FORMATION EVALUATION

PETE 663

ACOUSTIC LOGS

Summer 2010

POROSITY TOOLS

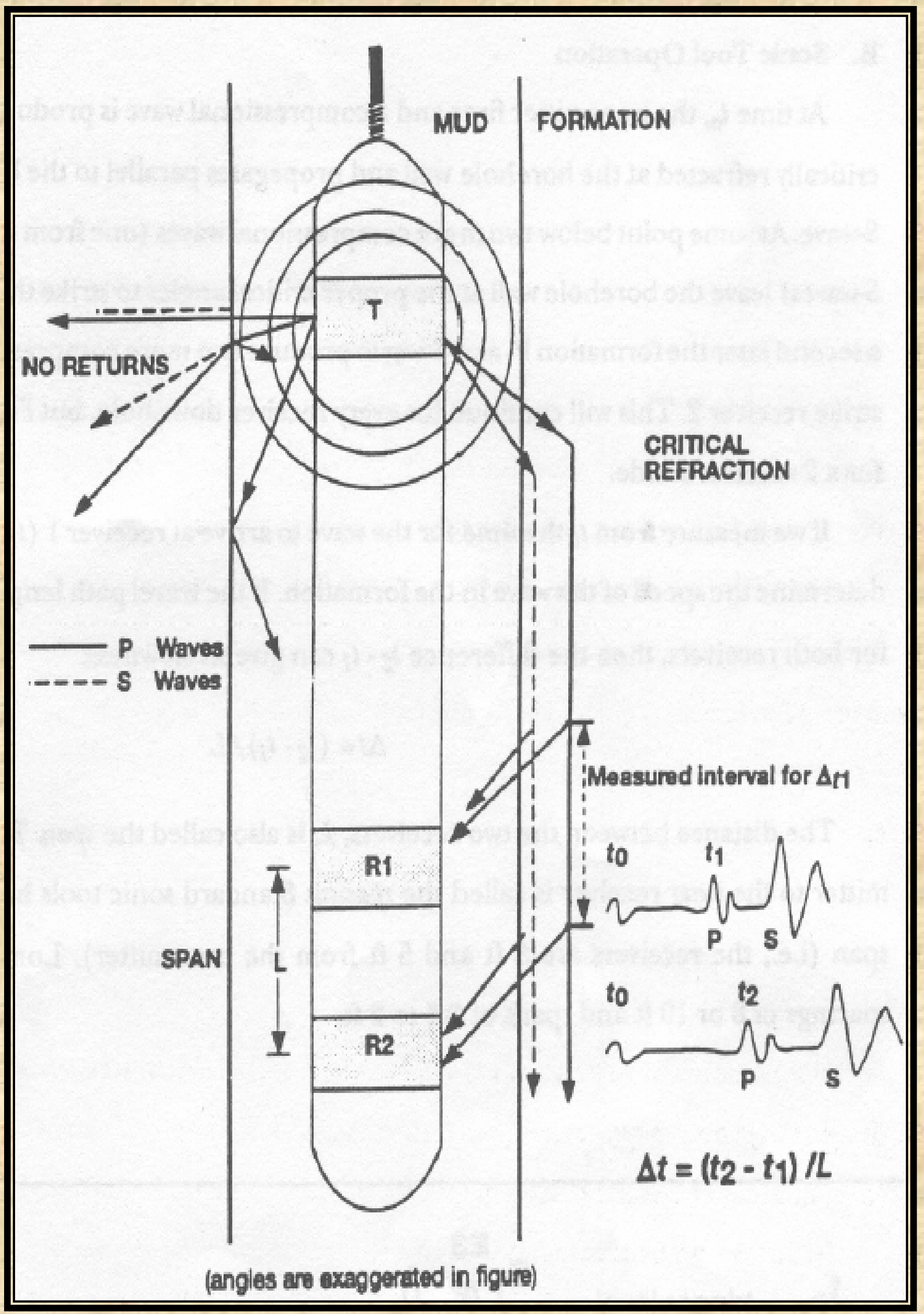
- **Sonic (acoustic)**
- **Density**
- **Neutron**

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

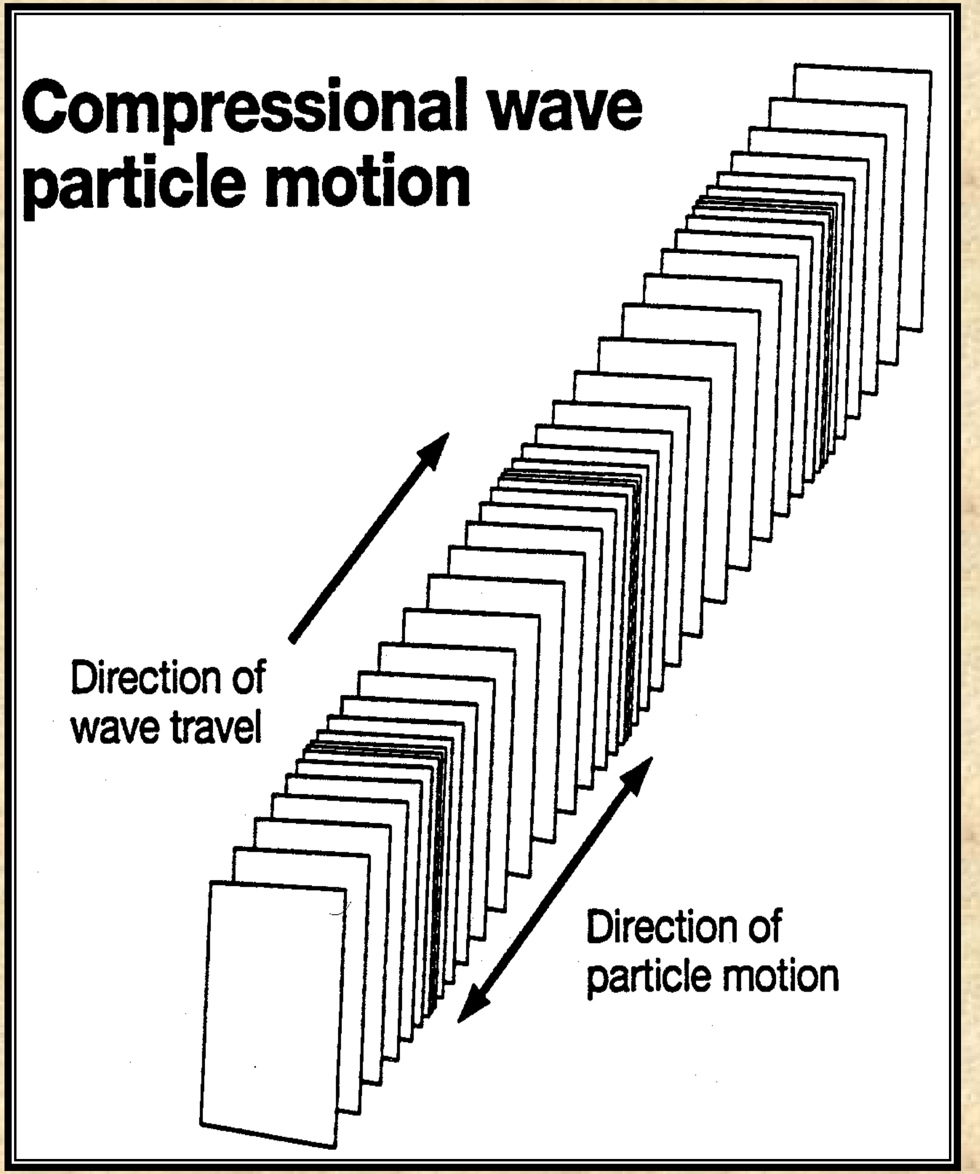
- Generate sound: “click”
- Detect sound: hearing / recording
- Analyzing sound
  - How fast ?
  - What type of wave ?
  - How strong / attenuated ?



SONIC TOOL OPERATION

P-WAVES

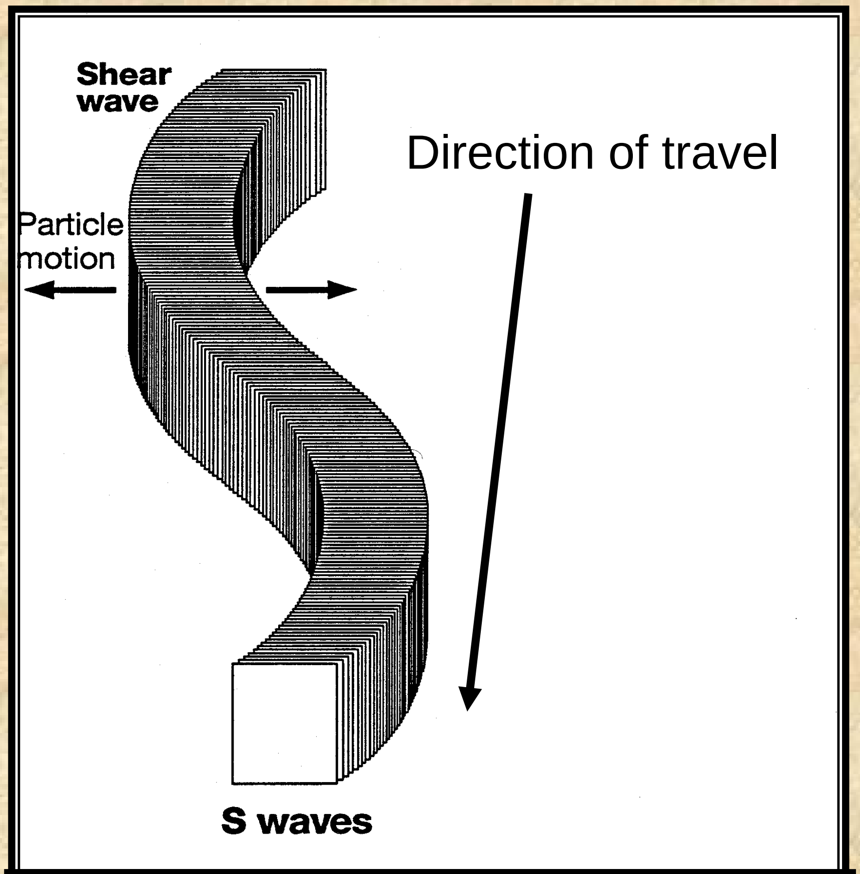
- Travels thru mud & rock
- Velocity depends on
  - Lithology
  - Porosity/Pore fluid(s)
- Fastest mode
  - mud 5,200 ft/sec (190 μsec/ft)
  - rock 18,000-25,000 ft/sec (55 – 40 μsec/ft)
- Weakest mode
  - Fracture insensitive



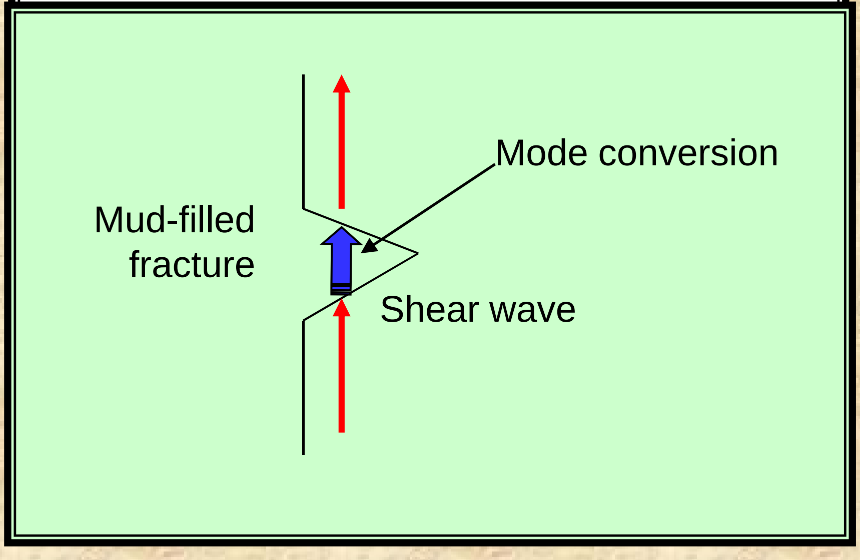
After Halliburton, 1991

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 µsec/ft)
- Stronger mode
  - Fracture sensitive
  - Shale sensitive

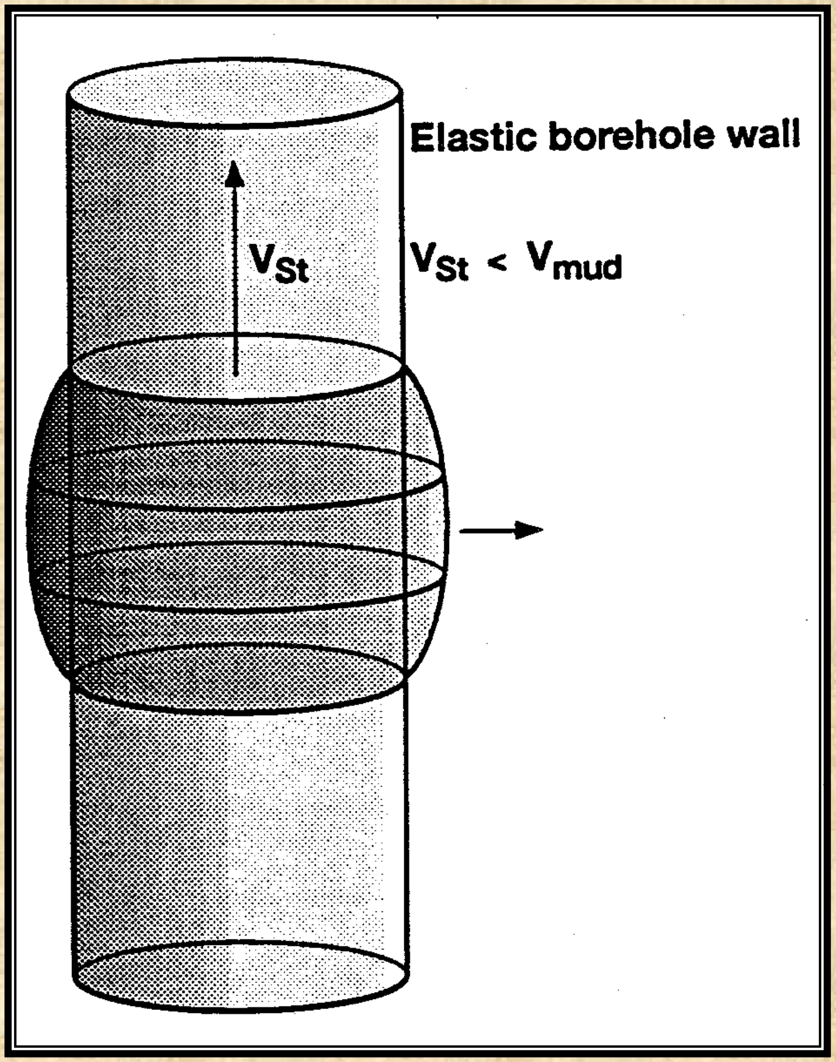


After Halliburton, 1991

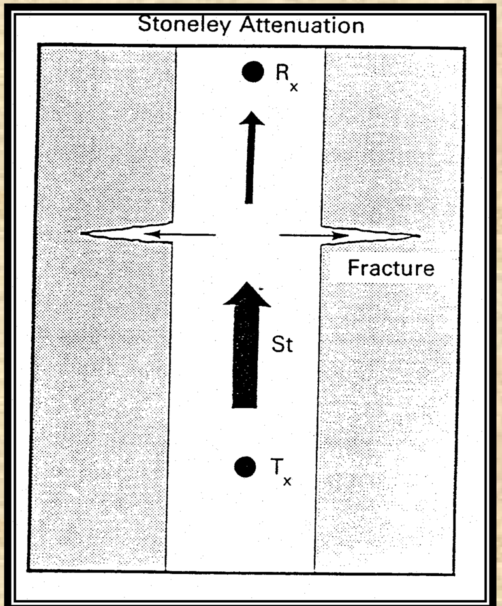


STONELEY WAVES

- Mud + rock mode
- Slowest mode (V_{St})
  - 3,300 – 5,000 ft/sec (300 –200 μsec/ft)
- Strongest mode
  - Fracture sensitive
  - Permeability sensitive

