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Research paper

Provenance identification and sedimentary analysis of the beach and bar systems in the Palaeogene of the Enping Sag, Pearl River Mouth Basin, South China Sea

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ABSTRACT

During deposition in the Palaeogene, the Pearl River Mouth Basin (Enping Sag) was filled by sediments derived from northern and southern source regions. The northern sources are the fold belt Caledonian and Hercynian metamorphic rocks that are widely exposed along the South China block and stacked with Mesozoic igneous rocks, and the southern sources are Mesozoic igneous rocks from the southern Panyu lower uplift. We analysed the characteristics of the provenance and sediment-dispersal patterns of the beach and bar systems in the Palaeogene third-order sequence framework on the basis of detritus, thin section, zircon and the geophysical response test data. The source and deposition areas were distinguished based on their palaeogeomorphology. The sedimentary material composition of the deposition area was determined based on the characteristics of the detrital assemblage and cathode luminescence, and the characteristics of the age distribution were determined in detail using detrital zircon U–Pb dating. This study suggests that the provenance system in the Palaeogene mainly consisted of Palaeozoic metamorphic rocks and Mesozoic igneous rocks, with a supplement of Proterozoic metamorphic rocks. The transport capacity of three large fault troughs that delivered the northern provenances gradually increased from the Wenchang Formation (E_2w) to the Enping Formation (E_3e), whereas the southern provenances were transported by four or five incised valleys in E_2w and then submerged in E_3e. In the 3D seismic area, the features of the beach and bar sedimentary systems were described and interpreted based an analysis of the well-based sedimentary facies, seismic reflection characteristics and multiple attribute clustering. The results show that the beach and bar systems by the short-axis braided deltas mainly developed in the upper member of E_2w and that the beach and bar systems on the subaqueous high in E_3e developed during the Palaeogene. In addition, the bedrock-beach bar sedimentary system in the lower member (E_3e^L) was transferred to the braided delta–beach bar sedimentary system in the upper member (E_3e^U).

1. Introduction

The rifted lacustrine basins in the South China Sea (SCS) are characterized by multiple faults and subsidence centres and have undergone multiple tectonic activation episodes (Taylor and Hayes, 1983; Cullen et al., 2010; Franke, 2013; Franke et al., 2014; Sun et al., 2014; Zhou et al., 2014). Complex basin architectures are well documented as rifted basins developed within the coexistence of

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multiple faults, uplifts and sags (Rosendahl, 1987; Morley et al., 1990; Schlische and Olsen, 1990; Schlische, 1991; Contreras et al., 1997; Gawthorpe and Leeder, 2000; Peacock et al., 2000; Henza et al., 2009; Schlische and Withjack, 2009). In addition, the proximal and multiple-sourced sediment supplies created distinctive patterns of multiple cycles, stages and depositional centres comprising diverse facies (Olsen, 1997; Gupta et al., 1998; Cope et al., 2010; Hsiao et al., 2010; Leeder, 2011; Masini et al., 2011). Gawthorpe and Leeder (2000) proposed a well-considered tectono-sedimentary model for active extensional basins and noted that the basin-fill architecture in a rift basin depends on a complex interaction among the three-dimensional (3-D) basement evolution through fault propagation, the evolution of drainages and drainage catchments, the effects of changing climate and base-level fluctuations. Sediment provenance analysis is an important tool for non-marine sedimentary basin analysis and is also helpful for identifying the essential elements of depositional systems including (1) sediment source areas, (2) source types and (3) sediment-transport pathways. These elements can aid in predicting the (1) palaeo-flow direction, (2) sedimentary facies distribution, (3) dispersal patterns of the depositional systems and (4) basin evolution history and palaeodepositional environment (Morton et al., 1991).

Conventional methods for sedimentary provenance analysis include heavy minerals (Blatt and Tooten, 1981), detrital component analysis (Dickinson, 1985; Roser and Korsch, 1988), pollen (Morton et al., 1991), fission-track thermochronology (Brandon and Garver, 1994) and geochemical and isotopic methods (Bhatia, 1983; Bonjour and Dabard, 1991; McLennan et al., 1993; Stevenson et al., 2000; Nemchin and Cawood, 2005; Miller et al., 2010), all of which require samples from either outcrops or cores. In the absence of rock samples, an alternative effective sedimentary provenance analysis approach using seismic and well data can be used (e.g., Wang et al., 2000; Zhao and Liu, 2003; Xu et al., 2007; Morley and Back, 2008).

Enping Sag is a hydrocarbon-rich region in the Pearl River Mouth Basin (PRMB) (Fig. 1a) (Liu et al., 2011), but the target layers are not yet well studied. Previous exploration has revealed that the Miocene Zhujiang Formation and the Oligocene Zhuhai Formation are the major reservoirs, followed by the Eocene Wenchang Formation and Oligocene Enping Formation, which are of secondary importance (Zhu and Mi, 2010). Despite the detailed documentation of the stratigraphy (Liu et al., 2013), sedimentology (Wang et al., 2011; Liu et al., 2015), tectonics (Wang et al., 2011) and petroleum exploration (Fu et al., 2007, 2009; Zhuo et al., 2007; Li et al., 2009; Wu et al., 2013), the petroleum geology of the Palaeogene is still not fully understood because of limited seismic and well data.

