

Biosteering carbonate reservoirs - the Upper Permian Khuff Formation of Saudi Arabia

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ABSTRACT: Biosteering in Saudi Arabia is successful in achieving greater contacts with the Khuff C Member pay zones. The procedure supports Underbalanced Coiled Tube Drilling (UBCTD) and has been applied since 2008 to improve gas and condensate recovery from development wells in the Upper Permian Khuff C carbonate of Saudi Arabia. Multiple laterals are drilled by re-entry of the mother-bore with the objective of maintaining the well-path trajectory within selected porous layers. This method of drilling permits the drill string to re-enter the mother-bore of older development wells and new infill wells. The drill commences a lateral path through a window milled in the mother-bore casing and has the advantage of rapid adjustment to the inclination and trajectory as well as enabling continued gas and condensate production while drilling. As wireline logging during slim-bore, coiled-tubing drilling is confined to the gamma tool, which follows the bit by approximately 30 ft, the only “real-time” source of stratigraphic control is provided by micropaleontological analysis, up to two hours ahead of the gamma data. Controlled drilling prohibits the use of rate of penetration (ROP) as an accessory stratigraphic guide. For instance, the use of water as a drilling medium enables cuttings to be received with a lag time of 10 to 20 minutes from 12,000ft, depending on the degree of gas contribution. By comparing the micropaleontology of cuttings samples with those recorded in a cored offset well, the stratigraphic position can be determined within 2 ft vertical thickness. Caving is minimal due to the sliding and non-rotational drilling method. This information enables the well-path trajectory to be monitored, as it approaches the planned layer, and real-time instructions provided to the directional driller whenever deviation from the targeted porosity layer is detected. This process is termed biosteering. The Upper Permian microfossils are typically less than 0.5 mm in size and can be well-preserved in small cuttings samples. In addition, the morphology of foraminifera, calcareous algae, bryozoa and other microfossils are sufficiently varied to enable confident species identification in randomly oriented thin-sections. Although of predominantly shallow marine origin, Khuff C depositional environments were highly varied leading to a succession of vertical microfacies variations that provide calibration with biofacies analyzed from cuttings in the “laterals”. As the Khuff C environment also varied across the region, no single microfacies scheme can be applied to all wells in the development area and necessitated establishment of a local reference zonation for each biosteered well. Such a local reference section is based on high-resolution micropaleontological and petrographic analysis of cored wells located as close as possible to the intended lateral trajectory. Knowledge of the micropaleontological diversity, abundance and good preservation in all post-Permian carbonate reservoirs provides the potential for biosteering in similar reservoirs in the Middle East and circum-Tethyan regions.

Keywords: Biosteering, Saudi Arabia, Upper Permian, Khuff Formation, biozonation, foraminifera, carbonate, reservoirs, coiled-tube drilling

INTRODUCTION

Biosteering has been an important component in reservoir development in Saudi Arabia since 2008 (Hughes 2009, 2014; Hughes et al. 2011). The technique has, however, been applied previously in younger and shallower reservoirs in the North Sea since the 90's, as described by Anderson et al. (1990), Kruse (1991), Fine et al. (1992), Jeppesen (1994), Holmes (1999), Payne et al. (1999), Shipp (1999) and Jones et al. (2005). The technique became refined in the Dan Field of the Danish Central Graben of the North Sea, in response to a request to perform high-resolution biostratigraphy to maintain drilling within the upper Maastrichtian carbonate reservoir (Shipp and Marshall 1994).

There is little published documentation on biosteering in the Middle East except for the upper Barremian Kharaib Formation of the Al Shaheen Field of the Qatar North Dome (Shipp and Marshall 1994), the Shu'aiba reservoir (Scott 1995), the Lower

Cretaceous Kharaib and Shu'aiba formations of the Sajaa Field in Sharjah, United Arab Emirates (Jones et al. 2005) and onshore Dubai (Marshall and Henderson 2013). In the Middle East, biosteering commenced in 1994 within the upper Barremian Kharaib Formation on the North Dome of Qatar (Shipp and Marshall 1994). This successful operation resulted in maintaining the drilling within the target level for 10,228 ft. Biosteering has been performed on the Shu'aiba, Kharaib, Lekhwair and Habshan reservoirs of the Sajaa Field of Sharjah, with support to UBCTD commencing in 2003. In Dubai, biosteering was performed in the Margham Field between 2006 and 2007 in the Shu'aiba and Lekhwair reservoirs. Biosteering commenced in 2008 in Saudi Arabia, with the development drilling of the Khuff C Member using a coiled tube drilling rig, the success of which led to an additional two rigs in 2010.

