Statistical Rock Physics

- Introduction

Book review 3.1-3.3

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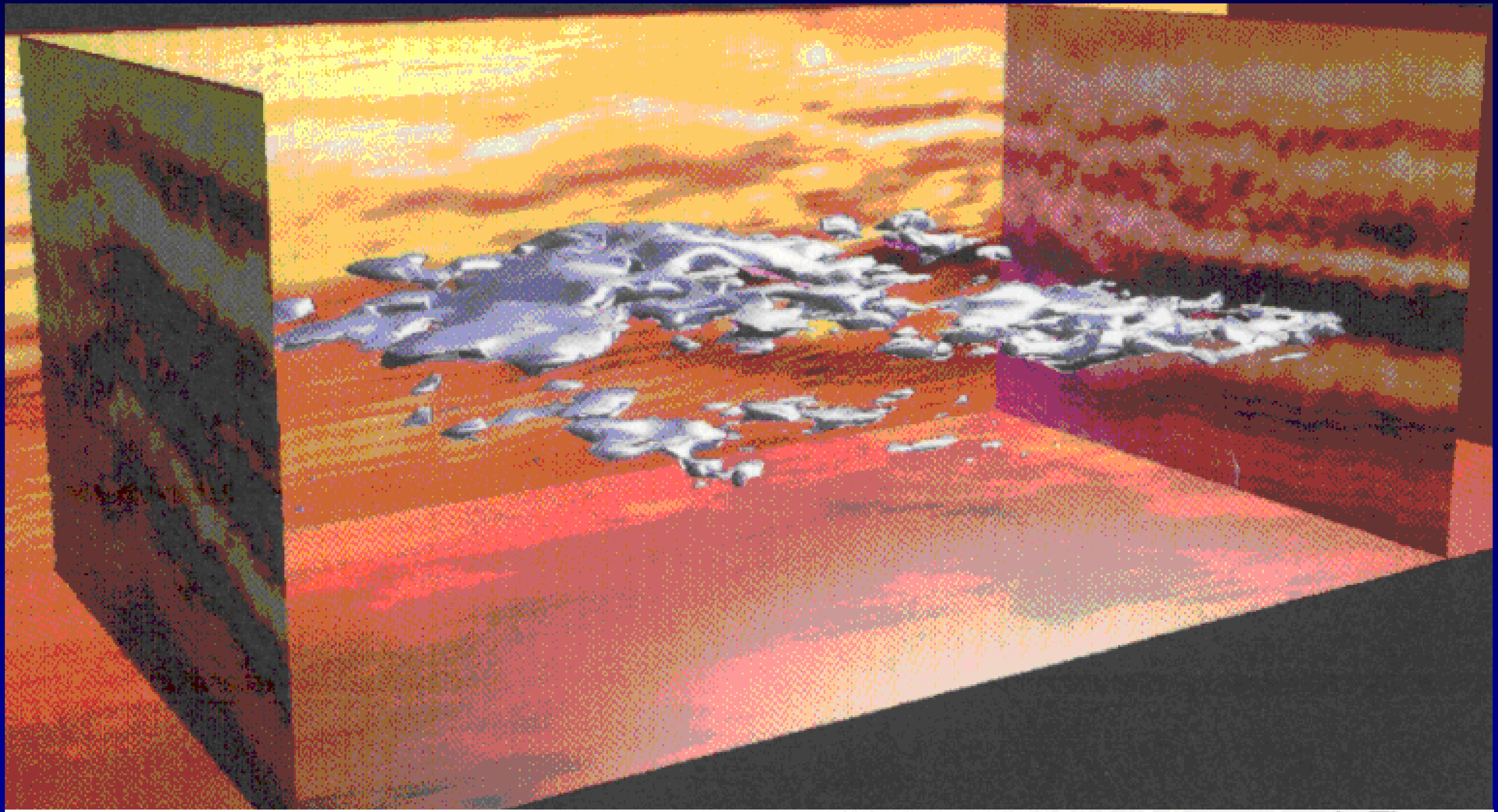


Plate 3.1 Iso-probability surface of 75% probability of oil-sand occurrence in a North Sea reservoir. The lateral extent is about 12 km along the long dimension. The total vertical extent is about 100 m. The probability estimates are obtained by combining well-log data, rock physics models, seismic impedance inversions, and statistical pattern recognition. This is a typical result from a statistical rock physics workflow.

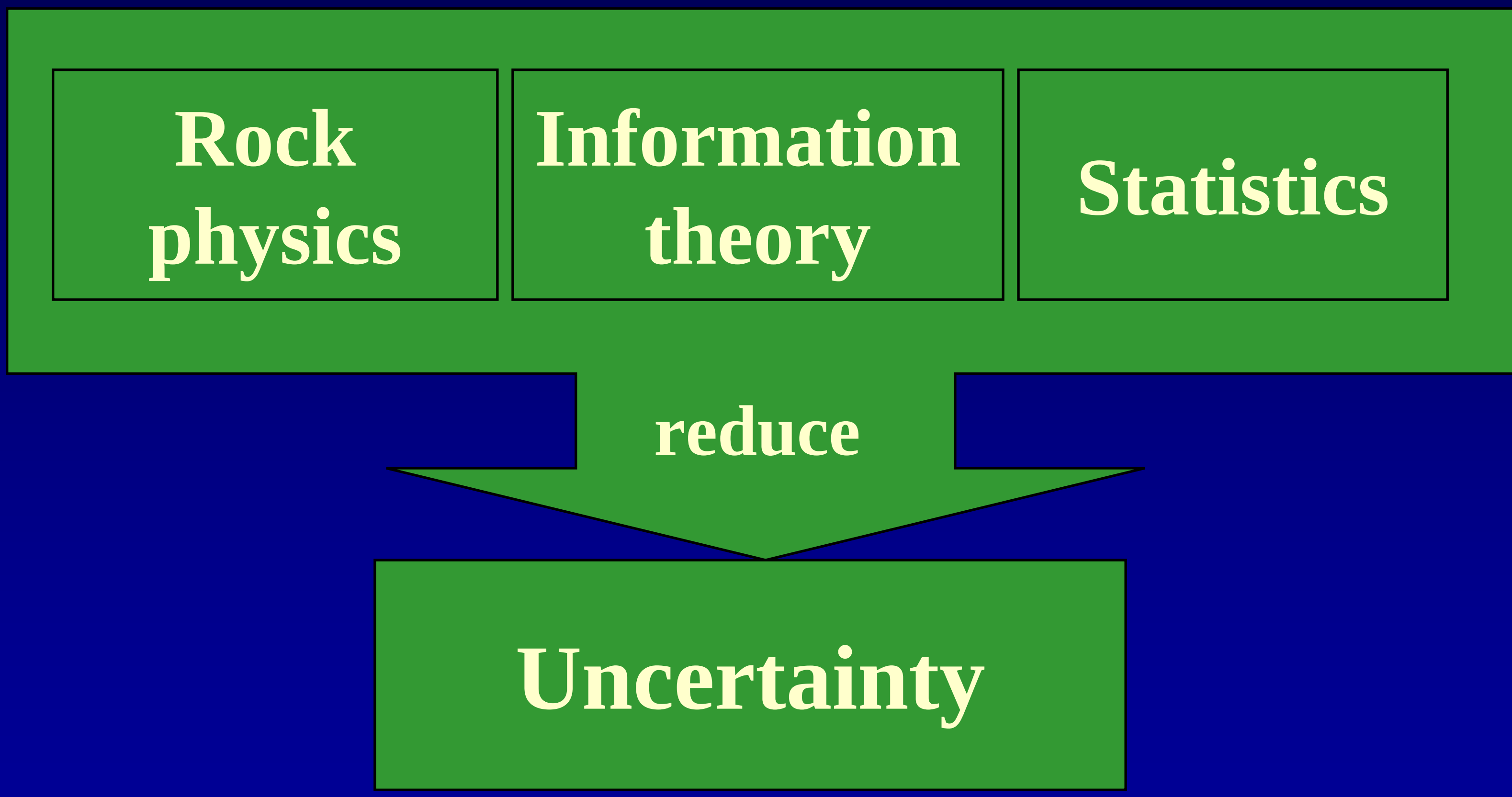
Outline

. What is Statistical Rock Physics

. Why we need Statistical Rock Physics

. How Statistical Rock Physics works

Statistical Rock Physics



Statistical Rock Physics

Rock physics

- link seismic response and reservoir properties (well log, geology)
- extend the available data to generate training data for the classification system.

