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Petrographic Characteristics and Depositional Environment Evolution of Middle Miocene Sediments in the Thien Ung - Mang Cau Structure of Nam Con Son Basin

Pham Bao Ngoc[1], Tran Nghi[2], Nguyen Trong Tin[3], Tran Van Tri[4], Nguyen Thi Tuyen[5], Tran Thi Dung[2], and Nguyen Thi Phuong Thao[5]

[1]PetroVietnam University
[2]Hanoi University of Science
[3]Vietnam Petroleum Geology Union
[4]General Department of Geology and and Minerals of Vietnam
[5]Insitute for Geo-Environmental Research and Adaptation of Climate Change

Corresponding author: ngocpb@pvu.edu.vn
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Abstract - This paper introduces the petrographic characteristics and depositional environment of Middle Miocene rocks of the Thien Ung - Mang Cau structure in the central area of Nam Con Son Basin based on the results of analyzing thin sections and structural characteristics of core samples. Middle Miocene sedimentary rocks in the studied area can be divided into three groups: (1) Group of terrigenous rocks comprising greywacke sandstone, arkosic sandstone, lithic-quartz sandstone, greywacke-lithic sandstone, oligomictic siltstone, and bitumenous claystone; (2) Group of carbonate rocks comprising dolomitic limestone and bituminous limestone; (3) Mixed group comprising calcareous sandstone, calcarinate sandstone, arenaceous limestone, calcareous claystone, calcareous silty claystone, dolomitic limestone containing silt, and bitumen. The depositional environment is expressed through petrographic characteristics and structure of the sedimentary rocks in core samples. The greywacke and arkosic sandstones are of medium grain size, poor sorting and roundness, and siliceous cement characterizing the alluvial and estuarine fan environment expressed by massive structure of core samples. The mixed calcareous limestone, arenaceous dolomitic limestone, and calcareous and bituminous clayey siltstone in the core samples are of turbulent flow structure characterizing shallow bay environment with the action of bottom currents. The dolomitic limestones are of relatively homogeneous, of microgranular and fine-granular texture, precipitated in a weakly reducing, semi-closed, and relatively calm bay environment.

Keywords: calcareous sandstone, calcarinate sandstone, calcareous clayey siltstone, bituminous calcareous claystone, turbulent flow structure, Thien Ung - Mang Cau structure

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Introduction

The Nam Con Son Basin covers an area of about 100,000km^2, and extends from 6^{0}00' to 9^{0}45'N and from 106^{0}00' to 109^{0}00'E (Hiep, 2009). It is bounded in the northeast by Tuy Hoa shear zone, in the northwest by Con Son uplift, in the southwest by Khorat - Natuna uplift and in the east by Tu Chinh - Vung May area (Figure 1) (Bat *et al.*, 2009; Tri and Khuc 2011). The Thien Ung – Mang Cau structure is a linear uplift belonging to block 04-3 in the center of the basin (Figure 2). This is one of structures considered to be of petroleum potential and has been studied by many entrepreneurs, especially by VIETSOV-PETRO (1998) Joint Stock Company. Prospecting and exploration work in block 04-3 started in the 1970s. In particular, the Thien Ung - Mang Cau

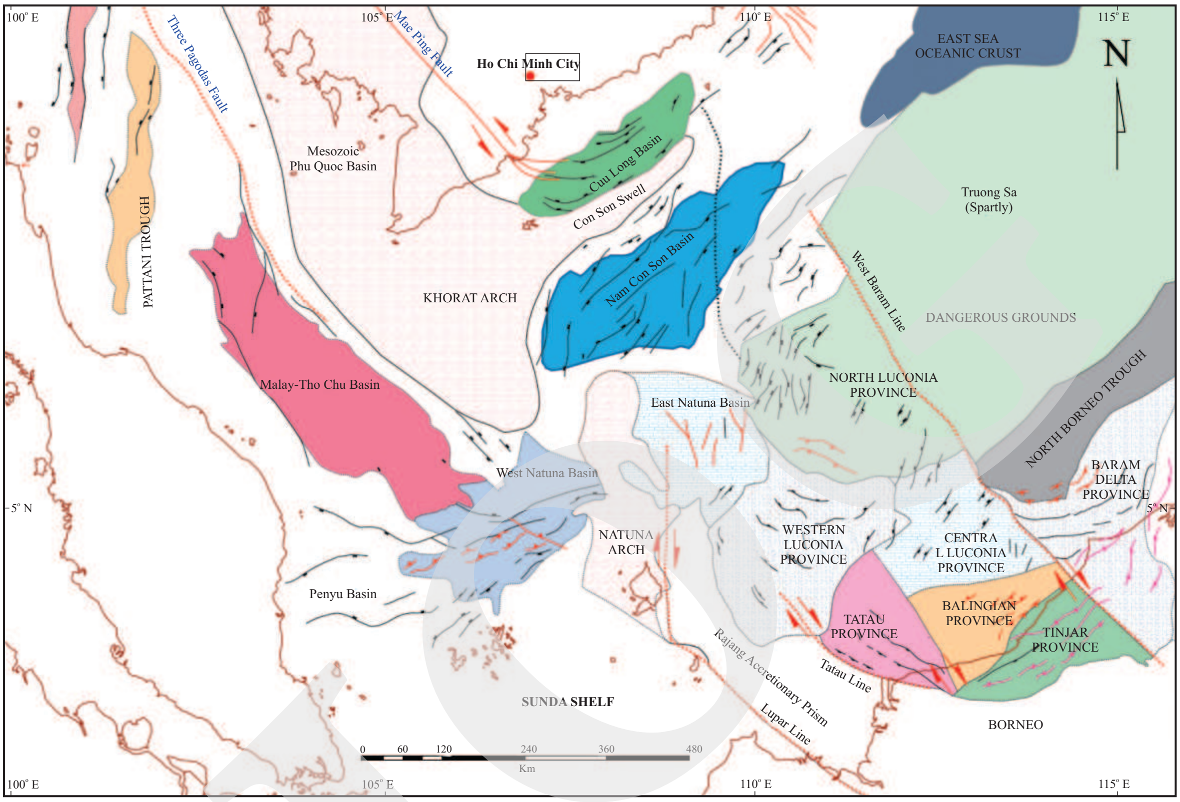


Figure 1. Location of the Nam Con Son Basin and its main tectonic and structural features (Tuan *et al.*, 2016).