The use of microfossils for determining the age and depositional environment of sediments is a well-established procedure to support

Series	Stage	Formation	Outcrop Member	Subsurface Member
Lower Triassic	Induan	Khuff	Khartam	Khuff A
Upper Permian	Changhsingian			Midhnab
			(evaporite)	
	Wuchiapingian		Duhaysan	Khuff C
				Huqayl
			Khuff D	

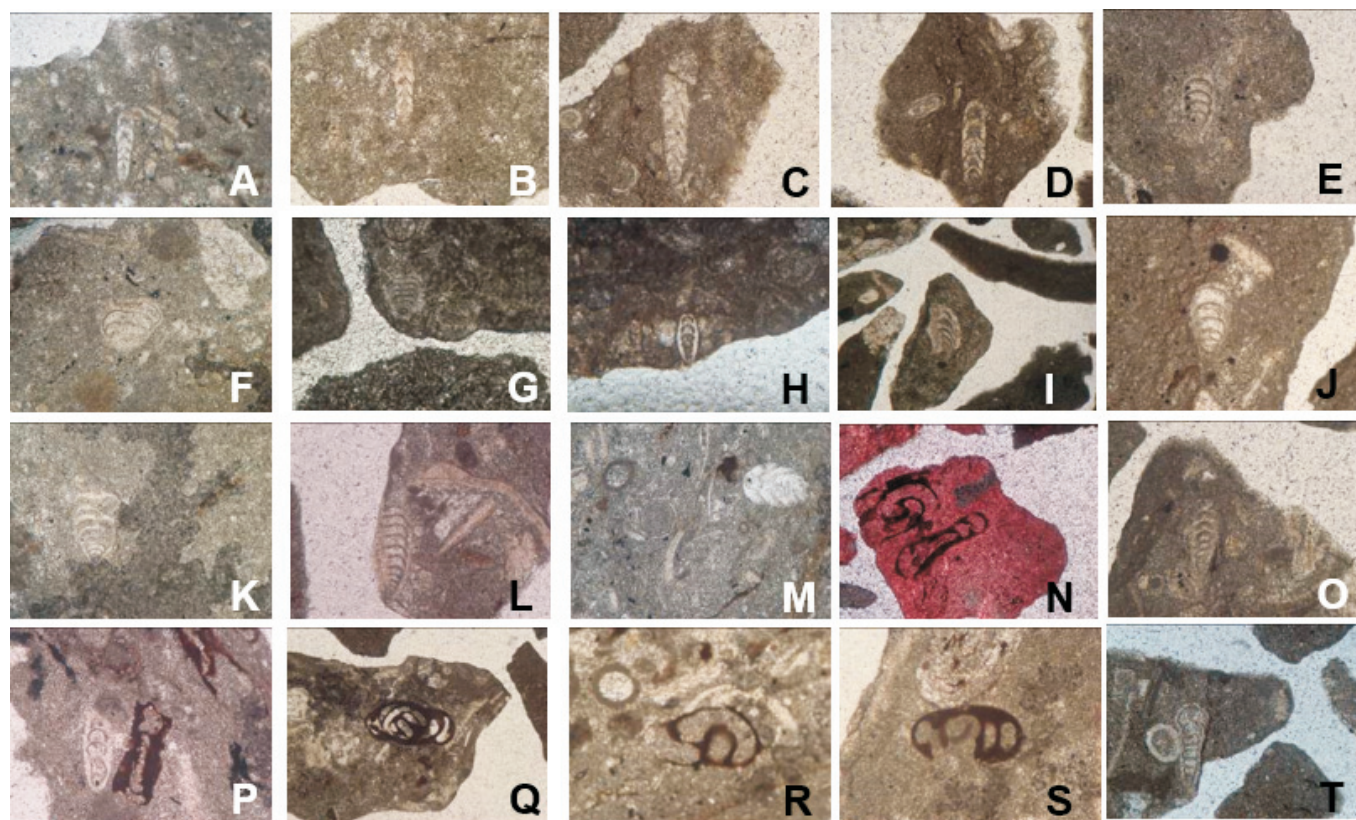
TEXT-FIGURE 1
Chronostratigraphy and lithostratigraphy of the upper and middle Khuff Formation in Saudi Arabia.

conventional exploration and development activities in carbonate and calcareous siliciclastic sediments. Micropaleontological analysis routinely takes place in the laboratory or, in the case of urgently required decisions that will impact drilling activities, at the rigsite. Species identification is based on analysis of picked, processed residues from friable mudstones, or by thin-section analysis of indurated carbonates. Wireline logs are typically available and are used with the micropaleontological data, to compare the drilled section with logs from nearby wells or to calibrate seismic sections.

Wellsite biostratigraphy on vertical or sub-vertical exploration and production wells is a long-established tool for the real-time stratigraphic monitoring of drilling, principally used to determine the stratigraphic position of the drill bit, and to pick coring and casing points and total depths. Another method of borehole placement using directional drilling is geosteering by using log-based information. This is well-established in Saudi Aramco and, in 2008 alone, the Geosteering Operation Centre (GOC) in Dhahran geosteered almost 610 km of reservoir section in 600 wells within 50 active oil and deep-gas reservoirs. Logging-while-drilling (LWD) sensors near the drill bit for each well transmit information about the reservoir and the trajectory of the well up the hole to the drilling rig from where the data is then transmitted by satellite to the GOC. The LWD and trajectory data determine the drill bit attitude in relation to the drilling plan and the reservoir target. In some fields, thin reservoirs can now be economically drilled and the hydrocarbon extracted using geosteered horizontal wells.

Micropaleontology-based biosteering provides a similar end-product to geosteering, but without the use of logging tools. It is performed using coiled tubing where the narrow drill pipe diameter ($2\frac{3}{8}$ in) inhibits the use of the range of logging tools used for geosteering apart from the gamma ray (GR) tool and rate of penetration (ROP) logs. Biosteering provides real-time impact on wellsite drilling processes, maximizes both the reservoir penetration and the production index in horizontal and high-angle wells. Recent experience has shown that coiled-tube drilling can successfully be steered using rapid thin-section production with micropaleontological and petrographic analyses of cutting samples. Stratigraphic location is achieved by reference to a local biozonation based on either core or cutting samples from the mother-bore or adjacent wells.