- seismic response

indirect, but spatially exhaustive, lateral and vertical information that are not available from well data.

Information theory

- rock property estimation
- simple yet powerful tools to quantify the attribute information for discriminating the different facies.
- Shannon's information entropy (3.4) : get "best" attributes that most reduce uncertainty in reservoir properties identification.

Statistical Rock Physics

Statistics

- **Quantify uncertainty**
- **Classification and estimation**
  - based on computational statistical techniques
    nonparametric Bayesian classification, bootstrap, and neural networks, etc
  - quantitatively measure interpretation uncertainty and the mis-classification risk at each spatial location.
- **Geostatistics**
  - add spatial correlation
  - add small-scale variability which is hard to identify from seismic only because of the limits of resolution.

. What is Statistical Rock Physics

. Why we need Statistical Rock Physics

. How Statistical Rock Physics works

Uncertainty - ubiquitous

interpretation uncertainty

- **Subsurface heterogeneities**
  lithology, pore fluids, clay content,
  porosity, pressure, temperature, etc
- **Subsurface properties**
  estimated from remote geophysical measurements
  many inevitable difficulties and ambiguities in
  data acquisition, processing, and interpretation.
- **Data have errors**
- **Models are approximate**
- **Our imperfect knowledge**

Uncertainty - quantified

Quantifying uncertainty to

- assess risk
- integrate data from different sources
- estimate value of additional data

Uncertainty – quantifying methods

- purely statistical

- Based on multivariate techniques
- Used in seismic reservoir characterization

- purely deterministic

- Based on physical models derived from elasticity theory and laboratory observations.

Derived distribution

combining deterministic rock physics models with the observed statistical variability to build a more powerful strategy for reservoir prediction

Uncertainty – quantifying tools

- **Probability**
  - **frequency**: long sequence of identical repetitions
  - **Bayesian**: degree of belief based on given evidence
- **Random variable**
  - to model uncertainty
- **pdf (probability density functions)**
  - Completely describe the random variables
  - Joint pdfs for the relations of multiple random variables

Uncertainty – quantifying tools

-pdf estimate

- Must from prior knowledge or available training data
- The training data need to be extended or enhanced using rock physics models
- methods
  - -parametric approach
  - -nonparametric approach
  - -histogram

Uncertainty – quantifying tools

Example. **nonparametric approach**

-Less rigid assumption

-Low dimensions

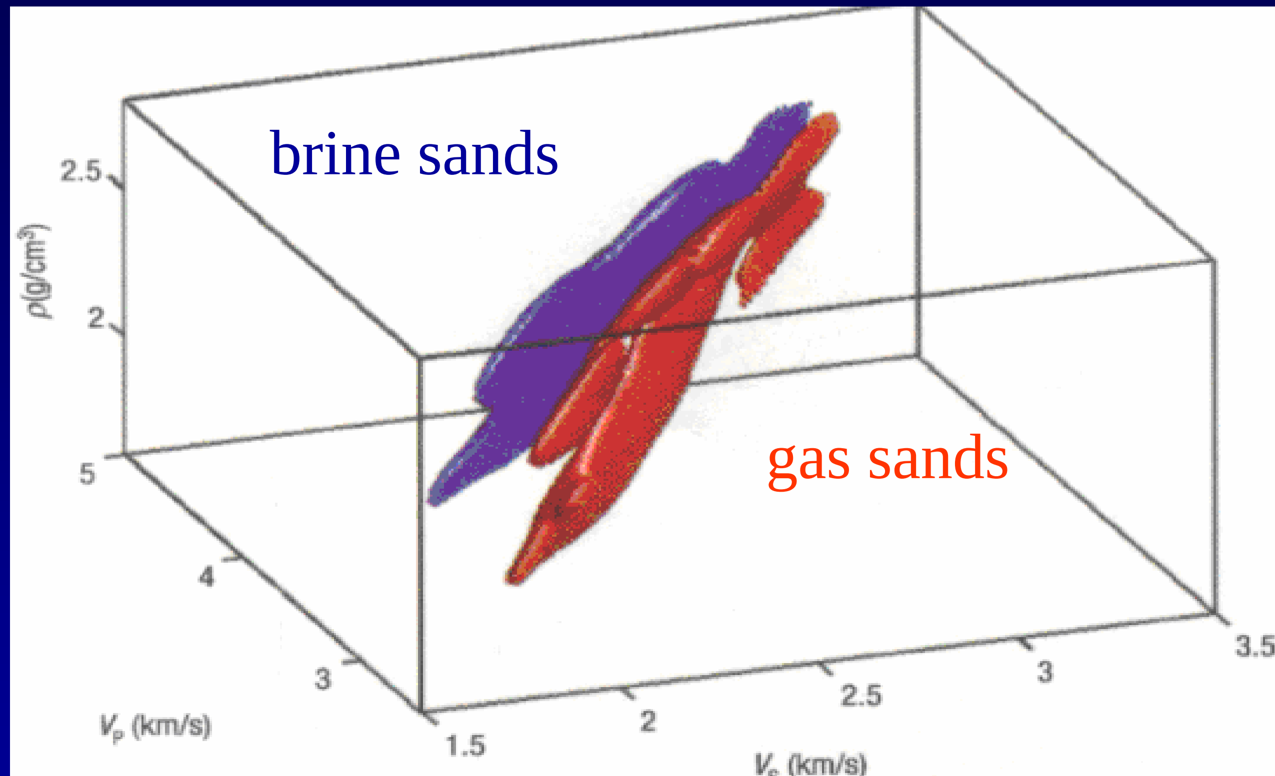


Plate 3.4 Iso-surfaces of trivariate nonparametric pdf estimate for V_P, V_S, and density. Blue indicates brine sands, and red indicates gas sands.

Uncertainty – quantifying tools

Example. **Histograms and kernel-based pdf estimates**

- **Oldest and simplest**
- **Explore data variability**
- **Kernel or window function**