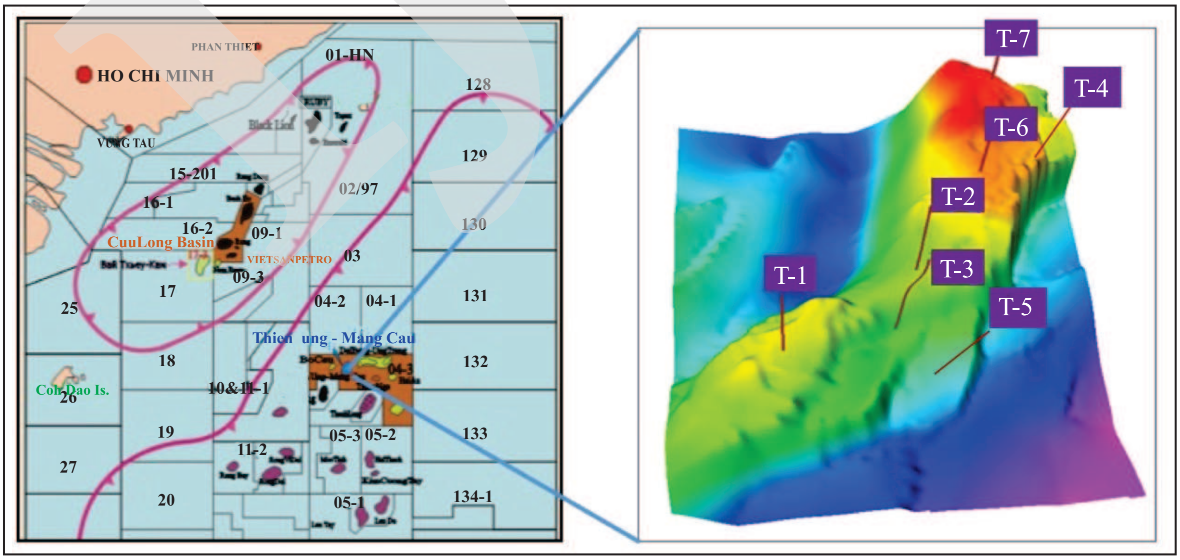


Figure 2. Location of the Thien Ung - Mang Cau structure in Nam Con Son Basin and the location of wells (T-1, T-2, T-3, T-4, T-5, T-6, and T-7) in the Thien Ung - Mang Cau structure.

structure was discovered by AGIP in 1979 while drilling into the Middle Miocene sediments. Since 1979 so far, seven exploratory drilling wells have been drilled, the oil and gas reservoir capability of the Middle Miocene formation has been confirmed and additional gas pools in the Lower Miocene formation and the basement rock have been discovered. The studies carried out so far have mainly focused on geologic structure as well general stratigraphic characteristics with the aim to evaluate the petroleum potential; no specific studies on petrographic characteristics as well as the depositional environment of the Middle Miocene sediments in the Thien Ung – Mang Cau structure. This paper will focus on clarifying somewhat this issue.

Geological Setting

The formation and development of Nam Con Son Basin have been directly affected by tectonic setting in Southeast Asia. In Paleocene, the south-east extrusion of the Indochina Block and southward drift of the proto East Vietnam Sea associated with the collision of Luconia micro continent and Borneo caused a series of right-lateral transform faults in the East Vietnam Shelf extending to the East Luconia. According to Ru and Pigott (1986), Hall (2002, 2009, 2013), Hutchison (2004), and Clift (2008), these tectonic activities were possibly derived from N-S extension in the Sunda Shelf. The formation mechanism of Nam Con Son Basin has related to the rifting which initiated in the Eocene and lasted to the Early Oligocene (Matthews, 1997; Gwang *et al*., 2000, and Fyhn *et al*., 2009). This rifting period was controlled by N-S extension, associated with E-W oriented faulting and deposition of rift fill sediments in local W-E trending sub-basins.

After the rifting phase as mentioned above, the spreading of East Vietnam Sea floor had the profound influence on Nam Con Son Basin. At about 25 Ma, the axis of the sea floor spreading shifted from WSW trend to SW trend (Andrew, 2010; Morley, 2007; Pubellier and Morley, 2014). There was the second extension phase at the SW of the rift tip including Nam Con Son Basin at the end of Early Miocene. This was caused by the southwestward propagation of the sea floor spreading continued by a continental breakup. As East Vietnam Sea floor spreading totally ceased at about 17 - 16 Ma, regional sea level fell during the late Middle Miocene leading to the erosion (up to several hundred meters) of the central part of the roll-over structures.

The second rifting phase was then followed by a thick post-rift sequence (Upper Miocene - Pliocene - Quaternary) due to the increase in sediment supply with respect to onshore uplift and magmatism (Cu *et al*., 2007; Fyhn *et al*., 2009; Hiep, 2007; Tri and Khuc, 2011.

In terms of stratigraphy, rock sequences in the basin are various, including pre-Cainozoic fractured granodiorite, clastic sediments of Lower Miocene, Middle Miocence, Upper Miocene and Pliocene - Quaternary (Hoang *et al*., 2008; Phuong *et al*., 1982; Que, 1998). However, the research focuses on Nam Con Son Formation in Middle Miocene (Figure 3).

Materials and Methods

This study is based on the following data those are core samples in the wells T-1, T-2, T-3, and T-4 in the Thien Ung - Mang Cau structure (Figure 4); sediment parameters analyzed from petrographic thin sections of within Middle Miocene formation of drilled wells T-1, T-2, T-3, and T-6 (Figures 5 - 22); and seismic section along line S13 interpreted by using a tectono-sedimentary relation approach.

The first method applied is analyzing thin sections through the optical microscope with the purposes to identify the different components of sedimentary rock (quartz, feldspar, rock fragments, and cements) as well as some sediment parameters which are roundness (Ro) and sorting

