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STRUCTURAL CONTROLS ON SYN-RIFT SEDIMENTS OF THE NORTHERN SONG HONG BASIN

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Summary

The study area is located in the northern part of the Song Hong basin which is the largest basin along the western margin of the East Sea stretching from north of Hanoi underneath the Song Hong Delta (Red River Delta) into the Gulf of Tonkin (Figure 1). The rift system underneath the Song Hong basin constitutes a world-class example of how extrusion tectonics drives continental rifting and transtensional basin development.

Many factors strongly influence the structural styles of rifting of the northern Song Hong basin: rifting occurred during later Eocene - Late Oligocene time forced by ASRRSZ left lateral shearing; latest Oligocene - earliest Miocene transpression and inversion brought rifting to a halt, after which left-lateral shearing decreased. Paleogene rift systems extended along the trail of the ASRRSZ are now outlined by lower to mid-crustal metamorphic core complexes. Rift termination in the northern Song Hong basin and exhumation of the metamorphic core complexes coincided with cessation of Paleogene rifting along the western margin of the East Vietnam Sea and a common causal mechanism are speculated.

Structures within rifting affect syn-rift depositional patterns by creating sites of uplift and erosion, by controlling pathways of sediment transportation, by the accommodation space for sediment deposition and preservation. These resulting from the growth of rifting may yield a tripartite stratigraphy such as fluvial, deep lacustrine and shallow lacustrine.

Key words: Rifting, syn-rift sediments, extension, transtension, lacustrine, fluvial, Song Hong basin.

1. Introduction

The study area is located in the northern part of Song Hong basin which is the largest basin along the western margin of the East Sea stretching from north of Hanoi underneath the 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 Cenozoic continental-scale left-lateral motion taking place across the shear zone [1].

The comprehensiveness of rift basin and their petroleum systems manifests a number of characteristic development trends and classification schemes such as a typical tripartite structural basin development with an early, maximum and late rift evolution. The structural relation between sediment input and formation of accommodation space causes basins to be under filled, balanced or overfilled, and a general discrimination of two major types of environment facies associations of fluvial - lacustrine, lacustrine [2 - 4].

Simultaneously, interpretation using 2D and 3D seismic data and well data during hydrocarbon exploration and production activities has identified and mapped the top syn-rift of the northern Song Hong basin. Among seismic, well data within driven model of rifting approaches have yielded valuable information about the structural styles and depositional patterns of syn-rift sediments in order to describe the variety of structures

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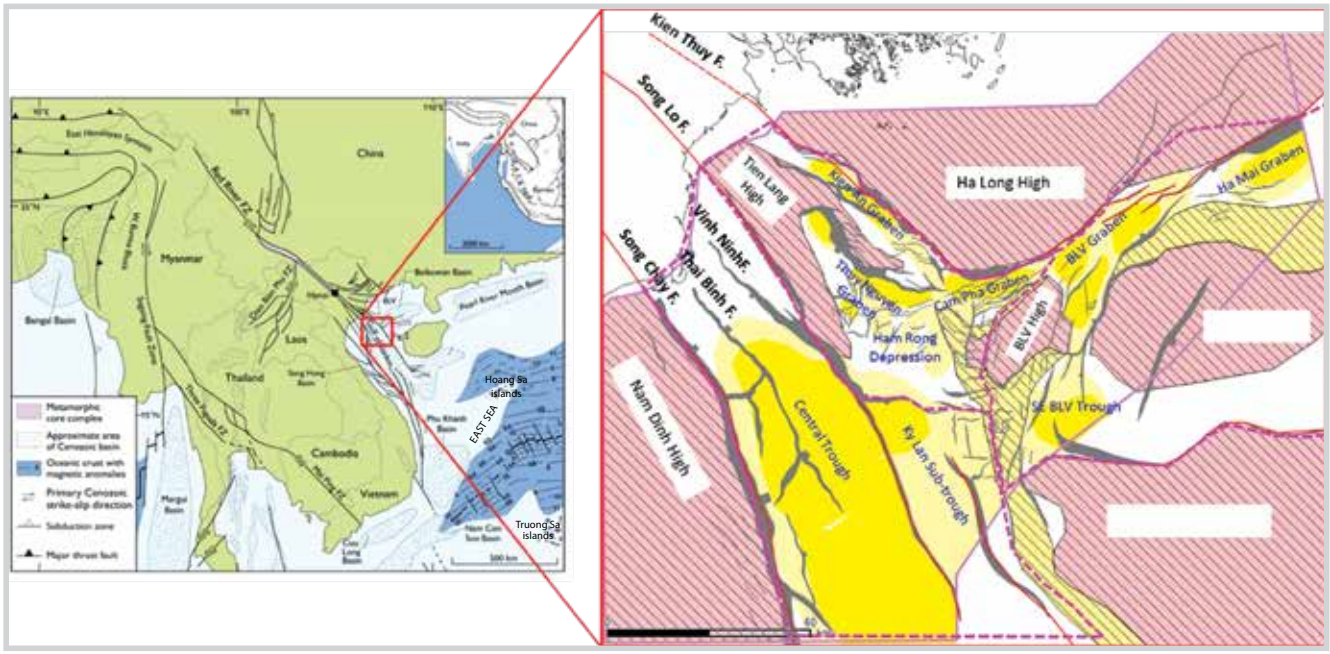

