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Architecture, depositional pattern of syn rift sediments in the Northern Song Hong basin and its petroleum system association

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Summary

Rifting with syn rift sediments originally was formed during two tectonic phases in three stages. The syn rift deposits were composed of four units that have been identified by distinct seismic facies. The seismic expression of these syn rift units gives an idea about the linkage of their deposition with different stages of rift evolution. The lowermost units have wedge shaped reflection packages and hummocky internal reflection configuration, representing initial rifting in early rift stage. The overlying two units comprising divergent reflection, prograding pattern with aggradations on footwall represent climax rift stage and the topmost unit with sub-parallel reflection configuration represents the late phase. The units deposited during the rift climax stage have a good source rock potential, whereas the unit deposited in the late rift stage possesses favourable reservoir facies making a complete petroleum system within syn rift sediments.

Core data indicates the Late Oligocene deep lacustrine succession of mainly organic-rich, world class oil-prone source rocks interbedded with mudstones and sandstones. The pelagic deposition of mud and organic algae matters with excellent source rock characteristics was frequently interrupted by river-fed mud flows, bringing mud and terrestrial organic matter to the lake bottom forming mudstones with a low source rock potential. Occasionally, low and high density turbidities, debris and hybrid flows interrupted mud deposition transport sands into the deep lake bottom forming potential carrier beds and reservoir sandstones.

The syn rift petroleum system association by predicting reservoir and source rock intervals are fundamental to exploration and can therefore help formulating a predictive exploration model of the Northern Song Hong basin.

Key words: Northern Song Hong basin, syn rift, deep lacustrine, shallow lacustrine, initiation rift, climax rift, late rift.

1. Introduction

The study area is located in the Northern part of Song Hong basin, which is the largest basin along the Western East Sea margin extending from North of Hanoi underneath the Red River Delta (Song Hong Delta) and into the Gulf of Tonkin (Figure 1). Situated at the extension of the onshore Ailao Shan - Red River Shear Zone (ASRRSZ), the formation of the Song Hong basin is often considered to be linked with the Cenozoic continental-scale left-lateral motion taking place across the shear zone [1, 5]. The Paleogene rift system flooring the basin is little studied, however, but holds vital information to unravel the tectonic history of the ASRRSZ [1].

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Based on a dense 2D with 3D seismic grid covering the Northern Song Hong basin and the well data, the Paleogene syn rift system of the study area has been mapped and analysed. By integrating the analytical results with all available geo-scientific knowledge, the Paleogene basin development was restored under the influence of two tectonic phases (Figure 2) and as following a model-driven within three stages of syn rift as initiation, climax and late (Figures 2 and 3). 4 markers have been identified in the syn rift section on the basis of log characters and bio-stratigraphic control (Figures 2 - 4). Equivalent seismic markers could be traced and were mapped regionally along with the top of the basement. The 4 syn rift units bounded by these seismic markers were named unit 1, unit 2, unit 3 and unit 4, from older to younger (Figures 2, 4 - 6). These unit tops were dated with the available paly-

