High-Angle and Horizontal Well Special Interest Group (SIG) Meeting
October 6, 2006
Hosted by: Chevron

3901 Briarpark, Houston, Texas

HA/HZ SIG Objective: The HA/HZ SIG is devoted to help the petroleum community (Geology, Geophysics, Formation Evaluation, Drilling, Reservoir Engineering) understand the challenges associated with the acquisition, interpretation, and integration of HA/HZ wellbore data.

HA/HZ SIG STEERING COMMITTEE MEMBERS:

- Co-chair - Quinn Passey – ExxonMobil (end of term with this meeting)
- Co-chair - Terry Quinn – Baker Hughes INTEQ (will continue for one more year)
    - Paul Boonen - Pathfinder
    - Jeff Brami - ExxonMobil
    - David Byrd - Devon
    - J. B. Clavaud – Chevron
    - Ron Deady - Halliburton
    - Jim Klein - ConocoPhillips
    - Robert Lieber - BP
    - Jim Oberkircher - IADD
    - John Rasmus - Schlumberger
    - Ed Stockhausen – Chevron (new co-chair for 2 years)

Agenda:

1	8:30	Welcome and safety – J. B. Clavaud (Chevron)
2	8:45	SIG Business – Quinn Passey (ExxonMobil)
	9:00	SIG "subcommittee" report outs (10 min each)
3		- HA/HZ Log example chartbook status - Jeff Brami (ExxonMobil)
4		- HA/HZ Bibliography status - Paul Boonen (Pathfinder)
	9:20	Break
	9:35	Invited talks (20 min each w/45 min discussion at end)
5		9:55 - Field and Benchmark studies of LWD Nuclear response in HA/HZ wells - H. Yin (ExxonMobil)
6		9:35 - LWD Density Response to Bed Laminations in HA/HZ wells - R. J. Radtke (Schlumberger)
7		10:15 - Environmental and petrophysical effects on density and neutron in highly deviated wells - A. Mendonza (Univ. Texas)
8		10:35 – Presentation by Ed Stockhausen
9	11:00	HA/HZ log exercise - the value of information - Terry Quinn (Baker Hughes) (45 min)
	11:45	Lunch
10	12:30	Discussion of technical topics presented in the morning.
11	1:00	Thickness determination in HA/HZ wells - Hezhu Yin (ExxonMobil) (15 min)
	1:35	Break
	1:45	Reports from other SPWLA SIGs (15 min each)
12		1:45 - Nuclear SIG status update - Ahmed Badruzzaman (Chevron)
13		2:00 - Depth SIG status update - Terry Quinn (Baker Hughes)
	2:15	Open presentations on other HA/HZ topics from audience w/discussion
14	2:50	Review action items and set next meeting date and location – Terry Quinn
	3:00	Adjourn

Meeting Minutes

Attendees: Approximately 65 people attended

#1 – Welcome and Safety – J. B. Clavaud

- Reviewed evacuation procedures
- Showed a series of humorous safety sharing slides – challenged next host to beat his slides

#2 - SIG Business – Reported by Quinn Passey

Slides shown as part of presentation

2005-06 HA/HZ SIG STEERING COMMITTEE

Co-Chair - Quinn Passey – ExxonMobil
Co-Chair -Terry Quinn – Baker Hughes INTEQ

Jeff Brami - ExxonMobil
David Byrd - Devon
J. B. Clavaud - Chevron
Jim Klein - ConocoPhillips
Robert Lieber - BP
Jim Oberkircher - IADD
John Rasmus - Schlumberger
Ed Stockhausen – Chevron

HA/HZ SIG STEERING COMMITTEE

- Met on August 3, 2006 in Chevron's Houston office
- Reviewed Steering Committee Membership and Officers
- Reviewed Current E-mail Membership
- Reviewed SIG Activities
  - –Veracruz HA/HZ SPWLA Workshop (6/4/06)
  - –AAPG session on mapping/modeling with HA/HZ well data (4/1-4/07)
  - –Rio de Janeiro, Brazil HA/HZ SIG meeting 10/27/06
- Updated Status of SPWLA SIG Web Page
- Set Topic and Date for October 2006 SIG meeting (today's meeting)
- Suggested Future SIG topics and locations (2007-08)

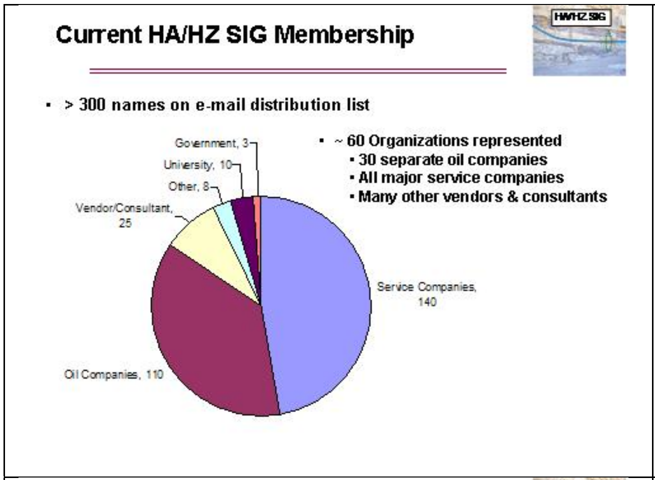
Steering Committee Membership Guidelines

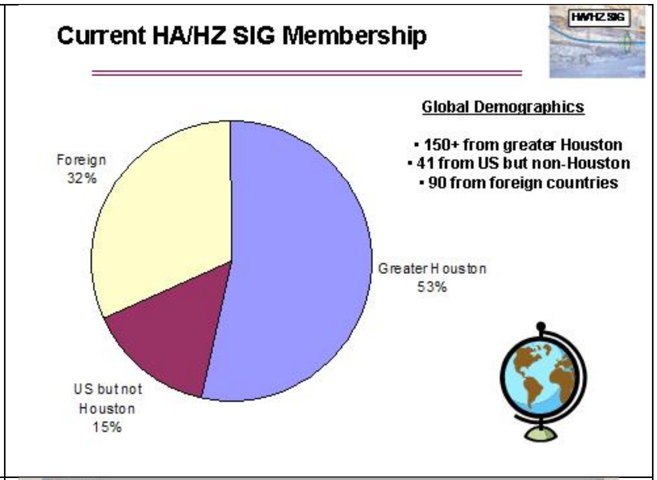
- HA/HZ Steering Committee to be limited to 12 members
- Ideally, ½ from oil companies and ½ from service companies
- Co-Chairs to be made up from oil company and service company representatives
- Co-Chairs are nominated by the Steering Committee and endorsed by active members (those in attendance) at appropriate SIG meeting
- Anyone can volunteer to participate on Steering Committee
  - Do not have to be nominated by others
- Removal from Steering Committee initiated by:
  - Personal request, or
  - Non-interest (lack of active participation)

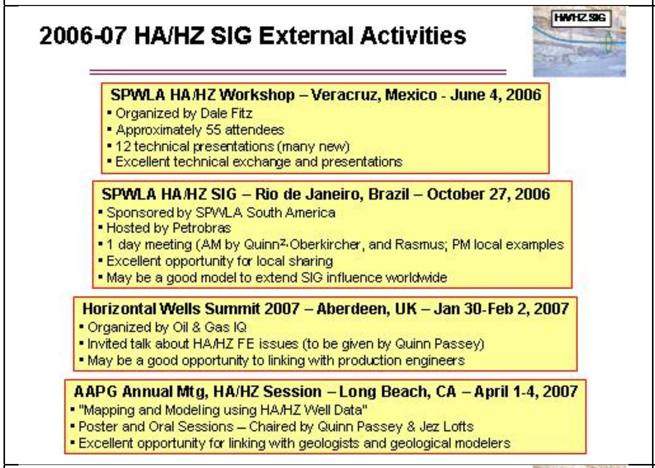
2007-08 HA/HZ SIG Steering Committee

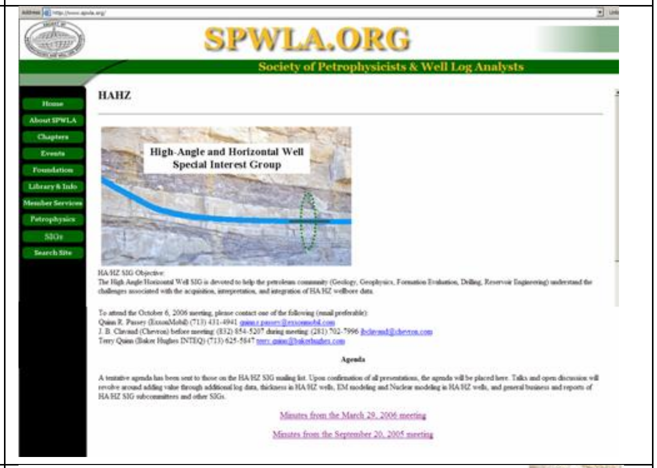
Co-Chair -Terry Quinn – Baker Hughes INTEQ
Co-Chair - Ed Stockhausen – Chevron

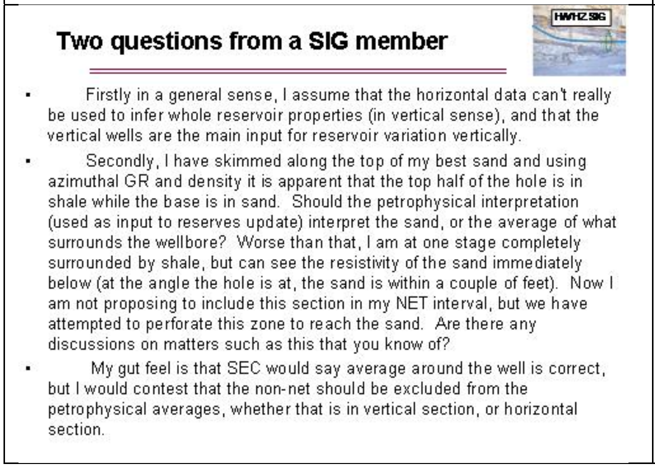
Paul Boonen – Pathfinder
Jeff Brami - ExxonMobil
David Byrd - Devon
J. B. Clavaud - Chevron
Ron Deady – Halliburton
Jim Klein - ConocoPhillips
Robert Lieber - BP
Jim Oberkircher – IADD
Quinn Passey – ExxonMobil
John Rasmus - Schlumberger

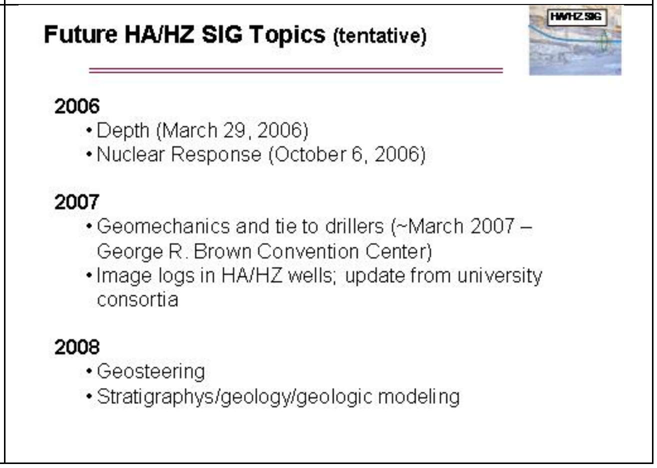

Current HA/HZ SIG Membership
HA/HZ SIG
• > 300 names on e-mail distribution list
• ~ 60 Organizations represented
• 30 separate oil companies
• All major service companies
• Many other vendors & consultants
Government, 3
University, 10
Other, 8
Vendor/Consultant, 25
Service Companies, 140
Oil Companies, 110


Current HA/HZ SIG Membership
HA/HZ SIG
Global Demographics
• 150+ from greater Houston
• 41 from US but non-Houston
• 90 from foreign countries
Foreign 32%
Greater Houston 53%
US but not Houston 15%


2006-07 HA/HZ SIG External Activities
HA/HZ SIG
SPWLA HA/HZ Workshop – Veracruz, Mexico - June 4, 2006
• Organized by Dale Fitz
• Approximately 55 attendees
• 12 technical presentations (many new)
• Excellent technical exchange and presentations
SPWLA HA/HZ SIG – Rio de Janeiro, Brazil – October 27, 2006
• Sponsored by SPWLA South America
• Hosted by Petrobras
• 1 day meeting (AM by Quinn²-Oberkircher, and Rasmus; PM local examples
• Excellent opportunity for local sharing
• May be a good model to extend SIG influence worldwide
Horizontal Wells Summit 2007 – Aberdeen, UK – Jan 30-Feb 2, 2007
• Organized by Oil & Gas IQ
• Invited talk about HA/HZ FE issues (to be given by Quinn Passey)
• May be a good opportunity to linking with production engineers
AAPG Annual Mtg, HA/HZ Session – Long Beach, CA – April 1-4, 2007
• "Mapping and Modeling using HA/HZ Well Data"
• Poster and Oral Sessions – Chaired by Quinn Passey & Jez Lofts
• Excellent opportunity for linking with geologists and geological modelers


SPWLA.ORG
Society of Petrophysicists & Well Log Analysts
HAHZ
High-Angle and Horizontal Well
Special Interest Group
Agenda
Minutes from the March 29, 2006 meeting
Minutes from the September 20, 2005 meeting


Two questions from a SIG member
HA/HZ SIG
• Firstly in a general sense, I assume that the horizontal data can't really be used to infer whole reservoir properties (in vertical sense), and that the vertical wells are the main input for reservoir variation vertically.
• Secondly, I have skimmed along the top of my best sand and using azimuthal GR and density it is apparent that the top half of the hole is in shale while the base is in sand. Should the petrophysical interpretation (used as input to reserves update) interpret the sand, or the average of what surrounds the wellbore? Worse than that, I am at one stage completely surrounded by shale, but can see the resistivity of the sand immediately below (at the angle the hole is at, the sand is within a couple of feet). Now I am not proposing to include this section in my NET interval, but we have attempted to perforate this zone to reach the sand. Are there any discussions on matters such as this that you know of?
• My gut feel is that SEC would say average around the well is correct, but I would contest that the non-net should be excluded from the petrophysical averages, whether that is in vertical section, or horizontal section.


Future HA/HZ SIG Topics (tentative)
HA/HZ SIG
2006
• Depth (March 29, 2006)
• Nuclear Response (October 6, 2006)
2007
• Geomechanics and tie to drillers (~March 2007 – George R. Brown Convention Center)
• Image logs in HA/HZ wells; update from university consortia
2008
• Geosteering
• Stratigraphys/geology/geologic modeling

#3 – A Guide to Log responses in Wellbores with High Incident Angles to Formations "Subcommittee" – Jeff Brami
Slides shown as part of presentation

Subcommittee Meeting ExxonMobil on 26 Sept, 2006
- Minutes from discussions 'Examples/cartoons illustrating logging tool responses'

NAME	COMPANY	Dave Hinz	Halliburton
Art Schnacke	ExxonMobil	Robert Gales	Weatherford
Paul Boonen	Pathfinder	Shinichi Sakurai*	OXY
Michael Manning*	INTEQ	Ian Shang	Shell
Wol Chaffe	PARADIGM	Zhiqiang Zhou	Baker Atlas
Rich Hardman	6FF40	Jeff Brami*	ExxonMobil

*Participated @ ExxonMobil on 26 September, 2006

Meeting results:

I. **The six modeled tool responses provided by Mike Manning (Baker Hughes) are good examples of what we need. Consensus of those present:**
   a. **Limit final illustrations so as not to overwhelm users of document.**
   b. **Keep same general format and add GR plus short paragraph describing what's in cartoon.**
   c. **Add a tool sketch to each cartoon illustrating sensor spacings & other key tool info.**
   d. **Include three case-histories to illustrate key points concerned w/ logs in wellbores w/ high incident angles w/ formations. Use previously published/released data.**

II. **Provide two volumes:**
   a. **Volume 1 - Low to moderately high angle intersections of the well and formations using simple diagrams showing sensor responses at 0°, 45° and 60°. Use these three intersection angles w/ several bed-boundary formation values (i.e. resistivity contrasts 100:1, 10:1). Start w/ GR & resistivity sensor responses. Density logs will be second.**
   b. **Volume 2 - High angle intersections to be used in geosteering applications (85°, 90°, and 95°). Intent in second volume is to show tool responses when tools are either entering or exiting a formation.**
   c. **Start w/ simple/common situations and let industry response guide future efforts & republish in a few years using input from first publication responses.**

III. **Document to be publish by professional society (SPWLA and/or SPE)**
   a. **Document may be included in handouts at a <u>Topical Conference</u>**
   b. **Conference may be in Taos – roughly January, 2008**
   c. **Potential topics for conference could be:**
      i. **Geosteering**
         1. **Rotary-steerable systems**
         2. **Reservoir navigation**
         3. **Borehole stability**
         4. **Mud systems for HWs**
         5. **Reservoir engineering (particularly reserves estimations)**
      ii. **Anisotropy**
      iii. **Imaging**

Future subcommittee meetings will determine which sensor-responses to pursue and search for released examples for inclusion in the first document.
Additional thoughts for this document

Title: A Guide to Log responses in Wellbores with High Incident Angles to Formations Version 1.0

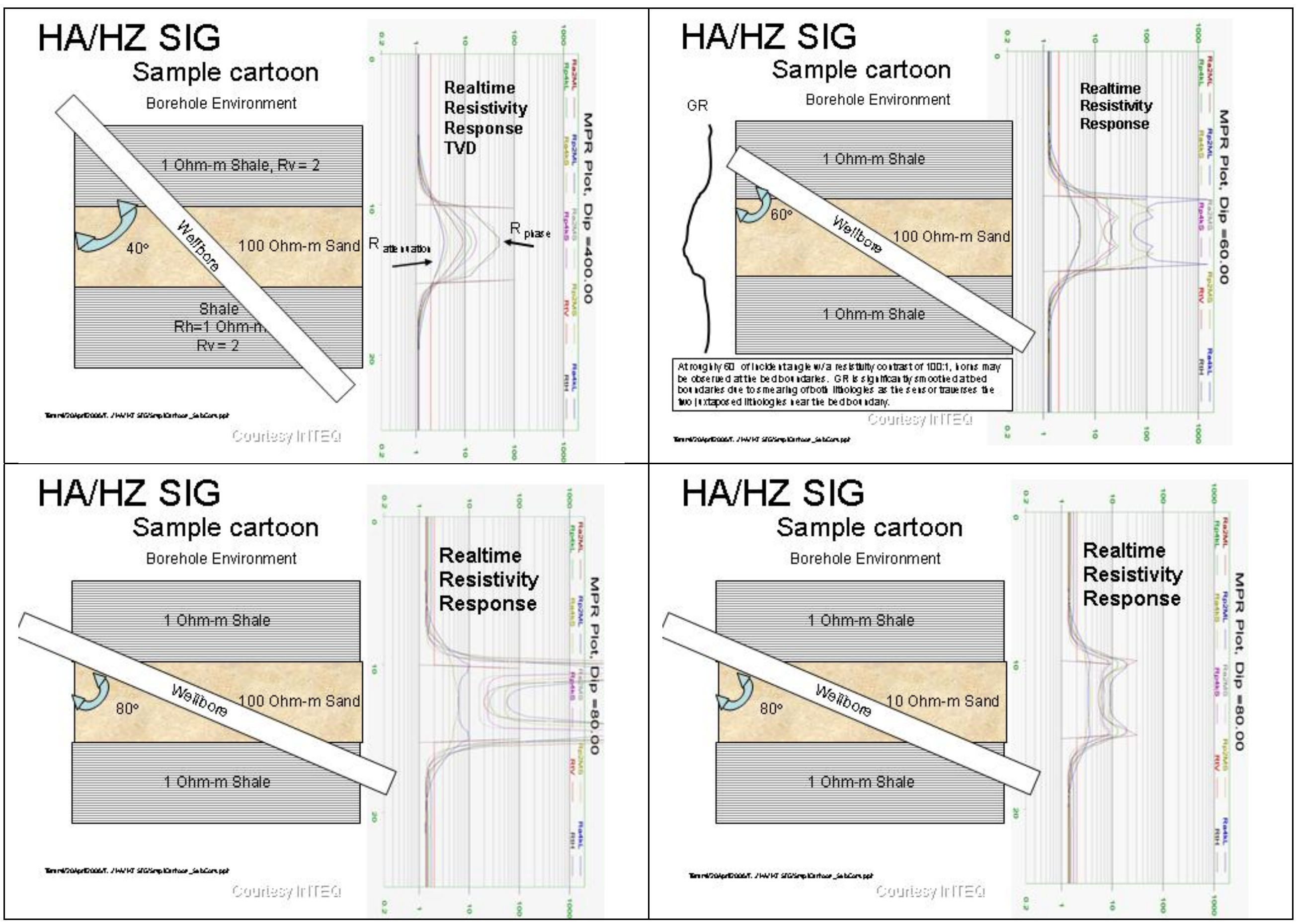
Introduction

- **Objectives of Guide**
- **Disclaimer**
- **Discussion on impact of drilling operations**
  - **ROP**
  - **Time delay between drilling/logging**
    - **Invasion**
    - **Washouts**
    - **Cuttings beds**
  - **RPM of LWD tools**
  - **Sampling rate of sensors**
  - **Software (smoothing, sensor limits (maximum range for a measurement to be reasonable)**

Possible Format

- **5 ½" X 8 ½"**
- **Tabs**
- **Color**

Definitions: especially Geometric factor, depth-of-investigation, vertical resolution



#4 – HA/HZ Bibliography Status – Paul Boonen (Pathfinder)

- **Preliminary list compiled of papers**
- **Could provide in searchable format or RFT or Word**
- **Would like to put on SPWLA webpage (Terry Quinn investigating)**
- **May evolve into an SPWLA reprint series of the "best" HA/HZ papers**
- **Current draft is attached in RFT format (see attachment and Action Items)**

#5 – Field and Benchmark Studies of LWD Nuclear Response in HA/HZ Wells – Hezhu Yin (ExxonMobil)

- **Repeat of 2006 SPWLA Symposium talk – see Paper AAA**
- **Illustrated how erroneous bed dips from density imaging tool can have impact on TVT**

#6 – LWD Density Response to Bed Laminations in HA/HZ wells – R. J. Radtke (Schlumberger)

- **Repeat of 2006 SPWLA Symposium talk – see Paper ZZ**
- **Noted that can detect thin beds better in HA/HZ well than in vertical well**
- **Resolution concept is different: in a vertical well, resolution is the usual vertical resolution along the tool axis; in a HA/HZ well, it is the depth of investigation radially outward from the tool.**

#7 – Environmental and Petrophysical Effects on Density and Neutron in Highly Deviated Wells – Alberto Mendonza (Univ. Texas at Austin)

- **Repeat of 2006 SPWLA Symposium talk – see Paper EEE**
- **Noted that processing for HA/HZ wells will be different for vertical wells**
- **Showed impact of geometric shifts on raw data**

#8 – Thin Beds and Nuclear Response in HA/HZ Wells – Ed Stockhausen (Chevron)

- **Showed example of where vertical well did not see thin tight bed but was clearly visible in HA/HZ well data**
- **Discussion options of using "alpha"-type processing and applicability to HA/HZ wells**

#9 – HA/HZ Log exercise – The value of information - Terry Quinn (Baker Hughes)

- **This was a repeat of the exercise developed for the June 2006 HA/HZ Workshop held in conjunction with the SPWLA Annual Symposium in Veracruz, Mexico**
- **HA/HZ well log interpretation exercise demonstrated the difficulty in interpreting logs in the absence of borehole images and a well path.**

#10 – Technical Discussion of Morning Talks - All

Q: Should all these porosity curve corrections be applied real-time?

1) How much you want to pay?
2) Alpha processing should not be a problem
3) However, the variety of other corrections is not easily implementable
4) Don't have enough depth shifting information realtime to do it.
5) Change of DOI for nuclear measurements vs. different lithologies.
    a. Neutron probably more difficult than density
    b. Requires all sector data
6) Perhaps geometrical correction is not possible real-time

Q: Is this realistic?

1) If only MCNP – probably not, but improvements can be made

Q: Same effects on NMR tool?