The Upper Permian carbonates of the Khuff D, C and lower B members contain a relatively high diversity of foraminifera. These, together with calcareous algae, brachiopods, ostracods and various micro- and macro organisms, responded to paleoenvironmental changes during the deposition of the carbonates, and enable recognition of depositional cycles. Biosteering relies on the recognition of vertical changes in the microfacies that indicate the rapid response of the microfossils and sediments to temporal changes in the environment caused mostly by paleo-marine transgressions and regressions of different scales. Although of shallow marine origin, Khuff C depositional environments were highly varied over short distances causing diachronous microfacies. It is thus necessary to establish reference, biofacies-based biozonations for each well using, where possible, the closest cored well for correlation.



TEXT-FIGURE 2

Photomicrographs (each representing 1mm width) of cuttings samples to illustrate the well-represented foraminifera in each cutting fragment. A-C *Polarisella hoae*, D *Nodosinelloides monilis*, E and J *Fronidina permica*, F-G and K-L *Geinitzina* spp., H-I *Pachyphoia schwageri*, M cf. *Polarisella* sp., N, P, R and S *Brunsiisipirella lineae*, O and T *Nodosinelloides monilis caucasica*, Q *Hemigordius irregulariformis*.

Stratigraphic control is possible to within 2ft vertical accuracy and enables near real-time critical instructions to be communicated to the directional driller ahead of the gamma ray data. As the “eyes” of the drill, this technique has enabled maintenance of the drill bit within the target reservoir and resulted in a significant increase in gas and condensate production at each well. In this paper, the methodology and application of the biosteering technique in the Khuff carbonate of Saudi Arabia is described.

AGE AND LITHOSTRATIGRAPHY OF THE KHUFF FORMATION IN SAUDI ARABIA

The Khuff Formation was first described by Powers et al. (1968). Aspects of the depositional environment, diagenesis and reservoir characteristics have been investigated by Al-Jallal (1989, 1995, 1996), Talu and Abu-Ghabin (1990) and Khalifa (2005). Alsharhan and Nairn (1994, 1997) provide a review of the Permian succession in Saudi Arabia. The Khuff Formation is considered as one major marine depositional cycle that transgressed unconformably over the Unayzah land surface. Shales of the Sudair Formation unconformably overlie the Khuff carbonates in outcrop. Four carbonate members have been determined for the outcrop (Le Nindre et al. 1990) and include, in ascending stratigraphic order, the Huqayl, Duhaysan, Midhnab and Khartam members (text-fig. 1). In the subsurface, a different four-fold member scheme has been established that consists,

also in ascending stratigraphic order, of the Khuff D, C, B and A members. This scheme is based on four major repeated carbonate-evaporite cycles of which the evaporites form the seals for each of the underlying carbonate reservoirs.

The age of the carbonates of the Khuff Formation across the Arabian Plate spans the upper Permian (Wuchiapingian) to Lower Triassic (Induan) (text-fig. 1). In Saudi Arabia, the Khuff Formation was originally dated (Steineke et al. 1958) as probably Late Permian, based on poorly preserved brachiopod and nautiloid evidence. This age determination was refined by Le Nindre et al. (1990) and Manivit et al. (1985, fig. 5) based upon a combination of micropaleontological and palynological evidence from stratigraphic drill-hole SHD-1. The presence of the foraminifera *Robuloides* aff. *gibus* and *Paradagmarita flabelliformis* with bisaccate (including striated forms) and monosaccate pollen provide an Upper Permian, Wuchiapingian (late Djulfian) age for the Huqayl and Duhaysan members, and a Changhsingian (early Dorashamien) age for the Midhnab and basal Khartam members. A basal Triassic, Induan (Scythian) age was given for the lower part of the Khartam Member based on the presence of the Induan (early Triassic) serpulid worm *Spirorbis phlyctaena* in the shallow well SHD-1 (Le Nindre et al. 1990). The Permo-Triassic boundary is known to be an event of major mass extinction of many Permian faunas and floras.

The Permo-Triassic boundary in offshore Iran (Virgone et al. 2000) is recognized as an intra-Khuff breccia and a level beneath a thrombolitic microbial facies. Al-Jallal (1995) provides $\delta^{13}\text{C}$ values for the upper part of the Khuff B and C members, of which the positive values for the Khuff C, and the negative values for the Khuff B would suggest that the Permo-Triassic boundary lies within the Khuff B member. Pöppelreiter and Obermaier (2013) display similar data for Oman. The precise position of the boundary is at the top of a distinctive and widely correlative brecciated paleosol coincident with a pronounced negative $\delta^{13}\text{C}$ isotope excursion.

ASPECTS OF COILED-TUBE DRILLING

Horizontal drilling provides distinct advantages to any reservoir development program, of which water and gas problems associated with oil can be controlled by less intraformational draw-down as the well runs parallel to gas and water surfaces. Reservoir drainage is improved by contacting a larger area and vertical fractures can be more advantageously intersected to improve the production rate. In UBCTD, the use of underbalanced water as a drilling fluid permits continuous gas production while drilling and allows the rig to remain productive and contribute gas and condensate to the gas plant during the work-over process.

