Factors Controlling Sedimentary and Petroleum System of Early Syn-Rift Plays in Faulted Margin of Continental Rift Basin: An Example in the Eastern Edge Cuu Long Basin, Offshore Vietnam*

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Abstract

Structural syn-rift reservoirs in faulted margins of continental rift basins are usually disregarded in exploration considerations due to concerns of absence of reliable top seal and diagenetic alterations that significantly reduce reservoir porosity and permeability. Not an exception to this trend, Early Oligocene reservoirs in the eastern margin of Cuu Long Basin (CLB), offshore Vietnam were overlooked in the past since they were interpreted as small and scattered structures without top seals. Recent exploration results in the eastern edge of CBL differ from past assessment regarding early syn-rift (ESR) reservoirs of the area. New seismic and exploration wells data confirm existent of the thick black lacustrine shale layers distributed widely across the area, acting as source rocks as well as top seals for potential prospects in the CLB eastern margin. The new data interpretation also put top of granitic Basement at a deeper depth than previously interpreted. As a result, syn-rift reservoirs which were small and insignificant have become larger scale and two- or three-way faulted structures. Key reservoirs discovered is the Basal sandstones, mainly composed of near-source sediment with mostly granitic fragments, were deposited right on top and shared a similar topography with the underlying Pre-Cenozoic granitic Basement. These Basal sandstones' porosity and permeability have been preserved better than shallower reservoirs. This article discusses the major factors affecting the completeness of the petroleum system in these ESR plays in the flank of continental rift basins based on an example of the eastern edge of CLB. The study results indicate the factors controlling the sedimentary and petroleum system of the faulted margin: tectonic, climate, original bedrocks and topography.

Introduction

Hydrocarbon plays associated with continental rift settings, especially the early syn-rift (ESR) reservoirs, have been assessed to be of negligible oil and gas potential due to inadequate top seals and even worse lateral or juxtaposition seal quality across faults. Another concern is the poor reservoir rocks' quality due to diagenesis that filled syn-rift formations' pore spaces with clay minerals which significantly reduced the reservoirs' porosity and permeability (Morley, 1999; San and Hoang, 2008). Structural ESR reservoirs formed on and along the uplifted flanks of faulted margin have been commonly assessed as small reservoirs with unproven local top seal. As a result, they often have been disregarded unless accompanied by other significant exploration targets.

Recently, a series of discoveries made in such ESR reservoir settings in eastern edge of Cuu Long Basin (CLB) offshore Vietnam have shown evidence of the presence of all petroleum system elements. In addition, the better preserved reservoir quality as well as more vertical and lateral reservoir extent have turned these once meager prospects into large scale structures. Therefore, the hydrocarbon potential of these ESR reservoirs becomes significant and deserves new in-depth studies and assessment. This article presents a case study in the eastern edge of CLB as an example for hydrocarbon potential in flanking ESR reservoirs as viable target for exploration and development. The study discusses and indicates controlling factors including tectonic, paleo-climate, paleo-topography and original bedrock that affect sedimentary accumulation and petroleum system in faulted margin of continental rift basin.

Geological Setting

CLB is an Early Cenozoic rift basin located off the southeast coast of Vietnam, covering an area of approximately 36,000 km^2. It borders with the continent to the northwest, with the Khorat-Natuna Basin to the southwest, with Phu Khanh Basin to the north and separated from the Nam Con Son Basin by the Con Son swell to the east-southeast (Figure 1). This basin is a typical continental rift trough formed and developed on Pre-Cenozoic crystalline basement.

CLB's pre-rift period was active from Late Jurassic to Paleocene, the period of formation and uplifting of extrusive magmatic basement, most of which are granitoid. The syn-rift period took place from Late Eocene through Late Oligocene. Due to vigorous subduction and extension activities, the major NE-SW fault system was formed in the early syn-rift phase in Late Eocene until Early Oligocene together with minor E-W trending faults. Along these faults, a series of grabens/half grabens was developed. These grabens were supplied and filled mainly with near-source coarse-grained sediments of fluvial-alluvial facies. As a result of continuous the rifting process, the deeper subsidence led the coarse-grained sequences passing upwards and into the lacustrine thick shale in Late Oligocene. The tectonic compression during Late Oligocene to Early Miocene caused a series of reverse faults, and positive and negative flower structures in the central trough of CLB. This also marked the erosion and pinching-out of sediments at the end of synrift phase. The post-rift phase commenced from the end of Early Miocene to the present day. Post-rift sediments were distributed extensively, un-displaced, unfolded and almost horizontal. At the end of Early Miocene, the NW-SE spreading of the East Sea of Vietnam weakened quickly and resulted in the deposition of the Bach Ho Formation, called as "rotalid shale", spreading throughout the basin in shallow marine environment. Bach Ho Shale plays the role of a good regional seal for CLB (Figure 1).

In general, the CLB structural units are differentiated based on sedimentary thickness and limited by fault or fault systems of considerable amplitude. The area with the busiest exploration/production activities so far is the Main Trough of the CLB which encompasses about three quarters of the basin total area and is further separated into smaller units such as Northwest Monocline, West Bach Ho Trough, Central High, East Bach Ho Trough, and South-East Monocline, etc. [3] The area of interest in this study is the eastern edge of CLB, within the pink dashed line. However, to correlate and illuminate the geological characteristics of the entire east-south eastern area, the research zone is also expanded to include East Bach Ho Trough and the Eastern Uplift Zone (the red dashed line in Figure 1B).

Exploration Results in Study Area

During the initial exploration period, only 1000 km^2 of 3D seismic were acquired and 5 exploration wells were drilled with hydrocarbon shows in the fractured granite Basement and/or Clastic Paleogene. However, petrophysical analyses indicated tight reservoir and well testing results did not achieved a natural flow rate to surface. Geological evaluation in this period mainly focused on fractured granite Basement target. On the other hand, the common verdict for Clastic reservoirs in the eastern edge of CLB was that their hydrocarbon potential is insignificant due to pinchout and/or onlap sediments that were thin. In some cases with thick Oligocene sandstones, the reservoir rock is tight with poor flowability. Recently, more and more exploration activities have been carried out for new targets, especially for the Eocene-Oligocene sandstones in the southeastern edge of CLB since the conventional reservoir targets in CLB have become exhausted. More than 2000 km^2 of new 3D seismic data were acquired covering the entire study area and fully correlated with 3D seismic data from other region in CLB. Over 10 new wells have been drilled to explore and appraise the study area leading to multiple oil and gas discoveries. The preliminary results are as follows.

Reservoirs

Discovery of hydrocarbons in Eocene-Oligocene sandstones, the main target being the Clastic Basal sandstone unit in the Tra Cu Formation, which was deposited on top and shared a similar topography to the underlying Pre-Cenozoic granitic Basement. These reservoirs achieved 1000-4500 bopd natural flow during testing (Figure 2). The Basal sandstones have been well preserved in terms of porosity and permeability as compared to shallower sequences (Figure 3).

Thicker and larger Basal reservoirs. Integrated analyses from seismic, petrography, side wall cores, borehole image log show distinguishable features of Basal sandstones that conventionally look similar to the underlying granite Basement. Therefore, the top of granite Basement is actually much deeper than previously picked by seismic interpretation, effectively increasing the thickness and extension of the Basal reservoirs (Figure 4).

Reservoir flowability: This is not easily predictable across the faulted margin region but varies significantly depending on specific migration path and other complex geochemical processes that altered the fluid and/or rock-fluid properties. Typical examples of this case are wells drilling through these syn-rift reservoirs near Con Son swell with thick hydrocarbon net pay and good porosity-permeability but tested with weak natural flow to surface, i.e. less than 500 bopd. One contributing factor could be due to the very high oil viscosity at sub 30 degC which makes it condense quickly and hinders the flow to surface. (Figure 5).

Seal and Source Rocks

There are two lacustrine black shale units identified throughout all drilled wells in the study area. The first is deposited at the bottom of Tra

Tan Formation and the second in the Tra Cu Formation with average thicknesses of 20 m to 50 m. On seismic data, these black shales, especially the black shale #2, can be easily recognized from upper and lower sequences based on the obvious contrast in velocities which are about 3000 m/s in these black shales and approximately 4500 m/s to 5500 m/s in others. Along and crossing seismic sections through the South-East Trough indicate continuous and widespread distribution of these competent black shales in the study area (Figure 6).

