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Research paper

Stratigraphic evolution of Eocene clinoforms from northern Santos Basin, offshore Brazil: Evaluating controlling factors on shelf-margin growth and deep-water sedimentation

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A B S T R A C T

In order to assess the controlling factors on the evolution of a shelf margin and the timing of sediment transfer to deep waters, a seismic stratigraphic investigation was carried out in the Eocene interval of northern Santos Basin, offshore Brazil. The studied succession configures a complex of prograding slope clinoforms formed in a passive margin and encompasses five seismic facies and their respective depositional settings: shelf-margin deltas/shorefaces, oblique slope clinoforms, sigmoidal slope clinoforms, continental to shelfal deposits and mass-transport deposits. These are stratigraphically arranged as seven depositional sequences recording a total shelf-edge progradation of about 35 km and a progradation rate of 1,75 km/My. Two main types of sequences can be recognized, the first one (type A) being dominated by oblique slope clinoforms and shelf-margin deltas/shorefaces in which shelf-edge trajectories were essentially flat to descending and extensive sandy turbidites were deposited on the foreset to bottomset zones. Sequences of this type are dominated by forced-regressive units deposited during extensive periods of relative sea-level fall. Type B comprises an upper part represented by aggradational shelfal deposits and a lower part composed of mass-transport deposits and high-relief sigmoidal clinoforms with descending shelf-edge trajectory. Steep slump scars deeply cut the shelfal strata and constitutes the boundary between the two intervals observed in type B sequences. Sandy turbidites occur at the same frequency in both forced- and normal-regressive units but are more voluminous within forced-regressive clinoforms associated with shelf-margin deltas/shorefaces. Major slope failures and mass-transport deposits, by the other hand, occurred exclusively in type B sequences during the onset of sea-level fall and their volume are directly related to the thickness of the shelfal sediments formed during the pre-failure normal regressions.

1. Introduction

Sequence stratigraphic models predict that the deposition of coarse-grained clastic sediment in deep marine environments occurs preferentially during base-level fall and/or lowstand, when accommodation in the shelf is reduced and fluvio-deltaic systems deliver sediment to the outer shelf and slope (e.g. Vail et al., 1977; Posamentier and Vail, 1988; Walker, 1990; Posamentier and Allen, 1999; Catuneanu, 2002). The falling and low sea level stands would be favorable for the generation of sandy submarine fans (turbidites), which constitute the main exploratory targets in continental margins (e.g. Williams and Hubbard, 1984; Shanmugam, 2000; Mutti et al., 2007; Chang et al., 2008). Other authors, however, argue that sediment supply is an equally important control on shelf-margin accretion (e.g. Carvajal and Steel, 2006; Monteverde et al., 2008; Carvajal et al., 2009; Dixon et al., 2013), and demonstrate the deposition of thick turbidite successions even during high and/or ascending relative sea level.

The timing of slope failure and mass-flow generation in deep water is also under debate (e.g. Moscardelli et al., 2006; Posamentier and Martinsen, 2011; Dalla Valle et al., 2013). Slope failure may generate thick and extensive mass-transport deposits (MTDs; volumes up to 3500 km^3; Moscardelli and Wood, 2008), which occur in close association with turbidites and play an important role as seal or reservoir in deep water petroleum systems (e.g. Moscardelli and Wood, 2008; Gamberi et al., 2011; Posamentier and Martinsen, 2011; Alves et al., 2014). Although

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slope instability generally results from a combination of local and regional factors (e.g. Alves and Cartwright, 2010; Olafiranye et al., 2013; Gong et al., 2014), the association between MTDs and base-level falls have been admitted because lowering of wave base causes instability in the outer shelf, which can promote slope failure and mass-flow initiation (e.g. Posamentier and Kolla, 2003; Catuneanu et al., 2011). On the other hand, case studies have demonstrated the emplacement of MTDs at any position of the relative sea level (e.g. Dalla Valle et al., 2013).

Erecting a genetic stratigraphic framework and stablishing its relationships to base-level changes and sediment supply is thus necessary for determining the timing of turbidite and MTD generation. When dealing with seismic data, traditional systems tracts and sequence schemes (e.g. Posamentier and Vail, 1988; Galloway, 1989; Embry and Johannessen, 1992) have been complemented by model-independent approaches (Catuneanu and Zecchin, 2013), such as the analysis of shelf-edge and shoreline trajectories (e.g. Johannessen and Steel, 2005; Henriksen et al., 2009; Steel et al., 2010; Dixon et al., 2012), and architectural styles of slope clinoforms (e.g. Driscoll and Karner, 1999; Gong et al., 2015).

In northern Santos Basin, offshore Brazil, the Eocene interval is composed of slope clinoforms formed during a phase of general low accommodation. The stratigraphic architecture is mainly characterized by prograding clinoform sets (e.g. Sydow et al., 1992) in which progradation were significantly higher than aggradation, and thick MTDs and turbidites were formed at the slope toe. The scope of this paper is to characterize this succession in order to evaluate the controlling factors on stratal geometries and stratigraphic stacking patterns, as well as on the timing of deposition of turbidites and mass-transport deposits in deep water.

