maynard, J.R., 1990, Transgression and regression: A model for the influence of tectonic subsidence, deposition and eustasy, with application to Quaternary and Carboniferous examples: *Geological Magazine*, v. 127, p. 117–128, doi:10.1017/S0016756800013819.
- Curry, J.R., 1964, Transgressions and regressions, in Miller, R.L., ed., *Papers in Marine Geology*: New York, MacMillan, p. 175–203.
- Dias, T.M., and Kjerfve, B., 2009, Barrier and beach ridge systems of the Rio de Janeiro coast, in Dillenburg, S., and Hesp, P., eds., *Geology and Geomorphology of Holocene Coastal Barriers of Brazil*: Berlin, Springer, p. 225–252.
- Dillenburg, S., and Hesp, P., eds., 2009, *Geology and Geomorphology of Holocene Coastal Barriers of Brazil*: Berlin, Springer, Lecture Notes in Earth Sciences, no. 170, 380 p.
- Dillenburg, S., Roy, P.S., Cowell, P.J., and Tomazelli, L.J., 2000, Influence of antecedent topography on coastal evolution as tested by the Shoreface Translation-Barrier Model (STM): *Journal of Coastal Research*, v. 16, p. 71–81.
- Dillenburg, S.R., Tomazelli, L.J., and Barboza, E.G., 2004, Barrier evolution and placer formation at Bujuru southern Brazil: *Marine Geology*, v. 203, p. 43–56, doi:10.1016/S0025-3227(03)00330-X.
- Dillenburg, S.R., Tomazelli, L.J., Hesp, P.A., Barboza, E.G., Clerot, L.C.P., and Silva, D.B., 2006, Stratigraphy and evolution of a prograded, transgressive dunefield barrier in southern Brazil: *Journal of Coastal Research*, Special Issue 39, p. 132–135.
- Dillenburg, S.R., Barboza, E.G., Tomazelli, L.J., Hesp, P.A., Clerot, L.C.P., and Ayup-Zouain, R.N., 2009, The Holocene coastal barriers of Rio Grande do Sul, in Dillenburg, S., and Hesp, P., eds., *Geology and Geomorphology of Holocene Coastal Barriers of Brazil*: Berlin, Springer, p. 53–92.
- Dominguez, J.M.L., 2009, The coastal zone of Brazil, in Dillenburg, S., and Hesp, P., eds., *Geology and Geomorphology of Holocene Coastal Barriers of Brazil*: Berlin, Springer, p. 17–51.
- Dominguez, J.M.L., and Wanless, H.R., 1991, Facies architecture of a falling sea-level strandplain, Doce River coast, Brazil, in Swift, D.J.P., Oertel, G.F., Tillman, R.W., and Thorne, J.A., eds., *Shelf Sand and Sandstone Bodies—Geometry, Facies and Sequence Stratigraphy*: Oxford, UK, International Association of Sedimentologists Special Publication 14, p. 259–281.
- Dominguez, J.M.L., Bittencourt, A.C.S.P., and Martin, L., 1981, Esquema evolutivo da sedimentação quaternária nas feições deltáicas dos rios São Francisco (SE/AL), Jequitinhonha (BA), Doce (ES) e Paraíba do Sul (RJ): *Revista Brasileira de Geociências*, v. 11, p. 227–237.
- Dominguez, J.M.L., Bittencourt, A.C.S.P., and Martin, L., 1983, O papel da deriva litorânea de sedimentos arenosos na construção das planícies costeiras associadas as desembocaduras dos rios São Francisco, Jequitinhonha, Doce e Paraíba do Sul: *Revista Brasileira de Geociências*, v. 13, p. 98–105.
- Dominguez, J.M.L., Martin, L., and Bittencourt, A.C.S.P., 1987, Sea-level history and Quaternary evolution of river mouth—Associated beach-ridge plains along the east-southeast Brazilian coast: A summary, in Nummedal, D., Pilkey, O.H., and Howard, J.D., eds., *Sea-Level Fluctuation and Coastal Evolution*: Tulsa,

- Oklahoma, Society for Sedimentary Geology Special Publication 41, p. 115–127.
- Dominguez, J.M.L., Bittencourt, A.C.S.P., Leão, Z.M.A.N., and de Azevedo, A.E.G., 1990, Geologia do Quaternário costeiro do Estado de Pernambuco: Revista Brasileira de Geociências, v. 20, p. 208–215.