Note: tool responses in previous studies
When valid – problem was understanding the problem
Maybe magnetic resonance without long/short space & fixed investigation volume might reduce geometrical influence and be easier to understand

#11 – Thickness determination in HA/HZ wells – Hezhu Yin (ExxonMobil)

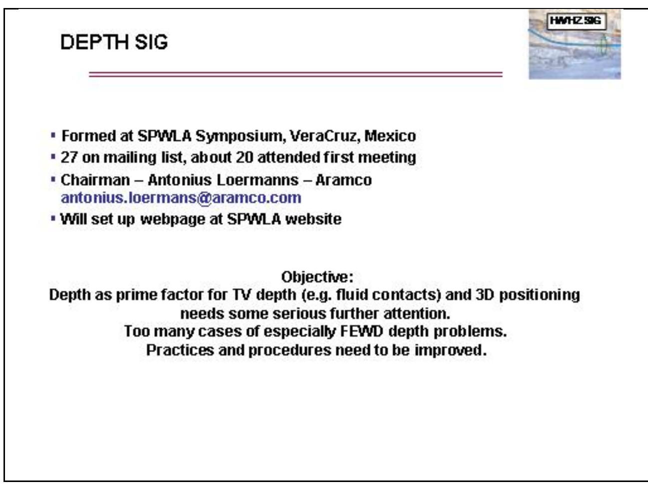
- **Conducted calculation exercise to determine uncertainty in hydrocarbon-pore-volume from logs**
- **Bottom line was that in highly deviated wells, the uncertainty in the true dip of the beds invokes higher uncertainty in HPV than uncertainty in porosity or Sw.**

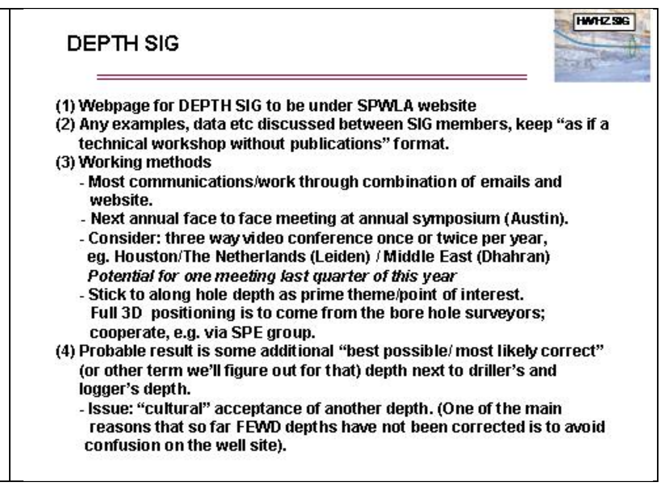
#12 – Update from SPWLA Nuclear SIG – Ahmed Badruzzaman (Chevron)

- **Reviewed objective and progress of Nuclear SIG**
- **Organized Nuclear SIG meeting for October 25, 2006 (please contact Ahmed directly if you would like copies of the minutes from the Nuclear SIG meeting. (Ahmed.Badruzzaman@chevron.com).**
- **Discussed concerns over the future of nuclear sources.**

#13 – Update from SPWLA Depth SIG – Terry Quinn (Baker Hughes)

- **Presentation slides below**





DEPTH SIG

(5) The case for improved depth might need to be proven to the larger community. Therefore:
- Writing/presenting cases with economic impact could be considered.
- Noted: This is not a trivial matter. The best examples, i.e. big economic loss case histories, might not be released.
- Consider forming a small group from the Depth SIG to work on this.

Action: those people interested in this "show impact group", please (re)confirm to me and we will start on it.

(6) Improvements from following best practices as developed in various places are needed. Another small group has been formed to start gathering examples as input.

Action: those people interested in this "best practices group", please (re)confirm to me and we will start on it.

(7) Having a pretty complete literature list of relevant/interesting articles must be a useful thing. Antonius will begin compilation.

Action: any suggestion for papers to be included: please let me know.

DEPTH SIG

(8) Current practices w.r.t. depth audit trail being provided routinely.
- In some areas wireline logs and "even" fewd logs a reasonable depth audit trail is provided, things are generally pretty poor in this respect. – Therefore:
- Find out/compile some for review.

"Imagine yourself as a pp ten years after a certain log has been taken. If you were to have any doubt on say the quality of the density, you have a suite of things to look at and check and thus quantify the uncertainty of the density values. The question now comes whether in case you'd have some question on depth (because the next well finds a contact 20 ft deeper), whether you'd have some reasonable indication on the quality of the depth numbers from the data recorded on/with the log."

Action: please feed results of checks to this effect in various places from "random" checks.

SPE Wellbore Positioning Technical Section (ISCWSA)

The Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA) is seeking to dispel the confusion and secrecy currently associated with wellbore surveying and to enable the industry to produce consistent, reliable estimates of survey-tool performance in today's wells. This will be achieved through the production and maintenance of standards covering the construction and validation of tool error models.

23 meetings to date
Various key papers published

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SPE Wellbore Positioning Technical Section (ISCWSA)

- Meeting held in San Antonio, September 28
- Approximately 50 in attendence representing service companies, operators, manufacturers, and software vendors
- Any member of the SPE can join & be a voting member
- Includes use of website (www.spe.org) where meeting minutes are stored
- Additional website established www.iscwsa.org with last meeting plus other information
- $90 fee for most recent meeting, member or non-member

Officers:
Chairman: Angus Jamieson – Tech21
Secretary: Harry Wilson - INTEQ
Webmaster & Sub-Committee Chair: Steve Grindrod - Copsegrove Developments Ltd

SPE Wellbore Positioning Technical Section (ISCWSA)

- Organized an Applied Technology Workshop on Multidisciplinary Well Positioning, to be held October 16-19 at Ste. Maxime in the south of France – fully subscribed

Latest Meeting:

- Technical presentation by Regis Studer of Total - paper SPE 102088 - analysis of BHA sag and sag corrections. Group discussion agreed that sag was not easily modeled and correction for sag is strongly encouraged.
- Roger Ekseth of Gyrodata then presented a preview of SPE paper 103734 - Asia Pacific Drilling Technology Conference in Bangkok, November 13-15, on "The Reliability Problem Related to Directional Survey Data" – findings of the QC section of the Technical Section, first of 2 parts.
- Benny Poedjono of Schlumberger presented "Well Collision Risk in Congested Environments" (paper presented at APOGCE, Australia, September 2006) - Methods of risk assessment and calculation of probability were described.

SPE Wellbore Positioning Technical Section (ISCWSA)

Latest Meeting continued):

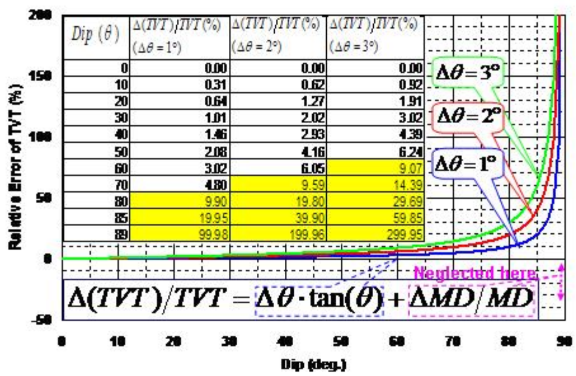
- Steve Grindrod (Copsegrove Developments) gave a brief talk on problems in determining vertical height using GPS. It is not uncommon for commercial GPS software to report elevations above MSL when they are in fact referenced to the ellipsoid. GPS software can also give unwanted flips in grid convergence when operated near the boundary between UTM zones.
- Steve Grindrod reported on the progress of the Error Model Maintenance Subcommittee - intent is to develop a combined MWD/Gyro model
- Simon McCulloch (Tech21) reported on development of the TVD Surveyor
- Bill Calhoun (Chevron) suggested that perhaps our error models are more complicated than necessary.
- Harry Wilson (Baker Hughes INTEQ) reported on the first meeting of the Collision Avoidance subcommittee.

__Next meeting.__
The next meeting will be hosted by Shell in or near Amsterdam, during the week of the IADC-SPE Drilling Conference in February 2007.

#14 – Thickness determination in HA/HZ wells – Hezhu Yin (ExxonMobil)

- **Conducted calculation exercise to determine uncertainty in hydrocarbon-pore-volume from logs**
- **Bottom line was that in highly deviated wells (>80°) a high uncertainty in HPV results from uncertainty in apparent dip of only ± a few degrees.**

Relative Error in TVT due to Uncertainty in Dip



Dip (θ)	$\Delta(TVT)/TVT(\%)$ ($\Delta\theta = 1°$)	$\Delta(TVT)/TVT(\%)$ ($\Delta\theta = 2°$)	$\Delta(TVT)/TVT(\%)$ ($\Delta\theta = 3°$)
0	0.00	0.00	0.00
10	0.31	0.62	0.92
20	0.64	1.27	1.91
30	1.01	2.02	3.02
40	1.46	2.93	4.39
50	2.08	4.16	6.24
60	3.02	6.05	9.07
70	4.80	9.59	14.39
80	9.90	19.80	29.69
85	19.95	39.90	59.85
89	99.98	199.96	299.95

Calculate and Hydrocarbon Pore Feet (HPF)
and Estimate Error and Uncertainty *in HA/HZ well*
(Example of an Answer)

Assumed a perfect horizontal reservoir (i.e. the total vertical thickness = the total stratigraphic thickness, TVT = TST) penetrated by a well with 80 degree deviation:

1. If MD=100 ft, calculate *TVT=TST=MD*COS(θ)*= **100 x 0.174 = 17.4 (ft)** ___, given *COS(80°)=0.174*.
2. Estimate Relative Error: $\Delta(TVT)/TVT = \Delta\theta \cdot \tan(\theta) + \Delta MD/MD$ = **2x9.898+0.5 = 20.3%,** based on your experience (assume P50 case) on the **absolute error** $\Delta\theta$, and **relative error** in $\Delta MD/MD$ _ **0.5 %,** given $\tan(80°) \times (\pi/180°) \times 100/\% = 9.898$ (Or using attached table/graph for $\Delta TVT/TVT$ estimation assumed $\Delta MD/MD \cong 0$).
3. Calculate $HPF = \Phi * (1-S_w) * TVT$ = 0.2x0.8x17.37 = **2.78 (ft)**_, given $\Phi=0.2$, and $(1-S_w)=S_o=0.8$.
4. Estimate Relative Error in HPF: $\left|\frac{\Delta HPF}{HPF}\right| = \left|\frac{\Delta\phi}{\phi}\right| + \left|\frac{\Delta S_w}{1-S_w}\right| + \left|\frac{\Delta TVT}{TVT}\right|$ = **5+10+__20.3__≅35%,** based your experience (assume P50 case), estimate the **relative error** in ϕ_**5%** Sw__**10%,** TVT **__20.3 %,__** and then calculate the total relative error in HPF.

#15 – Review Action Items and Set Next Meeting – Terry Quinn

__Additional Notes__:

- Ed Stockhausen made an announcement that Chevron is considering a Geosteering course open to oil & service companies as part of their technology center.

__Issues seeking discussion at Steering Committee meeting:__

- Paul Boonen – how should we distribute bibliography – EndNotes?, any possibility of a “corporate license”, does Paul need help on compilation/distribution?

- General discussion on whether we should consider a “Reprint” volume of the more important papers based in part on Paul’s bibliography, and whether we should work with the SPWLA & SPE to have an agreement on printing such a volume to avoid copyright issues.

Next Meeting:

- March 2007 (tentatively at Brown Convention Center in Houston in association with the IADD Convention)
- Tentative topic may be Geomechanics from Logs, pending Steering Committee input. May utilize talks presented at 2006 Fall SPWLA/CWLS Topical Conference on "Petrophysics Under Stress"

Plusses & Negatives Analysis	
Positives	**Things to change**
Food	Food (too much & too good)!
Log Exercise	Screen
Good organization	Microphone was not clear
	Temperature was not well controlled – too cold

HA/HZ SIG Bibliography
(Draft 06 Oct, 2006)

NOTE: This is a DRAFT of an ongoing project. If you have additional papers you think should be included, please contact Paul Boonen directly (paul.boonen@pathfinderlwd.com). Also, Paul has a version of this compilation that is searchable using *Endnotes*™ software. Ultimately, we hope to post an evergreen version on the SPWLA Web page.

Aguilera, R.,1991,*Horizontal Wells, Formation Evaluation, Drilling and Production*,Gulf Publishing Company,Houston, Texas,490 p.

Al-Riyami, A., Boyd, D., Dajani, N., 1996, Resistivity Measurement in Anisotropic Horizontal Carbonate Wells, SPE-36240, 7th Abu Dhabi International Petroleum Conference Proceedings, 13-16 Oct, 1996, Abu Dhabi.

> Conventional resistivity tools run in horizontal wells give misleading readings in highly anisotropic formations. These tools are designed to read beyond the invaded zone to obtain true resistivity of the formation. While this design feature is an advantage in vertical or deviated wells, it leads to errors in anisotropic horizontal wells where the tools are affected by neighboring layers. Conventional shallow resistivity measurements would not give true formation resistivity because of mud filtrate invasion.In horizontal injector wells with zones of actual water saturation exceeding 60%, logging with conventional resistivity tools resulted in calculated water saturation of less than 30%. Production testing of the formation and changing casing setting depths are parts of the consequences of the unexpected low water saturation. Four different resistivity tools were run in a well to investigate their relative responses.The logging while drilling Geosteering Tool (GST*) was used for the first time in the Middle East to determine Rt of a horizontal well. The tool is shallow reading with the resistivity measurement located at the bit to minimize the effect of invasion. This resulted in a realistic water saturation of 70 - 80% compared to 20 - 30% obtained from conventional tools. Model simulation of the readings of both conventional tools and GST confirmed the field measurements.For drill pipe conveyed application in horizontal wells, the Azimuthal Resistivity Imager (ARI*) provides 12 directional readings around the tool. Eliminating the adversely affected directional values allows proper Rt determination.The paper will compare the results of the Azimuthal Resistivity Imager, Geosteering Tool, Resistivity at Bit and conventional tools. Modeling demonstrates the different response of electrical tools in the vertical versus horizontal plane. The paper will highlight the advantages and limitations of each resistivity tool particularly in horizontal anisotropic carbonates.

Anderson, B., Druskin, V., Lee, P., Luling, G., Schoen, E., Tabanou, J., Wu, P., Davydycheva, S., Knizhnerman, L., 1997, Modeling 3d Effects on 2-Mhz Lwd Resistivity Logs, SPWLA 1997-N, 38th Annual Logging Symposium, 15-18 Jun, 1997, Houston.

> Steering directional wells through complex reservoirs frequently requires the use of 2-MHz logging-while-drilling (LWD) resistivity tools. In such situations, tools can encounter formation heterogeneities such a-s faults, asymmetric invasion and skewed fractures. Because vertical-well interpretation techniques assume azimuthal symmetry, they can result in significant errors when extended to high-angle wells. Azimuthal symmetry breaks down in deviated wells, where nearby beds parallel to the tool can cause polarization horns, and triaxial anisotropy has an increasing effect. In complex, deviated wells, 3D forward log simulation offers a reliable interpretation method for estimating formation resistivity We introduce a new modeling program that computes 2-MHz tool response to fully 3D formation geometries with triaxial anisotropy. This program uses the spectral Lanczos decomposition method to solve Maxwell?s equations on a staggered finite-difference grid. The program is similar to a program recently introduced for the interpretation of wireline induction logs in horizontal wells. A workstation-based graphical interface simplifies the

description and visualization of 3D geometries. This interface allows the user to assemble a formation model from elementary building blocks, such as layers, boreholes, arbitrarily shaped invasion fronts and skewed fractures. The graphical interface translates this formation model into an input file read by the modeling program. This graphical interface will become a module in an integrated reservoir description and analysis package. Effects of 3D formation features on 2-MHz field logs have been reproduced by modeling. Effects studied include invasion in horizontal wells, oil-base-mud-filled fractures, noncircular invasion fronts and dipping invaded beds with lamination anisotropy. A study of invasion in horizontal wells shows that while the deepest-reading curves are usually unaffected by invasion, they are influenced by proximity to adjacent layers located as far as 15 ft from the wellbore. At the same time, the shallowest-reading curves give a reliable interpretation of invasion until the tool is within 2 ft of an adjacent layer. For non-circular invasion fronts, modeling shows an increasing influence of the formation beyond the invaded zone on the shallowest-reading logs. However, the effect is so small that it can be ignored to first order in invasion interpretation. Drilling-induced fractures filled with oil-base mud can cause curve separations that resemble invasion profiles. Complex 3D resistivity interpretation problems can now be resolved with modeling, both for LWD and wireline tools, In addition, 3D modeling allows a better understanding of tool physics and provides the basis for the design of new tools and interpretation methods.

Anderson, B., et al.,1997,New Dimensions in Modeling Resistivity,Schlumberger Oilfield Review, **Vol 9**,No. 1: p. 40-56,1997.

Anderson, B., Barber, T., Davydycheva, S., Druskin, V., Dussan, E., Knishnerman, L., Lee, P.,1999,The Response of Multi-Array Induction Tools in Highly Dipping Formations with Invasion and in Arbitrary Geometries,The Log Analyst, **Vol. 40**,No. 5: p. 327-344,1999.

With the rapid expansion of horizontal drilling, the interpretation of logs, especially resistivity logs, has become an increasingly complex problem. The proximity of shale layers or of water legs can seriously affect deep resistivity logs, and invasion can strongly affect shallow resistivity logs. The current state of affairs is that determining R, in a horizontal or very high angle well is often impossible. Modeling techniques are now available for solving the full 3D problem necessary for deviated well interpretation. This paper describes a 3D modeling code and applies it to improve the interpretation of multiarray induction tool response. The code uses the Lanczos spectral-decomposition method to solve Maxwell's equations on a staggered finite-difference grid. The finite-difference code has been benchmarked against analytical solutions for subsets of the 3D geometry, and agreement is within three percent. Fifty ft of 3D log can be generated in under half an hour on a modern workstation or high-end PC. The code takes into account dipping beds and unsymmetrical invasion at the same time, as well as resistivity anisotropy. Several horizontal well interpretation problems are investigated with the code. One is the case of axisymmetric cylindrical invasion in a permeable zone below a cap shale interface. In this case modeling shows that for shallow invasion, the deepest Array Induction Imager tool (AIT) curves can be used to infer R, and proximity to the shale cap, while the shallowest curve indicates R,,. If deeper invasion is modeled, only the deepest induction curve indicates R,, while several of the shallow curves read R,,. The code is also used to analyze non-circular invasion fronts caused by either permeability anisotropy or buoyancy segregation typical in highly deviated wells. Both cases are characterized by a considerable quantity of filtrate shunted away from the well in preferential directions, resulting in less invading fluid near the wellbore. As a consequence, there is an increase of the influence of R, on the shallow AIT logs. These cases indicate ihai induction logs in complex formations still have geometrical interpretations, but that they are different than interpretations used in vertical wells. A log example illustrates the power of 3D modeling in interpreting multiarray induction logs in difficult wells. In a horizontal well with moderately salty invasion, modeling shows that a large separation between the deepest induction curves is caused by a combination of invasion effects and polarization horns near a cap shale. In addition, an annulus is present to complicate interpretation.

Anderson, B. I., Barber, T.D., Luling,M.G. , 1995, The Response of Induction Tools to Dipping, Anisotropic Formations, SPWLA 1995-D, 36th Annual Logging Symposium, 16-19 Jun, 1995, Paris,

France.

Directional wells, especially horizontal wells, are commonly drilled today to enhance reservoir productivity and minimize unwanted production of water or gas. At the steep apparent dip angles encountered, logging tool response characteristics change. Induction tools become more sensitive to bed boundary location. They also detect resistivity anisotropy, which remained largely invisible in vertical wells. The interpretation of induction logs in directional wells poses several challenges. Like all logging tools, induction tools were developed for wellbores perpendicular to the bedding planes. The measurements provide several radial depths of investigation. Separation of the logs is generally caused by invasion, and this separation provides a radial resistivity profile. However, in directional wells, a cap shale or an aquifer can cause induction curves to separate because the multiple depths of investigation have different sensitivities to beds adjacent to the zone of interest. Thus curve separation no longer indicates invasion exclusively. In anisotropic formations, induction tools sense a weighted average of the horizontal and vertical resistivities. This observed resistivity may differ considerably from the resistivity of a nearby vertical reference well where induction tools sense only the horizontal resistivity. In these complex formation geometries, forward modeling can provide a reliable resistivity interpretation of tool response in layered, anisotropic media. The computer modeling program generates logs for either dual induction or array induction tools. The tool can be tilted at any user-provided angle against a layer-cake formation. Each layer may have an intrinsic resistivity anisotropy. A major advantage of the program is that computer run-time is independent of the number of beds modeled. The modeling program is used to study the sensitivity of both array induction and dual induction tools to anisotropy. In thick beds, anisotropy alone can cause the induction curves to separate because the mixing of the horizontal and vertical resistivities distorts the skin effect correction. Curve separation is most noticeable in conductive zones and at high dip angles. At steeply dipping bed boundaries, polarization horns appear, similar to those occurring on 2-MHz resistivity logs. These horns are most prominent on the long arrays. A field log example is used to illustrate the use of tool response modeling in an iterative inversion for Rt. The induction interpretation is corroborated by 2-MHz resistivity measurements obtained while drilling. Logs are modeled in both vertical and near-horizontal wells in the same layered formation.

Angeles, R., Yuanand, C., Torres-Verdin, C., 2006, Spatial Sensitivity Functions for Formations Tester Measurements Acquired in Vertical and Horizontal Wells, SPWLA 2006-T, 47th Annual Logging Symposium, Jun 4-7, 2006, Vera Cruz, Mexico.

We develop a conceptual and quantitative methodology to assess the three-dimensional (3D) spatial zone of response of formation-tester measurements acquired in vertical and horizontal wells. Spatial sensitivity functions are calculated numerically from the variation of pressure transient measurements due to perturbations of petrophysical properties at a given point in space and time. Calculations are performed under the assumption of two-phase fluid flow and consider both packer- and point-sources as well as pressure and fractional-flow monitoring probes. We examine perturbations of a range of petrophysical properties to calculate the sensitivity function, including permeability, porosity, and permeability anisotropy. Conventional single-phase spherical- and radial-flow asymptotic solutions often used in the interpretation of formation-tester measurements can lead to significant errors in the construction of the sensitivity maps. Such errors can bias the estimation of permeability and permeability anisotropy because of unaccounted capillary pressure and relative permeability effects. In addition, non-symmetrical flow barriers distort the spatial zone of response, whereas presence of supercharging limits the ability of formation-tester measurements to probe radially deep into the formation. Damaged and stimulated zones near the wellbore can also modify the spatial resolution properties of the acquired measurements and significantly reduce their radial length of investigation. For cases of rock formations penetrated by horizontal wells, the spatial zone of response of formation tester measurements can be highly non-symmetrical. The spatial sensitivity functions described in this paper could be used to design measurement acquisition and interpretation strategies that maximize spatial resolution and depth of investigation in complex geometrical situations that include two-phase flow phenomena.

Bang, J. S., A., Mjaaland, S., 2000, Formation Electrical Anisotropy Derived from Induction Log Measurements in a Horizontal Well, SPE-62908, 2000 SPE Annual Technical Conference and Exhibition, Oct 1-4, 2000, Dallas TX.

An existing theory describes how electrical anisotropy in the formation affects the response of resistivity logging tools. We have related this theory to the processing of LWD induction logs, and are thus able to calculate the anisotropic resisticities directly from the logs.The method has been demonstrated by application to logs from a horizontal well section. Anisotropy ratios of 2-5, and occasionally higher values, were obtained for this formation. We also addressed the accuracy of these numbers by using independent sets of input logs. The results indicate that the logs are influenced by factors like invasion in addition to the anisotropy.Our approach provides a fast and efficient computer algorithm. The output is calculated at the depths of the input logs; hence, the resulting anisotropy becomes a depth-dependent formation property.

Barber, T., Broussard, T., Anderson, B., Dennis, B., 2000, 3d Induction Log Modeling as a Practical Aid to High-Angle and Horizontal Well Interpretation, SPWLA 2000-B, 41st Annual Logging Symposium Transactions, Jun 4-7, 2000, Dallas TX.

Induction logs have been used successfully for more than 40 years to extract resistivity and invasion profile information. However, these tools and most processing schemes-from charts to signal processing-are designed for vertical wells. At high angle, only inversion can separate out the conductivities of each bed. In horizontal wells, particularly at wireline time, making simplifying assumptions becomes much more difficult. Indeed, in some situations in horizontal wells, a tool may have more sensitivity to the resistivity in an adjacent bed or to invasion than to the true resistivity (Rt) in the bed it is logging. In these cases iterative forward modeling is often the only way to investigate tool sensitivity and to determine Rt.Previous work has shown it is possible to accurately model induction response in 3D formations. Recent advances in these 3D codes include building simple interfaces and, in particular, greatly improving speed. Run times of 10 to 20 seconds per logging station have been achieved on fast workstations. These advances now allow the use of 3D codes for practical log analysis in high-angle and horizontal wells, using the same ""iterative interpretation"" approach that was pioneered with ELMOD and similar 2D modeling codes.As a case study, we modeled multiarray induction response in horizontal and near-horizontal wells in a Middle East reservoir. The need is for an understanding of induction response for quick completion decisions. In the case of massive formations, the deep measurements can be used with some confidence in the center of the formation (invasion may influence only the shallower readings), with little effect of the adjacent beds on the deepest readings. However, in thin beds or those with complex geology leading to resistivity variations, the effect of adjacent beds combined with the invasion creates confusion in interpreting the logs. In this case, the sequence of the multiarray induction measurements with respect to depth of investigation does not make petrophysical sense and is considered to be a log anomaly that must be studied before a completion decision is taken.Current practice is to use lD forward modeling to illustrate the influence of the adjacent beds on the deepestmeasurements. The effects of invasion are ignored, and this simplistic approach to determining Rt is often incorrect. The 3D case study includes modeling the well path traversing facies and lithologies with the effects of invasion added to porosity and resistivity variations at a low angle. By carefully incorporating geological information, we refined the model to untangle confusing curve sequences and obtain more accurate values for Rt in individual facies. In addition, we extracted the geometrical structure of the formation layers and the invasion profile.

Barry, A., Burnett, P., Meakin, C., 1998, Geosteering Horizontal Wells in a Thin Oil Column, SPE 50072, SPE Asia Pacific Oil & Gas Conference and Exhibition, 12-14 Oct, 1998, Perth, Australia.

