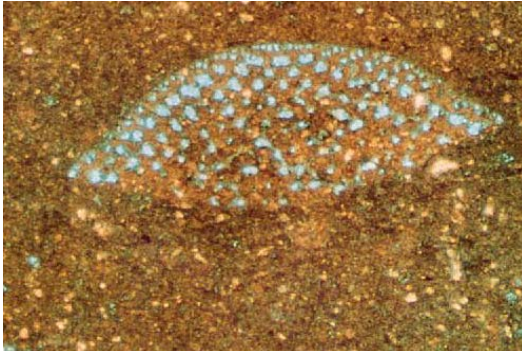


# *Carbonate Petrophysics*



30 pu Limestone  
Jerry Lucia



Rudist: Middle East Well  
Evaluation Review# 15, 1994  
Schlumberger



High Permeability Grainstone:  
Petrophysical and Geomechanical  
Issues in Carbonate Oilfields.  
Austin Boyd

[WWW.GeoNeurale.Com](http://WWW.GeoNeurale.Com)

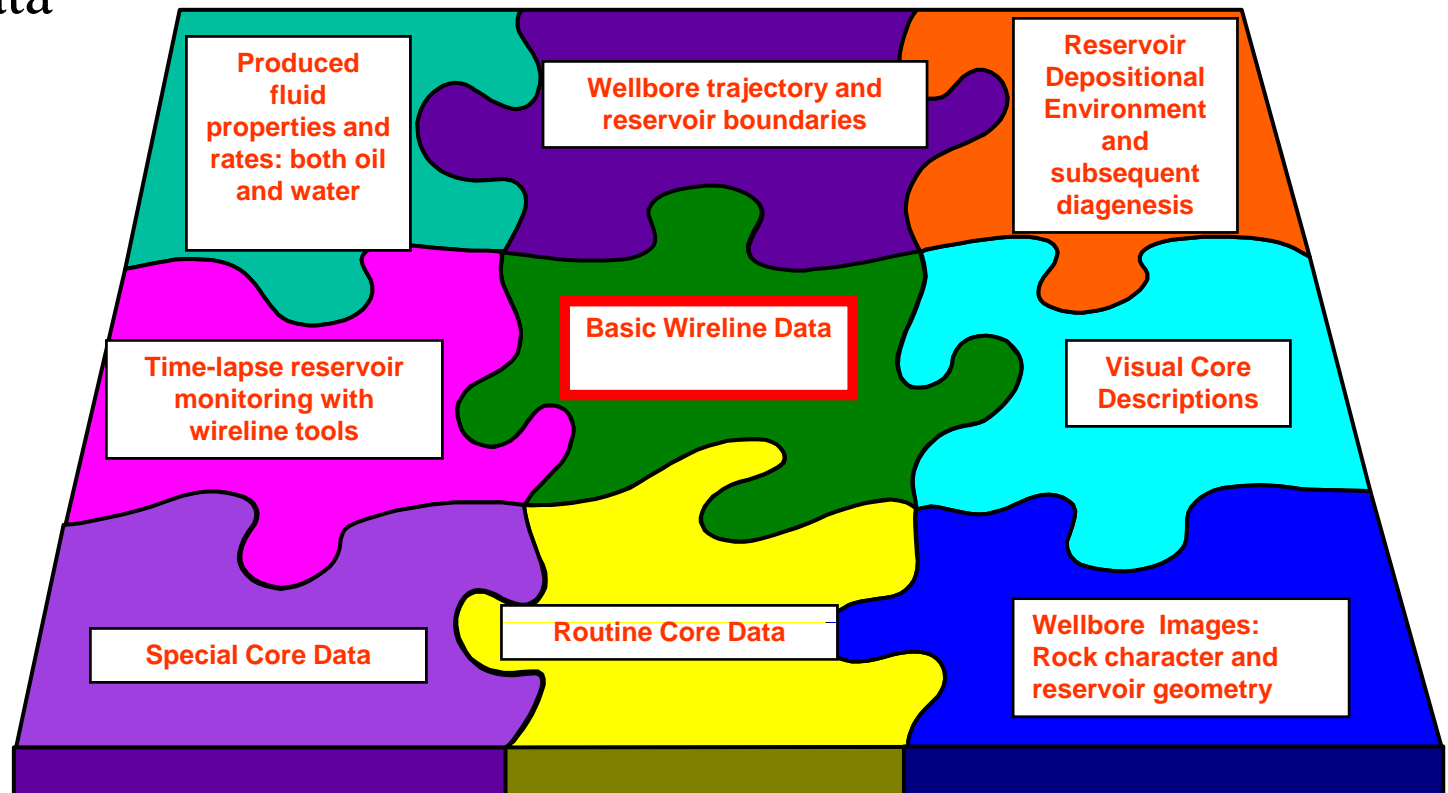
***R. E. (Gene) Ballay, PhD***

# Carbonate Petrophysics

- Course *philosophy*
  - Draw material from a *variety of sources*
    - SPWLA, SPE, AAPG, Leading Edge, etc
    - Service Companies
    - *Carefully reference* every source to allow Client follow-up
  - *Illustrate issues* with actual data to every degree possible
  - *Include parameters* and *equations*
    - Facilitate seamless Client application of course material
    - Distribute spreadsheets to allow Client “What If” calculations
  - *Do Not Champion* any particular Tool / Technique
    - Discuss strengths and weaknesses

# Carbonate Petrophysics

- Course *objective*
  - *Integrate across discipline and scale and timeframes*
    - *Wireline* (and LWD) measurements are *typically the basis for field development and depletion*
    - *Ultimate objective is an integrated / calibrated interpretation* of that data



# Carbonate Petrophysics

- Course *deliverables*

- Digital, Key Word Searchable* PDFs

- Presentation

- Exercises

- Can be “worked during class” or used as “Question / Answer” review

- Manual

- Related to the Presentation (above) as a Text Book is related to a Classroom Presentation

- Spreadsheets* used to construct supporting graphics

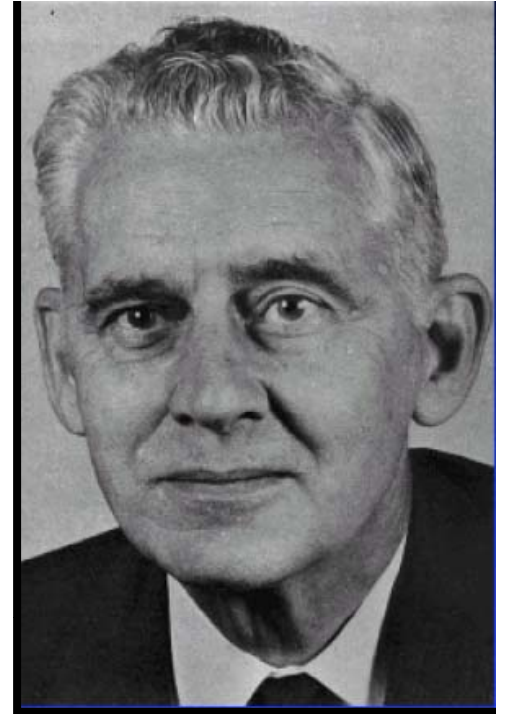
- Illustrates exactly how exhibits were developed

- Allow Client “What If” variations as need arises

