FORMATION EVALUATION

PETE 663

ACOUSTIC LOGS

Summer 2010
POROSITY TOOLS

• Sonic (acoustic)
• Density
• Neutron
APPLICATIONS OF SONIC LOGS

• Determine porosity and lithology
• Determine Rwa
• Determine formation mechanical properties, like poisson’s ratio
• Evaluate fractures and permeability
• Evaluate overpressure in basin
• Combined with density logs to produce seismic traces (synthetic seismograms)
• Evaluate cement bond
SONIC PRINCIPLE

• Generate sound: “click”
• Detect sound: hearing / recording
• Analyzing sound
  – How fast ?
  – What type of wave ?
  – How strong / attenuated ?
SONIC TOOL OPERATION
P-WAVES

- Travels thru mud & rock
- Velocity depends on
  - Lithology
  - Porosity/Pore fluid(s)
- Fastest mode
  - mud 5,200 ft/sec (190 μsec/ft)
  - rock 18,000-25,000 ft/sec (55 – 40 μsec/ft)
- Weakest mode
  - Fracture insensitive

After Halliburton, 1991
**S-WAVES**

- Travel thru rock only
- Velocity \((V_s)\) depends on
  - Lithology (weak)
  - Shear modulus
- Slower mode
  - 11,000 –14,000 ft/sec
  - (90 –70 \(\mu\)sec/ft)
- Stronger mode
  - Fracture sensitive
  - Shale sensitive

_after Halliburton, 1991_
STONELEY WAVES

- Mud + rock mode
- Slowest mode ($V_{St}$)
  - 3,300 – 5,000 ft/sec
  - 300 – 200 $\mu$sec/ft
- Strongest mode
  - Fracture sensitive
  - Permeability sensitive
SONIC PRINCIPLE
SONIC TOOLS

• BHC Sonic
  – Standard tool 1950’s - late 70’s
  – 3 ft & 5 ft R-T spacings
  – 2 ft resolution
  – Only measures $D_t_c$
  – Shallow reading (about 3 or 4 in)
  – Damaged zone effects
SONIC PRINCIPLE - WIRELINE

- Non-pad (mandrel) tool
- Pulsed transmitters
  - Fire alternately
  - Broadband
  - All directions (azimuths)
- Multiple receivers
  - Time window
  - All directions (azimuths)
  - Multiple modes
- Borehole compensation (BHC)

After Halliburton, 1991
• Note ray paths for the two transmitter-receiver sets

• Averaging the two $\Delta t$ measurements cancels errors from the sonde tilt and hole-size changes
SONIC TOOLS

• Long spaced sonic
  – 8 to 13 ft R-T spacings
  – 1 to 2 ft resolution
  – Deeper reading (about 6+in)
  – Reads beyond damaged zone
  – Usually $\Delta t_s$ and $\Delta t_c$

After Schlumberger, 1989
SONIC TOOLS

- Array/full-wave tool
  - Long R-T spacings
  - Deep reading (about 6 to 18 in)
  - High resolution (6 in)
  - Downhole processing
  - All modes Δ t’s and amplitudes

- Dipole tool
  - As array tool and
  - Shear in soft formations

After Schlumberger, 1989
CAUSES OF BAD SONIC LOGS

• Road noise
• Cycle skipping
ROAD NOISE

• Caused by tool movement along the borehole, generating a high frequency noise component that is superimposed onto the normal acoustic signal

• Far sonic detectors are more affected by road noise than near detectors because of the reduced signal amplitude with increased travel time
ATTENUATION

• Attenuation (decreased amplitude) of the compressional acoustic wave is the major cause of poor sonic logs.

• Attenuation results in the signal at the receiver crossing the threshold amplitude later than for a stronger signal.
CAUSES OF BAD SONIC LOGS

• Low sonic transmitter strength may result in less than optimal receiver signal amplitudes.

• Under extreme conditions this will result in cycle-skipping.
CYCLE SKIPS

Cycle skips occurs when only one of a pair of receivers is triggered by an arriving wave, which causes sharp deflections on the log.

