



Optimal Recovery from Low Permeability Reservoirs of Kalol Field, Cambay Basin, India - Some Key Issues.

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Summary

For low permeability reservoirs, innovative exploration/ exploitation strategy is required for optimal hydrocarbon recovery. The paper discusses about a low permeability reservoir K-VII of Kalol Field, which has a substantial reserve base and potential for exploration/exploitation. This reservoir has a substantial contribution in increasing production of Kalol field. From core studies it was found that the horizontal and vertical permeabilities (K_h and K_v) are in the range of 0.55 to 14.85 mD and 0.04 to 2.47mD respectively with permeability anisotropy (β) of about 2.5. The recovery from this reservoir is as such very less. The primary recovery methods have not given desired results. The production is generally obtained with hydrofracturing. The development scheme implemented for this reservoir has yielded good results in northern and eastern part of Kalol field but over all recovery is poor (< 7% of OIIP). This reservoir was identified for unconventional wells.

One multilateral well was completed successfully in this reservoir in 2001(incidentally this was the first Onland Multilateral well of India). Two barefoot child laterals of 250m each were placed 60° apart in the reservoir. The well has produced about 34,000m³ of oil in last 6 years and produces about 4 times more than the nearby conventional wells completed in K-VII reservoir. Observing performance of this well, unconventional wells were planned in a larger scale for improved recovery from this reservoir of Kalol Field. Recently three unconventional (horizontal/multilateral) wells have been completed in K-VII reservoir and one is under drilling by the time of writing of this paper. This paper discusses some key issues about the placement of child laterals/horizontal sections, ultrashort radius wells and underbalanced drilling. With improved technology multibranch/forked/stacked and dual-opposing laterals are suggested for this type of reservoirs to cross permeability barriers for improved recovery. The performance of recently completed unconventional wells shows that reservoir pressure in the fault blocks will also play an important role for productivity. The study also concludes that A/L Completions with Gas Lift will have an edge over SRP completions.

Introduction

Kalol field (Figure : 1) falls in the Ahmedabad-Mehsana tectonic block of Cambay basin. It is located about 16 Km north of Ahmedabad 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. The field is under exploration/exploitation with 608 wells as on date. There are 11 pay sands i.e. K-II to K-XII from top to bottom sequence occurring between 1250-1550m depths (Figure : 2). Pay sands K-II to K-XI fall in Kalol Formation where as K-XII falls in Chhatral member of Kadi

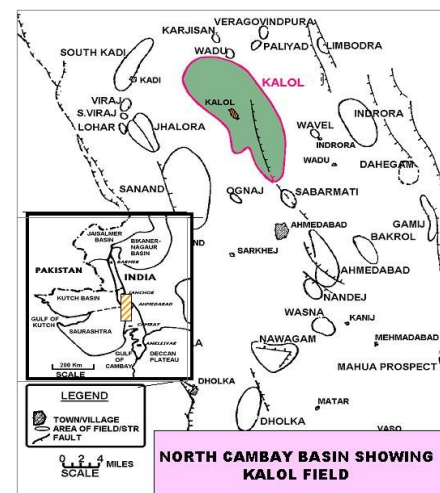


Figure : 1 Location Map of Kalol Field



formation. The pay sands from K-II to K-V belonging to Wavel Member and K-VI+VII to K-XI belong to Sertha Member of Kalol Formation. The trap mechanism is strati-structural in K-II to K-IV and K-XII pay sands and stratigraphic in K-VI+VII to K-XI. The predominant natural drive mechanism in major reservoirs like K-VI+VII, K-IX+X and K-XII is depletion drive and presently are operating under pressure maintenance. The dominant lithological assemblages of Kalol Formation are shale/ carbonaceous shale, sandstone, siltstone and coals and are composed of fine to very fine grained sandstone/ siltstone alternating with layers of shales and coals. The field has in-place oil of >120 MMt which is mainly distributed in K-IV, K-VI+VII, K-IX+X and K-XII

transmissibility with permeability barriers. The improvement in production is generally observed with hydrofracturing. The development scheme implemented for this reservoir has yielded good results in northern and eastern part of Kalol field. After extensive study (details discussed later in this report) this reservoir was identified for unconventional wells. With successful completion of a multilateral well in this reservoir in 2001, and observing performance of this well, unconventional wells were planned in a larger scale for improved recovery from this reservoir of Kalol Field. In this paper, our main focus of study for unconventional wells is K-VII reservoir. The other issues are discussed in brief are suitable Artificial lift for unconventional wells and underbalanced drilling of lateral sections.