The coiled tube can be at least 18,000 ft long. This offers additional advantages of which the ability to re-enter a cased mother-bore development well is considered a distinct economic benefit by providing almost immediate access to reservoirs that may be at depths in excess of 12,000 ft. The coiled tube has a quick directional response owing to its relatively increased flexibility when compared with conventional drill pipe. High drilling angles are achievable using the angular motor (AKO) bit in the initial 'build' section from a window milled in the mother-bore casing, following which long radius drilling proceeds, using a variety of steerable positive displacement motors (PDM). One motor, the Rib Steer Motor (RSM), provides build rates between 1 degree/100 ft and 8 degrees/100 ft. The build angle is controlled to direct the bit to enter the reservoir at optimal angle and locations. The ability to deploy and recoil the continuous coiled tube, termed 'trip-time', is also more cost-effective when compared with conventional drill pipe.

Unlike conventional drilling where drilling mud is used, coiled tube drilling uses water as the drilling medium, with additives confined to lubricants. Drilling fluid circulation time using water is much faster than with mud and will carry cuttings samples to the surface in a short time, providing near real-time reservoir evaluation. When gas is being produced, the cuttings can reach the surface in ten minutes, without gas and with nitrogen support, transit time for cuttings can be up to 25 minutes. The coiled-tube drilling rig allows quicker mobilization than conventional work over rigs, resulting in cost saving. For fast-track development campaigns, the coiled-tube approach provides immediate constraint on reservoir model iteration for additional sidetrack and lateral planning. A distinct advantage with respect to sample quality for micropaleontological content, is that the coiled tube slides along the bore. Thus, there is minimal caving, unlike with conventional drilling where the entire drill pipe is rotated, giving rise to possible physical breakage of the bore wall.

Disadvantages of the UBCTD operation are relatively few compared to conventional horizontal drilling. The diameter of the

coiled tube is too narrow to allow access of conventional downhole logging tools, except for the gamma sonde. This inability to provide logging control for stratigraphic and trajectory data in the procedure used by geosteering can be overcome by using biocomponents. As biostratigraphic control relies on the recovery of cutting samples of a size large enough to contain microfossils, the tendency to produce very small cuttings sizes by the Polycrystalline Diamond Compact (PDC) bits was of initial concern but found to be of little significance in practice. In addition, despite the 18,000 ft overall length of the coiled tube, the coiled tube has an average 'lock-up' length of 15,000 ft, when lateral movement stops owing to a combination of friction and drill-pipe weight.

SUITABILITY OF THE KHUFF FORMATION FOR BIOSTEERING

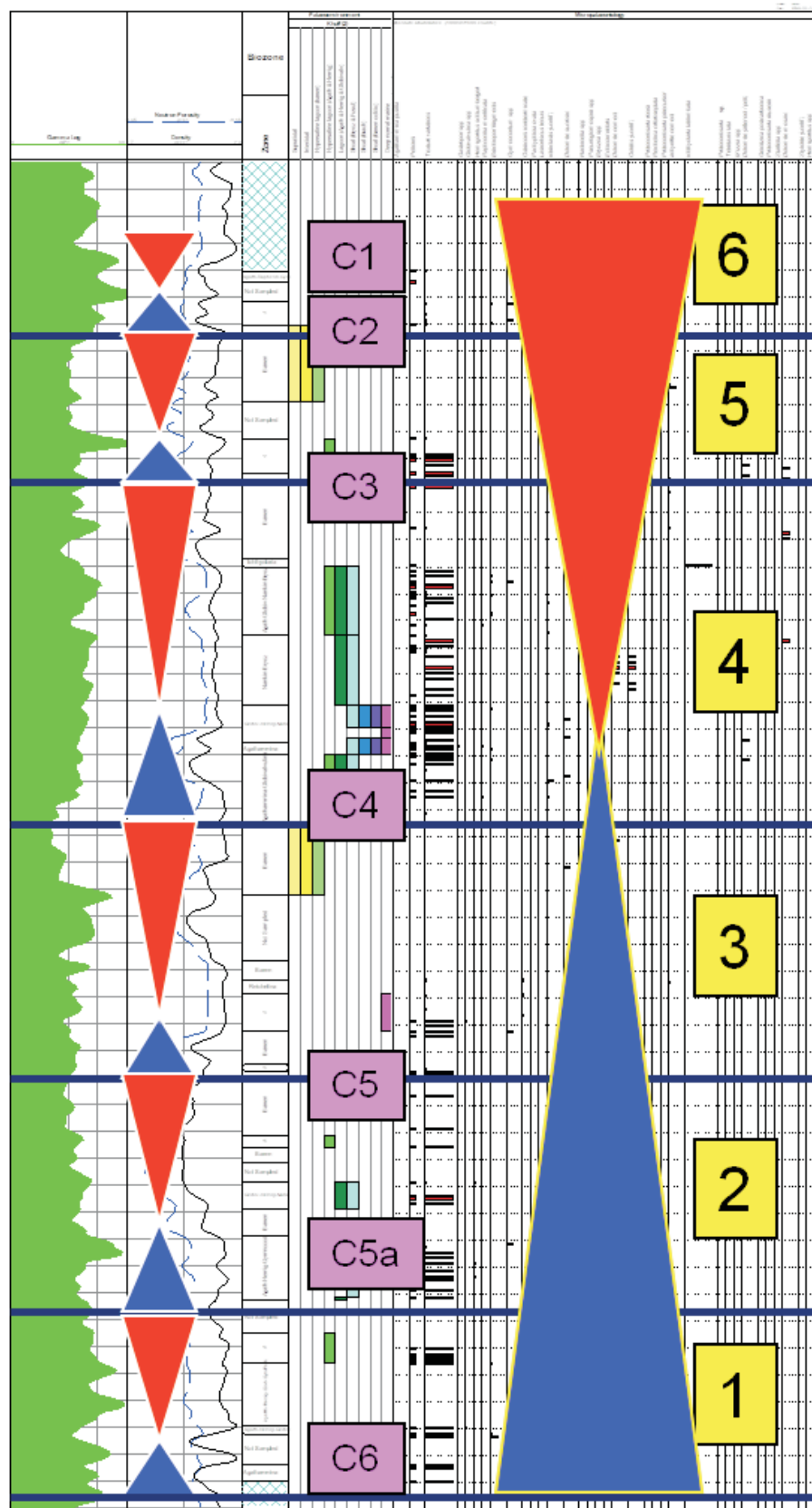
As the Khuff Formation had never been biosteered, a number of aspects of Khuff C micropaleontology had to be addressed to confirm whether biosteering would be a viable technique and to justify acquisition of a coiled-tube biosteering rig. Successful biosteering relies upon a series of essential criteria that are associated with the ability to stratigraphically locate cuttings samples using a core-based, high-resolution local biozonation.