In brief, recent exploration results have confirmed the existence of elements for a complete petroleum system during ESR phase (Lower Eocene-Oligocene) in the eastern edge of CLB. Concerns related to the absence of reliable top seal and reservoir rock's quality in these syn-rift structures have been erased. The sediment thickness as well as reservoir extent also become more significant than previous evaluation making the study area more attractive target for exploration and development. As a result, more in-depth studies such as sedimentary model, mechanism and controlling factors dictating the depositional facies as well as petroleum system in the ESR reservoirs are required to justify further operation effort.

Controlling Factors for Sedimentary Facies and Petroleum Systems of ESR Reservoirs in the Eastern Edge of CLB

A variety of factors affect the depositional processes and petroleum system. While tectonics play the most important role in facilitating and creating an accommodation for sedimentation, many other causes, including weathering and erosion processes, sea level changes, topography and original bed rock, also influence the size of sedimentary accumulation and facies distribution (Nichols, 2009). Among these various factors, such as weathering and rate of erosion, are dependent on others such as tectonics and climate. In other words, there are controlling as well as consequent factors influencing the accommodation and allocation of sedimentary facies (Figure 7) (Withjack and Schlische, 2002).

According to Southeast Asia and Southwest Pacific tectonic model (Hall, 2002), CLB was a continental rifting basin during Early Oligocene and did not directly connected to the ocean (Figure 8). Paleontological data as well as geochemical water analyses of wells drilled in the research area show that the environment was continental with fresh water (salinity of Oligocene sandstone reservoirs is less than 5g/l). Therefore, it is obvious that sea level changes did not directly affect CLB during ESR period. In addition, these findings agree well with the above tectonic model. As a result, the controlling factors regulating sedimentary of CLB during ESR phase were tectonics, climate, topography and original bedrocks.

Tectonic Impacts

Tectonic subsidence is essential in creating large spaces along surfaces and depth for the deposition of sediments during rifting. The slopes of the rift's faults dictate the subsidence rate and thus control the accommodation space for sediments and often the depositional facies (Lambiase and Morley, 1999).

In conventional sedimentary model, the eastern edge of CLB has been considered as a single-slope flank with localized and separate structures having thin sediment deposition. Recent research in rift basins (Hall, 2002; Lambiase and Morley, 1999; Olsen, 1990; Cohen, 2003) provides more detailed classifications for the structures in extensional rift basins in which the edge of the basins can be described as "hinged margin" or "faulted margin". Using this new concept in combination with updated seismic and well data, it could be concluded that the east-southeastern edge of CLB exhibits the characteristics of faulted margin. The stair-step fault systems at the faulted margin are parallel to the Con Son swell and are the bounding surfaces for most 2- and 3-way faulted structures formed during the rift phase of Early Oligocene in the study area (Figure 9).

Vigorous erosion rates during Early Eocene-Oligocene took place simultaneously in many areas and assisted the formation of various separate lakes in the initial stage of rifting. Based on correlated seismic data for the extended research area, it is observed that the eastern edge of CLB and neighboring structure units, including the East Bach Ho Trough and Eastern Uplift Zone, are closely linked as one unified trough, which could be considered as the eastern sub-basin during ESR phase (Figure 6). The eastern side of the central basement highs of CLB plays the role of a western dam for this sub-basin. Hence, the role of tectonics is intertwined with climate in controlling sedimentation and facies distribution.

Climate Impacts

Climate is fundamental in the sedimentation and petroleum potential of continental rift basins since the amount of water supplied to the basins varied in different periods. During prolonged periods of drought, the water levels of lakes and channels were low so they became narrow with little sediments. During wet seasons, the amount of water increased several times and expanded the covered areas of lakes much more than during drought periods such that more fine-graind lacustrine sediments were widely distributed. Climate also had great impacts upon the weathering process of source rocks. During warm and wet seasons, chemical weathering was dominant, creating clay-type sediments. During cold and dry seasons, physical weathering was dominant resulting in coarse-grained detrital sediments. Morley (2012) stated that there were fossils specific to certain climate cycles for each area. Based on biostratigraphy analysis of formations in Southeast Asian basins, he divided paleoclimate in this area into four periods in which the first three periods corresponds to the sedimentation period of Tra Cu to Lower Tra Tan formations of CLB: (1) Late Eocene-Early Oligocene (>33 Ma) with abundance of Barringtonia representative of rising sea level and Poaceae or Celtis without the existence of Bisaccase denoting dry seasons; (2) Early Oligocene (29.5-33 Ma) with abundance of Poaceae or Celtis without the existence of Bisaccase denoting dry seasons; (3) Late Early Oligocene-Early Late Oligocene (27.5-29.5 Ma) with abundance of Pinus and little to no Poaceae indicating dry seasons with much colder temperature; (4) Late Oligocene (24.84-27.5 Ma) with characteristics Shorea and abundance of Poaceae indicating raining seasons with tropical climate (Morley, 2012).

Using this approach to identify paleo-climate of the research area during the ESR phase, the group of palynologies in a cool climate includes Dacrydium spp., Phyllocladus spp., Alnipollenites spp., Piceapollenites spp., Tsugapollenites spp., Abiespollenites spp.; and the group of palynologies in dry terrestrial consists of Cicatricosisporites dorogensis, Crassoretitriletes nanhaiensis, Lycopodiumsporites neogenicus, Polypodiaceasporites. These two groups of palynologies are common during deposition period of the Tra Cu Formation. Thus, the basal and upper Tra Cu Formation was deposited under cool and dry climate condition except for the lascustrin back shale units.

Integrating the above tectonic and climate analyses of Eocene-Early Oligocene, the authors established the model for sedimentary system of the extended research area as illustrated in Figure 10. During wet seasons, most of the area was fully connected to form a single trough, bearing water with a rising level possibly up to the dashed black line with Con Son swell and the central CLB’s basement highs as the eastern and western shores, respectively. This large lake connected to the central CLB’s trough through relay ramps in between Basement highs which created opportunities for lacustrine shale to be formed during the ESR phase and distributed across the east-southeastern trough. The lacustrine shales have been matured and acted like the source rocks as well as top seal for Early Oligocene reservoirs at the east-southeastern margin of CLB (Figure 6) (Morley, 2012).

During dry seasons, the water level was lowered and the lake's area retracted (light blue area in (Figure 10). The area between the highest and lowest water level had sedimentary facies of fluvial deposits, mudflats, sandy alluvial fan that were one of the favorable conditions for the formation of detrital-deposit reservoirs in the research area. Detrital sediments formed during Eocene-Early Oligocene in the research area were majorly coarse-grained with dominant poorly-sorted, angular granitic rock fragments that were near-source sediments. In some locations on the slope, the deposited material could form potential stratigraphic traps under such conditions. This is out of the scope of this article but will be discussed in later work.

Original Bedrock and Topography Impacts

The composition of original bedrock is also critical in forming sediments and the distribution of depositional facies. For example, sediments of basaltic origin will form a different rock type from sediments of carbonate origin. A delta cannot be in-filled with sands if sediments coming from source rocks are composed of clays. Original bedrocks of CLB are usually granitic magma of extrusive igneous rocks, metamorphic rocks, or pre-Tertiary sedimentary rocks as exposed on Da Lat zone and surrounding areas in the mainland. Therefore, the composition of sediments in CLB during rifting was dominantly detrital sediments from weathering of intrusive magma. Petrography analyses show mainly Arkoses sandstones with minor of Feldspar greywacke (Figure 4). The major mineral composition comprises quarz, K-feldspar, plagioclase, mica, etc. The reservoir rocks contain many original granitic rock fragments (8-67%). The deeper and the closer to the fractured granite Basement, the more content of original granitic rock fragments are found. The sorting is poor to medium and roundness is angular to sub-angular. The above petrographic characteristics specify these rocks as near-source sediments. The overlaying sediments shared the same topography with Basement (Figure 2). These sediments' physical properties such as seismic velocities (about 4500-5500 m/s), density, and resistivity that are similar to those of basement rock commonly mislead the picking of basement top to overlap the Clastic Basal sandstones (Figure 11).