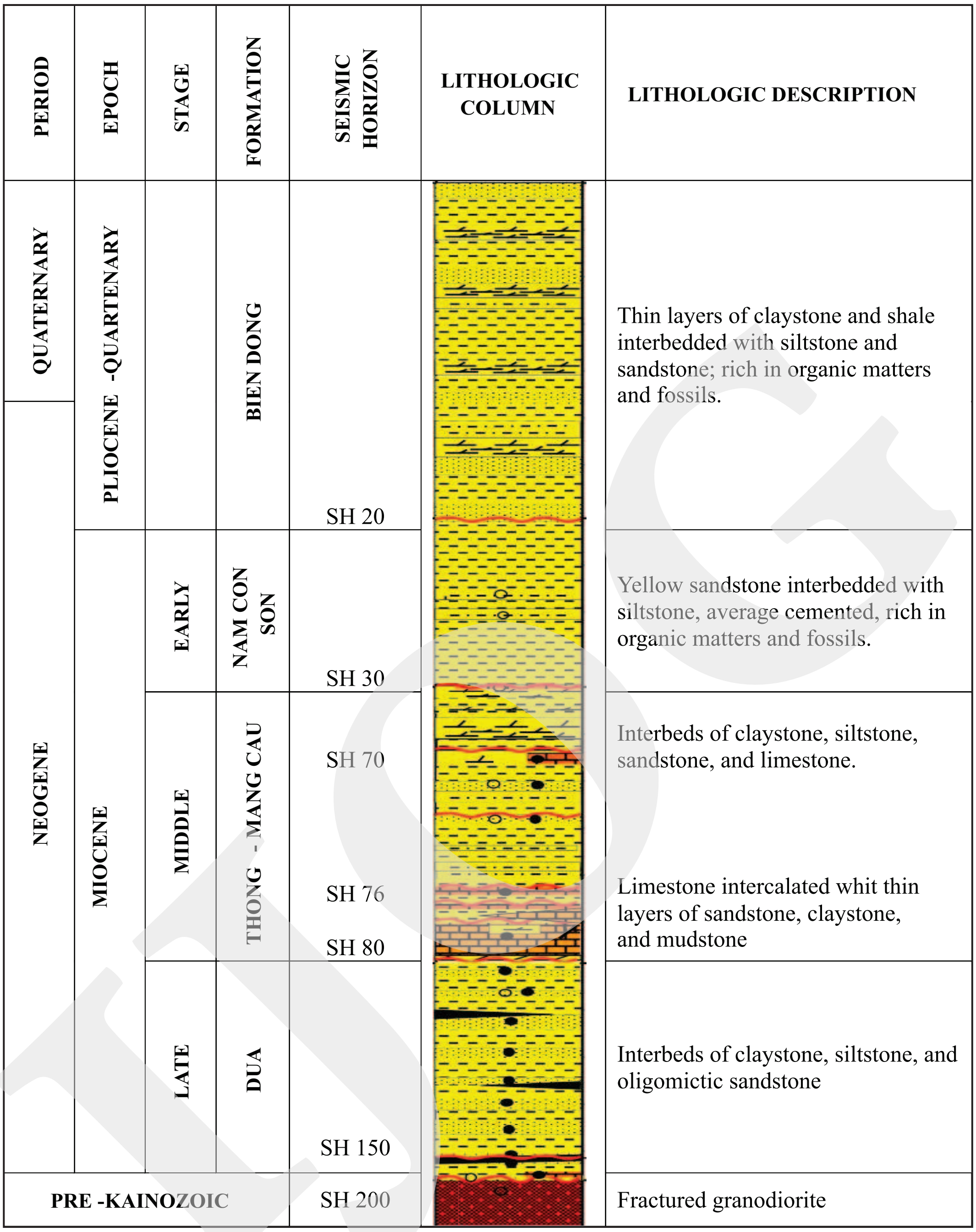


Figure 3. General stratigraphic column of the Thien Ung - Mang Cau structure.

(So). The sorting and roundness numerical classification used in the paper are based on Tran Nghi's classification (Nghi, 2012). The authors also analyzed sedimentary structures and interpreting depositional environments based on core samples from the wells in study area. Another method applied in the paper is interpreting seismic data in order to divide into three system tracts (LST, TST, and HST) in Middle Miocene.

Results and Discussion

Classification and Description of the Middle Miocene Sedimentary Rocks in the Thien Ung - Mang Cau Structure

In the study area, there exist three groups of sedimentary rocks comprising terrigenous group, carbonate group, and mixed group. The sedimentary group includes sandstone, siltstone,

Figure 4. Core samples in the wells T-2 (2,752.0 - 2,761.0 m), T-3 (2,772.6 - 2,775.25 m), and T-4 (2,630.00 - 2,632.65 m) in the Thien Ung - Mang Cau structure.

and claystone; the carbonate group consists of limestone and dolomite; and the mixed one includes calcareous sandstone, calcarinate sandstone, calcareous claystone, calcareous clayey siltstone, and sandy/silty/clayey limestones. The petrographic characteristics of these rock groups are described as follows:

Terrigenous group

In the study area, terrigenous rocks, consisting of sandstones, siltstones and claystones, are interstratified with each other, usually thin-bedded.

Sandstones

In well T-1, sandstones are encountered within the depth of 2650.60 - 2652.34 m; with irregular grain size, brown gray color, intercalated with coarse-grained siltstone with dolo-calcareous or clay cement, some thin layers of gray silty clay, increasing in number with depth. The rocks are different in grain size, consisting of fine-grained sandstone (at the depths of 2651.50 m, 2703.6 m and 2706.4 m (Figure 5 and 6), medium-grained sandstone (at the depth of 2711.6 m (Figure 7) and coarse- grained sandstone. They are separated from the overlying carbonate rocks by a clear erosion boundary. The beds are 20 - 150 mm in thickness, with different structures and unclear boundaries.

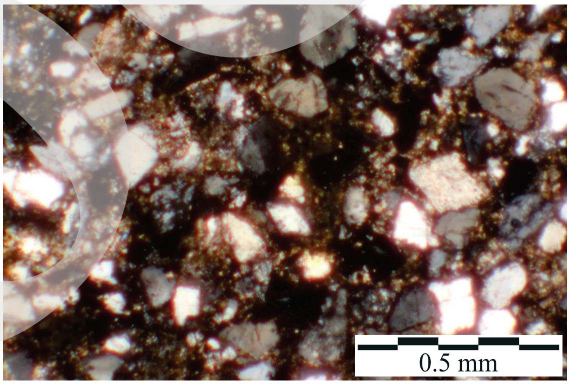


Figure 5. Photomicrograph of fine-grained greywacke sandstone, medium-sorted (So= 1.9), medium to well-rounded (Ro=0.5), with basal-pore-filling cement (matrix is more than chemical cement), at the depth of 2,703.6 m, well T-1; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

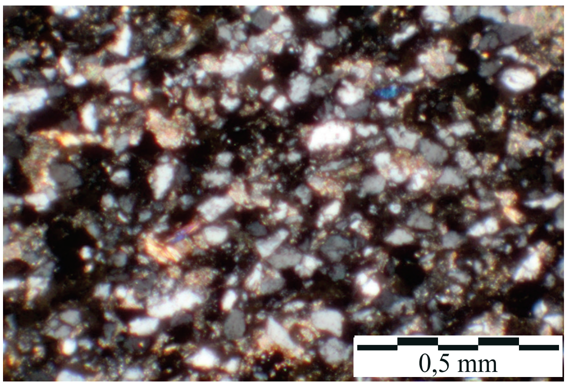


Figure 6. Photomicrograph of fine-grained arkosic sandstone, medium-sorted, medium to well-rounded at the depth of 2,706.4 m; well T-1; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

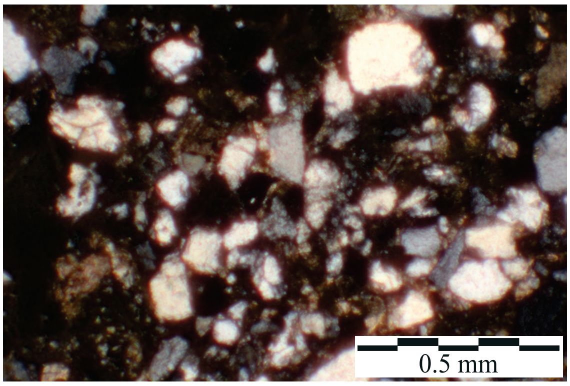


Figure 7. Photomicrograph of medium-grained greywacke sandstone, poorly-sorted (So=2.5), medium-rounded (Ro=0.4), basal-pore-filling cement (matrix is more than chemical cement), at the depth of 2,711.6 m; well T-1; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