A multi-disciplinary team utilising state-of-the-art Logging While Drilling (LWD) technology is able to geologically "steer" horizontal wells in real-time within a thin oil column. Excellent well performances support the general validity of the geosteering approach and a static pressure survey in one of the wells verifies the steering accuracy.The Tuna field M-l reservoir in the Glippsland Basin, Bass Strait, Australia contains a 12 m oil column overlain by a large gas cap and supported by a strong aquifer in multi-darcy sands. A total of 19 wells with horizontal sections of 300 to 1050 m in length are being drilled to develop the reserves, with all wells being steered using LWD data to maintain true vertical depth (TVD) control.Reservoir simulation defines the optimal horizontal well placement as 4 m above the oil-water contact (OWC), within a TVD tolerance window of +1.5 m. Industry standard error models show that this tight geometric tolerance over the length of the wells is not possible using MWD survey data alone. Tying the MWD survey data to the known gas-oil contact (GOC) during the landing operation reduces the geometric error prior to drilling the horizontal section, while control of the geometric error during horizontal drilling is achieved using the real-time resistivity and neutron-density data.Well log data show that the entire oil column is in transition, allowing an empirical algorithm to be developed relating the resistivity response to height above OWC for a range of rock qualities. For each wellpath, TVD is determined in real-time to verify the directional survey data and adjust the well trajectory when necessary.Comprehensive pre-planning, discussion, documentation and management approval of the decision making process empowers the project team. The process steps of landing the horizontal section, well trajectory error limit management, early well total depth decision-making and external packer placement are discussed.

Bedford, J., White, J., Cuddy, S., 1997, The Empirical Investigation of Density Anisotropy in Horizontal Gas Wells, SPWLA 1997-I, SPWLA 38th annual logging symposium transactions, Jun 15-18, 1997, Houston TX.

Following the introduction of horizontal wells into Southern UK gas fields, density readings were observed to be significantly lower than those measured in nearby vertical wells. A model relying on asymmetric invasion was proposed to explain this anomaly, but further support for this approach was needed. This took the form of numerical modeling, which supported the model, and in-situ readings from around the well-bore. The overall objective was to be able to quantify and use these anomalous density readings to obtain true formation porosities. To test our model, two density tools were run sequentially in a horizontal well drilled in BP?s Newsham field. The two densities were oriented at 90 degrees to each other, one focused down and the other to the side of the borehole. Based on the modeled invasion profile, the side density was expected to measure density values similar to the offset vertical wells. The down facing densities measured relatively low density, as predicted by the model. However, the side facing density log gave far lower densities than predicted, and intermediate density tool positions confirmed that the measured density varied dramatically around the borehole. Ultrasonic borehole images showed micro-fracturing along the side of this well. It is thought that these micro-fractures are caused by loop stresses that form around horizontal wells. These fractures contribute to the very low orthogonal density values seen in the well. This innovative application of density tools demonstrated two insights into horizontal well logging. First, unusual invasion profiles can be formed in horizontal wells, by formation anisotropy, causing the density log to read an apparent too-high porosity if normal filtrate invasion is assumed. Secondly, stresses around horizontal wells cause micro-fracturing at the side of the borehole which results in real increases in density porosity.

Belfield, W. C., Sovich, J. P.,1994,Fracture Statistics from Horizontal Wellbores,SPE/CIM/CANMET international conference on recent advances in horizontal well applications, HWC94-37:

Beliveau, D., 1995, Heterogeneity, Geostatistics, Horizontal Wells, and Blackjack Poker SPE 30745, SPE Annual Technical Conference and Exhibition, 23-25 Oct, 1995, Dallas TX.

This paper presents data on more than 1,000 horizontal wells specifically comparing their hydrocarbon production performance to offsetting vertical wells. The data are striking, revealing an approximate log-normal distribution of productivity improvement factors (PIF's). This distribution is ascribed primarily to geologic heterogeneities compounded by mechanical drilling and completion effects. Horizontal wells in conventional reservoirs show a mode or “most-likely” PIF=2; a median, or “50/50,” PIF=3; and a mean, or “average,” PIF=4. Somewhat higher PIF's are observed for heavy-oil horizontal wells and horizontal wells in heavily fractured fields. The data also show an operator's “expectation” should be based on the number of wells planned, with a larger number of wells yielding a higher “average” production per well. In some cases, comparing actual production results with those predicted by the operator was possible. This also showed some rather startling results. Although our “predictive models” appear quite accurate when averaged over several wells, the error expected for any individual horizontal well is >50%. Some simple gaming examples show that an error of this size should be expected for almost any reservoir calculation (perhaps a better phrase is reservoir estimate).

Bellay, G., Al-Waheed, H., Audah, T., 1996, Cyclic Borehole Effects in Deviated Wells, SPE 36288, 7th Abu Dhabi international petroleum exhibition and conference (ADIPEC), 13-16 Oct, 1996, Abu Dhabi.

Highly deviated wellbores sometimes suffer from a cyclic variation in borehole size. Even though the caliper oscillations may be relatively small, a salty mud can combine with the periodic hole size variation to produce wireline data that has been severely compromised. Interestingly, it may be the deepest reading tool (resistivity) which suffers the largest degradation. A straight-forward solution, calibrated to specific wellbore conditions, has been developed which facilitates a much more representative formation evaluation.

Berger, P. E., Sele, R., 1998, Improving Wellbore Position Accuracy of Horizontal Wells by Using a Continuous Inclination Measurement from a near B Inclination Mwd Sensor, SPE 50378, SPE international conference on horizontal well technology, 1-4 Nov, 1998, Calgary, Alberta, Canada.

Wellbore position calculations are typically performed by measuring Azimuth and Inclination at 10 - 30 meter intervals and using interpolation techniques to determine the borehole position between the survey stations. Input parameters are, Measured Depth (MD), Azimuth and Inclination, where the latter two parameters are measured with the MWD tool in a stationary mode (non-rotating). Output parameters are the geometric coordinates; True Vertical Depth (TVD), North and East. To maximize the exposure of a production well to the reservoir, horizontal wellbores are frequently being drilled. Furthermore, to maximize the production of hydrocarbons from these wells, their relative position within the reservoir is critical. Improving the accuracy of the Inclination measurement and thus reducing the uncertainty of the calculated TVD value will increase the confidence in wellbore position. The NaviGator™* geosteering tool or the AutoTrak™* rotary steerable system are frequently used to optimize the position of horizontal wellbores within the reservoir. Both these geosteering tools use a Near Bit Inclination sensor (NBI) to help the directional driller perform directional changes smoothly and accurately. Unlike traditional directional sensors the NBI sensor is capable of accurately measuring inclination while being rotated. Consequently NBI measurements can be performed continuously during drilling. The measurements can be used to more accurately calculate the wellbore trajectory. Results in the paper demonstrate that the NBI sensor is more accurately measuring inclination than other directional sensors in a horizontal well. Also, by continuously measuring the inclination during rotation, some error sources are reduced, resulting in improved TVD accuracy.

Boonen, P., Coombes, T., Holehouse, S., Hill J., 2001, An Alternative Approach to Porosity Determination Using Lwd Shear Sonic Logs in the Dunbar Field (Uk North Sea), SPWLA 2001-MM, 42nd Annual Logging Symposium, 17-20 Jun, 2001, Houston, Texas.

Operational experience in the Dunbar field had precluded the use of real-time radioactive LWD porosity services and pipe conveyed wireline nuclear logs. Several wells were completed without porosity information. As a consequence, an alternative porosity determination methodology had to be found. A sonic Logging-While-Drilling tool was run in Dunbar wells 3/14a-D21 pilot and 3/14a-D21Z horizontal. The pilot hole had a full wireline logging suite and was cored in the principal reservoir interval. The LWD sonic log, both compressional and shear slowness, compared favourably to the wireline sonic log in the pilot hole, although minor differences were apparent in the shale sections. The slower wireline readings were attributed to formation alteration effects in the time lapse between LWD and wireline logging. Formation porosity was determined using conventional wireline density – neutron crossplot techniques, wireline sonic (Wyllie equation) and LWD sonic algorithms. These porosity results were cross-checked against the conventional overburden corrected core porosities.

A Critical Porosity algorithm was used to compute porosity from the LWD shear slowness. A porosity computed from the shear slowness is independent of the fluid in the pore space and hence provides an effective porosity similar to the density-neutron cross-plot porosity. The shear porosity agrees very well with the core porosities. In addition, the velocity ratio and Poisson's Ratio display a good lithology response whereas the main lithology breaks cannot be recognized using the gamma ray or resistivity logs.

Based on the results in the pilot hole, it was determined that Logging-While-Drilling sonic logs would be a viable alternative to wireline acoustic logging in the horizontal drain within the thick reservoir sand package. The LWD sonic provided the sole porosity measurement in the horizontal drain, augmented only by an LWD gamma ray – resistivity log.

Boonen, P., Haugland, M., Laughlin, G., 2005, Analysis of Lwd Propagation Resistivity Data in Anisotropic, Thinly-Bedded Formations Identifies Significantly More Hydrocarbons, SPE 95894, SPE Annual Technical Conference and Exhibition, 9-12 Oct, 2005, Dallas Texas.

Thinly laminated pay zones are often anisotropic. The horizontal resistivity is dominated by relatively conductive shale layers, and the vertical resistivity is dominated by relatively resistive hydrocarbon strata. When the relative inclination is low, conventional induction and Logging-While-Drilling (LWD) propagation resistivity tools only sense the horizontal resistivity and triaxial wireline measurements can be used to estimate the vertical resistivity. However, the relative inclination is often high enough to enable accurate determination of the vertical resistivity from the LWD propagation resistivity data and estimates of the structural dips. The vertical resistivity values can then be used to improve identification and quantification of productive intervals. Cases discussed in this paper demonstrate the modeling software for determining these anisotropy parameters, even in thinly bedded sequences. In practice, the results can be determined rapidly enough to affect completion decisions. A data processing procedure involving anisotropy analysis, thin-bed modeling, and shaly-sand analysis is described in the context of examples wells which penetrate thinly laminated anisotropic beds. After the modeling exercise, it was evident that the vertical resistivity was significantly higher than indicated on any of the raw resistivity curves. Two shaly sand analyses were performed, the first using the raw resistivity curves, and the second using the modeled resistivity values. A comparison of the results from both shaly sand analyses showed that significantly more hydrocarbons were identified after the modeling was done.

Bristow, J. F., 2000, Real-Time Formation Evaluation for Optimal Decison Making While Drilling: Exampled from the Southern North Sea, SPWL 2000-L, 41st SPWLA Annual Logging Symposium, 4-7 Jun, 2000, Dallas, Texas.

In recent years there has been a rapid growth in horizontal well completions driven by the need to reduce field development costs. Logging while drilling (LWD) technology and geosteering techniques have advanced to ensure high rates of success in reaching reservoir targets that are smaller and less clearly defined than those attempted previously. Three recent examples illustrate the benefits of these techniques where LWD data are acquired at the rig-site, transmitted real-time to the operator's office and interpreted by a multidisciplinary asset team who update formation models to enable optimum geosteering decisions.Prior to drilling the horizontal wells, prejob forward modeling based on offset well data and structural information from the earth model is performed to predict the LWD log responses along the planned well trajectory. While drilling, the formation model is refined to minimize spatial uncertainties within the reservoir and to provide a predictive model of the formation relative to the wellpath. This is achieved by correlating the real-time LWD logs with forward-modeled log responses. The resulting correlations constrain the position of the bit in the formation, and so apparent formation dip can be computed. Synthetic LWD logs are predicted for the projected trajectory 150 ft ahead of the bit. Uncertainties in the formation structural model are further reduced by interpreting LWD azimuthal density images retrieved between bit runs. These are processed immediately on a workstation in the operator's office and provide dip information to constrain the structural interpretation and lateral changes in stratigraphic thickness. The image data also provide facies information and in these wells help identify zones of higher permeability.Three case studies show how using geosteering based on predictive real-time modeling can help manage the risk associated with drilling horizontal wells by reducing positioning uncertainties. They also show how optimizing well placement improves well productivity.

Brown, G. A., Kennedy, B., Meling, T., 2000, Using Fibre-Optic Distributed Temperature Measurements to Provide Real-Time Reservoir Surveillance Data on Wytch Farm Field Horizontal Extended-Reach Wells, SPE-62952, 2000 SPE annual technical conference and exhibition, 1-4 Oct, 2000, Houston TX.

BP-Amoco operated Wytch Farm has installed fibre optic distributed temperature systems on 2 of their recent ERD (extended reach drilling) wells in order to provide real time reservoir surveillance. This novel new approach to reservoir monitoring has provided important information about the well and reservoir performance. This type of zonal contribution and fluid data would normally be acquired by running production logs on the end of coiled tubing at infrequent intervals, however the dual completion on Wytch Farm's M-12 well made conventional production logging impossible. Distributed temperature data has been recorded over 2 years throughout well tests and shut-ins, as well as during normal periods of production. Data analysis is performed both visually, by correlating time related thermal events observed in the well with known reservoir and production anomalies, and theoretically by comparing recorded temperature data with that predicted by thermal profiles generated using nodal analysis fluid flow and heat transfer software*. Use of this software* allows estimates of production by zone to be compared to actual recorded temperature data, enabling a variety of production scenarios to be investigated and the most likely identified. The installation of real time fibre optic distributed temperature monitoring on Wytch Farm field has enabled the asset to recognise flow behind casing and cross flow during shut-in in the M-12 well and water finger encroachment to be identified in the M-17 well. This data has provided important information about both the reservoir and well performance in real time, which would not usually have become available until later in the wells life.

Cannon, D., E., Kienitz, C., 1999, Interpretation of Asymmetrically Invaded Formations with Azimuthal and Radial Lwd Data, SPWLA 1999-G, 40th SPWLA Annual Logging Symposium, 30 May – 03 Jun, 1999, Oslo, Norway.

In permeable, dipping formations, invasion of drilling fluid is often asymmetric because of gravity slumping of the filtrate. This effect can be observed within less than an hour of the bit penetrating a highly permeable, gas-bearing formation. Accurate interpretation of log data in such environments requires a technique that accounts for both azimuthal and radial distribution of filtrate. Logging-while-drilling (LWD) measurements, when rotated through the zone of interest, offer the data necessary to evaluate such formations. The interpretation process used combines azimuthal nuclear data with azimuthal and radial resistivity data to compute accurate values of porosity, water saturation and mineralogy.First, resistivity data are inverted for Rx0 (flushed zone resistivity), Rt (true resistivity) and Di (diameter of invasion) in four directions. Next, the different values of Di are used to compute individual invasion scalars for density and neutron log data based on their radial response functions. This is possible because the resistivity measurements used are similar in radial response to the density and neutron radial responses. Then, the log data and invasion scalars are entered into a petrophysical solver for the final results. The invasion scalars assist the solver in determining the magnitude of the hydrocarbon correction required, which is especially important in gas zones. Full correction of log data provides results that are in close agreement with core data.Understanding the effects of gas in three dimensions helps explain "lazy" neutron curves. In gas zones, the density log is highly affected by varying invasion, where as the neutron has an almost constant gas effect that is relatively independent of invasion as predicted by modeling.

Carlisle, W. J., Druyff, L., Fryt, M. S., Artindale, J. S., von der Dick, H., 1992, The Bakken Formation-an Integrated Geologic Approach to Horizontal Drilling, in *Geological Studies Relevant to Horizontal Drilling--Examples from Western North America*, J. W. Schmoker, Coalson, E. B., Brown, C. A. editors, Rocky Mountain Association of Geologists Denver Colorado, 215-225.

Chace, D., Wang, J., Mirzwinski, R., Maxit, J., Trcka, D., 2000, Applications of a New Multiple Sensor Production Logging System for Horizontal and Highly Deviated Multiphase Producers, SPE-63141, 2000 SPE annual technical conference and exhibition, 1-4 Oct, 2000, Dallas TX.

This paper focuses on the first applications of an improved, second-generation multiple sensor production logging system designed for use in horizontal and highly deviated multiphase producers. The system integrates several key measurements to provide a comprehensive analysis of well performance under a variety of conditions and flow rates. An expanded and improved 2-dimensional capacitance array is used to define flow regime and measure 3-phase holdup, velocities and flow rates. A new 3-detector pulsed neutron instrument provides an independent measurement of water velocity, 3-phase holdups, and formation water saturation. Auxiliary sensors include an acoustic transducer and distributed temperature sensors useful for gas entry, liquid entry, and behind-casing channel identification. A quartz-pressure gauge measurement is recorded which is also useful in mechanistic models of multiphase flow. While a brief description of the system components will be provided in order to familiarize readers with the measurement concepts, this paper will concentrate on field examples from the Middle East that demonstrate the first use of the improved logging system in horizontal openhole multiphase producing wells. Determination of multiphase holdups, cross-wellbore velocity profiling, and production inflow profiling is demonstrated. Openhole logs are also shown, including resistivity image data, which clearly differentiate the inflow points as producing bed layers or conductive fractures.

Cheng, Y., Yan, J., Wang, G., 1996, A Comprehensive Study of Wellbore Stability in Shale Formation and Its Application to Horizontal Drilling Operations, SPE-37080, SPE international conference on horizontal well technology, 18-20 Nov, 1996, Calgary, Alberta, Canada.

Though the mechanical studies of wellbore stability in the water-sensitive shale formations have been conducted for many years, there was almost no successful example of application in drilling operations. The main reason for this is that the in-situ mechanical properties, strength and hydrated stress of shales can not be accurately determined using traditional procedures.The project focuses on studying the shale strength in different water contents and the changes of hydrated stress in different in-situ stress, hydraulic drop and classification of shales. The shale samples were obtained from 53 group in Dagang Oilfield on the basis of plenty of multidisciplinary teamwork, the procedures for the comprehensive evaluation of the various properties of the shales, such as the in-situ strength, pore pressure, Yuang's modulus are given by virtue of a series of laboratory test data, log data and drilling information. In addition, a model that can be used to calculate the borehole collapse pressure, fracture pressure and to determine the suitable density of drilling mud is developed according to the theory of elastic mechanics in porous medium and the theory of partial molar free energy. The model is superior to the models provided in the past in the accuracy of prediction because its input parameters were synthetically identified with test data, log data and drilling information, and both the influences of drilling muds on the shale properties and hydrated stress were taken into account. The model has been successfully applied to the drilling operations of the horizontal wells in Dagang Oilfield, located in east China. It is confirmed that the optimum densities of the drilling muds predicted with the model are practical, indicated by the quite stable boreholes with very low hole enlargements (less than 10%) in shale formations for the horizontal wells.

Coghill, J., Poppitt, A., Benefield, M., Ware, P., 2001, Innovative Reservoir Navigation Techniques Ensure Optimal Wellbore Placement, SPWLA 2001-GGG, 42nd Annual Logging Symposium, 17-20 Jun, 2001, Houston TX.

Horizontal drilling has become a standard method of field development over the last decade. In order to maximize recoverable reserves it is crucial that a horizontal wellbore is optimally positioned within the reservoir. Recent innovations in rotary closed loop steerable drilling technology, three dimensional (3-D) visualization and logging while drilling (LWD) sensors have been integrated into a Reservoir Navigation Service focussing on maximizing the value recovered from each geosteered well. Industry standard geosteering techniques based on layer cake resistivity response modelling 1'2'3 have proven to be inadequate for the complex, faulted

geology of the North Sea. To effectively plan and geosteer horizontal wells in these fields a range of innovative techniques have been devised to achieve optimal wellbore placement. In this paper we review a valuable vizualization tool available to the reservoir navigation team and two case histories illustrating the key benefits of developing project specific solutions as summarised below. Integration of the earth model into the well-planning and wellsite geosteering process will significantly reduced both the time and cost involved in planning the well. Wellsite 3-D visualization can assist in real-time wellbore placement to ensure that the goals of the project are realised. 4 Near bit LWD 5 sensors were used to characterize formation dip and ensure effective navigation within the reservoir utilizing the improved steerability recently possible through Rotary Closed Loop drilling systems 6,7,8° Petrophysical geosteering techniques were pioneered for a heterolithic low resistivity reservoir. A real-time evaluation of net to gross combined with a geosteering decision matrix was used to optimize the exposure of the horizontal wellbore to better quality reservoir. These case histories are used to demonstrate how geosteering in complex North Sea reservoirs requires field specific techniques to be developed for both the planning and successful execution of a project.

Cowan, P., Wright, G., 1997, Investigations into Anomalous Responses of Gamma Density and Neutron Porosity Tools in Horizontal Gas Wells, SPWLA 1997-H, SPWLA 38th annual logging symposium transactions, 15-18 Jun, 1997, Houston TX.

Observations in horizontal wells in Southern North Sea gas fields (Cuddy 1994) show that gamma density and neutron porosity tools give anomalous responses compared to vertical wells in the same formation. One hypothesis given for these observations was nonuniform invasion around the horizontal borehole due to different horizontal and vertical permeabilities and fractures at the sides of the borehole caused by stress overburden. Several companies were interested in understanding and quantifying these observations, including Amoco, BP Exploration, Saga and Statoil who went on to sponsor a programme of work to investigate the hypothesis of non-uniform invasion. This was carried out by modelling the responses of laboratory gamma density and neutron porosity tools with the Monte Carlo code MCBEND. The Monte Carlo method is now a well established technique for predicting the response of nuclear logging tools. These calculations include explicit representation of the geometry, source and materials of the problem and of the physics of particle transport. They are thus numerical experiments, equivalent to a range of well controlled measurements in which all of the relevant parameters are known. This paper presents the results of these investigations. The hypothesis of a non-uniform invasion profile around the horizontal borehole does explain the observed density tool response. As a side benefit of this work, information on the depth of investigation of the tools and sensitivity of the tools to different formation regions were obtained. These results highlighted the differences between the gamma density and neutron porosity tool and the difficulty in determining porosity in gas wells with invasion. The results showed that logs need to be corrected or compensated for this gas effect Therefore a number of methods of determining formation porosity in horizontal gas wells were studied as part of this project. These methods included the square root method and an iterative method which is used in practice. This project helped to identify the methods which give the most accurate determination of porosity in horizontal gas wells.

Cunningham, A. B., Jay, K.L., Opstad, E.A., 1990, Applications of Mwd Technology in Nonconventional Wells, Prudhoe Bay, North Slope Alaska, SPWLA 1990-D, 31th SPWLA Annual Logging Symposium, 24–27 Jun, 1990, Lafayette, Louisiana.

As production from the Prudhoe Bay Field declines, greater emphasis is being placed upon nonconventional drilling as one method of increasing production rates and reserves. Identification of lithologic and fluid boundaries through the utilization of real-time and recorded Measurement-While-Drilling (MWD) technology enables optimum placement and completion of high angle, horizontal and inverted high angle wells. The use of MWD formation evaluation techniques has reduced nonconventional logging costs and allowed acquisition of data where adverse open hole conditions precluded the use of drillpipe-conveyed logging systems. Real-time gamma ray and resistivity data are employed while drilling to continually adjust build rates leading to precise stratigraphic placement of the nonconventional wellbore. Recorded measurements, including neutron and density, are made both while drilling (MWD) and after drilling (MAD) to identify gas,

light oil, heavy oil/tar, and water. Case studies of a number of selected wells are used to illustrate techniques and approaches used to identify lithologic and fluid boundaries. Overlay interpretation techniques which utilize resistivity and neutron profile models to account for changes in invasion between MWD and MAD runs are successfully used to identify fluid contacts. Repeat MAD logs are employed when sensors are placed far above the bit as is frequently required by the BHA designs typically used in nonconventional drilling. Invasion profiles are quantified using neutron, resistivity and formation exposure time data from tandem tool runs in the Ivishak Formation. Conventional models describing invasion profiles do not adequately explain all the resistivity and neutron profile changes seen in Prudhoe Bay nonconventional wells. In particular, gravity effects on oil based mud create changes in neutron porosity through time which are opposite to those normally seen or expected in the gas. Nonconventional drilling creates a dynamic interpretation environment influenced by variations in hole angle, mud type, drilling rate, sensor placement and formation exposure time. With flexible and innovative interpretation techniques, current MWD technology can not only provide information essential to accurate well placement, but can also offer formation evaluation opportunities unavailable from traditional wireline approaches.

Eaton, G., Blasdale, T., Heidenreich, K., 2005, Combining Slimhole Rotary Steerable Technology with Real-Time Geosteering to Rejuvenate a Mature North Sea Field, SPE 96801, Offshore Europe, 6-9 Sep, 2005, Aberdeen, UK.

More than 70% of the oil produced today comes from brownfield environments such as the North Sea. Increasingly complex geological targets demand a more sophisticated and reliable drilling system. The combination of a slimhole rotary steerable system (RSS) and a leading-edge geosteering solution can help operators optimize their well placement. In addition, a Web-based, real-time monitoring and data delivery system can produce the most accurate information possible for decision makers onshore. In this way, an integrated team can use modern logging-while-drilling (LWD) tools to make real-time well path corrections in a challenging environment. This paper presents a case study in which real-time decisions placed a well successfully and also increased production levels greater than the estimates. The drilling system components responsible for the success were an advanced slimhole RSS, a leading-edge real-time formation evaluation tool, and a Web-based real-time monitoring and data delivery system.

Edwards, J., 2000, Geosteering Examples Using Modeled 2-Mhz Lwd Response in the Presence of Anisotropy, SPWLA 2000-N, 41st SPWLA Annual Logging Symposium, 4-7 Jun, 2000, Dallas TX.

