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Sequence stratigraphy study of Miocene reservoirs in the South China Sea

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Abstract

Reservoir distribution on the shelf in the study area in the South China Sea is known by the drilled wells, although their potential still needs to be investigated. In addition, in the deepwater area sand distribution is not well known. Therefore, the purpose of this study is to investigate sand distribution within the Upper and Middle Miocene in this area with particular emphasis on the deepwater area using sequence stratigraphic analysis. Integration of 3D seismic data, wireline log data and biostratigraphic information was used. Nearly 1400 km^2 of 3D seismic data were interpreted and integrated with the well data to create structure and isochron maps which were created to evaluate the general structural style, the trend of thickness changes and the paleogeography. Seismic amplitude extractions were also used and four paleogeographic maps were constructed for the main intervals of interest.

The results reveal that within the study interval sands are distributed (1) in slope apron/turbidite systems, (2) in deep canyon cut systems and (3) in shelf and shoreface environments. Slope apron/turbidite systems are well developed within the Middle Miocene section. The lower Middle Miocene slope apron/turbidite system was fed by mud/sand mixed supply from the shelf, whereas the sediment supply of the upper Middle Miocene system varies from sand-rich to mud/sand mix. The sand-rich systems could be very good reservoirs in this area. Turbidite systems within the Middle Miocene are limited and are evaluated to be low-efficiency systems with fair reservoir quality. Canyon fill sands at the base of the lower Upper Miocene are potential reservoir targets in this interval, especially where they are fed by sand-rich shelf deposits. Storm-wave based sands in the shelf inter-bedded with mud layers, and sands in shoreface and coastal plain environments are also objectives in this Upper Miocene interval.

Keywords: South China Sea, slope aprons, turbidites, sand-rich canyon fills

1. Introduction

In petroleum exploration, finding prospective reservoirs is an important task, especially in areas where some oil and gas accumulations have already been discovered. In addition, understanding the distribution and type of depositional environments that sediments were deposited in helps to define relative scale and quality of each type of reservoir. This study focuses on this task by analyzing wells and a seismic data base located on the margin of the South China Sea Basin close to the Song Hong Basin, offshore China (Figure 1).

Four wells have been drilled in the area of interest and have some gas discoveries in Middle Miocene and Lower Miocene intervals. All four wells encountered similar inner to outer shelf depositional environments with sand packages interpreted to have variable thickness and porosity. Consequently, the distribution of sands based on depositional environment interpretation within a sequence stratigraphy framework would be useful in the evaluation of hydrocarbon potential in this area.

The aim of this study is to determine the distribution of depositional environments in the Upper and Middle Miocene sections within the area of interest to see what controlled reservoir distribution and from this analysis to predict areas of high reservoir potential within these intervals. The integration of wireline, biostratigraphy and 3D seismic data were input into this study to construct paleogeographic maps based on isochron maps, RMS maps and biostratigraphy data. These maps provide a better understanding of the distribution of reservoirs in different depositional environments which could be useful information for building 3D depositional models and improve prospect assessment in the future.

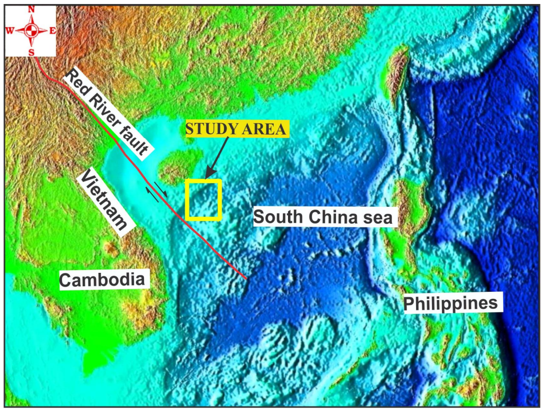

Figure 1. Location map of study area on the margin of South China Sea

2. Methodology

Seismic and well data (wireline log and biostratigraphy) were used to identify key surfaces such as sequence boundaries, trangressive surfaces, maximum flooding surfaces and marine onlap/ downlap surfaces.

