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An Integrated Assessment of Fault Seal Risk: A Case study from Kutch Offshore, India

Abstract

Fault seal risk assessment enables quantitative prediction of sealing potential of faults which leads to risk mitigation and improved estimation of prospects. This paper presents analysis of fault seal risks associated with lithological juxtaposition, fault-rock membrane and fault reactivation of GK-28/42 block in Kutch offshore. Paleo-juxtaposition situations of lithologies as well as active faults have been assessed through geological sequential restoration and are integrated in fault seal analysis. Present day faults with sand–on-sand juxtaposition and shale gouge ratio values <15% with high potential to reactivate are observed at Mid-Miocene and Early Eocene, indicating risk to seal breach. A hydrocarbon entrapment model has been built considering the migration and charging of individual fault blocks by episodic reactivation since Late Oligocene to Post Mid. Miocene. A quantitative fault risk probability at pay sands is estimated by combining risks of juxtaposition, fault-rock membrane and fault reactivation. Fault seal probability of Early Eocene pay sands S2 and S1 has been found to be moderately likely (0.63) to moderately unlikely (0.45) respectively.
The information gained on probability of sealing or non-sealing behavior of the individual faults facilitates quick look comparison with proven success/failure of prospect cases and substantially reduces the risks.

Introduction

Knowledge of the sealing or non-sealing capacity of faults significantly impacts success of exploration and the development strategy, particularly in areas of fault-bounded reservoirs. In GK-28/GK-42 area in Kutch offshore (Figure 1) hydrocarbon occurrences are associated with fault bounded entrapments and closures (Figure 2). Hydrocarbon pays have been established in Mid Miocene Chasra Formation, Early Eocene Jakahau formation, Paleocene Nakhtarana Formation, Deccan Trap and in Early Cretaceous Bhuj sandstone. However, the hydrocarbon distribution pattern in the block has been found to be highly unpredictable. The present study focusses on the role of faults in hydrocarbon accumulation and entrapment through fault seal analysis in a multidisciplinary approach encompassing juxtaposition of lithologies, membrane seal and fault reactivation in present day stress regime. A combined risk probability analysis of individual pay sand is also carried out incorporating the risks associated with above mentioned situation.

Structural Restoration

Sequential restoration along selected profiles in GK-28/42 block from Present day to Trap top has brought out the structural evolution of the block (Figure 3a, b, c & d). The episodic reactivations of most of the longitudinal faults (NNW-SSE) occurred in Post Mid Miocene (Post Chasra), Late Oligocene and Early Eocene period. During Early Eocene sediments were uniformly deposited within two minor structural lows. At each stage of structural evolution, different lithological juxtaposition situations existed due to fault reactivation. The structural setup since onset of critical moment of HC generation and expulsion played important role in entrapment. The risks associated at various stages have been examined in integrated fault seal risk analysis.

Figure1: Map showing the study area and wells drilled

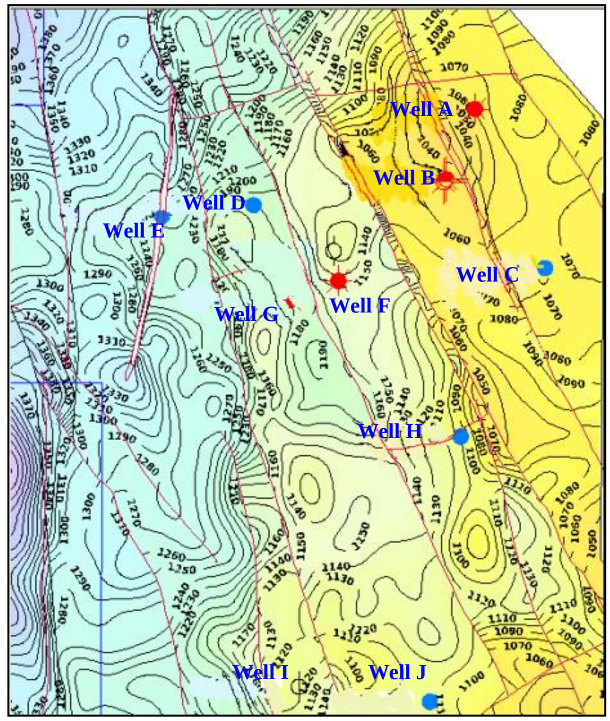


Figure 2: Structure map of GK-28/42 block showing wells and fault blocks (Source: WOB, Mumbai)

