# KMS Technologies – KJT Enterprises Inc.

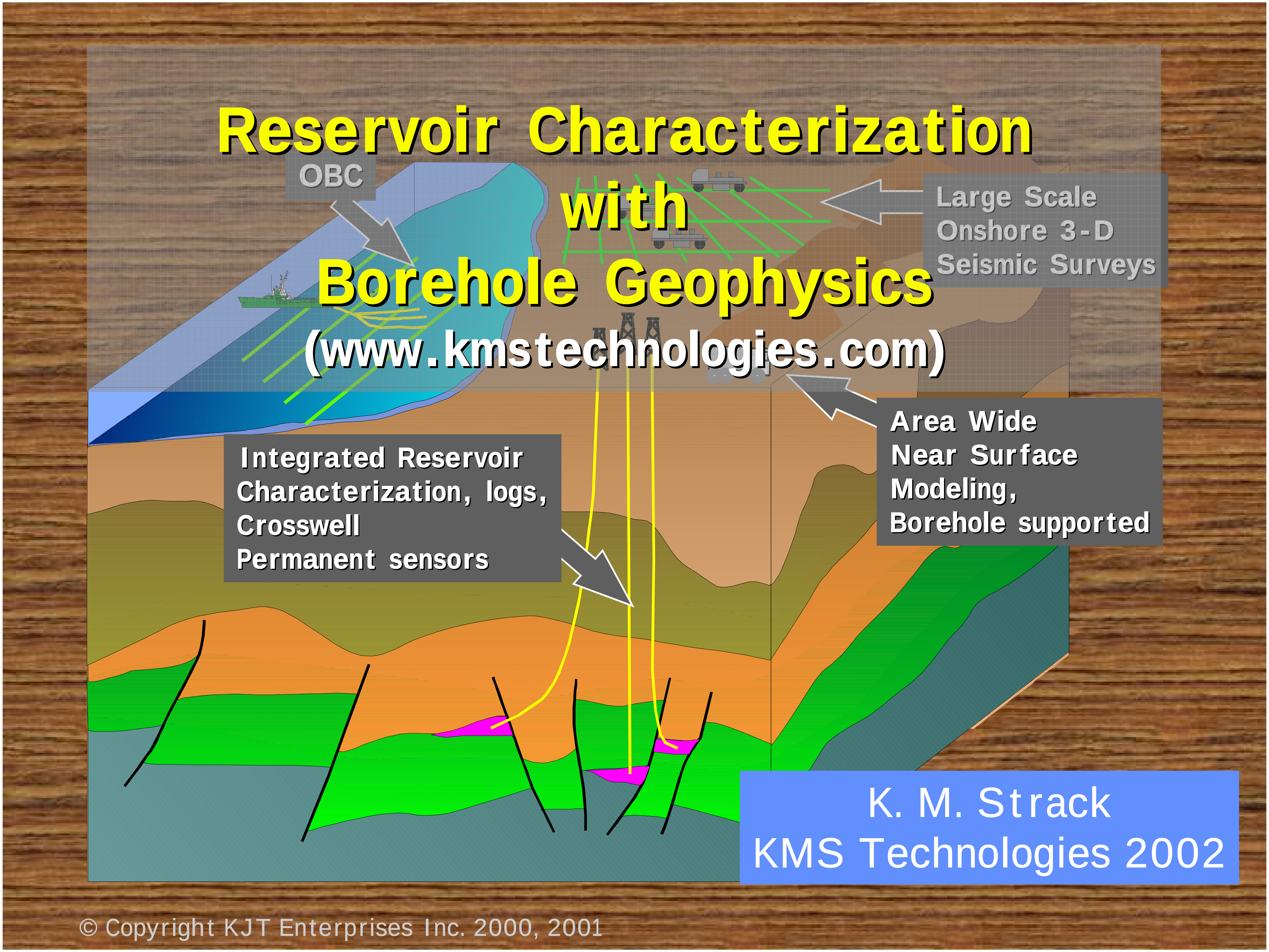
# Presentation

Strack, K. – M.

2002

# Reservoir Characterization with Borehole Geophysics

R. Sheriff's Reservoir Characterization Course,
University of Houston


Reservoir Characterization
with
Borehole Geophysics
(www.kmstechnologies.com)
OBC
Large Scale
Onshore 3-D
Seismic Surveys
Integrated Reservoir
Characterization, logs,
Crosswell
Permanent sensors
Area Wide
Near Surface
Modeling,
Borehole supported
K. M. Strack
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# Outline

- The critical link
- Rock Physics / Petrophysics
  - Pore space properties
  - Density of rocks
  - Natural radioactivity of rocks
  - Elastic properties
  - Anelastic properties
  - Electrical properties
  - Thermal & magnetic properties
  - Correlations between properties
- Seismic methods
  - VSP
  - Crosswell
  - Single well
  - Micro seismic monitoring
  - Seismic while drilling
  - Fracture monitoring
  - Passive seismic
  - 3D VSP
  - VSP for engineering applications
- Borehole Electromagnetics
  - The methods
  - Cross well EM
  - Single well EM
  - Seismoelectric measurements
- Borehole gravity
  - Gravity principles & examples
  - BHGM & Gradiometers
- Logging
  - Natural Gamma ray tools
  - Density tools
  - Borehole imaging
  - Resistivity logs
  - Sonic logs

# Outline

- Critical Link
- Rock Physics
- Seismic Methods
- Borehole EM
- Borehole Gravity
- Logging
- Summary

# References – rock physics

Schön, J.H., 1996, **Physical Properties of Rocks: Fundamentals and Principles of Petrophysics**, Handbook of geophysical exploration - seismic exploration (ed. K. Helbig, S. Treitel) 18, Pergamon Press **JS96**

Western Atlas, 1992, **Introduction to Wireline Log Analysis**, **WA92**

Schoen, J.H., Yu,G., & Strack, K.M. 1999, **Physical Properties of Rocks - Fundamentals**, lecture notes, Baker Atlas. **SYS99**

Reference list at the end

# Outline

- Critical Link
- Rock Physics
- Seismic Methods
- Borehole EM
- Borehole Gravity
- Logging
- Summary

# Borehole geophysics as critical link

- Establish ‘pain’ / Challenge
- The issues
- How do we solve it?

DeepLook

# The Challenge

**Breakthrough needed**

**Now** → **Vision 2010**

Bypassed production
Mis-positioned wells
Low well productivity
Expensive testing
Reserves uncertainty
Aquifer drive ??

**<35%**

Services - delivery vehicle

Subsurface Sensors

*Various*
Integration
*Geoscience tools*

*Reservoir Modeling*

Surface sensors

**70%+ recovery**

Optimal well targeting

Right facilities

Minimum water production

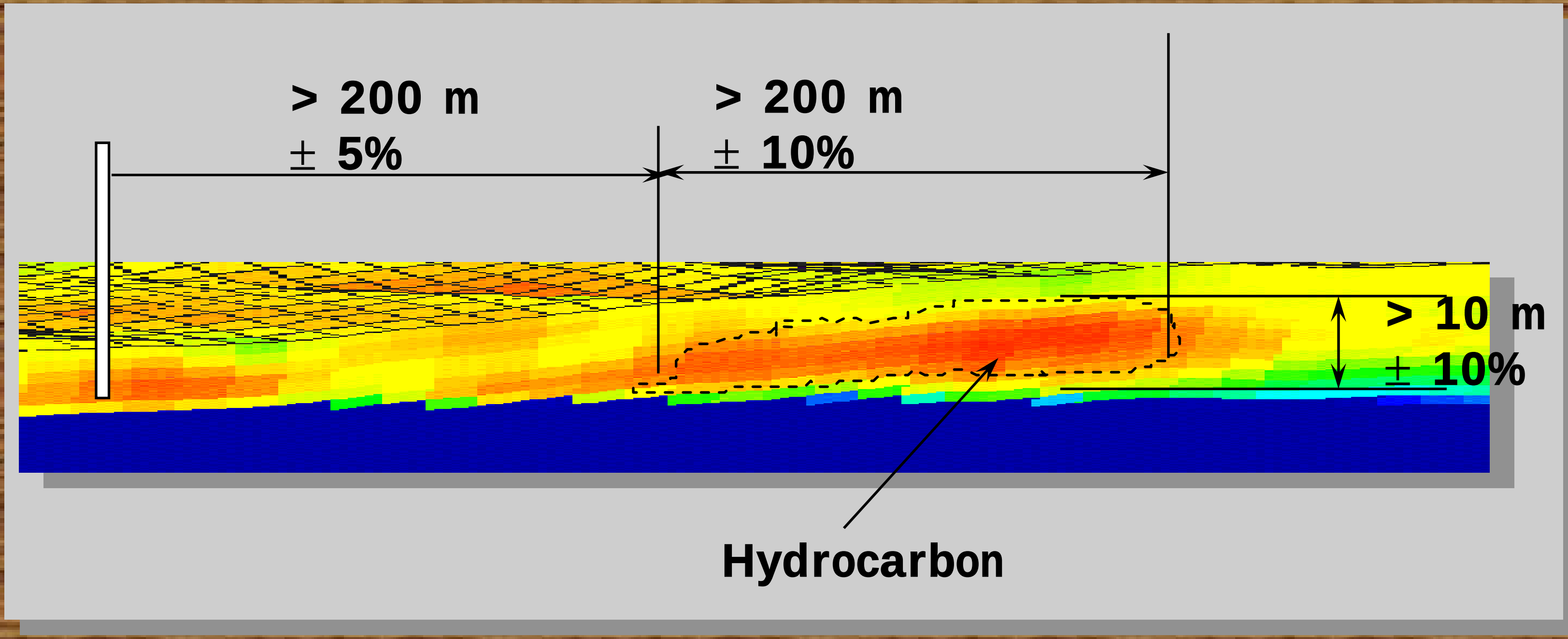
**70%**

After DeepLook consortium vision

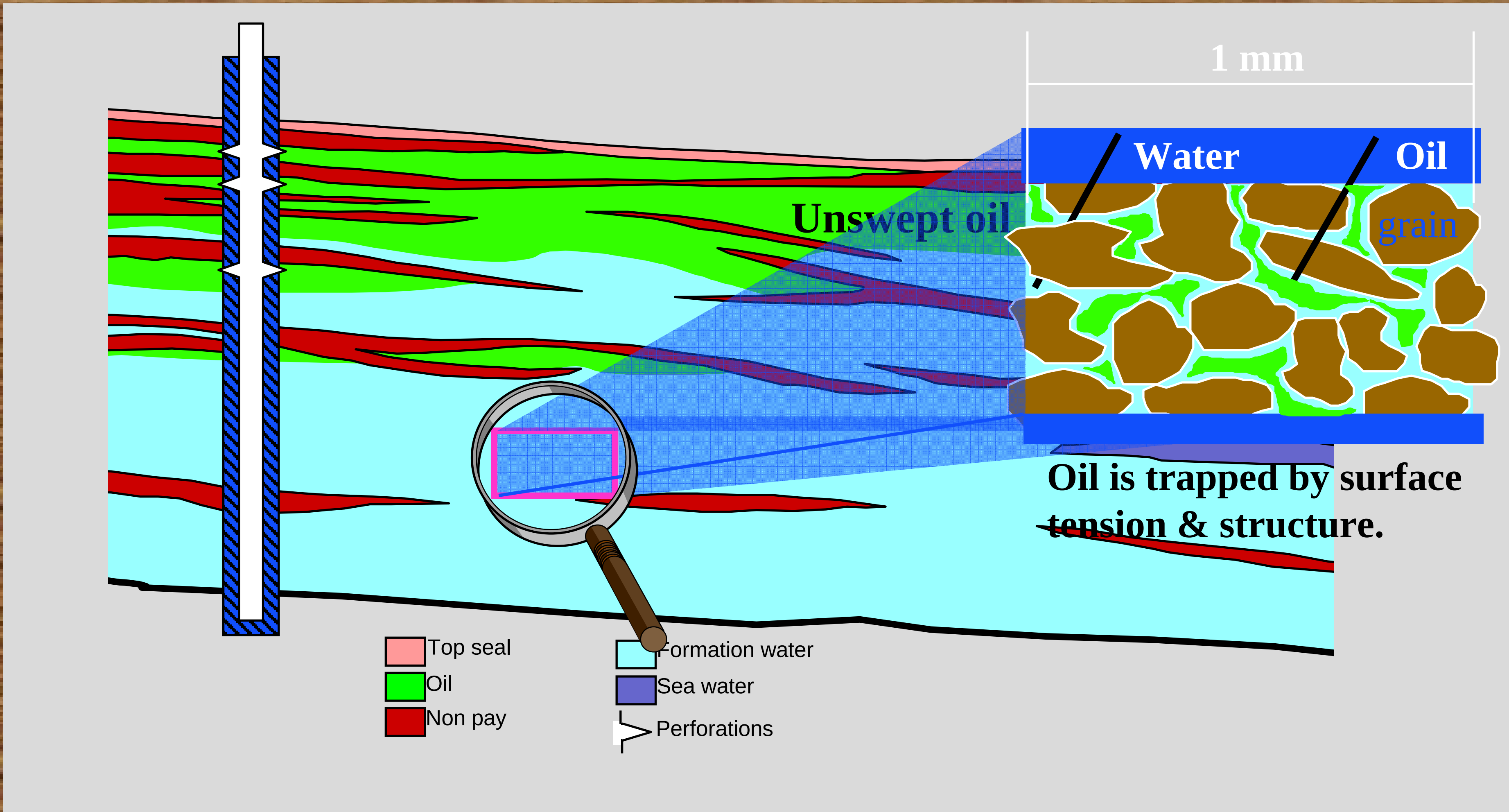
# Interwell sweet spots

## Challenges:

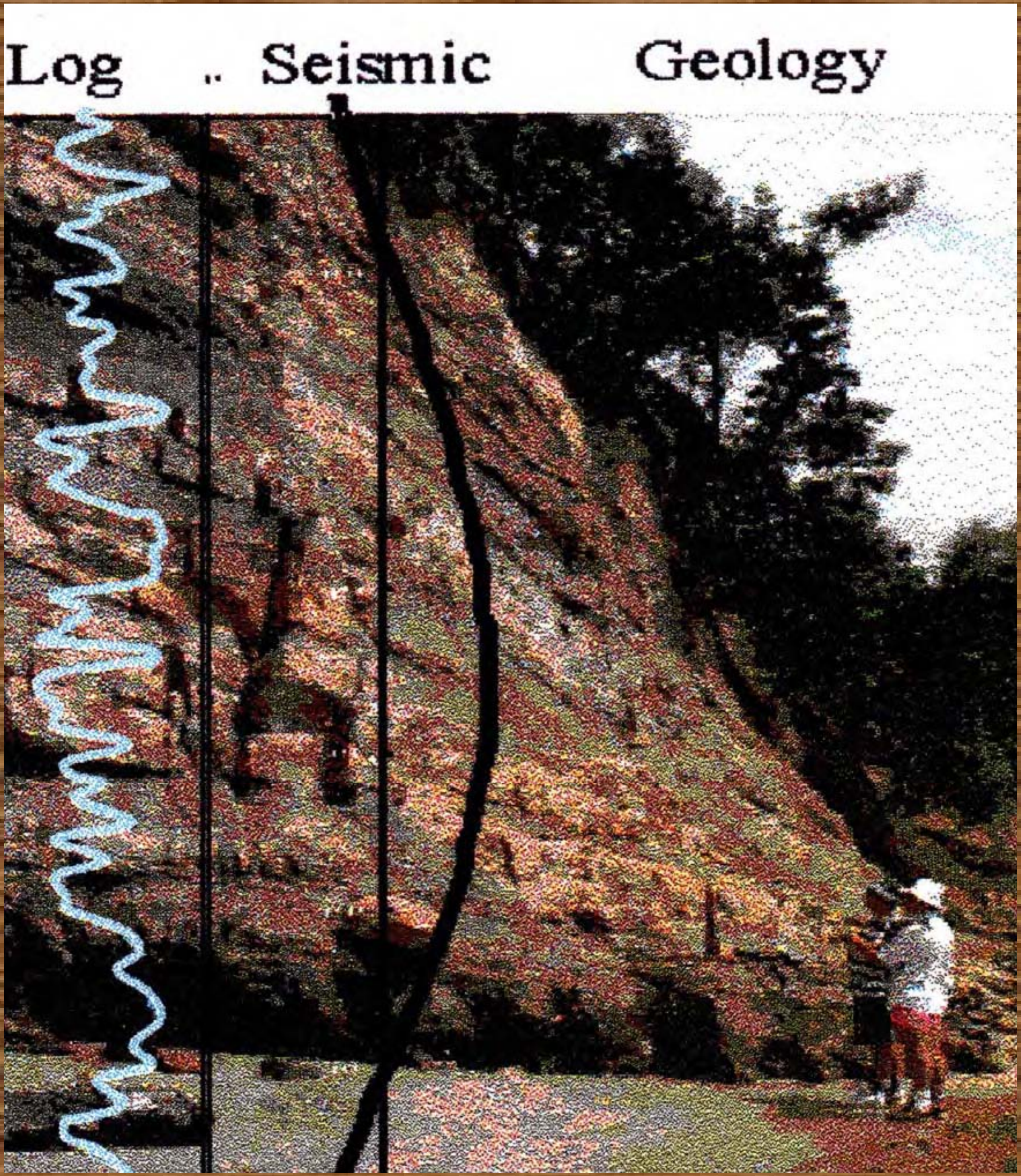
- No one method will meet the need, therefore new & existing technologies must be integrated to meet the need.
- To determine fluid distributions in the interwell space within 5 to 10 % error in accuracy.



# Scope of the Challenge

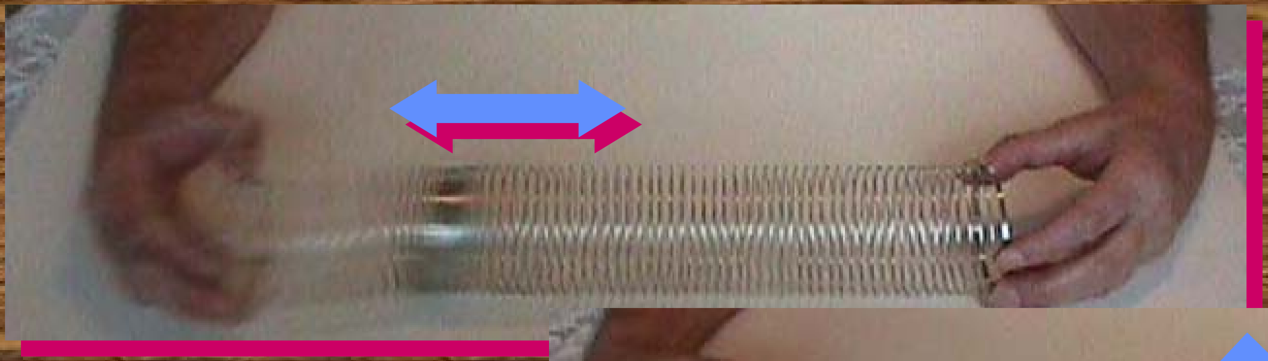


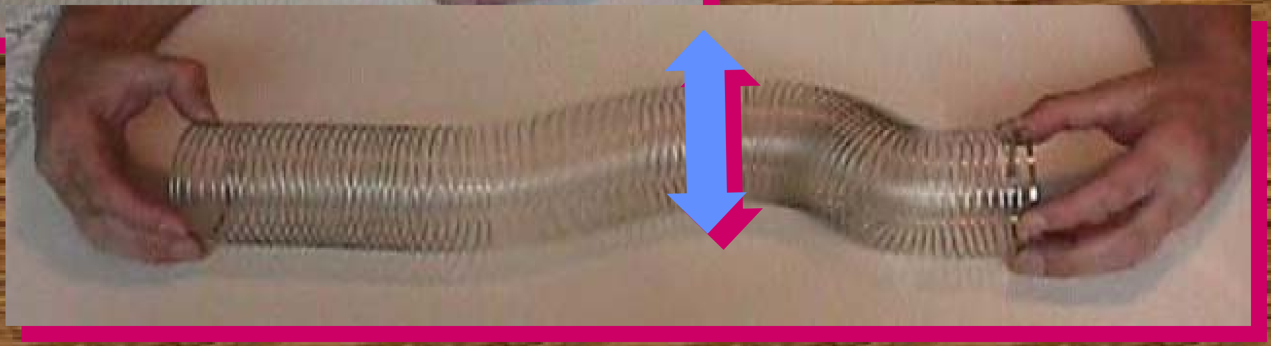
# The scale issue

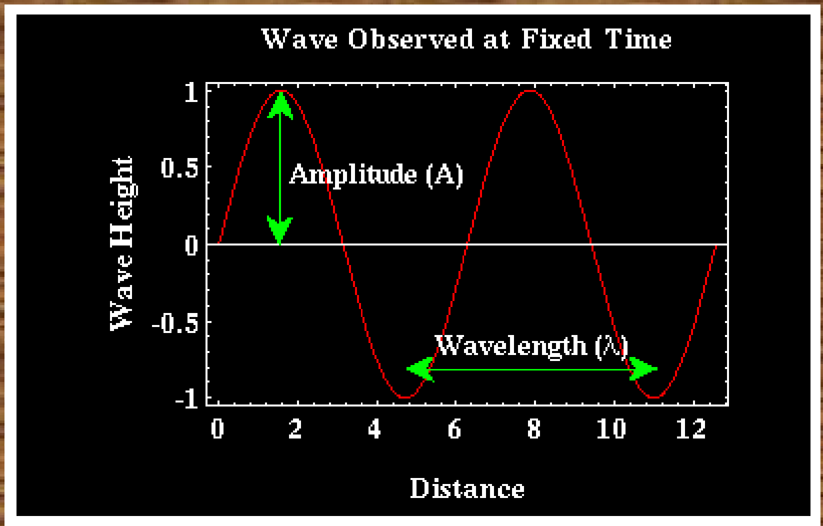


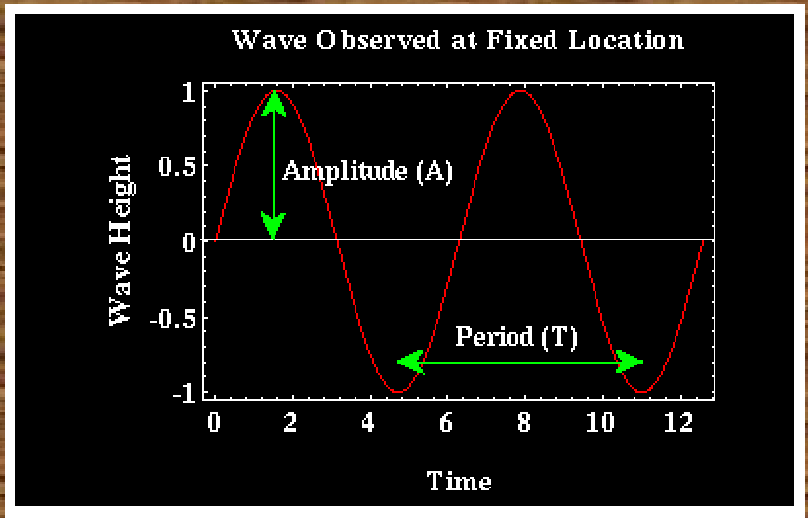

(after Peeters, pers. comm, 1998)

# Seismic waves

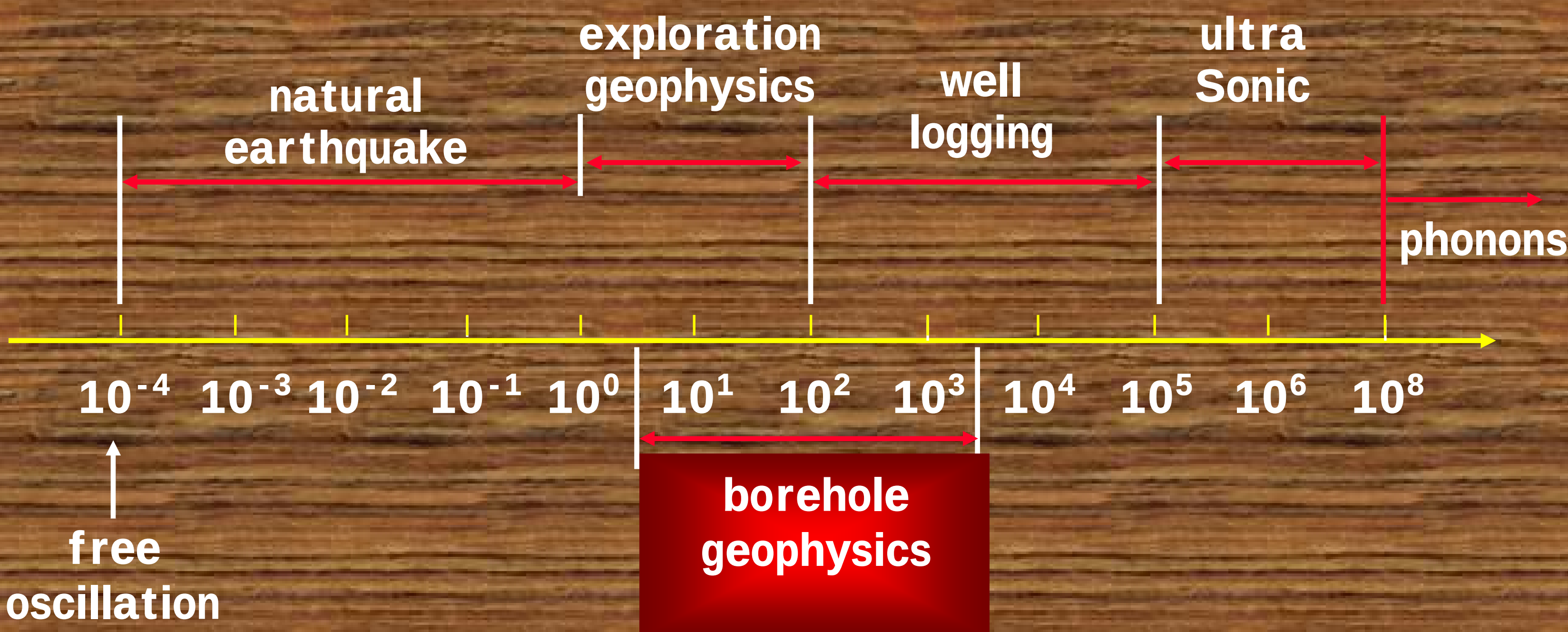




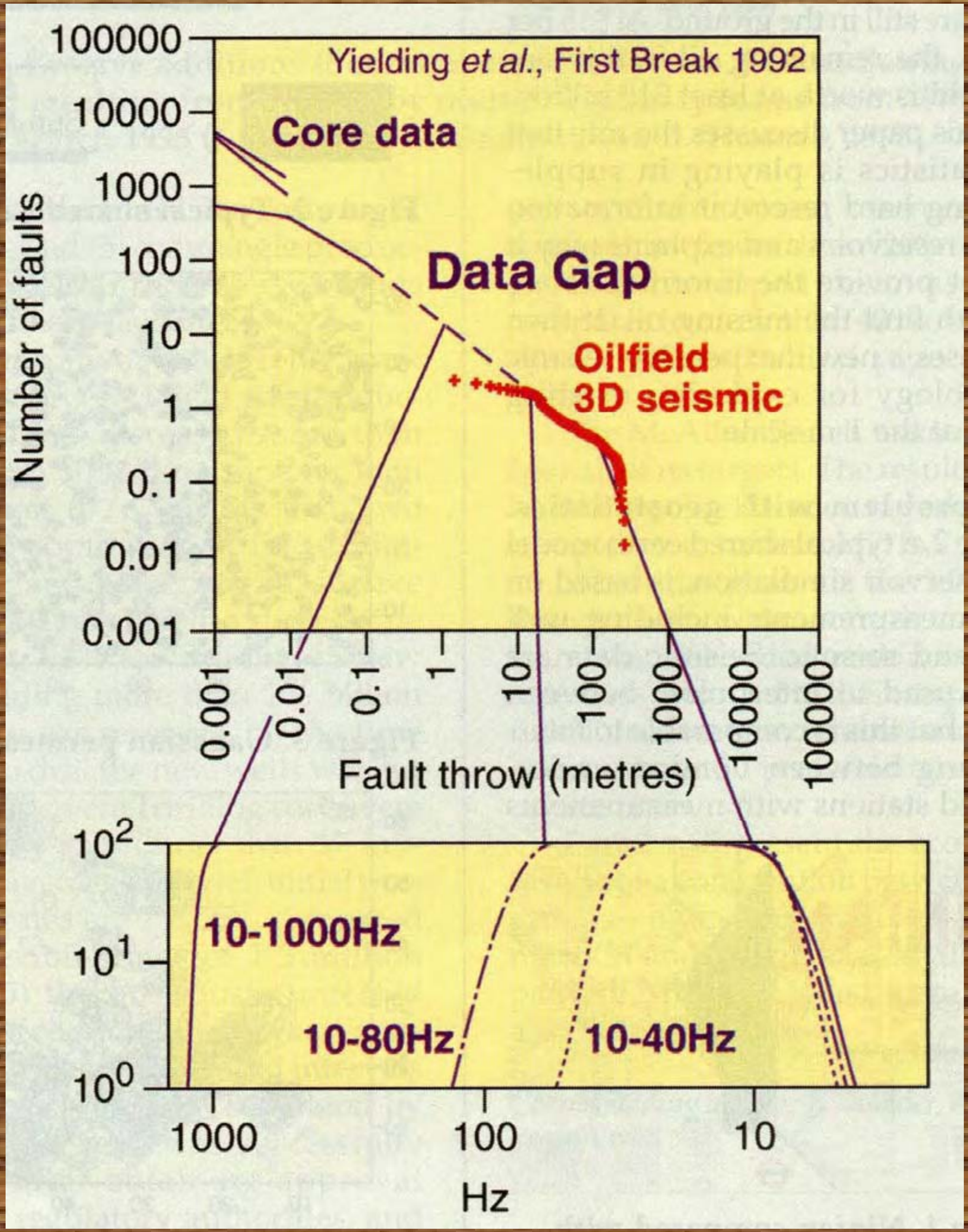


# SEISMIC SIGNAL FREQUENCIES



# The Data Gap

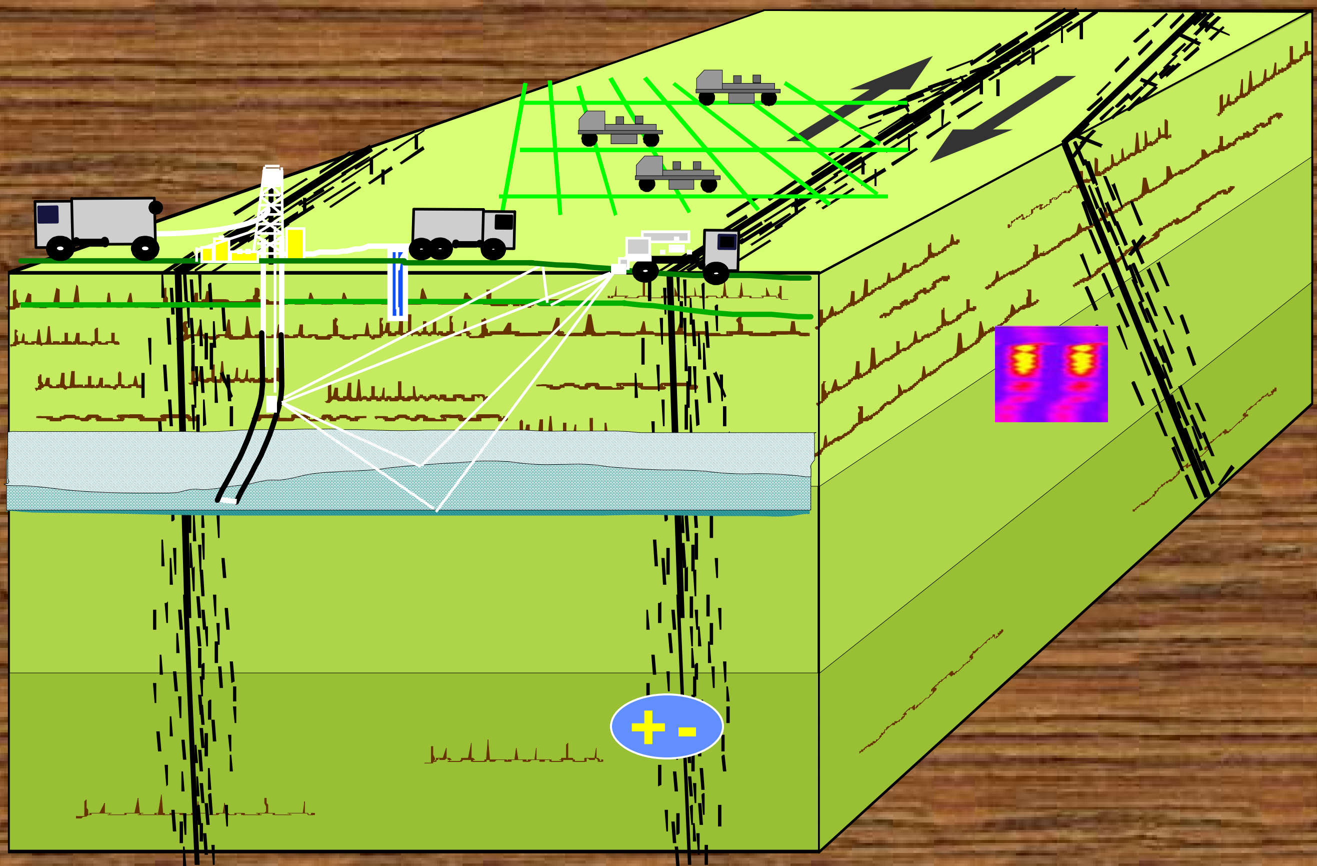



After Ziolkowski, 1999

# Benefits: Borehole Geophysics

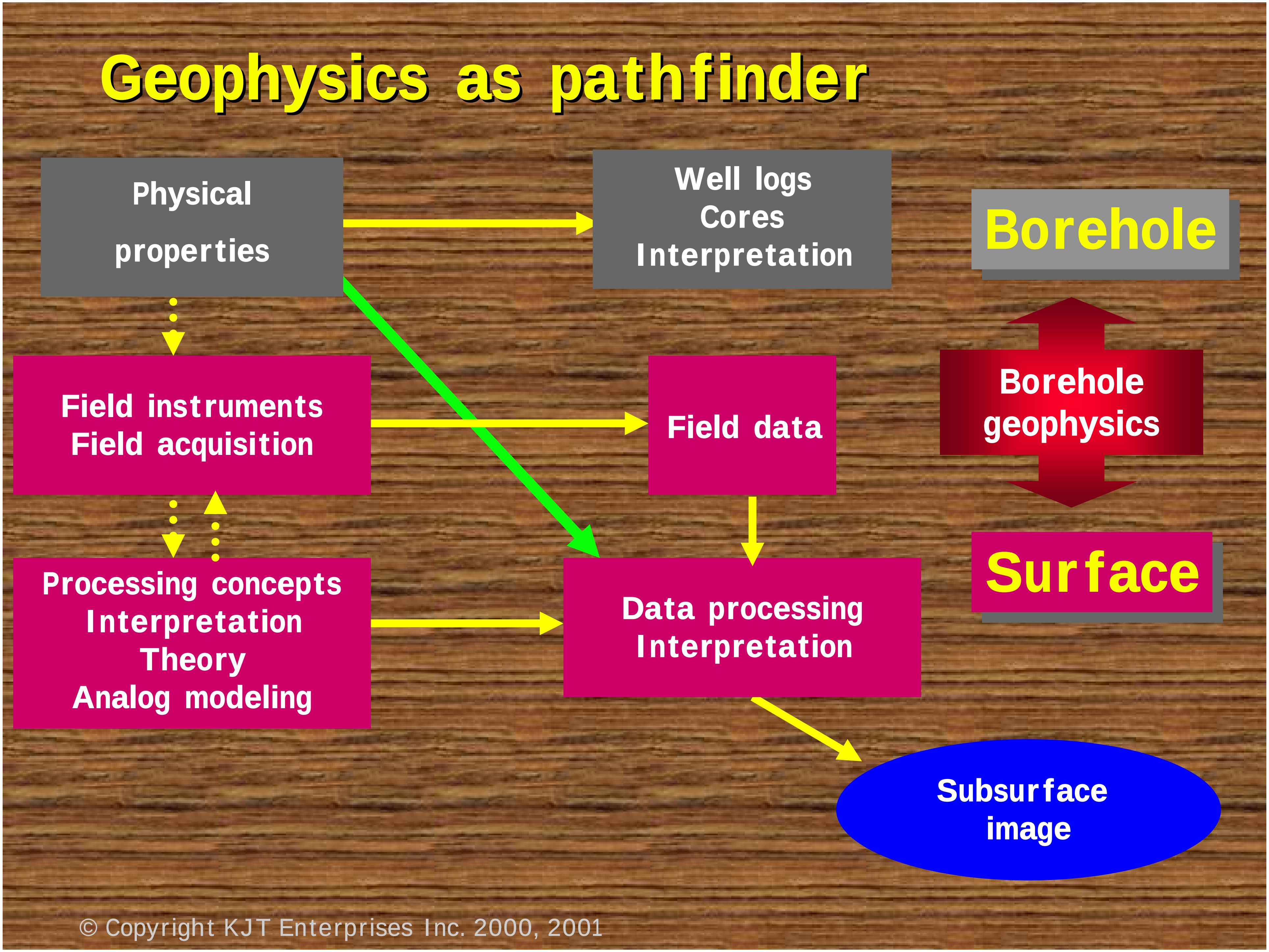
- Better link between data – less uncertainty
- Resolve feature at sub- seismic scale
- Extend borehole detail into formation
- Find bypassed reserves
- Predict ahead of the drill – risk reduction
- Optimized field development
- Monitor production – operating cost
- Increase recovery rate

