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Targeting Infill Wells in the Densely Fractured Lekhwair Field, Oman

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ABSTRACT

The oil bearing reservoirs of the Lekhwair A-North field in Oman consist of layered low permeability chalky limestones of the Lower Shu'aiba and the Kharaib formations. These have been waterflooded since 1992 by a 200 well development project. However, the field is more faulted and fractured than was anticipated prior to full-scale development and prolific early water breakthrough occurred in many producers (~20%), due largely to direct alignment of injectors and producers along the principal orientation of faults and fractures in the field. As a consequence, the waterflood is currently being converted from a vertical inverted 9-spot well pattern to a line drive orientated parallel to the dominant orientation of faults and fractures in the field. This will result in significantly improved reservoir sweep and oil recovery. Although initially disappointing, production from the field is now well on the way to meeting original expectations.

Several options were considered for implementation of the crestal pattern conversion. In heavily faulted and fractured areas, horizontal appraisal wells can aid the targeting of vertical infill wells by providing better definition of the local fracture network. Significant water-conductive features (faults) thus encountered can be targeted as natural injection planes by infill injectors, while infill producers can be better targeted with reduced risk of early water breakthrough. In relatively unfractured areas, the expense of such appraisal is not justified because the risk associated with infill drilling is small. Simple geometric pattern infill is adopted in these areas, with appropriate reference to reservoir simulation models. Significant scope for coiled tubing drilling exists for pattern infill activities, with potential cost savings. Identification of unswept reserves and improved mapping of the fault and fracture network has been achieved through extensive use of FMI / FMS logs in horizontal wells, correlation of production attributes, and production history matching using numerical simulation models.

INTRODUCTION

The Aptian Lower Shu'aiba and Barremian Kharaib reservoirs of the Lekhwair oil field in North Oman consist of layered low-permeability chalky limestones (Figures 1 and 2). On the crest of the field, where all of the layers are oil bearing with high oil saturations, development is by vertical wells. On the flanks, where only the Shu'aiba layers are oil bearing, horizontal wells (some multi-lateral) are employed in a horizontal line drive waterflood.

During implementation of the main waterflood development (1991-92) it became clear that the reservoirs are more fractured and faulted than had been anticipated. In particular, areas close to the northern and southern bounding fault zones were found to be heavily faulted and fractured. Fault maps based on (poor quality) seismic, fault cut-out, FMI and early production data have since been constructed and these maps are updated when new data becomes available. The way in which these fracture maps are constructed is outlined in this paper. The current fault map is shown in Figure 3.

Infill drilling in Lekhwair is currently on-going to convert the crestal inverted 9-spot vertical well pattern to a vertical line-drive, which will result in significantly improved oil recovery through increased reservoir sweep. In relatively unfaulted areas of the field, infill drilling has little associated risk. However, experience has shown that drilling wells in densely faulted and fractured areas of the field is risky. The chances of drilling close to previously unidentified faults is high and often these wells do not perform to expectation. A strategy for managing this variable drilling risk is outlined in this paper. Several options are considered for conversion of the well pattern to a line drive.

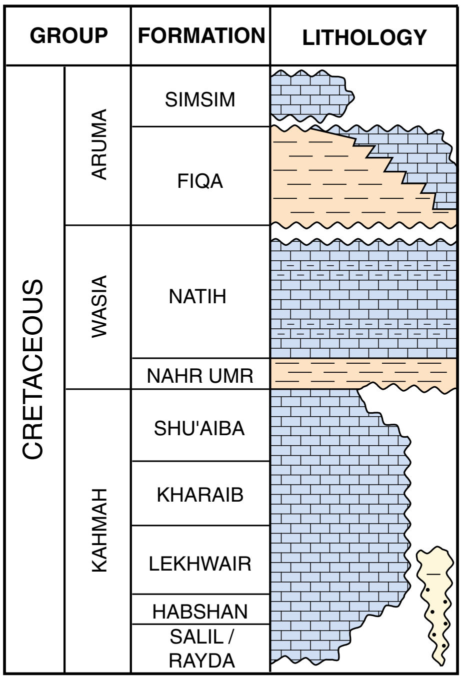

Figure 1: Stratigraphy of the Cretaceous sequence. Production at Lekhwair field is from the Shu'aiba and Kharaib formations.

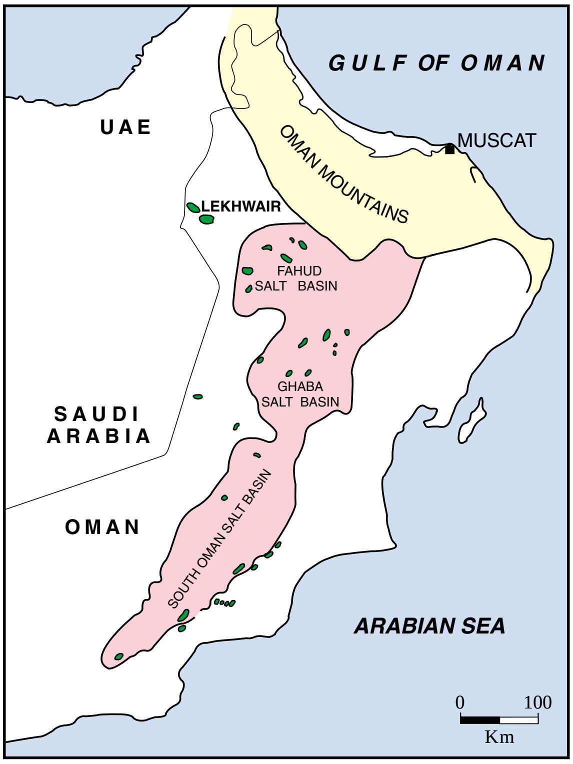

Figure 2: Location map of Lekhwair field.