Generalised Stratigraphy of Kalol Field				
Age	Formation	Member/ Horizon	Lithology	Lithological Description
Oligocene Lr. Miocene to Recent	Post- Babaguru & Babaguru			Arenaceous and argillaceous interbands.
		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 interfingering with transgressive shales. Also known as Kadi Formation.	
		K-XII		
		Below K-XII		
Lower Eocene	Older Cambay Shale	Chhatral Member		Dark grey monotonous marine shales.

Figure : 2 Generalised Stratigraphy of Kalol field

reservoirs. The first major study of the field was carried out in early eighties by an Indo-Russian team. On implementation of the recommendations production increased 2 fold to 1620 t/d during 1989-90 and gradually declined to about 800t/d in 1995-96. There was a marginal increase in production after drilling of new wells in K-VII reservoir. At present the field is producing around 1500t/d. Almost two fold increase in production from 1995-96 to 2006-07 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 study gives emphasis on K-VII reservoir which has good potential for increasing production of Kalol field. This reservoir has low permeability and heterogeneous in nature. The reservoir is segmented and has poor

K-VII reservoir and comparison of productivity index ratio of unconventional wells with a vertical well

The reservoir is composed of siltstone laminated with intervening shale/ carbonaceous shale bands. It comprises of lenticular to flaser bedded interlamination of very thin bedded dark grey coloured shale and starved ripple to laminated light grey to off white coloured silt/very fine sand. The siltstone/ fine-grained sandstone layers are frequently traversed with carbonaceous shale affecting vertical & horizontal permeability (Figure : 3a & b).

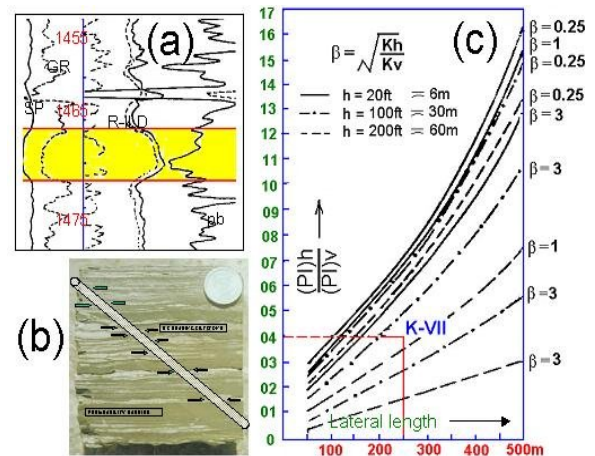


Figure : 3 (a) Typical log motif of K-VII reservoir (b) Core photograph of K-VII p.z. showing thin streaks of siltstone with intervening laminae of shale & schematic diagram of a slanted lateral crossing permeability barriers with more contact area. (c) Comparison of productivity index ratios of multilateral / horizontal wells vs vertical wells in three cases: normal anisotropy ($\beta=3$), complete isotropy($\beta=1$) and highly favourable anisotropy ($\beta=0.25$)



The density is high & the reservoir is shaly and tight in nature. The average permeability is < 10mD and effective porosities ranging from 15-20%. Sometimes the permeability is as low as 1-2mD. The initial and current reservoir pressure is about 150 and 100 Kg/cm² respectively. The wells completed in K-VII reservoir have average production of about 3m³/d per well. The recovery from this reservoir is very less (<7% of OIIP). Mostly production improvement is done by hydrofracturing. The primary recovery methods have not yielded the desired results. From laboratory core studies, it was found that the horizontal and vertical permeabilities (Kh and Kv) are in the range of 0.55 to 14.85 mD and 0.04 to 2.47mD respectively. Permeability anisotropy denoted by $\beta = \sqrt{K_h / K_v}$, where Kh is the horizontal permeability and Kv is the vertical permeability. From the relation given in Figure : 3c it is evident that when permeability anisotropy (β) is large (approximately $\beta = 10$ or $\beta = 3$ for common anisotropy), the productivity index (PI) ratio will be reasonably small. On the other hand if anisotropy is small,