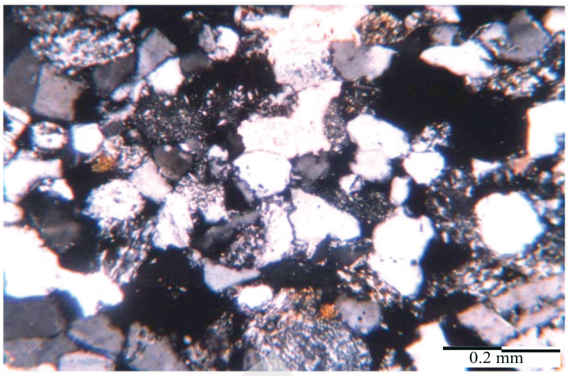


Figure 9. Photomicrograph of medium-grained arkosic sandstone, medium-sorted and medium-rounded (So= 2.1; Ro=0.5), pore-filling cement; tidal flat environment, at the depth of 3.031.2 m, well T-2; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

At the depth of 2756.5 m in well T-2, occurs sandstone of light gray and yellow gray colors, poorly sorted (Figures 8 and 9) with fine and fine-medium to irregular grain size, with various silt contents. In these sandstones are intercalated layers of siltstone and claystone containing organic materials. The sandstones also contain fragments of organisms up to 20 mm in size, consisting of poorly preserved benthic species such as Foraminifera, Echinoidea, Gastropods, and large fragments of Brachiopods.

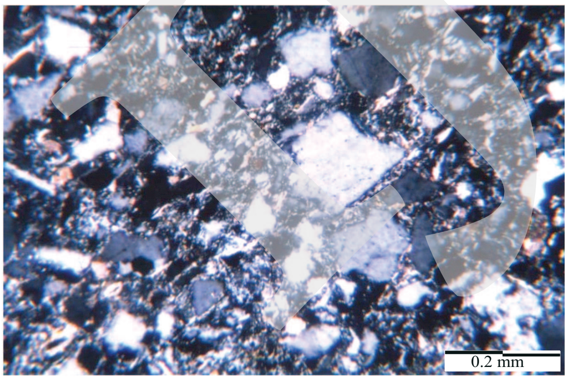


Figure 8. Photomicrograph of medium-grained greywacke sandstone, poorly-sorted (So=2.8), poorly- rounded (Ro<0.4); matrix is more than chemical cement, at the depth of 2,756,5 m; well T-2; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

Besides, fairly homogeneous, medium- to well-sorted and medium-rounded, fine-grained arkosic sandstones are encountered in well T-3 (Figures 10 and 11). In terms of petrographic composition, these sandstones are composed of light colored quartz, acidic plagioclase, pelitized potassium feldspar, muscovite, and pyrite.

Siltstones

In well T-1 are encountered poorly- to medium-sorted, medium- to well-rounded coarse–grained sandy and bituminous siltstones with calcarinate cement (Figure 12). Examination of core samples shows that the siltstones here are of thin-bedded structure with bedding thickness varying from 20 to 150 mm.

At the depth from 2757.1 m to 2816.9 m in well T-2 occur clayey and dolomitic siltstones

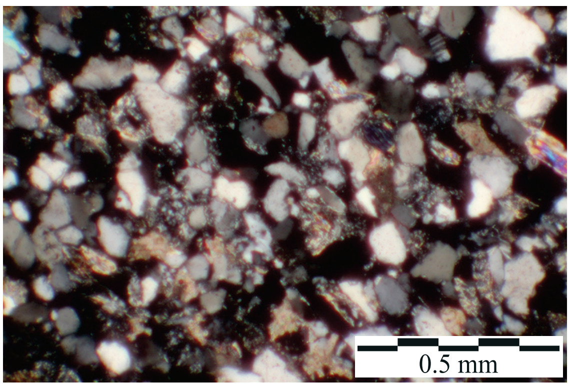


Figure 10. Photomicrograph of fine-grained arkosic sandstone, medium to well-rounded (Ro=0.6), well-sorted (So=1.5), with pore-filling cement, at the depth of 2,769 m; well T-3; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

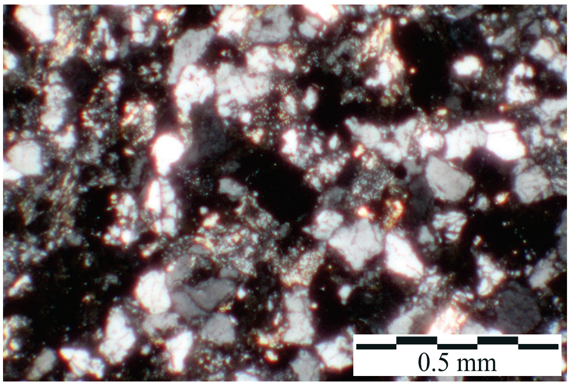


Figure 11. Photomicrograph of fine-grained arkosic sandstone,well-rounded and medium-sorted (So=1.6; Ro=0.6), with pore-filling cement; at the depth of 3,148.15 m, well T-3, Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

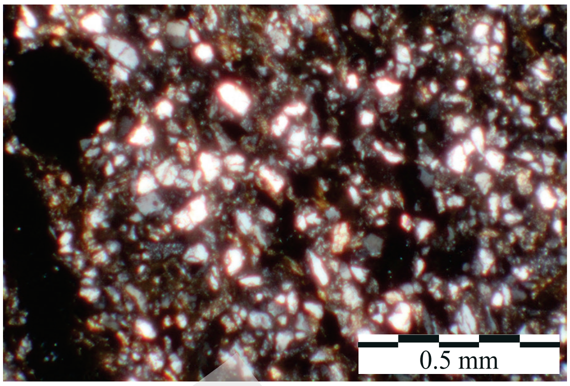


Figure 13. Photomicrograph of coarse-grained greywacke silstone, medium-well- rounded (Ro=0.6), medium sorted, with basal (calcarinate) cement (matrix is more than chemical cement), at the depth of 2,757.1 m,well T-2; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

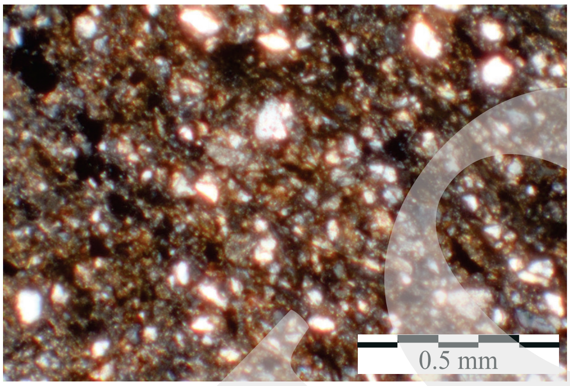


Figure 12. Photomicrograph of coarse-grained siltstone, medium to well-rounded (Ro=0.6), medium-sorted (So=2.0), with calcarinate cement, at the depth of 2,709.6 m; well T-1; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

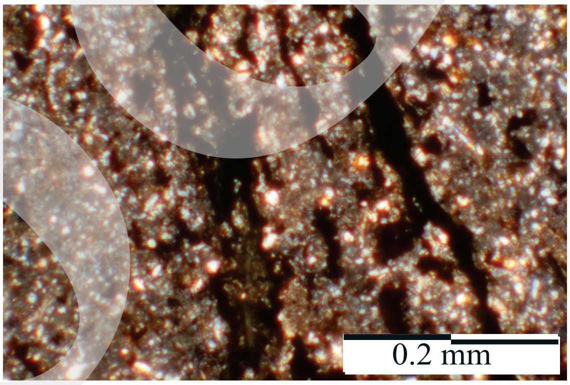


Figure 14. Photomicrograph of fine-grained siltstone, well-sorted, with directionally arranged, bituminized organic materials, at the depth of 2,815.6m, well T-2; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

with various clay and dolomite contents. The core samples have turbulent flow structure, alternated with fine-grained sandstones, siltstones, and claystones in the form of boudinage. The siltstones are mainly fine-grained (Figures 13 and 14), with basal-pore-filling cement. Their matrices are mainly composed of calcite, dolomite, clay, bitumen, and very fine materials. The rocks are poorly- to medium-sorted (Figures 13 and 14). Their clastic materials are composed of quartz, feldspar, mica, and rock detritus (Figure 15).

