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Research paper

Geochemical evolution of Oligocene–Middle Miocene sediments in the deep-water area of the Pearl River Mouth Basin, northern South China Sea

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A B S T R A C T

The deep-water area of the Pearl River Mouth Basin in the South China Sea has received much scientific attention since the Ocean Drilling Program (ODP) Leg 184 in 1999 due to its potential economic prospects and distinct tectono-sedimentary evolutionary processes. In this study, we present the composition of major and trace elements from two newly sampled deep-water boreholes (BY6 and LW3) in the Baiyun Sag of the southern Pearl River Mouth Basin. The geochemical evolution in the Oligocene–Middle Miocene, as well as potential controlling factors, are investigated based on a comparative study with previous data from ODP site 1148 and borehole PY33. The Chemical Index of Alteration (CIA) and A–CN–K plot reveal that the observed weathering trends are not compatible for the four discussed boreholes. Sedimentary sorting is primarily observed in borehole PY33, where data trend away from the A apex to the feldspar join in the A–CN–K plot and show a spread of Al_2O_3/SiO_2 and Nb/Zr ratios. Compared to chemical weathering and hydrodynamic sorting, provenance has a greater impact on sediment composition of the deep-water area. From the north, the Pearl River was the primary sediment supply. However, a positive Eu anomaly and the provenance discrimination diagrams (i.e., La/Th versus Th/Yb and Zr/Co versus Th/Co) reveal the mafic nature of borehole BY6 sediments in the Zhuhai–Lower Zhujiang (32.0–18.5 Ma) and Upper Hanjiang (13.8–10.5 Ma) formations. These compositions are unusual and differ from the well-defined felsic sources in the majority of the Baiyun Sag; these discrepancies are likely related to multistage magmatism. The sediments at site 1148 are characterized by slightly enriched heavy rare earth elements and relatively high Zr/Co ratios, which could possibly be caused by zircon enrichment from local sources.

1. Introduction

Following the golden period of mineralogical analysis in the mid-20th century, major advancements have been made in the use of bulk elemental analysis to provide quantitative insights into siliciclastic sediments and sedimentary rocks. Extensive geochemical studies have greatly widened the knowledge of sedimentary provenance, tectonic setting, and weathering, as well as crustal evolution (McLennan et al., 1993; Nesbitt et al., 1996; McLennan, 2001). Although detrital single-grain analysis is gaining popularity, whole-rock geochemistry is still worthwhile because of its wide applicability and holistic viewpoint. At the same time, the ever-increasing compositional databases and numerical–statistical analyses steadily facilitate the revision and invention of various geochemical diagrams and proxies (e.g., Sohn, 2013; Verma and Armstrong-Altrin, 2013).

Our understanding regarding the geological evolution of the South China Sea has benefited greatly from previous studies on the Ocean Drilling Program (ODP) Leg 184 in Feb–April 1999. The oldest sedimentary record of the Early Oligocene age, recovered from site 1148 (Fig. 1), provides excellent material for exploring the Asian Monsoon (Shipboard Scientific Party, 2000; Clift et al., 2014). Early geochemical studies on this site have revealed several

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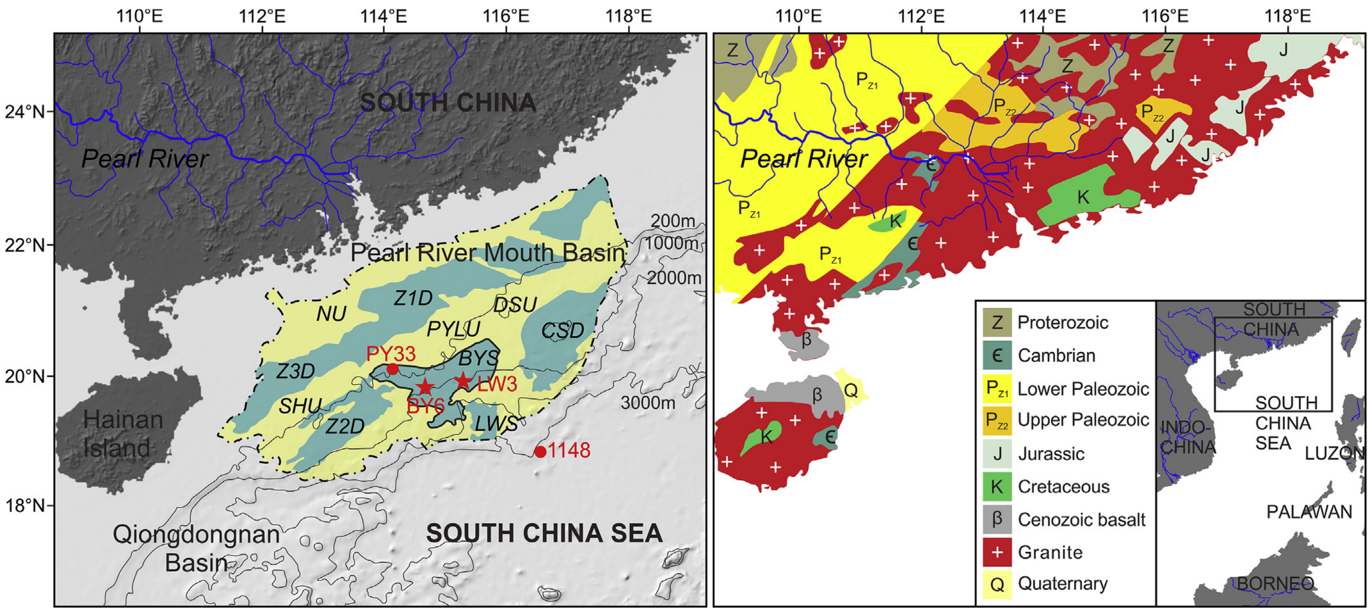