The deeper Basement's top couples with recent correction for accurate fault distribution and/or magnitude lead to larger structure with deeper spill point and obviously greater hydrocarbon potential of these Basal sandstones than previous evaluation as exampled on Figure 12. In this case, the T structure (formerly named as X2 and X3) was previously defined on map as two- and three-way faulted structures with maximum closing areas of 5 km^2 (Figure 12A). The newly interpreted structural map derived from updated seismic and well data demonstrates longer distribution of major faults that bound the structure, thus merging X2 and X3 structures into the newly defined T structure with maximum closing area up to 20 km^2 (Figure 12B). This updated tuning of seismic interpretation not only widens the most likely closure area of the structure but also deepens the lowest closing contour that is approximately 350 m deeper than previously defined (dashed yellow line in Figure 12C) leading to thicker Basal sandstone interval (as illustrated in Figure 5 and Figure 11). This has been confirmed by exploration/appraisal wells in this area. The tuning of bulk rock volume, therefore, logically makes the hydrocarbon potential of the structure much higher than previously estimated.

Conclusions and Recommendations

Recent Eocene-Lower Oligocene discoveries in the eastern edge of Cuu Long Basin have confirmed the complete elements of an ESR petroleum system. The following conclusions can be drawn.

The ESR sedimentary and petroleum system in the eastern edge of CLB are influenced by various factors in which the controlling factors include tectonics, climate, topography and components of the original bedrocks. The others are consequent of the controlling ones.

The depositional model of the eastern margin area of CLB during Eocene-Early Oligocene period is one part of the eastern sub-basin, formed mainly under tectonics and climatic controls. During wet climate periods, most of the area became a large lake creating opportunities for the deposition of lacustrine fine-grained sediments. These shales act like both source rock and cap rock for underlying reservoirs. This finding clears the concern of lacking of competent top seal for ESR plays in the flank of CLB faulted margin. During dry climate periods, water level dropped while alluvial fan and fluvial facies were formed in the areas of low water-level.

The major exploration target in the study area is the Basal sandstone unit deposited on top, sharing the same topography with the underlying granitic Basement. This Basal sandstone is a near-source deposit, mainly composed of arkoses and feldspar greywacke sandstones, which contain many unaltered granitic fragments. This is one of the major causes for preservation of porosity and permeability. New well data correlated with re-processed and re-interpreted seismic data put top of Basement to its proper place, at a greater depth than previously interpreted on old seismic data. Basal sandstone reservoirs, previously regarded as poor hydrocarbon potential plays, have become viable prospects.

Structures at the east-southeastern margin of CLB were formed during the Eocene-Early Oligocene period, enclosed and leaned on stepping faults parallel to Con Son swell, and belonged to the structural unit depicted as “faulted margin” of rift basins. The new 3D seismic with high resolution and the new well data help to tune the fault distribution and/or magnitude, leading to larger structures with deeper spill points and obviously greater hydrocarbon potential than former evaluation.

The existence of ERS stratigraphic traps in this area is recognized in this article but detailed study will be discussed in future work. In addition, some locations close to the Con Son swell have thick hydrocarbon net pay and good porosity-permeability but tested with weak natural flow to surface. It is recommended to conduct further integrated studies to determine the complex impact of fluid and rock properties to flowability.

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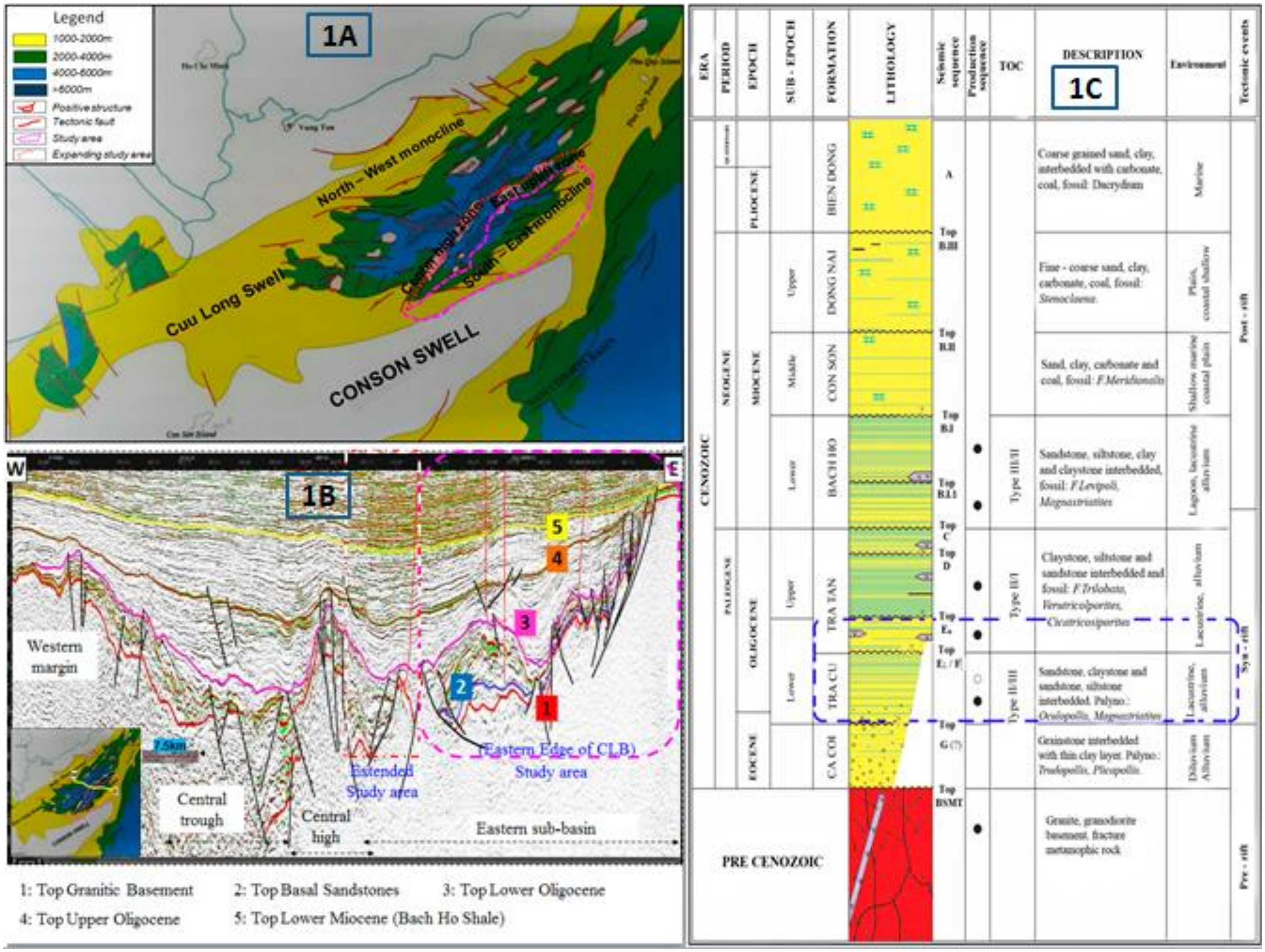

Figure 1. Geological setting of Cuu Long Basin (CLB). (1A) Structural units of CLB (modified from Dong and Hai, 2007). The study area is the eastern edge region of CLB (dashed pink curve) formerly evaluated as a monocline (extend to/contiguous to Con Son swell), which is influenced by the NE-SW trending or sub-latitudinal tectonic faults, forming some local structures. (1B) A crossing seismic section through CLB. The focused study area is the faulted margin. (1C) Stratigrapic column showing the pre-rift, syn-rift and post-rift lithology of CLB. This article targets are the ESR Tra Cu and Lower Tra Tan formations with a corresponding age of Late Eocene-Early Oligocene (dashed blue rectangle).