It is hard to recognize reflector terminations because this study area has complex structural geology. Therefore, flattening horizons was the best way to see onlap, downlap, toplap and truncation patterns in order to divide the intervals into depositional sequences.

Structural maps for key sequence boundaries were interpreted and from these isochron maps for sections between two sequence boundaries were generated. These maps were used to produce paleogeographic maps for further interpretation of reservoir distribution.

The Root Mean Square (RMS) seismic attribute extraction using Kingdom software was carried out with different time windows for each mapped horizon to capture possible sand body geometries penetrated by drilled wells. The RMS results were also used to interpret geomorphology which added to paleogeographic map construction

3. Results

3.1 Wireline and Biostratigraphy Integration

According to the results of wireline analysis, sands in the Middle Miocene and Upper Miocene have moderate to excellent reservoir quality. Upper Miocene and upper Middle Miocene sections have very high porosity (up to 35% porosity), while the lower Middle Miocene has low porosity because of compaction and high shale portion. Depositional environment evaluated from biostratigraphy at the four wells varies from shoreface to inner shelf to middle shelf with some short periods in coastal plain or deltaic environment or tidal influence (Figure 2). Within these variable depositional environments there are several intervals exhibiting good to excellent reservoir properties.

The Upper Miocene interval from 590-746m MD at well 1 is dominated by sandstone (Figure 2). It is a thick sand package deposited in middle shelf environment. Also, the Upper Miocene section at well 2 was deposited from shoreface to inner shelf environments with high sand proportion.

During the Middle Miocene depositional facies are back-stepping due to overall aggradation. In the upper part of this interval in the four wells, shale dominates over sandstone and limestone. At the top of this section there is a thick shale package which is considered as a regional seal sequence.

The Middle Miocene sequence of well 1 is interpreted to be deposited in inner shelf to middle shelf environment. In the middle and lower parts of this section, several thick sand intervals are observed.

Well 2 is dominated by shale deposited in prodelta environment in the upper part and the middle and lower parts have more sand and some thin coal and limestone layers. The interval between 2710 to 3015 m MD is dominated by deltaic sandstone with very high porosity (15-30%) which is highlighted in Figure 2.

According to biostratigraphy analysis, the depositional environment of the Middle Miocene sequence in well 3 is also inner shelf. Sand packages in the middle part of this section have high porosity (15-25%), whereas in the lower part sands have moderate porosity. A good example of reservoir in this interval is from 2109 to 2121m MD (Figure 2).

At the top of the Middle Miocene section in well 4 there is a thick shale layer deposited in inner shelf and this is underlain by sand intervals with high porosity (25-35%) and low water saturation. The depositional environments of this section vary from coastal plain/delta environment to inner shelf. A good example for a thick sand interval in the Middle Miocene section of this well is 2105-2145m MD (Figure 2).

In general, good sand intervals with high porosity and low water saturation are well distributed in the Middle Miocene section in the four wells. These sand packages were deposited in inner shelf to coastal plain/deltaic environments. However, these sand intervals are hard to correlate to each other because of long separation distance between wells and complex structural geology.

3.2 Seismic interpretation

Based on the available 3D data and using the biostratigraphy data from the wells, five main sequence boundaries were interpreted throughout the area (Figure 3).

All the interpreted horizons show significant amount of erosion associated with them and local truncation of underlying strata. The Middle Miocene horizons all show canyon incisions most likely caused by tectonic activity (Figure 3). Some of this section was significantly eroded to the north and northwest. Channelized erosional surfaces are common. At the top of Middle Miocene, this sequence boundary is an angular unconformity in the southwest and strongly truncated and eroded in high area to the northwest (Figure 4). It was also recognized by deep incisions and deep canyon cuts with a northwest-southeast orientation.

Within the Upper Miocene section marine onlap and a strong continuous reflector is observed at the Intra-Upper Miocene horizon. This horizon is truncated by top Upper Miocene in the northwest. Incisions and channel cuts are also observed to the southeast at this level. The Upper Miocene unconformity was recognized as a strong angular unconformity on the seismic and represents the end of significant tectonic folding. The section is truncated deeply in the eastern part.

