Internal Structure of the Incised Valley Fill in the Hangzhou Bay, Eastern China and Its Geological Implications

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Abstract This paper presents the sedimentary facies and formation of the Qiantangjiang and Taihu incised valleys, and the characteristics of shallow gas reservoir distribution, based on a large number of data of drilling, static sounding and chemical analysis obtained from the present Hangzhou Bay coastal plain. The incised valleys were formed during the last glacial maximum and were subsequently filled with fluvial facies during the post-glacial period. All commercial gases are stored in the flood plain sand lenses of the incised valleys.

Key words: sedimentary facies, incised valley, shallow biogenic gas, Hangzhou Bay, eastern China

1 Introduction

Incised valleys, resulting mainly from sea level fluctuation, have been formed through out the geological history, from the Precambrian to the present (Zaitlin et al., 1994; Smith and Read, 2000). The study of incised valleys will be of significance not only in stratigraphic division and understanding of sea level fluctuation, but also in effective hydrocarbon exploration. Recently, many studies have documented incised-valley deposit which accumulated from the last glacial sea-level lowstand to the present, and recognized that the fillings of incised valleys can be highly complex in individual cases, with sediments ranging from non-marine through estuarine to open marine environments (Allen and Posamentier, 1993; Dalrymple et al., 1994). The relations between internal structures of incised-valleys and gas reservoir occurrences were not clarified. Based upon description of the formation and evolution of the late Quaternary incised valleys in the coastal plain of Hangzhou Bay with special emphasis on its internal structures, this paper aims to document the features of the biogenic gas reservoirs in the incised valleys, and summarize their distribution rules.

2 Geological Settings

The coastal plain of the Hangzhou Bay refers to the area situated at 29°50′–30°50′N and 120°–122°E with an area of about 20,000 km^2. The coastal plain, surrounded by hilly lands to the west and south, inclines gently toward the east. The Qiantangjang River flows through the plain into the sea (Fig. 1). Neotectonism in the Zhejiang Coastal Plain region is characterized by weak uplifting of the hilly lands and gentle subsidence in the plain areas without intense folding. The subsidence rate is estimated at 1 mm/a–2 mm/a (Hu et al., 1992).

The coastline of the East China Sea at 15000 a BP is on the nowadays continental shelf 150–160 m below sea level (Zhu et al., 1979). Correspondingly, the coastal lines at 12000 a BP, 10000 a BP, 8500 a BP, 7500 a BP and 7000 a BP are 50 m, 28 m, 18 m, 5 m, and 4 m below the present sea level, respectively. The sea level at 6000 a BP was a bit higher than the present one and has been stable ever since (Yan et al., 1987). The rates of sea level rise corresponding to the periods of 15000–12000 a BP, 12000–7500 a BP and 7500–6000 a BP are 35.0 mm/a, 10.0 mm/a and 3.0 mm/a, respectively, but the average sedimentation rate in the estuary and sublittoral-marine bay is higher, at about 2.9 mm/a during the time interval of the last glacial stage (Lin et al., 1999). Since the late Quaternary, as the rate of sea level fluctuation is much higher than that of tectonic uplift, the occurrence and evolution of the sedimentary sequence of the last glacial stage was controlled dominantly by the eustatic sea level change.

3 Internal Structure of the Incised Valleys

3.1 Basement

Late Quaternary sediments are separated from the underlying basement by a wavy erosion surface in the incised valleys and by a depositional break in the interfluves (Fig. 2). Two types of basement underlying the late Quaternary sediments have been discerned: (1) vari-colored gravelly sandy clays 1.6–5.6 m in thickness, which may represent Pleistocene talus or diluvial sediments; (2) Cretaceous sequence composed of purplish red gravelly