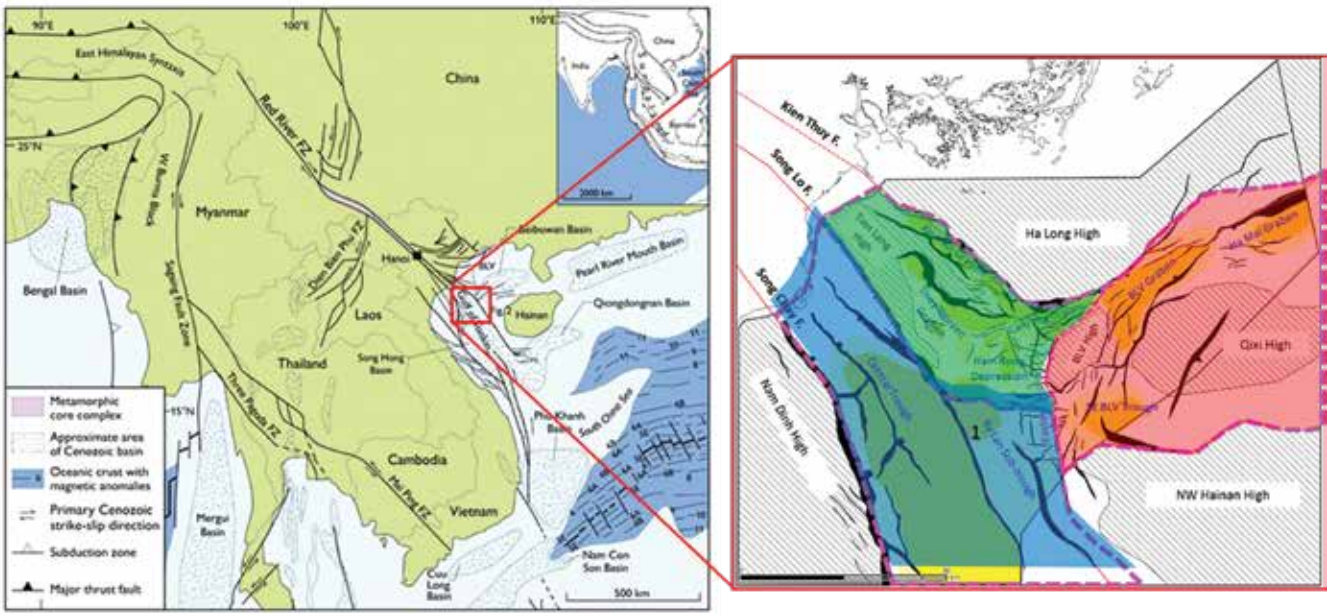


Figure 1. *Study area location map (left) and top basement structural map outline of the Northern Song Hong basin emphasising the main Paleogene faults, rift depressions and structural highs.*

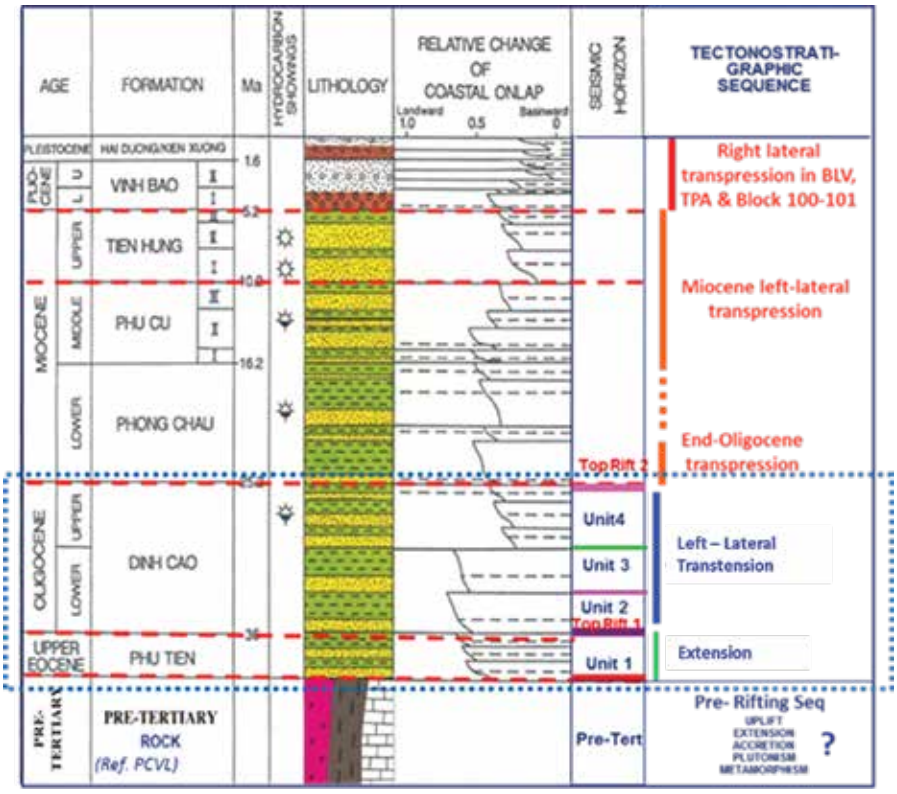


Figure 2. *Sequence stratigraphic column of the Northern Song Hong basin (modified from VPI).*

nological information. The tops of unit 1 (is also top Rift 1) and unit 4 (is also top Rift 2) (Figure 2) have been assigned as Phu Tien and Dinh Cao whereas unit 2 and unit 3 lie within Dinh Cao. These identified units have distinct seismic facies. The seismic facies within the units indicate their depositional environment associated with the stages of rifting. Unit 1 was deposited during the initial rift stage and distributed dominantly in the Northwestern part of the study area, however, no well records have been seen yet, it is only observed on the seismic data (Figures 3 and 4). It is difficult to observe unit 1 in the other parts. The climax rift stage persisted during deposition of unit 2 and unit 3, whereas, unit 4 was deposited during the late rift stage (Figures 2 - 5). It is observed that the potential and effective source is present in units 2 and 3, followed by unit 3 and better reservoir facies are developed in units 3 and 4. The good reservoir facies are also expected in the lower part of unit 2 where wedge sands and channels deposited in the initial stage of rifting. Therefore, the favourable petroleum system exists within the syn rift sediments [2, 4]. The basement structure map indicates three different sectors (Figure 1) which merged to form three stages at the initial, climax and late of rift (equivalent to 4 units of syn rift sediments) and were influenced by two tectonic phases (Figures 2 and 3). In the Northwestern sector (marked by green colour), alongate grabens and half grabens were strongly influenced by normal faults, bounded by the Tien Lang high and Ha Long shelf. Syn rift sediments are clearly