can be inferred that by increasing length of lateral, Productive Index (PI) ratio will not increase substantially unless they cross permeability barriers. To make this type of wells more favourable, high angle slanted wells with more contact area (like sub-vertical fractures) are more attractive. The placement of laterals is also important. If the laterals are placed perpendicular to sand lobe (channel/Bar) axis the productivity will be more because generally the preferred permeability (K-max) direction is along the sand bar/channel axis (Aguilera R. et al., 1991). For this reason length of horizontal/lateral sections have been restricted to 250-300m for optimal production and to avoid drilling complications.

Status of unconventional wells in Kalol field and future strategy

Unconventional wells like drain-hole drilling, multilateral drilling have been tried in Kalol field earlier. Five wells were tried with drain hole completions but the drain holes

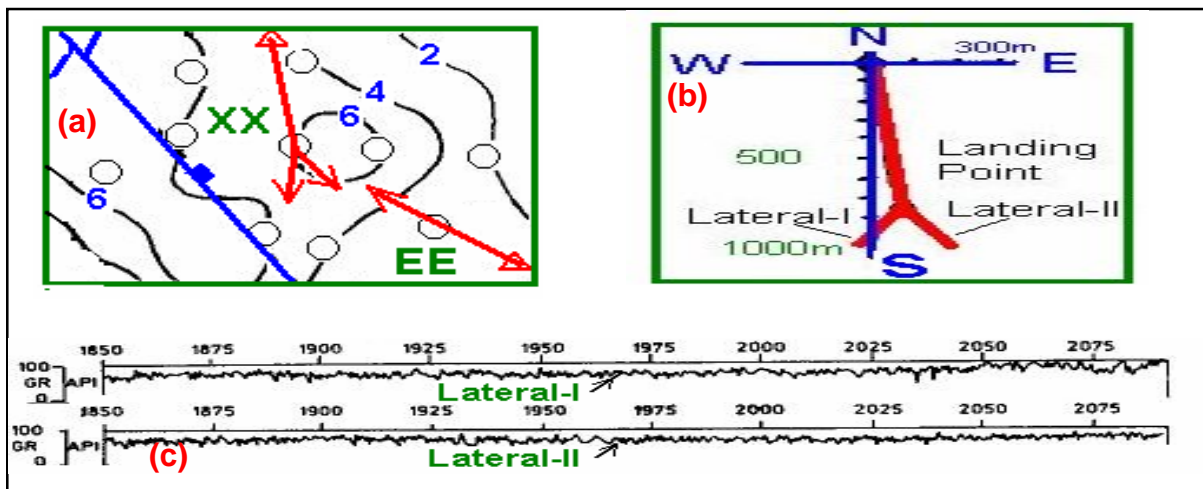


Figure : 4(a) Sand isolith map (a part of kalol field) showing multilateral well XX and planned horizontal location EE (b) Plan view of well XX (c) MWD GR log of laterals. It can be observed that end part of lateral - I is shaly after crossing the shaly layer, it has again entered sandy facies.

then productivity index ratio can be extremely large. The bed thickness (h) is also important. Multilateral wells are comparatively more attractive for thinner reservoirs. The productive index ratios are in descending order from thinner to thicker formations (Aguilera et al., 1991).

The average horizontal permeability (Kh) was found to be more in comparison to vertical permeability (Kv). Permeability Anisotropy (β) was calculated to be about 2.5. As evident from the curve trend (Figure 3c), for a thinner reservoir like K-VII (h = 4-6m) with permeability anisotropy of 2.5, the Productive Index (PI) ratio is about 4 for a lateral of 250m in comparison to a vertical well. It

