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Controlling Factors on Reservoir Quality of the Miocene in the Northern Yinggehai Area, Yinggehai Basin

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Abstract

With the increasing maturity of exploration in proven areas and main pay zones of the Yinggehai Basin, frontier zones and new formations have progressively become the focus of attention. The Northern Yinggehai area, situated on the northern margin of the Yinggehai Depression, possesses significant exploration potential; however, it remains under-explored, and systematic studies on its depositional systems and reservoir development are still lacking. Based on core observations, thin-section petrography, well-logging and mud-logging data, and geochemical analyses, reservoir characteristics of the HK2 and LG35 blocks were investigated to elucidate the principal controls on reservoir development. The results indicate that late-stage high-temperature and rapid burial compaction, together with authigenic clay minerals and carbonate cementation, represent the dominant factors governing reservoir quality evolution.

Keywords

Yinggehai Basin; Northern Yinggehai Area; Reservoir-controlling Factors; Diagenesis.

1. Introduction

The Yinggehai Basin is located on the northern continental margin of the South China Sea and is a marine sag-type basin. Benefiting from abundant source rocks, favorable sandy reservoirs and efficient hydrocarbon migration pathways, it has become the main battlefield for building a "trillion-cubic-metre gas province" offshore South China. The Miocene strata are the primary target for recent natural-gas exploration. The study area, the Northern Yinggehai area, lies between the Hanoi Sag and the Yinggehai Depression, covering ~7 000 km^2. It is adjacent to several Oligocene sub-sags and contains two important source-rock intervals: Oligocene and Miocene. The Miocene receives sufficient provenance supply and possesses high hydrocarbon-generation potential. Several large–medium gas fields have been discovered in the southeastern Yinggehai Depression, indicating considerable exploration potential. However, low prospecting density, scarce drilling and unclear reservoir-quality patterns of the Miocene restrict further exploration. This paper focuses on the Miocene in the LG35 and HK1 blocks, integrating well logs and thin-section observations to clarify reservoir characteristics and their controlling factors.

2. Regional Geological Setting

The Yinggehai Basin is situated between Hainan Island and the Indochina Peninsula and is a Cenozoic extensional petroliferous basin on the western shelf of the northern South China Sea[1-2]. Tectonically, the basin is subdivided into three first-order units: the Central Depression Belt, the Eastern Slope Belt and the Western Slope Belt.[3-4] The Central Depression Belt is further divided into the Hanoi Sag, the Linggao Uplift and the Yinggehai Depression. The Northern Yinggehai area is located on the Eastern Slope Belt (also called the Yingdong structural belt), which is a gentle monoclinal strata. Major faults include the Dongfang, Yingdong and No. 1 faults, which formed during the rifting stage and continued to influence

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sediment distribution and thickness during the post-rift stage.[5-8] Since the Cenozoic, the basin has experienced two evolutionary stages: (1) a Palaeogene rift stage controlled by fault activity, filling the basin with the Eocene and Oligocene Yacheng and Lingshui formations; (2) a Neogene thermal-sag stage dominated by thermal subsidence, during which sedimentation was controlled by eustatic changes, provenance supply and palaeogeomorphology, depositing the Miocene Sanya, Meishan and Huangliu formations, the Pliocene Yinggehai Formation and the Quaternary[9-10].