## Five Day Carbonate Petrophysics

• **Gus Archie** introduced the world to the term '*petrophysics*' in 1950. This fundamental vision was followed by a carbonate classification system in 1952 in which he commented

- in discussing the petrophysics of limestones, it is *necessary to first classify* them,
- the field application of petrophysical relationships in *limestone* can be much *more difficult than* in *sandstone*, because of variations in *pore size distribution*.



• This course begins with a *contrast of sandstone and carbonate depositional environments, diagenesis and routine log signatures*.

• Basic capillary pressure techniques are then introduced, thereby *setting the stage for the Lucia Petrophysical Classification*.

## Five Day Carbonate Petrophysics

- The ***Lucia System*** recognizes that if one is to characterize the relationship between rock fabric and petrophysical parameters, then ***the pore space must be classified*** as it exists today, in terms of petrophysical properties. The focus is then on ***petrophysical properties*** and ***not genesis***.
- Key issues are
  - ***interparticle vs vuggy porosity***
  - ***separate vs touching vugs***
- In addition to basic porosity (magnitude) determination, one should thus also consider ***pore size and pore type***.
- Common porosity tools (***density, neutron and sonic***) are introduced, and then ***contrasted as a means of achieving this objective***.
- Image logs and nuclear magnetic resonance*** are investigated as ***“modern” alternative, vuggy porosity identification options***.
- Vuggy porosity*** affects not only rock quality (porosity vs permeability), but also the ***Archie “m” exponent***, as is illustrated with ***laboratory measurements*** and ***thin sections***.
- Cementation ***exponent models***, for estimating “m” as a function of vuggy porosity content, are ***developed and evaluated***.