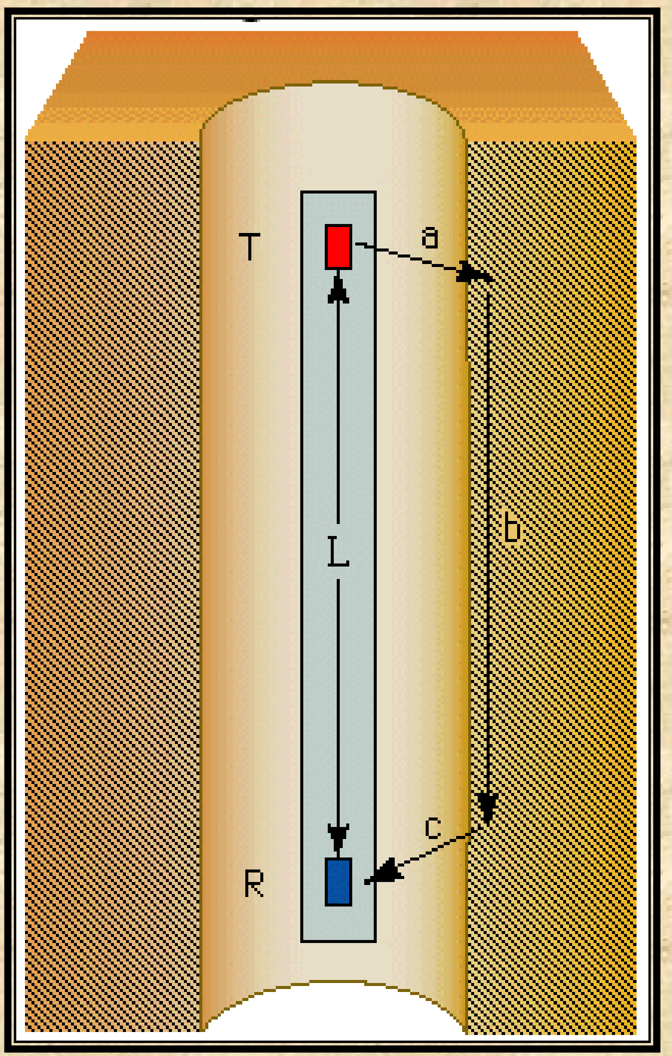


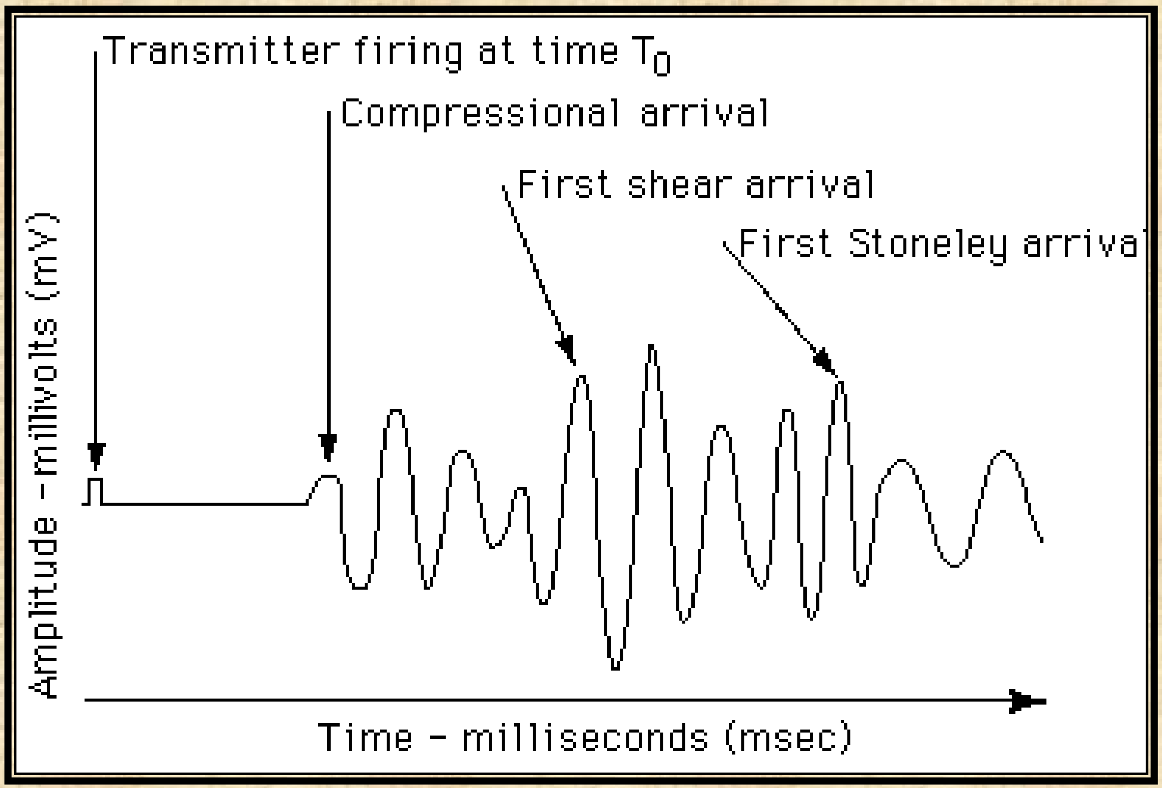
After Halliburton, 1991



After Ellis, 1987

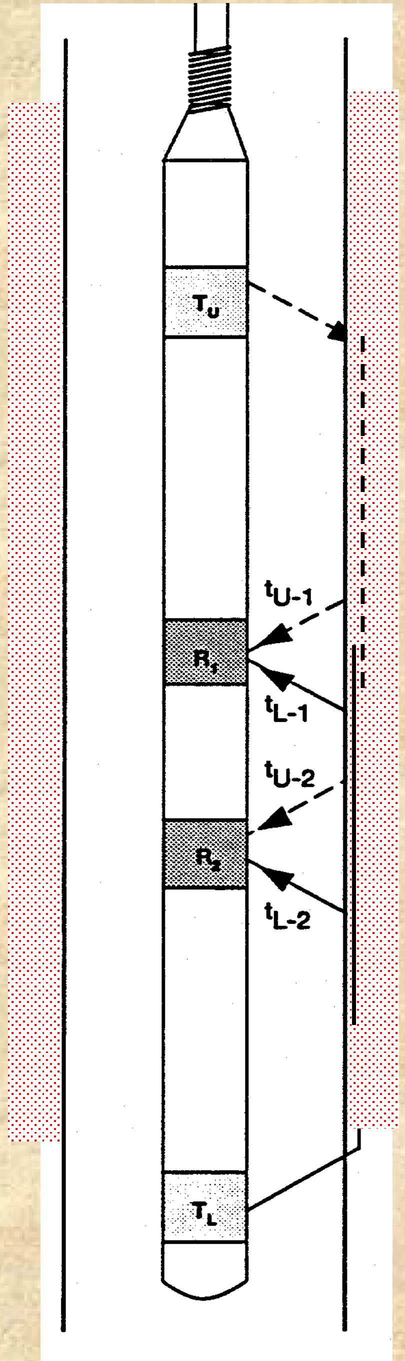
SONIC PRINCIPLE





SONIC TOOLS

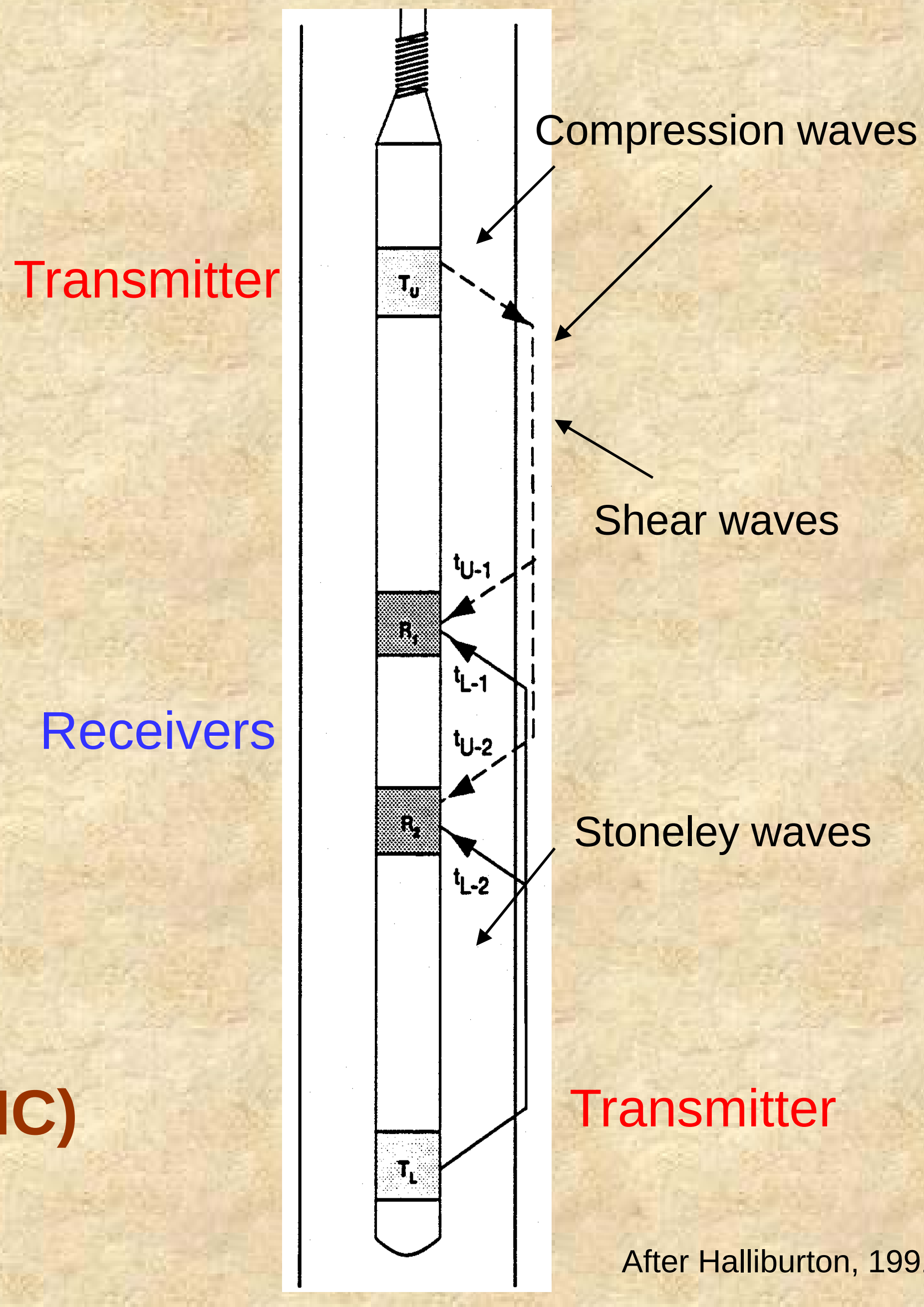
- BHC Sonic
  - Standard tool 1950's - late 70's
  - 3 ft & 5 ft R-T spacings
  - 2 ft resolution
  - Only measures Dt_c
  - Shallow reading (about 3 or 4 in)
  - Damaged zone effects



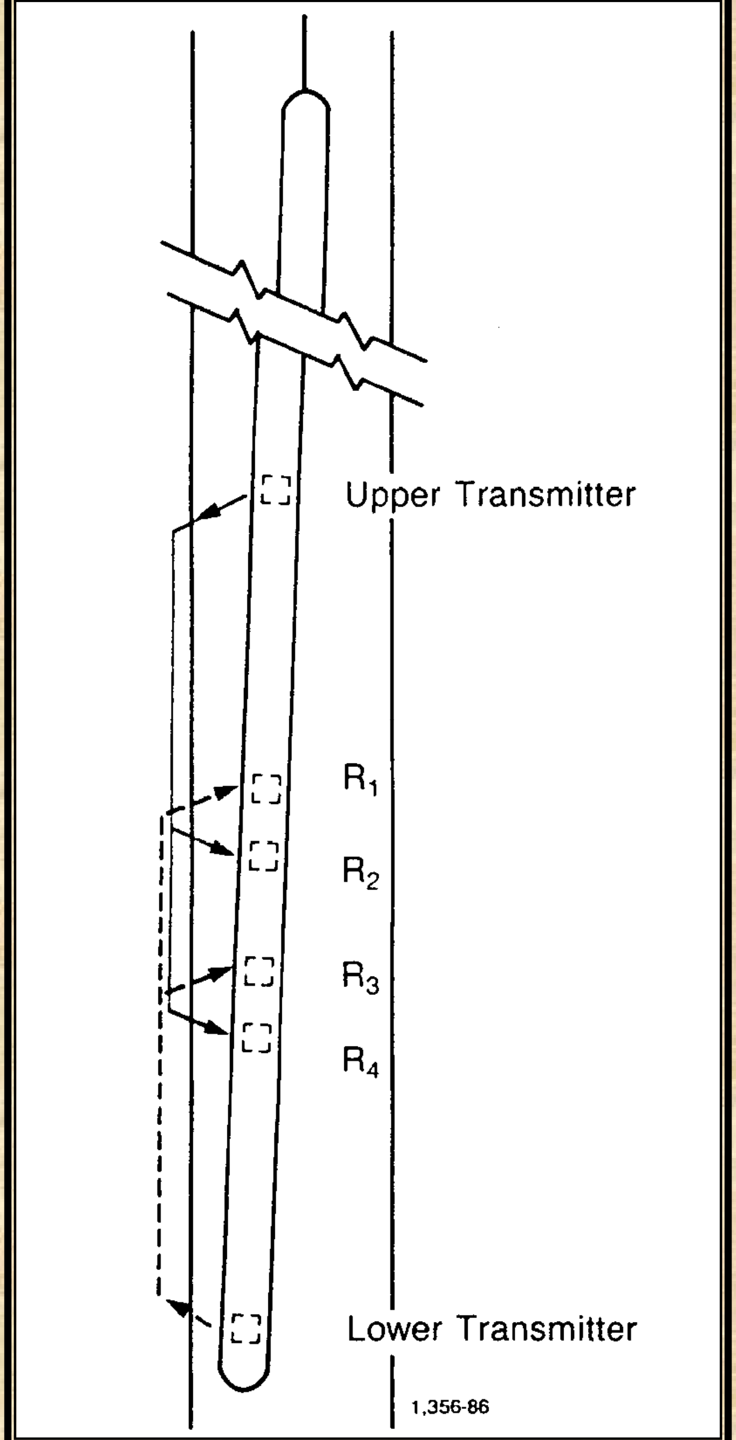
After Halliburton, 1991

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

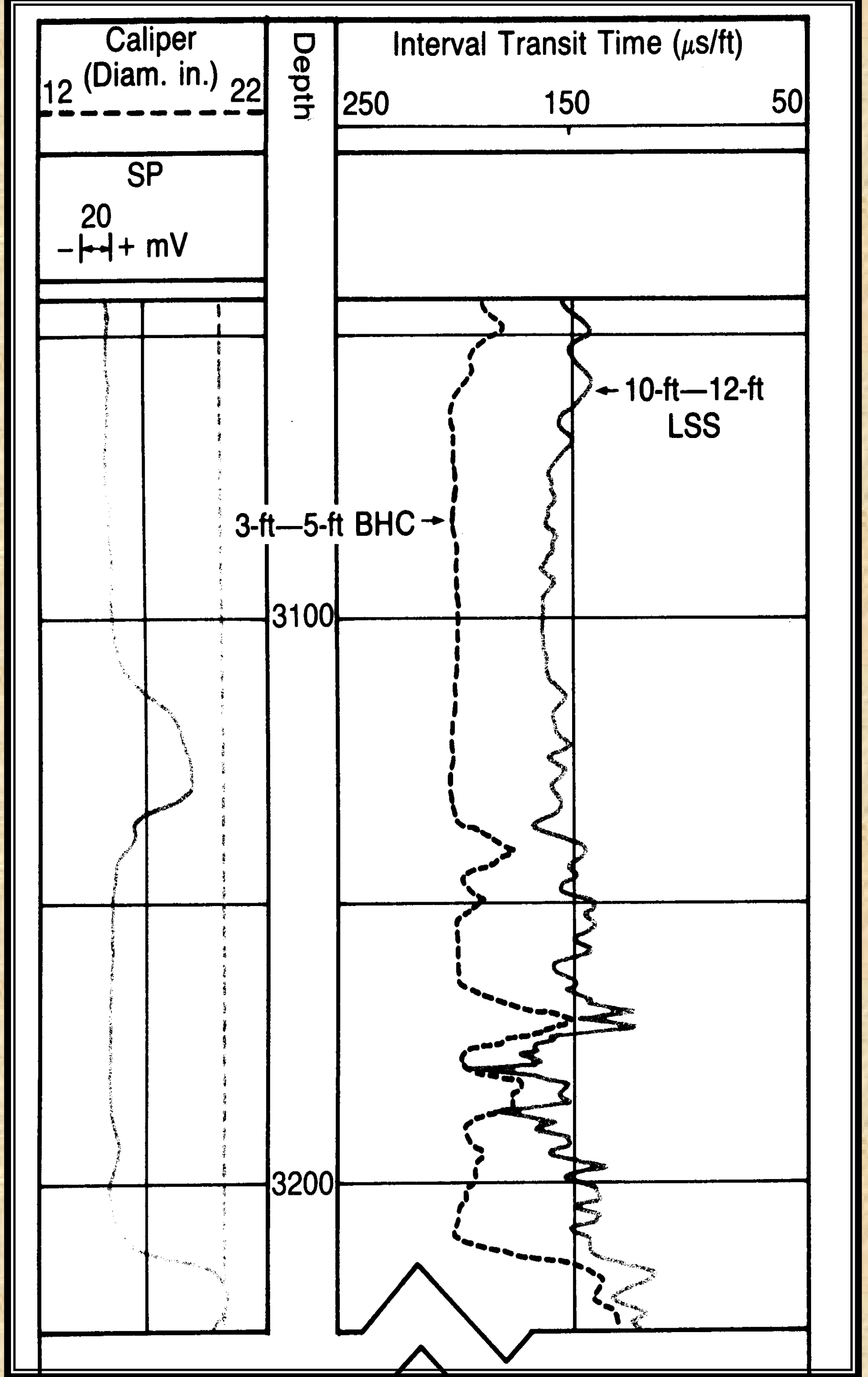


SCHEMATIC OF BHC SONDE

- Note ray paths for the two transmitter-receiver sets
- Averaging the two Δt measurements cancels errors from the sonde tilt and hole-size changes

SONIC TOOLS

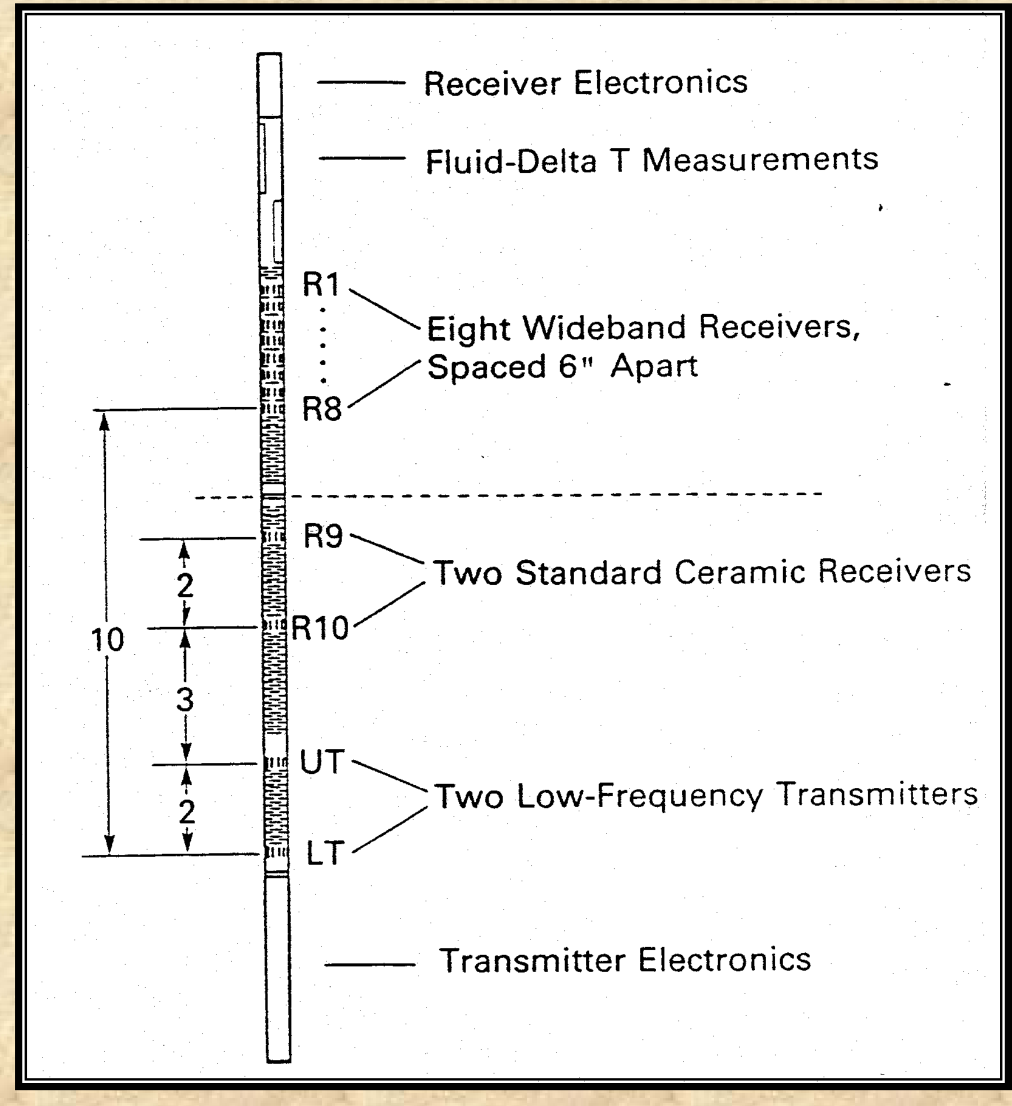
- Long spaced sonic
  - 8 to 13 ft R-T spacings
  - 1 to 2 ft resolution
  - Deeper reading (about 6+in)
  - Reads beyond damaged zone
  - Usually Δt_s and Δt_c



After Schlumberger, 1989

SONIC TOOLS

- **Array/full-wave tool**
  - **Long R-T spacings**
  - **Deep reading (about 6 to 18 in)**
  - **High resolution (6in)**
  - **Downhole processing**
  - **All modes ∆ 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 <u>cycle-skipping</u>**