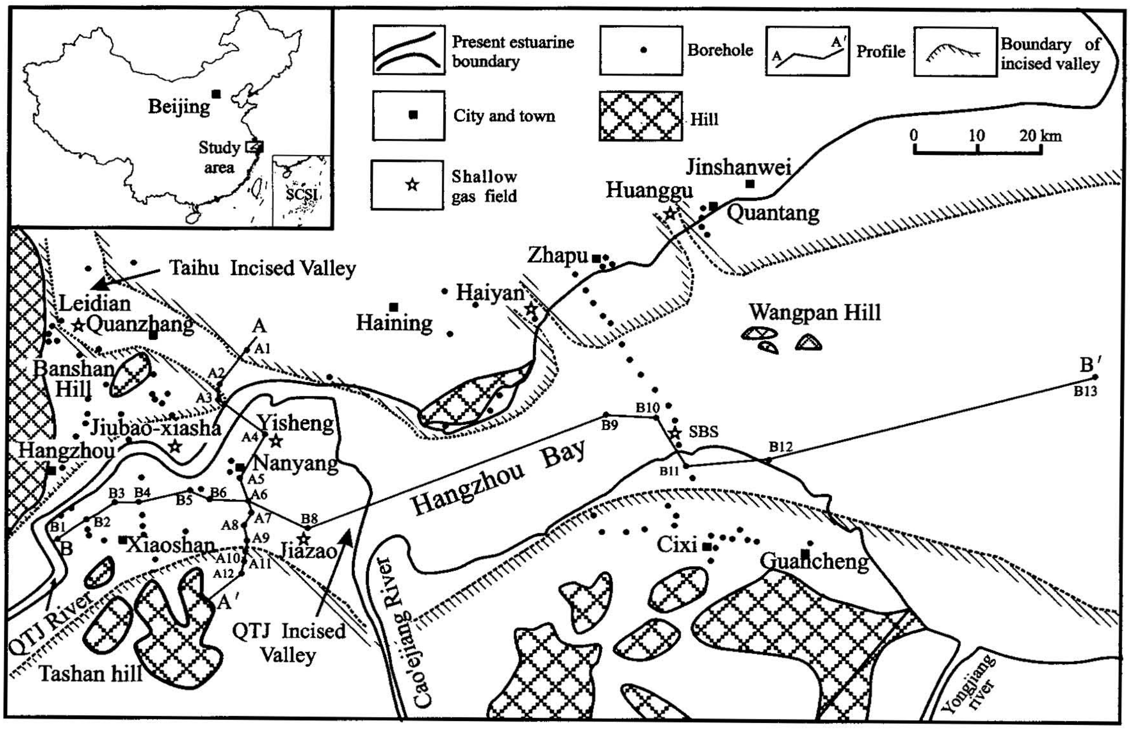

Fig. 1. Location of selected boreholes and profiles in the Hangzhou Bay.

sandstones, volcanic rocks and the weathering products of these rocks, which are found within the thalweg areas of the incised valleys due to deep cutting of the rivers.

3.2 Facies description and interpretation

Quaternary sediments are distinguishable from the underlying basement by their poor compaction, high porosity (40.7%–62.6%) and high water content (21.8% –57.1%). Based on their lithology, geochemistry and radiocarbon dating, the stratigraphic column of the incised valleys can be divided into 4 facies upsections: Facies IV, III, II and I (Fig. 2).

Facies IV occurs only in the incised valleys. Its basal sediments consist of gravel-containing coarse sand, showing normal grading and thinning upward. Trough cross-beddings can be seen, which are composed of well-sorted medium-sized sand to cross-laminated fine sand with sparse mud clasts. The absence of tide-influenced sedimentary structures such as sand-mud couplets suggests that this facies occurs upstream the tidal currents limit. No foraminifers or molluscan shells are found in the facies. These features indicate that this facies is part of the fluvial system and might be deposited in in-channel (Hori et al., 2001) to partly point-bar environments of a meandering river system (Zhong et al., 2002).