FIELD DEVELOPMENT AND PERFORMANCE HISTORY

The Lekhwair field was discovered in 1968 and brought into production in 1976. Initially, production increased rapidly. By 1979 it was apparent that the pressure in A-North had declined to below bubble point. In order to conserve reservoir energy and avoid excessive shrinkage losses, nearly all of the producing wells were closed in, pending the implementation of a fieldwide waterflood project.

In 1984 a pilot waterflood project was initiated, consisting of 12 producers and 6 injectors drilled on an inverted 5-spot pattern. The chosen site for the pilot waterflood was in the southeast of the A-North area, which was believed to be representative of the A-North area as a whole. It was thought that this area has a typical degree of faulting and fracturing because one side appeared to be adjacent to a main boundary fault. Based on the positive performance of the pilot and the favourable production forecast deduced from a pilot simulation study, it was decided to fully develop the field by pattern water flooding.

In 1986 a series of tests and studies were initiated in order to investigate the feasibility of water flooding under fracturing conditions (high pressure injection) which would allow the reservoir to be developed on an inverted 9-spot pattern, thus reducing the number of injectors required by 60% and capital expenditure by 30%. Based on the positive outcome of these studies the entire crest of the field was developed on an inverted 9-spot pattern with a 300 meter (m) well spacing (injector to nearest producer) in 1992. The flank areas were developed by horizontal wells because the oil column there is relatively thin. A large number of the new producers intercepted faults and cut water rapidly, which resulted in disappointing early performance of the development (field production 12,000 m^3/ day compared with expectation of 16,000 m^3/ day). The observed degree of fracturing and faulting was much greater than expected, with high watercut wells typically being situated to the northwest and southeast of injectors (the principal orientation of faults, natural fractures and injection-induced fractures in the field is northwest-southeast; see below). However, once voidage replacement had been achieved (1993), the positive effects of water injection on oil rates became clear. Oil rate declines were arrested and even reversed. In addition, the field water cut stabilised. Overall, the performance of the full field waterflood has been better than the early performance indicated.

Geological and reservoir performance studies carried out during 1994 and 1995 revealed the benefits of converting the current vertical inverted 9-spot into a vertical line-drive orientated northwest-southeast. Both matrix and fracture system are thus "charged up" by injection water, and oil is swept in a linear fashion towards producer lines without significant early water breakthrough. The drilling activities associated with this conversion project are currently well underway.

FAULT AND FRACTURE MAPPING

Seismic Faults

In 1987, PDO's first Vibroseis 3-D seismic survey was acquired over the Lekhwair A Area. Approximately 10-fold stack was achieved at the reservoir level (~800-850 milliseconds two-way time), but this proved to be insufficient for suppression of multiples from the overburden. Detailed interpretation of Shu'aiba and Kharaib reflections using the current 3-D seismic is therefore extremely difficult. Only large (>10 m throw) northwest-southeast trending faults on the northern and southern flanks of Lekhwair A-North are visible (Figure 3). These faults, which are thought to have been reactivated during the Tertiary, generally induce very severe losses when they are intercepted by horizontal wells.

A seismic re-shoot aimed primarily at greatly increasing the fold of coverage, thereby reducing the multiple problem and hopefully leading to greater resolution of small-scale faulting, was carried out recently. Heavily faulted and fractured areas of the field will not be targeted for infill drilling activity until this data has been fully interpreted.

