Fault Seal Analysis - It's Bearing on Development Plan of Clastic Reservoirs, Kalol Field, Cambay Basin, India

A. K. Jena*, R. Matta, A. J. Duggal, J. S. Bhosale and Ram Avtar
Subsurface Team, Oil & Natural Gas Corporation Ltd., Ahmedabad Asset Ahmedabad, Gujarat, India
E-mail: ajaya_jena@yahoo.co.uk

Summary

Fault sealing is one of the key factors controlling hydrocarbon accumulation and trap volumetrics that can play a significant role on reservoir performance during production. This paper discusses two situations of sealing and non-sealing faults which have played significant role in formulating development plan for two clastic reservoirs of Kalol field of Mehsana-Ahmedabad tectonic block of Cambay Basin.

In the first case, for K-II reservoir in the western part of Kalol Field, a sealing fault makes a separate fault block bounded by cross faults and a westerly dipping fault. This subseismic fault having throw of 5-10m has juxtaposition of reservoir to reservoir facies. With the precision of three dimensional mapping and interpolation of reservoir geometry and layer properties in vicinity of fault it was found that the fault is sealing with adjacent up-thrown block by shale gouge or smear in the fault zone. It was confirmed by the contrasting pressure regime in the up-thrown and down thrown blocks. The up-thrown block has a depleted pressure of about 40 KSC with a considerable period of production history in comparison to the higher pressure regime observed in the down thrown block with a reservoir pressure of about 120KSC. The down thrown block with a weak aquifer support has been considered as a favourable locale for hydrocarbon exploitation.

In another case, for K-VA reservoir in the eastern part of Kalol field, a non sealing fault plays a major role in fluid distribution. This fault is clearly marked with a missing section of about 22m in a well log of the up-thrown block. With precise geological modeling and well log analysis, a three dimensional picture of fault plane was mapped. It was found that there is no juxtaposition of reservoir to reservoir facies. Non-sealing nature of fault was confirmed by the reservoir pressure of about 125 KSC in both sides of the fault. This can be explained by re-activation of fault with a crushed zone. The fault zone acts as a conduit to fluid flow by developing permeability in the crushed zone with breaking down of shale continuity in fault zone or brittle units in fault zone. There is very weak aquifer support from Nardipur low side and the reservoir pinches out towards west. The non sealing fault with water injection and pressure maintainace scenario is giving excellent result from the optimum hydrocarbon recovery point of view.

The juxtaposition or shale smear analysis of subseismic faults can be applied in the fields with multilayered stacked clastic reservoirs of sand/ siltstone/ shale/ clay alternations in extensional normal fault bound blocks. This will help in estimating reserve volume, performance prediction of reservoirs with history match thereby adopting a suitable development strategy for optimal hydrocarbon recovery.

Introduction

Cambay basin in western part of India is a marginal aulacogen type of rift basin (S. K. Biswas, 1998) bounded on it's eastern and western margin by master faults (basin margin faults) trending parallel /sub-parallel to the basin axis. This Cenozoic extensional basin came into existence during late Mesozoic era with the development of major tensional faults along pre-existing basement trends followed by wide spread extrusion of basaltic lavas called Deccan trap. This basaltic floor formed the technical basement for the subsequent Cenozoic sediments. The developments of transfer zones and transfer faults have divided the basin into different fault blocks. The basin has been divided into five tectonic blocks based on the recognizable basement fault trends and subsurface ridges i.e. (1) Sanchor-Patan block (2) Mehsana-Ahmedabad block (3) Cambay-Tarapur block (4) Broach-Jambusar block and (5) Narmada –Tapti block (Mathur et al, 1966).

Kalol field (Figure 1) falls in the Mehsana-Ahmedabad tectonic block of Cambay basin over basement uplift. It is located about 16 km north of Ahmedabad City covering an area of around 300 Sq. Km. The field was discovered with the drilling of well Kalol #1 in June 1961 and put on production in 1964. In Kalol field hydrocarbons have been encountered in Olpad, Cambay shale and Kalol formations of Paleogene sequence between 1250-1550m