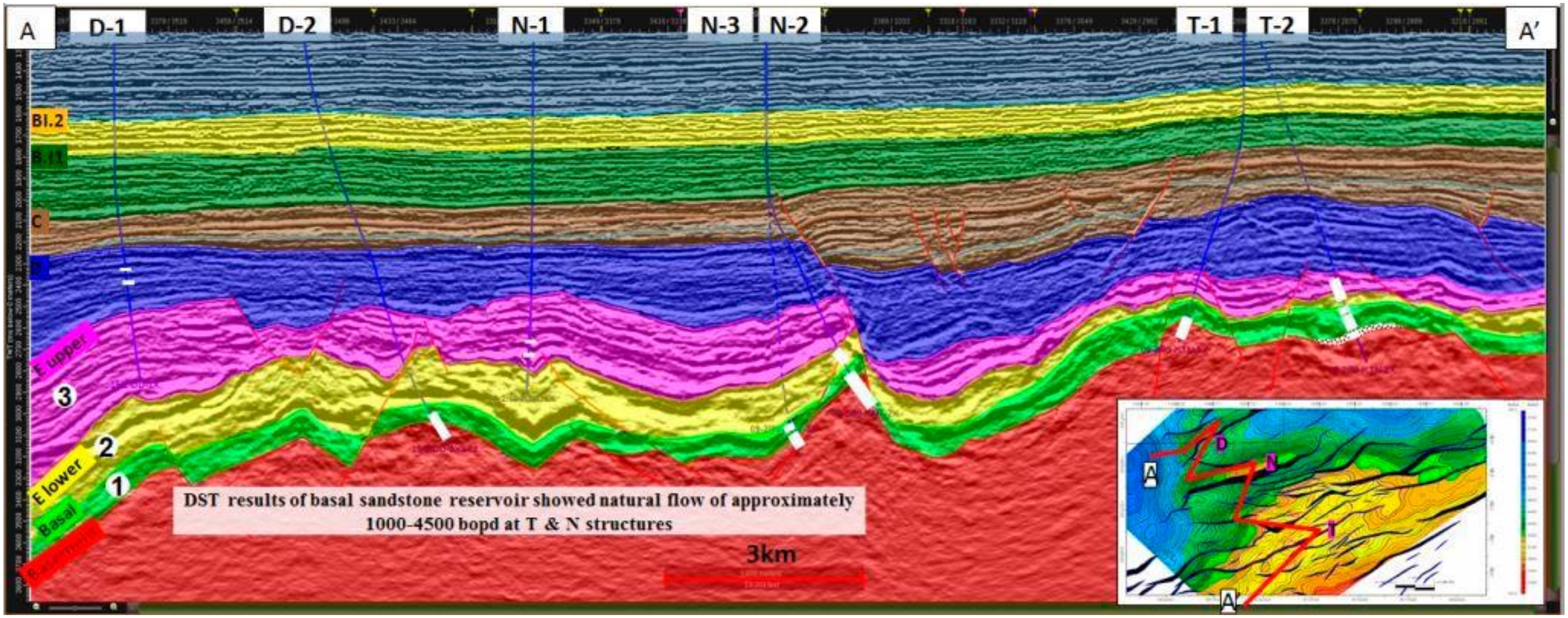

Figure 2. Seismic section A-A’ crossing through T, N and D structures in the eastern edge of Cuu Long Basin.

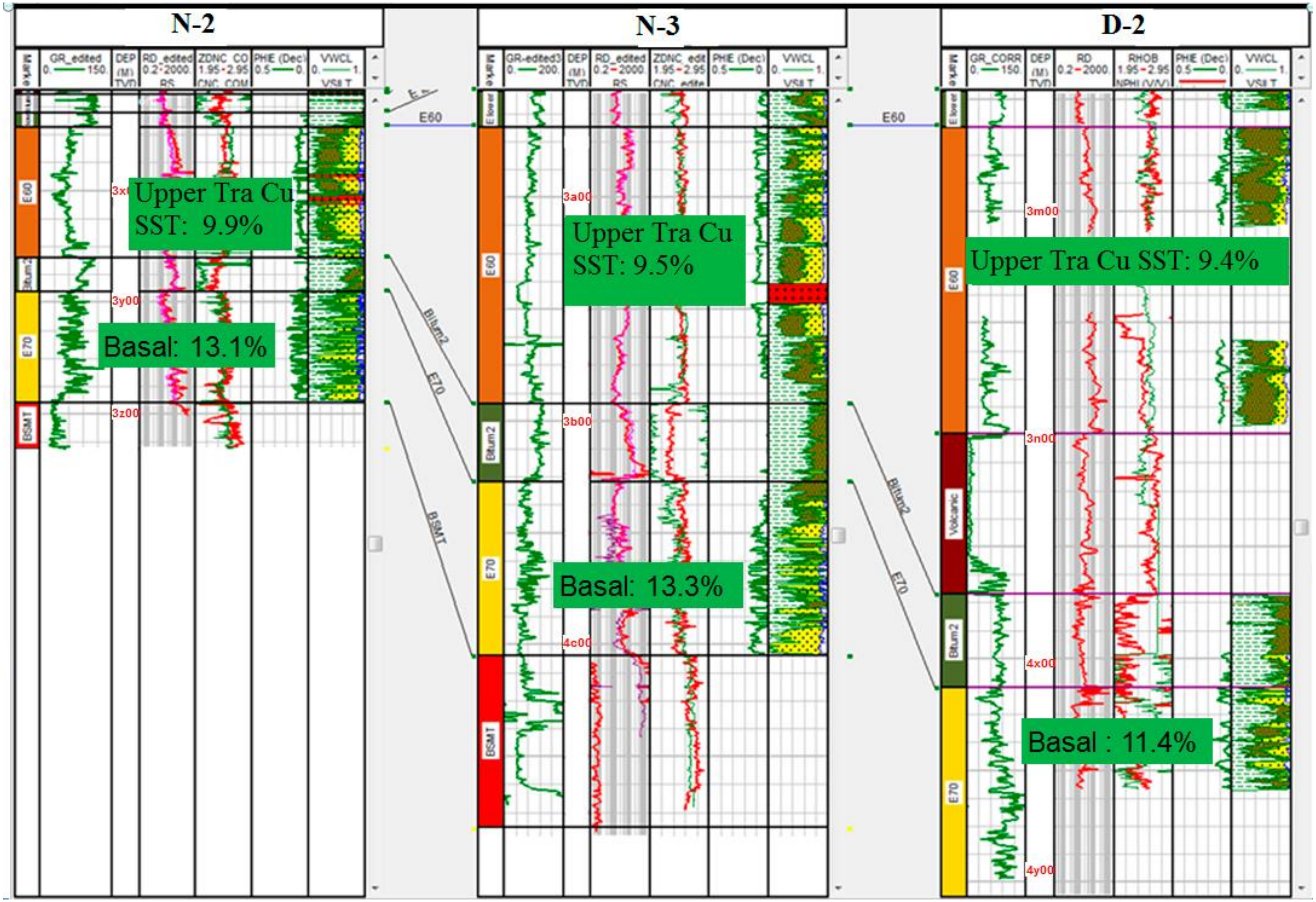

Figure 3. Petrophysical analysis results of the wells in the study area demonstrate better preserved porosity in Basal sandstone than in the above sandstone reservoir.