Resistivity modeling of logging-while-drilling (LWD) response from wireline logs can determine whether the well geosteering requirement is feasible. However, in the typical situation, the wireline logs are from vertical appraisal wells, and the geosteering wells are horizontal; if the formation is anisotropic, the prejob modeling will not account for the bed perpendicular resistivity. The presence of anisotropy can be unknown until the first LWD logs are run, when real-time model revision then becomes imperative to avoid compromising the well placement.The first example in the paper is geosteering for saturation in an oil rim. The reservoir development plan required the drain-holes to be 4 m -f-I- 1.5 m above OWC. Error models showed that because of the lateral displacement, this geometric tolerance was impossible using measurement-while-drilling surveys alone. Vertical logs showed the oil column was in transition, with capillary pressures decreasing the water saturation above the free-fluid level. An empirical algorithm was developed for this reservoir that related resistivity to the height above the OWC. Resistivity-derived height above contact was used to keep the drain-hole in the vertical window. After the first well, it was apparent that using the algorithm would require extracting the bed parallel resistivity from the LWD logs. This was done using the separation between phase and attenuation resistivity of the 2-MHz logs, while also accounting for the effect of adjacent beds in this dipping, thinly bedded clastic sequence. Resistivity anisotropy in this case was due to variations in grain size within the reservoir.The second example demonstrates geosteering around existing completions. The reservoir development required that new horizontal wells cross existing horizontal wells. Potential coning from fluid contacts required these crossings to be within a vertical separation of 2 m. Since this clearance is smaller than the closest approach possible using geometric collision avoidance, geosteering was used as the collision avoidance technique. The well crossings were made by geosteering in the formation layer either over or under the

existing well and required a detailed resistivity model of the stratigraphic sequence, which was used to establish the relative positions of the existing and new well-bores. This model was made using wireline logs from vertical wells and LWD logs from landing sections. The anisotropy apparent on the 2-MHz LWD logs was due to thin siderite layers. Both examples resulted in successful well placements, with production matching the reservoir simulation forecasts.

El Rabaa, W., 1989, Experimental Study of Hydraulic Fracture Geometry Initiated from Horizontal Wells, SPE 19720, SPE Annual Technical Conference and Exhibition, 8-11 Oct, 1989, San Antonio, Texas.

Horizontal wells drilled in tight formations are likely to be stimulated by acidizing and/or propped fracturing to increase productivity. propped fracturing to increase productivity. Normally, to control the placement of induced fractures in these wells, they are completed for later stimulation, i.e., cement cased and perforated. Unlike vertical well fracturing, fractures perforated. Unlike vertical well fracturing, fractures in horizontal wells can be induced along, or inclined to, or crossing the horizontal section. This orientation depends on deviation of the horizontal section from the minimum stress direction. An experimental study of fracture geometry from horizontal wells at various well azimuth deviations was conducted. Experiments were performed by applying triaxial loading conditions to rock blocks 6 x 12 x 18 in. surrounding cased and perforated boreholes. The borehole directions varied from 0 to 90 degrees from the applied minimum stress. Also, length of perforated interval was the second variable parameter in this study. After each experiment, rock blocks were sawed to observe the shape of induced fracture. The study showed that fracture geometry near the horizontal well is controlled by well deviation and length of perforated interval. From a stimulation viewpoint, perforated interval. From a stimulation viewpoint, the combined effects of these two parameters, if not investigated beforehand, may cause critical problems during fracturing. Laboratory observations problems during fracturing. Laboratory observations indicated the following stimulation related problems: problems: A. Creation of multiple fractures from the same perforated interval. B. Created fractures are nonplanar, with rough walls. C. Communication of fluid between the perforated section and fracture can occur through small channels. D. Interference between fractures conducted from separate perforated interval. Based on this study several recommendations are presented to help eliminate some of these presented to help eliminate some of these stimulation related problems.

Elkington, P. A. S., Spencer, M. C., Spratt, D. L.,2000,An Openhole Memory-Logging System for High-Angle Wells and Bad Hole Condition,SPE 87403,SPE Reservoir Evaluation & Engineering, **Volume 7**,Number 1: p. 33-39,February 2004.

A mechanism for conveying logging tools inside drillpipe has been developed that reduces the risk and cost of acquiring openhole formation evaluation data in high-angle wells and bad hole conditions. The measurement string is housed inside drillpipe, where it is protected while running in, and pumped into open hole close to final depth. Wireline tools are used for data-quality reasons, but the wireline has been eliminated, giving time, access, and well-control advantages relative to wireline pipe-conveyed logging (PCL). It is an alternative to the formation evaluation element of logging while drilling (FE-LWD), where steering decisions do not rely on real-time petrophysical analysis, particularly when the risk to the bottomhole assembly (BHA) is high. The system's ability to acquire data while conditioning the hole contributes to its efficiency and is advantageous in bad hole conditions. A 1.4-km horizontal test loop was constructed to help develop and prove the tool deployment and signaling mechanism. Insights gained during this process resulted in the development of novel payload delivery seals - key components in the system. Formation evaluation data have been acquired in 220 wells; they include horizontal wells for which other logging solutions are unattractive for reasons of accessibility and/or cost. Knowledge gained from the interpretation of these data sets has influenced completions in some wellbores and guided remedial action in others.

Elkington, P. A. S., 2000, The Role of Openhole Memory-Logging and Wireless-Conveyance Systems in the Evaluation of Hoorizontal Wells, SPE 65461, SPE/CIM International Conference on Horizontal Wells, 6-8- Nov, 2000, Calgary, Alberta, Canada

Open hole formation evaluation logs are not run where the perceived benefits are marginal. In many horizontal wells, the benefits are not fully assessed because cost and/or access difficulties override other considerations. In these cases, sub-seismic lateral variations in reservoir properties can only be inferred - they are rarely measured. Small diameter battery-powered logging tools operating without a wireline have collected high quality data in a broad range of high angle situations. Wireless conveyance techniques are faster and safer than wireline pipe conveyed logging, and have cost, access and data quality benefits over logging while drilling (LWD). Wireless tools have been conveyed in and on drill pipe, on coiled tubing without an electric line, and as part of a modified casing string. The tools can be deployed safely in underbalanced wells.

Ellis, D. V., Chiaramonte, J.M.,2000,Interpreting Neutron Logs in Horizontal Wells - a Forward Modeling Tutorial,The Log Analyst, **Vol. 41**,No. 1: p. 23-32,January - February 2000.

Evans, L. W., Thorn, D., Dunn, T. L., 1996, Formation Microimager, Microscanner, and Core Characterization of Natural Fractures in a Horizontal Well in the Upper Almond Bar Sand, Echo Springs Field, Wyoming, in *Stratigraphic Analysis Utilizing Advanced Geophysical, Wireline, and Borehole Technology for Petroleum Exploration and Production*, J. A. Pacht, Sheriff, R. E., Perkins, B. F. editors, SEPM Society of Sedimentary Geology Foundation Gulf Coast Section, 89-95.

Fair, P. S., Kikani, K., White, C.D.,1999,Modeling High-Angle Wells in Laminated Pay Reservoirs,SPE 54656,SPE Reservoir Evaluation & Engineering, **Volume 2**,Number 1: p. 46-52,February 1999.

Productivity improvement and acceleration projects have gained substantially from the success of horizontal well drilling technology. Successful placement of near-horizontal wells in difficult reservoir configurations has become routine. However, not all reservoir situations are amenable to horizontal drilling. Specifically, laminated reservoirs such as thinly bedded turbidites in the Gulf of Mexico (GOM) have been perceived as poor targets. Potentially large reserves are locked in these reservoirs. These laminated turbidite systems have near-zero vertical permeability at the Bouma sequence1 scale and extremely small kv/kh ratios k v/kh?0 at the full field, reservoir simulation grid-block scale. In general, a low well count helps minimize development costs. Highly deviated wells $(80{^{\circ}}\leq \theta {w} < 90{^{\circ}})$ cutting the entire sand package may make it possible to obtain both high field production rates and low well counts. Slanted wells have been known to improve productivity of wells with kv /kh?0. However, the slanted well model given by Cinco 2,3 does not predict any improvement in well productivity for such wells. This apparent paradox is reconciled in this paper. Bed thickness, well diameter, and well angle determine the geometric pseudoskin of these thin-bedded sequences. For wells that are nearly horizontal, a simple technique is introduced to calculate the geometric skin without complex modeling. The range of validity of this approximation was determined by comparison with fine-grid simulations. This paper provides a method to simulate a highly deviated well in a thin-bedded reservoir at field scale without the use of fine grids or local grid coarsening. These inflow relationships have been used to construct the well models for simulations of GOM reservoirs. A field example is presented with guidelines to determine the correct well kh as validated by a grid sensitivity study.

Fakolujo, K. M., Simon, R.D.K., Nwosu, C.J., 2004, Horizontal Short Radius Sidetrack Campaign Project in Spdc-East Nigeria: Petrophysical Challenges, SPWLA 2004-Q, 45th SPWLA Annual Logging Symposium, 6-9 Jun, 2004, Noordwijk, The Netherlands.

Horizontal well technology has provided the oil industry a new method of optimising production from brown fields, which would otherwise have been uneconomical to further develop. These fields are characterised by complex fluid displacement behaviours, gas/water coning, declining oil production, differential flushing e.t.c. In order to further develop these fields, with its associated challenges, the land asset team in conjunction with the well engineering department of SPDC-East in Nigeria recently embarked on the drilling of horizontal short radius sidetrack wells from existing wells. The campaign, at maturation was forecasted to add some 32Mbopd and develop 53MMstb reserve through construction of wells that are capable of delivering over 2,000bopd, at maximum of $1.5Mln. Given the anticipated scope of work, a campaign approach in two phases

was endorsed. To date, a total of 10 wells (in Dalume & Boloma North fields) have been drilled. Several challenges were encountered during the campaign. These include present fluid contacts delineation in producing brown field reservoirs, data acquisition in a high dogleg severity wells (17 ? 35deg/100ft), depth tie-in/control at sidetrack point and accurate well placement in thin oil columns. Some of these challenges were resolved by acquiring cased hole fluid contact monitoring data (Schlumberger?s RST) prior to start of campaign and taking gyro surveys with proper well correlations at sidetrack point. The application of the MWD tool response modelling module in LOGIC also helped in proper ?Petro?steering and post-mortem of the drilling operations. The result of this campaign show that about 20,000bopd tested production potential have been added with over 20MM stb developed in the project first phase. During the campaign, a significant reduction in cost of well delivery from $2.6Mln (first well) to some $1.5Mln average in the last four wells on the sequence was achieved. Some innovative completion methods were implemented primarily to reduce cost and improve well delivery. For instance, a combination of ESS and ECP was deployed for the first time in medium radius wells worldwide. This paper focuses on the petrophysical challenges involved in the planning and execution of the wells using shortmedium radius technology. It emphasizes data acquisition issues in high dogleg wells, anomalous fluid contacts movements in brown fields and the use of resistivity tool response modelling in placement of horizontal wells in thin oil columns. The report presents the technical analysis of the challenges and results of the petrophysics input and contribution to the short radius sidetrack campaign in Shell Petroleum Development Company Limited, Nigeria. Horizontal well technology has provided the oil industry a new method of optimising production from brown fields, which would otherwise have been uneconomical to further develop. These fields are characterised by complex fluid displacement behaviours, gas/water coning, declining oil production, differential flushing e.t.c. In order to further develop these fields, with its associated challenges, the land asset team in conjunction with the well engineering department of SPDC-East in Nigeria recently embarked on the drilling of horizontal short radius sidetrack wells from existing wells. The campaign, at maturation was forecasted to add some 32Mbopd and develop 53MMstb reserve through construction of wells that are capable of delivering over 2,000bopd, at maximum of $1.5Mln. Given the anticipated scope of work, a campaign approach in two phases was endorsed. To date, a total of 10 wells (in Dalume & Boloma North fields) have been drilled. Several challenges were encountered during the campaign. These include present fluid contacts delineation in producing brown field reservoirs, data acquisition in a high dogleg severity wells (17 ? 35deg/100ft), depth tie-in/control at sidetrack point and accurate well placement in thin oil columns. Some of these challenges were resolved by acquiring cased hole fluid contact monitoring data (Schlumberger?s RST) prior to start of campaign and taking gyro surveys with proper well correlations at sidetrack point. The application of the MWD tool response modelling module in LOGIC also helped in proper ?Petro?steering and post-mortem of the drilling operations. The result of this campaign show that about 20,000bopd tested production potential have been added with over 20MM stb developed in the project first phase. During the campaign, a significant reduction in cost of well delivery from $2.6Mln (first well) to some $1.5Mln average in the last four wells on the sequence was achieved. Some innovative completion methods were implemented primarily to reduce cost and improve well delivery. For instance, a combination of ESS and ECP was deployed for the first time in medium radius wells worldwide. This paper focuses on the petrophysical challenges involved in the planning and execution of the wells using shortmedium radius technology. It emphasizes data acquisition issues in high dogleg wells, anomalous fluid contacts movements in brown fields and the use of resistivity tool response modelling in placement of horizontal wells in thin oil columns. The report presents the technical analysis of the challenges and results of the petrophysics input and contribution to the short radius sidetrack campaign in Shell Petroleum Development Company Limited, Nigeria.

Fang, s., et al., 2005, Design of a New Ultra-Deep Resistivity Tool for Real-Time Geosteering Applications, paper 37, OMC 2005, 2005,

Farruggio, G., Rasmus, J., Low, S., Ingold, C., Jackson, K., Curtis, C., 1999, Innovative Use of Bhss and Lwd Measurements to Optimize Placement of Horizontal Laterals, SPE/IADC-52825, SPE/IADC Drilling Conference, 9-11 Mar, 1999, Amsterdam, Netherlands.

More than 50 horizontal laterals averaging 4600 feet in length have been drilled in a shallow, heavy oil reservoir in eastern Venezuela. Precise navigation through the formations was necessary to optimize placement of the lateral drainholes and maximize the percentage of reservoir sand exposed. To meet this requirement, an optimized bottom hole assembly (BHA) design and logging while drilling (LWD) interpretation technique were developed based on field experience. Measurement while drilling (MWD) continuous directional measurements were used to steer the well through the reservoir, along a specific well path chosen from three-dimensional (3D) seismic that covers the field area. The LWD azimuthal and bit electrode measurements were integrated with the 3D seismic to allow an interactive interpretation of the stratal boundaries present within the reservoir which resulted in continual refinements to the planned well path. Using the information derived from the LWD azimuthal and bit electrode measurements, the location of shale stringers, bed boundaries, and pay sand relative to the BHA could be determined and the well then steered in the appropriate direction to maintain an optimum position within the oil reservoir. As a result, the number of sidetracks was reduced and the percent sand encountered increased. The longest horizontal lateral in Venezuela was also drilled and completed as part of this project.

Fearn, P. C. W. P.,1997,Logging Horizontal Wells; Using New Technology to Improve Efficiency and Reduce Costs,Offshore Mediterranean conference (OMC97),

Follows, E.,1997,Integration of Inclined Pilot Hole Core with Horizontal Image Logs to Appraise an Aeolian Reservoir, Auk Field, Central North Sea,Petroleum Geoscience, no. 1: 43-56.,

Frenkel, M. A., Geldmacher, I.M., Georgi, D.T., Mezzatesta, A.G., Rabinovich, M.B., Tabarovsky, L.A., Meyer, W.H., and Fidan. M., 2000, Application of Array Resistivity Measurements in Horizontal Wells, SPE 62913, SPE Annual Technical Conference and Exhibition, 1-4 Oct, 2000, Dallas, Texas.

When interpreting array resistivity measurements in horizontal wells, the objectives are quite different from traditional data interpretation in vertical or near vertical boreholes. While the emphasis for the latter is put on resolving the invasion profile and “true” formation resistivities, the former measurements are aimed at the identification of any nearby geometry, e.g., cap rock or oil-water contacts in the vicinity of the wellbore. In order to accomplish this, new algorithms have been developed ranging from real-time “geosteering” applications to sophisticated inversion-based processing. Early resistivity tools were complex devices that utilized bucking coils and guard electrodes to “focus” the measurement onto a particular region in the formation, for example, shallow and/or deep. These analog focusing methods were designed for and worked well in quasi-horizontally layered formations penetrated by a near vertical well. In the last decade array tools offering a multitude of electrode or coil arrangements have been introduced. By combining data from different electrodes or receiver coils and transmitters, it is possible to mathematically focus in on a particular formation area, such as illuminating the invasion profile and obtaining a better estimate of the formation resistivity. In horizontal and highly deviated wells, the array data still can be used to characterize the invaded zone, but, more importantly, the array data can be used to probe the layered structure above and below the well. Interpreting the response of today's array resistivity tools in these situations is critical to the drilling and formation evaluation process. In horizontal wells, the response of resistivity tools in even a simple layered formation is complicated and may differ significantly from our vertical well-based intuition. However, forward modeling of the expected formation earth model and inversion techniques, from the simplest to the most sophisticated approach, can assist both the driller and the petrophysicist in extracting required information. In this paper we demonstrate the use and effectiveness of the array resistivity tools in horizontal and near-horizontal wells. We focus on the use of the array data collected by the logging-while-drilling (LWD) Multiple Propagation Resistivity (MPR) tool as well as the wireline or pipe-conveyed driven High-Definition Induction Log (HDIL) and High-Definition Lateral Log (HDLL). For each tool the interpretation process is illustrated with field examples.

Frenkel, M. A., Zhou, Z., 2000, Improved Estimation of Hydrocarbon Reserves Using High-Definition Lateral Log Array Data in Vertical and Highly Deviated Wells, SPE 62912 SPE Annual Technical Conference and Exhibition, 1-4 Oct, 2000, Dallas, Texas.

The conventional dual laterolog (DLL) instrument, providing valuable information on formation resistivities, has been used in the petroleum industry for many years. However, in many situations, physical limitations of the DLL (e.g., limited vertical resolution, poor radial resolution in the presence of deep invasion, incorrect readings due to the Groningen effect, artifacts occurring in deviated wells) do not allow the interpreter to obtain the required information. Moreover, DLL data interpretation is normally accomplished on a level-by-level basis (1-D), which may result in overlooking hydrocarbon-bearing formations, underestimation of reserves, and low confidence in the interpretation results. Currently, when oil production originates in thinly laminated reservoirs penetrated by vertical or highly deviated wells, the DLL tool alone cannot satisfy industry requirements for accurately predicting formation resistivity. The new High-Definition Lateral Log (HDLL) tool was developed to provide high-resolution array resistivity measurements and overcome most of these shortcomings. The HDLL array tool performs a detailed radial sounding of the formation to evaluate the drilling fluid invasion profile. The tool provides a high vertical resolution detecting thin beds up to a 9-in. thickness. The data does not suffer from the Groningen effect and borehole dip artifacts. The resistivity image of the formation around the borehole, delivered at the well site, provides information necessary to delineate permeable zones and supports immediate operational decisions. Application of 2-D/3-D inversion-based interpretation allows the interpreter to recover the true formation resistivity and thus more accurately delineate and estimate the hydrocarbons. The scope of the paper is to briefly introduce the HDLL technology and present quantitative results of petrophysical interpretations derived by the application of conventional and array-type resistivity measurements. Two case studies for vertical and highly deviated wells from Oman and the North Sea demonstrate the added value provided by the HDLL technology. In the presented cases, HDLL-based interpretations show not only improved delineation of the known reservoirs but also extra pay intervals overlooked by DLL-based interpretations. The hydrocarbon saturation derived with the application of HDLL data is higher than the hydrocarbon saturation derived by the application of the conventional petrophysical interpretation. Use of the entire data suite of array data provides a much higher level of confidence in the presented hydrocarbon estimates.

Frenkel, M. A., Nuic, I., Walker, M.J., Wolters, F.L., 2004, Integration of Lwd and Wireline Array Technologies to Improve Estimation of Hydrocarbon Reserves, SPE 88638 SPE Asia Pacific Oil and Gas Conference and Exhibition, 18-20 Oct 2004, Perth, Australia.

This paper presents a new method for determining formation resistivity via sequential interpretation of the LWD and Wireline (WL) resistivity logs. The LWD logs can be used to determine the Rt, but they may not contain enough information to accurately determine parameters of invaded zones. The inversion-based interpretation of the WL Array resistivity logs provides a direct way of determining the hydrocarbon-bearing formation model. However, interpretation of WL data may be unstable and provide an incorrect equivalent solution due to a strong non-uniqueness of the inverse problem. To find the true model from an unlimited number of equivalent solutions, we propose a stable method that leads to a gradual increase of the formation model complexity.

The major steps are:

Estimation of Rt using deep-reading LWD data inversion.

Estimation of Rxo using an Rxo WL log.

Estimation of Lxo using WL data inversion.

Simultaneous corrections of the final model parameters using WL data inversion.

To establish the effectiveness of our method, we first successfully tested it on 2-D and 3-D benchmark models. To examine the practical validity of the method, we applied it to LWD induction data and the Array Lateral Log WL data acquired in a salt-saturated mud environment in a deviated well located in the South China Sea. Our objective was accurate determination of hydrocarbon saturations. Application of our method allowed us to accurately determine the formation resistivity and translate it directly to accurate Sw estimates. We demonstrate that the suggested method

provides a lower Sw saturation than the sole WL data interpretation.

Fung, L. S. K., Wan, R. G., Rodriguez, H., Bellorin, R. S., Zerpa, L.,1996,An Advanced Elasto-Plastic Model for Borehole Stability Analysis of Horizontal Wells in Unconsolidated Formation,CIM Petroleum Society 47th annual technical meeting, paper 96-58:

Fung, L. S. K., Wan, R.G., Rodriguez, H., Bellorin, R.S., Zerpa, L.,2000,An Advanced Elasto-Plastic Model for Borehole Stability Analysis of Horizontal Wells in Unconsolidated Formation,Journal of Canadian Petroleum Technology, **Vol. 38**,No. 12: p. 41-48,

Gianzero, S., Chemali, R., Su S. M., 1989, Induction, Resistivity and Mwd Tools in Horizontal Wells, SPWLA 1989-N, 30th Annual Logging Symposium, 11-14 Jun, 1989, Denver, Colorado.

Conventional induction and focused resistivity tools are designed to measure resistivity from a vertical borehole surrounded by a cylindrically invaded zone while minimizing the signal contribution from adjacent horizontal beds. In recent years our understanding of these devices was extended to include beds exhibiting a large dip relative to the borehole as in the case of a highly deviated well. We shall investigate the applicability of induction and resistivity devices to horizontal wells, where the borehole runs parallel to the bed boundaries. The presence of the borehole may be simply ignored for induction sondes and the tool response is computed via an analytic solution. Because of the relative simplicity of the induction solution, the log response is computed for entire trajectories for the more common radii of curvature used in the drilling process. On the other hand, for focused resistivity devices such as the dual laterolog or the MWD toroid sonde the borehole is an essential part of the problem. The tool response is evaluated using a numerical solution to simulate accurately the complex physical situation. The modeling results for the resistivity devices indicate that the measurement is more sensitive to conductive than to resistive shoulder beds. Typically, for the MWD sonde fifty percent of the resistivity signal comes from the adjacent conductive bed when it is half a foot away from the approaching borehole wall. A similar sensitivity to a resistive adjacent bed is not attained until the borehole has actually penetrated the bed. The reverse physical situation is evidenced with induction devices; resistive adjacent beds are more readily detected than conductive adjacent beds.

Gillen, K. P., 1998, Paleomagnetic Orientation of Fractures in Cores from Southwestern Manitoba for Horizontal Well Planning, in *8th International Williston Basin Symposium Proceedings*, J. E. Christoper, Gilboy, C. F., Paterson, D. F., Bend, S. L. editors, Saskatchewan Geological Society Special Publication, **No. 13:** 202-208.

Gravem, T., Halvorsen, C., Normann, H.P., Buysch, A., Daykin, C., Kroken, A., 2005, Lwd Pressure and Mobility Measurements in Challenging Environments, SPWLA 2005-J, 46th SPWLA Annual Logging Symposium, 26-29 Jun, 2005, New Orleans, Louisiana.

Formation pressure and mobility testing while drilling has over the last two years evolved from being a newcomer to a mature member of the Logging While Drilling (LWD) technology family. Formation pressure data have always been one of the main parameters in reservoir management. The introduction of a reliable LWD formation pressure tester which allows acquiring these data while drilling has opened up a number of new applications. Traditionally, these data have been acquired with wireline formation testers, upon reaching section or well TD. In high angle wells this is a time-consuming operation, as the tools have to be conveyed by drill-pipe. Apart from the traditional applications of such data for gradient and fluid contact determination, real-time knowledge of pore pressure ultimately allow to optimize ECD management, increase ROP, and improve safety but also assess reservoir connectivity, optimize casing plans, and help in geosteering. The main challenges associated with acquiring formation pressure in real-time while drilling and how these challenges have been overcome will be discussed. The paper uses several cas histories in a wide range of hole sizes (8 ½ " - 13 ½ ") performed on offshore fields in the Norwegian Continental Shelf to review the major benefits acquiring and utilizing these data while drilling, considering different field specific applications. Having the formation pressure data available when drilling is advantageous to the petrophysicist, reservoir engineer and the drilling engineer. The paper discusses in detail the benefits of these data to the different disciplines and also addresses the effects on overall safety and cost savings. In tight formations, pressure measurements may be affected by supercharging, leading to data unsuitable for gradient work or fluid contact identification. When acquiring pressure data with wireline tools several days after the formation has been drilled, one can only assume that there is little influence from super-charging. However, with this LWD tool, time lapse pressure measurements are now possible in suspect zones, which are readily identifiable by the mobility values derived in real-time. Thus, the same formation can be tested minutes after having been drilled and then again when the BHA is being pulled, be it for a bit change or upon reaching section TD. The paper illustrates the progress that has been made in the understanding of this phenomenon with the help of time lapse pressure data.

Greiss, R. M., Webb, C., White, J., McDonald, B., Flanagan, K., Rodriguez, J., Scholey, H., 2003, Real-Time Density and Gamma Ray Images Acquired While Drilling Help to Position Horizontal Wells in a Structurally Complex North Sea Field, SPWLA 2003-Z, 44th SPWLA Annual Logging Symposium, 22-25 Jun, 2003, Galveston, Texas.