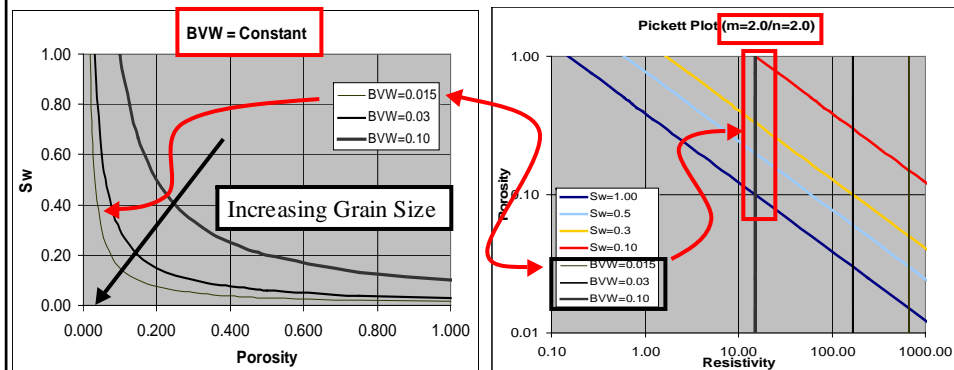
## Five Day Carbonate Petrophysics

- In the years since Archie's ground-breaking work, a number of so-called *non-Archie (ie non-resistivity-based) formation evaluation approaches* have become possible
  - Each methodology is developed and then evaluated, with actual carbonate data
    - Pulsed neutron
    - Dielectric
    - Borehole gravity meter
    - Nuclear magnetic resonance
- Since NMR is the most commonly used alternative, it receives the most attention
  - *Basic NMR* is followed by *Carbonate NMR*
  - Carbonate NMR addresses two *key carbonate limitations*
    - pore size coupling
    - vuggy porosity of sufficient size that surface relaxation no longer dominates the tool response
- In addition to non-Archie formation evaluation, the *Specialty Sonic* offers *Shear Wave identification / orientation of fractures* and *Stoneley Wave permeability estimates*

## Five Day Carbonate Petrophysics

- Additional, *supplemental tools / techniques* that are investigated in the Course include
  - *Visualization* by *CT Scan*
  - *Laboratory* determination of *mineralogy* (XRD/XRF/etc)
  - *Laboratory* measurement of *porosity*
  - *Pressure profiles*
  - *Quick Look formation evaluation* ( $S_w$  from resistivity ratio, etc)
  - *Double Duty Pickett Plots*
    - Bulk volume water and / or Permeability grids, superimposed on routine PP

- Grids of constant BVW values can be displayed on the Pickett Plot
- **BVW=Constant, for a specific Rock Type, will generally identify water-free production**



Grids below the  $S_w = 100\%$  line are for visual reference only

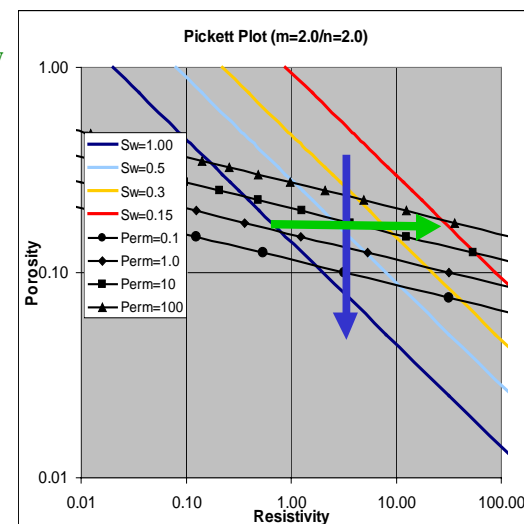
- Locally appropriate permeability relations can be super-imposed on the Pickett Plot

- At a **specific porosity**, increases in resistivity infer increased permeability (lower  $S_{wi}$  => better rock quality)

- At a **specific resistivity**, lower porosities infer lower perms, and higher  $S_{wi}$

- Perm estimate is *only valid far above the transition zone*

- Linear extrapolation to left of  $S_w = 100\%$  line (graphic at right) is for visual reference only