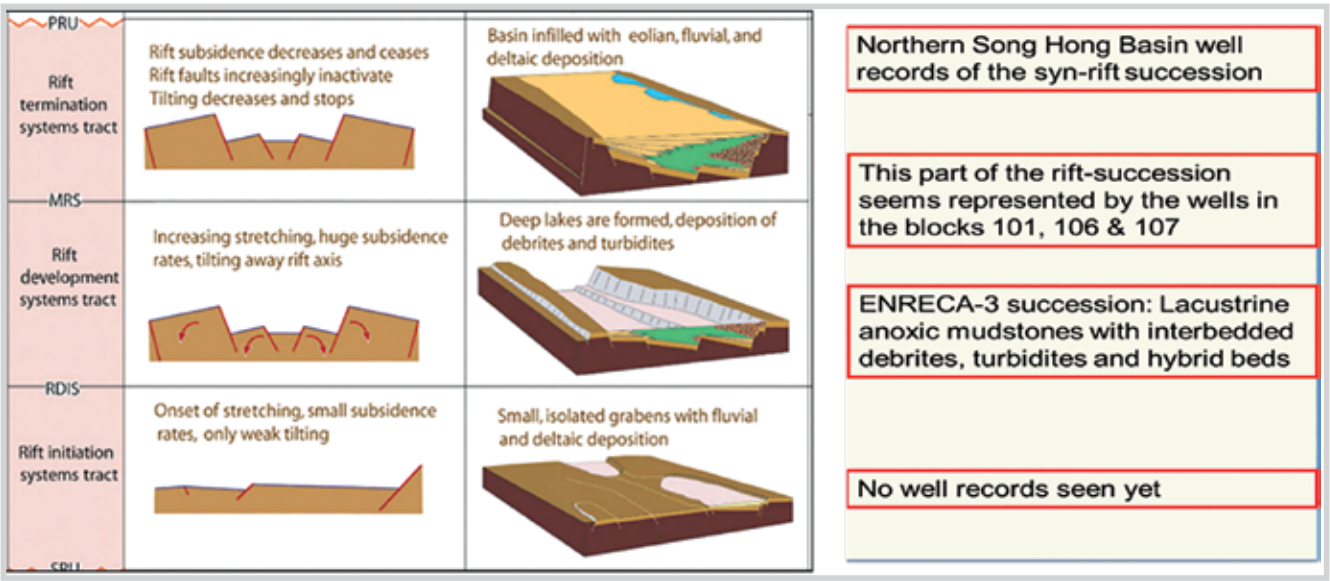


Figure 3. *The 3 stages of syn rift model in the Northern Song Hong basin (modified from [4]).*