Newly developed logging-while-drilling (LWD) real-time borehole imaging technology brings value to geosteering and optimizing well placement within the North Sea. This new technology aids in targeting the increasingly smaller geological structures that are critical to the continuing economic success of smaller oil and gas fields but previously were very costly to pursue. Improved data telemetry rates while drilling have enhanced and enabled real-time images to match the quality of those stored in the memory of the tool. Real-time images are now available from density, gamma ray and resistivity sensors enabling images to be obtained in all drilling fluid environments.. The real-time structural information provided by these images in conjunction with other real-time LWD petrophysical logs provides a close-to-the-bit visualization for in-time geosteering decisions. By capturing a more detailed analysis of the formation, structure and reservoir geometry, we have a greater ability to optimize well placement and reservoir extent.

Gruber, N. G., Gardner, R., Bujnowicz, R., 1995, The Role of Laboratory Analysis in Horizontal Well Evaluation, CIM 95-18, CIM Petroleum Society 46th Annual Technical Meeting,

Guzman-Garcia, A. G., 2002, Analysis of Lwd and Wireline Logs in Highly Deviated Boreholes Penetrating Deepwater Turbidites: Anisotropy, Polarization Horns, and Net-Sand Derivation, SPWLA 2002-U, 43rd SPWLA Annual Logging Symposium, 2-5 Jun, 2002., Oiso, Japan.

This article documents the petrophysical analysis of two highly deviated wells in deepwater turbidite formations. LWD and wireline logs are used to estimate net-to-gross, porosity, and hydro- carbon saturation. The reservoirs consist of a series of stacked, deepwater turbidite deposits in confined channel complexes penetrated by several bore- holes. Well A consists of a pilot borehole and a horizontal sidetrack. Well B consists of a main borehole, a pilot borehole, and a horizontal, sinu- soid-shaped borehole that penetrates several reser- voirs separated by two faults. LWD resistivity logs acquired with two differ- ent 2-MHz instruments have been checked for ex- traneous responses resulting from the complicated geometry of the boreholes. Deepwater turbidite de- posits are electrically anisotropic because of thin sand-shale laminations. Such anisotropy affects the resistivities derived from the phase and attenuation signals of the LWD measurement. The LWD resis- tivity response is distorted by the relative dip angle between the formation and the borehole. Polariza- tion horns, the large peaks observed in resistivity logs, also originate at steeply dipping bed bounda- ries. The ratio between the horizontal and vertical resistivities of the formation, combined with po- larization horns, complicates the estimation of hy- drocarbon reserves. Resistivity-tool modeling has shown that for dip angles greater that 60 degrees, phase-shift resistivity depends more on the vertical resistivity than attenuation resistivity. This results in separation of the phase-shift and attenuation re- sistivity curves. The curve separation can then be used to derive estimates of horizontal and vertical resistivities (Rh and Rv) of the formation. In well A, computer modeling was done to de- rive Rh and Rv, which were in turn used to estimate a true resistivity (Rt) of the formation. A compari- son is presented on the evaluation of hydrocarbon reserves based on one of the phase resistivity curves and the modeled Rt. In well B, a comparison of net/gross derived as a function of true-vertical depth (TVD) versus true-vertical thickness (TVT) shows that TVT provides a more accurate repre- sentation of net/gross in highly deviated wells.

Hakvoort, R. G., Fabris, A., Frenkel, M.A., Koelman, J.M.V.A., Loermans, A.M., 1998, Field Measurements and Inversion Results of the High Definition Lateral Log, SPWLA 1998-C, 39th SPWLA Annual Logging Symposium, 26-29 May, 1998, Keystone, Colorado.

The High-Definition Lateral Log (HDLL) tool is a type of a Multi-Electrode Resistivity Tool (MERT). It is a new tool that has been developed in a joint project between WALS (Western Atlas Logging Services) and Shell. The tool was developed to address shortcomings with conventional dual laterolog (DLL) technology (restricted vertical resolution, artefacts in deviated boreholes), The new tool has a single current-injection electrode and 18 potential measurement electrodes at various distances from the injection electrode.The tool measures absolute potentials and first differences (potential difference between two neighbouring electrodes). The raw responses are combined in such a way as to produce a shallow-, a medium-, and a deep-reading synthetically focussed curve at the well-site. In addition, inversion is given as a postprocessing HDLL service. The inversion method is based on a direct inversion of the raw measured data, both in 2D (layered formation, including effects from borehole and invaded zone) and in 3D (layered, dipping formation, including effects from deviating borehole and invaded zone).In this paper, two case studies are discussed. The first one is a vertical well in a formation that includes many thin layers. The second is a highly deviated well. For both cases, the well-site deliverables and the inversion results are shown. A comparison with DLL measurements shows clear advantages of the HDLL compared to the conventional DLL technology (better vertical resolution, fewer artefacts in deviated boreholes).

Hearn, F. P., Meyer, W.H., Wisler, M.M., 1998, Advanced Processing Methods for a New Generation Propagation Resistivity Tool Improves Interpretation Methodology, SPE 49135, SPE Annual Technical Conference and Exhibition, 27-30 Sep, 1998, New Orleans, Louisiana.

Much more accurate formation evaluation is now made possible by new generation propagation resistivity tools that make more measurements than previous systems. The additional measurements provide new information from the borehole and the near borehole environment as well as the formation itself. They also provide the capability to identify and differentiate between environmental effects. An new, advanced processing method combines many of the measurements collected by the tool then identifies and corrects for environmental effects. This includes a new method for dielectric constant correction. The method also calculates horizontal (Rh) and vertical resistivity (Rv) for high angle wells where anisotropic effects are present. A global solution for Rh and Rv is derived using a minimum of four measurements. This eliminates uncertainty where multiple solutions of Rh and Rv are possible. After corrections are made for environmental effects the method then generates four resolution-matched resistivity curves with fixed depths of investigation (radii) at 10", 20", 35", and 60". This format facilitates invasion interpretation, particularly where both resistive and conductive invasion are occurring proximal to one another. Field comparisons to wireline array resistivity measurements demonstrate the robustness of the method under a variety of formation resistivity environments and clearly shows where interpretation methodology is improved.

Helgesen, T. B., Fulda, C., Meyer, H.W., Thorsen, A.K., Baule, A., Iversen, M., Ronning, K.J., 2005, Reservoir Navigation with an Extra Deep Resistivity Lwd Service, SPWLA 2005-I, 46th SPWLA Annual Logging Symposium, 26-29 Jun, 2005, New Orleans, Louisiana.

Traditional geosteering with deep resistivity allows navigation along a resistivity boundary at a distance of 0 - 3 meters. Baker Hughes INTEQ has developed an extra deep resistivity service called DeepTrak™ to navigate at a distance of up to 12 meters from a resistivity boundary. This goal is accomplished by adding an electromagnetic wave propagation tool which operates at lower frequencies and with longer transmitter-receiver distances to the normal propagation resistivity service. Combining the measurements at the various frequencies and transmitter-receiver distances allows investigation of the volume around the wellbore with radii from 1 to 12 meters. Typically, six resistivity curves of different depth of investigation are transmitted in real time. An automated process determines the best fit of this data with a selection of previously calculated forward resistivity models, thus indicating the height above the oil water contact (OWC), the top or the bottom of the reservoir. The well trajectories based on directional surveys and on transmitted resistivities are both calculated and visualized by a web-based data communications system. This improves TVD control and aids detection of approaching bed boundaries. The service has been run in several wells in the Grane field in the North Sea. The objectives were to stay at a specific distance above the oil water contact, and to detect and possibly avoid shales. Data from offset wells indicate an irregular oil water transition zone in the field. However, the cause of this variation is not apparent from other lithology logs like gamma ray and porosity logs. Consequently, this irregularity necessitates the broad depth of investigation range. The combined use of deep resistivity and extra deep resistivity data provides a more reliable distance calculation than achieved only using standard propagation resistivity data. A method for analyzing the sensitivity of the real time distance calculations has been developed, and is adding confidence to the utilization of the data for proactive Reservoir Navigation. The usefulness and limitations of this technique are illustrated with field data examples.

Hibbin, G. N., Frenkel, M.A., Wang, T, Strack, K.M., Engels, O.,1999,Using Forward Modeling and Inversion to Interpret Array Lateral Log Resistivity Data from Horizontal Wells,London Petrophysical Society, **DiaLog**,No. 8:

Holden, A. J., Thorsen, A.V., Gravem, T., Busengdal, C., 2006, Applications and Interpretation of Multiple Advanced Lwd Measurements in Horizontal Wells", SPWLA 2006-WWW, 47th SPWLA Annual Logging Symposium, 4-7 Jun, 2006, Vera Cruz, Mexico.

Over the last 20 years, the oil industry has seen a dramatic increase in the complexity and the reach of production wells. These advances have been made possible by the introduction of sophisticated rotary steerable drilling and formation evaluation systems, enabling Hydro and other operators to place wells into targets in a more accurate and cost-efficient manner than ever before. This environment has placed an increased reliance on Logging-While-Drilling (LWD) measurements. In this paper, we will review a number of high-angle and horizontal wells drilled and logged on one of Hydro's mature North Sea fields and how the application of a number of advanced LWD technologies have enhanced answers through acquiring comprehensive formation evaluation data in a single run. The LWD technologies that will be presented range from standard measurements such as Gamma Ray (GR), multiple propagation resistivity, neutron porosity and density to real-time GR and density imaging, formation pressure and mobility and acoustic LWD compressional and shear measurements in both fast and slow formations. During late stages of field development where bypassed oil is to be drained, the data acquisition program will change substantially to acquire relevant information to ensure both optimal wellbore placement and maximum hydrocarbon drainage. Maximum available technology on LWD is applied to such complex horizontal and extended reach wells. The economic advantage with respect to time saving operations in the high-cost environment of the North Sea is obvious. The wells that are drilled in these offshore brownfield environments would not be possible without the high level of accuracy available from LWD tools today. The real-time aspect of LWD data acquisition is key to delivering answers while drilling that reduce reservoir and drilling uncertainty. Also, handling of the data in real time to ensure service quality and pro-activity, along with the post-processing of LWD data, are discussed and illustrated with examples to demonstrate the value of these technologies in achieving the goal of optimized reservoir access and productivity. The benefits from accessing the data while drilling will be discussed, including how real-time formation pressure measurements identify type of reservoir fluid early in the drilling process, as well as lithostratigraphic and petrophysical interpretation in horizontal wells to determine key petrophysical parameters, structural interpretation from LWD imaging and acoustic LWD including soft rock shear input to improve seismic resolution and well tie.

Hupp, D., Schnorr, D.R., 1999, Evaluating High-Angle Wells with Advanced Production-Logging Technology, SPE 57690, SPE Annual Technical Conference and Exhibition, 3-6 Oct, 1999, Houston, Texas.

High- angle wells with longer and longer departures are being drilled at an ever- increasing pace on the North Slope of Alaska and around the world. This type well is used to penetrate new oil

reservoirs and increase oil recovery in older maturing oil fields. The older maturing oil fields are being waterflooded with gas reinjection to maintain reservoir pressure, which results in wells that produce oil with high water cuts and high gas- oil ratios. These complex downhole production profiles create a difficult production logging environment. A totally new logging tool is being used to determine the production profile when a high- angle well is producing oil with high water cut and high gas- oil ratios. This compact tool directly measures water holdup and gas holdup distribution around the wellbore, along with velocity data and X- Y caliper all 18 in. above the bottom of the tool. Pressure, temperature, inclination, with gamma ray and casing collar locator, are also included in this compact tool. All measurements can be run with an electric line unit or in memory mode. The memory mode eliminates the need for electric line when logging horizontal wells or wells that have high surface flowing pressures. Sigma/ porosity and carbon- oxygen measurements can be combined with this short production logging tool, when run on electric line, so that the production profile and the reservoir behind the casing can be evaluated on a single trip into the well. The combination of the production profile and formation evaluation is then used to determine how to produce the well and manage the reservoir to maximize oil production and recovery. Production profiles from four different wells demonstrate the value of these direct measurements and how they were used in planning the remedial work to increase oil production and reduce or eliminate unwanted gas and water production.

Ishak, I. B., Steele, R.P., Macaulay, R.C., Stephenson, P.M., Al Mantheri, S.M., 1995, Review of Horizontal Drilling, SPE 29812, SPE Middle East Oil Show, 11-14 Mar, 1995, Bahrain.

Petroleum Development Oman (PDO) has drilled 350 horizontal wells in the past 8 years in 33 different oil and gas fields. Since the first wells were drilled the technology and its applications have evolved considerably. The paper describes that rapid evolution Wing four fields as examples. There has been a diversification of well designs as we have learnt how to tailor horizontal drilling most effectively to different situations. In many cases wells can be drilled faster and cheaper than 5 years ago, but there are also examples where more elaborate designs have been applied. The geological targeting and evaluation of the wells has also improved. Further evolution is planned with the next step likely to be the wider we of multiwell bore horizontals.

Iverson, M., Fejerskov, M., Skjerdingsatd, A., Clark, A., Denichou, J.M., Ortenzi, L., Seydoux, J., Tabanou, J., 2003, Geosteering Using Ultradeep Resistivity on the Grane Field, Norwegian North Sea, SPWLA 2003-J, 44th SPWLA Annual Logging Symposium, 22-25 Jun, 2003, Galveston, Texas.

The Grane field consists of massive, homogeneous marine turbidite sandstones with excellent reservoir properties. The contained oil has high density (21 °API) and viscosity (12 cp), and hence an extended transition zone height of about 25 m. The reservoir topography and drainage strategy impose certain geosteering challenges including landing and drilling production wells at a fixed distance above the oil- water contact (OWC), or as close to the bottom of the reservoir as possible in areas where the base reservoir is above the OWC. Similarly, gas injectors need to be drilled as close to the top of the reservoir as possible. Appraisal wells from the field suggested consistent resistivity and saturation profiles, and geosteering based on resistivity vs. height functions was planned. Actual experience, however, showed that the height above the OWC derived from LWD resistivity data was variable and often inconsistent with the survey data. The likelihood that this was caused by subtle facies variations and/or local variations in the OWC meant, that an alternative measurement on which to base geosteering decisions was needed. To meet this need Schlumberger developed a new tool in collaboration with Norsk Hydro. The tool has the ability to detect resistivity-contrast boundaries tens of meters from the wellbore. Thus, it allows wells to be drilled at fixed distances above the OWC, while shales approaching from above and below the well path can be detected and avoided. If a shale is penetrated, the tool is able to indicate distance back to sand. The acquired data can also aid in detecting and calibrating drifting survey data, in sidetrack planning and in geomodel updating. The possility to avoid shale adds direct value by increasing the length of production intervals in the wells.

Jackson, C. E., 1997, Using Pay Zone Steering in High-Angle and Horizontal Wells, SPE-37819, 10th SPE Middle East oil show proceedings, 15-18 Mar, 1997, Bahrain.

This paper examines the benefits of Pay Zone Steering, an integrated approach to drilling high-angle and horizontal wells incorporating advanced resistivity forward modeling into the overall planning and drilling phases. Pay Zone Steering provides quick detection of geological changes and allows for subsequent adjustments to the well plan. Key to this method are (1) the forward modeling of the responses of logging-while-drilling (LWD) resistivity tools, as well as other LWD devices, for different scenarios and the provision of complete and clear communications among all members of the drilling team throughout all phases of well construction. This paper addresses the necessary steps required for a successful steering operation. The theory of the forward modeling technique and the way it identifies a well's critical features are discussed, as well as applications for post-well analysis. The Pay Zone Steering process, from establishing objectives to final completion, is illustrated with case studies. The paper also demonstrates the benefits of this geological steering method, which include recognition of true-vertical-depth shifts in the well's trajectory, recognition of unexpected lithology, and improved capability to keep the well within the desired reservoir. An appendix is included that discusses a means of resolving any discrepancies between the model and the actual resistivity measurement.

Kennedy, W. D., 1995, Induction Log Forward Modeling: A Rigorous and Synthetic Approach to Model Construction, SPWLA 1995-G, 36th SPWLA Annual Logging Symposium, 26-29 Jun, 1995, Paris, France.

In many instances the apparent resistivity response of the 6FF40 induction logging instrument is not a good estimate of the true formation resistivity. In some cases this is true in beds up to 200 feet thick. Traditional chart book corrections do not usually remedy this condition; however, when conditions warrant one-dimensional forward modeling can convert induction log apparent resistivity responses into more accurate estimates of formation resistivity. With the advent of commercially available, fast modeling codes packaged in easy-to-use interfaces, application of l-d forward modeling has become a feasible interpretation option with the potential of substantially increasing reserve estimates. Unfortunately, the modeling of several hundred to several thousand feet of induction log response may seem a daunting task regardless of the speed of computer codes and the convenience of user interfaces and the experience of the analyst. However, it has been discovered that, regardless of how complicated a log may appear, log responses can be catalogued into six easily recognized responses. The responses have been named for convenience: (1) the impulse response; (2) the step response; (3) the ramp response; (4) the whole space response; (5) the thin bed (blind frequency and anti-correlation) responses; (6) mixed responses. Responses not falling into these categories can be recognized and identified as two-dimensional responses or in some cases erroneous responses due to, e. g. , incorrectly set sonde errors. The six responses are founded in the tool physics, but they can also be used as practical rules of thumb; using the six responses to construct initial models and refine the subsequent results significantly reduces modeling time. Both field and theoretical examples of each type of response are illustrated. Recognition of the cataloged responses permits efficient forward modeling.

Kloos, J., Munkholm, M., Benallegue, F, Bencherif, D., Rabinovicg, M., Tabarovsky, L., 2002, Maximizing Production for Horizontal Wells in Hassi R’mel Field (Algeria) with Resistivity Interpretation and Modeling, SPE 77717, SPE Annual Technical Conference and Exhibition, 29 Sep-2 Oct, 2002, San Antonio, Texas.

Water flooding and gas coning are potential problems in the horizontal wells drilled to penetrate the oil column in the channel sands of the Hassi R'Mel field. This field is operated by Sonatrach, the Algerian National Oil Company. High Definition Induction Logging (HDIL) in such environments has been used to build a reliable geological model along the wellbore, identify potential problem intervals, and minimize the risk of perforating and producing gas and/or water. The new generation of induction tools - array induction tools - has an advantage of acquiring unfocused data that can be numerically focused to any part of the formation at the post-acquisition stage. Operating at low frequencies with relatively large transmitter-receiver spacings, the wireline array induction measurements can provide reliable information from geological targets up to a 6-m (20 ft) distance from the borehole, depending on resitivity contrasts. In horizontal wells, the induction data may be influenced by adjacent layers located above or below the reservoir. In such cases, when evaluating the water saturation in the near wellbore region, we must, firstly, correct for the influence of the remote layers. Secondly, after correcting the deep HDIL measurements for the presence of the borehole and invasion, we use them to determine both the distance to and the resistivity of remote beds. To integrate the HDIL results into the geological model, a number of issues must be considered. First of all, in the Hassi R'Mel field remote conductive shoulder beds may be either conductive shales or water-bearing horizons. Therefore, to distinguish between the two, their resistivities must differ and, in the interpretation stage, be compared with that of the remote shoulder bed interpretation. In addition, as the measurements do not have a sense of direction, they cannot distinguish between remote beds above or below. Interpretation of the location of an identified remote layer must therefore be based on the geological model for the field as well as other log data. Finally, although an interface between two resistive layers is more difficult to resolve, remote oil-gas contacts may in some cases be found from the interpretation. Presently, every logging job in Hassi R'mel includes an HDIL tool in a string, and the data are usually processed within 48 hours. Providing the geological model and perforating recommendations prior to well completion improves the economics of the well due to increase in oil production and the reduced cost of well recompletion.

Koelman, J., van der Horst, M., Lomas, A. Koelemij, A. Bonnie, J., 1996, Interpretation of Resistivity Logs in Horizontal Wells: An Application to Complex Reservoirs from Oman, SPWLA 1996-G, 37th SPWLA Annual Logging Symposium, 16-19 Jun, 1996, New Orleans, Louisiana.

The design and interpretation of resistivity tools commonly used for quantitative evaluations has been based on the analysis of the response in vertical wells intersecting horizontally layered formations. When these tools are run in highly deviated or horizontal wells, artefacts in the response are encountered that are nor corrected for with the standard processing techniques. Using 3D forward modelling and inversion schemes we are able to recover formation resistivity profiles with associated synthetic resistivity tool responses that are in accordance with field logs obtained in highly deviated wells.Application on horizontal well resistivity logs from carbonate and clastic reservoirs in Oman demonstrate that this is the preferred way to correct laterolog and induction tool readings in highly deviated wells for the combined effects of layering, apparent dip, borehole and invasion.

Kristiansen, J. I., Sognesand, S., Bergum, R., 1996, Determination and Application of Mwd/Lwd and Core Based Permeability Profiles in Oseberg Horizontal Wells, SPE-36857, SPE European Petroleum Conference, 22-24 Oct, 1996, Milan, Italy.

Quicker and better quantitative partial perforation strategy has been possible by applying more accurate predicted permeability profiles along horizontal wells in the simulation models. A newly developed methodology for predicting permeability in non-cored horizontal wells that uses measurement/logging-while-drilling (MWD/LWD) data and a multivariate technique makes this possible. Data from the Oseberg Field in the North Sea illustrate the technique. The permeability modelling is done with a Partial-Least-Squares (PLS) regression technique. The underlying calibration model is founded on logs and core data from selected wells. Gamma ray, neutron, density, resistivity logs and air permeabilities as measured on core plugs constitute the applied calibration data set in the present context. In subsequent prediction phases, new logging data are fed into the established model to produce the permeability profile. The underlying model building is briefly outlined. In the actual Oseberg case, various permeability models are established. Their use depends mainly on formation, height above free water level and the data quality. The analysis shows that quantitative permeability profiles can be predicted within an acceptable precision if the input data quality is satisfactory. The predictions are fast and so far, tenth's of wells have been modelled. The enhanced quantitative application of all available log information is the major difference from previous applied permeability prediction procedures. The contrast is use of single log information and qualitative argumentation. The methodology is considered to have a significant contribution towards a tool for quicker and better quantitative partial perforation strategy in horizontal wells completed with cemented liners. Improved areal sweep and thereby increased recoverable reserves lead to cost effective production. It also enhances the possibility to obtain a better pre-knowledge of expected inflow profiles and it adds information that is useful in evaluating subsequent production logged inflow.

Two examples of permeability profiles from Oseberg horizontal wells are given and their applicability for well simulation modelling to predict inflow is illustrated. The results are discussed and compared with production logged inflow. Further applications of the prediction procedure are presently evaluated. This relates to improved field wide permeability mapping and the real-time geosteering aspects.

Lah, M. Z. C., Seering, L., Bakar, A. A., Sundal, E., Daudey, J., 2000, Real-Time Data Analysis While Drilling Provides Risk Management for Both Geological and Geometric Uncertainties in the Sotong K2.0 Reservoir, SPE 64477, SPE Asia Pacific oil and gas conference and exhibition, 16-18 Oct, 2000, Brisbane, Australia.

Modern communication systems can transmit data from the wellsite to shore in real time, allowing full utilization of advanced drilling technology, 3D seismic and geological earth modeling. While drilling, real-time data can then be analyzed by all available experts to refine well plans and geological models for optimized well placement. This case study demonstrates how the application of this technology optimized production and drainage efficiency through the successful drilling of several horizontal wells with complex objectives. The methodology clearly has definite application in field development planning and reservoir simulation studies. The Sotong 4 well is one of five planned multilateral horizontal wells to drain the Sotong field K2.0 reservoir in Malaysia. The 14-m oil column is overlain by a large gas cap and has a moderately active aquifer. In-house studies on exploration wells confirm that gas coning will result in rapidly decreasing oil production and that a conventional field development would exhibit marginal economics. Reservoir simulation defined the optimal horizontal well placement as 2 m above the OWC, within a ±0.5-m tolerance of TVD. Industry survey error models clearly show that this tight geometric control is not achievable using MWD survey data alone and additional techniques are required to control the geometric TVD error. An empirical model was developed from offset well data, allowing LWD data to be used to position the wellbore within the oil column. The TVD could then be determined in real time and the well trajectory refined. All three laterals of Sotong A4 were drilled within ±0.15-m TVD tolerance and production tests on Sotong A3 proved the validity of the model. The preparation and use of the geological model, as well as the challenges of landing and drilling the horizontal section, are discussed, with particular emphasis on survey error management and steering decision-making.

Lesso Jr, W. G., Kashikar, S.V., 1996, The Principles and Procedures of Geosteering, SPE 35051, IADC/SPE Drilling Conference, 12-15 Mar, 1996, New Orleans, Louisiana.

The management of directionally drilled wells has recently progressed to the stage where targets have been reduced in size to a point in the earth with no tolerances. These targets can and are changed during the drilling process. The management of these point moving targets, usually in high angle or horizontal wells, is a precise form of directional drilling now called geosteering. It is this precise placement of the wellbore that creates the value in drilling these wells. Several technologies have made this advancement possible. These include reliable steerable systems, improved and new physical formation measurements, log data modeling, sensors near the bit and instrumented motors, and detailed reservoir mapping with the help of 3D seismic processing. Most papers on geosteering have concentrated on one of these advances. This paper addresses how these technologies are merged to execute the successful geosteering project. New systems, sensors, and computations have created a mass of data and control parameters that require real-time decisions by operator personnel based on technical recommendations from service companies. These decisions have a critical impact on the net worth of a project. The team involved must rely on each other's expertise and understand the overall objective of a geosteering project. To do this, it is paramount that data from these different technological areas be merged into a 3D visualization encompassing geological structures and drilling trajectories. Patterns in procedures have developed from these projects over the past three years which demonstrate the difference between a successful project and a failure. The examples in this paper illustrate the techniques that will enable a change in the outlook, towards precision directional drilling and completion projects.

Li, Q., Rasmus, J., Cannon, D., 1999, A Novel Inversion Method for Interpretation of a Focused Multisensor Lwd Laterolog Resistivity Tool
SPWLA 1999-AAA, 40th SPWLA Annual Logging Symposium, 30 May - 03 Jun, 1999, Oslo, Norway.

