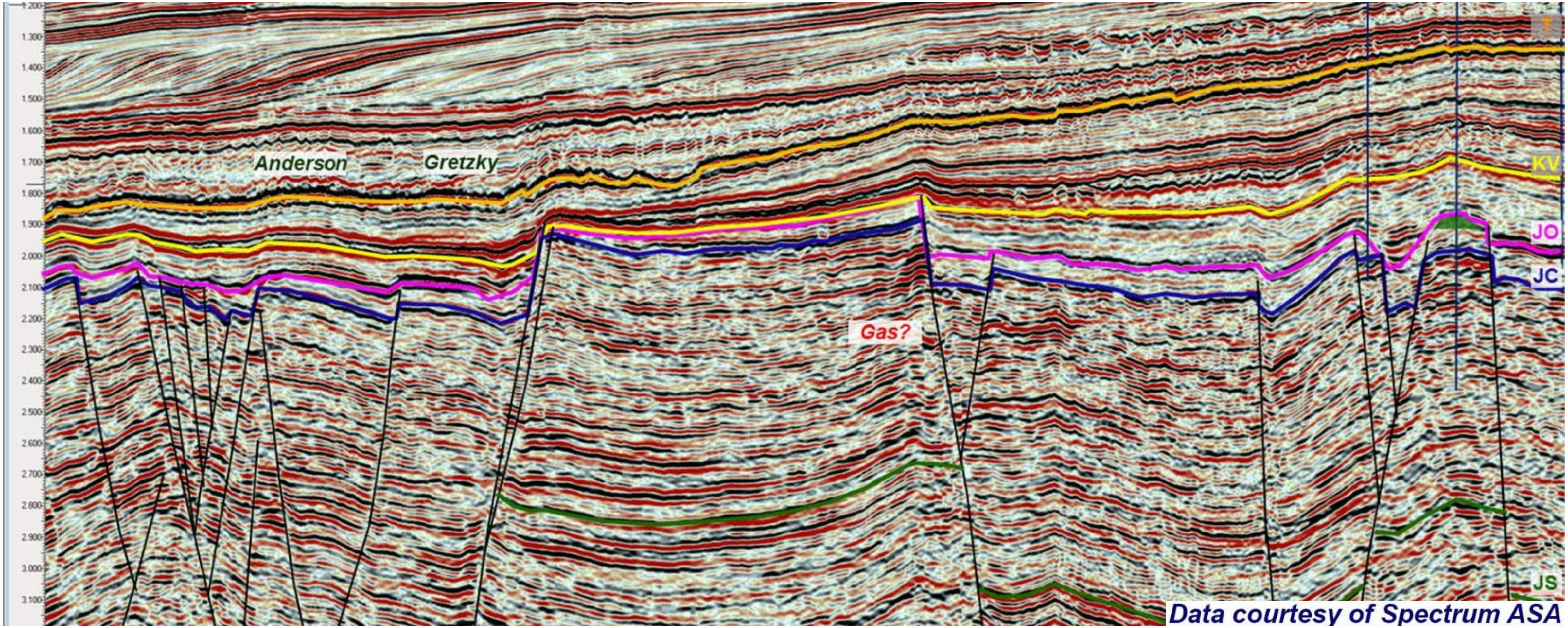
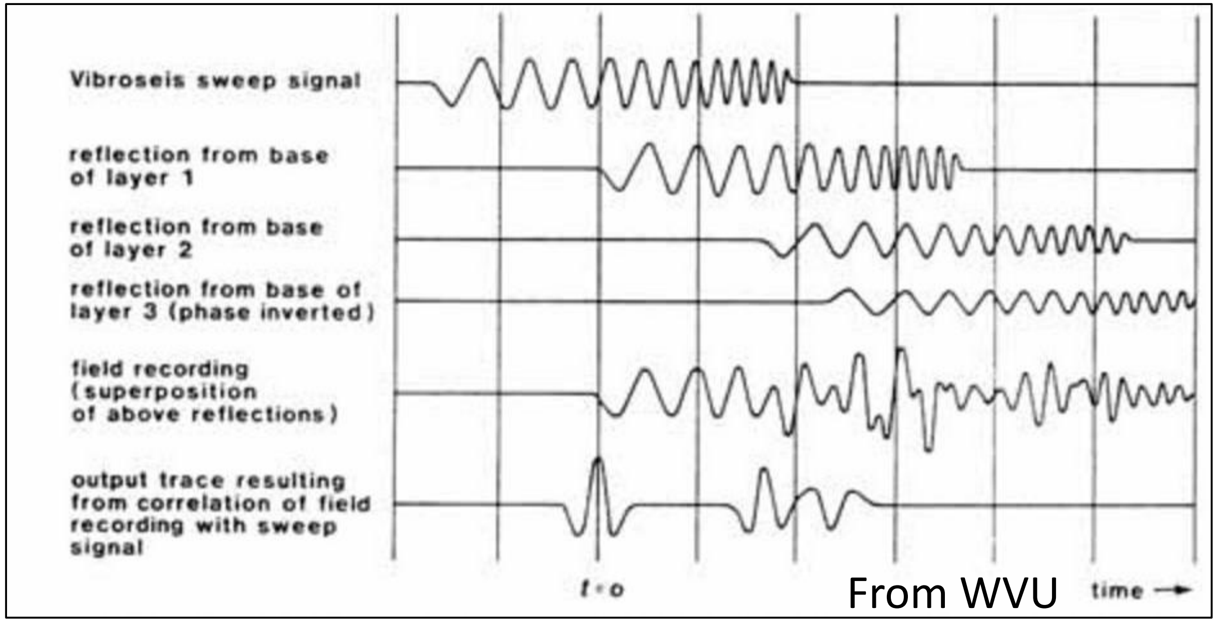
How do we get this image?

The Seismic Method

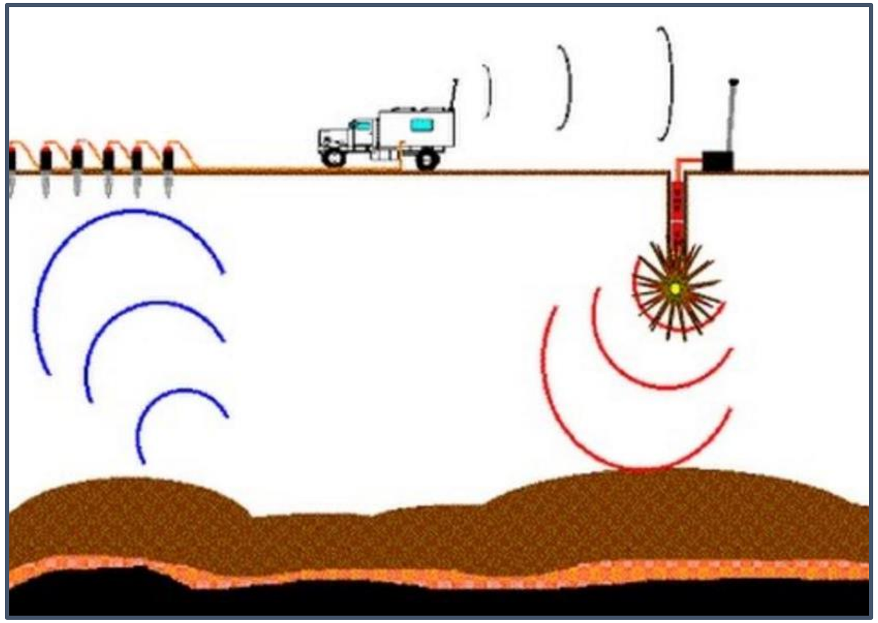


How do we get this data? - Land

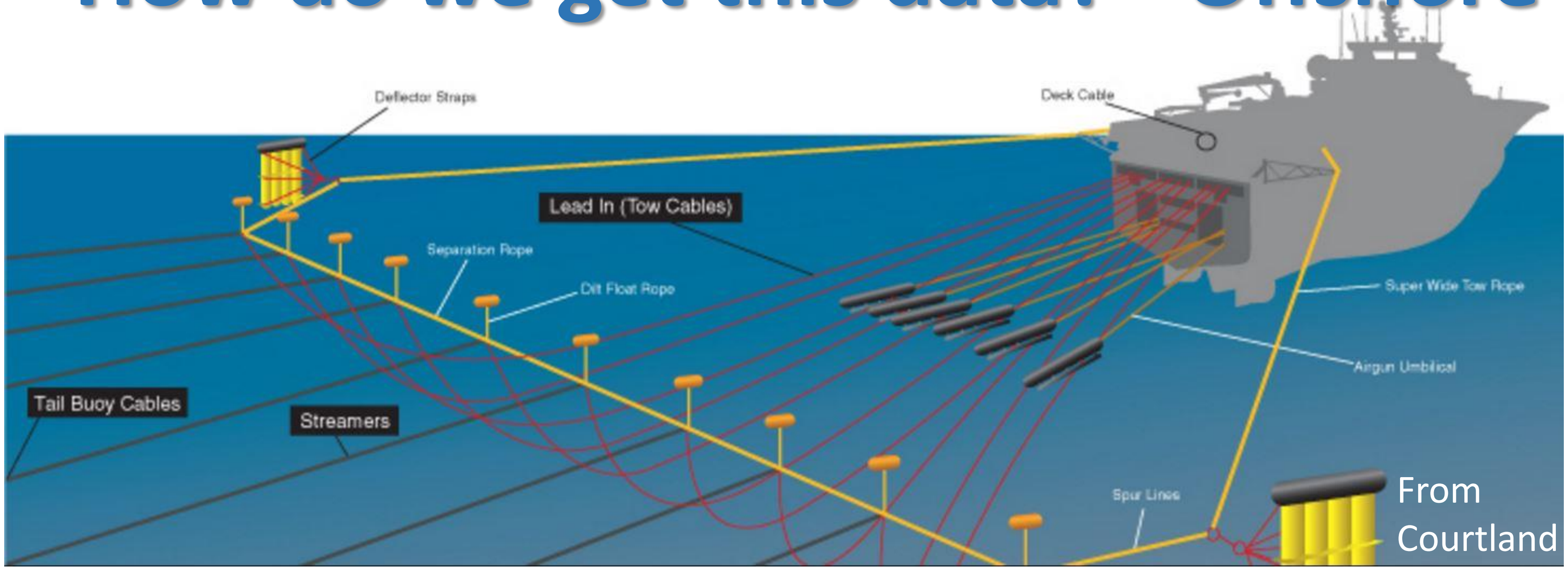

Courtesy Dawson



From WVU

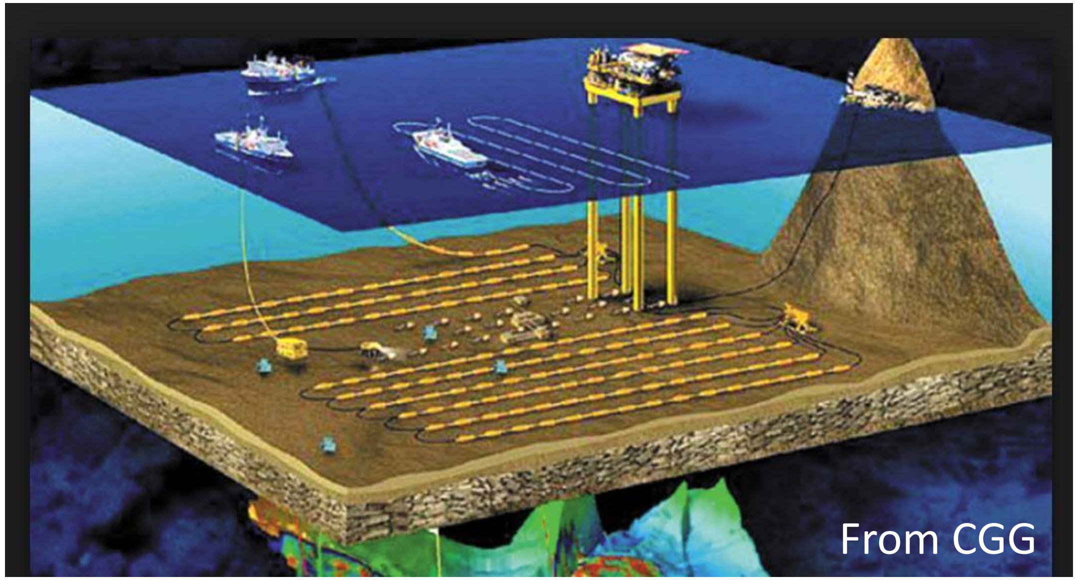


How do we get this data? - Offshore



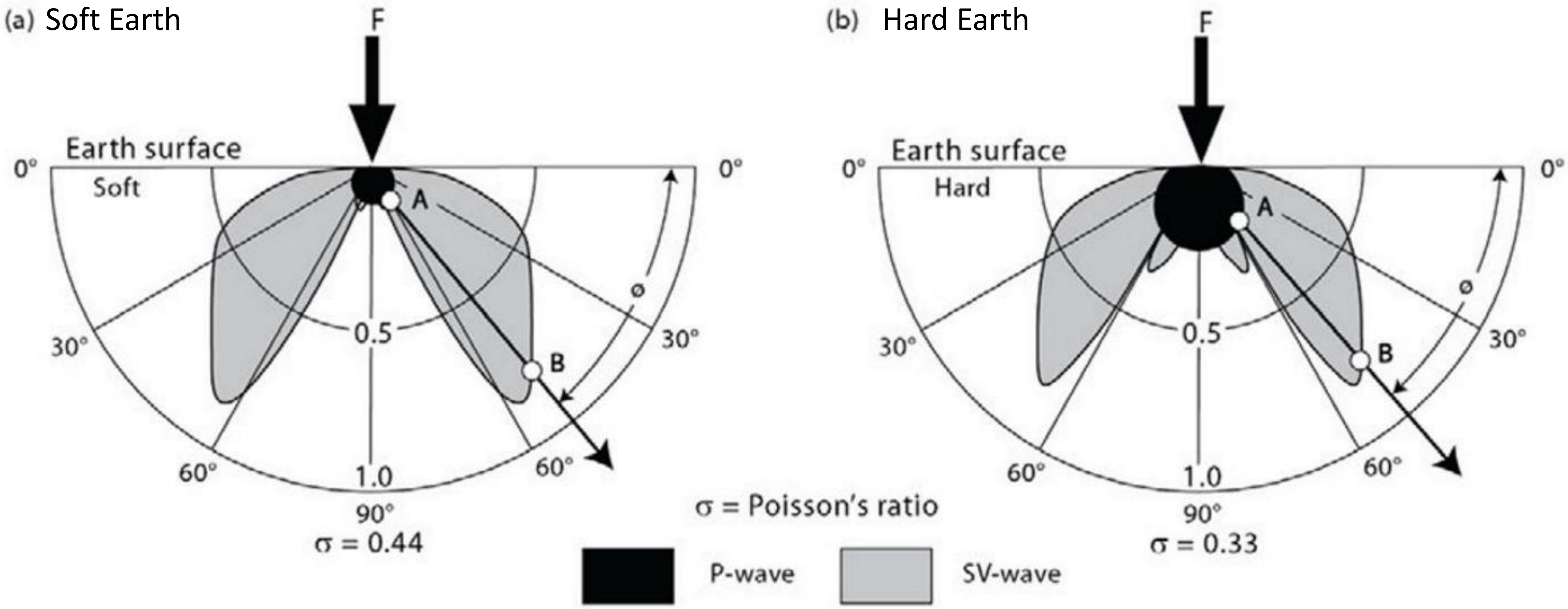
Streamer Seismic

Ocean Bottom Cable
Ocean Bottom Node
Seismic



Whats the advantage of OBC/OBN?

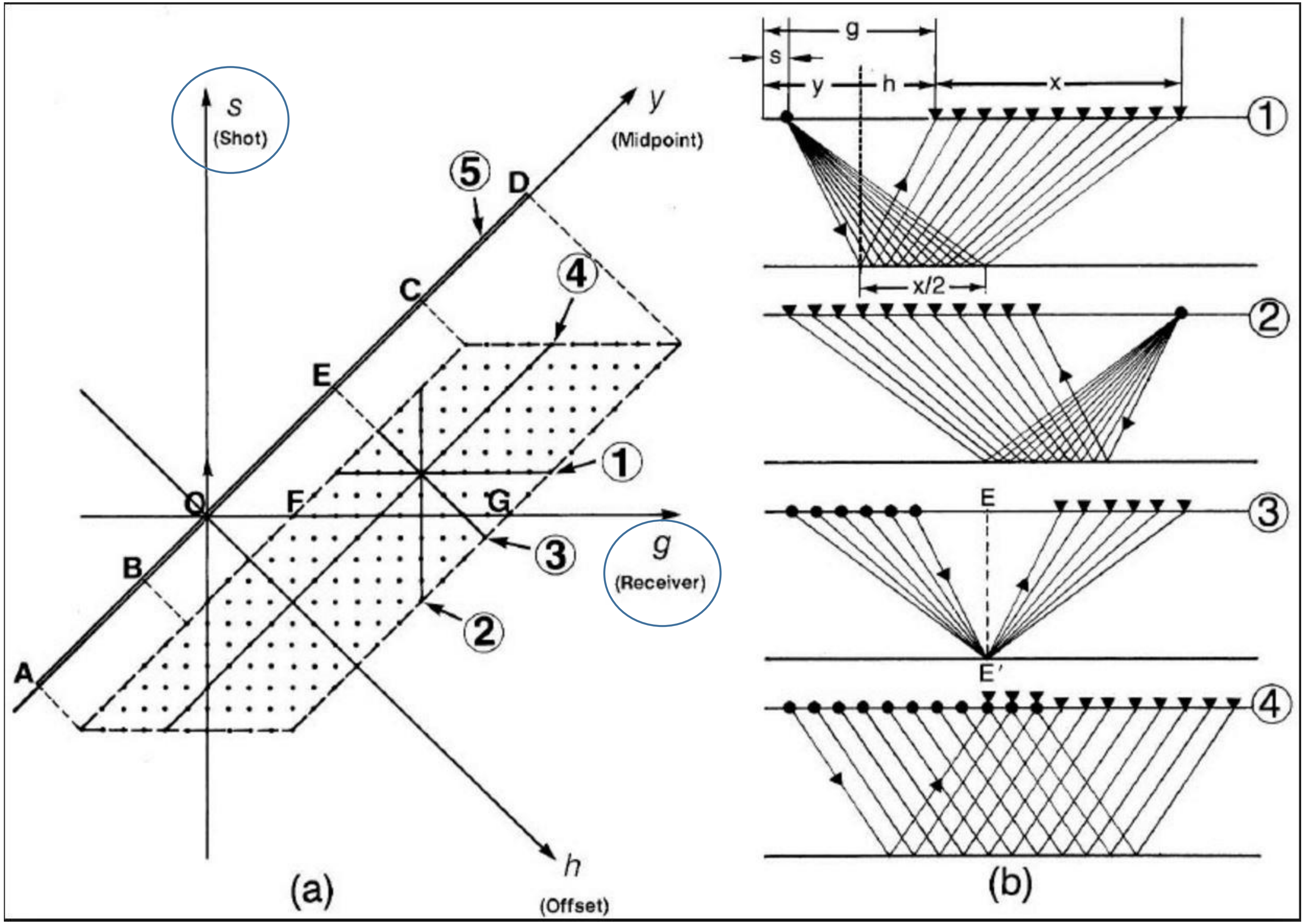
Land - Vertical Source Radiation Pattern



Why do we mostly record P-waves?

