Sequence Stratigraphic Framework and Reservoir Architecture of the Lingshui-3 Member, Yacheng 13-1 Gas Field, South China Sea

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ABSTRACT

The Yacheng 13-1 gas field is the largest offshore gas field in China. The primary reservoir is the Middle/Late Oligocene Lingshui-3 Member sandstones, which were developed during a major marine transgression in response to the continued opening-up of the South China Sea. The thermal subsidence during late syn-rift stage created substantial accommodation space that contributed to the development of overwhelmingly thick succession (over 150 m) of reservoir sandstones with excellent reservoir quality. The Lingshui-3 Member reservoir sandstones were deposited in tidally-dominated deltaic systems or tidally-dominated estuarine environments. The reservoir can be divided into six zones (or potential flow units) with tidal fluvial/fluvial channel sands at the base. There is increasing marine/tidal influence upwards; reservoir quality generally improves from the base to top of the reservoir. The tidally estuarine reservoir sands are capped with transgressive shoreline sands (upper shoreface/foreshore deposits), which have the best reservoir quality. The first order reservoir heterogeneity is the intercalated shale intervals. These shales tend to be encapsulated in the extremely sand-rich succession, some of which may only be of local importance in constraining fluid flow (i.e. laterally discontinuous). That some shale intervals may vertically compartmentalize the Lingshui-3 reservoir and act as baffles or flow barriers influencing the reservoir performance is witnessed by (1) vertical variation in fluids composition, and (2) pressure and production data. The second order of reservoir heterogeneity is reflected in the presence of thin muddy interbeds, which are laterally discontinuous. The recognition of reservoir heterogeneity and stratigraphic compartmentalization is critical for the continued field development and reservoir management of the Yacheng gas field.

Regional Geology

The Yacheng 13-1 Gas Field lies at the junction between the dominantly strike-slip system of the Red River Fault and the extensional system of the South China Sea Rift (*Fig. 1*). The Red River Fault is a sutured boundary between the South China crustal plate to the north and the Indo-China and other micro plates to the south. Several hundred kilometres of Oligocene to Miocene sinistral movement was succeeded in Pliocene to recent times by approximately 30km of significantly slower dextral movement. Suturing and movement along this boundary is typically related to the ‘escape tectonics’ of the Himalayan collision, complicated by island arc collisions in the Philippine Sea (Hall, 2002).

More locally, the Field is at the western edge of the Cenozoic Qiong Dong Nan ("QDN") Basin. This basin was mainly filled by Tertiary deposits with a maximum thickness of over ten thousand metres. The Field is located at the west margin of the Yanan Sag, and adjacent to the Ying Ge Hai ("YGH") Basin. The western edge of the Field is defined by the NW-SE trending No.1 Fault, the probable offshore extension of the Red River Fault System (*Fig. 1*).

The Eocene syn-rift lacustrine-dominated facies are succeeded by an Oligocene south-facing shoreline complex fed by a fluvial system. This sequence has an increasingly marine influence towards the top, and the primary reservoir in the Field, the Lingshui-3 ("LS3") reservoir, is contained within the transgressive sandy shoreline sequence. The lithofacies and thicknesses of the overlying predominantly marine Sanya and Meishan formations are influenced by a series of unconformities that eroded varying thicknesses of sediments. Late Miocene and younger sediments reflect an overall deepening of water depth, albeit with the proximity of a nearby source of sediment.