2. Geological setting

The Santos Basin is located in the southeastern sector of the Brazilian continental margin, and is bounded in the north by the Cabo Frio high and in the south by the Florianópolis high (Fig. 1). The geologic evolution of this basin is associated with the breakup of Gondwana and opening of the South Atlantic Ocean, during which three major tectonic phases are recognized – a Barremian to Early Aptian rift phase, an Aptian to Early Albian evaporitic sag phase, and an Albian to present divergent margin (Moreira et al., 2007). The main chronostratigraphic horizons recognized in the basin (according to Contreras et al., 2010) are shown in the regional dip-oriented seismic section of Fig. 2.

Following a Turonian maximum marine flooding, the basin experienced a long-term progradational phase (~60 My), known as the Jureia progradation (Macedo, 1989). This progradational phase was driven by a significant increase in sediment supply associated with uplifting and denudation on the Serra do Mar range, which outpaced the accommodation created by eustatic sea-level rise and regional subsidence (Cainelli and Mohriak, 1999). As a result, extensive progradations and associated deep-water depositional systems (Fig. 1) took place during the Late Cretaceous, Paleocene and Eocene (Mohriak and Magalhães, 1993). Sediment load has contributed to trigger salt movements basinward and to generate important sin-sedimentary regional faults (e.g. Cabo Frio fault zone), structural highs and mini-basins (Assine et al., 2008; Badalini et al., 2010).

The Eocene corresponds to the latest phase of the Jureia progradation, in which sediment supply derived from the ancient Paraíba do Sul river system (Ribeiro, 2007) was controlled by exhumation of the uplifted Serra do Mar and intense rainfall associated with the Eocene Thermal Maximum (Lourens et al., 2005; Zalán and Oliveira, 2005). Uplifting at the Serra do Mar range and tectonic adjustments affecting the Atlantic hinge line drove relative sea-level falls at the basin margin and reduced subsidence rates at the shelf and upper slope during the Eocene (Cobbold et al., 2001; Zalán and Oliveira, 2005; Contreras et al., 2010) (Fig. 2). These tectonic processes leaded to periods of negative accommodation, ultimately resulting in forced regressions.

The Eocene-Oligocene boundary records an important environmental change in the Santos Basin, with the beginning of a global cooling period (Duarte and Viana, 2007; Sahy et al., 2015) and the shift of the Paraíba do Sul river to the north, which, at this time, started to deliver its load to Campos Basin (Karner and Driscoll, 1999). As a result of this dramatic decrease in sediment supply, a major transgression occurred in Santos Basin (Assine et al., 2008; Badalini et al., 2010), leading to sediment starvation and reworking by bottom currents (Duarte and Viana, 2007).

In the study area, the Eocene succession displays clinoforms with moderate to high shelf to base of slope relief (up to 800 m; Carvajal et al., 2009; Hubbard et al., 2010). At the slope and basin areas, conspicuous gravity-driven sandy and muddy deposits have been recognized (e.g. d'Ávila et al., 2008), but there is no agreement amongst previous authors about the timing of these deposits during the stratigraphic evolution of the interval (e.g. Modica and Brush, 2004; Moreira and Carminatti, 2004; Assine et al., 2008; Henriksen et al., 2011; Dixon, 2013).

3. Database and methods

The study area is located in northern Santos Basin, approximately 150 km offshore from the city of Rio de Janeiro (Fig. 3). Database consists of 20 2D seismic lines and logs from six wells (Fig. 3) provided by the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP), covering an area of approximately 2300 km^2. Seismic data are from different surveys performed since the 1990's, including 0228 SANTOS 11A, 0231 Santos 18A, 0247 CABO FRIO 3A, 0261 VB99 2D BMS, and R0003 0259 2D SPP 2Q 1999.

The stratigraphic succession was investigated through seismic facies analysis (e.g. Veeken and van Moerkerken, 2013), sequence stratigraphy concepts (e.g. Catuneanu, 2006) and shelf-edge trajectory analysis (e.g. Henriksen et al., 2009). Seismic interpretation started with the determination of reflector termination patterns and the definition of key surfaces (downlap, onlap and truncation surfaces). Seismic facies analysis helped in the interpretation of the depositional settings, sequence boundary determination and definition of depositional trends. The identification of seismic facies was based on the reconnaissance of the configuration of reflectors considering their geometry, lateral continuity, seismic amplitude and frequency as seem in strike and dip-oriented seismic sections. Well logs were tied to seismic sections and used as a support to the interpretation of depositional settings. Time-to-depth conversion tables from three wells were used to detect thicknesses (wells 1-BRSA-144-RJS, 1-BSS-0066-BS and 4-BRSA-450-RJS) (Fig. 3).

In this paper we use the concept of depositional sequence as a unit bounded by subaerial unconformities or its correlative conformities that represent maximum falls of relative sea level (Catuneanu, 2006). The interpretation of depositional trends and relative sea-level changes were done for stratigraphic hierarchies recognizable by seismic resolution and were based on the following criteria: 1) mapping of coastal onlap in dip-oriented seismic sections and its projection in chronostratigraphic charts (Wheeler diagrams; e.g. Vail et al., 1977); 2) mapping of shelf-edge (clinoform rollovers) trajectories, considering it as a proxy for shoreline trajectory (e.g. Steel and Olsen, 2002; Helland-Hansen and Hampson, 2009; Henriksen et al., 2009, 2011). Rising relative sea level were recognized in association with landward migration of coastal onlap and/or rising shelf-edge trajectories, whereas falling relative sea