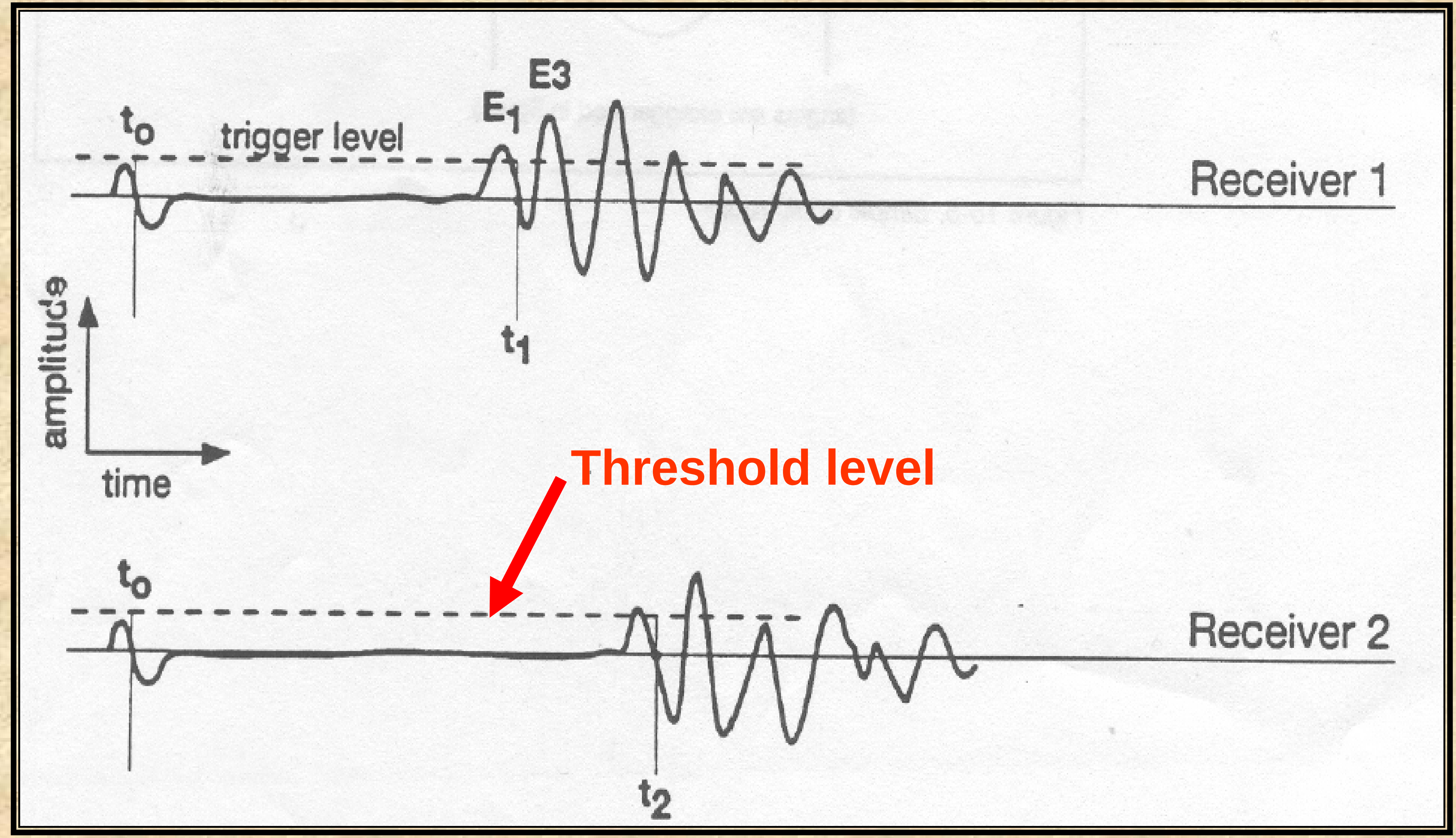
CYCLE SKIPS

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

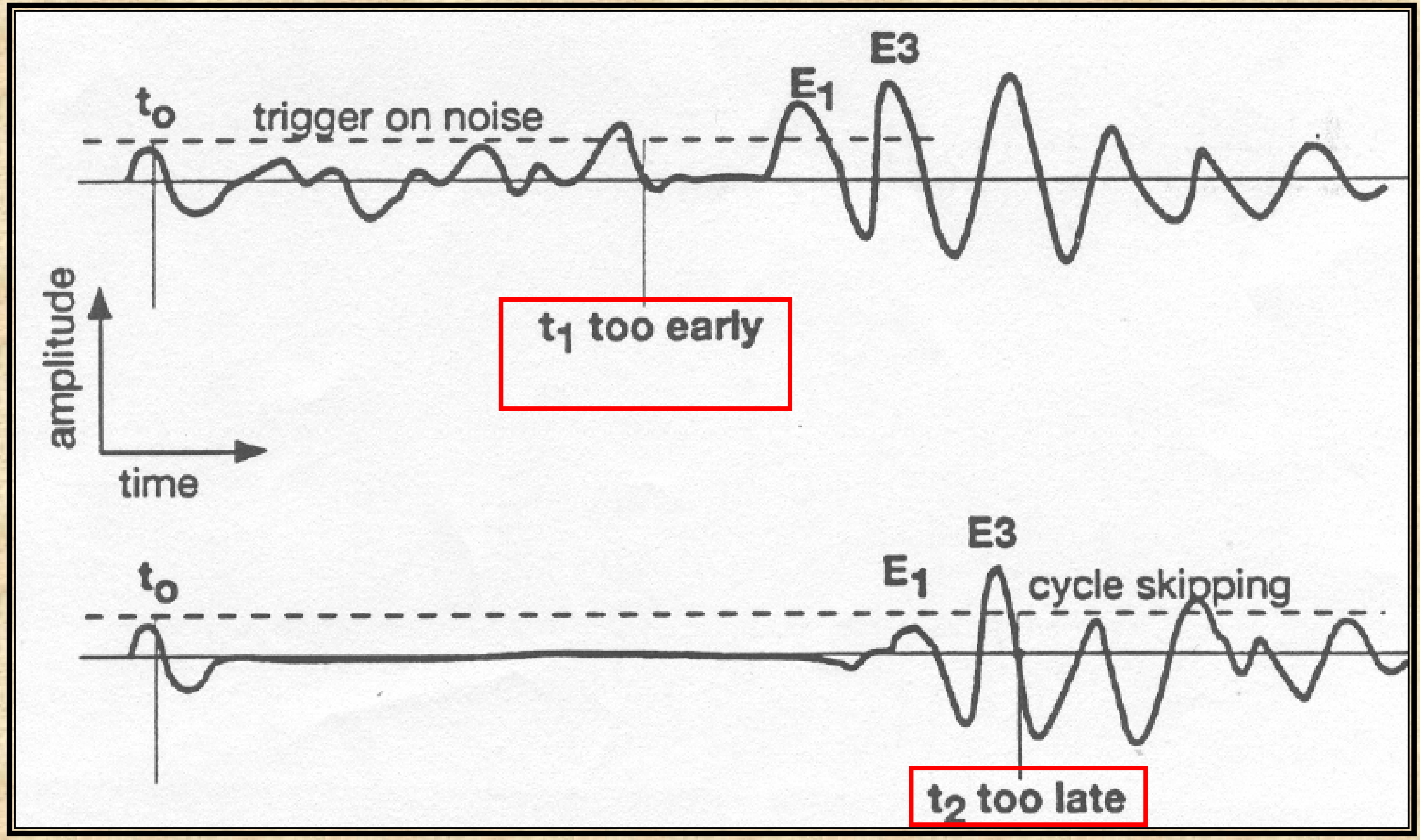
Occurrences

- **If the threshold level is set low**
- **If there are washouts**
- **Presence of gas in mud**

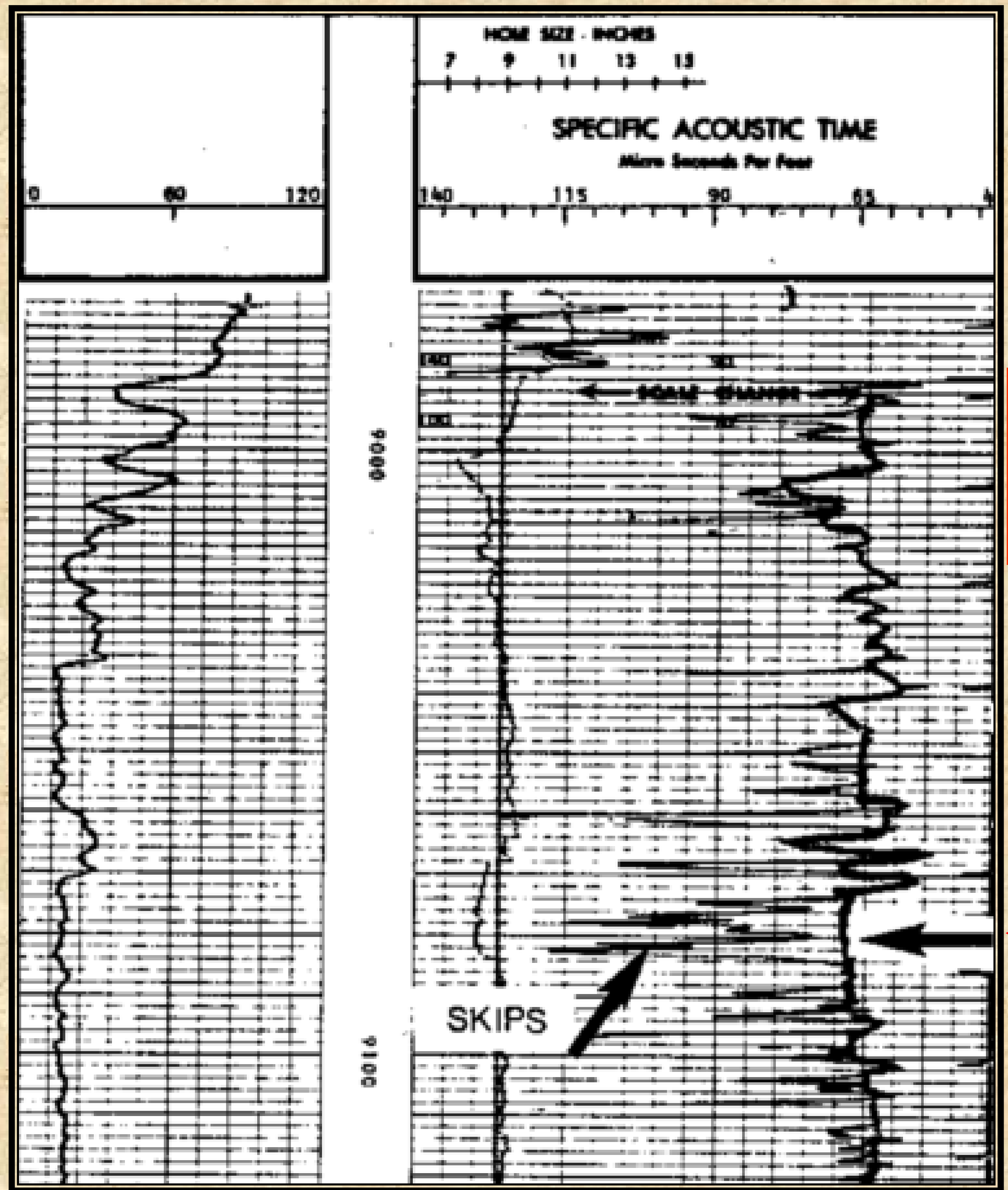
MEASUREMENT PRINCIPLE



THEORY OF CYCLE SKIPS



CYCLE SKIPS



Abrupt spikes in sonic log indicates cycle skips

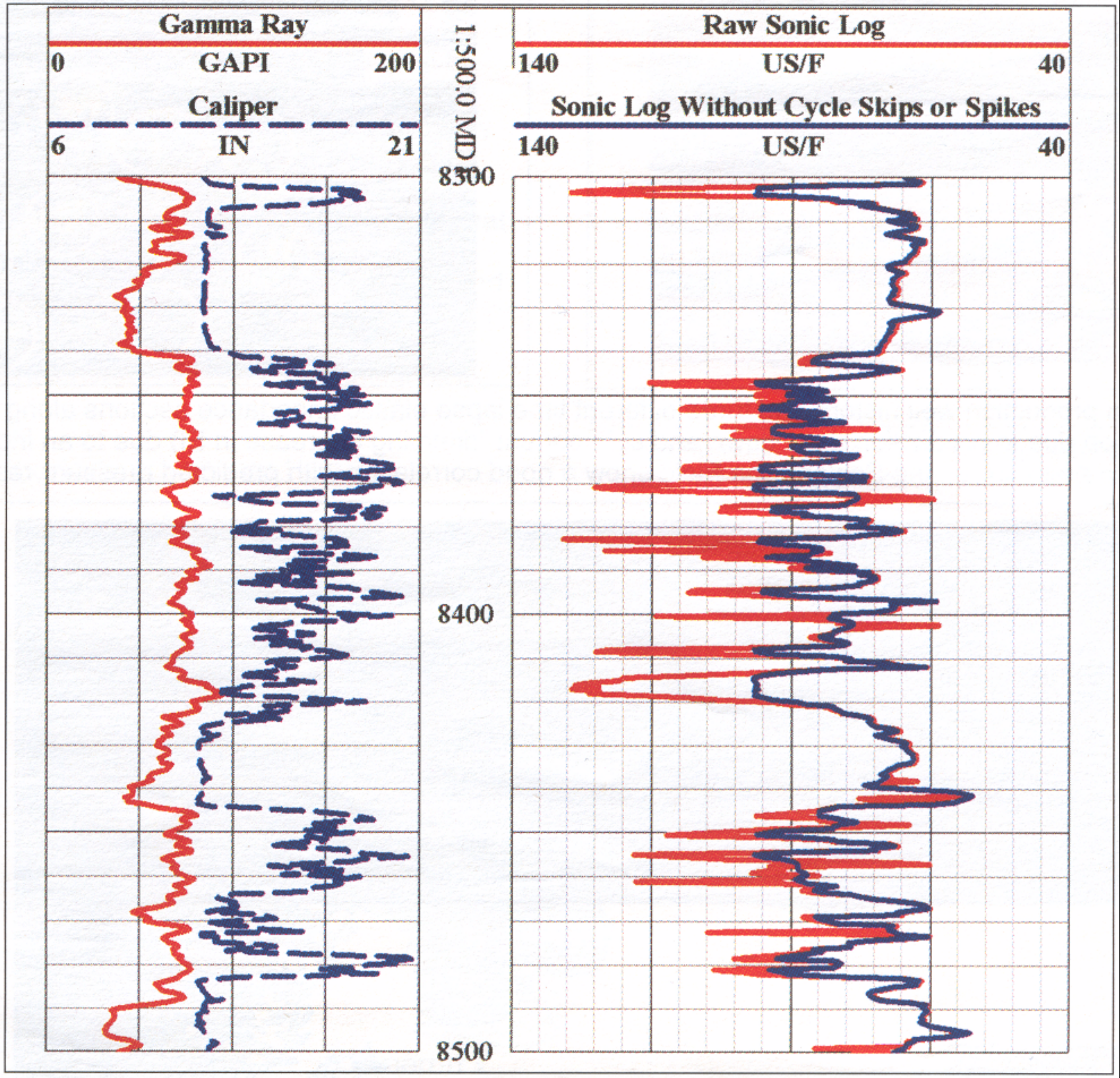


Figure 1 – Comparison of a raw sonic log (red curve, right track) that has problems with cycle skips and noise due to the poor borehole condition, and the same sonic log after replacement (blue curve, right track) of bad data with pseudo sonic data modeled from the conductivity. Note the poor borehole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

Ray, 2002

APPLICATIONS -

SONIC AS A POROSITY TOOL

Sonic affected by:

Primary

1. **Lithology**
2. **Porosity**

Secondarily

1. **Fluids**
2. **Compaction/consolidation**

Table 6. Sonic Velocities and Interval Transit Times for Different Matricies. These constants are used in the Sonic Porosity Formula (after Schlumberger, 1972).

	V_{ma} (ft/sec)	Δt_{ma} (μsec/ft)	Δt_{ma} (μsec/ft) commonly used
Sandstone	18,000 to 19,500	55.5 to 51.0	55.5 to 51.0
Limestone	21,000 to 23,000	47.6 to 43.5	47.6
Dolomite	23,000 to 26,000	43.5 to 38.5	43.5
Anhydrite	20,000	50.0	50.0
Salt	15,000	66.7	67.0
Casing (Iron)	17,500	57.0	57.0

Δt_c INTERPRETATION - 1

Transit time Δt or slowness

- **Transit time is the reciprocal of velocity**
- **Unit : Δt = μsec/ft or μsec/m**
- **Two porosity models**
  - **Wyllie time average (clean, consolidated fm)**

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

  - **Raymer-Hunt-Gardener**

$$\phi_S = 0.7 \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_{log}}$$

Δt_c INTERPRETATION - 2

- **Wyllie Typical values (μsec/ft)**
  - **Matrix Δt: 51-55 SS; 47.5 LS; 43.5 DOL**
  - **Fluid Δt: 189 - salt water**

    218 – fresh water

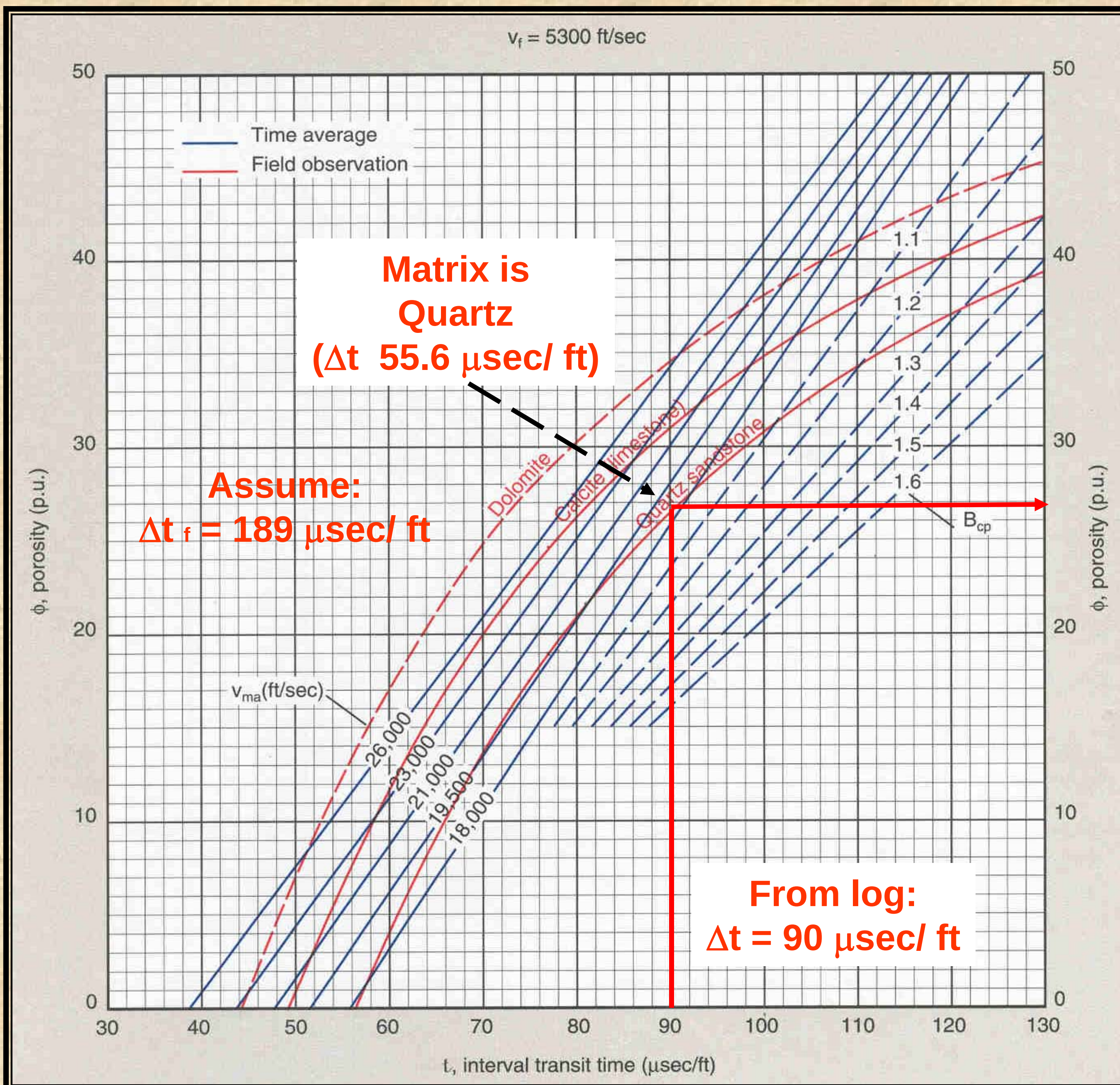
    238 – oil

    626 – methane

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

- **RHG Typical values (μsec/ft)**
  - **Matrix Δt: 56 SS; 49 LS; 44 DOL**

$$\phi_S = 0.7 \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_{log}}$$



CHART

Por-3 (S)
Por-11 (H)

φ = 26.7%

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

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

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

$$\phi_S = 25.8$$

WTA

Δt_c INTERPRETATION - 3

Estimating Rw: The Rwa Method

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

$$S_w^n = \frac{aR_w}{\phi^m R_t}$$

- Define $R_{wa} = R_t/F$
- Calculate R_{wa}
- Take $(R_{wa})_{min} = R_w$

$$S_w^n = \frac{R_w}{R_t / F} \leq 1 \text{ or}$$

$$\frac{R_t}{F} \geq R_w \text{ so}$$

$$R_{wa} \geq R_w$$

RWA EXAMPLE - PROJECT 3 LOGS

- **SS @ 156 ft:**
  - Rild = 0.32Ω-m
  - Δt = 83μs/ft
- **Chart ϕ = 23%**
- **<u>Assume</u>**
  - a = 0.81
  - m = 2