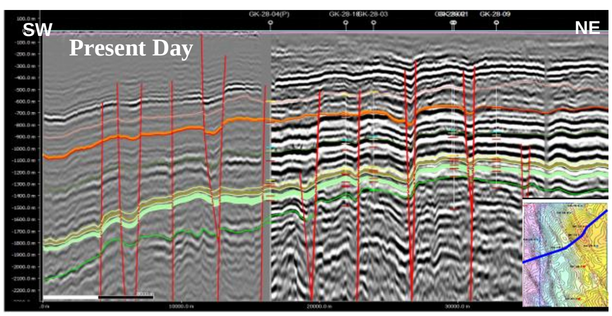


Figure 3a: Seismic section (along wells A,B, F and G) showing present day structural configuration

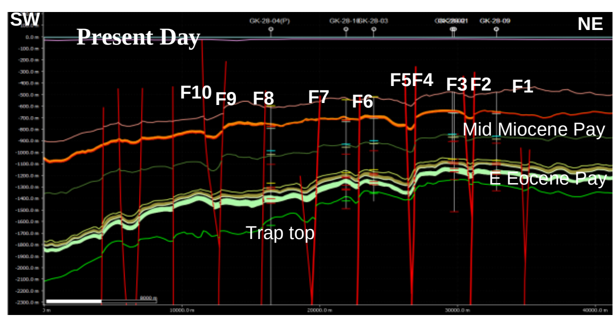


Figure3b: At MM Pay sand on shale juxtaposition and at S1&S2, sand and on sand juxtaposition present. Seal risk expected

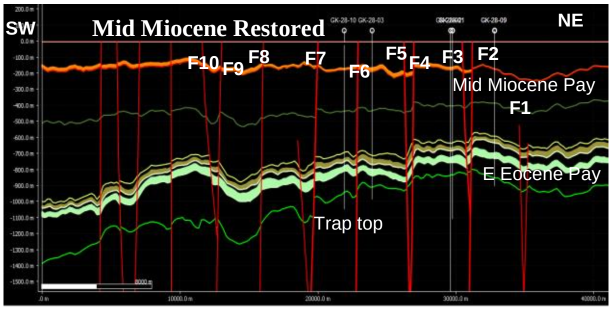


Figure 3c: Mid Miocene restored section. Reservoir non – reservoir juxtaposition at MM pay and S2 pay sand. At S1 pay sand-sand juxtaposition existed. Risk of HC entrapment

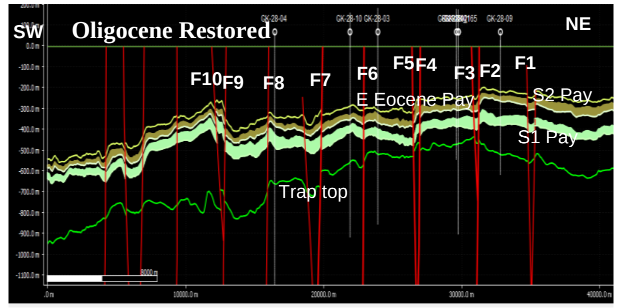


Figure.3d: Late Oligocene restored section. Early Eocene pay sands were in continuity with Eastern faults active

Fault Seal Analysis

In the present study fault seal assessment of major faults is analysed through geometric juxtaposition of reservoir against non-reservoir lithology, sealing potential of the faults, fault reactivation potential and Shale Gouge Ratio (SGR)-a robust algorithm to predict the sealing capacity of reservoir-reservoir juxtaposition on a fault plane (Yielding, 2000).

Triangular Juxtaposition Fault Seal

Triangular diagram showing lithological juxtapositions as a function of throw along the fault have been generated for different fault blocks of GK-28/42 area. At Mid Miocene pay sand level for throws greater than 10m, sand–shale juxtaposition was observed whereas for throw less than 10m, sand-sand juxtaposition exist (Figure 4a). The sand-sand juxtaposition field in triangular plots correspond to SGR values greater than 20%. At S2 level sand–shale juxtaposition was observed for throw > 10m and for throw <10m, sand-sand juxtaposition was observed where SGR values were less than 15% (Figure 4b).

Membrane Seal Analysis of Faults

Seal potential of individual faults are analysed through Allan diagrams (Allan, 1989). Analysis along two major faults F1 and as been carried out as below (Figures 5&6).