Structurally, this area is dominated

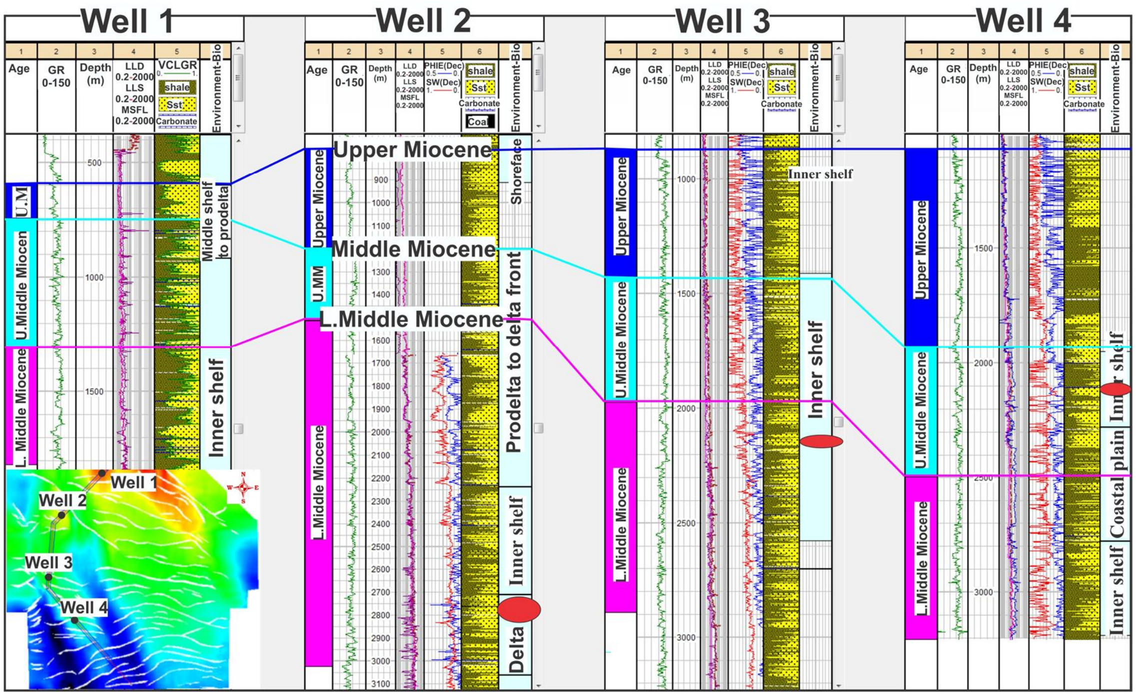

Figure 2. Correlation of four wells in study area highlighting good sand intervals in each well