# Five Day Carbonate Petrophysics

## Day 1

Start	Stop	Duration	Topic
830	915	45	Course Introduction
915	930	15	Carbonate vs Sandstone
930	945	15	Break
945	1000	15	Thin Sections
1000	1045	45	Lucia Petrophysical Classification
1045	1100	15	Break
1100	1200	60	Lucia Classification (+ Exercise)
1200	1300	60	Lunch
1300	1400	60	Capillary Pressure (+ Exercise)
1400	1415	15	Break
1415	1500	45	Rock Quality and Cutoffs
1500	1515	15	Break
1515	1545	30	CT Scan with Carb Examples
1545	1615	30	GR in Carbonate (+ Exercise)
1615	1630	15	Review and Feedback

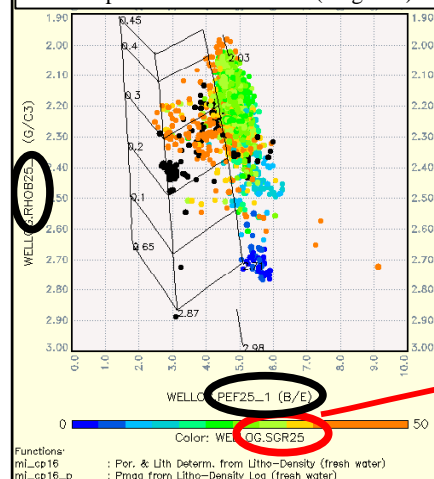
## Day 2

Start	Stop	Duration	Topic
830	945	75	Sonic in Carbonate (+ Exercise)
945	1000	15	Break
1000	1100	60	Carb Rhob / Pef (+ Exercise)
1100	1115	15	Break
1115	1145	30	Carb LWD Rhob / Pef
1145	1200	15	Carbonate Neutron
1200	1300	60	Lunch
1300	1345	45	Carb Neutron (+ Exercise)
1345	1400	15	Break
1400	1500	60	Identification of Vuggy Porosity
1500	1515	15	Break
1515	1615	60	Specialty Sonic in Carb (+ Exercise)
1615	1630	15	Review and Feedback

- In the **clastic** world, **GR** activity is often (but not always) a result of clay, and therefore **indicative of a decrease in rock quality**
- In **carbonates** it's not uncommon to find the **GR** being driven by **uranium**, in a fashion that is **not necessarily indicative of rock quality**
  - The presence of uranium, and the associated **higher GR, can signal stylolites, fractures, super-perm and / or general increases or decreases in quality and / or mineralogy**
- One **key distinction between sand and carbonate** is then the **utility and meaning (or lack thereof) of SP/ GR response**

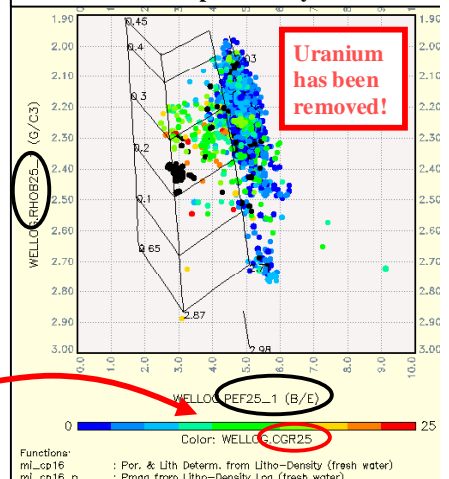
### Carbonate versus Sandstone

- Trend parallel to LS line, but offset
- Pef is qualitative, not quantitative
- Higher GR corresponds to better quality limestone and increase in dolomitization
- Black points are invalid data (ie ignore)



### •Limestone generally clean, throughout

- LS GR activity was essentially all uranium
- Dolomite is higher non-uranium GR activity
- Did dolomitization occur in rock which was depositionally different?



# Five Day Carbonate Petrophysics

Day 3				Day 4			
Start	Stop	Duration	Topic	Start	Stop	Duration	Topic
830	915	45	Phi / Mineralogy from Core	830	900	30	Quick Look Techniques
915	945	30	XRD/XRF/etc Mineralogy	900	930	30	Pickett Plot
945	1000	15	Break	930	945	15	Break
1000	1045	45	Resistivity Tools & Constraints	945	1030	45	Pickett Plot (+ Exercise)
1045	1100	15	Archie's 'm' Exponent	1030	1045	15	Pulsed Neutron Log
1100	1115	15	Break	1045	1100	15	Break
1115	1200	45	Archie's 'm' Exp (+ Exercise)	1100	1200	60	PNL (+ Exercise)
1200	1300	60	Lunch	1200	1300	60	Lunch
1300	1345	45	Cmnt Exp Variations & Pore Geometry	1300	1345	45	PNL Log-inject-log
1345	1415	30	"m" Estimates From Vuggy Porosity Ratio	1345	1400	15	Break
1415	1430	15	Break	1400	1445	45	BH Gravity Meter
1430	1500	30	"m" Estimates From Vuggy Porosity Ratio	1445	1530	45	Pressure Profiles (+ Exercise)
1500	1530	30	Archie's "n" Exponent (+ Exercise)	1530	1545	15	Break
1530	1545	15	Break	1545	1615	30	Correlation Techniques
1545	1615	30	Low Resistivity Pay in Carbonates	1615	1630	15	Review and Feedback
1615	1630	15	Review and Feedback				