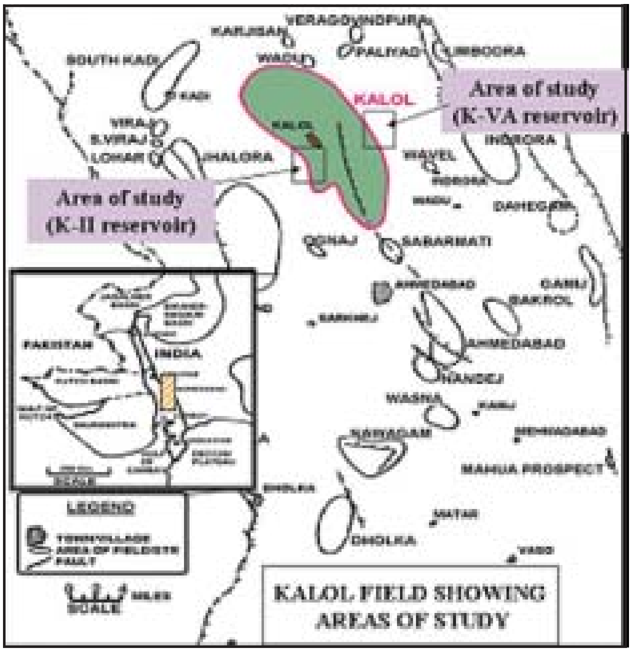

Fig. 1: Location Map of Kalol Field

depths (Figure 2). Pay sands K-II to K-XI fall in Kalol Formation whereas K-XII falls in Chhatral Member of Kadi Formation.

Within Kalol Formation K-II to K-V belong to Wavel Member. The trapping mechanism is strati-structural in K-II to K-V and K-XII pay sands and stratigraphic in K-VI+VII to K-XI. The predominant drive mechanism in major reservoirs is depletion drive and presently these reservoirs are operating under pressure maintenance.

Generalised Stratigraphy of Kalol Field

Age	Formation	Member/ Horizon		Lithology	Lithological Description
Lr.Miocene to Recent	Post-Babaguru & Babaguru				Arenaceous and arigillaceous interbands.
Oligocene	Tarapur Shale				Monotonous shaly sequence.
Middle Eocene	Kalol Formation	Wavel Member	K-II		Mainly siltstone to fine sandstone sequence intercalated with shale and coals, occurring at a depth of 1250 to 1600m MSL.
			K-III		
			K-IV a		
			K-IV b		
			K-V		
		Kansari Shale			
		Sertha Member	K-VI		
			K-VII		
			K-VIII		
			K-IX+X		
			K- XI		
	Younger Cambay Shale	Nandasan Shale			Sandstone lenses interfinguring with transgressive shales. Also known as Kadi Formation.
		Chhatral Member	K-XII		
Lower Eocene			Below K-XII		
	Older Cambay Shale				Dark grey monotonous marine shales.

Fig.2: Generalised stratigraphy of Kalol Field

Overall recoveries are poor from the field (< 10% of in place oil) and the reason is mainly attributed to reservoir heterogeneity. Almost two fold increase in production from 1995-96 to 2004-05 is attributed to the implementation of development schemes for K-VA, K-X and K-VII reservoirs, adopting technologies like multilateral/ horizontal / drain hole drilling and MEOR to improve recovery.

The dominant lithological assemblages of Kalol Formation are shale/ carbonaceous shale, sandstone, siltstone and coals. The pay-sands from K-II to K-V belonging to Wavel Member of Kalol Formation are composed of fine to very fine grained sandstone/ siltstone alternating with layers of shales and coals and appear to have been deposited in lower to sub-aqueous delta plain regime as distibutary

Generally the reservoir character is better in the sands belonging to Wavel Member unlike the Sertha Member which have relatively poor petro-physical character. Two clastic reservoirs K-II and K-VA (Wavel Member) of Kalol Formation in western and eastern part of Kalol field respectively are discussed here (Figure 1). Kalol field is compartmentalised into a number of fault blocks with sublistric normal faults and cross faults. The sealing or non sealing nature of faults plays a significant role in fluid distribution, pressure and production behavior of these reservoirs.

Sealing Fault and it's bearing on development plan of K-II reservoir

K-II pay-sand is developed in the central part of Kalol field having roughly an ENE-WSW depositional trend. (Figure 3).The sand thickness varies from 5 to 10m.

