Predicting Water Cut - A Geological Profile

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Abstract

The Wytch Farm Oilfield produces ≈ 95 mstb/d oil from a Triassic fluvial sandstone reservoir. Water cut has increased over recent years at a rate of 1500b/d/month.

Plots of water cut against time for individual wells reveal two characteristic profile types, either smooth or erratic. Analysis of production data, production logging data and core data indicates that water cut behaviour is controlled by heterogeneity of the sand over the interval perforated.

Where production logging data indicate fluid production from a single, thick homogeneous sand, water cut develops with a smooth, progressive profile. Core data show that these sands have a uniform vertical permeability and water cut develops with a progressive, gravity stable, flood front.

In wells where most of the flow is from a small number of thin sands, water cut develops in a step change manner. Core reveals that these thin, highly productive sands have permeabilities >1000 mD and are sandwiched between thick sequences dominated by low permeability (<50 mD), non-productive sands. The "steps" are caused as successive high permeability sands switch abruptly from oil to water.

The relationships described above occur as end members of a continuum. Wells develop a unique water cut profile depending on the nature and distribution of sands perforated. Using this geological model, remedial well operations have been successfully optimised to maximise field productivity.

Introduction

The Wytch Farm Oilfield is located on the south coast of England (Figure 1) and produces ≈ 95 mb/d. Discovered in 1974, Wytch Farm oil is produced from three oil bearing formations, the Frome, Bridport and Sherwood.

The Sherwood, a Triassic sandstone at 1535 mTVD, is the largest and most prolific reservoir and contains reserves estimated at 270 MMstb. Oil was first produced from the Sherwood in 1980. Production from the initial phase of development reached 6 mb/d by 1984.

During the period 1984 to 1990, a second stage of development took place which saw a \$750 million investment. This included the drilling of 41 wells from 9 onshore wellsites, the construction of a new process facility to handle oil, gas and LPG, the laying of oil, gas and LPG export lines and the

The map displays the coastal region of Dorset, England, with labels for POOLE, BOURNEMOUTH, POOLE HARBOUR, and PURBECK. A scale bar at the bottom left indicates distances from 0 to 4 Kilometers. A legend in the bottom right corner defines the symbols used: a white area for the Sherwood Sandstone Reservoir 1565m TVD subsurface, a square with 'A' for Well Sites, a solid circle for Bottom Hole Locations, and a solid diamond for Appraisal Well Locations. An inset map in the top right corner shows the location of WYCH FARM in the UK. The main map shows a network of well locations and connections, with appraisal wells (diamonds) and bottom hole locations (circles) distributed across the study area. A north arrow is located in the top left corner.

studies were undertaken to understand the nature of water cut development in these wells.

To date, water cut in offshore wells is minimal. Consequently, this paper addresses the development of water cut only in the onshore area where wells have been in production for four years or more.

Field Characteristics

The geological framework of the field has been fully documented elsewhere (Colter & Havard, 1981; Dranfield *et al.*, 1987; Selley & Stonley, 1987). The Sherwood Sandstone was deposited in an E-W Early Triassic rift system created by extension along a pre-existing Variscan thrust front. The sandstone lies unconformably on mudrocks of the Permian Aylesbeare Group and is conformably overlain by the Mercia Mudstone Group caprock. The field structure is a series of inverted, east-west elongate fault terraces, formed during Early Cretaceous extension. Locally, the field can be

Figure 2: Sherwood reservoir oil and water production profiles from 1990

Figure 3: Field map showing principal structural elements and oil water contact

divided into a shallow, upthrown, Northern Fault Block, and a deeper, Southern Fault Block, separated by a prominent east-west trending fault (Figure 3).