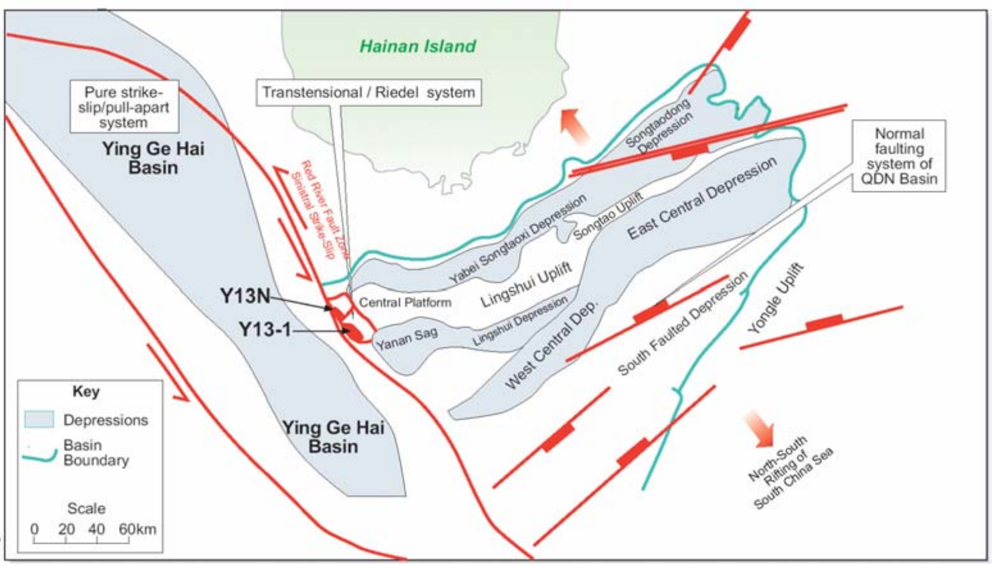

Fig. 1: Location of the Yacheng 13-1 gas field and local structural setting

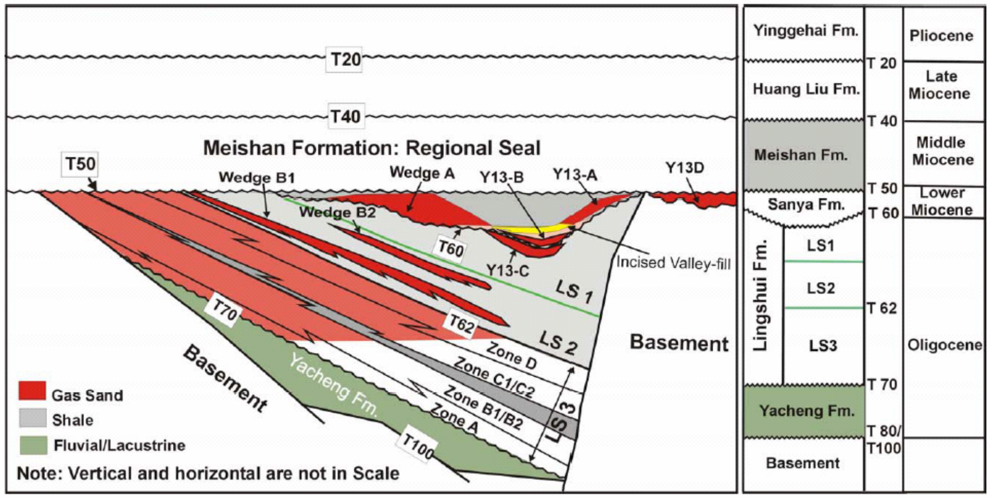

Fig. 2: Generalized stratigraphy of the Yacheng 13-1 gas field

The QDN Basin and the YGH Basin contain multiple gas-prone source rocks of appropriate maturity, capable of contributing gas to charge the Field's traps. Hydrocarbon kitchens containing significant source rock drainage volumes lie both to the east and west of the present-day accumulation. Maturity considerations and geochemical correlation indicate that the bulk of the charge was derived from coals and coaly mudstones belonging to the Eo-Oligocene Yacheng Formation, with possibly subsidiary input from marine Lingshui downdip equivalents, the Sanya and/or Meishan Formations. A bipolar charging model, as proposed by multiple previous authors (Chen et al., 1998; Hao et al., 1998) remains the most likely, but with the bulk of the hydrocarbon charge from the Yanan Sag. Thermal modeling of the system shows that the Field has been receiving charges from the hydrocarbon sources for the past 3 to 4 million years.

As shown in *Fig. 2*, the Oligocene-Miocene sequence constitutes a favorable configuration for hydrocarbon generation and accumulation: the coal-bearing shaly sediments of the Yacheng Formation as source rock at the base, the sand-rich intervals of Lingshui and Sanya Formations as reservoirs in the middle, and the shaly intervals of Meishan Formation as a regional seal. The primary gas reservoir is the lower part of the Lingshui Formation, the Lingshui-3 Member ("LS3"). In addition, significant discovered gas reservoirs and other likely gas-bearing sands are also present in the Sanya Formation, and Lingshui 1 ("LS1") and Lingshui 2 ("LS2") members.

Sequence Stratigraphic Framework

The LS3 Member is the primary reservoir of the Field. In general, the LS3 Member was deposited in a tidally-dominated estuarine environment in a low-relief embayment bounded by structural features now forming the Yacheng Spur to the southwest and the Central Platform to the northeast. Sediments were derived from a generally northern provenance. The interplay of source terrain lithology and fluvial and strong tidal processes resulted in very coarse-grained, sand-rich deposits.