**Occurrences**

- If the threshold level is set low
- If there are washouts
- Presence of gas in mud
THEORY OF CYCLE SKIPS

- $t_0$: trigger on noise
- $E_1$, $E_3$: cycle skipping
- $t_1$: too early
- $t_2$: too late
Abrupt spikes in sonic log indicates cycle skips

CYCLE SKIPS
Figure 1 – Comparison of a raw sonic log (red curve, right track) that has problems with cycle skips and noise due to the poor borehole condition, and the same sonic log after replacement (blue curve, right track) of bad data with pseudo sonic data modeled from the conductivity. Note the poor borehole condition as seen on the caliper log (left track).
Sonic affected by:

**Primary**
1. Lithology
2. Porosity

**Secondarily**
1. Fluids
2. Compaction/consolidation
<table>
<thead>
<tr>
<th>Material</th>
<th>$V_{ma}$ (ft/sec)</th>
<th>$\Delta t_{ma}$ (μsec/ft)</th>
<th>Commonly Used $\Delta t_{ma}$ (μsec/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>18,000 to 19,500</td>
<td>55.5 to 51.0</td>
<td>55.5 to 51.0</td>
</tr>
<tr>
<td>Limestone</td>
<td>21,000 to 23,000</td>
<td>47.6 to 43.5</td>
<td>47.6</td>
</tr>
<tr>
<td>Dolomite</td>
<td>23,000 to 26,000</td>
<td>43.5 to 38.5</td>
<td>43.5</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>20,000</td>
<td>50.0</td>
<td>50.0</td>
</tr>
<tr>
<td>Salt</td>
<td>15,000</td>
<td>66.7</td>
<td>67.0</td>
</tr>
<tr>
<td>Casing (Iron)</td>
<td>17,500</td>
<td>57.0</td>
<td>57.0</td>
</tr>
</tbody>
</table>

Table 6. Sonic Velocities and Interval Transit Times for Different Matrices. These constants are used in the Sonic Porosity Formula (after Schlumberger, 1972).
\( \Delta t_c \) INTERPRETATION - 1

**Transit time** \( \Delta t \) or **slowness**
- Transit time is the reciprocal of velocity
- Unit: \( \Delta t = \mu \text{sec/ft or } \mu \text{sec/m} \)
- Two **porosity models**
  - Wyllie time average (clean, consolidated fm)
    \[
    \phi_S = \frac{\Delta t_{\log} - \Delta t_{\text{ma}}}{\Delta t_{\text{fl}} - \Delta t_{\text{ma}}}
    \]
  - Raymer-Hunt-Gardener
    \[
    \phi_S = 0.7 \frac{\Delta t_{\log} - \Delta t_{\text{ma}}}{\Delta t_{\log}}
    \]
\( \Delta t_c \) INTERPRETATION - 2

• Wyllie Typical values (\( \mu \text{sec/ft} \))
  – Matrix \( \Delta t \): 51-55 SS; 47.5 LS; 43.5 DOL
  – Fluid \( \Delta t \): 189 - salt water
    218 – fresh water
    238 – oil
    626 – methane

\[
\phi_S = \frac{\Delta t_{\text{log}} - \Delta t_{\text{ma}}}{\Delta t_{\text{fl}} - \Delta t_{\text{ma}}}
\]

• RHG Typical values (\( \mu \text{sec/ft} \))
  – Matrix \( \Delta t \): 56 SS; 49 LS; 44 DOL

\[
\phi_S = 0.7 \frac{\Delta t_{\text{log}} - \Delta t_{\text{ma}}}{\Delta t_{\text{log}}}
\]
From log:
$\Delta t = 90 \ \mu\text{sec}/\text{ft}$

Assume:
$\Delta t_f = 189 \ \mu\text{sec}/\text{ft}$

Matrix is Quartz ($\Delta t = 55.6 \ \mu\text{sec}/\text{ft}$)

$\phi = 26.7\%$

$\phi_S = \frac{\Delta t_{\log} - \Delta t_{ma}}{\Delta t_{fl} - \Delta t_{ma}}$

$\phi_S = \frac{90 - 55.6}{189 - 55.6}$

$\phi_S = \frac{34.4}{133.4}$

$\phi_S = 25.8$
Estimating $R_w$: The Rwa Method

- Needs porosity and resistivity logs
- Assumes
  - Archie’s (second) law
  - $Sw \leq 1$

- Define $R_{wa} = \frac{R_t}{F}$
- Calculate $R_{wa}$
- Take $(R_{wa})_{min} = R_w$
RWA EXAMPLE - PROJECT 3 LOGS

- **SS @ 156 ft:**
  - \( R_{ild} = 0.32 \Omega \text{-m} \)
  - \( \Delta t = 83 \mu s/\text{ft} \)

- **Chart \( \phi = 23\% \)**

- **Assume**
  - \( a = 0.81 \)
  - \( m = 2 \) (Tixier)
  - \( F = \frac{0.81}{\phi^2} \)

