



Sediments Evolution of Napo Formation in the Slope Belt of Oriente Basin—A Case Study of Block T

Chao-qian Zhang^{1(✉)}, Wen-song Huang¹, Shi-yao Lin², Ke-xin Zhang¹, He-ping Chen¹, Zheng Meng¹, Yu-sheng Wang¹,
and Fang Xu¹

¹ Research Institute of Petroleum Exploration & Development,
PetroChina, Beijing, China
{zhangchaoqian, hwshws6, zhangkexin, chenheping1,
mengzheng, wangyus, xufang1984}@petrochina.com.cn
² CNPC International Andes Petroleum Company, Quito, Ecuador
shiyao.lin@andespetro.com

Abstract. The Napo Formation of the Oriente Basin plays an important role in the hydrocarbon exploration and production of the Ecuador. This study is based on the data of T block which is located in the eastern part of Ecuador. Evolution sequence is divided through seismic and logging data; facies is determined by core description for each sequence; and finally, the sediment evolution of the Napo Formation can be delineated clearly. The Napo Formation is a transgressive system, where five sequences were formed with the changing sea level. Superimposed retrogradational facies is typical in these sequences. Facies analysis indicates that “T,” “U,” and “M1” units are tide-dominated estuarine deposits involving tidal channel, tidal bar, sand flat, and marsh. In addition, residual delta sandstones were found in the lower part of the “M1” unit, but which is distributed in restricted zones and is hard to identify. Those delta sandstones may indicate that there is a delta before the tide-dominated estuarine deposits. Sedimentary facies changed to shallow-marine shelf in the upper parts of the sequences due to the rising sea level, and marlstone deposited. Based on

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the facies and sequence study, the sedimentary system and sediments evolution can be known in the Napo Formation. This is helpful to understand the sedimentary conditions of the Napo Formation in the slope belt of the Oriente Basin.

Keywords: Oriente basin · Napo Formation · Sequence stratigraphy · Facies features · Sediments evolution

1 Introduction

The Oriente Basin, about $10 \times 10^4 \text{ km}^2$, is one of the foreland basins in the South American continent. The Vaupes and Macarena uplifts are located on the north, the Marañon Basin on the south, the Brazilian Shield, and the Cordillera Mountains on two sides of the Oriente Basin [1] (Fig. 1). The Shushufindi field, the first oil field in the scale of billion tons, was discovered in 1959 [2]. After that, several oil fields were found and put into production. The Napo Formation is the most important oil-bearing formation in those oil fields.



Fig. 1. Workplace in the eastern part of the Basin

According to the tectonic unit, the Oriente Basin can be divided into thrust belt, foreland belt, and slope belt [3]. Affected by the Andes fold, many anticlines and high-dip compressive torsional faults are developed in NS direction on the western Oriente

Basin. On the eastern part, impacted by the Laramide movement, the structure is gentle [4, 5]. This basin experienced three evolutionary stages, from a crustal basin to a rift basin, and finally to a foreland basin. The Cretaceous-Tertiary sediment is more than 5000 m thick and formed a broad asymmetric syncline [6–8].

The study place, T block, is in the northern part of the Oriente Basin, with an area of about 493 km². The formation in this area shows a low slope from east to west, at a dip of about 1–3.5°. In addition, a series of high-dip reverse faults and low-relief structural traps are distributed in the area. Hydrocarbon is contained in the Hollin Formation, Napo Formation, and Tena Formation, of which the “M1,” “U,” and “T” units of the Napo Formation are the most important. Based on drilling and logging data of T block, sedimentary facies and stratigraphic evolution characteristics of the Napo Formation were investigated in this study.

2 Sequence Stratigraphy

The South American plate formed in the Triassic-Jurassic period due to the disintegration of the Gondwana. Many grabens formed in this period, and acidic volcanic rocks and continental sediments formed at the basin basement. The Oriente Basin mainly deposited during the Cretaceous period when the tectonic activity was relatively weak. But the tectonic movement was not the key factor controlling the sedimentation of this basin. In fact, it is a depression basin receiving Cretaceous sediments mainly from the Brazilian Shield [6, 9, 10].