Figure 1. *The northern Song Hong basin within structural outline emphasising the main faults, rift depressions and structural highs [5].*

associated with continental rifting and to infer the influence of these structural styles on the depositional patterns within them.

This paper summarises the integration of analytical results with all available geo-scientific knowledge to bring out an understanding of regional structures within rifting that affects depositional patterns of syn-rift sediments in the northern Song Hong basin.

2. Stratigraphic units of northern Song Hong basin rifting

Song Hong basin is underlain by the interconnected Beibuwan, Song Hong and Qiongdongnan basins (Figure 1). There are many factors strongly influencing the structural styles of basin rifting: the mechanical behaviour of the pre-rift and syn-rift packages, the tectonic activity before rifting, the obliquity of rifting, and the tectonic activity after rifting [6]. In the northern Song Hong basin, the rift onset unconformity is subtle because of the limited uplift and erosion which occurred during the early stages of rifting. Thus, much of the pre-rift package is preserved beneath the syn-rift package and the most basic stratigraphic units associated with the northern Song Hong basin rifting are the syn-rift and post-rift packages (Figures 2 and 3). A distinct unconformity caps

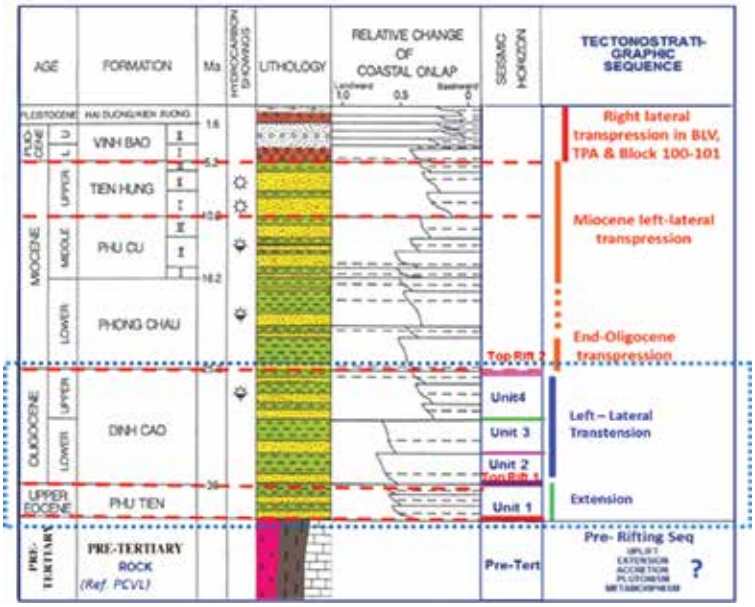

Figure 2. *Sequence stratigraphic column of the northern Song Hong basin (Modified from VPI).*