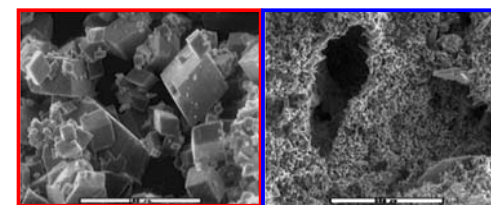
• **Carbonate** - Diagenesis includes .....*dissolution*

• Surface example of how carbonate reservoir rock can be modified.

• One *key distinction between sand and carbonate* is that of *clay effects versus pore size distribution*



Eureka Springs, Arkansas



• Environmental scanning electron microscope images.

• On the *left*, a crystalline dolomite with  $\phi = 47\%$  and  $m = 1.95$ .

• On the *right*, a moldic bioclastic packstone with  $\phi = 36\%$  and  $m = 3.27$ .

• This large variation in  $m$  illustrates the importance of rock texture on petrophysical evaluation.

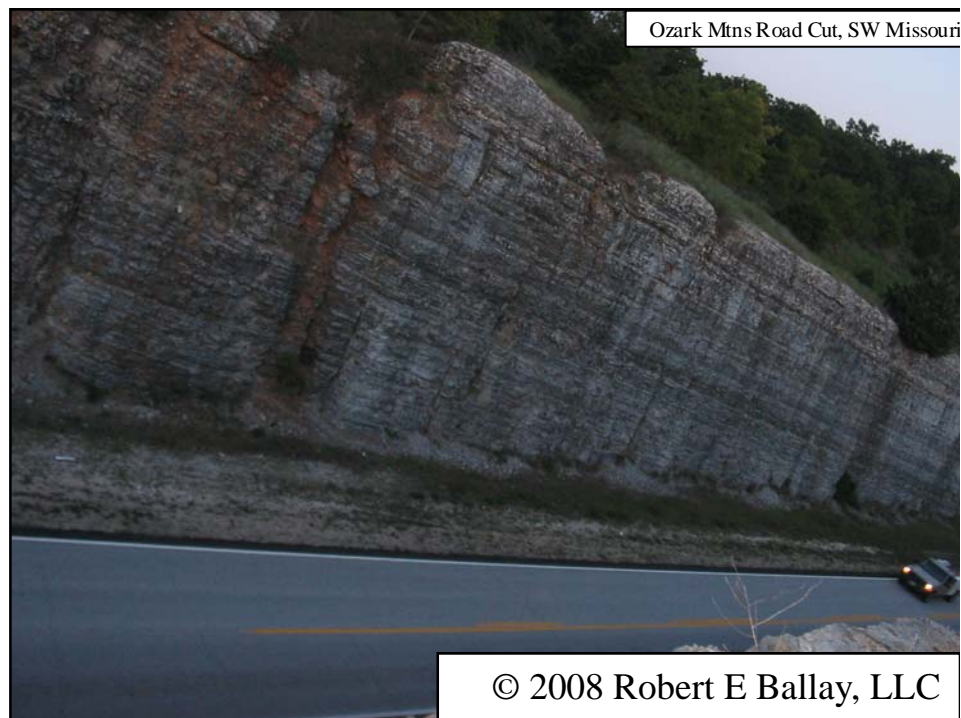
Electrical Properties of Porous Rocks by Carlos Torres-Verdin, University of Texas

• In many regards, a *key distinction between sand and carbonate*, is also one of accounting for *clay conductivity* 'short circuits' *versus variations in pore system tortuosity* associated with changes from intercrystalline / interparticle to vuggy porosity.