- **\( F = 15 \)**

- **\( R_{wa} = \frac{R_{ild}}{F} \)**
  - \( = \frac{0.32}{15} \)
  - \( = 0.021 \Omega \text{-m} \)

\[ F = \frac{a}{\phi^m} \]

\( a \) is a constant; \( m \) is cementation factor
RWA EXAMPLE - 2

<table>
<thead>
<tr>
<th>Depth</th>
<th>Δt</th>
<th>ϕ</th>
<th>Rild</th>
<th>Rwa</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>87</td>
<td>25</td>
<td>45</td>
<td>3.5</td>
</tr>
<tr>
<td>156</td>
<td>83</td>
<td>23</td>
<td>0.32</td>
<td>0.021</td>
</tr>
<tr>
<td>204</td>
<td>90</td>
<td>26</td>
<td>0.30</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Two further points
• Works best in clean formations
• Applies to flushed zone, too
SONIC FAMILY TOOLS & APPLICATION

Borehole
Application
Output
Final Use

Open Hole
Mechanical Properties
Youngs Modulus
Bulk Modulus
Sheer Modulus
Poisson Ratio
Velocities

Formation Evaluation
Porosity
Gas Identification
Lithology

Casing Bond
Casing Corrosion

Cement Quality
Reservoir Isolation
Casing Quality

Seismic Parameters
Seismic Calibration
Reservoir Appraisal
Fluid Determination

Perforation...
APPLICATIONS OF SONIC LOGS

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• Determine Rwa
• Determine formation mechanical properties, like poisson’s ratio
• Evaluate fractures and permeability
• Evaluate overpressure in basin
• Combined with density logs to produce seismic traces (synthetic seismograms)
• Evaluate cement bond
SONIC LOGS USED FOR FRACTURE DETECTION

In fractures, amplitude of stonely waves and shear waves are attenuated.

Red – least attenuated
Blue – highly attenuated
SONIC AS A POROSITY TOOL

Sonic affected by:

- Lithology
- Porosity
- Fluids
- Compaction/consolidation
- Borehole conditions
- Gas in drilling mud
SUMMARY

• Sonic physics
  – Several modes
  – Borehole compensation

• Tools and spacings

• Interpretation
  – Two $\Delta t$ models for porosity
  – Rwa method
SANDSTONE POROSITY
WATER-WET

\[ \theta < 90^\circ \]

SOLID (ROCK)

OIL

WATER

FREE WATER

OIL-WET

\[ \theta > 90^\circ \]

SOLID (ROCK)

OIL

WATER

BOUND WATER

FREE WATER

OIL

GRAIN

OIL RIM

Ayers, 2001
VARIATION IN PORE PROPERTIES AND PERMEABILITY WITHIN A FORMATION

**Fig. 2.6**—Family of capillary-pressure curves in a sandstone formation (modified after Archie\(^1\)).

**Fig. 2.7**—Family of capillary-pressure curves in a limestone formation (modified after Archie\(^1\)).

Modified from Jordan and Campbell, 1984, vol. 1
GEOLOGICAL AND PETROPHYSICAL DATA USED TO DEFINE FLOW UNITS

Core Lithofacies | Core Plugs | Pore Types | Petrophysical Data | Gamma Ray Log | Flow Units
--- | --- | --- | --- | --- | ---
1 | 2 | 3 | 4 | 5

Modified from Ebanks et al., 1992
Sedimentary Facies vs. Porosity

Porosity (%)

Facies

S3
S11
S11'
S2

φ = 12%
**PRIMARY** (ORIGINAL) POROSITY

- Developed at deposition
- **Typified by**
  - Intergranular pores of clastics or carbonates
  - Intercrystalline and fenestral pores of carbonates
- Usually more uniform than secondary porosity

**SECONDARY** POROSITY

- Developed after the sediments were deposited
- More complex and usually less predictable than primary porosity
- **Typified by**
  - Dissolution pores of clastics or carbonates
  - Cementation (clays)
  - Fractures
FACTORS AFFECTING PERMEABILITY

• Size and shape of grains
• Sorting
• Rock – fluid interactions
  – Dissolution
  – Cementation
• Fractures
• Stress
• Formation damage
FACTORS THAT AFFECT POROSITY

PRIMARY
- Particle sphericity and angularity
- Packing
- Sorting (variable grain sizes)
- Texture

SECONDARY (DIAGENETIC)
- Cementing materials
- Overburden stress (compaction)
- Vugs, dissolution, and fractures
PACKING AND SORTING
OF SPHERES (CLASTICS)