Multisensor and array logging-while-drilling (LWD) tools are becoming routinely available. These tools can provide sufficient information to compute accurate two-dimensional (2D) characterizations of the formation environment surrounding the borehole. However, reducing these measurements to petrophysical parameters requires full knowledge of the tool response and substantial computation. Such processing may require a significant amount of time after data acquisition. An alternative one-dimensional (lD) approach that is simple, robust, fast and accurate is highly desirable.This paper presents a novel approach to 1D inversion based on an intuitive equivalent circuit model that can accurately reproduce the response of a focused array laterolog tool. This approach is well suited to focused, high resolution measurements, which have minimal shoulder bed effects. The equivalent circuit model of these measurements offers a representation of the response to the borehole and invaded zone. The parameters of the model are obtained from finite-element (FE) modeling of the tool response with the tool centered in a circular borehole with a step invasion profile. Since the tool response is entirely characterized as a function of physical parameters, a conjugate-gradient method is employed to minimize the cost function in the inversion.This model permits simultaneous inversion for borehole diameter, invasion diameter, true formation resistivity and invaded zone resistivity. In certain instances, this same technique may be applied to azimuthal measurements to provide useful information on borehole shape and invasion profiles. The computed borehole shape can be useful for wellbore stability analysis and log quality control.The inversion algorithm is verified with synthetic logs from modeling and its robustness is proven with several applications from actual field logs from an azimuthal LWD array laterolog tool. It is well known that laterolog measurements can be affected even if the invasion is relatively shallow. These examples illustrate the need of computing an R1 for both shallow and deep depths of invasion. The technique of automatically solving for the borehole diameter leads to more accurate R, values in overgauge and oval boreholes. An example of using the computed borehole shape to characterize breakouts is also provided.

Li, Q., Liu, C., Maeso, C., Wu., P., Smits, J., Prabawa, H., Bradfield, J., 2003, Automated Interpretation for Lwd Propagation Tools through Integrated Model Selection, SPWLA 2003-UU, 44th SPWLA Annual Logging Symposium, 22-25 Jun, 2003, Galveston, Texas.

Petrophysicists often have difficulty interpreting logs from today's multispacing, multifrequency logging- while-drilling (LWD) propagation resistivity tools. Which of the many resistivity curves represents the true formation resistivity? The logs may be affected to varying degrees by borehole effect, tool eccentering, shoulder-bed effects, fractures, invasion, anisotropy and/or dielectric effects. These effects may occur individually, or multiple effects may be present in the same zone. Identifying these effects and correcting for them is challenging, especially when conclusions are needed quickly. Much of the information required to answer these questions is contained in the array measurements themselves. This paper presents a general automated scheme that can help analysts to identify environmental effects and to select the appropriate environmentally corrected formation resistivity. It answers the key question of how to select the correct model amongst many candidates, based primarily on inversion of the tool response and possibly other additional information. The key idea is to invert different formation models that may apply and select the one most consistent with the measurements of the tool and with auxiliary data from user inputs and/or other logs. When a dominant effect is identified, the correction is applied automatically, the relevant environmentally corrected data are generated, and confidence of interpretation is assigned. When none of the models result in an adequate fit, the data is flagged to indicate that an automatic interpretation could not be made because of more complicated or compounded environmental effects. In addition, petrophysicists can accept or reject certain models and impose petrophysical constraints to improve the interpretation. The program based on this approach has been used to process field logs with diverse formation characteristics, and it has been evaluated by experienced petrophysicists. The program includes borehole, invasion, dielectric, and anisotropy models in its database. Results show that the algorithm successfully identifies most environmental effects and highlights zones that need further analysis because of complex or compounded effects. The benefits of such an integrated-interpretation-through-model-selection approach will be demonstrated through numerous field log examples. Availability of these results at the wellsite is expected to improve both the timeliness and the quality of decisions made based on resistivity data.

Li, Q., Omeragic, D., Chou, L., Yang, L., Duong, K., Smits, J., Yang,. J., Lau, T., Liu, C., Dworak, R., Dreuillault, V., Ye, H, 2005, New Directional Electromagnetic Tool for Proactive Geosteering and Accurate Formation Evaluation While Drilling, SPWLA 2005-UU, 46th SPWLA Annual Logging Symposium, 26-29 Jun, 2005, New Orleans, Louisiana.

A new logging-while-drilling (LWD) technology has been developed and field-tested, which introduces directional electromagnetic (EM) measurements through the use of tilted and transverse current-loop antennas. The multispacing and multifrequency directional measurements enable monitoring distance to formation boundaries and their orientation to facilitate proactive well placement. In combination with conventional LWD resistivity, these directional EM measurements allow for accurate structure and formation resistivity interpretation around the wellbore, independent of mud type. Furthermore, specific antenna combinations provide the capability to detect and characterize resistivity anisotropy in near-vertical wells while drilling. The directional EM tool is designed with a symmetrical transmitter-receiver configuration that optimizes the sensitivity to the desired formation parameters. While canceling the influence of anisotropy and formation dip, adding the symmetrical directional measurements together maximizes the sensitivity to bed boundaries, which is optimal for geosteering. The fact that the antennas are mounted on a conductive collar significantly reduces the large borehole effects that are normally associated with transverse EM measurements in conductive mud. In addition to exploring the physics of the new directional propagation measurements, we will demonstrate their unique applications with field test examples. By detecting and tracking, in real time, formation boundaries up to 15 ft around the wellbore, the directional propagation tool allows for sufficient time to make trajectory adjustments and stay within the reservoir. The bedding orientation information also answers the question, in what direction to steer, which is often ambiguous when relying on traditional propagation measurements. Particularly interesting applications are the placement of wells in thin oil rims and in reservoirs with complex structures such as intrabedded shale silts. Field test examples will also be shown of the enhanced formation evaluation capabilities offered by directional measurements in high-angle and horizontal wells, where formation resistivities can now be determined while accurately accounting for proximate bed boundaries. The ability to measure resistivity anisotropy in near vertical wells will be demonstrated by a field test example where the anisotropy measurement was confirmed by comparing with a conventional propagation resistivity measurement run in a near-by high-angle well.

Lofts, J., Deady, R., Johnston, S., 2005, Technical and Commercial Lwd Challenges for Service Companies in Crossing Multidisciplinary Boundaries, SPWLA 2005-B, 46th SPWLA Annual Logging Symposium, 26-29 Jun, 2005, New Orleans, Louisiana.

This invited paper will review key technical and commercial challenges faced by service companies in providing Logging While Drilling (LWD) formation evaluation in today's complex drilling environments. Technical challenges ??The Real-time Challenge - getting the most out of the downhole drilling and formation evaluation system while-drilling ??The effect on log quality of faster drilling with rotary steerable systems (RSS) ??Evolution of the Operators asset team, and the service company's role within that team ??Conflicts between the drilling and geological and geophysical objectives and that conflict's effect on LWD planning and communication Commercial challenges ??Return on Investment from LWD technology ??Shrinking operator research and development (R&D) spending and the shift to service companies: The effect on trends and opportunities for the future ??Wide-scale bulk tendering: Does it always bring value to the operator?

Lofts, J. C., Bedford, J., Boulton, H., Van Doorn, J. A., Jeffreys, P., 1997, Feature Recognition and the Interpretation of Images Acquired from Horizontal Wellbores, in *Developments in Petrophysics*, M. A. Lovell, Harvey, P. K. editors, Geological Society London, **Special Publication No. 133:** 345-365.

Lott, S. J., Dalton, C.L., Bonnie, J.H.M., Roberts, M.J., Cooke, G.P., 2000, Use of Networked Geosteering Software for Optimum High-Angle/Horizontal Wellbore Placement: Two U.K. North Sea Case Histories, SPE 65542, SPE/CIM International Conference on Horizontal Well Technology, 6-8 Nov, 2000, Calgary, Alberta, Canada.

> This paper presents two case histories that demonstrate the effectiveness of an active geosteering approach using computer networking between rig site and operator office. A satellite link was used to update well trajectory and LWD data in StrataSteer™ geosteering software located within the operator's asset group. This link provided the key advantage of allowing subsurface staff to become an integral part of the geosteering process. The geosteering software enables a geological / petrophysical model to be created based on offset well log data and seismic profiles. The LWD log responses are modeled along the planned well trajectory and then compared to the actual LWD log responses (gamma, multi-depth resistivity, neutron, and density). The responses are then used to adjust the geological model and take geosteering decisions. The amended geological situation enabled immediate and enhanced decision-making regarding adjustments to the well path in order to remain within the optimum reservoir zone. Good communication between all parties involved, both onshore and offshore, undoubtedly contributed to the success of both operations. The two example wells, “A” and “B”, present different challenges. In both cases, it was clear prior to drilling that active geosteering would be necessary. Well A was planned as a horizontal oil producer. The vertical thickness of the pay section was estimated at 13 ft, and the bed dip was expected to vary between 0 and 2 degrees in the direction of drilling. Following successful landing of the well, a total of 1300 ft of target reservoir was drilled using the geosteering software to actively guide the well path. Production rates from this well were significantly above pre-drill expectations. The objective in Well B, a deviated sidetrack, was to drill through four reservoir zones, two on either side of a major fault. Recognition of the fault in real-time was critical due to different reservoir thickness and bed dips across the fault and significant uncertainty regarding the position of the fault. The use of geosteering software enabled the fault to be quickly recognized when it appeared — some 450 ft along hole earlier than expected. The geological model was quickly revised and the well path adjusted to optimize placement in the final two targets.

MacCallum, D., Dautel, M., Phillips, C., 1998, Determination and Application of Formation Anisotropy Using Multiple Frequency, Multiple Spacing Propagation Resistivity Tool from a Horizontal Well, Onshore California, SPWLA 1998-E, 39th SPWLA Annual Logging Symposium, 26-29 May, 1998, Keystone, Colorado.

> As part of a Department of Energy cost share program, a horizontal well was drilled in thin heterogeneous Miocene age turbidite sands. The challenge was to economically drill and exploit remaining reserves in the 60 year old Wilmington Field (Long Beach, California). The solution was to use new technology and sidetrack an existing wellbore with a horizontal lateral to capture hydrocarbon reserves uneconomically recoverable with historically used conventional methods. The new technologies included detailed reservoir characterization, 3-D geologic modeling, geosteering in thin beds and modeling the Logging While Drilling (LWD) responses.Propagation resistivity measurements can be affected by eccentricity, invasion, variations in dielectric permittivity and thin beds. In situations of high relative dip, adjacent beds and formation anisotropy become significant factors in the log response. The use of a multiple spacing, multiple frequency propagation resistivity tool enables the calculation of multiple independent sets of vertical and horizontal resistivities. In addition to identifying and quantifying anisotropy, this also helps to determine additional borehole and formation effects.This case history demonstrates the application of forward modeling and inversion processing to enhance understanding of the horizontal log response and the reservoir structure of a complex horizontal well drilled onshore California.Current geosteering techniques frequently use offset wireline or LWD data from vertical or low angle wells. These logs predominantly measure the horizontal resistivity of the formation.

Vertical resistivity cannot be accurately determined, if at all, in these situations. At high relative dip angles (e.g. in horizontal wells), a model generated from horizontalresistivity alone will not be representative of the actual log response.Horizontal and vertical resistivities derived from the inversion processing and subsequent modeling were in excellent agreement with both the offset wireline data and the actual LWD log.

Mallan, R. K., Torres-Verdin, C., 2006, Effects of Petrophysical, Environmental and Geometrical Parameters on Multi-Component Induction Measurements Acquired in High-Angle Wells, SPWLA 2006-PPP, 47th Annual Logging Symposium, 4-7 Jun, 2006, Vera Cruz, Mexico.

This paper describes a numerical study examining the effects of petrophysical, environmental, and geometrical parameters on multi-component electromagnetic (EM) induction logging measurements. Coaxial and coplanar measurements enable the estimation of resistivities parallel and perpendicular to reservoir layers. However, borehole, geometrical, environmental and petrophysical effects can significantly bias these measurements. Understanding such biasing effects will aid in the interpretation of induction measurements and subsequently provide a more accurate and reliable formation evaluation via inversion. We perform numerical simulations of multi-component induction logging measurements with a 3D finite difference modeling code. A suite of models is considered, including a layered reservoir with variable conditions such as borehole dip angle, invasion, and electrical anisotropy. Analysis is carried further to examine the sensitivity of the multi-component measurements to the extent of the invasion zone in a deviated well and in the presence of shoulder-bed anisotropy. Finally, we examine the response due to non-uniform invasion, generated from mud-filtrate invasion in a horizontal well. Simulations show that shoulder-bed effects across sand layers become substantial in the presence of shoulderbed anisotropy, even at low values of dip angle. Measurements centered about sand layers exhibit sensitivity to the depth of mud-filtrate invasion. In particular, coplanar measurements exhibit different responses for symmetric and non-symmetric invasion fronts, indicating the potential ability of multi-component tools to detect non-uniform invasion. In addition, shoulder-bed anisotropy has a considerable effect on these sensitivities, to significantly alter the assessment of invasion in terms of resistivity, depth, and front shape.

Mallary, C. R., Edwards, J. E., Guillory, R. J., Ramos, G. G., 1996, Case History of an Azimuthally Geosteeered Horizontal Well in a Thin, Poorly Consolidated Oil Sand, SPE-37042, SPE International Conference on Horizontal Well Technology, 18-22 Nov, 1996, Calgary, Alberta, Canada.

Atlantic Richfield Indonesia, Inc. (ARII) recently drilled a well with a 1500-foot horizontal leg in a ten foot thick poorly consolidated sand. This paper describes the planning and drilling of this well, focusing on the use of real-time geosteering technology to maximize well placement in the pay zone. Additional topics include drilling fluid design to ensure borehole stability while minimizing formation damage, and the role of rock strength analysis from cores in designing the open hole completion. A narrative of the drilling and completion of the well is given, along with the initial production history.

Maricic, N., Mohaghegh, S.D., Artun, E., 2005, A Parametric Study of Horizontal and Multilateral Wells in Coalbed-Methane Reservoirs, SPE 96018, SPE Annual Technical Conference and Exhibition, 9-12 Oct, 2005, Dallas, Texas.

Recent years have witnessed a renewed interest in development of coalbed methane (CBM) reservoirs. The success stories in San Juan basin and other CBM horizons have triggered this renewed interest. Many operators are asking questions regarding the most optimum way of producing CBM reservoirs. Drilling horizontal and multi-lateral wells are gaining popularity in many different coalbed reservoirs with varying results. This study concentrates on many variations of horizontal and multi-lateral wells and their potential benefits. It has been the rule of thumb that vertical wells are appropriate for thicker CBM reservoirs such as those found in San Juan basin and horizontal and multi-lateral wells should be used in thinner beds. Recently some operators are drilling horizontal and multi-laterals even in thicker beds and are claiming economic success. In this study, we identify the most appropriate drilling patterns for coalbed methane reservoirs of different thickness and with different characteristics. The reservoir characteristics

that have been studied include gas content, permeability, and desorption characteristics. The yard-stick for comparing different drilling configurations in this study is the net present value (NPV). This way cost of drilling has been taken into account when different horizontal and multi-lateral configurations are compared with one another. Furthermore, we have compared dual-, tri- and quad- laterals with fish-bone (also known as pinnate) configurations. In these configurations, the total length of horizontal wells as well as the spacing between laterals (SBL) has been studied. CBM Background. Coal represents an unusual reservoir rock due to its highly complex reservoir characteristics. One of the characteristics that distinguish coal seams from conventional gas reservoirs is that coal represents both the source and the reservoir rock at the same time. Unlike conventional sandstone reservoirs, where the gas is found in free state within the pore structure of the rock, the methane gas is adsorbed onto the internal structure of the coal, which allows significant amount of gas to be stored in the coal rock[1]. Coal seam system is a naturally fractured heterogeneous reservoir characterized by macropores (fracture system, also known as cleat system) and micropores (coal matrix system). In general, the coal cleat system is orthogonal with one direction cross-cutting the other and varies from the case to the case, having significant impact on the coal deliverability1. The CBM production depends highly on the fracture system - fracture spacing and fracture interconnection. If the cleat system for any reason is not developed enough, the gas production could be very difficult. This occurs due to the low values of porosity and permeability in the matrix, making it almost inpossible for gas to move from matrix into the fractures. At the beginning, the coal system is in equilibrium and typically, water must be produced continuously from coal seams to reduce the reservoir pressure and release the gas. Gas from the coal can be produced only after initial dewatering of the system, and upon reaching low reservoir pressure. The dewatering process can take anywhere from few days to several months, which depends on CBM well configuration. Generally, the water production declines until the gas rate reaches the peak value. This ‘time-to-peak-gas’ is a critical parameter since the gas production starts declining after reaching the maximum[2]. Upon reaching the peak, gas production starts to decline and behavior of CBM production becomes similar to conventional reservoirs.

McDonald, P., Lorenz, J. C., Sizemore, C., Schechter, D. S., Sheffield, T., 1997, Fracture Characterization Based on Oriented Horizontal Core from the Spraberry Trend Reservoir--a Case Study, SPE-38664, SPE Annual technical conference and exhibition, 5-6 Oct, 1997, San Antonio, Texas.

As detailed fracture characterization of the Spraberry Trend continues, there exists an imbalance in the primary sources of fracture data. Measurements of spacing, density, permeability and orientation have traditionally been calculated or inferred from pulse and/or tracer type tests. To date, no direct measurement of Spraberry fracture properties from core in a horizontal plane are known. Approximately 400' of horizontal core was recently taken from the two main pay sections in the Upper Spraberry (1U and 5U) in Midland County, Texas. This paper will describe the acquisition, orientation, and subsequent analysis of the first ever horizontal core taken from the Spraberry Trend.

McInally, G., Hallundbaek,J., 1997, The Application of New Wireline Well-Tractor Technology to Horizontal Well Logging and Intervention, SPE-38757, SPE Annual technical conference and exhibition proceedings, 5-8 Oct, 1997, San Antonio, Texas.

Through close co-operation between Statoil MWS and Welltec, a working Well Tractor has been successfully introduced into operation in the North Sea. The Well Tractor technology has been extensively field proven and has demonstrated significant cost savings for operating companies when compared to previous methods of performing well intervention operations in horizontal wells. In some cases, use of the Well Tractor technology can mean the difference between whether or not required well intervention operations can be carried out. Careful prejob planning is necessary to ensure success, since the Well Tractor technology adds a new dimension to the techniques required in normal wireline logging and well intervention.

McLellan, P. J.,1996,Assessing the Risk of Wellbore Instability in Horizontal and Inclined Wells,Journal of

Canadian Petroleum Technology, no. 5: 21-32.,

Mendoza, A., Preeg, W., Torres-Verdin, C., Alpak, F.O., 2005, Monte Carlo Modeling of Nuclear Measurements in Vertical and Horizontal Wells in the Presence of Mud-Filtrate Invasion and Salt Mixing, SPWLA 2005-PP, 46th SPWLA Annual Logging Symposium, 26-29 Jun, 2005, New Orleans, Louisiana.

This paper describes a study undertaken to quantify the influence of mud-filtrate invasion on neutron compensated and density measurements acquired in vertical and horizontal wells. Our objective is to assess the influence of non-axial symmetric spatial distributions of fluid saturation on generic nuclear tools. The case of horizontal wells is of primary interest due to the complex spatial distribution of fluids around the borehole due to mud-filtrate invasion combined with fluid density contrasts, permeability anisotropy, fluid mobility, and gravity segregation, among other factors. Invasion was simulated under the assumption of a water-base mud filtrate invading a gas-bearing formation. In addition, we simulated the mixing of salt between mud-filtrate and connate water. This approach accurately reproduced the effects of porosity, permeability, permeability anisotropy, relative permeability, capillary pressure, and fluid density, on the spatial distribution of fluids and salt concentration around the borehole. The Monte Carlo N_Particle (MCNP) code was used to simulate the response of nuclear tools with consistent source-sensor configurations. To this end, we introduced generic models of thermal neutron and density tools referred to as Longhorn Nuclear Well Logging Tools." Calibration of the simulations of nuclear measurements was performed against standard industry models to appraise their reliability and accuracy. Results from this study indicate that presence of mudfiltrate invasion reduces, and even eliminates the effect of gas on neutron-tool measurements. It was also found that salt concentration of connate water caused an effect opposite to that of gas on the simulated neutron measurements. More importantly, the effect of salinity contrast, caused by fresh mud filtrate displacing salty connate water, increased the gas effect on neutron measurements for the case of shallow invasion. The effect of salt mixing was less critical for the case of density measurements. It was also found that presence of non-axial symmetric distributions of mud filtrate and salt concentration biased the estimates of density and apparent neutron porosity. Similarly, for the horizontal well case, depending on the location of the tool around the perimeter of the wellbore, both neutron and density measurements were influenced by nonaxial symmetric spatial distributions of fluids resulting from invasion. This effect was most noticeable for tool locations at the top and bottom of the borehole. Tool standoff significantly biased both measurements.

Mendoza, A., Torres-Verdin, C., 2006, Environmental and Petrophysical Effects on Density and Neutron Porosity Logs Acquired in Highly Deviated Wells, SPWLA 2006-EEE, 47th Annual Logging Symposium, 4-7 Jun, 2006, Vera Cruz, Mexico.

Conventional interpretation methods of nuclear measurements for vertical wells can produce incorrect calculations of porosity in complex rock formations. The case of logs acquired in highly deviated wells relative to sand beds may yield inaccurate estimates of bed boundary depth and porosity. We describe a systematic sensitivity analysis of petrophysical and environmental effects of neutron and density measurements acquired in highly deviated wells that penetrate sand-shale laminated sands. The study focuses primarily on the effects caused by the angle between the wellbore and formation layering. Raw nuclear tool responses are calculated with Monte Carlo simulations of generic source-sensor configurations via the code MCNP. Our objective is to quantify the effect of complicated formation conditions, such as thin laminations and high deviation angle of the wellbore with respect to the formation, on raw nuclear measurements. Moreover, we quantify the shift in vertical resolution with respect to angle of deviation. Of special interest is the case of synthetic composite rock formations of sand–shale laminations for various formation thicknesses. Simulated neutron and density porosity logs for the case of highly deviated wells are compared against the logs simulated for the case of a vertical well penetrating the same formation. Our study also describes the effect, on the vertical resolution and bed boundary detection, of azimuthal tool position around the perimeter of the wellbore for the case of a deviated well. Finally, we show simulations for the case of a gas-saturated sand bed penetrated by a high-angle well. Results from this study indicate that shoulder beds can have a significant impact on the nuclear response of thin layers penetrated by high-angle wells. Shifts in vertical resolution of 10 and 11 in. were observed in high-angle wells (70 and 85 degrees of deviation

from the vertical) for a 30 in. sand bed bounded by shale beds for the case of density; similarly, shifts in vertical resolution of 14 and 16 in. were observed for the case of neutron measurements. In the case of a well deviated 70 degrees from the vertical, azimuthal effects on density measurements can originate biases on bed boundary detection up to 2.4 in., and up to 2.8 in. for neutron measurements. These results strongly suggest that improved interpretation methods are necessary to accurately estimate the porosity of laminated formations penetrated by high-angle wells.

Meyer, W. H., 1998, Interpretation of Propagation Resistivity Logs in High Angle Wells, SPWLA 1998-D, 39th SPWLA Annual Logging Symposium, 26-29 May, 1998, Keystone, Colorado.

The interpretation of propagation resistivity logs at very high relative dip angles is much more challenging than the interpretation of vertical logs. Several effects degrade the usefulness of propagation resistivity data when the borehole is horizontal or the relative dip angle is very high (over 70°). These effects include anisotropy, non-circular invasion, and eccentricity in oddly shaped boreholes. Some of these effects cannot be properly quantified so their effect on the data cannot be fully removed. Other effects can be removed, but the remaining presence of these unquantified effects makes this more difficult. An entirely new strategy is necessary to interpret horizontal and high angle wells, and even then the results will not be as accurate as they are in low angle wells.The first problem with interpretation of high angle wells is the inability to remove the effects of differing vertical resolution (more properly called axial resolution in this case). Lateral changes in the formation itself may have a larger impact on the data than the progress of the tool vertically through the formation (which is very slow at high relative dip angles). As a result, a normal inversion will increase the size of the changes within the formation more than it will reduce the effects of nearby bed boundaries. In addition, high angle wells often use the resistivity data to geosteer the well. Geosteering recognizes the nearby bed boundaries as variables and any attempt to eliminate these variables by inversion techniques is not desirable. Therefore, a strategy which treats the distance to the bed as a variable is required. This strategy must also reduce the effects of anisotropy, anomalous dielectric permittivity, and invasion. All of these effects have to be interpreted simultaneously because they all result in various types of separation of the apparent resistivity curves. If one of the parameters is analyzed individually, the resulting attempt to explain all of the separations with a single effect will cause an error in that parameter. In addition, it will then be impossible to determine the other parameters.In this paper several of these formation effects have been simultaneously inverted to produce "true" formation parameters. This method has been used to interpret some field logs. While the results demonstrate the advantage of this strategy over previous methods, the interpretation is still not as effective as interpretation in low dip angle formations. However, it is still possible to produce accurate resistivity curves at fixed depths of investigation.

Morton, A. C., Safton, K., Mundy, D. J. C., Passingham, B., Sargent, M.,2001,Geosteering Horizontal Wells on Ross Field Using Heavy Mineral Analysis,Offshore International, no. 4: 64, 66, 169.,

Mullane, T. J. and et al.,1994,Actual Vs. Predicted Horizontal Well Performance Weyburn Unit, S.E. Saskatchewan,SPE/CIM/CANMET Horizontal Well Conference, 20-23 Mar, 1994.

