SENSITIVITY ANALYSIS IN SHALE GOUGE RATIO AND FAULT PERMEABILITY MODEL FOR POST MORTEM RE-EVALUATION OF “M” CLOSURE, OFFSHORE TIMOR SEA, INDONESIA

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Abstract

Since gas discovery in Abadi Gas Field, Offshore Timor Sea, many exploration works have been conducted in adjacent area, including “M” closure. However, no gas findings were reported in “M” closure. In order to determine post mortem evaluation of “M” closure, evaluating fault seal is critical to understand trapping mechanism uncertainty in “M” closure. This evaluation is carried out at Triassic Challis sandstone reservoir, utilizing well data to obtain volume shale properties as well as 2D seismic data to map fault throw, orientation and juxtaposition. Shale Gouge Ratio (SGR) and Fault Permeability (Kf) model will be calculated using Yielding and Manzocchi algorithm. “M” closure is a horst structure, bounded by two NNE-SSW trending vertical faults as part of extensional event in Mesozoic. Based on three sensitivity analysis conducted in this study, SGR model revealed that bounding faults in “M” closure mostly have more than 0.2 while Kf model have 0.1 mD. Utilizing reference from earlier studies, it indicates that those bounding faults are categorized as likely sealed faults. Post mortem re-evaluation suggests that fault breaching is not the main geological risk issue in “M” closure. Furthermore, opportunities for discovery in Offshore Timor Sea are still wide open. There are many undrilled tilt-block closures similar to “M” Closure which can be potential for further development by determining its position relative to hydrocarbon charge and migration pathway.

Keyword: Shale Gouge Ratio, Fault permeability, Challis reservoir

Introduction

“M” closure is situated in Offshore Timor Sea, Eastern of Indonesia which has water-depth 500 – 700 meters. Geologically, it is included in Ashmore Platform, Northwest of Bonaparte Basin. Bonaparte Basin, especially in northwestern area, is well-known as main hydrocarbon producer (Figure 1). Many hydrocarbon discoveries have been found in this region, mostly in Australian territory, starting from Sunrise-Troubadour gas field in 1974-1975, Evan Shoals gas field in 1988 and Bayu-Undan gas field in 1995 (Nagura et al., 2003). In Indonesian territory, Abadi gas field is the only successful exploration within Northwestern Bonaparte Basin. It was discovered in 2000 with Abadi-1 exploration well drilled by INPEX Masela, Ltd. (Zushi et al., 2009).

In contrary to Australia, some exploration studies in Indonesia were failed to discover other fields similar to Abadi. “M” closure, drilled in 1999 with M-1 exploration well, is one example of unsuccessful exploration within this region. M-1 well status is plugged and abandoned with no report of hydrocarbon show. The main reason of this unsuccessful drilling is still ambiguous whether hydrocarbon charges – migration pathway failure or fault-seal failure. In order to understand the main failure, post mortem re-evaluation is necessary to give clearer exploration opportunities within area with new concept of petroleum play.
Main objective of this study is a sensitivity analysis for fault-seal potential within “M” closure to evaluate geological risk of trapping mechanism point of view.

**Geological Settings**

Eastern Indonesia lies within a complex tectonic zone formed as a result of Neogene collision and interaction of the Australian and Eurasian continental plates and the Caroline and Philippine Sea oceanic micro-plates (Barber et al. 2003). Tectonic history of this area is affected by multi-phase extensional and compressional episodes during Late Paleozoic to Neogene. Orthogonal and curvilinear geometry of basin morphologies in the study area are implied to these tectonic episodes.

Mesozoic Extensional Event as representation of Vulcan, Malita and Calder Graben, formed during Triassic through Jurassic to Early Cretaceous rifting and continental breakup of the NW Shelf Australia (Barber et al. 2003). Based on seismic interpretation, this event has massive impact to the study area, characterized by multiple series of NNE-SSW horst-graben structures (Figure 2). Geometry of these horst-graben systems are typically vertical and have major fault throw.

The regional Valanginian Event, happened in the post-breakup sequence, created massive erosion in surrounding study area, such as Londonderry High and Ashmore Platform. This break was probably due to a relative fall in sea level (MacDaniel, 1988). In Vulcan sub-basin, non-depositional hiatus was expressed while in study area, massive erosion was commenced and entirely eroded Jurassic sequence, such as well-known Plover Formation as major gas reservoir in most of NW Australian Shelf.

In the Miocene to Pliocene, the Australian Plate collided with the Banda volcanic arc which caused down-warping of the Australian continental margin and led to flexure of the Australian Plate (Cadman and Temple, 2003; Amir et al., 2010). This event created major thrust-belt system in north of Timor Trough.

