Journal of Zhejiang University SCIENCE
ISSN 1009-3095
http://www.zju.edu.cn/jzus
E-mail: jzus@zju.edu.cn

Imaging technologies in oilfield applications

XIE C.G.[1], NORTH R.[2], WILT M.[3], ZHANG P.[3], DENACLARA H.[3], LEVESQUE C.[4]

(*[1]Schlumberger Cambridge Research Limited, Cambridge CB3 0EL, UK*)
(*[2]Schlumberger Beijing GeoScience Center, Beijing 100084, China*)
(*[3]Schlumberger-EMI, Richmond, California 94804, USA*)
(*[4]Schlumberger Middle East S. A., Abu Dhabi, UAE*)
E-mail: xie@cambridge.oilfield.slb.com; robnorth@beijing.oilfield.slb.com; mwilt@richmond.oilfield.slb.com; pzhang1@richmond.oilfield.slb.com; hdenaclara@richmond.oilfield.slb.com; levesque@abu-dhabi.oilfield.slb.com

Received Aug. 8, 2005; revision accepted Oct. 11, 2005

Abstract: In this paper, we describe some recent imaging technologies developed by Schlumberger for oilfield downhole multiphase flow production logging (PL) and cross-well electromagnetic (EM) survey applications. FloScan Imager (FSI^{TM}) has been introduced as a 3-phase oil/gas/water flow PL tool for deviated and horizontal wells. FSI sensors can map fluid velocity and holdup profiles along a vertical diameter of the wellbore at every survey depth, enabling a robust estimate of the individual phase flow rates in complex flow regimes. The cross-well EM survey is based on cross-borehole induction logging technique and provides resistivity distribution at a reservoir scale. It is a useful tool for reservoir management and is most effective in dynamic fields where fluid saturations are variable in time and space. The tool can be used to identify (water or steam) flooded and bypassed regions. By monitoring changes in the resistivity spatial distribution with time, cross-well EM survey is very effective at mapping inter-well temperature and structure. Some field examples are shown for both FloScan Imager PL tool and cross-well resistivity imaging survey.

Key words: Oilfield, Production logging (PL), Multiphase flow, Imaging, Tomography, Cross-well resistivity
doi:10.1631/jzus.2005.A1394 **Document code:** A **CLC number:** TB126

INTRODUCTION

Imaging technologies have been widely used in oilfield applications, from micro-scale (mm) X-ray tomography of rock core samples to macro-scale (km) seismic imaging for oil-gas reservoir exploration.

In this paper, we describe some recent imaging technologies developed by Schlumberger for oilfield downhole multiphase flow production logging (PL) (multiphase pipe flow rate measurement) and reservoir-scale cross-well electromagnetic (EM) survey applications. Some field examples are shown for both applications.

FLOSCAN IMAGER (FSI)

Based on the engineering and research work at Schlumberger's Riboud Product and Cambridge Research Centers, FloScan Imager (FSI) has recently been introduced as a 3-phase oil/gas/water flow production logging tool for deviated and horizontal wells (Vu-Hoang *et al*., 2004). It comprises five micro-spinners and six pairs of electrical and optical probes deployed on a downhole tool-string (Fig.1). Each micro-spinner will measure local fluid velocity, whereas each electrical and optical probe will measure respectively the local water and gas holdup (Fig.2). When deployed, these sensors are positioned in such a way that their measurements will yield a map of fluid velocities and holdups along a vertical diameter of the wellbore at every survey depth. This enables robust estimate of individual phase flow rates in complex flow regimes (Fig.3).

FloScan Imager—monitor box and inflow profiler

FloScan Imager software developed at Schlumberger Riboud Product Centre optimizes and displays the raw data sent uphole from the spinners, probes, and tool orientation sensors. Two views are constantly updated with real-time acquisition data (Fig.3). One view shows relative fluid velocities measured by the spinner array, while the other shows phase distribution across the pipe section. In the spinner view, a vertical cross-section is displayed along the axis of the pipe. Five rectangles are plotted with lengths proportional to the rotational velocities of the corresponding spinners. Each rectangle is divided into color-coded sections with widths proportional to the three phase holdups determined by the electrical and optical probes. In the phase distribution view, a vertical cross section is displayed perpendicular to the axis of the pipe with tool orientation and caliper measurements precisely orienting the position of each sensor. Each layer is color coded to represent the phase with the highest holdup seen by the probes. The values of holdup of the two remaining phases are represented by proportionate numbers and sizes of bubbles.