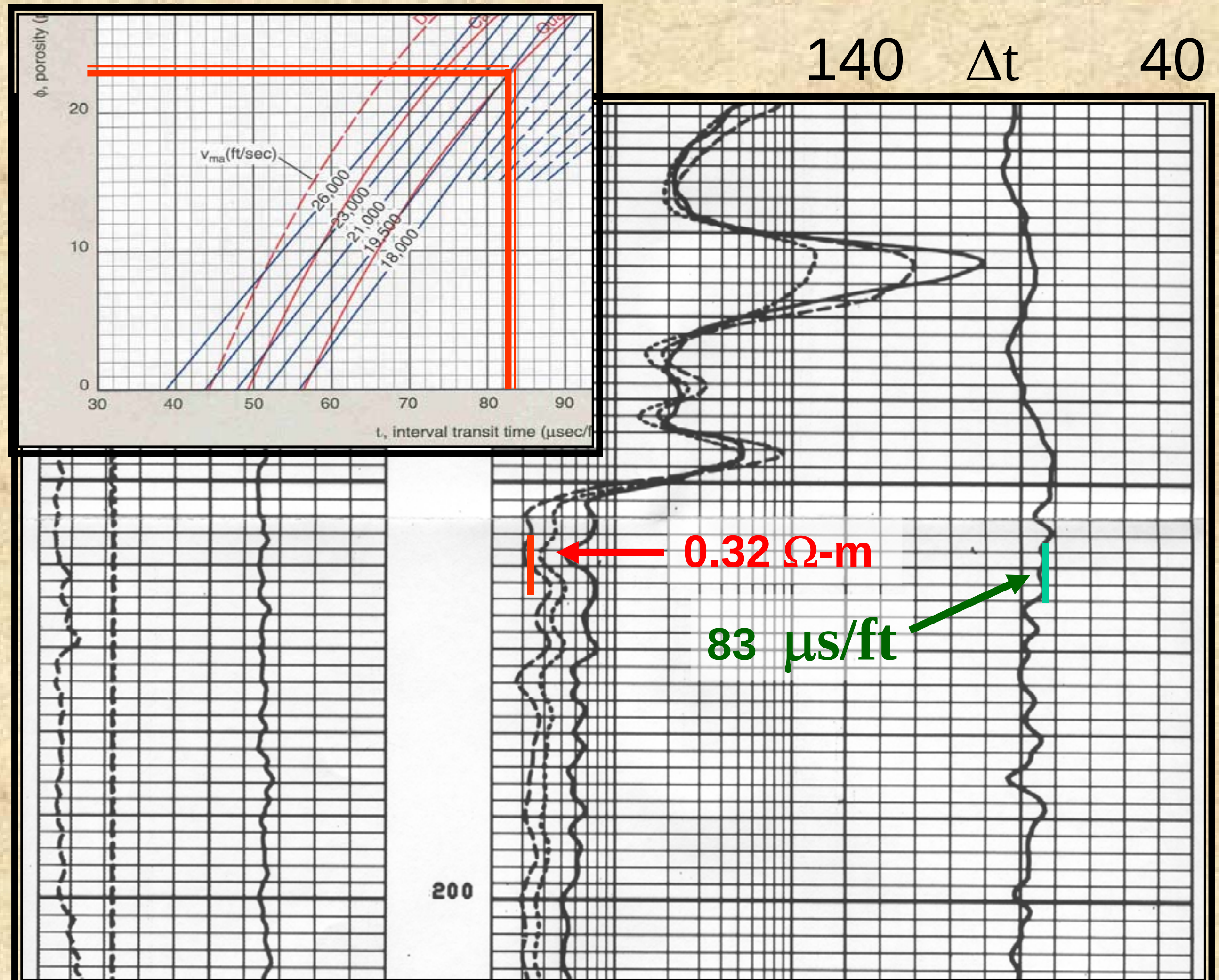
  (Tixier)

  $F = 0.81/\phi^2$
- **F = 15**
- **Rwa = Rild/F**

  = 0.32/15

  = 0.021 Ω-m

140 Δt 40



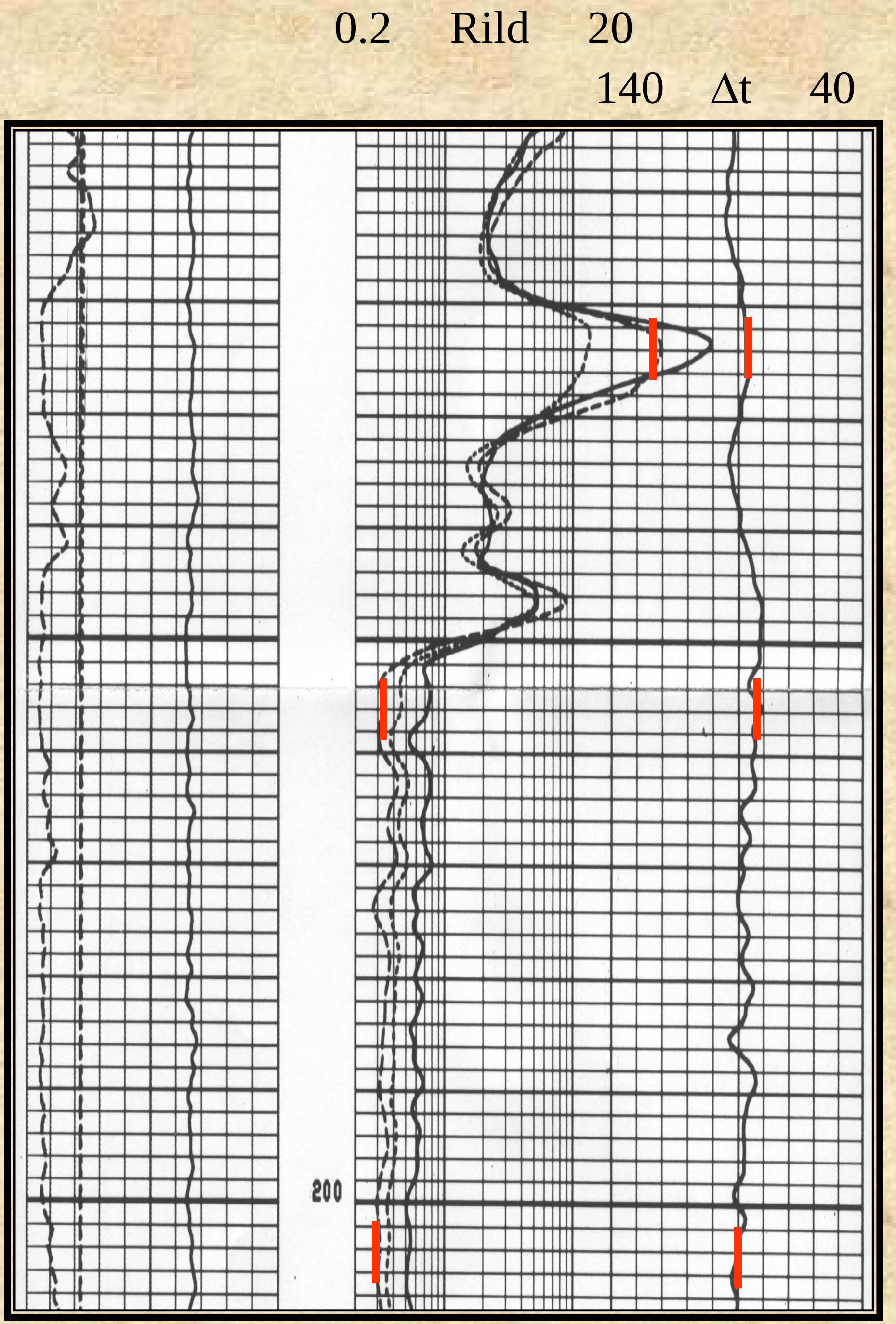
0.2 Rild 20

$$F = \frac{a}{\phi^m}$$

a is a constant;
m is cementation factor

RWA EXAMPLE - 2

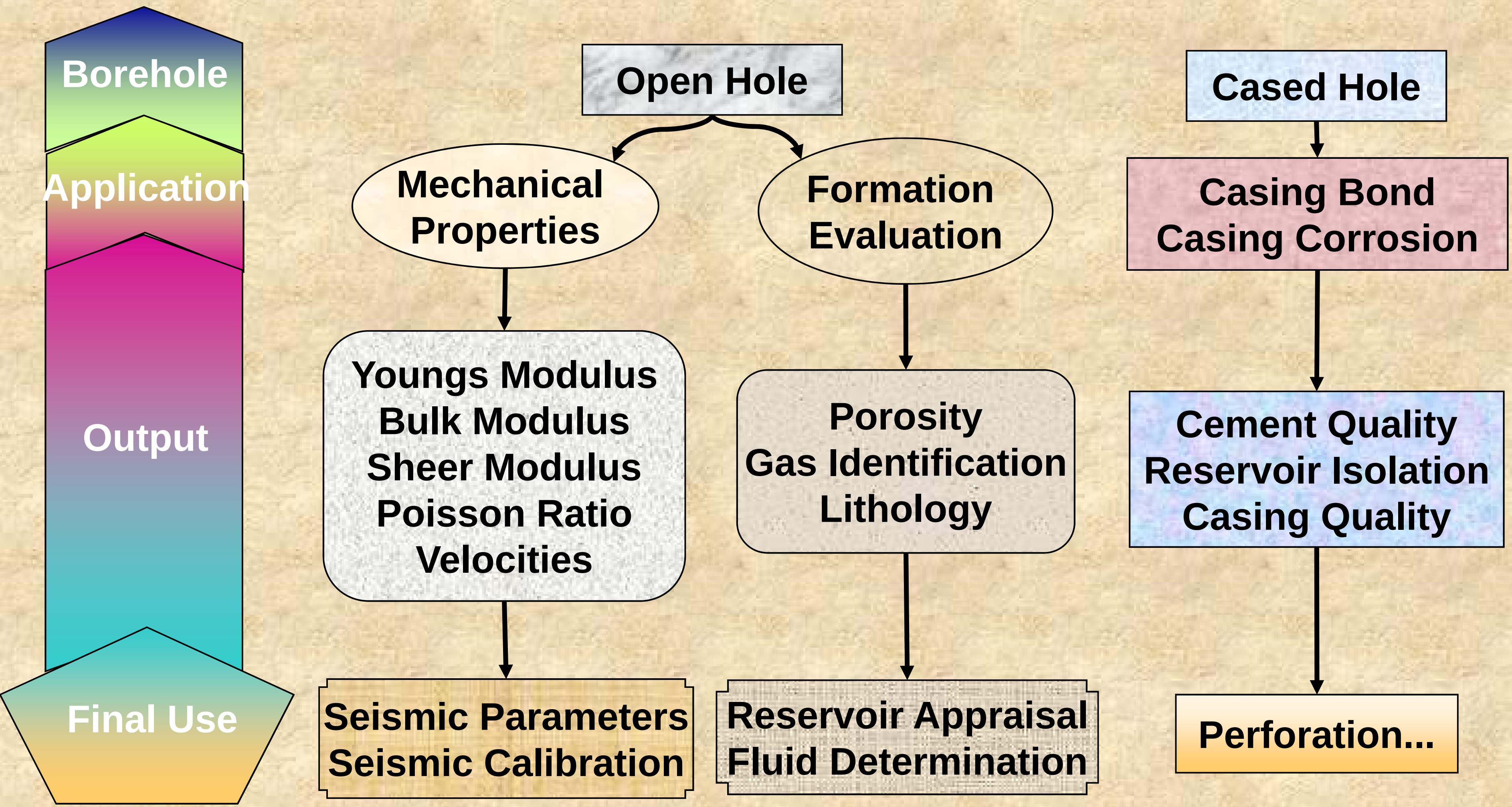
Depth	Δt	ϕ	Rild	Rwa
125	87	25	45	3.5
156	83	23	0.32	0.021
204	90	26	0.30	0.025



<u>Two further points</u>

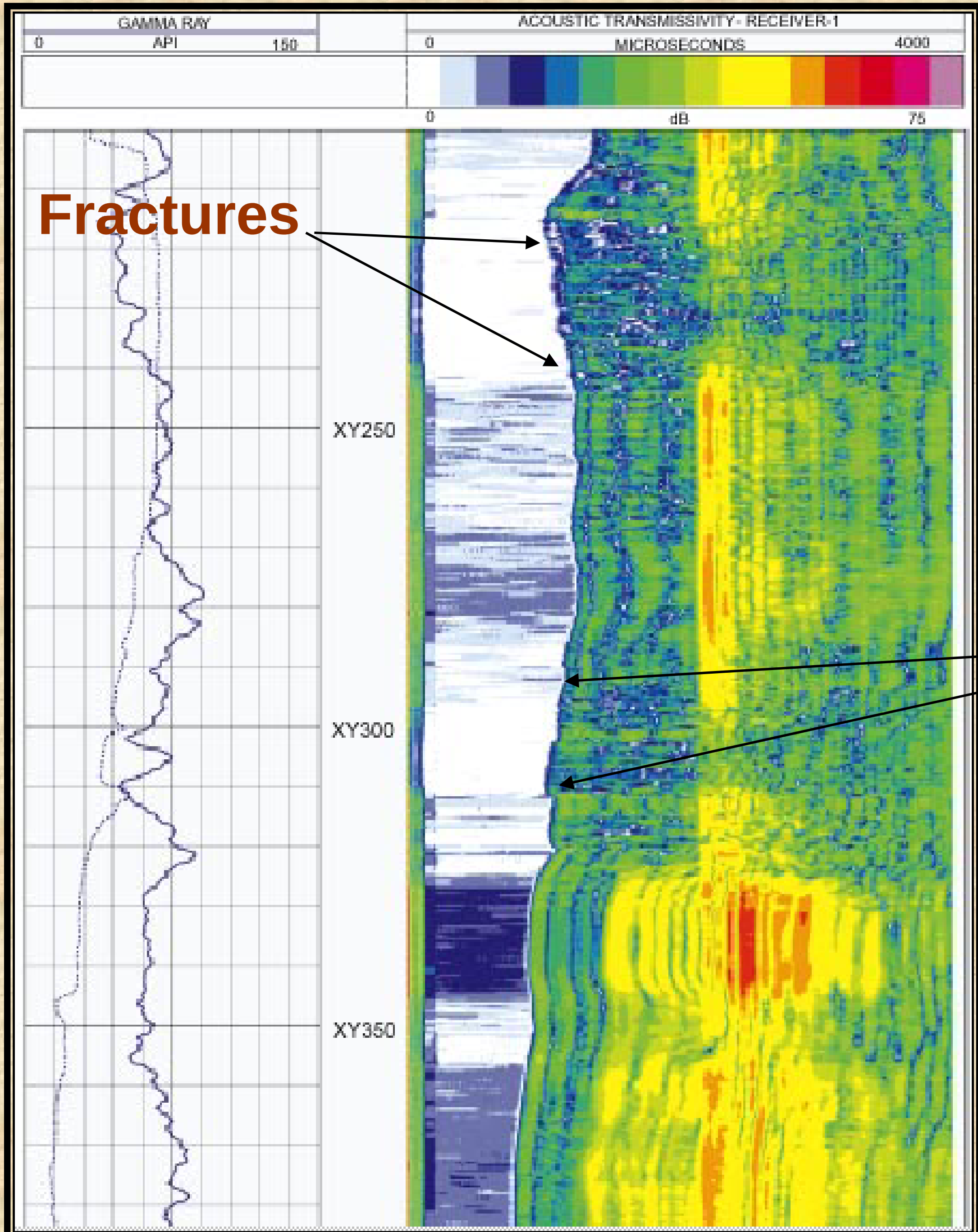
- Works best in clean formations
- Applies to flushed zone, too

SONIC FAMILY TOOLS & APPLICATION



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 LOGS USED FOR FRACTURE DETECTION

Fractures

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

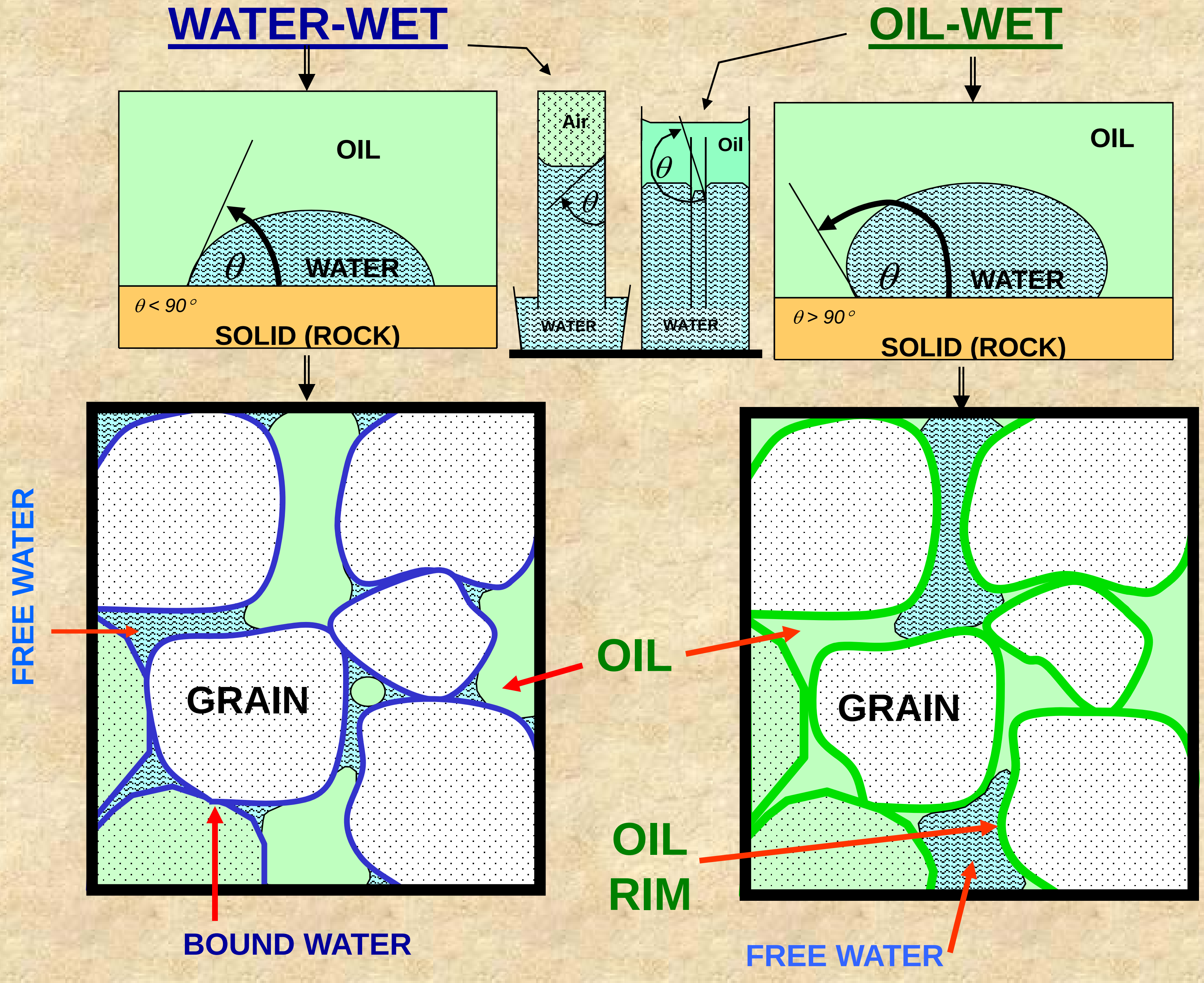
SUMMARY

- **Sonic physics**
  - Several modes
  - Borehole compensation

- **Tools and spacings**

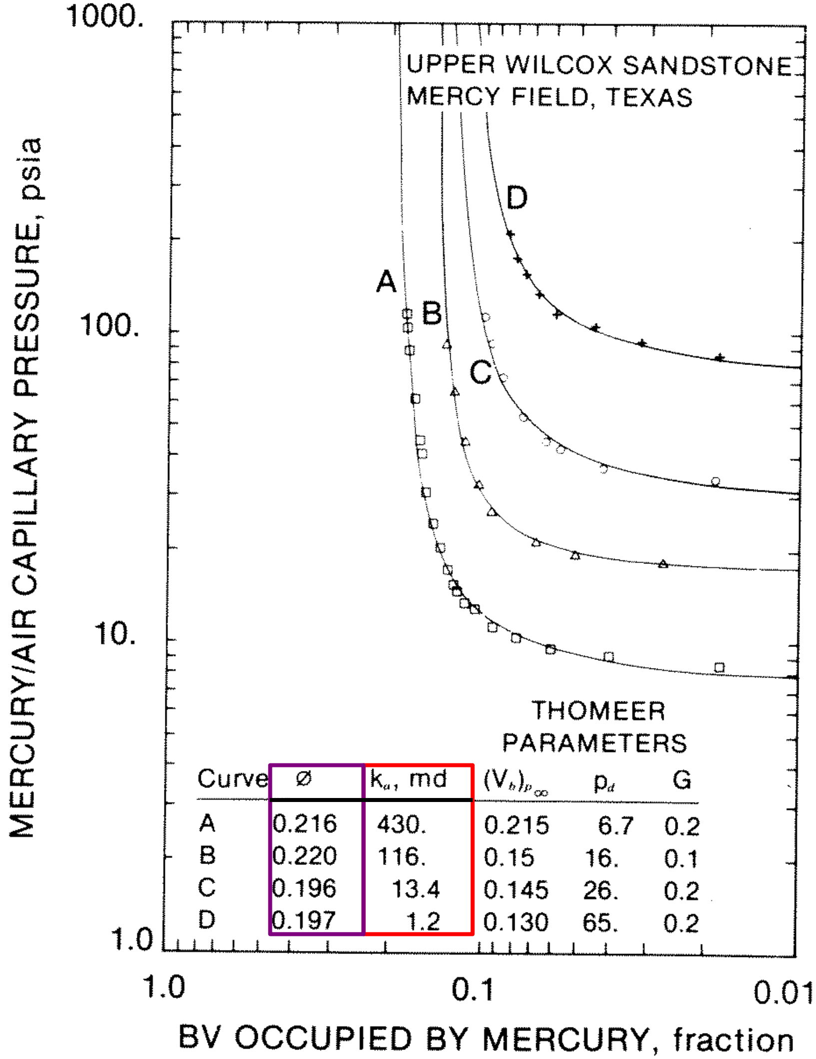
- **Interpretation**
  - Two Δt models for porosity
  - Rwa method

