The role of fluid migration system in hydrocarbon accumulation in Maichen Sag, Beibuwan Basin

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Abstract. Fluid migration system is of great significance for hydrocarbon accumulation, including the primary migration and secondary migration. In this paper, the fluid migration system is analysed in Maichen Sag using seismic, well logging and core data. Results show that many factors control the hydrocarbon migration process, including hydrocarbon generation and expulsion period from source rocks, microfractures developed in the source rocks, the connected permeable sand bodies, the vertical faults cutting into/through the source rocks and related fault activity period. The spatial and temporal combination of these factors formed an effective network for hydrocarbon expulsion and accumulation, leading to the hydrocarbon reservoir distribution at present. Generally, a better understanding of the hydrocarbon migration system can explain the present status of hydrocarbon distribution, and help select future target zones for oil and gas exploration.

1. Introduction
After generation, oil and gas migrate from source rocks to porous strata, fractures and faults, and this process is known as primary migration [1-8]. Then, driven by dynamic actions like buoyancy, hydrodynamic force and residual pressure, oil and gas migrate again according to the laws of fluid dynamics, which is defined as secondary migration[1-8]. The starting point of hydrocarbon migration is source rocks, and the termination is effective traps. The migrating route from the starting point to the termination is the study focus of hydrocarbon pool-forming dynamics, which is a complex process which is of great significance for hydrocarbon distribution at present [4-8]. The hydrocarbon accumulation process is controlled by many factors. For example, source rocks should be mature, often with higher TOC and Ro values, by which the threshold depth of hydrocarbon generation can be drawn[8-11]. Hydrocarbon expulsion time should be later than the formation of effective traps, with permeable pathways for vertical and lateral migration. In this study, the authors try to accurately describe the framework of the hydrocarbon migration system based on the structural and sedimentary features of Maichen Sag, which may help selecting target zones for oil and gas exploration. To achieve this objective, well logging data, seismic data and numerical simulation results are used in this paper to understand the fracture distribution, physical properties of reservoir, the connectivity of the sand bodies, and summarize related hydrocarbon accumulation model.
2. Geological setting

Beibuwan basin is a Cenozoic faulted basin on the northern continental slope of the South China Sea, featured by multiple sags and highs in interphase arrangement [1-7]. Beibuwan basin is bounded by Qixi uplift and Xuwen high, and can be divided into three depressions, the Northern depression, the Southern depression and the Eastern depression (Figure 1). Beibuwan basin is characterized by long period of terrigenous depositional environment, late seawater intrusion, weak early volcanism and strong epigenetic volcanism. Beibuwan basin has experienced two tectonic evolution stages and formed two sets of depositional systems. The early evolution stage is a rifting period, featured by well-developed faults, big subsidence, and terrigenous deposition. The late evolution stage is an after-rifting period during which the faulting was less active, the subsidence was featured by a large scale and whole motion, and the sedimentation was characterized by marine sediments depositing in a depression. As a result, most sub-basins in Beibuwan basin have double layer structure, faulted basin at the bottom and depression on the top.

Figure 1. Location map of the study area.

Figure 2. Stratigraphic column and tectonic evolution of Maichen Sag.
Maichen sag is located in the Southern depression of Beibuwan basin, which is a half-graben depression formed above the pre-Tertiary basement and has a fault-depression double layer structure. The lower faulted basin experienced multiple activity of rifting-extension evolution in Early Paleogene, and mainly filled by sediments of terrigenous lacustrine facies and river marsh facies. The above depression formed in the Late Neogene during which period occurred thermal subsidence, and was mainly filled by sediments of marine facies and littoral facies.

In Beibuwan basin, the sedimentary Cenozoic strata mainly include Paleogene sediments of terrigenous lacustrine and river marsh facies and Neogene sediments of marine facies, which is consistent with the fault-depression double layer structure [7] (Figure 2). The paleogene strata include Changliu Formation, Liushagang Formation and Weizhou Formation, while the Neogene strata include Xiayang Formation, Jiaowei Formation, Dengloujiao Formation and Wanglougang Formation. The pre-Tertiary basement is mainly composed by upper Paleozoic (Carboniferous-Permian) limestone, lower Paleozoic metamorphic rocks Mesozoic granite. According to previous studies, the mudstones in Liushagang Formation are the main source rocks, and the source rock and oil source correlation analysis in Maichen sag shows that the hydrocarbons are mainly from Member II and III of Liushagang Formation, with average TOC of 2.29% and 1.96% respectively [2,4,6,8]. Previous geochemical studies also indicate that the threshold depth of hydrocarbon generation is 2800 m and the hydrocarbon generation and expulsion period is from Weizhou Formation to present [4,6,8]. The major reservoirs include Palaeocene Changliu Formation, Eocene Liushagang Formation and Oligocene Weizhou Formation.