Lithologically it is fine to very fine grained sandstone to siltstone with intervening shale/carbonaceous shale laminations and occasionally sideritic. It is overlain by shale/ silty-shale sequence and underlain by a shale sequence followed by K-III coal. The sand is slightly shaly towards bottom and having a coarsening upward sequence (Figure 4a, b and c). The reservoir has good porosity and permeability and pinches out towards north as well as south of the Kalol field. It appears to have been deposited in a lower to sub-aqueous deltaic regime. Towards Wamaj low

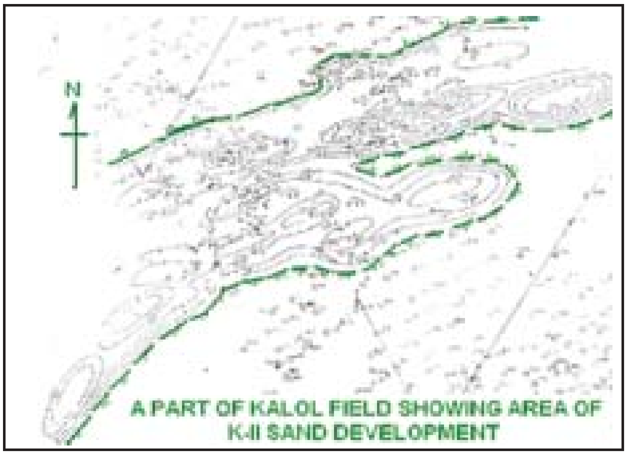

Fig. 3: Sand isolith map of K-II sand (a part of Kalol Field)

side it is water bearing followed by oil and gas in the structural higher positions towards east. Initially, it was considered to be mainly gas bearing reservoir with a small oil rim. With exploratory effort when the reservoir was delineated towards Wamaj low side in west, it was found that the reservoir is oil bearing with weak aquifer support. In one of the exploratory well OWC was observed at -1342m (msl). The beds are gently dipping towards the low. There are a number of normal faults almost parallel to main axial fault of Kalol field and the transfer faults are slightly oblique to these faults.

It was found that some of the structurally higher wells were behaving differently with depleted pressure and structurally lower wells are flowing on self with almost virgin pressure. The plausible answer to the anomalous behaviour of the structurally higher wells could be a permeability barrier in the form of sand pinching out towards east or a fault with a substantial throw isolating the two set of wells. When zone transfer was done in one of the wells, it was found that the reservoir is highly depleted (pressure about 40 KSC). It necessitated the identification of the permeability barrier. On log analysis it was found that the sand is well correlatable and the thick sand unit (8-10m) is quite in continuation in both structurally higher and lower wells(Figure No : 4b). Missing section was not observed in any of the well. On studying seismic sections it was difficult to visualise the fault. In one section, it was marked with a fair degree of certainty (Figure 5). Taking clue from the seismic section a three dimensional conceptual geological model was prepared to visualize the position of the fault. From depth contour map(Figure : 6a & b), it was difficult to visualize the non-sealing nature with juxtaposition theory as the throw is about 5 to 10m and thickness of sand varies from 5 to 10m.

With a normal fault of 5-10m throw there will be juxtaposition of reservoir to reservoir facies (Figure 7a & b), and is likely to be nonsealing. In this case the fault is sealing. This is possible with shale smear in the fault zone (Koledoye et al., 2003and Doughty Ted P., 2003). When faulting takes place with increased dragging the shale layers/ laminae will form a layer in the fault zone.