Ogawa, N., Minh, C. C., 1997, Log Interpretation Problems and Their Partial Solutions in Horizontal Wells Drilled Offshore-Neutral Zone between Kuwait and Saudi Arabia, SPE-37775, 10th SPE Middle East Oil Show, 15-18 Mar,1997, Bahrain.

Formation Evaluation in Horizontal wells drilled offshore Khafji poses two acute problems. First, the cyclic grooves on the borehole wall created by the drilling process affect adversely the Density-Neutron logs. The use of oil-based mud for wellbore stability control amplifies the adverse effect because of the added hydrocarbon effect. Typical Density-Neutron logs in the field shows large cyclic variations which, without proper corrective actions, make the determination of porosity very difficult if not impossible. Second, the well trajectory seldom stays in the target reservoirs, but goes in and out of the sands and shales layers. Because of the change in the geometry of the wellbore with respect to the formation layers, interpreting Rt from Resistivity logs can be very challenging. Often, the deepest resistivity reading is affected by the surrounding

shales, while the shallowest resistivity is affected by invasion. Essentially, without the knowledge of Porosity and Rt, no water saturation calculation is possible and this complicates the decision where to perforate and produce the reservoirs. We present some typical examples and the techniques that are used locally to overcome these basic formation evaluation problems. For the first problem, a fast and effective filtering algorithm is used to retrieve the valid information from the Density-Neutron logs. The typical runtime of the algorithm is in the order of 1 minute per 2000 feet of logs on a desktop PC. Details of the algorithm are given in the paper. For the second problem, we use the multi-depth of investigation resistivity curves from the Array Induction Tool (AIT*) to derive the best possible Rt for use in water saturation calculation. We show that the multi-depth of investigation resistivity curves are necessary to resolve the problem of proximity of beds with large resistivity contrast, which is the case when the well was drilled through a high resistivity pay zone sandwiched between a low resistivity shale above and a low resistivity water zone below.

Oguntona, J. A., Kelsch, K., Osman, K., Ingebrigtsen, E., Butt, P., Saha, S., 2004, Thin Sand Development Made Possible through Enhanced Geosteering and Reservoir Planning with While-Drilling Resistivity and Nmr Logs: Example from Niger Delta, SPE 88889, Nigeria Annual International Conference and Exhibition, 2-4 Aug, 2004, Abuja, Nigeria.

The horizontal well placement within a thin sand with structural dip and economically produce these reserves are a challenge for the oil industry. New Reservoir Management and Formation Evaluation techniques are making these very thin hydrocarbon sands accessible and economic for development. Upfront planning by multi functional team to define well placement, uncertainty management and tool selection are key. Next execution of landing and lateral require maximum flexibility and accuracy from tools and team. In this paper, two case studies are presented where Logging-While-Drilling (LWD) resistivity and Nuclear Magnetic Resonance (NMR) were utilized to geosteer a horizontal section through a thin sand and to geo-stop the horizontal well after drilling an optimal drain hole length. Resistivity and NMR-LWD provides critical formation evaluation information such as resistivity at bit, up and down resistivities, structural dip, formation porosity, bound-fluid volume, free-fluid volume and permeability. Obtaining this information while drilling has a significant impact on drilling and completion decisions in Niger Delta. In the first case study, based on the information of NMR LWD from a pilot hole, a horizontal sidetrack was optimised in the high permeable section of the thin reservoir. In addition, NMR logs demonstrate the horizontal section was placed generally within the sweet spot of high free fluid section. Drawing experience from the first case study, a more difficult situation of drilling a horizontal well with a six feet window was addressed. The objective was to place the well within the sand and drill an optimal length that will meet hydrocarbon deliverability. First, resistivity at bit was used to restrict the well within the target sand. Within this heterogeneous sand, the while-drilling resistivity image and up and down deep Resistivity measurements allowed the geosteering team to stay in the “sweet spot” of the reservoir. Concurrently, permeability was estimated from the NMR log. Based on this permeability, hydrocarbon producibility was computed and decision was reached to drill the optimal length. This novel approach combining geosteering techniques using flexibly LWD tools are key to future development of thin hydrocarbon reservoirs.

Okland, D., Cook, J.M., 1998, Bedding-Related Borehole Instability in High-Angle Wells, SPE 47285, SPE/ISRM Rock Mechanics in Petroleum Engineering, 8-10 Jul, 1998, Trondheim, Norway.

In the Oseberg field in the Norwegian sector of the North Sea, extended reach drilling (ERD)has been employed to increase oil recovery. Wells up to 9,327 m total depth (TD) have been drilled. Hole stability problems were experienced in the Upper Jurassic Draupne Formation (Kimmeridgian shale) in a number of very highly inclined wells; these problems had not been experienced at lower inclinations. A rock mechanical study was carried out to explain and overcome the stability problems. A series of thick-walled hollow cylinder (HC) tests were carried out on core material and analogous outcrop samples in order to identify the mechanisms of the hole problems, together with triaxial tests to obtain modelling parameters. Hole deformations were measured during external pressurization of the cylinders, and after testing the samples were sectioned and exiunined for damage. A very strong influence was found of the angle between the

HC axis and the bedding plane of the shale. Specifically, if the HC axis lay more than approximately 100 away from the bedding plane, the hole was relatively stable; if the HC axis was parallel to bedding, the hole was highly, and catastrophically, unstable, forming very large regions of cavings. An anisotropic elastic model for the stresses around the hole did not predict such a sudden change in behaviour. It was finally concluded that the borehole instability related to strength anisotropy associated with the pronounced bedding of the organic-rich Draupne shale. Spallings from the high side and the low side of the hole occurred at a number of different mud densities when the inclination was sufficientiy high. The decision was made to modify the wellpath so that the "angle of attack" between the well trajectory and the bedding planes in the Draupne Formation always exceeded 200. The world record well C-26 (9,327 m; 7,853 m horizontal reach) was sidetracked due to stuck pipe after an unsuccessful high-angle Draupne penetration. The sidetrack was stable at practically the same mud density, but with a lower inclination. The reported type of hole instability is widely recognized in hard-rock applications of rock mechanics (mining, tunnelling), but is relatively new to petroleum-related rock mechanics.

Omeragic, D., Li, Q., Chou, L., Yang, L., Duong, K., Smits, J., Lau, T., Liu, C.B., Dworak, R., Dreuillault, V., Yang, J., Ye H., 2005, Deep Directional Electromagnetic Measurements for Optimal Well Placement, SPE 97045, SPE Annual Technical Conference and Exhibition, 9-12 Oct, 2005, Dallas, Texas.

A new logging-while-drilling (LWD) tool that incorporates directional antennae and long measurement spacings has been developed and field tested. The directional electromagnetic (EM) tool measurements are more sensitive to approaching resistivity boundaries than existing propagation resistivity tools. Combining measurements from symmetrically arranged pairs of antennae further amplify this boundary effect while minimizing undesirable sensitivity to dip and anisotropy. Novel data processing and structure visualization software was developed to aid the decision-making and planning process. Field test results from Oman and the North Sea illustrate how the directional EM measurements fulfill the requirements for geosteering in thin, dipping, and curving targets with lateral resistivity variations. In addition, the directional EM tool also enables improved characterization of resistivity and resistivity anisotropy in high-angle and horizontal wells.

Passey, Q. R., Yin, H., Rendeiro, C. M., Fitz, D. E., 2005, Overview of High-Angle and Horizontal Well Formation Evaluation: Issues, Learnings, and Future Directions, SPWLA 2005-A, 46th SPWLA Annual Logging Symposium, 26-29 Jun, 2005, New Orleans, Louisiana.

High-angle and horizontal (HA/HZ) wells are commonly drilled and often the logging suite is selected primarily to aid geosteering the well to a specific target. In many situations, these wells penetrate zones or portions of the reservoir for which no vertical appraisal wells are available. In these situations, the logs acquired will be used for routine formation evaluation of net-to-gross, porosity, and possibly water saturation. Comparison of log responses in a given formation from vertical wells to responses in HA/HZ wells indicates that significant differences can exist. For example, recent studies show that porosity values can be off as much as 6 p.u., water saturation uncertainty can exceed 50%, and true stratigraphic thickness can be off by 200- 300% because of uncertainty in apparent dip in highly deviated wells. Thus, routine formation evaluation approaches for vertical wells may not be adequate for accurate characterization of formations and fluids in HA/HZ wells. Many causes for different responses exist, but most relate to the fact that many logging tools were designed for vertical wells with near-horizontal strata. In extremely high-angle to horizontal wellbores, our interpretation schemes must be modified to account for 1) geometry of beds relative to the borehole, 2) circumferential direction of the measurement, 3) formation anisotropic effects on resistivity, acoustic, and nuclear responses, 4) unusual invasion profiles, and 5) gravity causing eccentering of tools and cuttings bed accumulation on the bottom of the wellbore. Although borehole image logs may be the best approach for characterizing relative bed dip in near-horizontal wellbores, issues still exist in obtaining sufficiently accurate dips when wellbore deviation exceeds 80°. Cuttings beds can have a significant effect on both density and nuclear log responses. Since logging of these wellbores is challenging, it is critical to establish a protocol for distinguishing poor log responses from "unusual" log response just due to geometry, anisotropy, and other borehole effects. In November 2004, an SPWLA Topical Conference was held in Taos, New Mexico to address formation evaluation challenges in HA/HZ wellbores. A survey of participants at the end of the conference indicated that the standard qualitative use of logs in HA/HZ wells for geosteering would not be sufficient for many future situations. In many locations vertical assessment wells cannot be drilled and it is critical to evaluate formations using extended reach wells (e.g., drilling from onshore to reach reservoirs offshore). A general consensus was that our current interpretation schemes developed for near-vertical wells often are not adequate for HA/HZ wells. Addressing these challenges will require collaboration between the operating companies and service companies. Operators need to be willing to share examples of the interpretation problems and difficulties currently encountered in evaluating field data. Service companies need to be willing to share current limitations of tool responses and provide additional aids in interpretation (e.g., tool response functions for modeling and chart books) to assist in interpreting HA/HZ wells. Both operators and service companies agreed that some new tool designs are required to obtain quantitative characterization from HA/HZ wells.

Polyakov, V., Habashy, T., Kocian, R., Pabon, J., Anderson, B., 2004, Interactive Log Simulation and Inversion on the Web, SPE 90909, SPE Annual Technical Conference and Exhibition, 26-29 Sep, 2004, Houston, Texas.

Log simulation is critical for understanding and interpreting logging tool responses. It helps the log analyst understand near-wellbore measurements in complex environments, and particularly in anomalous situations. Simulated logs can also be used in “what-if” scenarios or as part of an iterative scheme to invert for the formation's geometry and material properties. We describe our implementation of a forward modeling and inversion environment with a multitier, Web-based architecture. The Web platform offers universal access from the user's desktop through a common Web browser to the simulator engine, running on a high-performance compute server. The application also allows the user to invert for near-wellbore rock properties from a set of logs. In addition to user-accessible Web pages for interactive use of the application, a programmatically accessible log simulation Web Service is created. Regardless of the host platform, this allows any networked application to access the simulator library without the need to replicate code, thus facilitating the development of formation evaluation applications. Because the library is hosted on a high-performance cluster (HPC), the computational engine always runs in the shortest possible time.

Rabinovich, M., Beard, D., Geldmacher, I., Tabarovsky, L., Fidan, M., 2000, Interpretation of Induction Logging Data in Horizontal Well, SPWLA 2000-AAA, 41st Annual logging symposium transactions, 4-7 Jun, 2000, Dallas, Texas.

We have developed a new technique for interpreting induction logging data in horizontal wells. In addition to the accurate formation and invasion resistivity distribution near the borehole wall, the new inversion algorithm allows us to determine the distance to remote layers and their resistivities.The High Definition Induction Logging (HDIL) instrument collects data at multiple frequencies and various transmitter-receiver spacings. Focusing and inversion algorithms are designed for vertical and deviated wells to determine an invasion profile, to measure resistivity deep into the formation, and to provide high vertical resolution.In horizontal wells, the objectives are different. In addition to the resistivity distribution in the borehole vicinity, we wish to determine distances to remote cap rocks and water-bearing horizons. The vertical resolution (or, more accurately, the resolution along the borehole trajectory) is no longer important due to the relatively small lateral variation of the formation parameters. What becomes important is the depth of investigation. Low operating frequencies and long transmitter/receiver spacings allows the HDIL tool to provide reliable information from layers located up to 20 ft away from the instrument.The new inversion algorithm for interpreting induction logging data in horizontal wells consists of three components. First, we determine the parameters of the near zone formation using shallow and medium investigation measurements. At this stage, fast 2-fl inversion allows us to recover invasion and formation parameters without being affected by remote layers. Second, we correct the medium and deep measurements for the presence of the borehole and invasion using the results of the near zone interpretation. Third, we interpret the corrected medium and deep measurements using l-D layered inversion to characterize remote layers.We validate the new approach with a synthetic model consisting of a borehole, invaded formation, and a remote layer. All parameters of interest, such as formation and invasion resistivities (Rt and Rxo), invasion depth (Rxo), and the distance to the remote layer, are recovered with high accuracy (errors less than 10%).We also present a case study for a horizontal well in the North Sea. Successful completion of thewell required distinguishing between low resistivity water-flooded zones with movable water and an underlying tight layer that exhibits low resistivity. The developed algorithms allow quantitative estimation of the distance to, and resistivity o~ the tight layer as well as the resistivity of the permeable formation. The distance to the tight layer correlates with information from seismic data.

Radtke R. J, E., M., Rasmus, J. C., Ellis, D. V., Chiaramonte, J. M., Case, C. R., Stockhausen, E., 2006, Lwd Density Response to Bed Laminations in Horiztonal and Vertical Wells, SPWLA 2006-ZZ, 47th SPWLA Annual Logging Symposium, 4-7 Jun, 2006, Vera Cruz, Mexico.

Despite the increasing prevalence of thinly bedded reservoirs, questions relating to the response of nuclear LWD tools in such fields have gone largely unanswered in the literature. Motivated by specific anomalies in well logs from a field in West Africa, response modeling of a commercial LWD density tool in a layered medium was performed to answer some of these questions. A rich variety of responses was revealed. In a vertical well, an axial geometric factor, the scale of which was set by the source-to-detector distance, determines the response. For layers thinner than this scale, the measured density does not represent the true bed density of the individual layers. In fact, for layers much thinner than this scale, the measured density is the average of the densities of the individual layers. In horizontal wells, a radial geometrical factor governs the response. Although also related to the source-to-detector distance, the scale of the radial geometrical factor is much smaller than that of the axial geometric factor. Consequently, the density measurement in horizontal wells is able to resolve much thinner beds than in vertical wells. Field examples of the LWD tool response to bed laminations in a horizontal well are presented that verify the principles learned from the modeling. Comparisons of the vertical wireline (WL) log response with the horizontal LWD log response reveal the layer geometries in which these logs provide the formation density directly and the layer geometries in which advanced processing and/or modeling are required. The examples confirm that the LWD density logs in high-angle wells can read the true bed density in much thinner beds than a density log in a vertical well can. The result is a more accurate determination of layer porosities, net pay, and hydrocarbons in place.

Rasmus, J. C., Kashikar, S., Liu, A., 1997, Techniques for Accurate Geological Correlations in Highly Deviated and Horizontal Wells When Drilling through Dipping Beds, SPE 37148, International Conference on Horizontal Well Technology, 18-20 Nov, 1997, Calgary, Canada.

Our ability to drill highly deviated and turned wells (sometimes exceeding both 90 degrees of build and turn) has increased significantly. This has necessitated the need for better tools for making accurate log correlations while drilling to keep the well in the pay zone. A new technique is presented which allows for the changing wellbore trajectory geometry, horizontal displacement, and the dip of the bed to be accounted for simultaneously. This allows the beds to be represented accurately in space so that meaningful correlations can be made while drilling. This impacts steering decisions which aim to keep the wellbore in the pay zone.

Rendeiro, C., Passey, Q., Yin, H., 2005, The Conundrum of Formation Evaluation in High-Angle/Horizontal Wells: Observations and Recommendations, SPE 96898, SPE Annual Technical Conference and Exhibition, 9-12 Oct, 2005, Dallas, Texas.

Over the last two decades the process of drilling high-angle and horizontal (HA/HZ) wells has changed from cutting-edge to almost routine. While the industry has developed technologies to log and acquire data from these wells, it has not yet developed the technology to interpret the data quantitatively on a routine basis. Generally, hydrocarbon pore volume (HPV) is calculated from the height, porosity, and water saturation derived from logs in near-vertical wells. Case studies have shown that application of similar procedures in high-angle and horizontal wells can result in values significantly different than those calculated from near-vertical wells. As the apparent wellbore deviation angle increases, so increases the uncertainty in the log-derived properties. Using currently available technology, our observation is that in wells with a relative

angle to the formation greater then 80º, HPV cannot be calculated from logs with the same confidence as from near-vertical wells. While historically this has not been a problem, the impact of increased uncertainty associated with the reliance on HA/HZ wells for reservoir assessment needs to be recognized and addressed.

Rose, P. T. S., 1999, Reservoir Characterization in the Captain Field:Integration of Horizontal and Vertical Well Data, in *5th Petroleum Geology of Northwest Europe Conference*, A. J. Fleet, Boldy, S. A. R. editors, **v. 2:** 1101-1113.

Ryan, N., Hayes, D., 2001, A New Multiphase Holdup Tool for Horizontal Wells, SPWLA 2001-V, 42nd SPWLA Annual Logging Symposium, 17-20 Jun, 2001, Houston, Texas.

Traditional PL analysis requires phase holdup and fluid velocity measurements. Flow in a horizontal well may feature regions of segregated, intermittent and distributed flow, the principle reason being segregation of different density fluids combined with the effects of well deviation (no horizontal well is truly horizontal). Because of phase separation, the measurement of true holdup in horizontal wells using centre-sampling PL tools is difficult, if not impossible. As an approach to obtaining a true holdup in horizontal wells, a new tool has been developed which uses multiple sensors that can be deployed either around the circumference of the pipe or at dual radii. Being at the same depth position in the well, the sensors measure phase holdup with greater confidence. The sensors used are micro-capacitance sensors, which respond to the permittivity (dielectric constant) of the surrounding fluids. Capacitance sensing circuits output different frequencies for gas, oil and water making this a 3 phase tool. The tool is termed the ""Capacitance Array Tool "" (CAT).

Samuel, G. R., Miska S., 2000, Formation Characterization of a Horizontal Well While Drilling: An on-Site Tool, SPE-59129, IADC/SPE Drilling Conference, 23-25 Feb, 2000, New Orleans, Louisiana.

This paper describes a method of predicting formation pore pressure and permeability in a horizontal well during the drilling phase of a well development. Dependable and more accurate information about reservoir parameters such as permeability, pore pressure are indispensable for taking proper well completion decisions at a stage when the formation damage is minimal. In this study, a technique is described which can be used as an onsite tool for the evaluation of formation properties for horizontal wells. Method of analysis is based upon the buildup data collected during a test conducted at various stages of the wellbore penetration in the horizontal section while drilling. Modified well testing theory pertaining to horizontal wells is used for the interpretation of the test results. Examples of using simulated data are provided to demonstrate the practical application of the method. These examples using the proposed approach elaborated in this paper illustrate its practicability and the ease of usage as an onsite tool.

Santoso, U. S., Sunarto, K., 2001, Using the Resistivity and a Gr Log for Guide Control+/- 415 M Slimhole Horwell Section in the 3-5 M Baturaja Limestone Oil Rim Thickness, between Gas Cap and Waterzone at Musi-28 Well, Prabumulih, South Sumatra, SPWLA 2001-Z, 42nd annual logging symposium, 17-20 Jun, 2001, Houston, Texas.

Musi structure is located approximately 120 kilometers West of Prabumulih (Fig 1). It is divided into western and eastern block, based on the structural phenomena defined on the seismic profile. West Musi structure is mainly a gas reservoir. According to the nine wells drilled in this block, it's indicated the reservoar thickness between 80 to 100 meters with a 24 to 36 meters gas cap of Baturaja limestone East Musi accumulation comprises gas cap and oil rim in the reservoir. Based on the log correlation, the gas cap was found between 70 to 80 meters thick, while the oil water rim was only from three to five meters thick above the water zone. A precise horizontal drilling is an alternative solution to optimally penetrate in to this thin oil rim, between the strong gascap & water drive mechanism. Based on the three dead wells (Musi-04, 05 and 06) two wells are no longer producing gas, while the other well gas plugged due to mechanical problem. It is assumed that the oil water contact (OWC) is flat, especially surround in the local area. This assumption was used to propose a horizontal well to drain the oil rim within the Baturaja limestone and. the drilling proposal comes in associated with many major dicipline as teamwork

(Fig. 1). Resistivity and Gamma Ray log sensor that're set on the logging while drilling (LWD) and measured while drilling (MWD) tools, were used to control the horizontal drilling operation. As a result, a total of 415 meters horizontal section was perfectly openhole penetrated with a production test result of 780 barrels oil per day (BOPD) and 8 % to 10 % water cut. This success case will be applied similarly to the up-coming horizontal wells in the local field.

Soliman, M. Y., Boonen, P., 1996, Review of Fractured Horizontal Well Technology, SPE 36289, SPE International Exhibition and Conference, 13-16 Oct, 1996, Abu Dhabi.

Since its introduction in the late 1980's, fracturing of horizontal wells has become a viable completion option. In certain reservoir conditions, horizontal wells offer significant production improvement over vertical wells, however, to maximize their return on investment, it may be necessary to fracture horizontal wells. This is especially true in case of tight gas formations. This paper reviews the technology developed in the area of fracturing horizontal wells. The paper includes discussion on the rock mechanics, the operational, and the reservoir engineering aspects of fracturing horizontal wells. The rock mechanics discussion reviews the various theoretical and experimental work that has been done in the area of fracturing horizontal wells. It also reviews the various phenomena such as creation of transverse and longitudinal fractures, creation of multiple fractures, and fracture reorientation among others that are associated with creation of a fractured horizontal well. Stability of the horizontal well as it relates to stimulation is also discussed. The reservoir engineering portion of the paper discusses the production performance and testing aspects of a fractured horizontal well. Emphasis is given to fracturing tight gas formations, since this area is the one in which this technique is considered to be the most effective. The performance of a longitudinal fracture is examined and compared to a fractured vertical well and to the more popular transverse fractured horizontal well. Because performance of a longitudinal fracture is similar to that of a fractured vertical well, the existing solutions for fractured vertical wells may be applied to longitudinal fractures. This approximation is valid for moderate to high dimensionless conductivity. In the case of transverse fractures, the outer fractures outperform the inner fractures. However, for most cases, more than two fractures are necessary to efficiently produce the reservoir. Operational aspects of fracturing horizontal wells for both transverse or longitudinal fractures are discussed, and advantages and disadvantages of each type will be outlined. Examples and case histories are discussed. The paper also presents guidelines for stimulation of a horizontal well and includes both propped and acidized fracturing as well as matrix acidizing.

Soliman, M. Y., Boonen P.,2000,Rock Mechanics and Stimulation Aspects of Horizontal Wells,Journal of Petroleum Science and Engineering, **25**,187-204,

In certain reservoir conditions, horizontal wells can offer significant production improvement over vertical wells; however, fracturing is often required to maximize the return on investment for these wells. Since its introduction in the late 1980's, the practice of fracturing horizontal wells has become a viable completion option. This is especially true in the case of tight gas formations. This paper reviews best practices in the fracturing of horizontal wells and includes a discussion on the rock mechanics, operational strategies, and the reservoir engineering aspects of fracturing horizontal wells. The rock mechanics discussion reviews the theoretical and experimental work and creation of: (1) transverse and longitudinal fractures, (2) multiple fractures, and (3) fracture reorientation among othe factors tha are associated with creation of a fractured horizontal well. Stability of the horizontal well as it relates to stimulation is also discussed. The reservoir engineering portion discusses the production performance and testing aspects of a fractured horizontal well. Emphasis is given to fracturing tight gas formations since this area is theone in which this technique is considered to be the most effective. The performance of a longitudinal fracture is examined and compared to a fractured vertical well and to the more popular transverse-fractured horizontal well. Because performance of a longitudinal fracture is similar to that of a fracture in a vertical well, the existing solution for fractured vertical wells may be applied to longitudinal fractures. This approximation is valid for moderate to high dimensionless fracture conductivity. In the case of transverse fractures, the outer fractures outperform the inner fractured. However, for most casess, more than two fractures are necessary to efficiently produce the reservoir. Operational aspects of fracturing horizontal wells for both transverse and

longitudinal fractures are discussed, and advantages and disadvantages of each type are outlined. Examples and case histories are given. The paper also presents guidelijnes for stimulation of a horizontal well and includes both propped- and acidized fracturing as well as matrix acidizing.

Stacey, E. S., Rogers, C.T., Bowman, J.K., Noblett, B.R., Cooney, M.F., 1992, Case History of a Horizontal Well Using a High-Angle Pilot Hole, SPE 23880, SPE/IADC Drilling Conference, 18-21 Feb, 1992, New Orleans, Louisiana.