The stratigraphic distribution in this study area can be divided into pre-Cretaceous, Cretaceous, and Paleogene sediments. The pre-Cretaceous sediments are the Jurassic and Paleozoic, without hydrocarbon accumulation. The Cretaceous Hollin and Napo Formations are main oil-bearing targets in Block T. The Napo Formation deposited above the “C limestone” which is the boundary between the Hollin and Napo Formations.

The Napo Formation can be subdivided into “T,” “U,” “M2,” and “M1” sandstone units by stable marlite intervals (“B limestone,” “A limestone,” and “Napo shale”). The residual Tena Formation unconformably contacts with the underlying Napo Formation (Fig. 2).

Based on the global sea level during the Cretaceous, the sea-level fluctuation experienced from rising to descending, and the rising process lasted relatively longer, so the sediments can be considered as a complete second-order sequence. On seismic sections, the angular unconformity between the Hollin Formation and the pre-Cretaceous Formation can be clearly identified. This unconformity can be used as the bottom of the Cretaceous second-order sequence. On the top of the second-order sequence, there is another unconformity between the Napo and the Basal Formations, but it is not obvious locally.

According to seismic and logging data, five sequences in the Napo Formation: KSQ1 including “T” sandstone—“B” limestone units; KSQ2 including “U” sandstone—“A” limestone units; KSQ3 including “M2”—“M1” limestone units; KSQ4 including

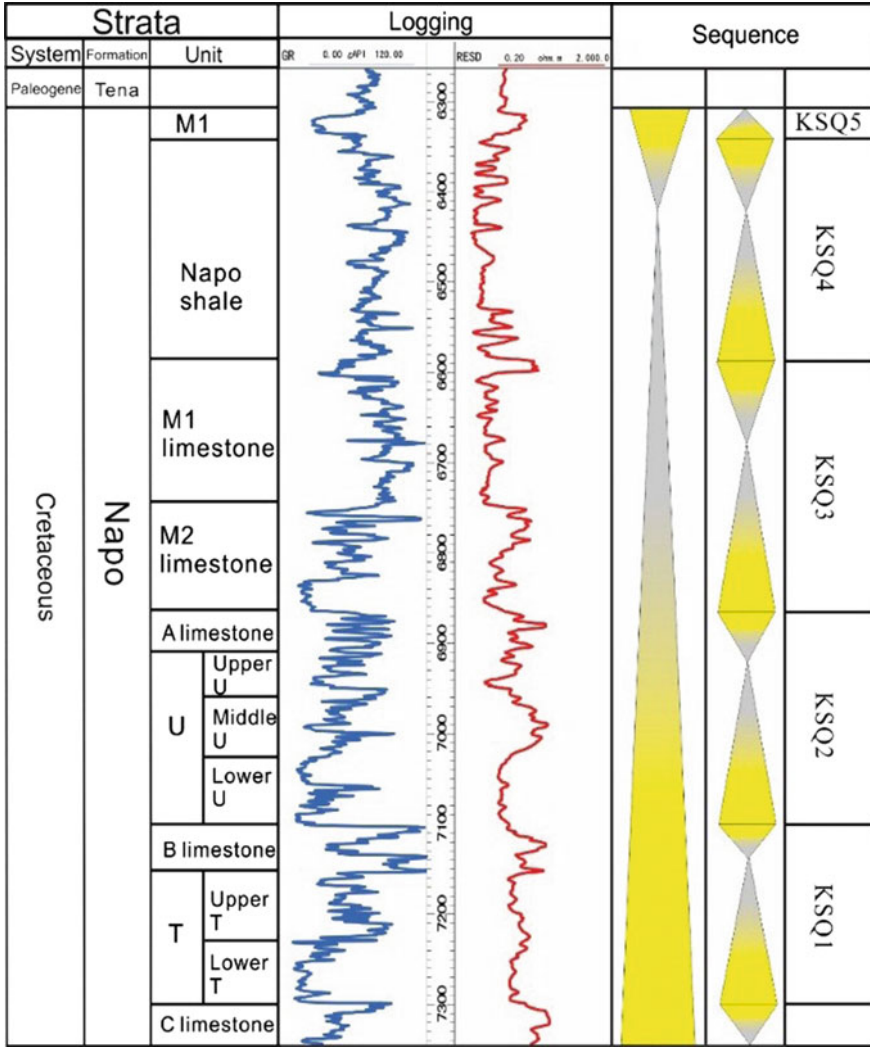


Fig. 2. Stratigraphic classification of Napo Formation

“Napo shale” unit; and KSQ5 including “M1” unit. All of boundaries of the five sequences are the surfaces of lithologic change. Their seismic reflections are obvious and continuous [11].