*Fault-1 (Well-A/ -B): F*ault F1 has high SGR values in the range 25-40% at Mid Miocene pay level at sand-sand juxtapositions, a sealing nature is expected. At S2 pay level, SGR values of 25-40% are observed. Lower SGR values (<15 %) with seal risk are present in the southern part (Figure 5).

Fault F2 (Well-B/F): SGR map of the fault shows high SGR values (> 25%) at Mid Miocene Pay sand. SGR value at S2 pay sand are in the range of 20-30%, but values < 15% are estimated in the northern part of the fault surface (Figure 6).

Fault Reactivation Analysis

Geomechanics based risking technique is applied to assess the likelihood of reactivation of faults. Maximum horizontal stress (SHmax) direction in Gulf of Kutch is oriented in N10^0 (Kundan et al, 2015). The gradients for SHmax, Sv, and Hmin were determined as 0.37 ksc/m, 0.22 ksc/m and 0.18 ksc/m respectively, indicates strike slip stress regime in present day. The reactivation probability of faults is assessed and displayed on Mohr's diagram. The NW-SE oriented faults at the depth of 650m (Mid Miocene pay) have slip tendency values in range 0.5-0.8 (Figure 7a) and the NW-SE oriented faults at the depth of 1150m (S2 Pay) have slip tendency values in range 0.5-0.6 (Figure 7b). Geomechanical analysis of the faults indicates that the faults are more critically stressed at the Mid Miocene Pay level vis- a- vis at S1 and S2 pay levels.

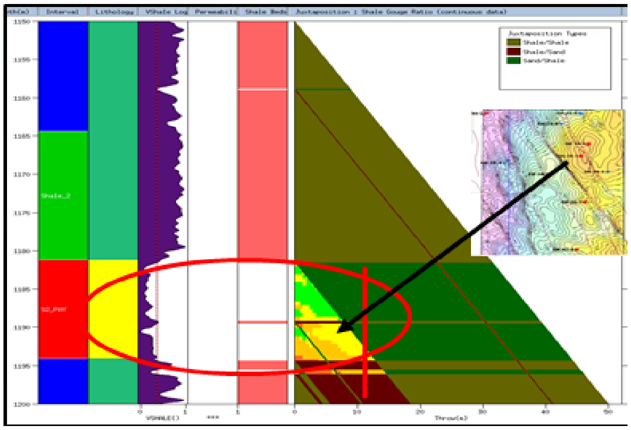


Figure 4a: Triangular juxtaposition diagram at Mid Miocene Pay sand level for GK-A1/ GK-B block. Sand –Shale juxtaposition observed for throw > 10m and at sand- sand juxtaposition SGR values > 20 % is observed

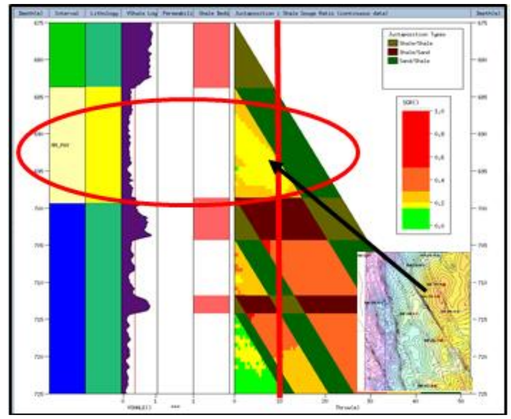


Figure 4b: Triangular juxtaposition diagram at S2 Pay sand level for GK-A/ GK-B block. Sand –Shale juxtaposition observed for throw > 10m and sand- sand juxtaposition SGR values < 15% for throw<10m.