# Borehole seismics – the critical link



# Outline

- Critical Link
- Rock Physics
- Seismic Methods
- Borehole EM
- Borehole Gravity
- Logging
- Summary


Geophysics as pathfinder
Physical properties
Well logs
Cores
Interpretation
Borehole
Field instruments
Field acquisition
Field data
Borehole geophysics
Processing concepts
Interpretation
Theory
Analog modeling
Data processing
Interpretation
Surface
Subsurface image
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# What is “Petrophysics”?

"Petrophysics"as pertaining to physics of particular rock types. ... Study of physical properties of rock related to pore & fluid distribution ..."

G. E. Archie, 1950, pioneer in application & quantification of rock physics in petroleum engineering

# Rocks Physics fundamentals

- Pore space properties
- Density of rocks
- Natural radioactivity of rocks
- Elastic properties
- Anelastic properties
- Electrical properties
- Thermal properties
- Correlations between properties
- Summary & conclusions

# Pore space properties

**Pore volume**

porosity $\Phi$

**Fluid flow in pore channels**

permeability $k$

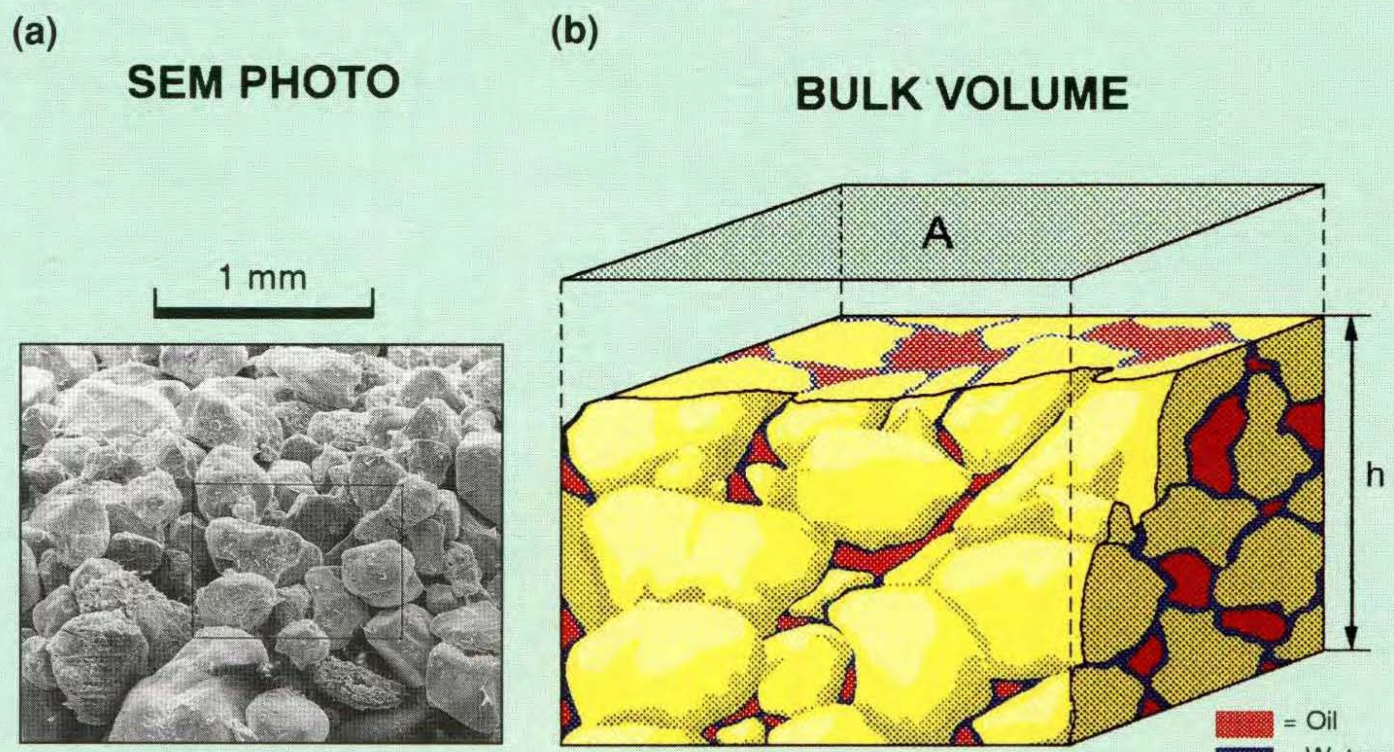
**Interface grain surface-fluid**

specific surface $S$

SYS99

# Quartz sand scan

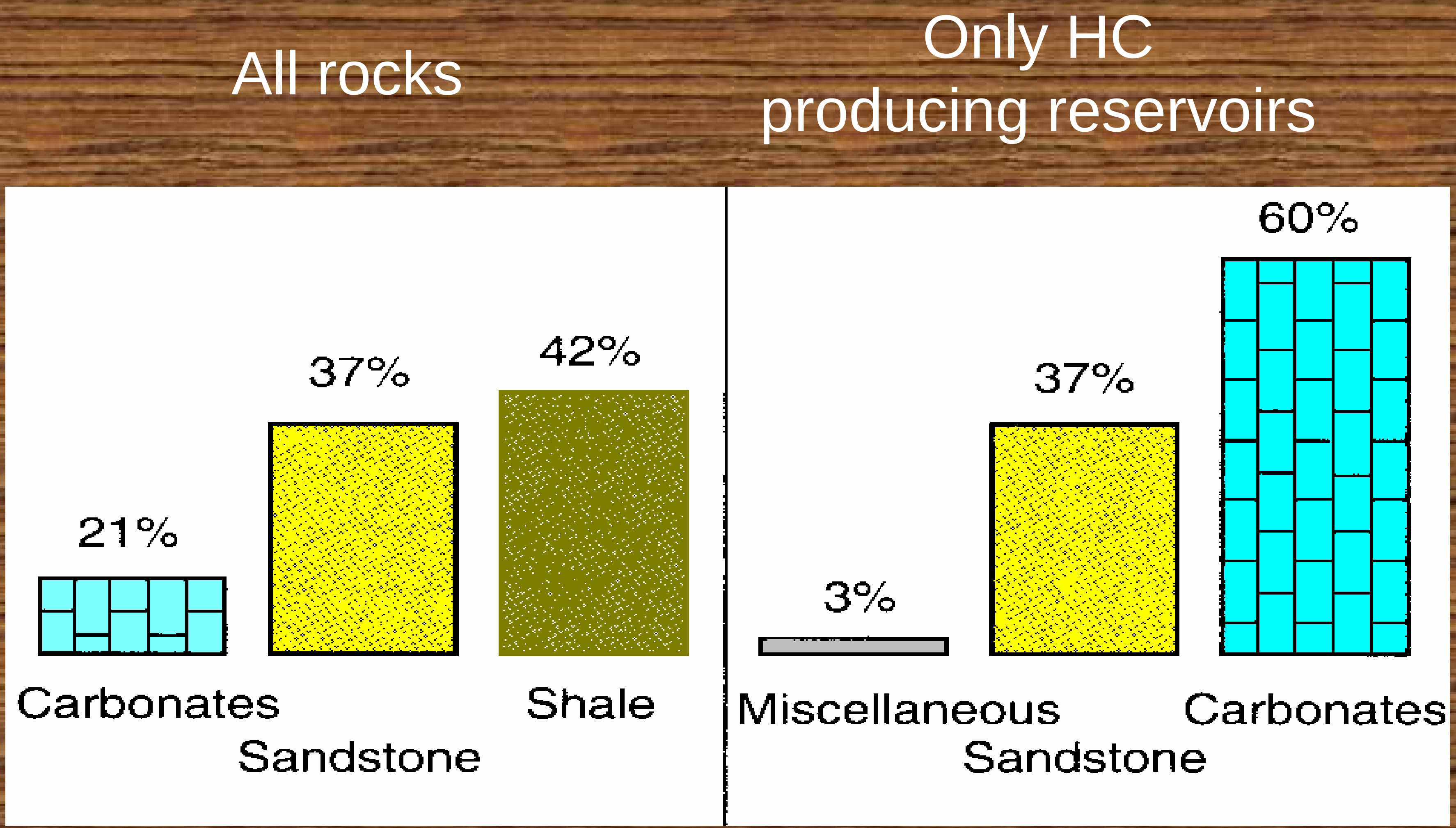
Scanning Electron Microscopy (SEM) photograph of quartz sand. The total bulk volume (v) is comprised of grains and fluid filled pores (v = A x h)



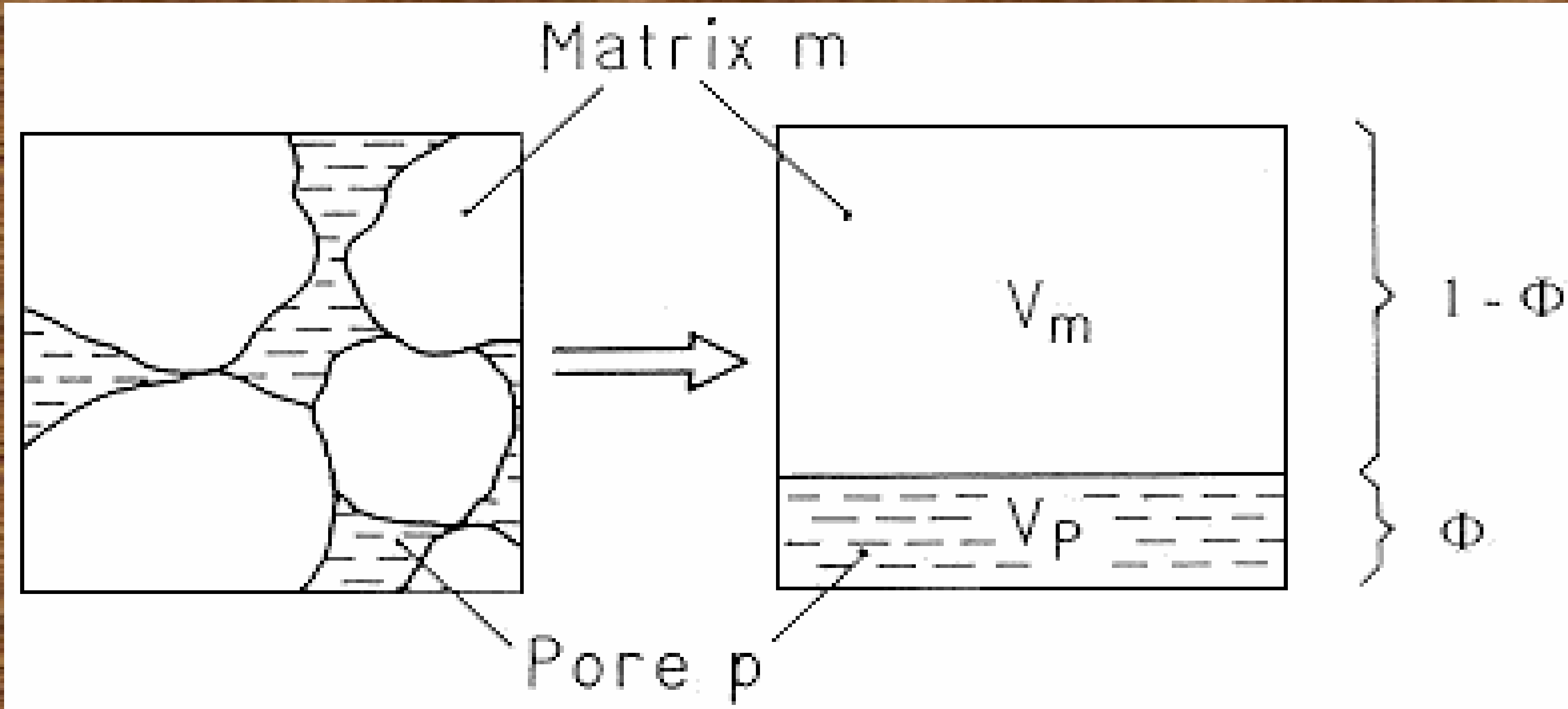

Porosity is the bulk volume fraction found in pores. Hydrocarbon saturation is the volume fraction of pores filled with hydrocarbons.

(after van Ditzhuijzen, 1994)

# Rock type distribution



# Porosity - definition




$$\text{porosity} = \frac{\text{volume of pores}}{\text{total volume of sample}} \qquad \Phi = \frac{V_{pores}}{V_{sample}}$$

SYS99

# Fluids in the pore space
# - the term "saturation"

$$\text{saturation}_{\ i} = \frac{\text{volume fluid i}}{\text{pore volume}}$$

**a volumetric model**


SYS99

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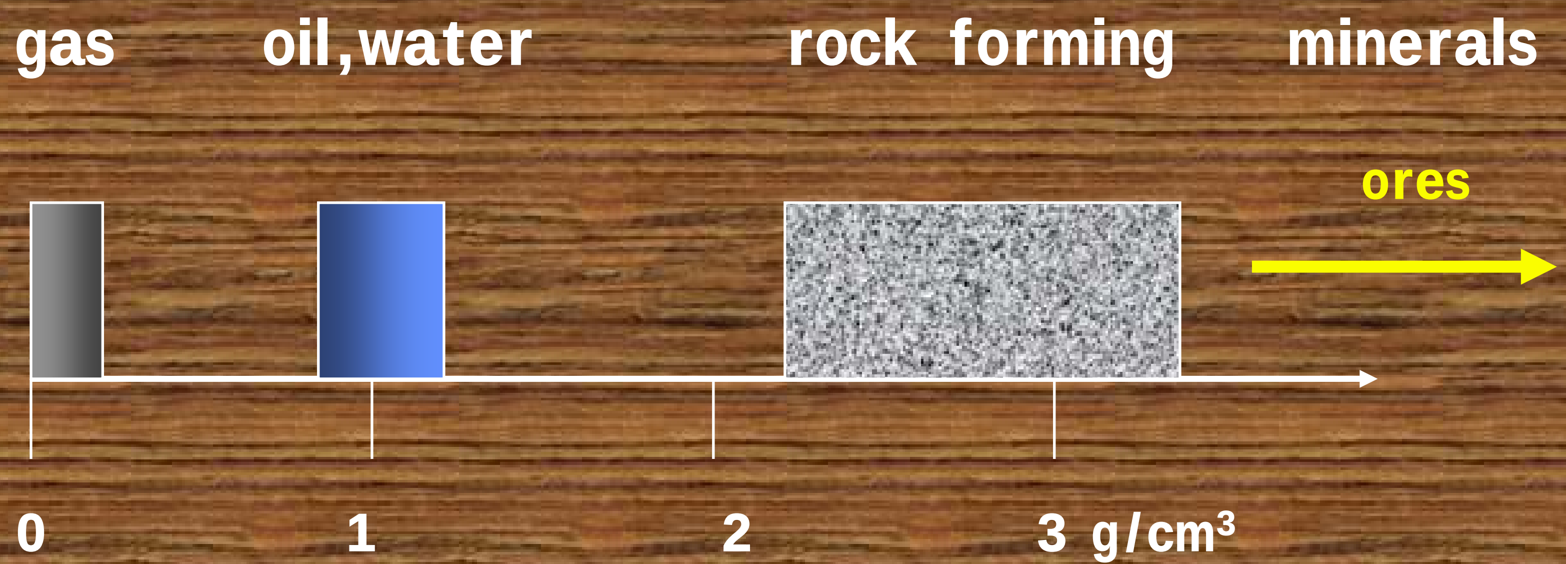
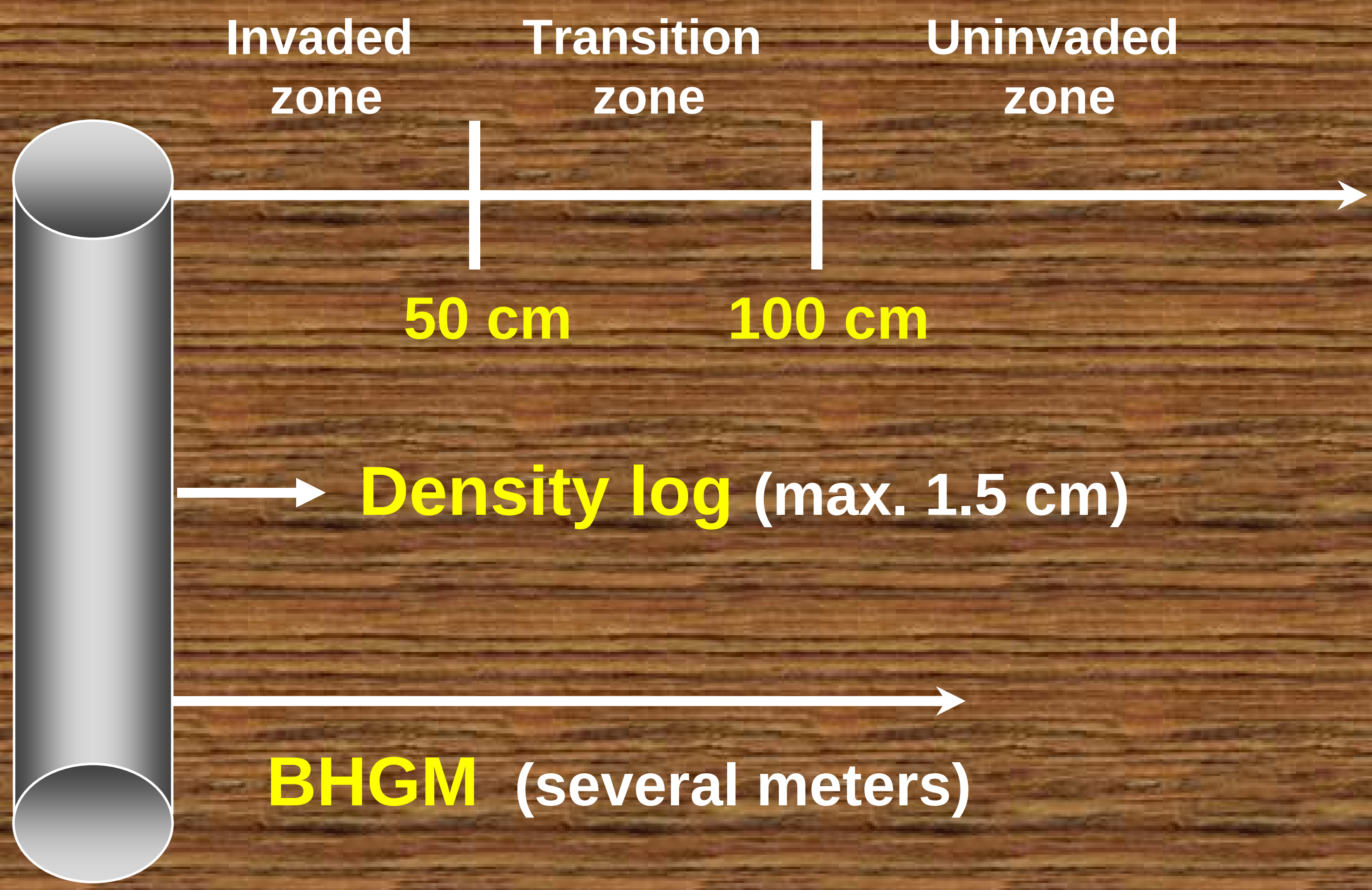
# Density of rock constituents




Rock density decreases with increasing porosity

Porous rock density increases with increasing water saturation

# Borehole Gravity Meter (BHGM) depth of investigation



# Rocks Physics fundamentals

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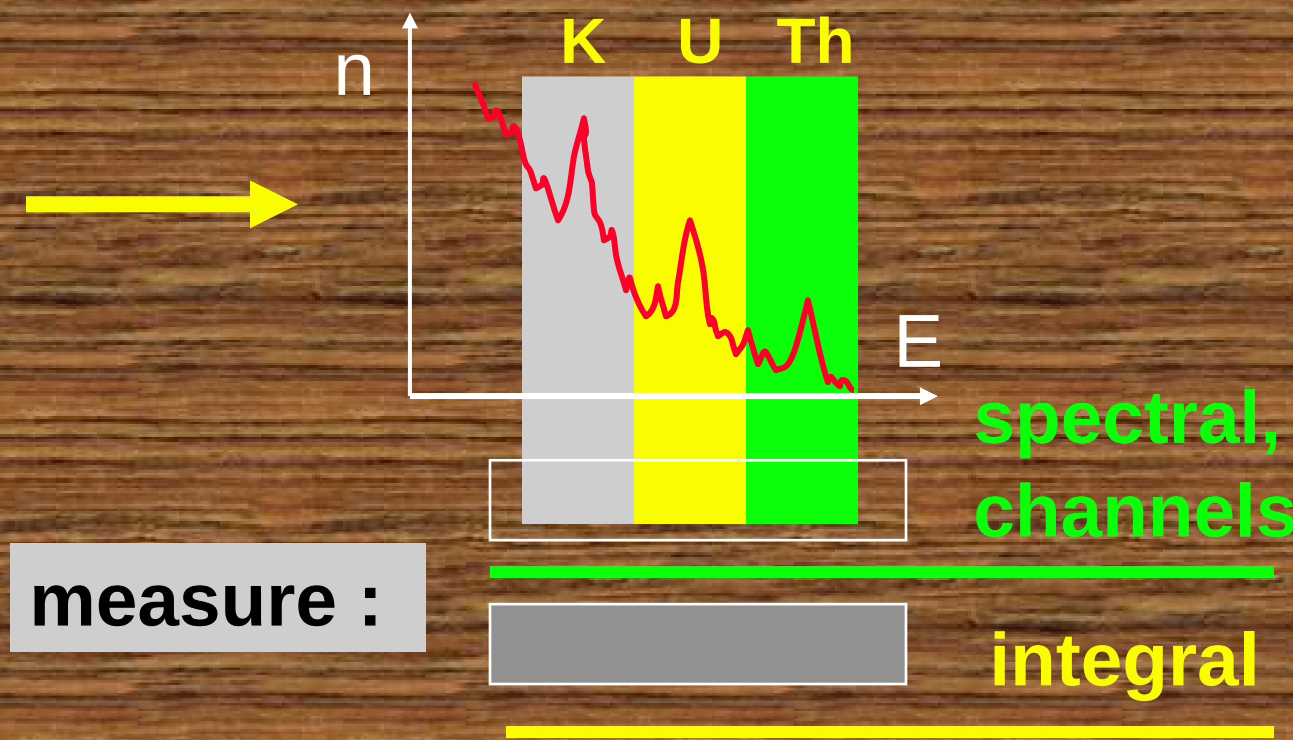
# Natural gamma activity of rocks
# - Types of measurement

Origin of natural radioactivity is

**U, Th, K**

content of rock

**Produces a gamma spectrum**

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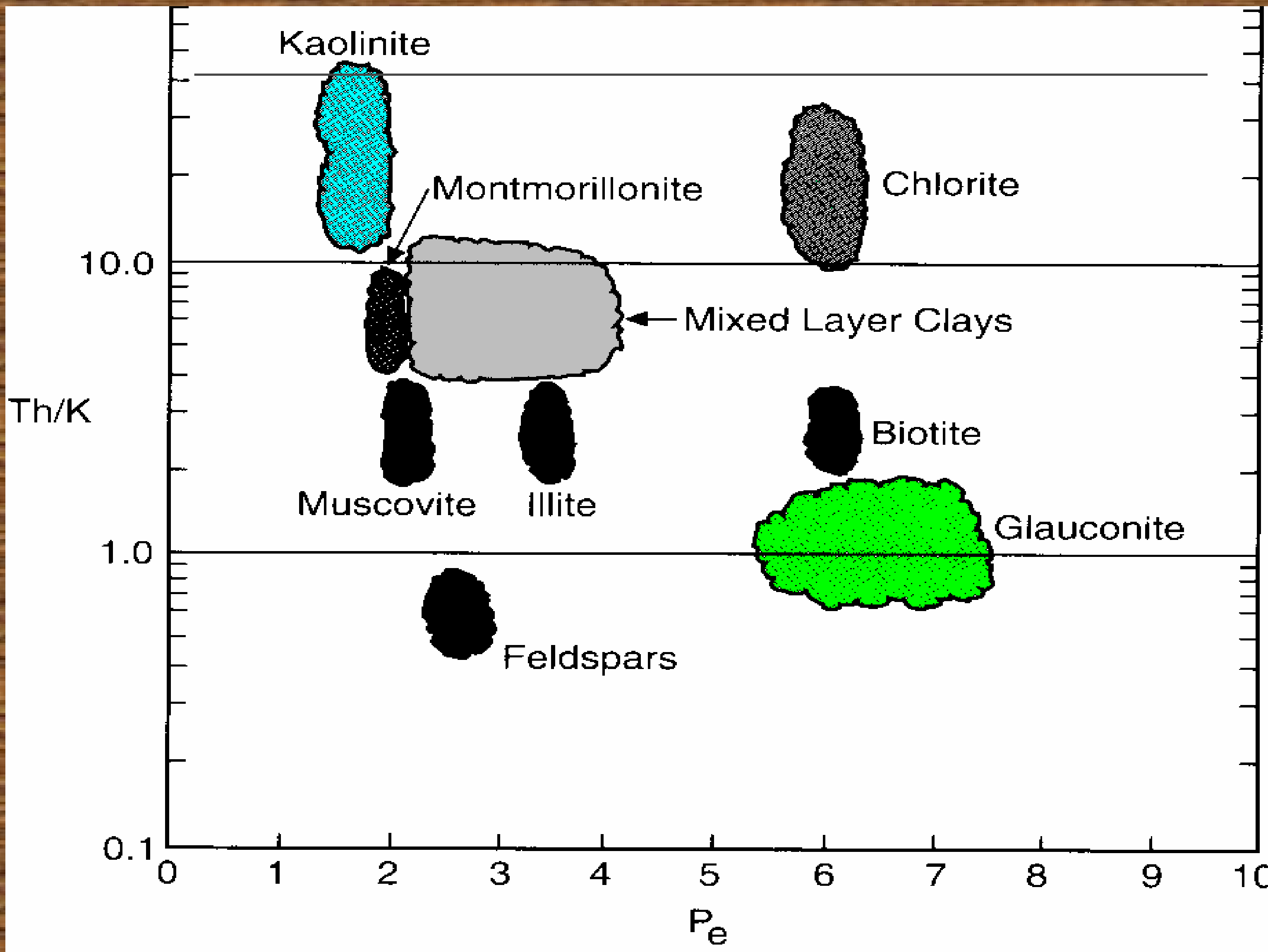
# Th/K - Pe crossplot