# Five Day Carbonate Petrophysics

## Day 5

Start	Stop	Duration	Topic
830	945	75	Image Log (+ Exercise)
945	1000	15	Break
1000	1030	30	Dielectric Log
1030	1045	15	Wireline "m" Estimates Compared to Core
1045	1100	15	Break
1100	1200	60	Basic NMR (+ Exercise)
1200	1300	60	Lunch
1300	1315	15	Basic NMR (Hydrocarbon Effects)
1315	1400	45	Carbonate NMR
1400	1415	15	Break
1415	1500	45	Carbonate NMR (+ Exercise)
1500	1530	30	Core Calibrated Wireline "m" Estimates
1530	1545	15	Break
1545	1600	15	Daily Review and Feedback
1600	1615	15	Jerry Lucia: Here is how it works
1615	1630	15	Course Summary



# Uncertainty in Archie's Equation

Where to spend time, and money,  
in search of an improved  $S_w$  estimate

Identifying the **Biggest Bang for the Buck**

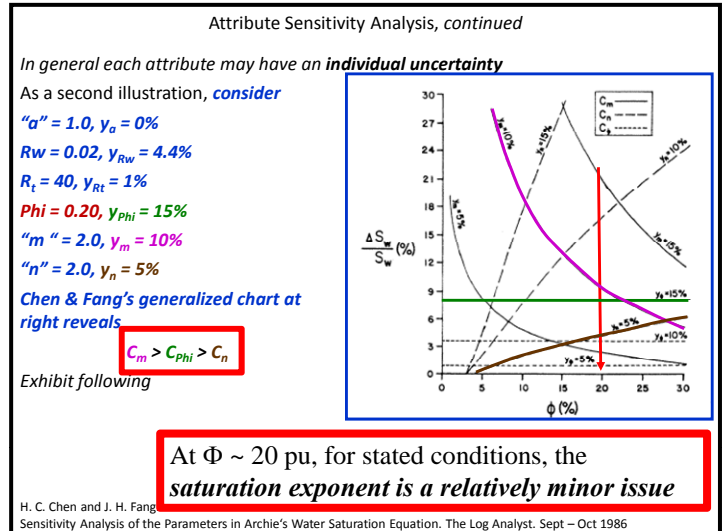


## Identifying the Biggest Bang for the Buck

•Chen & Fang performed a *differential analysis of Archie's equation* to allow an *In Depth look at uncertainty in  $S_w$* , as a function of input attribute values and respective uncertainties

•They produced *generic charts to facilitate locale specific evaluation*

•Their results have been *coded to an Excel spreadsheet, to facilitate locale specific, digital evaluation*



## Supplemental Discussions

ArchieUncertainty.xls [Compatibility Mode] - Microsoft Excel

Attribute Sensitivity Analysis, *continued*

•If the **Best Estimate**, and **Standard Deviation** of each attribute are known, the **relative attribute impact on  $S_w$  (Archie)** may be deduced

•At the simplest level, one might **assume that each attribute is subject to a similar, percentage-wise, uncertainty**

•Following Chen & Fang's notation, **denote this percentage-wise uncertainty as "y%"**

•Exhibit following

$$C_\alpha = \left(\frac{\alpha}{a}\right)^2 \quad (6.1)$$

$$C_{R_w} = \left(\frac{\sigma_{R_w}}{R_w}\right)^2 \quad (6.2)$$

$$C_{R_t} = \left(\frac{\sigma_{R_t}}{R_t}\right)^2 \quad (6.3)$$

$$C_m = \left(m \cdot \frac{\sigma_m}{m}\right)^2 \quad (6.4)$$

$$C_n = (n \sigma_n)^2 \quad (6.5)$$

$$C_n = (n(S_w) \sigma_n)^2 \quad (6.6)$$

$$C_\alpha = \left(\frac{\alpha}{a}\right)^2 = \left(\frac{a}{a}\right)^2 (\pm y\%)^2 = (y\%)^2 \quad (8.1)$$

$$C_{R_w} = \left(\frac{\sigma_{R_w}}{R_w}\right)^2 = \left(\frac{R_w}{R_w}\right)^2 (\pm y\%)^2 = (y\%)^2 \quad (8.2)$$

$$C_{R_t} = \left(\frac{\sigma_{R_t}}{R_t}\right)^2 = \left(\frac{R_t}{R_t}\right)^2 (\pm y\%)^2 = (y\%)^2 \quad (8.3)$$

$$C_m = \left(m \cdot \frac{\sigma_m}{m}\right)^2 = m^2 (y\%)^2 \quad (8.4)$$

$$C_n = (n(\Phi) \sigma_n)^2 = (n(\Phi))^2 (y\%)^2 \quad (8.5)$$

$$C_n = m^2 [n(\Phi)]^2 (y\%)^2 = n^2 [n(S_w)]^2 (y\%)^2 \quad (8.6)$$

H. C. Chen and J. H. Fang  
Sensitivity Analysis of the Parameters in Archie's Water Saturation Equation. The Log Analyst. Sept - Oct 1986

Equations

ArchieUncer... M...