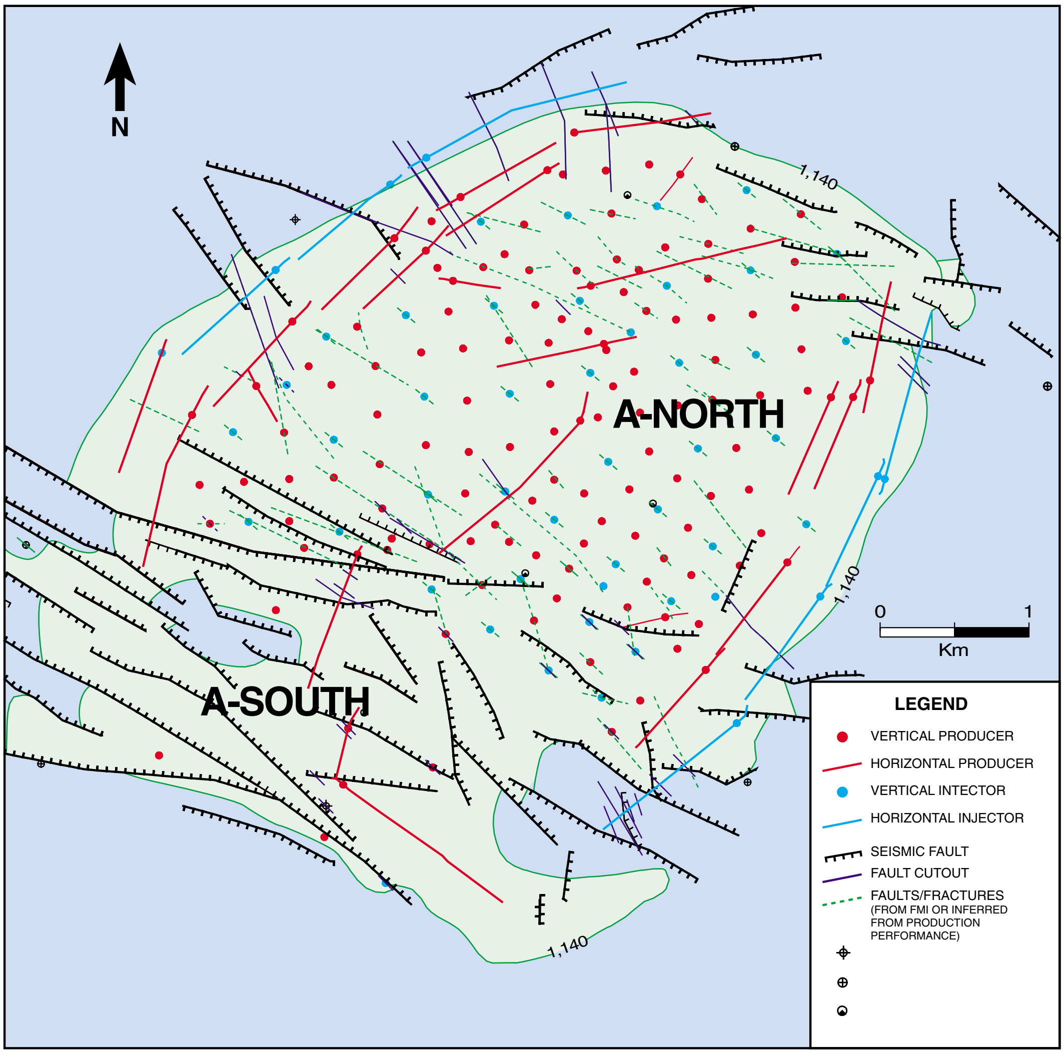

Figure 3: Fault map of Lekhwair field.

Sub-Seismic Faults

Many faults with small throws (<5 m) have been encountered in horizontal wells drilled in A-North. These faults cannot be resolved with current 3-D seismic and occur with a typical spacing in the order of about 500 m (Figure 3). Several vertical wells in A-North have also encountered small fault cut-outs. These features can be identified with confidence as a result of the very consistent log character and nearly uniform reservoir unit thicknesses over the field. Many (but not all) of the small-scale faults in Lekhwair are associated with heavy mud losses during drilling (20-30 m^3/hour).

A number of the small faults encountered in A-North have a clear association with early water breakthrough from nearby injectors. In one case, a producer which cut 100% water from the outset showed a direct response (52 minutes) in a communication test with an injector located 400 m away. Faults observed in adjacent horizontal wells correlate in a dominant northwest-southeast orientation over distances of more than 500 m. In view of the small throw of these faults, such large fault lengths are unlikely unless a wrench component exists, or the faults in fact consist of *en echelon* arrays of shorter fault segments.

Fractures

An extensive campaign of Formation Micro Image/Formation Micro Scan (FMI/FMS) acquisition has been carried out in Lekhwair A-North. Images from 16 horizontal wells and 21 vertical wells in A-North have been used to help characterize the distribution and orientation of minor faults and fractures. Most of the horizontal wells are located on the flanks of the field and demonstrate a predominant northwest-southeast orientation for minor fracturing. The intensity of observed fracturing varies across the field between about 5-25 fractures/50 m, with the higher fracture densities occurring towards the northern and southern boundary fault zones. Faults are often (but not always) characterized by narrow but intense fracture zones.

Different reservoir layers in A-North appear to have different fracture intensities. Crestal horizontal appraisal well L-215 was drilled and logged with an upper lateral section in the Lower Shu'aiba (A1) layer and a lower lateral in the Kharaib (K5) layer. Figure 4 demonstrates that although the fracture densities in the two layers have broadly similar patterns, their relative absolute densities differ by a factor of 2 to 3. This is an indication that these small-scale fractures (which have dips of 60-90°) are most likely joints which formed during uplift of the A-North structure. Higher fracture densities in the A1 layer have probably resulted from a greater degree of argillaceous interbedding compared with the more homogeneous Kharaib K5 layer, which reduces the effective bed thicknesses for fracture containment. It is certainly clear that individual small-scale fractures do not cut through the entire reservoir sequence to connect with the aquifer, although fracture networks may connect with nearby faults.

Reservoir Simulation

The A-North full-field waterflood has now been in operation for four years. Although this time is still short relative to the expected life of the field, it was worthwhile to perform an early history match for long term forecasting of the current development, for better fracture and fault definition, and assessment of possible future developments.

The size of the field and the number of wells make full field simulations impractical. In addition, pattern development does not really require a full field type of simulation approach since patterns far apart do not interfere with each other. In the Lekhwair simulations much attention has therefore been paid to easy construction of reservoir simulation input decks for sectors of the field. The data gathering process and construction of input decks has been automated and tailored to the PDO database environment. The only parameters which need to be provided in order to generate an input deck (including the heterogeneous fracture data) are the corner coordinates for the area to be simulated and the number of blocks which are required. Experience has shown that within a few minutes a smoothly running input deck can be generated for any chosen sector of the field.

