Marine and Petroleum Geology 88 (2017) 676–695

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Three-dimensional stratigraphic-sedimentological forward modeling of an Aptian carbonate reservoir deposited during the sag stage in the Santos basin, Brazil

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ARTICLE INFO

Article history:
Received 25 February 2017
Received in revised form
20 August 2017
Accepted 13 September 2017
Available online 18 September 2017

Keywords:
3D stratigraphic-sedimentological forward modeling
Aptian carbonates
Lacustrine sag carbonates
Carbonate reservoir
Rifted margin

ABSTRACT

Stratigraphic-sedimentological forward modeling is a useful technique to test the role of parameters that may act in the depositional processes of sedimentary rocks. The technique was applied to the Santos basin, Brazil, using the software program DIONISOS to test possible depositional scenarios for an Aptian section of a lacustrine carbonate platform developed during the late sag stage (uppermost pre-salt section) of the basin. Different parameters were tested in a set of numerical simulations with the aim of reproducing the carbonate facies spatial distribution and the overall stratigraphic stacking pattern of the platform, as observed in the available well data. Several models were simulated, and four of them are discussed in this paper. Based on the available descriptive data from 10 wells, Model 3 is considered to produce the best fit to explain the development of the 100-m thick Aptian carbonate platform, occurrences of grainstones and stromatolites as proximal and intermediate facies, respectively, and the overall carbonate stacking pattern. Thus, based on 3D stratigraphic-sedimentological forward modeling, the best set of environmental conditions able to explain the pattern of carbonate deposition observed in the study area are (1) a slow carbonate depositional rate (0.08 mm/y over an interval of 2.4 My), which is indicative of a larger microbial contribution, and (2) lake-level oscillations, which were essentially induced by arid climatic conditions. These results also enable new perspectives for the application of stratigraphic-sedimentological forward modeling as a predictive tool for hydrocarbon exploration in carbonates and for the development of depositional models of other sag carbonate platform settings.

1. Introduction

The offshore Santos basin, which is located on the southeastern Brazilian continental margin, is a huge hydrocarbon province. In the early 2000s, oil discoveries in deep and ultra-deep waters in the Barremian-Aptian carbonate section of the rift and sag basin stages resulted in new and massive economic interest in the area. Oil reserves within such stratigraphic sequences are estimated to exceed 45 billion barrels (Szatmari and Milani, 2016).

The rift-sag carbonate section is also known as the *pre-salt sequence* due to its location under an impressively thick evaporite layer that is 2000–2500 m thick (Chang et al., 1990; Pereira and Macedo, 1990; Dias, 1998). Such thick salts above the carbonate reservoir and the low contrast rock densities compromise seismic imaging and the application of seismic attributes for the prediction of sedimentary body geometries and distribution of facies. Forward stratigraphic-sedimentological modeling therefore appears to be an alternative method that is applicable to simulations of sedimentary facies distributions, including those of carbonate environments (e.g., Warrlich et al., 2008). Forward modeling provides quantitative tools for testing and appraising the control parameters in multiple stratigraphic scenarios of a basin's evolution, making predictions of facies distributions and geometries between data points, supporting subsurface data interpretations, and conducting sensitivity tests to evaluate the major stratigraphic controls of

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http://dx.doi.org/10.1016/j.marpetgeo.2017.09.013
0264-8172/

basins (Lawrence et al., 1990).

In this paper, we model the stacking pattern and sedimentary facies distribution of an Aptian lacustrine carbonate platform that composes the uppermost sedimentary succession of the sag stage in the Santos basin through tests and simulations of six parameters that act in the depositional process of carbonate rocks: (i) initial lake paleobathymetry; (ii) run time; (iii) lake level oscillation curves; (iv) values of subsidence rates extracted from the literature; (v) carbonate depositional rates (in mm/y); and (vi) different bathymetric intervals for carbonate deposition This study aims at the determination of a facies model to reproduce the sedimentary stacking pattern observed in well data and, finally, to propose a useful conceptual geological model for the deposition of the studied carbonate platform.