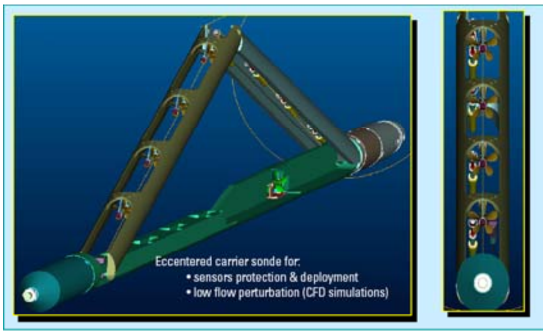
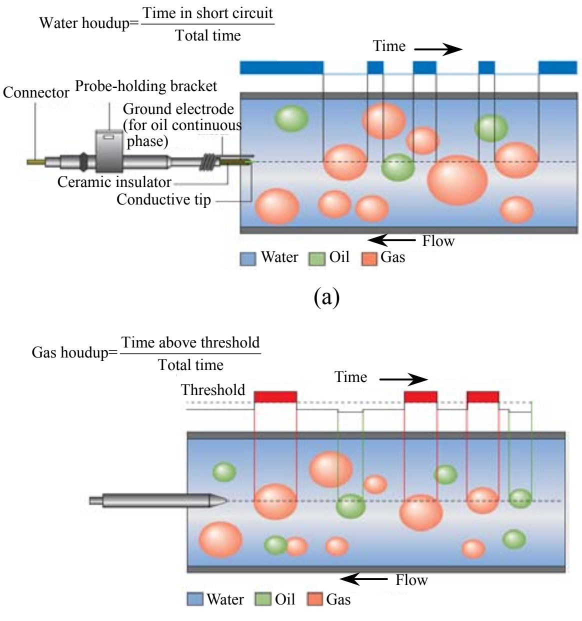


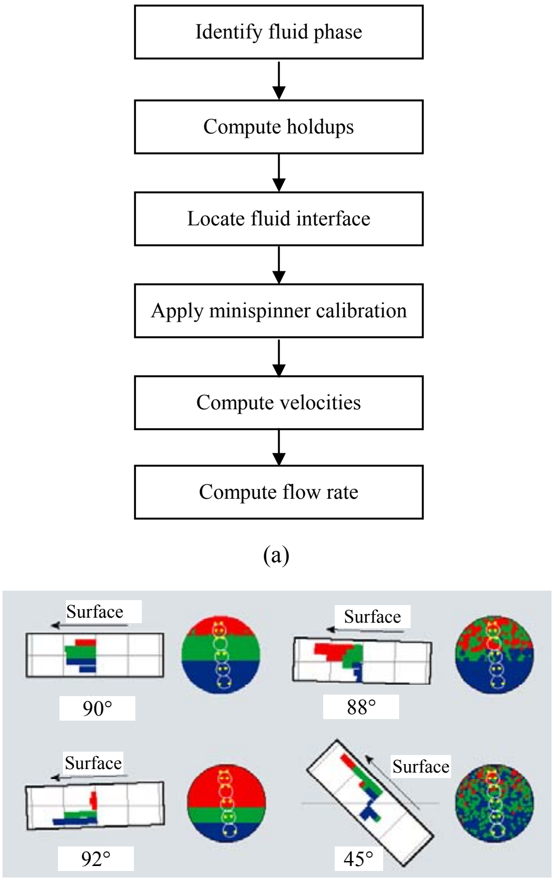
Fig.1 Illustration showing FloScan Imager (FSI) tool design and shape



(a)

(b)

Fig.2 Operation of the FloScan Imager electrical FloView probe for water holdup (a) and the optical GHOST probe for gas holdup (b). The FloView probe has a conductive tip separated from a ground. When surrounded by a conducting medium, such as water, current flows. When the tip encounters gas or oil, the circuit is broken. Water holdup is calculated based on the time the circuit is complete. The GHOST (Gas Holdup Optical Sensor Tool) probe discriminates gas from oil or water by the amount of light reflected back from the probe tip. Gas holdup is determined by the length of time of high reflectance above a predetermined threshold (Baldauff *et al*., 2004)