In sequence stratigraphic terms, the LS3 reservoir belongs to the lower part of the “Lingshui Sequence”, which is bounded by the T70 unconformity across the entire Field at the base of the LS3 reservoir and the T60 regional unconformity at the top of the LS1/LS2 members. Because of its overall marine transgressive characteristics, the LS3 has been interpreted as a Transgressive Systems Tract of the “Lingshui Sequence”. The high gamma-ray marine shale interval of the lower LS2, locally a cap-rock of the LS3 reservoir, probably represents the relatively condensed section associated with the maximum marine flooding within the sequence (*Fig. 3*).

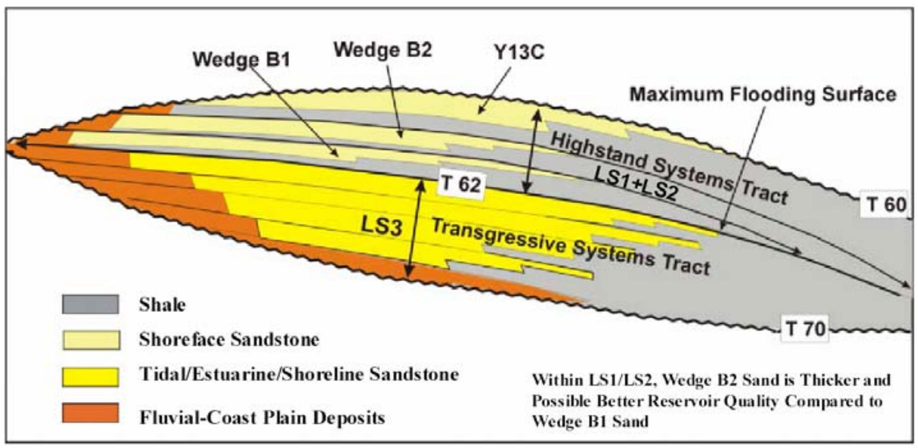

Fig. 3: Schematic model showing the Transgressive systems tract of LS3 and Highstand systems tract of LS1/LS2

The LS3 sandstones are vertically interrupted by shale intervals, which range from 0.5-6.0 metres thick. On wireline logs they are characterized by high gamma-ray spikes and a sharp contact with the underlying sandstone intervals. These shales are interpreted as reflecting intermittent periods during which the overall transgressive nature of the sequence dominated the influence of coarse sediment input. The sandstone intervals deposited between these transgressive shales can be regarded as parasequence sets, which are building blocks for the “Lingshui Sequence”.

Reservoir Architecture and Depositional Model

Through the recognition and correlation of intercalated shales, the LS3 reservoir has been subdivided into six zones (from bottom to top): Zones A, B1, B2, C1, C2, and D, each representing a parasequence set (*Fig. 4*). The shale intervals are correlative among most of the wells, especially the thicker shales.

Typically Zone A is characterized by interbedded trough/planar cross-stratified sandstones, conglomeratic sandstones, and thin mudstones with occasional coaly seams, which are interpreted to be fluvial/tidal fluvial channel deposits.

Zone B1 is comprised of trough/planar cross-stratified coarse-grained sandstones and conglomeratic sandstones intercalated with mudstones; these are interpreted as tidal channel/estuarine channel deposits. The mud drapes (bundles) within bedding sets are evident in these tidal channel sands, indicating tidal processes in the system. Zone B2 is characterized by planar/trough cross-stratified sandstones/conglomeratic sandstones, and variably bioturbated sandstones with muddy interbeds of varying thickness; these are interpreted to be tidal channel/estuarine channel, tidal sand bar, tidal sand flat/mud flat deposits. The top of Zone B2 marks a marine flooding event, which resulted in a relatively thicker shale that marks the boundary between Zone B2 below and Zone C1 above. Zones C1 and C2 are characterized by planar cross-stratified sandstone and conglomeratic sandstones, variably bioturbated sandstones, and intercalated muddy sandstones and mudstones; these are typical tidal channel/tidal bar and tidal sand/mud flat deposits. Zone D is a very clean, planar cross-stratified and/or parallel laminated sandstone unit, representing possibly transgressive sandy shoreline (foreshore/upper shoreface) deposits.