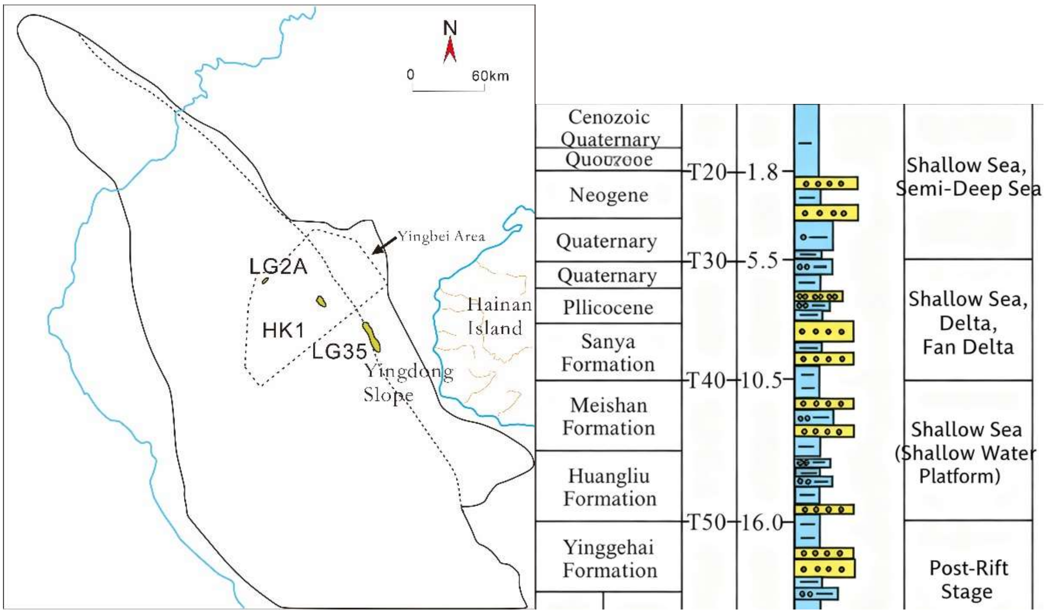
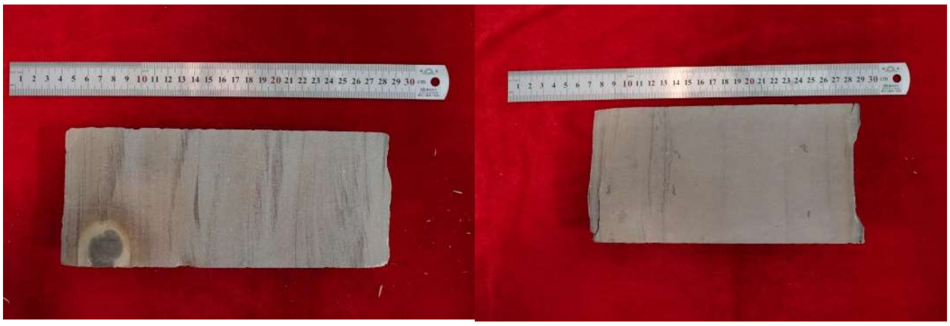


Figure 1. Geographical Location of the Study Area and Comprehensive Stratigraphic Column of the Neogene in the Northern Yinggehai Are

3. Reservoir Characteristics

3.1. Petrology

Miocene Sanya Formation reservoirs are dominated by clastic rocks, locally intercalated with carbonates and volcaniclastic rocks. Sandstones are the most abundant and act as the principal gas reservoirs. Core observations (Figure 2) show grey-white siltstone and greyish-brown fine-grained sandstone, commonly with wavy bedding and minor pyrite concretions. Sandstones are mainly fine- to silt-sized, with minor argillaceous siltstone and thin mud drapes; some turbiditic sandstones are also present.



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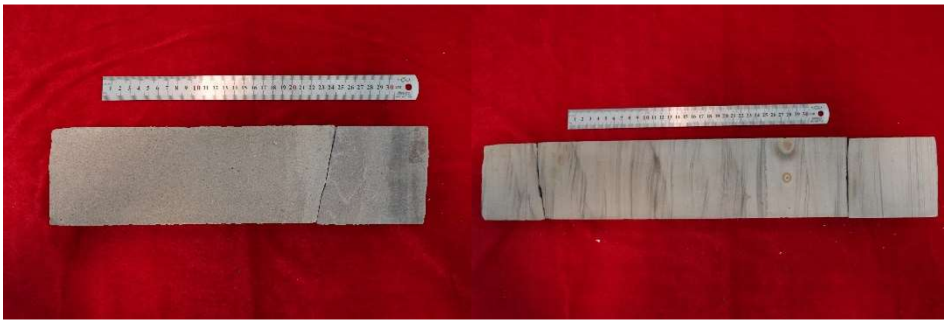