3. Hydrocarbon migration system

3.1. Primary migration

The process of primary migration of oil and gas is complicated, and there are three widely accepted patterns for hydrocarbon expulsion which are corresponding to compaction, diffusion and microfractures respectively [9-11]. Compaction related hydrocarbon expulsion mainly occurs in the fast compaction period, during which time the sediment porosity decreases dramatically and lots of fluids are expelled. However during the fast compaction period, the sediments are not deeply buried, the temperature is comparatively low, and the in situ kerogen cannot degrade into hydrocarbons. As a result, the hydrocarbons expelled by compaction are limited and mainly biogenic. Diffusion related hydrocarbon expulsion is driven by the concentration gradient, migrating from the high concentration area to the low concentration area until an equilibrium concentration is reached. Diffusion related hydrocarbon expulsion is much more effective on light hydrocarbons [10]. Microfractures related hydrocarbon expulsion is common in deeply buried source rocks which can hardly be compacted. The permeability of the source rocks is poor, and the limited porous spaces are isolated or poorly connected. As the thermal degradation of kerogen increases gradually, lots of hydrocarbons are generated which filled the pores and microfractures of the source rocks. The hydrocarbon expulsion, especially the heavy hydrocarbons, is probably not related to compaction and diffusion because of the poor permeability of the deeply located source rocks. In the study area, the threshold depth of hydrocarbon generation for the source rocks of Liushagang Formation is deep, ~ 2800m. The hydrocarbon expulsion is episodic according to previous studies. As a result, microfracture related hydrocarbon expulsion is regarded as the major pattern of primary migration.

3.1.1. Distribution of the microfractures. Based on the 3D seismic data, the top horizon of Member II of Liushagang Formation was interpreted to study the characteristics of microfracture distribution in VVA software. Results show that microfractures are heterogeneously distributed in elongate bands in map view, mainly along active faults that extend for long distances (Figure 3). According to the core observation of well XWX1, the whole core sample is broken into fragments of different sizes and shapes. Apart from factors such as coring technology and rapid formation pressure drop, the pre-existing microfractures may also play a role in breaking the source rocks. Core observations show that
the microfractures extend for a few centimetres with very small widths. The microfractures are open without fillings, and crosscut each other forming irregular latticework shape. These microfractures can act as space storing hydrocarbons and pathways expelling hydrocarbons outside.

Microfractures are prone to form in areas of strong tectonic stress where fractures and faults may also occur, and all of these help form a favourable corridor for hydrocarbon expulsion. In three dimensions, the microfractures in the source rocks combine with vertical faults cutting into/through the source rocks, forming an effective network for hydrocarbon expulsion which is the basis of hydrocarbon primary migration.

![Image](image_url)

**Figure 3.** Distribution map of the predicted microfractures of Member II top of Liushagang Formation.

3.1.2. **Formation mechanism of the microfractures** Many scholars have studied the excess pore pressure which is able to facilitate the failure of sediment layers in an overpressure system [12]. Hunt proposed that microfractures may form when the pore pressure exceeds the sediment tensile strength [13]. Some experts on quantitative simulation assume that hydrofracturing occurs when the pore pressure reaches 85% of the hydrostatic pressure of overlying strata [13-15]. Sibson (1981) proposed the stress requirement for hydrofracturing under low stress difference which is: \( \sigma_1 - \sigma_3 < 4T \) [16]. Hydrofracturing will occur when \( Pf \geq \sigma_3 + T \), in which \( \sigma_1 \) and \( \sigma_3 \) are maximum and minimum principal stresses separately, \( Pf \) is the pore fluid pressure, and \( T \) is the tensile strength of rock.

The tensile strength of rock in the study area is not available. According to experience, the tensile strength of competent rock is \(<10\text{MPa}\). As a result, the stress condition can satisfy the low stress difference when \( \sigma_1 - \sigma_3 < 4T \approx 40\text{MPa}\). Under this condition, the formula \( Pf \geq \sigma_3 + T \) can be used to analyse when the rock will occur hydrofracturing. Statistical analysis of the rock mechanics parameters for well XWX6 show the value of \( \sigma_1 - \sigma_3 \) is \( 21\sim30\text{MPa} \) which is \(<40\text{MPa}\), satisfying the low stress difference condition: \( \sigma_1 - \sigma_3 < 4T \) (Figure 4). But both measured stratum stress data and calculated stress data by AC logging curve and analysing data of rock mechanics show that the pore fluid pressure of Member II of Liushagang Formation is smaller than the minimum principal stress. Therefore, the condition of \( Pf \geq \sigma_3 + T \) cannot be reached and no hydrofracturing will occur.