Facies III also occurs mainly in the incised valleys, and consists of dark gray clays and gray silty clays. Siderite nodules, vivianite and rotted or half-rotted plant fragments are common. Several sand lenses are intercalated in the facies, which are surrounded by impermeable clays. Foraminifers and other marine fossils are rare in the middle and lower portions of the sedimentary column, while limnic and sub-brackish mollusks have been found in the upper portion. *Ammonia beccarii* var, *Elphidium advenum,* and *Pistocytheris bradyformis* appear occasionally in the upper part. Most of them are juveniles with small and seriously abraded shells. The shells increase in amount toward the top and the sea, implying that tides affected the formation of the upper part of the facies. Therefore, this facies can be interpreted as flood plain deposits affected by tides.

Facies II directly overlies the flood plain facies, and is comprised mainly of gray mud, with intercalated lenses of sand. Occasionally, black or yellowish-brown half-rotted rootstocks are found in the lower part. Abundant foraminifers are contained in the sediments, and counted up to 100 pieces per 50 g of dried samples, of which benthonic foraminifers are dominant, comprising 90%–95% in weight. The oryctocoenose resembles the living groups in shallow-water areas of the East China Sea (Wang et al., 1981). This facies can be interpreted to have been deposited in a sublittoral-marine bay environment.

Facies I is comprised mainly of well-sorted gray silt. The total weight of fine sand and mud is usually less than 10%, lower than that in any other facies. There are abundant foraminifers and ostracoda, although not so abundant as in Facies II. This facies is likely to represent an estuarine sand

