AV Field Cases of the Combined Deterministic Petrophysical Inversion of Gamma-Ray, Density, and Resistivity Logs Acquired in Thinly Bedded Clastic Rock Formations*

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Abstract

Limited vertical resolution of logging tools causes shoulder-bed effects on borehole measurements; therefore biases in the assessment of porosity and hydrocarbon saturation across thinly bedded rock formations. Previously, a combined inversion procedure was developed for induction resistivity and density logs to improve the petrophysical assessment of multi-layer reservoirs. In this article, we include the inversion of gamma-ray (GR) logs in the interpretation method and evaluate three field cases that comprise hydrocarbon-saturated Tertiary turbidite sequences. Formations under consideration are unconsolidated to poorly consolidated. All wells were drilled with oil-base mud (OBM), logged with triple-combo tools, and sampled with whole and sidewall cores.

We transform layer-by-layer inversion results into petrophysical properties via a shaly-sand model. On average, inversion results yield 19% better agreement to core measurements and lead to 28% increase in hydrocarbon reserves when compared to standard well-log interpretation procedures.

The wide variety of sand-shale distributions and layer thicknesses included in the example data sets enables us to generalize recommendations for best practices of combined inversion, including criteria for bed-boundary detection, sensor selection, and modification of our “UT Longhorn Tool” flux sensitivity functions (FSFs) to replicate those of commercial tools. The most critical step for reliable and accurate inversion results is the detection/selection of bed boundaries. Inversion of field data also indicates that the minimum bed thickness resolvable with combined inversion is about 0.7ft, and that inflection points of density logs are the best option for bed-boundary detection.

We show that combined inversion allows the detection of noisy, inconsistent, and inadequate measurements, including cases of abnormal measurement-correction biases otherwise difficult to diagnose on processed logs.

Reference

Campbell, C.V., 1967, Lamina, laminaset, bed and bedset: Sedimentology, v. 8/1, p. 7-26.

FIELD CASES OF THE COMBINED DETERMINISTIC PETROPHYSICAL INVERSION OF GAMMA-RAY, DENSITY, AND RESISTIVITY LOGS ACQUIRED IN THINLY BEDDED CLASTIC ROCK FORMATIONS

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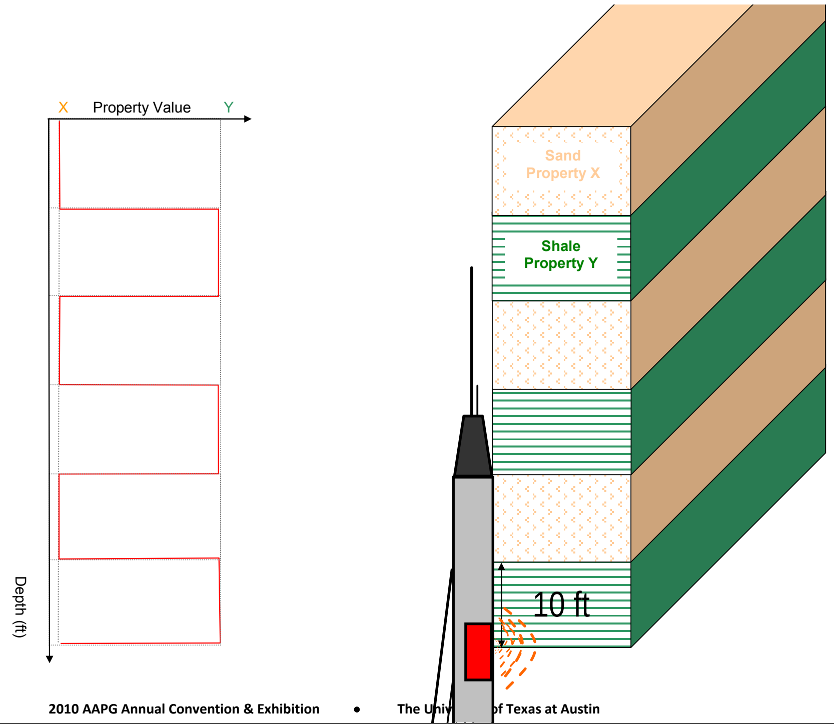
Outline

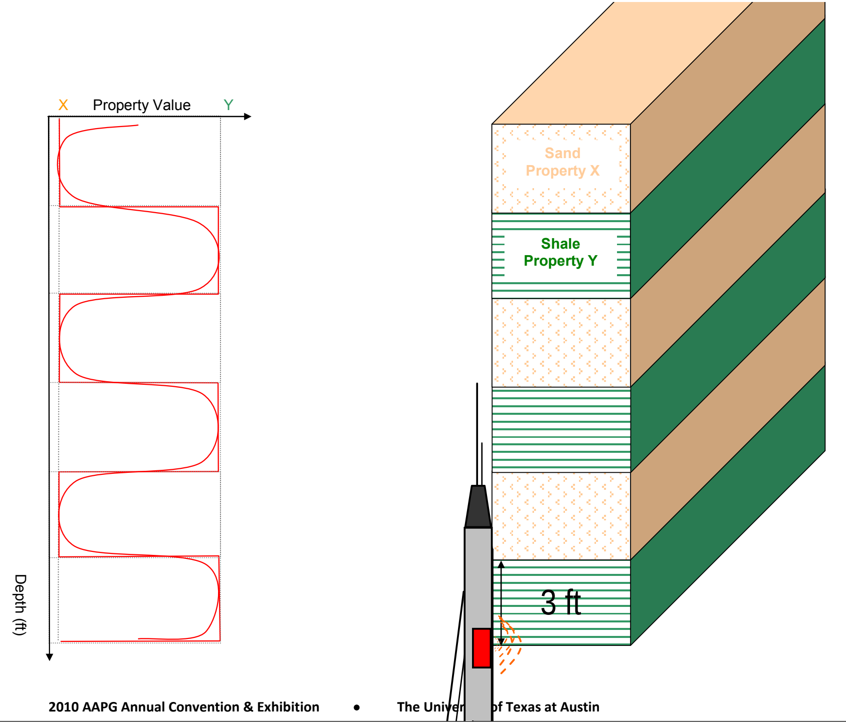
- Introduction to shoulder-bed effect on logs and inversion
- Field cases
  - Well No. 1
  - Well No. 2
  - Well No. 3
- Considerations for inversion
- Log Quality Control through inversion
- Conclusions

Shoulder-Bed Effects



Notes of Presenter:

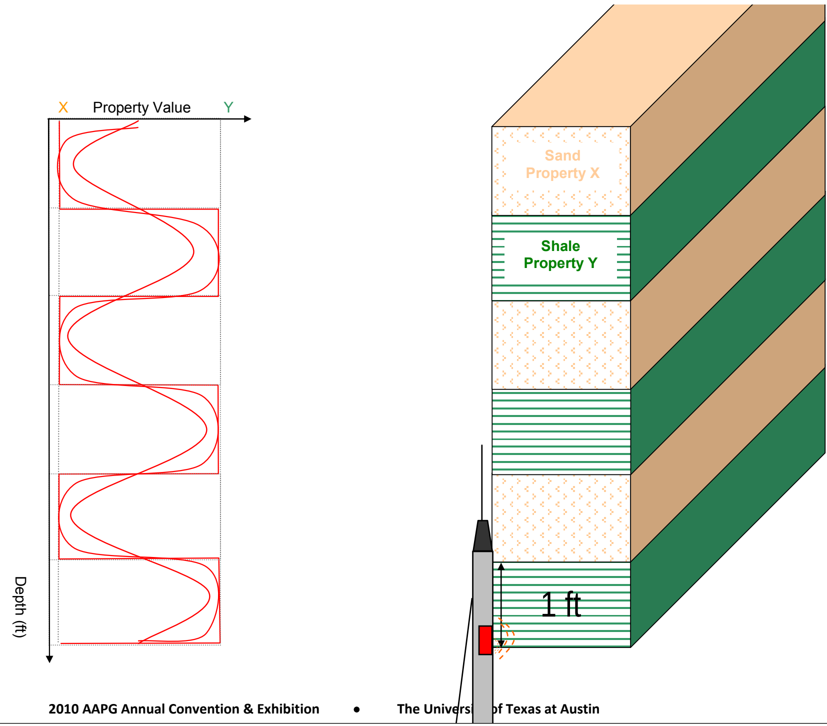
Consider a formation composed by equally spaced layers of sand and shale--thick, first.



Notes of Presenter:

Consider a formation composed by equally spaced layers of sand and shale—medium in this case.