(a)

(b)

Fig.3 (a) The sequential algorithm used in the FloScan Imager workflow process; (b) Examples of multiphase flow velocity and phase distributions in horizontal and deviated pipes, displayed on the FSI monitor. The relative positions of the sensors are shown, with circles for the spinners and dots for the probes

The Inflow Profiler provides a forward model to interpret the raw FSI data and display results in real time. The processing flow is sequential (Fig.3a). Phase distributions of gas, oil, and water are generated based on probe readings and holdup models. A velocity profile is then defined using phase dependent spinner response parameters. The holdup and velocity profiles are then combined, with the aid of velocity-slip models where necessary, to derive individual phase flowrates. The Monitor Box and Inflow Profiler are often run together to show both raw and interpreted data simultaneously (Fig.4).

FloScan Imager case history

Aging reservoirs in the Gulf of Suez produce viscous oils at high water cuts through deviated to horizontal completions. It is often difficult for conventional PL tools to define the complicated flow regimes and identify areas for water shutoff to maximize oil recovery as a field nears its economic limit. One well with an inclination of 37° was producing with gas lift through six open intervals. Production was 2058 B/D (barrel per day) with 97% water cut. When a conventional PL survey was unable to evaluate individual interval contributions or accurately identify sources of water production, the FloScan Imager tool was deployed on wireline.

Fig.5 compares logs from the FSI and conventional PL surveys. The FSI flow profile shows that approximately 25% of the oil and 85% of the water were being produced from perforations below X400 feet. The remainder of the water and some oil were produced from perforations at X390 feet. The two perforations above X390 feet were producing clean oil; more than half of the oil was flowing from the top perforation. Conventional PL sensors could not detect oil entering the top perforations because the spinner was affected by water recirculation, and the resolution of the gradiomanometer was too low to resolve oil contributions. As a result, 90% of the oil production was erroneously attributed to the lower perforations with the conventional tool analysis.

Based on the FSI results, a workover operation was planned to optimize the oil production. After cross-referencing the log results with geologic information on the location of a sealing layer of shale, the operator set a plug at X400 feet to isolate the majority of the high water-cut zones in the bottom of the well. The resulting production of 556 BOPD (barrel of oil per day) and 2532 BWPD (barrel of water/day) represented a 9-fold increase in oil production. Payback of the evaluation and re-completion costs was accomplished in less than a week.

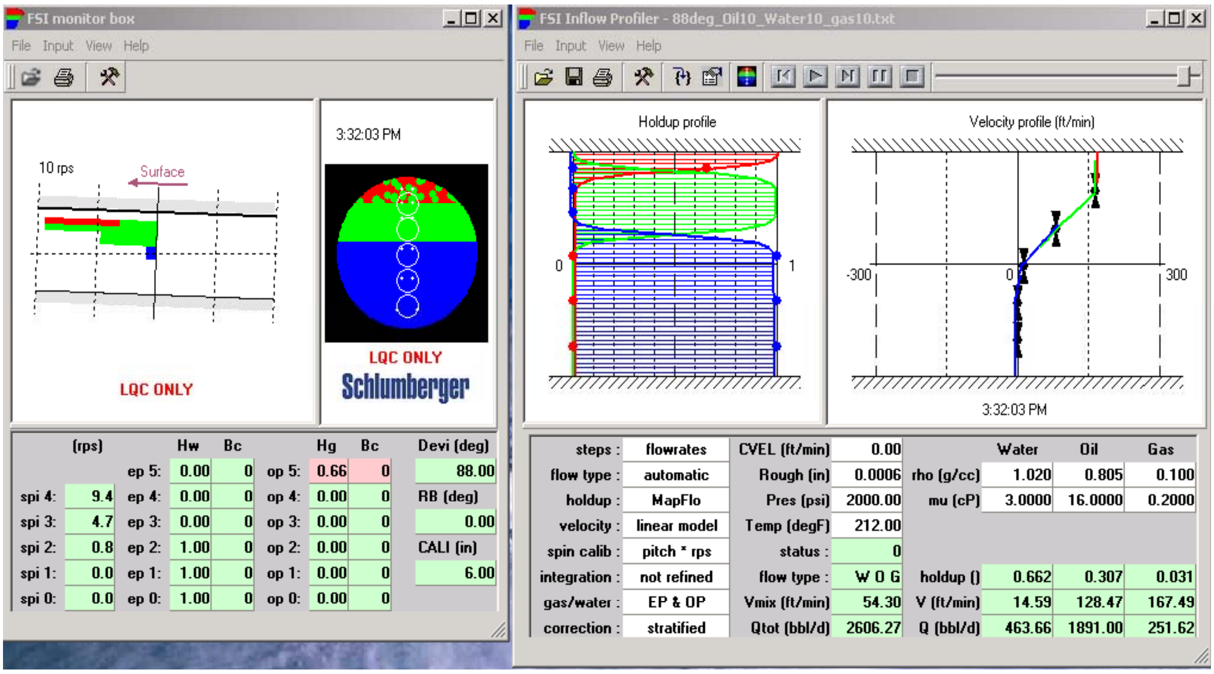
Production Log Advisor (PLA)