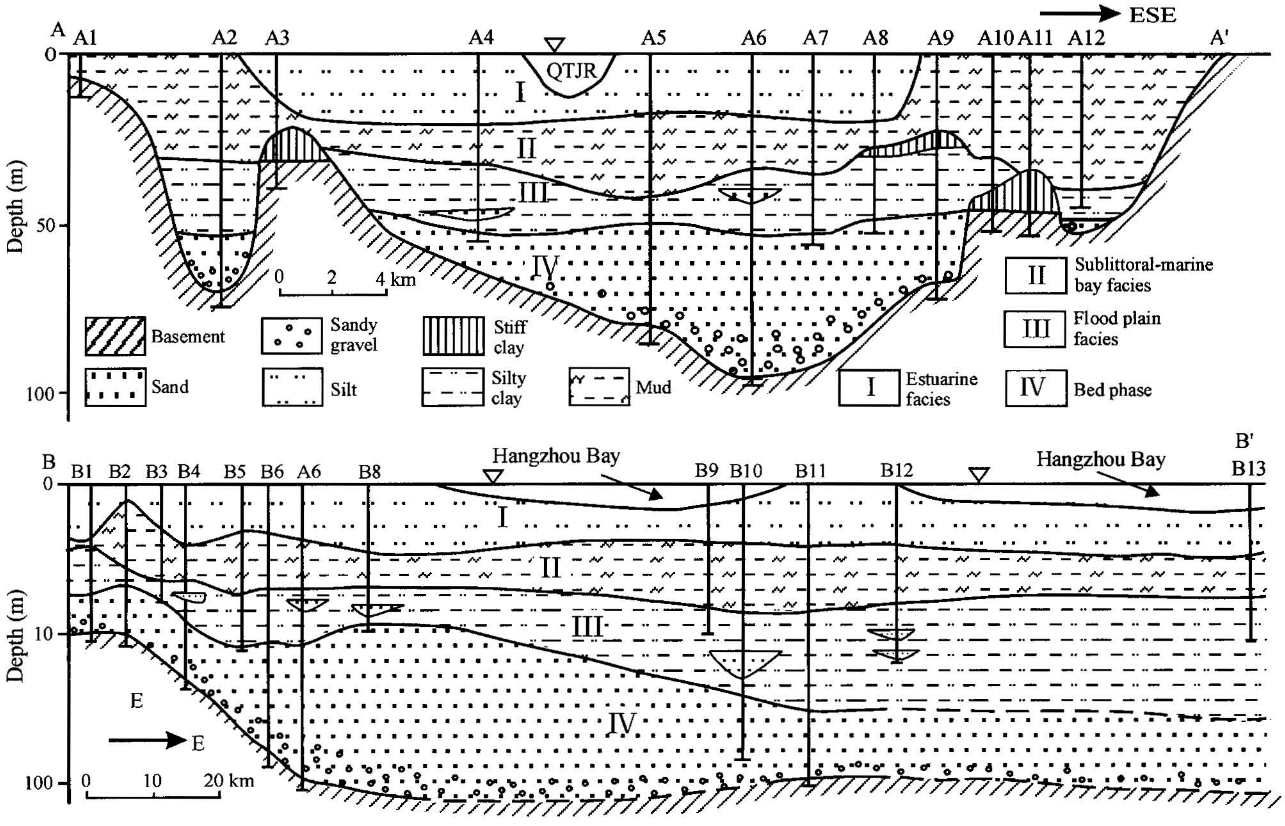

Fig. 2. Cross sections of Late Quaternary strata in the Hangzhou Bay.

bar environment.

4 Evolution of the Incised Valleys

Based on the studies of a large number of drill cores, paleontology, ^{14}C dating and geochemistry (Yan et al., 1987; Li et al., 1993; Lin et al., 1999), it has been realized that the sea level of East China has undergone since the last glacial period a half cycle from lowstand sea level through fast transgression to stable highstand sea level. With the varying sea levels, the development of incised valleys in the Hangzhou Bay region also underwent three stages: the deep-cutting stage, the rapid-filling stage and the burial stage.

4.1 Deep-cutting stage

The Qiantangjiang River strongly incised the underlying old sediment basement during the last glacial maximum (LGM, 18000–15000 a BP), resulting in the formation of the Qiantangjiang incised valley and the Taihu incised valley (Figs. 1 and 2). Sediments laid down in the incised valleys are now buried 40–120 m deep with an unconformity at its base. The incised valleys are 36–64 m deep and 6.5–60 km wide (Figs. 1 and 2), and can be delineated by the 10-m isopach of the flood plain deposit (Facies III). At this stage, most the detritus carried by the valleys were dumped into the estuary mouth. Only the fluvial gravel-containing coarse sand was left over on the river beds, forming lag-deposit layers (the basal sediments of Facies IV, Fig. 2). Rocks on the walls of the incised valleys have been exposed for a long time. Away from the valleys are interfluve hills.

4.2 Rapid-filling stage

When warmer climate came, the sea level rose quickly and the land was submerged (15,000–7,500 a BP). The eroded valleys began to receive transgressive sediments including most parts of Facies IV and the whole of Facies III. Normally, the thickness reaches its maximum in the valley thalweg. Paleosol is deposited in interfluves. Facies IV varies in thickness from several meters to 45.5 m with an average of 12.9 m. The total volume of these sediments is estimated at about 591×10^8 m^3. Facies III has a thickness of 10–15 m with an average of 13 m, and maximum up to 38.5 m. The total volume is estimated to be about 1741×10^8 m^3 (Lin et al., 1999).

4.3 Burial stage

The incised valleys began to be buried during the maximum transgression (7,500–4,000 a BP), when the sea flooded the incised valleys, inundated adjacent interfluves, and even reached the feet of hills. The coastline migrated landward over the valley fill. The thickness of sediments in the sublittoral-marine bay is normally 10–20 m with a maximum up to 38.5 m and an average of 17.1 m (Lin et al., 1999). The Qiantangjiang incised valley evolved towards a sublittoral-marine bay, whereas the Taihu incised valley towards an estuary.

At the later half of the burial stage (4,000 a BP to present), the sea level was relatively stabilized. Sedimentation rate exceeded that of sea level rise, resulting in a seaward shift of the coastline and the formation of the estuarine sand bars (Facies I). Afterward, the Taihu estuary was gradually filled and eventually separated from the sea, resulting in a lacustrine bog as we can see today. As the two sides were silted up and finally merged onto the lands, the Qiantangjiang estuary contracted to form an estuary mouth as also seen nowadays (Fig. 1).