Regional stratigraphy of “M” closure can be referred from Vulcan Sub-basin. Oldest sequence is Late Permian Cape Hay Sequence, mostly consists of shale. Typically deltaic system in the Bonaparte Basin but may change into pro-delta to marine environment further NW (Mory, 1991). Overlying Cape Hay, development of a broad carbonate platform along the northern margin Bonaparte Basin was established (MacDaniel, 1988), forming Dombey Limestone member. In Middle Triassic event, mixed clastic - carbonate sequence was deposited in shallow-marine environments. This event created two conformable sequences, which are Mt. Goodwin and Challis-Pollard. Mt. Goodwin expected as potential marine source, even though unproven (Kennard et al., 2003). Second sequence consists of siliciclastic reservoirs with interbedded shale, carbonates (Challis, as primary reservoir target in this study), and mixed carbonate siliciclastic reservoir in lower part, known as Pollard member. Challis reservoir in some oil fields was reported that it was deposited on the margin of a protected macrotidal estuary or bay with marine conditions to the south and a major fluvial system to the northeast. This Triassic petroleum bearing units of the Challis field comprises migratory channel sequences within a broad estuary or bay. Intercalated with the channels are tidal shoals and shoreline-oriented barrier island sands (Cadman and Temple, 2003). Valanginian event then massively eroded almost entirely Jurassic sequence. Starting from Cretaceous to Early Tertiary, outer shelf carbonates developed widespread in north westernmost of Bonaparte Basin (Mory, 1991). This event created thick marl-shale sequences as regional seal, starting from of Echuca Shoal, Wangarlu and Johnson.
Method

Triassic Challis sandstone is the target for this research as the primary reservoir in this area. In M-1 well, Challis is divided into three zones, such as R1, R2 and R3. All zones have typical blocky GR log characteristic.

The method of this research can be divided into two major groups. Seismic analysis, first group, was conducted to reveal subsurface maps and fault identification. In subsurface analysis, seismic interpretation of several key horizons was observed to build depth structure map. Ladinian event was picked as the lowermost of Challis interest zone. R2 and R3 zone markers were picked as well as the interest zone while Valanginian unconformity was included as the uppermost part of Challis. Two bounding faults of “M” Closure would be modeled in this research, Northwest Fault (NWF) and Southeast Fault (SEF). Both are extensional faults as product of Mesozoic Extensional Event. Fault attributes, such as horizontal-vertical throw as well as dip-azimuth fault.

Petrophysical analysis, second group, was also utilized to reveal reservoir and seal zone identification within Challis interval. Volume shale (VSH) analysis was also conducted for Shale Gouge Ratio (SGR) calculation in next stage.

Both groups then combined to gain geobody modeling for further fault modeling. For calculating SGR, Yielding algorithm was applied as follows:

\[
SGR = \frac{\sum (V_{sh} \times \Delta z)}{\text{throw}}
\]

SGR = Shale Gouge Ratio (fraction)
Vsh = shale volume fraction
\(\Delta z\) = thickness of each layer
throw = fault throw

For fault permeability calculation (Kf), Manzocchi algorithm (1999) was utilized as follows:

\[
\log Kf = -4 \times SGR - 0.25 \times \log(D) x (1 - SGR)^5
\]

Kf = fault zone permeability (mD)
SGR = Shale Gouge Ratio (fraction)
D = fault displacement (m)

Data Analyses

R1 zone is the deepest reservoir with 18.8 meter thick. VSH calculation in R1 revealed VSH in range of 0.1 to 0.4 with an average of 0.19. R2 zone appeared as thinnest zone with only 12.85 meter. VSH range is slightly higher than R1, 0.12 to 0.43, and average value is 0.25. R3 is the shallowest zone and thickest as well, 20.31 meter. VSH calculation showed range of 0.11 to 0.79 and average 0.24. High value of VSH indicates that some thin shale layers occurred in between R3 zone.

“M” closure is bounded by NWF in southern part and interpreted as a product of Mesozoic Extensional Event. NWF is categorized as NNE – SSW trending vertical fault with dip angle 54.5 deg in average. The average dip azimuth is N49.8\(^\circ\)W and it is categorized as NW facing fault. Vertical throw of NWF is quite high, 72.08 m in average (Figure 3). In section 1, southwest part of area, NWF has major throw (83.51 m) and quite vertical dip angle (52.36 deg). Further east, dip angle of NWF is remain parallel (48.66
deg); however fault throw is changed to 35.74 m. In northeastern section, fault throw is slightly higher (46.3 m) with dip angle around 51.55 deg.

SEF is the southern bound fault of “M” closure. Similar to NWF, this fault also has NNE-SSW trend and occurred during Mesozoic Extension Event. Vertical angle of this fault is slightly higher than NWF, 56.2 deg in average. This fault is SE facing fault with mean dip azimuth is N131.35°E. Mean vertical throw is slightly lower than NWF, 70.02 m in average (Figure 4). Section 1 suggests that fault throw and dip angle of SEF is low (40.99 m and 47.01 deg) and getting lower further section 2 (15.6 m and 44.49 deg). However, fault throw in northeastern section depicts high value (93.56 m) as well as dip angle (61.67 deg).