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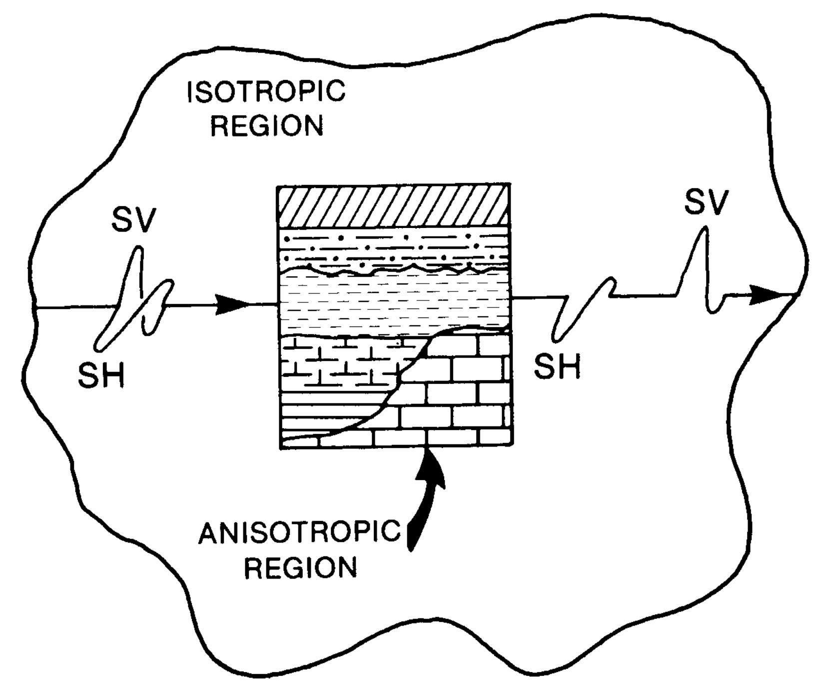
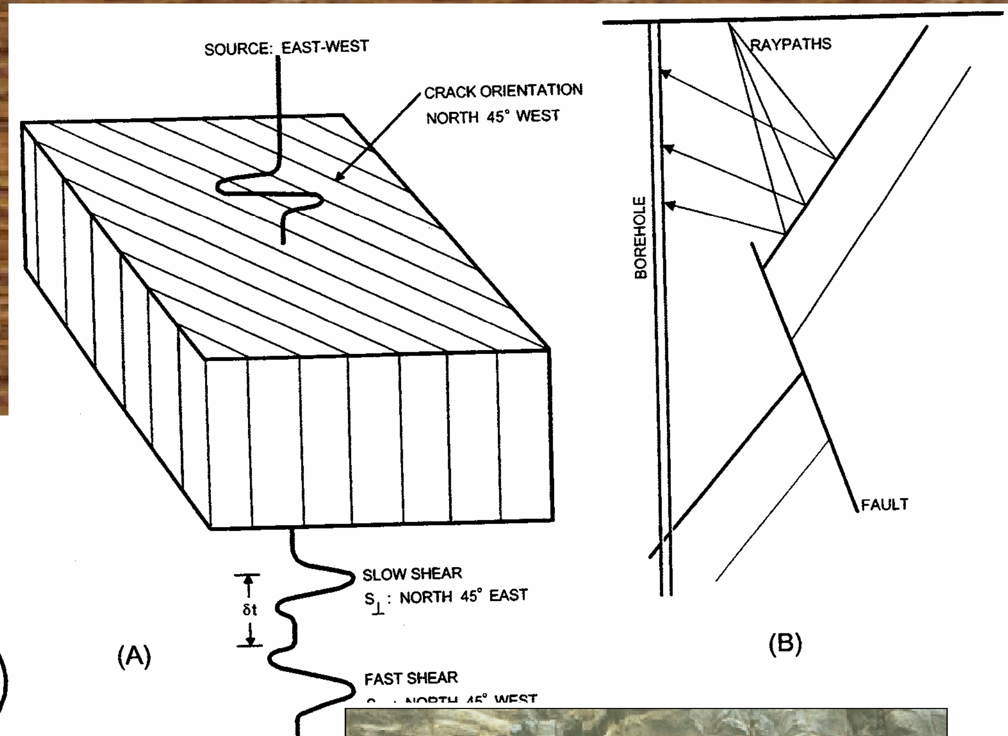
# Wave propagation in rocks

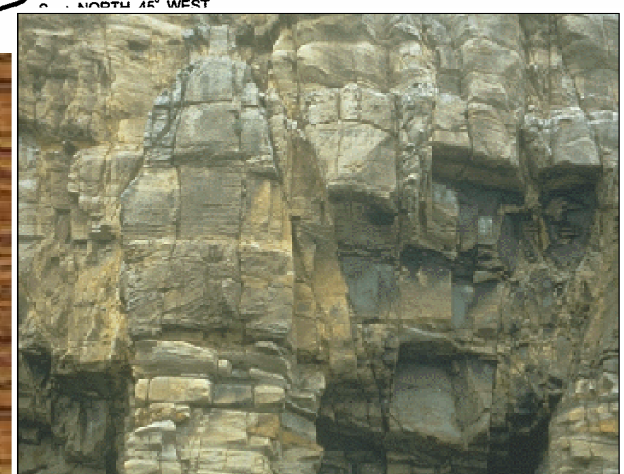
- Gassmann (1951) – theory of elasticity in porous rocks; assumes relative motion between solids & fluids is negligible
- Biot (1956) – extension to Gassmann incl. dynamic effects such as pore connectivity, fluid viscosity and hydraulic skeleton permeability.
- Geertsma & Smit (1961) equations in terms of compressibility & frequency

# Borehole seismic example




(MODIFIED AFTER CRAMPIN, 1984)



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# Rocks Physics fundamentals

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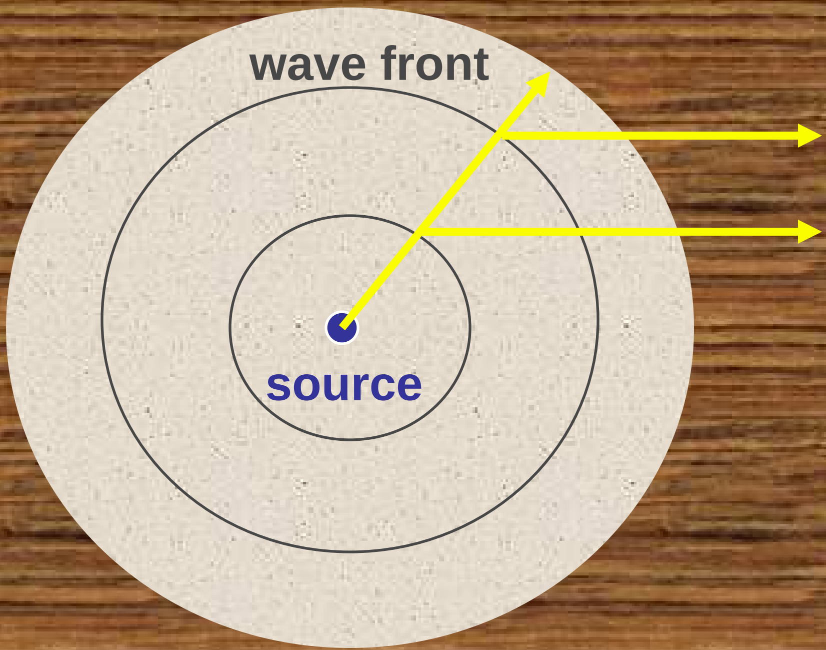
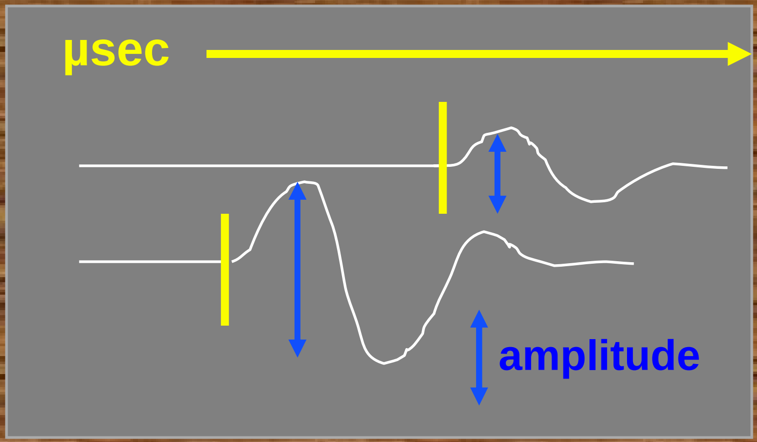
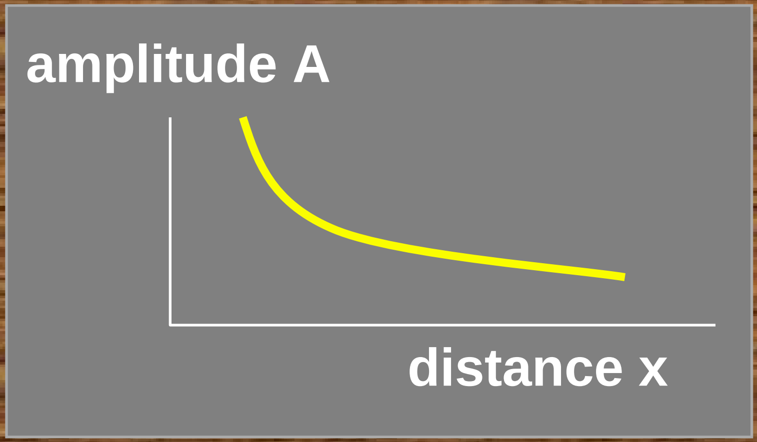
# Elastic wave attenuation

## Definitions & parameters




**Travel time difference → Velocity**

**Amplitude difference → Attenuation**

SYS99

# Rocks Physics fundamentals

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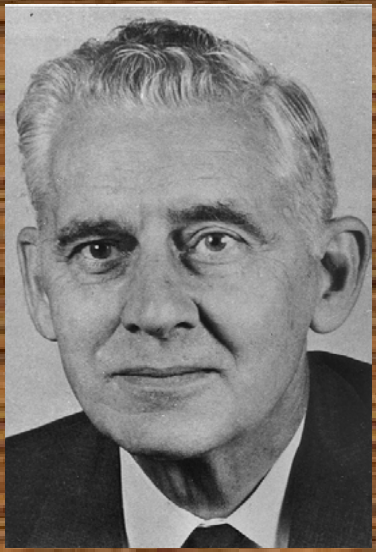
# Electrical resistivity of "clean" porous rocks - ARCHIE's equations



**The logical walk:**

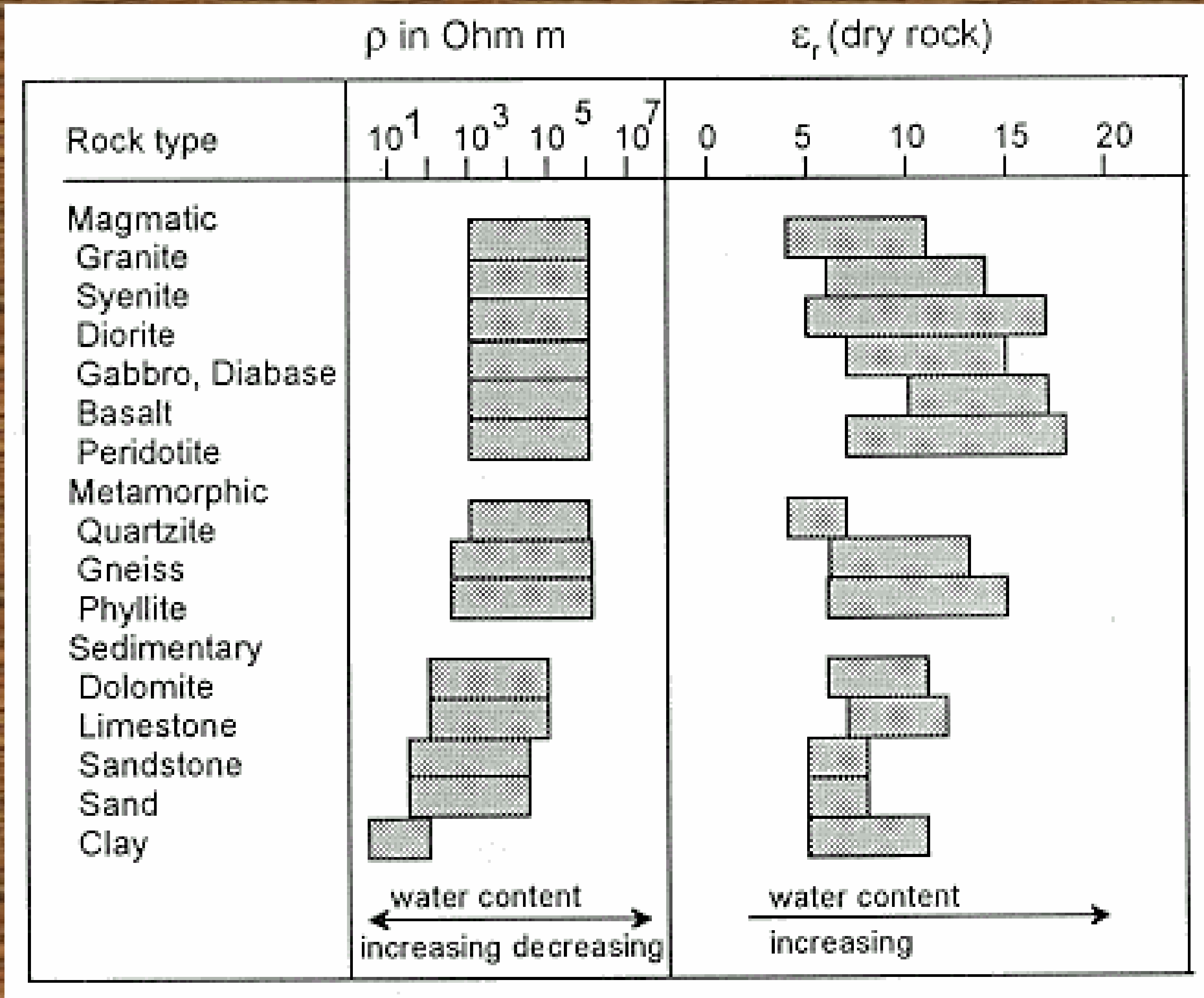
**Clean porous rock: no clay or another conductor than pore water.**

**Rock conductivity (or resistivity) is proportional to water conductivity (or resistivity).**

**Rock conductivity is controlled only by water conductivity, amount & distribution or geometry of "conductor water"**

SYS99

# Resistivities & dielectric constants




JS96

# Highlights electrical methods

- Sensitive to fluid
- Used to define OIP
- Largest number of different methods
  - Induction
  - Galvanic
  - Dielectric
  - Imaging
  - Diplog
  - Casing inspection
- Largest number of different tools

# Rocks Physics fundamentals

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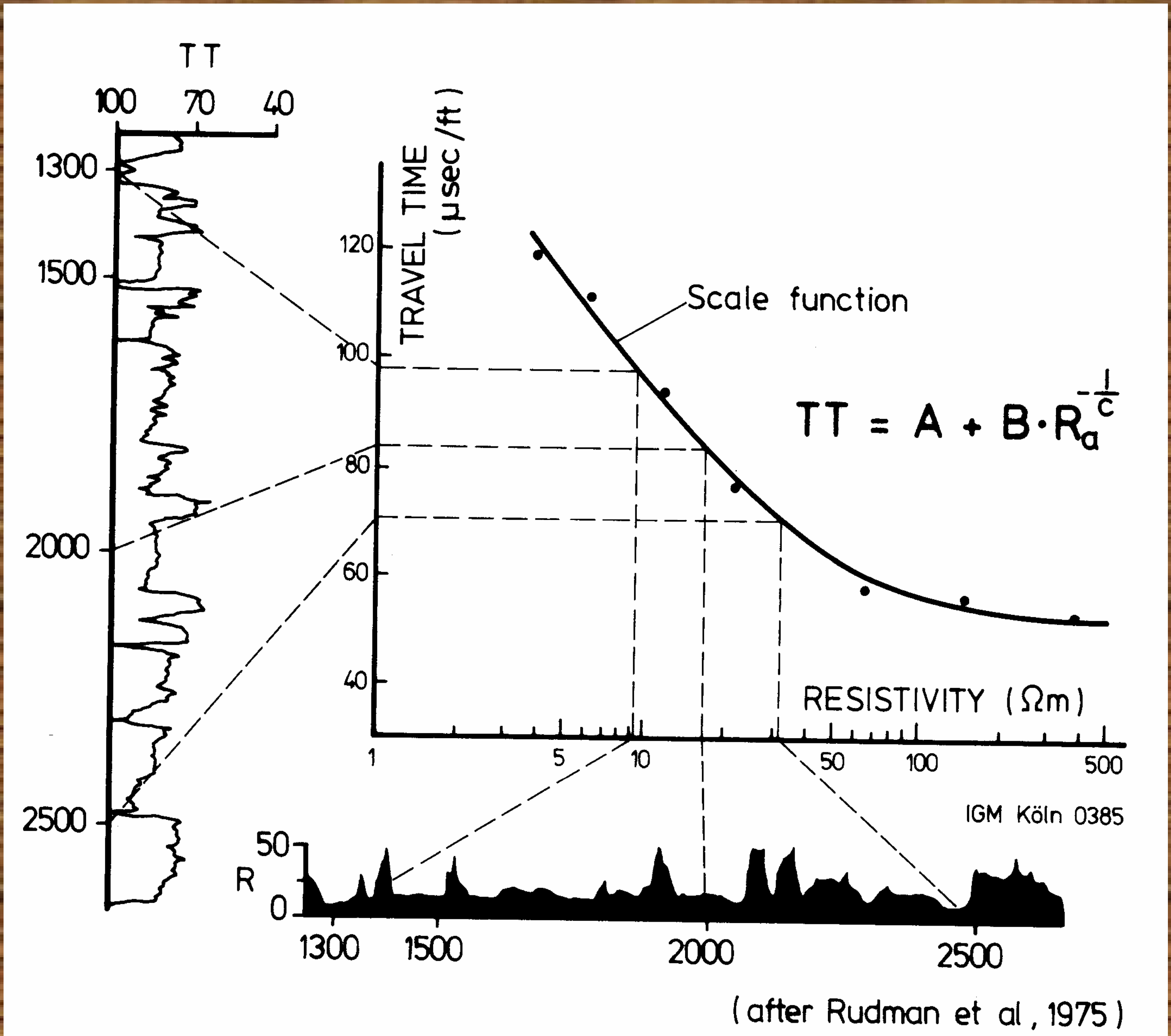
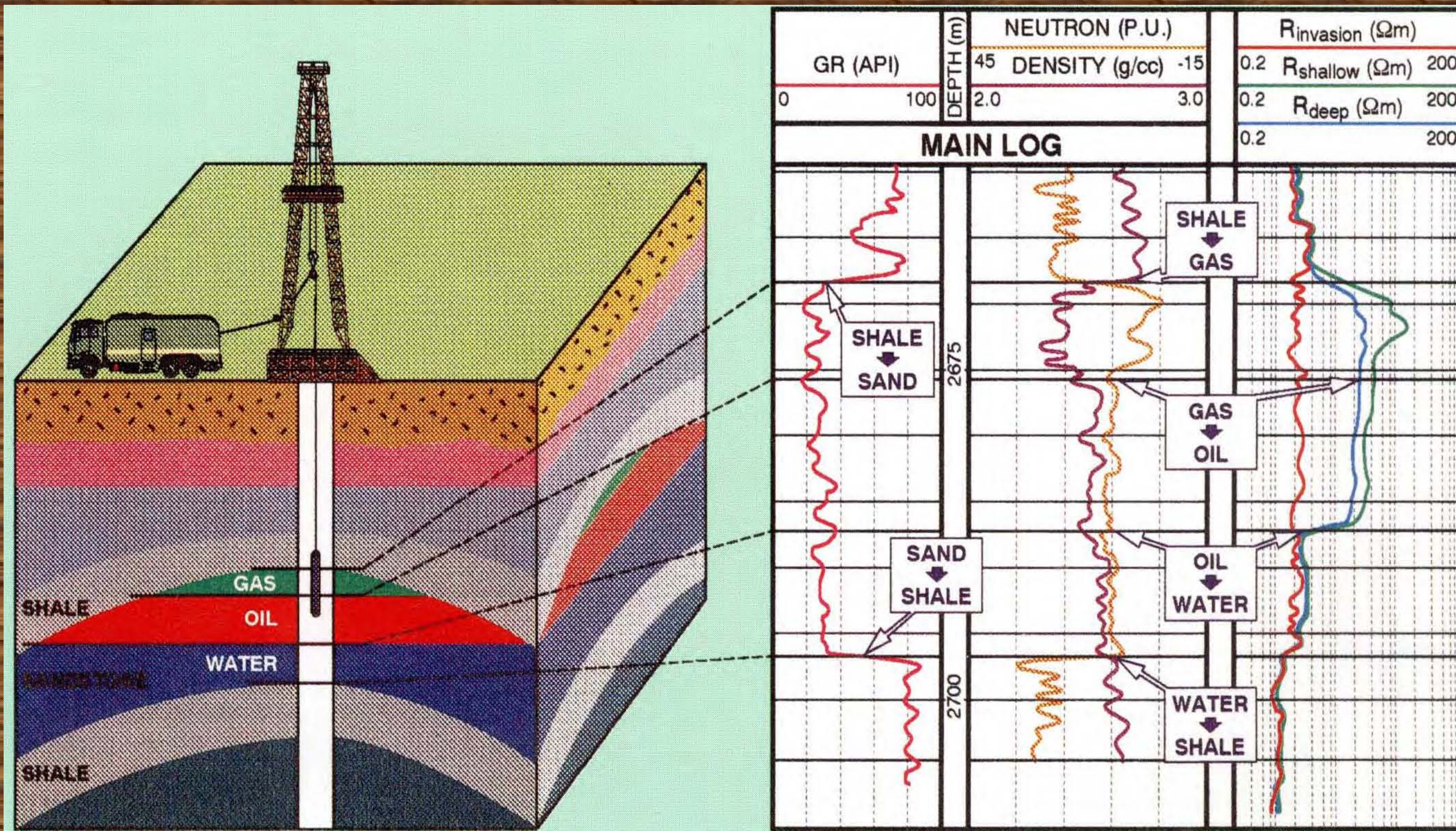
# Resistivity – velocity: Rudman formula



# Basic interpretation principles

- Natural gamma rays used for lithology definition; high gamma rays – high shale content
- Gamma- gamma density; bulk density
- Neutron density – hydrogen concentration
- Resistivity; fluids (oil –water)

# Integration example




(after van Ditzhuijzen, 1994)

# Outline

- Critical Link
- Rock Physics
- Seismic Methods
- Borehole EM
- Borehole Gravity
- Logging
- Summary

- Seismic methods
  - VSP
  - Crosswell
  - Single well
  - Micro seismic monitoring
  - Seismic while drilling
  - Fracture monitoring
  - Passive seismic
  - 3D VSP
  - VSP for engineering applications

# Outline

- **Seismic methods**
  - VSP
  - Crosswell
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  - Passive seismic
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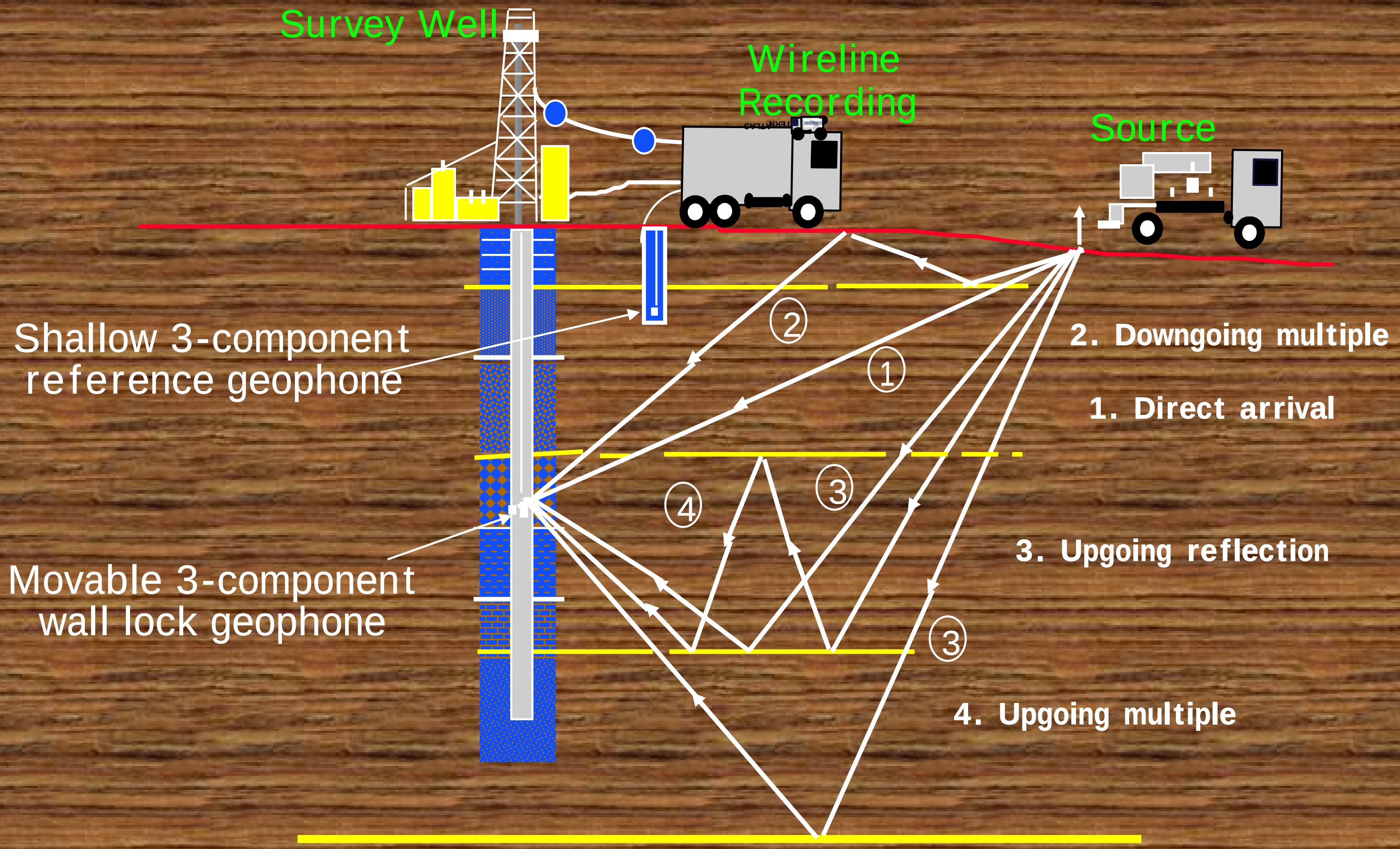
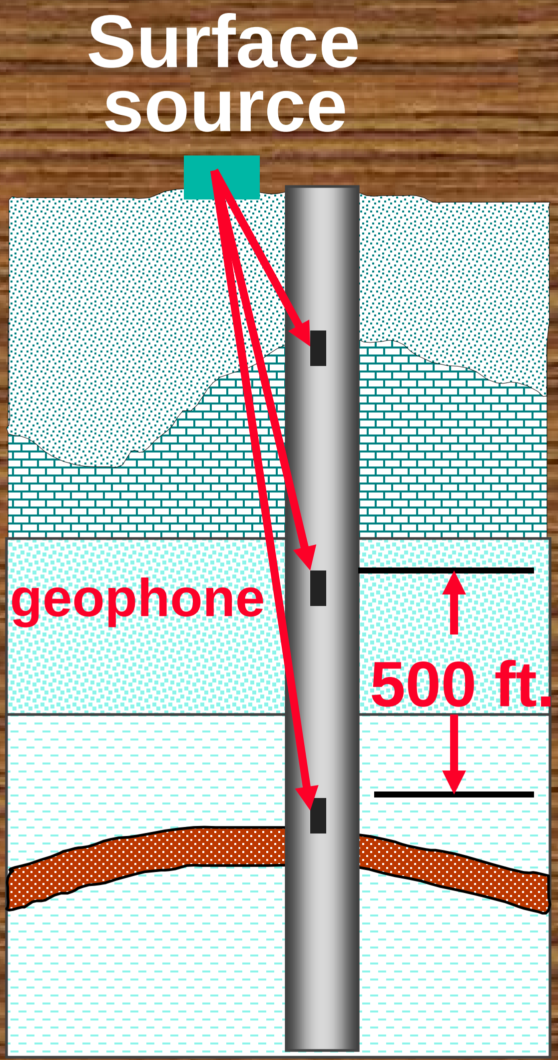
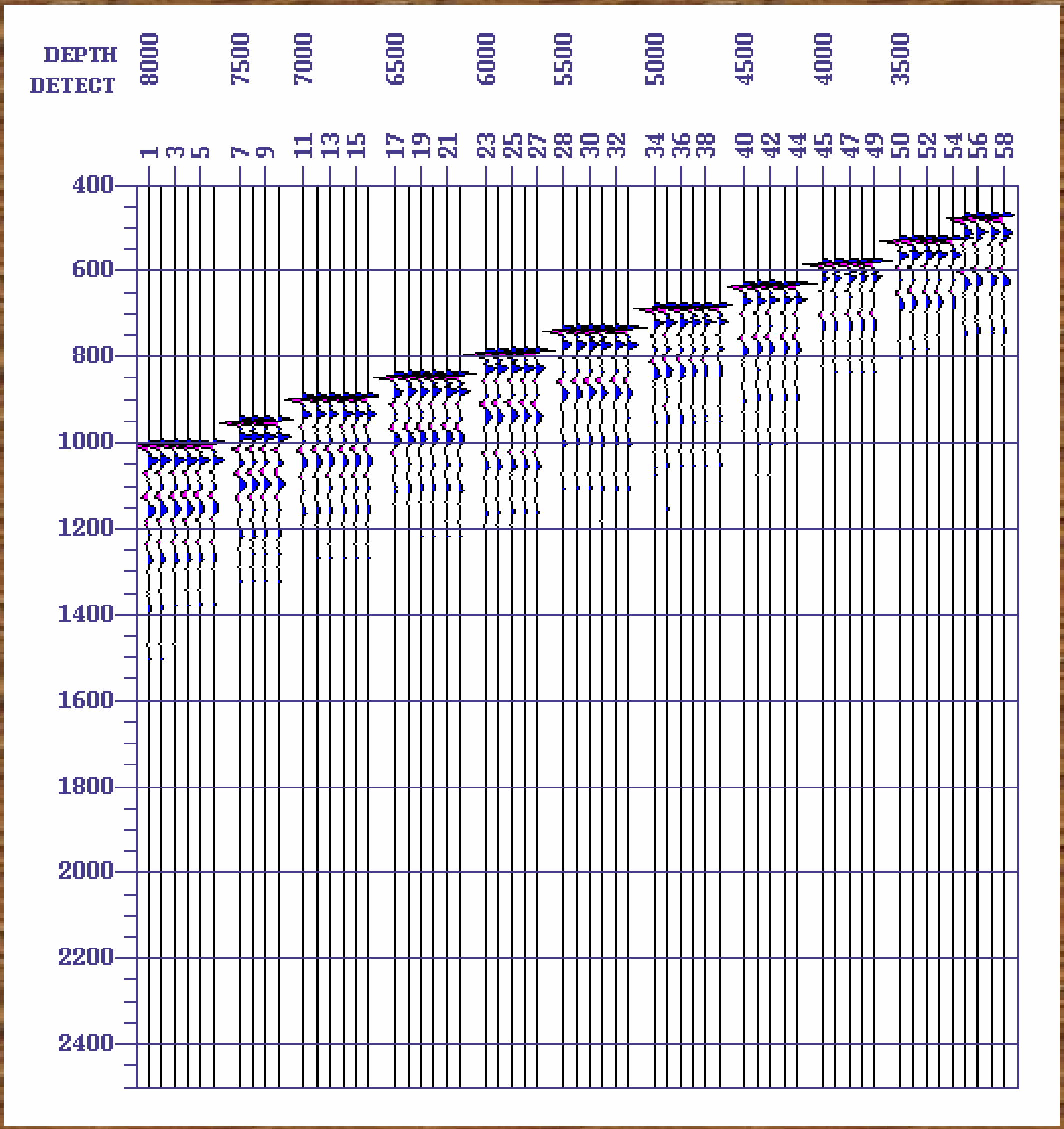
# Borehole seismic ray paths



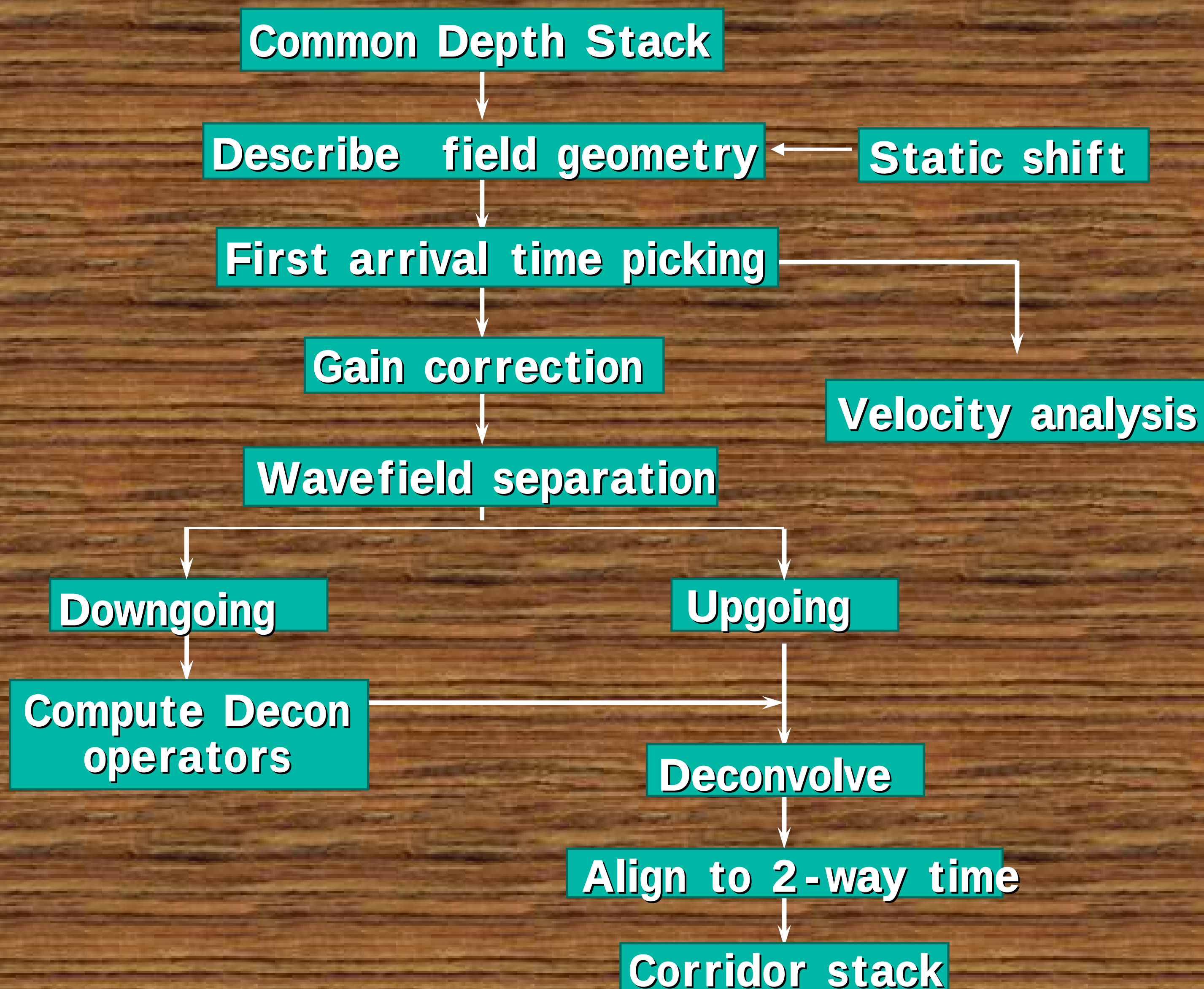
# Raw VSP data (Checkshot survey)