As mentioned above, natural hydrofracturing is not the reason for the microfracture formation in the study area. The microfractures are tectonic stress fractures formed in periods of strong tectonic activities, probably related to bending and folding of the strata. The spatial relationship between the microfractures and adjacent larger faults indicates that they are genetically related, and these microfractures were probably formed after Weizhou Formation when the hydrocarbons started to expel. Then these microfractures can act as pathways for fluid expulsion in active tectonic periods. When the tectonic movements end and the pressure of the mudstones decreases, the microfractures will close, making the mudstone a comparatively closed system. At the same time, the pre-existing microfractures reduce the breakdown stress condition for the strata.
3.2. Secondary migration
Secondary migration indicates all the migration after the hydrocarbons enter the carrier layer, including the migration along permeable sandstones, faults, fractures, unconformities, and the remigration from the accumulated traps due to changes in external conditions [17].

3.2.1. Faults. The episodic movement of oil and gas along faults is the most important way for hydrocarbon accumulation. Many large and medium-sized oil and gas fields were discovered along faults, indicating that faults, especially the large faulting zone, are the main channel for oil and gas migration. But not all fractures are hydrocarbon expulsion pathways. Some faults were only active before the source rocks are mature, and some fractures do not cut into the source rock or into the fracture system that is connected with the source rocks. Effective faults for hydrocarbon migration have two features. First, they were active during or after the time of hydrocarbon generation. Second, the faults should cut into the source rocks or into the fracture system that is connected with the source rocks.

In the study area, there are many active faults in each period, but only a small part of these faults can be used for hydrocarbon expulsion. In the early period of hydrocarbon expulsion, the distribution of mature source rocks is limited and only the boundary faults and related branch faults can act as pathways for hydrocarbon expulsion. As the distribution area of mature source rocks increases, more faults can be used as the hydrocarbon expulsion conduits. According to the analysis on the fault activity, three obvious active periods of fault development were recognized, Liushagang Formation, Member I-II of Weizhou Formation and Xiayang Formation (Figure 5). Among them, the faults developed in Liushagang Formation have no contribution to hydrocarbon expulsion because the source rocks are not mature at that time. The roles of other faults in hydrocarbon expulsion are also different, which is affected by other factors such as the distribution of mature the source rocks and the microfractures for the primary migration.

![Figure 4](image1.png)  
**Figure 4.** The rock mechanics parameters of well XWX6.

![Figure 5](image2.png)  
**Figure 5.** The distribution of active faults during Member I-II of Weizhou Formation in Maichen Sag.
3.2.2. Connected permeable sand bodies. In the continental clastic sedimentary system, terrigenous detrital sediments input controls the distribution, connectivity, and the changes of grain size and pore throats of the sand bodies. In the half-graben fault depression, the slope zones tend to develop river delta (fan delta) - lacustrine facies depositional system due to the long extension and the slow angle of the slope. The distribution of sand bodies is featured by sandstone percentage, thickness and particle diameter increasing downwards the slope. The superimposition of sandstone bodies is vertically controlled by the phase sequence of sedimentary microfacies, affected by the water level change. According to Walther's Law, sandstone bodies in one sedimentary system are connected to some extent.

A rapidly deposited system of alluvial fan, subaqueous fan and fan deltas is prone to develop on the boundary fault side of the half-graben fault depression, which is near the provenance source and of coarser grain size. On the low angle slope side of the half-graben fault depression develops a distal delta depositional system. These two depositional systems are separate with respective sediment supplies and sand body distributions. Generally, the spatial distribution of the sedimentary microfacies, sand bodies, and physical properties, in combination, control the migration of hydrocarbons in one deposited system. However, the sandstone bodies in different sedimentary systems are hardly connected, and hydrocarbon migration between different systems needs more pathways such as fractures, faults, direct superimposition or lateral contact of the sand bodies.

In Maichen sag, Liushagang Formation-Weizhou Formation is a transgression-regression sedimentary cycle, forming a sedimentary sequence of delta, lacustrine, fan delta, meandering river delta, and fluvial deposits from the bottom up. Among them, Member II of Liushagang Formation is composed of mudstones of semi-deep lacustrine deposits. The sedimentary facies study of Maichen sag shows that there were two sets of sedimentary systems since Liushagang Formation, the southern one and the northern one. They are controlled by two different sediment sources from the south and the north separately, and have different sand body distributions. From north to south, the grain size sandstones decreases gradually and the connectivity of sand bodies becomes poorer.