  e.g. triangular

  Gaussian

  Epanechnikov
- **Discretization**

  vs. Smoothing

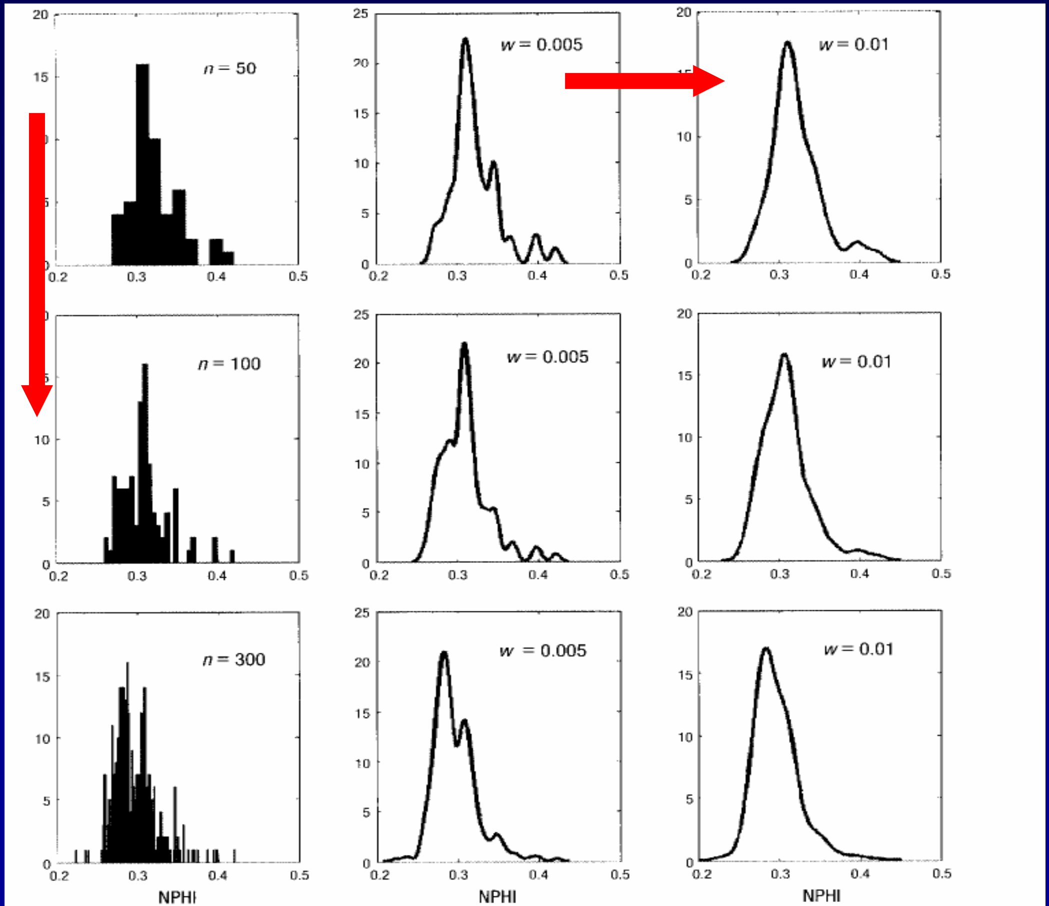


Figure 3.3 Histograms and kernel estimates for pdf of neutron porosity from well data. Increasing number of data points, *n*, from top to bottom, and for two different kernel bandwidths, *w*, for a Gaussian kernel. Larger bandwidth gives a smoother pdf estimate.

Uncertainty – flaw of averages

Example. **Ignoring the variability of rock properties can drastically distort decisions**

Backus average – ignoring the variability of sand and shale velocity, density, and impedance

Monte Carlo simulation – incorporate the variability

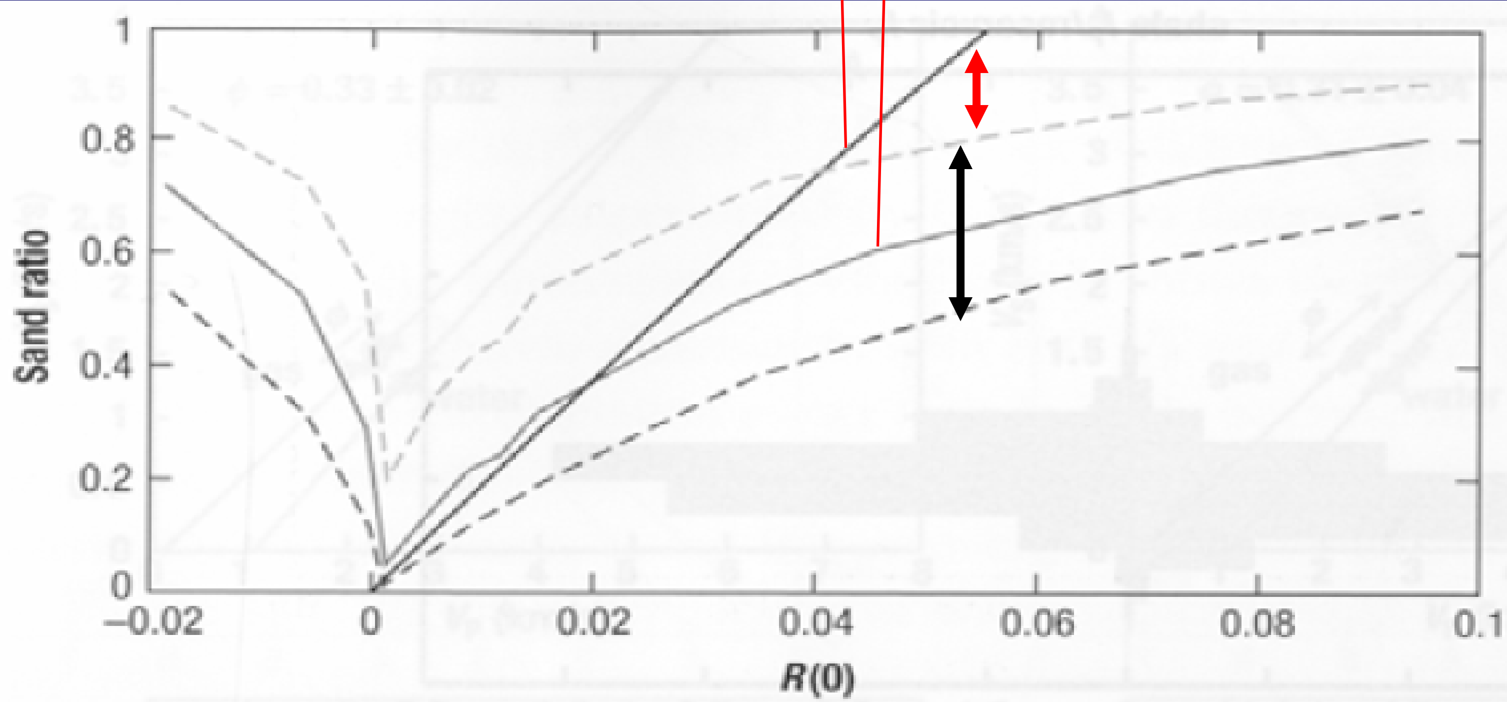


Figure 3.6 Relation between normal-incidence reflectivity and sand/shale ratio in very thin bedded sand/shale layers.