Claystones

The claystones in the area form thin layers intercalated in siltstones. Their mineral components include hydromica, kaolinite, chlorite, and montmorillonite. The clays are of weathering genesis, coming from the erosional domains of Nam Con Son uplift. However during a long period in a marine environment, montmorillonite started to be formed. Among the wells drilled in the Thien Ung-Mang Cau structure, claystone was encountered in wells T-2, T-3, T-4, and T-5. They are black gray in color due to bitumen contained in thin intercalating sandstone layers.

In thin sections from the Thien Ung wells in the central area of Nam Con Son Basin, bitumen has been observed with uneven distribution. Typically, at the depth of 3033.8 m in well T-2, claystone has been encountered to contain bitumen in the form of bands directionally arranged following the sericitization pattern of the clay (Figure 16).

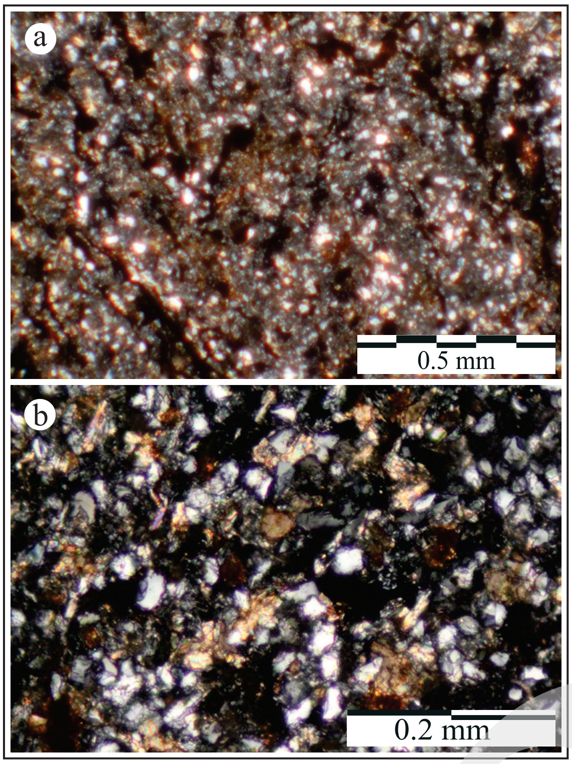


Figure 15. Photomicrographs of fine-grained siltstone, medium sorted, with bituminous clay cement (a and b); at the depth of 2,816.90 m; deposited in bay environment; well T-2; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

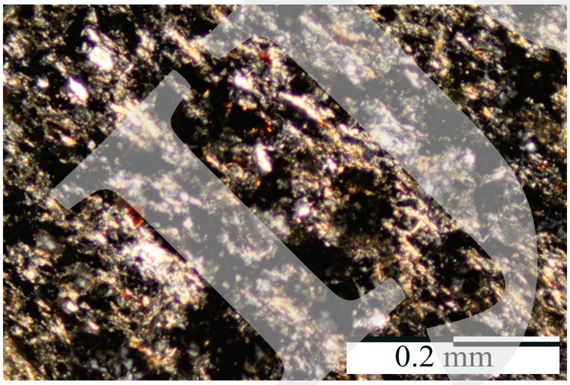


Figure 16. Photomicrograph of claystone containing bitumen in the form of bands directionally oriented following the sericitization pattern of the clay; at the depth of 3,033.8 m, well T-2; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

Within the depth between 2678.8 m and 2686.0 m in well T-3, have been encountered thin layers of claystone in the form of undulated lenses alternates with siltstones and fine-grained sandstone, forming a shallow marine turbidite structure. This type of structure is formed by the effect of quite strong bottom currents, which mix up sediment layers with different particle sizes when they are still in loose state.

Carbonate rock group

Carbonate rocks are obsserved in the Thien Ung - Mang Cau structure. Among wells T-1, T-2, T-3, and T-4, the Middle Miocene carbonate rocks are encountered in well T-1, between 2643.70 m and 2650.30 m (about 6.6 m in thickness). They are of grey, yellowish, and bright grey color and diverse textures, consisting of platy, coarse-grained calcite intermingled with fine-grained and microgranular dolomite containing some bioclastics (Figures 17 - 19). Some microfissures and vugs are seen on thin sections.

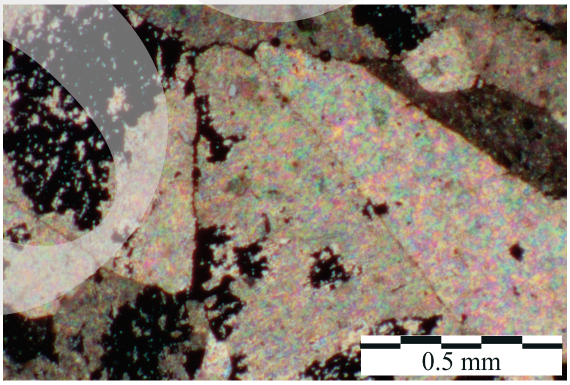


Figure 17. Photomicrograph of microgranular limestone, at the depth of 2,644.2 m, well T-1; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

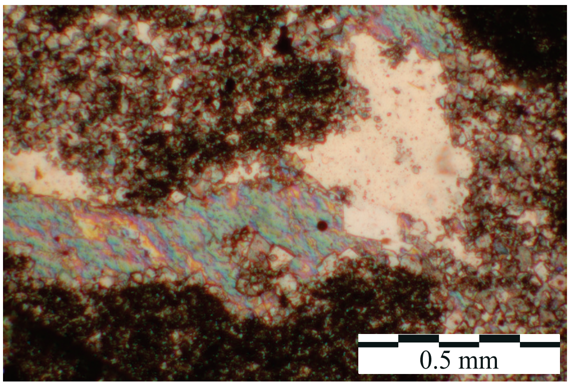


Figure 18: Photomicrograph of microgranular dolomitic limestone containing bituminized organic matter; at the depth of 2,645.2 m; well T-1; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