Hardage, UT-A

Seismic Data Acquisition - Land



Why do we bother with non-NI data acquisition?

SEG Wiki

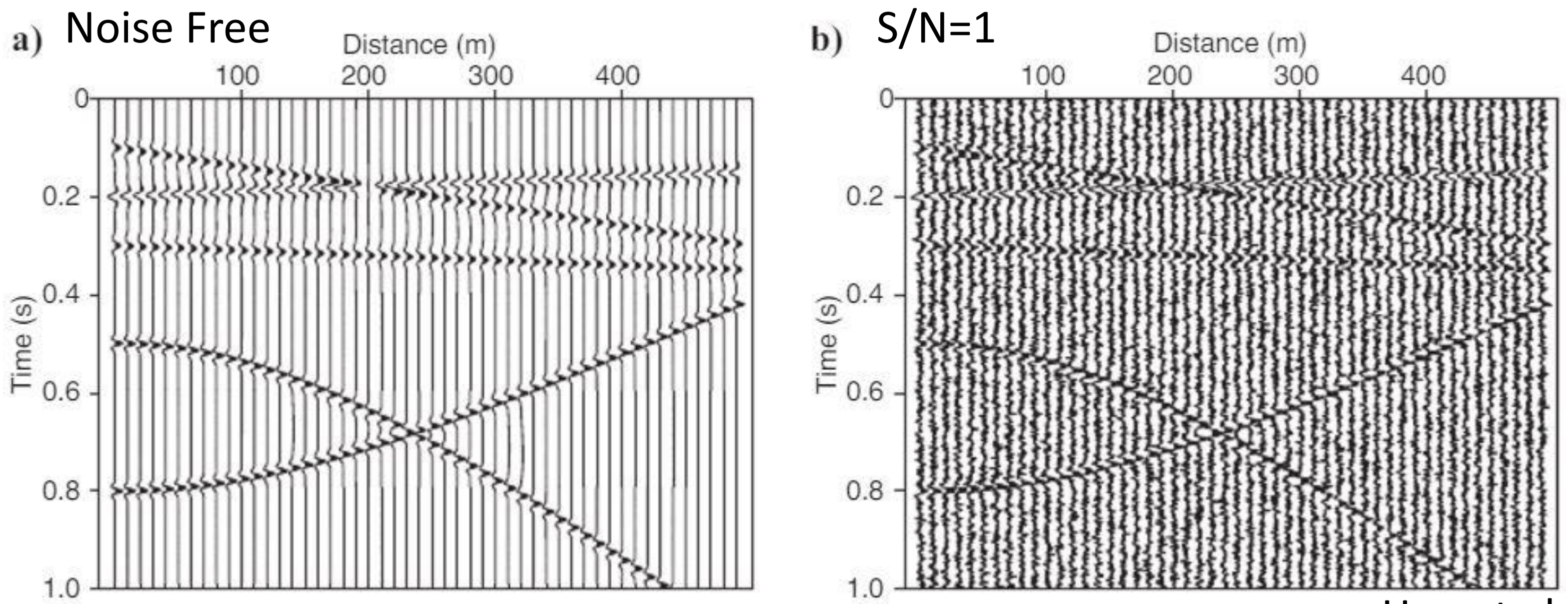
Seismic Data Acquisition - Land

Full Fold = 0.5 x number of active channels per spread x (ΔReceiver/ΔSource)

For 62 channels/receivers per spread, and ΔReceiver=25m, ΔSource=25m; What is the Fold?

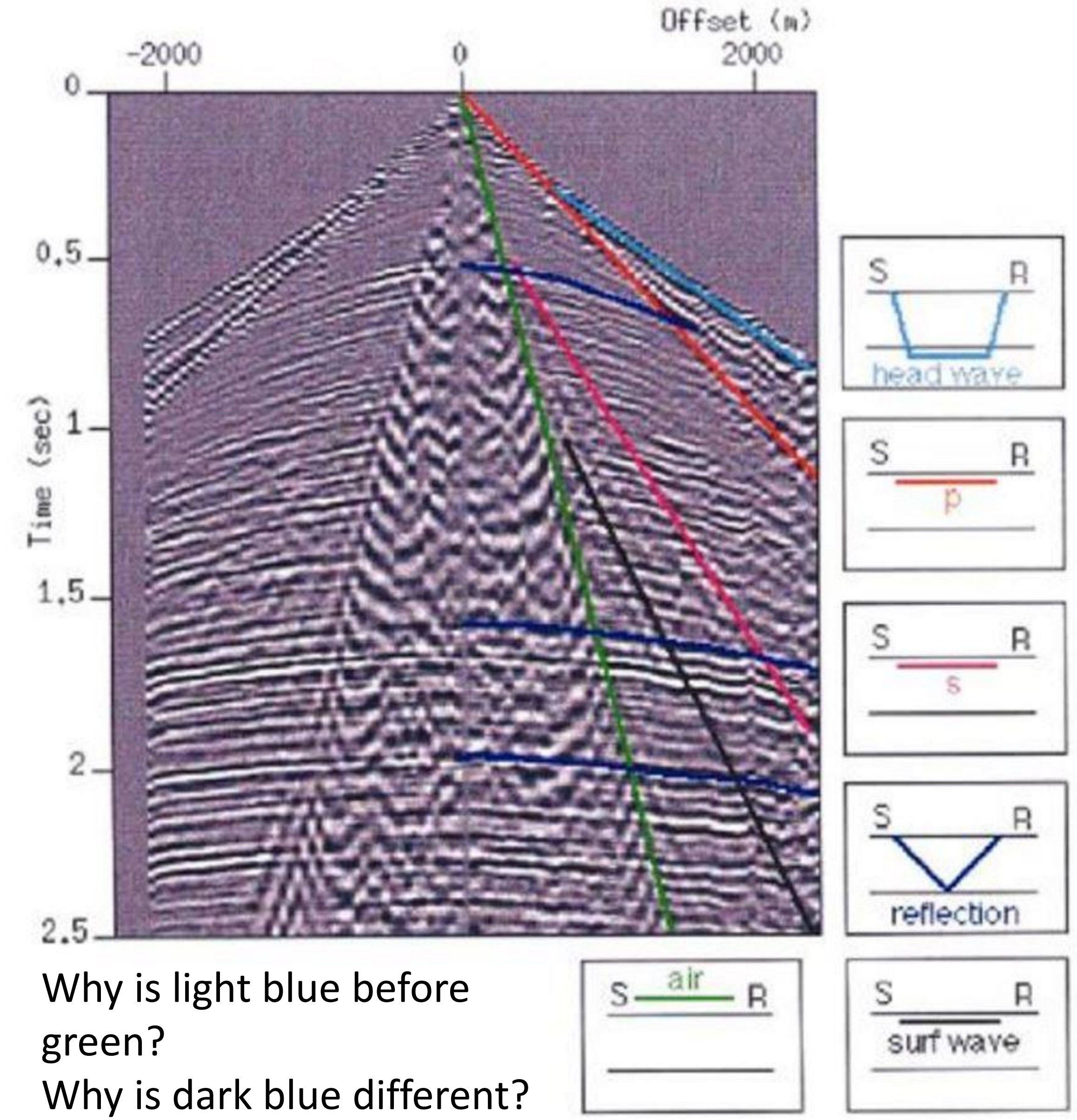
Signal/Noise ration ~ SQRT(Fold)

Calculate S/N ration for 1 Fold, 25 Fold, 50 Fold, 100 Fold

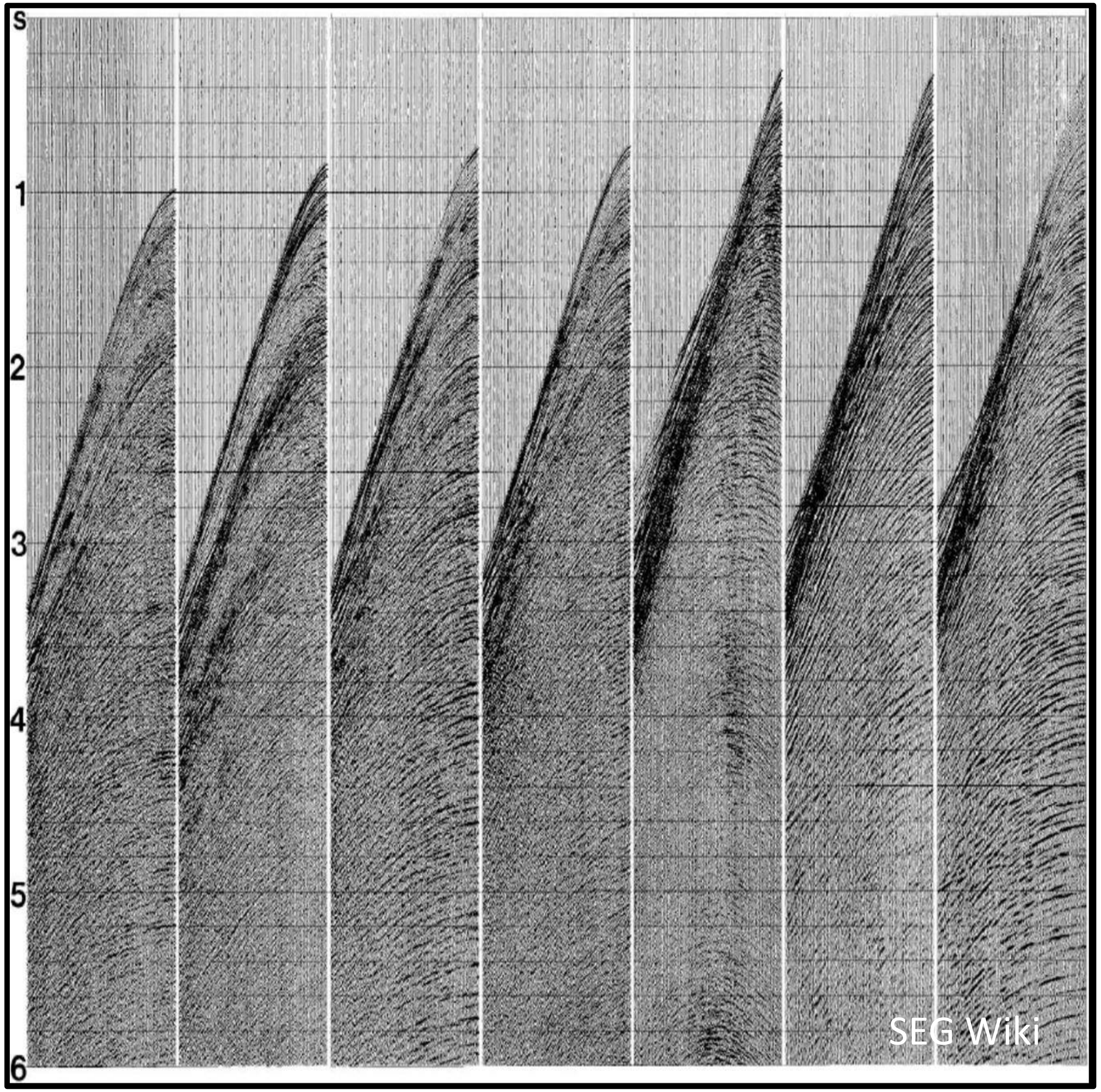


Han et al., 2014

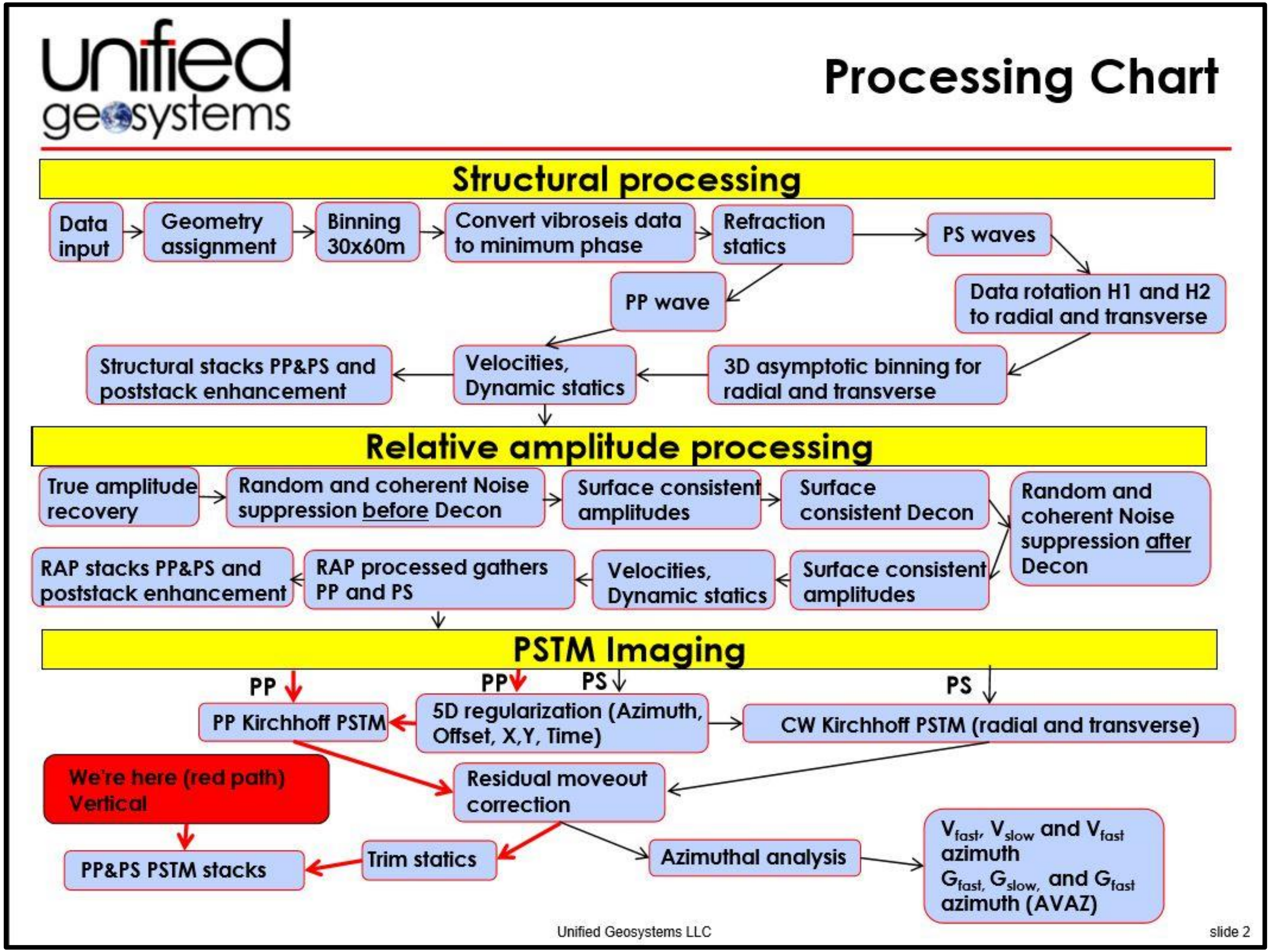
Seismic Data – Land/Marine



Why is light blue before green?
Why is dark blue different?