Lithologically, the reservoir is a thick ($\approx 160\text{m}$) succession of sandstones deposited in a variety of fluvial, lacustrine and aeolian depositional systems. Facies variability within the sands is interpreted to be the depositional response to climatic changes (MacKie *et al.*, 1995). Generally, the reservoir sands become finer grained, muddier and more heterolithic towards the top and can be divided into an Upper and Lower Sherwood. The Lower Sherwood is dominated by multilateral channel-fills, typically 2-6 m in thickness, forming belts that may be correlated for up to 2 km. The mud-rich Upper Sherwood is characterised by isolated channels of about 1m thickness, ephemeral stream and sheetflood sandstones.

Compositionally, the sandstone is arkosic with mean K-feldspar content of 33%. Texturally, they range from silt to coarse sand grade, with an inverse relationship between grain size and detrital clay content. The principal cements are K-feldspar, calcite and anhydrite. Reservoir quality is governed by grain size and detrital clay content. Overall reservoir quality deteriorates towards the top of the reservoir. At the base, sandbodies are thick and laterally continuous, with mean porosities of 18% and permeabilities commonly $>1500\text{mD}$. In

contrast, the Upper Sherwood sandbodies are poorly connected. Average porosities are between 10% and 15% and permeabilities $\approx 50\text{ mD}$. The average net to gross ratio of the sands is 0.7. This architecture forms a strongly layered reservoir with K_v/K_h values of 0.01 in the Lower Sherwood compared with a K_v/K_h ratio of 0.001 in the Upper Sherwood (Bowman *et al.*, 1993).

MacKie *et al.* (1995) recognise a hierarchy of climatically driven cycles within the Sherwood which permits high resolution correlation within successive cycles. This enables the reservoir to be subdivided into 10 zones using mud-rich units that form field-wide transmissibility barriers (Figure 4). These are dominated by flood-plain mudrocks and heterolithic mud, silt and fine-grained sandstones. These mud-rich intervals represent major reductions in fluvial sediment input.

Reservoir fluids are characterised by a light 38°API crude with a GOR of 357scf/bbl giving an oil formation factor of 1.231rb/stb. The bubble point of the oil is 1086psi. Reservoir pressure prior to production start-up was 2436psi. The reservoir has a single field wide oil-water-contact (OWC) at 1623.5mTVD. The average oil column over the onshore area of the reservoir is 50m and is underlain by an active aquifer.

Figure 4:
Summary lithostratigraphy
and basic facies
distribution of the Triassic
Sherwood Sandstone
Group in the Wytch Farm
reservoir

Figure 5 (below right):
Typical Wytch Farm
Electrical Submersible
Pump Completion

Field Dynamics

At the time of study, 23 wells were producing from the onshore reservoir. The gross monthly production from the Sherwood was 102mb/d comprising 68mbbl of stabilised crude and 34mbbl of water. Although the field benefits from an active aquifer, reservoir pressure is maintained with the assistance of 9 peripherally located water injection wells. These wells re-inject produced water into the aquifer and a further 40mb/d of sea water.

The oil production wells have been drilled from 9 land based well sites. They are completed with 7" cemented and perforated liner (Figure 5). The reservoir section is usually perforated with a shot density of 6 shots per foot at 60° phasing over the entire reservoir interval. Blank spacer intervals have been left in most wells at horizons of non-pay. The deepest perforations are usually positioned allowing a "stand-off" 10m above the oil water contact. Because of low initial reservoir pressures, the oil has to be pumped to surface using Electrical Submersible Pumps (ESP). Production logging of these wells is facilitated using a logging by-pass.

Figure 6: Regional distribution of Productivity Index in Sherwood wells

Regional Production Characteristics

Combining reservoir structure, vertical and areal distribution of reservoir quality and well completion, results in a characteristic response to production. This can be discussed in terms of a regional and stratigraphic perspective.

The regional production characteristics of the onshore reservoir can be summarised in terms of the distribution of Productivity Index for each well (Figure 6). In the Southern Fault Block where production rates are generally low, the highest PI values (10-22) are found in wells located on the crest of the structure e.g. F-01, D-02 and K-05. These levels of PI decrease towards down-dip wells to values of <5 as only the poorer quality upper reservoir sands are oil bearing, with much of the high quality lower reservoir in the water leg.