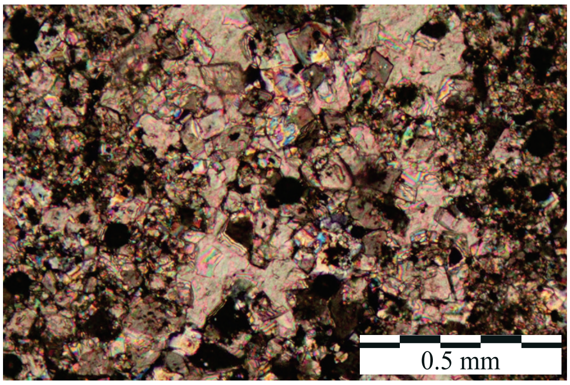


Figure 19: Photomicrograph of fine-grained dolomitic limestone, composed of euhedral rhombic dolomite crystals, platy calcite crystals, evenly disseminated black bitumen, distorted pyrite crystals, deposited in bay environment, at the depth of 2,650.1 m; well T-1; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

Calcareous dolomites are quite common at the depth 2645.80 - 2650.30 m. The rocks have four main components: authigenic dolomite in the form of irregularly distributed small rhombic crystals, accounting for 70% of the whole rock mass, followed by sporadically distributed platy calcite accounting for 15%, the rest being disseminated bitumen and distorted pyrite crystals (Figure 17).

Mixed sedimentary rocks

Calcareous and calcarinate sandstones

Quartz-lithic sandstones with basal cement composed mainly of microgranular calcite and dolomite are recognized in well T-1 at the depth of 2711 m. The clastic materials account for 70%, the basal calcite and dolomite cement accounts for 30%. Among the clastic materials quartz accounts for 60%, medium rounded (Ro = 0.6), rock detritus accounts for 30 %, mainly composed of quartzite, rhyolite and dacite; the feldspar content is quite low - 10% (Figure 20).

Sandy limestone

This type of mixed sedimentary rocks is encountered quite commonly in well T-1 (Figure 21) at several depths such as 2644.0 m, 2646.0 m, 2646.30 m, 2648.4 m, and 2650.5 m, with the sand content varying with the depth. For example,

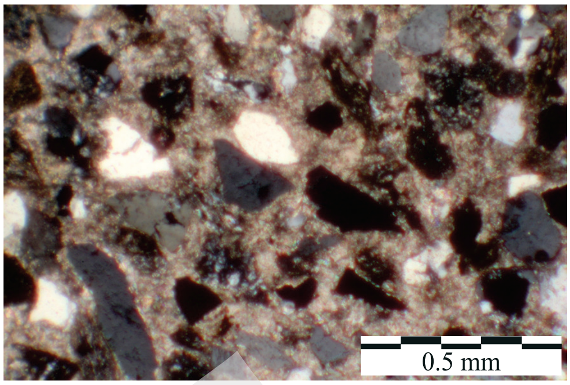


Figure 20: Photomicrograph of coarse-grained calcarinate quartz-lithic sandstone with basal microgranular dolo-calcareous cement, deposited in bay environment, at the depth of 2,711.0 m, well T-1; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

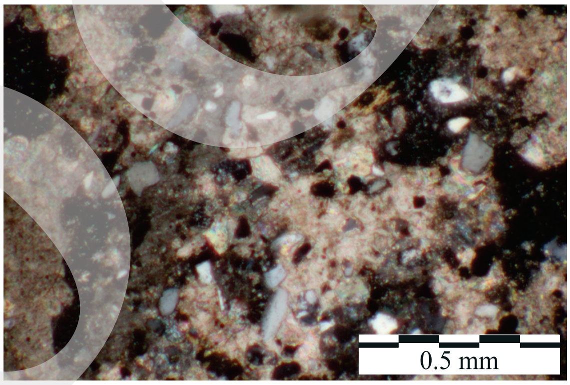


Figure 21: Photomicrograph of sandy limestone, at the depth of 2,650.5 m; well T-1; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

at the depth of 2644 m, sand accounts for 10%, with poikilitic texture, with calcite matrix on which stand out quartz sand grains; whereas at the depth of 2646 m the sand content is lower, only about 5%; and at the depth of 2,646.3 m it is rather high, in some places reaching 25%.

Besides sand, the limestones and dolomites in the area also contain bitumen, as observed at the depth of 2648.4 m in well T-1, where the sand is fine- to medium-grained and poorly sorted.

Silty calcareous claystones

Silty calcareous claystones are encountered rather commonly in the Thien Ung wells at the center of Nam Con Son Basin. Specifically, they are present in well T-2 (at the depth of 2755.8 m) and well T-4 (at the depth of 2630.4 m, 2635.3 m and 2637.2 m). In well T-2, clay consists of hydromica and kaolinite accounting for about 50%, the rest being microgranular and cryptocrystalline calcite accounting for 20%; especially it contains organic matter (about 15%) (Figure 22). Besides, other minerals also occur, such as chlorite with banded and granular ores. In well T-4, the calcareous claystones contain silt which is arranged in irregular bands. The rocks are of horizontal parallel bedding structure; in particular at the depth of 2637.2 m, the claystone contains bitumen, which is unevenly distributed. Authigenic calcite is present in all silty calcareous claystone samples.

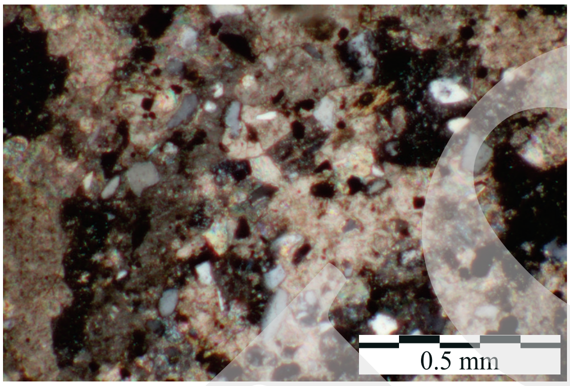


Figure 22. Photomicrograph of silty calcareous claystone at the depth of 2,630.4 m; well T-4; Crossed Polarized Light (CPL), Middle Miocene (N_1^2).

Depositional Environment Evolution in Relation to Sea-level Changes

Between petrographic composition and depositional environment there is a causative relationship. In the meantime, depositional environments always change subject to the cycles of global (*i.e.* eustatic or absolute) and local (or relative) sea level changes. In the Thien Ung - Mang Cau structure, the global sea level in Middle Miocene created a sediment sequence corresponding with a facies association extending laterally from the margins to the center of the basin and vertically from the bottom to the top of the sequence. In vertical section, the Middle Miocene sequence consists of three systems tracts: lowstand systems tract (LST), transgressive systems tract (TST), and highstand systems tract (HST) (Ngoc and Nghi, 2016).