Figure 2. Core Photos of the Sanya Formation, Neogene, Northern Yinggehai Area

Meishan Formation sandstones are rich in quartz (generally <80 %), feldspar (>10 %) and lithic fragments (10–25 %), indicating a composition between quartz and feldspathic arenite, implying short-distance transport from a relatively proximal source. Sanya Formation sandstones, by contrast, are quartz-rich (>80 % quartz, <10 % feldspar, 10–25 % lithic fragments), suggesting long-distance transport and high textural maturity. (Figure 3)

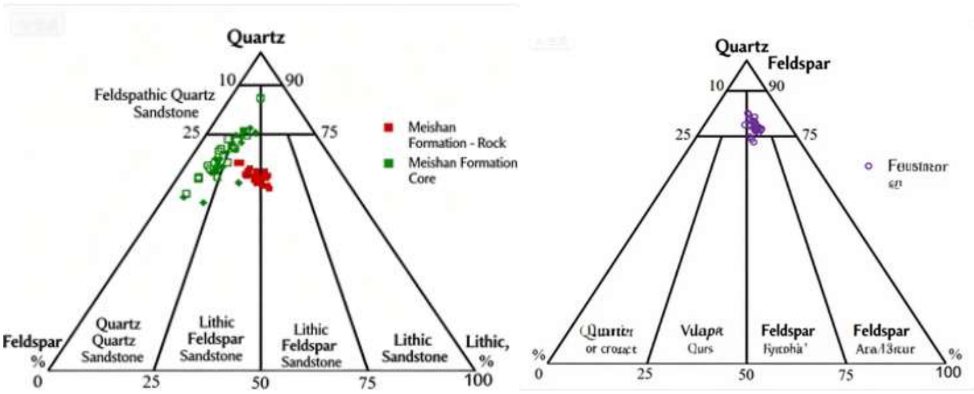

Figure 3. Diagenetic Classification of Sandstones in the Neogene LG Area, Northern Yinggehai

X-ray diffraction shows that interstitial material in the HK1 block is dominated by authigenic clay minerals (mainly illite and illite/smectite mixed-layer) and minor carbonate cements, giving a "low carbonate, high clay" signature (Figure 4).

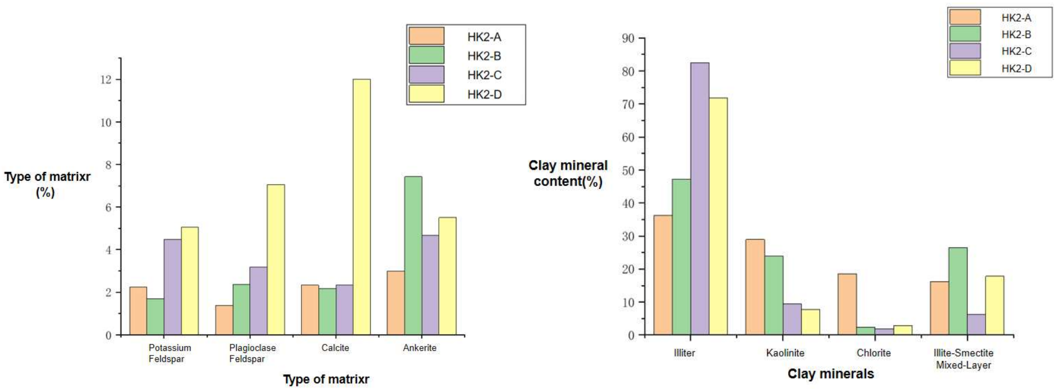

Figure 4. Characteristic Diagram of Interstitial Material and Clay Content in the First Member of the Sanya Formation, Neogene, HK1 Area, Northern Yinggehai

3.2. Pore Types

The Sanya Formation reservoir is primarily composed of secondary pores, which are small and poorly connected, exhibiting characteristics of medium to high porosity and extremely low

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permeability. The reservoir develops residual primary pores, dissolution pores, and moldic pores, with the dissolution materials mainly being feldspar. According to statistics, the Sanya Formation reservoir is dominated by secondary pores such as moldic pores and intergranular dissolution pores, with intragranular dissolution pores being secondary, and intergranular pores are extremely underdeveloped (Figure 5).