Porosity = 48%

Porosity = 27%

Compare sizes of pores and pore throats

Porosity = 14%
GRAIN-SIZE SORTING IN SANDSTONE

Very Well Sorted
Well Sorted
Moderately Sorted
Poorly Sorted
Very Poorly Sorted
TYPES OF TEXTURAL CHANGES SENSED BY THE NAKED EYE AS BEDDING

- Change of Composition
  - Sand
  - Shale

- Change of Size
  - Slow Current
  - Fast Current

- Change of Shape
  - Eolian
  - Fluvial

- Change of Orientation
  - River
  - Beach

- Change of Packing
SANDSTONE COMPOSITION, Framework Grains

Potassium Feldspar is stained yellow with a chemical dye. Pores are impregnated with blue-dyed epoxy.

Norphlet Sandstone, Offshore Alabama, USA
Grains ~0.25 mm in Diameter/Length

Photo by R. Kugler
PORE-SPACE CLASSIFICATION

- Total porosity, $\phi_t = \frac{\text{Total Pore Volume}}{\text{Bulk Volume}}$

- Effective porosity, $\phi_e = \frac{\text{Interconnected Pore Volume}}{\text{Bulk Volume}}$

- **Effective porosity** — contains the mobile fluid
DIAGENETIC PROCESSES

• “Diagenesis” includes all physical and chemical changes that affect sediments after deposition
• Diagenetic processes may increase or decrease porosity and/or permeability

Examples
1. Compaction
2. Cementation
3. Grain dissolution in sandstones or carbonates
4. Vugs and solution cavities in carbonates
5. Fractures
MECHANICS OF COMPACTION

- Platy Grains (e.g., clays)
- Non-Platy Grains (e.g., qtz., feldspar)

Rotation and Closer Packing

Ductile Grain Deformation

Breakage of Brittle Grains

Pressure Solution At Grain Contacts

Chemical Compaction - Styolites

Ductile Framework Grain, e.g., Shale Rock Fragment

Modified from Jonas and McBride, 1977
Influence Of Clay-Mineral Distribution On Effective Porosity

- **Dispersed Clay**
  - Pore-filling
  - Pore-lining
  - Pore-bridging
  - Slight affect - $\Delta T$

- **Clay Lamination**
  - Greatest affect - $\Delta T$

- **Structural Clay**
  - (Rock Fragments, Rip-Up Clasts, Clay-Replaced Grains)
  - Little affect - $\Delta T$
**Laminated Shale**
- Interlayered with sand
- Reduces por., perm.
- Common
- Example – shale laminae
- Assume composition similar to nearby shale
# TYPES OF SANDSTONES POROSITY

<table>
<thead>
<tr>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intergranular</strong></td>
<td>Interstitial Void Space Between Framework Grains</td>
</tr>
<tr>
<td><strong>Secondary</strong></td>
<td><strong>Micropores</strong></td>
</tr>
<tr>
<td><strong>Primary</strong></td>
<td><strong>Small Pores Mainly Between Detrital Framework Grains or Cement</strong></td>
</tr>
<tr>
<td><strong>Dissolution</strong></td>
<td><strong>Partial or Complete Dissolution of or Authigenic Grains (Can Also Occur Within Grains)</strong></td>
</tr>
<tr>
<td><strong>Fractures</strong></td>
<td><strong>Breakage Due to Earth Stresses</strong></td>
</tr>
</tbody>
</table>
FOUR COMPONENTS OF SANDSTONE

- Framework
- Matrix
- Cement
- Pores

Note different use of “matrix” by geologists and engineers.

Geologist's Classification

Ayers, 2001
SANDSTONE COMPOSITION, Framework Grains

Norphlet Sandstone, Offshore Alabama, USA
Grains ~0.25 mm in Diameter/Length

KF = Potassium Feldspar
PRF = Plutonic Rock Fragment
Q = Quartz
P = Pore

Potassium Feldspar is Stained Yellow With a Chemical Dye
Pores are Impregnated With Blue-Dyed Epoxy

Photo by R. Kugler
DUAL POROSITY IN SANDSTONE

1. Primary and secondary “matrix” porosity system
2. Fracture porosity system
3. Diagenesis

Sandstone Comp.
- Framework
- Matrix
- Cement
- Pores

Ayers, 2001
FRACTURE CHARACTERISTICS FROM MICROSCOPIC THIN SECTIONS OF SANDSTONE

Fractures cross grains and cements

From Laubach et al., 1996
PORE-LINING MINERALS IN SANDSTONE

Pores Provide the Volume to Store Hydrocarbons

Pore Throats Restrict Flow

Scanning Electron Micrograph
Norphlet Formation, Offshore Alabama, USA

Photomicrograph by R.L. Kugler
CEMENTATION AND ROCK – FLUID INTERACTIONS

Pore Throats in Sandstone May Be Lined With A Variety of Cement Minerals That Affect Petrophysical Properties