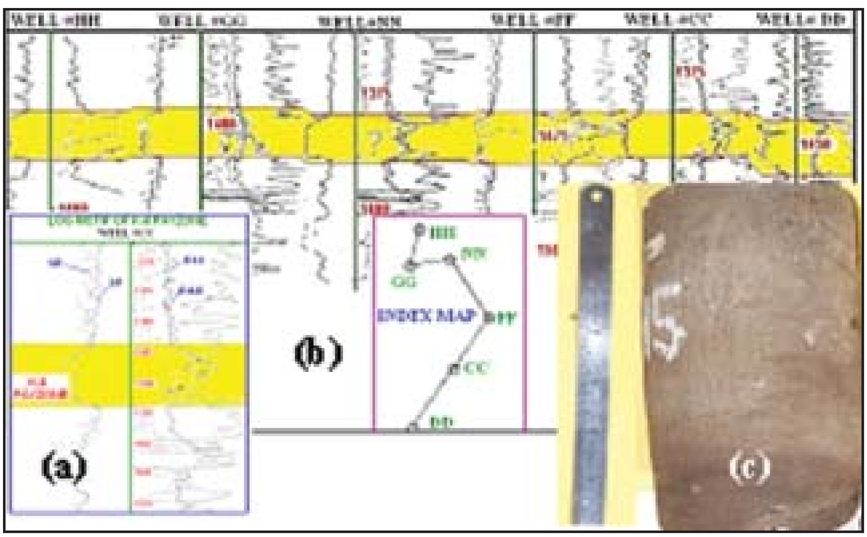

Fig. 4: (a) Log motif of K-II reservoir with layers of shale and coal (b) a log correlation profile shows the continuity of sand from south to north. (c) the core piece shows very fine grained sand stone/siltstone layers with small scale trough cross bedding.

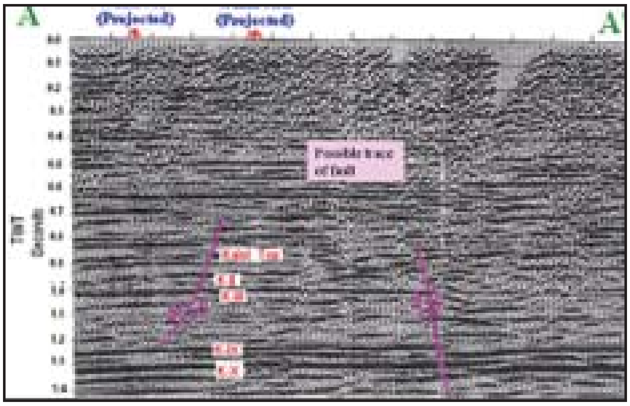

Fig.5: Part of a seismic section AA’ showing the possible trace of fault between well # FF and well #BB. Note that the fault is not very clear.

isualising the fault plane geometry, the shale layers reveal a smearing process by which the shale units reduce their thickness or vanish by thinning perpendicular to the fault plane stretching parallel to the fault plane. The reduction of pore throat size through granulation and the presence of clay or shale in the fault zones will make it impervious. In case of lithified clastic sediments shale/ clay smear is recognized as the dominant sealing mechanism where shale/clay smear forms primarily by abrasion and secondarily by shearing of the host sediments along faults. (Lindsay et al., 1993, Knippe, 1997). On the other hand faults in unlithified sediments are believed to form clay/ shale smear by injection of highly ductile shale/clay beds into the fault zone (Lehner and Pilaar, 1997; Weber et al., 1978; Van der Zee and Urai, 1998). This looks to be a valid answer for the subseismic fault which is sealing where other parameters (continuation of reservoir, favourable juxtaposition and minimal throw) do not answer the sealing property of the fault. The sealing parameter of the fault is validated by the difference in reservoir pressure in up thrown and down thrown blocks. The up-thrown block has a depleted pressure of about 40 KSC (with a considerable period of production history) in comparison to the higher pressure regime (120KSC) in the down thrown block. The sealing fault between well# FF and well #BB which differentiates the high pressure down thrown block and depleted up-thrown block plays an important role for exploitation of the reservoir. The block is bound by two cross faults in NW and SE direction. Towards west the reservoir is having very weak aquifer support from Wamaj low side.

Thus this fault block becomes a favourable locale for development of K-II reservoir. The reserve volume was re-estimated taking into consideration of the above discussed parameters. A central line drive injection pattern with infill producers having spacing of 500 x 500m have been planned for development of K-II reservoir for optimum recovery in this fault block.

Non sealing Fault and it’s bearing on development plan of K-VA reservoir

Pay-sand K-VA is developed in the eastern part of Kalol field in the rising flank of Nardipur low. Two sand

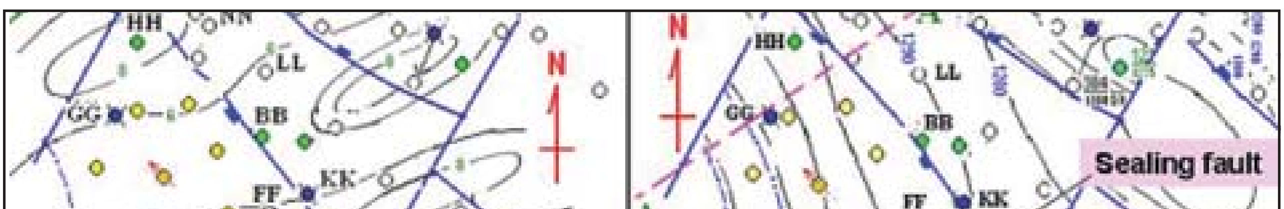

Fig. 6: (a) Sand isolith map of K-II paysand shwoing almost an east west trend (OWC is projected on it) (b) Structure contour map close to top of K-II sand with the sealing fault between well # FF and BB.The seismic section is AA’

