Marine and Petroleum Geology 77 (2016) 179–189

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Evolutionary history and controlling factors of the shelf breaks in the Pearl River Mouth Basin, northern South China Sea

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A R T I C L E I N F O

Article history:
Received 9 January 2016
Received in revised form
12 June 2016
Accepted 13 June 2016
Available online 15 June 2016

Keywords:
Shelf break
Pearl River Mouth Basin
South China Sea
Hinge zone

A B S T R A C T

The migration history of shelf breaks in the stratigraphy of a basin contains significant information about sediment-budget partitioning into the deep water area, which is thus important in predicting the distribution and quality of deepwater reservoirs. Previous studies primarily focused on the sedimentary-dominated shelf breaks (e.g., progradational-type), which are controlled by sediment supply and relative sea-level changes. The location and migration pattern of structure-controlled shelf breaks are comparatively less well documented.

The evolutionary history of shelf breaks in the Pearl River Mouth Basin from 30 Ma to present is examined here. Shelf breaks are picked from 280 2-D depositional dip-oriented seismic profiles in the forced regressive systems tracts of 20 3rd-order sequences (SQ 1-20) in four super sequences (SSQ 1-4). Planview distribution maps indicate these shelf breaks can be divided into two groups of different character. Shelf breaks in SSQ 1 (30–23.8 Ma) have migrated progressively and considerably basinward (~50 km) along with the progradation of shelf-margin deltas, which were propelled by a very strong sediment supply even under the background of relative sea-level rise. They are consequently classified as sedimentary-dominated types. In contrast, shelf breaks in SSQ 2-4 have stayed fairly close (~20 km) to the boundary between the Panyu Low Uplift and the Baiyun Sag, which is identified as a tectonic hinge zone across which subsidence rate increased abruptly basinward. Shelf breaks were close to the hinge zone even in SQ 11 and 12, in which the depositional shoreline breaks were located ~80 km further landward. They are classified as structure-controlled types. Our study indicates that through the evolutionary history of the Pearl River Mouth Basin, the locations and migration pattern of the shelf breaks were mainly sediment-supply controlled during 30–23.8 Ma but changed to structure-controlled (i.e., tectonic hinge zone) during 23.8 Ma-Present.

1. Introduction

The shelf break, which is also commonly referred to as shelf edge or shelf margin, is defined as the point where the first major change in slope gradient occurs at the outer most edge of the continental shelf (Porebski and Steel, 2003; Vanney and Stanley, 1983; Wear et al., 1974; Winker and Edwards, 1983). It separates the gently dipping continental shelf (average angle of 0.3°) from the much steeper continental slope (average angle of 3°) (Dietz and Menard, 1951; Pinet, 2003). On the continental shelf, depositional processes are dominated by traction flows (e.g., current, wave and tide) (Steel et al., 2008), which change to sediment gravity flows across the shelf break on the continental slope (Vanney and Stanley, 1983). Shelf-break migration through geological time and the shelf-to-slope configuration are primarily controlled by the regional geological structures, by relative sea-level change and by

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http://dx.doi.org/10.1016/j.marpetgeo.2016.06.009
0264-8172/

sedimentary processes (Mougenot et al., 1983; Vanney and Stanley, 1983; Winker and Edwards, 1983).

Mapping of ancient shelf breaks is a challenging task for several reasons: (1) complicated shelf-to-slope configuration (e.g., multiple step-like terraces); (2) structural deformation (e.g., folding, diapirism); and (3) erosion or slump (May et al., 1983; Ingersoll and Graham, 1983; Winker and Edwards, 1983). Previous studies have mostly picked shelf-break points on a dip-oriented seismic section (Gong et al., 2016), without giving much consideration to these factors, which could possibly impede the analysis results, especially in area with complex structural evolutionary histories. However, provided the structure and tilting can be restored, a quantitative method of determining the position of the shelf break was given by Olariu and Steel (2009).

A review of 24 continental shelf margins worldwide by Gong et al. (2016) suggests that their migration pattern and architectural style contain significant information about sediment-budget partitioning into the deep water area and are very important in predicting the distribution and quality of deep-water reservoirs for hydrocarbon exploration. However, shelf breaks have been poorly studied given their importance (Vanney and Stanley, 1983; Wear et al., 1974), except recent research on shelf-margin clinoforms (Gong et al., 2015; Henriksen et al., 2009; Johannessen and Steel, 2005; Olariu et al., 2012).