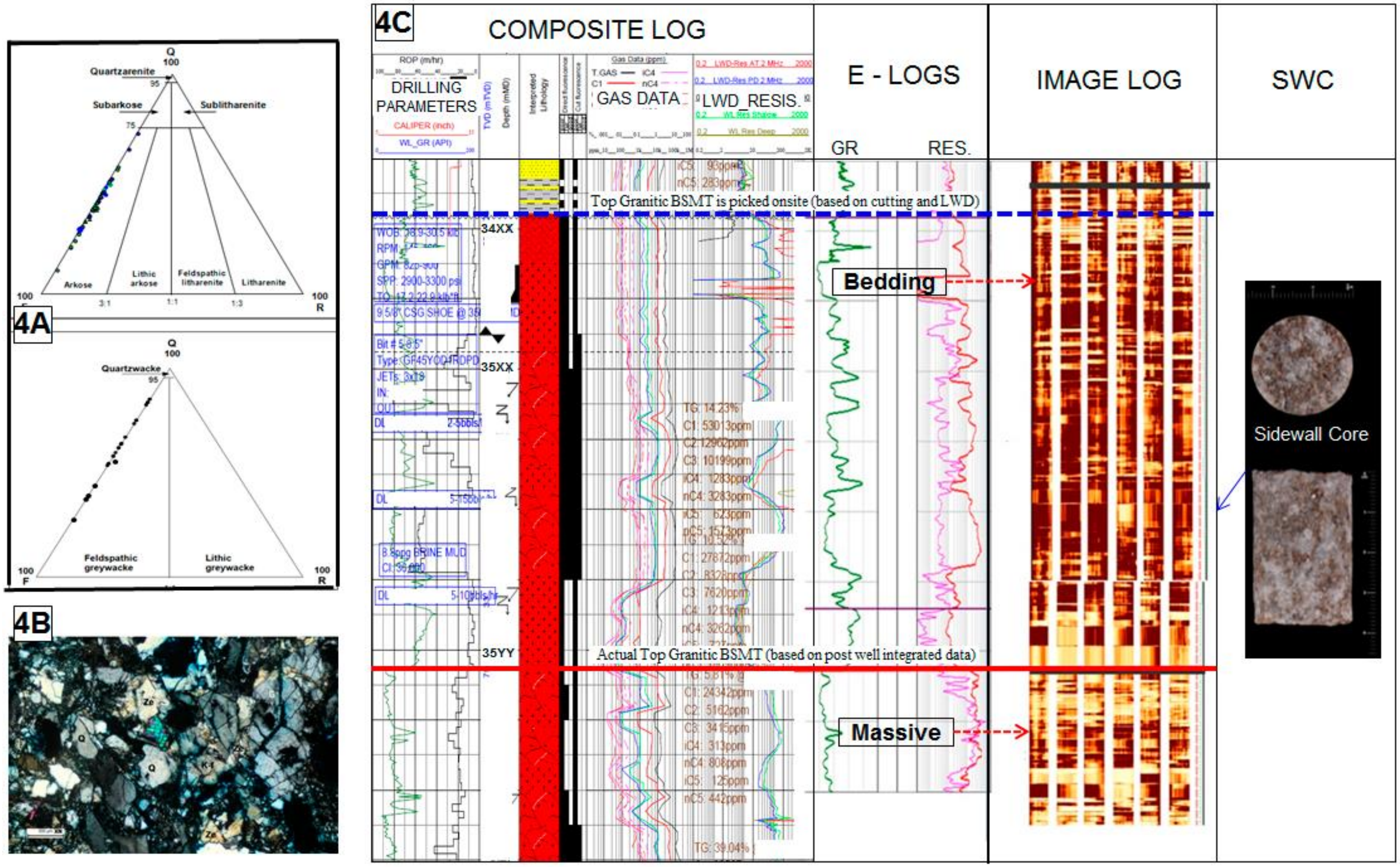

Figure 4. Integration of petrographic and petrophysical analyses to determine vertical distribution of Basal sandstones reservoir or top of Basement in the wells in the eastern edge of Cuu Long Basin (CLB). (4A) Petrography analysis indicates Arkoses (upper triangle) and feldspathic greywacke sandstones (lower triangle). (4B) Thin section of Basal sandstone sample of T-1 well predominant quarzt, feldspar kali, granitic fragment. (4C) Wellsite geologists usually pick top of Basement based on (i) at the depth of appearance of granite fragments in the cutting samples, and (ii) similar Gamma Ray and resistivity curve reading to values in granite Basement (GR is low, Res is high). The top of Basement was corrected after image logs which show the Clastic zone (layering) and granite Basement (massive). Other evidence is that the Basal sandstone can be chrono-stratigraphically correlated throughout the study area by its seismic characteristics of fair internal reflection continuity and medium-to-high amplitudes (Figure 2).The final integrated analyses indicate that these Basal sandstones are apparently not the "granite wash" as previously identified by several authors (Selley, 1998).

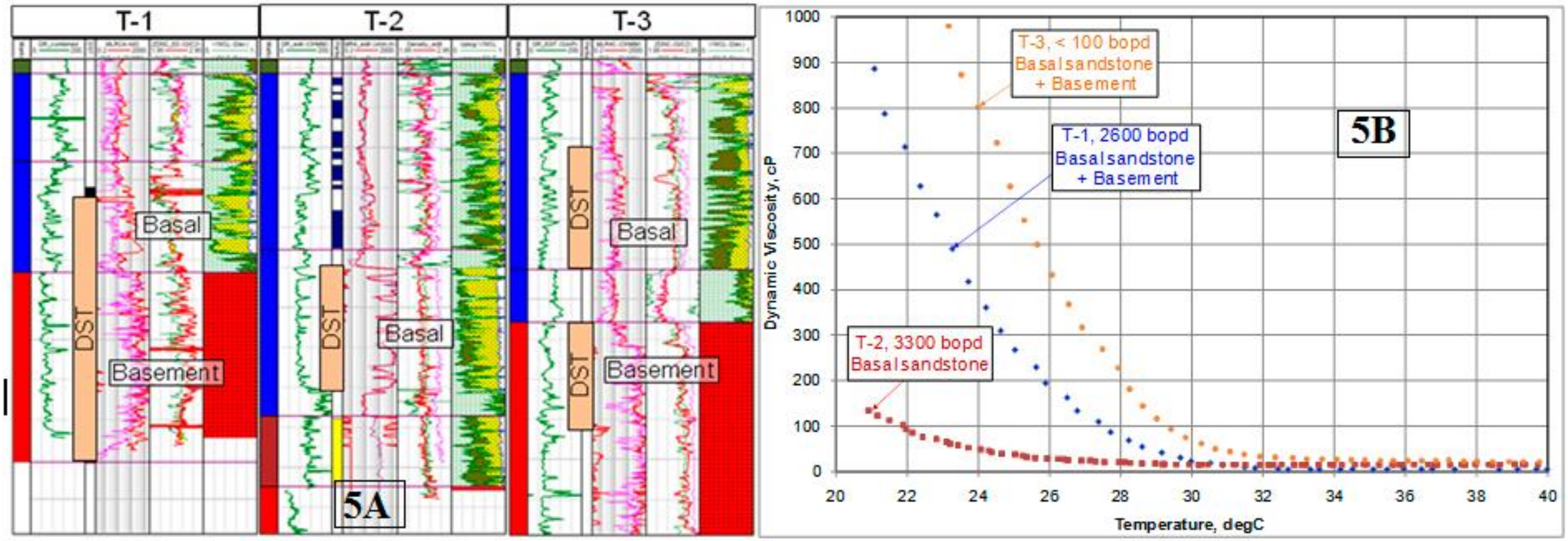

Figure 5. Well petrophysical analysis of DST intervals involving Basal sandstones showing consistent reservoir properties in (5A) but different flow-to-surface-ability which could be due to oil properties such as sharp increase in dynamic viscosity in (5B).