- Dominguez, J.M.L., Bittencourt, A.C.S.P., and Martin, L., 1992, Controls on Quaternary coastal evolution of the east-northeastern coast of Brazil—Roles of sea-level history, trade winds and climate: Sedimentary Geology, v. 80, p. 213–232, doi:10.1016/0037-0738(92)90042-P.
- Dominguez, J.M.L., Andrade, A.C.S., Almeida, A.B., and Bittencourt, A.C.S.P., 2009, The Holocene barrier strandplains of the state of Bahia, in Dillenburg, S., and Hesp, P., eds., Geology and Geomorphology of Holocene Coastal Barriers of Brazil: Berlin, Springer, p. 253–288.
- Engelhart, S.E., Horton, B.P., and Kemp, A.C., 2011, Holocene sea level changes along the United States' Atlantic Coast: Oceanography, v. 24, no. 2, p. 70–79, doi:10.5670/oceanog.2011.28.
- FitzGerald, D.M., Cleary, W.J., Buynevich, I.V., Hein, C.J., Klein, A.H.F., Asp, N.E., and Angulo, R.J., 2007, Strandplain evolution along the southern coast of Santa Catarina, Brazil: Journal of Coastal Research, Special Issue 50, p. 152–156.
- FitzGerald, D.M., Fenster, M.S., Argow, B.A., and Buynevich, I.V., 2008, Coastal impacts due to sea-level rise: Annual Review of Earth and Planetary Sciences, v. 36, p. 601–647, doi:10.1146/annurev.earth.35.031306.140139.
- FitzGerald, D.M., Hein, C.J., Cleary, W., de Menezes, J.T., Klein, A.H.F., Scolaro, T., Buynevich, I.V., and Petsch, S.T., 2011, Climatic and sedimentological forcing of strandplain progradation at Tijucas, central Santa Catarina, Brazil, in Proceedings, International Union of Quaternary Research, XVIII International Union for Quaternary Research—Congress, Abstract 2791.
- Folk, R.L., and Ward, W.C., 1957, Brazos River bar: A study of significance of grain size parameters: Journal of Sedimentary Petrology, v. 27, p. 3–26, doi:10.1306/74D70646-2B21-11D7-864800102C1865D.
- Forbes, D.L., Taylor, R.B., Orford, J.D., Carter, R.W.G., and Shaw, J., 1991, Gravel-barrier migration and overstepping: Marine Geology, v. 97, p. 305–313, doi:10.1016/0025-3227(91)90122-K.
- Fornari, M., Giannini, P.C.F., and do Nascimento, D.R., Jr., 2012, Facies associations and controls on the evolution from a coastal bay to a lagoon system, Santa Catarina coast, Brazil: Marine Geology, v. 323–325, p. 56–68.
- Gandolfo, O.C.B., Souza, L.A.P., Tessler, M.G., and Rodrigues, M., 2001, Estratigrafia da Ilha Comprida (SP): Um exemplo de aplicação de GPR: Revista Brasileira de Geofísica, v. 19, no. 3, p. 251–262.
- Giannini, P.C.F., 1993, Sistemas Depositionais no Quaternário Costeiro entre Jaguaruna e Imbituba, SC [Ph.D. thesis]: São Paulo, Brazil, Instituto de Geociências, Universidade de São Paulo, 439 p.
- Giannini, P.C.F., Guedes, C.C.F., do Nascimento, D.R., Jr., Tanaka, A.P.B., Angulo, R.J., Assine, M.L., and de Souza, M.C., 2009, Sedimentology and morphological evolution of the Ilha Comprida barrier system, southern São Paulo coast, in Dillenburg, S., and Hesp, P., eds., Geology and Geomorphology of Holocene Coastal Barriers of Brazil: Berlin, Springer, p. 177–224.
- Hein, C.J., FitzGerald, D.M., Carruthers, E.A., Stone, B.D., Barnhardt, W.A., and Gontz, A.M., 2012, Refining the model of barrier island formation along a paraglacial coast in the Gulf of Maine: Marine Geology, v. 307–310, p. 40–57, doi:10.1016/j.margeo.2012.03.001.