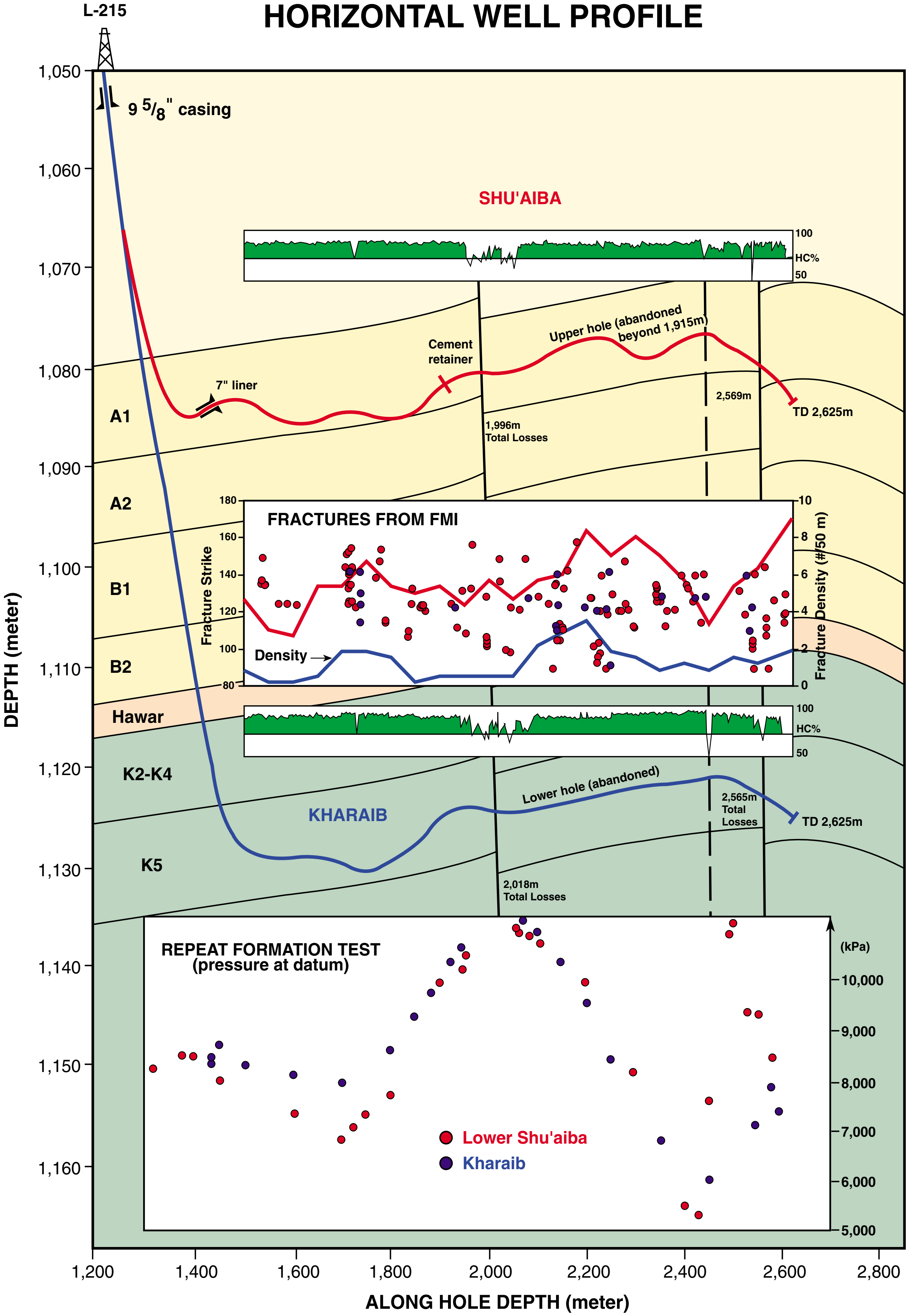

Figure 4: Results of crestal horizontal appraisal well drilled into Lower Shu'aiba (red trajectory) and Kharaib layer (blue trajectory). Green inside logs indicates oil.

The Lower Shu'aiba and underlying Kharaib reservoirs are simulated separately. Pressure data show that only in a limited number of wells does communication via faults or fractures exist across the shale layer which separates the Lower Shu'aiba and Kharaib. Therefore only minor cross-flow between the Lower Shu'aiba and the Kharaib is expected and deviations between model results and actual performance will be small.

The key parameters and uncertainties in production history matching are unquestionably the attributes of the fracture network. Observed water cuts and production rates can only be understood by the presence of fractures. The length, orientation and distance of the fractures to the wells are major parameters for obtaining a water cut and a gross rate match. The fracture and fault map derived from the methods described above was used as a starting point for history matching. Faults/fractures were added, diverted or removed from the working map where recorded rates vastly disagreed with model predictions. In addition, injectors which operate under fracture conditions have all been attached to an inferred 70 m long fracture. The orientations of the inferred fractures and faults have been deduced from local available fracture orientation (FMI) data. The resulting fracture layout map for the Lower Shu'aiba is shown in Figure 3.

CRESTAL PATTERN INFILL DEVELOPMENT

Development in Relatively Unfractured Areas

Vertical Well Line Drive Concept

It is now recognised that infill drilling is required to increase recoverable reserves from the field, and that in particular the proportion of injectors must be greatly increased if efficient reservoir sweep is to be achieved. This approach contrasts sharply with the previous focus on minimising the number of injectors drilled, which led to adoption of an inverted 9-spot development (Figure 5a).

For relatively unfractured crestal areas, conversion from the present vertical well inverted 9-spot to a vertical well line drive is the basis for further development. The orientation of the line-drive conversion is such that injectors and producers line up northwest-southeast, along the dominant orientation of faults and natural fractures in the field. Both matrix and fracture system are thus “charged up” by injection water, and oil is swept in a linear fashion towards producer lines without significant early water breakthrough. Although vertical wells appear rather conventional, they have the significant advantage of providing (relatively cheap) access to all oil-bearing layers. In relatively unfractured areas of the field, relatively low risk locations can be identified from fracture maps, in combination with simulation sector models.

Pattern Conversion to Line Drive

Two new vertical producers per pattern have to be drilled and the pattern corner producers have to be converted into an injector to transfer the current 9-spot pattern to a line drive (Figures 5a,b). The ratio of producers and injectors per pattern increase from the current 3:1 to 4:2, resulting in better sweep and larger volumes of water which are flushed through the reservoir, accelerating tail-end production. The main disadvantage of this scenario is the conversion of possibly good producers into injectors.