A new processing workflow engineered by Schlumberger's Beijing GeoScience Center, China, is designed to image downhole flow performance of multi-zone completions to guide workover decisions in a timely manner. The interface includes interactive tools to input various completion and reservoir parameters and image the effects on the production profile. Visual outputs allow rapid screening of possible scenarios and show the predicted profile after intervention. It combines reservoir deliverability as defined by production logging measurements with nodal analysis evaluation. Nodal analysis techniques provide a method to model the effects of fluid properties and completion configuration as the fluids are produced to the surface. When combined, production logging answers and nodal analysis provide a unique insight into reservoir-completion performance and potential for improvement.

PLA was employed to evaluate potential remedial action for the subject well (Fig.6). The results after modelling the plug set at X400 feet indicated an oil production of 609 B/D and a water production of 2447 B/D. These values are very close to the actual results of 556 B/D and 2532 B/D illustrating the usefulness of PLA as a powerful predictive tool.

CROSS-WELL EM SURVEY

Schlumberger-EMI have been developing cross-well EM survey technology with operating frequency from 1 Hz to 1000 Hz, inter-well spacing up to about 1 km for open holes (to about 0.5 km and 0.3 km for steel-cased/ open and steel cased/cased holes, respectively). Contrast between resistive hydrocarbons and conductive formation water is the basis for hydrocarbon detection. The underlying physics principle of cross-well EM survey is the same as that of the borehole induction logging tool (Fig.7). The cross-borehole induction logging provides resis-



	(rps)		Hw	Bc		Hg	Bc	Devi (deg)
		ep 5:	0.00	0	op 5:	0.66	0	88.00
spi 4:	9.4	ep 4:	0.00	0	op 4:	0.00	0	RB (deg)
spi 3:	4.7	ep 3:	0.00	0	op 3:	0.00	0	0.00
spi 2:	0.8	ep 2:	1.00	0	op 2:	0.00	0	CALI (in)
spi 1:	0.0	ep 1:	1.00	0	op 1:	0.00	0	6.00
spi 0:	0.0	ep 0:	1.00	0	op 0:	0.00	0	

steps :	flowrates	CVEL (ft/min)	0.00		Water	Oil	Gas
flow type :	automatic	Rough (in)	0.0006	rho (g/cc)	1.020	0.805	0.100
holdup :	MapFlo	Pres (psi)	2000.00	mu (cP)	3.0000	16.0000	0.2000
velocity :	linear model	Temp (degF)	212.00				
spin calib :	pitch * rps	status :	0				
integration :	not refined	flow type :	W O G	holdup ()	0.662	0.307	0.031
gas/water :	EP & OP	Vmix (ft/min)	54.30	V (ft/min)	14.59	128.47	167.49
correction :	stratified	Qtot (bbl/d)	2606.27	Q (bbl/d)	463.66	1891.00	251.62

Fig.4 FSI-Monitor Box and Inflow Profiler running side-by-side (Inflow Profile delivers real time interpretation of water, oil and gas flow rates)