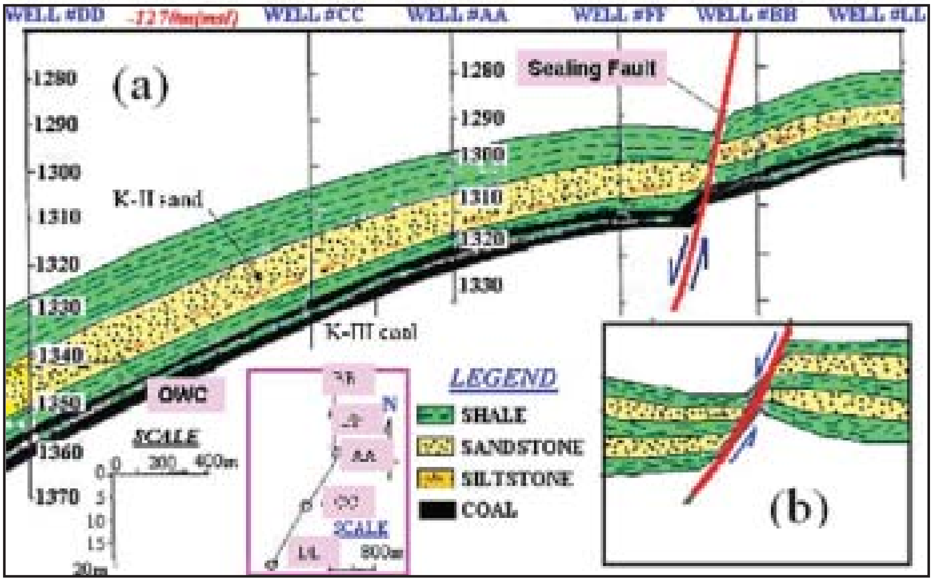

Fig. 7: (a) A geological cross section across the sealing fault with K-II sand overlain and underlain by shale and coal layers.There is juxtaposition of sand to sand but the fault is sealing due to shale smearing.(b)Shale smearing along fault zone with thinning of shale layers

units are developed in K-V horizon, one below the regionally correlatable coal and the other above coal. The upper unit is K-VA and the lower unit is K-VB, (Figure 8 a). K-V horizon is underlain by Kansari shale of about 20m thickness and overlain by a shale layer of about 5-7m thickness followed by K-IV bottom coal. Lithologically it consists of fine to very fine grained sandstone/siltstone with laminations/bands of carbonaceous shales and coals-VA sand unit is developed with sand maxima of about 8-10m. and has a coarsening upward sequence. The sand isolith map shows a roughly NNW-SSE depositional trend from Wadu-Paliyad area in north to Kalol, Motera and