To prevent this loss of production potential an intermediate step in the development can be taken. Instead of converting the corner producers, two additional injectors are drilled to convert the pattern flood of Figure 5a into an elliptic type of displacement pattern (Figure 5c). Once the corner wells have watered out they can be converted into injectors, thereby completing the full line drive geometry (Figure 5d). For the elliptic pattern the number of producers and injectors per pattern increases from the current 4:2 to 5:3, resulting in an even better sweep than for the line drive. After conversion of corner wells the number of producers and injectors per pattern is 4:4.

Scope for Coiled Tubing Drilling

Further optimisation of the sweep can be obtained once cheap coiled tubing drilling techniques are available. Short horizontal side-tracks (maximum 200 m) from existing vertical wells into the various layers could effectively convert the injector and producer rows into a dense network of injection and off-take sources (Figure 6a). A cost reducing application of the coiled tubing technique might be the drilling

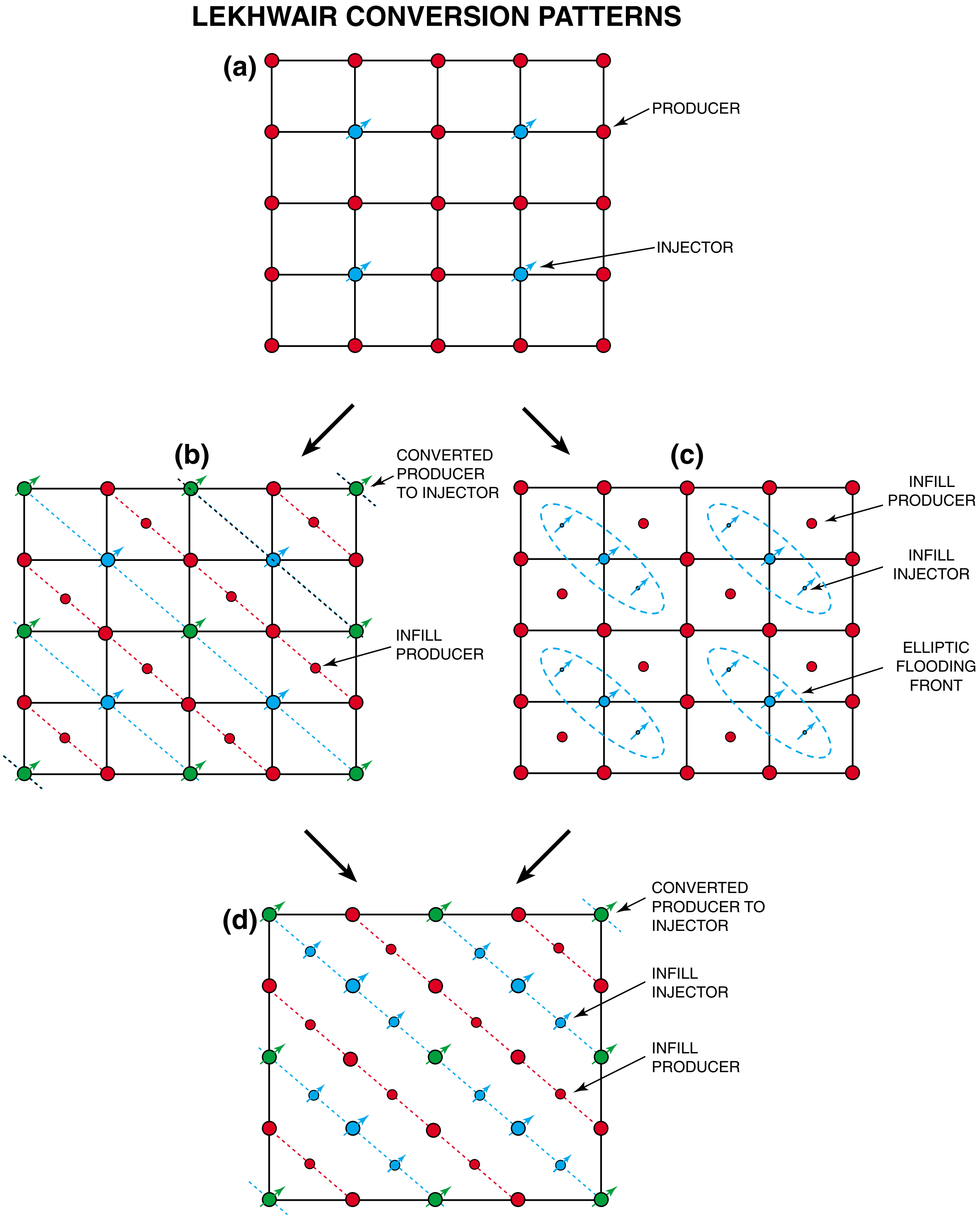

Figure 5: (a) Current inverted 9-spot pattern (producer/injector = 3:1); (b) Pattern converted to line drive (producer/injector = 4:2); (c) Pattern converted to partial line drive (producer/injector = 5:3); and (d) Pattern converted to full line drive geometry (producer/injector = 1:1).