Uncertainty – reduced by additional data

Example 1

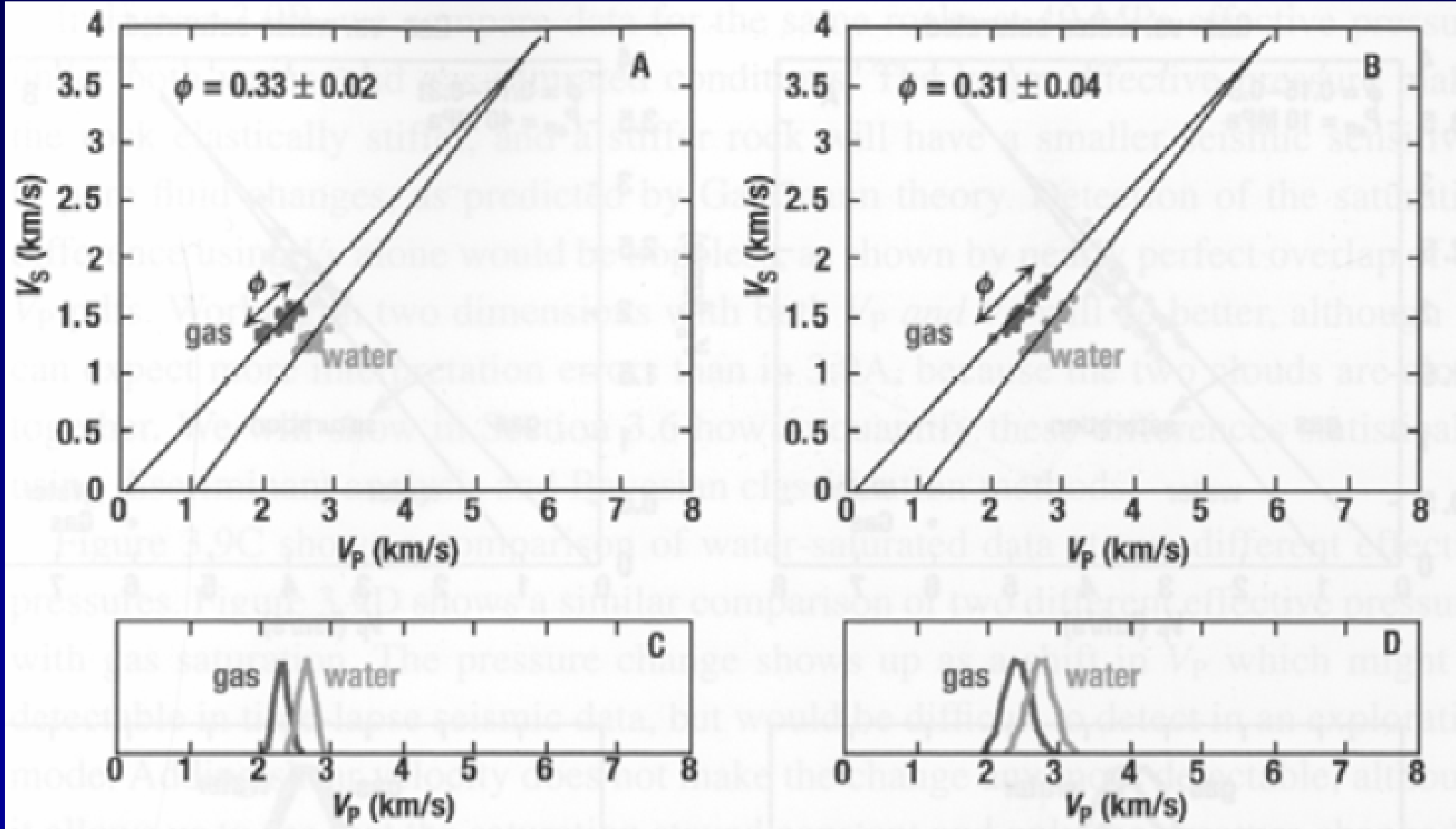


Figure 3.8 Changes in natural variability of porosity and velocity can become comparable to fluid effects.

Uncertainty – reduced by additional data

Example 2

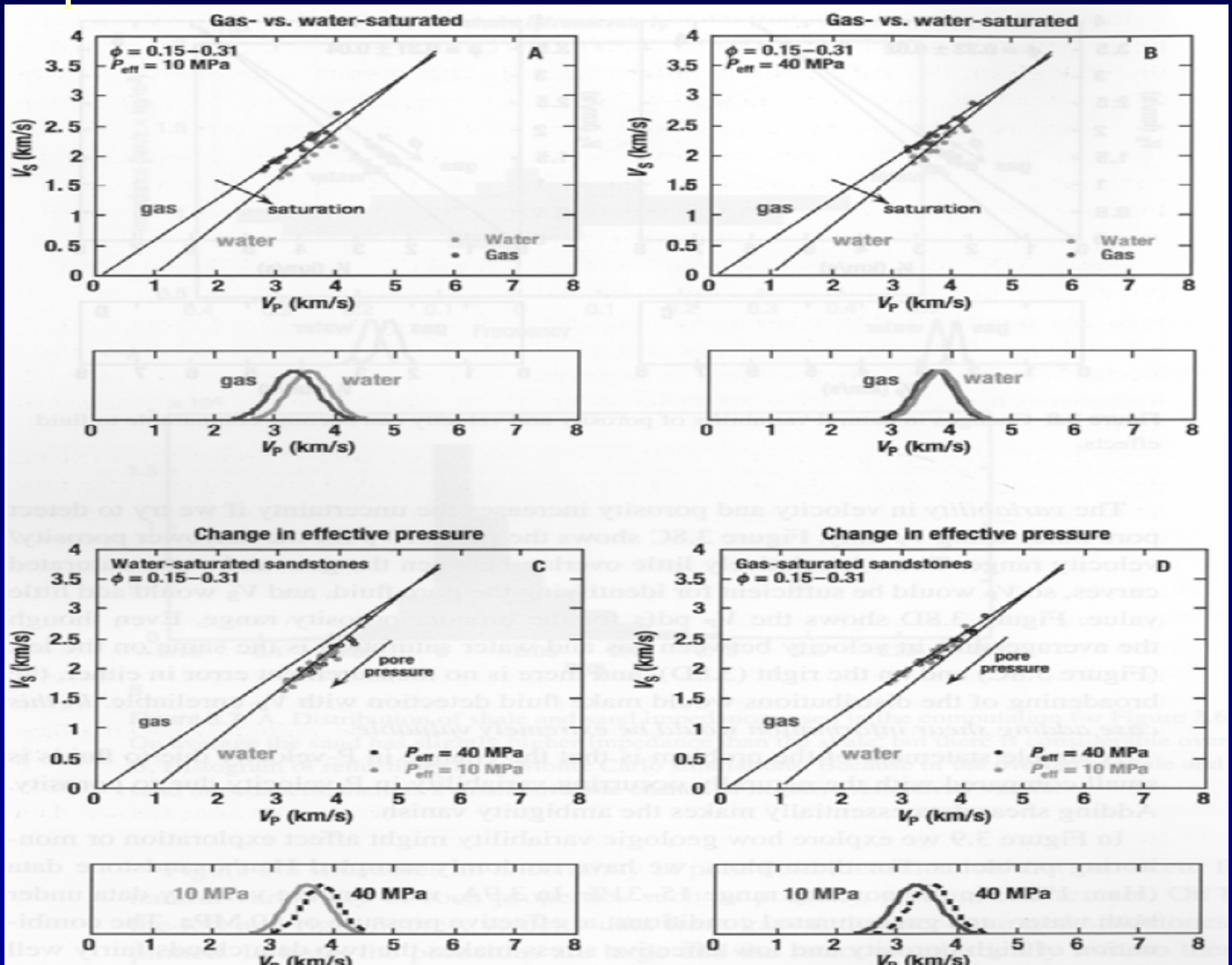


Figure 3.9 Subsets of Han's sandstone data. A, Data at 10 MPa, showing the separate gas- and water-saturated clouds. B, Data at 40 MPa, showing the gas- and water-saturated clouds, now with less separation. In both A and B, V_P alone would not be very valuable for separating the clouds, as seen by the overlap of the smoothed histograms. C, Water-saturated data, showing the overlapping clouds for high and low effective pressures. D, Gas-saturated data, showing the overlapping clouds for high and low effective pressures.

b. best - discriminant analysis and Bayesian classification (3.6)

C. D. Vp shift might be detectable in time-lapse seismic data

- What is Statistical Rock Physics
- Why we need Statistical Rock Physics
- How Statistical Rock Physics works

Workflow

facies definition

↓

pdf estimation

↓

statistical classification

↓

Geostatistics

The steps modified depending on the stage in the cycle of exploration , development, and production.

Workflow – 1. Facies definition

identifying variables (facies or categorical groups) from well log and geology analyses

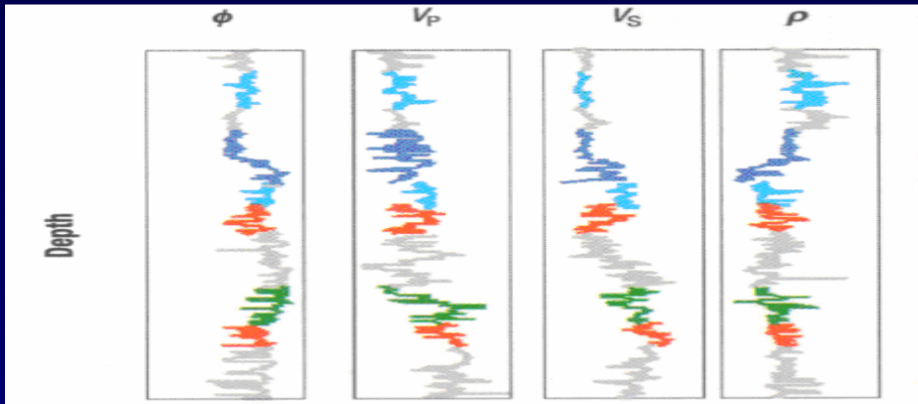
- Facies

- Collection of geologically similar rocks that span a range of petrophysical and seismic properties.
- Not necessarily only by lithology type, facies <> single rock.