the Paleogene syn-rift. The Dinh Cao formation sub-cropping the unconformity has been documented to include Upper Oligocene strata and the Phong Chau formation immediately overlying the unconformity has been more firmly defined as Lower Miocene based on both planktonic foraminifera, nanofossils and palynology [1, 7]. Syn-rift sediments are clearly observed as four units which are more prominent and widespread in these grabens. In the area of the eastern and northeastern 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 (Figures 1, 5 and 6). The eastern sector, which was earlier connected to the western sector deepest low at basement level, got well differentiated as

the rift progressed and became shallower and localised towards the southwestern margin. Moreover, Ham Rong - Ky Lan - Bach Long Vi spur in the central part gradually becomes more prominent and widespread towards NW, bifurcating the two lows.

3. Syn-rift sediments within structural components of the northern Song Hong basin

The northern Song Hong basin is defined as a continental rift and characterised as elongate crustal depressions bounded on both sides by basement-involved normal faults that cut the basement (Figures 1, 3 - 6). These extensional features are up to 8 km deep, more than 15 km wide, and around 80 km long (Figures 3 and 4). This rift is collections of stepping (Figure 2) and associated with continental breakup, and rift systems can form in a variety of tectonic settings [1, 6, 8]. It was formed through Paleogene rifting followed by Late Cenozoic thermal sagging [1, 2] and has been affected by various Neogene phases of extension and inversion with the most recent inversion continuing to the present in the area (around Bach Long Vi island) [1] (Figure 5).

The northern Song Hong basin rifting has complex features defined by several large-scale structural components (Figure 1). Major NW-striking extensional faults stretch along the axis of the central northern Song Hong basin and delineate a major Paleogene syn-rift depocenter of these faults. The Song Chay fault lies in direct continuation of the brittle Song Hong and Song Chay faults that flank the Con Voi mountains metamorphic core complex [1] (Figures 1 and 3). The central part of the Song Hong basin broadens southeastward. In the northwest, the narrow central depression of the Song Hong basin is limited to a roughly 10 km broad belt in between the Vinh Ninh and the Song Chay faults. The basin broadening reflects left-steps in the NW-SE-striking faults that border the eastern basin margin. On the southwestern flank of the basin, imbricate extensional faults with a 10 - 20° counterclockwise angle to the Song Chay fault contribute to the southeastward depocentre broadening (Figures 1 and 3). Along the flanks of the Song Hong basin and towards the Beibuwan basin, the base of the Cenozoic is marked by a strong "hard-kick" reflector (Figure 4). The pre-Cenozoic is acoustically transparent across much of the northern Nam Dinh basement high located at the western flank of the Song Hong basin. In addition, subtle stratigraphic sub-Cenozoic reflectors and mounded

