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Origin of buried, bottom current-related comet marks and associated submarine bedforms from a Paleogene continental margin, southeastern Brazil

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ABSTRACT

Bottom current-related bedforms, such as depositional and erosive features, are useful indicators of oceanographic circulation and sedimentary balance conditions in both modern and ancient marine environments. The Eocene-Oligocene transition in northern Santos Basin is seismically expressed as a prominent, high-amplitude reflector (horizon H8.1) that truncates Eocene prograding clinoforms and records a major transgression in the basin associated to global and local environmental changes. This surface is punctuated by circular depressions, elongated depressions, mounds and conic features, which, based on seismic interpretation, are associated with the escape of gas on the paleoseafloor. Elongated negative features with a head and an erosive tail (comet marks) are associated with the erosive action of bottom currents that, when encounters an obstacle or bottom irregularity such as pockmarks, create a downflow, linear furrow (tail). The occurrence of carbonate mounds and mud volcanoes may affect the erosive power of the flow by deflecting and/or focusing undercurrents. In the study area, parallel to subparallel comet marks occur abundantly on the former outer shelf and upper slope, being up to 1.2 km long, 200 m wide, and 30 m deep. These dimensions allow the classification of such bedforms as giant comet marks, which form as a result of erosion of the irregular sea floor by currents as fast as 0.6 m s^{-1}. The strong alignment of the comet tails indicates paleocurrents to the NE on the Oligocene outer shelf and upper slope. Conditions for comet mark formation include the development of pockmarks due to gas seeps, reworking of pockmarks by vigorous and long-lived bottom currents and low sediment supply during the Eocene-Oligocene transition, a period marked by the opening of the Drake Pass and the establishment of undercurrents through the connection of the Atlantic and the Pacific oceans. Bottom-current related bedforms on H8.1 in Santos Basin may thus be related to such paleoenvironmental changes. Although no pre-Quaternary comet marks have been reported before, their identification and mapping through 3D seismic data is a unique opportunity to assess paleoenvironmental conditions and paleo-circulation on continental margins.

1. Introduction

Bottom currents are important agents in shaping marine morphology by both depositing (contourites) and eroding the sea floor. Moreover, well-sorted sands winnowed or deposited by strong bottom currents may form high-quality hydrocarbon reservoirs (Rebesco and Stow, 2001; Viana, 2002; Duarte and Viana, 2007; Viana et al., 2007; Mutti et al., 2014). Contourite drifts were first described in slope settings (e.g. Heezen et al., 1966), but current-generated bedforms have been also identified in shallower waters, including the outer shelf and upper slope (e.g. Flemming, 1978; Flemming, 1980; Viana et al., 1998; Carmelenghi et al., 2001; Galloway, 2001; Laberg et al., 2001; Viana, 2002; Foglini et al., 2016). Although not considered contourites *stricto* sensu (Stow et al., 1998; Viana et al., 1998), these shallow-water bedforms testify that bottom-current activity is not restricted to deep-marine settings.

In modern basins, bottom currents frequently interact with irregularities on the sea floor such as pockmarks, mounds, tectonic ridges and diapirs, which can act as obstacles to the flow (e.g. Bøe et al., 1998; Faugères et al., 1999; Llave et al., 2001; Somoza et al., 2003; Andresen et al., 2008; García et al., 2009; Palomino et al., 2011; Stow et al., 2013; Schattner et al., 2016; Vandorpe et al., 2016). Recent papers show that such obstacles can increase the velocity of the bottom currents and consequently their capability of transporting sediments and eroding the

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Table 1
Comparison of the main characteristics of comet marks described in the literature, in terms of dimensions, environmental context and type of obstacle for the flow. Note that all previously described comet marks were identified in the present-day seafloor.

Authors	Location of the research	Context	Obstacle	Depth	Length	Width	Length/width ratio
Werner and Newton (1975)	Langeland Belt, Baltic Sea – present	Shelf – up to 30 m deep	Boulders	up to 15 cm	5–200 m	1–6 m	5.0 to 33.33
Caston (1979)	Dover straight, UK – present	Shelf – up to 60 m deep	Wrecks	up to 2 m	up to 100 m	–	–
Flemming (1980); Flemming (1984)	Durban/Port Elizabeth, South Africa – present	Shelf – up to 60 m deep	–	–	50–200 m	6–135 m	4.5 to 33.33
Kenyon (1986); Masson (2001); Kuijpers et al. (2002)	Shetland Isles, UK – present	Upper slope to mid slope – up to 700 m deep	Ice-rafted blocks	–	up to 100 m	up to 20 m	5.0
Kuijpers et al. (1993)	Skagerrak, Denmark – present	Shelf – up to 70 m deep	Ice-rafted blocks	–	7–50 m	–	–
Xia et al. (1998)	Bohai Sea, China – present	Shelf – up to 60 m deep	Subaqueous dunes	–	up to 100 m	–	–
Gee et al. (2001)	Atlantic coast, North Africa – present	Deep ocean – up to 1000 m deep	Blocks	–	up to 2000 m	–	–
Verdicchio and Trincardi (2006); Trincardi et al. (2007); Bonaldo et al. (2016); Foglini et al. (2016)	Adriatic Sea, Italy – present	Shelf edge, slope and deep ocean – up to 900 m deep	Slide blocks	–	up to 2000 m	–	–
Jolivel et al. (2015)	Hudson Bay, Canada – present	Shelf to upper slope – up to 85 m deep	–	–	up to 40 m	–	–
Loncke et al. (2015); Tallobre et al. (2016)	Demerara margin, north South America - present	Deep ocean – up to 4500 m deep	Pockmarks and/or mass-transport deposits	5–90 m	100–10,000 m	100–2000 m	1.0 to 5.0
Present paper	Santos Basin, Brazil – early Oligocene	Shelf to upper slope	Pockmarks	10–30 m	300–1200 m	40–200 m	4.2 to 5.5