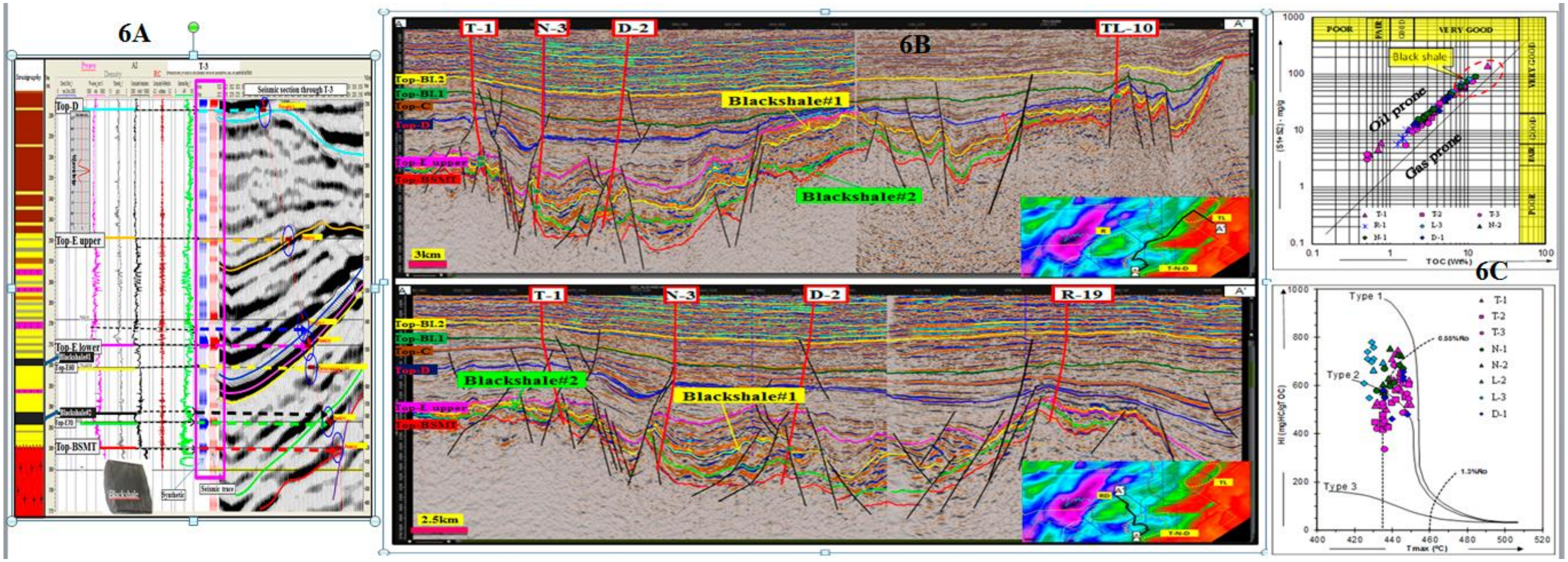

Figure 6. Characteristics of bituminous shale layers in the study area: (6A) Synthetic seismogram of N-3 well showing the diagnostic characteristics of very low acoustic impedances for two bituminous shale layers in wells. (6B) Seismic sections along (upper middle figure) and cross (lower middle figure) the southeast subbasin showing the interpretation of two horizons of black shales throughout the study area thanks to their seismic continuity. Chronostratigraphic correlation also shows that these two black shale layers are widely distributed in the study area. (6C) Hydrocarbon source potential of Black Shale layers in southeastern Cuu Long Basin (CLB). Chart of TOC versus S1+S2 (upper right) shows very good source potential in oil window. Chart of HI and Kerogen type versus Tmax (lower right) shows fresh water lacustrine depositional environment containing Type I and II Kerogen with very high HI (>500 mg/g).

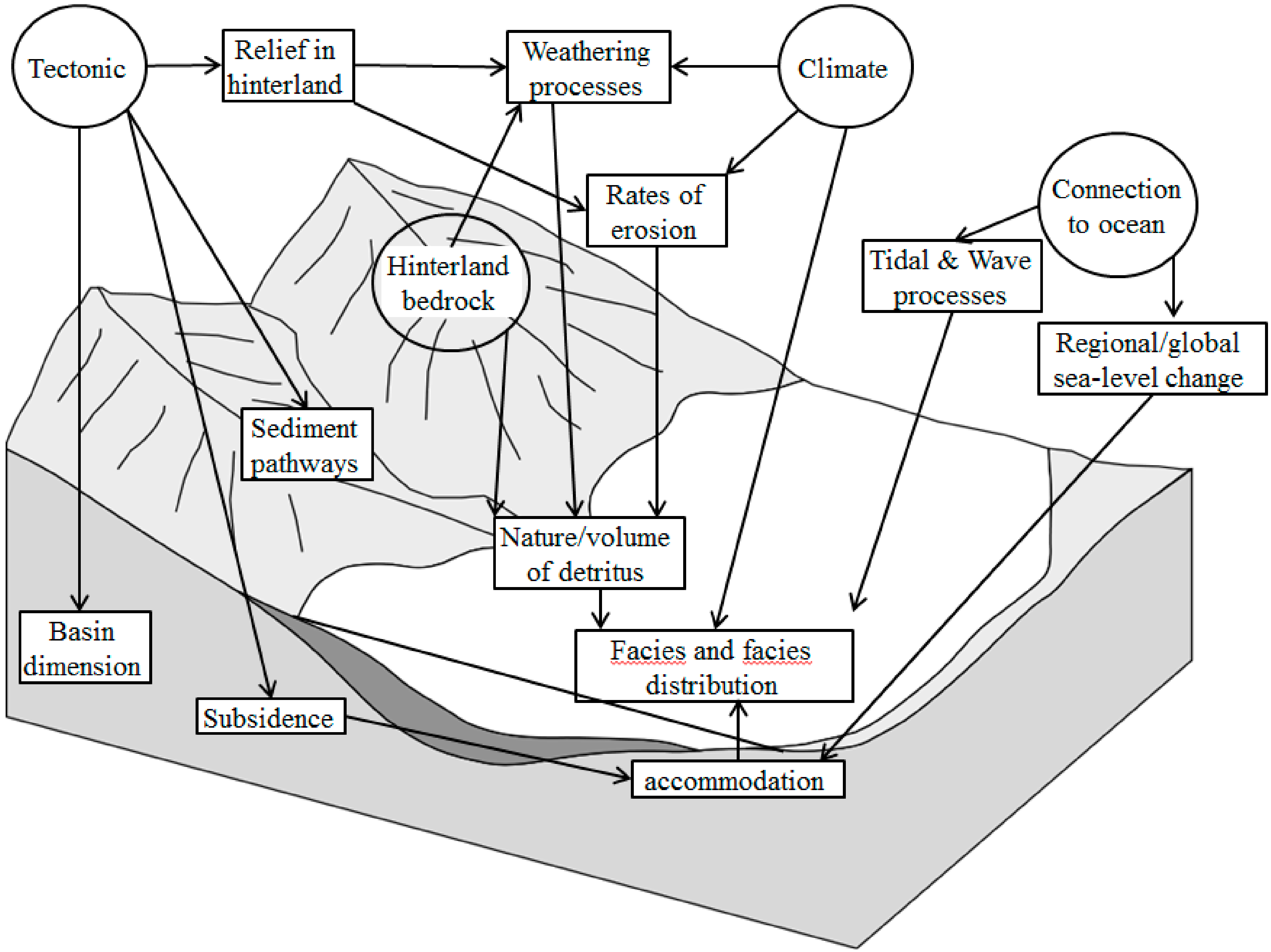

Figure 7. Factors influencing sediment accommodation and facies distribution (modified from Nichols, 2009), divided into two groups: controlling factors (round circles) and consequence (rectangular boxes).

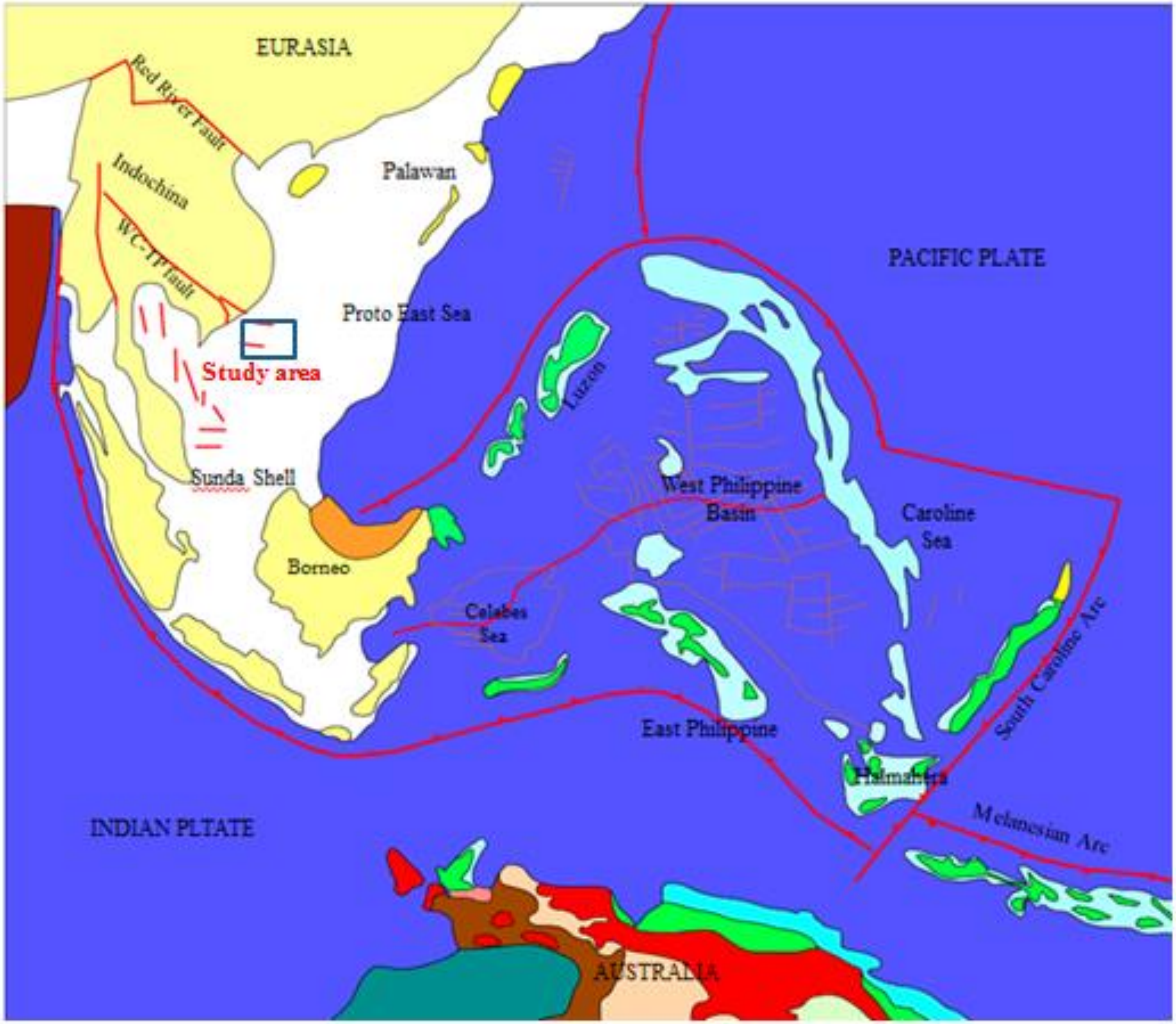

Figure 8. Southeast Asia and Southwest Pacific tectonic model (Hall, 2002).