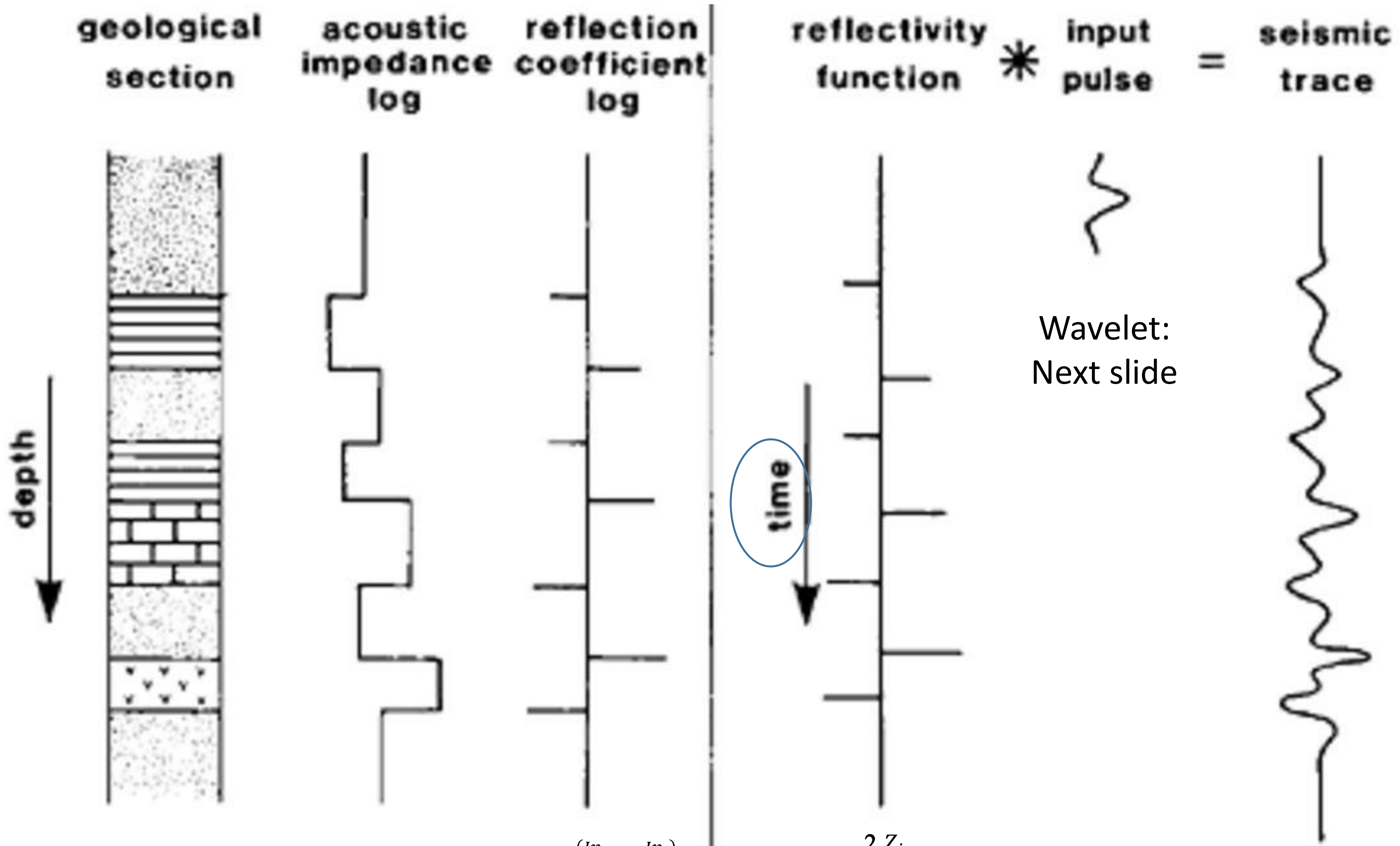


Seismic Data Processing - Land



Galikeev, 2017

1D Normal Incidence Reflection Coefficient

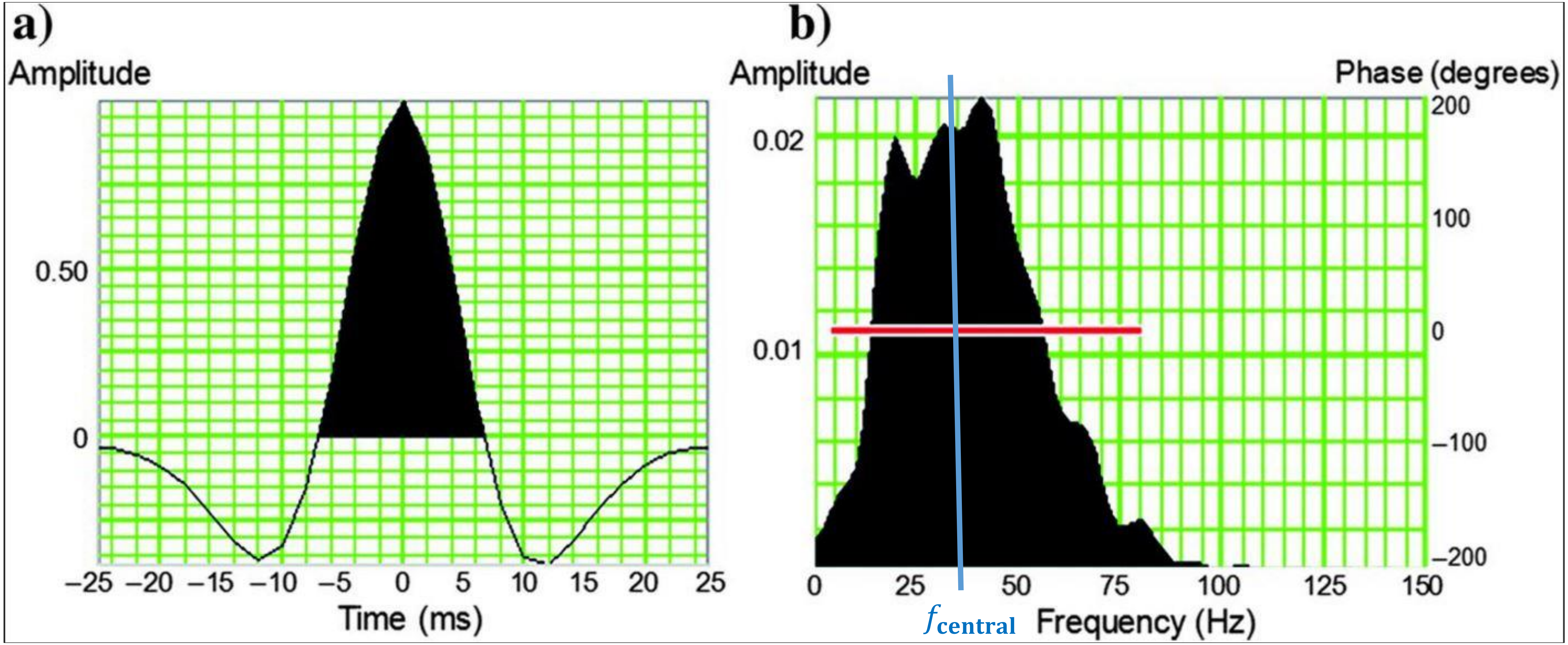


Wavelet:
Next slide

$[\boldsymbol{Vp}, \boldsymbol{Vs}, \boldsymbol{Rho}]$ $\boldsymbol{Ip} = \boldsymbol{Vp} * \boldsymbol{Rho}$ $\Delta \boldsymbol{Ip} = \frac{(Ip_{i+1} - Ip_i)}{(Ip_{i+1} + Ip_i)}$ $\Delta t_i = \frac{2\, Z_i}{Vp_i}$

Kearey et al, 1991

Seismic Wavelet – Sweep/Explosion/Airgun

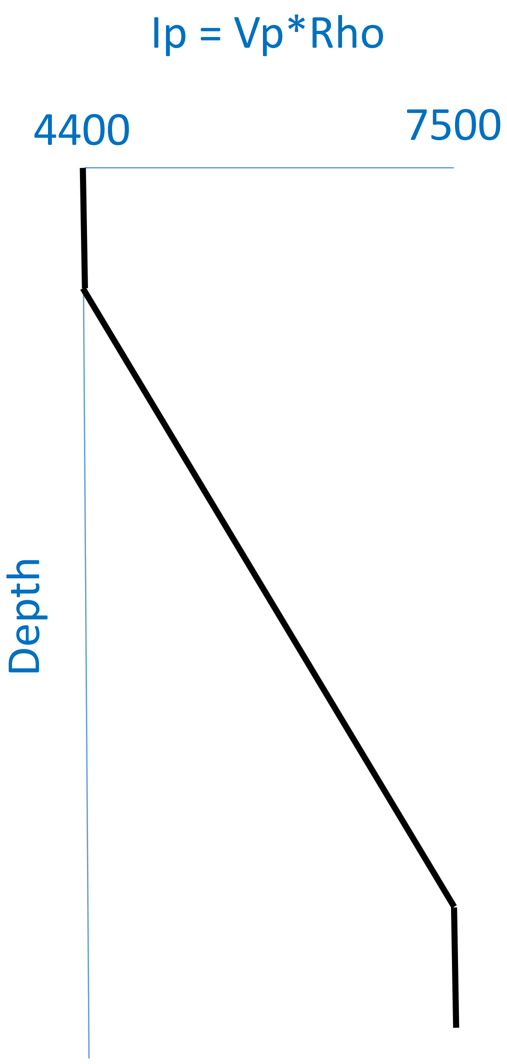


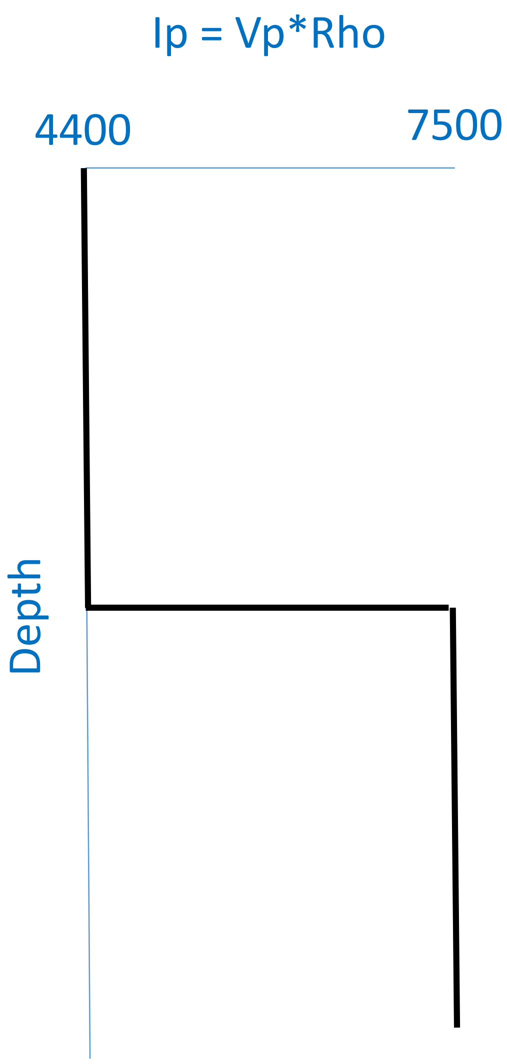
What would the wavelet look like in the time domain if I had all frequencies?

What happens to f_central when we have higher frequencies?

Liang, 2017

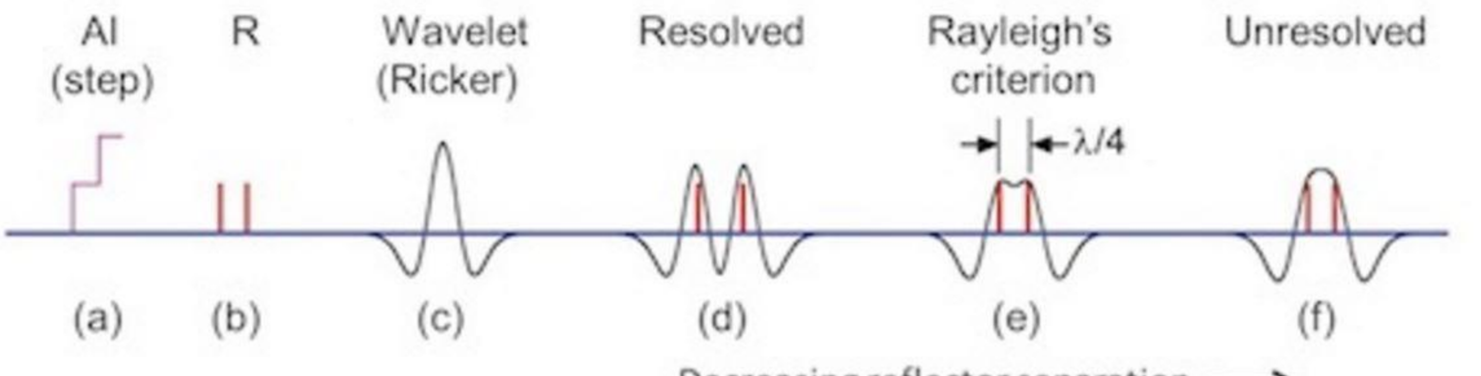
Seismic Trace Computation



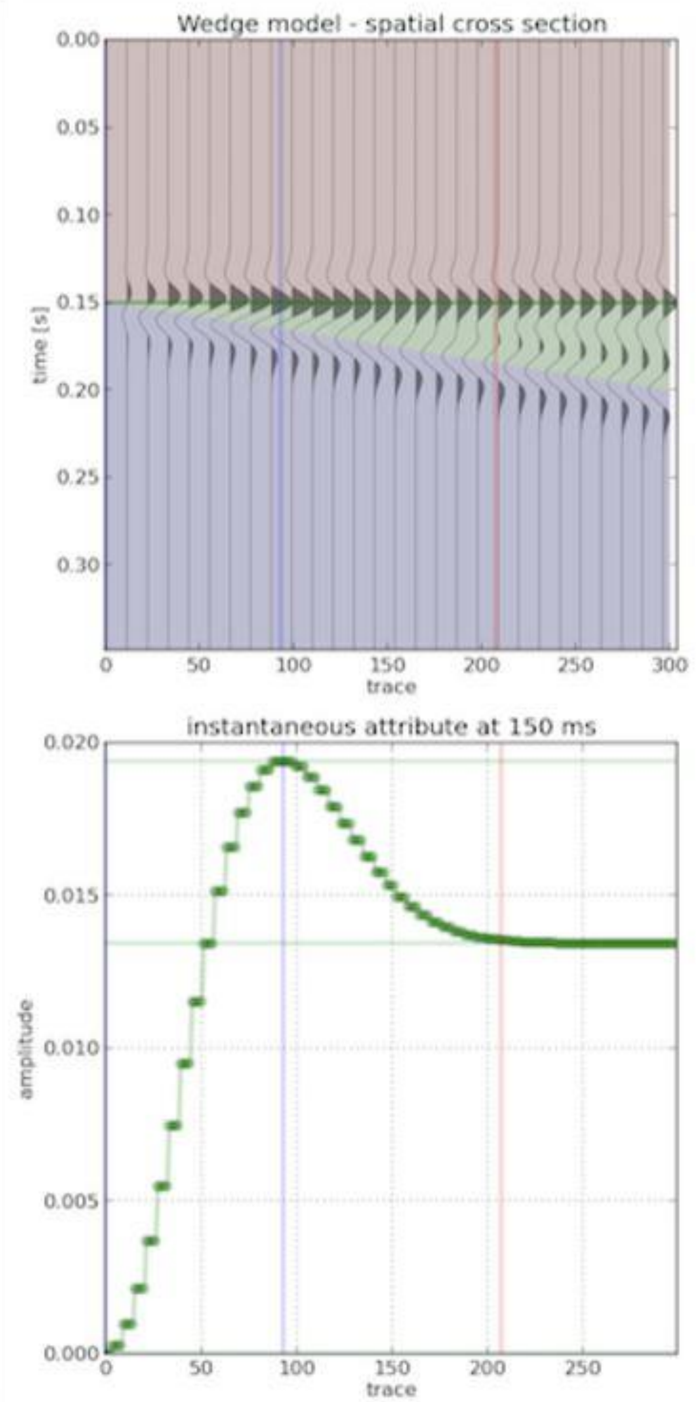


Draft what the NI seismic trace would look like.

Vertical Seismic Resolution



Amundsen & Landro, 2013



Vertical seismic resolution is ~ ¼ (Seismic Wavelength at Reservoir):

$$\lambda_{\mathbf{res}}/4 \; = (V_{\mathbf{res}}/f_{\mathbf{central}})/4$$

What is the vertical seismic resolution for a reservoir with:
Vp = 3200 m/s and wavelet frequency bandwith of 10-70 hz (1/s)?

R_Vert = (3200/40)/4 = 80m/4 = 20 meters! ~ 66 ft!

Classical Seismic Attributes

Seismic Attribute Categories		
CATEGORY	**TYPE**	**INTERPRETIVE USE**
Instantaneous Attributes	Reflection Strength, Instantaneous Phase, Instantaneous Frequency, Quadrature, Instantaneous Q	Lithology Contrasts, Bedding Continuity, Porosity, Direct Hydrocarbon Indicators, Stratigraphy, Thickness
Geometric Attributes	Semblance and Eigen-Based Coherency/Similarity, Curvature (Maximum, Minimum, Most Positive, Most Negative, Strike, Dip)	Faults, Fractures, Folds, Anisotropy, Regional Stress Fields
Amplitude Accentuating Attributes	RMS Amplitude, Relative Acoustic Impedance, Sweetness, Average Energy	Porosity, Stratigraphic and Lithologic Variations, Direct Hydrocarbon Indicators
AVO Attributes	Intercept, Gradient, Intercept/Gradient Derivatives, Fluid Factor, Lambda-Mu-Rho, Far-Near, (Far-Near) Far	Pore Fluid, Lithology, Direct Hydrocarbon Indicators
Seismic Inversion Attributes	Colored Inversion, Sparse Spike, Elastic Impedance, Extended Elastic Impedance, Prestack Simultaneous Inversion, Stochastic Inversion	Lithology, Porosity, Fluid Effects
Spectral Decomposition	Continuous Wavelet Transform, Matching Pursuit, Exponential Pursuit	Layer Thicknesses, Stratigraphic Variations

Roden et al, 2015

Time-structure Maps

- Pick horizon(s)
- Start with water bottom – polarity check, easy to pick
- Show time/depth in map view
- Fixed geological age – see deposition spatially
- Flatten to see changes in burial history

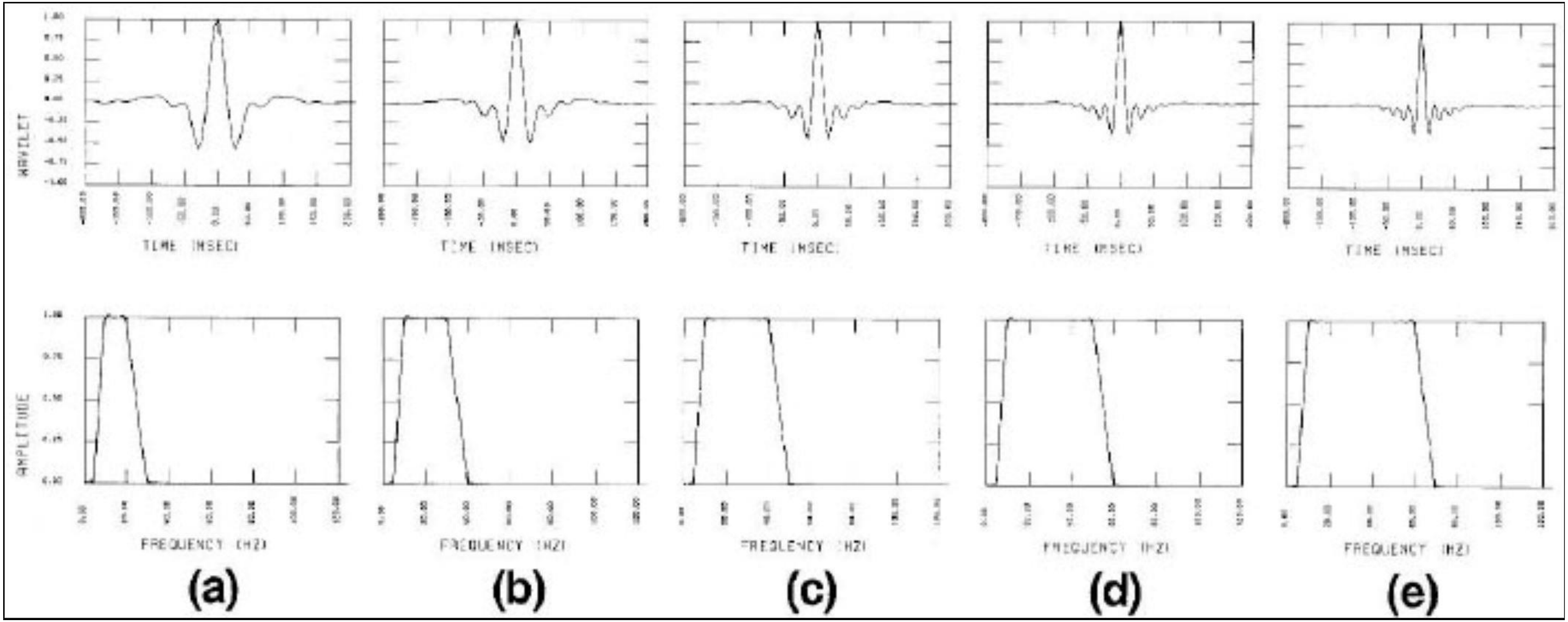
- Two horizons: convert to depth -> Thickness – reservoir volume input

Classical Seismic Attributes

Seismic Attribute Categories		
CATEGORY	**TYPE**	**INTERPRETIVE USE**
Instantaneous Attributes	Reflection Strength, Instantaneous Phase, Instantaneous Frequency, Quadrature, Instantaneous Q	Lithology Contrasts, Bedding Continuity, Porosity, Direct Hydrocarbon Indicators, Stratigraphy, Thickness
Geometric Attributes	Semblance and Eigen-Based Coherency/Similarity, Curvature (Maximum, Minimum, Most Positive, Most Negative, Strike, Dip)	Faults, Fractures, Folds, Anisotropy, Regional Stress Fields
Amplitude Accentuating Attributes	RMS Amplitude, Relative Acoustic Impedance, Sweetness, Average Energy	Porosity, Stratigraphic and Lithologic Variations, Direct Hydrocarbon Indicators
AVO Attributes	Intercept, Gradient, Intercept/Gradient Derivatives, Fluid Factor, Lambda-Mu-Rho, Far-Near, (Far-Near) Far	Pore Fluid, Lithology, Direct Hydrocarbon Indicators
Seismic Inversion Attributes	Colored Inversion, Sparse Spike, Elastic Impedance, Extended Elastic Impedance, Prestack Simultaneous Inversion, Stochastic Inversion	Lithology, Porosity, Fluid Effects
Spectral Decomposition	Continuous Wavelet Transform, Matching Pursuit, Exponential Pursuit	Layer Thicknesses, Stratigraphic Variations