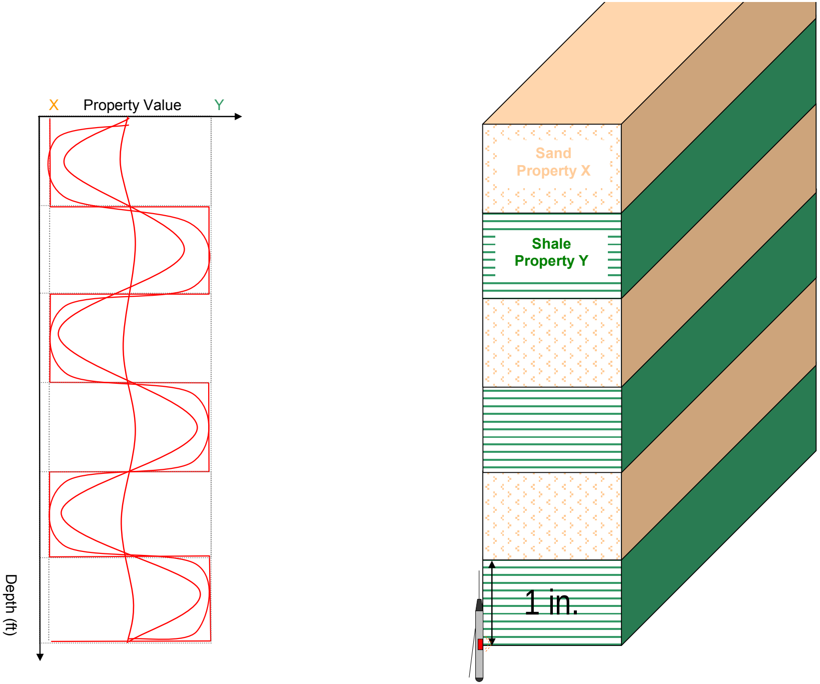
Shoulder-Bed Effects



Notes of Presenter:

Consider a formation composed by equally spaced layers of sand and shale—thin in this case.

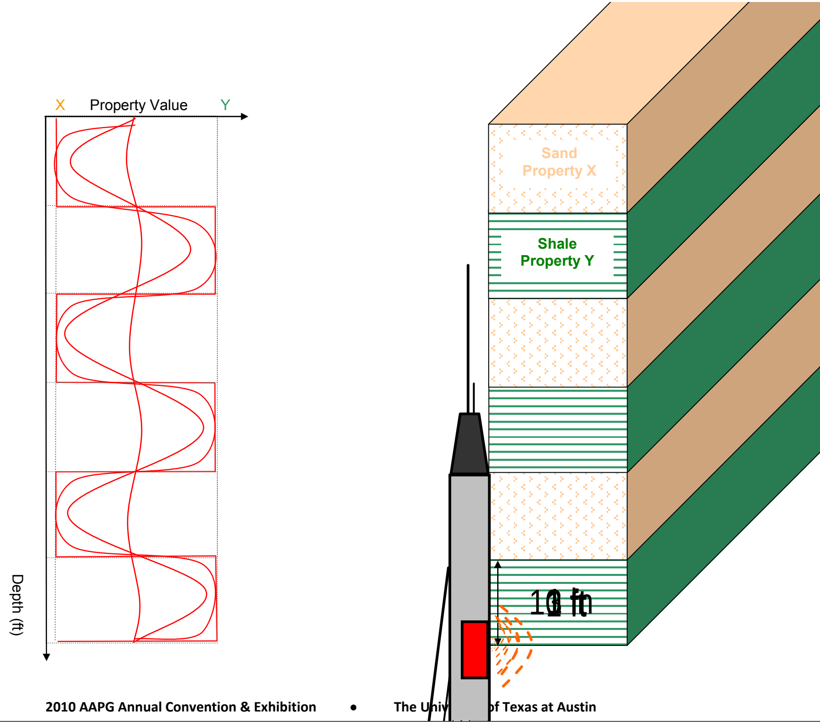
Shoulder-Bed Effects



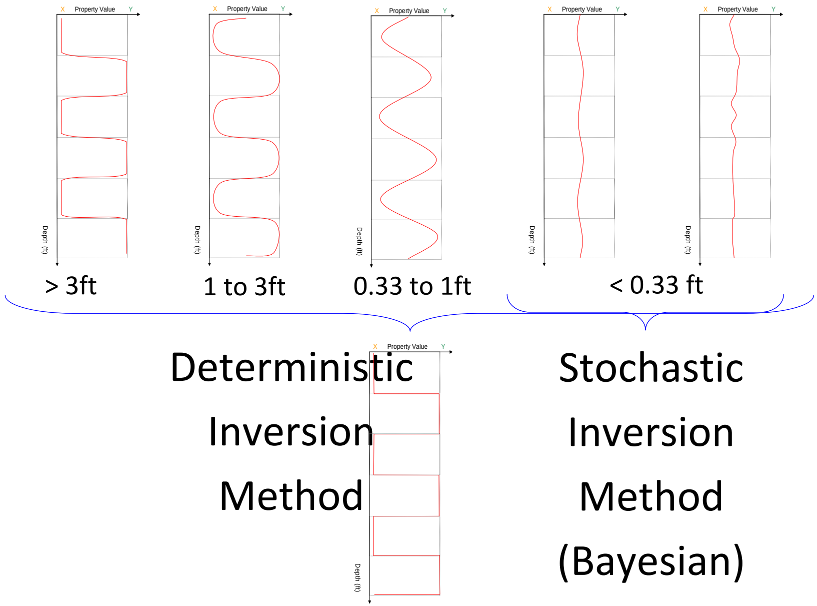
Notes of Presenter:

Consider a formation composed by equally spaced layers of sand and shale—lamination.

Shoulder-Bed Effects



Deterministic and Stochastic Methods



Notes of Presenter:

Thus the objective is to correct logs affected by shoulder-bed effects …wavy… square or true properties of a multilayer model.

Deterministic Combined Inversion Steps

1. Detection of bed boundaries of the multilayer model.
2. Separate inversion of density, GR, and induction resistivity logs based on raw measurements.
3. Forward simulation of inverted layer properties to calculate data misfits.
4. Calculation of petrophysical properties from inversion results based on a shaly-sand saturation equation (e.g. Dual-Water, Waxman-Smits, etc.)

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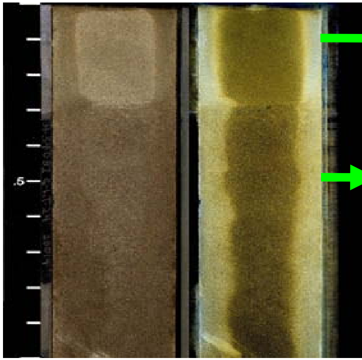
Field Cases: Outcrop Example

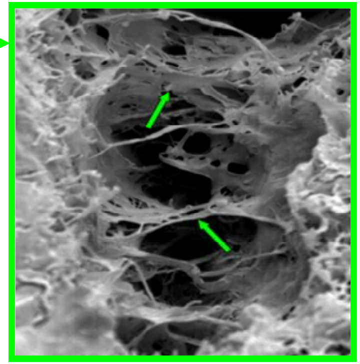
Example of a Permian channel margin in the Laingsburg area, Karoo, South Africa (photograph by Ian Westlake, BHP Billiton).

Field Cases: Why a Dispersed Shaly-Sand Model?



SEM photo at 10.6ft

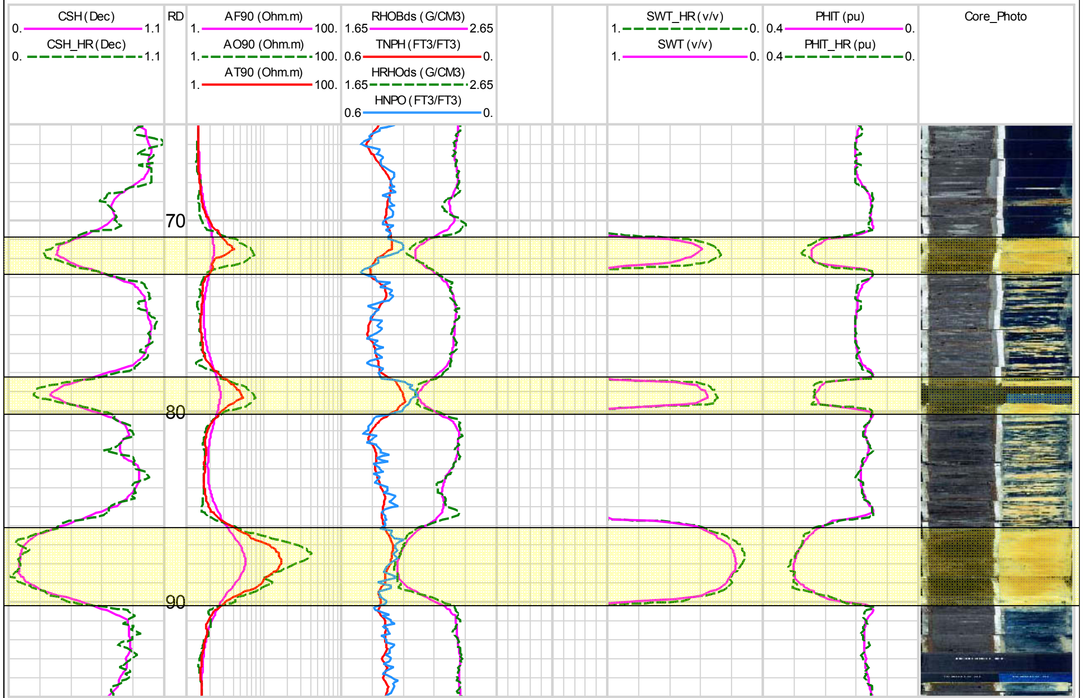
C_{sh}=15% at 11.0ft



Notes of Presenter:

Ultraviolet and normal-light photograph of core retrieved in Well No. 3 between 10.5 ft and 11.5 ft. The scanning electron microscope (SEM) photograph indicates pore-bridging illite at 10.6 ft. Laser-grain tests measured Csh=15% at 11.0 ft.