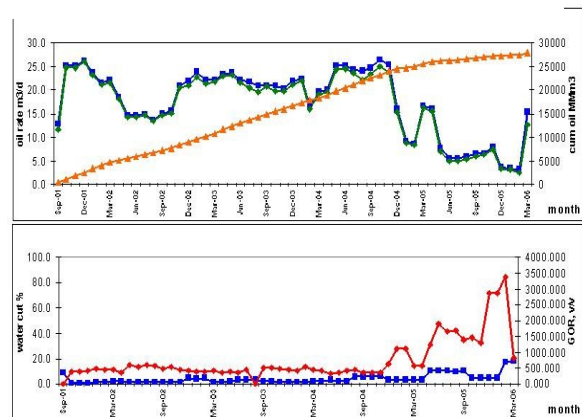


Figure : 5 Performance of multilateral well XX



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could not be steered in desired direction in the target reservoir. Drain hole could be placed only in one well which has cumulatively produced about 6,500m³ of oil. Multilateral drilling was attempted in two wells in payzone K-VII and K-X respectively. The well completed in K-X payzone has produced about 18000m³ oil. Due to drilling completions, it had to be completed with a barefoot child lateral (8 1/2") of 30m and a child lateral of 101m covered with slotted 7" liner.

But the multilateral well targeted for K-VII reservoir was completed successfully in 2001. Incidentally this was the **first onland multilateral well of India**. The well was drilled with polymer based, low solid, non-damaging drilling fluid with careful well control by MWD gamma-ray & azimuthal control. The mother well was geo-steered with the help of MWD GR log matching it with prominent stratigraphic markers and detailed study of the cuttings and there by steering it in the required trajectory. Mother well was successfully landed in K-VII pay zone at 1462.27m. TVD. Two bare foot child laterals of 252.32m & 250.68m length were placed successfully in the pay sand in 208.5° & 149.44° direction (at end point) respectively with respect to landing point (LP) of the mother well. (Figure 4 a,b& c). It produced oil @ 60m³/d through 6mm bean initially. The well has produced about 34000m³ of oil (Figure: 5) in last 6 years and produces about 4 times more than the nearby conventional wells completed in K-VII reservoir. Considering the encouraging performance of the multilateral well completed in K-VII reservoir and the geological parameters discussed earlier this reservoir was found quite suitable for unconventional wells in a larger scale.

For the first multilateral well XX, eastern part of Kalol field was selected after consideration of all the reservoir aspects of K-VII discussed earlier. Three dimensional geological modeling was done carefully to understand the K-VII sand continuity integrating sand isolith and sand relief map. The dip of the beds and fault plane configurations were mapped to avoid complications. Sand isolith map helped to know the maximum sand thickness and elongation of sand lobes. Fence diagram was prepared to know the sand continuity in a three dimensional view. It was planned to place the laterals of the multilateral well in the best part of the reservoir with maximum thickness (within 6m thickness contour) in a relatively undrained area with a spacing of 600m from nearby vertical wells. The laterals were planned perpendicular to the sand lobe axis, which is also the preferred permeability (K-max) direction.

After testing success, unconventional wells were planned in a larger scale for K-VII reservoir in entire Kalol field taking into consideration the structure, sand maxima, fault pattern and pressure/production history of fault blocks. Six

horizontal and two multilateral wells are planned for K-VII reservoir. In case of locations AA and BB in north western part of Kalol field (Figure: 7a & b), sand thickness and production history of nearby conventional wells were taken into account. Considering the position of the NE trending fault almost perpendicular to the planned trajectory of the wells, the horizontal sections were later converted to high angled trajectories. The well BB is under drilling by the time of writing of this paper. In this fault block, the production of nearby wells is good and the reservoir has good pressure-production history.

The landing point of well CC (Figure : 7b) had been planned below a shallow well completed in K-IV payzone. The objective was to place the horizontal section in relatively undrained area.