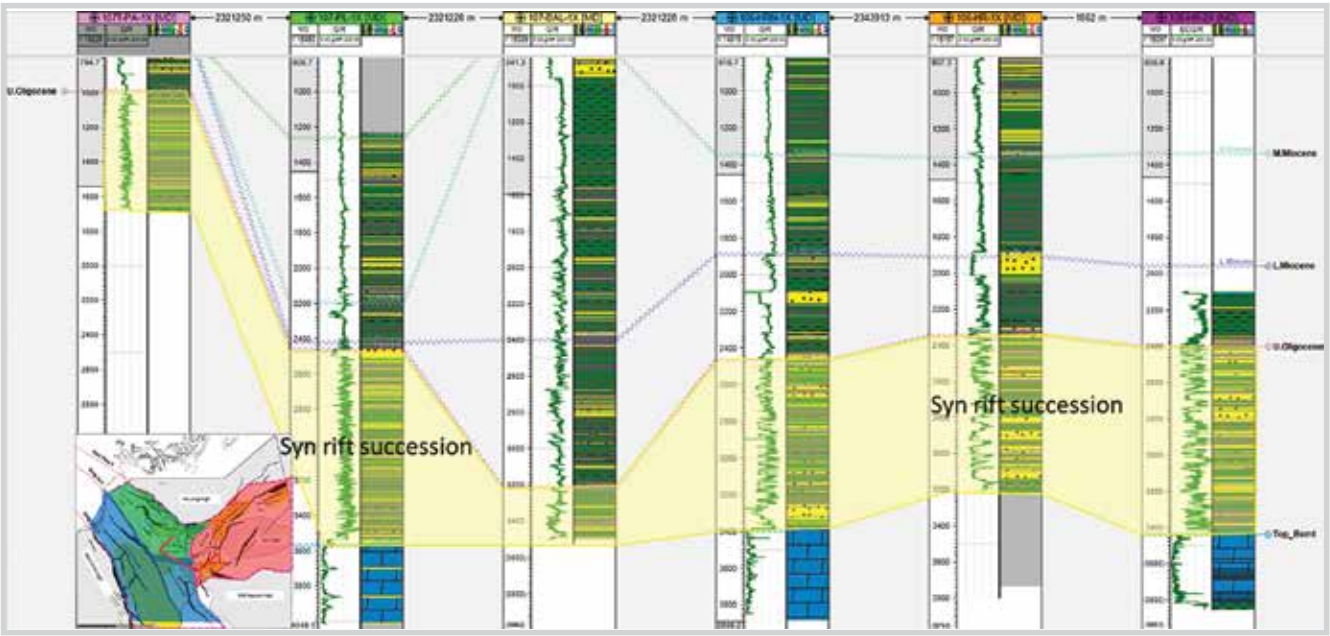


Figure 4. *Regional stratigraphic correlation.*

observed as four units which are more prominent and widespread in these grabens. In the area of the Eastern (marked by pink colour) and Western (marked by yellow colour) sectors, the syn rift sediments seem to be observed as 3 units because the rift climax stage prevailed during deposition of the upper part of unit 2 and unit 3. The Eastern sector which was earlier connected to the Western sector deepest low at the basement level got well differentiated as the rift progressed and becomes shallower and localised towards the South-Western margin. Moreover, Ham Rong - Ky Lan - BLV spur in the central part gradually becomes more prominent and widespread towards NW, bifurcating the two lows. The available core data indicates that the sediments were originally transported by fluvial drainage with considerable distance of transportation and deposited in the shallow marine setup. The sedimentation was later dominated by sandy debris flow along with intermittent bottom current activity in shallow marine condition [3].

2. Log correlation and seismic analysis

There are 16 wells encountering syn rift sediments in the Northern Song Hong basin which have been used for the studies. The regional stratigraphic correlation in direction along the axial part of three sectors of the study is shown in Figure 4. Log correlation combining with seis-

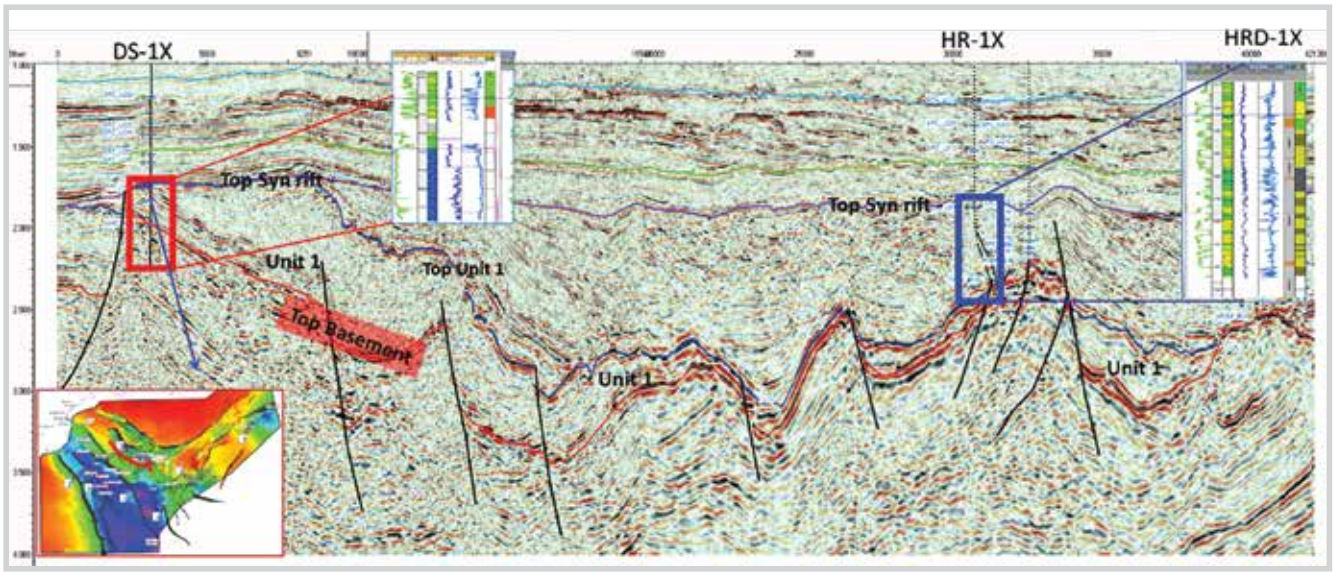


Figure 5. *Top syn rift is calibrated as top of Oligocene (top of Dinh Cao formation).*

mic profiles representing differential sectors (Figure 6) is analysed to understand the sedimentation of syn rift sediments. On the logs the top of syn rift is characterised by typical higher gamma, higher resistivity and low Δt values with respect to younger sediments. This typical syn rift top log marker is biostratigraphic calibrated as top of Oligocene (top of Dinh Cao formation) from palynological study [6].