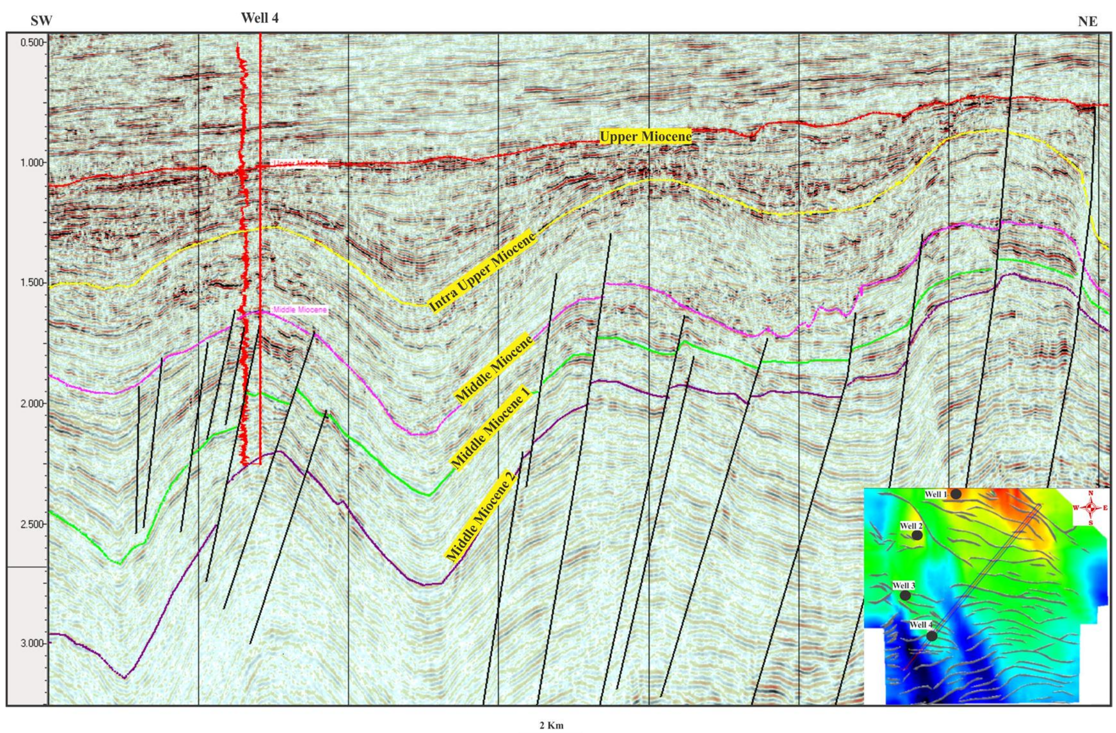

Figure 3. Interpreted key sequence boundaries (unconformities). Note significant erosion at top Middle Miocene and top Upper Miocene.

by a northwest-southeast trending series of high amplitude anticlines. All of these features resulted from inversion tectonic activities during the Early to Late Miocene.

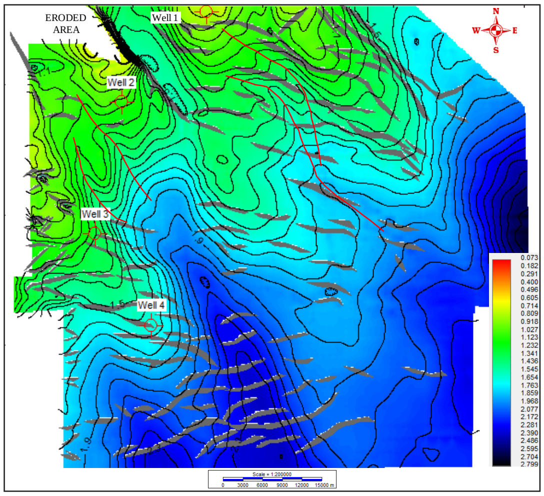

Figure 4. Top Middle Miocene TWT structure map shows incisions (red curves) and erosion

4. Discussion

4.1 Paleogeographic maps

Four paleogeographic maps were built for Lower Middle Miocene, Upper Middle Miocene, Lower Upper Miocene and Upper Upper Miocene intervals in order to better understand depositional facies distribution and the associated reservoirs. Construction of these maps was based on interpreting depositional environments from the integration of wireline logs, biostratigraphy, isochron maps and seismic amplitude extractions.

4.2 Distribution of sand in Middle Miocene

The Middle Miocene section defined by the Middle Miocene 2 to Top Middle Miocene horizons (Figure 3) shows an overall aggradational geometry and associated active incisions and erosion as indicated by numerous deep channel cuts throughout the interval. Relative sea level falls were common most likely due to tectonic activity. The shelf would be exposed and active erosion took place on the shelf and slope, forming significant canyons. The eroded sediment was transported to fill into canyons or bypassed and deposited at the slope and basin floor. These deposits can be characterized as slope apron / turbidite deposits which can be quite variable in nature.