- Hein, C.J., FitzGerald, D.M., Cleary, W.J., Albernaz, M.B., de Menezes, J.T., and Klein, A.H.F., 2013, Geophysical examination of an embayed Brazilian strandplain system: Implications for complex coastal response to environmental change: Sedimentology, v. 60, p. 469–502, doi:10.1111/j.1365-3091.2012.01348.x.
- Hesp, P.A., 2006, Sand beach ridges: Definitions and redefinition: Journal of Coastal Research, Special Issue 39, p. 72–75.
- Hesp, P.A., Dillenburg, S.R., Barboza, E.G., Tomazelli, L.J., Ayup-Zouain, R.N., Esteves, L.S., Gruber, N.L.S., Toldo, E.J., Jr., Tabajara, L.L.C.d.A., and Clerot, L.C.P., 2005, Beach ridges, foredunes or transgressive dunefields? Definitions and initiation, and an examination of the Torres to Tramandai barrier system, southern Brazil: Anais da Academia Brasileira de Ciências, v. 77, no. 3, p. 493–508, doi:10.1590/S0001-37652005000300010.
- Hesp, P., de Castilhos, J.A., Moit da Silva, G., Dillenburg, S., Martinho, C.T., Aguiar, D., Fornari, M., Fornari, M., and Antunes, G., 2007, Regional wind fields and dunefield migration, southern Brazil: Earth Surface Processes and Landforms, v. 32, p. 561–573, doi:10.1002/esp.1406.
- Hesp, P.A., Giannini, P.C.F., Martinho, C.T., Moit da Silva, G., and Neto, N.E.A., 2009, The Holocene barrier systems of the Santa Catarina coast, southern Brazil, in Dillenburg, S., and Hesp, P., eds., Geology and Geomorphology of Holocene Coastal Barriers of Brazil: Berlin, Springer, p. 94–133.
- Hijma, M.P., Cohen, K.M., Roebroeks, W., Westerhoff, W.E., and Busschers, F.S., 2012, Pleistocene Rhine-Thames landscapes: Geological background for hominin occupation of the southern North Sea region: Journal of Quaternary Science, v. 27, p. 17–39, doi:10.1002/jqs.1549.
- Horn-Filho, N.O., and Ferreti, O., 2010, Implantação do Plano Estadual de Gerenciamento Costeiro—Fase I: Diagnóstico Socioambiental—Setor Litoral Central: Florianópolis, Brazil, Secretaria de Estado do Planejamento—Diretoria de Desenvolvimento das Cidades/Ambiens Consultoria Ambiental, 470 p., scale 1:300,000.
- Hoyt, J.H., 1967, Barrier island formation: Geological Society of America Bulletin, v. 78, p. 1125–1136, doi:10.1130/0016-7606(1967)78[1125:BIF]2.0.CO;2.
- Irion, G., de Morais, J.O., and Bungenstock, F., 2012, Holocene and Pleistocene sea-level indicators at the coast of Jericoacoara, Ceará, NE Brazil: Quaternary Research, v. 77, p. 251–257, doi:10.1016/j.yqres.2011.10.007.
- Isla, F.I., 1989, Holocene sea-level fluctuation in the southern hemisphere: Quaternary Science Reviews, v. 8, p. 359–368, doi:10.1016/0277-3791(89)90036-X.
- Jennings, S.C., Carter, R.W.G., and Orford, J.D., 1993, Late Holocene salt marsh development under a regime of rapid relative-sea-level rise: Chezzetcook Inlet, Nova Scotia: Implications for the interpretation of palaeomorph sequences: Canadian Journal of Earth Sciences, v. 30, p. 1374–1384, doi:10.1139/e93-118.
- Jol, H.M., and Bristow, C.S., 2003, GPR in sediments: Advice on data collection, basic processing and interpretation, a good practice guide, in Bristow, C.S., and Jol, H.M., eds., Ground Penetrating Radar in Sediments: Geological Society of London Special Publication 211, p. 9–27.
- Kemp, A.C., Horton, B.P., Donnelly, J.P., Mann, M.E., Vermeer, M., and Rahmstorf, S., 2011, Climate related sea-level variations over the past two millennia: Proceedings of the National Academy of Sciences of the United States of America, v. 108, p. 11,017–11,022, doi:10.1073/pnas.1015619108.
- Klein, A.H.F., 1997, Regional climate, in Seeliger, U., Odebrecht, C., and Castello, J.P., eds., Subtropical Convergence Environments: The Coast and Sea in the Southwestern Atlantic: Heidelberg, Germany, Springer-Verlag, p. 5–7.