These criteria include:

- the presence of microfossils in the Khuff C carbonates and for these microfossils to be small enough to be present in small cuttings samples after drilling with a PDC bit.
- that the microfossils have sufficiently-complex morphologies for species identification in randomly oriented thin-sections.
- that microfossil diversity and vertical variations are enough to provide high-resolution biostratigraphy and enable drilling to be maintained within a 5 ft reservoir layer of the Upper Permian carbonates at depths in excess of 10,000 ft and for distances up to 4,000 ft away from the mother-bore.
- that thin-section preparation and analysis can be performed quickly enough for efficient biosteering.
- that microfossil barren lithologies, such as dolostones and oolitic grainstone fabrics, can be biosteered using biostratigraphic control in layers above and below such barren beds.

A pilot study was performed on samples from 18 cored wells drilled in the region to be biosteered. For this study 3,200 samples were analyzed at a spacing of 1 ft by the first author. The study showed that:

- The Khuff C contains microfossils that include foraminifera, calcareous algae, brachiopods, ostracods and echinoid fragments.
- The smaller foraminifera were of sufficient morphological diversity to enable their identification in thin-sections (text-fig. 2).
- Fragments of internally complex foraminifera, such as *Nankinella* spp., are readily recognizable in thin-sections.
- Many of the microfossil biofacies were of a high diversity and displayed a high vertical variability. Microfacies with low diversity and low vertical variability are also present and would tend to reduce the accuracy of biosteering. Where microfossil



TEXT-FIGURE 3

Six depositional cycles (yellow boxes) recognized in the upper Khuff C carbonates, related to the C1 to C6 reservoir layers. The column on the right displays each depositional cycle associated with microfacies variations during their transgressive (blue triangle), maximum and regressive (red triangle) elements. Gamma ray (green), biozones and paleoenvironmental variations are displayed.

diversity is sufficiently high it was considered feasible for drilling to be maintained within a 5 ft reservoir layer of the Upper Permian carbonates at depths in excess of 12,000 ft and for distances up to 4,000 ft away from the mother-bore.

- The microfossil distribution revealed a succession of deepening-shallowing upwards cycles that were interpreted to represent depositional cycles (text-fig. 3). Their boundaries were found to coincide with all reservoir layers except C5a.

- Thin-section preparation was accelerated using fast-setting embedding resins enabling thin-sections to be prepared within ten minutes of receiving the sample. Semi-quantitative analysis of the thin-section was shown to be possible in under five minutes with species identification and resulting advice given to the directional driller in the shortest possible time.

- Samples that are barren of microfossils, such as dolostones and oolitic grainstone fabrics, can only be biosteered by using the presence of microfossils below and above the barren section. The difference between the two provides guidance by indicating if the section has been exited at the base or top.

Biosteering methodology

Biosteering relies primarily on the ability of the micropaleontologist to correctly and consistently identify the microfossils. For the Khuff carbonates the taxonomies published by Vachard et al. (2005) and Gaillot and Vachard (2007) proved highly informative and proved important for the operation for which the following procedure was established:

- Perform high-resolution, semi-quantitative micropaleontology and petrography of a cored section from the vertical well that will be biosteered. If core is not available from the well, then another 'offset' well should be selected that is stratigraphically equivalent, and located as close as possible to that planned for biosteering. Ideally, all cored wells in the area surrounding the target well which will be biosteered should be analyzed as this will give important insights to the possible lateral variations of the microfacies.

- From careful inspection of the distribution of the microfossils, lithology and pore type, subdivide the studied section into a series of biozones and sub-biozones (Hughes and Kamal 2000).

- Provision of enough micropaleontologists and technicians to provide 24 hr thin-section preparation and micropaleontological analysis.