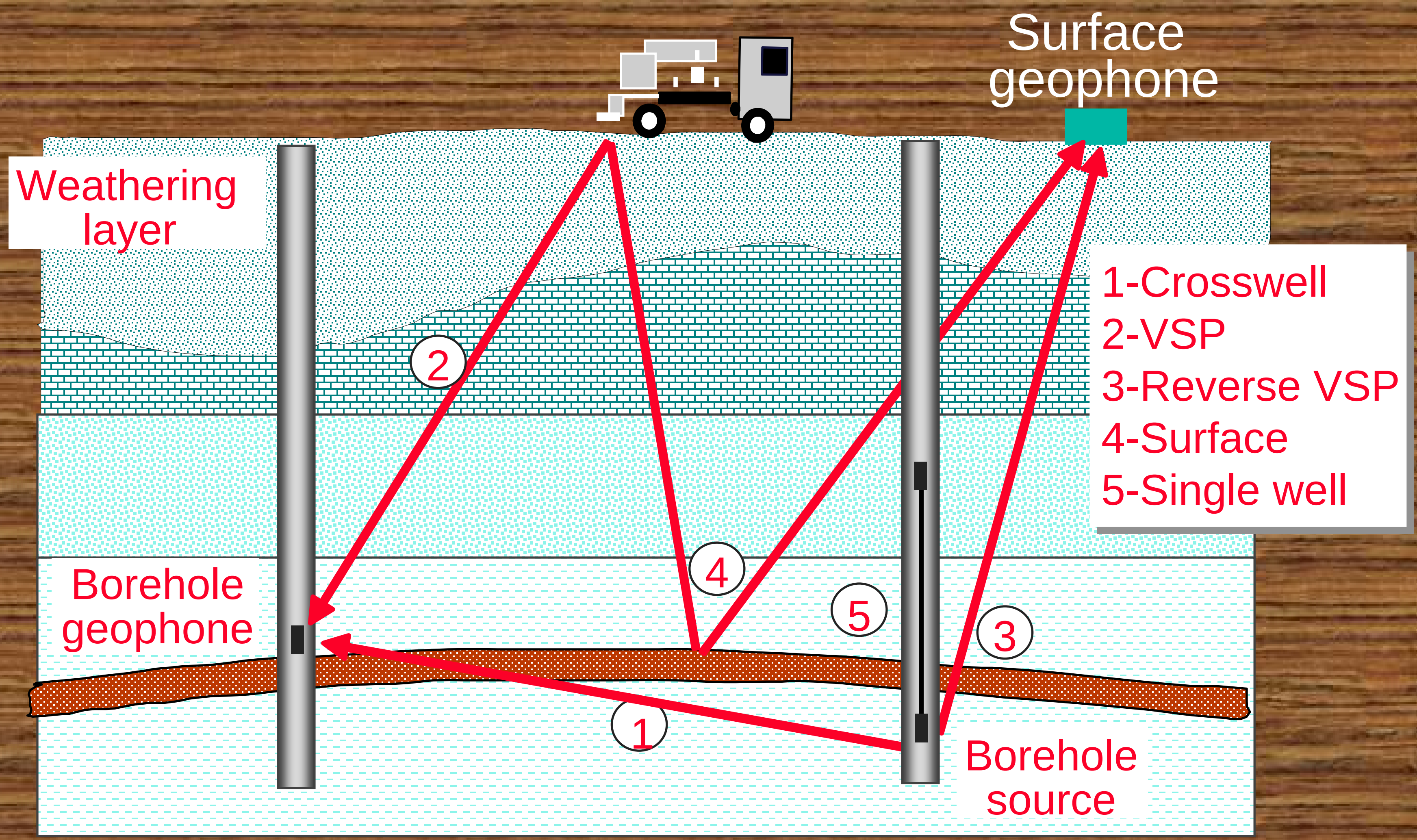

Courtesy Western Atlas Logging Services

# Basic VSP Processing Flow



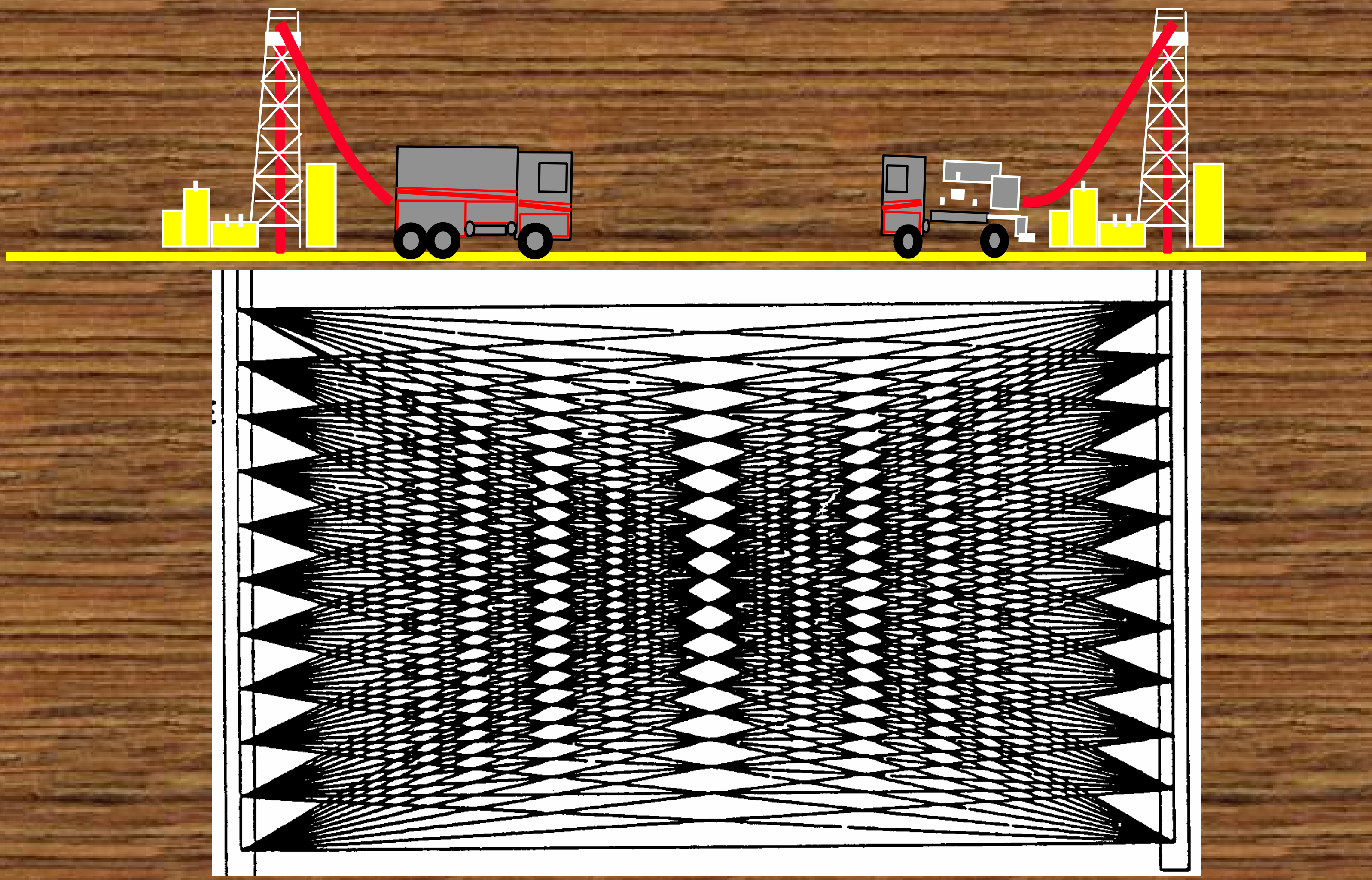

BA1997

# Crosswell seismic surveys

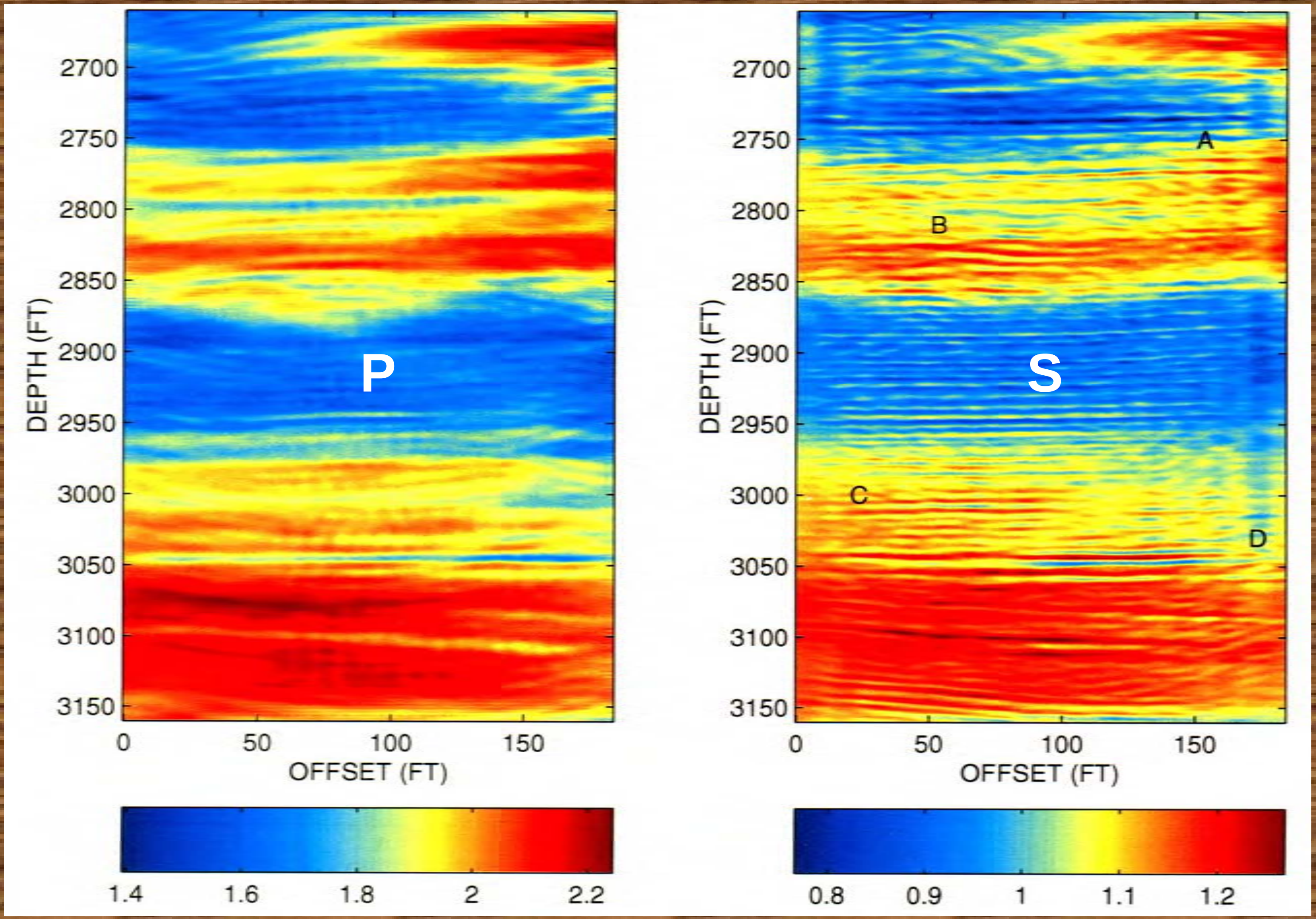


# Cross-well

## Acquisition layout & tomographic coverage



# P-velocity & S-velocity tomogram

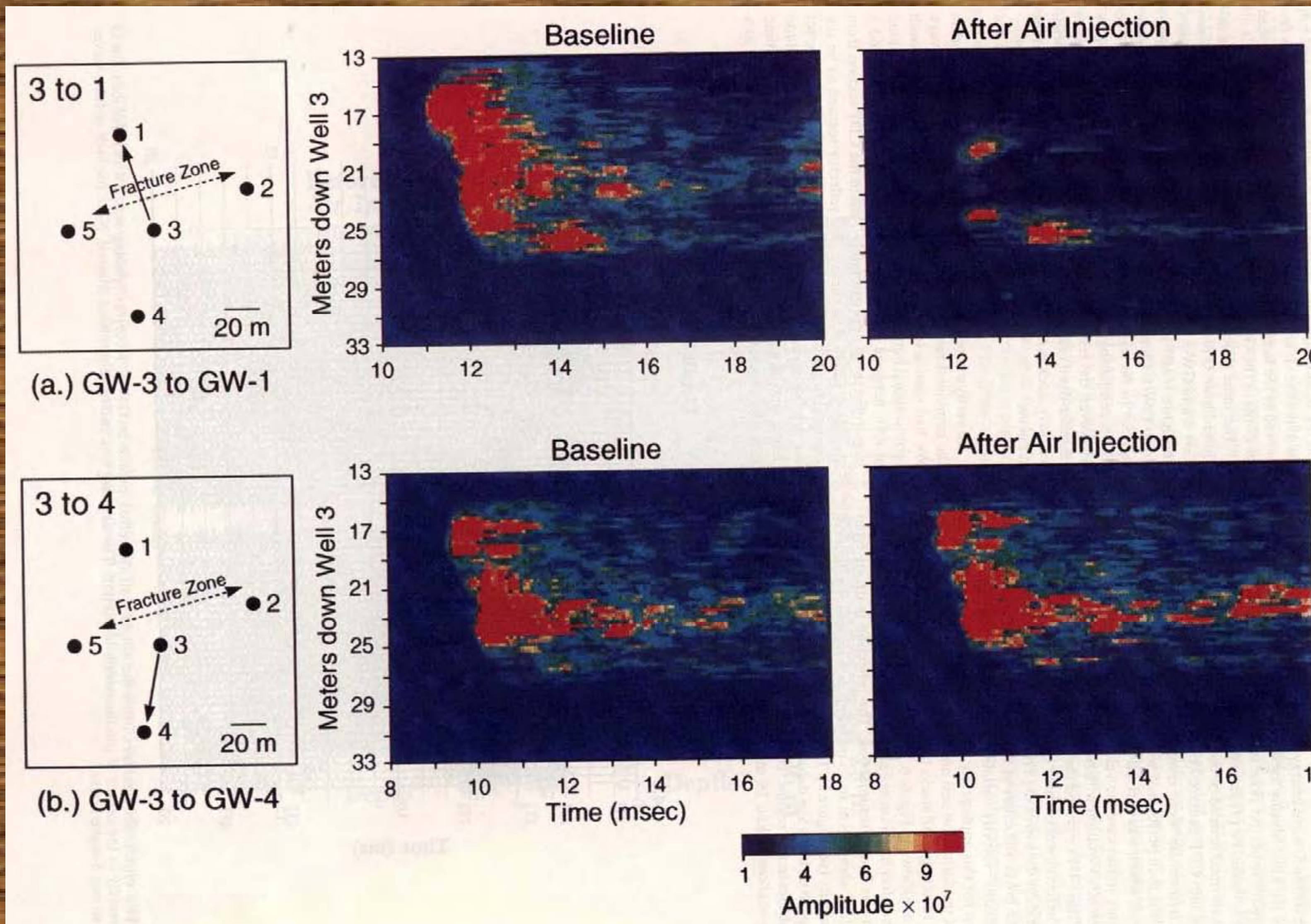



Courtesy Baker Atlas

$V_P$ (X $10^4$ ft / S)

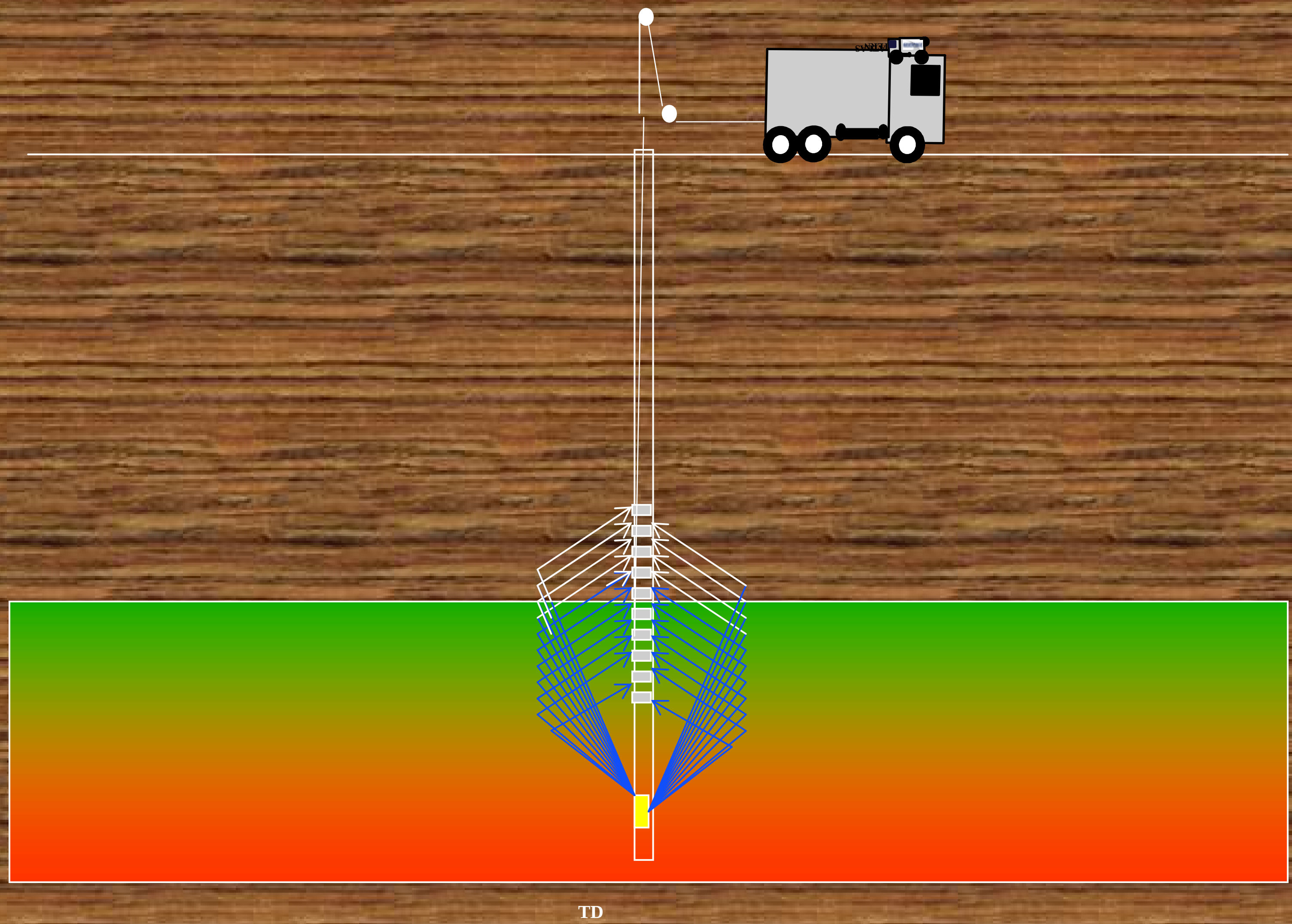
$V_S$ (X $10^4$ ft / S)

# Crosswell example

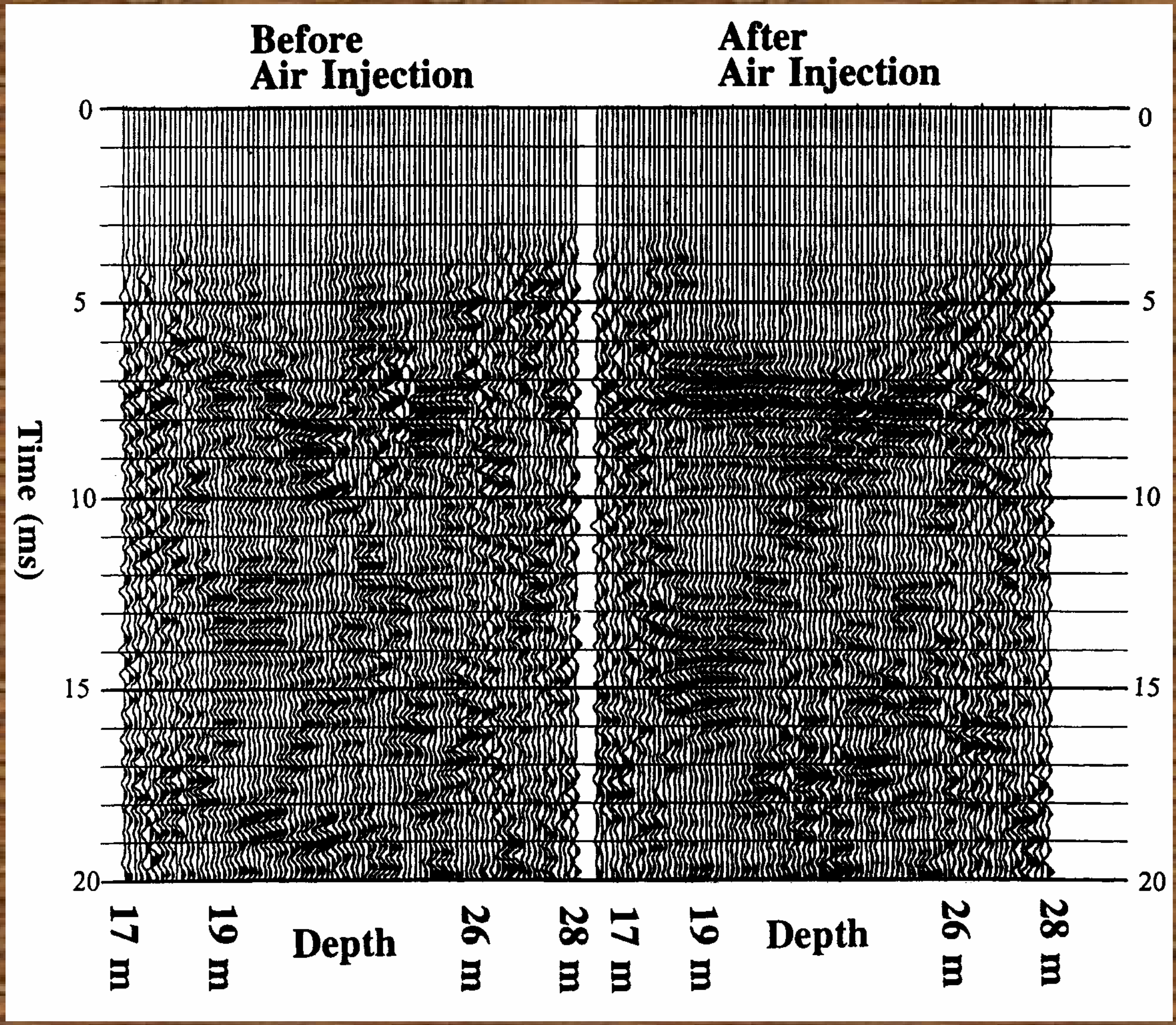



(after Majer et al., 1997)