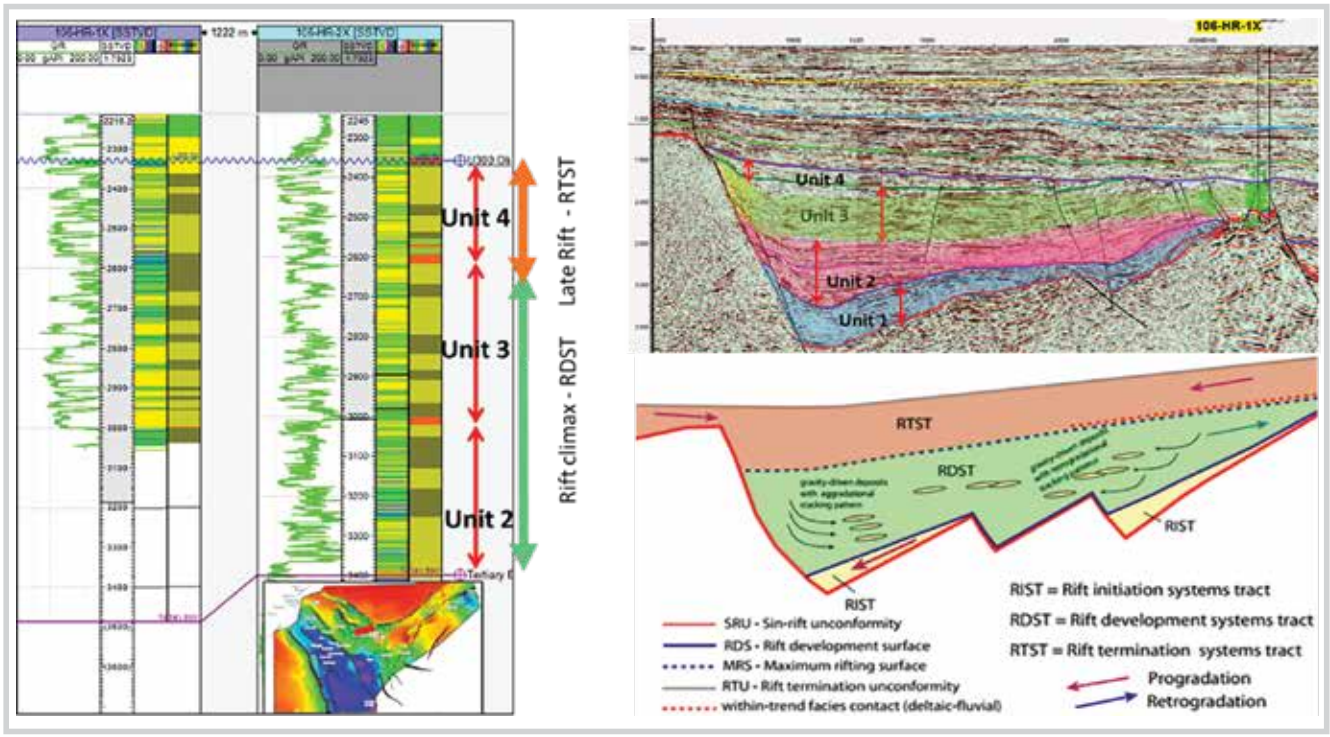
The syn rift sediments are divided into four units, namely units 1, 2, 3 and 4. This division is primarily developed from the wells which encountered the Oligocene sediments in the Northern part of Song Hong basin. These units (except for unit 1 - it is mainly observed on the seismic data) are identified and correlated on the basis of distinct gamma trends and patterns (Figure 4). The tops of these units on well log are also correlated on the seismic section through these wells (Figures 4 - 6), where they are characterised by regionally developed strong reflectors. The tops of these units are also age calibrated where biostratigraphic data permitted.

The seismic characters showing different units within the syn rift sediments indicate the distinct stages of rift evolution and associated depositional system (Figures 6 and 7).