- Klein, A.H.F., 2004, Morphodynamics of headland bay beaches [Ph.D. thesis]: Faro, Portugal, Universidade do Algarve, 450 p.
- Klein, A.H.F., and Menezes, J.T., 2001, Beach morphodynamics and profile sequence for a headland bay coast: Journal of Coastal Research, v. 17, p. 812–835.
- Klein, A.H.F., Ferreira, Ó., Dias, J.M.A., Tessler, M.G., Silveira, L.F., Benedet, L., Menezes, J.T., and Abreu, J.G.N., 2010, Morphodynamics of structurally controlled headland-bay beaches in southeastern Brazil: A review: Coastal Engineering, v. 57, p. 98–111, doi:10.1016/j.coastaleng.2009.09.006.
- Kraft, J.C., 1971, Sedimentary facies patterns and geologic history of a Holocene marine transgression: Geological Society of America Bulletin, v. 82, p. 2131–2158, doi:10.1130/0016-7606(1971)82[2131:SFPAGH]2.0.CO;2.
- Lessa, G.C., and Angulo, R.J., 1995, A framework for the stratigraphy and evolution of the Paranaguá coastal plain—Paraná, Brazil, in Anais do II Congresso da Associação Brasileira de Estudos do Quaternário: Niterói, Rio de Janeiro, Brazil, Associação Brasileira de Estudos do Quaternário (ABEQUA), p. 92–98.
- Lessa, G.C., Meyers, S.R., and Marone, E., 1998, Holocene stratigraphy in the Paranaguá Bay estuary, southern Brazil: Journal of Sedimentary Research, v. 68, p. 1060–1076, doi:10.2110/jsr.68.1060.
- Lessa, G.C., Angulo, R.J., Giannini, P.C., and Araujo, A.D., 2000, Stratigraphy and Holocene evolution of a regressive barrier in south Brazil: Marine Geology, v. 165, p. 87–108, doi:10.1016/S0025-3227(99)00130-9.
- Maia, M.C.A., Martin, L., Flexor, J.M., and de Azevedo, A.E.G., 1984, Evolução holocênica da planície costeira de Jacarepaguá (RJ), in Anais do XXXIII Congresso Brasileiro Geologia, Rio de Janeiro, v. 1, p. 105–118.
- Martin, L., and Dominguez, J.M.L., 1994, Geological history of coastal lagoons, in Kjerfve, B., ed., Coastal Lagoon Processes: New York, Elsevier Oceanography Series 60, p. 41–68.
- Martin, L., and Suguío, K., 1976, O Quaternário marinho do litoral do Estado de São Paulo, in Anais do 29º Congresso Brasileiro de Geologia: Belo Horizonte, Minas Gerais, v. 1, p. 281–294.
- Martin, L., and Suguío, K., 1992, Variation of coastal dynamics during the last 7000 years recorded in beach-ridge plains associated with river mouths: Example from the Brazilian coast: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 99, p. 119–140, doi:10.1016/0031-0182(92)90010-3.
- Martin, L., Suguío, K., Flexor, J.-M., Bittencourt, A.C.S.P., and Vilas-Boas, G.S., 1979, Le quaternaire marin brésilien (littoral pauliste, sud fluminense et bahianais): Cahiers—ORSTOM, Série Géologie, v. 11, no. 1, p. 95–124.
- Martin, L., Flexor, J.-M., and Suguío, K., 1984, Enregistrement des périodes de fortes et faibles énergies à l'embouchure d'un fleuve—Le cas du Rio Paraíba do Sul (Brésil): Implications climatiques, in Académie des Sciences, ed., Comptes-rendus des séances de l'Académie des Sciences, Série II, Mécanique-physique, chimie, sciences de l'univers, sciences de la terre: Paris, Gauthier-Villars, v. 299, no. 10, p. 661–664.
- Martin, L., Flexor, J.M., Blitzkow, D., and Suguío, K., 1985, Geoid change indications along the Brazilian coast during the last 7000 years, in International Association for Biological Oceanography, Committee on Coral Reefs: Proceedings of the Fifth International Coral Reef Congress: Tahiti, v. 3, p. 85–90.