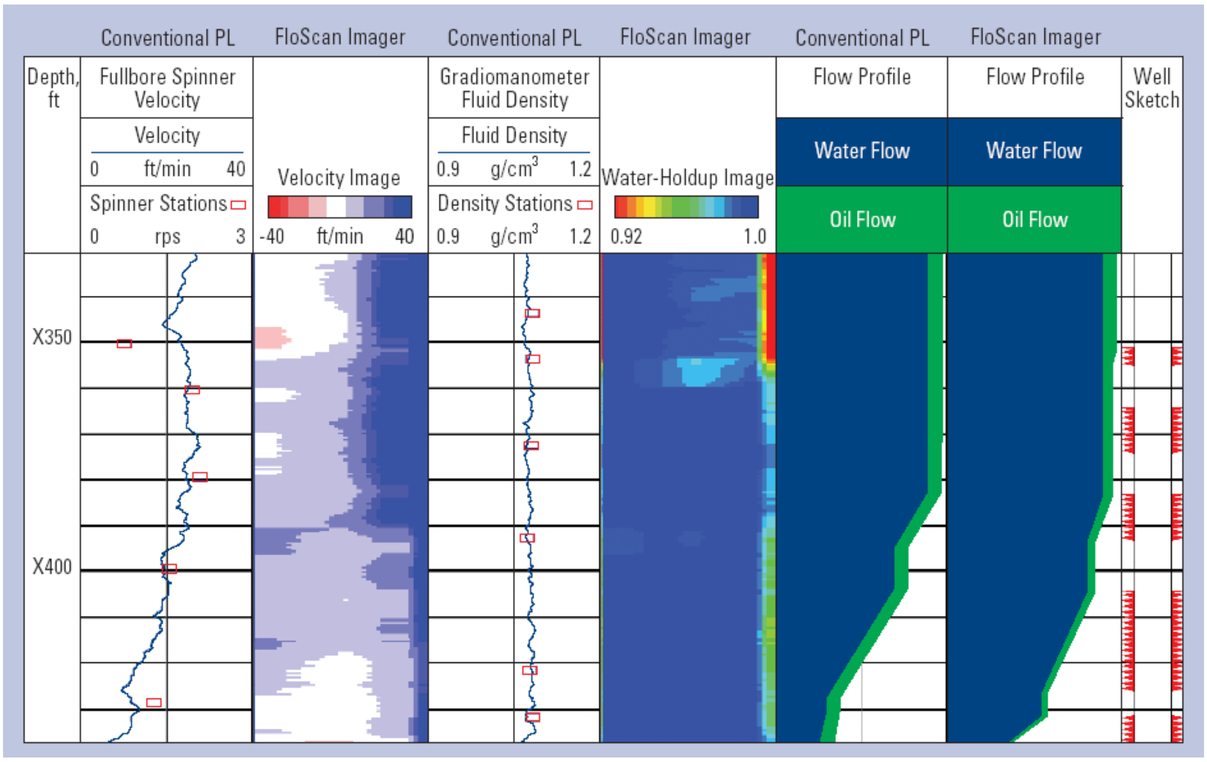


Fig.5 The FloScan Imager identified and quantified zonal oil and water production in this well in the Gulf of Suez after conventional PL had failed. A workover operation led to a 9-fold increase in oil production

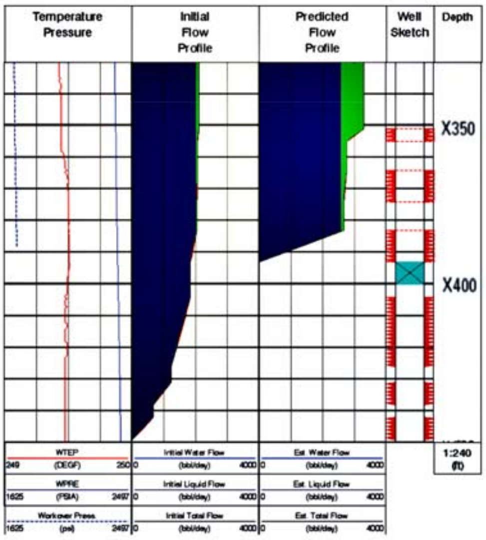


Fig.6 PLA evaluation imaging the production profile results of the plug setting at X400 feet. The predicted results match the actual production test after setting the plug

tivity distribution at a reservoir scale; the survey planning, data collection and inversion interpretation are more involved[1].