The lowstand systems tract (LST) is characterized by terrigenous sediments consisting of (1) poorly-rounded, poorly-sorted greywacke silty sandstone deposited in a river-bed environment (LST) lying on an erosion-incision surface (Figure 8), and (2) medium rounded, medium to well rounded arkosic sandstone deposited in a tidal flat environment with wave action (amr LST) (Figure 9). As regards petrographic composition, the mixed sedimentary rocks are absent in the lowstand systems tract (LST). The greywacke sandstone has basal cement, which accounts for 15 %, contains no calcite and dolomite. The matrix is higher in content than chemical cement such as $Fe_2O_3.nH_2O$ and $SiO_2.H_2O$. The arkosic sandstone deposited in coastal environment has pore-filling cement (<15%), with the absence of authigenic calcite, although this tidal flat sand facies are located at the lowest position of the shoreline and overlies the marl sediments deposited previously in shallow bay environment. On seismic sections, the seismic wave fields are of rough, chaotic pattern, reflected with low frequency reflection, indicating the sediments are coarse-grained with cross-bedded or isotropic cross-bedded structure.

The sediment accumulation space in the transgressive systems tract (TST) is similar to that in the lowstand systems tract (LST). However, as the transgression occurred within a rather long period, the depositional environment changed consecutively from coastal to shallow marine. This caused the formation of the group of mixed sedimentary rocks described above, which includes dolo-calcareous sandstone (Figure 20), sandy limestone (Figure 21), and silty calcareous claystone (Figure 22). As observed on core samples, these mixed sedimentary rocks have a turbulent flow structure (Figure 23). This is an extremely interesting phenomenon in sedimentary geology, which proves a long-lasting and continuous transgression phase.

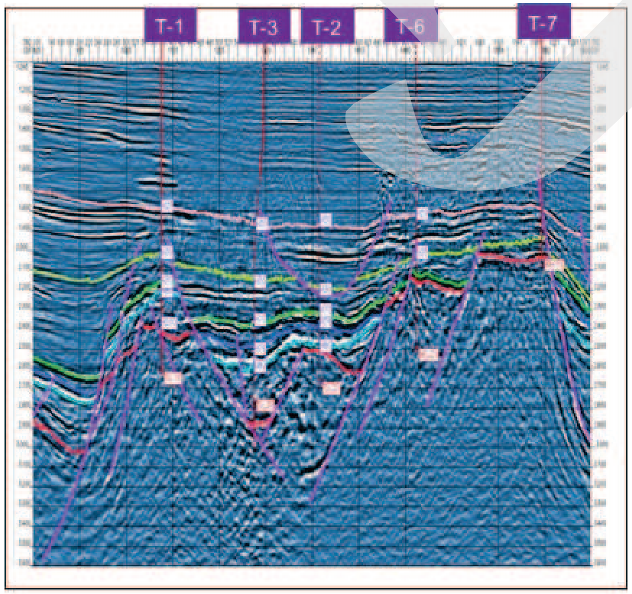
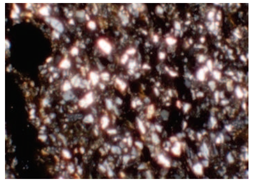
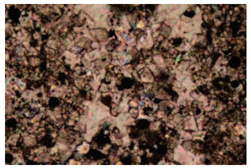
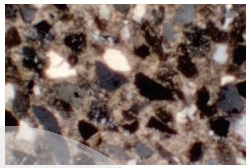
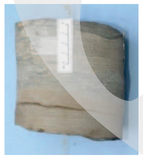
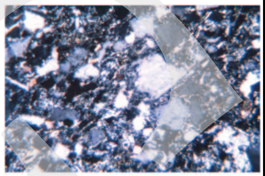
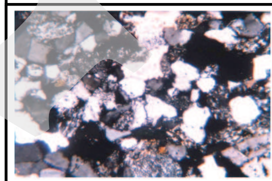
Seismic Section	Sedimentary Depositional Environments	Systems Tracts	Core Samples	Thin Sections	Lithological Characteristics
	Highstand Deltaic Environment, characterized by fine - grained terrigenous sediments (siltstone, claystone)	Highstand Systems Tracts (HST)	Well T-1, 2816.43-2816.63 m in depth 		Core Sample: fine-grained sandstone mixed with siltstone and claystone containing bitumen; planar or laminated bedding. Thin Section: Siltstone containing bitumen, medium sorting and well - roundness (amr HST).
	Transgressive shallow marine and bay environment, characterized by complex sedimentary rocks (calcareous and calcarinate sandstone, silty calcareous claystones)	Transgressive Systems Tracts (TST)	Well T-2, 2755.10-2755.25 m in depth 		Core Sample: planar bedding structure. Thin Section: dolomitic limestone created in the bay environment (MtTST).
					Core Sample: sandstone, siltstone, and claystone with "pseudo-turbidite structure created by bottom currents. Thin Section: Calcarinate sandstone with based cement (mtTST).
	Lowstand systems tract river channel and river-mouth environment, characterized by sedimentary rocks with stratification structure	Lowstand Systems Tracts (LST)	Well T-3, 2820.08-2820.20 m in depth 		Core Sample: Sandstone with stratification structure. Thin Section: graywacke sandstone, poor sorting and poor roundness, river channel environment (ar LST).
					Core Sample: Cross-bedding. Thin Section: arkosic sandstone, medium sorting, medium - well roundness, tidal environment.

Figure 23. Correlation of seismic reflection pattern, core samples, and thin sections of the Thien Ung – Mang Cau structure, Nam Con Son Basin.

This process can be explained for each type of rock as follows:

As regards the calcareous and calcarinate sandstones, they are well-rounded and well-sorted, consist of two petrographic components deposited in two different environments. The allogenic clastic material composed of quartz and feldspar was deposited in the tidal flat environment with wave action, thus well rounded and well sorted. In the meantime, the authigenic matrix composed of calcite and dolomite was precipitated in the shallow bay environment with pH $\geq$ 8.5. The question is, why do these two different components, which are not paragenetic, occur together? This is explained as follows: due to the transgression, the tidal flat environment changed into the shallow bay environment, which was suitable for the precipitation of calcite and primary dolomite. However, as in shallow bays, there were always bottom currents in action, the sand and carbonate sediments were mixed up into mixed sediments. After the lithification process, they turned into calcareous sandstone or calcarinate sandstone, depending on the percentage of carbonate precipitated.

As regards other mixed sedimentary rocks, such as silty calcareous claystone and bitumino-calcareous claystone, the explanation is similar. According to the rules of mechanical and chemical differentiation, silt with carbonate cement and lime clay, characterized by shallow sea, are deposited closer to the shore than carbonate materials.

When the sea level rises, these fine sediments are brought to a greater depth with pH $\geq$ 8.5 and calcite and dolomite start to be precipitated.

In summary, the sediments in the transgressive systems tracts (TST) continuously change in facies from the margin to the center of the basin, because all the sediments deposited in the lowstand period were covered by precipitated dolo-calcareous mud, then these sediments were redistributed and mixed up by the bottom currents to form mixed sedimentary rocks, ranging from dolo-calcareous claystone through dolo-calcareous siltstone to dolo-calcareous sandstone (amt TST) (Figure 24). At the maximum transgression, the shallow bay environment with elevated pH (8.5-9) was maintained for a long period, so a rather thick dolomitic limestone layer was formed overlying the mixed sedimentary rocks (mt TST) (Figures 17 - 19).