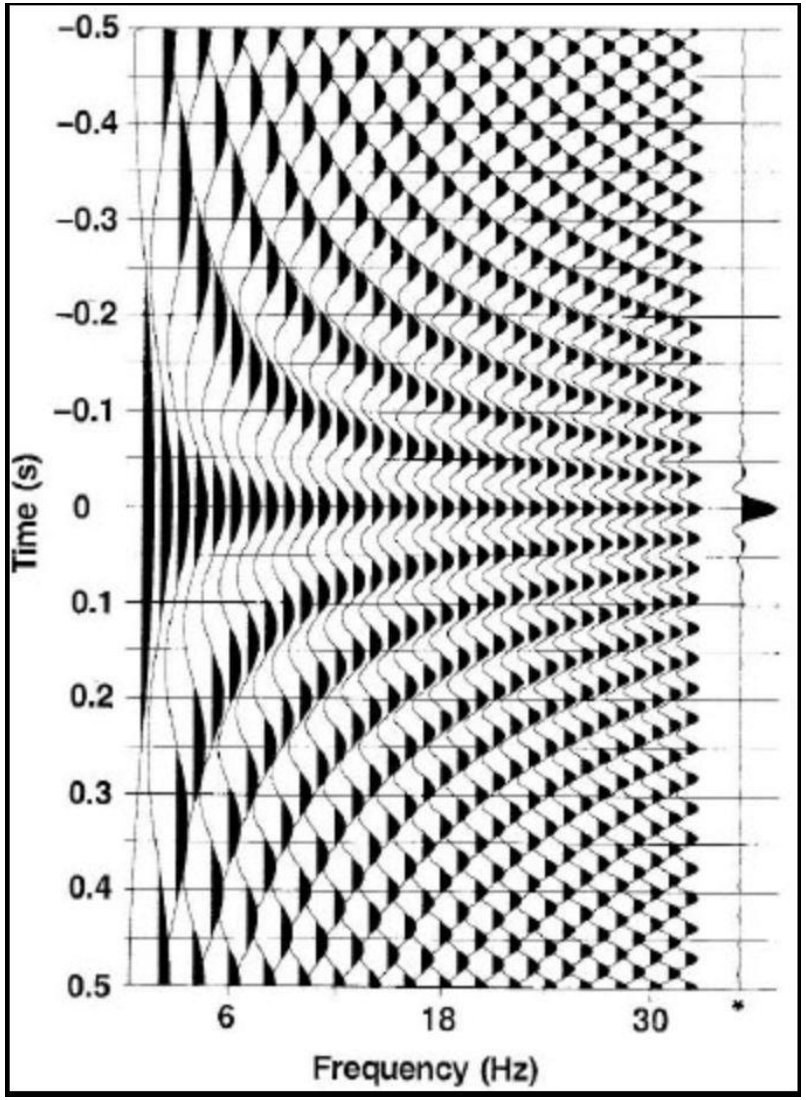
Roden et al, 2015

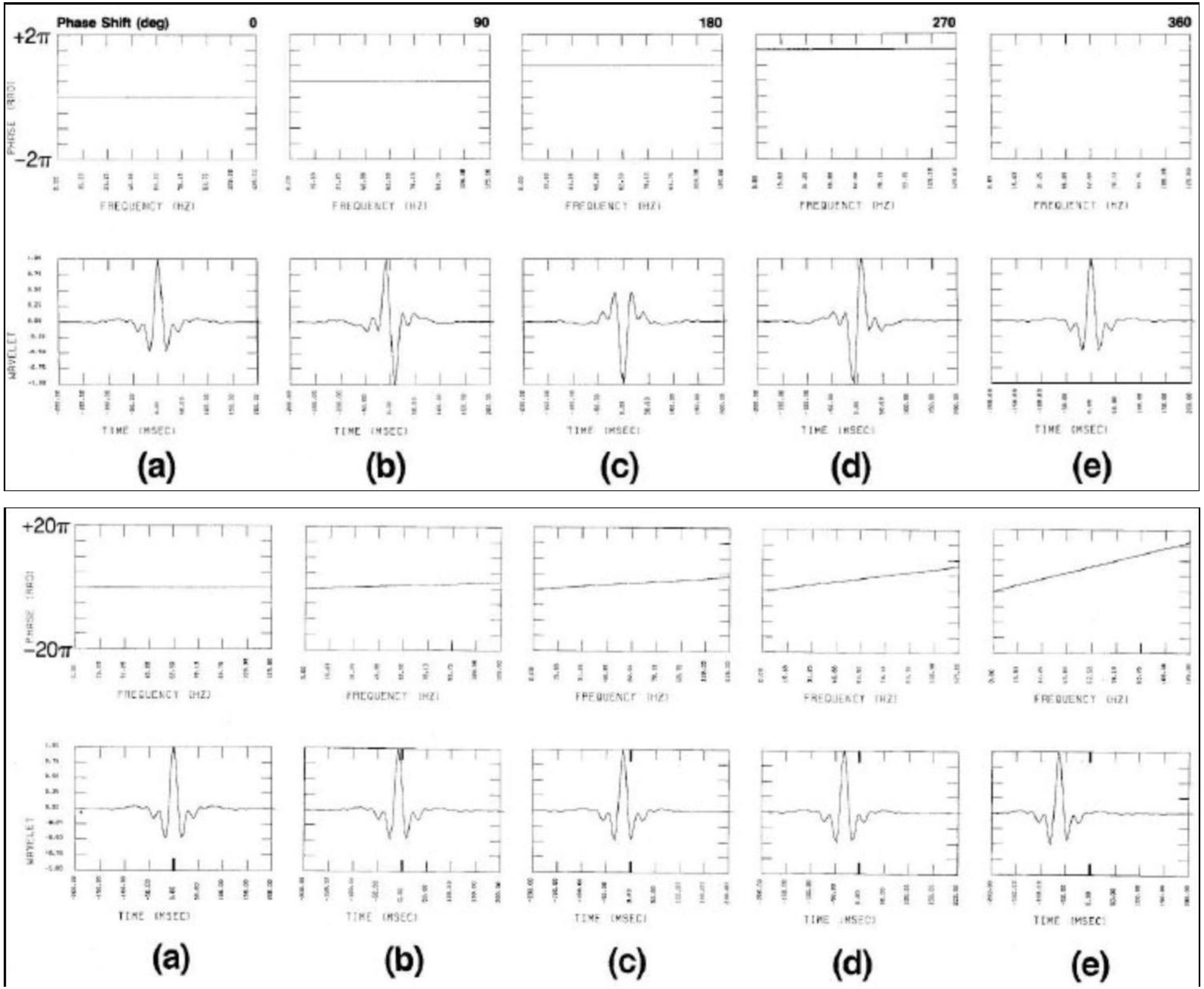
Amplitude Spectrum



Yilmaz, 2001

Phase Spectrum





Yilmaz, 2001

Instantaneous Amplitude, Phase, Frequency & Quadrature

$u(t) = x(t) + iy(t)$ — $x(t)$ is the recorded trace, $u(t)$ is the analytical trace and $y(t)$ is the quadrature (90^o phase shifted version)

$y(t) = \frac{1}{\pi\, t} * x(t)$ — $y(t)$ is Hilbert transform of $x(t)$ - **Quadrature**

$u(t) = \left[\delta(t) + i\frac{1}{\pi\, t}\right] * x(t)$ — ***To get analytical trace apply bracket term to recorded trace***

$u(t) = R(t)\, exp[i\varphi(t)]$ — Express in polar form

$R(t) = \sqrt{x^2(t) + y^2(t)}$ — ***Instantaneous Amplitude***: Reflectivity and Energy -> e.g. Bright/Dim spots (forms **trace envelope**)

$\varphi(t) = Im[ln\, u(t)]$ — ***Instantaneous Phase***: Continuity of events (in t-direction!) -> e.g. Pinchouts, Faults, onlaps, prograding reflections

$\omega(t) = \frac{d\varphi(t)}{dt} = Im\left[\frac{1}{u(t)}\frac{du(t)}{dt}\right] = \frac{2}{\Delta t} Im\left[\frac{u_t - u_{t-\Delta t}}{u_t + u_{t-\Delta t}}\right]$ — ***Instantaneous Frequency***: Frequency attenuation -> e.g. Condensate, Gas reservoirs

At a certain time t – not average over a time interval!

Instantaneous Quality (Q) Factor

$$q(t) = \frac{-\pi\,\omega(t)}{decay(t)} = \frac{-\pi\,\omega(t)\,R(t)}{\frac{dR(t)}{dt}}$$

$decay\ (t)$ is the instantaneous decay rate = First derivative of trace envelope/trace envelope.
$\omega(t)$ is the instantaneous frequency
$R(t)$ is the trace envelope

Indicates local variation of attenuation – liquid/gas content, relative absorption of beds

Sweetness Attribute

$$\boldsymbol{Sweetness} = \boldsymbol{R(t)}/\sqrt{\boldsymbol{\omega(t)}}$$

The sweetness attribute is a plain and simple tool to highlight:
1) thick clean reservoir, and/or 2) hydrocarbons (HC) filled reservoir.

Principle is you divide a amplitude attribute with a frequency attribute.

For reservoir (low AI sand embedded in shale) the effects are that when the reservoir gets cleaner or thicker, the amplitude term increases due to higher reflectivity and frequency of the combined reflections lower as the thicknesses increases.

For HC presence (assuming an AVO 3 environment, where introduction of HC leads to brightening), the effects are when HC gets introduced that amplitude increases due to higher reflectivity and frequency of the reflection is lower due to the combined effects of HC on the frequency content.

Instantaneous Attributes

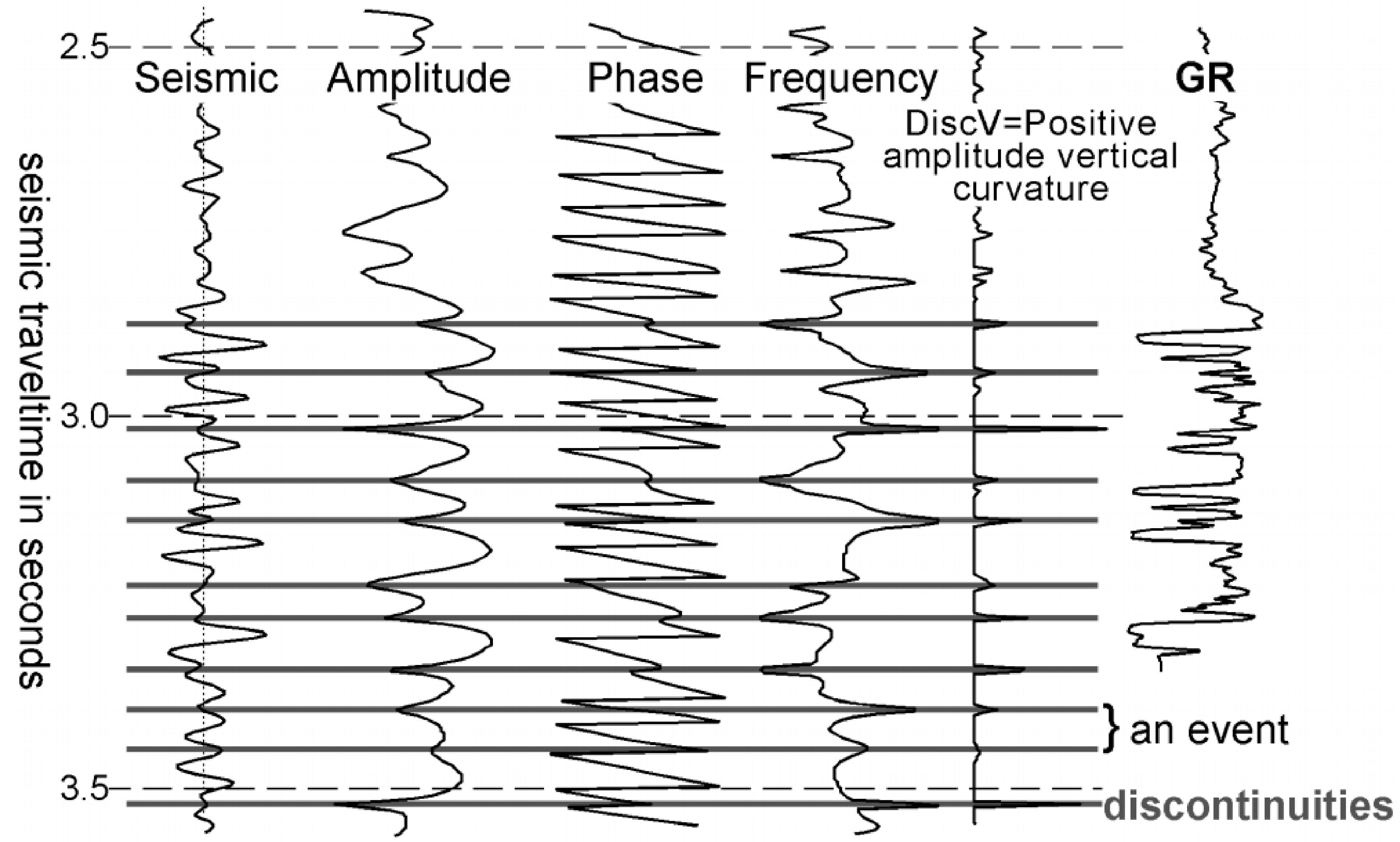
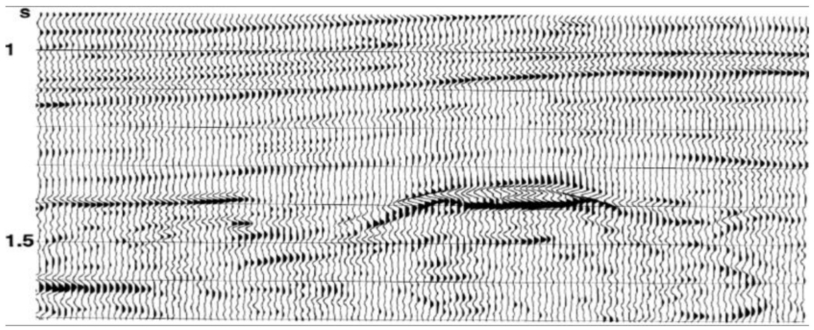


Figure 4. A comparison of seismic attributes for the seismic trace at North Gorgon 2.

Radovich and Oliveros, 1998

Bright Spot Example



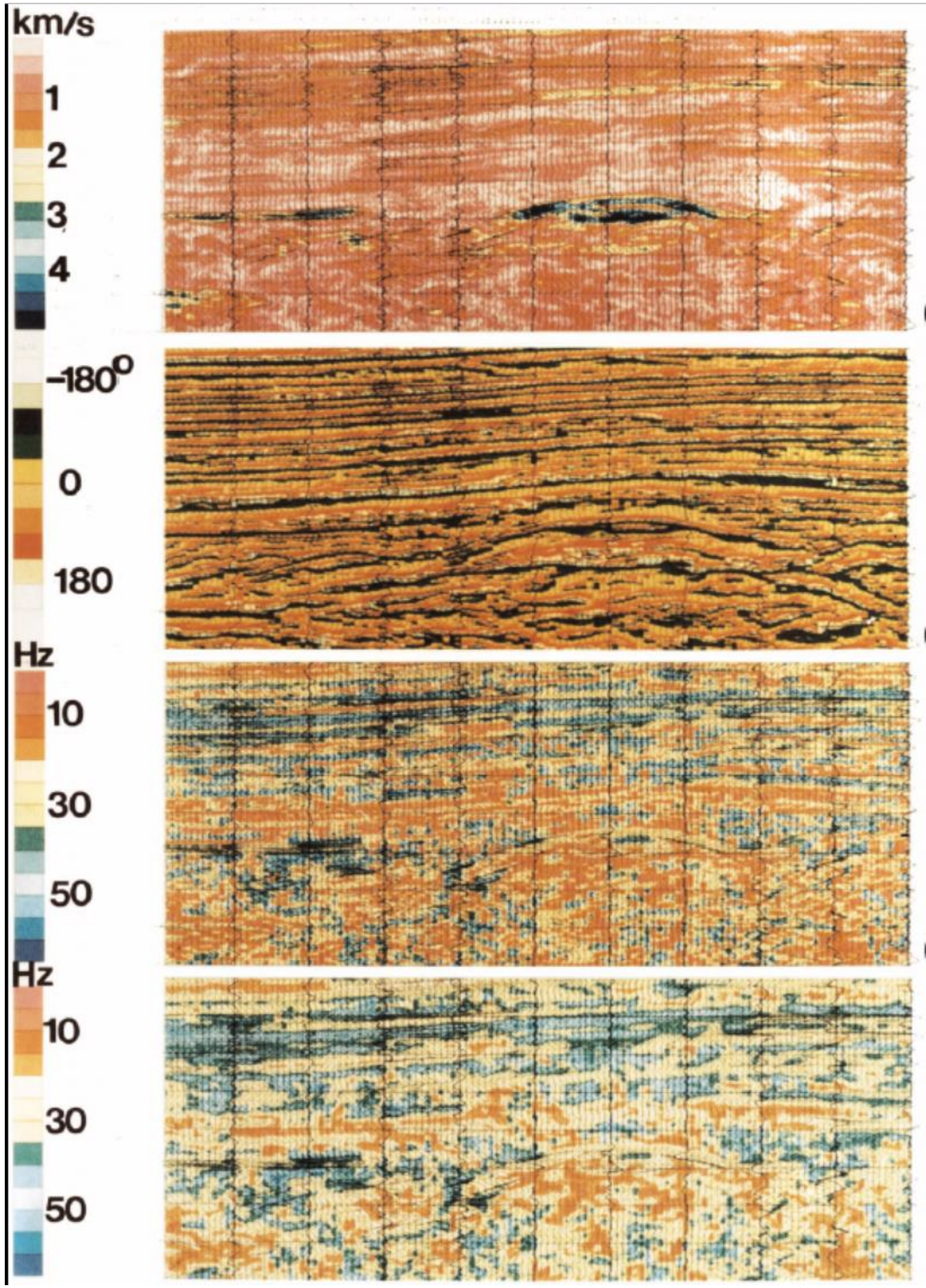
Original Bright Spot Seismic

Instantaneous Amplitude

Instantaneous Phase

Instantaneous Frequency

Smoothed Frequency



SEG Wiki

Classical Seismic Attributes

Seismic Attribute Categories		
CATEGORY	**TYPE**	**INTERPRETIVE USE**
Instantaneous Attributes	Reflection Strength, Instantaneous Phase, Instantaneous Frequency, Quadrature, Instantaneous Q	Lithology Contrasts, Bedding Continuity, Porosity, Direct Hydrocarbon Indicators, Stratigraphy, Thickness
Geometric Attributes	Semblance and Eigen-Based Coherency/Similarity, Curvature (Maximum, Minimum, Most Positive, Most Negative, Strike, Dip)	Faults, Fractures, Folds, Anisotropy, Regional Stress Fields
Amplitude Accentuating Attributes	RMS Amplitude, Relative Acoustic Impedance, Sweetness, Average Energy	Porosity, Stratigraphic and Lithologic Variations, Direct Hydrocarbon Indicators
AVO Attributes	Intercept, Gradient, Intercept/Gradient Derivatives, Fluid Factor, Lambda-Mu-Rho, Far-Near, (Far-Near) Far	Pore Fluid, Lithology, Direct Hydrocarbon Indicators
Seismic Inversion Attributes	Colored Inversion, Sparse Spike, Elastic Impedance, Extended Elastic Impedance, Prestack Simultaneous Inversion, Stochastic Inversion	Lithology, Porosity, Fluid Effects
Spectral Decomposition	Continuous Wavelet Transform, Matching Pursuit, Exponential Pursuit	Layer Thicknesses, Stratigraphic Variations