Cross-well EM is a useful tool for reservoir management. The technique is most effective in "dynamic" fields where fluid saturations are variable in time and space. It can be used to identify (water or steam) flooded and bypassed regions, and high porosity volumes (Wilt *et al.*, 1997; Zeng *et al.*, 2000). By monitoring changes in the resistivity distribution with time, the cross-well EM survey is very effective at mapping inter-well reservoir changes. The technique is also a very effective tool for reservoir characterization, and can be used to define control structure or process.

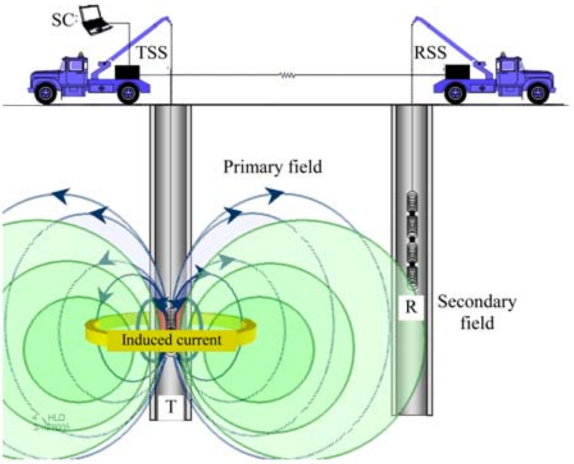


Fig.7 Principles of Cross-well EM: magnetic dipole transmitter T (loop) induces currents in the formation surrounding the borehole (10^5 times stronger than borehole induction tools. Induced current depends on the transmitter (moment) strength, operating frequency and the formation conductivity and is inversely proportional to square of distance). Receiver R detects direct field (primary) and induced field (secondary); secondary field (formation) is typically 10%~50% of the total. Formation resistivity is derived from secondary field measurement by the inversion process

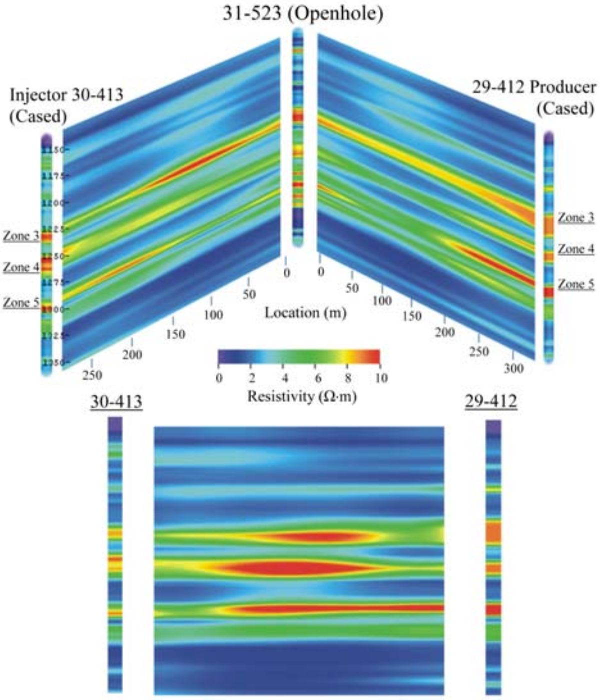


Fig.8 Example cross-well EM imaging survey performed in China Shengli (Gudao) oilfield. The separation between the steel-casing well pair 412 and 413 is 265 m

---

[1] Survey Planning: First selection of candidates is done by completing the survey planning questionnaire or tool planner. In view of the questionnaire and provided logs, simulation can be required to validate candidate. Modeling is performed for simulation and/or post acquisition processing. Survey parameters are computed. Modeling or Simulation is to understand the geological and petrophysical problems, to demonstrate the application, to reduce the operation risk factor and to help post-data processing and inversion. Data Collection involves several thousands T-R combinations per survey. Sensor spacing is about 2%~5% of well spacing. Data profiles are bell-shaped curves due to geometry. Vertical (axial) and 3-component receivers are used (the axial is faster, 3-component with higher resolution). Data precision is about 1%. Interpretation is performed with 2D/3D inversion code (finite difference type). Starting model is based on induction logs. Spatial resolution is about 5% well spacing (for vertical-to-horizontal aspect ratio >1). Data misfit is usually <2%. "Non-uniqueness" is managed by using knowledge about the field (e.g. logs and geology)

The cross-well EM system can be used specifically, for example, to monitor changing reservoir conditions as a result of waterflood (Wilt *et al.*, 2001), with a significant resistivity decrease being related to water injection and resistivity increase to productive hydrocarbon intervals or compaction. The time-lapse 3D images are useful for oil companies to identify oil reservoir drainage processes and bypassed pay zones, and to better plan injection, production and (infill) drilling. There are more than 30 cross-well EM surveys made in USA, Canada, Oman and China since the field tests were initiated in early 2003 in Schlumberger.

