2D petroleum system modeling to reduce exploration well deployment risks: a case study from the Pearl River Mouth Basin, South China sea

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Abstract. To overcome the limitations of traditional way of exploration well deployment, an innovative workflow was developed to focus on dynamic factors with 2D petroleum system modeling technology. It was applied in the Zhu1 depression of the Pearl River Mouth Basin, Southern China, helping geologists to improve their understanding of the dynamic elements such as the generation of the source rocks and migration pathways along faults. Simulation show that source and migration can be screened from six risk factors, “Source”, “Reservoir”, “Cap”, “Migration”, “Trap” and “Preservation”. More simulations focused on two of the factors for different geological scenarios, fault properties, such as active period, and source rock properties, such as thickness, total organic carbon, hydrogen index. faults are the main migration control as their active period matches the main oil migration time. Of them, those cut through source rock layers and have the same inclination as that of the source rock formation acted as good migration paths. Source rock properties not only control the amount of oil generated, but also influence the vertical and lateral migration distances. Drilling result proves clearly that this new workflow is valuable for studying geological uncertainties and reduce exploration ricks.

1 Introduction
Traditionally, exploration well deployment studies are focused on static factors, including structure (trap), reservoir (lithology), and other qualitative results such as oil generation and migration. Subsequently predicted profiles across potential wells are drawn manually based on all research results (Figure 1).

One limitation of these workflows is that it is hard to access the coupling among multiple factors, such as the main migration age and trap-forming times. Another drawback is the method’s subjectivity. As a result, when the understanding of the reservoir’s changes, the predicted profiles must be redrawn, which requires considerable efforts from geologists.

To overcome the current limitations and let geologists focus on research instead of mapping, an innovative workflow has been developed, introducing dynamic factors with 2D petroleum system modeling (PSM) technology to replace currently used geological sections. This new workflow has been applied successfully in the Pearl River Mouth Basin, South China sea.
2 Geological Background

The study area includes the Lufeng and Huizhou sag, located in the Zhu1 depression of the Pearl River Mouth basin, southern China (Figure 2) [1][2]. The Shenhu formation is the basement; the main source rocks are the Wenchang and Enping formations; the reservoirs include the Zhuhai, the Zhujiang and the Hanjiang formations; and the seals are shale beds in the Enping, the Zhujiang and the Hanjiang formations[3][4]. Due to small sag and the limited generation mass of the source rock, only one well drilled into an oil layer; another five wells were dry. Previous studies focused on static features such as structural interpretation and reservoir prediction based on seismic data[5][6]. To reduce exploration risks, a 2D PSM workflow was introduced to help geologists to improve their understanding of the dynamic elements such as the generation mass of the source rocks, migration pathways along faults and sand carrier beds and charging of potential traps.

3 Petroleum System Model creation

A petroleum system is composed of the geologic components and processes necessary to generate and store hydrocarbons, including a mature source rock, migration pathway, reservoir rock, trap and seal. Appropriate relative timing of formation of these elements and the processes of generation, migration and accumulation are necessary for hydrocarbons to accumulate and be preserved[7]. Generally, a petroleum system model is built through input structural data including horizons and faults. Then model parameters such as lithology, source rock and boundary condition (heat flow, water depth and temperature) should be set to “infill” the structural framework to assign geological meaning for model[8].

In contrast to a conventional geological model with qualitative lithology, such as sandstone, shale, etc., lithology in petroleum system modeling (PSM) is a quantitative parameter, which requires that the compaction curve be updated with real well data. Three rock types were defined for this study, sandstone, shale and siltstone. First, depth-porosity(D-P) data was extracted from petrophysical
interpretation. Then all well data were processed to create D-P data for one rock type in one sag. The data was used to calibrate a standard compaction curve (from Athy’s law) of each lithology to create a customized curve for the study area. A different compaction curve for each lithology of each layer will influence the porosity-permeability relationship and pressure, which impact migration and accumulation results. The structural model framework was built based on seismic interpretation results, such as horizons and faults in the depth domain[9]. Geological age was set from stratigraphic column in Fig.2. Lithology was assigned from four wells along a cross-section line. Because the two top layers are not reservoirs, mixed lithologies were used for the Quaternary (shale 63%, silt 22% and sand15%) and the Hanjiang(shale 57%, silt 32% and sand11%). The final model is shown in Figure 3.

![Figure 3. 2D PSM model (Yellow: sandstone; brown: siltstone; gray: shale; black: source rock; purple: granite; blue: mixed sand and shale).](image)

Boundary conditions included heat flow (HF), paleo water depth (PWD) and sediment water interface temperature (SWIT). Model parameters are shown in Table 1.

| Age (Ma) | HF (mW/m²) | PWD(M) | SWIT(°C) |
|----------|------------|--------|----------|
| 0        | 42         | 110    | 18       |
| 21       | 43         | 70     | 18       |
| 33       | 47         | 10     | 20       |
| 38       | 45         | 0      | 20       |
| 47       | 42         | -25    | 20       |

4 Thermal simulation and calibration
Thermal simulation with no migration is the first of two steps in PSM simulation. The step focuses on temperature and pressure evolution; the results will indicate oil/gas windows. This step is the basis of PSM simulation, it is an important indicator of petroleum generation. Temperature and Vitrinite reflectance (Ro) data from three wells can be used to calibrate simulation results (Figure 4). Thermal simulation shows that Enping source rocks are in early and main oil window and Wenchang source rocks are in main and late oil window and entered gas window at deepest part of the two western sags.