- Obtain the predicted encounters of Khuff C layers, TVD, thickness and dip at the location, with depths in the mother-bore, from the development field geologist.

- Samples are usually collected as soon as drilling out of the mother-bore commences and throughout the time when the drill is building angle from the vertical to enter the target reservoir zone. Cuttings samples are collected usually between 5 and 10 ft spacing, depending on the rate of penetration (ROP). Because of the high-pressure conditions in the drill pipe, sample collection is not from a 'shale-shaker' but from a dedicated low-pressure side pipe.

- The sample is cleaned, washed and a thin-section is prepared.

- Analyze microfossils, lithology, cement types and visible porosity.

- Correlate the sample with the established biozone / sub-biozone from the mother-bore or offset well (text-fig. 4).

- Plot the sample and biozone using estimated true vertical depth (TVD) and vertical section (VS) in Excel-based software that was developed in Saudi Aramco (text-fig. 5).

- Relate the biozone to the equivalent Khuff layer.

- If the target layer has not been penetrated, continue to monitor penetration of successive biozones in downhole succession until the target biozone has been penetrated.

- As soon as the target layer has been penetrated and if the biozone is the same as the previous biozone and reservoir layer, continue with the existing drill trajectory; if the biozone is lower or higher than the previous biozone, then calculate the change of dip required to redirect the bit back up or down into the target.

- Continue to tabulate the TVD and VS in the Excel-based software. Also, retrieve the gamma log and ROP from the MWD engineer and import them to the software to plot them next the well trajectory (text-fig. 5).

- The rig foreman and directional drilling engineer, in-town development geologist, and in-town reservoir engineer are provided with all updates.

Biosteering Software

The need for a software to document and communicate the operations to all involved parties is essential, requiring high-end computing power, sophisticated software and 24/7 technical support which can also generate well cross-sections and correlation panels in a timely manner. The remote desert location for the rig-based biosteering operation, however, prevents utilizing the Geosteering Center technologies. The first biosteered wells were controlled using hand-drawn paper copies, with inherent limitations on predictive accuracy of trajectory geometry. There was a need for laptop-based biosteering software that could store all the biostratigraphic and petrographic data as well as providing trajectory profiles and display easily-modified structural cross-section models of the Khuff C reservoirs. The remote working location also required that software technical issues could easily be resolved by a biosteerer.

An Excel-based software was developed in-house to meet these demands to generate cross-sections (text-fig. 5) that show the well trajectory, the Khuff C layers structural model, the gamma log, and ROP log. The structural model is based on a layer-cake sedimentary succession. As the drilling bit penetrates the different layers, the software calculates the apparent structural dip based on the new penetration and the vertical mother-bore penetration. Once the drilling bit approaches the target layer in the landing section, the biosteerer will have an estimate of the apparent dip to land and start the horizontal section. In the horizontal section, the model can be easily modified by the biosteerer to fit his interpretation of the subsurface structure. The gamma and ROP log can be incorporated and used in the interpretation and communication.

Layer	Biozone	Characteristic microfossils	Biosubzone	Characteristic microfossils
Khuff C 1	C1-1	<i>Polarisella</i> - <i>Nodosinelloides</i>	a	<i>Polarisella elabugae</i>
			b	<i>Globivalvulina</i> - <i>Geintzina</i>
			c	<i>Agathammina</i>
	C1-2	(not sampled)		
	C1-3	Barren mudstone		
Khuff C 2	C2-1	Mouldic packstone	a	Barren
			b	<i>Agathammina</i>
			c	<i>Permocalculus fragilis</i>
	C2-2	Barren-Poor Fauna	a	Barren
			b	Peloid-brachiopod
			c	Peloid-bryozoa
Khuff C 3	C3-1	<i>Nodosinelloides</i>	a	<i>Froncina</i> - <i>Paraglobivalvulina</i>
			b	<i>Pachyphloia</i> - <i>Palaeotextularia</i>
			c	<i>Grainstone-Pachyphloia</i> - <i>Permocalculus-Geintzina</i> - <i>Globivalvulina</i>
	C3-2	<i>Bryozoa</i> - <i>Nodosinelloides</i>	a	<i>Globivalvulina</i> - <i>Permocalculus</i> - <i>Geintzina</i> - <i>Hemigordius</i>
			b	Poor fauna
			c	<i>Nodosinelloides ronda</i> - <i>Hemigordius/ Glomospirina</i>
			d	<i>Barren - brachiopod</i>
				<i>Bryozoa</i>
Khuff C 4	C4-1	<i>Praeglobivalvulina</i> - ooid / coated grain	a	<i>Globivalvulina</i> - <i>Froncina</i> - <i>Pachyphloia</i> - <i>Palaeotextularia</i> - <i>Geintzina</i> - <i>Praeglobivalvulina</i>
			b	<i>Bryozoa</i>
			c	<i>Barren mud</i>
	C4-2	<i>Poor Fauna</i> - <i>Globivalvulina</i> - ooid	a	<i>Nodosinelloides</i>
	C4-3	<i>Permocalculus</i> - compressed peloids	a	Ooid - coated grain
			b	<i>Bryozoa</i> - coated grain
Khuff C 5	C5-1	<i>Agathammina</i> - echinoid	c	<i>Agathammina</i> - <i>Globivalvulina</i> - <i>Pachyphloia</i>
			a	Bivalve moulds
			b	Barren / not analysed
	C5-2	Barren - dolomite	c	Ostracod-brachiopod-gastropod- <i>Permocalculus</i>
			a	<i>Gymnocodium</i>
Khuff C 6	C5-3	<i>Pachyphloia</i>	b	<i>Froncina</i> - <i>Paraglobivalvulina</i> - <i>Globivalvulina</i> - bryozoa
	C6-1	Upper mud		
	C6-2	"Spicular" packstone		
Khuff C 7	C6-3	Lower mud		
	C7-1	<i>Agathammina</i> - brachiopod		
	C7-2	(Not analysed)		
	C7-3		a	<i>Nankinella</i> - ooid - <i>Hemigordius</i>
			b	
Khuff C 8	C7-4	<i>Bryozoa</i> - <i>Globivalvulina</i> - gastropod		
	C8-1	<i>Nodosaria</i> - <i>Globivalvulina</i> - bryozoa	a	
Khuff C 8			b	<i>Pachyphloia</i> - <i>Palaeotextularia</i>
			c	
			d	<i>Staffella</i>
			a	<i>Praeglobivalvulina mira</i>