Cross-well EM China case history

The survey was made in March 2004 at the Gudao oilfield in Shandong Province in China. Gudao is an anticlinal trap located along the Yellow River delta in central China. The field consists of channel and deltaic sands deposited in an ancient flood plain. Large parts of the field are characterized by continuous deltaic sands and other parts by distinct channels but generally both channel and flood sands are present in each area. The configuration of the sands and the controlling structure is crucial in understanding the ongoing waterflood and in optimizing the oil production strategy. At present it is estimated that 25% of the reserves in this field has been recovered; another 15% is recoverable with improved reservoir knowledge. Improvement of this knowledge is one of the key goals to the Gudao. It was to provide inter-well resistivity data to help better understand the waterflood dynamics and locate bypassed reserves (thus to provide an improved reservoir definition in this part of the Gudao field).

The project consists of 3 separate surveys using 3 well pairs. Well 29-412 (412) is a producer (steel cased), well 30-413 (413) is a water injector (cased) and well 31-523 (523) is a newly drilled open-hole producer that was used in the tomography (Fig.8 in the preceding page). The wells are located in a mature part of this waterflood. Flooding started in this part of the field in 1985 and has progressed continually since then[1]. The flooding and production is centred in three principal zones (Fig.8); zones 3 and 4 are well-defined continuous deltaic sands that range in thickness from 4 m to 12 m. Zone 5 is a less continuous zone with heavier oil that has had less success in water flooding operations. At present a cyclic steaming strategy is being used with some success in this layer.

The tomography covered the depth interval between 1150 m and 1350 m. The system operates with a stationary 4 level receiver string and a moving transmitter. The transmitter moves from the bottom to the top of the interval at a rate of 3~6 m/min; data is collected every 1~2 m depending on the amount of signal averaging and the logging rate. After each transmitter profile the receivers are repositioned and the process is repeated until the entire depth interval is covered[2].

The 32-Hz image between well pair 523 and 413 is shown in Fig.8 (top left of the fence image). The image is a smooth section consistent with a flat-lying multilayered section and concordant with the well logs at the margins. The low resistivity upper section represents clays and silts; within this section there are thin discontinuous higher resistivity sands (maybe oil bearing); note for example the layer at a depth of 1150 m. The oil-bearing zones 3, 4 and 5 are associated with continuous high resistivity layers. Layer three is higher in resistivity near well 523 and grades gradually lower towards well 413. The layer thickness stays relatively constant. Layer 4 stays roughly constant in resistivity but seems to thicken gradually from well 523 to well 413. The most interesting part of the image is near location 80 m where the 4 layer basal zone 5 grades at well 523 into a 2~3 layer section. The section also indicates slight stratigraphic thinning in layers 3 and 4 and some variation in the overburden silts and muds at this same lateral position.

Variations in layer resistivity may be associated with saturation and/or water salinity. Clearly the resistivity has fallen from the initial 20~25 Ω·m to the present day 8~10 Ω·m due to replacement of oil by injected water. As the oil de-saturation continues this trend will continue but it can be offset by variations in

---

[1] After years of water flooding the resistivity of the oil sands typically decreases to 8~10 Ω·m from 15~25 Ω·m, as a result of saturation changes. The induction logs indicated that the oil sands have an initial resistivity of 15~25 Ω·m, and the background silts and clay have a resistivity of 2~4 Ω·m. The logs suggest that there are three main continuous oil-sand horizons and several other discontinuous horizons.