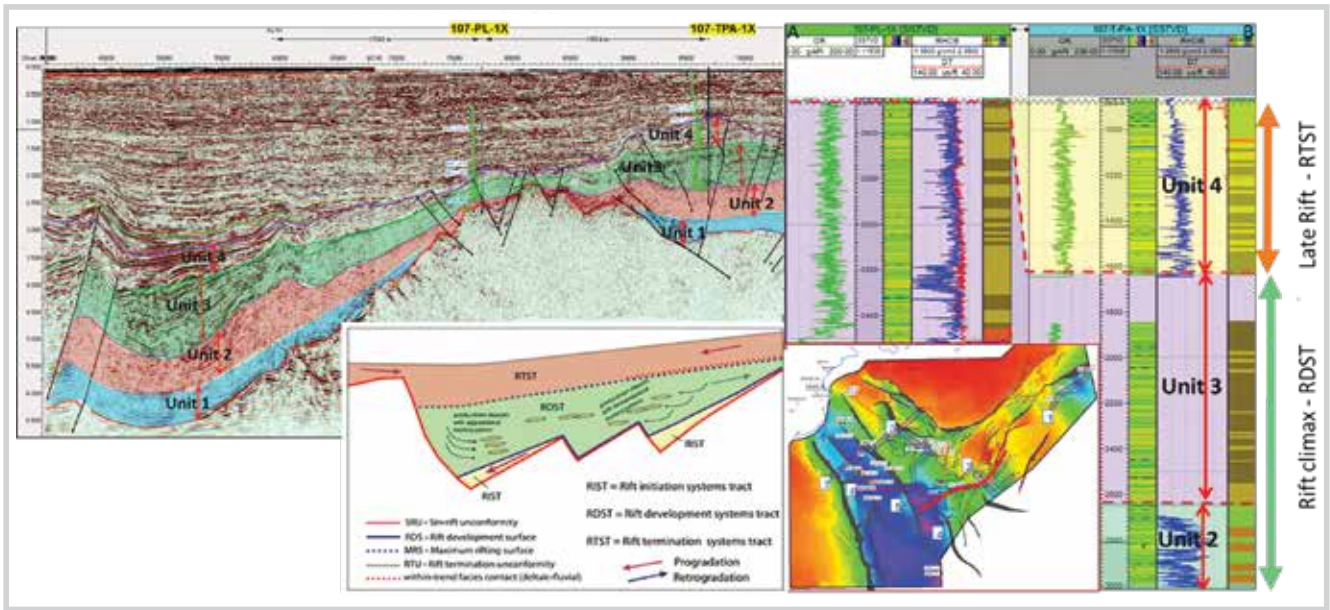
The Northern Song Hong area records an early stage of major NW-striking extensional faults stretching along the axis of the basin and delineating a major Paleogene syn-rift depocentre [1, 2]. The early stage of rift development is characterised by numerous fault bounding basins with displacement switching to major basin bounding fault during the rift climax. The phenomenon is well demonstrated in the Eastern sector (Ha Mai, BLV graben, SE BLV trough) and the Northwestern sector (Kien An, Thuy Nguyen, and Cam Pha graben) as grabens and troughs bounded by smaller faults seen on the basement levels finally switched to two major troughs having main displacement fault (Figures 1, 3 and 6).

In the period of initial rifting, stretching increased, the rate of fault displacement is relatively low while during the peak rift stage, the rate of fault displacement increases markedly with abundant sedimentation. In the initial rift stage, faulting is most active, and a significant topography is created. The patterns of lithofacies development are surprisingly consistent. Sediment supply to the basin is usually limited in this stage (It is only observed on the seismic data on significant highs, no well records have been seen yet) and, where the fault-driven subsidence rate is high the reflection geometry looks like an overall wedge shaped geometry. The hummocky discontinuous reflectors show a fluvial system. Prograding reflector geometry was in the very lowest fill, implying sedimentation was able to infill the space created through extension (Figure 6). The similar pattern is seen in unit 1 and the lower part of unit 2, which demonstrates the early rift stage during deposition.

During the climax rift stage, the maximum rate of displacement on fault causes sedimentation out paced by extension or exceeds subsidence and the basin topography gradually becomes filled with a lake deposit. This is typically most developed in syn-rift cycles, where shallow



(a)



(b)

Figure 6. *Log correlation combining with seismic profiles through (a) Northwestern sector, (b) West Eastern sector.*

and deep lake fluvio-lacustrine to lacustrine source rocks of excellent quality are commonly developed. On the seismic section, the peak rift is characterised by an aggradation reflector with divergent forms related to continue tilting of the hanging wall during deposition (Figure 6). Units 2 and 3 were formed during rift climax with distinct seismic facies (Figure 6). The onset of peak rift started during the lower part of deposition of unit 2; the whole upper part of unit 2 and unit 3 are rift climax which has been deposited in mid and late peak rift stage and associated with the point at which transgression of the hanging wall slope occurs. The late peak rift is characterised on seismic section as a draping reflector that can be traced across the area onto the adjacent footwall and hanging wall crests (Figure 6).

The late rift stage corresponds to a period of waning fault activity, tilting decreases and stops when sediment