3 Lithofacies

The sea level dropped to the lowest level during the deposition of the Hollin Formation, and then, it began to rise slowly. The process lasted almost all the Napo stage. During the long-term sea-level rising process, the sea level reached the deepest at the

“Napo shale” interval, and then, the M1 sand deposited with the dropped sea level and formed a completed second-order sequence. In addition, there are many secondary fluctuations formed during this sea-level ascending process, which resulted in third-order sequences (KSQ1–KSQ5). All the sequences followed a lithofacies evolutionary pattern from continental to marine facies (Fig. 3). And the logging data of every sequence show an upward-fining trend (Fig. 2), indicating a typical transgressive depositional environment.

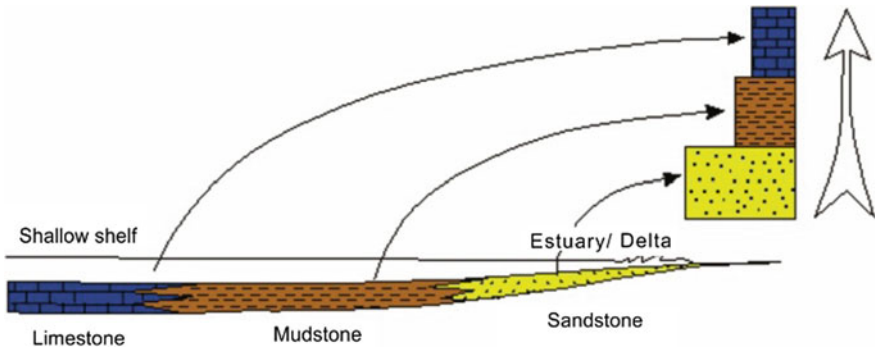


Fig. 3. Sedimentary model of Napo Formation

Facies evolution (Fig. 3) shows: First, fluvial facies and transitional facies deposited at low water level period, parallel bedding can be observed at the bottom of “M1,” “U,” and “T” units, and coarse-grained sandstone with shale of a relative high content is developed in this interval; second, many tidal-related sediments can be found above the fluvial deposition; tidal bidirectional cross-bedding, double mud layers, and reactivation surfaces are typical; and medium-fine sandstone is dominated with low shale content in this part. In addition, white calcareous interbeds can be found, and a few biological relics also can be found in cores. They are main evidences to determine the depositional environment—a tide-controlling high-energy transitional environment (Fig. 4).

Finally, as the water level rose, the shale content increased. Wavy or lenticular bedding became rich, indicating the water energy was relatively low, and the tidal influence was still obvious. When the water level reached the highest, the environment became the shallow sea shelf. The cores of “Napo shale” unit are mud shale (Fig. 4), which was formed in the shallow sea shelf environment. The “A limestone,” “B limestone,” “M2 limestone,” and “M1 limestone” units were also developed in that environment. These facies may be identified only on logging data because they are not pay zones and there are no core data from them. However, the dark green glauconitic sandstone should be paid attention to, which is distributed in the upper part of T unit. It also belongs to shallow shelf with rich glauconitic sediments.