Roden et al, 2015

Geometric Attributes

- Compare neighboring traces:

- Coherency
- Curvature
    - Maximum, Minimum, Most positive, Most negative, Strike, Dip

Coherency:
On a time-slice

- Take a time slice
- Calculate trace-to-trace coherence
- Locations with faults will show a sharp discontinuity in coherence…

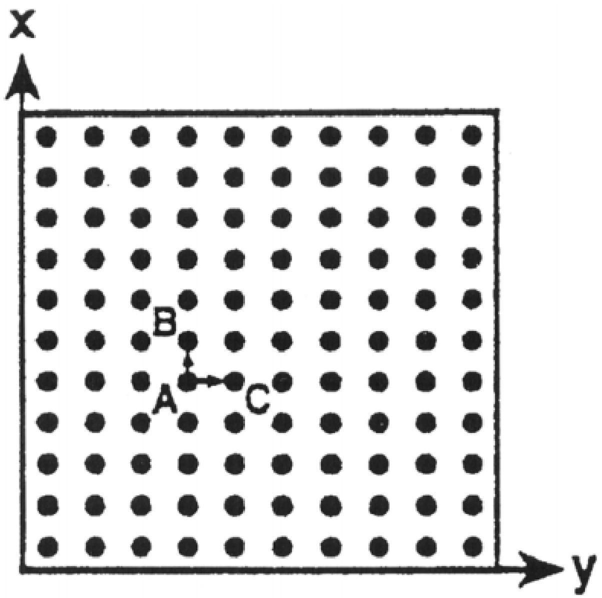


Figure 2.3-D coherence may be measured by calculating seismic trace similarity in the inline and crossline directions. A three-trace operator is depicted. This is the minimum size required for a 3-D calculation although more traces can be used. Coherence may be measured from trace A to trace C and from trace A to trace B. A combination of these 2-D measurements provides a measure of 3-D coherence. For a nine-trace operator, coherence

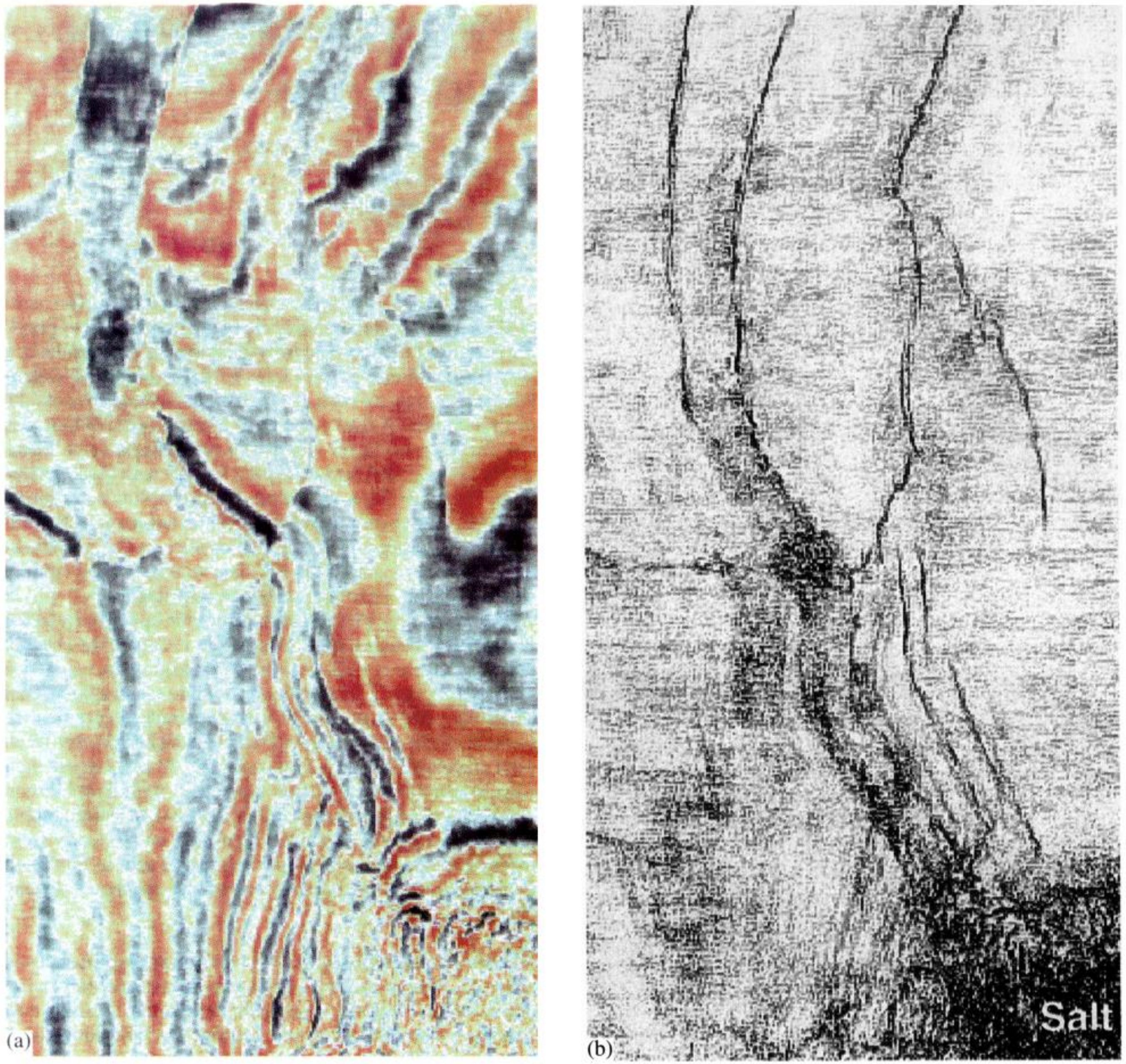


Figure 1. (a) Traditional 3-D seismic time slice. Faults parallel to strike are difficult to see. (b) Coherency time slice. Faults are clearly visible.

Bahorich and Farmer, 1995

Coherency:

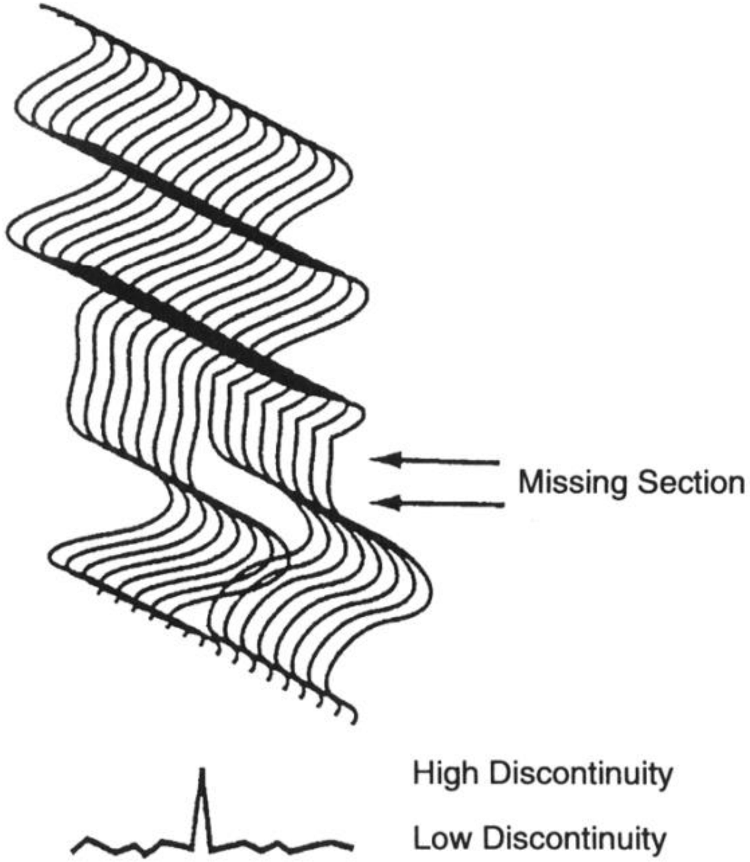


Figure 3. Faults are highlighted by the 3-D coherence technique because traces are not identical on opposite sides of a fault. In this example, missing stratigraphic section from one side of a fault to another generates slightly different reflectivity on one side of the fault. The coherence is lower when the traces are less similar.

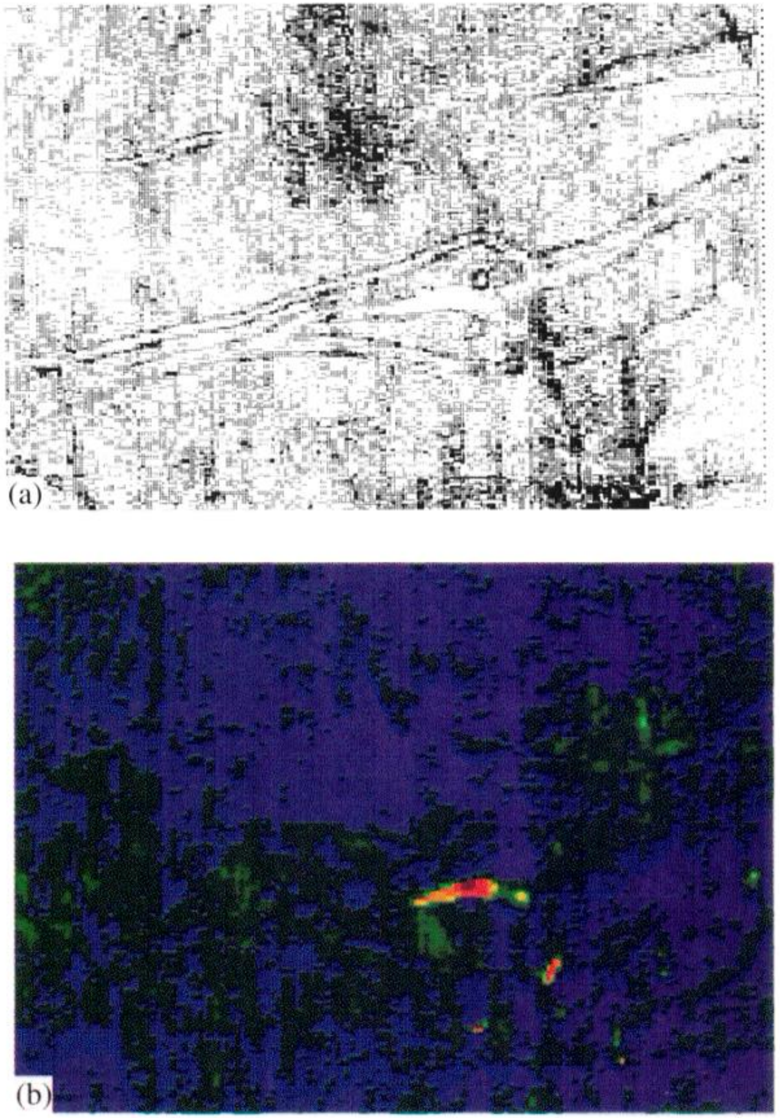


Figure 4. (a) Coherence slice across a channel system. Coherence images the stratigraphic context better while amplitude data in the next panel image hydrocarbons more clearly. (b) Average amplitude over a series of time slices. Note that the bright spot is located within the channel seen on the coherence display.

Bahorich and Farmer, 1995

Curvature

For a two-dimensional curve, curvature is defined as the reciprocal of the radius of a circle that is tangent to the given curve at a particular point (Figure 1). Curvature will be large for a curve that is tightly folded and will be zero for a straight line, whether horizontal or dipping. As a convention, anticlinal features are assigned a positive and synclinal surfaces a negative value.

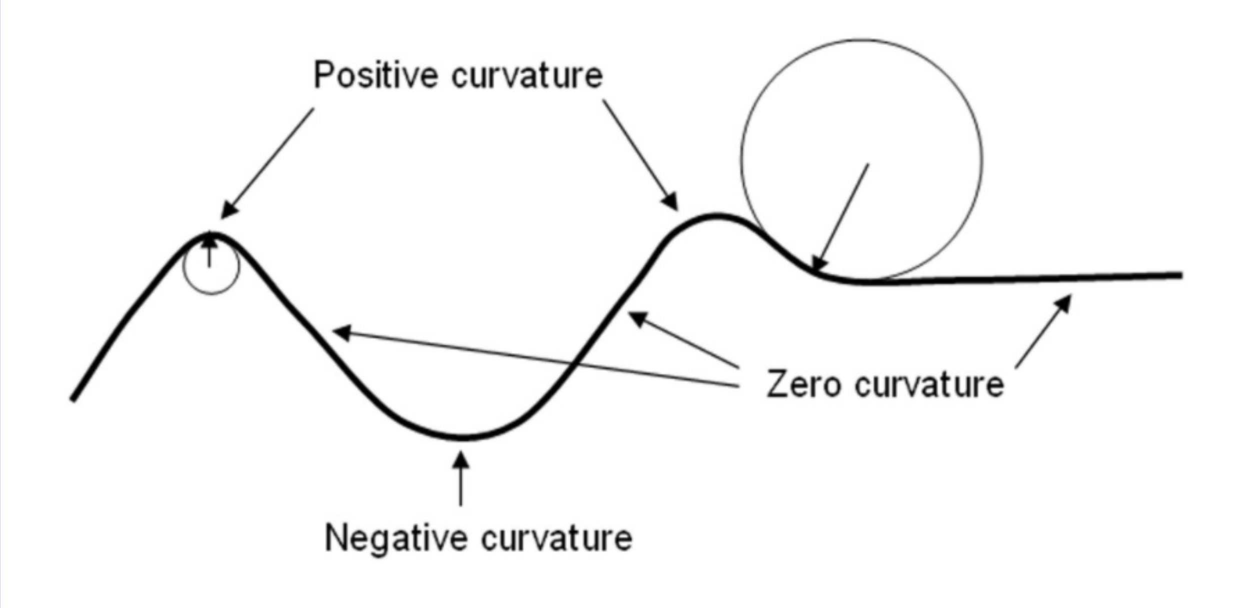


Figure 1. 2D curvature of a line. Anticlinal features have positive curvature, synclinal features have negative curvature and planar features (horizontal or dipping) have zero curvature.

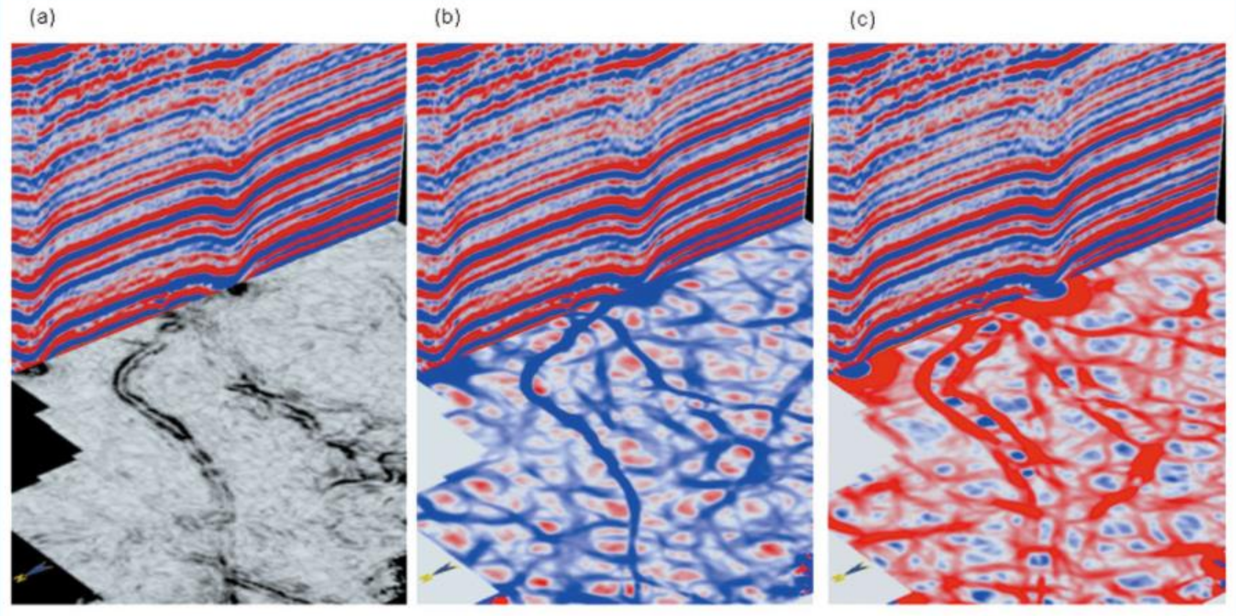


Figure 4. Zoom of chair-displays where the vertical display the same seismic line shown in Figure 3. The horizontal displays are time slices through (a) coherence (b) most-positive and (c) most-negative curvature attribute volumes. Channel features on the curvature attributes are seen clearly and correlate with their seismic signatures.

Chopra and Marfurt, 2007

Conclusions

Like all attributes, curvature is valuable only when coupled with a geologic model of structural deformation, stratigraphic deposition, or diagenetic alteration. Curvature is particularly sensitive to flexures and faults. Curvature can be a powerful tool in mapping channels, levees, bars, contourites, and other stratigraphic features, particularly in older rocks that have undergone differential compaction such as the examples shown here.

Discrete fractures often appear on most negative curvature, though the cause can be either due to sags about the fractures or due to local velocity changes associated with stress, porosity, diagenetic alteration, or fluid charge. Although curvature attributes run on time surfaces after spatial filtering can often provide valuable results, volumetric curvature attributes provide valuable information on fracture orientation and density in zones where seismic horizons are not trackable. The orientations of the fault/fracture lineaments interpreted on curvature displays can be combined in the form of rose diagrams, which in turn can be compared with similar diagrams obtained from image logs to gain confidence in calibration.