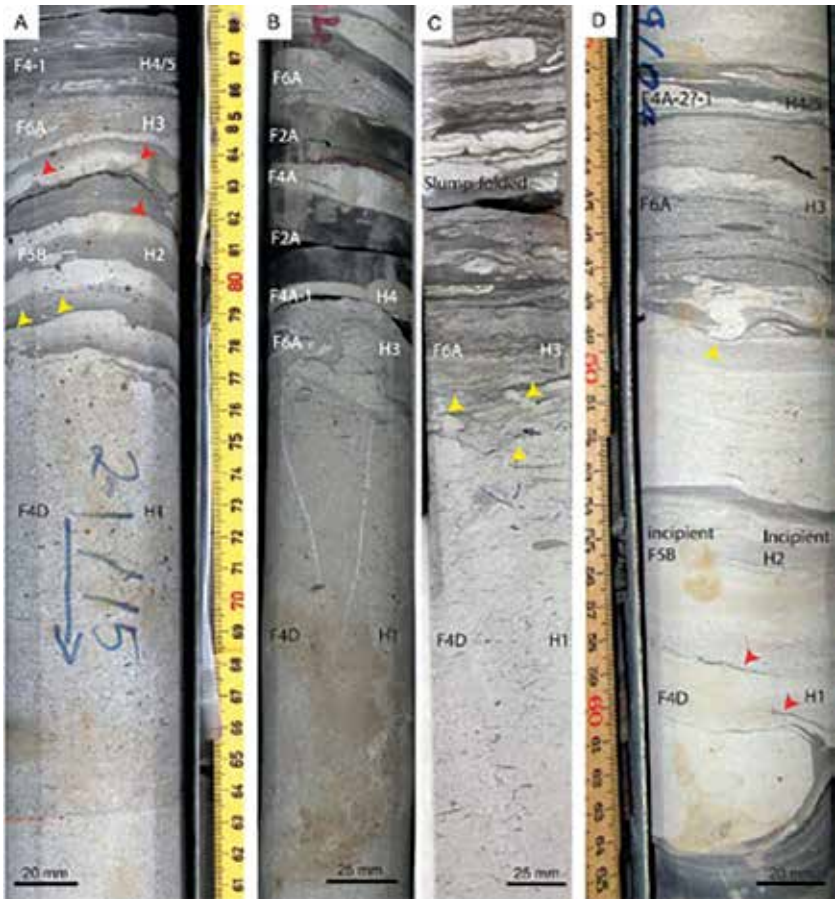


Figure 7. *Core segments from syn rift sediments of well ENRECA-3 [3, 7].*

supply keeps pace with subsidence resulting in the deposition of well sorted clastics which would act as good reservoir. Seismic pattern is observed as more continuous and parallel reflectors than the earlier sequences (Figure 6). Unit 4 had been deposited in the late syn rift stage and expected to have better reservoir characteristics.

3. Core analysis

The data derived from the core will be extrapolated to comparable successions elsewhere in the Northern Song Hong basin, where core data are not available. The core represents a unique window to deep lake deposition along the flanks of the Song Hong basin during the rift climax phase. The data indicates that several hundreds of metres thick of highly oil-prone petroleum source rock successions exist in the area and that source rock facies can be directly interbedded with thin sandstone successions potentially assisting oil expulsion.

The core data indicates that the sandstones of syn rift deposits show changes in flow type from turbidity current to debris flow during a single flow event, debrites and deposits of high-density turbidites (Figure 7). Core segments from syn rift sediments in Figure 7 show: A) Top part of an approximately 25-cm-thick structureless sandstone (F4D; H1) overlain by an interval of banded sandstone-muddy sandstone (F5B; H2), and further thin tabular unit comprising muddy sandstone (F6A; H3). In the top, H3 is sharply overlain by millimetre-scale heterolithic interlamination showing local pseudo nodular siltstone lenses (H4-5). Yellow arrows, water escape structures; red arrows, flame structures and mudstone injections; dashed red line, intra H1 boundary recording abrupt increase in organic-matter fragments. B) Top part of an approximately 22-cm-thick structureless sandstone (H1) overlain by chaotic muddy sandstone (H3), and ripple cross-laminated fine-grained sandstone topped by millimetre-scale clay drape (H4-H5). Top of the figure shows interbedded structureless clayey mudstone beds (fluid mud), ripple cross-laminated sandstone, and muddy sandstone (debrite) beds. (C) 25-cm-thick structureless sandstone (H1) overlain by a chaotic muddy sandstone interval (H3). The muddy sandstone is slump folded and mixed with well-sorted sandstone facies.

The ENRECA-3 core section is interpreted to have formed during rift climax in the Bach Long Vi graben, allowing the establishment of a deep lake due to the outpace of subsidence relative to sedimentation [3, 7]. Similar rift-climax sections will be identified in adjacent areas based on seismic sections and well data, which will be done in an attempt to predict the gross depositional outline of the syn rift sediments in the study areas (Figure 8), and thereby contribute to the prediction of source and reservoir rock intervals.

4. The syn rift association petroleum system

Source rock: This is typically developed best in units 2 and 3 in the climax syn-rift stage, where shallow and deep lake fluvial-lacustrine to lacustrine source rocks of excellent quality were commonly developed (Figures 3, 6 and 8). They contain good quality organic matter (up to 8.99% TOC, average: 3.33) which is present in the lacustrine of Dinh Cao formation [6]. Two distinct types of