SANDSTONE POROSITY


WATER-WET
OIL-WET
OIL
WATER
θ
θ < 90°
SOLID (ROCK)
Air
Oil
WATER
WATER
OIL
WATER
θ
θ > 90°
SOLID (ROCK)
FREE WATER
GRAIN
OIL
GRAIN
BOUND WATER
OIL
RIM
FREE WATER

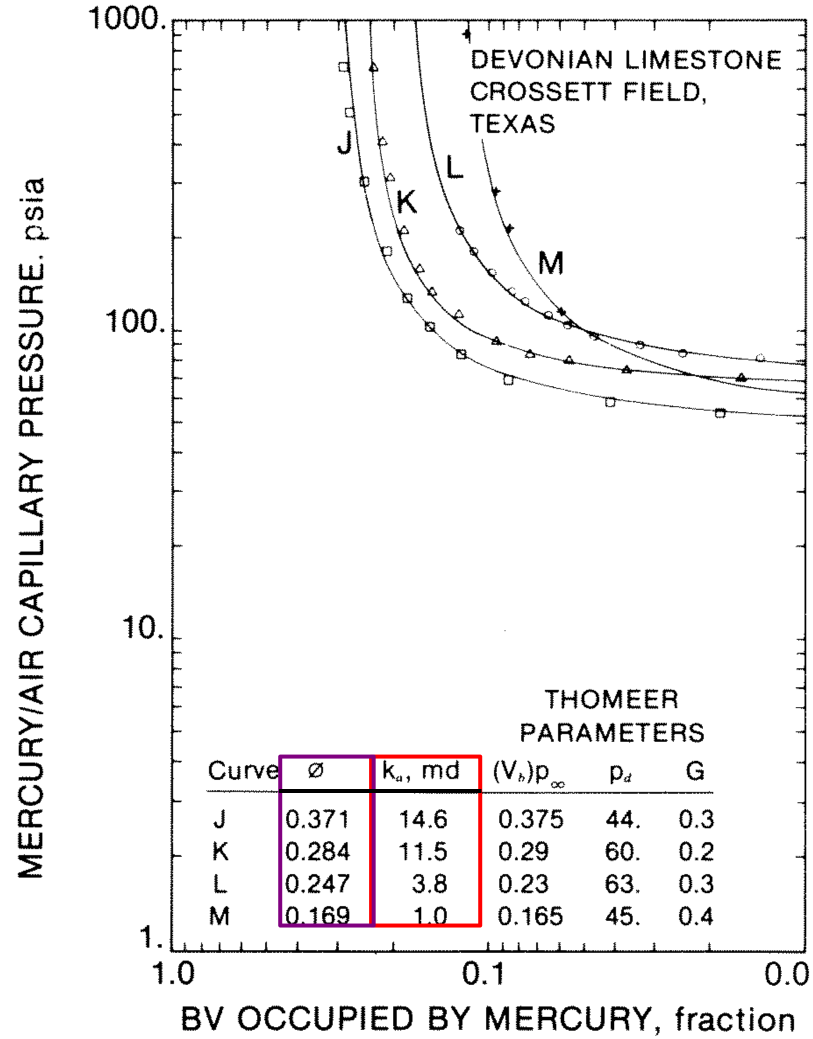
Ayers, 2001

VARIATION IN PORE PROPERTIES AND PERMEABILITY WITHIN A FORMATION



Curve	Ø	k_a, md	$(V_b)_{p_\infty}$	p_d	G
A	0.216	430.	0.215	6.7	0.2
B	0.220	116.	0.15	16.	0.1
C	0.196	13.4	0.145	26.	0.2
D	0.197	1.2	0.130	65.	0.2

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

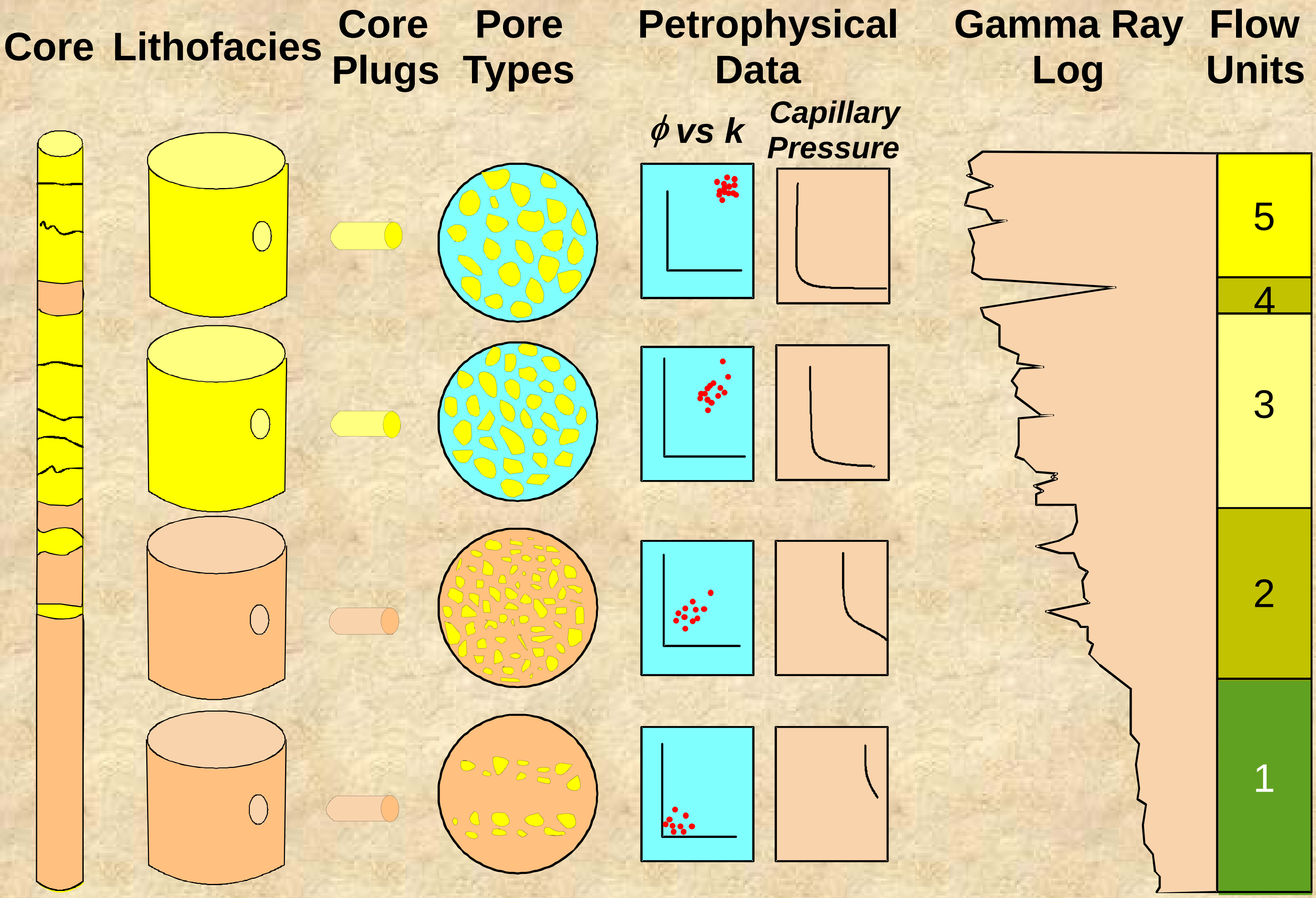


Curve	Ø	k_a, md	$(V_b)p_\infty$	p_d	G
J	0.371	14.6	0.375	44.	0.3
K	0.284	11.5	0.29	60.	0.2
L	0.247	3.8	0.23	63.	0.3
M	0.169	1.0	0.165	45.	0.4

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

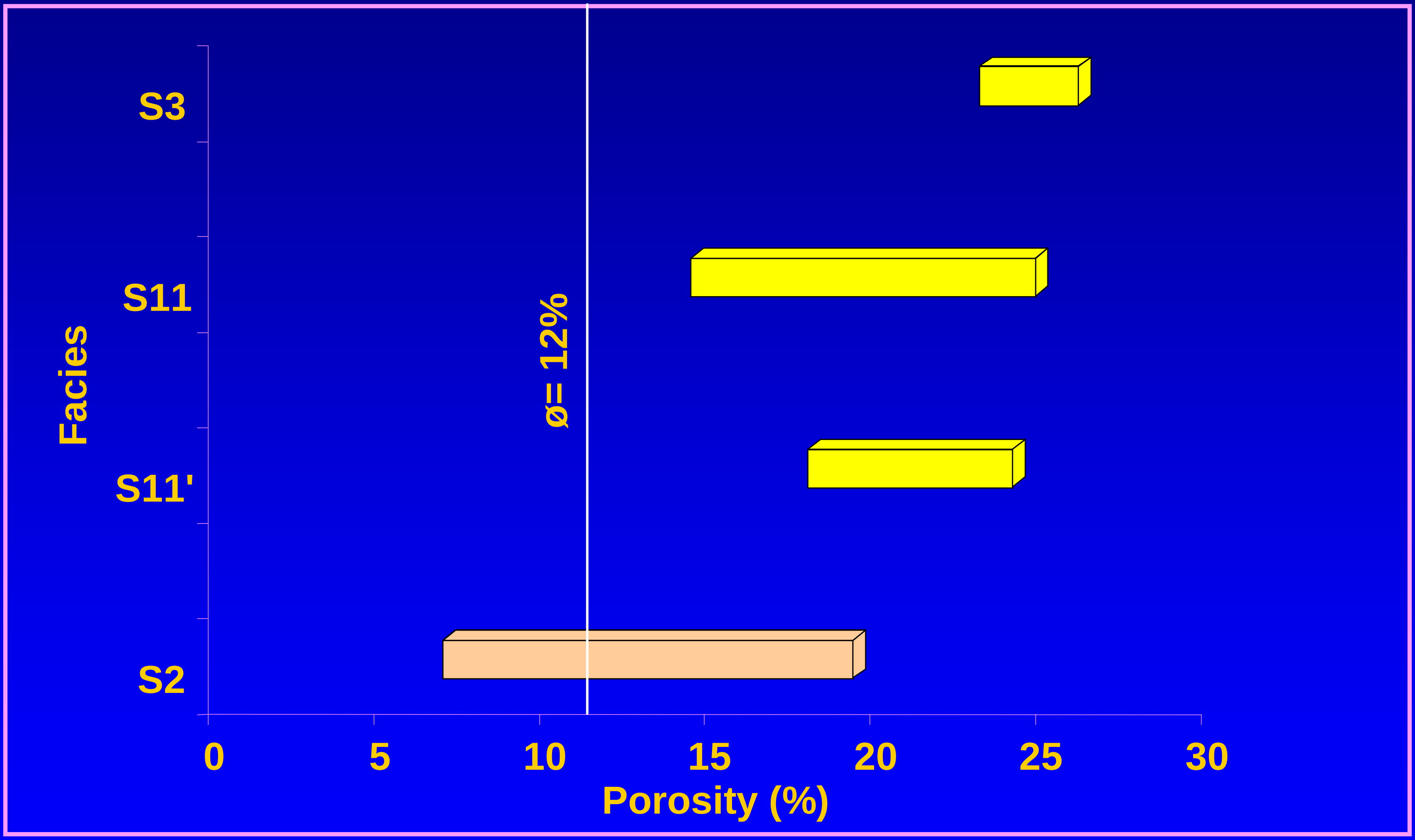
Modfied from Jordan and Campbell, 1984, vol. 1

GEOLOGICAL AND PETROPHYSICAL DATA USED TO DEFINE FLOW UNITS



Modified from Ebanks et al., 1992

Sedimentary Facies vs. Porosity



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

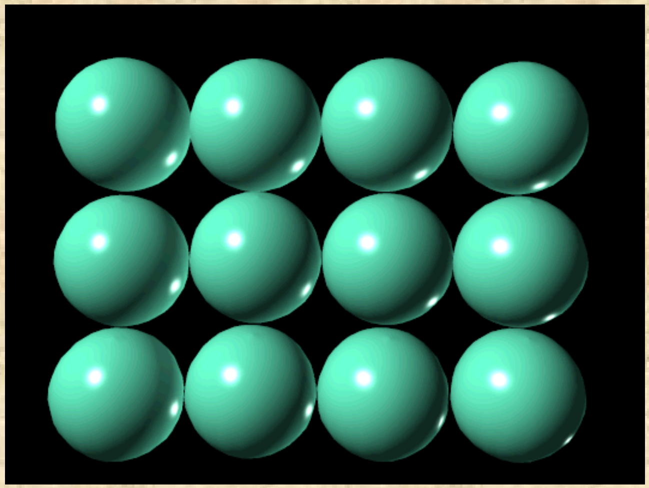
- Particle sphericity and angularity
- Packing
- Sorting (variable grain sizes)
- Texture

SECONDARY (DIAGENETIC)

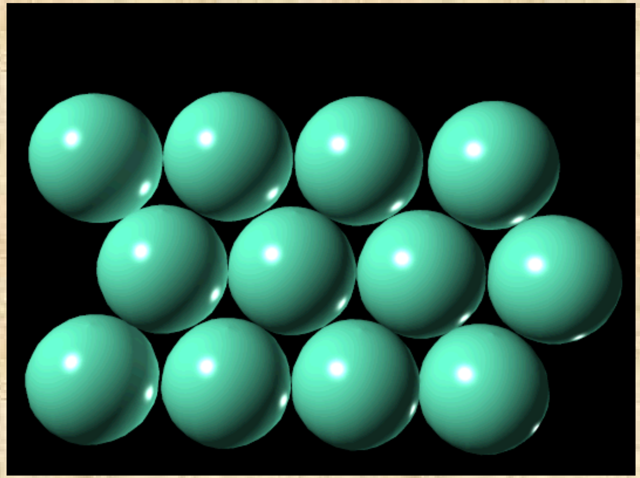
- Cementing materials
- Overburden stress (compaction)
- Vugs, dissolution, and fractures

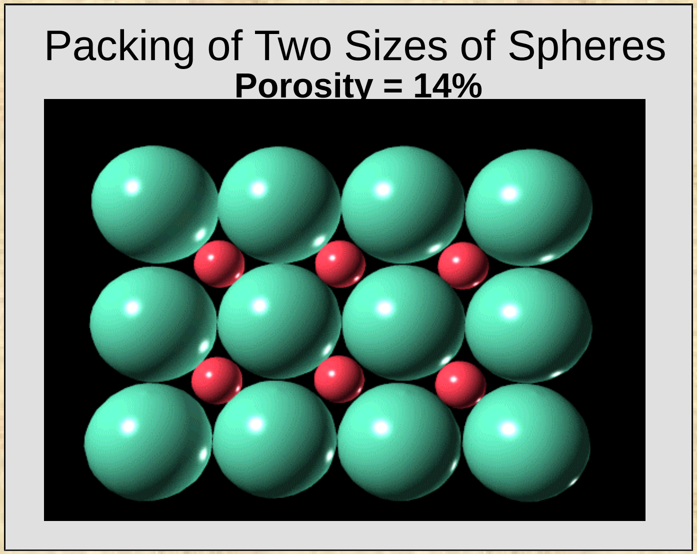
PACKING AND SORTING OF SPHERES (CLASTICS)