Chopra and Marfurt, 2007

Dip Azimuth and Dip Magnitude

Horizon:

- Calculate from time structure
- Display on horizon
- When combined with a light source and observer location it will generate a 'shaded-relief' map – common in most interpretation packages
- Can scan many angles between light source and observer
- Can highlight channels, faults, karst type features

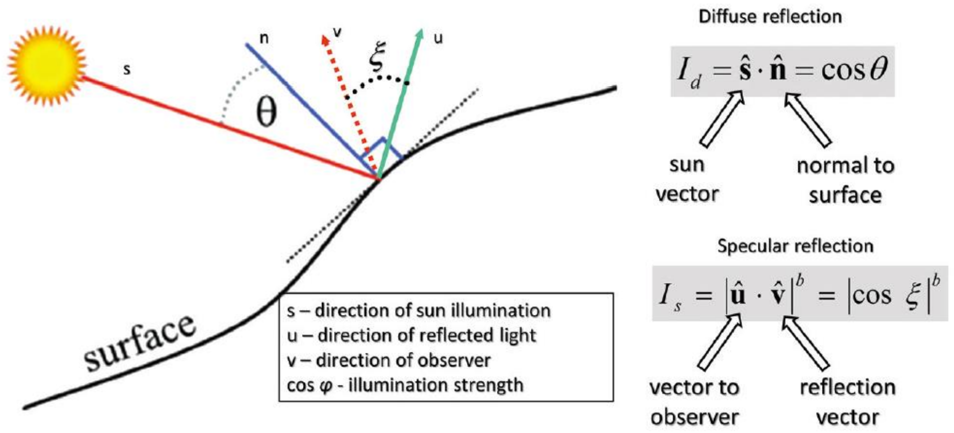


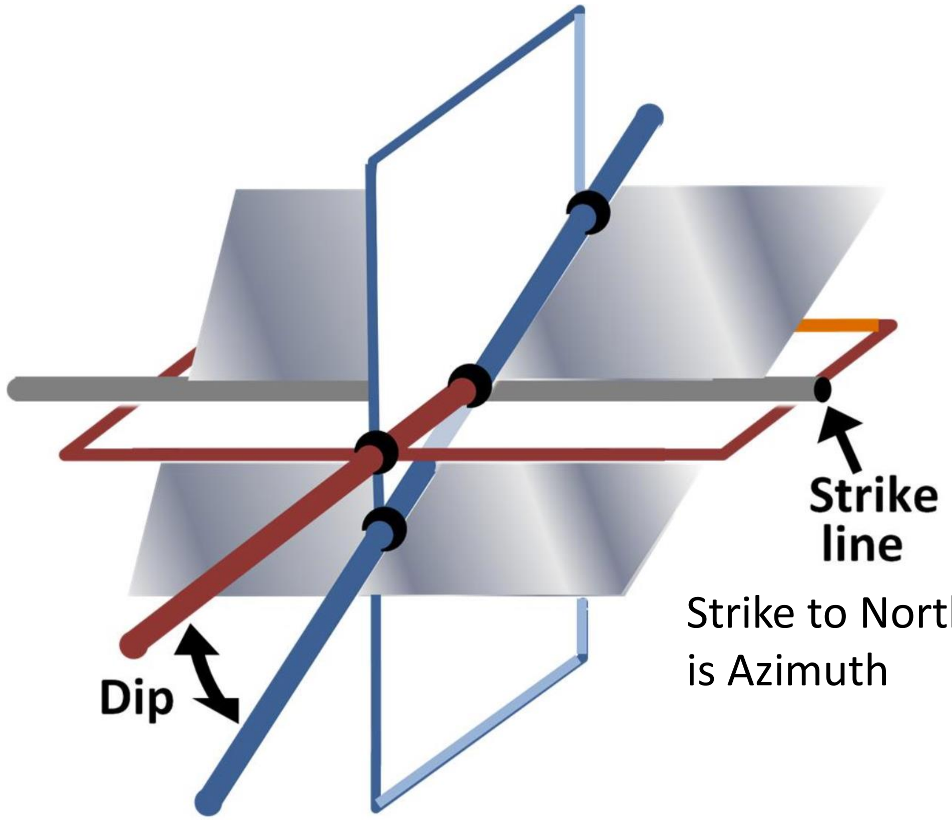
Figure 4. The illumination model for light reflected specularly. Unit vector **n** is the surface normal, **s** points to the light source, **v** is the direction of specularly reflected light, **u** points to the observer, and ξ is the angle between **u** and **v**. Illumination *I* is a function of the cosine of ξ and a user-defined exponent *b* that defines the "shininess" of the surface. After Figure 3 of Barnes (2002). Reprinted by permission of the AAPG, whose permission is required for further use.

Marfurt, 2018

Dip Azimuth and Dip Magnitude

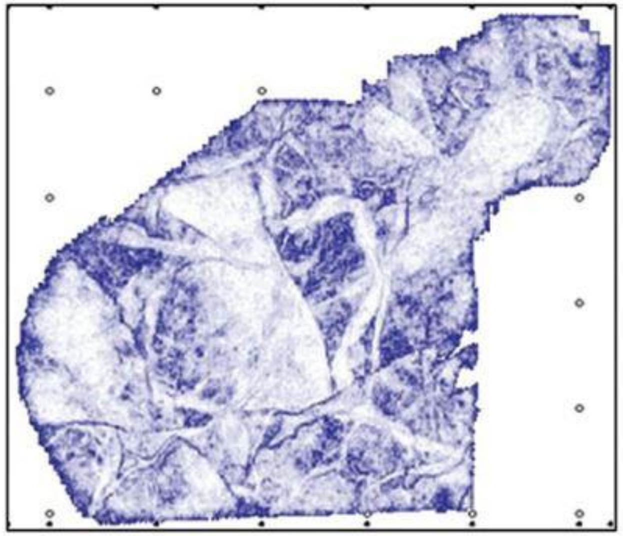
Volume:

- Compute on volume of seismic data
- Find dip of planer reflector in search window
- Calculate largest semblance form 2-D dip search (similar to velocity analysis). Calculate inline and crossline dip
- Repeat search for a group of traces (say 5) and time window (say +/- 30ms).

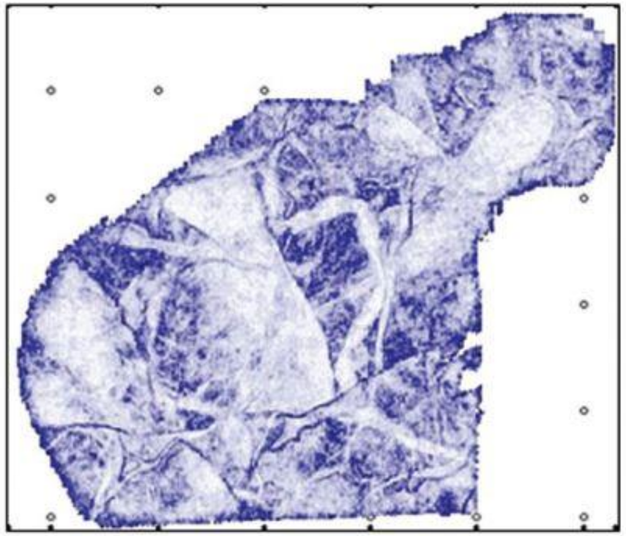


Strike to North
is Azimuth

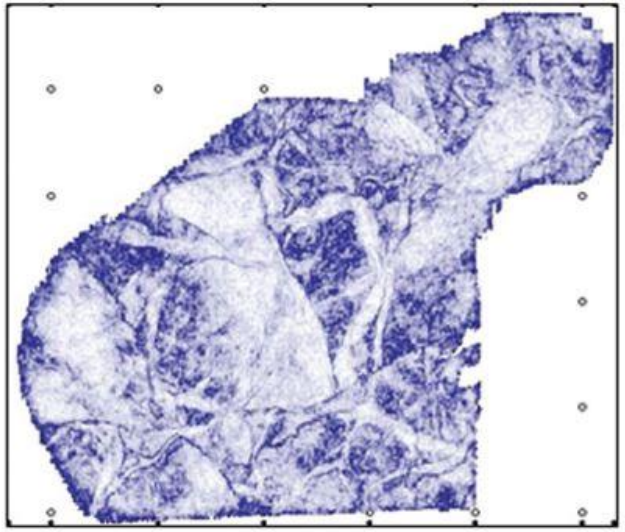
Seismic Geometric/Continuity Attributes



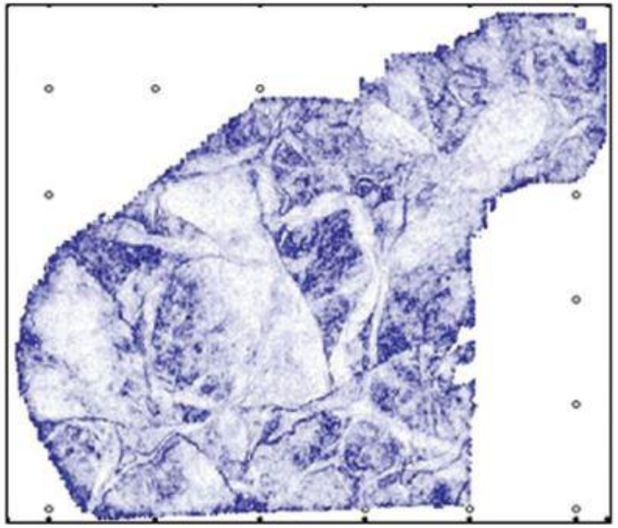
Correlation



Semblance



Covariance



Weighted Correlation

Roden et al, 2015

Classical Seismic Attributes

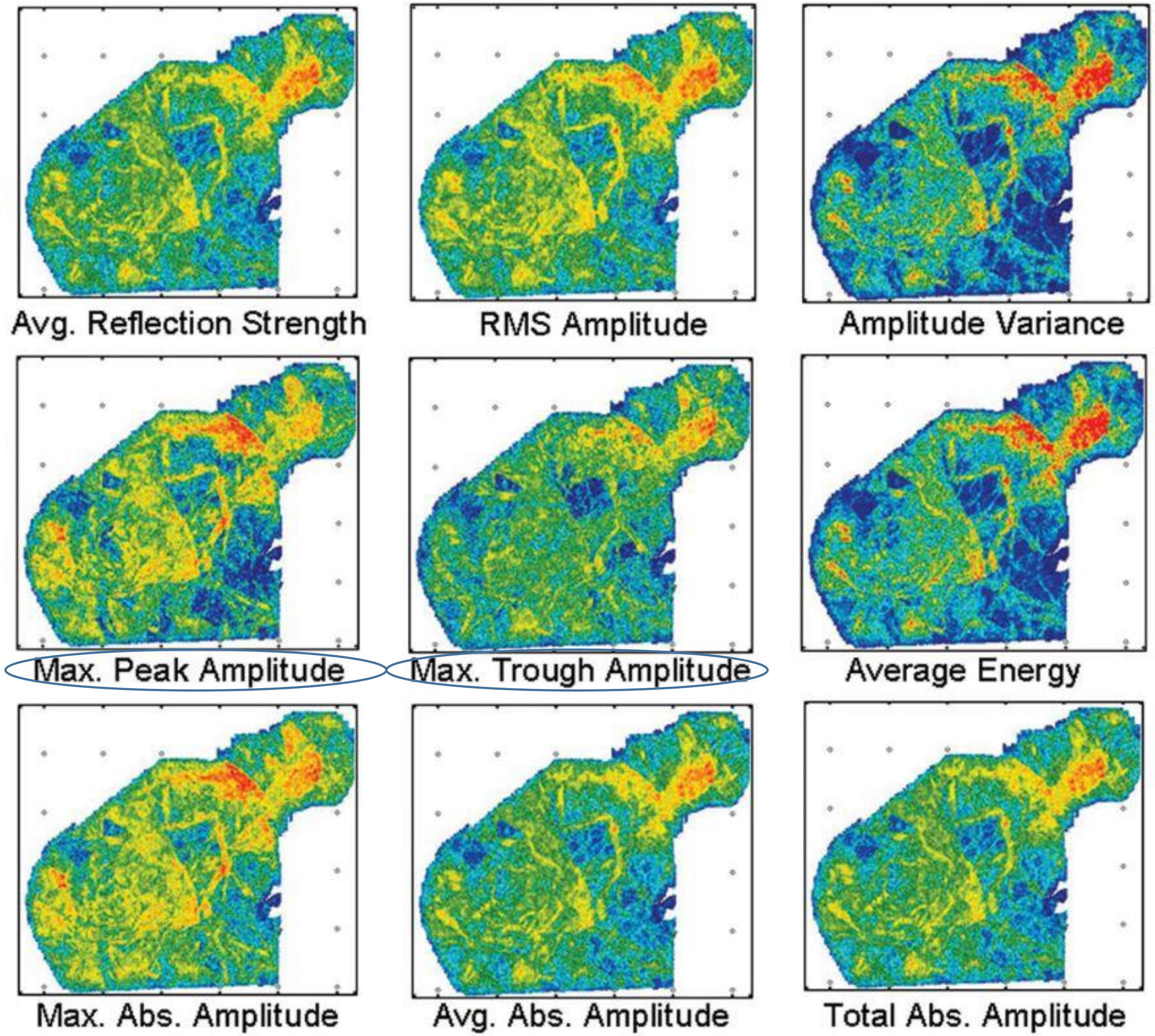
Seismic Attribute Categories		
CATEGORY	**TYPE**	**INTERPRETIVE USE**
Instantaneous Attributes	Reflection Strength, Instantaneous Phase, Instantaneous Frequency, Quadrature, Instantaneous Q	Lithology Contrasts, Bedding Continuity, Porosity, Direct Hydrocarbon Indicators, Stratigraphy, Thickness
Geometric Attributes	Semblance and Eigen-Based Coherency/Similarity, Curvature (Maximum, Minimum, Most Positive, Most Negative, Strike, Dip)	Faults, Fractures, Folds, Anisotropy, Regional Stress Fields
Amplitude Accentuating Attributes	RMS Amplitude, Relative Acoustic Impedance, Sweetness, Average Energy	Porosity, Stratigraphic and Lithologic Variations, Direct Hydrocarbon Indicators
AVO Attributes	Intercept, Gradient, Intercept/Gradient Derivatives, Fluid Factor, Lambda-Mu-Rho, Far-Near, (Far-Near) Far	Pore Fluid, Lithology, Direct Hydrocarbon Indicators
Seismic Inversion Attributes	Colored Inversion, Sparse Spike, Elastic Impedance, Extended Elastic Impedance, Prestack Simultaneous Inversion, Stochastic Inversion	Lithology, Porosity, Fluid Effects
Spectral Decomposition	Continuous Wavelet Transform, Matching Pursuit, Exponential Pursuit	Layer Thicknesses, Stratigraphic Variations

Roden et al, 2015

Amplitude Attributes

- Pick horizon(s) - snapped to peak or through.
- Calculate on horizons:
  - Seismic Amplitude (peak, through) along picked horizon (porosity, fluids-DHI)
- Calculate around horizons but in a time window – more stable:
  - Mean Amplitude = $\frac{x_1+x_2+\cdots+x_N}{N}$
  - RMS Amplitude = $\sqrt{\frac{x_1^2+x_2^2+\cdots+x_N^2}{N}}$
  - Average Energy = $\frac{x_1^2+x_2^2+\cdots+x_N^2}{N}$

Seismic Amplitude Attributes



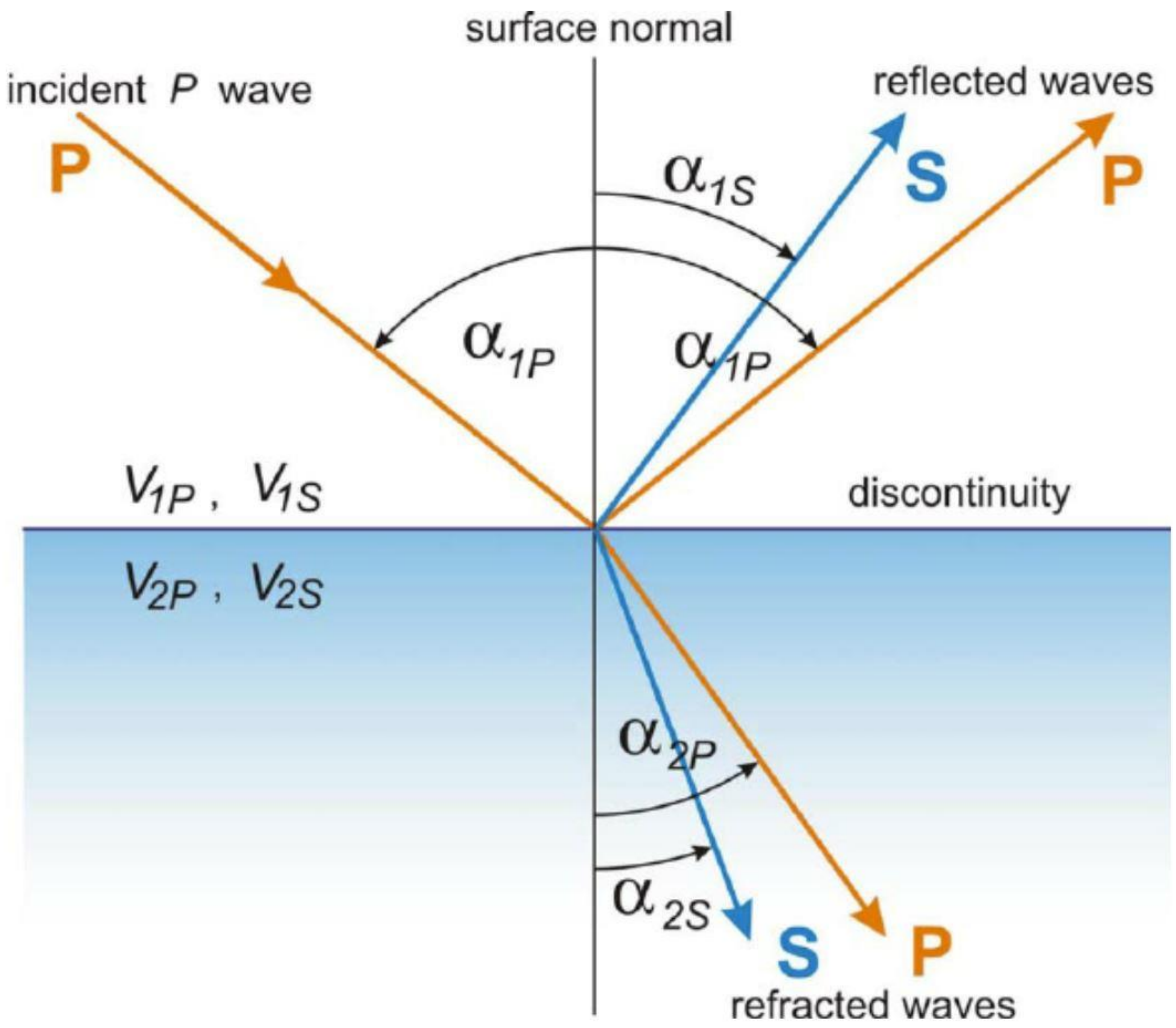
Roden et al, 2015

Classical Seismic Attributes

Seismic Attribute Categories		
CATEGORY	**TYPE**	**INTERPRETIVE USE**
Instantaneous Attributes	Reflection Strength, Instantaneous Phase, Instantaneous Frequency, Quadrature, Instantaneous Q	Lithology Contrasts, Bedding Continuity, Porosity, Direct Hydrocarbon Indicators, Stratigraphy, Thickness
Geometric Attributes	Semblance and Eigen-Based Coherency/Similarity, Curvature (Maximum, Minimum, Most Positive, Most Negative, Strike, Dip)	Faults, Fractures, Folds, Anisotropy, Regional Stress Fields
Amplitude Accentuating Attributes	RMS Amplitude, Relative Acoustic Impedance, Sweetness, Average Energy	Porosity, Stratigraphic and Lithologic Variations, Direct Hydrocarbon Indicators
AVO Attributes	Intercept, Gradient, Intercept/Gradient Derivatives, Fluid Factor, Lambda-Mu-Rho, Far-Near, (Far-Near) Far	Pore Fluid, Lithology, Direct Hydrocarbon Indicators
Seismic Inversion Attributes	Colored Inversion, Sparse Spike, Elastic Impedance, Extended Elastic Impedance, Prestack Simultaneous Inversion, Stochastic Inversion	Lithology, Porosity, Fluid Effects
Spectral Decomposition	Continuous Wavelet Transform, Matching Pursuit, Exponential Pursuit	Layer Thicknesses, Stratigraphic Variations

Roden et al, 2015

Reflected P-wave with Offset in isotropic Media…



PP-wave Reflection Isotropic:

$$R_{pp}(\theta) = \frac{1}{2}(1+\tan^2\theta)\frac{\Delta Ip}{Ip} - 4\left(\frac{Vs}{Vp}\right)^2 \sin^2\theta\frac{\Delta Is}{Is} - \left[\frac{1}{2}\tan^2\theta - 2\left(\frac{Vs}{Vp}\right)^2\sin^2\theta\right]\frac{\Delta\rho}{\rho}$$

So, Isotropic PP-reflection depends on ***Vp, Vs and density***!