- Martin, L., Suguío, K., Flexor, J.-M., Dominguez, J.M.L., and Bittencourt, A.C.S.P., 1987, Quaternary evolution of the central part of the Brazilian coast - the role of relative sea-level variations and longshore drift, in Quaternary coastal geology of West Africa and South America: United Nations Educational, Scientific and Cultural Organization Reports in Marine Science, v. 43, p. 97–115.
- Martin, L., Suguío, K., Flexor, J.M., and de Azevedo, A.E.G., 1988, Mapa geológico do Quaternário costeiro dos estados do Paraná e Santa Catarina: Brasília, Brazil, DNP (Departamento Nacional de Produção Mineral) Serie Geologia 28, Seção Geologia Básica 18, 40 p.
- Martin, L., Suguío, K., Flexor, J.-M., Dominguez, J.M.L., and Bittencourt, A.C.S.P., 1996, Quaternary sea-level history and variation in dynamics along the central Brazilian coast: Consequences on coastal plain construction: Anais da Academia Brasileira de Ciências, v. 68, no. 3, p. 303–354.
- Martinho, C.T., Dillenburg, S.R., and Hesp, P.A., 2008, Mid to late Holocene evolution of transgressive dunefields from Rio Grande do Sul coast, southern Brazil: Marine Geology, v. 256, p. 49–64, doi:10.1016/j.margeo.2008.09.006.
- McCormac, F.G., Hogg, A.G., Blackwell, P.G., Buck, C.E., Higham, T.F.G., and Reimer, P.J., 2004, SHCAL04 Southern Hemisphere calibration, 0–11.0 cal kyr BP: Radiocarbon, v. 46, p. 1087–1092.

- McTaggart-Cowan, R., Bosart, L.F., Davis, C.A., Atallah, E.H., Gyakum, J.R., and Emanuel, K.A., 2006, Analysis of Hurricane Catarina (2004): Monthly Weather Review, v. 134, p. 3029–3053, doi:10.1175/MWR3330.1.
- Mellet, C.L., Hodgson, D.M., Lang, A., Mauz, B., Selby, I., and Plater, A.J., 2012, Preservation of a drowned gravel barrier complex: A landscape evolution study from the north-eastern English Channel: Marine Geology, v. 315–318, p. 115–131, doi:10.1016/j.margeo.2012.04.008.
- Milliman, J.D., and Farnsworth, K.L., 2011, River Discharge to the Coastal Ocean: A Global Synthesis: Cambridge, UK, Cambridge University Press, 392 p.
- Milne, G.A., Long, A.J., and Bassett, S.E., 2005, Modelling Holocene relative sea-level observations from the Caribbean and South America: Quaternary Science Reviews, v. 24, p. 1183–1202, doi:10.1016/j.quascirev.2004.10.005.
- Mitrovica, J.X., and Milne, G.A., 2002, On the origin of late Holocene sea-level highstands within equatorial ocean basins: Quaternary Science Reviews, v. 21, p. 2179–2190, doi:10.1016/S0277-3791(02)00080-X.
- Moore, L.J., List, J.H., Williams, S.J., and Stolper, D., 2010, Complexities in barrier island response to sea level rise: Insights from numerical model experiments, North Carolina Outer Banks: Journal of Geophysical Research, v. 115, F03004, doi:10.1029/2009JF001299.
- Mörner, N.A., Rossetti, D., and Toledo, P., 1999, Sea-level changes in NE Brazil, regional eustasy and local tectonics, in Fletcher, C.H., and Matthews, J.V., eds., The non-steady state of the inner shelf and shorelines: Coastal change on the time scale of decades to millennia in the late Quaternary: Inaugural Meeting of ICP Project 437—Coastal Environmental Change During Sea-level Highstands, Abstracts with Programs: Honolulu, Hawaii, the University of Hawaii, p. 112.
- Muehe, D.O., 1984, Evidências de recuo dos cordões litorâneos em direção ao continente no litoral do Rio de Janeiro, in de Lacerda, L.D., de Araújo, D.S.D., Cerqueira, R., and Turcq, B., eds., Restingas: Origem, Estrutura, Processos: Anais do Simpósio sobre Restingas Brasileiras: Rio de Janeiro, Brazil, CEUFF, Niterói, p. 75–80.
- Muehe, D.O., 1998, O litoral brasileiro e sua compartimentação, in Guerra, A.J.T., and Cunha, S.B., eds., Geomorfologia do Brasil: Rio de Janeiro, Brazil, Bertrand, p. 273–349.