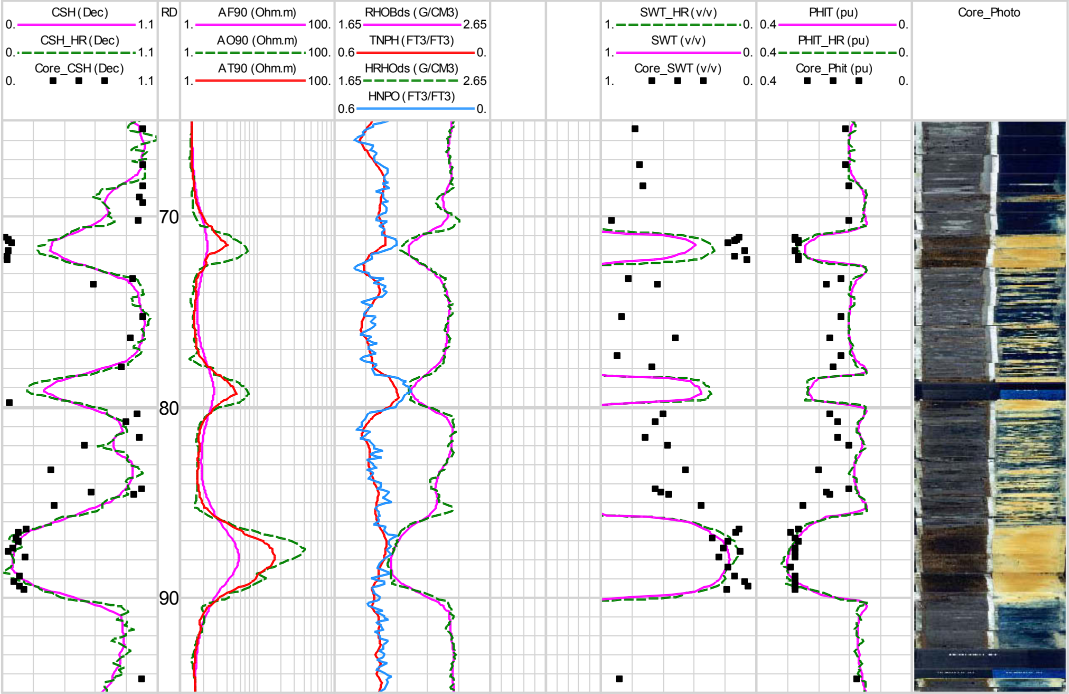
Well No. 1 SR/HR Interpr.



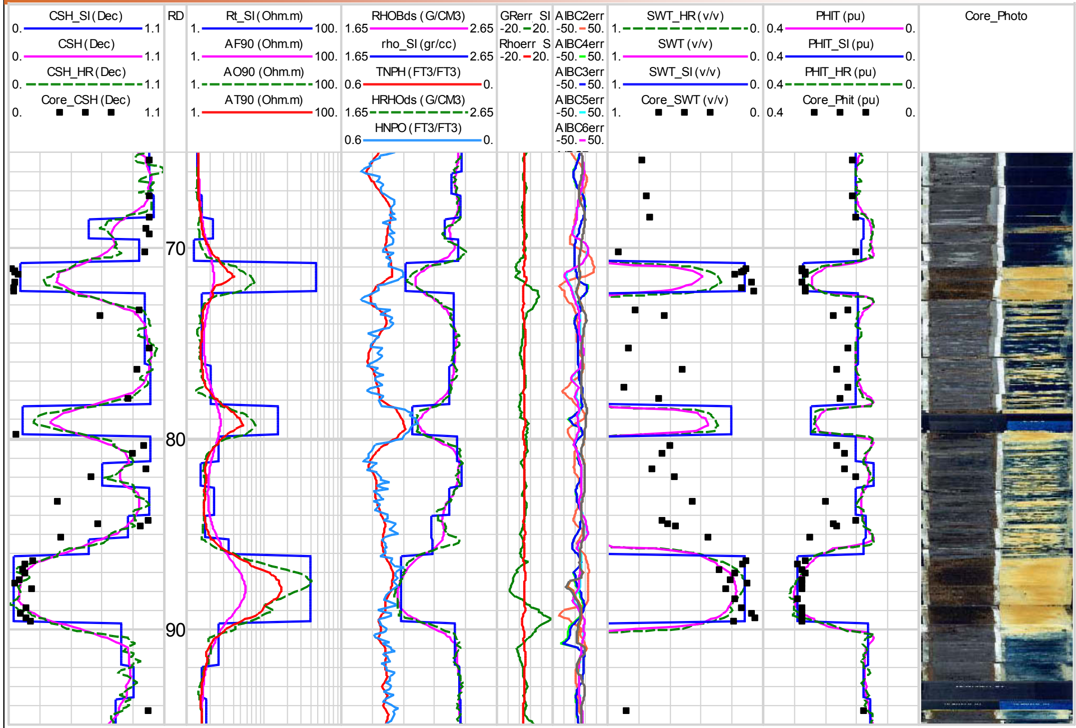
Notes of Presenter:

Formation composed of 3 sand layers separated by mud-rich heterolithic shaly sands. These sands have different properties, by just looking at the logs, but core data shows very similar properties.

Well No. 1 SR/HR Interpr. with Core Meas.



Well No. 1 SR/HR/SI Interpr. with Core Meas.



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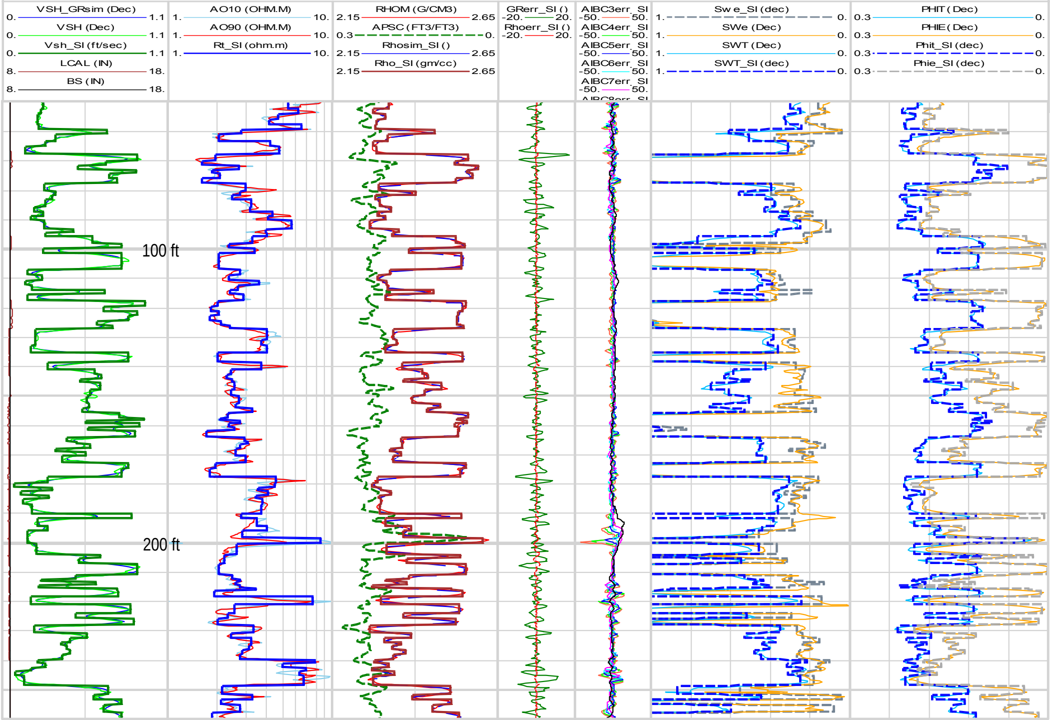
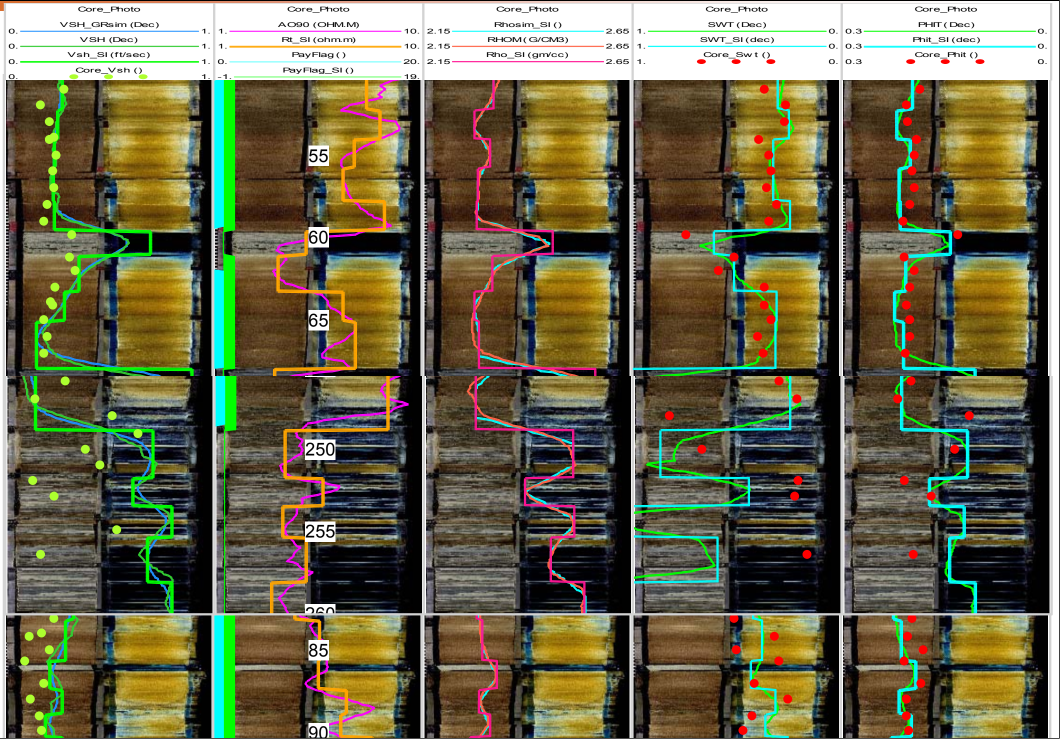
Well No. 3 Inversion and Interpretation



Notes of Presenter:

260 ft amalgamated and non-amalgamated sheet sands intercalated with heterolithic shaly units.