Attribute Uncertainty Estimate On  $S_w$  (Archie)

Attribute	Individual Uncertainty	Best Estimate	Relative Uncertainty On $S_w$ (Archie)
a	0.0%	1.00	0.00%
R <sub>w</sub>	4.4%	0.02	4.40%
Phi	15.0%	0.10	9.00%
m	10.0%	2.00	21.21%
n	5.0%	2.00	2.24%
R <sub>t</sub>	1.0%	40.00	0.01%
S <sub>w</sub>		22%	
S <sub>w</sub> <sup>n</sup>		5%	
Sum			22%
S <sub>w</sub> <sup>n</sup> =0.367 is an inflection point.			

UnequalUncertainty

Chen & Fang's results have been *coded to an Excel spreadsheet, to facilitate locale specific, digital evaluation*

These same relations *may be coded into nearly any petrophysical s/w package, to facilitate foot-by-foot evaluation*

Attribute Sensitivity Analysis, *continued*

The **relative uncertainties are a function of the magnitude of the porosity**

**Dropping porosity to 10% also alters the order of the uncertainties and requires a complete refocus on where Biggest Bang For The Buck is to be found**

$\alpha = 1.0, \gamma_\alpha = 0\%$   
 $R_w = 0.02, \gamma_{R_w} = 4.4\%$   
 $R_t = 40, \gamma_{R_t} = 1\%$   
 $\Phi = 0.10, \gamma_\Phi = 15\%$   
 $m = 2.0, \gamma_m = 10\%$   
 $n = 2.0, \gamma_n = 5\%$

The generalized chart and spreadsheet, both indicate

$C_m \gg C_\Phi \gg C_n$

Exhibit following

H. C. Chen and J. H. Fang  
Sensitivity Analysis of the Parameters in Archie's Water Saturation Equation.

Attribute	Individual Uncertainty	Best Estimate	Relative Un On $S_w$ (Archie)
a	0.0%	1.00	0.00%
R <sub>w</sub>	4.4%	0.02	4.40%
Phi	15.0%	0.10	9.00%
m	10.0%	2.00	21.21%
n	5.0%	2.00	2.24%
R <sub>t</sub>	1.0%	40.00	0.01%
S <sub>w</sub>		22%	
S <sub>w</sub> <sup>n</sup>		5%	
Sum			22%
S <sub>w</sub> <sup>n</sup> =0.367 is an inflection point.			

## Precision, Accuracy and Uncertainty

### What Are The Differences And What Can We Do About It?



Modeling and Forecasting

An Alternative (or supplement) To Experience

## Statistical Definitions and Illustrations

- Accuracy vs Precision
  - Examples from Every Day Petrophysics
  - Data Normalization
- Simple linear models
  - “x on y”, “RMA” and “x on y”
  - Pitfalls associated with “routine displays”
    - “Depth oriented” and “logarithmic”
- Stochastic systems and Monte Carlo modeling
  - Normal, Log Normal and Triangular Distributions
  - Monte Carlo with Excel
- GeoStatistics and the Variogram
  - Illustrative Applications

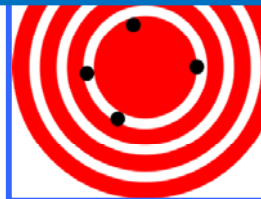
## Supplemental Discussions

• **Accuracy** is the *degree of correctness* while **precision** is the *degree of reproducibility*.

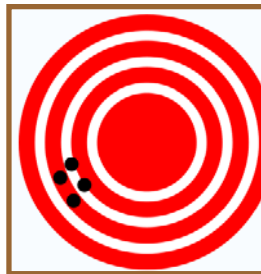
• **Precision** is sometimes *thought of as two components*:

• **Repeatability**: the variation arising when *all efforts are made to keep conditions constant by using the same instrument and operator, and repeating during a short time period*.

• **Reproducibility**: the variation arising using the same measurement process among different instruments and operators, and over longer time periods.