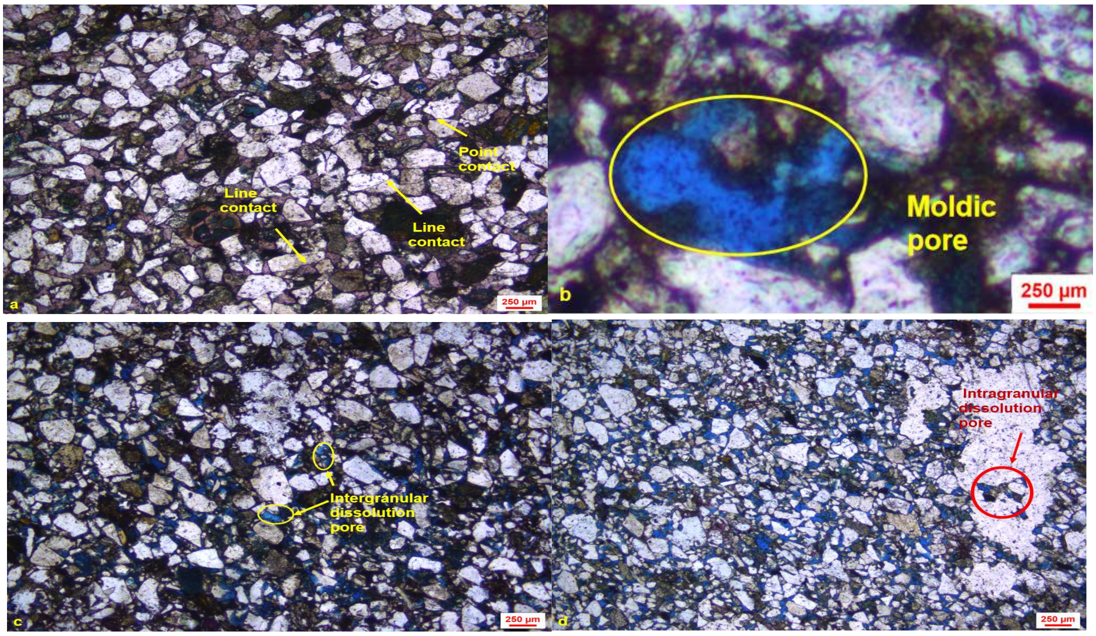

Figure 5. Microscopic Observations of Thin Sections from the Sanya Formation, Northern Yinggehai Area

In the core samples of the Sanya Formation reservoirs, natural fractures are not well developed; the few present may be desiccation fractures formed by the dehydration and expansion of minerals (Figure 6). The micro-fractures referred to here include tectonic micro-fractures and diagenetic micro-fractures, among others. These fractures can serve as storage spaces and also as seepage pathways for fluids.

Figure 6. Fracture Development in the First Member of the Sanya Formation, HK1 Area, Northern Yinggehai

3.3. Petrophysical Properties

The petrophysical data analysis of the core samples from the HK1 area of the study zone indicates that the permeability distribution of the Huangliu Formation reservoirs is greater than 0.5 mD, while the permeability distribution of the Meishan Formation reservoirs is mostly between 0.5 mD and 1.0 mD. The Sanya Formation reservoirs have the poorest properties, all below 0.5 mD, with peak values mainly concentrated around 0.2 mD. Statistical results show

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that the permeability of the reservoirs in the study area decreases with increasing depth, showing a negative correlation between permeability and depth, and exhibiting low-permeability to ultra-low-permeability characteristics in the Sanya Formation (Figure 7).