![Figure 4. Thermal simulation results and calibration.](image)
5 Migration simulation and key migration factors summary

The second step in PSM simulation is simulation for petroleum migration and accumulation. Migration methods include flow path, Darcy flow and invasion percolation (IP). Of these, flow path is good for high-permeability formations such as sandstone, Darcy flow is suitable for low-permeability layers such as shale or limestone, and IP is a new mechanism method that has advantages for fluid migration along faults. Considering the geological background in the study area in which faulting plays a key role in oil migration from the lower source to upper reservoir, both IP and Darcy flow method were used for migration simulation. Darcy flow was for oil migration in the source, and the IP method was used to simulate gas migration from the lower source rock to the upper reservoir along faults and lateral migration in the highly permeable carrier bed. Migration and accumulation simulation results are shown in Figure 5. Among four wells, only one well in the middle sag drilled oil layer in the Zhuhai formation; others are dry wells.

![Figure 5. Migration and accumulation simulation results.](image)

Although simulation results match with well discoveries, there are still many geological uncertainties that must be studied. In the 2D PSM model, sandstone and shale are reservoir and seal, and anticline and fault block are traps structure that promoted stable sedimentation after Enping deposition that supported good preservation[10][11]. Source and migration can be screened from six risk factors: source, reservoir, cap, migration, trap and preservation[12]. The following simulations will focus on two factors for different geological scenarios, for example, source thickness and properties, such as total organic carbon (TOC), hydrogen index (HI) and fault properties, such as open/closed or active period.

6 Geological scenarios simulation

Previous study of the adjacent sags indicates that there are two different source rocks. One is a deep lacustrine facies with TOC 3.36% and HI 611, the second is a shallow lacustrine facies with TOC 2.01% and HI 240. Because there was no direct data about source in the study area, two source rock scenarios were simulated. The first one is a deep lacustrine source for all sags. The second is a shallow lacustrine source for the western and middle sags and a deep lacustrine source for the eastern sag(Figure 6).
Figure 6. Scenario simulation results-source rock uncertainty (Top, same source for all sags; bottom, different source type for different sags).

Comparing simulation results of both scenarios, it can be seen that the big difference is in the middle sag. In the first scenario, more oil can migrate from the source layer to the Zhuhai and Zhujiang along faults; The oil can then migrate further along carrier beds and accumulate on some traps, including one dry trap. This scenario does not match drilling results. The simulation results of the second scenario match drilling results, with the oil mainly accumulating in traps near the fault. No long lateral migration took place. The second main controlling factor is migration. Both faults and sand can be migration paths. For the fault property, two scenarios were simulated. In the first, the fault is open from 56 Ma to the present. For the second, the fault is open during from 56 to 33.9 Ma, closed during 33.9 to 10 Ma, and open from 10 Ma to the present. After simulation, results are almost same. The reason for this is shown in source maturity history which indicates the source rock started to expel oil at 10 Ma, and migration along faults happened after that.

The stratigraphic contacts of the Wenchang and the Enping formations have an uncertainty. There is an erosion event after Wenchang deposition. This raised the question of whether the sand in the Wenchang formation is in contact with the sand in the Enping formation, thereby forming a migration path that allowed oil generated in the Wenchang source to enter the Enping reservoir? To study this uncertainty, two scenarios were simulated for contact between Enping and Wenchang. In the first scenario, there is a shale between the Wenchang and the Enping, and in the second, there is a sand that is the contact between the Wenchang source and the Enping sand. Simulation showed that there is only oil accumulation in the Wenchang formation, and no oil entered the Enping in the first scenario. In the second scenario, both the Wenchang and the Enping have oil accumulation (Figure 7).
Figure 7. Scenarios simulation results-stratigraphic contact uncertainty (Top, shale between the Enping and the Wenchang; bottom, sand forms the contacts between the Wenchang source and the Enping reservoir).

Conclusions
Simulations show that faults are the main migration control and their active period matches the main oil migration time. Among faults, faults that cut through source rock layers acted as good migration paths. They will be most favorable factor if their inclination is the same as that of the source rock formation. Source rock properties, especially kinetics, not only control the amount of oil generated, but also influence the migration abilities and vertical and lateral migration distances. Based on the study results, two exploration targets were proposed: one drilled an anticline close to source rocks in the Wenchang formation and the other drilled fault-related nose structure in the Enping formation.

One of the two wells was drilled and discovered a 4-m oil layer in the Enping formation. This proves clearly that this new workflow is valuable for exploration work. This was the first time 2D PSM technology was applied in the current exploration well optimization, and it clearly helped reducing geological uncertainty and exploration risks. This innovative workflow enables the exploration geologists to reduce time spent in mapping and helps them concentrate more on understanding the dynamic behavior of their basins and associated reservoirs.

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