- Neal, A., 2004, Ground-penetrating radar and its use in sedimentology: Principles, problems, and progress: Earth-Science Reviews, v. 66, p. 261–330, doi:10.1016/j.earscirev.2004.01.004.
- Nimer, E., 1989, Climatologia do Brasil, 2ª edição: Rio de Janeiro, Brazil, Instituto Brasileiro de Geografia e Estatística, 421 p.
- Oertel, G.F., Kraft, J.C., Kearney, M.S., and Woo, H.J., 1992, A rational theory for barrier-lagoon development, in Wehmler, J.F., ed., Quaternary Coasts of the United States: Marine and Lacustrine Systems: Society for Sedimentary Geology Special Publication 48, p. 77–87.
- Otvos, E.G., 2000, Beach ridges—Definitions and significance: Geomorphology, v. 32, p. 83–108, doi:10.1016/S0169-555X(99)00075-6.
- Peltier, W.R., 1998, Postglacial variations in the level of the sea: Implications for climate dynamics and solid-Earth geophysics: Reviews of Geophysics, v. 36, p. 603–689, doi:10.1029/98RG02638.
- Perrin, P., 1984, Evolução da costa fluminense entre as pontas de Itacoatiara e Negra: Preenchimentos e restingas, in de Lacerda, L.D., de Araújo, D.S.D., Cerqueira, R., and Turcq, B., eds., Restingas: Origem, Estrutura, Processos: Anais do Simpósio sobre Restingas Brasileiras: Rio de Janeiro, Brazil, CEUFF, Niterói, p. 65–73.
- Ponçano, W.L., and Gimenez, A.F., 1987, Reconhecimento sedimentológico do estuário do Itajaí-Açu: Revista Brasileira de Geociências, v. 17, no. 1, p. 33–41.
- Posamentier, H.W., and Vail, P.R., 1988, Eustatic controls on clastic deposition II—Conceptual framework, in Wilks, C.K., Hastings, B.S., Posamentier, H., Waggoner, J.V., Ross, C.A., and Kendall, C.G.St.C., eds., Sea-Level Changes: An Integrated Approach: Tulsa, Oklahoma, SEPM Special Publication 42, p. 125–155.
- Rahmstorf, S., 2007, A semi-empirical approach to projecting future sea-level rise: Science, v. 315, p. 368–370, doi:10.1126/science.1135456.
- Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., and Weyhenmeyer, C.E., 2009, IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP: Radiocarbon, v. 51, p. 1111–1150.
- Reinson, G.E., 1992, Transgressive barrier island and estuarine systems, in Walker, R.G., and James, N.P., eds., Facies Models: Response to Sea-Level Change: St. John's, Newfoundland, Geological Association of Canada, p. 179–194.
- Rossetti, D.F., 2003, Delineating shallow Neogene deformation structures in northeastern Pará State using Ground Penetrating Radar: Anais da Academia Brasileira de Ciências, v. 75, p. 235–248, doi:10.1590/S0001-37652003000200009.
- Rossetti, D.F., Valeriano, M.M., Góes, A.M., and Thales, M., 2008, Paleodrainage on Marajó Island, northern Brazil, in relation to Holocene relative sea-level dynamics: The Holocene, v. 18, p. 923–934, doi:10.1177/0959683608091798.
- Roy, P.S., Cowell, P.J., Ferland, M.A., and Thom, B.G., 1994, Wave-dominated coasts, in Carter, R.W.G., and Woodroffe, C.D., eds., Coastal Evolution: Late Quaternary Shoreline Morphodynamics: Cambridge, UK, Cambridge University Press, p. 121–186.
- Schaeffer, M., Hare, W., Rahmstorf, S., and Vermeer, M., 2012, Long-term sea-level rise implied by 1.5°C and 2°C warming levels: Nature Climate Change, v. 2, p. 867–870, doi:10.1038/nclimate1584.
- Schettini, C.A.F., Carvalho, J.L.B., and Jabor, P., 1996, Comparative hydrology and suspended matter distribution of four estuaries in Santa Catarina State—Southern Brazil, in Proceedings, Workshop on Comparative Studies of Temperate Coast Estuaries (IAPSO): Bahía Blanca, Argentina, The Inter-American Institute for Global Change Research, p. 29–32.