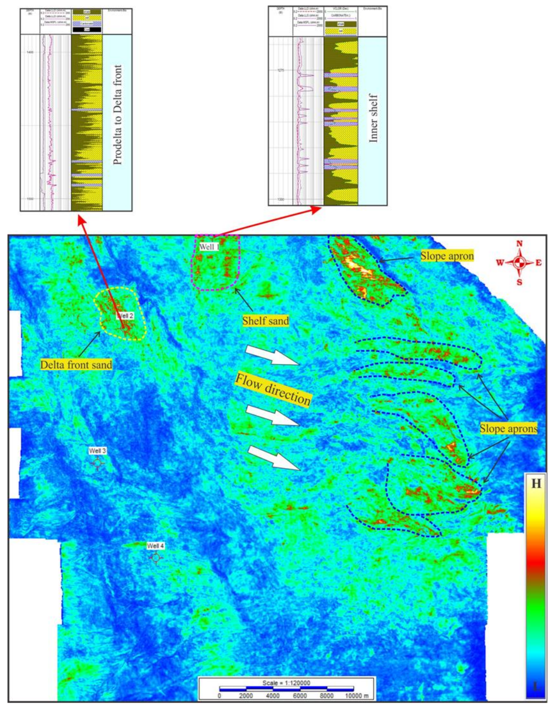

Figure 5. RMS map of upper Middle Miocene section showing sands distributed on the slope/basin interpreted as slope apron/turbidite systems with sand-rich sediment supply in the north. Sand distribution on the shelf and delta front also interpreted.

For the upper Middle Miocene interval, a slope apron/turbidite system fed by mud/sand rich system is interpreted with a concentration of high amplitude anomalies located along the boundary between slope and basin floor in the north (Figure 5). This could be due to the fact that the coastal plain and shelf in the north is more sand rich. Also, according to wireline analysis of the four wells, sands in the upper Middle Miocene section are expected in inner shelf and delta front environment within the highstand system tract. Generally, shelf sediments are normally thick mud layers interbedded with very fine thin sand beds. However, in this area the shallow shelf has wave and storm-dominated environments which can have quite thick sand layers interbedded with mudstone. These sands are fine grained and good quality. Figure 5 shows high amplitude around well 1 which extends to the south which are interpreted to be sands deposited in inner shelf environment with a thickness of about 25m estimated from wireline log. Sand distribution in delta front (well 2) which also shows high amplitude in RMS map of Upper Middle Miocene is also a potential reservoir in this interval.

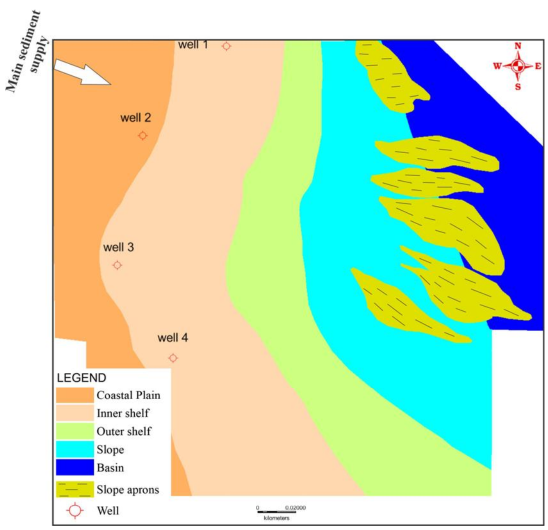

Figure 6. Paleogeographic map of Upper Middle Miocene based on isochron map and RMS extraction

Overall, slope apron/turbidite systems are well developed in the upper Middle Miocene interval (Figure 6). In the north, slope apron / turbidite are formed from sand-rich sediment supply from the coastal plain and the shelf which is considered to be the best reservoir in this system. In addition, storm-wave base sands on the shelf and delta front sands are also potential reservoirs for this section. Potential turbidites are expected to be deposited further out in the basin to the east.

4.3 Distribution of sand in Upper Miocene

The Upper Miocene section is bound at its base by the Middle Miocene unconformity which has significant canyon erosion associated with it, and at its top by the top Upper Miocene unconformity. There is significant uplift and erosion associated with this upper unconformity, particularly to the north and northwest. Much of the upper Upper Miocene is missing over a large area