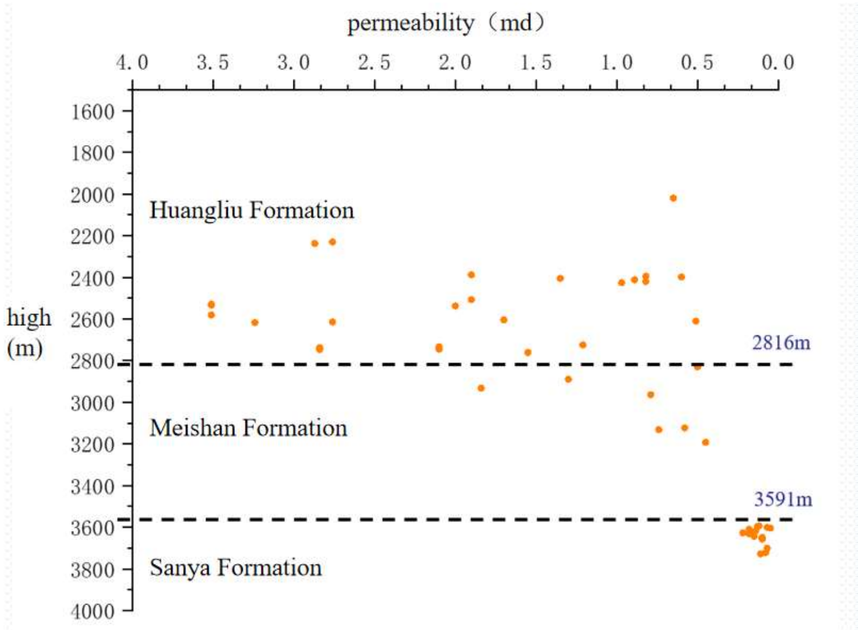

Figure 7. Relationship between Permeability and Depth in the HK1 Area of the Sanya Formation, Northern Yinggehai Area

The statistical results of the correlation between porosity and permeability of the reservoirs in the Meishan Formation of the LG35 area indicate that porosity and permeability show a positive correlation in the coordinates, with porosity and permeability increasing exponentially, indicating a good correlation. The average porosity is 19.75%, and the average permeability is 9.9 mD (Figure 8), meeting the criteria for medium to high porosity and low permeability sandstone reservoirs, reflecting the development of high-quality reservoirs in the LG35 area. The statistical results of the correlation between porosity and permeability of the Sanya Formation reservoirs in the HK1 area show that, overall, permeability increases with increasing porosity (Figure 8), demonstrating a clear positive correlation. The reservoirs of the Sanya Formation generally exhibit characteristics of medium to low porosity and extremely low permeability, indicating poorer reservoir quality in the HK1 area and greater difficulty in development.

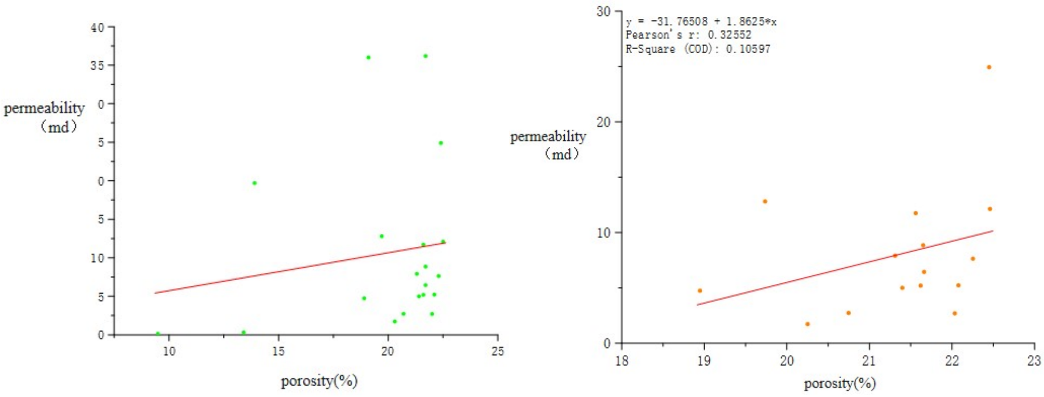

Figure 8. Correlation Diagram of Pore Permeability of Reservoirs in the Meishan Formation, LG35 and HK1 Areas, Northern Yinggehai Area

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The rock structure of clastic sediments affects the size, shape, and development of initial intergranular pores in clastic reservoirs. By conducting petrophysical grain size analysis using the Folk-Ward Formula, and calculating grain size parameters such as mean grain size, sorting coefficient, skewness, and kurtosis (KG), it was found that there is a linear relationship between kurtosis (KG) and permeability. As kurtosis increases, permeability gradually decreases (Figure 9).