- Siegle, E., and Asp, N.E., 2007, Wave refraction and long-shore transport patterns along the southern Santa Catarina coast: Brazilian Journal of Oceanography, v. 55, no. 2, p. 109–120, doi:10.1590/S1679-87592007000200004.
- Silva, C.G., 1987, Estudo da evolução geológica e geomorfológica da região da Lagoa Feia, RJ [M.S. thesis]: Rio de Janeiro, Brazil, Universidade Federal do Rio de Janeiro, 160 p.
- Silva, C.G., 1991, Holocene stratigraphy and evolution of the Açu River Delta, Rio Grande do Norte State, northeastern Brazil [Ph.D. thesis]: Durham, North Carolina, Duke University, 800 p.
- de Souza, M.C., Angulo, R.J., and Pessenda, L.C.R., 2001, Evolução paleogeográfica da planície costeira de Itapoá, litoral norte de Santa Catarina: Revista Brasileira de Geociências, v. 31, p. 223–230.
- Souza-Filho, P.W.M., Cohen, M.C.L., Lara, R.J., Lessa, G.C., Koch, B., and Behling, H., 2006, Holocene coastal evolution and facies model of the Bragança macrotidal flat on the Amazon Mangrove Coast, northern Brazil: Journal of Coastal Research, Special Issue 39, p. 306–310.
- Souza-Filho, P.W.M., Lessa, G.C., Cohen, M.C.L., Costa, F.R., and Lara, R.J., 2009, The subsiding macrotidal barrier estuarine system of the Eastern Amazon coast, northern Brazil, in Dillenburg, S., and Hesp, P., eds., Geology and Geomorphology of Holocene Coastal Barriers of Brazil: Berlin, Springer, p. 347–375.
- Stuiver, M., and Reimer, P.J., 1993, Extended ¹⁴C data base and revised Calib 3.0 ¹⁴C age calibration program: Radiocarbon, v. 35, p. 215–230.
- Suguio, K., and Martin, L., 1981, Significance of quaternary sea-level fluctuations for delta construction along the Brazilian coast: Geo-Marine Letters, v. 1, p. 181–185, doi:10.1007/BF02462431.
- Suguio, G., Martin, L., and Flexor, J.M., 1976, Les variations relatives du niveau moyen de la mer au Quaternaire recent dans la region de Cananéia-Iguape, São Paulo: Boletim IG: Instituto de Geociências, v. 7, p. 113–129.
- Suguio, K., Martin, L., and Dominguez, J.M.L., 1982, Evolução do “delta” do Rio Doce (ES) durante o Quaternário—Influência das variações do nível do mar, in Atas do IV Simpósio do Quaternário no Brasil, Rio de Janeiro: Rio de Janeiro, Brazil, Sociedade Brasileira de Geologia, p. 93–116.
- Suguio, K., Martin, L., Bittencourt, A.C.S.P., Dominguez, J.M.L., Flexor, M., and de Azevedo, A.E.G., 1985, Flutuações do nível relativo do mar durante o quaternário superior ao longo do litoral brasileiro e suas implicações na sedimentação costeira: Revista Brasileira de Geociências, v. 15, p. 273–286.
- Suguio, K., Martin, L., Flexor, J.M., and de Azevedo, A.E.G., 1986, The Quaternary sedimentary deposits in the States of Paraná and Santa Catarina coastal plains, in Rabassa, J., ed., Quaternary of South America and Antarctic Peninsula: Rotterdam, A.A. Balkema, p. 3–35.
- Timmons, E.A., Rodriguez, A.B., Matheus, C.R., and DeWitt, R., 2010, Transition of a regressive to a transgressive barrier island due to back-barrier erosion, increased storminess, and low sediment supply: Bogue Banks, North Carolina, USA: Marine Geology, v. 278, p. 100–114, doi:10.1016/j.margeo.2010.09.006.
- Titus, J.G., Anderson, K.E., Cahoon, D.R., Gesch, D.B., Gill, S.K., Gutierrez, B.T., Thieler, E.R., and Williams, S.J., 2009, Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic Region: Synthesis and Assessment Product 4.1, Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research: Washington, D.C., United States Environmental Protection Agency, 320 p.
- Toldo, E.E., Jr., Dillenburg, S.R., Corrêa, I.C.S., and Almeida, L.E.S.B., 2000, Holocene sedimentation in Lagoa dos Patos Lagoon, Rio Grande do Sul, Brazil: Journal of Coastal Research, v. 16, p. 816–822.