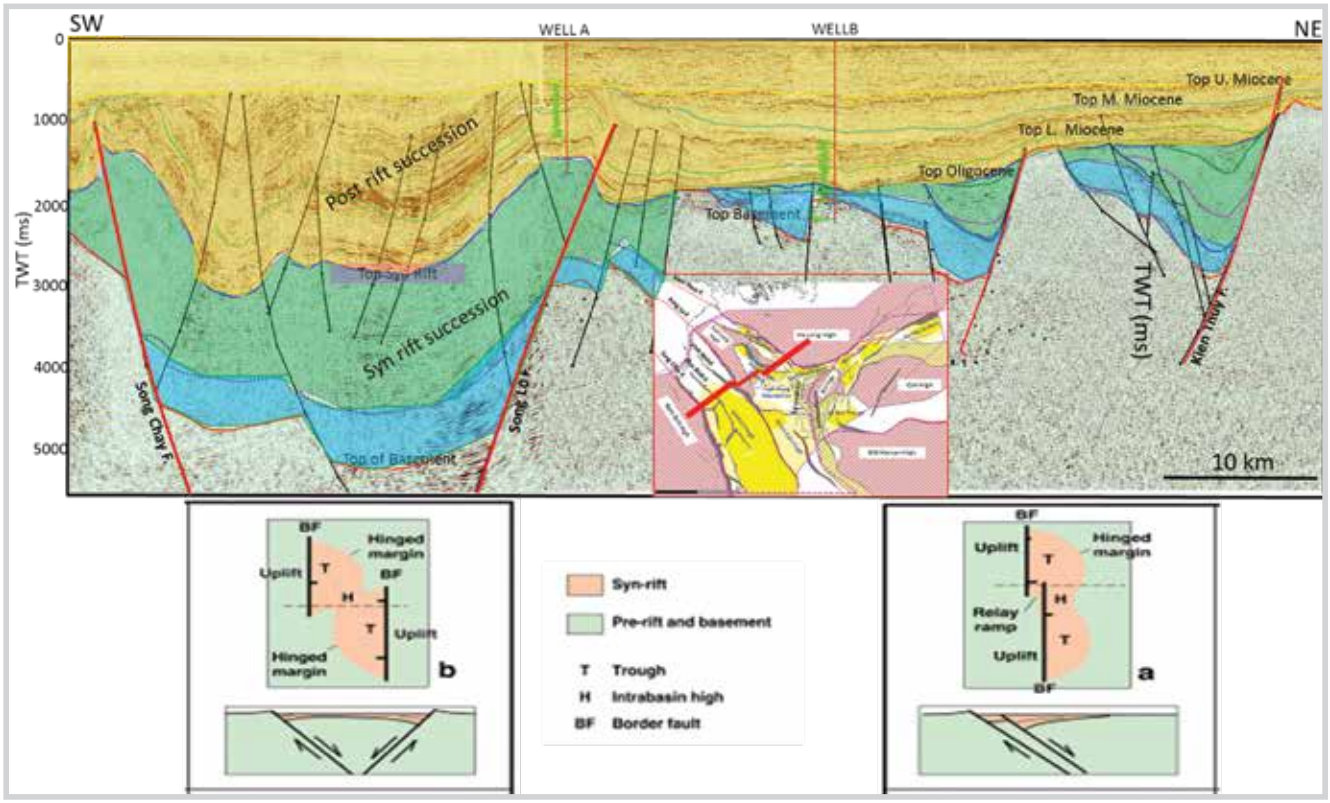

Figure 3. *Seismic transect across the northern Song Hong basin illustrating the deep Paleogene rift and the strong Middle - Late Miocene inversion affecting the central part of the basin. EW-striking extensional faults continue into the lower Upper Miocene together with the transpressional structures. Karstified Upper Paleozoic carbonates sub-cropping the Cenozoic (wells A and B).*

features often cored by a chaotic reflection pattern can be distinguished especially in the southwest. On the eastern basin flank, distinctly reflected pre-Cenozoic stratigraphy generally underlies the top of the pre-Cenozoic. In some areas, the pre-Cenozoic is outlined by mounded features with strong internal reflectivity documented as karstified Devonian - Permian carbonates in Wells B and C (Figures 3 and 4). The basin depth of the central Song Hong basin decreases from more than 6,000 ms. TWT in the southeast to a little more than 1,500 ms. TWT farthest northwest (Figures 3 and 4). The central basin fill is offset and deformed by long NW-SE-striking faults and folds. In between the Vinh Ninh and the Song Chay faults, the Thai Binh fault zone delineates a through-going fracture zone in the northern central Song Hong basin (Figures 1 and 3). The fault zone is traceable within the Lower Miocene and Upper Paleogene sections and must be rooted in the basement, but the fault root is concealed underneath the thick Cenozoic overburden. In addition, roughly EW-striking extensional faults offset strata in the basin centre, but the deeper extent of these faults is unconstrained by the seismic data due to the great basin depth (Figures 3 and 4). The base of the Cenozoic across the Nam Dinh basement high is inclined towards the basin in the northeast (Figure 1). The surface is sporadically faulted, especially along the basin confining margin, but is mostly buried only by Neogene deposits except for a few isolated minor, possibly Paleogene grabens (Figures 3 and 4). Rifting was terminated by major latest Oligocene to the earliest Miocene inversion reflecting a change to left-lateral transpression. In comparison to the early phases of shearing, the Neogene was affected only by moderate amounts of lateral displacement. This points towards left-lateral shearing and extrusion tectonics initiating sometime during the Late Eocene and further corroborates a latest Oligocene or earliest Miocene slowdown of left-lateral shearing and termination of ductile deformation observed along the ASRRSZ onshore (Figure 4).