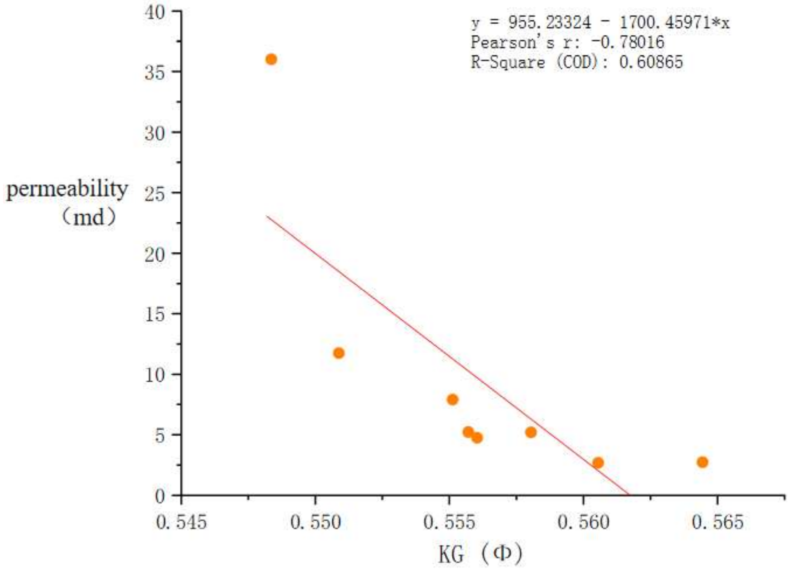

Figure 9. Permeability-Grain Size Correlation Diagram of Reservoirs in the Meishan Formation, LG35 Area, Northern Yinggehai Area

4. Controlling Factors on Reservoir Quality

4.1. Depositional Control

Miocene strata on the slope were deposited mainly in shallow- to semi-deep-marine settings. Sea-level fluctuations and provenance supply from Hainan Island produced stacked submarine-fan and axial-channel sand bodies (Table 1).

Table 1. Relationship between Depositional Microfacies and Pore Permeability of the First Member of the Sanya Formation, Neogene, Northern Yinggehai Area

Well No.	Stratigraphic Unit	Depositional Microfacies	Depth (meters)	Porosity(%)			Permeability(×10-3μm2)		
				Max	Min	Avg	Max	Min	Avg
HK1-1	SQ3	Branched Channel-Main Channel-Shallow Sea Mud	3591-3773	17.32	8.79	13.40	4.47	0.11	0.51
HK1-2	SQ3	Sheet Sand-Shallow Sea Mud-Branched Channel-Main Channel	3512-3735	17.0	8.56	13.65	8.56	0.04.	0.52
HK1-3	SQ3	Shelf Mud-Beach Bar-Shallow Sea Mud-Turbidite Sand-Branched Channel-Main Channel	3659-3931	-	-	-	-	-	-
HK1-3	SQ3	Branched Channel-Main Channel-Interbay	3465-3877	17.8	8.3	13.20	0.50	0.007	0.17
HK1-3	SQ3	Branched Channel-Main Channel-Shallow Sea Mud-Turbidite	3416-3877	18	4.08	11.89	18.8	0.08	2.98

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In terms of porosity, the average values do not differ significantly, but there is a trend of decreasing average porosity from west to east, which is due to the occurrence of extremely low porosity in the HK2-3 zone. Regarding permeability, there is a large difference in average values, with an increasing trend from west to east, and the permeability in HK1-3 has improved. These phenomena are related to the depositional sequence.