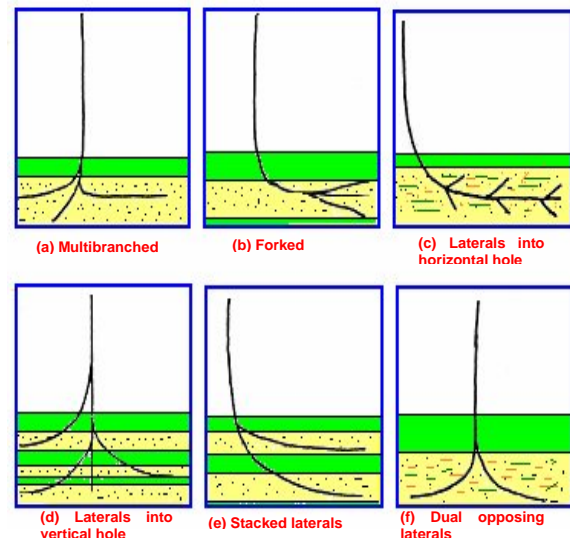


Figure : 6 Different type of unconventional wells. For K- VII reservoir *multibranching*, *forked* and *laterals to horizontal hole* types are well suited to cross permeability barriers.

In case of DD (Figure : 7c) the pressure of the segmented reservoir is comparatively less, but considering the sand maxima (>6m) a 300m barefoot horizontal section was placed. The well produced @21m³/d initially and has produced about 1100m³ cumulatively on G/L.

The horizontal location EE (Figure : 4a) is placed with a spacing of 600m close to the multilateral well XX. Considering the performance of the multilateral well a good production is expected. For the multilateral location FF (Figure : 6d) the sand thickness and relatively undrained area has been taken into consideration.

The area for locations GG and HH (Figure : 7e & f) fall in southern part of Kalol field where the reservoir is quite tight with poor transmissibility. The cumulative production



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from the wells in this area is very poor even after repeated hydrofracturing and other stimulation jobs. Location GG has been planned with a horizontal section of 300m.

The multilateral well HH has been drilled with two slanted laterals of 250m each in southern part of Kalol field. It has produced about 16.5m³/d initially and has produced about 800m³ cumulatively. In eastern and northern part of Kalol field the reservoir character is better but compartmentalisation due to permeability barriers still needs to be addressed. In all these unconventional wells the child laterals/horizontal sections are planned suitably considering the sand lobe axis for better drainage. There is a plan for ultrashort radius wells where the drain holes will be drilled from existing vertical wells which are poor producers.

the multilateral well completed in K-X reservoir in western part of Kalol field. We had to be satisfied with a 30m barefoot and 101m lateral covered with slotted liner though the planning was for 250m each. In case of wells AA and BB to avoid complications arising out of an envisaged fault midway of the well course, the wells were planned with high angled laterals. If the laterals are covered with liner/slotted csg it will be easy for future work over jobs, which in turn will increase the well life & a sustained production. Multilateral wells can substitute hydrofracturing as the steering of the well in the reservoir in a planned trajectory is a better option unlike the hydrofracturing where we do not have any control over fracture propagation/orientation. The production behaviour of wells CC, DD and HH shows that the pressure of the reservoir in the fault block and