sea floor (e.g. García et al., 2009; Palomino et al., 2011; Vandorpe et al., 2016). Although the configuration and distribution of bottom current-related bedforms depends on the energy of prevailing currents, their flow direction and the amount and caliper of available sediments (e.g. Kenyon, 1970; Kenyon and Belderson, 1973; Kenyon, 1986; Flemming, 1978; Werner et al., 1980; Kuijpers et al., 2002; Stow et al., 2009; Rebesco et al., 2014; Kuijpers and Nielsen, 2016), the presence of bottom irregularities can be effective in modifying bottom circulation and the generation of bedforms (e.g. Somoza et al., 2003; Vandorpe et al., 2016).

Under low sediment supply, bottom currents potentially form erosive features on the shelf and upper slope, with little or no expressive sediment accumulation (e.g. Flemming, 1980; McLean, 1980; Bøe et al., 1998; Galloway, 2001; Kowsmann and de Carvalho, 2002; Andresen et al., 2008). Most bottom current-related erosive features, such as comet marks (Werner and Newton, 1975), are elongated, asymmetrical and oriented according to prevailing currents. Their identification and mapping can thus provide information regarding ocean circulation in both modern and ancient open marine settings. To date, comet marks have been described only from modern sea floors (Table 1) (e.g. Werner and Newton, 1975; Flemming, 1980; Flemming, 1984; Kuijpers et al., 1993; Bonaldo et al., 2016; Foglini et al., 2016; Tallobre et al., 2016). The identification of these bedforms in the stratigraphic record, as first documented in the present paper, is an excellent guide to determine the dynamics of bottom current activity in the past and, consequently, to assess prevailing paleoenvironmental conditions.

In northern Santos Basin, offshore Brazil, circular to elongated, negative and positive bedforms punctuate the early Oligocene paleo-seafloor. The stratigraphic surface on which the bedforms are located marks the top of an Eocene progradational wedge and records a major marine flooding in northern Santos Basin (Moreira et al., 2001; Berton and Vesely, 2016a, 2016b). This event is genetically related to climatic and tectonic adjustments that happened in the South Atlantic domain during the early Oligocene and that profoundly affected bottom-current circulation in the Santos Basin (Duarte and Viana, 2007; Viana et al., 2007) and other South American Atlantic basins (e.g. Hinz et al., 1999; Hernández-Molina et al., 2009; Hernández-Molina et al., 2016). In this paper we describe these bedforms in order to interpret their origin and to discuss potential implications for bottom-current circulation patterns during the Eocene-Oligocene transition in the Brazilian continental margin. The study is based on the interpretation of oil industry 3D seismic data under a seismic geomorphology approach (e.g. Posamentier and Kolla, 2003; Carlotto and Rodrigues, 2009; Jobe et al., 2011; Prather et al., 2012; Sylvester et al., 2012).

2. Geological setting

The Santos Basin (offshore SE Brazil) is a segment of the South Atlantic rifted margin and is bounded in the north by the Cabo Frio high, and in the south by the Florianópolis high (Fig. 1). The basin comprises three main evolutionary stages: a Barremian to Aptian *syn*-rift phase, an Aptian to Albian transitional restricted marine phase, and an Albian to modern divergent-margin phase (Moreira et al., 2007).

From the Turonian to the late Eocene, uplifting at the Brazilian southeastern margin and the consequent denudation of the Serra do Mar range increased sediment supply leading to a strongly progradational phase, known as Juréia progradation (Fig. 1) (Macedo, 1989). This long-term regressive phase (lasting for approximately 60 My) resulted in extensive deltaic progradations during the Late Cretaceous, Paleocene and Eocene (Figs. 1 and 2) (Mohriak and Magalhães, 1993). The sediment load contributed to trigger salt movements basinward and to generate *syn*-sedimentary regional faults, structural highs and mini-basins (Figs. 2 and 3) (Assine et al., 2008; Badalini et al., 2010).

By the Eocene, a global warming event (Eocene Thermal Maximum) (Lourens et al., 2005; Zachos et al., 2008) increased rainfall on the Serra do Mar region, leading to enhanced sediment supply (Zalán and