In the Northern Fault Block, PI increases progressively from values of <5 in the west to values in excess of 30 in the east. Here, deterioration of PI does not appear to be linked only to structural depth and an increase in the abundance of clean sands from west to east explains the observed productivity distribution. The most easterly wells access a large number of channel sands not only within Zone 70 but also within Zone 50 (Figure 4).

Zonal Production Characteristics

Given that the perforation strategy used to complete the wells involves perforating the entire net reservoir section from the top of the reservoir down to the "stand-off". The reservoir is presently flowing from six productive reservoir zones. The relationship between production and original reserves is shown in Table 1 below.

TABLE 1: SHERWOOD RESERVOIR - ONSHORE PRODUCTION & RESERVES

ZONE		ORIGINAL RESERVES %	PRODUCTION %
10-30	Upper Sherwood	17.5	5
50	Upper Sherwood	30	20
70	Lower Sherwood	40	55
80	Lower Sherwood	12.5	20

(Note: Zones 20, 40 and 60 are non-net)

Only six wells produce from the deepest Zone 80 and these contribute $\approx 20\%$ of the total production. These wells all lie in the shallow Northern Fault Block. Zone 70 has been perforated in all 23 wells and is most prolific, contributing $\approx 55\%$ of the total field production. Ten of the 23 wells produce in excess of 75% of their individual contribution from Zone 70. The high productivity of Zones 70 and 80 can be explained by the presence of clean, coarse grained, multilateral channel sands.

Zone 50 has also been perforated in all 23 producers but contributes only $\approx 20\%$ of the total field production. This is, in general, due to a lack of good quality sands combined with restricted vertical pressure communication in the reservoir.

The upper reservoir zones 10-30 have also been perforated in all wells but contribute only $\approx 5\%$ to the total field production. Eleven of the 23 wells do not produce from the upper reservoir at all. This poor performance is a direct result of poor quality,

fine grained, mud rich sediments and restricted vertical pressure communication.

In summary, most production is from sands located at the base of each well, reflecting the good quality sands found in the lower reservoir. Also, the production characteristics suggest that the deeper layers close to the aquifer are relatively highly pressured, whereas the upper layers are remote from the underlying pressure support.

Water Cut Development in Individual Wells

Water cut profiles were constructed for each well from daily well head samples and routine periodic test data. The constructed plots revealed two characteristic signatures:

- Smooth - progressive build-up (Figure 7)
- Step Change - erratic build-up (Figure 8).

Figure 7:
Progressive water cut development: Well L-1SP

Figure 8:
Erratic water cut development: Well F-9SP

The evolution of each is discussed in turn below.

Progressive/Predictable Water Cut Development

The first type of water cut response is characterised by a gradual or progressive build-up in water rate. Examples of this type of response are displayed in ten wells. PLT data (Figure 9) indicate that production is evenly distributed from throughout the perforated section.

Core recovered from a well displaying this type of behaviour indicates production from a thick homogeneous sand body of relatively uniform reservoir quality. A gravity stable, bottom-up, flood front develops, giving a progressive water cut profile. A model for this type of water cut development is shown schematically in Figure 10.

Figure 10: Model for progressive water cut development

Figure 9: Production log: Well L-1SP

Erratic Water Cut Development

To date, nine wells display this second type of water cut development. Typically, water production in a specific well increases to high levels in a series of abrupt jumps. Examination of PLT data from such a well (Figure 11) shows $\approx 80\%$ of the contribution is from one or two, 1-2m thick sands. In these wells, the productive sands have core permeabilities in the order of 1000mD and even as high as 2000-3000mD.

These productive intervals occur within a thick sequence dominated by poor quality, fine grained sheet flood sands, silts and mudstones with permeabilities generally $<50\text{mD}$. Where these prolific sands are deep in the oil column, close to the OWC, high rates of production cause water to "finger" through the reservoir into the well bore. A model for this type of water cut development is shown schematically in Figure 12.