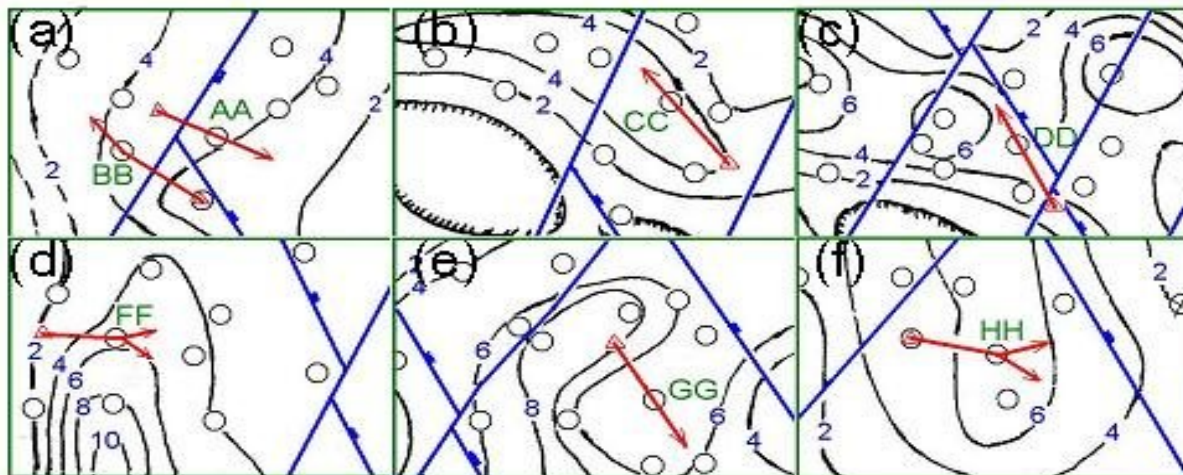


Figure 7: (a) Sand isolith map (part of NW Kalol field) showing planned horizontal location AA and BB (b) Sand isolith map (part of NE Kalol field) showing horizontal well CC (c) Sand isolith map (part of NE Kalol field) showing horizontal well DD (d) Sand isolith map (part of sothern Kalol field) showing planned multilateral location FF (e) Sand isolith map (part of sothern Kalol field) showing planned horizontal location GG (f) Sand isolith map (part of SE Kalol field) showing multilateral well HH

Underbalanced drilling of lateral sections is planned for minimal well bore damage.

Discussion

For successful geosteering of a multilateral/horizontal well an accurate prediction of target reservoir top by careful three dimensional geological modeling is the most important requirement. Here our experience with planning of trajectories of well AA and BB tells a lot about it. We know encountering fault on well course is a geologist's nightmare. A smooth geosteering of a lateral will suddenly land up in an undesired formation/shale and correcting course in a shale section is really difficult when the section is almost horizontal. Either you plug the hole or complete the well prematurely. That's exactly what happened with

placement of the laterals also play an important role. Moreover with less influx and high angled trajectory of well, SRP operation is also a problem. Pumps can not be lowered below 30° angle. Even in case of first multilateral well XX, the A/L mode had to be shifted from SRP to G/L mode because of operational problem. For this type of wells, Gas lift is well suited but availability of gas in vicinity is a deterrent factor. In isolated areas and areas where gas is not available large compressing units can be used where absolute economics of the costs involved will matter. Completions with Gas Lift will have an edge over SRP. So far as work-over operations and re-entry into the laterals concerned, we have re-entered the lateral covered with slotted liner in one of the multilateral well completed in K-X reservoir. But well bore cleaning in barefoot laterals have not yet been tried. But suggestions are there to drill



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another lateral in a suitable direction to expose the lateral to more undrained area. But this is possible only with barefoot completions. The multilateral/horizontal wells have been put on Gas lift with packer completion. So the future work over strategies have to be adopted carefully. The cost of the well completed in K-VII reservoir was about 3 times the cost of a nearby vertical well with same reservoir as target. Another issue is shortage of suitable modern rigs to complete these type of wells. With the spiraling crude price it will not be a matter of concern with the additional advantages we get from this type of wells. In southern part of Kalol field, K-VII reservoir is tight with very poor producibility. The poor production is attributed to the poor petrophysical character and poor transmissibility. With improved technology multibranching/forked/stacked and dual-opposing laterals (Figure: 6) are suggested for this type of reservoirs to cross permeability barriers for improved recovery. Proper well architecture can be selected to alleviate the problem of reservoir heterogeneity and compartmentalisation of the fault blocks. A number of unconventional wells are planned in this area including short and ultrashort radius drain holes from existing poor producers. The short radius and ultra short radius wells from existing poor producers will help in cost reduction and infill locations can be avoided. Horizontal/multilateral wells will also help in polymer flooding in K-II reservoir with viscous oil so as to improve sweep efficiency. So these are some of the key issues faced while adopting unconventional wells in a large scale. The question is : Are we equipped properly to address these problems ? The future of improved recovery from low permeability clastic reservoirs depends on the above mentioned issues discussed.

Conclusions

- For low permeability heterogeneous clastic reservoirs like K-VII, unconventional wells will be very effective for improvement in recovery and effective water injection. Hence unconventional wells should be adapted in large scale for field development.
- The southern part of Kalol field, slanted Multilaterals/ horizontal multibranching/ forked/ stacked and dual-opposing laterals wells will be more effective for field re-development as they will cross more permeability barriers with increased contact area.
- The placement of child laterals/horizontal sections, proper geosteering of the mother well with careful three dimensional geological modeling plays an important role for improved recovery.

- The reservoir pressure of the fault blocks plays an important role for productivity of unconventional wells.
- Completions with Gas Lift will have an edge over SRP completions.

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