Note: Actually very hard to get third term: (Δρ/ρ)….

($\theta = \alpha_{1p}$)

AVO Amplitude Attributes – Pre-stack Seismic

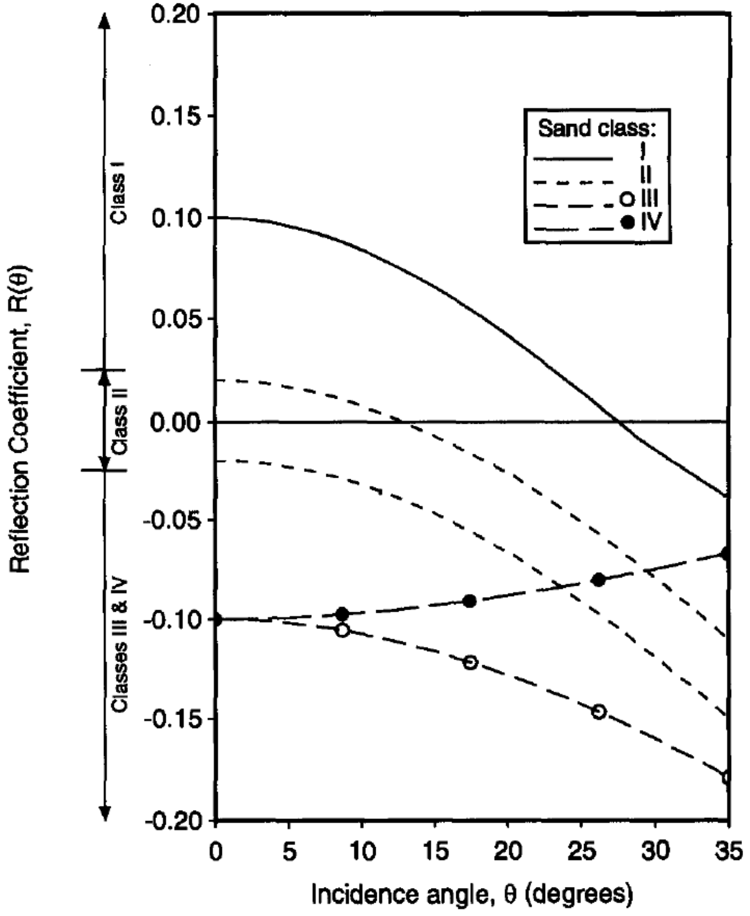
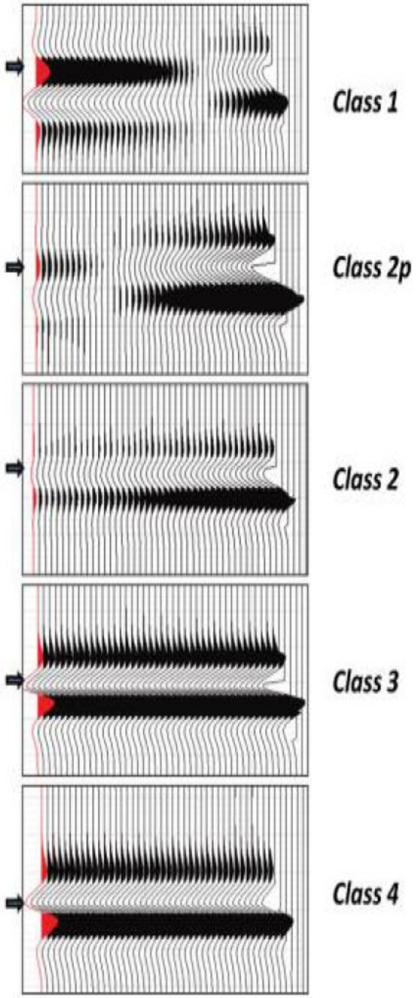


FIG. 7. Plane-wave reflection coefficients at the top of each Rutherford and Williams (1989) classification of gas sand. Class IV sands, not discussed by Rutherford and Williams, have a negative normal-incidence reflection coefficient, but decrease in amplitude magnitude with offset.



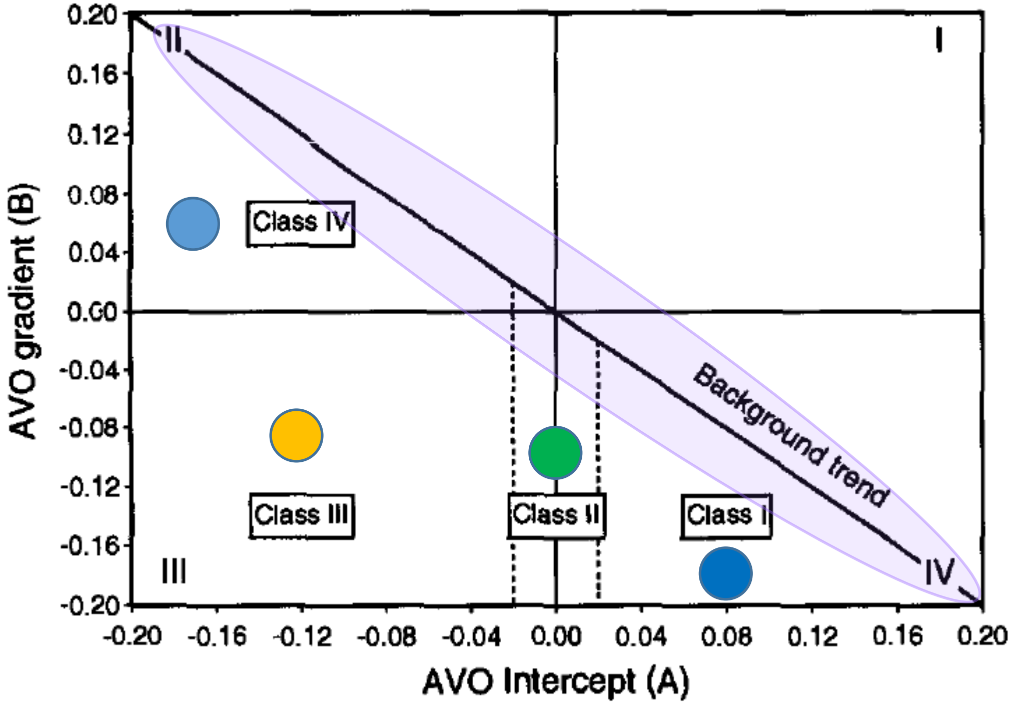


FIG. 6. AVO intercept (A) versus gradient (B) crossplot showing four possible quadrants. For a limited time window, brine-saturated sandstones and shales tend to fall along a well-defined background trend. Top of gas-sand reflections tend to fall below the background trend, whereas bottom of gas-sand reflections tend to fall above the trend. Augmented Rutherford and Williams (1989) gas sand classes are also indicated for reference.

Castagna et al, 1998
Roden et al, 2014

Classical Seismic Attributes

Seismic Attribute Categories		
CATEGORY	**TYPE**	**INTERPRETIVE USE**
Instantaneous Attributes	Reflection Strength, Instantaneous Phase, Instantaneous Frequency, Quadrature, Instantaneous Q	Lithology Contrasts, Bedding Continuity, Porosity, Direct Hydrocarbon Indicators, Stratigraphy, Thickness
Geometric Attributes	Semblance and Eigen-Based Coherency/Similarity, Curvature (Maximum, Minimum, Most Positive, Most Negative, Strike, Dip)	Faults, Fractures, Folds, Anisotropy, Regional Stress Fields
Amplitude Accentuating Attributes	RMS Amplitude, Relative Acoustic Impedance, Sweetness, Average Energy	Porosity, Stratigraphic and Lithologic Variations, Direct Hydrocarbon Indicators
AVO Attributes	Intercept, Gradient, Intercept/Gradient Derivatives, Fluid Factor, Lambda-Mu-Rho, Far-Near, (Far-Near) Far	Pore Fluid, Lithology, Direct Hydrocarbon Indicators
Seismic Inversion Attributes	Colored Inversion, Sparse Spike, Elastic Impedance, Extended Elastic Impedance, Prestack Simultaneous Inversion, Stochastic Inversion	Lithology, Porosity, Fluid Effects
Spectral Decomposition	Continuous Wavelet Transform, Matching Pursuit, Exponential Pursuit	Layer Thicknesses, Stratigraphic Variations

Roden et al, 2015

Seismic Inversion

Going from interface properties to layer properties:

- Poor mans inversion: -90^{o} phase-shift

- Post-stack seismic inversion – Ip only
- Pre-stack seismic inversion – Ip, some Is, not really density (see PP-reflection equation)
- Joint PP and PS pre-stack inversion – Ip, better Is and density (see PP and PS-reflection equation)
  - Needs:
    - Wavelet estimation with reflection angle
    - Low frequency model interpolated from wells
    - Uses constrained Sparse-Spike Inversion

- Geostatistical inversion – high frequency but non-unique -> range of inversions…
  - Needs spatial statistics from wells – PDF -> Historgrams, Variograms. Posterior PDF via Bayesian inference

Phase & Quadrature

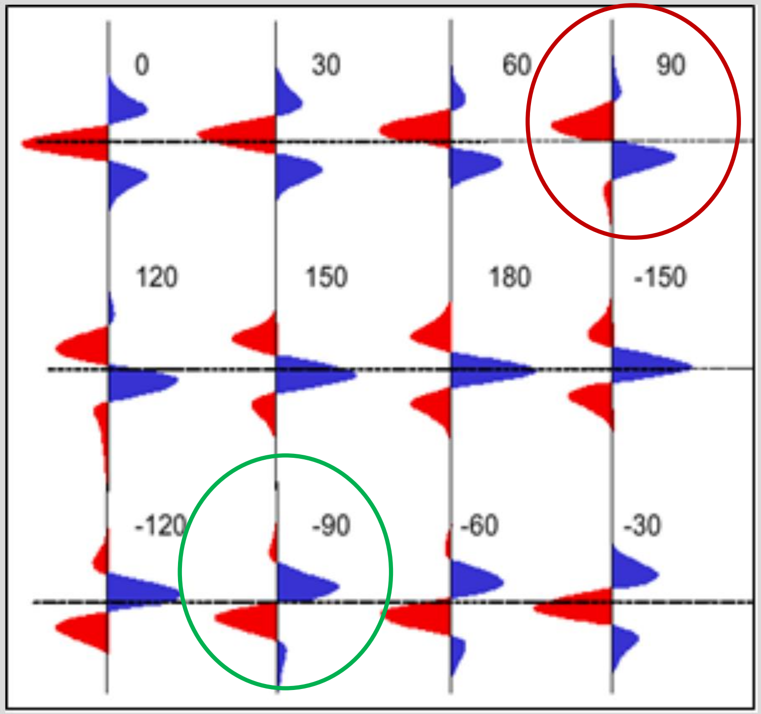
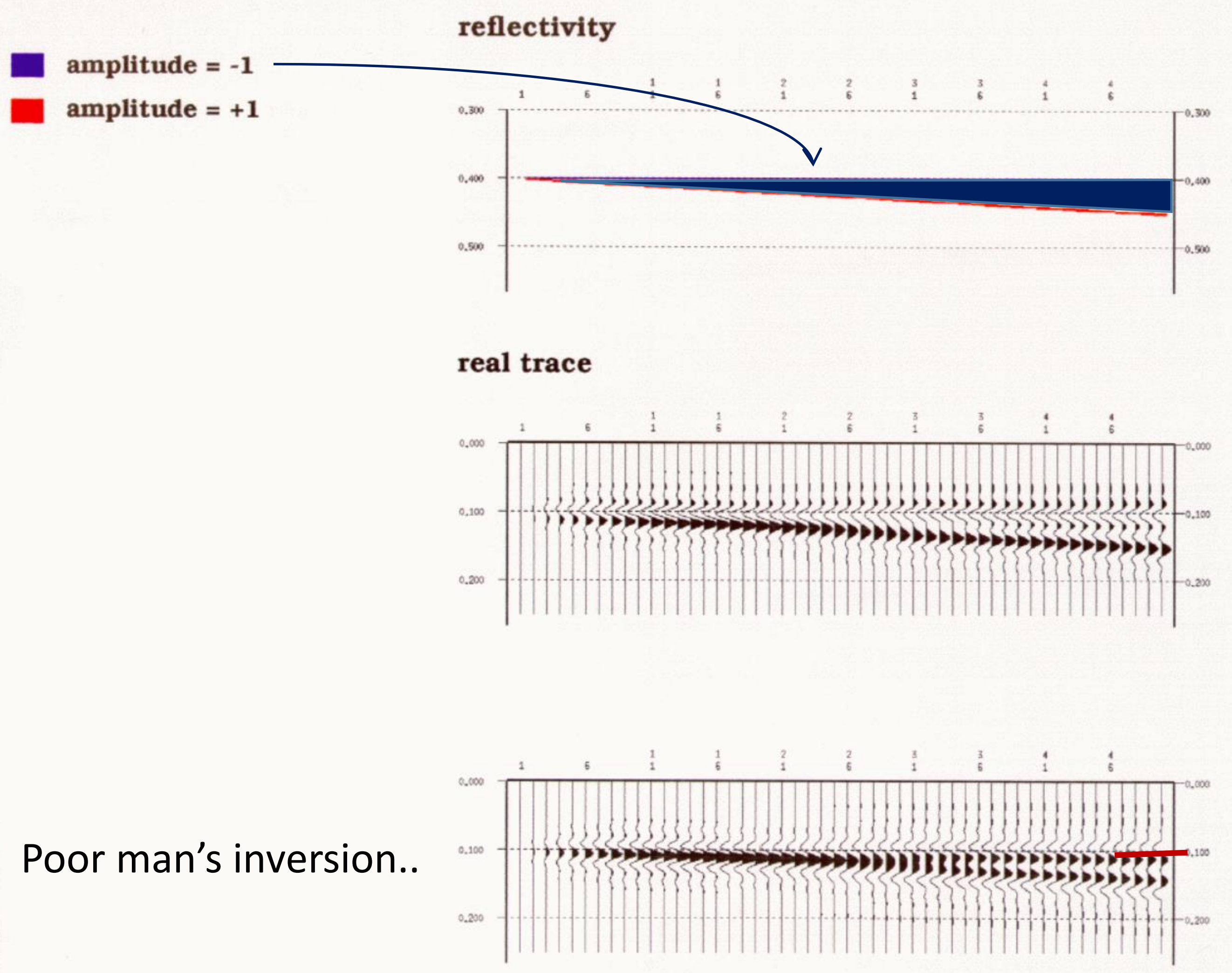


Figure-6.Phase rotation of a zero phase (0^0 of phase) wavelet showing phase reversal while rotated 180^0.



Poor man's inversion..

Partyka

Classical Seismic Attributes

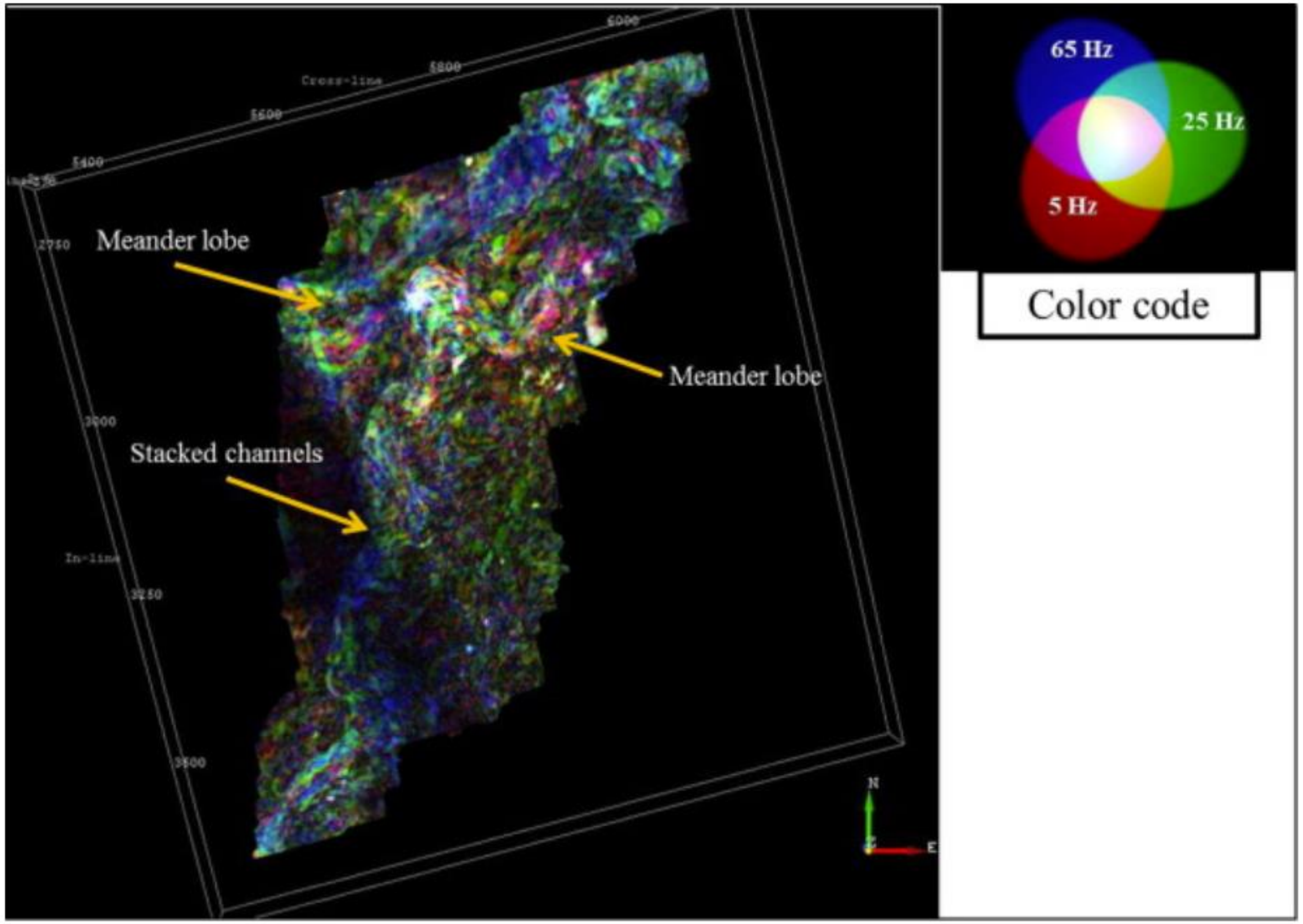
Seismic Attribute Categories		
CATEGORY	**TYPE**	**INTERPRETIVE USE**
Instantaneous Attributes	Reflection Strength, Instantaneous Phase, Instantaneous Frequency, Quadrature, Instantaneous Q	Lithology Contrasts, Bedding Continuity, Porosity, Direct Hydrocarbon Indicators, Stratigraphy, Thickness
Geometric Attributes	Semblance and Eigen-Based Coherency/Similarity, Curvature (Maximum, Minimum, Most Positive, Most Negative, Strike, Dip)	Faults, Fractures, Folds, Anisotropy, Regional Stress Fields
Amplitude Accentuating Attributes	RMS Amplitude, Relative Acoustic Impedance, Sweetness, Average Energy	Porosity, Stratigraphic and Lithologic Variations, Direct Hydrocarbon Indicators
AVO Attributes	Intercept, Gradient, Intercept/Gradient Derivatives, Fluid Factor, Lambda-Mu-Rho, Far-Near, (Far-Near) Far	Pore Fluid, Lithology, Direct Hydrocarbon Indicators
Seismic Inversion Attributes	Colored Inversion, Sparse Spike, Elastic Impedance, Extended Elastic Impedance, Prestack Simultaneous Inversion, Stochastic Inversion	Lithology, Porosity, Fluid Effects
Spectral Decomposition	Continuous Wavelet Transform, Matching Pursuit, Exponential Pursuit	Layer Thicknesses, Stratigraphic Variations