[2] For these surveys receivers were spaced 5 m apart on this interval and the transmitters covered the same interval at 1 m measurement spacing. The tomography required 20~35 h for completion for each cross-well survey; the longer time periods were for the dual casing surveys.

injected water salinity. The injected water supply for this field has changed a number of times, but the salinity is uncertain. This therefore adds an uncertainty to associate higher oil saturated intervals with a higher resistivity.

The section for well pair 523-412 in Fig.8 (top right of the fence image) is quite similar to that for well 523-413. The layers are also continuous except for a thinning near 120 m in both zones 4 and 5. In zone 5 this image indicates a clear convergence of the 4-layer section to a two-layer section shown on the log in well 412. This is important as it indicates that the 4-layer section visible in 523 is likely connected to the 2-layer section in well 412. Note also that this convergence occurs at about 120 m and is associated with a thinning of zone 5.

The dual casing cross-section shown in Fig.8 (lower plot) is similar in appearance to the other sections. This section seems to indicate a thickening and increase in formation resistivity in all three layers near the middle of the section from 100~150 m (compare this to the observed thinning in the 523-413 section). It is suspected that these layers vary in thickness continuously throughout this part of the field due to the depositional conditions. This thickness variation probably also affects the water flood sweep efficiency and as such it is a worthwhile property to map. The layers also vary in resistivity, probably due to the water saturation and salinity. There likely exist significant bypassed reserves in the higher resistivity section. An offset well was actually drilled after the cross-well EM survey close to that section and oil was produced from layer 5. This suggested that the higher resistivity in layer 5 represents bypassed oil.

CONCLUSION

FloScan Imager (FSI) is an effective 3-phase oil/gas/water flow production-logging tool for deviated and horizontal wells. It can provide a visual image of fluid velocity and holdup profiles along a vertical diameter of the wellbore at every survey depth, enabling a robust estimate of individual phase flow rates in complex flow regimes. In the case history shown for a well in the Gulf of Suez, the FloScan Imager identified and quantified zonal oil and water production after conventional PL had failed. A subsequent workover operation led to a 9-fold increase in oil production after the operator set a plug to isolate the majority of the high water-cut zones.

The cross-well EM survey in China Shengli (Gudao) Oilfield was very successful. Geologically the sections interrogated were very continuous, showing a coherent thinning in only one of the layers in an area associated with the convergence of the 4 layers into 2. The observed variations in the inter-well resistivity are consistent from section to section although they may represent variations in water salinity as well as oil saturation variations. The cross-well EM survey has helped detect the by-passed pay in the layer zone 5; this was later confirmed by the oil production from an offset well drilled close to the layer.

ACKNOWLEDGEMENT

The team members at Schlumberger's Riboud Product, Cambridge Research and Beijing Geo-Science Centers developed the hardware and software for the FloScan Imager. The China Shengli (Gudao) Oilfield is thanked for the permission to present the cross-well EM field test data.

References

Baldauff, J., Runge, T., Cadenhead, J., Faur, M., Marcus, R., Mas, C., North, R., Oddie, G., 2004. Profiling and quantifying complex multiphase flow. *Oilfield Review*, **16**(3):4-13.

Vu-Hoang, D., Faur, M., Marcus, R., Cadenhead, J., Besse, F., Haus, J., Di-Pierro, E., Wadjiri, A., Gabon, P., Hofmann, A., 2004. A Novel Approach to Production Logging in Multiphase Horizontal Wells. SPE Annual Technical Conference and Exhibition, 26-29 September 2004. Houston, Texas. SPE paper 89848.

Wilt, M., Schenkel, C., Daley, T., Peterson, J., Majer, E., Murer, A.S., Johnston, R.M., Klonsky, L., 1997. Mapping steam and water flow in petroleum reservoirs. *SPE Reservoir Engineering*, **12**(4):284-287. SPE paper 37532.

Wilt, M., Zhang, P., Morea, M., Julander, D., Mock, P., 2001. Using Crosswell Electromagnetics to Map Water Saturation and Formation Structure at Lost Hills. SPE Western Regional Meeting, 26-30 March 2001. Bakersfield, California. SPE paper 68802.

Zeng, W., Zhao, W., Wilt, M., 2000. Three Successful Large-Scale Field Tests of Crosshole Electromagnetic Tomography Technology. SPE Annual Technical Conference and Exhibition, 1-4 October 2000. Dallas, Texas. SPE paper 63143.