4. Structural controls on syn-rift sediments

The accommodation space created by faulting is the primary control on the large-scale sedimentary systems within the study area [1, 3, 6] (Figure 5). In this paper, we present only structural controls on the syn-rift sedimentary systems.

Rift basin stratigraphy commonly records an early stage of major NW-striking extensional faults stretching along the axis of the central northern Song Hong basin and delineates a major Paleogene syn-rift depocentre [1 - 3]. The Paleogene rift basin development with stratigraphic information is controlled by two tectonic phases (Figure 2) and as following a model-driven within three stages of syn-rift as initiation, climax and late. Four equivalent syn-rift units bounded by these seismic markers were named as Unit 1, Unit 2, Unit 3 and Unit 4, from older to younger (Figures 2, 5 and 6). The tops of Unit 1 and Unit 4 have been assigned as Phu Tien and Dinh Cao whereas Unit 2 and Unit 3 lie within Dinh Cao (Figure 2). 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

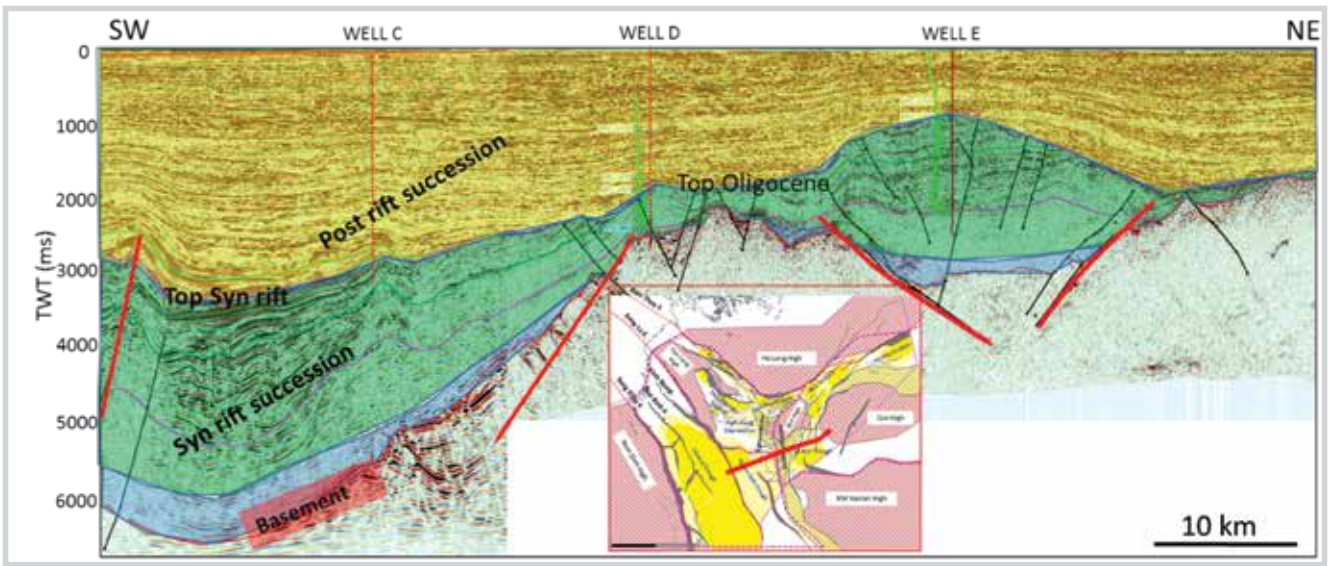

Figure 4. *The seismic section illustrating the deep Paleogene rift. The northern Song Hong basin broadening reflects left-steps in the NW-SE-striking faults that border the eastern basin margin. The base of the Cenozoic is marked by a strong "hard-kick" reflector.*