Petro-Hunt Corporation drilled a horizontal well in the Austin Petro-Hunt Corporation drilled a horizontal well in the Austin Chalk in Gonzales County, Texas. A high-angle pilot hole was used to determine a target interval and horizontal borehole orientation, while satisfying a variety of operational and geological considerations. The well was directionally drilled to an angle of 44 degrees and intermediate casing was set. The pilot hole was then drilled at the same angle through the target formation and evaluated using openhole logs, including a circumferential acoustic imaging device. After evaluation, the pilot hole was plugged back, and the horizontal borehole was kicked off and drilled to a horizontal displacement of 3,578 ft. This method allowed the entire target formation to be evaluated prior to committing the well bore to a particular interval, while prior to committing the well bore to a particular interval, while avoiding potential operational problems associated with a vertical pilot hole. The acoustic imaging log allowed the operator to select the optimum stratigraphic interval in which to locate the horizontal borehole, and confirmed the proper borehole orientation. The well was successfully completed on schedule and within budget. The planning and drilling of the well is reviewed, with emphasis placed on operational and geological considerations and the placed on operational and geological considerations and the evaluation of the pilot hole.

Stockhausen, E. J., Lesso Jr., W.G., 2003, Continuous Direction and Inclination Measurements Lead to an Improvement in Wellbore Positioning", SPE 79917, SPE/IADC Drilling Conference, 19-21 Feb, 2003, Amsterdam, The Netherlands.

The measurement of continuous real-time inclination provides near instantaneous calculations of the build-up rate tendency of a bottom hole assembly in both rotary and slide drilling modes. The addition of an azimuthal measurement now allows for the calculation of wellbore position with this continuous data. The true nature of the wellbore curvature in slide/rotate directional drilling with steerable systems is lost when using the typical 90-foot survey interval. Continuous surveying shows this effect. When wellbore position is calculated with the continuous surveys, a significant positional discrepancy from the stationary surveys can occur.

A study was conducted using both stationary and continuous survey data from over 20 wells in Nigeria, Angola, the Gulf of Mexico, the North Sea and Indonesia. The objective was to determine the magnitude and scope of TVD positional error caused by the different slide and rotate curvatures between stationary surveys on a wide range of wells. These curvatures are not reamed out as commonly thought. They can still be seen in continuous gyro surveys taken after drilling has finished. This positional effect is not a function of the sensor accuracy, but it is a result of the environment in which surveys are measured. We show that in a horizontal well the effect can accumulate up to plus/minus 25 ft TVD. The implications of these results are far reaching. Survey positions are used in creating structure and reservoir maps, which are used in determining reserves and recovery efficiencies, and in turn for making field management decisions.

This paper highlights the results of the field studies. A review of rotary steerable system operations shows that the effect is much less than with steerable motors, but can still be of concern.

A low-cost solution for effectively determining when to slide and rotate with respect to the stationary survey is presented. This procedure results in a positional accuracy that can be maintained without changing survey data management practices.

Stockhausen, E. J., Smith, G.E., Peters, J.A., Bornemann, E.T., 2003, Flexible Well-Path Planning for Horizontal and Extended-Reach Wells, in *Horizontal Wells: Focus on the Reservoir*, T. R. Carr, Mason, E.P., Feazel, C.T. editors, AAPG Methods in Exploration, **No.14:** p. 227-248.

Tabanou, J., Bruce, S., Bonner, S., Wu, P., 1997, Time Lapse Opens New Opportunities in Interpreting 2-Mhz Multispacing Resistivity Logs under Difficult Drilling Conditions and in Complex Reservoirs SPWLA 1997-II, SPWLA 38th Annual Logging Symposium, 15-18 Jun, 1997, Houston, Texas.

Curve separation between 2-MHz resistivity multi-depth-of-investigation logs is often the first indicator at the well site that ?something? is happening in the reservoir that does not fit a preconceived paradigm. Such curve separation can result from dynamic hole damage by heavy mud, anisotropy in highly deviated wells or permeability variations in carbonates. The thrust of this paper is to emphasize the importance of time-lapse logging. Time-lapse logging helps in differentiating curve separation caused by reservoir geometry, such as layered reservoirs drilled in high-angle wells, from separations induced by fluid displacement and formation damage. Several examples of ARC5 Array Resistivity Compensated tool logs are discussed that demonstrate the power of 2 MHz multidepth of investigation resistivity logs when combined with advanced modeling capabilities and multipass logging.

Tabanou, J., Anderson, B.,Bruce, S., Borneman,T., Hodenfeld, K., Wu, P., 1999, Which Resistivity Should Be Used to Evaluate Thinly Bedded Reservoirs in High-Angle Wells?, SPWLA 1999-E, SPWLA 40th Annual Logging Symposium, 30 May - 03 Jun, 1999, Oslo, Norway.

Thinly bedded sandstone reservoirs are being developed extensively offshore. Most wells in these developments are high-angle or horizontal and logging-while-drilling (LWD) is the common choice of data acquisition. These reservoirs reveal a large resistivity anisotropy when logged with 2-MHz tools in high-angle wells. Log data can be inverted to compute horizontal resistivity (Rh) and vertical resistivity (Rv). However, the anisotropy effect can be hidden if invasion is sufficiently deep. Furthermore, relative dip is required for accurate inversion of Rv . But even when an accurate Rh and Rv estimation is made, the question remains "which resistivity should be used to calculate hydrocarbon reserves?"Firstly, with three-dimensional (3-D) modeling, this paper establishes the conditions of invasion under which Rv and Rh estimates can be used reliably. Density images from a LWD tool provide a means to calculate the relative dip for use as required input to the Rv Rh inversion.Secondly, traditional methods for determining water saturation that use only Rh require accurate inputs of shale volume and bound water resistivity. This paper proposes a method of using Rv , Rh and an input for the resistivity of the shale laminations to derive the resistivity of the clean sand layers and the net-to-gross ratio. Hydrocarbon volume is similarly calculated by either the traditional Rh method or by the proposed method using both Rh and Rv. A universal interpretation chart is presented for Rv Rh space to facilitate quick-look detection of thinly bedded pay sands and the estimation of oil in place. Log examples demonstrating the use of these techniques are presented.

Tamarchenko, T., Frenkel, M.A., Mezzatesta, A.G., 1999, Three-Dimensional Modeling of Microresistivity Devices, in *Three-Dimensional Electromagnetics*, M. Oristaglio, Spies, B. editors, SEG Geophysical Development Series, p. 600-610.

Tarouilly, L., Rabinovich, M., Wang, T., Pedron, B., 2003, 3d Simulation of Array Induction Logging in Deviated Well Environments: A Mahakam Delta Case Study, SPE 84600, SPE Annual Technical Conference and Exhibition, 5-8 Oct, 2003, Denver, Colorado.

Array induction measurements have been routinely used in the Mahakam Delta, Indonesia, in near vertical wells with oil-based mud and little or no washouts. In these conditions, even a small separation of the shallow focused curves from the deep curves gives a reliable indication of the mud filtrate invasion. The presence or absence of resistive invasion has been used as an indicator of water or hydrocarbon-bearing reservoirs. However, in deviated wells (above 30-40 degrees) the standard focused induction curves may exhibit erratic spikes and curve separation. Therefore, without proper corrections for the dip effects, the separation of the focused curves cannot be used as a reliable indicator of invaded zones and consequently for hydrocarbon typing in deviated wells. To investigate the effects of the relative dip on the array induction measurements in the Mahakam Delta's specific environment of thinly laminated shaly sands and whether these effects can be properly dealt with, a 3D forward modeling project was conducted.

Two 80-m intervals were selected from a neighboring vertical well to build a resistivity model. 2-D inversion was applied to recover the bed boundaries and resistivities. The resistivity model was used in the 3-D forward modeling to produce an array induction response in the 45-degree deviated well. To reduce the computational costs, intervals with no invasion were simulated with a 1-D modeling algorithm without a borehole, since the borehole effect could be easily corrected for the oil-based mud. The 3-D synthetic response combined with the 1-D response for both standard vertical well processing and well-site enhanced processing (Inhomogeneous Background Focusing -IBF) allowing for the dip-effect correction. The results clearly indicate that the dipping bed effects for the 45-degree deviated well can significantly distort the focused curves, if data are processed as in a vertical well. These distortions manifest themselves as an artificial separation that does not permit fluid typing. After the dip-effect correction with the IBF processing, the focused curves show no separation in an uninvaded formation (as desired) and depict appropriate separation in invaded layers, which again allows for reliable fluid typing.

Verzhbitskii, V. V.,1997,Forward Problems of Electrical Logging in a Horizontal Well,Izvestiya Physics of the Solid Earth, no. 3: 233-236,

Werngren, O., Clay, T., 2000, Geo-Oriented Horizontal Drilling in the Rotliegend?A Learning Experience, SPE 65166, SPE European petroleum conference (EUROPEC), 24-25 Oct, 2000, Paris, France.

This paper describes the successful application of geo-oriented LWD technology to the precision drilling of 4 horizontal reservoir sections in complex Rotliegend wells in the UK Southern North Sea (SNS). Detailed planning, teamwork and acquisition of real-time data enabled the sub-surface team to drill the wells efficiently, applying continuous improvements to the geo-orienting technique through an inherent feedback and learning process. As a result, a significant reduction in cost/foot was achieved throughout the campaign. One of the field developments was subsequently benchmarked as a Best In Class project by the 1999 IPA benchmarking report.

Williamson, H. S., 1999, Accuracy Prediction for Directional Mwd, SPE 56702, SPE Annual Technical Conference and Exhibition, 3-6 Oct, 1999, Houston, Texas.

This paper describes a new method for predicting wellbore position uncertainty which responds to the current needs of the Industry. An error model applicable to a basic directional MWD service is presented and used for illustration. As far as possible within the limitations of space, the paper is a self-contained reference work, including all the necessary information to develop and test a software implementation of the method. The paper is the product of a collaboration between the many companies and individuals cited in the text.

Woodhouse, R., Opstad, A., Bryce Cunningham A., 1991, Vertical Migration of Invaded Fluids in Horizontal Wells, SPWLA 1991-A, 32nd SPWLA Annual Logging Symposium, 16-19 Jun, 1991, Midland, Texas.

The vertical migration of water and oil based mud filtrates has been observed for many years in conventionally drilled wells. This work investigates the nature of these same phenomena in horizontal wells. Here, the vertical migration of invaded fluids is not along the well axis, but rather moves normal to, and away from the borehole. In formations with moderate to high permeability and high Kv/Kh ratios, invaded filtrates will migrate vertically, propelled by density contrasts between the mud filtrate and formation fluid. In horizontal wells this process acts to pull water-base filtrates down and away from the well, allowing hydrocarbons originally present in the formation to migrate back toward the wellbore. Density contrasts similarly influence the migration of oil-base mud filtrates which rise in water bearing formations and fall in gas bearing formations. Cross-sections taken through a theoretical well model for a series of increasing formation exposure times illustrate expected fluid migration patterns. Field, examples of neutron and other Formation-Evaluation-While-Drilling (FEWD) logs support fluid saturation changes predicted by our model. As expected, oil based filtrate invasion in the oil column did not alter reservoir fluid saturations above the transition zone, and showed no gravitational segregation effects. In gas bearing formations, near wellbore gas saturation initially decreases due to filtrate invasion, then increases through time as oil or water-base filtrates drop away from the horizontal wellbore. This dynamic behavior is documented by time-lapse MWD logging.

Wu J.Q., W. M., Barnett, W.C., 1991, Bed Boundary Detection Using Resistivity Sensor in Drillling Horizontal Wells
SPWLA 1991-B, 32nd SPWLA Annual Logging Symposium, 16-19 Jun, 1991, Midland, Texas.

Naturally formed geological bed boundaries are not necessarily horizontal and may not be perfect planes. A predetermined course of drilling cannot ensure that the well being drilled stays in the producing bed. One of the most important technical issues in horizontal drilling is, therefore, how to detect the bed boundary as early as possible so that the well can stay in the hydrocarbon producing bed. In this paper, we study the use of 2 MHz dual resistivity readings to detect bed boundaries in horizontal and near horizontal wells. The resistivity tool consists of one transmitter antenna and two receiver antennas. The distances between the transmitter and the near and far receiver antennas are 27. 5 and 34. 5 inches, respectively. A schematic diagram of the tool is shown in figure 1. In the following, we first examine the theoretical tool responses when the tool is near a bed boundary at large dip angles. Features that can be used to detect bed boundaries are discussed. Then, two horizontal well logs are analyzed. Qualitative comparisons are made between the model responses and the logs.

Wu, J. Q., Wisler, M. M., Meyer, W. H., 1997, Measurement of Dip Angle and Horizontal and Vertical Resistivities Using Multiple Frequency Propagation Resistivity Tools, SPWLA 1997-C, 38th SPWLA Annual Logging Symposium, 15-18 Jun, 1997, Houston, Texas.

It has been shown that using resistivity tools with axial-dipole antennas one can measure horizontal resistivity and a function of vertical resistivity and relative dip angle. Without additional information, the vertical resistivity and relative dip angle can not be uniquely determined no matter how many antenna spacings and/or frequencies are used in the measurement. The determination of horizontal resistivity and the function of vertical resistivity and relative dip angle using resistivity tool measurements is a nonlinear inversion process. Stability and uniqueness of the solution are two problems associated with the nonlinear inversion process. To accurately and uniquely determine the horizontal resistivity and the function more than two measurements are required At high frequencies where the dielectric effect becomes important, the horizontal resistivity can not be determined with only two measurement in deviated wells. When dielectric effect is significant, the antenna readings are affected by five formation parameters: two resistivities, two dielectric constants and the dip angle. Four independent parameters derived from the five formation parameters completely determine the antenna readings. Therefore, all five formation parameters can not be determined without using a piece of information from sources other than the tool readings. Factors causing the resistivity anisotropies necessarily cause dielectric anisotropies. The resistivities and dielectric constants of a given formation are not independent of each other. Once the relationship between them is established for a given formation type, one can use the four parameters measured plus the formation anisotropy model to uniquely determine all five formation parameters. If the relative dip angle is known, the resistivities and dielectric constants can be determined without any formation models.

Wu, P. T., Tabanou, J.R., Bonner, S.D., 1996, Petrophysical Interpretation of a Multispacing 2-Mhz Mwd Resistivity Tool in Vertical and Horizontal Wells, SPE 36547, SPE Annual Technical Conference and Exhibition, 6-9 Oct, 1996, Denver, Colorado.

The multiple phase shift and attenuation resistivities from a 2-MHz array resistivity tool provide the log analyst with the measurements needed to resolve complex interpretation problems associated with high relative dip formations typical in horizontal and highly deviated wells. With the support of modeling, productive zones can be located that may otherwise be missed. In high relative dip formations, the interpretation of multispacing 2-MHz resistivity tools and the comparison with wireline logs are not straightforward. Therefore, it is imperative for the log analyst to understand the unique response characteristics of these measurements in both vertical and horizontal wells. In high relative dip formations, the primary factors that may cause the resistivity curves of different spacings to separate are borehole effects, invasion, bed boundary proximity and anisotropy. With the help of forward modeling codes and inversion algorithms, the log analyst can resolve most of the interpretation ambiguities. The responses of a 2-MHz array resistivity tool, with five measurement spacings, to the above factors are illustrated and

discussed. Traditional rules of thumb based on vertical well must be modified significantly. Productive zones that would be missed by logs made in a vertical well can easily be detected by logs made in a high-angle or horizontal well through the same formation. A comparison of the resistivity responses of a 2-MHz tool in low and high relative dip formations helps explain the differences between logs made in low-angle and high-angle wells.

Xiao, J., Geldmacher, I., Rabinovich, M., 2000, Deviated-Well Software Focusing of Multiarray Induction Measurements SPWLA 2000-DDD, SPWLA 41st Annual Logging Symposium, 3-7 Jun, 2000, Dallas, Texas.

In highly deviated wells or when the relative dip angle between formation layering and wellbore axis is large, array induction measurements exhibit erratic spikes, misleading curve separations, and inaccurate resistivity values, preventing log analysts from accurately evaluating invasion and formation resistivities.To address these problems, various correction methods and inversion techniques have been developed. The correction methods, however, only yield satisfactory results when the relative dip angle is low to moderate, and inversion techniques are typically very time consuming.Conventionally, dipping bed effects are considered in terms of a charge effect and a volumetric effect. As even more complex earth models are considered, we find that formation anisotropy also exaggerates the dipping effect, manifested by misleading curve separations in the array instrument readings. Our newly developed deviated-well software focusing (DSF) method simultaneously accounts for all these dipping effects.The DSF method is derived from the Born approximation. The induction response is separated into two portions: a background response and a perturbation response. An inhomogeneous, anisotropic background formation model is used to calculate the background response, and the perturbation response is interpreted through a software focusing technique. The combination of the two solutions is the final result.After description of the theory and methodology, this paper presents synthetic and field examples. We show that our method significantly reduces spurious separation between shallow and deep reading curves and minimizes the confusion between apparent and real invasion.

Yamamoto, H., Watanabe, S., Koelman, J. M. V., Geel, J., Brie, A., Fujii ,K., Coates, R., 2000, Acoustic Reflection Survey Experiments in Horizontal Wells for Accurate Well Positioning, SPE 65538, SPE/CIM international conference on horizontal well technology, 6-8 Nov, 2000, Calgary, Alberta, Canada.

Reservoir management optimization requires a detailed description of the geometry and the properties of the reservoir. For horizontal wells, knowing accurately the position of the borehole in the reservoir is critical. However, seismic techniques do not have sufficient resolution to provide the position of the well with respect to the reservoir boundaries with desired accuracy. Sonic measurement on the other hand has the potential to provide such information. We conducted experiments in horizontal wells in Oman using a commercial multi-receiver sonic tool modified for imaging, with extended spacing between the transmitter and the receivers. Although the tool characteristics are not optimized for the imaging, we obtained interesting results when the reflectors have sufficient strength, thus showing the potential of this technique. The pre-processed and migrated sonic images provided useful information on the geometry of the reservoir, which could be compared with seismic interpretation and field knowledge. Furthermore, we developed a specific processing technique that uses the four different waveforms acquired around the tool at each receiver station to separate the reflections coming from above the well and the ones coming from below. In this way, we could obtain images that could be interpreted more easily. In some instances, the position of the reservoir boundaries could be determined with an accuracy of 1 m up to a maximum distance of 10 m.

Yang, J., Omeragic, D., Liu, C., Smits, J., Wilson, M., 2005, Bed-Boundary Effect Removal to Aid Formation Resistivity Interpretation from Lwd Propagation Measurements at All Dip Angles, SPWLA 2005-F, 46th SPWLA Annual Logging Symposium, 26-29 Jun, 2005, New Orleans, Louisiana.

Logging-while-drilling (LWD) resistivity measurements are frequently affected by shoulder or proximity beds. Traditional corrections to formation resistivity at the center of the bed based on premodeled charts are not practical for horizontal wells, for which the distance to boundary and shoulder resistivities is usually not known. The fact that such corrections must be applied over thousands of meters adds to the difficulty. This paper presents a model-based inversion approach to remove the shoulder-bed effect in multispacing LWD propagation resistivity tool measurements in high-angle and horizontal wells by inverting for the true formation and shoulder resistivities and the distance to the shoulder at the same measurement depth. A three-bed effective model to approximate the formation effect above and below is used. This model greatly reduces the complexity of the problem, allowing petrophysicists a practical interpretation. Although formation layers above and below influence the measurements, the paper demonstrates that the responses are not sensitive to the fine details of the shoulder-bed formation and that an effective three-bed model is accurate enough to represent complex layered formations for shoulder-bed correction purposes. A heuristic-based strategy selects the best solution from multiple candidates to improve the consistency of the inversion results and remove ambiguity caused by multiple solutions. Considerable optimization speeds up the inversion for quick interpretation. The algorithm has been tested successfully against synthetic and actual field logs. When it is a dominant environment effect, the shoulder-bed effect can be removed and true formation resistivity obtained. In certain situations, the distance to the boundary can be determined when within 3 ft true vertical depth of the boundary. Integration of bed boundary correction with those of other single environmental effects will also be presented.

Yang, W., 2005, Numerical Simulation of Dual-Laterolog Measurements in the Presence of Dipping, Anisotropic and Invaded Rock Formations, SEG Annual Conference,

Yin, H., Han, X., Xu, L., Guo, W., Shebata, A., Gardner, R.P., 2006, Field and Benchmark Studies of Lwd Nuclear Tool Response in High Angle and Horizontal Wells, SPWLA 2006-AAA, 47th SPWLA Annual Logging Symposium, 4-7 Jun, 2006, Vera Cruz, Mexico.

With more and more high-angle and horizontal (HA/HZ) wells drilled for hydrocarbon exploration and exploitation, some significant differences have been observed between nuclear logs from vertical wells and logs from HA/HZ wells in the same stratigraphic section. These differences are noted even when the vertical and HA/HZ wells nearly intersect. Benchmark Monte Carlo simulations with generic LWD neutron and density tool specifications were conducted to understand these differences. The benchmark simulation cases include (a) bed boundary and depth of investigation effects; (b) azimuth and dip effects; (c) oval-shaped borehole shape and cuttings effects; (d) thin bed or anisotropy effects.

Yost II, A. B., Javins, B.H., 1991, Overview of Appalachian Basin High-Angle and Horizontal Air and Mud Drilling, SPE 23445, SPE Eastern Regional Meeting, 22-25 Oct, 1991, Lexington, Kentucky.

The United States Department of Energy's Morgantown Energy Technology Center has been investigating the potential of using high angle and horizontal drilling technology to improve gas production from low permeability reservoirs for more than 20 years. A chronology of 45 high angle and horizontal wells have been identified to show the date, type well, type build curve, location, formation and the type of application. The historical well drilling events that have taken place since the first well are place since the first well are discussed to evaluate the progress in developing the technology. Detailed discussion about how the drilling technology developed in the Appalachian Basin for directional drilling and completion was provided. provided. A discussion of the types of applications for high and horizontal drilling in the Appalachian Basin were identified. A summary of four jointly funded DOE/Industry horizontal wells were discussed to illustrate how the air horizontal drilling technology developed and learning curves for drilling cost and feet per day were provided to illustrate the provided to illustrate the improvement in the technology and equipment reliability.

Yu, L., Kriegshauser, B., Wang, T., 2004, Real Time Processing of Multicomponent Induction Tool Data in Highly Deviated and Horizontal Wells SPWLA 2004-ZZ, 45th SPWLA Annual Logging Symposium, 6-9 Jun, 2004, Noordwijk, The Netherlands.

Interpretation of multicomponent induction data acquired in vertical or moderately deviated (?near? vertical) wells has matured over recent years. However, the interpretation for highly deviated (>70 degrees) wells remains an area of challenge. We found that interpretation schemes and strategies that work very well in the ?vertical? well scenario might not be applicable anymore in highly deviated wells, with relative dip angles greater than 70 degrees. The reason is the tool behavior for high deviation angles is different from that for vertical wells and, more importantly, the pancake-layered models frequently used for vertical well interpretation require an accurate formation dip estimate. To address this challenge, we propose a new and robust processing and interpretation technique based on an anisotropic whole-space model, i.e., a model without bed boundaries and borehole. The whole-space model has also been used for near vertical well interpretation. However, because the tool response is different in highly deviated wells, the procedure must be used differently. For near vertical wells, the conventional Hzz-component is solely sensitive to the horizontal resistivity, Rh, of the formation. The skin effectcorrected Hxx- and Hyy-components depend primarily on the vertical resistivity, Rv. For highly deviated wells, however, the skin effect-corrected Hxx and Hyy data depend on Rh and the Hzz data depend on both Rh and Rv. To remove the borehole and/or near-zone effects in the data, we routinely apply a dual frequency transformation of the data or apply multi-frequency focusing. The sum of the dual frequency Hxx and Hyy data depends mainly on Rh and is independent of a relative formation azimuth. With these observations, we derive a new iterative approach that allows us to approximate Rh and Rv for highly deviated wells using either single and/or dual-frequency measurements. The synthetic results discussed in this paper demonstrate that the inverted horizontal and vertical resistivities are close to the true values in most layers. The field data example shows that the inverted Rh and Rv values are well constrained by the conventional, array inductionderived resistivity. The algorithm is extremely fast, hands-off, and can be implemented for real-time processing to allow decision-making on the wellsite. These results can then be further refined in postprocessing. Interpretation of multicomponent induction data acquired in vertical or moderately deviated (?near? vertical) wells has matured over recent years. However, the interpretation for highly deviated (>70 degrees) wells remains an area of challenge. We found that interpretation schemes and strategies that work very well in the ?vertical? well scenario might not be applicable anymore in highly deviated wells, with relative dip angles greater than 70 degrees. The reason is the tool behavior for high deviation angles is different from that for vertical wells and, more importantly, the pancake-layered models frequently used for vertical well interpretation require an accurate formation dip estimate. To address this challenge, we propose a new and robust processing and interpretation technique based on an anisotropic whole-space model, i.e., a model without bed boundaries and borehole. The whole-space model has also been used for near vertical well interpretation. However, because the tool response is different in highly deviated wells, the procedure must be used differently. For near vertical wells, the conventional Hzz-component is solely sensitive to the horizontal resistivity, Rh, of the formation. The skin effectcorrected Hxx- and Hyy-components depend primarily on the vertical resistivity, Rv. For highly deviated wells, however, the skin effect-corrected Hxx and Hyy data depend on Rh and the Hzz data depend on both Rh and Rv. To remove the borehole and/or near-zone effects in the data, we routinely apply a dual frequency transformation of the data or apply multi-frequency focusing. The sum of the dual frequency Hxx and Hyy data depends mainly on Rh and is independent of a relative formation azimuth. With these observations, we derive a new iterative approach that allows us to approximate Rh and Rv for highly deviated wells using either single and/or dual-frequency measurements. The synthetic results discussed in this paper demonstrate that the inverted horizontal and vertical resistivities are close to the true values in most layers. The field data example shows that the inverted Rh and Rv values are well constrained by the conventional, array inductionderived resistivity. The algorithm is extremely fast, hands-off, and can be implemented for real-time processing to allow decision-making on the wellsite. These results can then be further refined in postprocessing.