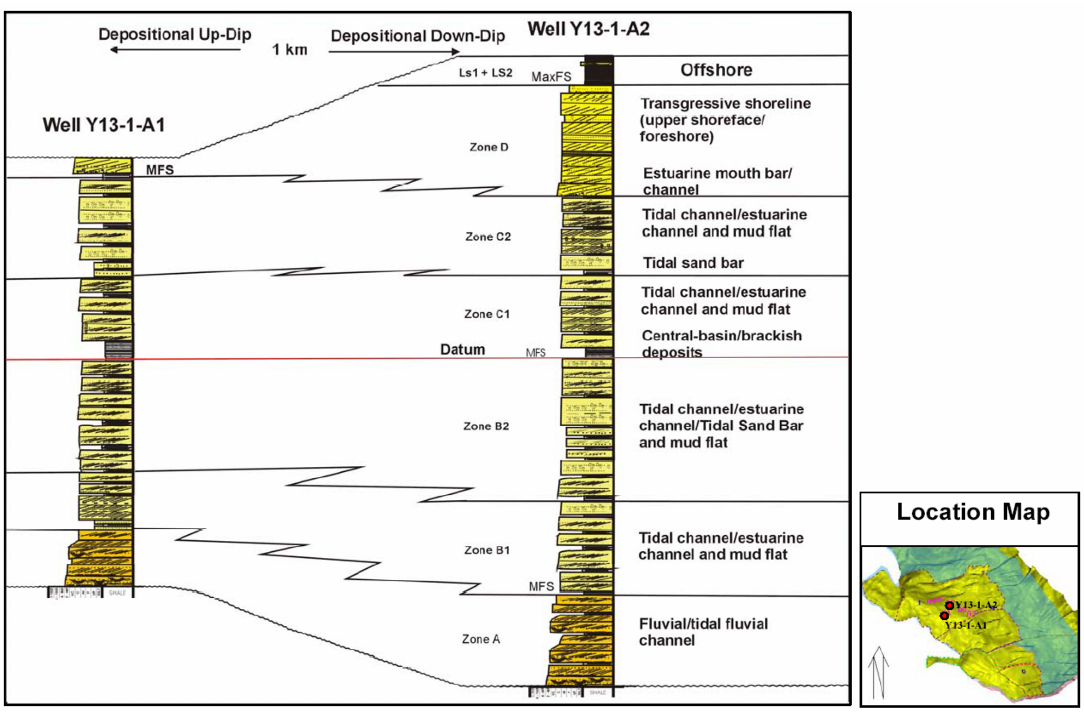

Fig. 4: Stratigraphic correlation of the LS3 reservoir sand between wells A1 and A2

Core study of the fully cored LS3 intervals of wells A1 and A2 indicates that the LS3 reservoir is characterized by increasing marine/tidal influence and reservoir quality from bottom to top.

Palaeoenvironmentally, a majority of the samples in both wells A1 and A2 have yielded brackish water/marine microplankton suggesting the prominence of estuarine and estuarine/marine conditions throughout much of the LS3 intervals. Abundance of tidal influences and heavy bioturbation with low diversity were observed in most of the cores, suggesting the estuarine and marginal shallow marine origin. Ichnofacies assemblages include *Ophiomorpha, Teichichnus, Paleophycus, Thalassinoides,* and *Planolites*, indicating typical brackish environments.

A three-stage depositional model has been proposed to explain the origins of the LS3 reservoir sand (*Fig. 5*). During early LS3 time, the Y13-1 sub-basin was dominated by a tidally influenced bay-head delta within an estuary (Stage 1). The tidal and tidal fluvial characteristics are evident in Zone A and Zone B1.

During middle LS3 time, with accumulation of sandy sediments at the entrance to the estuary, marine-sand bars/plugs were deposited (Stage 2). Zones B1 to C2 were deposited in these typical tidal channel/tidal bar/estuarine channel and tidal inlet environments. The intercalated shale layers are intermittent marine flooding deposits within the estuarine environment. At the end of Zone B2 time, a wider flooding event occurred, resulting in a more extensive shale interval within LS3 reservoir.

Relative sea level rises continued towards the end of the LS3 reservoir deposition and the shoreline shifted landwards, resulting in high-energy foreshore/washover sands (or sand waves) overlying most of the LS3 estuarine complex due to strong tidal/marine reworking processes. At the end of LS3 time (Stage 3), the open shoreline/beach environment was quickly replaced by continued marine transgression, leading to widespread highstand marine shelf environments (LS2/LS1 time)