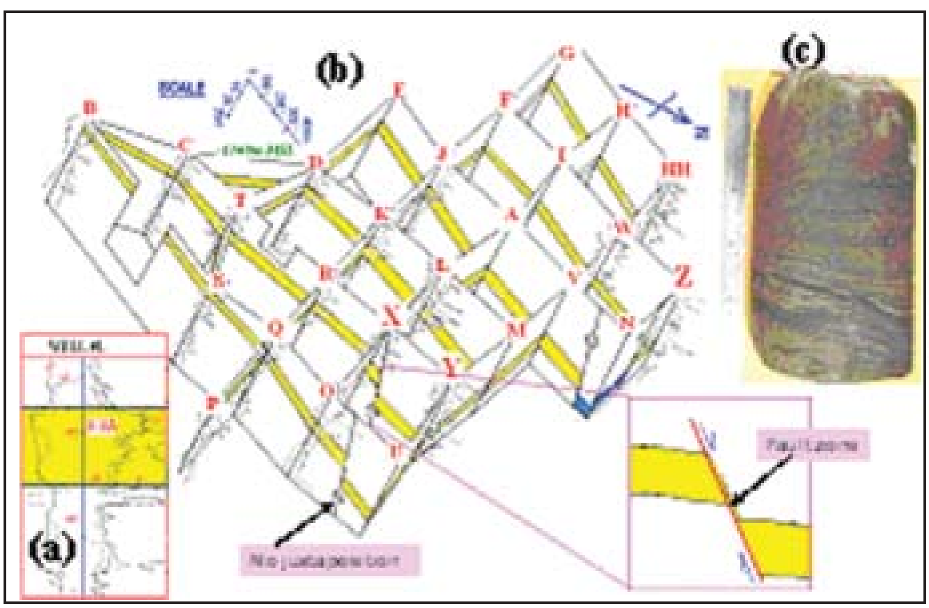

Fig. 8: (a) Log motif of K-VA sand (b) Fence diagram showing K-VA sand distribution with the fault zone.(c) Core of K-VA reservoir showing very fine grained sandstone/siltstone with carbonaceous silt layers.

Ahmedabad Field in south right across Nardipur low area (Figure 9a). In eastern part of Kalol field it is well developed and towards south it has isolated occurrences in Motera and Ahmedabad fields. The sand detoriates towards south west direction and pinches out in the west. In Nardipur low area, the sand is water bearing with thickness of about 8-10m. Where as in the rising western flank of Nardipur low it is hydrocarbon bearing in Kalol field. The sand may have been deposited as meandering channel/stacked channels in Wadu-Paliyad area in upper delta plain depositional regime while in Kalol area the sand looks to be deposited as distributary mouth bars in lower deltaic regime. Further south in Motera and Ahmedabad area this sand is developed as isolated lenses of offsore bars in sub-aqueous deltaic regime.

Eastern part of Kalol field is dissected by a number of NNW-SSE normal faults almost parallel to the basin margin and NNE-SSW trending cross faults making a number of fault blocks(Figure : 9 b). A three dimensional mapping of the faults was carried out with log analysis, core studies, depth contour maps and fence diagrams integrating with reservoir pressure data of the fault blocks. In one of the well log a missing section of about 22m was observed. Comparing the log of well #X with log of well #Y, it was found that a portion of K-IVB sand unit and sand/shale sequence of entire K-IVA section is missing. Integrating this data with depth contour map a NE-SW trending fault zone was mapped. The fault zone was interpreted to be passing through K-IVB sand unit of well # X in the up-thrown foot wall block. Undisturbed lithological sequence in well #Y was in down thrown hanging wall block (Figure 10).With fence diagram, juxtaposition diagrams were prepared taking into account the throw of the fault and thickness of the reservoir. It was found that there is no juxtaposition of reservoir to reservoir. Further north, the continuation of fault was mapped with almost same throw. It was confirmed by the fluid anomaly observed in well # Z and well # N. In well # Z the sand is totally oil bearing, where as in well #N the sand is totally water bearing (Figure 8b). Though there is no juxtaposition, the fault is interpreted to be non-sealing as the reservoir pressures are same in down thrown and up-thrown blocks (125KSC).

This can be explained by fault zone permeability on reactivation. A fault may seal if deformation process has created a membrane seal or if it juxtaposes sealing non-reservoir facies against reservoir facies and fault zone has not been activated subsequent to hydrocarbon charging upon reactivation of faults, a crushed zone is formed which creates a fracture permeability. The fault zone acts as a conduit to fluid flow by developing permeability in the crushed zone with breaking down of shale continuity in fault zone or brittle units in fault zone.

The fault zone remains permeable parallel to fault plane with crushed sand/shale mixtures. Cemented tight reservoirs are more prone to fracture creation. Multiple reactivation episodes without subsequent fault gouge healing would make it always a weak zone. (Jones Richard M. et al., 2002) In vicinity of fault zone shearing of sandstone/siltstone/shale layers takes place creating unhealed fractures. The shearing/fracturing of the sandstone/shale depends on the ductility of the layers. This can be marked in cores with