Roden et al, 2015

Spectral Decomposition

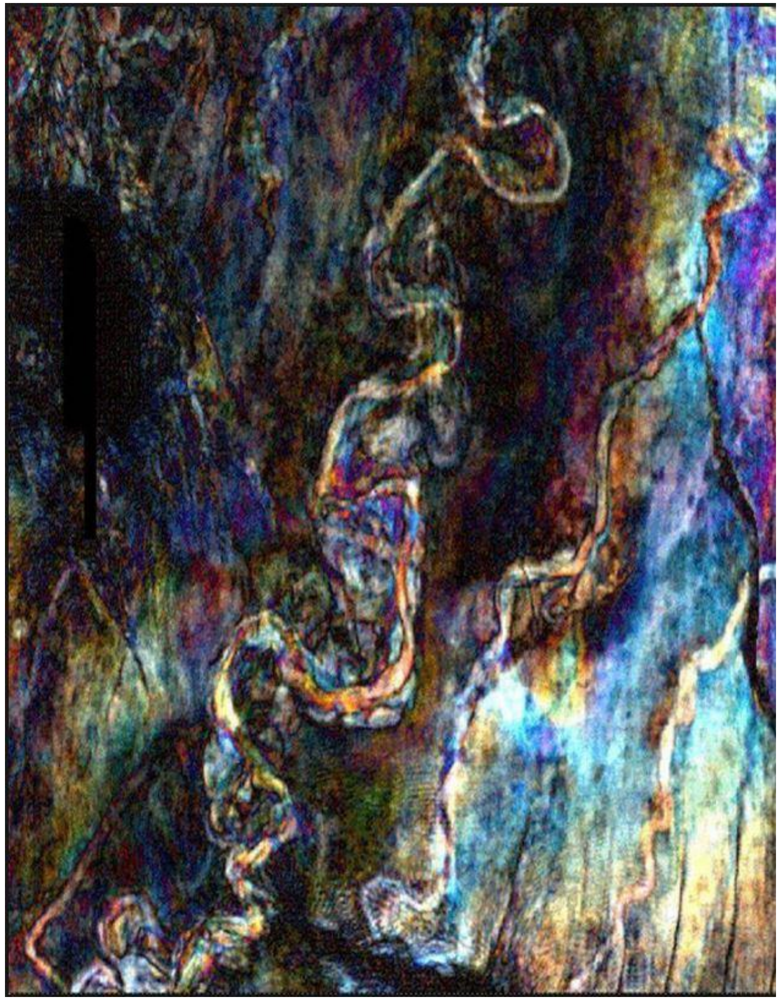
The spectral decomposition workflow focuses on processing Discrete Fourier Transform (DFT) around a very smooth seismic horizon interpretation, transforming the amplitude or phase data into the frequency domain.

We used the Red–Green–Blue (RGB) color blended maps; where each color corresponds to a specified frequency range. The three frequency ranges are: 5 Hz (the lowest frequency range in the seismic dataset) in Red color, 25 Hz (the dominant frequency in the seismic dataset) in Green color, and 65 Hz (the highest frequency range in the seismic dataset) in Blue color (Fig. 5).

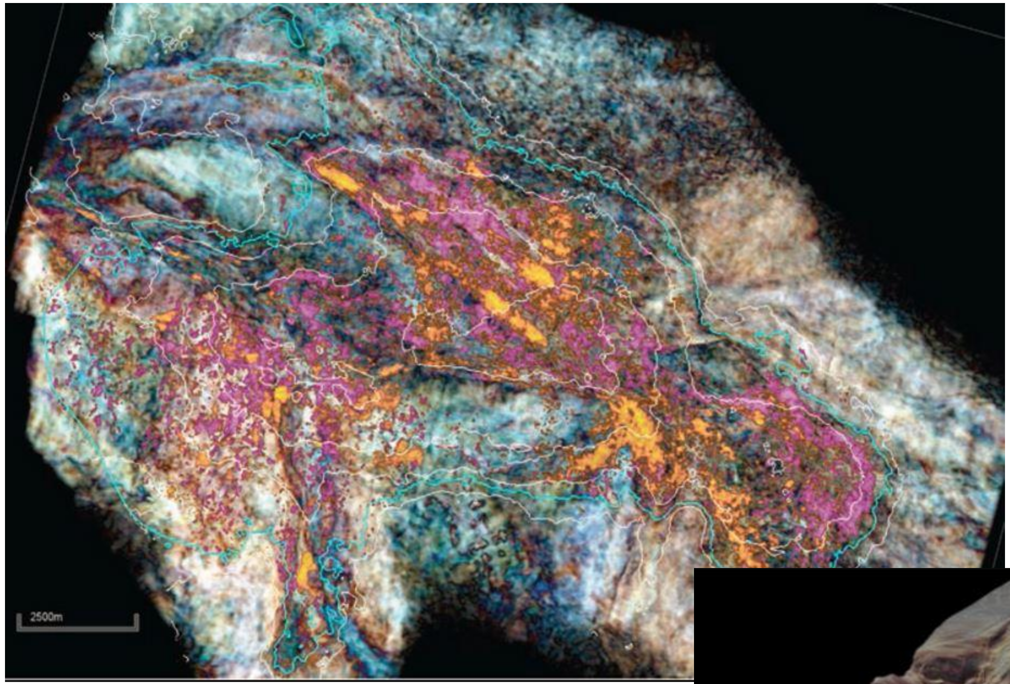


Othman et al, 2015

High end combined attributes

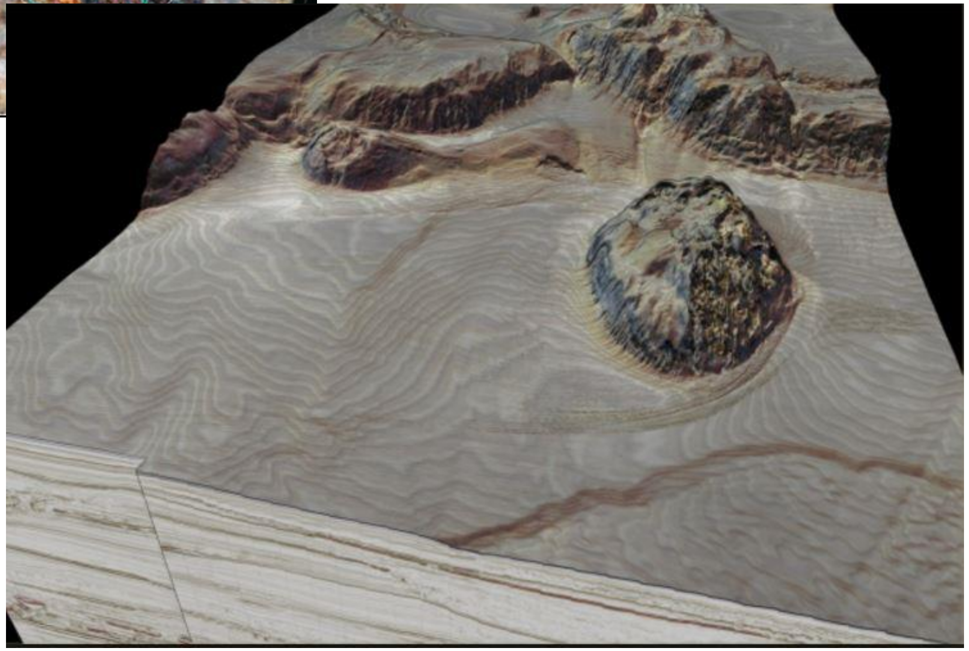


Channels



Fill via amplitudes/structure

Deepwater Seafloor 3D structure



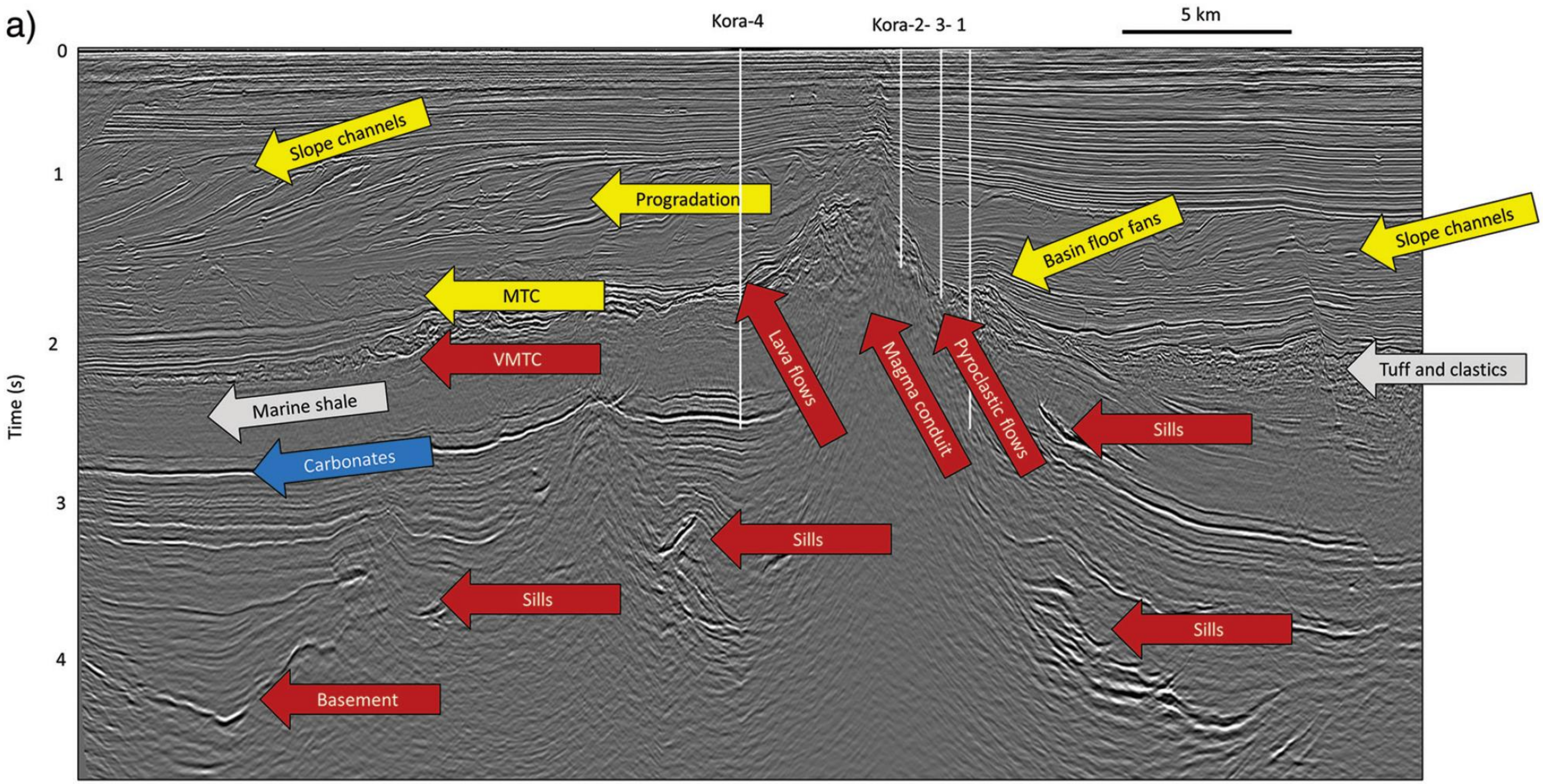
Schlumberger, Petrel

Strategy for analysis:

- Compute several ***key*** attributes right away on multiple horizons (top, base, etc) or as 3-D volume:
  - Time/depth structure (map)
  - RMS amplitude in a window (map)
  - Reservoir thickness (map)
  - Quadrature (volume)
  - Coherency (volume)

  - Wedge model using up-scaled well logs (if you have a well)
  - AVO Cross-plots (if you have pre-stack data)

- After you understand these basic attributes, choose more case specific attributes to generate



Marfurt, 2018

Table 1. The visual and attribute expressions of the geologic facies highlighted in Figure 1b through 1p. Figure 1a shows a complete seismic line containing many of these facies. Human interpreters often identify seismic facies by comparing their internal reflector configurations to the overlying, underlying, and laterally shifted reflector configurations. To limit the size of the table, only six of the more common attributes are included. Seismic noise such as that shown in Figure 1p and 1q has its own amplitude and attribute expression and is used by seismic processors in noise-suppression workflows. The table was constructed by Lennon Infante of the University of Oklahoma (OU). Used by permission.

Geologic facies	Figure no.	Visual expression		Attribute expression					
		Internal reflection configuration	External forms	Amplitude	Coherence	Dip and convergence	Curvature	Spectra	GLCM entropy
Marine shales	1b	Parallel to subparallel; low amplitude	May lie unconformably on deeper strata	Low to moderate, often with low S/N values	Moderate to high	Parallel to subparallel, convergent at onlap surfaces	Low curvature and aberrancy	Moderate to high spectral response	Low entropy, except where contaminated by noise
Incised valleys	1c	Subparallel reflectors, often with smaller-scale incisements and possible lateral accretion	Incisement of regional pattern; external pattern usually differs in amplitude, phase, and frequency	Variable, depending on fill	External and internal low-coherence edges	Parallel to subparallel, convergent at edges of incisement if channel base is imaged	Possible anomalies associated with compaction; composite anomalies associated with stacked channels	Variable spectral response to variable fill thickness; typically different from host sediments	Variable, depending on fill
Progradations	1d	Clinoforms	Sigmoidal form bound by bottom sets and top sets; often cut by slope channels	Moderate to high	Moderate to high; low at terminations	Subparallel, convergent at downlap and toplap surfaces	Positive and negative curvature anomalies where channel cut	High spectral response	Low entropy
Mass-transport complexes (MTCs)	1e	Locally subparallel bedding to completely chaotic	Piecewise rotated blocks	Variable	Piecewise coherent	Piecewise parallel, convergent across blocks or massive (all possible dips)	Anomalies associated with lateral changes in block orientation	Variable; difference in each block	High entropy interspersed with high homogeneity
Volcanic MTCs (VMTCs)	1f	No continuous reflections	Chaotic flow with coarse inclusions	Variable, low to high	Incoherent, different waveform	Convergent across blocks or massive (all possible dips)	Anomalies associated with lateral changes in block orientation	Variable; difference in flow components or in different blocks	High entropy

Marfurt, 2018

Volcanic tuff	1g	Moderate reflectivity, salt -and-pepper-like	Locally thick package with unconformable base and relatively smooth top	Moderate	Relatively incoherent because of lower S/N values	Parallel, near flat if discernible	No meaningful anomalies	Moderate to high-frequency response	Moderate to high entropy due to lack of reflectivity
Lava flows	1h	Tongue-like patterns	Emanating from the volcanic cone	High amplitude	Possible anomalies associated with vents and fissures	Subparallel to flanks of volcanic cone	Possible anomalies associated with vents and fissures	Broadband response	Low entropy
Stratovolcanic cones	1i	High-amplitude reflectivity, can be steeply dipping, chaotic in places, coherent about lava flows	Cone-shaped with onlapping reflectors; deeper conduit poorly imaged due to velocity pull up and steep dips	High to moderate amplitude	Internally low-coherence, except for lava flows	Steep dips, locally high convergence, but low convergence in area of lava flows	Can exhibit rapid lateral changes	Low-frequency response	Variable, low entropy over lava flows, high entropy elsewhere
Igneous sills	1j	Strong positive amplitude, often saucer-shaped	Often subparallel to sedimentary layers, may step up along zones of weakness from level to level; may give rise to forced folds in upper layers	High amplitude	Piecewise coherent	Sometimes parallel, but often having little relationship to surrounding dip	Often saucer-shaped; anomalies possible if vertical linkages between sills are imaged	Lower-frequency response, perhaps due to rugosity	Low entropy
CO_2- and CH_4-charged sands	1k	Bright spots	High-amplitude anomalies, possibly with different phase; flat, discontinuous	High amplitude; negative reflectivity in shallow section; possible lateral change in phase from non-charged facies	Coherent	Flat dip	No meaningful anomalies	Broadband to low-frequency response	Low entropy
High-impedance carbonate layers (abyssal plain in this survey?)	1l	Continuous reflectors	Parallel reflectors configuration	High amplitude due to impedance contrast with clastic sediments	Coherent	Changes in dip due to faulting and folding (possible fractures)	Positive- and negative-curvature anomalies associated with faulting and folding	Typically lower frequency due to the faster velocities of carbonates	Low entropy

Marfurt, 2018

Table 1. (*Continued*) The visual and attribute expressions of the geologic facies highlighted in Figure 1b through 1p. Figure 1a shows a complete seismic line containing many of these facies. Human interpreters often identify seismic facies by comparing their internal reflector configurations to the overlying, underlying, and laterally shifted reflector configurations. To limit the size of the table, only six of the more common attributes are included. Seismic noise such as that shown in Figure 1p and 1q has its own amplitude and attribute expression and is used by seismic processors in noise-suppression workflows. The table was constructed by Lennon Infante of the University of Oklahoma (OU). Used by permission.

Geologic facies	Figure no.	Visual expression		Attribute expression					
		Internal reflection configuration	External forms	Amplitude	Coherence	Dip and convergence	Curvature	Spectra	GLCM entropy
Magma conduits	1m	Extremely low amplitudes	Lies beneath volcanic cone	Absence of reflections	Incoherent	Massive	No meaningful anomalies	No meaningful anomalies	High entropy
Slope channels	1n	U- to V-shaped; low to high amplitude	Crosscutting relatively flat reflectors	Low to moderate amplitude (depends on impedance contrast of the fill and the base layers)	Internal: depends on the fill; external: sharp edges	Parallel to subparallel, convergent at edges of incisement if channel base is imaged	Possible anomalies associated with compaction; composite negative anomalies associated with stacked channels	Variable spectral response to variable fill thickness; typically different from host sediments	Variable, depending on fill
Estuary channels	1o	Erosional through subparallel reflectors, often with smaller-scale incisements and possible lateral accretion	Incisement of regional pattern; external pattern usually differs in amplitude, phase, and frequency (distinguishable from slope channels because the flow is in the opposite direction in map view)	Variable, depending on fill	Internal: depends on the fill; external: sharp edges	Parallel to subparallel, convergent at edges of incisement if channel base is imaged	Possible anomalies associated with compaction; composite negative anomalies associated with stacked channels	Variable spectral response to variable fill thickness; typically different from host sediments	Variable, depending on fill
Channelized turbidites	1p	Parallel to subparallel; moderate to high amplitude	May lie unconformably on deeper strata	Moderate to high	Moderate to high	Parallel to subparallel, convergent at edges of incisement if channel base is imaged	Anomalies associated with edges	Moderate to high spectral response	Low entropy

Marfurt, 2018