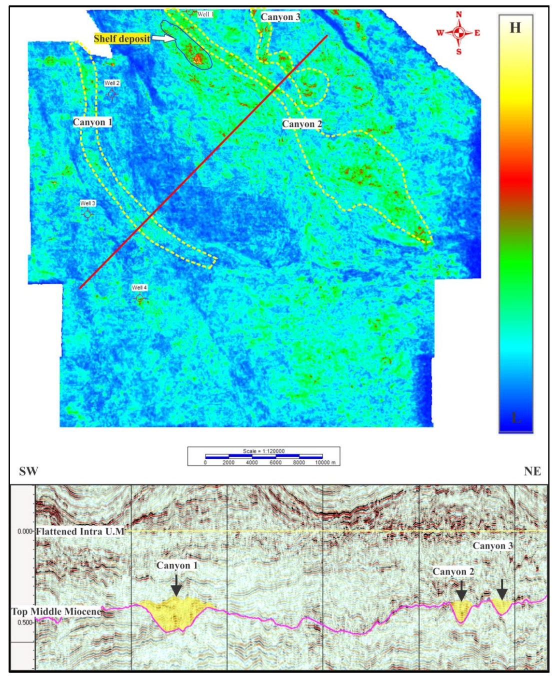

Figure 7. Interpreted sand distribution along canyons and shelf deposit on the shelf interpreted by RMS map with time window of 100ms above top Middle Miocene horizon

The Lower Upper Miocene is a regressive highstand system tract recognized by its progradational geometry to the east. It has extensive canyons at its base. The RMS amplitude extraction map with a time window of minus 100ms above the top Middle Miocene horizon (Figure 7) shows high amplitudes along three canyon cuts. From seismic interpretation, deep canyon cuts are very common at the top Middle Miocene level.

Canyons 2 and 3 (Figure 7) have higher amplitudes associated with them than canyon 1, so these canyons might incise further into the coastal plain and have transported coarse sediment from coastal plain and shoreface environment to the shelf and slope areas. Also, canyons 2 and 3 branch off into many small channels having fan shapes. The upper fan is dominated by channel and levee complex and has low amplitude, the middle fan shows depositional lobes and has scattered high amplitudes and the lower fans are sheets but very dim. These features suggest the sediment supply being a mix of sand and mud. Canyon 1 has scattered high amplitudes and becomes dim in the slope area and is most likely mud-filled. High amplitudes in the basinal area are considered to be turbidites, but they are in small areas and very dispersed.

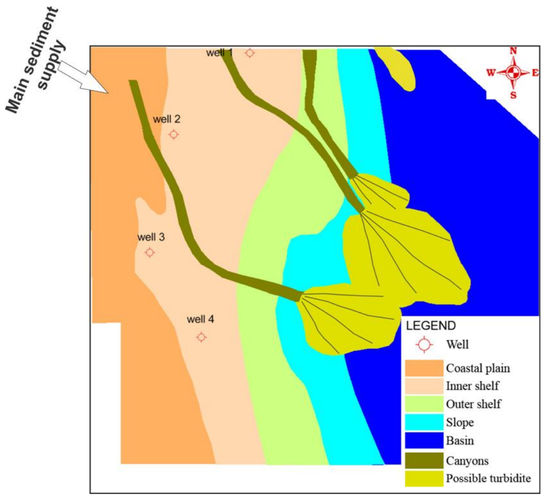

Figure 8. Paleogeographic maps of Lower Upper Miocene based on isochron map and RMS map

Overall, potential sands in canyons at the base of the Upper Miocene section and in submarine fans are the main potential reservoirs in this interval (Figure 8). The canyons filled and transported both mud-rich and mix of mud and sand-rich sediments. In addition, shelf deposits are also reservoir targets in this interval (Figure 8).

5. Conclusions

Based on integrated analysis and paleogeographic reconstructions, the following is concluded:

- Slope apron / turbidite systems are well developed in the slope areas within Middle Miocene interval supplied from sand-rich to mud/sand mixed shelf deposits and have potentially good reservoir distribution.
- Sand-rich canyon fills on the shelf are very good reservoir targets in the Lower Upper Miocene.
- Sands in the shoreface and shelf environment distributed along anticline trends are priority targets in the shelf areas although reservoir quality is variable. More detailed analysis of this section is needed to define prospective areas.
- Further turbidite systems could be developed on the basin floor eastwards and are expected to have more run-out and higher reservoir potential.
- Play evaluation for deepwater sediment should be carried out in basinal areas to the east.
- 3D basin modeling is necessary to analyse and understand the petroleum generation and migration in this study area, especially in deepwater areas to the east.

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