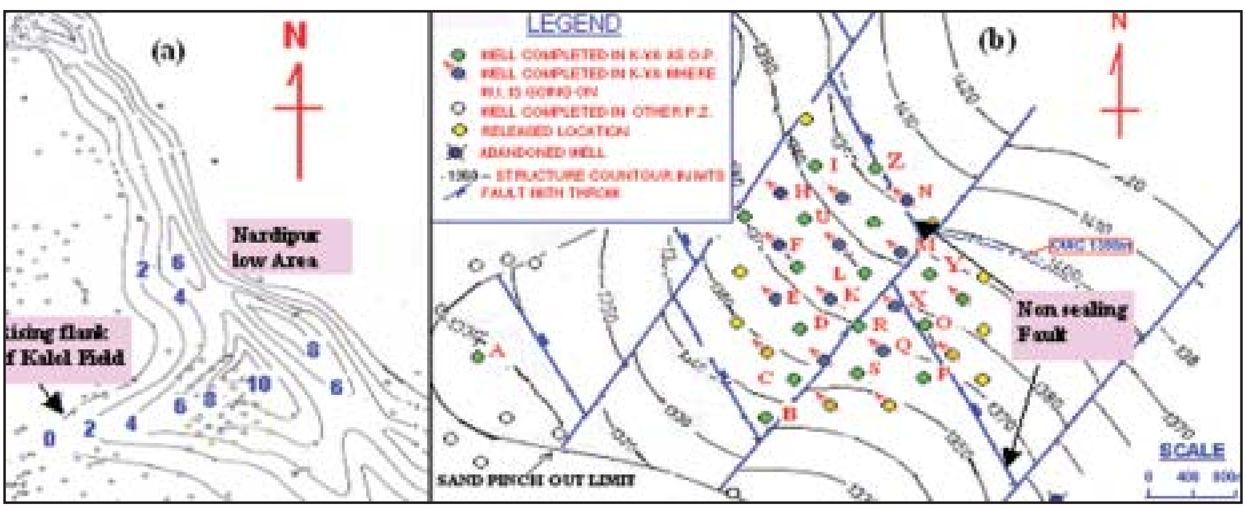

Fig.9: (a) Sand isolith map of K-VA paysand (b) Structure contour map at top of K-VA paysand showing the non sealing fault.

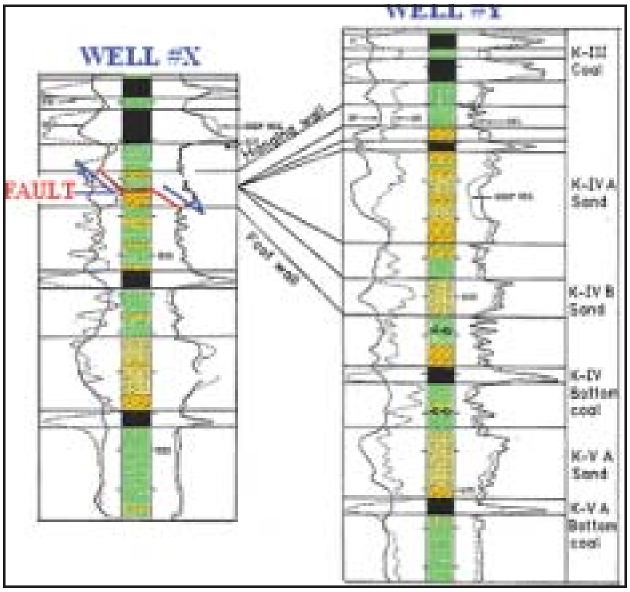

Fig.10: Missiing section in well # X.It can be noted that about 22m of section belonging to K-IVB and total K-IVA sand unit is missing.

deformed/sheared layers and small scale faults with slip surfaces in vicinity of fault zone (Kim Jin-wook et al., 2003). In this case a core taken from well #N, K-IVB sand unit shows small scale deformation and faults with slip surfaces (Figure : 11). The well falls in the vicinity of the fault zone and these minor faults and deformations in sandstone/ siltstone /shale bands in the core sample may be due to shearing during reactivation of the fault.

There is very weak aquifer support from Nardipur low side and the reservoir pinches out towards west. The faults are communicating in nature from reservoir pressure point of view. The sand has good porosity and permeability. An inverted five spot pattern with 400 x 400m spacing is planned for development of this reservoir for optimum recovery. At present the reservoir is under exploitation with 11 injectors and 14 producers and additional 5 producers and 5 injectors are planned. This reservoir is a prolific producer with well designed pressure maintenance. The non sealing fault with water injection and pressure maintain ace scenario is giving excellent result from the optimum hydrocarbon recovery point of view. The confirmation of the continuation of the fault with substantial throw and water bearing nature of well #N helped in avoiding additional locations east of this fault.