Well No. 3 Inversion, Interpretation and Core



Reserve Calculations Statistics

Type of Logs Used			Well No.			Aver
GR	ρ_r	R_t	1	2	3	
NGR Change Respect SR Logs (%)						
SR	SR	SR	-	-	-	**-**
HR	HR	HR	12.7	-2.5	6.3	**5.5**
SR	SI	SI	-1.8	-2.0	5.7	**0.6**
SI	SI	SI	22.7	2.5	19.8	**15.0**
HPV Change Respect SR Logs (%)						
SR	SR	SR	-	-	-	-
HR	HR	HR	20.5	1.7	7.3	**9.8**
SR	SI	SI	25.9	4.4	8.3	**12.9**
SI	SI	SI	54.5	9.1	19.9	**27.8**

Agreement to Core Measurement Statistics

Type of Logs Used					Well No.			Aver
		GR	ρ_r	R_t	1	2	3	
Average	R^2	SR	SR	SR	-	-	-	**-**
		HR	HR	HR	1.4	7.0	-8.6	**-0.1**
		SR	SI	SI	0.1	13.5	11.2	**8.3**
		SI	SI	SI	4.9	29.6	14.7	**16.4**
	RE %	SR	SR	SR	-	-	-	**-**
		HR	HR	HR	-8.1	8.9	6.6	**2.4**
		SR	SI	SI	-6.7	-9.6	-4.4	**-6.9**
		SI	SI	SI	-38.4	-16.8	-9.0	**-21.4**

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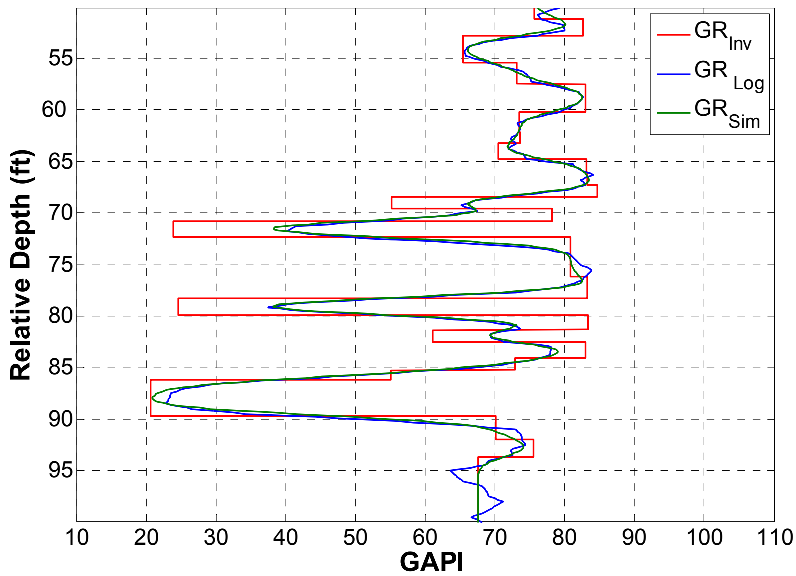
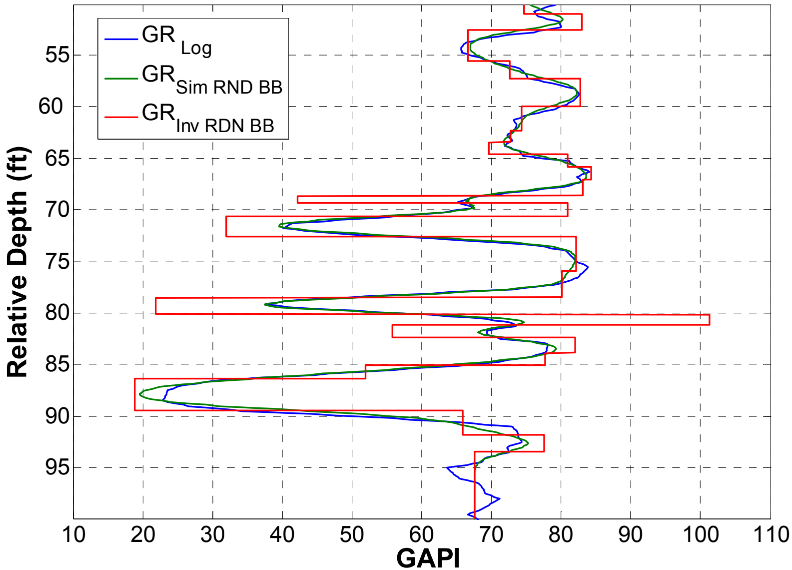
Considerations for Inversion

- Log Operations
- Selection of Input Logs
- Detection of Bed Boundaries
- Regularization of GR and Density Logs
- Stretching of Sensitivity Functions
- Analysis of Data Misfits
- Mono-sensor Selection

Shifting BB's ±0.2ft for Well No. 1 GR Inv.



Shifting BB's ±0.2ft for Well No. 1 GR Inv.



Detection of Bed Boundaries (BBs)

- How to find the BBs?

  Inflection points of logs
- Which log to use for detection of BB ?

  Density log
- Should we use standard or high res logs for BBS?

  Standard resolution
- What is the minimum size for BBs?

  0.7ft to 1ft

  Very thin layers lead to non-uniqueness in the inversion
- What if we have an electrical image log or core data?

  Use it to refine and verify layer thicknesses
- How to improve the precision of the logs?

  Reduce logging speed

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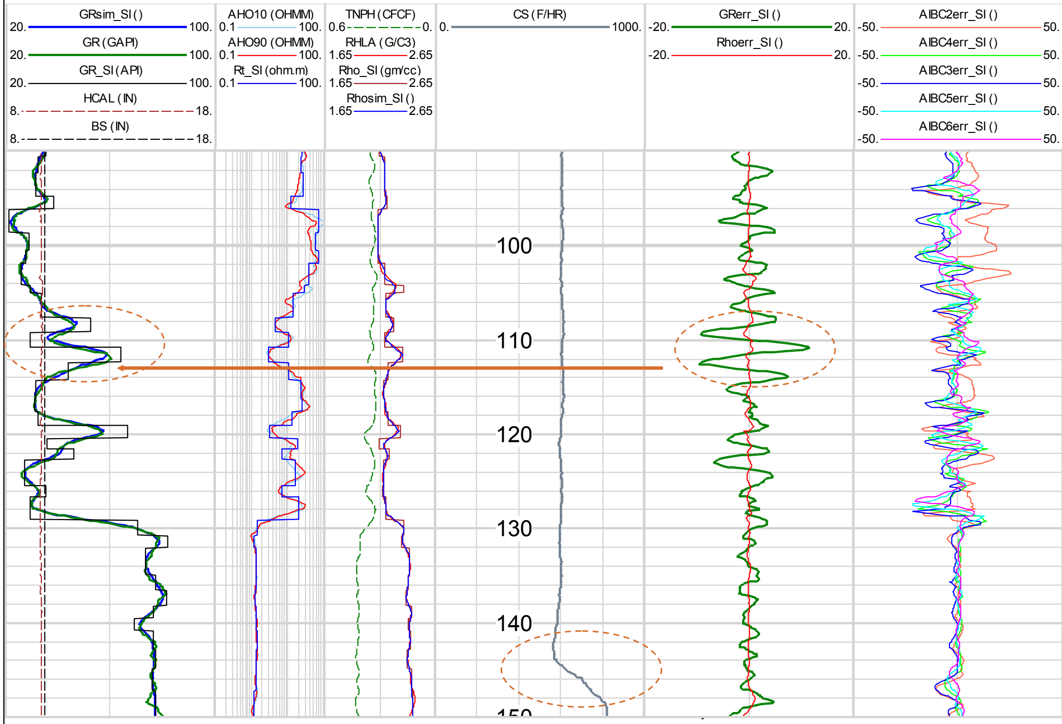
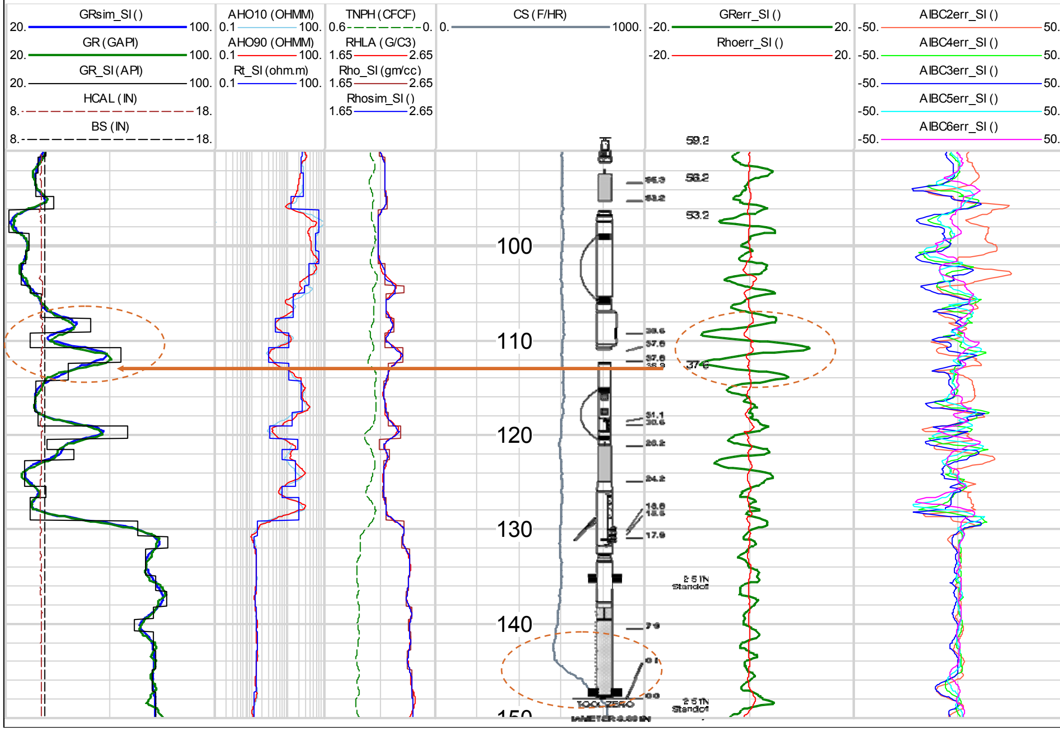
Extra Value of Inversion: Log Quality Control