# Single Well acquisition



# Single well: time lapse

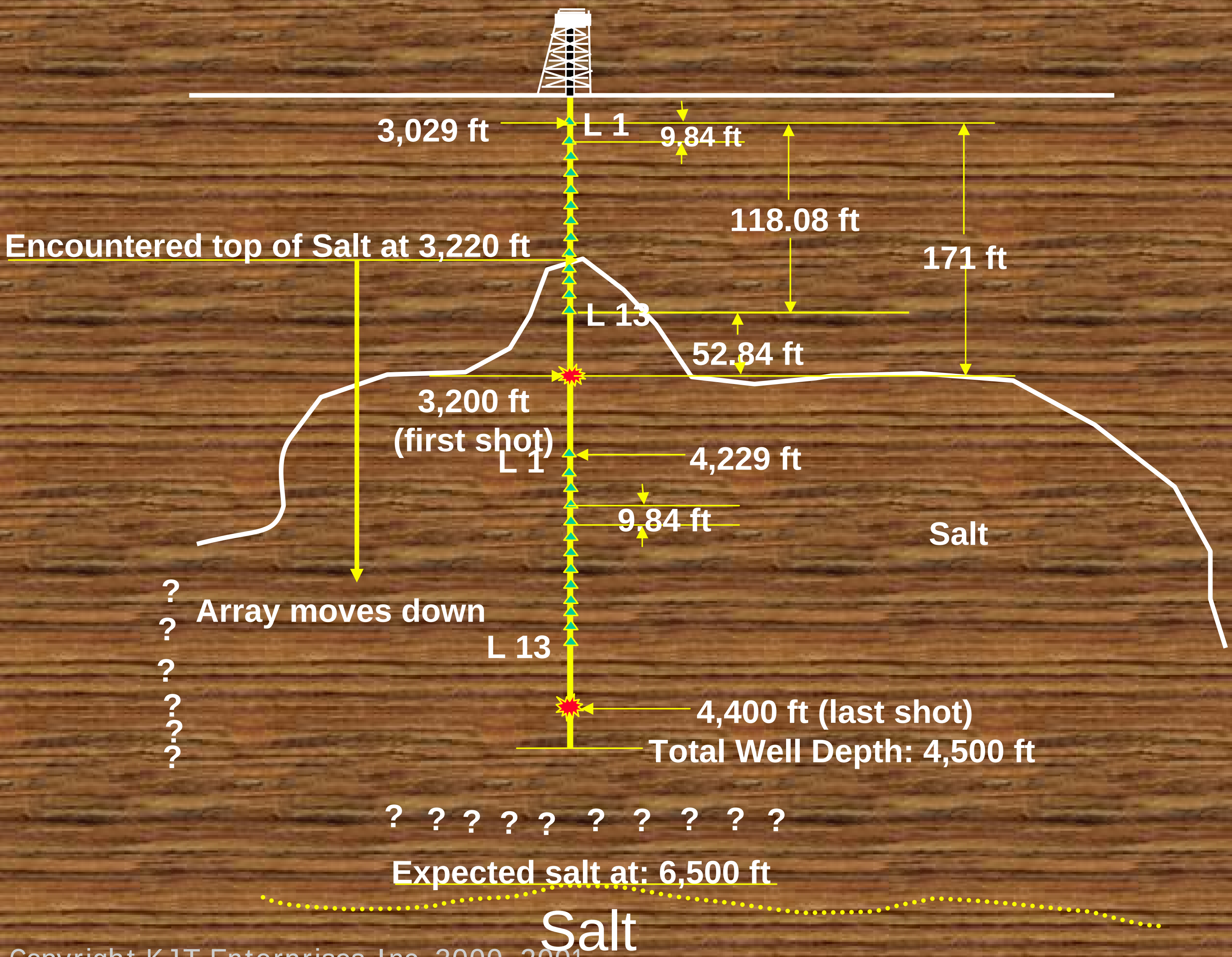



After Majer et al. 1997

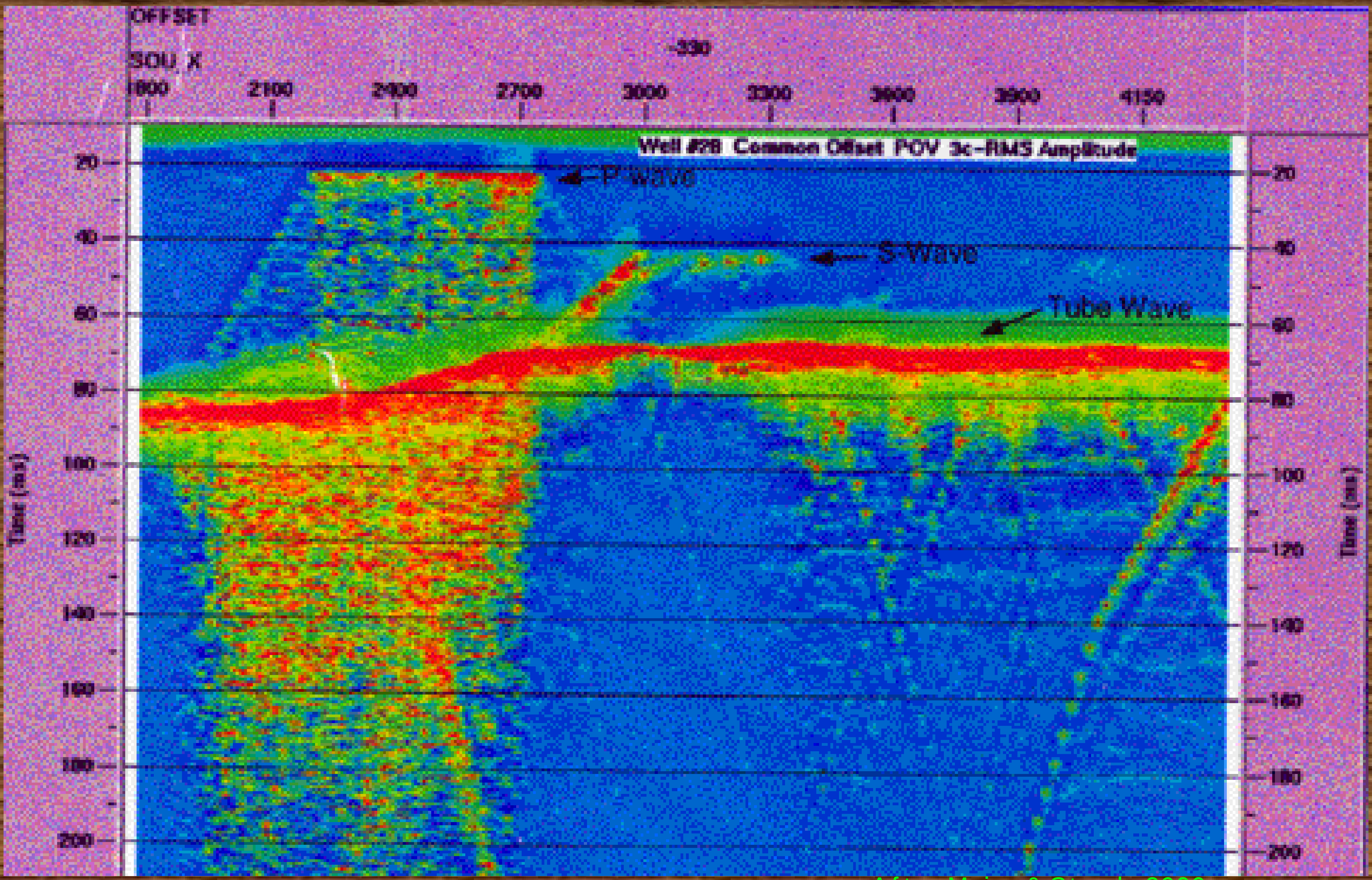
# Fracture drilled afterwards


After Majer et al. 1997

# Single Well Imaging in Gulf of Mexico



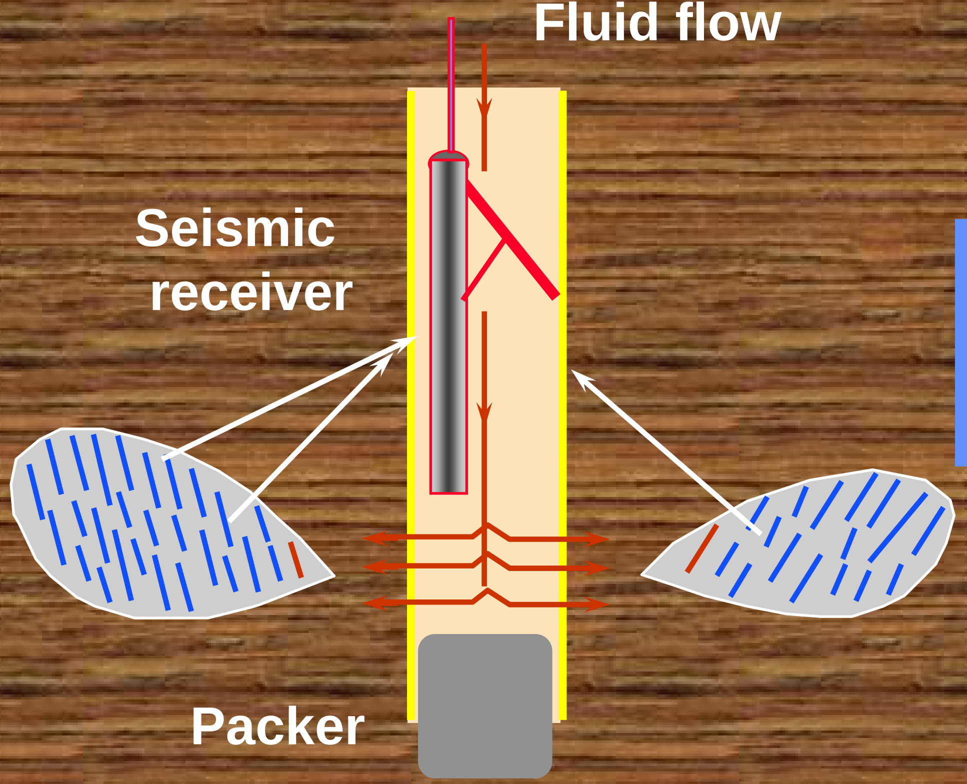
# Large scale SWS example




After Majer & Strack, 2000

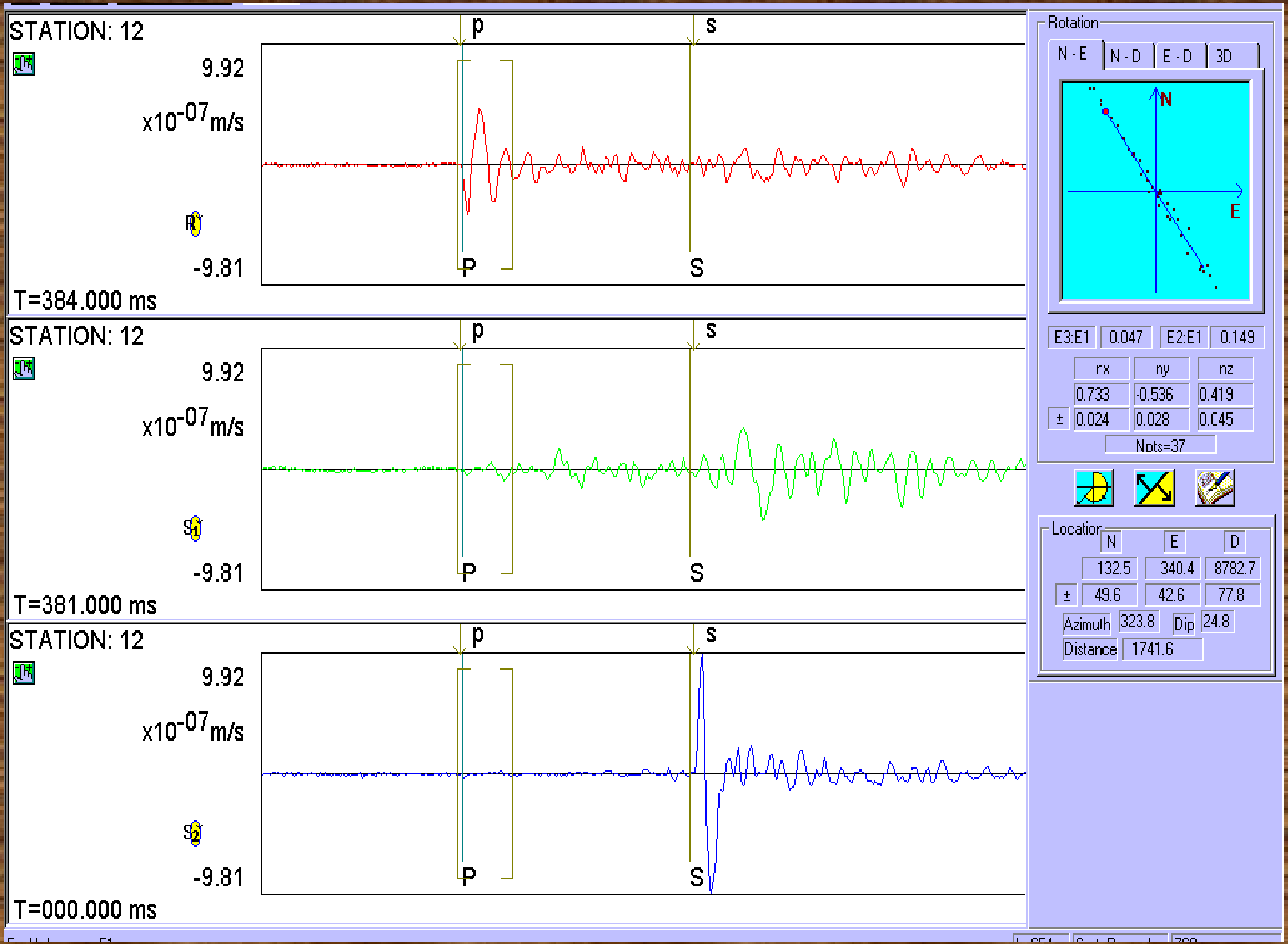
# Fracturing monitoring

- Mini-frac monitoring - single well
- Hydraulic fracturing monitoring - multi well



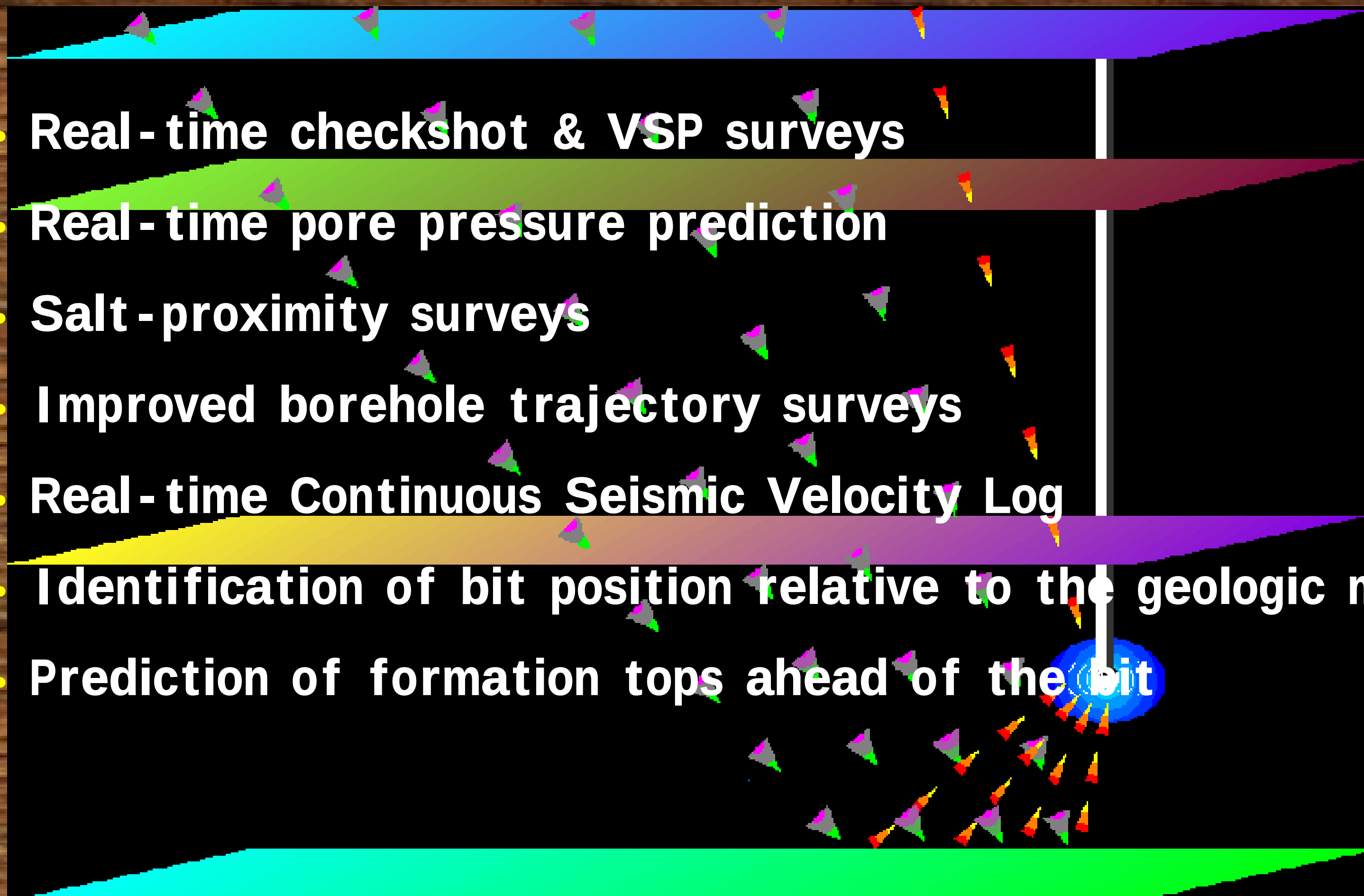

**Mini-frac survey**

# 3 C hydro frac data example




(After Walter et al., 2000)

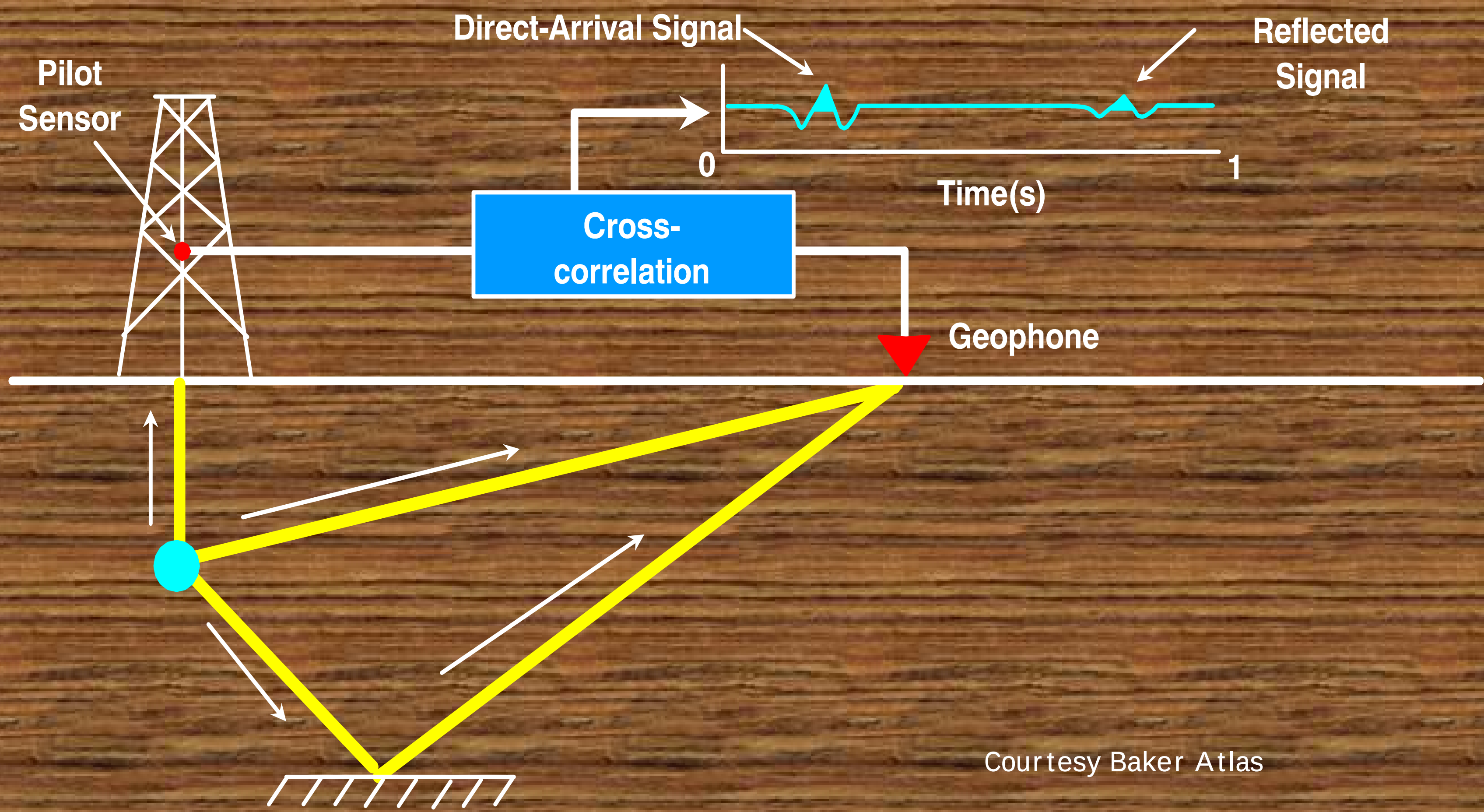
# Looking ahead of the bit



- Real-time checkshot & VSP surveys
- Real-time pore pressure prediction
- Salt-proximity surveys
- Improved borehole trajectory surveys
- Real-time Continuous Seismic Velocity Log
- Identification of bit position relative to the geologic model
- Prediction of formation tops ahead of the bit

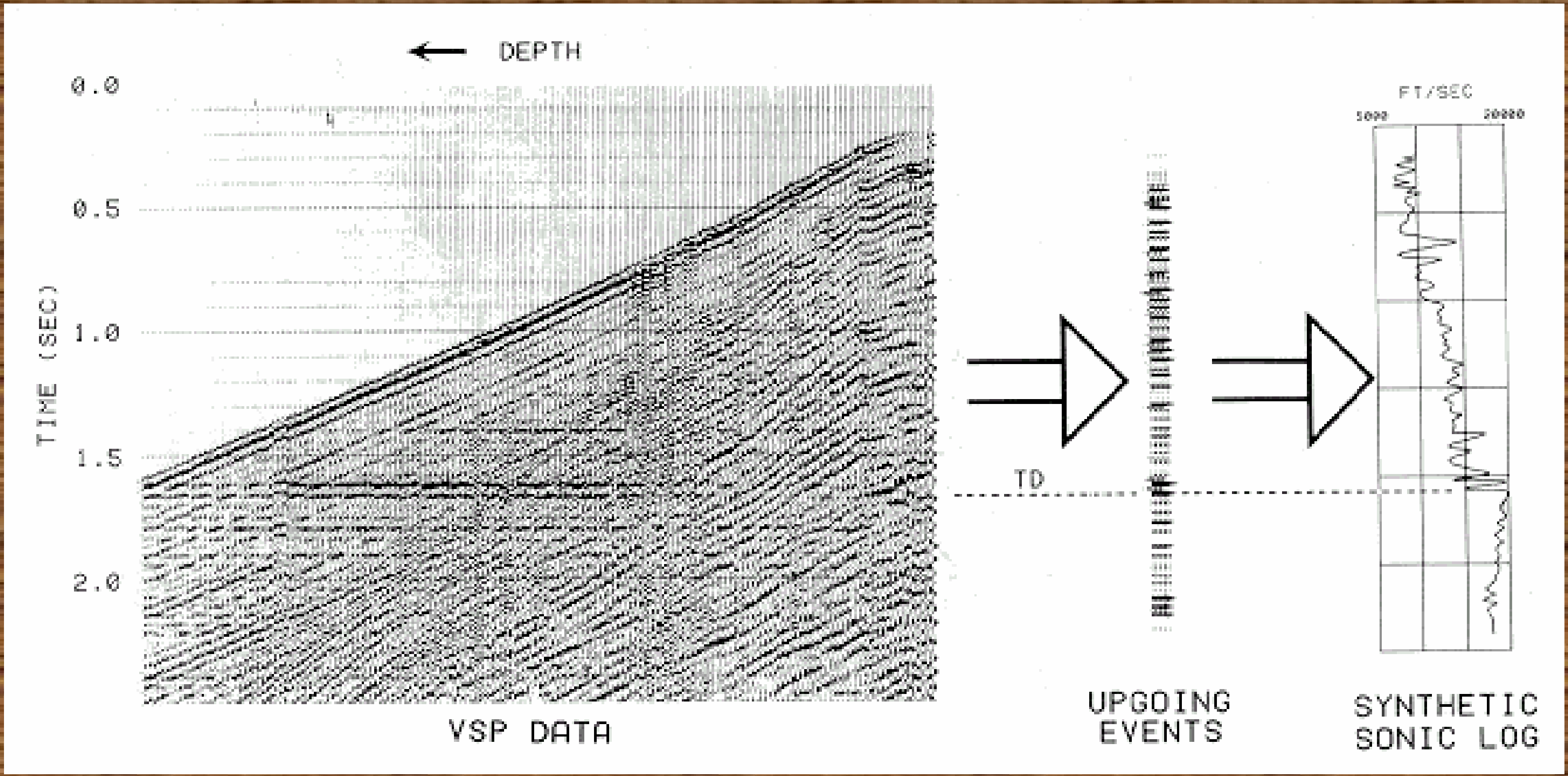
Courtesy Baker Atlas

# Seismic-While-Drilling principles




Courtesy Baker Atlas

# Looking ahead of the bit

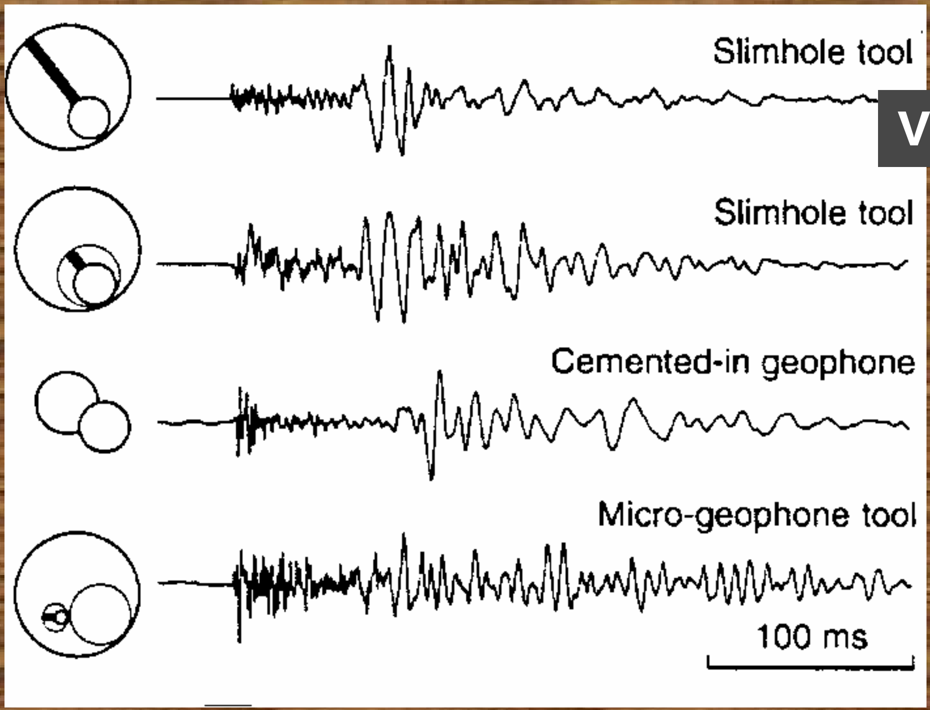



BAH2000

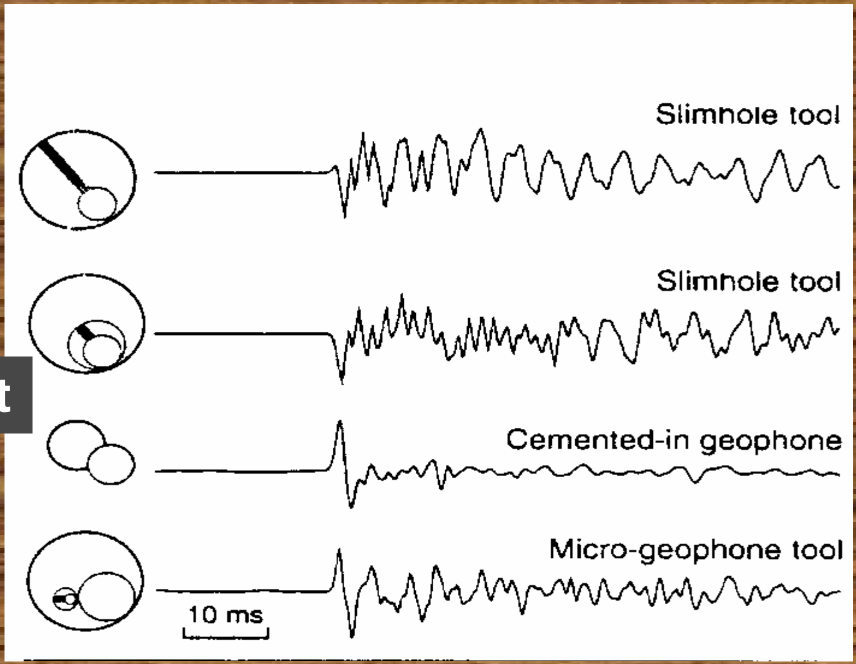
# Outline

- **Seismic methods**
  - VSP
  - Crosswell
  - Single well
  - Micro seismic monitoring
  - Seismic while drilling
  - Fracture monitoring
  - Passive seismic
  - 3D VSP
  - VSP for engineering applications

# Clamping/cementing effects




Vertical component, horizontal waves



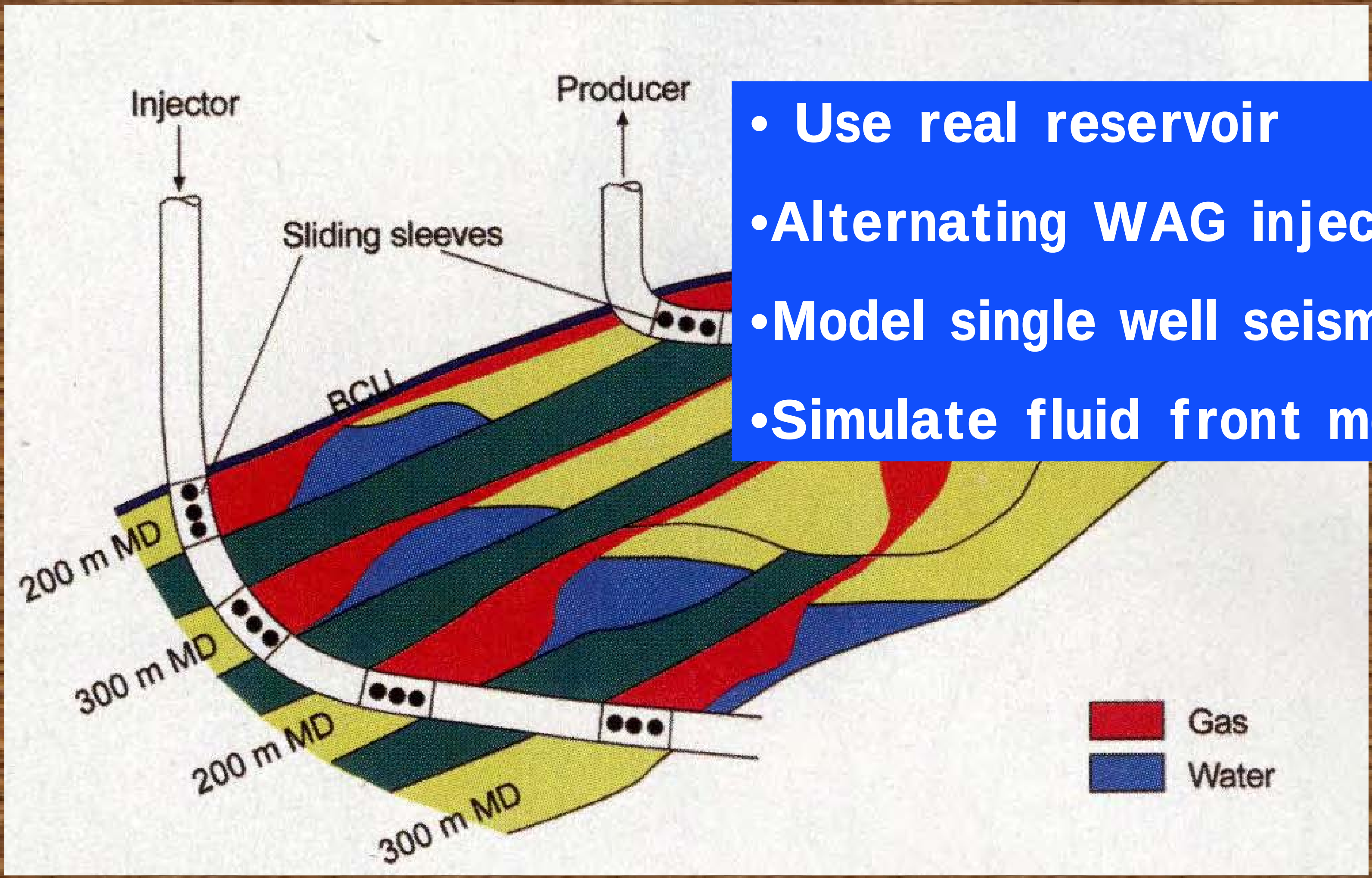

Vertical component, 30° wave incident

After Hardage, 2000

# Seismic sensors

After Hottman & Curtis, 2001

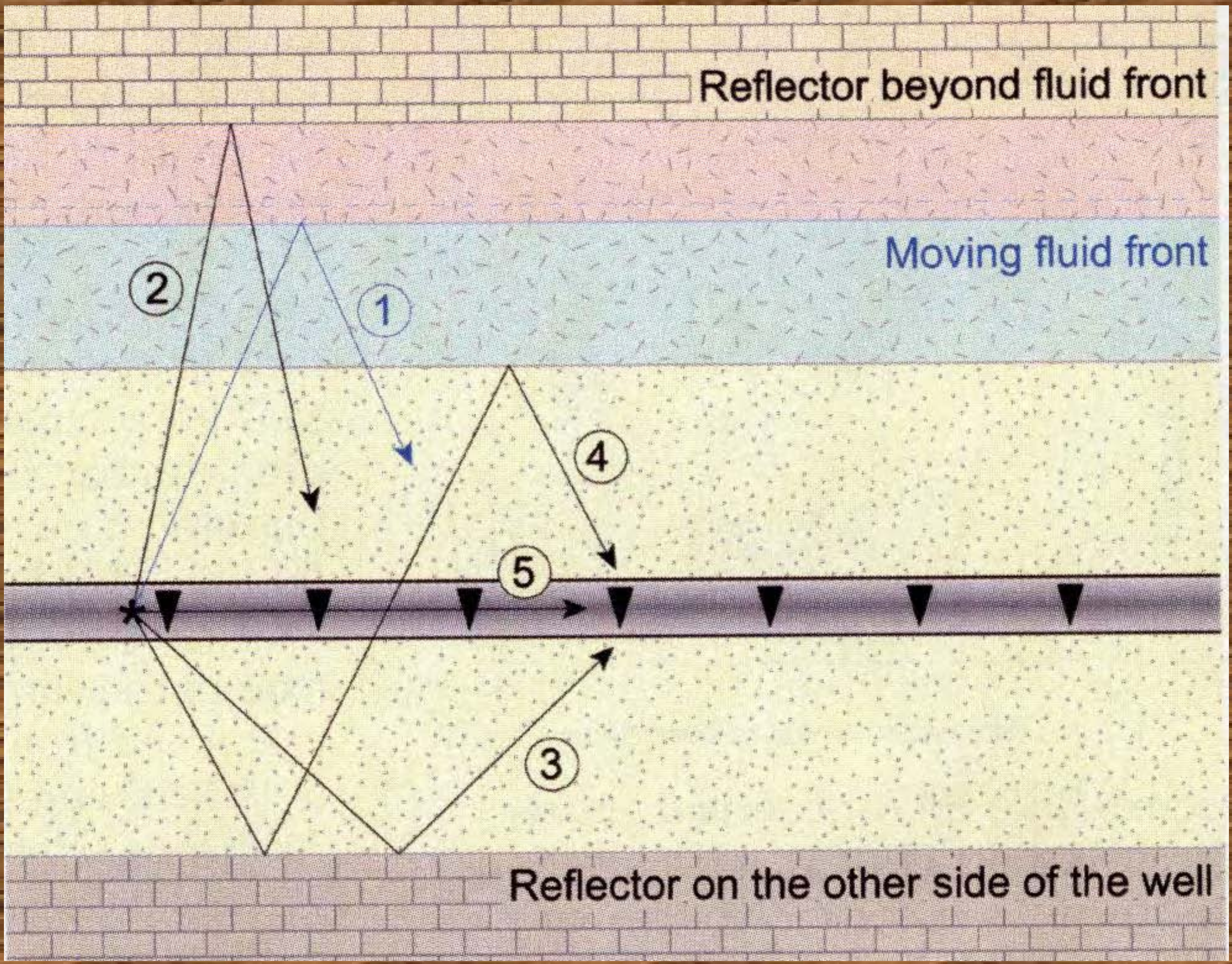
# Model study: intelligent well seismic




- Use real reservoir
- Alternating WAG injection
- Model single well seismic
- Simulate fluid front move