TEXT-FIGURE 4

An example of biozonation and biosubzonation of the Khuff C carbonates with their characteristic microfossils, related to the eight layers C1 to C8.



TEXT-FIGURE 5

Typical chart displaying true vertical depth (TVD) and vertical section (VS). True vertical depth of the lateral hole is calculated from the length and angle of the drill pipe and provided by the directional driller at rigsite. The vertical section is a theoretical two-dimensional plane to which the three-dimensional lateral position of the drill bore is related. The ROP log is plotted below the well trajectory, where yellow log means fast ROP and black means slow. The gamma log is plotted above the well trajectory, where green means high API, and purple means low API.

Importance of biosteering despite the presence of a gamma sonde

The gamma sonde is the only electric tool that is narrow enough to travel down the bore drilled by the coiled-tube array. As the gamma tool provides a useful directional guide for geosteering, the need for biosteering has often been questioned, but can easily be justified. The gamma tool is one of many drilling components that follow the drill bit and is typically located at least 30 ft behind the bit.

With reference to text-figure 6, it can be seen that during the 15 minutes that the cuttings take to travel to the surface, and at an ROP of 10 ft per hour (typical in drilling non-reservoir section), the bit will have continued to drill 2.5 ft. During the following 15 minutes, while the thin-section is prepared and analyzed, the bit will have drilled a further 2.5 ft. As the gamma sonde is 30 ft behind the bit, the biosteering data will have been achieved while the gamma sonde still has 25 ft to travel, taking an additional two hours before it reached the location sampled for biosteering. Delays in making decisions based on gamma log alone means blind drilling for two hours and this could potentially take many hours of expensive drilling to correct, whereas the biosteering data would enable minor changes to be carried out very quickly, efficiently and cost effectively. In addition, many of the targeted zones in Khuff-C have no sharp gamma signature, which will make it difficult, if not impossible, to correctly determine the location of the bit without the additional micropaleontological data.

The procedure established for the Khuff carbonates can be readily applied to any microfossil-bearing carbonate reservoirs, depending on the extreme sensitivity of microfossils to high-

frequency depositional variations. Biosteering of microfossil-barren reservoirs, such as ooid grainstones or dolomites, can be achieved if they are bound by microfossil-bearing limestones to provide the stratigraphic constraint.

MICROFACIES AND PALEOENVIRONMENTS

In the present study, interpretation of the depositional environment has relied upon an integration of the microfossil information and sedimentology. All biocomponents have been recorded together with their semi-quantitative abundance. Paleoenvironmental aspects of the Khuff carbonate microfossils are discussed in detail by Vachard et al (2005), Hughes (2005, 2009), Insalaco et al. (2006), Walz et al. (2013) and Adam and Kaminski (2018). Microfacies encountered are listed below:

Barren mudstones

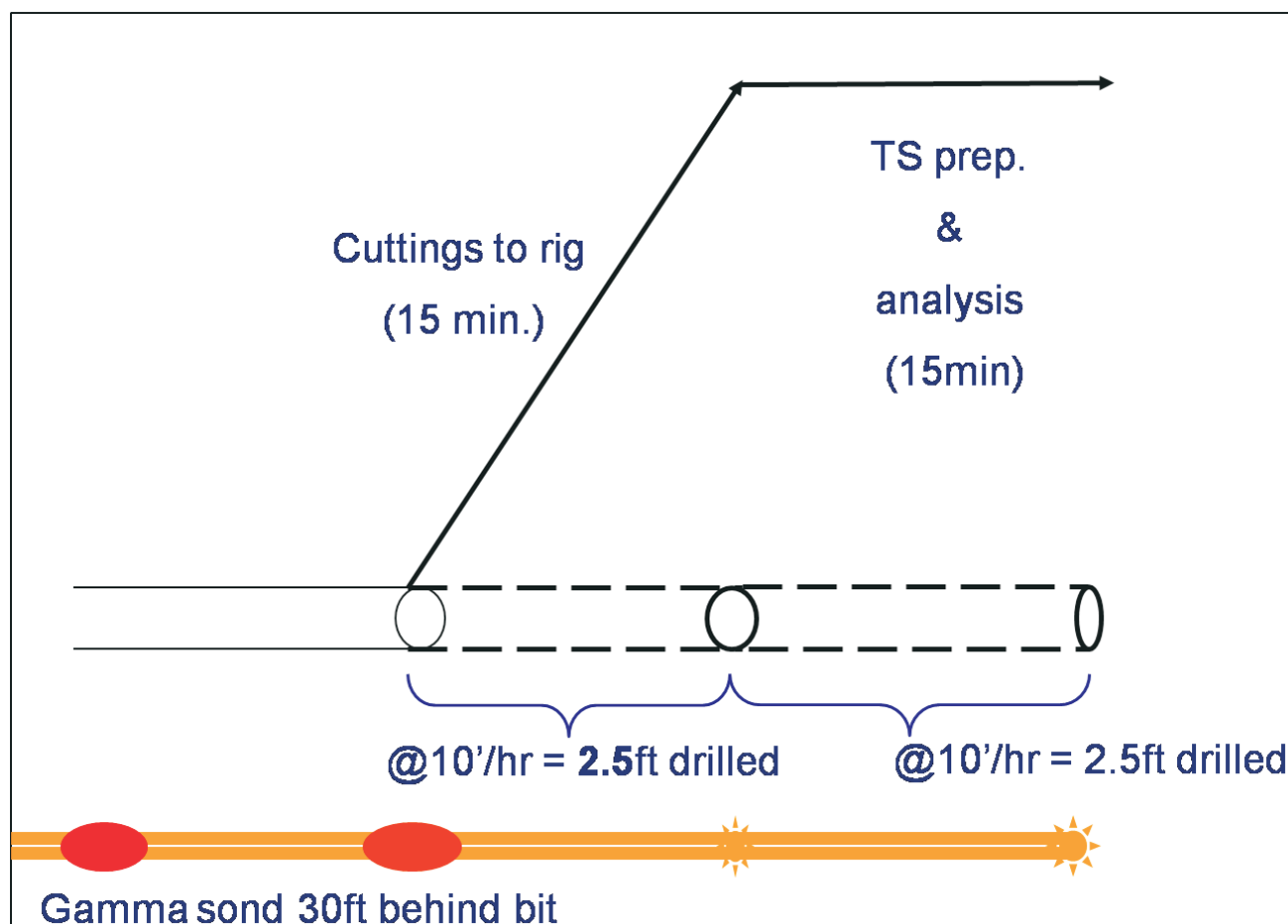
Mudstone lithology but without biocomponents. It is possible that hypersaline conditions inhibited fossil-forming life in low energy settings in a nearshore or proximal lagoon environment.

Sparsely fossiliferous mudstones

Muds with localized hypersaline-tolerant miliolid foraminifera, especially *Agathammina pusilla* and occasionally *Hemigordius schlumbergeri* together with brachiopods. A low energy elevated salinity setting is interpreted, within a proximal lagoon.

Mudstones and wackestones with low diversity microfossils

Low diversity foraminiferal assemblages dominated by *Agathammina pusilla* but often associated with *Hemigordius brunni* and *Globivalvulina bulloides*. This microfacies is considered to represent subtidal, open marine, normal salinity conditions typi-



TEXT-FIGURE 6

Diagrammatic representation of the relative time taken between the acquisition of biosteering and gamma data.

cal of high-frequency marine transgressive cycle bases within a lagoon.

Wackestones and packstones with high diversity microfossils

Moderately rich foraminiferal assemblages containing predominantly “smaller” benthonic foraminifera such as *Fronidina permica*, *Geinitzina postcarbonica*, *Reichelina criboseptata*, *Protonodosaria rauserae*, *P. ronda* and *Raphconilia modificata*. This microfacies is considered to represent subtidal, open marine, normal salinity conditions typical of high-frequency marine transgressive cycle bases within a deep, distal lagoon or inter-shoal depressions.

Ooid packstones and grainstones

Grainstones and packstones with bryozoa, brachiopod fragments, the calcareous red alga *Gymnocodium belerophontis* and *Permocalculus* cf. *tenellus* (Hughes 2017), robust foraminifera such as *Nankinella orbicularis* and *Staffella* spp. This microfacies is considered to represent shoal flanks, mostly subtidal but locally emergent, open marine, normal salinity conditions.

Peloid packstones and grainstones

Calcareous algae, *Globivalvulina bulloides* with miliolid foraminifera *Agathammina pusilla* and *Hemigordius schlum-*

bergeri. This microfacies is considered to represent subtidal shoal flanks.

CONCLUSIONS

Reservoir limestones of the Upper Permian Khuff C Member in the subsurface of Saudi Arabia contain microfossils of sufficient abundance and diversity to permit successful coiled tube directional drilling guided by biosteering. The microfossils mostly include benthonic foraminifera, calcareous algae, ostracods, brachiopods and echinoid fragments which are used to establish a high-resolution biozonation. Paleoenvironmental conditions during deposition of the limestones were mostly shallow marine and ranged from inner lagoon mudstones to ooid shoal grainstones, with corresponding modifications of the microfacies.

Biosteering has established itself as the essential “eye” to guide coiled-tube horizontal drilling and to maintain the bit within a vertical range that is often as small as 2 ft. This technique has the potential to biosteer all microfossil-bearing carbonate reservoirs.

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