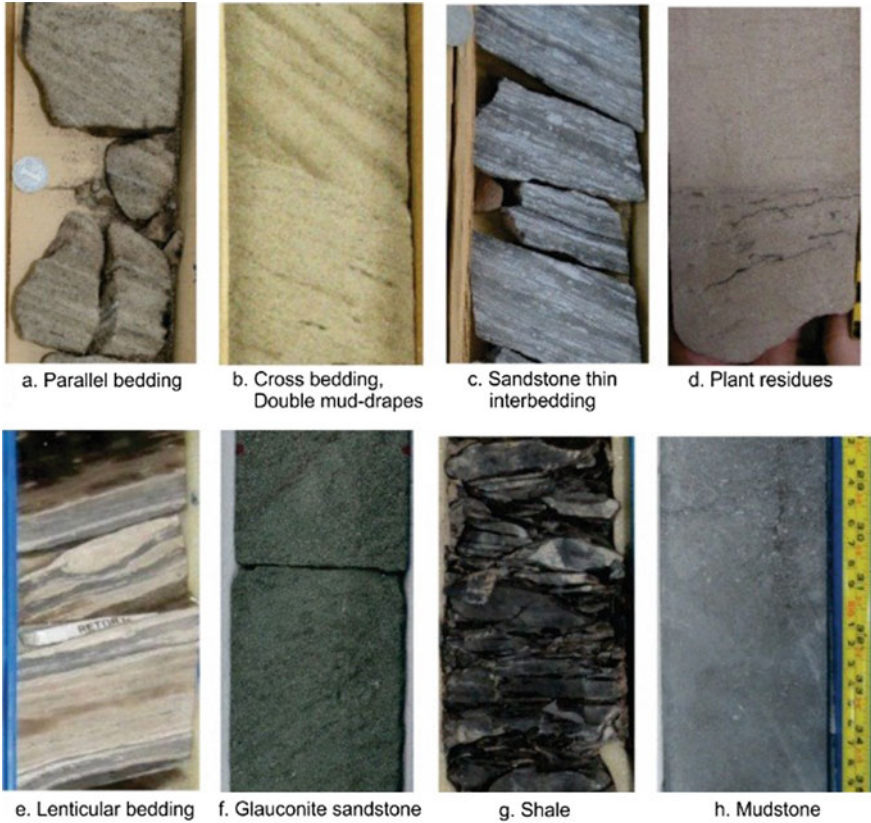


Fig. 4. Core data of Napo Formation

4 Sedimentary Facies

From the above analysis, the Napo Formation belongs to a transitional environment, and its facies can be divided into tidal estuary, tidal delta, shallow shelf.

4.1 Tidal Estuary

The estuary is an estuarine area flooded by sea, where is a confluence of river and tide, and the energy of tidal action is strong. During the sea invasion, the downstream valley is beneath the sea level, and then, a funnel-shaped bay formed in the coastal area. In the Napo Formation, the depositional system can be divided into tide-dominated delta and tide-dominated estuary.

Dalrymple [12] proposed a classical tide-dominated estuary model and studied the sedimentary facies characteristics of delta and estuary. The main differences of them are: (1) sedimentary background: It is generally believed that delta deposit is regressive product, and formed progradational succession, whereas the superimposed

retrogradational facies belongs to estuary which formed under transgressive conditions. In addition, the understanding of estuaries in the past few years is no longer confined to the valley system, and the abandoned part of the delta under the transgressive condition is also estuary. (2) Water energy and grain size: In the coastal area, the grains are very coarse. Bidirectional water action caused by river and tide influences the facies and grain size. Due to the strong tidal energy in the estuarine environment, the influence of tide can reach inland. A low-energy area formed in the fluvial-marine transition area far from sea, and fine grains deposited in this area. The grain size increases seaward from the fluvial-marine transition area and increases landward from the transitional area to deep estuary [13]. However, the fluvial action is strong in the delta environment, the low-energy area is located in the outer part of the river mouth, so the grain size decreases seaward. In addition, the shale in the delta is higher than in the estuary because of the relative strong fluvial process.

Sand units of the Napo Formation are mainly composed of pure sandstone showing superimposed transgressive facies, and the tidal deposition is obvious, so all of them deposited in the tidal estuary condition. The microfacies include fluvial channel, tidal channel, tidal bar, sand flat, and marsh.