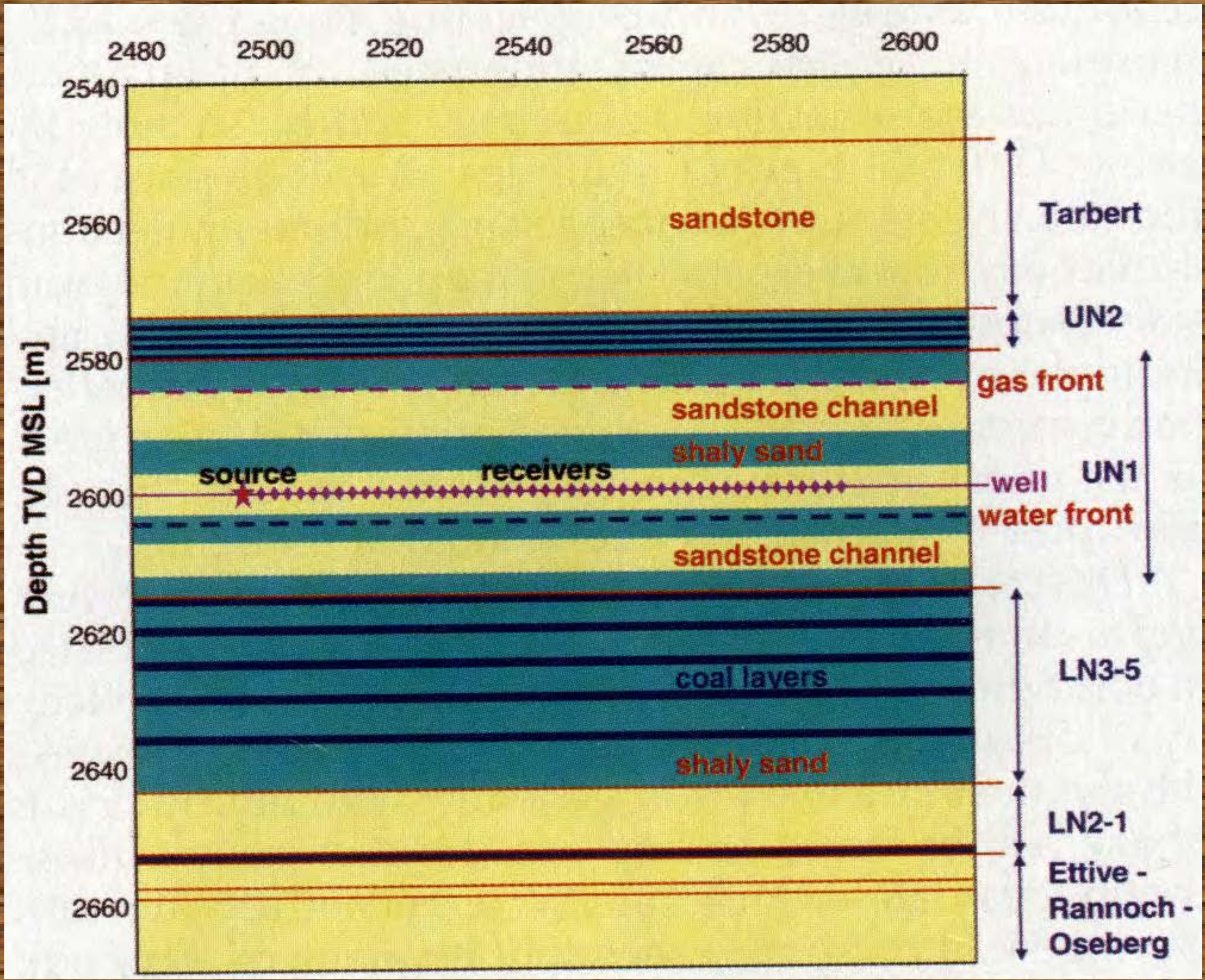
After Mjaaland et al, 2001, TLE 20-10

# Model study: different models




After Mjaaland et al, 2001, TLE 20-10

# Model study: geometry

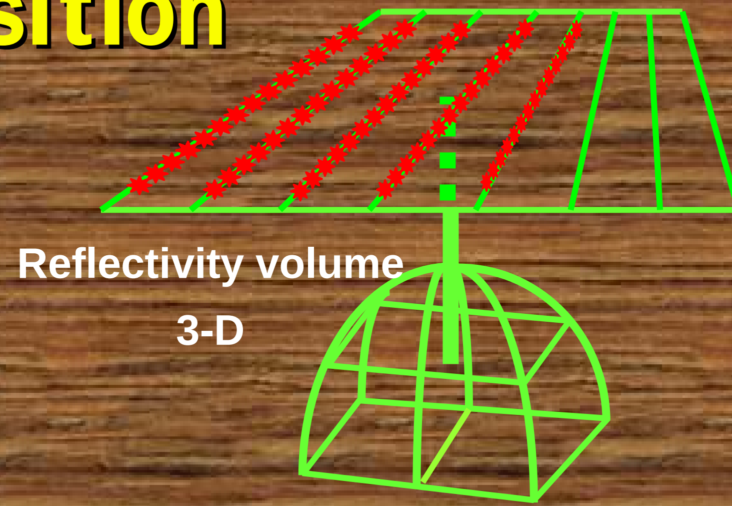




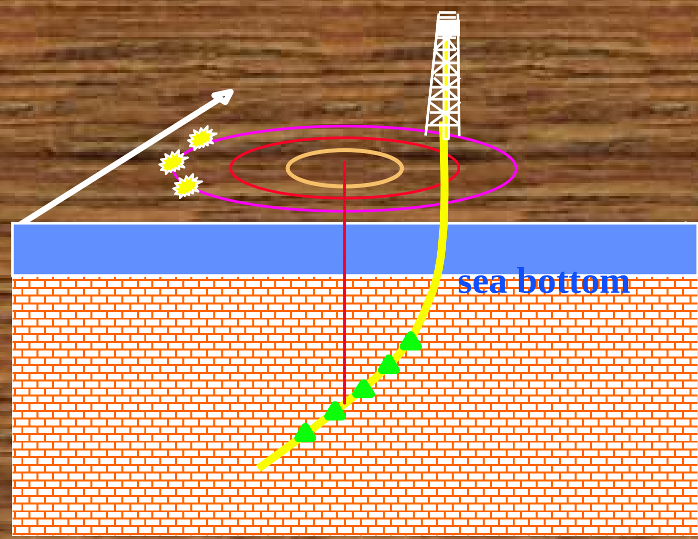

After Mjaaland et al, 2001, TLE 20-10

# 3D VSP Data Acquisition

- Purpose-built, integrated data acquisition system
- Multi-level 3-component downhole receivers
- Advanced energy source controller speeds up operations & improves data quality
- Advanced navigation system integrates all borehole seismic, navigation, & source sync data
- Simultaneously acquiring 3-D VSP & 3-D surface seismic data reduces costs & maximizes synergy



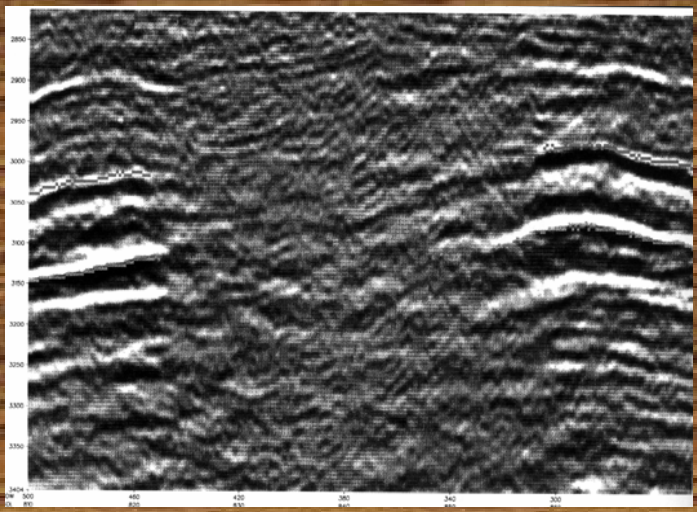

Rectangular grid acquisition



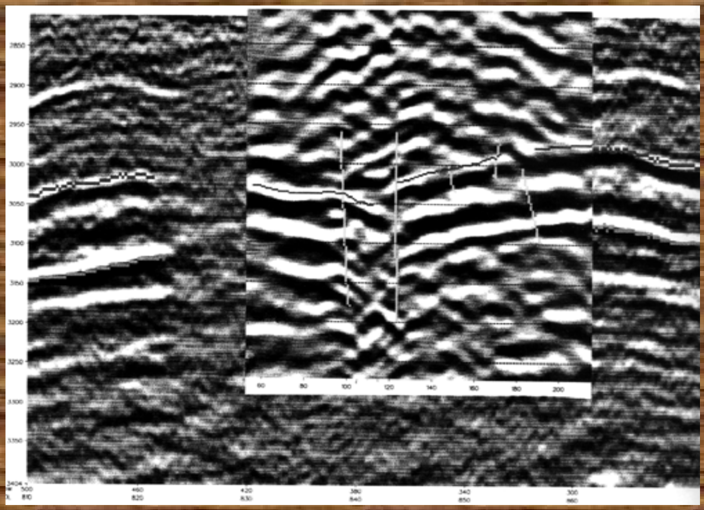

Circular or spiral acquisition

# Why 3-D VSP?

Surface Seismic 3-D

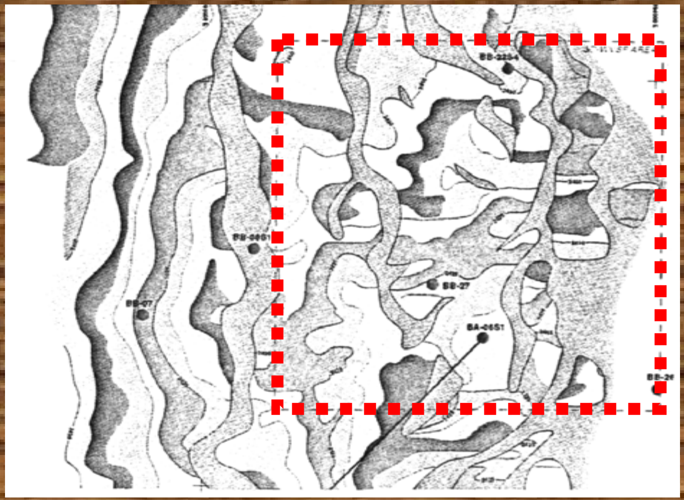


3-D VSP

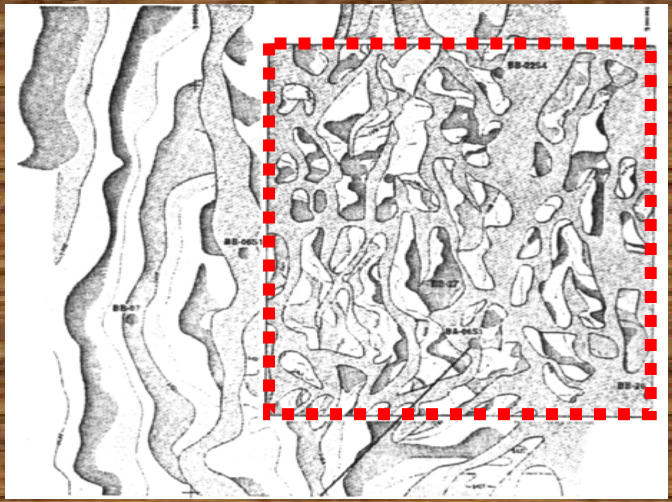


*Ekofisk, North Sea (from Dangerfield, 1996)*

Surface Seismic 3-D



3-D VSP

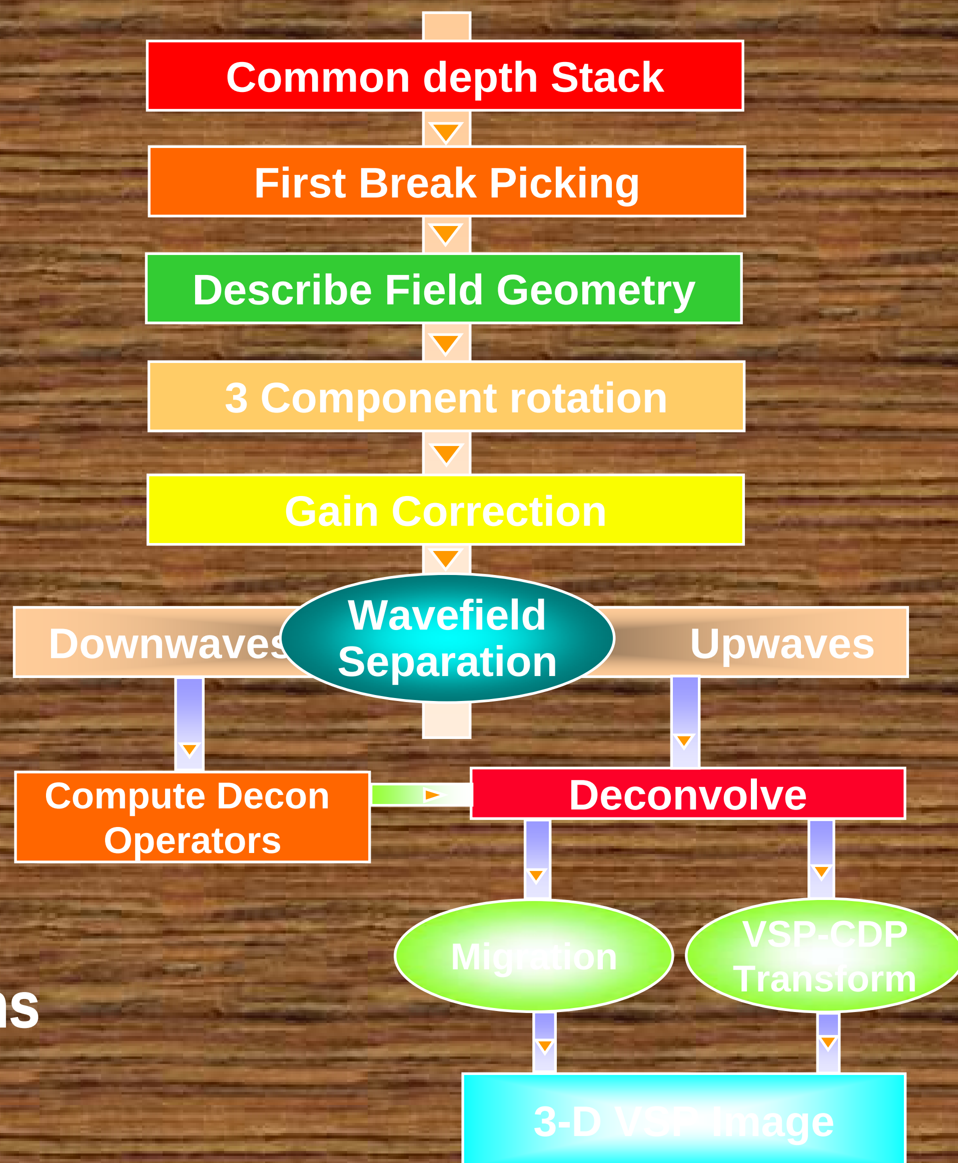


*Brent, UK North Sea (from van der Pal et al., 1996)*

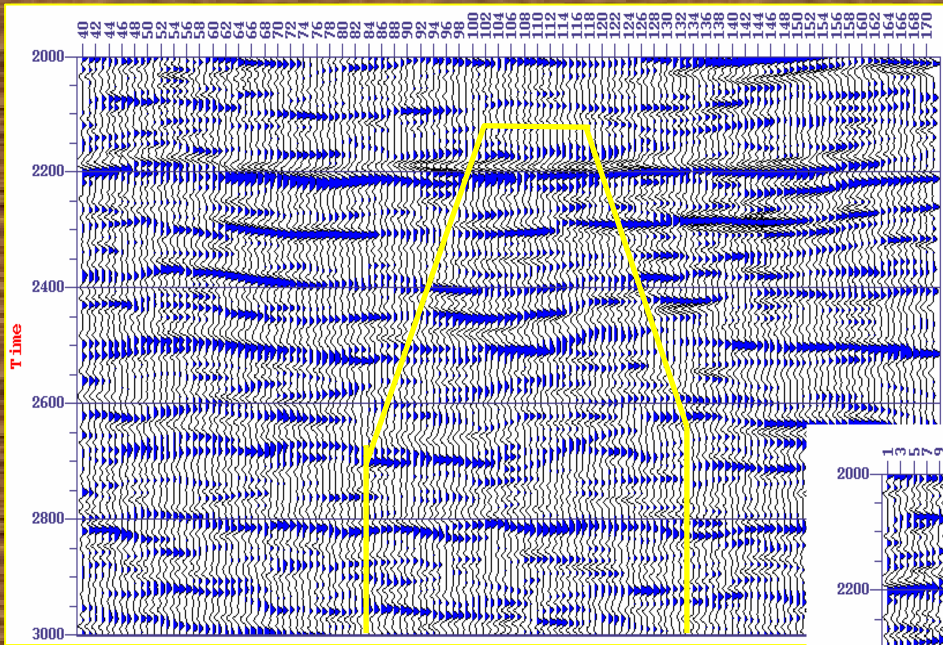
# Data Processing

- Standard procedures
- Pre-survey modeling
- Special processing
  - Statistical tool orientation
  - Statics' application
  - Wavefield separation
  - Velocity inversion
  - Imaging
    - Kirchhoff migration
    - VSP-CDP transformation
- 3D Visualization
- Data volume considerations

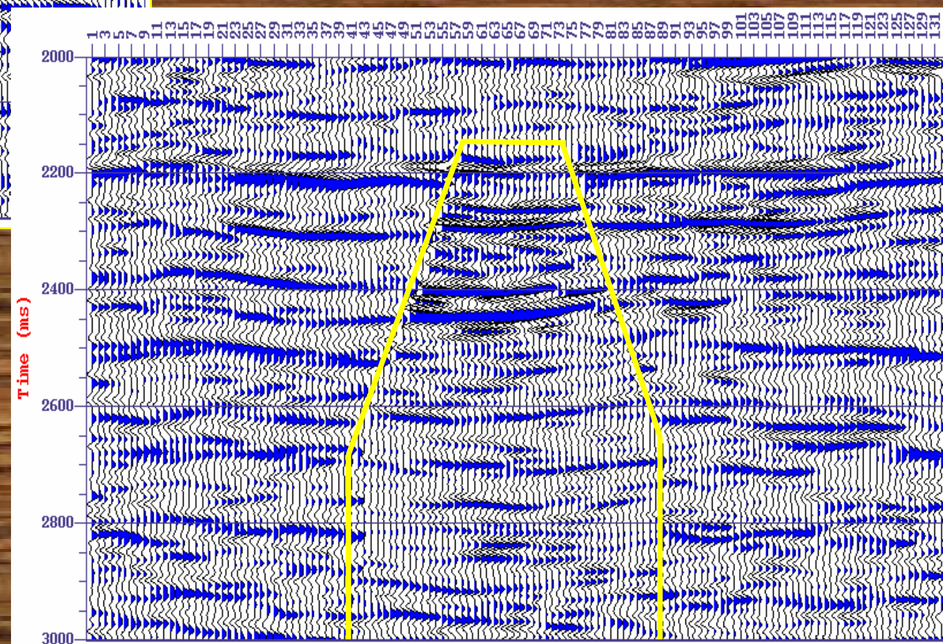
3-D VSP Processing Flow



# Oseberg 3-D VSP Migration

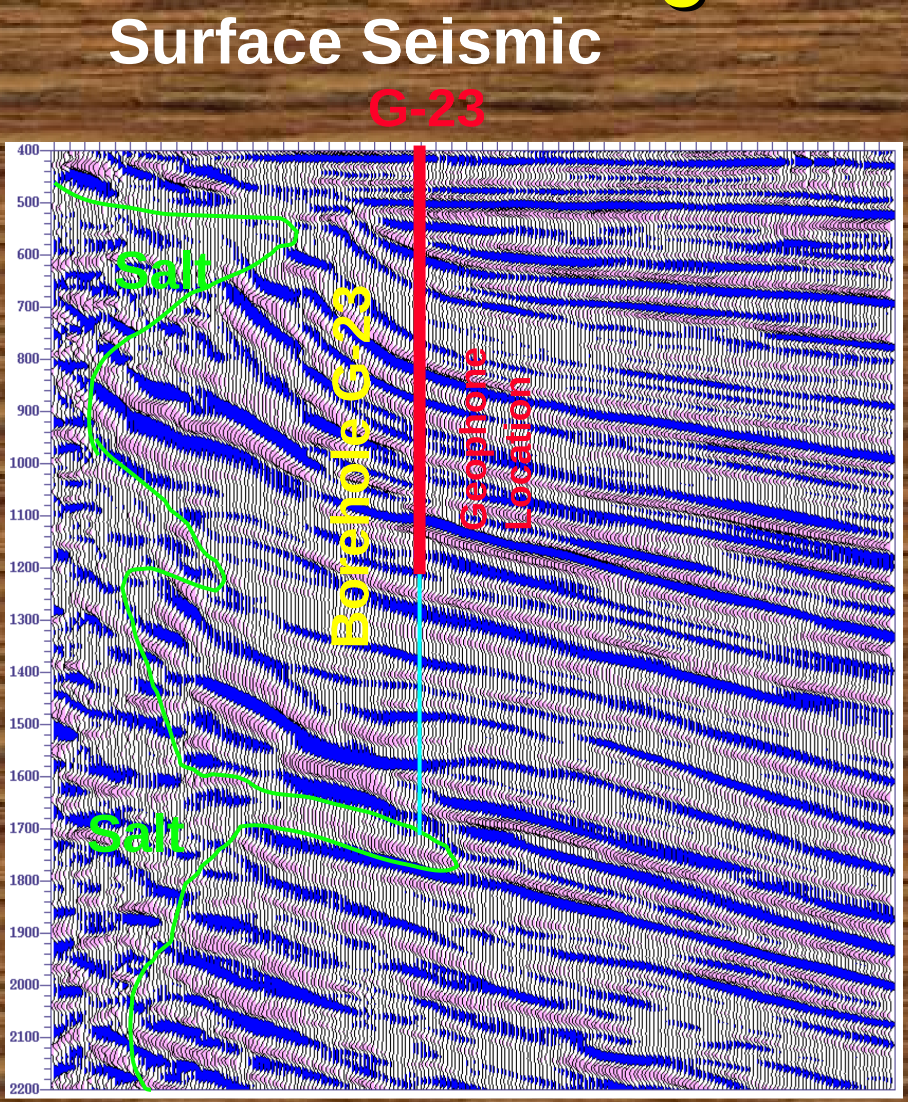



3-D surface seismic inline section (processed by Elf)

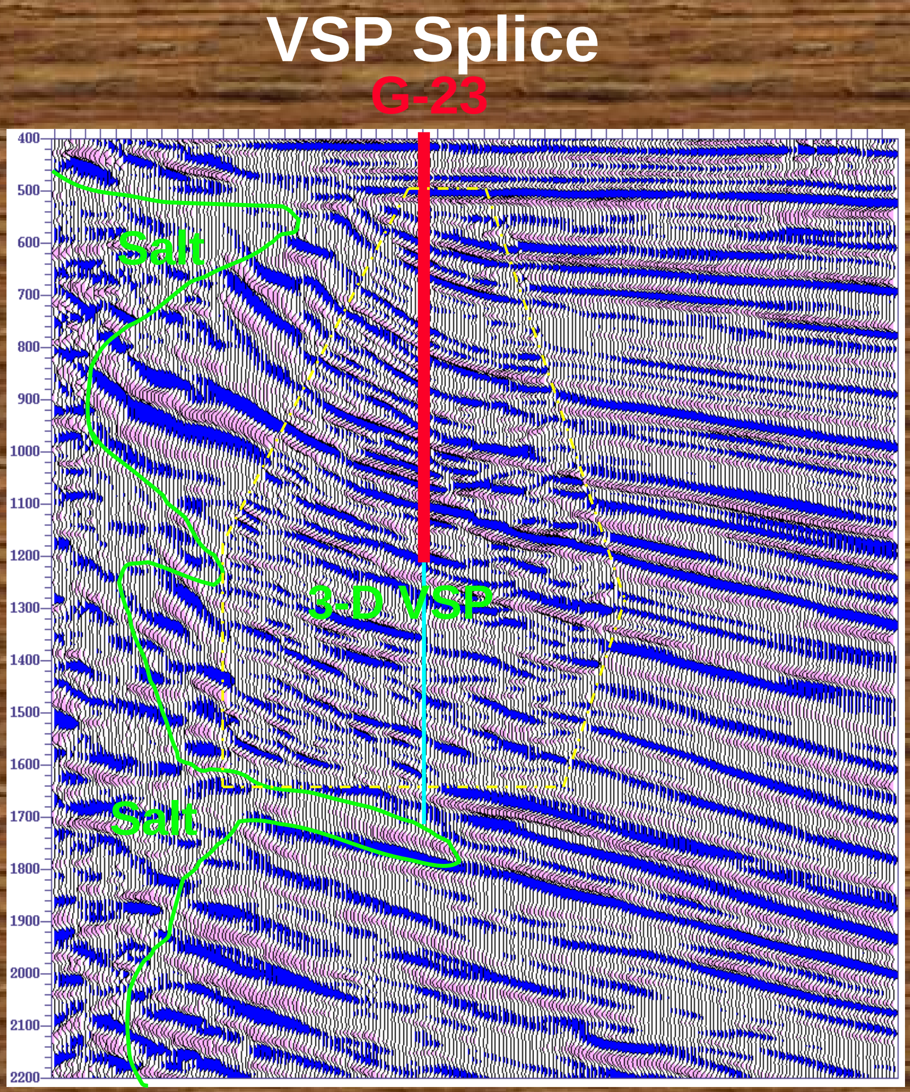



3-D VSP migrated section pasted in surface seismic inline section

# 3-D VSP Migration



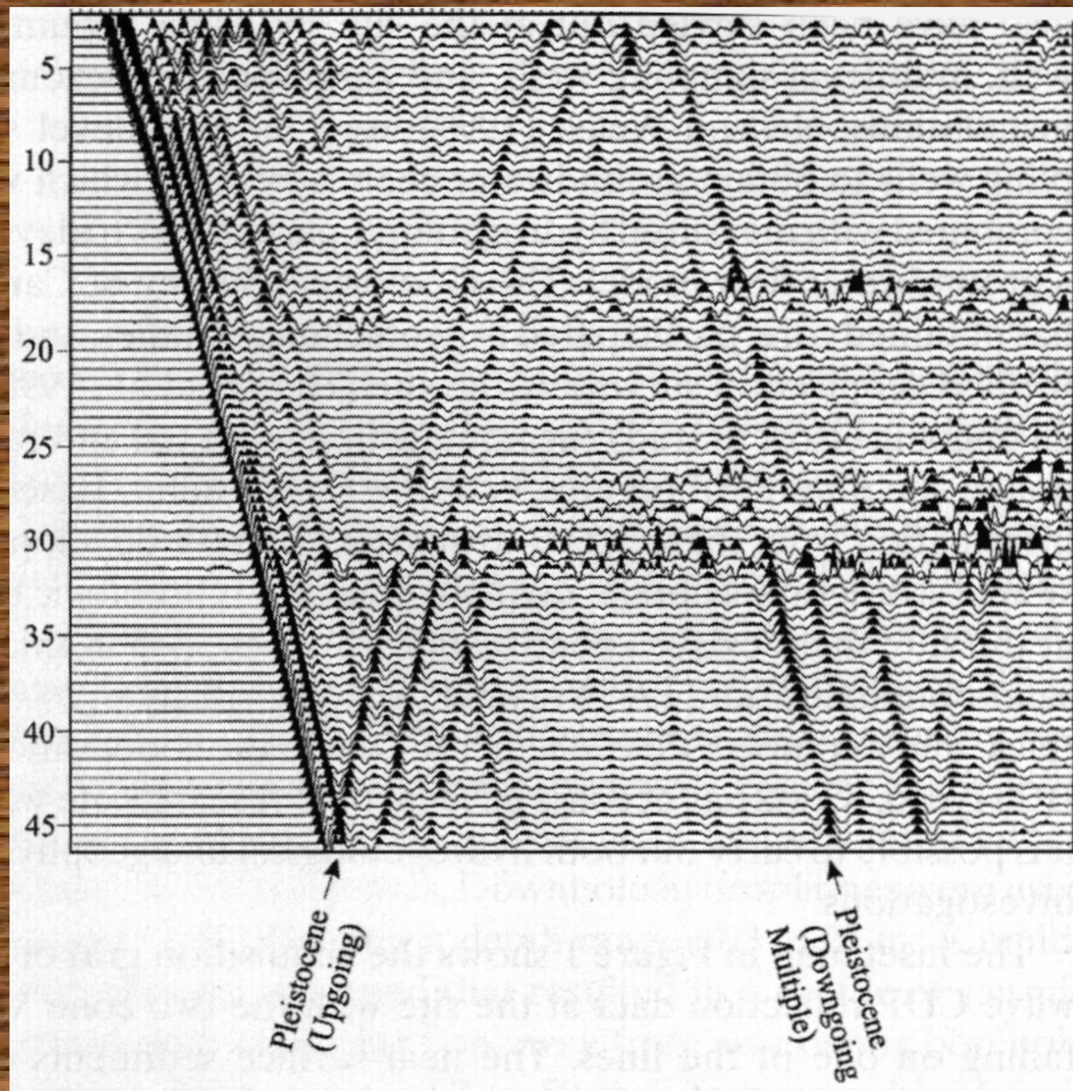

3-D Surface Seismic Section




Combined 3-D Surface Seismic & 3-D VSP Section

# Near-surface VSP: VSP 2

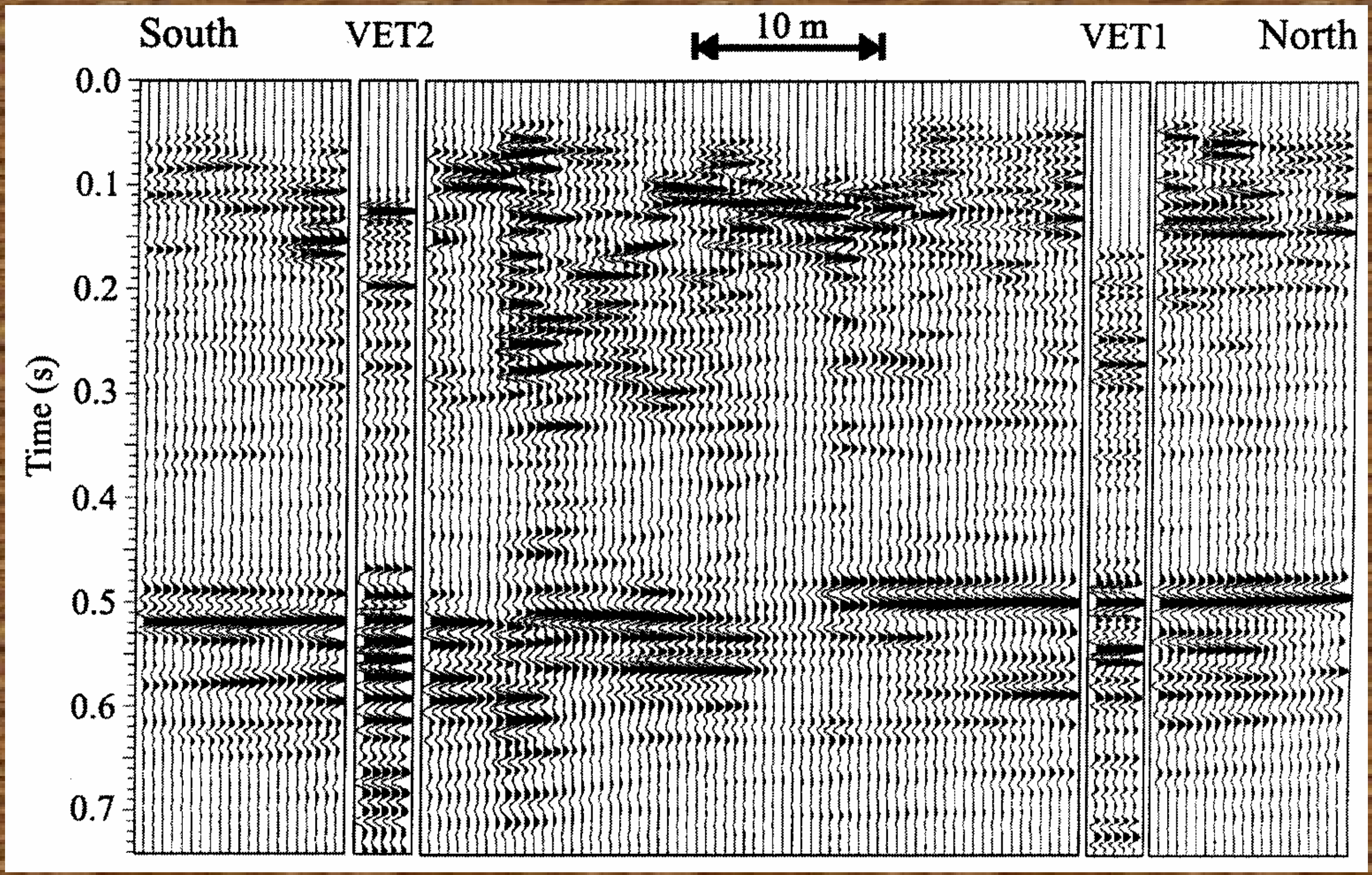
After spherical divergences and band pass




(after Jarvis & Knight., 2000)

(after Jarvis & Knight., 2000)

# Near-surface VSP: SH CDP section




(after Jarvis & Knight., 2000)



(after Jarvis & Knight., 2000)

# Outline

- Critical Lin
- Rock Physi
- Seismic Mo
- Borehole EM
- Borehole Gravity
- Logging
- Summary

- Borehole Electromagnetics
  - Cross well EM
  - Single well EM
  - Seismoelectric measurements

# Outline

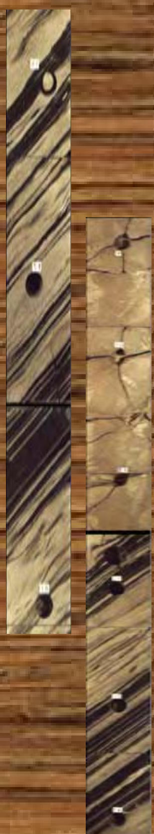
- **Borehole Electromagnetics**
  - Cross well EM
  - Single well EM
  - Seismoelectric measurements