- Integration of logs
- Detection of depth mismatches (due to speed changes, yoyos, etc.)
- Detection of noisy data
- Appraisal of raw data
- Detection of adverse borehole conditions or tool malfunctions

LQC Example: Change of Speed Affects GR



LQC Example: Change of Speed Affects GR



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Conclusions

- Combined inversion provides a better agreement between petrophysical interpretation and core measurements and increases hydrocarbon reserves compared to standard resolution logs:
  - 19% better agreement to core measurements.
  - 15% and 28% extra reserves in terms of NGR and HPV.
- Minimum bed thickness necessary for successful deterministic inversion was approximately 0.7 ft.
- The most critical step for inversion was the detection of bed boundaries.

Conclusions

- Bed boundaries should be selected from the density log and refined based on core measurements, repeat sections, image logs, or other logs with high vertical resolution.
- Log depth mismatches have to be corrected before inversion.
- Combined inversion is a valuable tool for log quality control.

Acknowledgments

- Special thanks to BHP Billiton for the opportunity to work on this project during an internship in 2008.

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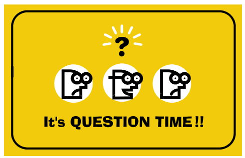
StatoilHydro
BR
PETROBRAS
RWE
The energy to lead
TOTAL
Weatherford

Notes of Presenter:

The most important thank you to the people who are paying our tuitions in the University, the members of The University of Texas at Austin's Research Consortium on Formation Evaluation.

Any Questions ?



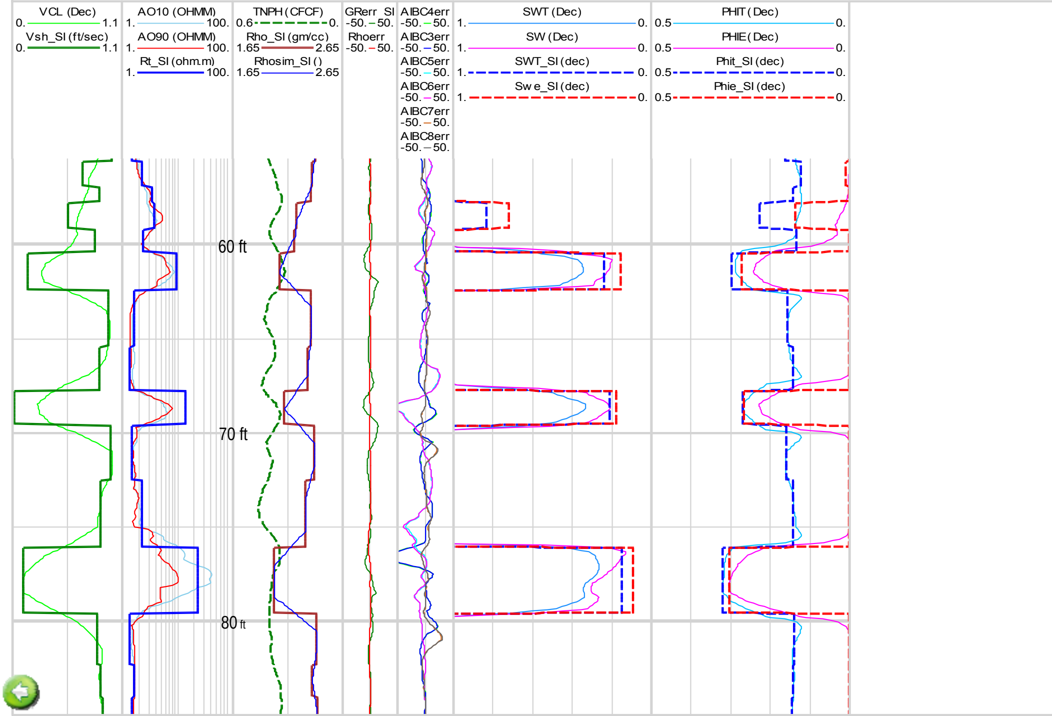
Appendix I

- Well No.1 ST1 Inversion and Interpretation
- Well No. 2 Inversion and Core Data Xplots
- Well No. 3 Inversion and Core Data xplots
- Extra Considerations for Inversion
- Log Depth Mismatches
- Example Fitting Errors Well No. 2
- Fitting Errors
- Mono-Sensor Density Selection for Inversion
- AIT sub-arrays selection for inversion

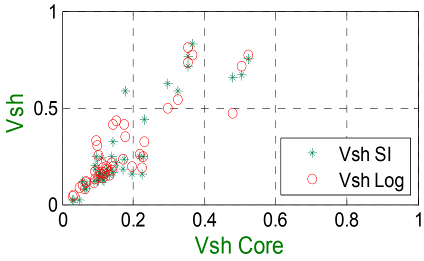
Appendix II

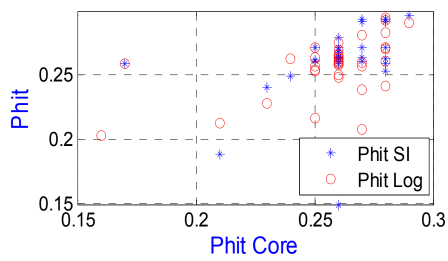
- Classification of Layers
- Stretching of FSF
- Difficulties on BB Detection
- Regularization
- Vertical Resolution of GR Tool
- Noisy AIT Data
- Well No. 1 Inversion, Standard and High Res.
- Well No. 2 Results

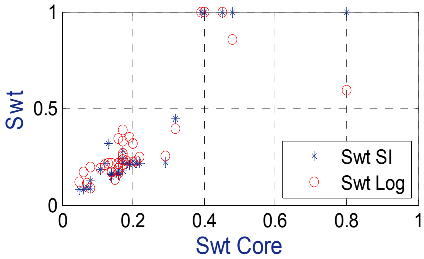
Well No.1 ST1 Inversion and Interpretation