- Intrinsic variability of rock properties

- One of the biggest challenges of quantitative seismic interpretation :
  when does an observed attribute change indicate a significant change across facies rather than a minor fluctuation within a facies.

Workflow – 1. Facies definition



A "Classified" well logs (each depth level has been identified as belonging to a particular facies).

- identifying facies
  - based on well information
    cores, thin sections, geology, logs, production data, etc.
  - cluster separation
    common practices using cross-plots
  - algorithms
    supervised learning - on the basis of expert knowledge

Workflow – 2. pdf estimation

Rock physics modeling, Monte Carlo simulation and pdf estimation

-rock physics modeling (chapter 1, 2)

- Basic rock physics relations are defined for the facies: Vp, Vs, etc

- "What ifs": extend the training data to simulate different physical conditions

- translate production or geologic information into elastic properties that condition the seismic response

Workflow – 2. pdf estimation

-Monte Carlo simulation (3.5)

- **assumption for correlated Monte Carlo simulation**
  the well-log data extended by rock physics modeling will be statistically representative of all the possible values of Vp, Vs, and density that might be encountered in the study area.
- **Monte Carlo realizations**
  - drawn from the distributions of each facies
  - used in models to calculate seismic observables and attributes
    - an attribute is any characteristic that can be extracted from the seismic data:
      AVO intercept, gradient, P- and S- wave impedance, etc
- **extend the pdfs**
  situations that are of interest but not encountered in the wells

Workflow – 2. pdf estimation

-pdf estimation

- select attribute

- the easiest way is by color-coded comparative histogram plots or cross-plots of attributes.
- union or division of attributes may be used to separate priori defined facies : cluster analysis
- Information entropy (3.4)

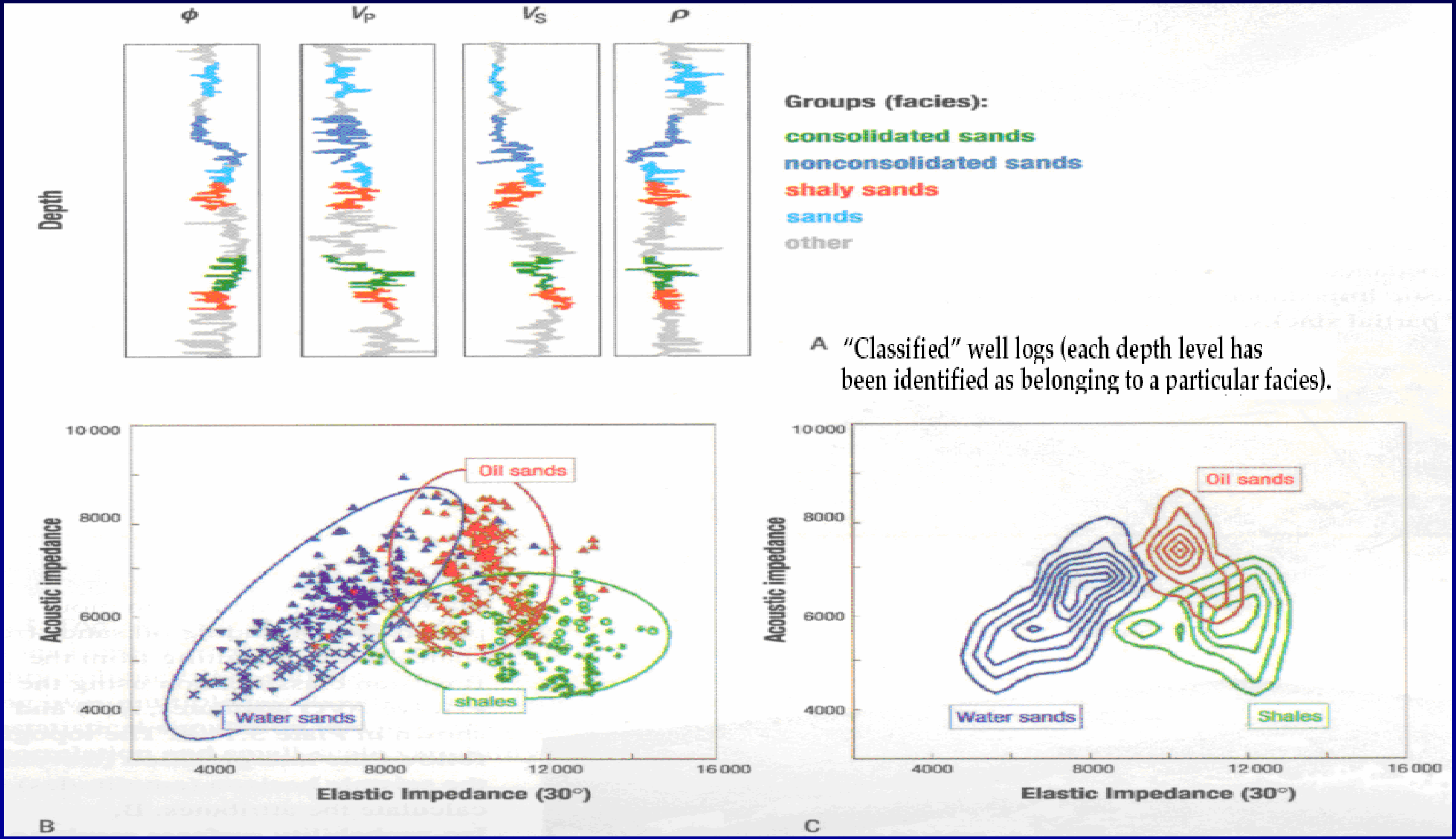
- estimate pdfs for each defined facies

- discretization and smoothing

Feasibility check

- Compute seismic attributes and estimate their pdfs
- Guide for designing surveys suitable for extracting the most promising attributes
- Decide which attributes should be extracted from the field seismic data.