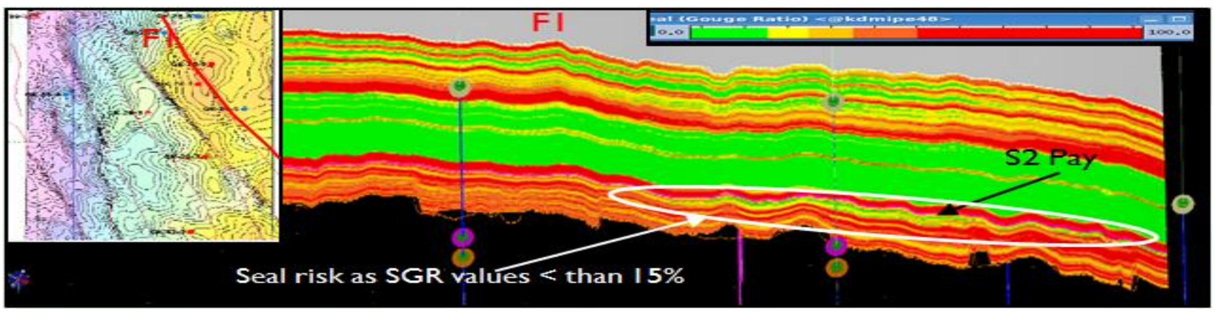


Figure 5: Fault plane diagram of F1 (Well A/B) showing SGR value. View towards west. At Mid Miocene Pay sand level high SGR values observed. At S2llevel lower SGR in the northern part of fault plane is observed

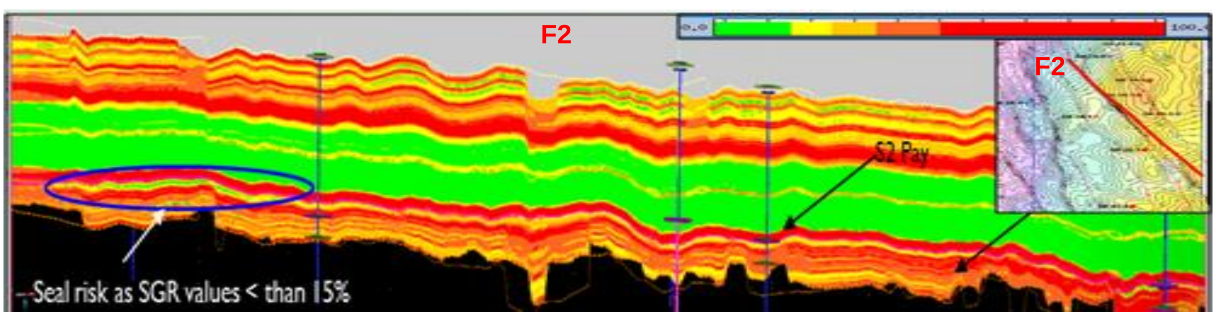


Figure 6: Fault plane diagram of F2 (Well B/F) showing SGR value. View towards west. At Mid Miocene Pay sand level high SGR values observed. At S2 level lower SGR in the southern part of fault plane is observed.

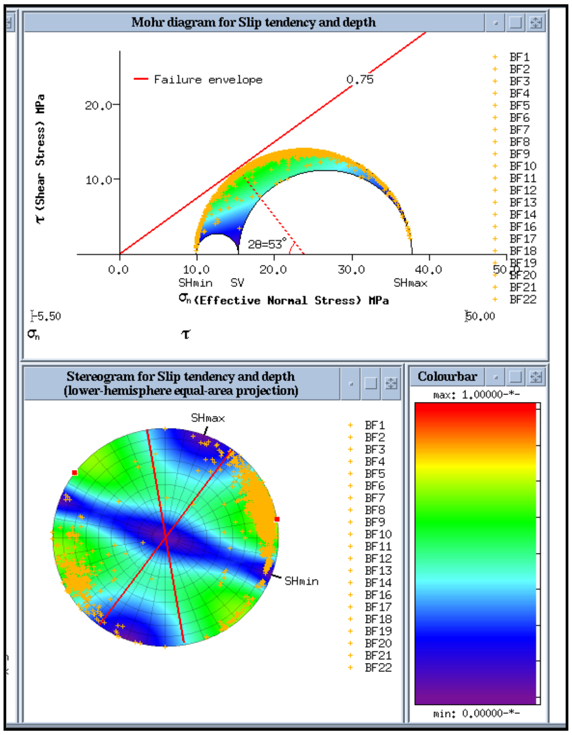


Figure 7a: Slip tendency o faults displayed on Semi –Mohr's circle and stereo plots at Mid Miocene Pay level (`650m). Fault planes are represented as poles on these diagrams. Slip tendency is in range 0.6-0.8.