Different sedimentary systems have different net gross ratios and physical property data such as porosity and permeability, and these factors affect the connectivity of sand bodies. Direct contact is the necessary condition for the connection of different sand bodies, which means the sand bodies should be superimposed or connected with each other in 3D space to form a carrier bed. The relationship representing this kind of connectivity is called geometry connectivity. Hubbert (1953) studied the connectivity problem between the superimposed sand bodies using the percolation theory [18]. They proposed a threshold value of net gross ratio, regarding the sand bodies of net gross ratio lower than the threshold value to be not connected. As the net gross ratio value increases, the sand bodies begin to superimpose on others and develop into a cluster to connect the sand bodies. When the net gross ratio reaches the threshold value, the connected sand bodies is through the whole research unit and develops into a carrier bed. Therefore, this net gross ratio threshold is called “percolation threshold”. For an infinite concept system of isotropic sand body, its 3D percolation threshold is 0.276, and its 2D percolation threshold is about 0.668. Based on the spatial distribution probability model of sand bodies by Hubbert (1953), Luo et al. (2012) used the Gaussian Fitting to calculate the connectivity probability (P) of the sand bodies in the carrier bed, and built a diagram showing the geometrical connectivity [18,19] (Figure 6). Guided by this diagram, the connectivity of the sand bodies in the carrier bed can be assessed using the connected percolation threshold (C0) and the net gross ratio of completely connected sand bodies (C) whose connectivity probability is > 0.95.

Using the same method as Luo et al. (2012), the connectivity of two carrier beds in Maichen sag were analysed, which are Member III of Weizhou Formation and Member III of LiuShagang Formation (Figure 7). For both carrier beds, C0 and C are 0.2 and 0.5 respectively. For both carrier beds, the connectivity in the west is better than the east, and there is a good connectivity in the outer slope sand bodies, evolving into medium connectivity into the inner slope and the sag centre. Additionally the connectivity of the sand bodies in Member III of Weizhou Formation is better than that in Member III of LiuShagang Formation.
4. Hydrocarbon accumulation patterns

Microstructures, faults, and permeable sandstone layers constitute the network grid of hydrocarbon expulsion and migration (Figure 8). Two hydrocarbon accumulation patterns have been recognized in the study area based on the different sedimentary systems in the north and south, different fault
activity periods, and different oil and gas expulsion and accumulation periods (Figure 9). One is the fault-fan zone in the south, and the other is the fault-delta zone in the north.

The southern fan-fault zone can be divided into two tectonic units, a boundary fault in the west and fault step zone in the east. Controlled by the tectonic features and sediment input, subaqueous fan developed in the west and fan delta system occurred in the eastern area. Both sedimentary systems are in small size, with vertically superimposed thick sand bodies. This fan-fault zone is close to the petroleum generative depressions which is a positive condition for oil accumulation. However, the physical properties of the reservoir at the threshold depth of the hydrocarbon generation are poor due to the influence of sedimentary facies and diagenesis effect, which inhibit the migration of oil and gas along the sand bodies. At shallower depth, the reservoirs of good physical properties need long-lived faults to guarantee vertical hydrocarbon transport.

![Figure 9. The hydrocarbon accumulation model in the study area.](image)

As mentioned before, the faults developed in Liushagang Formation are not active during hydrocarbon expulsion, and the migration pathway is the widely distributed sand bodies of Liushagang Formation. Weizhou Formation developed fan delta, especially the delta plain and delta front subfacies, with widely distributed sand bodies of higher sandstone content. These sand bodies, combined with the active hydrocarbon expulsion faults, formed the migration network in the northern fault-delta zone.

5. Conclusions
The role of fluid migration system in hydrocarbon accumulation is analysed in Maichen Sag using seismic, well logging and core data, and the following conclusions are summarized.

1. Mudstones of Liushagang Formation are the main source rocks, especially occurring in Members II and II;
2. Microfracture related hydrocarbon expulsion is regarded as the major pattern of primary migration. Microfractures are prone to occur in areas of strong tectonic stress where developed faults extending for long distances;
3. The secondary hydrocarbon migration pathways mainly include faults and connected permeable sand bodies. Effective faults for hydrocarbon migration should be active during or after the time of hydrocarbon generation and they cut into the source rocks or into the fracture system which is connected with the source rocks.
4. Many factors control the hydrocarbon migration process, including hydrocarbon generation from source rocks, microfractures in the source rocks, the connected permeable sand bodies, the vertical faults cutting into/through the source rocks and related fault activity period. The spatial and temporal combination of these factors forms an effective network for hydrocarbon expulsion and accumulation, leading to the hydrocarbon accumulation status at present.
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