A few studies of shelf breaks have been carried out in the Pearl Mouth River Basin, northern South China Sea (Gong et al., 2015; Liu et al., 2011), which focus primarily on the sedimentary aspects of shelf-break migration and their control on reservoir characteristics in deep marine area. Different from previous studies, the current work focuses on evaluating the roles that regional structure and sedimentary processes have played during different stages of shelf-break evolution based on the result of a new way of picking and mapping shelf breaks in the Pearl Mouth River Basin.

2. Geological background

The study area is located in the southern part of the Pearl River Mouth Basin, northern South China Sea (Fig. 1). It covers four tectonic units, namely the Panyu Low Uplift, Baiyun Sag, Centre Low Uplift and Liwan Sag. The present shelf break is approximately aligned with the boundary between the Panyu Low Uplift and the Baiyun Sag (Fig. 1).

The Pearl River Mouth Basin is an extensional sedimentary basin, which is characterized by half graben and horst structures. It was initiated in the Late Cretaceous as a result of continental rifting and sea floor spreading in the South China Sea area (Ding et al., 2013). The tectonic evolution of the Pearl River Mouth Basin can be divided into three stages: rifting (65–30 Ma), transition (Zhou et al., 2015) (i.e., mid-ocean ridge spreading and developing of a breakup unconformity) (30–23.8 Ma) (Ding et al., 2013) and thermal subsidence (23.8 Ma-present) (Fig. 2), the beginning of which are marked by the Shenhu event, Nanhai event and Baiyun event, respectively (Fig. 2) (Sun et al., 2008; Pang et al., 2009; Xie et al., 2014).

The Pearl River Mouth Basin is primarily filled with Paleogene to Quaternary sediments, consisting of shallow lacustrine, fluvial to deltaic and deep-water mudstone and turbidite facies (Fig. 2). This study will focus particularly on the Oligocene to Quaternary sedimentary package.

3. Data

Data used for this research include 280 2-D seismic profiles, which are oriented in the depositional dip direction (i.e., NW-SE) and an exploration well (well-A) (Fig. 3a and b). The 2-D seismic data, which were acquired between 1979 and 2011 have been normalized and converted into zero phase to improve resolution. They were recorded at a 4 ms sample interval and have a primary frequency of 20–40 Hz. Given an average vertical velocity of 2000 m/s for the P wave, the 2-D seismic data is estimated to have a vertical resolution of ~20 m.

The well-A is located in the northwest part of the Baiyun Sag. It has penetrated Oligocene and is drilled down to the Middle Eocene. A suite of well logs and biostratigraphy data from well-A are used for detailed lithofacies and age analysis. The well-A is tie to the seismic data through synthetic seismogram generated by acoustic and density logs.

Seismic interpretation and shelf break picking are primarily done in Geoframe, with some illustrations drawn with Surfer.

4. Method and work flow

4.1. Sequence stratigraphy analysis

Since several morphological shelf breaks may present in a sequence, we decided to pick the one on top of the forced regressive systems tract, mainly because it commonly represents the most seaward location in the sequence and is probably also the easiest and most obvious to be identified. This also enables meaningful comparison of shelf break locations through different sequences.

To do that, firstly a high-resolution sequence stratigraphic framework is established following the four systems tract model by Hunt and Tucker (1992). Sequence boundaries are identified based on seismic reflection termination patterns (i.e., toplap and truncation below; onlap and downlap above the surface). Each sequence is divided into forced regressive, lowstand normal regressive, transgressive and highstand normal regressive systems tracts from bottom to top.

4.2. Structural deformation and erosion reconstruction

Structural deformation and erosion make it difficult and in cases impossible to identify shelf breaks. In this study, we make sure shelf breaks are picked correctly by firstly reconstructing the strata to their pre-deformation and pre-erosion forms by performing seismic horizon flattening (i.e., on maximum flooding surfaces) and filling erosion by extrapolation of depositional surfaces.

4.3. Shelf break identification

In this study, we define a shelf break where the dip angle of a surface increases from $0.02^\circ \pm 0.02$ to $>2^\circ$ on a dip-oriented seismic section. Shelf breaks are mostly picked manually in previous studies, which can be time-consuming and is subject to human errors and inconsistency. One exception is by Olariu and Steel (2009), who programed to pick the shelf break at the point where the gradient ratio between that point to 30 km basinward, and between the shore line and that point is maximum. In this study, we have developed a method of calculating the dip angle of a surface with the following equation:

$$A_d = arctan(D_w/L)$$

where, A_d is the dip angle, D_w is the paleobathymetry, and L is the horizontal length of the slope. D_w is calculated with the following equation:

$$D_w = (T \times V/2) \times C$$

where, T is the two-way travel time of P wave through the overlying