- (1) Fluvial channel. Fining-upward sequence can be found at the bottom of the sand units of the Napo Formation, which is the same as the fluvial deposit sequence. GR logging data show a relatively low value and an aggraded superimposition pattern. However, fluvial deposit is hard to preserve on the tidal estuary background due to strong tide energy. With less cored wells, it is difficult to identify only based on logging data.
- (2) Tidal channel. Tide played a more important role than fluvial in the facies. The grain size is mainly medium-fine. On the core of "M1" unit (Fig. 5), cross-bedding shows the influence of fluvial and tide. And typical tide indicators, such as tidal bimodal cross-bedding and double mud drapes, are developed at the middle-upper part of the sand body formed in a tide-dominant environment.
- (3) Tidal bar. Tide played a primary role in the facies which is commonly distributed in the outer part of the estuary. The facies can be found in "M1," "U," and "T" units. Middle-fine grain sandstone is dominant, but the shale content is low. In the "M1" unit (Fig. 5) and "U" unit (Fig. 6), tidal bidirectional cross-bedding is obvious, which is a typical indicator of tide-dominating condition. Interlayer is not rich in this tidal bar. There are a few gray thin calcareous interlayers found in the reservoir, which deposited in relatively low-energy period. The facies often shows a box type on GR logging curve.
- (4) Sand flat. Zhao [14] considered the sand flat is of typical estuary facies, which formed in high-energy conditions. It is usually distributed at the top of the estuary bay where tide energy is very strong and easy to form the purest sand sandstone and parallel bedding. The facies is found at the top of "M1" unit of well D20 (Fig. 5), which reflects a continuously rising water level.