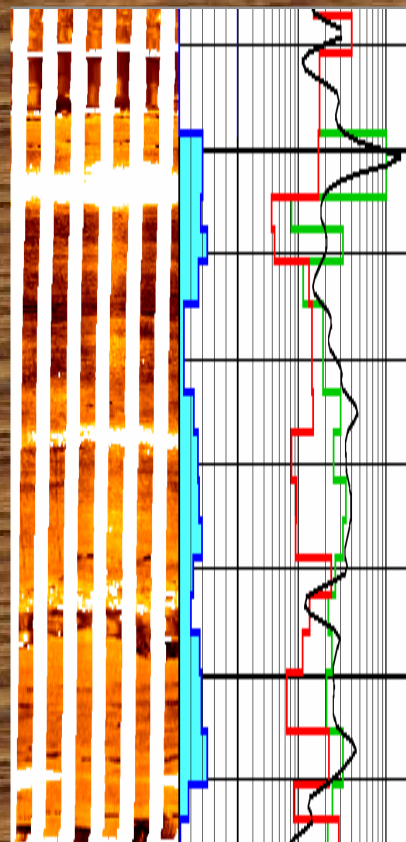
# Upscaling...upscaling...upscaling

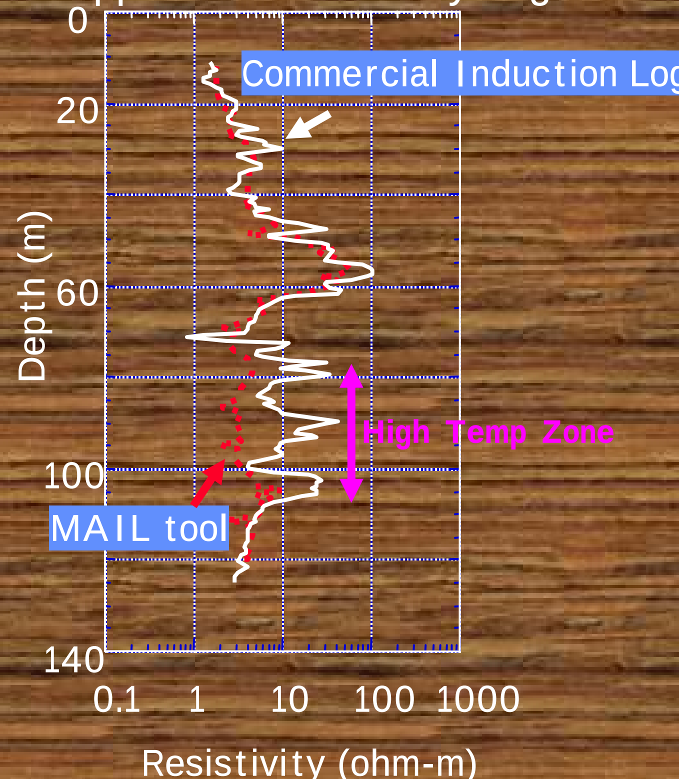
0.01 | 0.1 | 1 | 10 | 100

← Pore studies | Image logs | Surface geophysics →

Core plugs | Whole cores | Well logs | Borehole geophysics

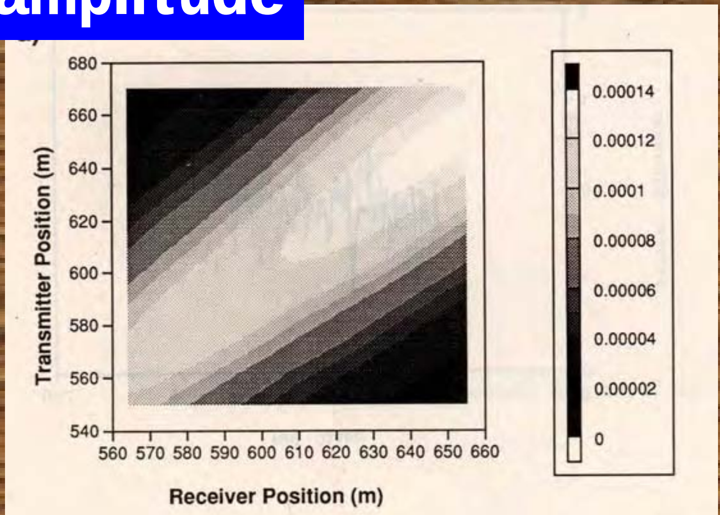




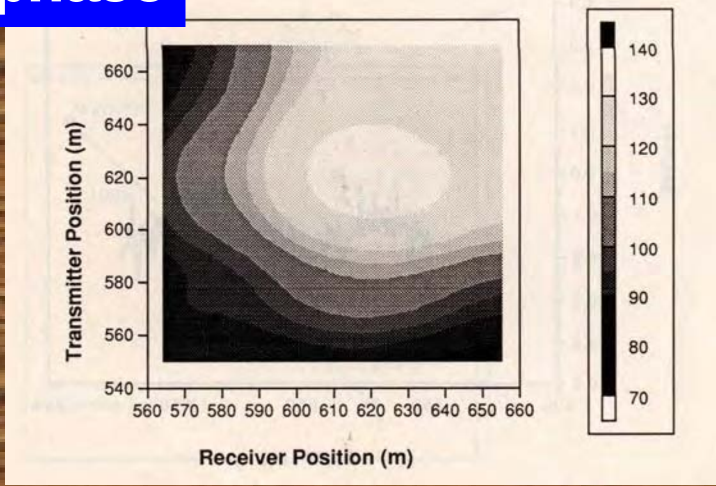


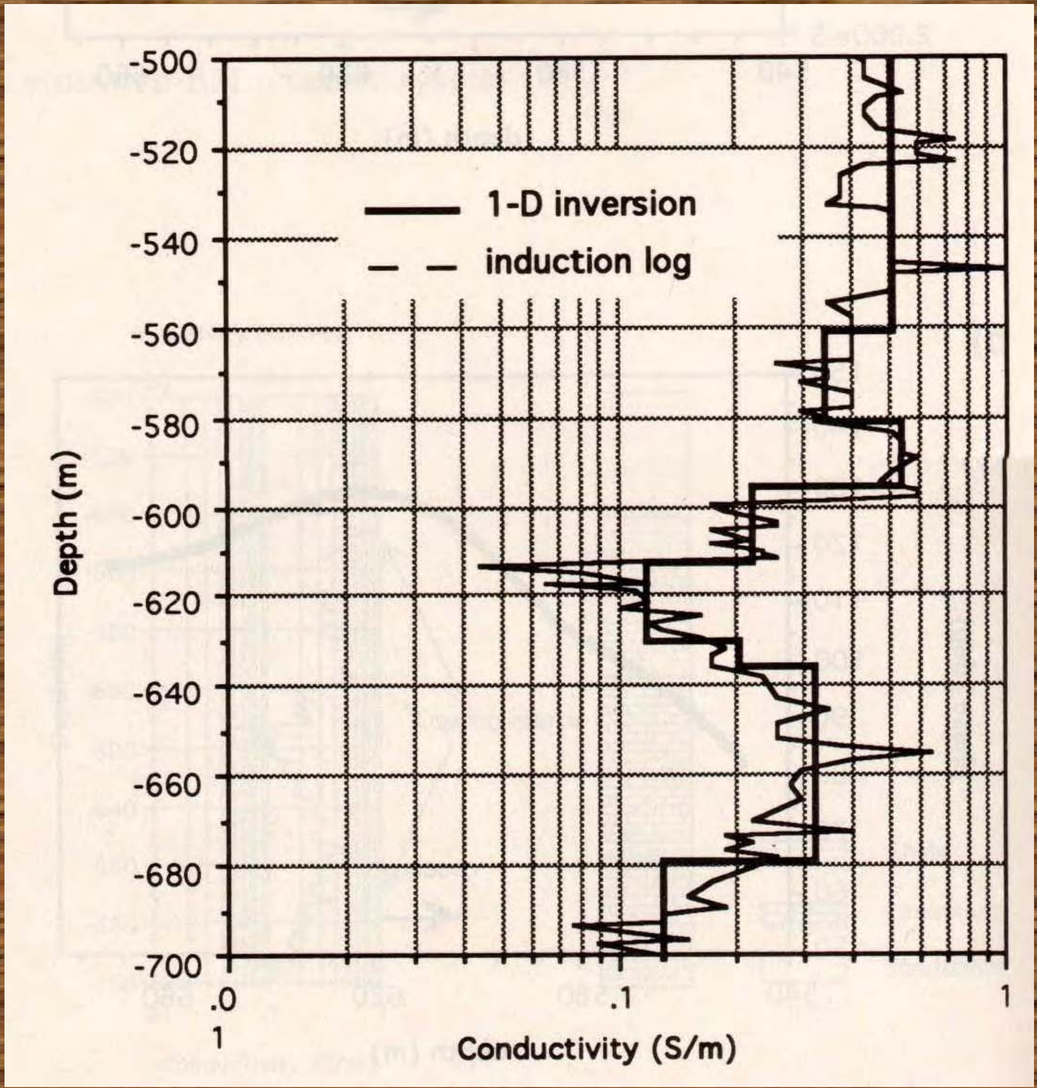
# Devine test: data & inversion

**amplitude**




**phase**

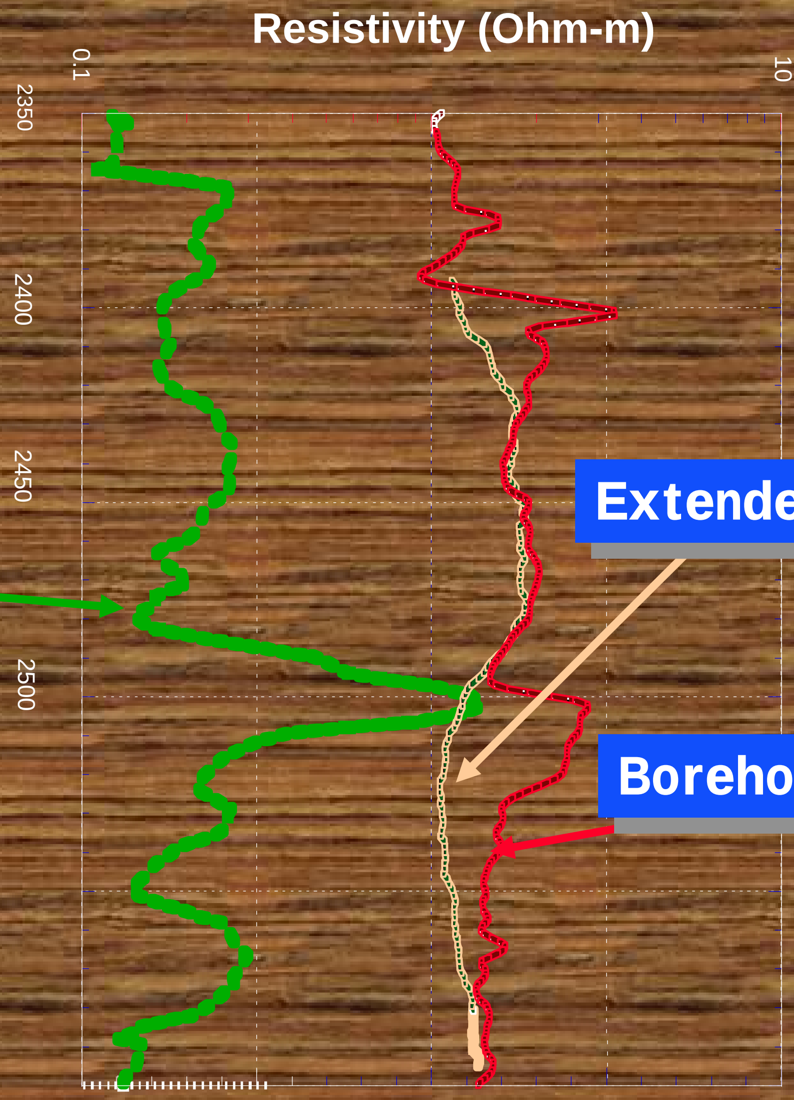



After Wilt et al, 1995

# Single well EM

SCIL tool

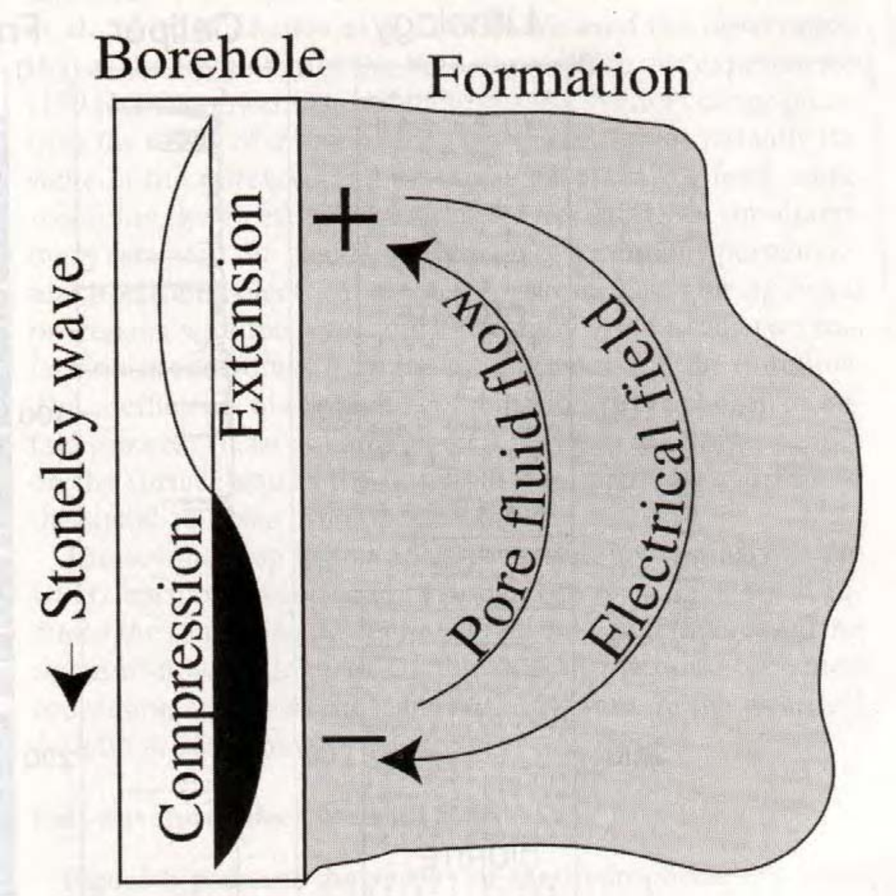



Courtesy of EMI Inc.

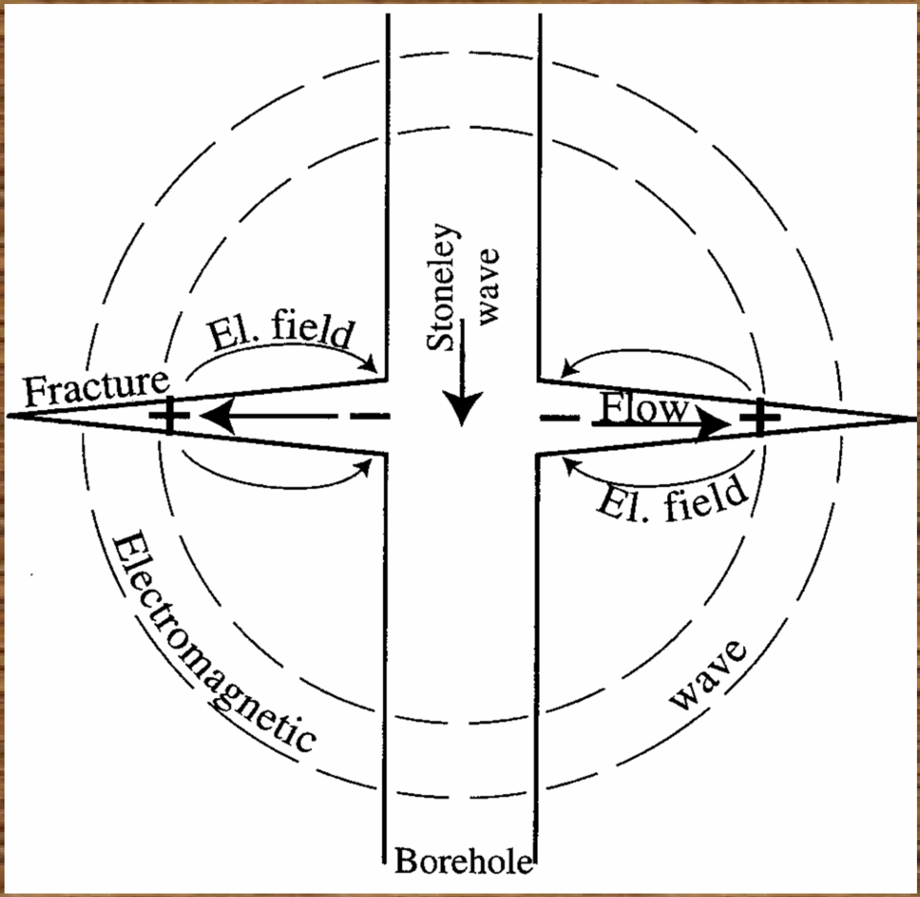
After Wilt & Alumbaugh, 1998

# Seismoelectrics: signal origin

**Stonely wave generated**

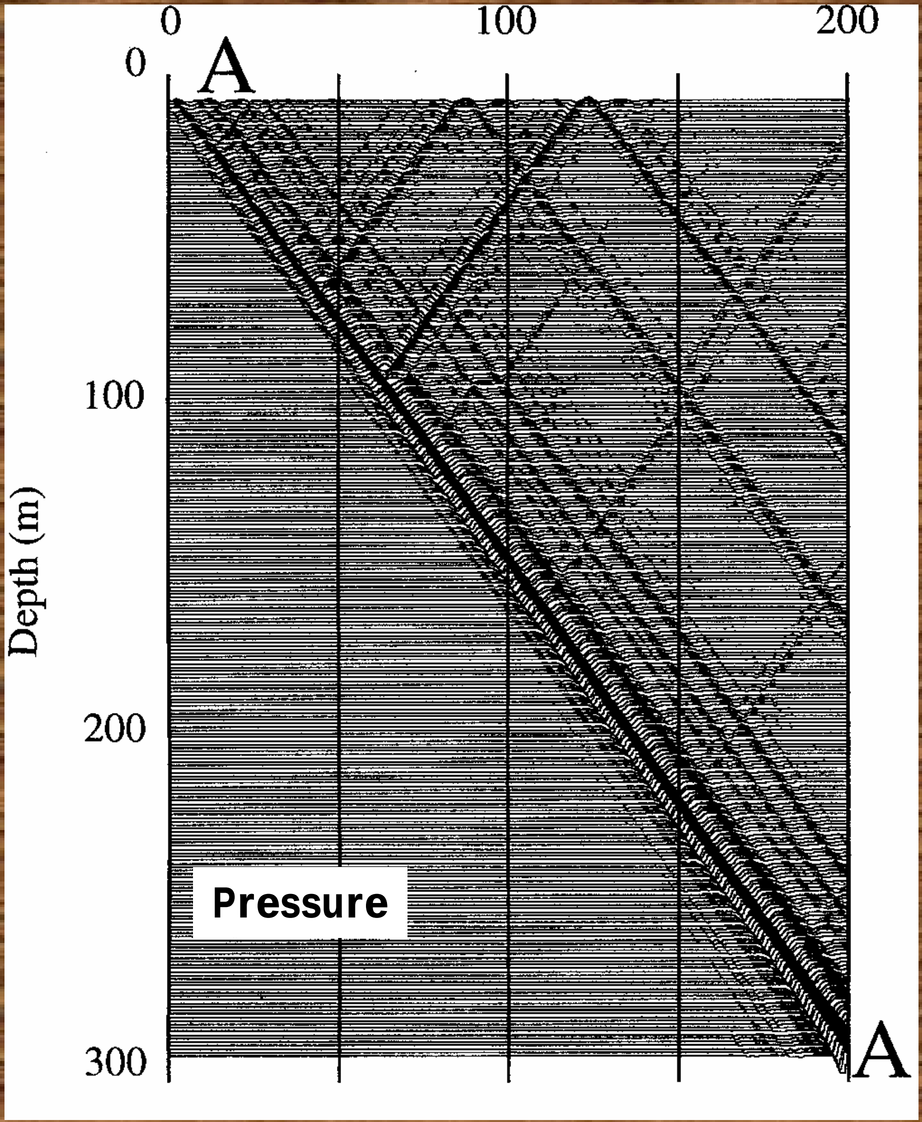


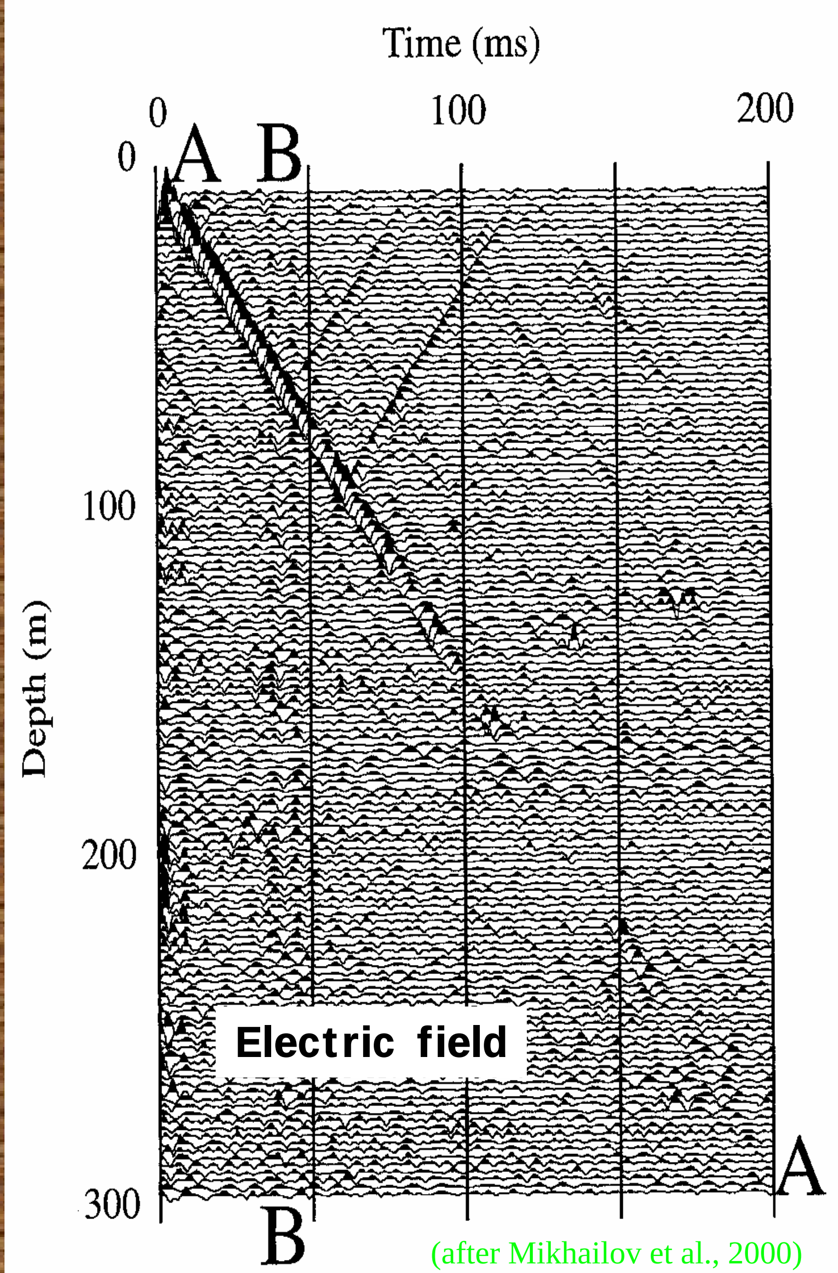

**Fracture generated**




(after Mikhailov et al., 2000)

# Seismoelectrics:



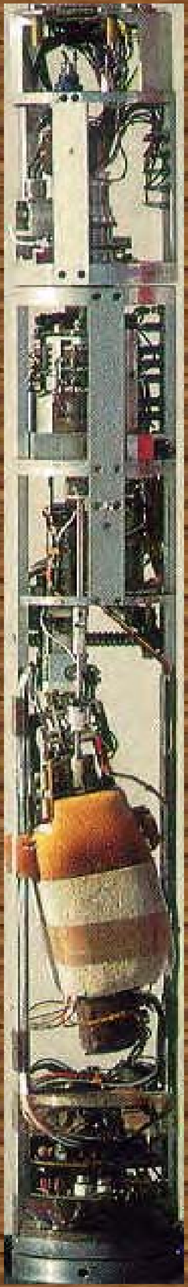

(after Mikhailov et al., 2000)

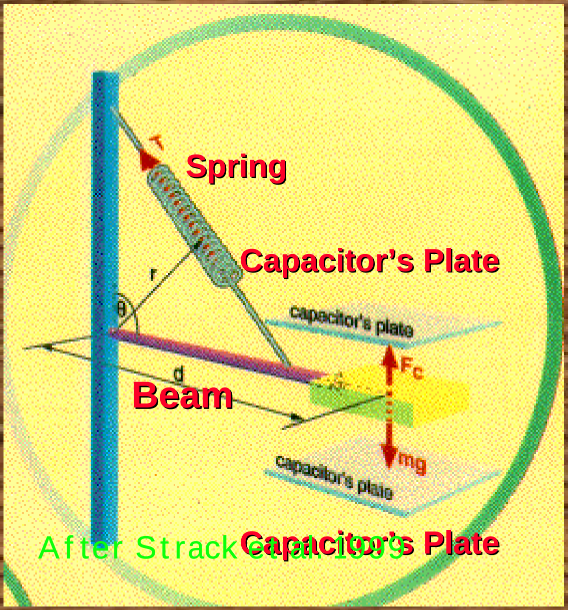
# Outline

- Critical Link
- Rock Physics
- Seismic Methods
- Borehole EM
- **Borehole Gravity**
- Logging
- Summary

# Borehole Gravimeter (BHGM)

- L&R “zero-length” spring balance
- Capacitor force related to gravitational acceleration
- Standard deviations **3 μGal**.

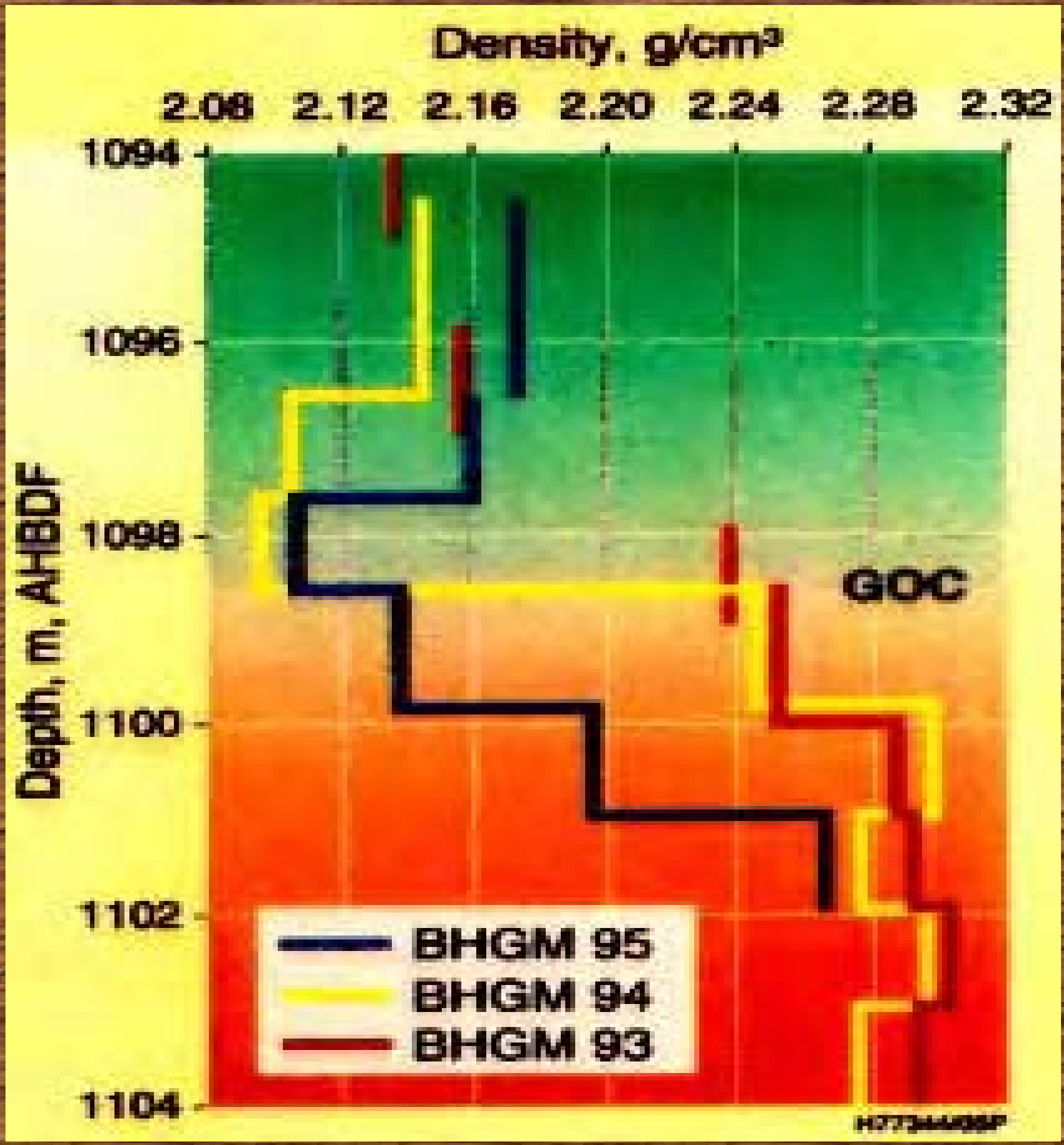




# Single well BHGM ( 3 years)

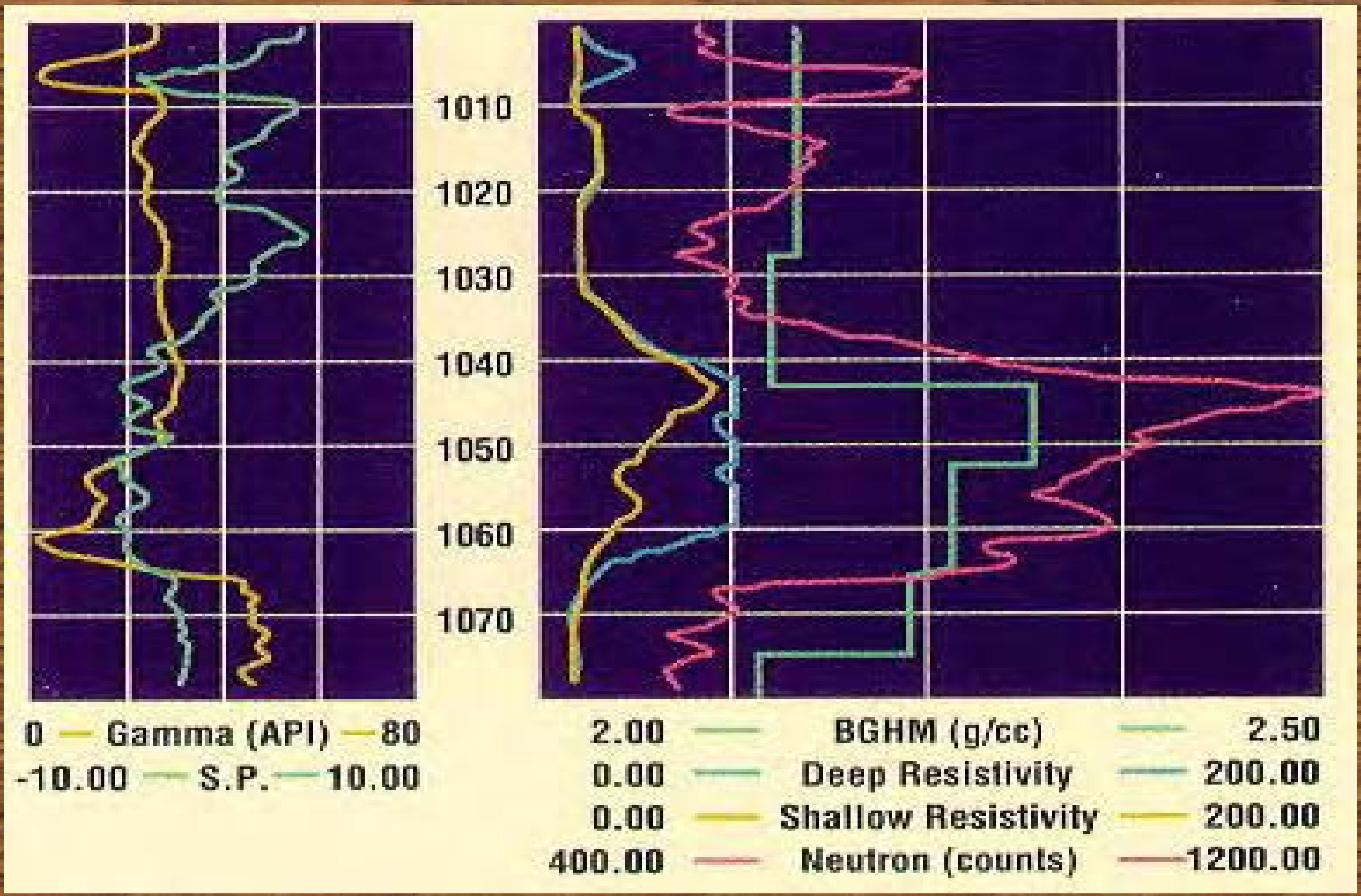
**Repeat BHGM across Rabbi field gas/oil contact in Gabon.**