Porosity = 48%



Porosity = 27 %

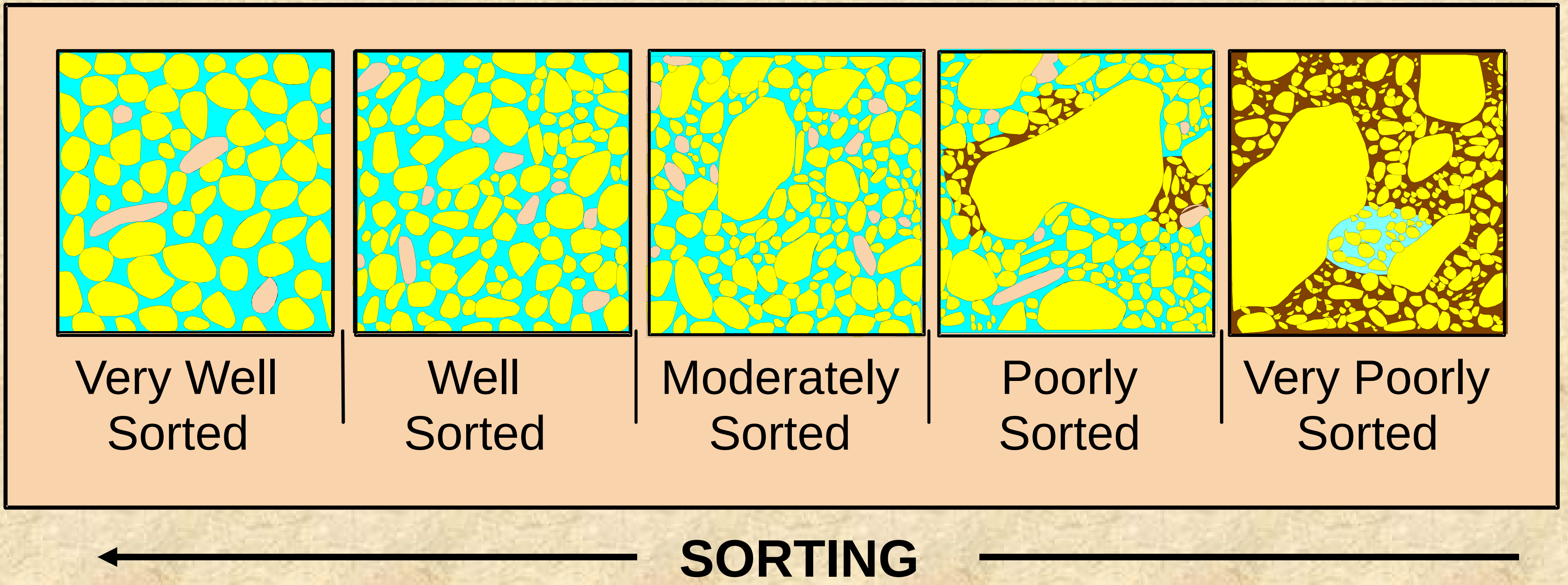




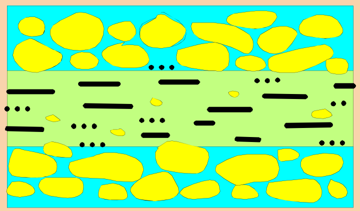
COMPARE SIZES OF PORES AND PORE THROATS

Porosity = 14%

GRAIN-SIZE SORTING IN SANDSTONE



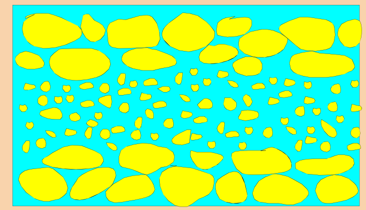
TYPES OF TEXTURAL CHANGES SENSED BY THE NAKED EYE AS BEDDING



Sand

Shale

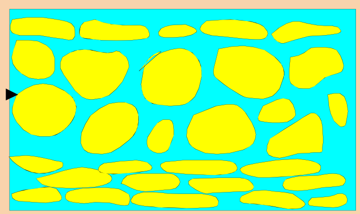
Change of Composition



Slow Current

Fast Current

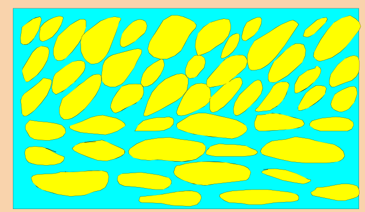
Change of Size



Eolian

Fluvial

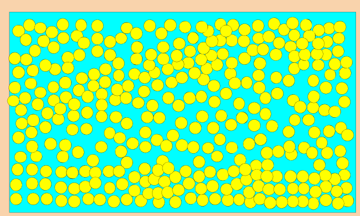
Change of Shape



River

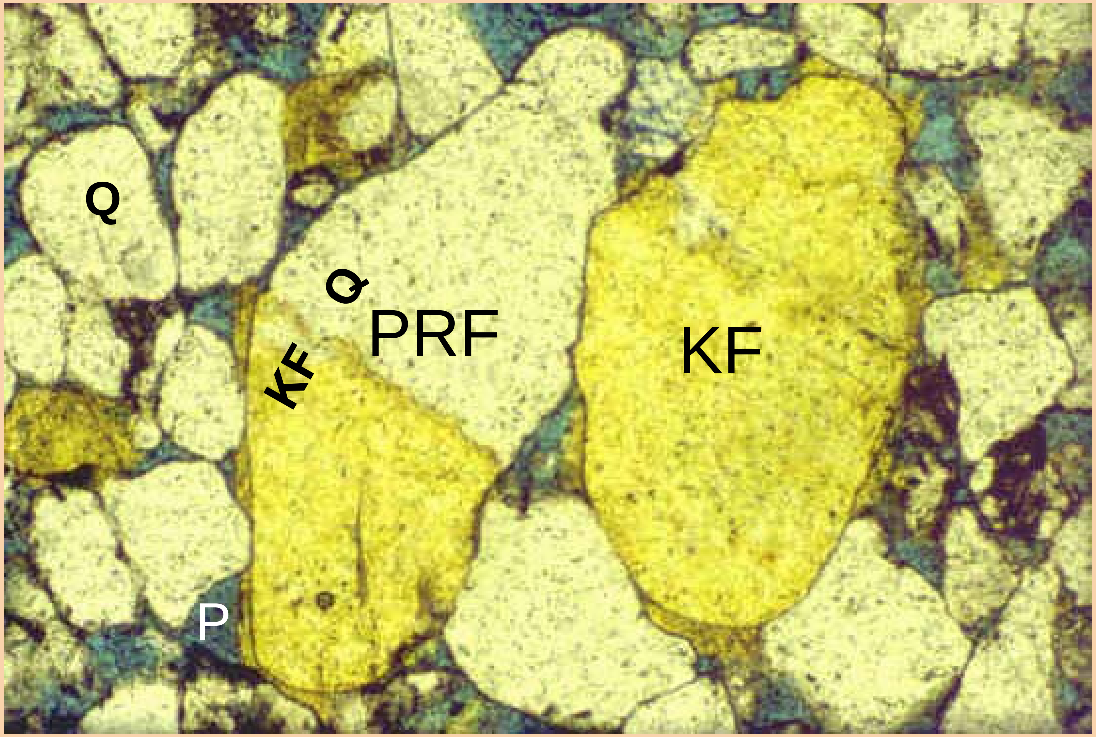
Beach

Change of Orientation



Change of Packing

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

PORE-SPACE CLASSIFICATION

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

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

- **Effective porosity – contains the mobile fluid**

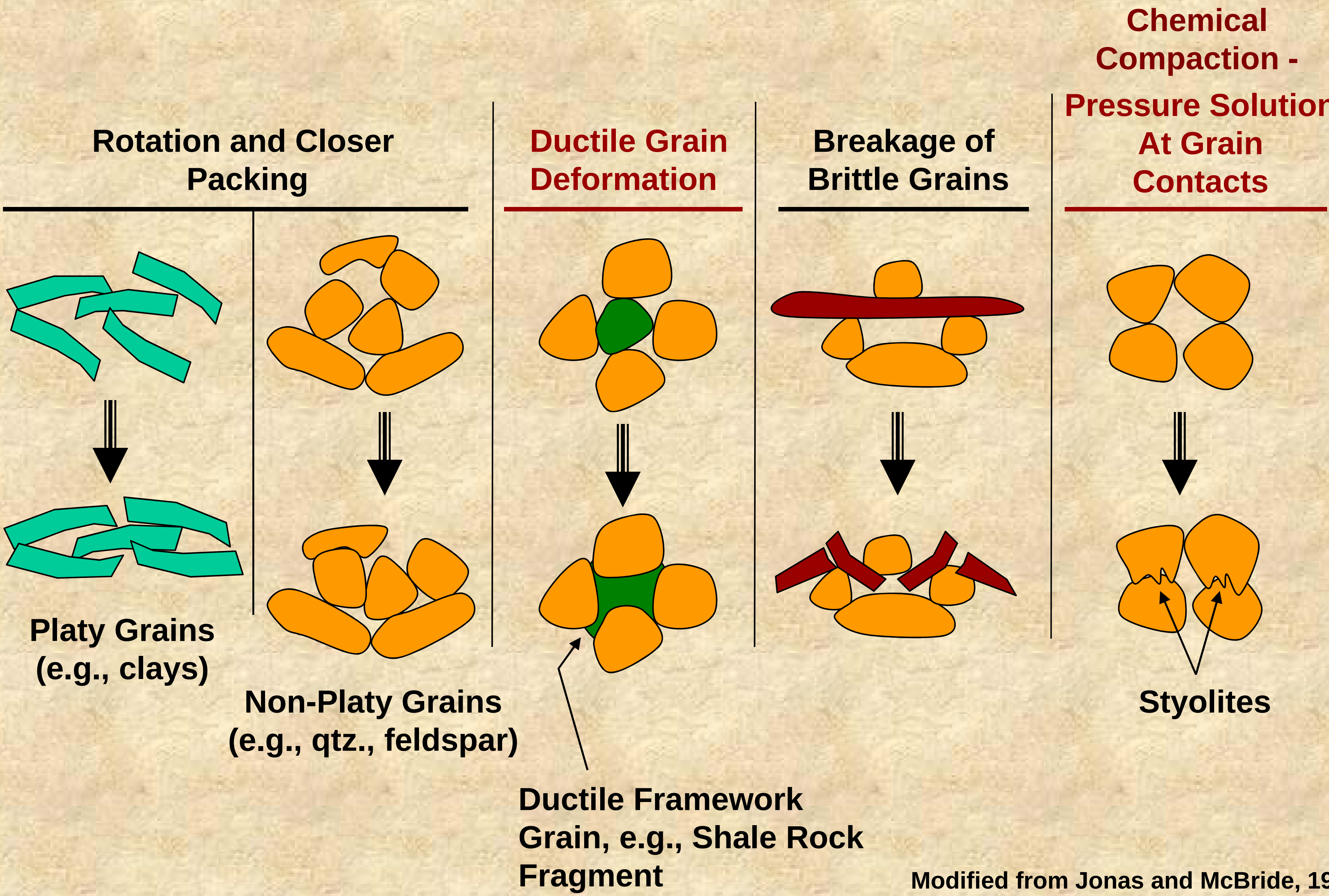
DIAGENETIC PROCESSES

- **"Diagenesis" includes all physical and chemical changes that affect sediments after deposition**
- **Diagenetic processes may <u>increase</u> or <u>decrease</u> porosity and/or permeability**

<u>Examples</u>

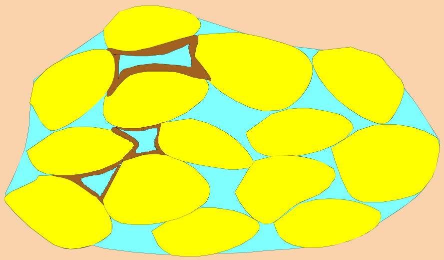
1. Compaction
2. Cementation
3. Grain dissolution in sandstones or carbonates
4. Vugs and solution cavities in carbonates
5. Fractures

MECHANICS OF COMPACTION



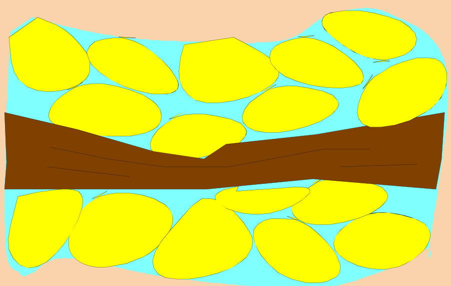
Modified from Jonas and McBride, 1977

Influence Of Clay-Mineral Distribution On Effective Porosity



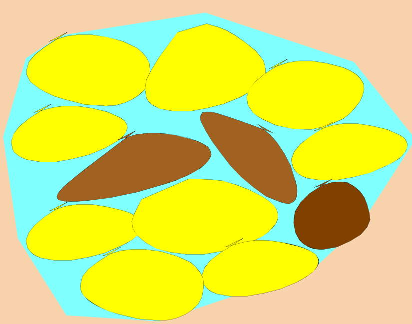
Dispersed Clay
- Pore-filling
- Pore-lining
- Pore-bridging

Slight affect - ΔT



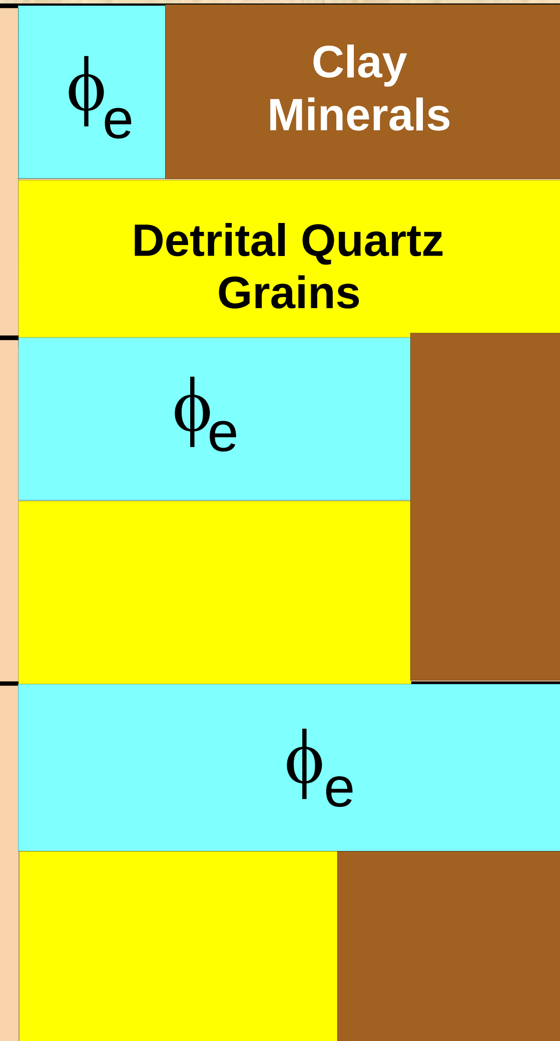
Clay Lamination

Greatest affect - ΔT



Structural Clay
(Rock Fragments, Rip-Up Clasts, Clay-Replaced Grains)

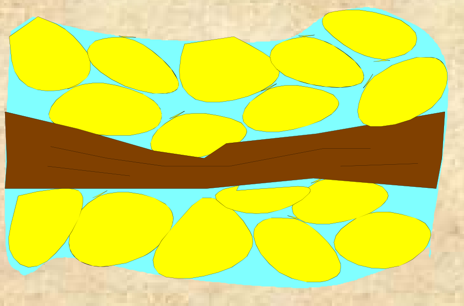
Little affect - ΔT



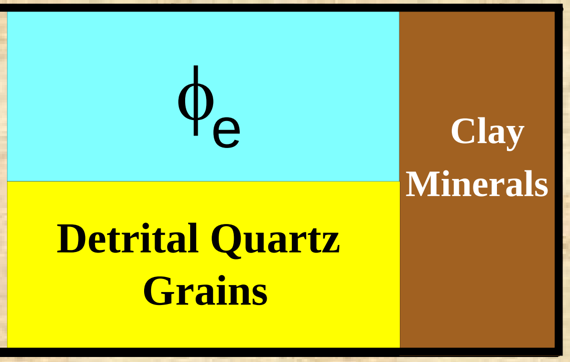
HOW DO SHALES/CLAYS OCCUR? - 2

Laminated Shale

- Interlayered with sand
- Reduces por., perm.
- Common
- Example – shale laminae
- Assume composition similar to nearby shale



Clay Lamination



TYPES OF SANDSTONES POROSITY

Primary	
Intergranular	Interstitial Void Space Between Framework Grains
Secondary	
Micropores	Small Pores Mainly Between Detrital Framework Grains or Cement
Dissolution	Partial or Complete Dissolution of or Authigenic Grains (Can Also Occur Within Grains
Fractures	Breakage Due to Earth Stresses

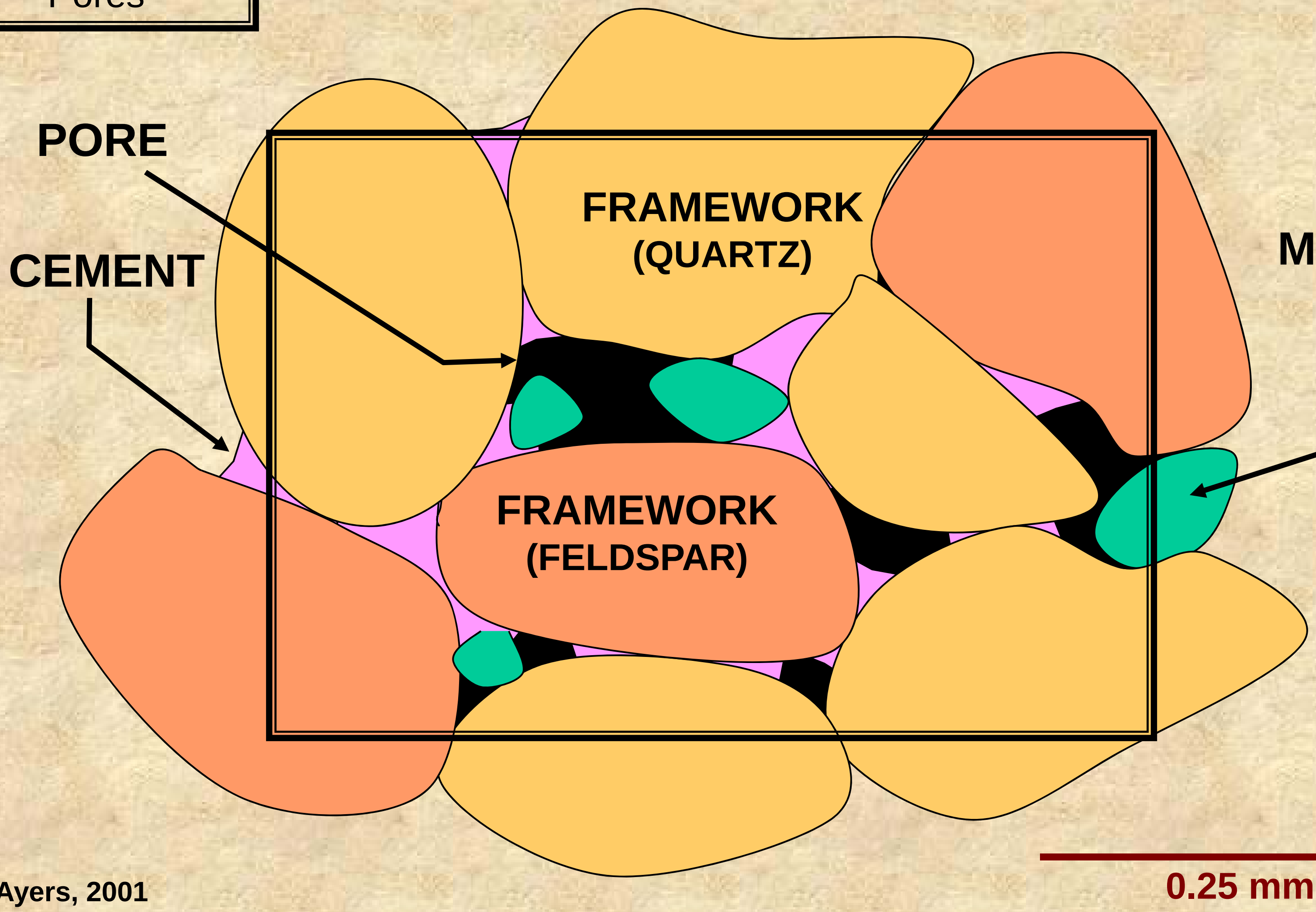
FOUR COMPONENTS OF SANDSTONE

Geologist's Classification

1. Framework
2. Matrix
3. Cement
4. Pores

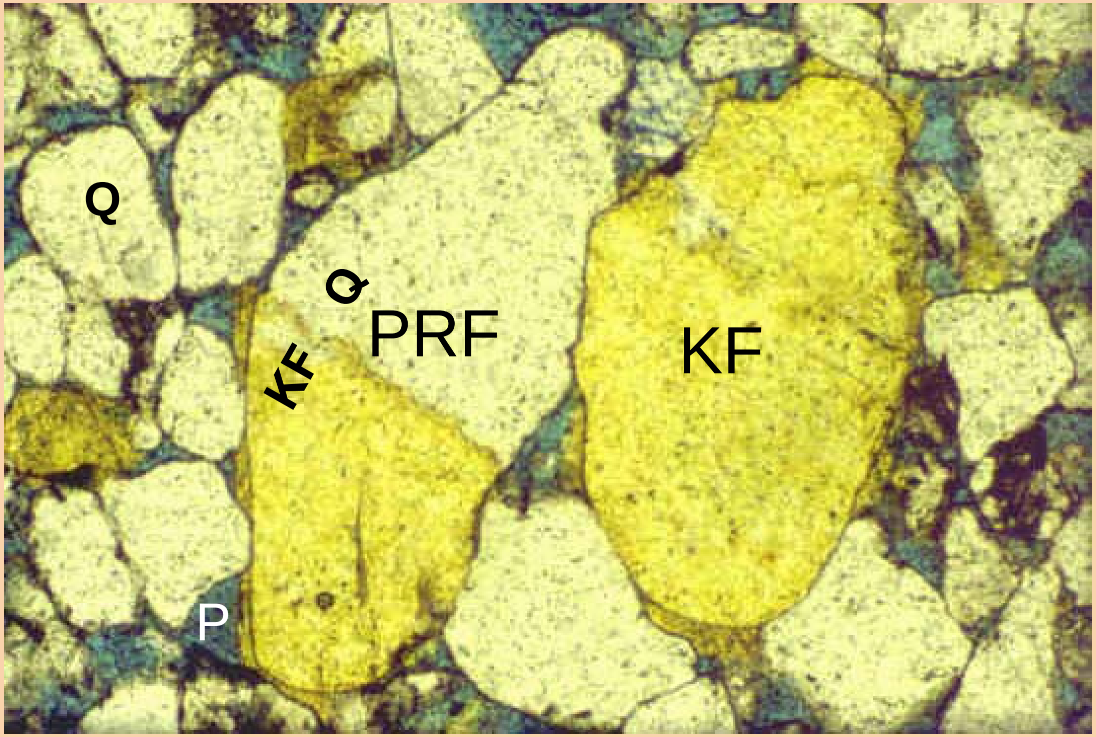
Engineering "matrix"