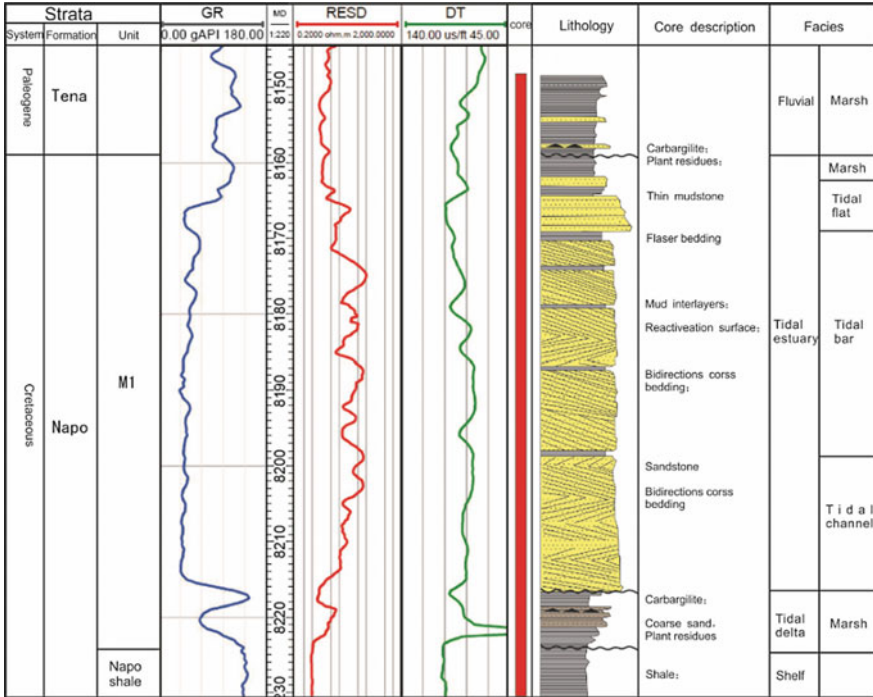


Fig. 5. Core description of M1 unit of D20 well

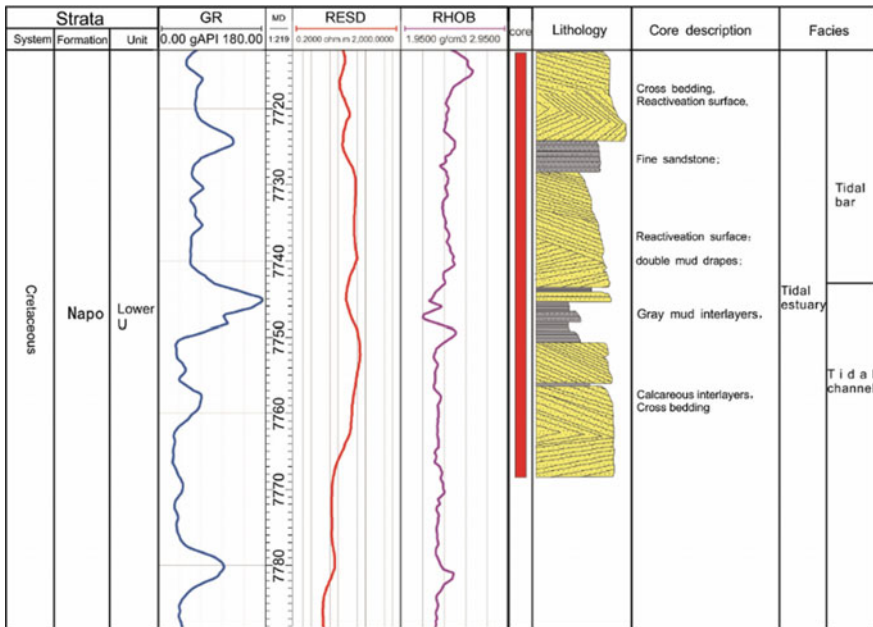


Fig. 6. Core description of U unit of M05 well

- (5) Coastal marsh. With the sea level rising, the accommodation space of the estuary was full filled, so the estuary was gradually abandoned, and the environment changed to a coastal plain. Taking the “M1” sand unit as an example, there is a stable shale zone at the top of “M1” unit, and plant roots can be found in some cores. DT logging data of some wells show very low values, indicating coal deposits. However, there is not coal in the limited core data, indicating the coal distribution is unstable in the coastal marsh.

4.2 Tidal Delta

Tidal delta is the product of sea regression, during which the river process was stronger than the tidal effect. But the tidal delta has not been clearly understood with less model examples of the tidal delta. Walker et al. believe that there is no tidal delta. Of course, it is not the mainstream in academic knowledge. Dalrymple established a relatively complete tidal delta model based on the Fly River delta, which includes delta plain, delta front and fore-delta, and the sandstone grain becomes thin seaward. Tidal estuary and tidal delta are both under the tidal-dominating condition. It is hard to identify the two depositional systems only based on sediment structures. Sedimentary sequence is the primary indicator to differentiate those two facies. The progradational sequence formed in the delta regression environment. The superimposed pattern of the progradational facies can be found at the bottom of the “M1” unit (Fig. 5). Gravel and sandstone are mixed, shale content is high, and plant roots are well preserved, which belong to delta plain. Those deposits formed a clear contact with the clean estuary sandstone. Therefore, it is believed the tidal delta is the first deposit in the study area, and then with the sea level rising, the delta was gradually abandoned. This means the environment turned to transgression, and the tidal delta became a tidal estuary [13]. This process is similar to the study by Dalrymple about the change from tidal delta to tidal estuary.

4.3 Shallow-Marine Shelf

Shallow-marine shelf is located between the continental shelf and the continental slope, where the water depth is generally 200 m, and is the upper limit under the wave table. The sedimentary environments of the “A limestone,” “B limestone,” “C limestone,” and “Napo shale” units belong to the shallow-marine shelf. The hydrodynamics is generally weak and the lithology is mainly mudstone and limestone, in which logging curve shows high GR and dense limestone intervals.

In addition, with continuous exploration and development, a lot of glauconite sandstone reservoirs were found in the upper part of the “T” unit (Fig. 7). The existence of the glauconite made the logging data of this interval show high GR values and high density, which was deemed as non-reservoirs. According to the glauconite deposit, it is believed that these sand bodies are shelf sand ridge [15]. According to the core data of well MN01, a thick section of green glauconite sandstone is located in the upper part of the “T” unit, and local glauconite may be above 50%. Biological disturbances in the facies are abundant, so that there are a few sedimentary constructions found in the core data.