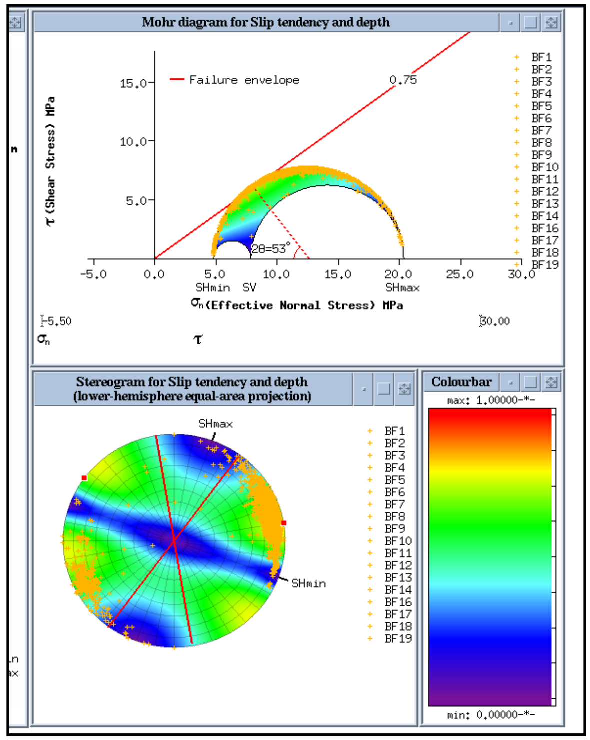


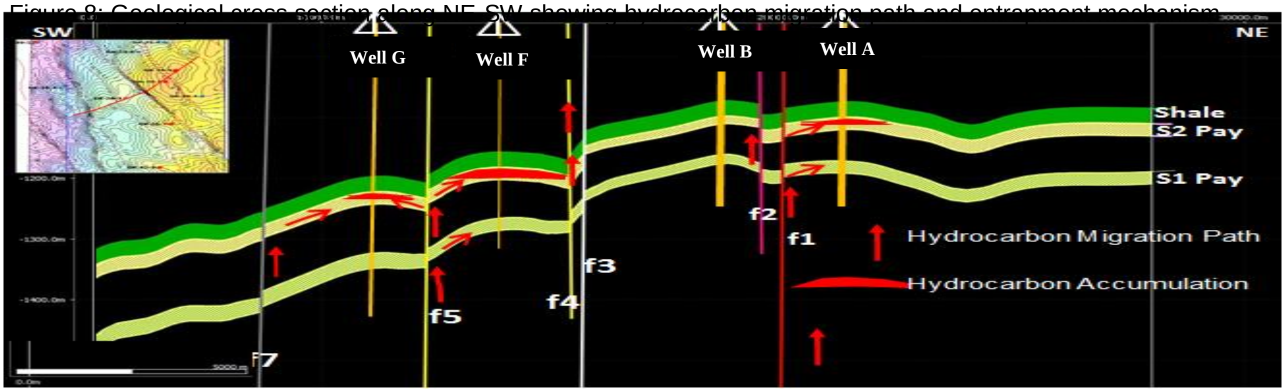
Figure 7b:Slip tendency of the all the faults displayed on Semi –Mohr's circle and stereo plots at S2 Pay level (`1150m). Fault planes are represented as poles on these diagrams. Slip tendency is in range 0.5-0.6.

Hydrocarbon Entrapment Model

Petroleum system of Kutch Offshore suggests hydrocarbon generation from deeper, matured source rock of Mesozoic sequences and migration via vertical faults (Crossley, 2005). Structural restoration establishes that the major faults remained active since Early Eocene till the end of Mid Miocene, enabled vertical fluid migration and also created lateral barrier through lithological juxtaposition of permeable and impermeable units.

Hence, hydrocarbon distribution pattern is controlled by combination of structural set up and sealing potential of faults. The geological cross section in NE-SW direction (Figure 8) shows migration entrapment model explained by the sand–shale and sand-sand juxtapositions situations in different fault blocks.

Figure 8: Geological cross section along NE-SW showing hydrocarbon migration path and entrapment mechanism



Fault Seal Risk Assessment

An integrated probability of fault seal risk has been estimated for pay sands S1 and S2 by integrating the risks associated with juxtaposition seals, fault-rock membrane seals, and fault reactivation. Fault seal probability is expressed as: FS= {1- [(1 - a) (1 - b)]} x (1- c), where a, b, and c are the probabilities of deformation process sealing, juxtaposition sealing and fault reactivation.
The integrated probability of fault seal for S1and S2 pay is displayed on fault-seal risk (FSR) web (Jones and Hills, 2003) illustrating the probability and seal condition (Figure 9).
The critical parameter for fault-seal risking at GK-28-42 prospect is the ability of faults to support large hydrocarbon columns at sand on sand juxtapositions with low SGR. This aspect is controlled mainly by amount of throw. Situations having throw <10m have sand on sand situation with SGR<10m. Evaluation of individual components fault sealing are made for throw situations <10m and >10m and tabulated below