Scanning Electron Micrograph
Tordillo Sandstone, Neuquen Basin, Argentina

Photomicrograph by R.L. Kugler
INTERGRANULAR PORE AND MICROPOROSITY

- Intergranular Pores Contain Hydrocarbon Fluids
- Micropores Contain Irreducible Water

Backscattered Electron Micrograph Carter Sandstone, Black Warrior Basin, Alabama, USA

(Photograph by R.L. Kugler)
Clay Minerals in Sandstone Reservoirs, Authigenic Chlorite

Secondary Electron Micrograph

- Iron-Rich Varieties React With Acid
- Occurs in Several Deeply Buried Sandstones With High Reservoir Quality
- Occurs as Thin Coats on Detrital Grain Surfaces

Jurassic Norphlet Sandstone Offshore Alabama, USA

~ 10 μm

(Photograph by R.L. Kugler)
Clay Minerals in Sandstone Reservoirs, Authigenic Kaolinite

Secondary Electron Micrograph

- Significant Permeability Reduction
- High Irreducible Water Saturation
- Migration of Fines Problem

Carter Sandstone
North Blowhorn Creek Oil Unit
Black Warrior Basin, Alabama, USA

(Photograph by R.L. Kugler)
Clay Minerals in Sandstone Reservoirs, Fibrous Authigenic Illite

Electron Photomicrograph

- Significant Permeability Reduction
- Negligible Porosity Reduction
- High Irreducible Water Saturation
- Migration of Fines Problem

Jurassic Norphlet Sandstone
Hatters Pond Field, Alabama, USA

(Photograph by R.L. Kugler)
Dissolution of Framework Grains (Feldspar, for Example) and Cement may Enhance the Interconnected Pore System

This is Secondary Porosity

Thin Section Micrograph - Plane Polarized Light
Avile Sandstone, Neuquen Basin, Argentina

Photo by R.L. Kugler
DISSOLUTION POROSITY

Scanning Electron Micrograph
Tordillo Formation, Neuquen Basin, Argentina

Dissolution Pores May be Isolated and not Contribute to the Effective Pore System

Partially Dissolved Feldspar

Photo by R.L. Kugler
CARBONATE POROSITY
## CARBONATES POROSITY TYPES

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interparticle</td>
<td>Pores between particles or grains</td>
</tr>
<tr>
<td>Intraparticle</td>
<td>Pores within individual particles or grains</td>
</tr>
<tr>
<td>Intercrystal</td>
<td>Pores between crystals</td>
</tr>
<tr>
<td>Moldic</td>
<td>Pores formed by dissolution of an individual grain or crystal in the rock</td>
</tr>
<tr>
<td>Fenestral</td>
<td>Primary pores larger than grain-supported interstices</td>
</tr>
<tr>
<td>Fracture</td>
<td>Formed by a planar break in the rock</td>
</tr>
<tr>
<td>Vug</td>
<td>Large pores formed by indiscriminate dissolution of cements and grains</td>
</tr>
</tbody>
</table>

Generally, porosity in carbonates is lower than in clastics, and its occurrence is more complex.
Idealized Carbonate Porosity Types

- Interparticle
- Intraparticle
- Intercrystal
- Moldic

Fabric Selective
- Fenestral
- Shelter
- Growth-Framework

Non-Fabric Selective
- Fracture
- Channel
- Vug

Fabric Selective or Not Fabric Selective
- Breccia
- Boring
- Burrow
- Shrinkage

(modified from Choquette and Pray, 1970)
CARBONATE POROSITY - EXAMPLE

**Moldic Pores**
- Due to dissolution and collapse of ooids (allochemical particles)
- Isolated pores
- Low effective porosity
- Low permeability

Blue areas are pores.

Thin section micrograph - plane-polarized light
Smackover Formation, Alabama

(Photograph by D.C. Kopaska-Merkel)
CARBONATE POROSITY - EXAMPLE

Moldic and Interparticle Pores

- Combination pore system
- Moldic pores formed through dissolution of ooids (allochemical particles)
- Connected pores
- High effective porosity
- High permeability

Thin section micrograph
Smackover Formation, Alabama
Black areas are pores.

(Photograph by D.C. Kopaska-Merkel)
APPLICATIONS OF SONIC LOGS

- Determine porosity and lithology
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