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Cenozoic tectonic subsidence in deepwater sags in the Pearl River Mouth Basin, northern South China Sea

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ABSTRACT

The Cenozoic tectonic subsidence of the deepwater area in the Pearl River Mouth Basin, northern South China Sea is studied by subsidence analysis via backstripping calculations based on data of newly interpreted sequence boundaries. In the subsidence analysis local porosity–depth parameters were estimated based on well data, the paleo-water depth parameters and lithology were estimated for all grid nodes based on well data and sedimentary system maps, and ages of sequence boundaries were adjusted according to the International Chronostratigraphic Chart v2013/01. Sensitivity analysis shows that these are essential to ensure the quality of the subsidence analysis in the slope areas. Maps of tectonic subsidence rates of 18 Cenozoic sequences were constructed and spatial–temporal variations of the tectonic subsidence were discussed. The subsidence was restricted in the Baiyun and Liwan Sags before 30 Ma and extended to uplifts after 30 Ma. This indicates that the 30 Ma unconformity is the breakup unconformity that separated the syn-rift and post-rift sequences. Four substages of post-rift subsidence were identified by cyclic changes in the rate and pattern of tectonic subsidence at boundaries of 23.3 Ma, 17.2 Ma and 11.9 Ma, respectively. Anomalous post-rifting tectonic subsidence was significant and totaled to ~1200 m at the center of the Baiyun Sag, and punctuated by rapid subsidence and uplift events. The Baiyun Event was manifested in the study area by a short-lived uplift event in 23.9–23.3 Ma followed by a short-lived rapid subsidence in 23.3–19.8 Ma in the central study area. This localized rapid subsidence caused northward jump and anti-clockwise rotation of the shelf break. Two-order teeterboard (seesaw)-like subsidence was observed in the study area in the post-rifting stage, suggesting elastic deformations of the crust and lithosphere.

1. Introduction

The South China Sea is one of the largest marginal seas in western Pacific. Its northern continental margin is dominated by extensional basins, among which the Pearl River Mouth Basin is the largest one. The Baiyun Sag and its neighboring Liwan Sag are two deepwater sags of the Pearl River Mouth Basin, with a total area of over 30,000 km^2, sediment thickness over 14 km in the center, and water depth ranging from 200 to 3000 m (Fig. 1). Exploration in the last decade revealed high potential for hydrocarbon in these deepwater sags (Chen et al., 2003; Pang et al., 2004, 2006, 2007a, Zhu et al., 2008, 2010). Six gas fields have been discovered by the China National Offshore Oil Corporation (CNOOC) in the Baiyun Sag. Among these the LW3-1 field discovered in 2006 has verified geological reserve of (1000–1700) × 10^8 m^3 natural gas (Zhu et al., 2010). The Baiyun Sag and the Liwan Sag (Fig. 1) have attracted attention from both oil companies and marine scientists. The studies on these sags marked the beginning of the research in China on offshore deep water sags.

In this paper we studied the tectonic subsidence of the deepwater area in the central segment of the Pearl River Mouth Basin, including the Baiyun Sag, the Liwan Sag, and a part of the Panyu Low uplift, the Dongsha Uplift and the Southern Uplift, with a total area of over 40,000 km^2 (Fig. 1).

Throughout the paper the term "subsidence" is used as synonym of the term of "tectonic subsidence", which is defined as the vertical motion (positive downward) of basement at a site that is induced by tectonic forces such as thermal contraction, tectonic deformation, and dynamic topography. In order to obtain subsidence information, corrections need to be made for the effects of compaction and sediment loading, changes in paleo-water depth, and global sea level changes. This process is called as "subsidence analysis", which is made through backstripping of individual sedimentary layers for calculating balanced basement depths (Sclater and Christie, 1980; Stam et al., 1987; Steckler and Watts, 1978).

Previous studies on the Cenozoic subsidence in the Pearl River Mouth Basin have been reported in a number of papers (Clift and Lin, 2001; Clift et al., 2002a; Liao et al., 2011; Ru and Pigott, 1986; Xie et al., 2006; Zhao et al., 2011). Most studies were based on seismic and well data from continental shelf areas.

With the proceeding of hydrocarbon exploration to deepwater areas, new 2D and 3D multi-channel seismic data have been acquired. In 2009 to 2010 the CNOOC launched a new round of sequence

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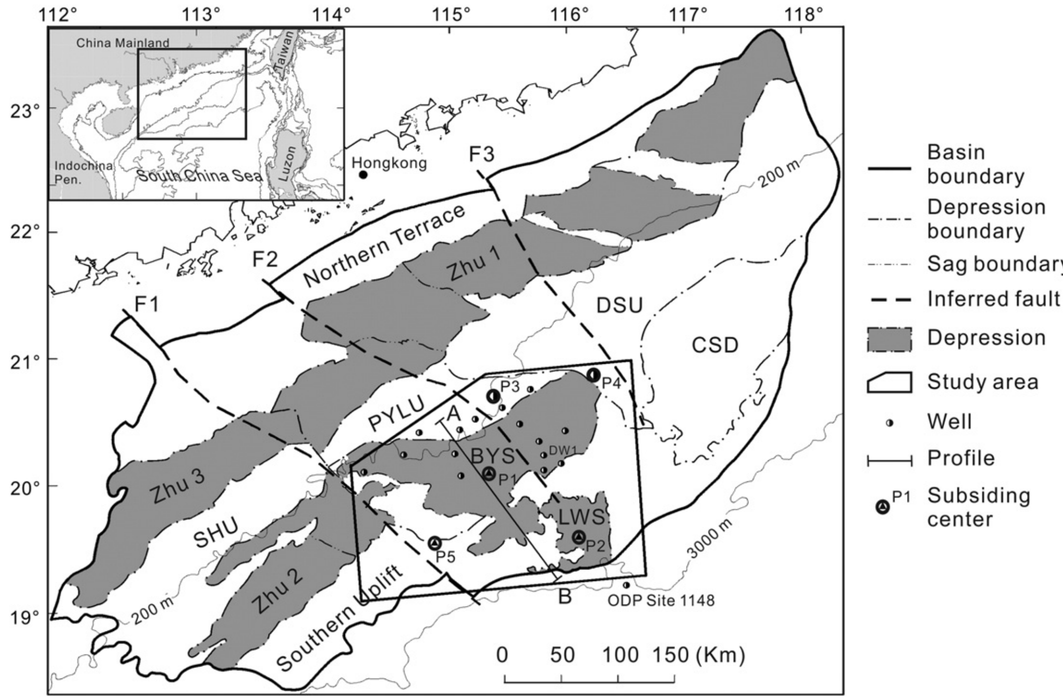