Figure 12: Model for erratic water cut development

The "ramps" of the water cut profile have steep gradients and are the result of individual sands rapidly watering out. The "flat" sections of the profile are controlled by the remaining sands producing constant volumes of dry oil.

Figure 11: Production log: Well F-9SP

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Discussion

Because lithological heterogeneity is a principal control on water cut development, the distribution of the two types of well and their relationship with field geology and production can be predicted.

The areal distribution of the two types of response (Figure 13) shows that the predictable water cut occurs in wells which are either located structurally shallow, or are located to the east of the field. In these wells, perforations access the thick homogeneous multilateral channel sands of Zones 50 and 70.

Those wells with unpredictable water cut tend to be located either in the thin oil column to the west and north-west of the shallow Northern Fault Block. Here wells are perforated only in the upper reservoir. Similarly, wells in the Southern Fault Block are located structurally deep and those to the west access only reservoir where thin discrete sands dominate.

Figure 13: Areal distribution of predictable and erratic water cut response

The Influence of Rate

A secondary factor influencing water cut profile in a well is production rate. High rates exaggerate the effect of permeability contrast and increase the likelihood that a well will develop an erratic "ramp and flat" profile.

Wells which produce at high rates from a thick sequence of relatively homogeneous sands with limited permeability contrast also produce a "ramp and flat" profile although the "flat" sections are of limited time.

Conversely, wells which produce at low rates from only one or two sands in a section with high permeability contrast may also produce smooth, predictable profiles because the water is given a greater opportunity to stabilise under gravity and permeate into the underlying poorer quality sands. This effect is observed in the low rate producers (e.g. F-7SP and K-4SP) located towards the east of the Southern Fault Block.

Injection Wells

PLT surveys carried out on the injection wells indicate that the bulk of the injection water enters the aquifer in Zone 80, stratigraphically deeper than the flowing intervals in neighbouring producers. In some cases however, significant quantities of injection water enter the reservoir at the same levels as neighbouring producers (L-5SP, F-1SP, F-7SP and F-14SP). In such cases, proximal injection enhances production rates observed from the deep

perforations in these wells. This will exaggerate the effects of permeability contrast in relatively homogeneous sands and promote an erratic water cut response.

Conclusions

The models for water cut behaviour described above can be regarded as extremes. They are end members of a continuum.

In reality, wells may develop a unique water cut profile depending on the nature and distribution of sands within the well bore and the rate at which the well is produced. It is probable that wells which produce from a mixture of thick, homogeneous and thin, discrete sands will have both smooth and "ramp and flat" sections.

The flow profiles measured in individual wells combined with the models described above have been used successfully to predict the water cut behaviour in dry oil wells.

Furthermore, there is a clear financial benefit as an understanding of the mechanisms operating in each well has assisted greatly in successful water shut-off operations. Water production has now stabilised following successful shut-off operations.

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Nomenclature

stb	=	Stock Tank Barrels
MMstb	=	Million Stock Tank Barrels
mb/d	=	Thousand Barrels per Day
mbbl	=	Thousand Barrels
ERD	=	Extended Reach Drilling
ESP	=	Electrical Submersible Pump
ft	=	feet
LPG	=	Liquefied Petroleum Gas
m	=	metre
km	=	kilometre
MWD	=	Measurement While Drilling
PI	=	Productivity Index (stb/d/psi)
scf	=	Standard Cubic Feet
scf/d	=	Standard Cubic Feet per Day
mmscf/d	=	Million Standard Cubic Feet per Day
scf/bbl	=	Standard Cubic Feet per Barrel
TVD	=	True Vertical Depth
OWC	=	Oil Water Contact
GOR	=	Gas Oil Ratio
PLT	=	Production Logging Tool
mD	=	milli Darcy
rb/stb	=	Reservoir Barrels per Stock Tank Barrel

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