Note different use of "matrix" by geologists and engineers



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

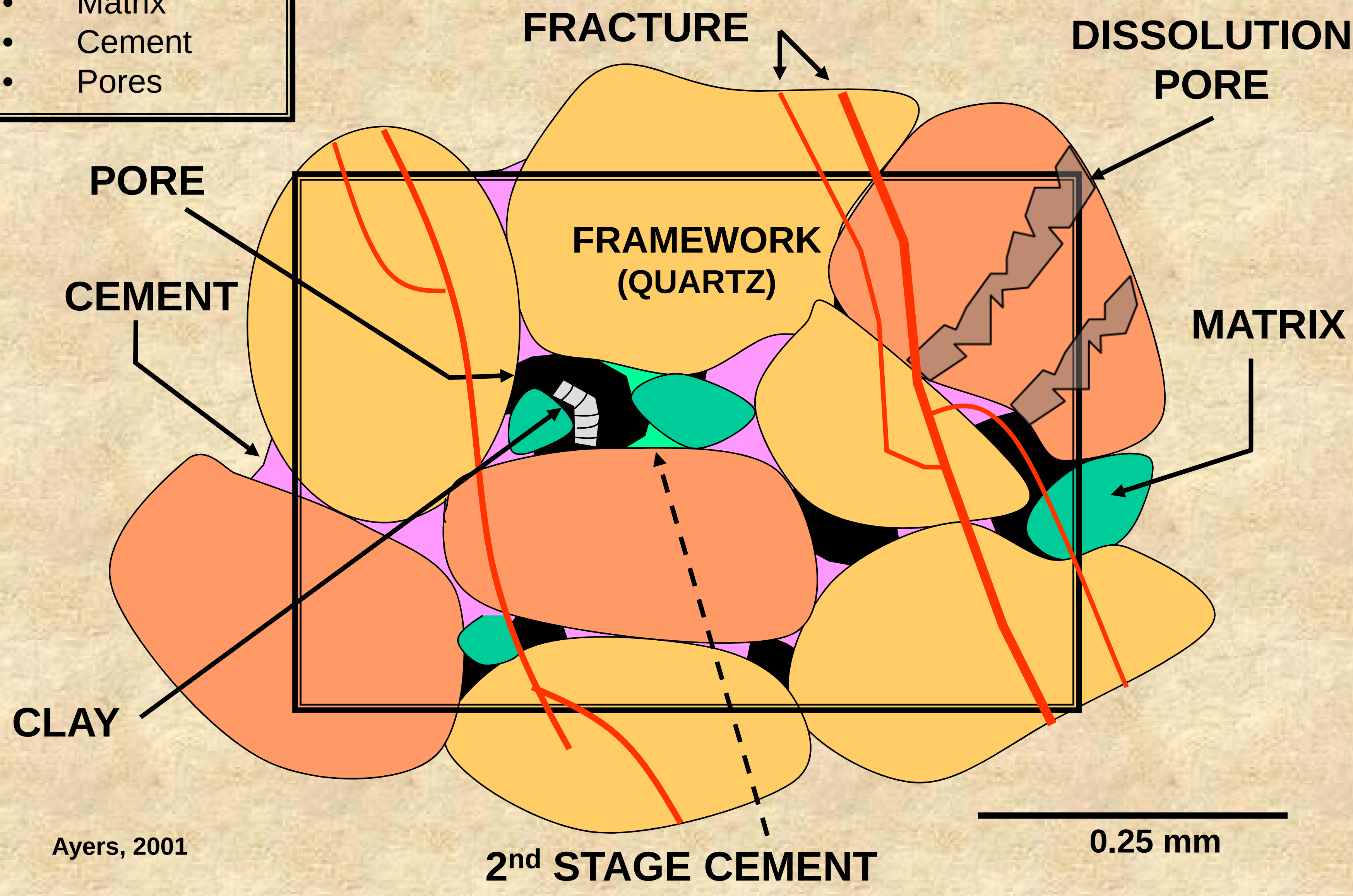
Pores are Impregnated With Blue-Dyed Epoxy

Photo by R. Kugler

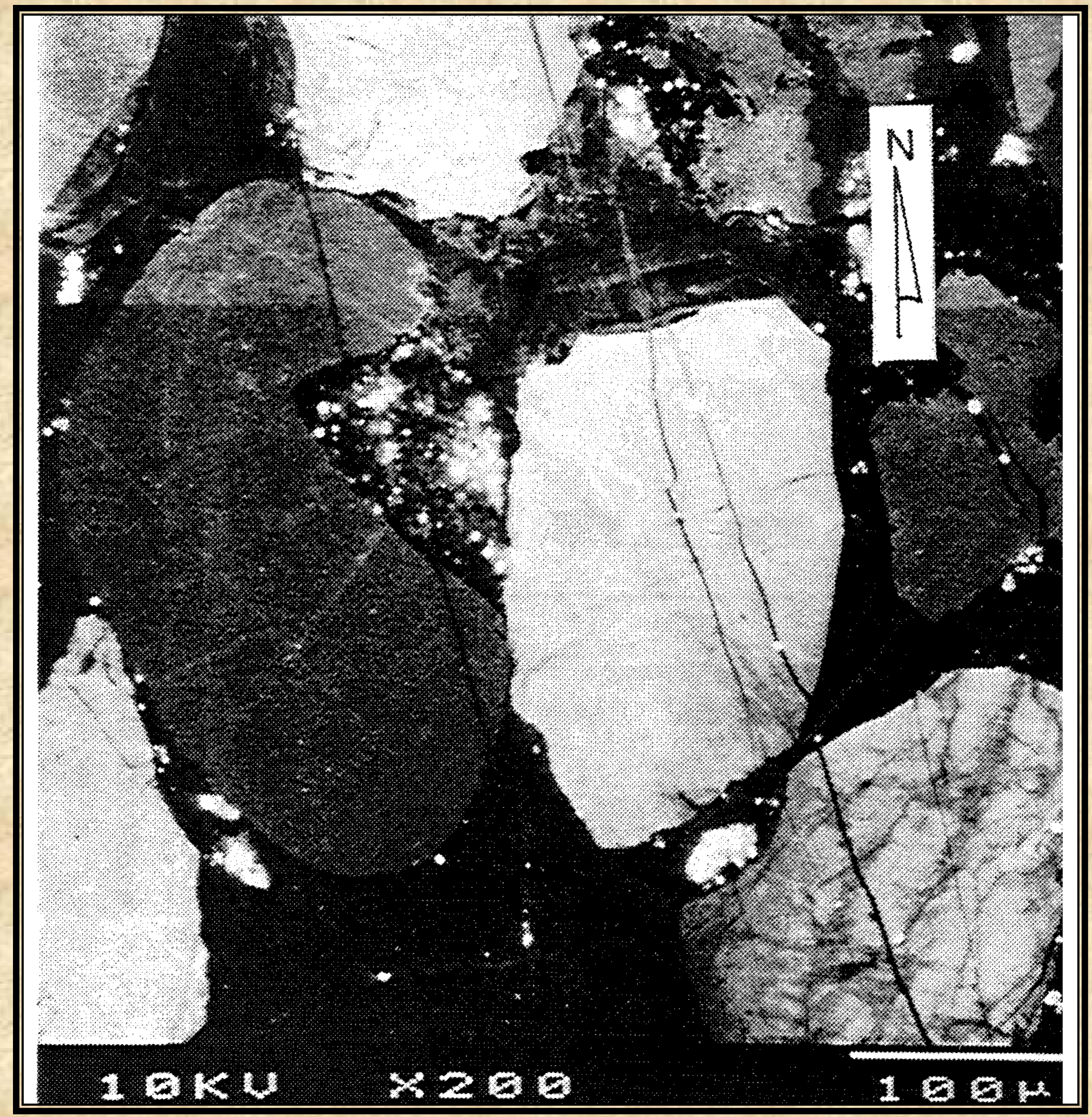
DUAL POROSITY IN SANDSTONE

Sandstone Comp.
- Framework
- Matrix
- Cement
- Pores

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



Ayers, 2001

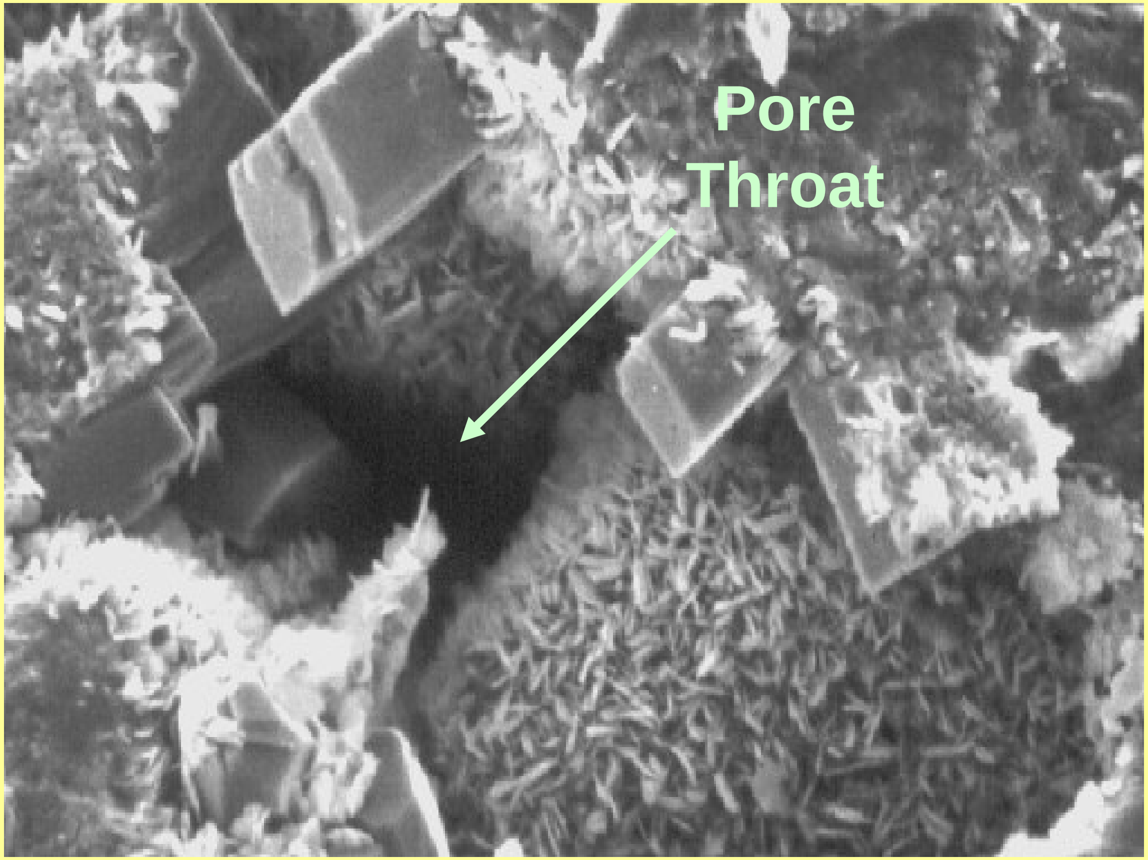


FRACTURE CHARACTERISTICS FROM MICROSCOPIC THIN SECTIONS OF SANDSTONE

Fractures cross grains and cements

From Laubach et al., 1996

PORE-LINING MINERALS IN SANDSTONE



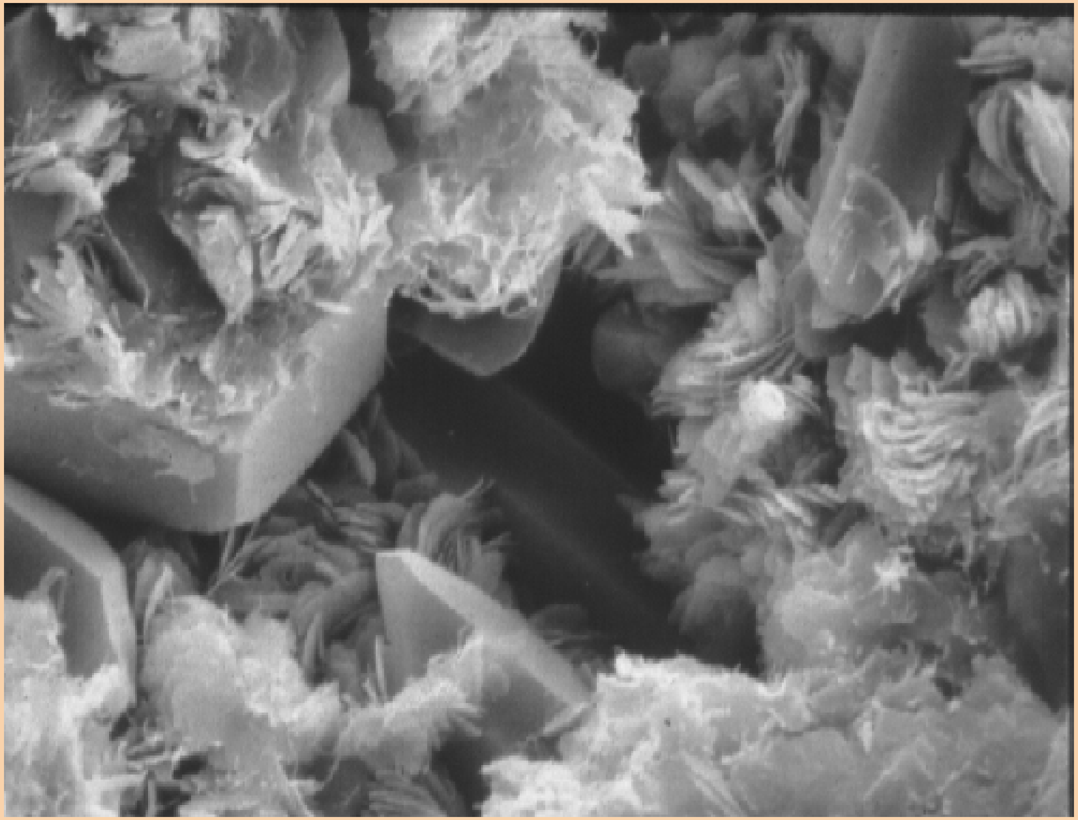
Scanning Electron Micrograph
Norphlet Formation, Offshore Alabama, USA

Pores Provide the Volume to Store Hydrocarbons

Pore Throats Restrict Flow

Photomicrograph by R.L. Kugler

CEMENTATION AND ROCK – FLUID INTERACTIONS

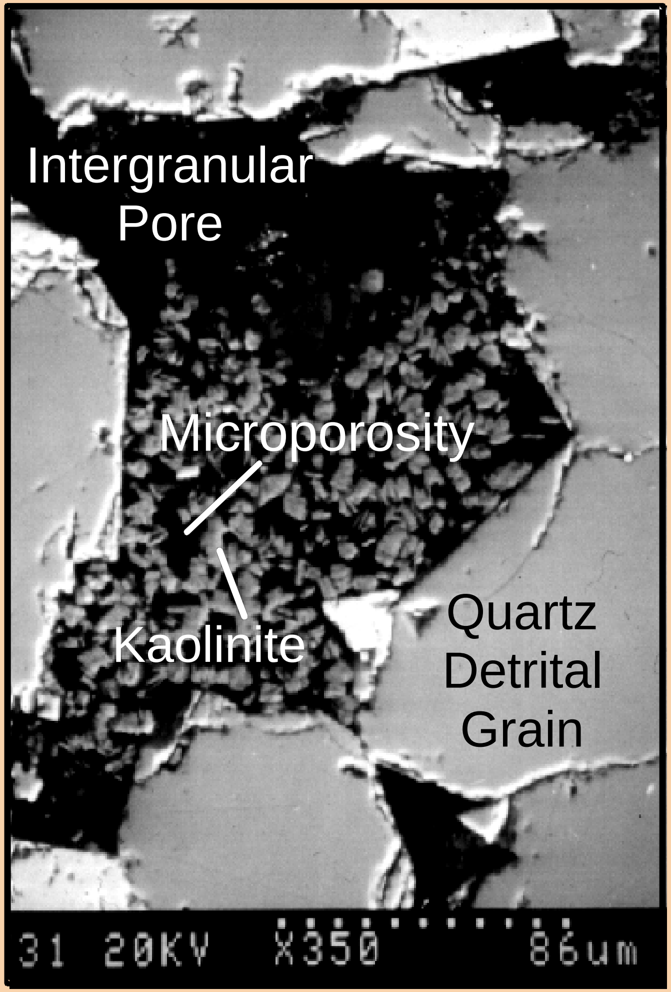


Scanning Electron Micrograph
Tordillo Sandstone, Neuquen Basin, Argentina

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

Photomicrograph by R.L. Kugler

INTERGRANULAR PORE AND MICROPOROSITY



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

- Intergranular Pores Contain Hydrocarbon Fluids
- Micropores Contain Irreducible Water

(Photograph by R.L. Kugler)

Clay Minerals in Sandstone Reservoirs,
Authigenic Chlorite

Secondary Electron Micrograph

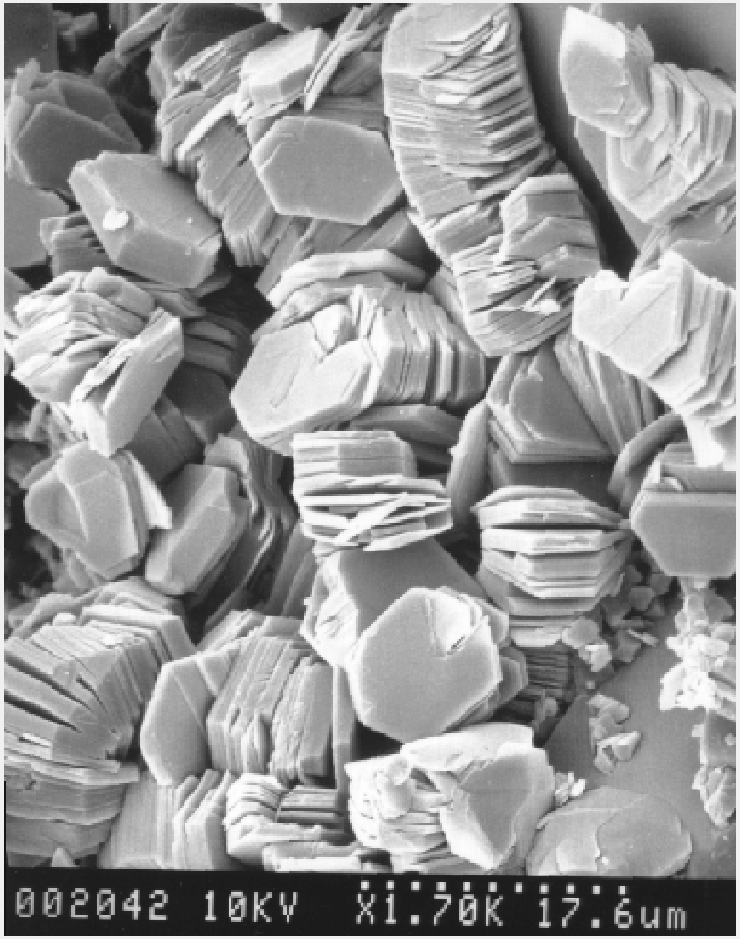
Jurassic Norphlet Sandstone
Offshore Alabama, USA

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

(Photograph by R.L. Kugler)