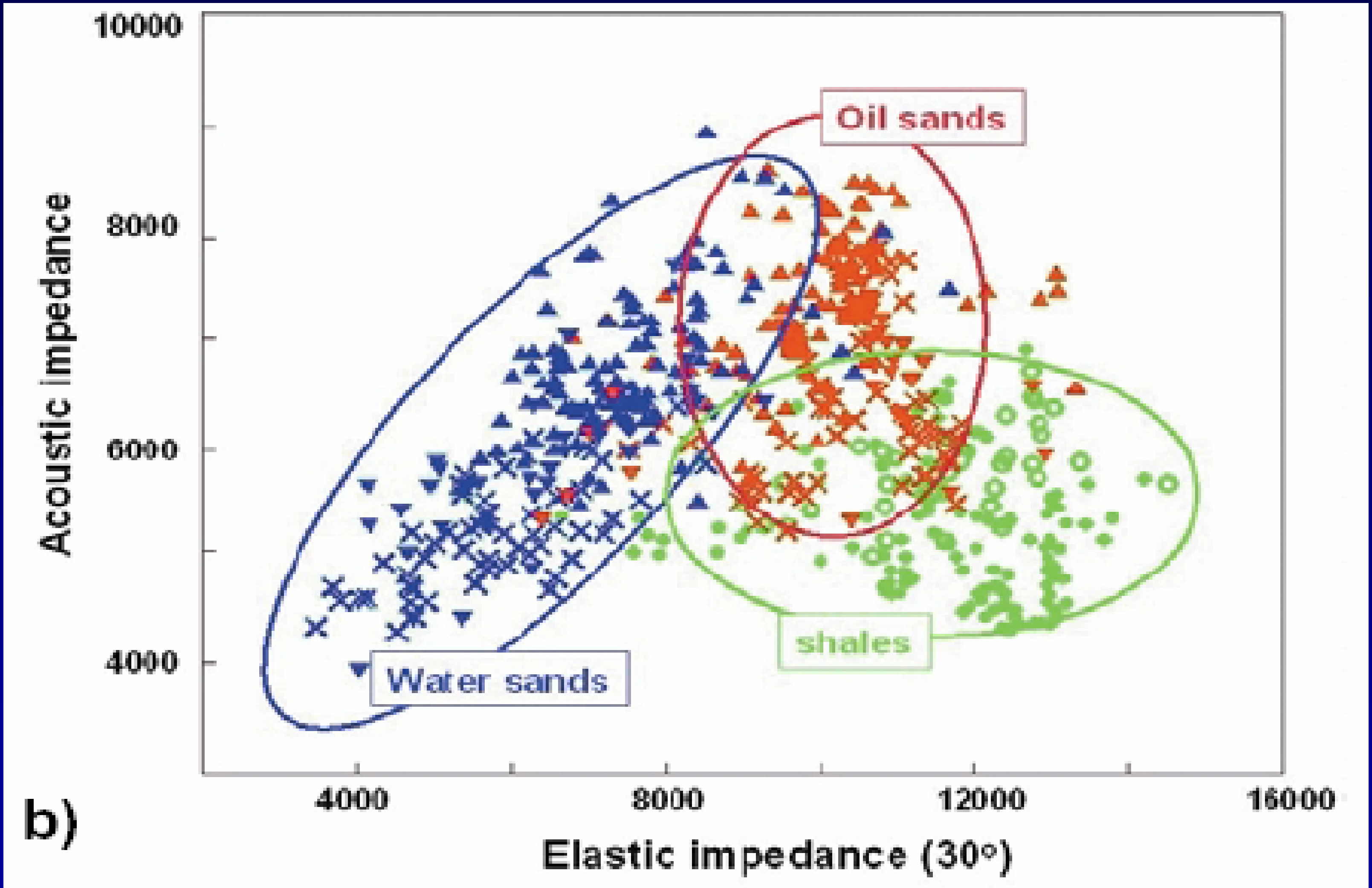
Workflow – 2. pdf estimation



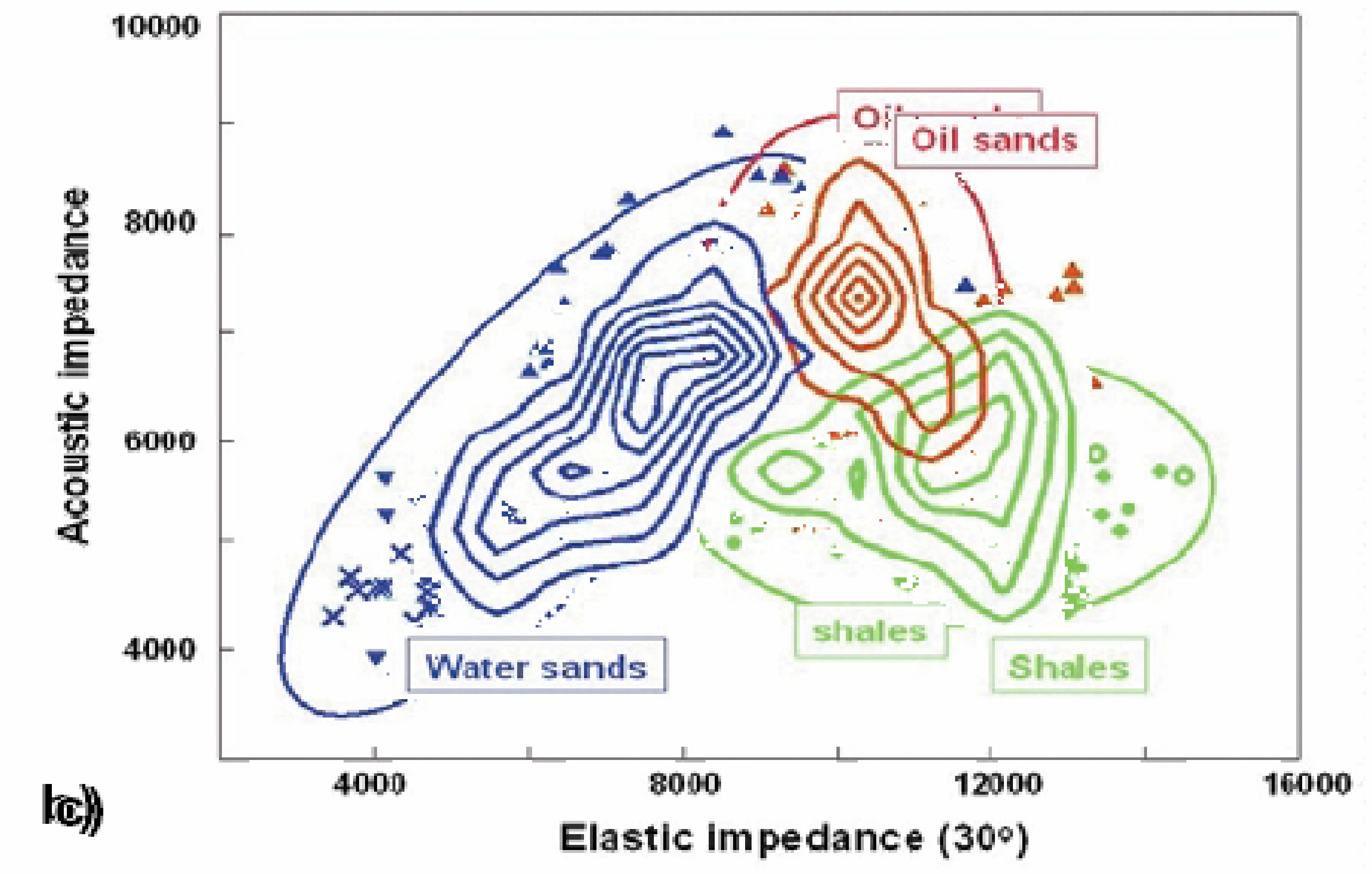
B. A cross-plot of AI vs. EI calculated with well logs.

C. Pdf contours extended by Monte Carlo simulation

Workflow – 2. pdf estimation



Workflow – 2. pdf estimation



Workflow – 3. statistical classification

Seismic inversion, calibration to well pdfs, and statistical classification

- get seismic attributes

a. **derived from seismic data**

by different processing, analysis, or inversion.