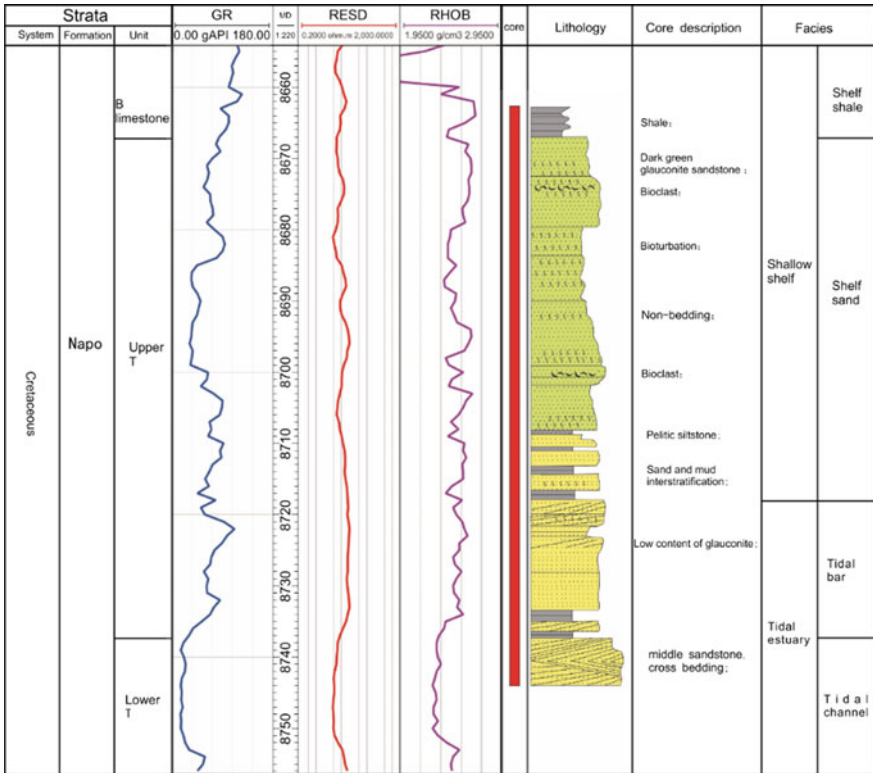


Fig. 7. Core description of T unit of well MN01

5 Sedimentary Evolution

The sand units of the Napo Formation are the product of sea-level fluctuation. Based on the sequence study, the sedimentary evolution can be divided into four stages.

5.1 Tidal Estuary “T” Unit

This stage corresponds to sequence KSQ1, which includes the “T” and “B limestone” units. After the deposit of the “C limestone” unit, the seawater rapidly rose, and the “T” unit deposited on the background of transgression, which is characterized by an upward-fining sequence. The “T” unit can be subdivided into “Upper T” and “Lower T.” The facies of the “Lower T” is tidal estuary, which is mainly composed of medium-fine particles with low shale content. The composition and structure are highly mature. By contrast, sedimentary environment of “Upper T” unit changed because the sea level was rising during this period. Mudstone interbeds developed, and the content of glauconite became rich. Then, the sea level reached the deepest in this stage,

“B limestone” unit deposited, which is featured with shelf shale and limestone. The whole stage reflects the superimposed pattern of an upward-fining facies, indicating a typical transgressive sedimentary condition.

5.2 Tidal Estuary “U” Unit

This stage corresponds to sequence KSQ2, which includes the “U” and the “A limestone” units. After the deposition of the “B limestone” unit, the sea retreated and made the “U” unit deposit, which can be subdivided into three sections vertically. The “Lower U” contains tidal estuarine sediments. At that time, tide played the main role, and tidal channels developed in the eastern part of the work area and tidal bars developed in the western part. The composition and structure of the sandstone are highly mature, which is the main reservoir section. The logging curve is characterized by an upward-fining sequence, which can be judged mainly for three channel deposit stages. The tidal influence is obviously stronger than the early stage, indicating that the sea level was still rising. During the deposition of the “Middle U,” the sedimentary environment gradually developed from land to sea, and a stable mudstone section deposited. When the “Upper U” deposited, a thin tidal sand layer deposited with small-scale regression. Then, the sea level reached to the highest, a section of shale and limestone deposited in the shelf environment, which is the “A limestone.” The evolution in this stage is similar to the “T” unit.

5.3 Shallow Sea Shelf

This stage corresponds to KSQ3 and KSQ4 and involves “M2 limestone,” “M1 limestone,” and “Napo shale” units. During the stage, the sea level was still relatively high, and the shallow sea shelf environment was dominant. Since the “A limestone” deposited, the sea had risen to a higher level. During the deposition of “M2 limestone” unit, the sea level decreased relatively, and a thin tidal sandstone deposited. However, the sea level rose again and led to thick “M2 limestone” and “M1 limestone” units. During the deposition of the “Napo shale,” the sea level was the deepest in the Napo Formation.