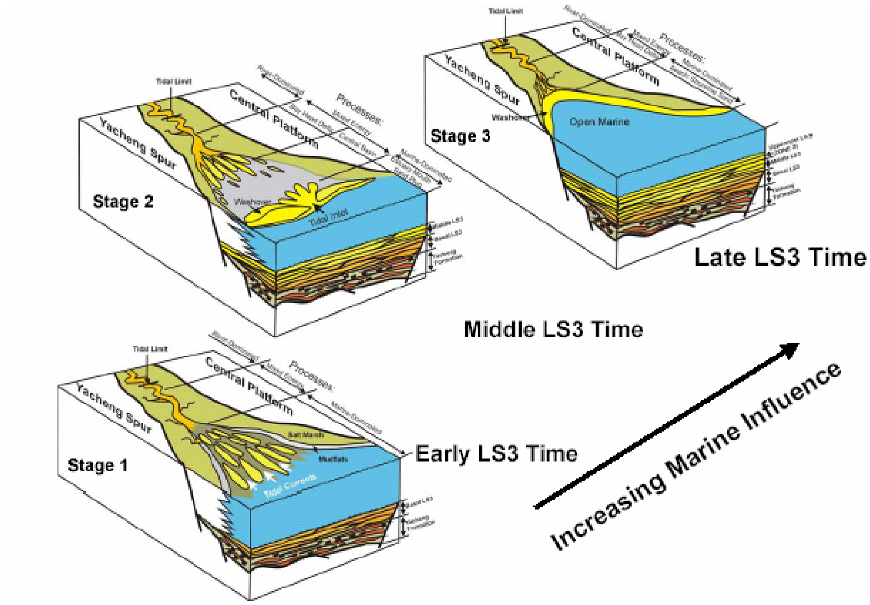

Fig. 5: Depositional Model of LS3 reservoir, Yacheng 13-1 gas field

Reservoir Quality and Heterogeneity

The fully cored LS3 intervals of wells A1 and A2 offer the opportunity to determine the depositional history and reservoir architecture of the LS3 Member. As discussed above, there is increasing marine/tidal influence upwards within the LS3 reservoir. Reservoir quality improves from the base to top of the LS3 with Zone D having the best reservoir quality (highest N/G values and permeability). Lower portions of the LS3 reservoir (i.e. Zones A and B1) are characterized by greater reservoir heterogeneity and stratigraphic complexity.

As indicated by well-log correlation and examination of LS3 cores, the first-order reservoir heterogeneity is the intercalated shale intervals. These shales appear to be encapsulated in the extremely sand-rich succession (about 90% N/G), some of which may only be of local importance in constraining fluid flow (i.e. laterally discontinuous). Two relatively thicker shale intervals at the boundaries of Zones A/B1 and Zones B2/C1 appear to be laterally correlative and relatively continuous; they have the potential to act as baffles or flow barriers influencing the reservoir production performance. That a few of these shaly intervals may vertically compartmentalize the LS3 reservoir is witnessed by: a) vertical variation in fluids composition (e.g. CO_2); b) the pressure and production data before and after adding new perforations in deeper LS3 zones, and various pressure ‘breaks’ in the RFT/MDT pressure measurements in the newly drilled development wells.

The second-order heterogeneity is reflected in the reservoir architecture of the LS3 reservoir. Apart from Zone D, which is fairly homogeneous and is very well-connected based on the available data, the other LS3 zones are comprised of intercalated tidal channel medium-grained to coarse-grained sands, variably bioturbated tidal bar sands, fine-grained tidal sand flat, and mud flat muddy interbeds. These heterogeneous characteristics of the LS3 reservoir are well demonstrated in the rapid and repeated variations of core-derived permeability versus depth. However, the LS3 reservoir is extremely sand-rich and dominated by high-quality tidal channel sands derived from strong tidal/marine reworking processes. Overall, the LS3 reservoir interval has excellent reservoir quality.

Summary

Sedimentary characteristics recognized from the cores suggest that the LS3 reservoir was deposited in a possibly strong tidally influenced estuarine embayment or alternatively bay-head deltaic system in the overall West-East trending shoreline. The overwhelmingly coarse clastic input along the axis of the embayment has produced a high quality reservoir over 150 metres thick. This outstanding reservoir quality is attributable to the proximity of high relief source terrains to the area of deposition (i.e. Y13-1 sub-basin), and to tidal channels and tidal bars derived from reworking very coarse, pebbly sands delivered into marginal shallow marine environments from adjacent source terrains.

With the occurrence of intercalated shale intervals, six zones are recognized within the LS3 reservoir: Zones A, B1, B2, C1, C2, and D (from bottom to top). Two of the relatively thicker shale intervals (at the boundaries of Zones A and B1, and Zones B2 and C1) are seen to be laterally pervasive and have the potential to act as baffles or barriers influencing reservoir depletion.

Reservoir quality improves from the base to top of the LS3 with Zone D having the best reservoir quality (highest Net/Gross values and permeability). The lower portions of the LS3 reservoir are characterized by greater reservoir heterogeneity and stratigraphic complexity.

The recognition of reservoir heterogeneity and stratigraphic compartmentalization is critical for the continued field development and reservoir management of the Yacheng gas field.

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