Well No. 2 Inversion and Core Data Xplots

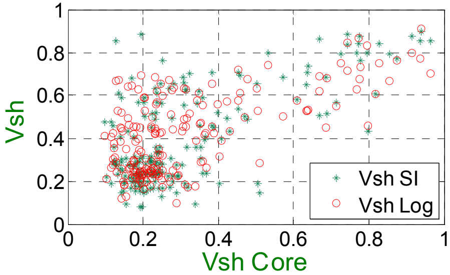


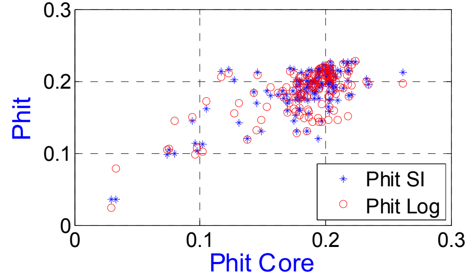


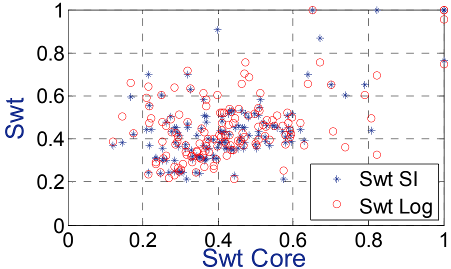


	R^2 Log to Core	R^2 SI to Core
Vsh	0.76	0.81
Phit	0.28	0.42
Swt	0.56	0.77

Well No. 3 Inversion and Core Data Xplots





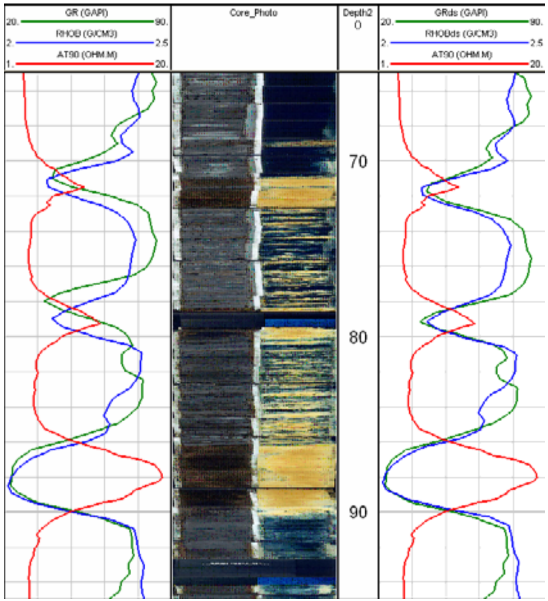


	R^2 Log to Core	R^2 SI to Core
Vsh	0.41	0.46
Phit	0.47	0.55
Swt	0.24	0.28

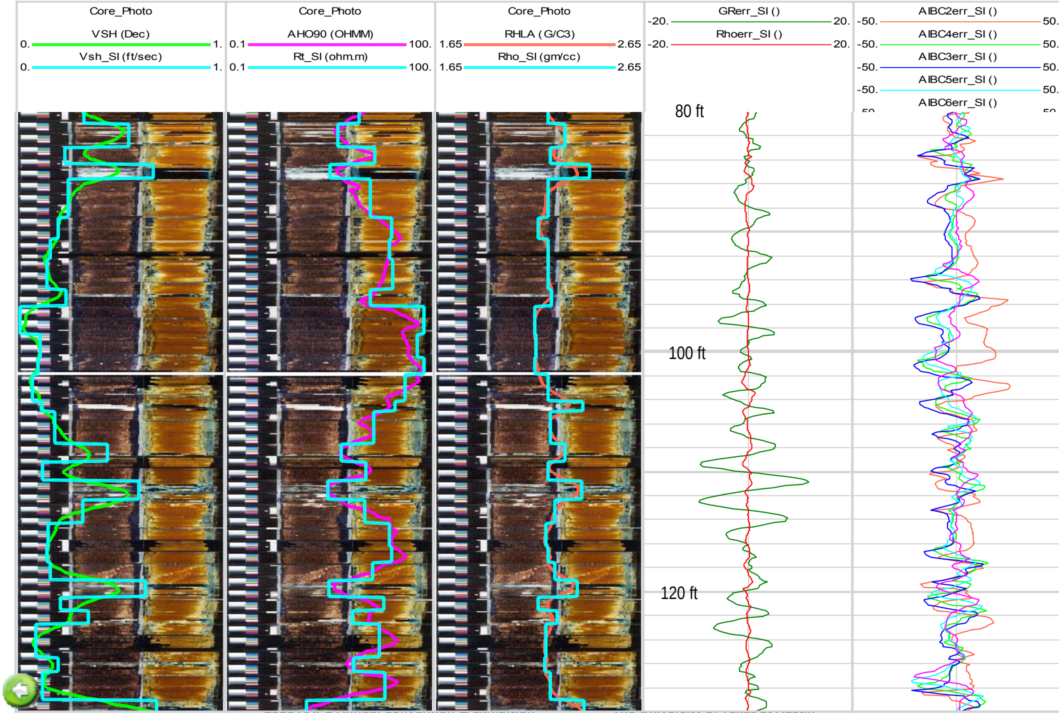
Extra Considerations for Inversion

- Logs Depth Mismatches
- Fitting Errors
- Density Mono-Sensor Selection for Inversion
- Induction Tool Sub-array Selection for Inversion

Log Depth Mismatches



Example Fitting Errors Well No. 2



Fitting Errors

- How big could the fitting errors be?
  - For GR < 20%
  - For Density < 10%
  - For resistivity up to 50% (when contrast of resistivity is high)

- Why we don’t get 0-1% error?
  - Limitations of the code. We are assuming horizontal layers, step invasion, and linear inversion for GR and density.
  - Thin layers.
  - Depth mismatches.
  - Severe borehole conditions or tool malfunctions.

Mono-Sensor Density Selection for Inversion

Which mono-sensor density should be used?

- Ideally both, but if SS density is resolution matched to LS, LS density should be used
- Generally LS is very similar to final density provided by service companies

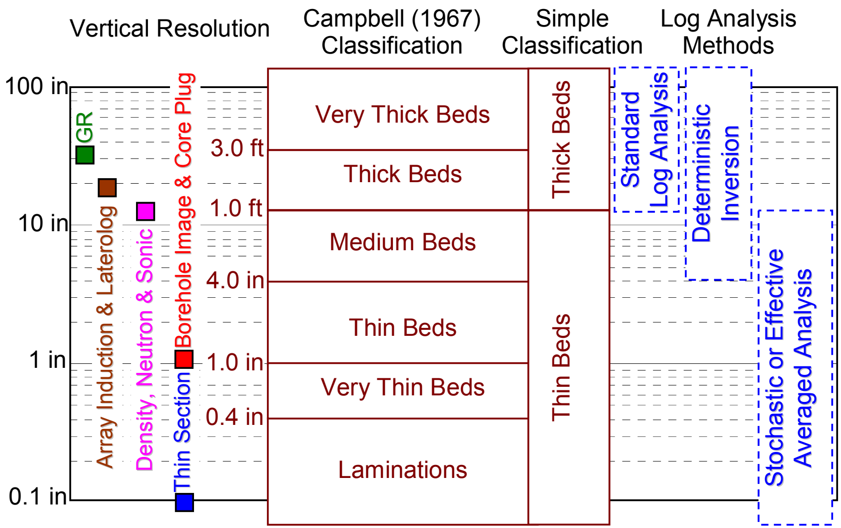
AIT sub-arrays selection for inversion

Which sub-arrays should be used?

The selection depends on each case, for example:

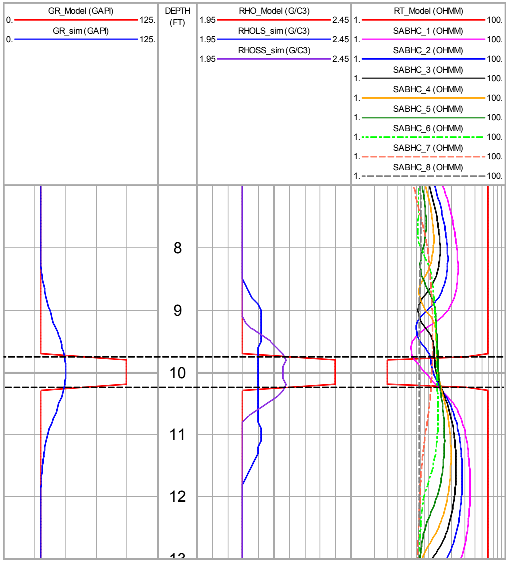
- Avoid noisy sub-arrays
- If beds are dipping or well is deviated, it is better to avoid the very deep sub-arrays
- In general sub-array 1 is the one that gives the higher fitting errors