	Throw m)	Membrane Seal (a)	Juxtaposition (b)	Fault Reactivation (c)	Fault risk
S2 Pay sand	<10	Moderately unlikely(0.4)	Moderately unlikely0.4	(0.3)unlikely	0.25
	>10	Extremely Likely (0.9)	Extremely Likely (0.9)	(0.3) unlikely	0.63
S1 Pay sand	<10	Intermediate (0.5)	Unlikely (0.3)	(0.3) unlikely	0.46
	>10	Moderately likely (0.6)	Unlikely (0.3)	(0.3) unlikely	0.50

S2 Pay sand risk web **S1** Pay sand risk web

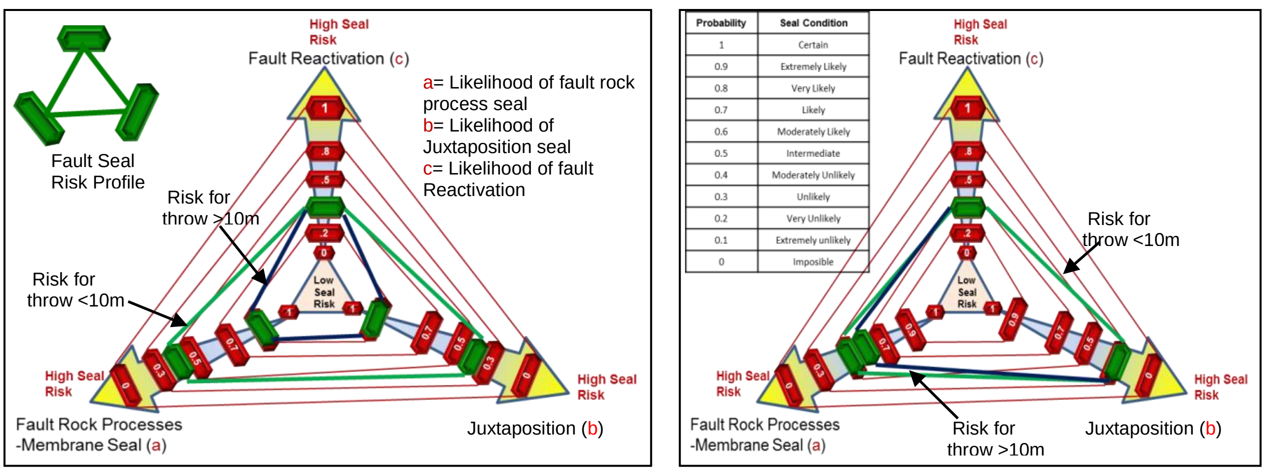


Figure 9: Fault-seal risk web, risk profiles, and integrated prospect fault-seal risk for S1 and S2 pay sand at throw <1m- and >10m. Increased fault seal risk associated with the lower throw and in S1 pay sand.

The overall fault seal probability of S2 sand is 0.63 and 0.25 for throw >10m and < 10m respectively. The likelihood of fault seals for S1 sand is 0.5 and 0.45 for throw >10m and < 10m respectively

Conclusions

Integrated fault seal analysis in GK-28/GK-42 area of Kutch offshore has been carried out encompassing juxtaposition of lithology, fault membrane seal and fault reactivation in varying stress regimes. At Mid

Miocene pay and Early Eocene pay sand levels, for throw values greater than 10m sand–shale juxtaposition was observed and for values less than 10m, sand-sand juxtaposition exists. Fault zones with SGR values < 15%, at sand – sand juxtaposition are identified as areas of high seal risk. Fault reactivation analysis indicates the faults have higher slip tendency at Mid Miocene pay (0.5-0.8) than the Early Eocene pay levels. Hydrocarbon distribution pattern is controlled by combination of structural set up and sealing potential of faults. The probability of fault seal risk estimates for Early Eocene pay sands S1 and S2 has been made by combining the risks associated with juxtaposition seals, fault-rock membrane seals. Fault seal probability has been estimated to be moderately likely (0.63) to moderately unlikely (0.45).The sealing and non-sealing behavior of the individual faults and associated risk obtained by the present study is valuable input for exploration and development planning in the block.

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