Clay Minerals in Sandstone Reservoirs,
Authigenic Kaolinite

Secondary Electron Micrograph



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

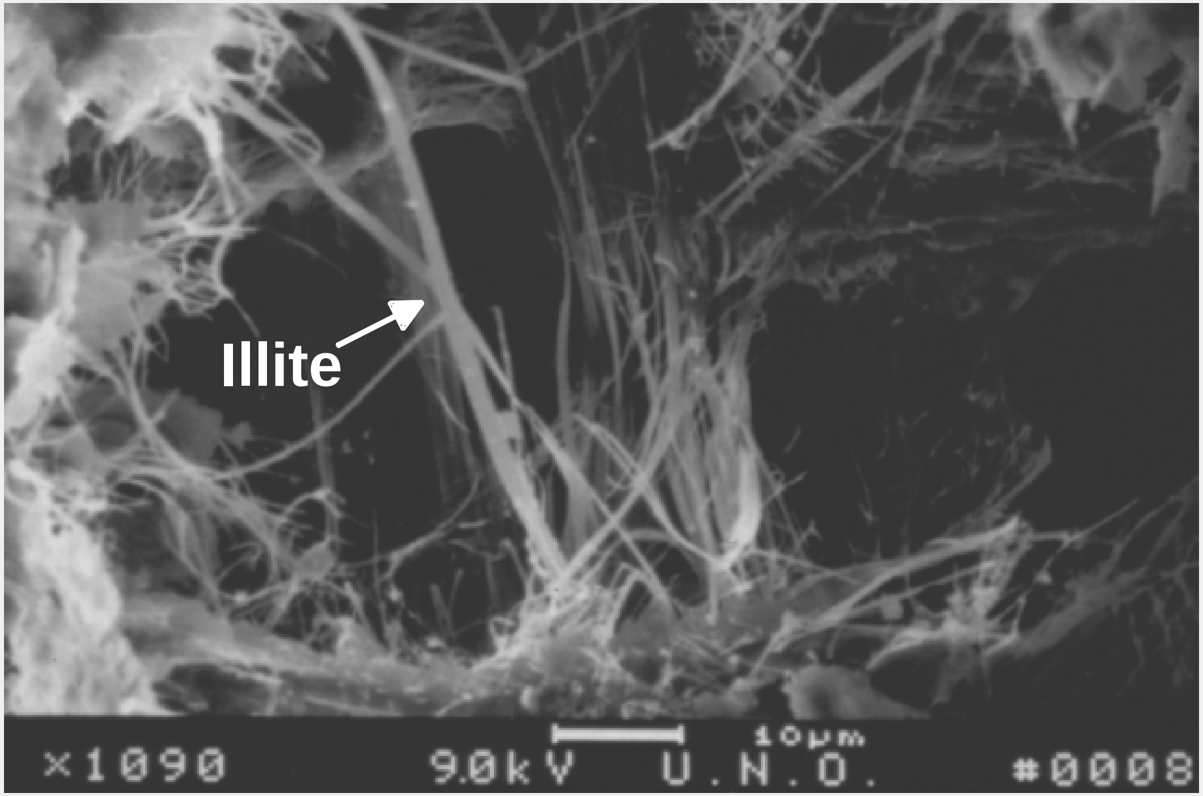
- Significant Permeability Reduction
- High Irreducible Water Saturation
- Migration of Fines Problem

(Photograph by R.L. Kugler)

Clay Minerals in Sandstone Reservoirs,

Fibrous Authigenic Illite

Electron Photomicrograph

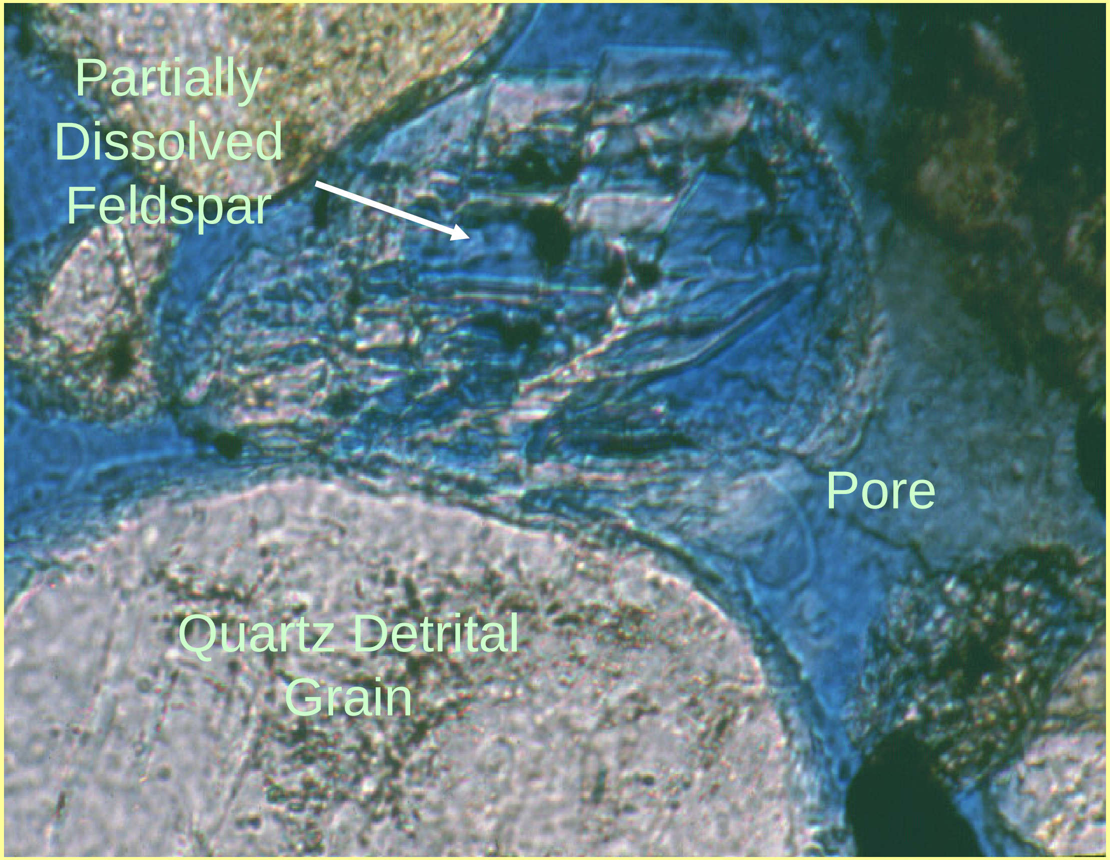


Jurassic Norphlet Sandstone
Hatters Pond Field, Alabama, USA

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

(Photograph by R.L. Kugler)

DISSOLUTION POROSITY



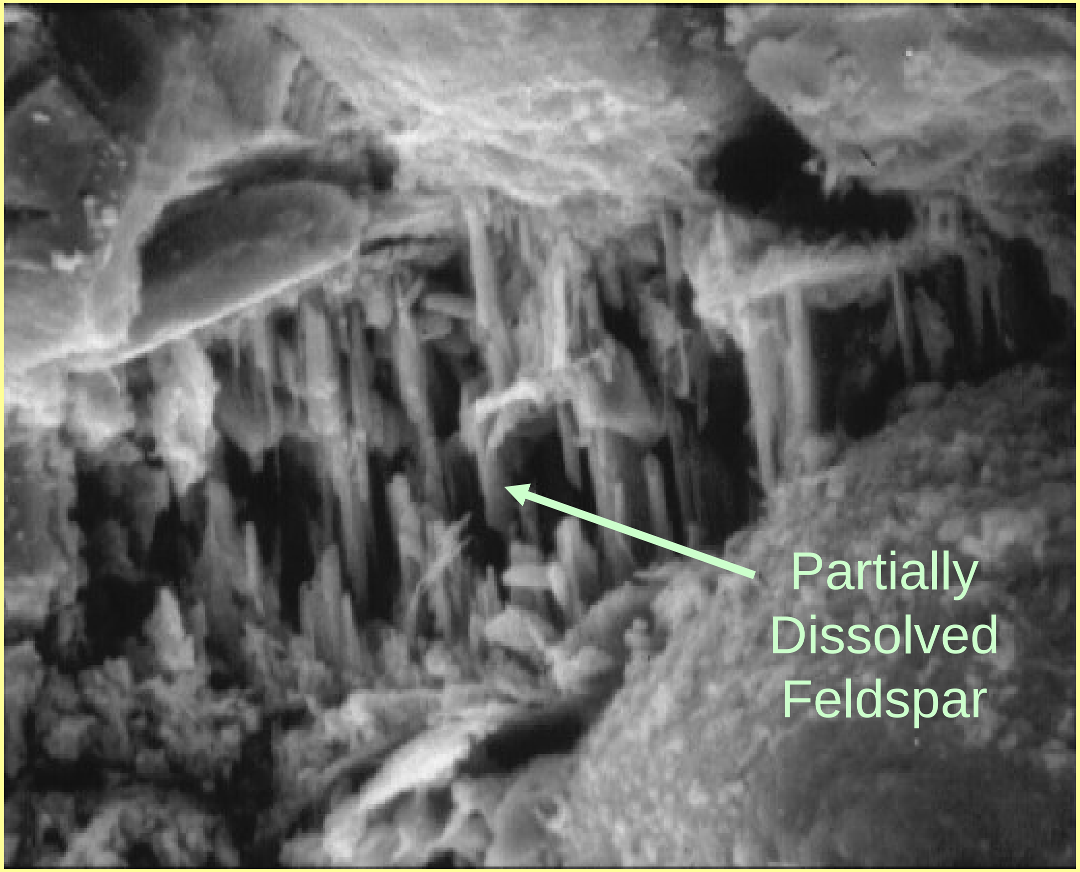
Thin Section Micrograph - Plane Polarized Light
Avile Sandstone, Neuquen Basin, Argentina

Dissolution of Framework Grains (Feldspar, for Example) and Cement may Enhance the Interconnected Pore System

This is Secondary Porosity

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

Photo by R.L. Kugler

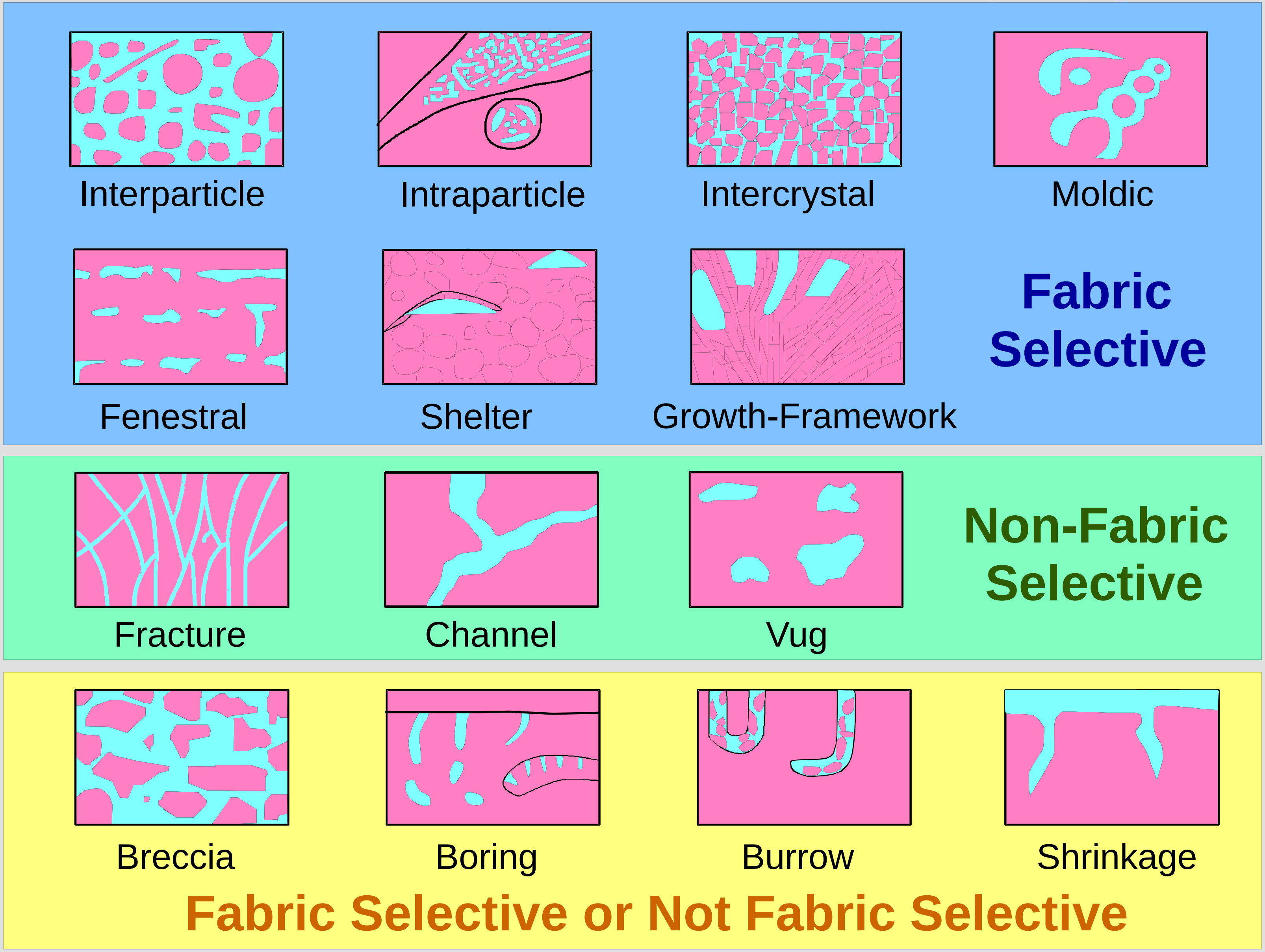
CARBONATE POROSITY

CARBONATES POROSITY TYPES

Interparticle	Pores between particles or grains
Intraparticle	Pores within individual particles or grains
Intercrystal	Pores between crystals
Moldic	Pores formed by dissolution of an individual grain or crystal in the rock
Fenestral	Primary pores larger than grain-supported interstices
Fracture	Formed by a planar break in the rock
Vug	Large pores formed by indiscriminate dissolution of cements and grains

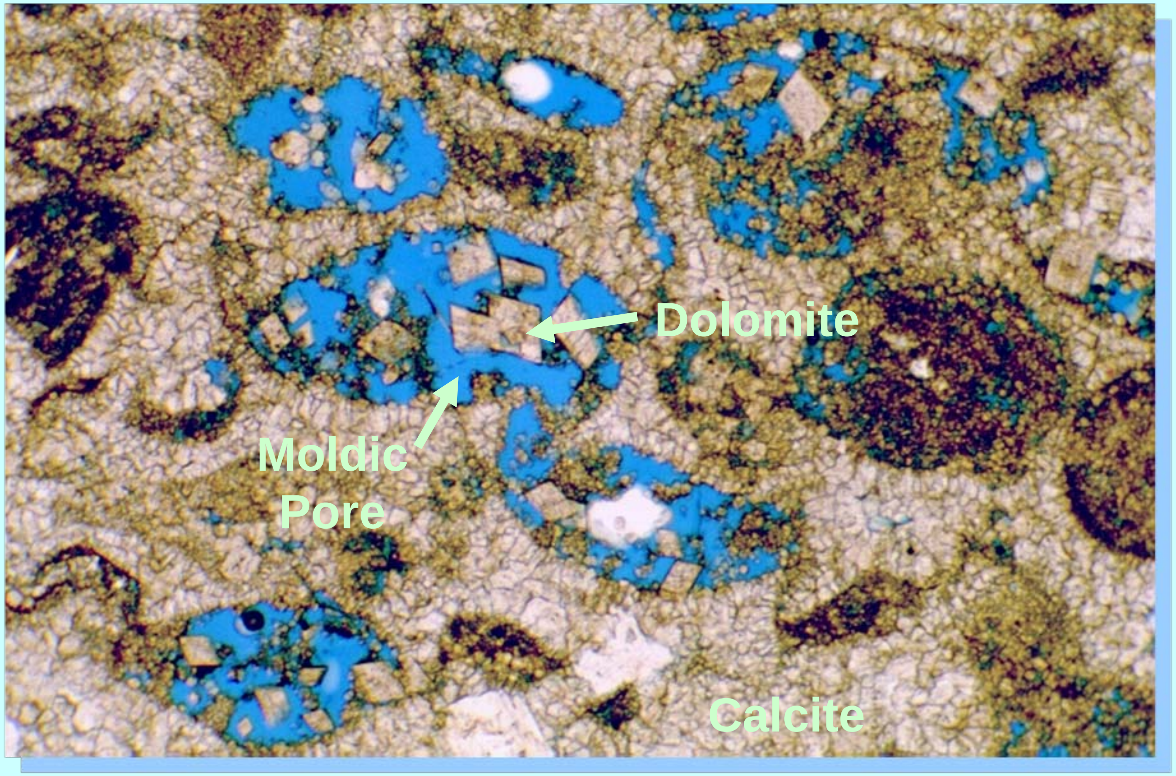
Generally, porosity in carbonates is lower than in clastics, and its occurrence is more complex

Idealized Carbonate Porosity Types



(modified from Choquette and Pray, 1970)

CARBONATE POROSITY - EXAMPLE



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

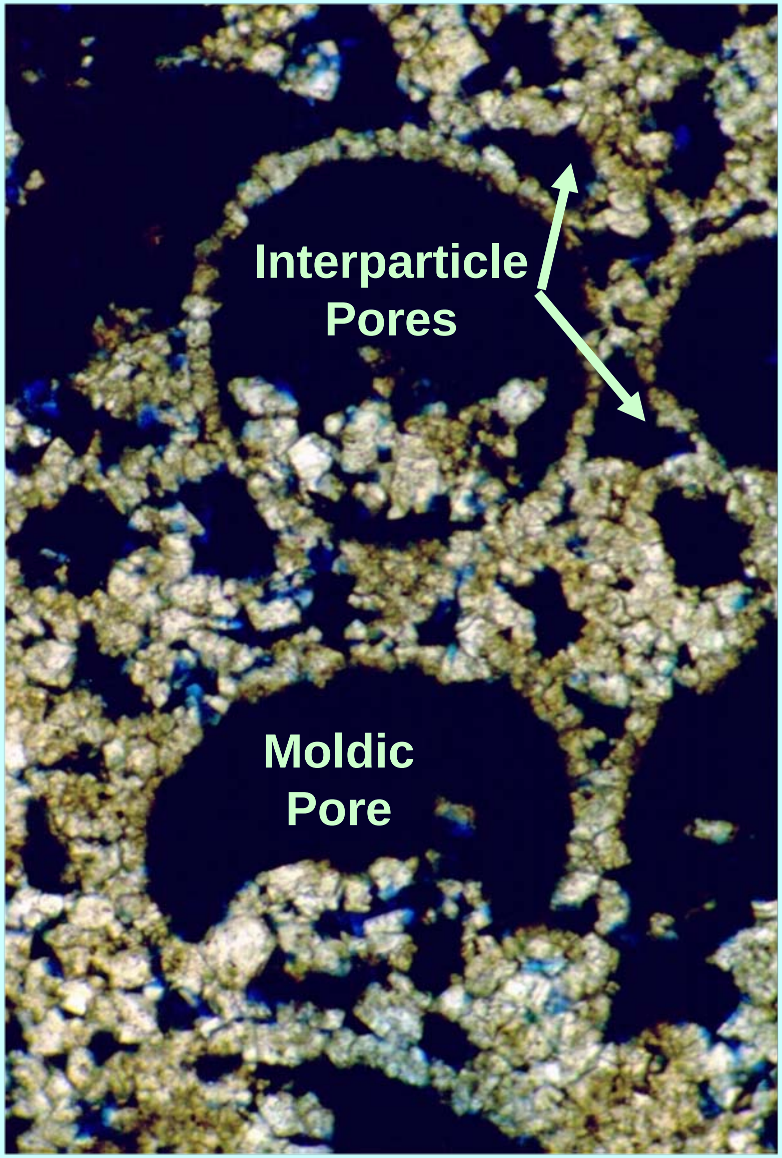
Moldic Pores

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

Blue areas are pores.

(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
- 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