Classification of Layers

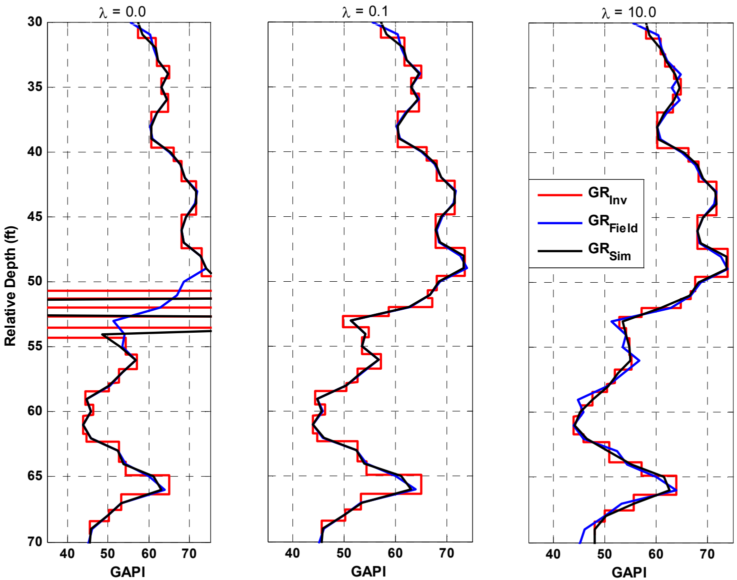


After Campbell, 1967

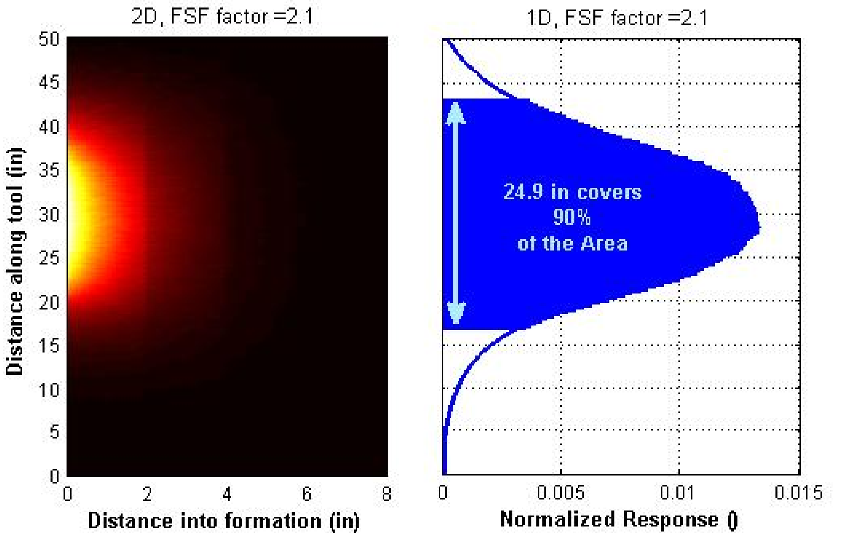
Difficulties on BB Detection



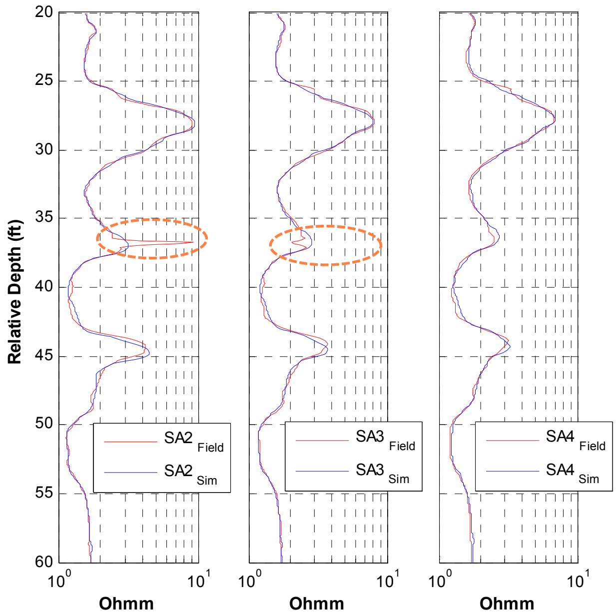
Regularization



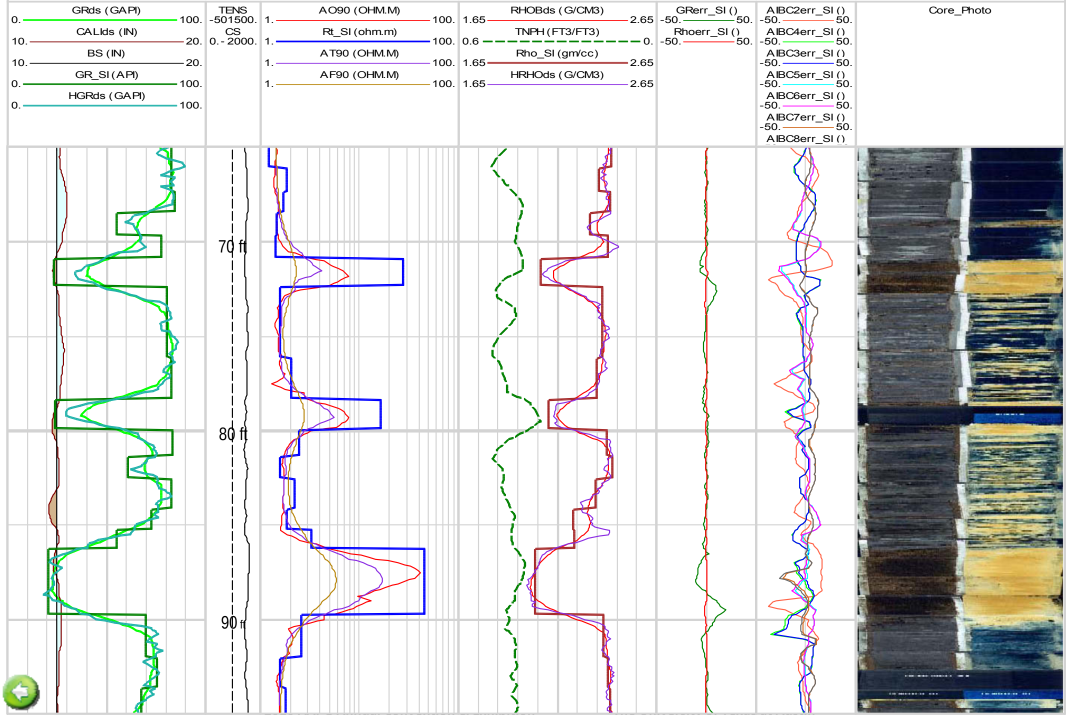
Vertical Resolution of GR Tool



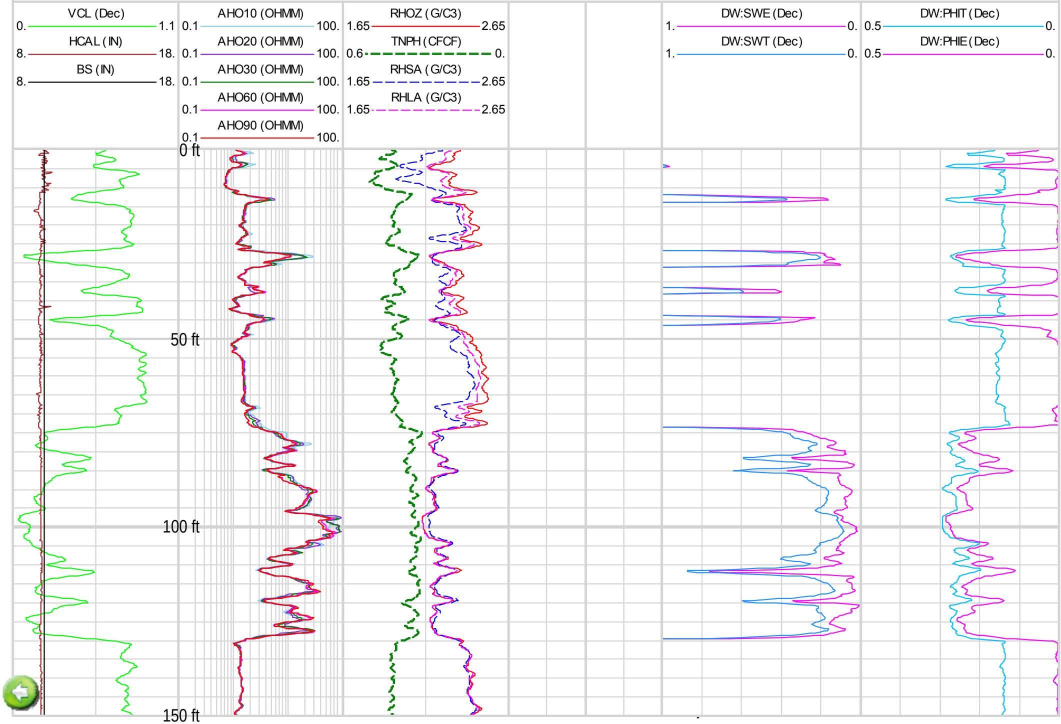
Noisy AIT Data



Well No. 1 Inversion, Standard and High Res.