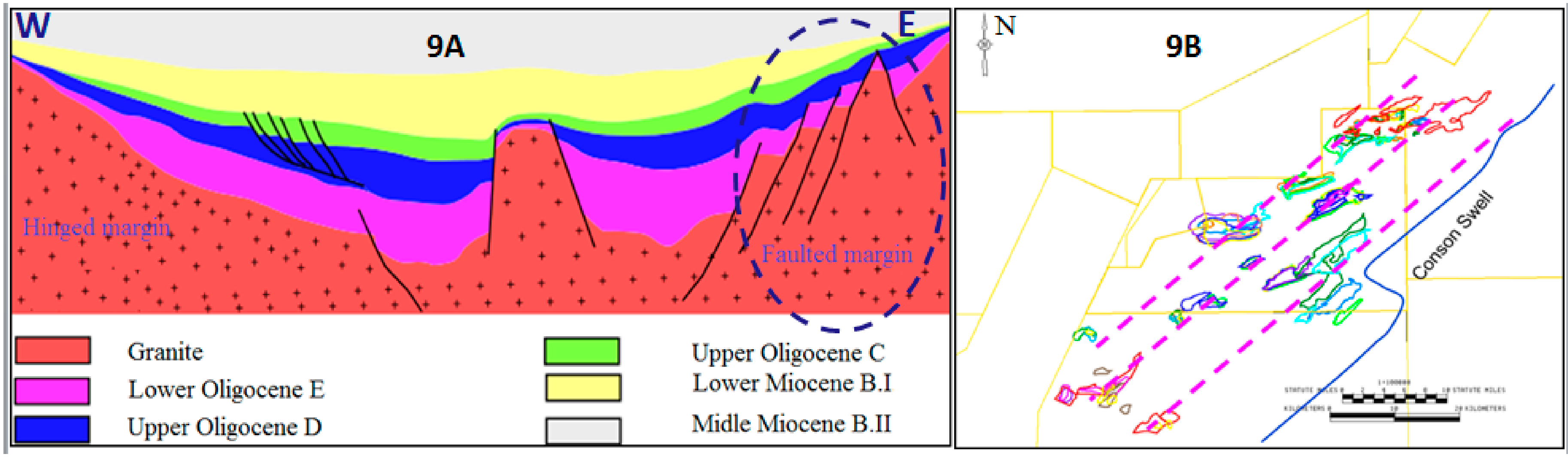

Figure 9. Faulted margin in the eastern edge of Cuu Long Basin (CLB) during the early syn-rift (ESR) phase. (9A) Schematic section across CLB showing faulted margin in study area. (9B) The ESR structures parallel to the Con Son swell.

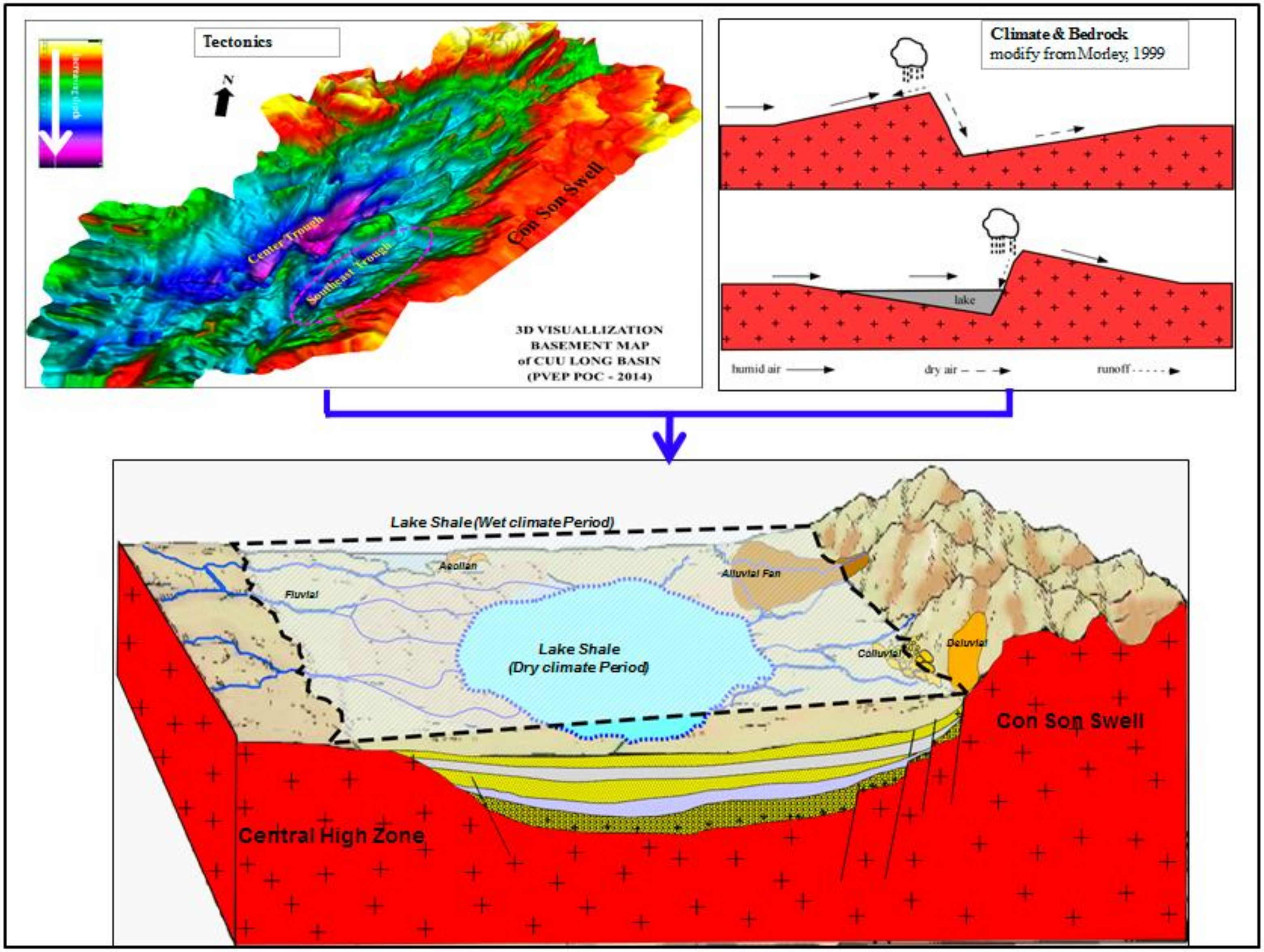

Figure 10. Illustrations of Cuu Long Basin eastern sub-basin through different climate conditions: Cycles of alternating long periods of wet and dry climate extend or shrink the fluid covered area of the lake. During dry climate periods, the uncovered area became a fluvial/alluvial depositing place for near-source sediments and subsequently evolved into reservoirs. During long periods of wet climate, the lake covered area spread out allowing lacustrine facies deposition such as black shale making capable seals for underlying reservoirs formed during dry climate periods.