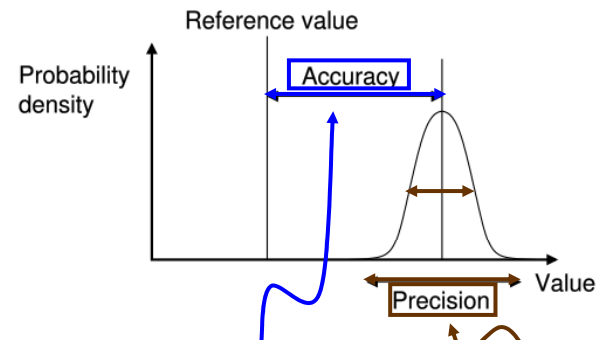
Accurate, but with Low Precision



Precise, but with Low Accuracy

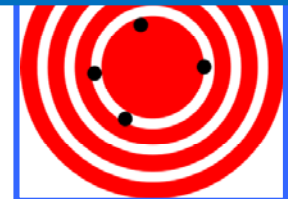
• **Precision** is usually *characterized in terms of the standard deviation of the measurements*.

• **One standard deviation** encompasses **68.3%** of the measurements, **two sigma 95%** and **three sigma 99.7%**.

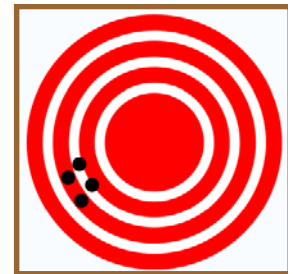


• **Accuracy** is the *degree of correctness* while **precision** is the *degree of reproducibility*.

<http://en.wikipedia.org/wiki/Accurate>



Accurate, but with Low Precision

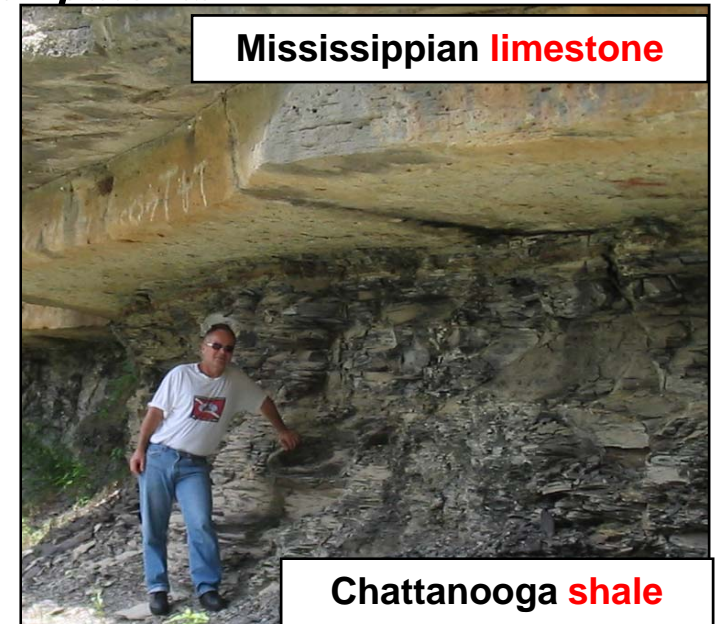


Precise, but with Low Accuracy

R. E. (Gene) Ballay's *31 years in petrophysics* include *research and operations* assignments in Houston (Shell Research), Texas; Anchorage (ARCO), Alaska; Dallas (ARCO Research), Texas; Jakarta (Huffco), Indonesia; Bakersfield (ARCO), California; and Dhahran, Saudi Arabia. His carbonate experience ranges from individual Niagaran reefs in Michigan to the Lisburne in Alaska to Ghawar, Saudi Arabia (the largest oilfield in the world).

He holds a *PhD* in *Theoretical Physics* with *double minors in Electrical Engineering & Mathematics*, has *taught physics in two universities*, *mentored Nationals* in Indonesia and Saudi Arabia, published *numerous technical articles* and been designated *co-inventor on both American and European patents*.

At retirement from the Saudi Arabian Oil Company he was the senior technical petrophysicist in the Reservoir Description Division and had represented petrophysics in three multi-discipline teams bringing on-line three (one clastic, two carbonate) multi-billion barrel increments. Subsequent to retirement from Saudi Aramco he established Robert E Ballay LLC, which provides physics - petrophysics consulting services.



He served in the *U.S. Army* as a Microwave Repairman and in the *U.S. Navy* as an Electronics Technician, and he is a *USPA Parachutist* and a *PADI Dive Master*.