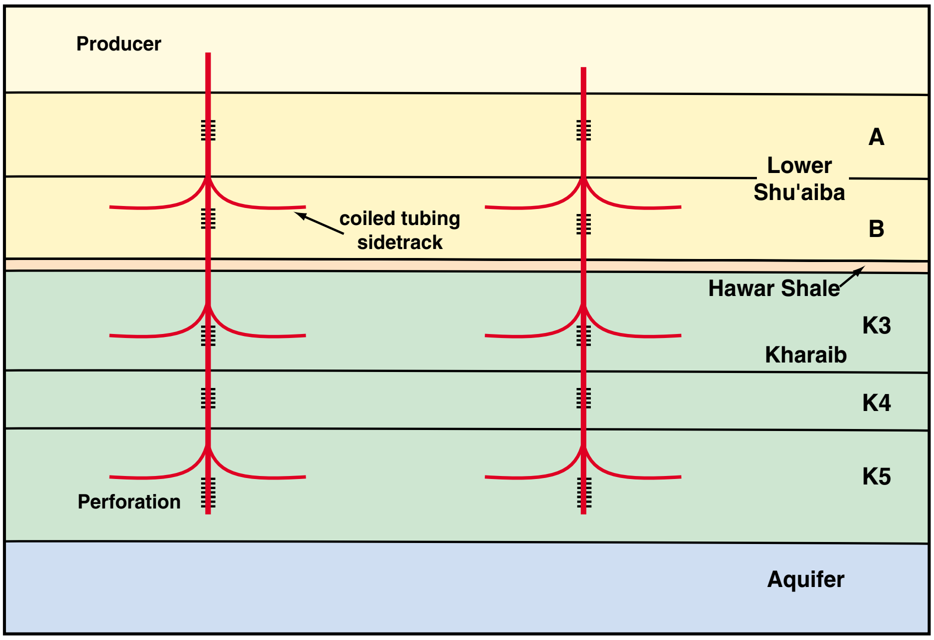

Figure 6a: Short horizontal side-tracks from vertical stem well.

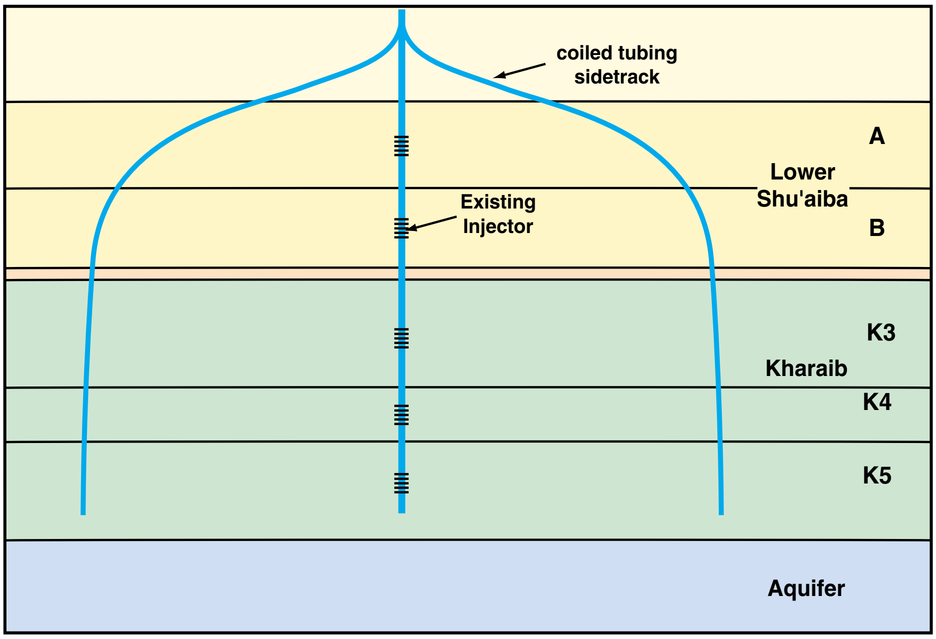

Figure 6b: Vertical side-tracks from vertical stem well.

of the two vertical injectors in the elliptic-drive pattern as side-tracks from the existing vertical injectors (Figure 6b). Similarly, two producers could be drilled from one vertical hole. Trials of such coiled tubing drilling in the Lekhwair environment are planned, but their ultimate field-wide application is subject to economic competitiveness compared with new vertical infill wells.

Application of Long Horizontal Mutilateral Wells

The large number of reservoir layers (5 to 7) over the crestal part of Lekhwair does not make this area an attractive candidate for long (~1,000 m) multilateral wells. The technology to provide accessible horizontal drain holes in each layer, complete with selective isolation, is currently too immature. In addition, a 9-spot vertical well pattern is sub-optimal for infilling with long multilateral wells, therefore the scope of multilateral wells for infill development in Lekhwair is considered limited. On the flanks of the field, where only a few layers are oil bearing, greater scope for multilateral wells exists.

Development in Heavily Faulted and Fractured Areas

Fault Line Drive Concept

In the more densely fractured areas along the northern and southern boundaries of the field, the risk that vertical infill wells might penetrate faults or intensely fractured zones is considered to be great. Major conductive features (faults) are candidates to serve as injection planes in a fault line drive. This may be achieved by injecting directly into the fault zones, which will subsequently flood towards offset producer rows.

Flooding from faults is apparent from the logs of many horizontal wells which have intercepted faults connected to injectors or the underlying aquifer (Figure 7). These wells demonstrate significant oil de-saturation in the vicinity of the faults. A potential problem with this method is that much of the injected water might be lost to the underlying aquifer. However, it has been observed in RFT's of several horizontal wells that pressure support is in fact provided from relatively large faults connected to injectors (e.g. Figure 4).

Application of Horizontal Appraisal Wells

A means of reducing the risk of locating infill vertical wells suboptimally in between the injection fault planes is to utilise horizontal (appraisal) wells to locally refine the fracture and fault maps. The horizontal wells are ideally drilled perpendicular to the fault and fracture trend for maximum fracture detection (Figure 8a).