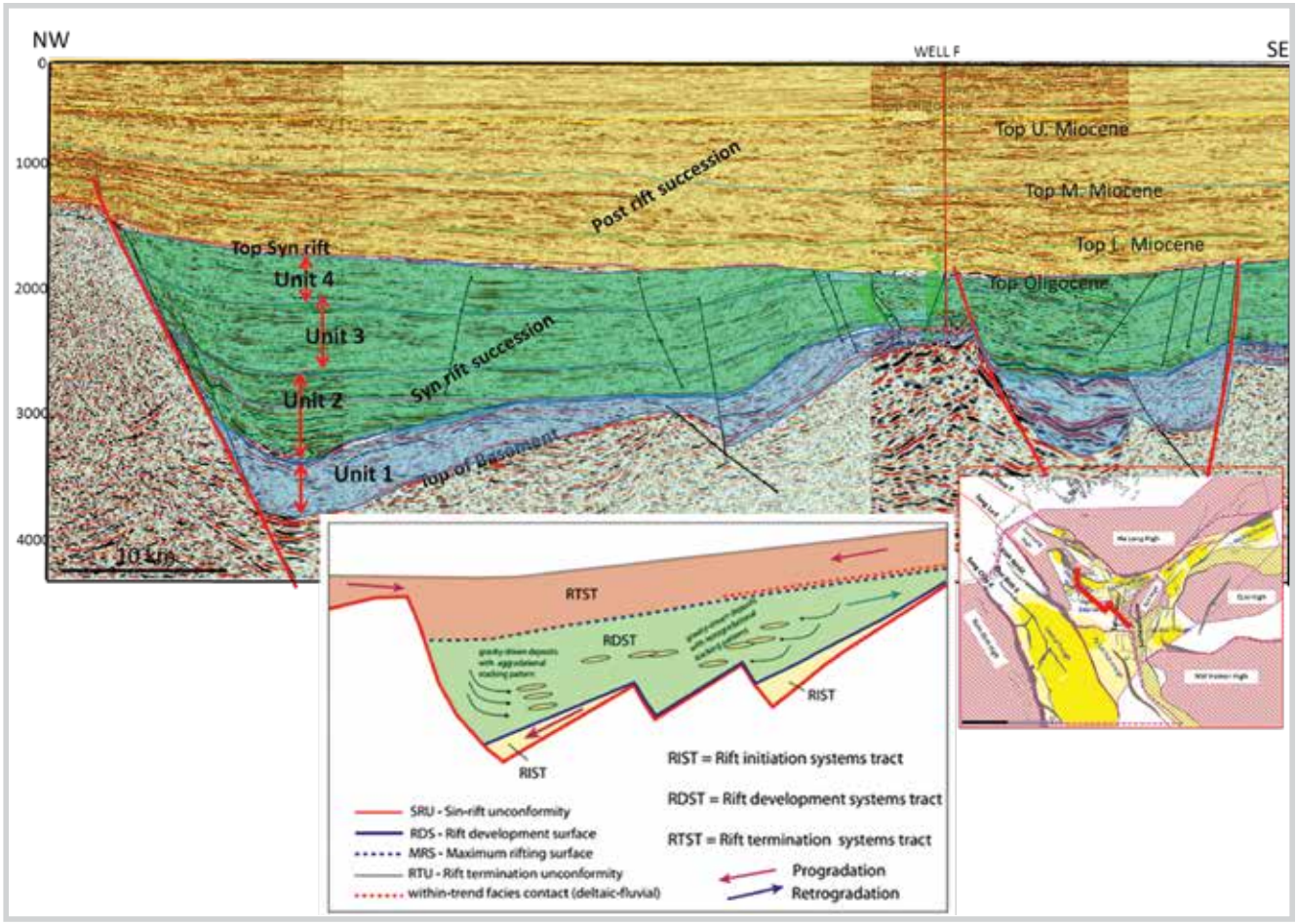

Figure 5. *The seismic section illustrating the rift system. The accommodation space created by faulting and fault related topography is the primary control on the large-scale sedimentary systems within northern Song Hong basin.*

initial rift stage and distributed dominantly in the western part of the study area. However, no well records have been seen yet. It is only observed on the seismic data (Figures 3 - 6). It is difficult to observe Unit 1 in other remaining parts. The climax rift stage persists during deposition of Unit 2 and Unit 3. Whereas, Unit 4 was deposited during the late rift stage (Figures 2 - 5). In cross sections perpendicular to the border-fault system (Figures 5 and 6), syn-rift succession exhibits a variety of depositional patterns. The scarcity of Paleogene syn-rift deposits on the western margin of the Song Hong basin suggests that this area behaved as an uplifted rift shoulder flanking the main basin [1]. In contrast, the base of the Cenozoic along the northeastern margin of the Song Hong basin is strongly rifted with horst structures and grabens and half grabens filled by thick Paleogene alluvial and lacustrine deposits intersected in wells (Figures 3 - 6).

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, Bach Long Vi graben, SE Bach Long Vi trough) and northeastern sector (Kien An, Thuy Nguyen, Cam Pha graben) as grabens and troughs bounded by smaller faults seen on basement levels, finally switched to two major troughs having main displacement fault (Figures 3 - 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. The succession begins with a fluvial unit. In the initiation 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 (observed only on the seismic data on significant highs, no well records 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