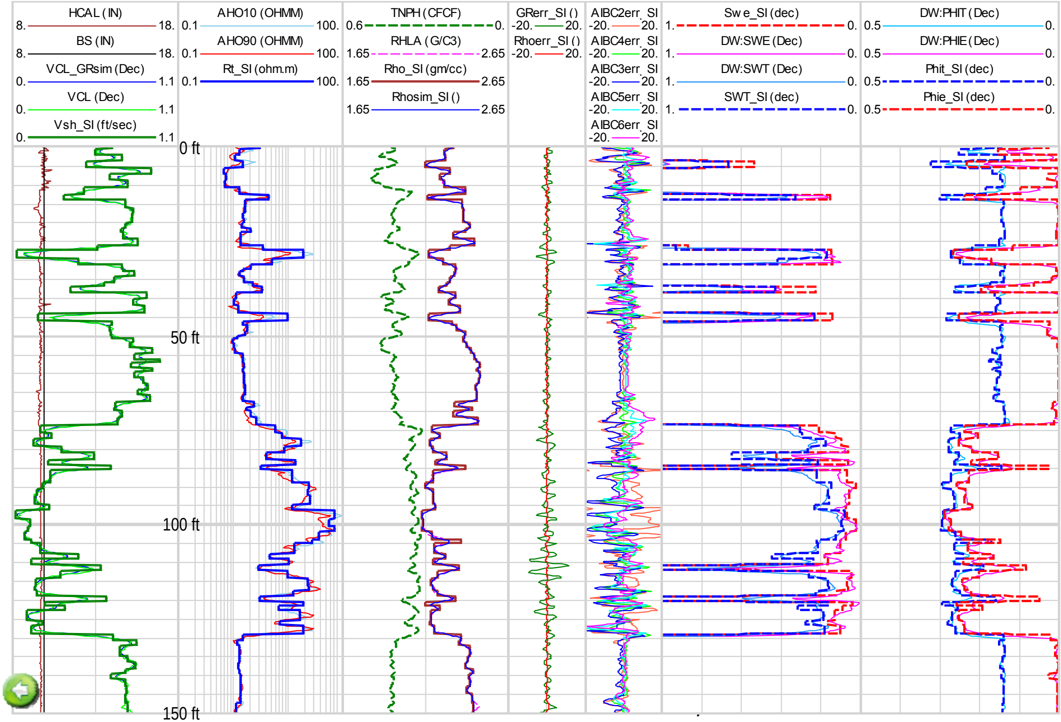
Well No. 2 Standard Interpretation



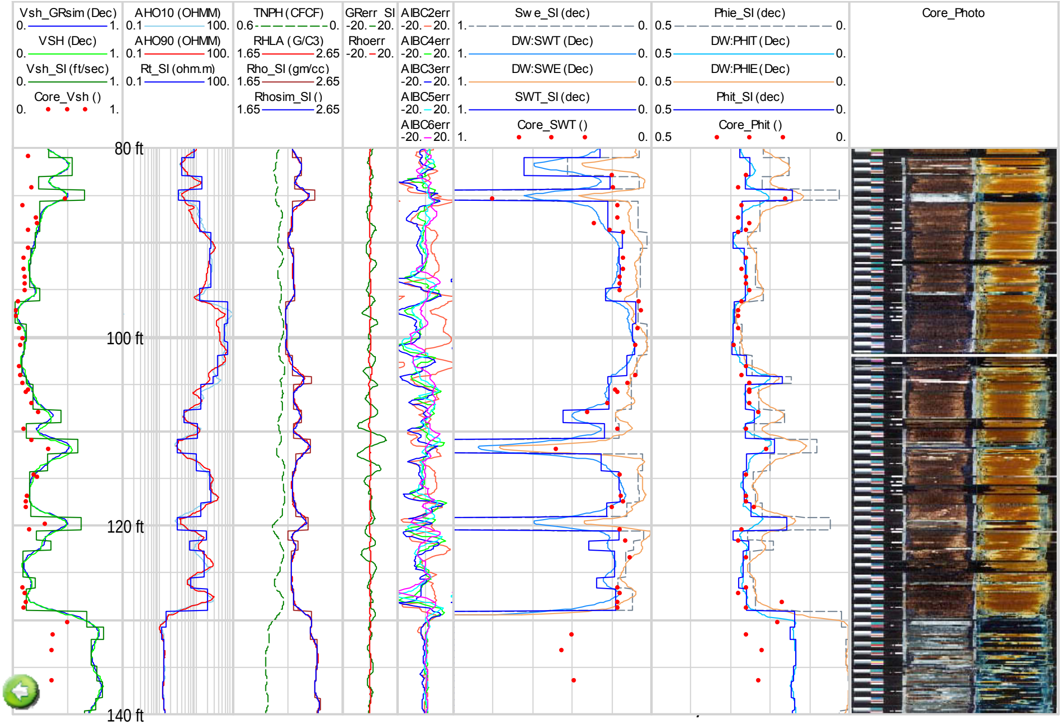
Notes of Presenter:

150ft of amalgamated and non-amalgamated sheet sands on top of heterolithic shaly sands.

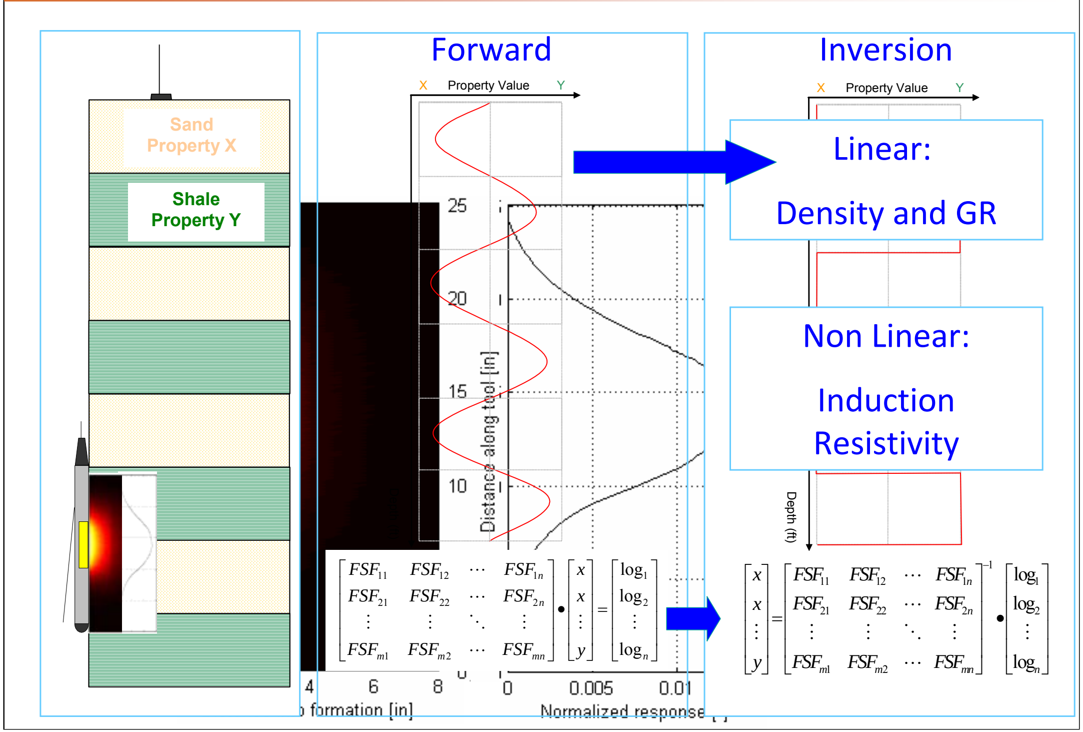
Well No. 2 Inversion and Interpretation



Well No. 2 Inversion, Interpretation and Core



Inversion and Sensitivity Functions



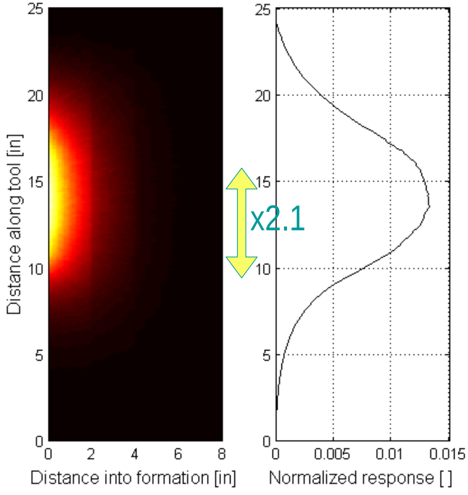
Notes of Presenter:

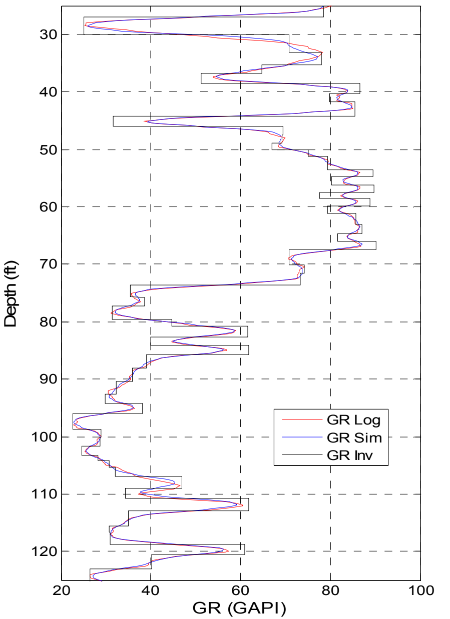
How the inversion works…. the steps of out inversion method are:

1. Select bed boundaries of the multilayer model.
2. Perform separate inversion of density, GR and resistivity based on raw data. We use mono-sensor density and sub-arrays resistivity measurements.
3. Combined . . .

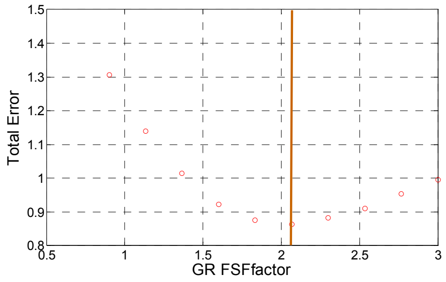
In this way we do a separate inversion for GR, rho and res; the results are combined into a a Shaly sand model.

Stretching of the Sensitivity Functions





Stretching of the Sensitivity Functions



Well	GR	Density	
	SGTL*	LDT * LS	LDT SS
Well 1	2.10	1.25	3.50
Well 1 ST1	2.16	1.30	4.30
	HGNS *	TLD * LS	TLD * SS
Well 2	2.04	1.10	3.20
Well 3	2.07	1.11	4.11

- Why do we need to apply stretching factor to the sensitivity functions?
  - We have only general “UT Longhorn Tool” sensitivity functions
  - To compensate for filters applied to raw data

*Marks of Schlumberger