The South China fold system and Panyu lower uplift have been two important sediment sources since the Palaeogene (Fig. 1a). Previous investigations based on two-dimensional (2-D) seismic facies interpretation have suggested the presence of numerous fan deltas and braided deltas developed around the South China fold system and Panyu lower uplift (Lv et al., 2008; Wang et al., 2011). The Palaeogene sediments in the Enping sag were in fact mainly derived from the South China fold system and Panyu lower uplift. However, a detailed view of the influence of the uplifts and the spatial distribution of the sedimentary facies, especially beach and bar systems in the southern slope belt, is lacking because of poor provenance data and the lack of 3-D seismic data that cover the entire block.

In the study area, only six wells penetrate the interval of interest (Fig. 1b). Recently acquired 3-D seismic data (in-line and cross-line spacing of 25 m and 25 m, respectively), which cover the main Enping sag (with the area approximately 1800 km^2), makes it possible to investigate the characteristics and diversity of the provenances between the South China fold system and the Panyu lower uplift.

The primary objective of this study is to investigate the sediment provenance and sediment-dispersal patterns of the beach and bar systems using zircon provenance and 3-D seismic data. Specifically, this study seeks an (1) interpretation of the sediment-transport pathways and determination of the sediment source areas, (2) recognition of the prime material components in the sedimentary area through fragment composition and cathodoluminescence characteristics analyses, (3) identification of the sedimentary age provenance using zircon U–Pb dating, (4) documentation of the lateral lithological variations of the sand-prone and shale-prone areas, especially beach and bar systems, derived from well-based sedimentological characteristics, seismic facies and attributes and (5) the delineation of the planar distribution of the sedimentary facies for predicting the dispersal patterns of the beach and bar systems.

2. Geological setting and stratigraphy

As one of the largest marginal seas in the western Pacific, the South China Sea (SCS), which is located at the junction of the Eurasian, Pacific and Indian Ocean plates, has experienced a complicated tectonic and sedimentary evolutionary history (Briais et al., 1993; Gong et al., 1997; Sun et al., 2009). The Pearl River Mouth Basin (PRMB), located in the central part of the northern South China Sea margin, is one of the most important petroliferous basins in the entire region. The PRMB consists of five tectonic units; from south to north they are southern uplifted zone, southern depression zone, central uplifted zone, northern depression zone (including the Zhu-I and Zhu-III depressions) and northern uplifted zone (Fig. 1a). The basement of the PRMB consists of Jurassic and Cretaceous granites in its central and northern area, unmetamorphosed Mesozoic sedimentary rocks in the east and Palaeozoic quartzite and other metamorphic rocks in the west (Zhou et al., 2008).

The PRMB is an extensional basin on a continental margin. The evolution of the PRMB can be divided into an early faulting stage (the syn-rift stage) and a later subsiding stage (the post-rift stage) (Chen and Pei, 1993; Huang et al., 2003). During the syn-rift stage (56–30 Ma, Fig. 2), widespread crustal thinning and normal faulting accompanied by uplift and erosion contributed to the development of a series of grabens and half grabens along major NE and NW-trending fault sets (Chen and Pei, 1993; Li and Rao, 1994) (Fig. 1). Subsequently, the basin went into a postrift stage (30 Ma to the present, Fig. 2), which is divided by most investigators into two periods (e.g., Ru and Pigott, 1986; Su et al., 1989; Li and Rao, 1994; Chen, 2000). During the Late Oligocene to Middle Miocene, the basin was affected by extensional-shear and flower structures in the central area. After the Middle Miocene, tectonic movements were usually accompanied by extrusive volcanism that resulted in the large-scale hiatus of deposits and revival of faults.

The PRMB is a sedimentary system with terrestrial deposits followed by marine facies. Fig. 2 shows the generalized Cenozoic stratigraphy in the PRMB. The syn-rift sediments are composed of the Shenhu (E_1s), Wenchang (E_2w) and Enping (E_3e) Formations (Chen and Pei, 1993; Zhang et al., 2003; Zhu and Mi, 2010). The Shenhu Formation is dominated by red or mottled alluvial fan sands and conglomerates associated with volcanic sediments, which have little or no hydrocarbon-generating potential. The Wenchang Formation, which was deposited during the peak stage of lake expansion, mainly consists of grey to black organic-rich lacustrine shale interbedded with sandstone with a thickness of 1–2 km. The Enping Formation, which was deposited during the stage of lake regression, is dominated by fluvial-lacustrine-paludal shale, sandstone and thin coal beds with a thickness of