2. Geological setting

The Aptian carbonate platform focused on in this study is located in the central portion of the Santos basin, approximately 310 km off the coast of the São Paulo state (Fig. 1). The origin and evolution of the basin are related to the breakup of the Gondwana Supercontinent, but the Santos basin consists of a specific area that forms a kinematic buffer between the Austral and Central segments of the South Atlantic Ocean (Moulin et al., 2010, 2012). Breakup initiated during the Early Cretaceous and culminated with the opening of the South Atlantic Ocean and implantation of the Brazilian marginal basins in the so called Brazilian Rift System (Chang et al., 1992). In a regional context of rift development from south to north along the southeastern and eastern continental margins, the Santos basin progressed from small grabens and lakes to a regional subsidence setting that created extensive sag-phase lacustrine deposits (Carminatti et al., 2008; Quirk et al., 2013). Thermal subsidence was then implemented by setting up a restricted environment, with extensive deposition of evaporites during the Aptian. At the beginning of the Albian, a shallow carbonate platform was generated with the progression of the South Atlantic opening. From the Middle Albian onwards, the shallow carbonate platform was progressively drowned, leading to the development of an open ocean setting in a passive margin tectonic environment (Mio, 2005).

The stratigraphic sequence of the studied carbonate platform was deposited during the Neoaptian sag phase of the basin (Fig. 2). The depositional environment of this sequence was marked by a transitional setting between continental to shallow marine conditions. Its upper limit is the base of the 113 My evaporites that mark the passage from a mixed clastic-carbonate sedimentary sequence to an evaporitic environment (Moreira et al., 2007).

There are no published and available models regarding the morphological configuration of the sag lacustrine environments of the studied carbonate platform. However, Szatmari and Milani (2016) proposed a configuration model for the lakes of the South Atlantic rift province that may be appropriate to the studied carbonate platform, which developed during the sag phase of the Santos basin. According to that model, structural highs (horsts) would separate two distinct lakes, which would eventually communicate as a result of the rising of lake levels (due to combinations of low evaporation and high precipitation rates) and become isolated again with the decrease in lake levels (due to

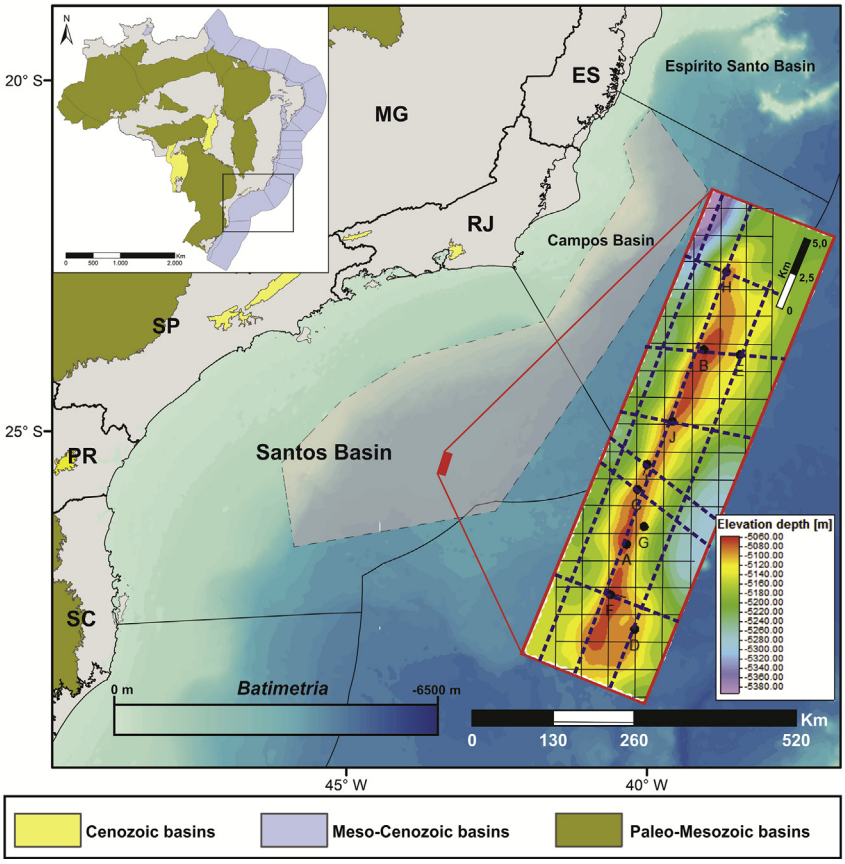

Fig. 1. Location map of the study area. The dashed gray polygon marks the limit of the pre-salt field's occurrence in the Santos and Campos basins. The structural map (base of salt) of the platform, where the study was developed based on the availability of 10 wells (A to J) and seismic grid, is outlined in red. The dashed blue lines are the nine seismic sections where structural restorations were performed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)