b. **responded to interface properties:**

e.g. reflectivity, AVO

c. **responded to interval properties:**

e.g. acoustic impedance, elastic impedance

Workflow – 3. statistical classification

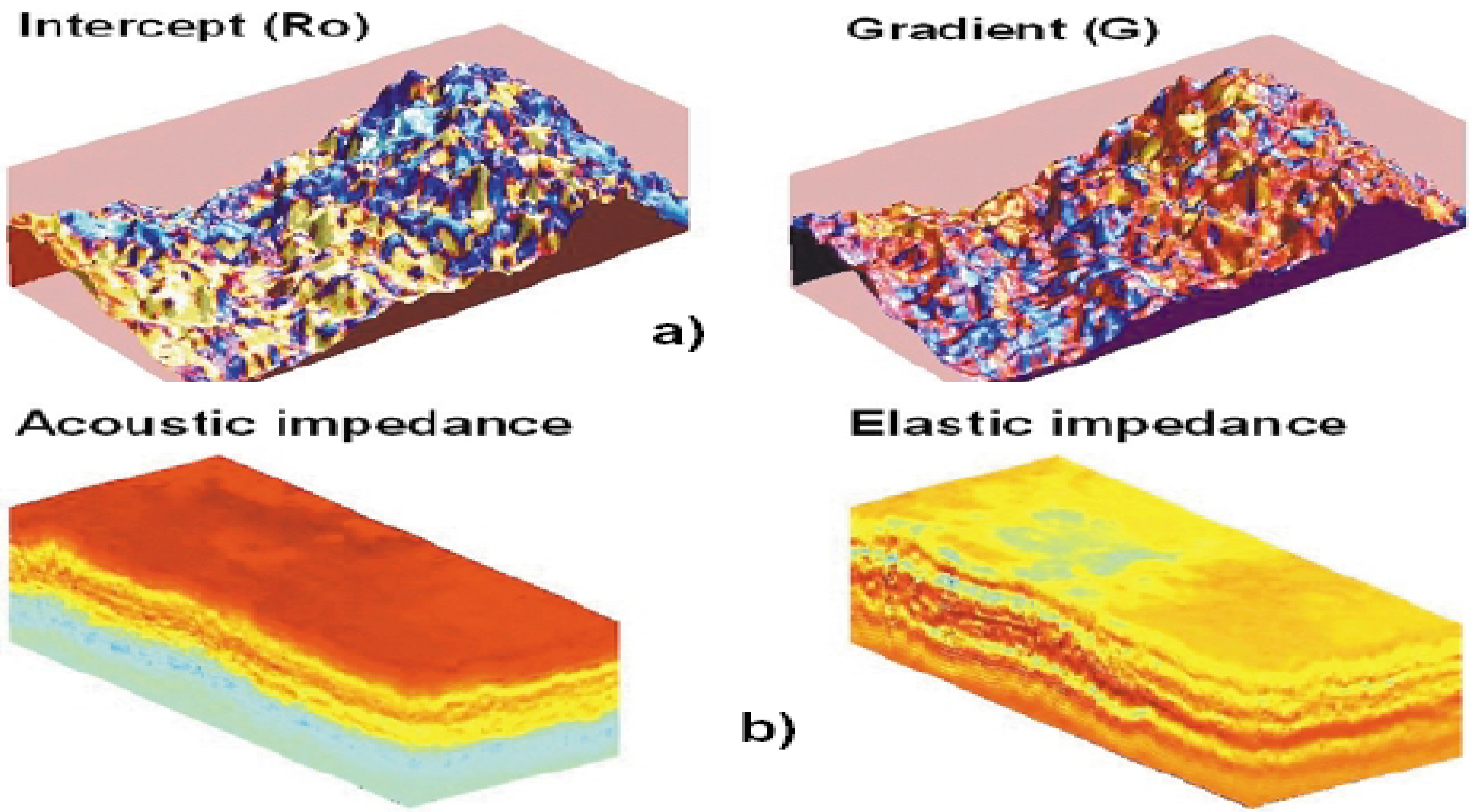


Plate 3.11 A, P-wave AVO attributes as defined by Shuey: $R(0)$ (intercept) and G (gradient) extracted from seismic data. The topography follows the traveltime interpretation of the seismic horizon along which the reflectivity and gradient were estimated from AVO analyses of pre-stack data. B, Acoustic and elastic impedance (at 30°) volumes. These two attributes respond to the reservoir interval properties. The far-offset elastic impedance implicitly contains shear-wave information. These were estimated by impedance inversion of partial stacks.

Workflow – 3. statistical classification

-calibration to well pdfs

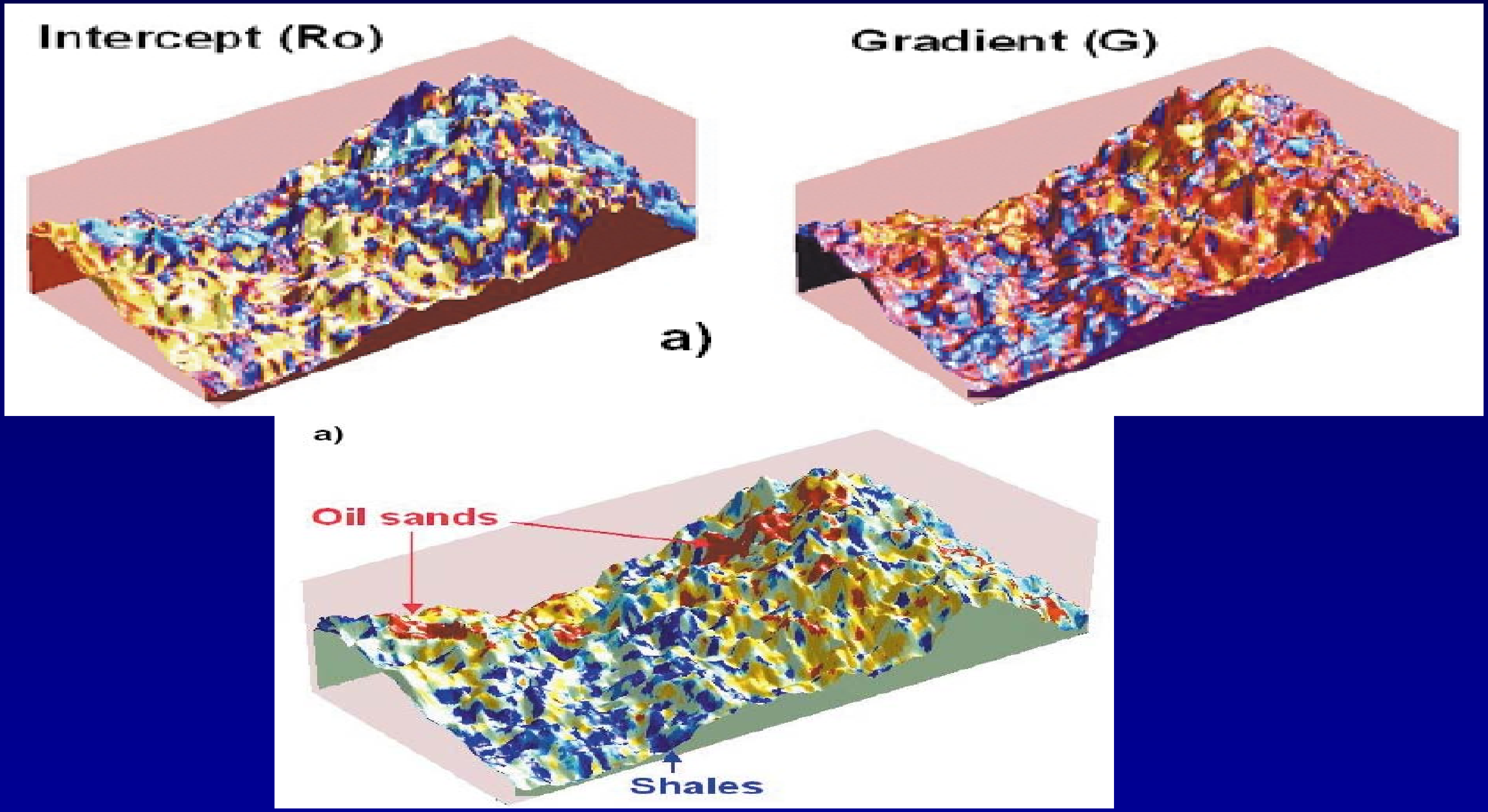
-Differences between the computed and extracted attributes

caused by - simplifications of the models
- imperfections in the data processing
- arbitrary scaling of the field amplitudes
- different measurement scales
- noisy data

-statistical classification or pattern recognition (3.6)