In Lekhwair, crestal horizontal wells drilled to date have had the primary objective of appraising the local fracture density and orientation. In a number of cases these wells have also been used to identify infill locations for vertical wells which target all the oil-bearing layers. This concept of drilling horizontal appraisal wells for the definition of relatively risk free vertical infill locations has potential for wider application in the heavily fractured and faulted areas of the field. However, the cost of horizontal appraisal wells in Lekhwair is approximately twice that of vertical wells, therefore in most cases the definition of infill vertical well locations cannot be their sole justification. An alternative option is to drill the infill vertical wells "blind" and accept a number of failures. The relative economics of these options must be considered in each case.

An exposure of drilling conventional horizontal wells in an inhomogeneous waterflooded reservoir can be the difficulty in managing the large pressure differentials which are often encountered along hole. If significant faults are encountered then a simultaneous losses / inflow situation can ensue, and differential sticking is common (such situations might be managed more effectively by drilling under-balanced). Production of these wells should also be considered carefully since local reservoir depletion can seriously hamper the initial production of subsequent pattern infill wells.

Scope for Coiled Tubing Drilling

An enhancement of this concept would be to drill horizontal appraisal wells in the top reservoir layer and subsequently drill coiled tubing (vertical) side tracks into the underlying layers at relative unfractured zones (Figure 8b). In this case, the economics of appraising for infill locations alone would be much more favourable.

Application of Slanted Wells

Slanted wells (~70° deviation) drilled in Lekhwair to date have not produced at significantly higher (stabilised) rates than conventional vertical wells. Pressure waves in the thin layers quickly obtain a radial cylindrical shape resulting in a similar inflow performance as a vertical well. However, the big advantage of a slanted well is their greater capability to isolate water-conductive features. By cementing a liner in these wells and by selective perforation, water-conductive features can be isolated. The main drawback of slanted wells is the sub-optimal sweep they provide when placed in an existing vertical well development. However, on an individual basis (especially on the flanks), pockets of oil may be drained effectively by slanted wells where this could not be achieved with single vertical wells.

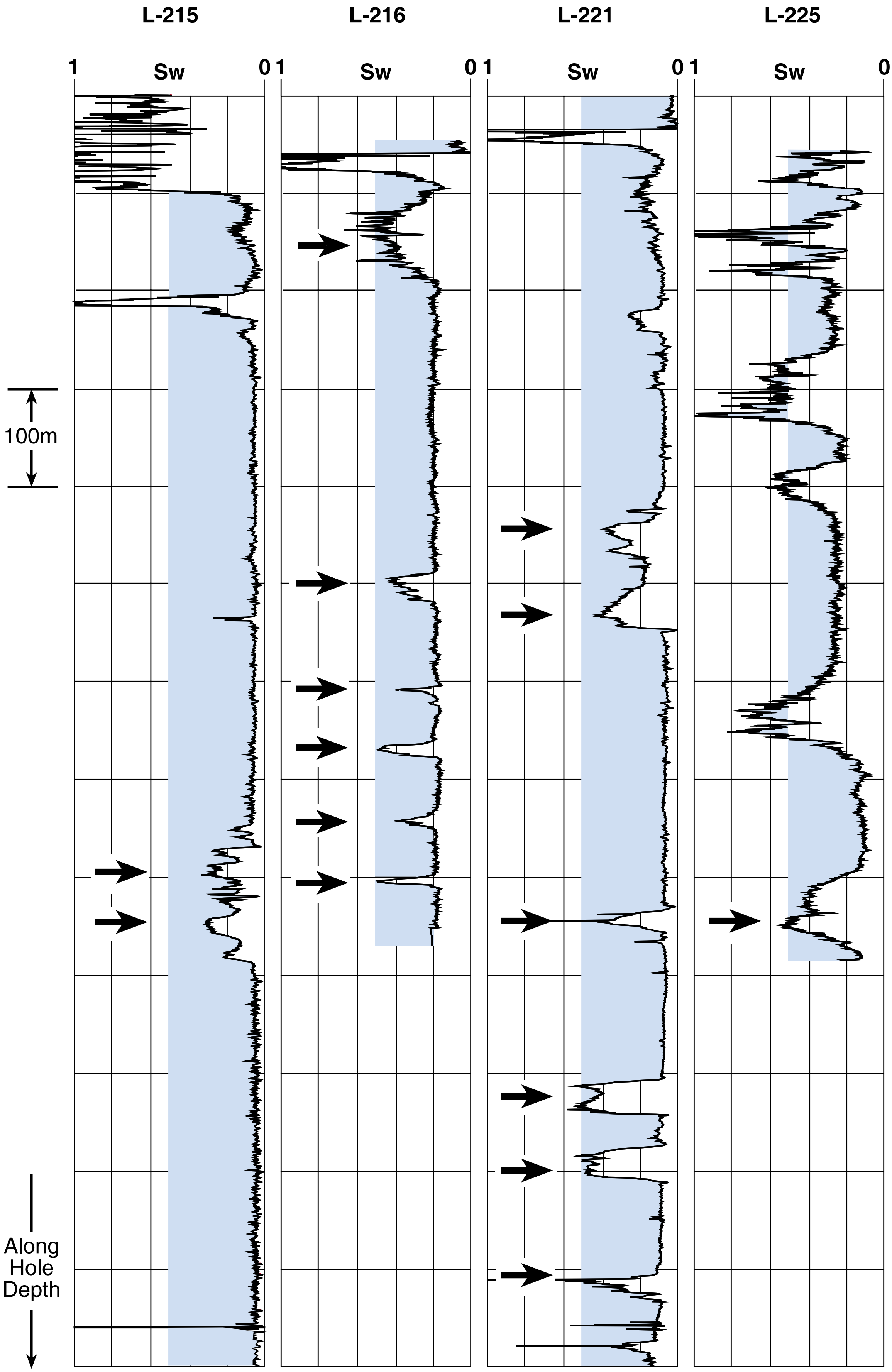

Figure 7: Flushed zones encountered in Lekhwair A-North horizontal wells are indicated by arrows. These zones are assumed to be associated with faults. Green inside logs indicates oil.