5.4 Tidal Delta–Tidal Estuary “M1” Unit

The sea was still at a relatively high level at the later stage of the “Napo shale” unit, and then, the large-scale regression happened. The tidal sandstone of the “M1” unit directly covered the “Napo shale” unit. To this large-scale regression, more data are needed to determine whether it is related to the Andes orogeny. Chapter 3 pointed out that there are residual tidal delta sand bodies at the bottom of the “M1” unit, which unconformably contacts with the overlying sand bodies. It is suggested that at the beginning of the large-scale regression a set of delta sand bodies deposited firstly. Upward-coarsening grains can be found on logging data of some wells. After the sea level began a slow rising process, the tidal effect was significantly strengthened, so that delta sand bodies shifted to pure estuary sand bodies with less shale and undeveloped interlayers.

When the depositional space was full filled, a muddy coastal plain formed, where stable mudstone layers and limited coal deposited.

After the deposition of the “M1” unit, the whole sedimentary evolution of the Napo Formation finished. The “T,” “U,” and “M1” units developed high-quality reservoirs, and the shelf layers act as good caprock and source rock (Fig. 8).

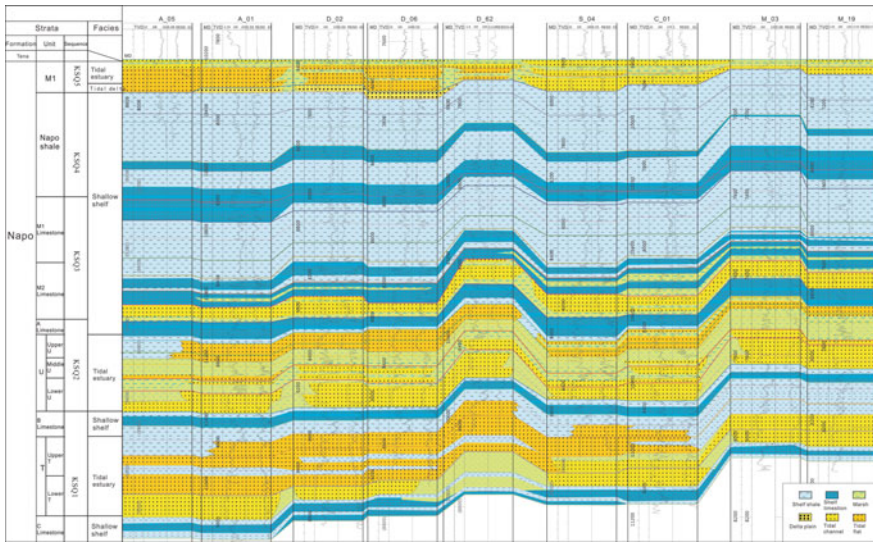


Fig. 8. Sedimentary section of Napo Formation (west–east)

6 Conclusion

The Napo Formation is composed of transitional sediments on transgressive background. The fluctuating sea level is the main factor controlling the sedimentary process and led to three oil-bearing units, “T,” “U,” and “M1,” in the Oriente Basin. And their internal sedimentary patterns are all retrograded. Core observation found pure sand bodies in the “T,” “U,” and “M1” units, where the shale content is low, and the interlayer is not developed. Bidirectional cross-bedding, double mud drapes, and reactive surfaces are their typical indicators of tidal influence. Based on the sequence and facies study, it is believed that the sedimentary environment of those sand units is tidal estuary. The estuary microfacies can be subdivided into fluvial channel, tidal channel, tidal bar, sand flat, and marsh. After the deposition of the estuary, the environment changed to shallow sea shelf with the rising sea level. In this process, shale-limestone sections were developed in the Napo Formation, such as “A limestone” and “Napo shale.” In addition, residual delta was found at the bottom of the “M1” unit, but no direct evidence indicates delta in the “T” and “U” units, due to limited core data. Finally, the sedimentary evolution of the Napo Formation can be divided into four

stages: tidal estuary “T” unit, tidal estuary “U” unit, shallow sea shelf and tidal delta-tidal estuary “M1” unit. These sand units and their neighboring shale-limestone units formed good source-reservoir-caprock assemblages. These sand units are key targets in the Napo Formation for exploration and development.

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