**Fault Modeling**

SGR model of NWF as well as SEF can be described in Figure 6. SGR of NWF in R1 zone has in range of 0.32 to 0.46. In R2 zone, SGR value is slightly increasing 0.42 to 0.53. R3 zone has SGR in range of 0.39 – 0.50. In SEF, SGR value on R1 zone is 0.3 – 0.47 while R2 zone has in range of 0.42 – 0.51 and R3 has 0.33 – 0.53. Based on SGR modeling, all reservoir zones have SGR more than 0.2. In fault permeability derived from Manzocchi algorithm, all reservoir zones in both fault, SEF and NWF, have lower than 0.1 mD. Generalized classification of faults is made by Yielding based on SGR value. He suggested that SGR 0.2 or lesser are typically with cataclastic fault gouge and it is unlikely for sealing. However, if the value is greater than 0.2, the faults will tend to be more potential for sealing as the occurrence of some clay smears (Sahoo et al., 2010).

**Sensitivity Analysis**

Fault modeling conducted in this study was controlled only by M-1 exploratory well. In modeling, lateral distribution of VSH property in all reservoirs was assumed to have similar value. This is unlikely for geological understanding, especially in case of depositional environment. The difficulty to understand the exact condition of fault-seal modeling is also occurred when data are limited. In this research, sensitivity analysis was proposed to acknowledge possibility of variation in lateral distribution using regional paleogeography during Triassic as timing of Challis reservoir adopted from Mory (1991). Mory stated that further NW, deposition of Triassic sequence was more distal to marine condition. It can be assumed that in such condition, VSH of reservoir zone will be higher (Figure 7). On the other hand, VSH will drop further SE as the environment is changing into more proximal (deltaic area). Three scenarios (12.5%, 25% and 50%) have been applied and developed to accommodate the rise or drop of VSH. These scenarios, as the sensitivity point of view, will be able to see the “pessimistic and optimistic” case of fault-sealing in “M” closure.

SEF is located in SE of the study area with more proximal and has sandier tendency. The value of SGR as well as fault permeability of all reservoir zones will be pessimistic for sealing due to its condition. In 12.5% scenario, the decreasing of SGR potency is slightly lower, with minimum SGR is around 0.29. In more pessimistic scenario, 25% scenario, SGR potency is down into 0.26. In extremely pessimistic scenario which has 50% difference, minimum SGR potency is dropped into 0.23 (Figure 8). In term of sealing potency, those numbers can be included as sealing fault. However, if the value near to 0.2, as limit of sealing fault proposed by Yielding et al. (2010), some of cataclastic fault gouge may reduce the capability and act as poor sealing. Maximum fault permeability in extreme pessimistic 50% scenario still suggests low number, 0.26 mD. In other scenarios, the fault permeability value will be lesser than 50% scenario.
NWF is assumed to have shalier tendency because its position relative to “M” closure tends to be more distal. Both SGR and fault permeability are assumed to be optimistic for sealing capacity. SGR potency in NWF for zone R1 to R3 is slightly higher in 12.5% scenario, with minimum SGR is around 0.38. In 25% scenario, SGR potency is going up into 0.44 and further optimistic scenario (50%), minimum SGR potency reached until 0.51 (Figure 9). Based on these multiple scenario observations, NWF is interpreted to have more clay smears and will act as moderate sealing fault.

Conclusions

This evaluation suggests that most of sensitivity scenarios have SGR more than 0.2 in all reservoir zones (R1, R2 and R3). It can be concluded that those bounding faults are above threshold for faults sealing hydrocarbon and potentially hold sufficient amount of hydrocarbon column. No hydrocarbon indication or show in “M” closure is likely due to failure in migration pathway or hydrocarbon charge rather than fault-breach.

As result, exploration opportunities for hydrocarbon discovery in Offshore Timor Sea are still widely open. There are many undrilled tilt-block closures similar to M “Closure” which could be potential if geochemical or source rock study can determine its position relative to kitchen area, hydrocarbon charge and migration pathway. However, advanced geochemical and migration pathway analysis are critical because fault-seal also gives major impact to the direction of migration pathway. Migration of hydrocarbon, if any, will be strictly limited and localized the interest area by the occurrence of these sealing faults.

References


**Figure 1.** Location of “M” Closure, relative to (A) Timor Sea water-depth map and (B) NW shelf of Australia (modified from Amir et al., 2010).

**Figure 2.** NW-SE seismic line shows multiple series of NNE-SSW horst-graben structures in “M” closure.
Figure 3. Northwest Fault (NWF) attributes histograms.

Figure 4. Southeast Fault (SEF) attributes histograms.
Figure 5. NW-SE cross-sections of fault juxtaposition.

Figure 6. NWF and SEF fault modeling.
Figure 7. Multiple scenarios of VSH property distribution adopted from Triassic paleogeography map from Mory (1991).

Figure 8. SEF sensitivity in Shale Gouge Ratio model.
**Figure 9.** NWF sensitivity in Shale Gouge Ratio model.