5 Distribution and Characteristics of Shallow Gas Reservoirs

5.1 Distribution rules of shallow biogenic gas reservoirs

Reservoirs of the late Quaternary in the Hangzhou Bay area can be classified into four types in ascending order (Fig. 2): (1) gravel-containing coarse sand and sand beds of in-channel to partly point-bar deposits of a meandering river, (2) sand lenses of the flood plain facies, (3) sand lenses intercalated in sediments of the sublittoral-marine bay facies, (4) silts of the estuarine facies. According to the exploration data available, all the commercial gas fields are developed in flood plain sand bodies of incised valleys.

Since 1991, six gas fields (Jiazao, Yisheng, Jiubao-Xiasha, Haiyan, Huanggu and Leidian) and one reservoir (the Sanbei Shoal, SBS) have been discovered in the Hangzhou Bay area. With the exception of the gas at Leidian that occurs in the Taihu incised valley, these gas fields and reservoirs are controlled by the Qiantangjiang incised valley and its branches (Fig. 1). The Yisheng gas filed, Jiazhao gas filed and the SBS shallow gas reservoir are better than the others in terms of proven reserves, producibility and duration of stable production (Lin et al., 2004). This may be attributed to the relatively large size of the Qiantangjiang incised valley. A deeper and wider incised valley will receive a larger volume of sedimentary fillings, hence a higher gas production from the source rocks and there will be more extensive distribution of flood plain sand lenses. The small size of the Taihu incised valley and the branches of the Qiantangjiang incised valley (Fig. 1) are unfavorable for the development of large gas reservoirs.

5.2 Lithology of the reservoirs

Sand bodies formed in flood plain environments are greatly variable both in thickness (from 0.5 to over 10 m) and burial depth (from 28 to 58 m). Even in neighboring boreholes, the depth difference of sand bodies may be over 10 m (Figs. 2 and 3). In some cases, in a borehole up to 3–4 sand layers may be encountered, with a total thickness of 7–8 m (Li et al., 1993; Lin et al., 1997; Lin et al., 2004), but no sand layers are penetrated in neighboring boreholes. All the sand bodies are surrounded entirely by clay, and are thus actually separated lenses appearing like string beads with horizontal tops and convex bottoms (Fig. 3).

The sizes of sand bodies are also variable. Small bodies are found only in one borehole, but large ones can extend up to several kilometers. A sand body group will form when a number of bodies overlap laterally. One body group can cover an area up to several kilometers in width and 10 km in length. The production of a gas field is apparently constrained by larger sand bodies.

6 Conclusions

The fall of global sea level during the last glacial maximum enhanced the fluvial gradient and river cutting,

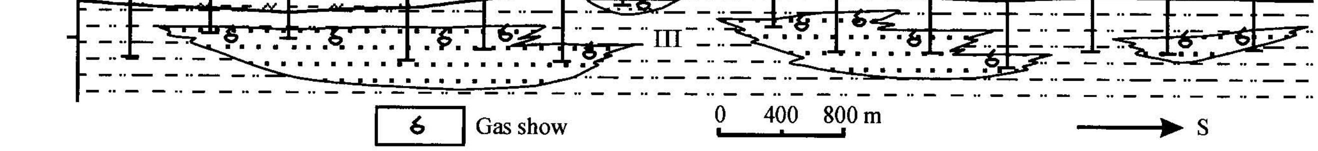

Fig. 3. A borehole profile across the Yisheng shallow gas field based on static sounding.

resulting in the formation of the Qiantangjiang and Taihu incised valleys. During the post-glacial period, these incised valleys were entirely filled rapidly by fluvial sediments, and then buried by sublittoral-marine bay and estuary sediments. Deep cutting of the incised valleys and rapid filling and burial of the sediments provided favorable conditions for the generation, accumulation and preservation of biogenic gas.

All commercial gases are stored in flood plain sand lenses of the incised valleys. Three to four transgression and regression cycles can be recognized from the Quaternary strata in the coastal areas of eastern China (Wang et al., 1981; Yan et al., 1987). Other well-developed incised valleys should be paid attention to for next exploration of shallow biogenic gas.

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