Fig. 1. Bathymetric map of the study area in the northern South China Sea showing the location of two sampled boreholes (BY6 and LW3; stars) and simplified geological map of the Pearl River drainage basin. Topography data are from Ryan et al. (2009). The tectonic units of the Pearl River Mouth Basin are shown: BYS, Baiyun Sag; CSD, Chaoshan Depression; DSU, Dongsha Uplift; LWS, Liwan Sag; NU, Northern Uplift; PYLU, Panyu Low-uplift; SHU, Shenhu Uplift; Z1D, Zhu-1 Depression; Z2D, Zhu-2 Depression; Z3D, Zhu-3 Depression. Previous borehole PY33 and ODP site 1148 are also displayed with circles.

occurrences of compositional variations in the Oligocene strata (Li et al., 2003; Shao et al., 2004), but the interpretation of their syn-rift sedimentary provenance remains controversial. For example, Li et al. (2003) and Wei et al. (2012) propose a southern provenance from either Northwest Borneo or North Palawan, whereas combined evidence from clay mineralogy, Nd isotopes, and palynology (e.g., Clift et al., 2002; Wu et al., 2003; Shao et al., 2008) suggests a northern source from South China. Notwithstanding the uncertainty of sedimentary source, elemental concentrations and ratios of the Miocene transgressive deposits remain largely constant across studies. Although most researchers interpret this as a relatively stable provenance from the Pearl River (Li et al., 2003; Wei et al., 2012), another plausible explanation could be that site 1148 is far away from the main sedimentary body, rendering its composition relatively insensitive to provenance and eustatic sea level change (Pang et al., 2006a). The modern Pearl River is the largest river at the northern margin of the South China Sea (Fig. 1), with a drainage area of 490,000 km^2 and a discharge of 260 km^3/a (Milliman and Farnsworth, 2011). Lithology within the Pearl River drainage basin is complicated, but largely consists of carbonate and sedimentary rocks in the upstream region and acidic igneous rocks in the coastal area of South China (Fig. 1). Sediment composition derived from the Pearl River seems to have changed since the Oligocene, possibly due to the stepwise westward expansion of the Pearl River drainage basin in the Miocene (Shao et al., 2013b) as well as the anthropogenic activities in the Holocene (Hu et al., 2013).

Before the mid-1990s, a lack of knowledge regarding regional geology resulted in multiple failures of deep-water exploration efforts in the Pearl River Mouth Basin (Pang et al., 2007). Although it was once believed that the deep-water area lacked economic prospects, sandy sources from the large-scale Pearl River delta system could be abundant. Following the discovery of natural gas reservoirs (e.g., borehole PY33; Fig. 1) on the northern side of continental slope (Pang et al., 2006b), the geological evolution of the deep-water area has received widespread attention. Extensive seismic surveys reveal that the deep-water depressions actually experienced more complex tectono-sedimentary evolution than revealed during early studies of site 1148. This includes anomalous post-rift subsidence (Xie et al., 2006, 2014), unidirectional migration of submarine canyons (Zhu et al., 2010; Ding et al., 2013; Gong et al., 2013), and episodic intrusions of magma and fluid (Sun et al., 2012, 2014a). However, geochemical analysis in this area is still scarce. In this study, we discuss the composition of major and trace elements in Oligocene–Middle Miocene sediments from two deep-water boreholes (BY6 and LW3). Previous data from ODP site 1148 (Li et al., 2003) and commercial borehole PY33 (Shao et al., 2005, 2008) are compared with new data to fully evaluate the regional-scale implications for chemical weathering, hydrodynamic sorting, sedimentary provenance, and tectonics.

2. Geological setting

In this paper, the “deep-water area” refers to the area of bathyal water depths (>200 m) in the northern South China Sea. The sampled boreholes (BY6 and LW3) are located at the middle part of the deep-water Baiyun Sag, at water depths of 1020 m and 1480 m, respectively (Fig. 1). The Baiyun Sag is one of the largest depressions in the Pearl River Mouth Basin with an area of approximately 20,000 km^2. The maximum thickness of its Cenozoic sedimentary sequences reaches 11 km, which can be partitioned into the fluvial–lacustrine–neritic shelf facies of the Paleogene syn-rift and the deep-water slope–bathyal facies of the Neogene post-rift (Fig. 2; Pang et al., 2008).

Since the Late Cretaceous, the pre-existing Andean-type volcanic arc has been replaced by the passive continental margin in the South China Sea (Taylor and Hayes, 1983). The subsequent extensional setting is explained by several driving mechanisms, such as the Indochina extrusion, the proto-South China Sea subduction, and the upwelling mantle plume (Leloup et al., 2001; Hall, 2002; Xu et al., 2012). In the Early Oligocene (~33 Ma; Li et al., 2015), crustal extension reached a point where seafloor spreading was initiated, forming a widespread breakup unconformity in the South China Sea (Taylor and Hayes, 1983). After a short period of uplift and