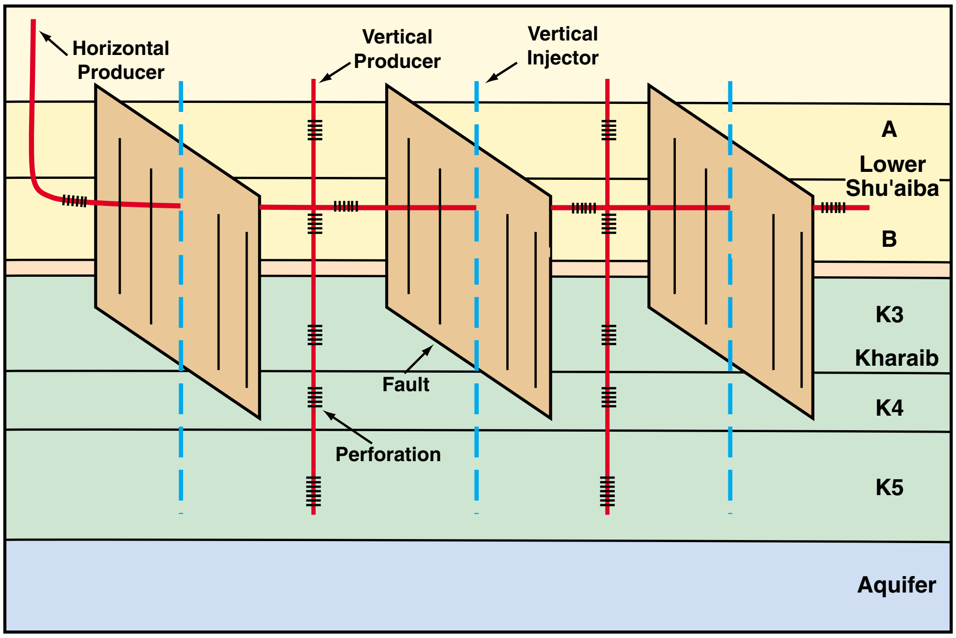

Figure 8a: Optimization of vertical well locations by horizontal appraisal.

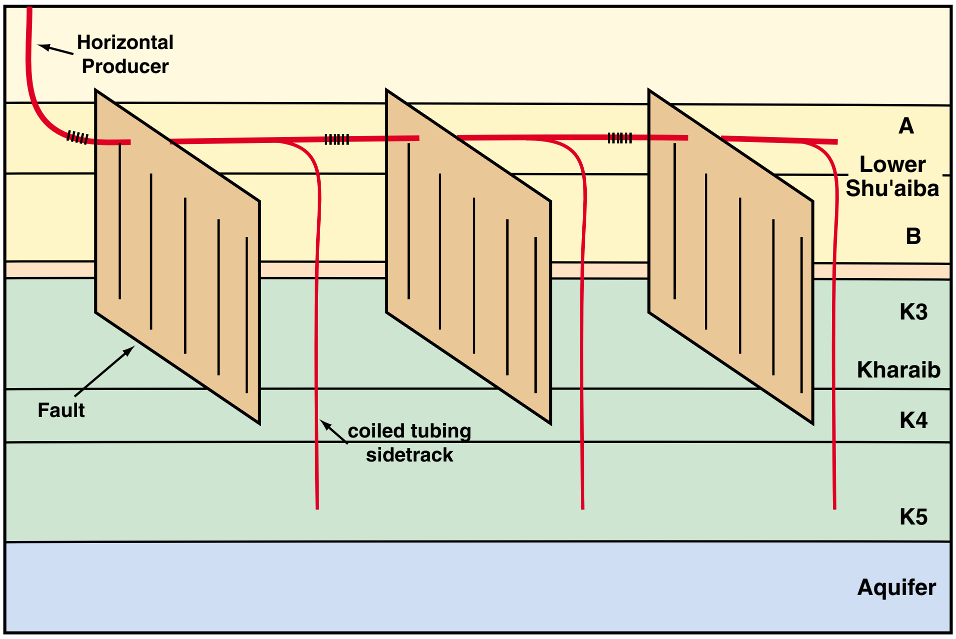

Figure 8b: Vertical sidetracks from stem horizontal (appraisal) well.

CONCLUSIONS

Early water-breakthrough in Lekhwair resulted largely from direct alignment of injectors and producers along the principal orientation of faults and fractures in the field.

The on-going conversion from an inverted 9-spot pattern to a vertical well line-drive orientated parallel to the dominant orientation of faults and fractures in the field will result in significantly improved reservoir sweep and oil recovery.

Improved mapping of the fault and fracture network and identification of unswept reserves has been achieved in the Lekhwair field through seismic mapping, extensive use of FMI and FMS logs in horizontal wells, and production history matching using numerical simulation models. The improved fault maps in combination with numerical simulation modeling serve to optimise new well locations.

Simple geometric infill, with appropriate reference to reservoir simulation models, is adequate for targeting of vertical infill wells in relatively unfractured areas.

In heavily faulted and fractured areas, appraisal by horizontal wells should be considered to precede the targeting of vertical infill wells. Significant water-conductive features (faults) thus encountered may be targeted as natural injection planes by infill injectors, while infill producers can be better targeted with reduced risk of early water breakthrough. Significant scope for coiled tubing drilling exists for the identified pattern infill activities.

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