The sedimentary rocks in the highstand systems tract are also of monomictic composition, similar to those in the lowstand systems tract. In the Thien Ung – Mang Cau structure are frequently seen the deltaic silty sand facies (amr HTS). These facies were formed in the conditions ranging from highest to the medium sea-level. However, from the highest sea-level to the boundary between the erosional and depositional regions in the high regression phase occurs delluvial gravelly sand and alluvial silty sand facies; while in the submerged space from the tidal environment to the center of the basin, regressive sediments (mrHST) were deposited. In seismic sections, the seismic wave fields are usually of accretionary wedge (downlap) structure. From the margin to the center of the basin, the sediments change gradually from the tidal flat oligomictic silty sand facies to the shallow marine silty clay facies and finally to bay dolo-calcareous mud facies (Figure 24).

As the sediment composition depends on the cycles of global sea level changes and the relative sea-level changes are sometimes caused by tectonic movements, in the vertical section the sedimentary facies are of rhythmic structure. In each transgressive or regressive rhythm, there are intercalations of opposite facies. For example, in the transgressive sandy mud facies rhythm, there are lenses of regressive silty sand with downlap structure, forming the complex facies amr/mt TST. In the contrary, the highstand deltaic silty sand facies rhythm are usually intercalated lenses of transgressive mud or calcareous clay facies, forming the complex facies mt/amr HST.

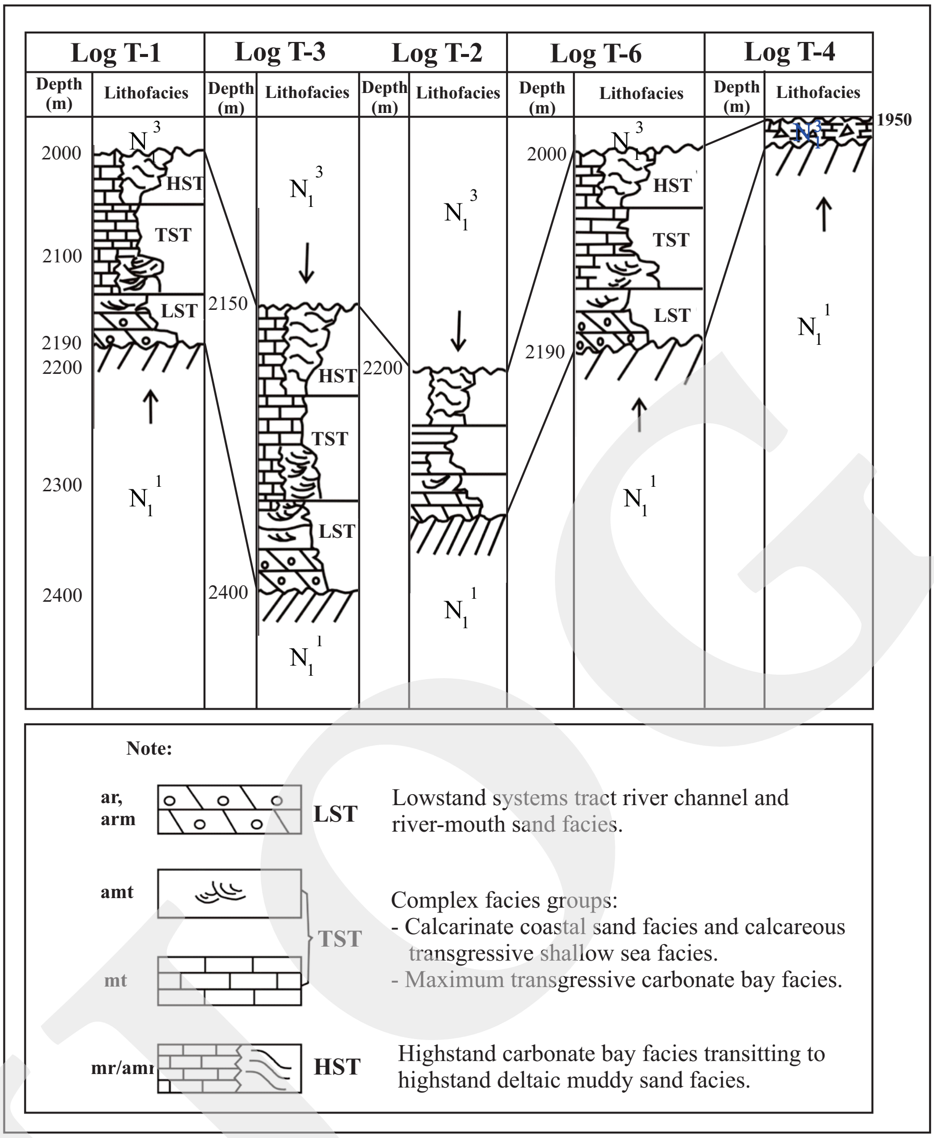


Figure 24. Cross-section correlation of three system tracts (LST – lowstand system tract, TST – transgressive system tract, HST – highstand system tract) in Middle Miocene through wells T-1, T-2, T-3, T-4, and T-6, the Thien Ung-Mang Cau structure, Nam Con Son Basin (a - alluvial, m - marine, t - transgressive, r – regressive; mt/amr – mixed depositional environment between mt and amr).

Conclusion

Petrographic characteristics

In the area of the Thien Ung – Mang Cau structure occur three groups of sedimentary rocks as follows:

(1) The clastic rocks consist of poorly-rounded and poorly-sorted polymictic arkosic, greywacke sandstones and siltstones; occurring in the lower part of the formation and surrounding the uplifts playing the role as erosional domains. The farther from the erosional domains, the more common the well sorted and well-rounded tidal flat sand facies. This monomictic rock group characterizes the lowstand systems tracts (LST) and highstand systems tracts (HST). The claystones pertain to shallow marine clay facies, occurring far away from the shore in the form of lenses and thin layers, which change laterally into the tidal flat sand and offshore bay calcaerous mud facies.

(2) The monomictic carbonate rocks consist of dolomitic limestone and calcaerous dolomite with fine-grained to microgranular texture.

(3) The mixed sedimentary rocks consist of calcareous and calcarinate sandstone, calcareous siltstone, calcareous claystone and bituminous claystone, occurring offshore, characterizing transgressive systems tracts (TST). The calcareous and calcarinate sandstones have two main components: allogenic clastic material and authigenic calcite-dolomite.

The distribution of the above petrographic groups in different environments is controlled by sea-level change cycles. The group of monomictic non-calcareous sandstones characterizes the lowstand systems tracts (LST) and highstand systems tracts (HST). The monomictic claystones are of horizontal bedding, extend in a large area usually called "submerged plain", were formed in the stage of maximum transgression. The mixed-sedimentary rocks were formed in the transgressive phase and characterize the transgressive systems tracts (TST). They reflect two depositional processes and two depositional environments which took place continuously, ranging from the coastal environment with strong wave action to the shallow bay environment with pH ≥ 8.5 suitable for precipitating calcareous mud and dolomite. The bituminous siltstones and claystones characterize weakly reducing bay environment with development of algae in both transgression and regression phases.

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