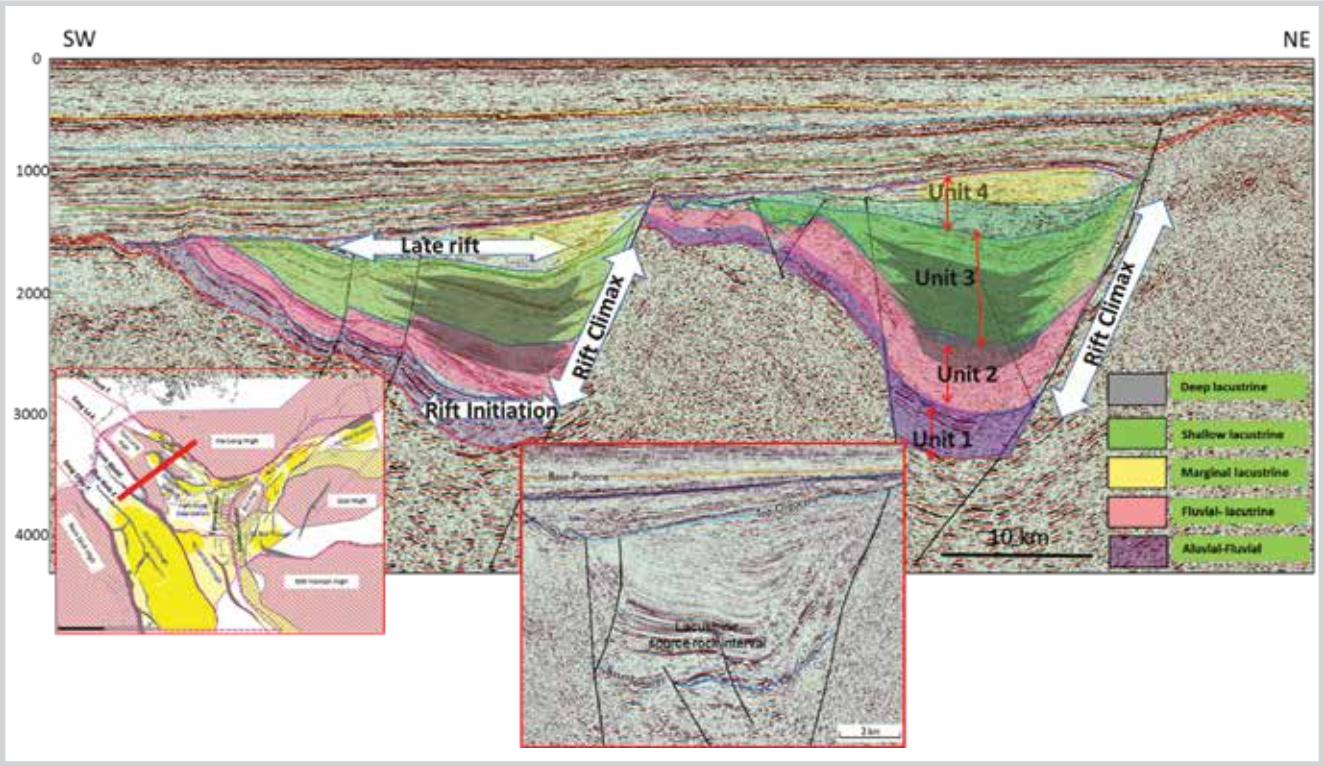

Figure 6. *The seismic section illustrating the syn-rift succession formed under three stages of syn-rift as initiation, climax within tripartite stratigraphy: fluvial, deep lacustrine and shallow lacustrine.*

show a fluvial system. Prograding reflector geometry is observed 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 outpaced by extension or exceeds subsidence. The basin topography gradually becomes filled with lake deposits [2 - 6, 8]. This is typically developed best in syn-rift cycles with a lacustrine unit that demonstrates a rapid deepening-upward interval to a lake highstand interval. 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 (Figures 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 parts of Unit 2 and Unit 3 are rift climax which have been deposited in mid and late peak rift stage and associated with the point at which transgression of the hanging wall slope occurs. Rift climax sections identified in the study area based only on seismic sections and well data show that shallow and deep lake fluvio-lacustrine to lacustrine source rocks of excellent quality are commonly developed [3, 4], which will be done in an attempt to predict the gross depositional outline of the Oligocene in these areas, and thereby contribute to the prediction of source and reservoir rock intervals (Figure 6). 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 supply keeps pace with subsidence resulting into 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 has been deposited in the late syn-rift stage and expected to have better reservoir characteristics.

5. Conclusions

The northern Song Hong basin is a continental rift basin and possesses complex features defined by several large-scale structural components. Major NW-striking extensional faults stretch along the axis of the central northern Song Hong basin and delineate a major Paleogene syn-rift depocentre.

The rift onset unconformity is subtle because of limited uplift and erosion occurring during the early stages of rifting. The most basic stratigraphic units associated with the northern Song Hong basin rifting are the syn-rift and post-rift packages.

The Paleogene rift basin development with stratigraphic information is controlled by two tectonic phases and as following a model-driven within three stages of syn-rift as initiation, climax and late and sediments were generated by successive collapses triggered by tectonic instability in the syn-rift lake.

The syn-rift stratigraphic architecture is known as a tripartite stratigraphy. The succession begins with a fluvial unit. and is overlain by lacustrine sediments. Lacustrine deposited as a result of accommodation space exceeds sediment supply in the rift climax sections with shallow and deep lake fluvio-lacustrine to lacustrine source rocks of excellent quality commonly developed in the troughs.

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