4.2. Diagenetic Control

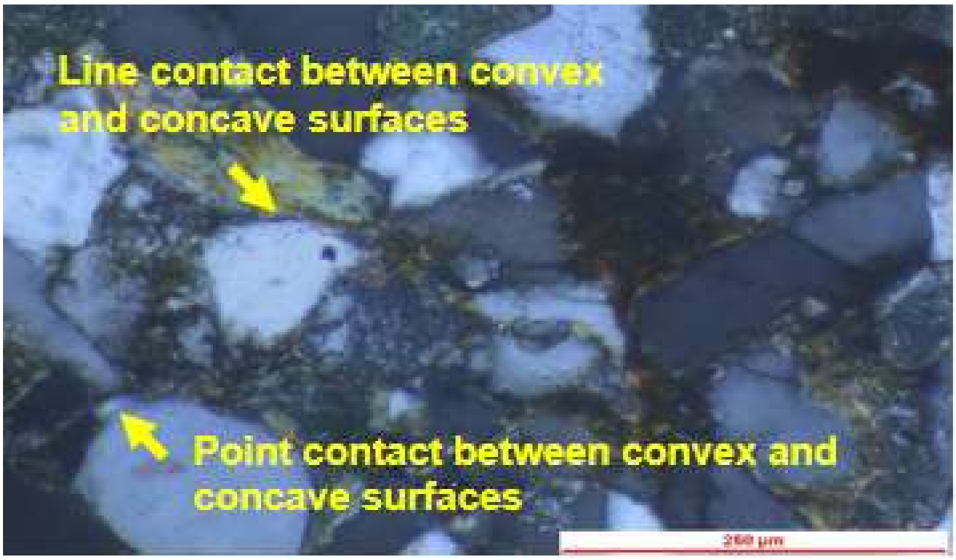

Figure 10. Contact Surfaces in the First Member of the Sanya Formation, Neogene, HK1 Area, Northern Yinggehai Area

Compaction is the most detrimental process. With rapid burial, grain contacts evolve from point to line, concavo-convex and eventually sutured, dramatically reducing porosity and permeability (Figure 10).

Cementation includes authigenic illite (platy/honeycomb morphology), quartz overgrowths and minor carbonate cements (Figure 11). Illite extensively fills pores, whereas quartz cementation reduces porosity but may enhance rigidity against compaction.

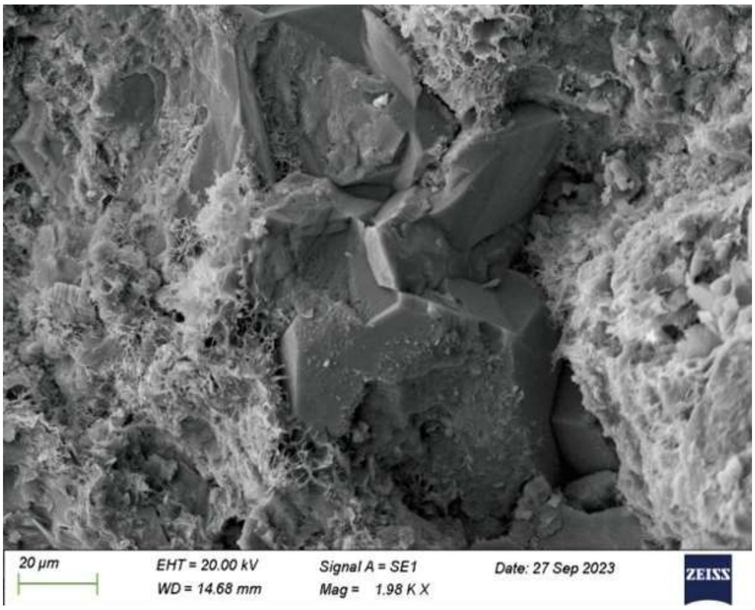

Figure 11. Scanning Electron Microscope (SEM) Images of Sandstone from the Sanya Formation, Neogene, HK1 Area, Northern Yinggehai Area

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Dissolution of feldspar and lithic fragments by organic acids is constructive, generating secondary porosity.

5. Conclusion

(1) In the LG35 block, permeability is negatively correlated with burial depth and kurtosis but positively correlated with porosity. Meishan reservoirs exhibit medium–high porosity and low permeability, representing high-quality intervals.

(2) HK1-block reservoir development is controlled by depositional facies; the best reservoirs occur in distributary-channel–main-channel–turbidite associations.

(3) Rapid burial compaction, together with authigenic clay-mineral, quartz and carbonate cementation, are the principal factors deteriorating Miocene reservoir quality in the Northern Yinggehai area, with compaction being the most detrimental.

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