Fig. 1. Map of structural divisions of the Pearl River Mouth Basin. Zhu 1, Zhu 2, and Zhu 3 are names of depressions; CSD—Chaoshan depression; SHU—Shenhu uplift; PYLU—Panyu Low uplift; DSU—Dongsha uplift; BYS—Baiyun sag; LWS—Liwan sag. Black box indicates the study area of this paper. The small halved dots are the locations of existing wells within the study area. The large dots with black triangles indicate the area of fastest tectonic subsidence for sags or uplifts (P3 and P4 are also the location of wells). The straight line AB shows the location of the seismic profile in Fig. 3.
Inferred faults are after Sun et al. (2008).

stratigraphy analysis for the Baiyun Sag and the Liwan Sag, which resulted in high-quality isobath maps in the area of 44,500 km^2 for 19 sequence boundaries (including seabed), as well as maps of sedimentary systems of selected sequences. In order to update our understanding on the tectonic subsidence and geodynamics of these deepwater sags, we conducted subsidence analysis via backstripping calculations based on these newly acquired data. Parameters for the calculation were carefully derived based on local well data, and the computer program of Stam et al. (1987) was revised to take account of the significant variation in lithology and paleo-bathymetry in deepwater areas. These actions have improved the reliability of the calculation as shown by sensitivity analysis. Maps of tectonic subsidence and its rates of the 18 sequences were constructed. Spatial and temporal variations of tectonic subsidence were revealed, and several rapid subsidence events and uplift events were identified. These have provided new information on the formation and evolution of the deepwater sags and of the Pearl River Mouth Basin, even of the South China Sea, as discussed in this paper.

2. Geological setting

The South China Sea was formed by seafloor spreading during Late Oligocene to Miocene (Briais et al., 1993; Taylor and Hayes, 1983). The extension in the South China Block started in the Late Cretaceous – Early Paleocene and resulted finally in the opening of the South China Sea (Zhou et al., 1995). The origin of the extensional forces is controversial (Flower et al., 1998; Holloway, 1982; Tapponnier et al., 1982, 1986; Taylor and Hayes, 1983).

The date for the onset of seafloor spreading in the South China Sea is also unsettled. A widely accepted pattern of magnetic anomalies in the South China Sea indicates that the seafloor spreading started first in the eastern and northwestern subbasins at linear magnetic anomaly C11 and propagated to the southwestern subbasin at the time of anomalies C6b–C7 and anomaly C6. Accordingly the onset of seafloor spreading is dated as 32 Ma by the date of anomaly C11 according to the magnetic time scale of Patriat (1987) (Briais et al., 1993; Taylor and Hayes, 1983). But this date should be changed to 30 Ma, which is the new date of anomaly C11 according to the revised geomagnetic polarity timescale of Cande and Kent (1995).

The ODP Site 1148 drilled at water depth of 3294 m of the southeast corner of the study area (see Fig. 1 for the location of the Site) terminated at 861 m below seafloor in marine sedimentary rocks dated as Early Oligocene 32.8 Ma with no unconformity penetrated at Early Oligocene ~30 Ma (Shipboard Scientific Party, 2000). Thus the breakup of the South China Sea was thought to be earlier (Li et al., 2005). This was echoed by Hsu et al. (2004), who identified anomaly C17 in the northeastern South China Sea and proposed the breakup of the South China Sea at 37 Ma. However, the 37 Ma onset model has not been widely recognized because the magnetic anomalies are weak and the correlations are unconvincing. In addition, Barckhausen and Roeser (2004) identified the anomaly C12 in the northwestern subbasin of the South China Sea and thus proposed the onset of seafloor spreading at 31 Ma.

In this study we adapt 30 Ma as the age of the breakup unconformity, bearing in mind the uncertainty in dating.

The Pearl River Mouth Basin lies in the northern continental margin of the eastern and northwestern subbasins of the South China Sea, with a total area of 200,000 km^2. The basin is composed of two depression zones separated by three uplift zones, namely from the north to the south, the northern terrace, the northern depression zone consists of Zhu 3 and Zhu 1 depressions, the central uplift zone consists of Shenhu, Panyu, and Dongsha uplifts, the southern depression zone consists of the Zhu 2 and Chaoshan depressions, and the southern uplift zone along the margin of the deep-sea basin (Fig. 1). The basement of the Pearl River Mouth Basin consists of Jurassic and Cretaceous granites in its central and northern portions, un-metamorphosed Mesozoic sedimentary rocks in the east, and Paleozoic quartzite and other metamorphic rocks in the west (Zhou et al., 2008a). The crust that underlain the basin thins from ~30 km near the coast in the north to ~11 km near the deep-sea basin in the south (Huang et al., 2005; Kido et al., 2001; Nissen et al., 1995). Beneath the centers of sedimentary depressions, the Moho surface shoals significantly, for example, the crust