Discussion

The juxtaposition of reservoir to reservoir or no juxtaposition does not exactly explain the sealing or non-

Fig.11: Core sample in one of the well #Z in vicinity of fault zone. A minor fault in siltstone band is marked with slip surface.

sealing nature of a fault. Earlier it has been shown that for sub-seismic faults with minimal throw it is very difficult to conclude the fault plane geometry. In juxtaposition technique the hanging wall and foot wall stratigraphy and fault plane are projected on to a three dimensional model to know the sealing or non-sealing nature of the fault. Here the fault plane is assumed to be a single plane, generally the faults have multiple segments. So in this case shale-smear distribution is evaluated in fault zone with segmented model of faults. (Koledoye and Aydin et al., 2003). In case of K-II sand the trace of fault is not clear in seismic sections. The sand is quite continuos in both up-thrown and down thrown block. So unless a close look is given to the possible permeability barrier between the wells with depleted pressure and higher pressure regimes, it will be difficult to sink a new well or formulating a suitable development plan. A zone transfer may be useless or a well may miss the target reservoir unless the exact position of fault zone is identified. The thickness variation, differential throw and lithological variation along fault plane also have bearing on the sealing or non-sealing nature of fault. Once the sealing parameter of the fault block is evaluated the reserve volume can be estimated and a proper development plan with suitable pressure maintainance can be formulated for the reservoir. The presence of small scale faults and slip surfaces in a core belonging to one of the well in the vicinity of fault zone favours the fault zone transmissibility with a damaged zone.

These are two contrasting situations of analyzing sealing and non-sealing nature of faults, but there is always uncertainty in predictive edge of a fault seal analysis based on three dimensional geological modelling with fence diagrams, seismic analysis and log analysis to gather evidences in favour of fault to act as a barrier or conduit to fluid flow because of lithological variations, differential throw of fault and sub-seismic nature of faults with minimal throw. The shale smear factor looks to be more valid for stacked multilayered clastic sediments with sand /shale/clay alternations. Similarly re-activation aspect of the fault has to be studied carefully as it has bearing on regional scale. Other studies like RLT (Reservoir Limit Test), SFT (Selective Formation Test) and MDT (Modular Dynamic Test) help to know the possible limit of a fault or the pressure regime and nature of fluid in the reservoir before conclusion is drawn. The integration of these methods in fault analysis and studies of the processes by which fault zone forms can also contribute to the understanding of hydrocarbon flow models and provide better history matches and predictions of reservoir performance. In the case for K-II reservoir the placing of additional development locations were restricted to the western part of the sealing fault, where as for K-VA reservoir after ascertaining the throw of the non-sealing fault and analyzing the water bearing nature of well # N, additional locations were avoided in the down thrown block.

Conclusions

- Identification of fault sealing or non sealing parameter is very important as this may lead to a dry well with missing pay-zone or sinking the well in water bearing sand or depleted pressure regime. Identification of fault zone helped in avoiding additional locations in case of K-II and K-VA reservoirs in depleted and water bearing fault blocks respectively.
- The sealing sub-seismic fault having a throw of 5-10m and juxtaposition of reservoirs in case of K-II reservoir can be explained with shale smear in fault zone where the shale layers thin perpendicular to fault plane to make permeability barrier.
- In case of K-VA reservoir where the throw of fault is marked by a missing section of about 22 m in one of the well without juxtaposition of reservoirs, the non-sealing nature of fault can be explained by fault zone permeability with breaching of fault seal by breakdown in the continuity of shale smear or brittle units in fault zone by re-activation.
- Deformation/shearing/faulting of reservoir layers in cores taken from wells in vicinity of fault zones can throw light on the possible nature of fault zone. RLT (Reservoir Limit Test), SFT (Selective Formation test) and Modular Dynamic Tester (MDT) can be carried out in the wells in vicinity of predicted fault zones to confirm permeability barriers and explain pressure regimes and fluid anomalies.
- The juxtaposition or shale smear analysis of sub-seismic faults can be applied in the fields with multilayered stacked clastic reservoirs of sand/ shale/ clay alternations in extensional normal fault bound blocks. This will help in estimating reserve volume and history match of the reservoirs thereby adopting a suitable exploitation strategy for optimal hydrocarbon recovery.

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