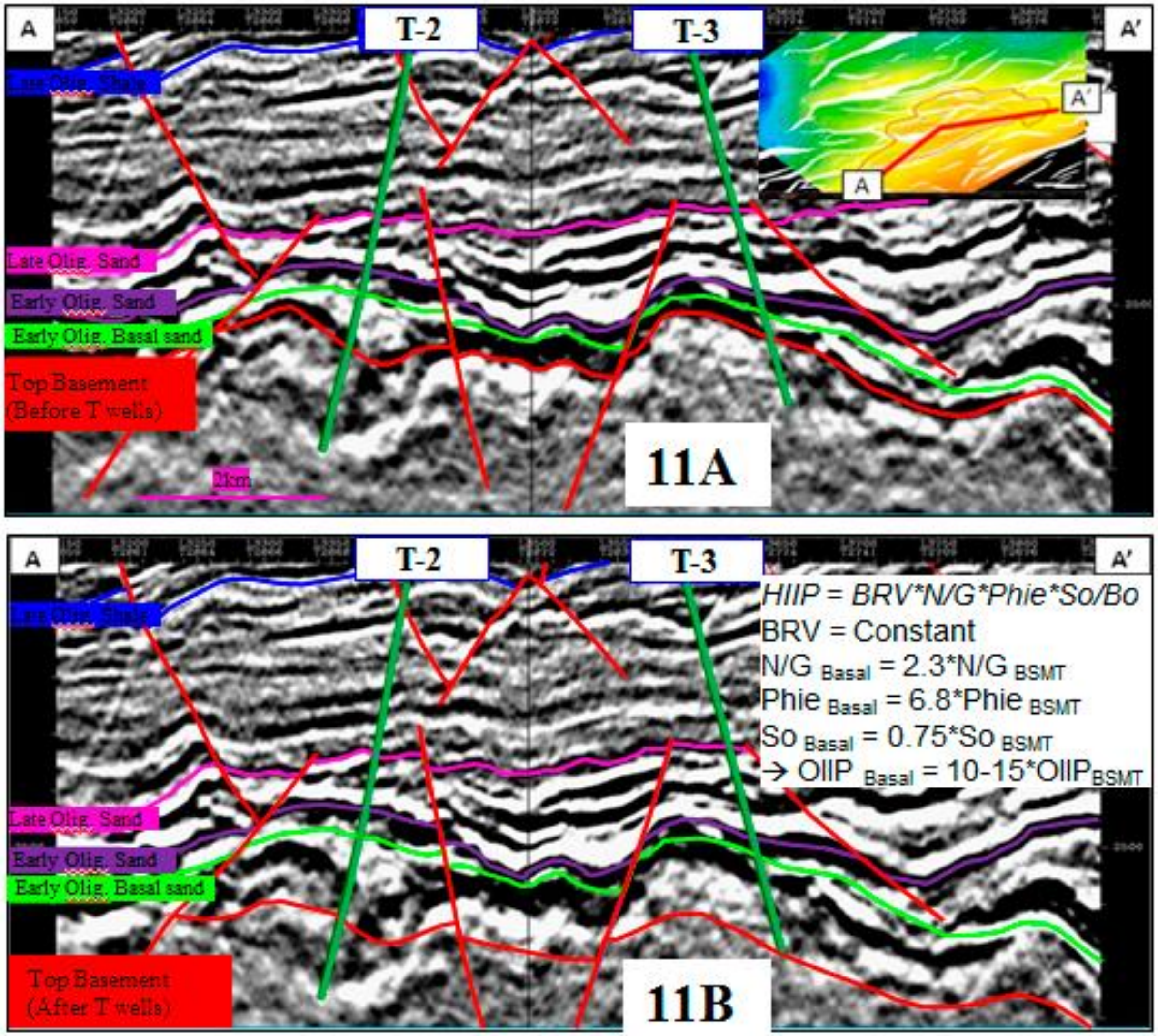

Figure 11. Comparison of OIIP estimated before and after recent exploration drilling through Basal sandstones and fractured granite Basement in T structure. (11A) Prior to T wells, granitic Basement was interpreted as strong positive seismic phase at the bottom of seismic section. Thus, Early Oligocene basal sandstone was assessed to be thin or pinched out. (11B) After T wells, granitic Basement was interpreted as a weak seismic phase at about 2-3 phases below the bottom strong phase (depending on locations). Therefore, Early Oligocene Basal sandstone became thicker than previously assessed. The reservoir properties, including porosity and net-to-gross, of Basal sandstones are much higher than fractured Basement leading to about 10-15 times higher OIIP estimation post-drilling. Similar prospects in eastern edge of Cuu Long Basin, previously interpreted as pinch-out traps, were re-assessed as two- or three-ways faulted structural traps.

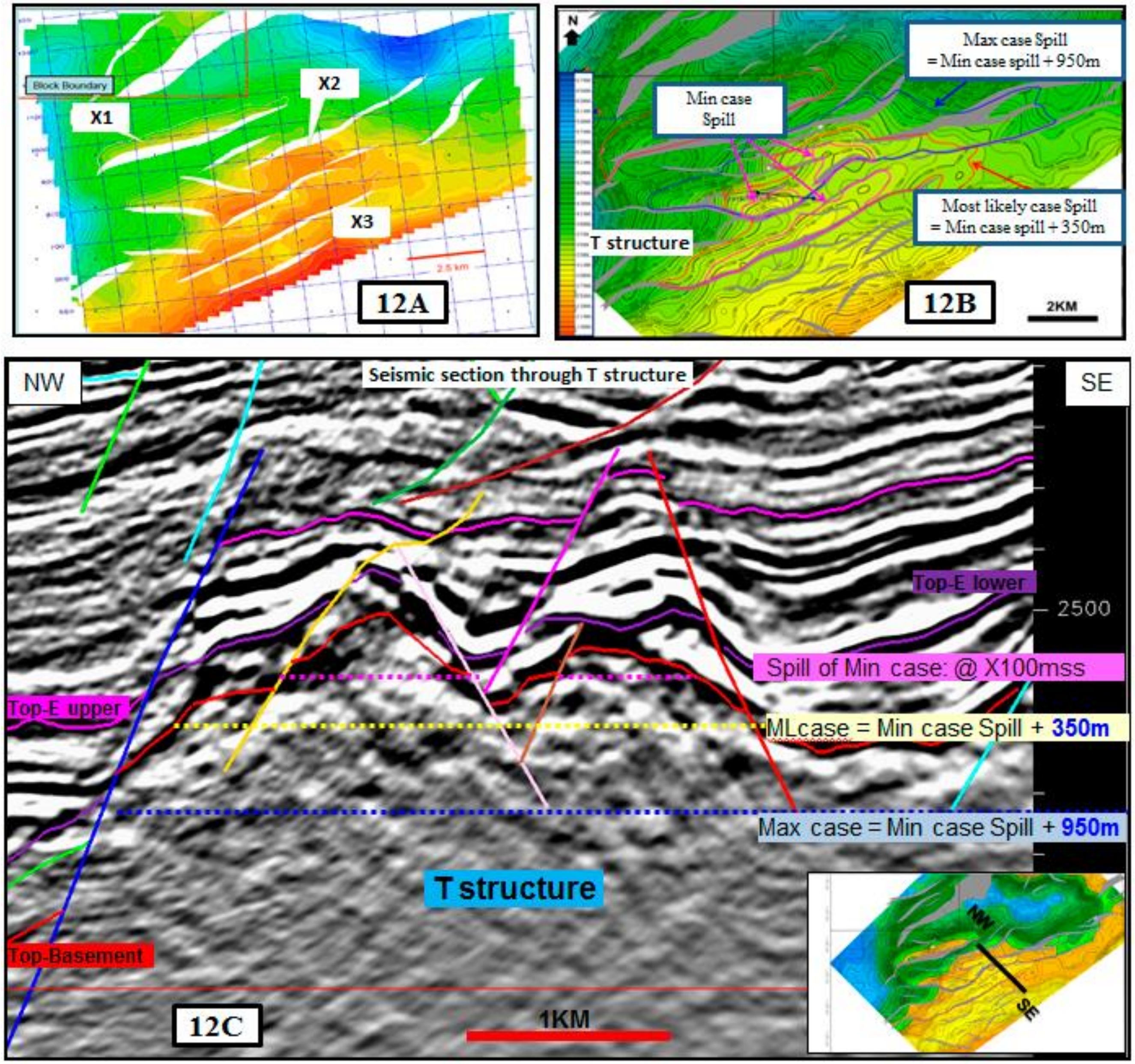

Figure 12. T structure: (A) Previous depth structural map. (B) Newly interpreted depth map from updated tuning of seismic and well data. (C) Typical seismic section across T structure showing three scenarios for structural spill point of Basal. Well data confirmed an oil column down to the most likely case of spill point.