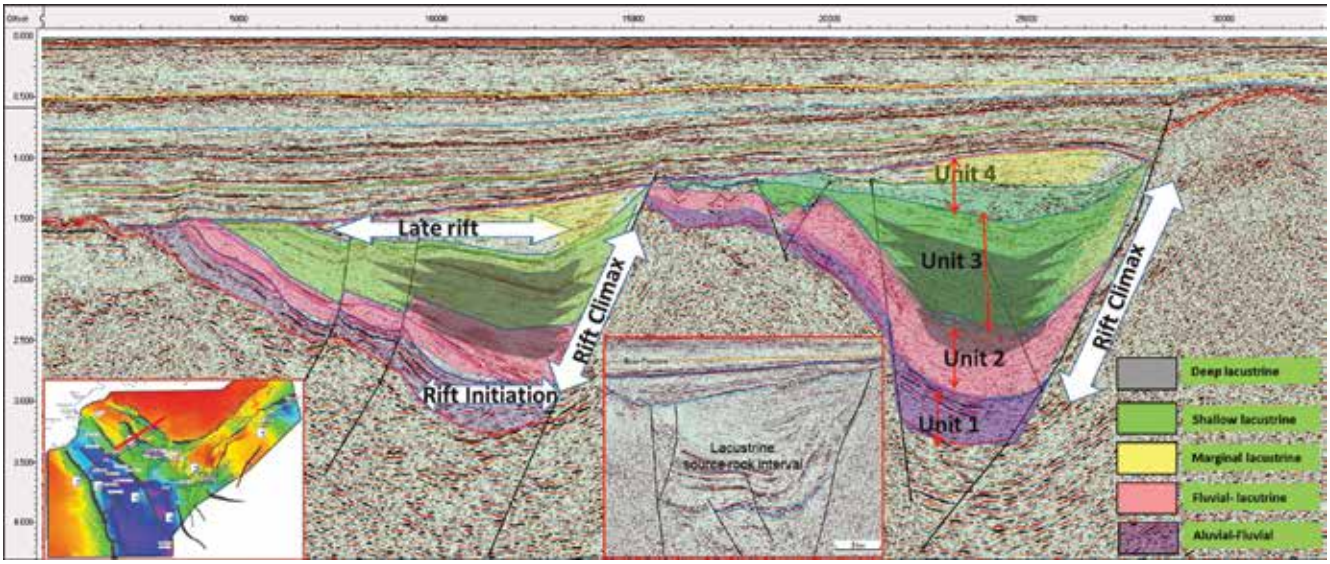


Figure 8. *Depositional outline of the syn rift sediments, lacustrine source rocks of excellent quality are commonly developed in the grabens of Northern Song Hong basin.*

organic facies are identified within the source sediments as: 1) Type III organic matter (gas prone) in early mid phase of maturation; 2) Type III with minor type II organic matter (gas + sub. oil prone), in early phase of maturation.

The distribution pattern of effective source rock in the study area suggests that better source rock potential exists in the Northwestern sector of the Northern part of Song Hong basin (Figures 2 and 8) lying in the grabens identified in this study. Source rock accumulation can be explained by three syn rift phases and the potential source rocks and effective source are present in unit 2, and followed by the lower part of unit 3. Unit 2 has the best source rock potential as it was deposited during the climax rift stage.

Reservoirs: The integrated analysis of well data and seismic data has brought the presence of abundant reservoir facies in the syn rift sediment interbedded with source rock facies. The prediction depositional result (Figure 8) shows reservoir facies (fluvial, fluvial/lascutrine) development mainly in units 1, 2 and 3. The reservoir facies are also expected in unit 1 in fan wedges, channels as it was deposited in the early stage of rifting.

Traps: Structures and fault bounded closure in the syn rift sequences are prospective entrapments. Besides them, the important entrapment can be provided by stratigraphic traps formed by the wedge outs and pinch out of the syn rift reservoir strata. The wedge out phenomenon is observed at the faults shoulders and more characteristically at the paleo-highs at the grabens and troughs.

5. Conclusions

An attempt has been made to bring out a regional understanding of syn rift architecture by integrating available geo-scientific data and to analyse hydrocarbon prospectivity of syn rift sediments in the Northern Song Hong basin.

Rifting with syn rift sediments was formed along the two tectonic phases within 3 stages of syn rift. The 4 syn rift units bounded by these seismic markers named as units 1, 2, 3 and 4 from older to younger. These identified units have distinct seismic facies, which express their depositional environment associated with the stage of rifting. Most of unit 1 was deposited during the initial rift stage. The climax rift stage prevailed during deposition of unit 2 and unit 3, whereas, most of unit 4 were deposited during the late syn rift stage.

The available core data indicates that the sediments were transported by fluvial drainage with considerable length of transportation and deposited in the lake system. The sediments were dominated by sandy debris flow along with intermittent bottom current activity in lacustrine condition.

The syn rift associated petroleum system by predicting reservoir and source rock intervals are fundamental to exploration and can therefore help formulating a predictive exploration model of the Northern Song Hong basin such as: The reservoir characteristics of units 1, 2 and 3 was having moderate to good primary porosity, better reservoir facies are developed in units 3 & 4. The favourable reservoir facies are also expected in unit 1 in fans and chan-

nels deposited in the early stage of rifting; The potential source is present mainly in units 2 and 3. Unit 2 has the best source rock potential as it was deposited during the climax rift stage.

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