- Tomazelli, L.J., and Villwock, J.A., 1996, Quaternary geological evolution of Rio Grande do Sul coastal plain, southern Brazil: Anais da Academia Brasileira de Ciências, v. 68, no. 3, p. 373–382.
- Tomazelli, L.J., Dillenburg, S.R., Villwock, J.A., Bachi, F.A., and Dehnhardt, B.A., 1998, Significance of present-day coastal erosion and marine transgression, Rio Grande do Sul, southern Brazil: Anais da Academia Brasileira de Ciências, v. 70, no. 2, p. 221–229.
- Tomazelli, L.J., Dillenburg, S.R., and Villwock, J.A., 2000, Late Quaternary geological history of Rio Grande do Sul coastal plain, southern Brazil: Revista Brasileira de Geociências, v. 30, p. 470–472.
- Tomazelli, L.J., Dillenburg, S.R., and Villwock, J.A., 2006, Geological evolution of Rio Grande do Sul coastal plain, southern Brazil: Journal of Coastal Research, Special Issue 39, p. 275–278.
- Travessas, F.A., Dillenburg, S.R., and Clerot, L.C.P., 2005, Estratigrafia e evolução da barreira holocênica do Rio Grande do Sul no trecho Tramandaí-Cidreira: Boletim Paranaense de Geociências, v. 57, p. 57–73.
- Truccolo, E.C., 1998, Maré meteorológica e forçantes atmosféricas locais em São Francisco do Sul—SC [M.S. thesis]: Florianópolis, Brazil, Universidade Federal de Santa Catarina, 100 p.
- Turcq, B., Coe Neto, R., and Froidefond, J.M., 1986, Variability of beach ridges on the coast of Maricá (Rio de Janeiro, Brazil), in Rabassa, J., ed., Quaternary of South America and Antarctic Peninsula: Rotterdam, A.A. Balkema, p. 45–57.
- Turcq, B., Martin, L., Flexor, J.-M., Suguio, K., and Tasayaco-Ortega, L., 1999, Origin and evolution of the Quaternary coastal plain between Guaratiba and Cabo Frio, State of Rio de Janeiro, Brazil, in Knoppers, B., Bidone, E.D., and Abrão, J.J., eds., Environmental Geochemistry of Coastal Lagoon Systems of Rio de Janeiro, Brazil: Icaraf, Niterói, Rio de Janeiro, Brazil, Universidade Federal Fluminense / Programa de Geoquímica Ambiental, Série Geoquímica Ambiental 6, p. 25–46.
- van Heteren, S., FitzGerald, D.M., McKinlay, P.A., and Buynevich, I.V., 1998, Radar facies of paraglacial barrier systems: Coastal New England, USA: Sedimentology,

- v. 45, p. 181–200, doi:10.1046/j.1365-3091.1998.00150.x.
- Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: Concepts for high-resolution correlation of time and facies: Tulsa, Oklahoma, American Association of Petroleum Geologists, Methods in Exploration Series 7, 55 p.
- Villwock, J.A., 1984, Geology of the coastal province of Rio Grande do Sul, southern Brazil: A synthesis: *Pesquisas*, v. 16, p. 5–49.
- Villwock, J.A., Tomazelli, L.J., Loss, E.L., Dehnhardt, E.A., Horn, N.O., Bachi, F.A., and Dehnhardt, B.A., 1986, Geology of the Rio Grande do Sul coastal province, in Rabassa, J., ed., *Quaternary of South America and Antarctic Peninsula*: Rotterdam, A.A. Balkema, p. 79–97.
- Vital, H., 2009, The mesotidal barriers of Rio Grande do Norte, in Dillenburg, S., and Hesp, P., eds., *Geology and Geomorphology of Holocene Coastal Barriers of Brazil*: Berlin, Springer, p. 289–324.
- Wallace, D.J., and Anderson, J.B., 2013, Unprecedented erosion of the upper Texas coast: Response to accelerated sea-level rise and hurricane impacts: *Geological Society of America Bulletin*, v. 125, p. 728–740, doi: 10.1130/B30725.1.
- Wolinsky, M. A., and Murray, A. B., 2009, A unifying framework for shoreline migration: 2. Application to wave-dominated coasts: *Journal of Geophysical Research*, v. 114, F01009, doi:10.1029/2007JF000856.

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