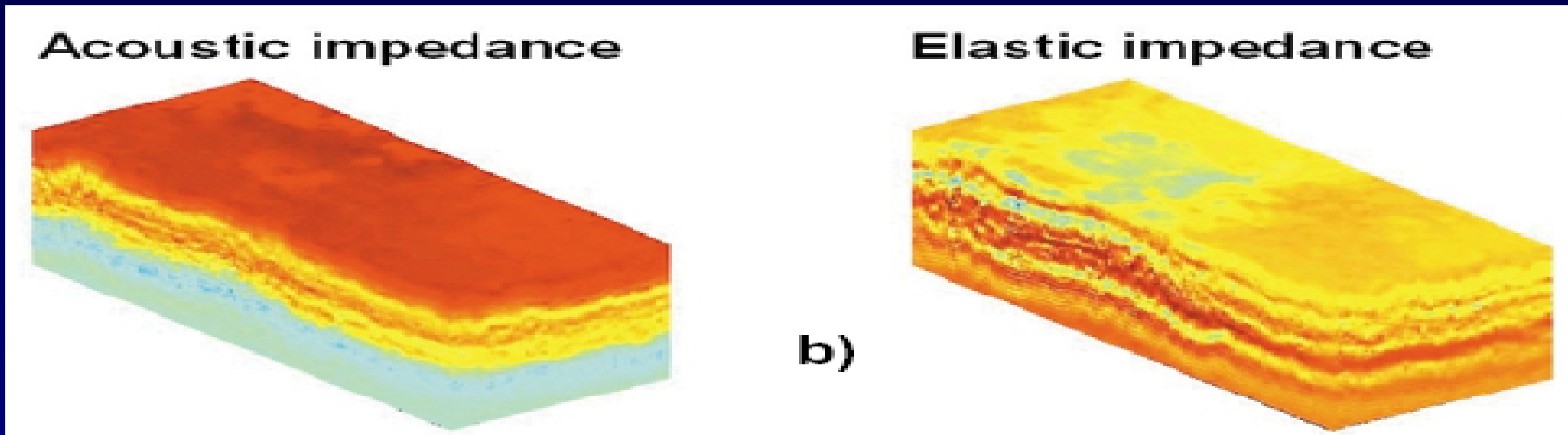
- Discriminant analysis
- K-nearest-neighbor classification
- Neural networks
- Classification trees
- Bayes classification

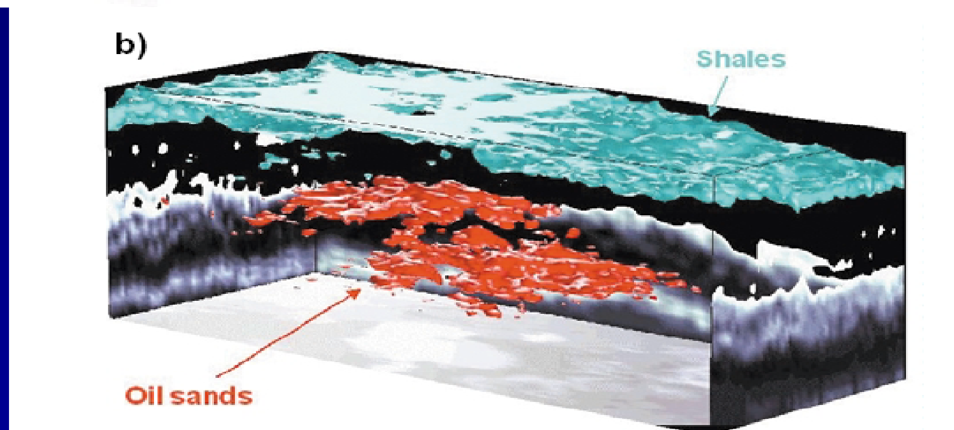
Workflow – 3. statistical classification



(a) The result of the Bayesian classification using *P*-wave AVO attributes R **and G.**

Workflow – 3. statistical classification





(b) Isoprobability surfaces resulting from applying a statistical classification process (nonparametric Bayesian) using the acoustic and elastic impedance

Workflow – 4. Geostatistics

Geostatistical simulations incorporating spatial correlation and fine-scale heterogeneity

- **Spatial correlation incorporated by**
  - variograms
  - multiple-point spatial statistics
- **Small-scale variability**
  - not captured in seismic data because of their limited resolution
- **One of the main benefits**
  - estimate joint spatial uncertainty
- **One of the pitfalls**
  - black-box mode without understanding the underlying physics and spatial models.

Workflow – 4. Geostatistics

- **A powerful tools for spatial data integration and an important role at various stages of reservoir exploration and development**

a. early stages

- **delineate reservoir architecture**

  geostatistically combine seismic traveltime data and sparse well horizon markers.

- **obtain geostatistical simulation of reservoir properties**

  e.g. lithofacies, porosity, and permeability

- **impart the appropriate spatial correlation structure to the seismic impedance inversions.**

b. late stages

- **incorporate production data into the analysis.**

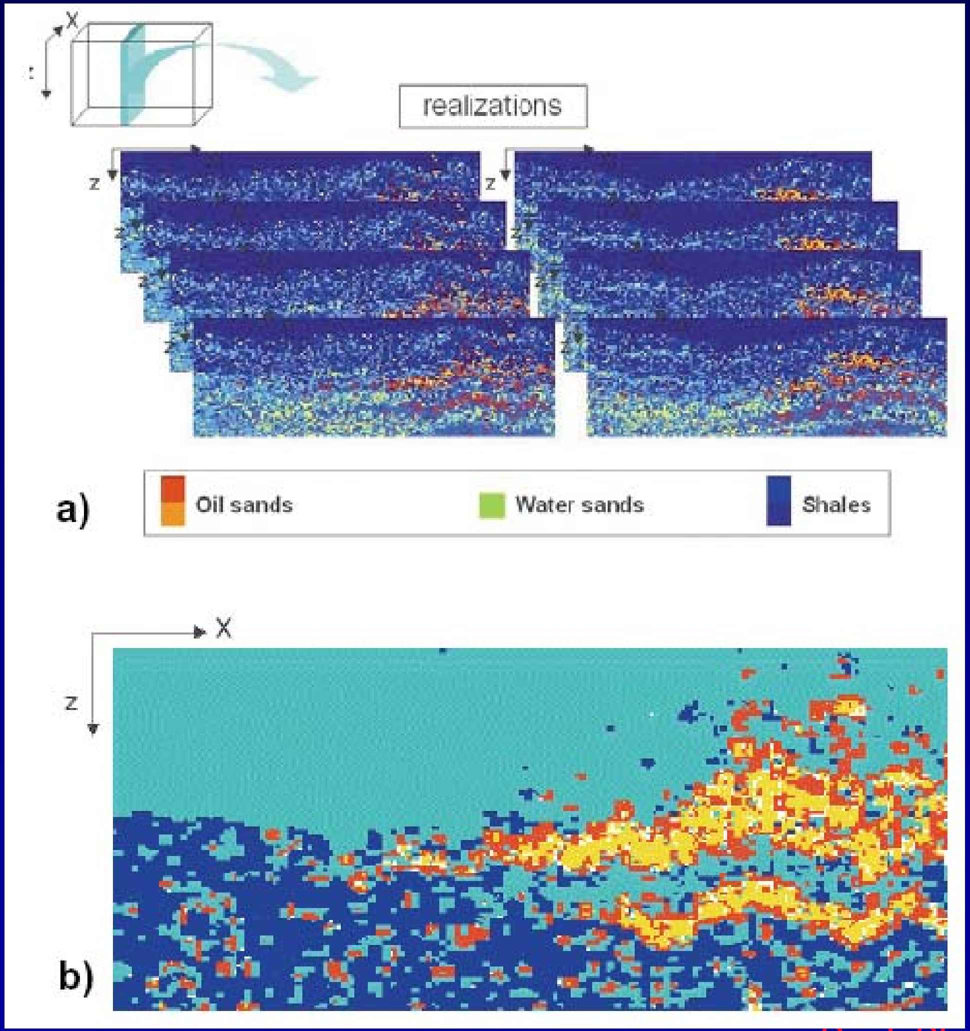
Workflow – 4. Geostatistics

Example : **indicator simulation**

indicator: 1 facies present
0 otherwise

(top):
vertical section of the multiple equiprobable volumes generated using indicator simulation

(bottom):
prior pdfs
- given the seismic attributes
posterior pdfs
- given seismic attributes, the spatial correlation, the facies indicator data from the wells.
Updated by the Markov-Bayes indicator formalism
(Deutsch and Journel, 1996).



Our most precise description of nature must be in terms of probabilities.

- Richard Phillips Feynman

Statistical Rock Physics

Combining deterministic physical models with statistical techniques leads to new methods to describe reservoir rock properties more precisely.

Thanks

Notes

. Variograms

key function in geostatistics as it will be used to fit a model of the temporal/spatial correlation of the observed phenomenon.

This is an example of a variogram produced using ArcGIS's Geostatistical Analyst.