**Porosity: 24%**
**Gas $\rho$ : 0.082 g/cc**
**Oil $\rho$ : 0.780 g/cc**



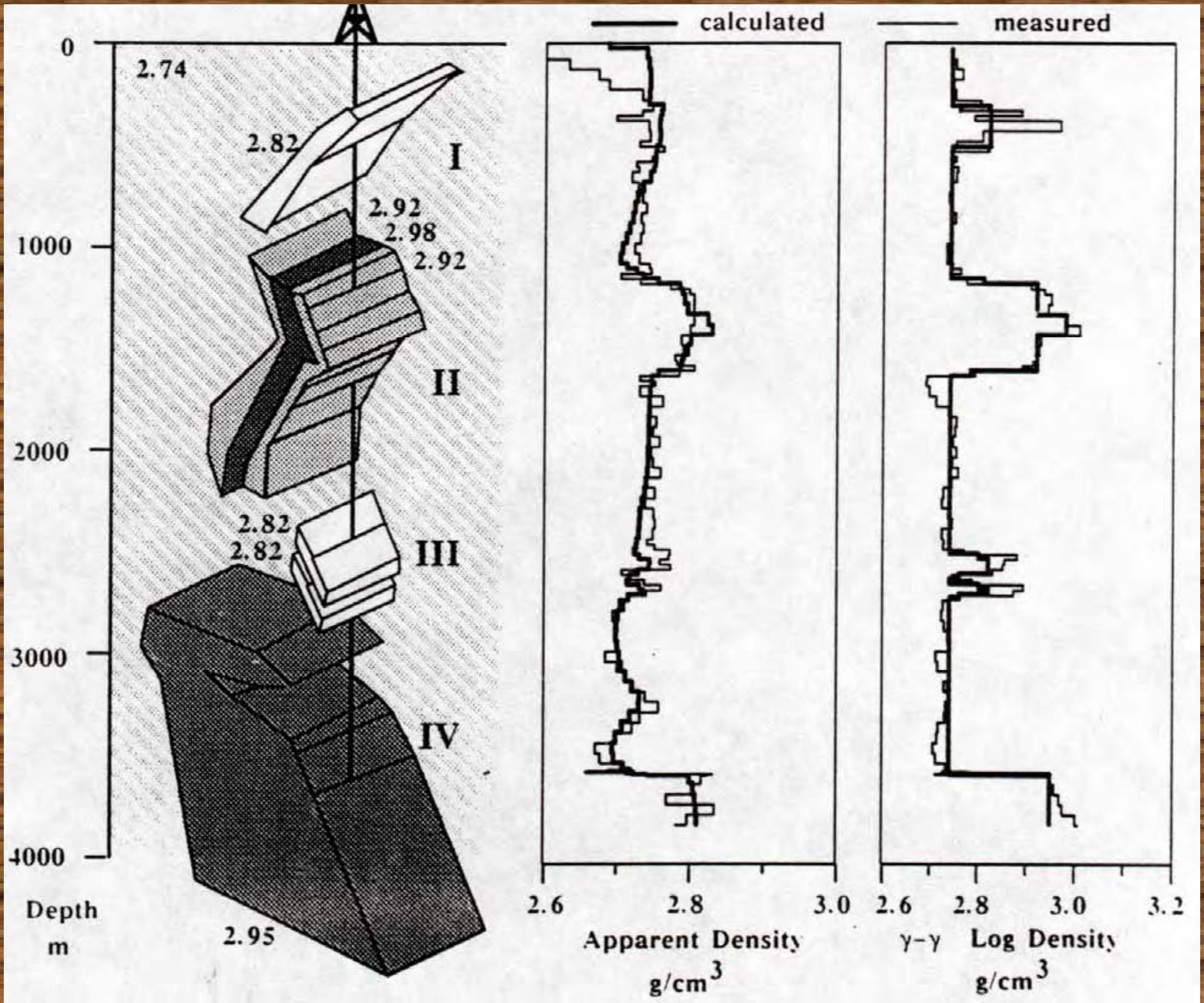

After Majer & Strack, 2000

# High resistivity, High N counts, High density=Tight Zone




After Edcon 1994

# KTB: final interpretation




After Wolfgram et al., 1992

# Outline

- Critical Link
- Rock Physics
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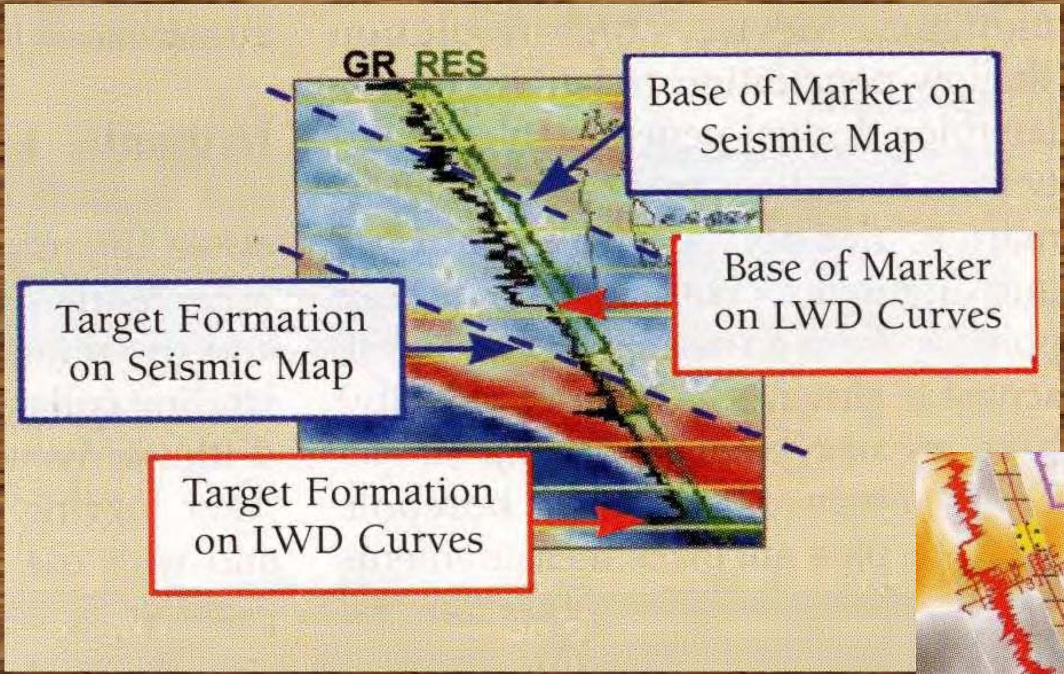
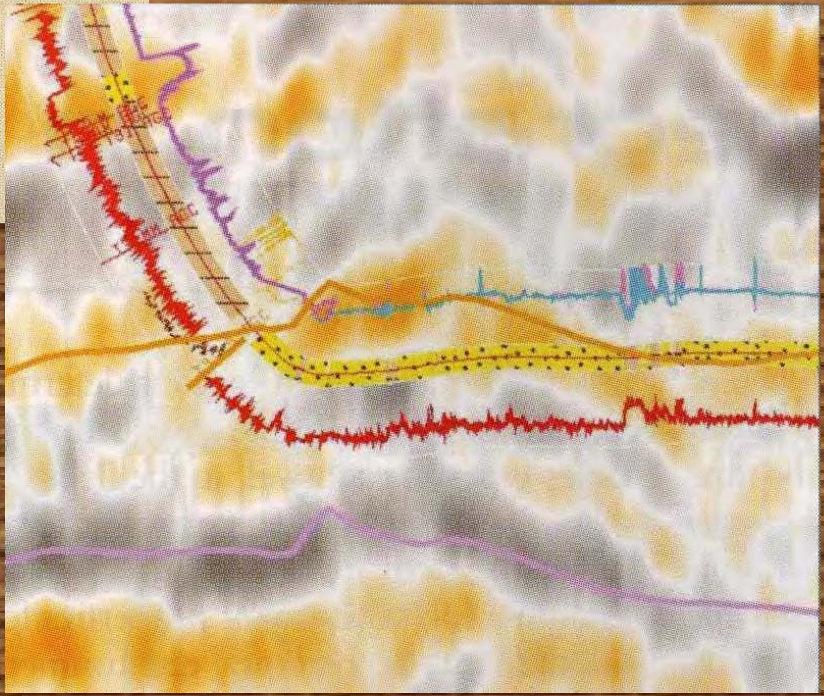
- Borehole EM
- Borehole Gravity
- **Logging**
- Summary

# Borehole information components

- Mud logging ………… see geology lecture
- Core analysis………… see geology lecture
- Measuring/Logging while drilling – MWD/LWD
- Wireline logging
- Borehole seismics…...see above
- Formation testing….. Reservoir engineering
- Well completion …….. Reservoir engineering
- Production logging …. Reservoir engineering

# LWD/MWD geosteering examples



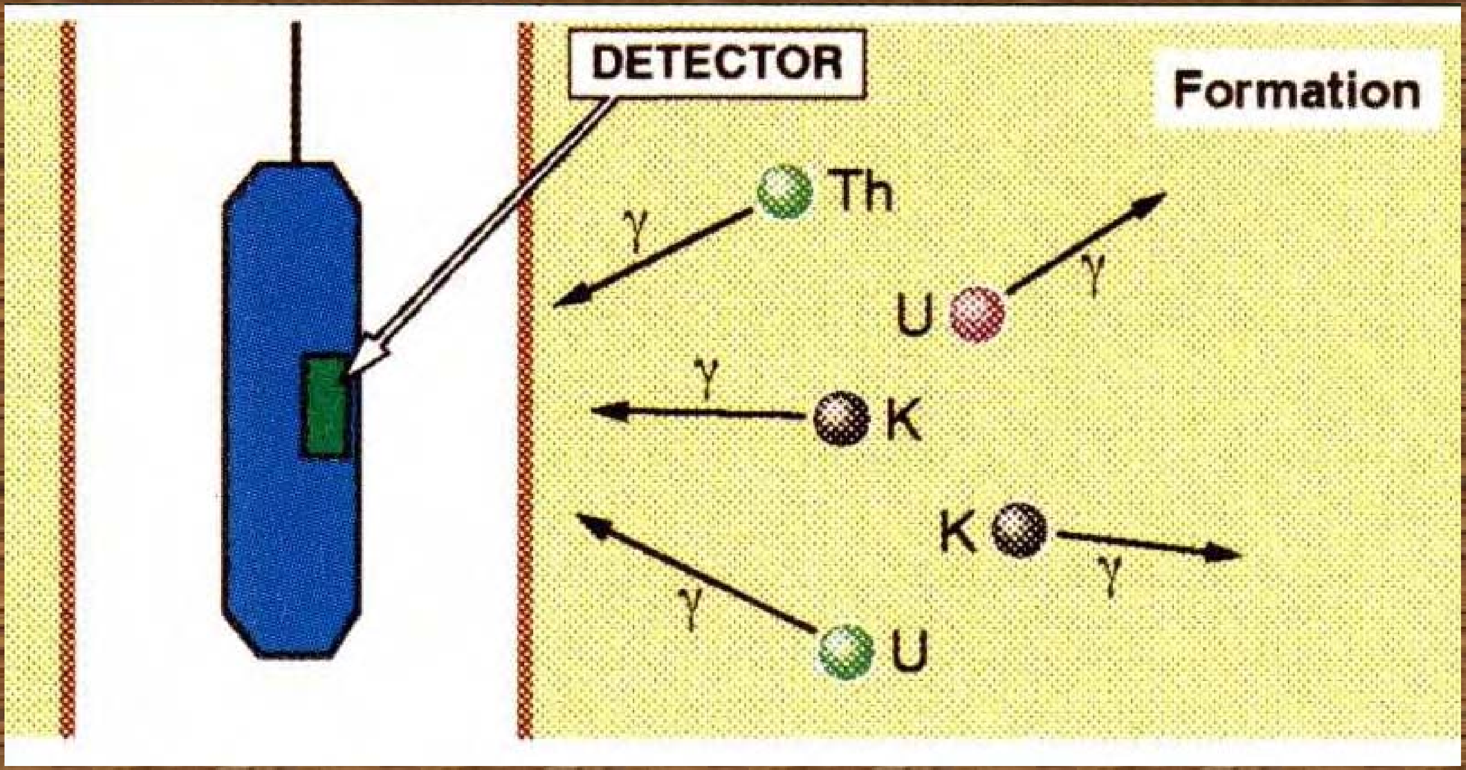
After Marshall et al., 2000

# Outline

- Logging
  - Natural Gamma ray tools
  - Density tools
  - Borehole imaging
  - Resistivity logs
  - Sonic logs
  - NMR

# Natural Gamma log principle

- measured in API units (U of H test pit)
- Gamma rays are emitted by K, U, Th




(after van Ditzhuijzen, 1994)

# Energy spectrum

**U Uranium series**

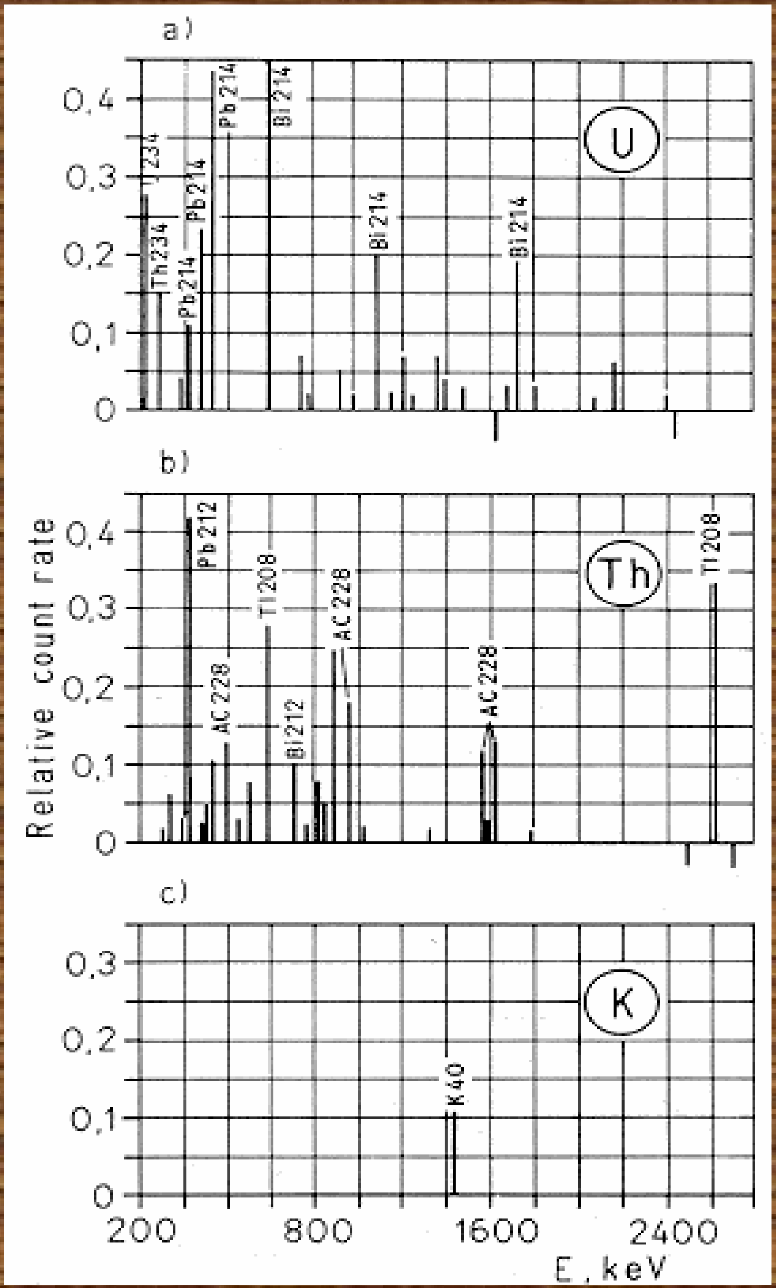
**spectrum with typical energy 1.76 MeV ($^{214}$Bi)**

**Th Thorium series**

**spectrum with typical energy 2.61 MeV ($^{208}$Th)**

**$^{40}$K Potassium isotope**

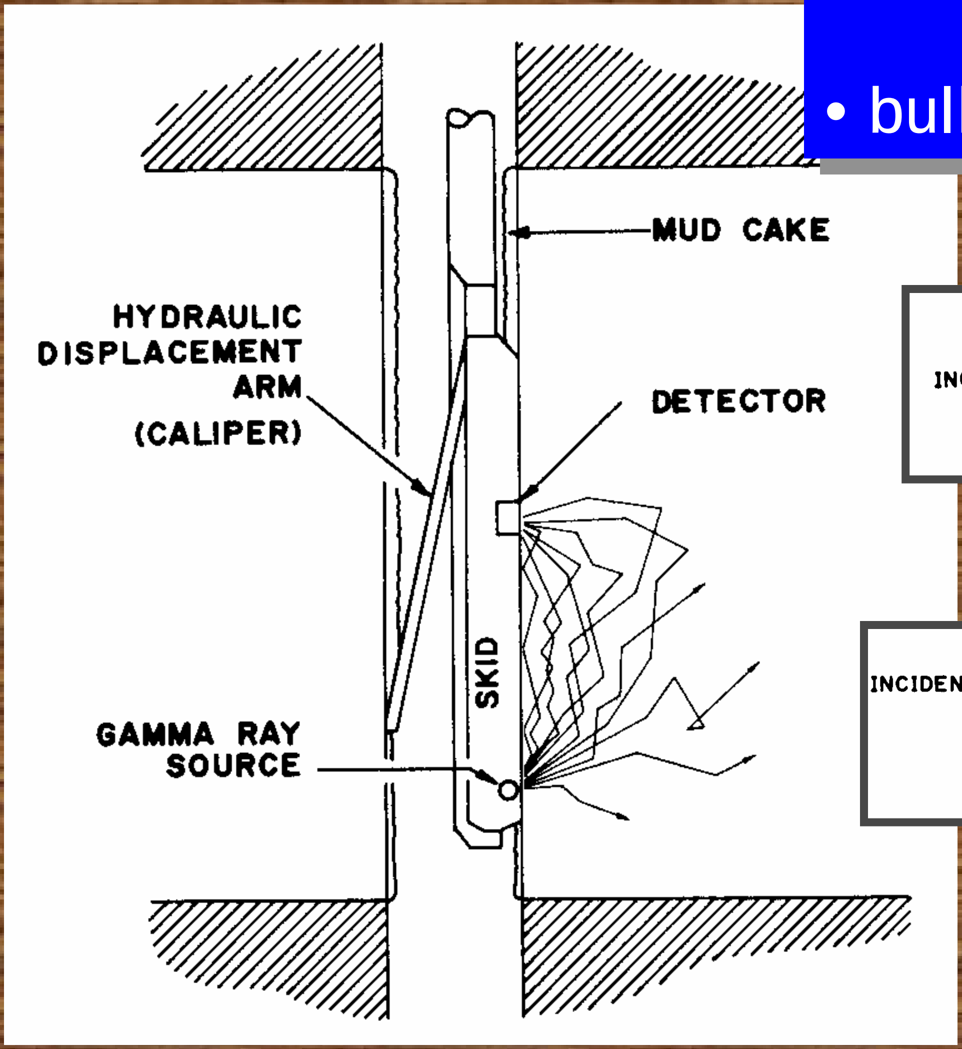
**monoenergetic 1.46 MeV**

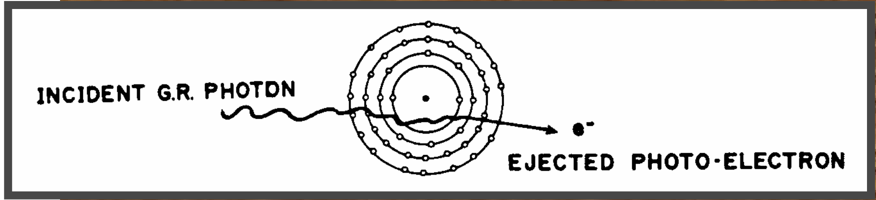


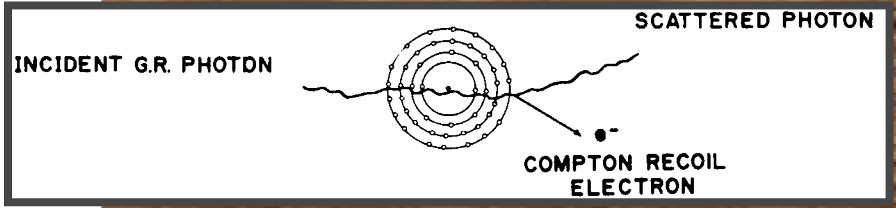

(Hearst & Nelson, 1985)

# Gamma – gamma density principle

- gamma rays are absorbed by formation
- bulk density measurement



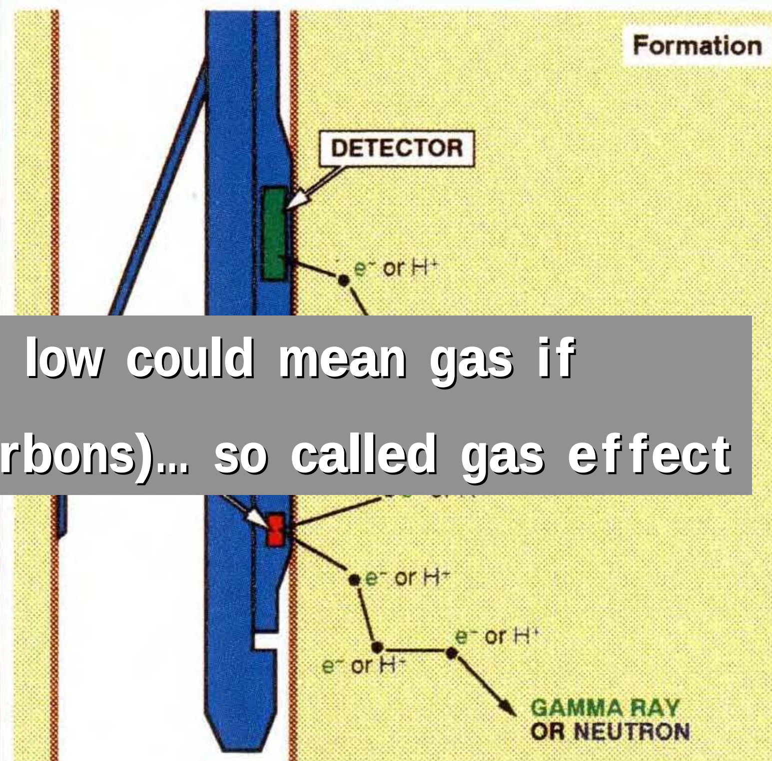



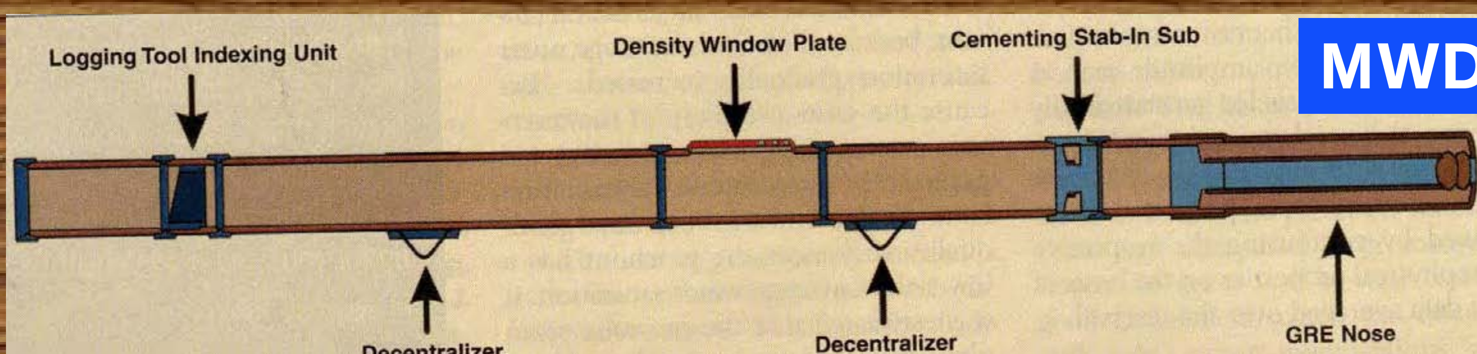

(Labo, 1987)

# Density logs (γ-γ ; neutron)

| | | |
|---|---|---|
| Gamma ray absorption | Bulk density (g/cc) | Gamma rays are emitted by tool. Degree of gamma ray absorption by the formation is directly related to formation bulk density. |
| Therm… neutr… | … (porosity unit) | … determined by the hydrogen concentration, which is related to porosity. |




- γ-γ density gives bulk density; low could mean gas if
- neutron is high (high hydrocarbons)… so called gas effect




**MWD tool**

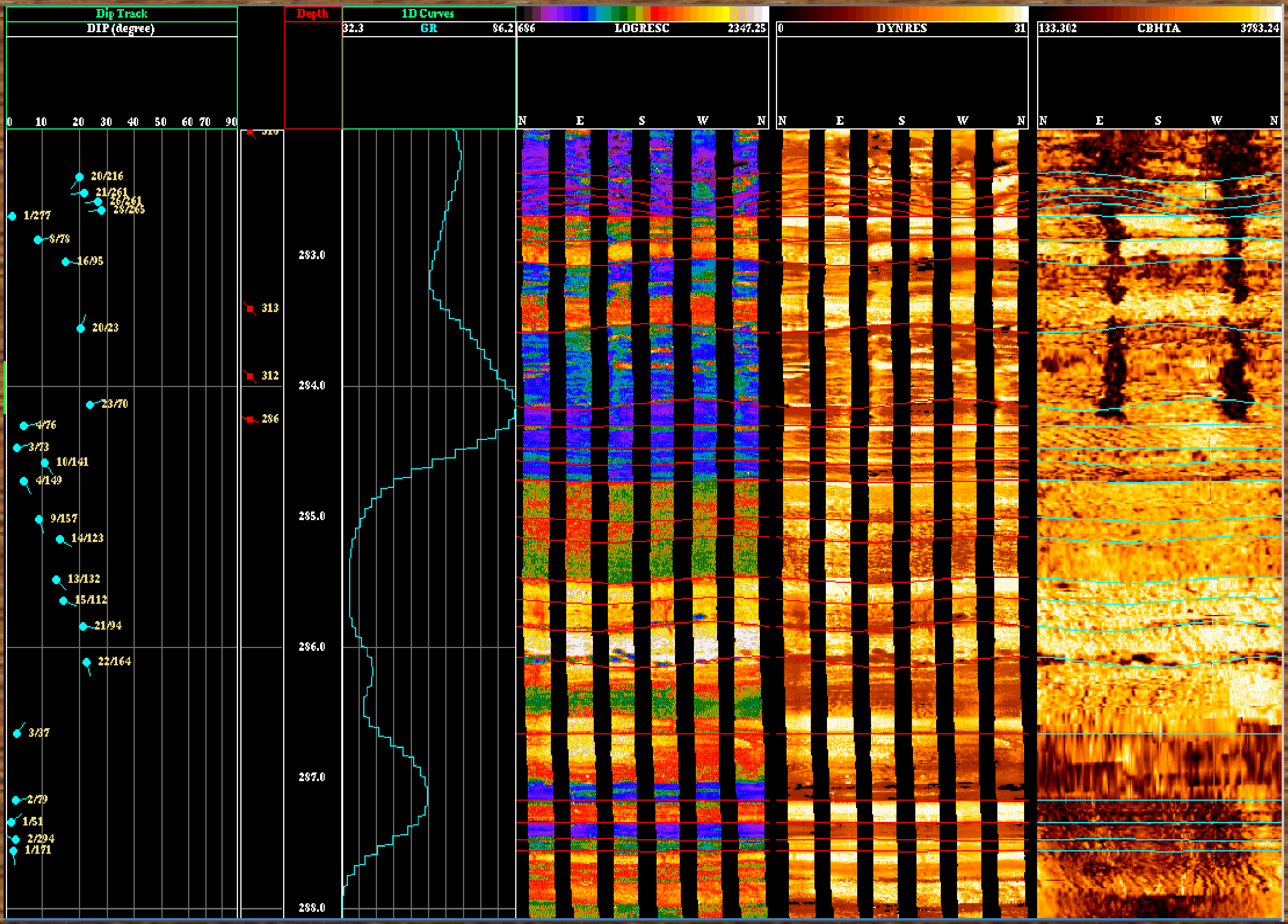


(after van Ditzhuijzen, 1994)

# Outline

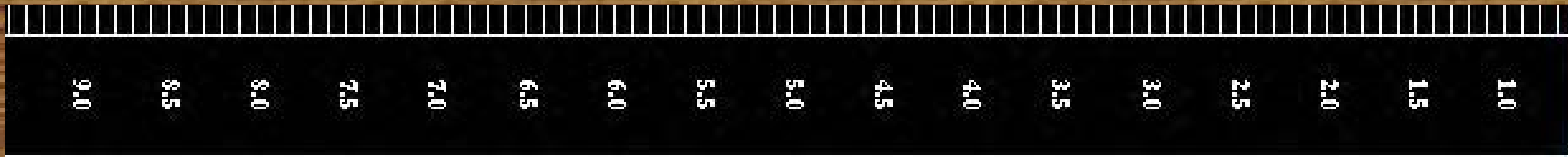
- Logging
  - Natural Gamma ray tools
  - Density tools
  - Borehole imaging
  - Resistivity logs
  - Sonic logs
  - NMR

# VISION™ Screen

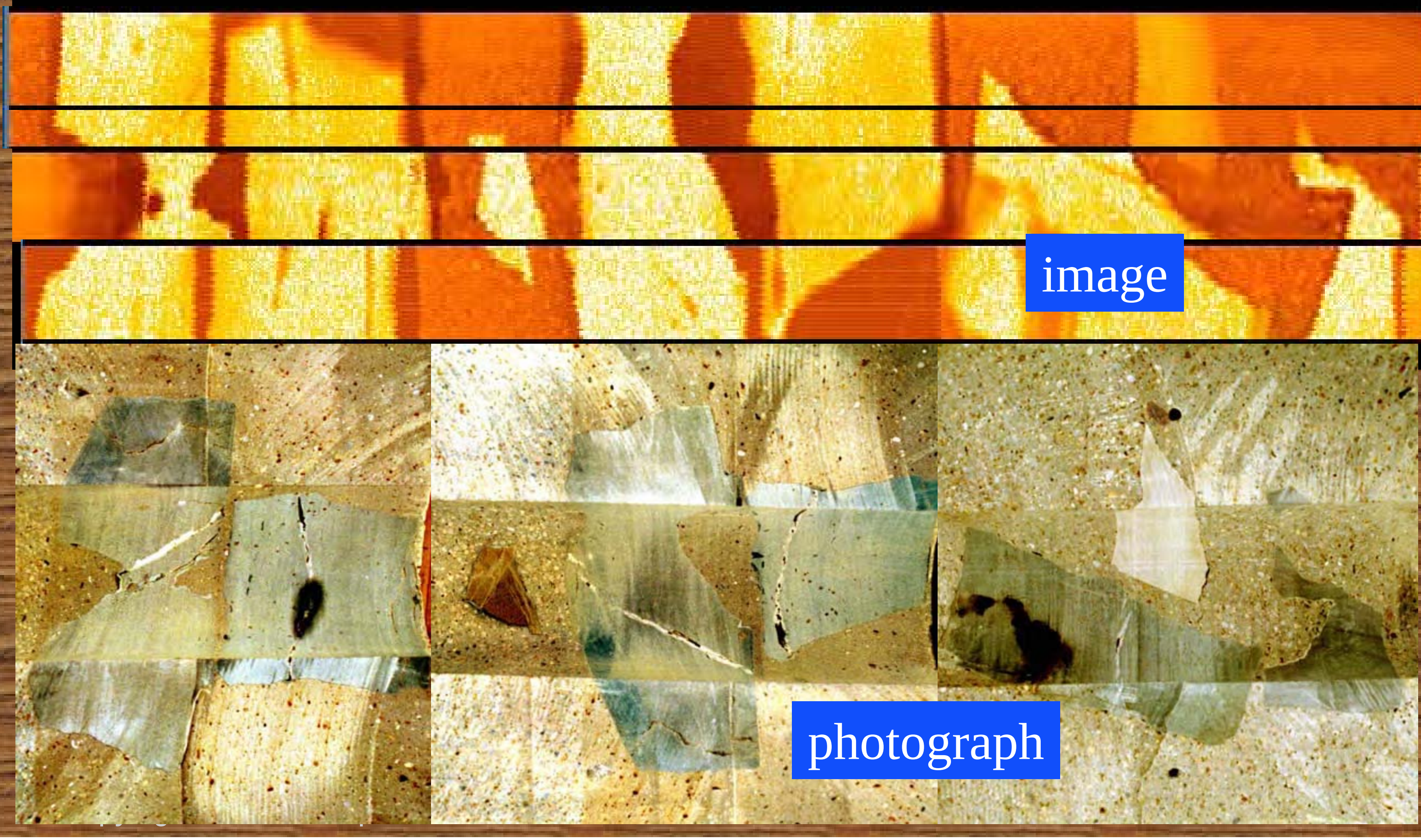





Courtesy Baker Atlas




# Combined photo & image



## Summary: Progress

- Quantitative use of borehole seismics
- Passive monitoring is growing
- Borehole EM being considered
- Borehole gravity is there but very limited
- Logging extends depth and scaling

# Summary: Future

- Anisotropy will be key in scaling
- Pore pressure prediction we need hard data
- Deep Reading Single Well will appear
- Fracture mapping will grow

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