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

Rock physics → Information theory → Statistics → reduce Uncertainty
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](image-url) 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

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

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

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, Vp 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.
. What is Statistical Rock Physics
. Why we need Statistical Rock Physics
. How Statistical Rock Physics works
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

- 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

"Classified" well logs (each depth level has been identified as belonging to a particular facies).
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: \( V_p, V_s, \) 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
- 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

“Classified” well logs (each depth level has been identified as belonging to a particular facies).
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
(a) The result of the Bayesian classification using $P$-wave AVO attributes $R$ and $G$. 
(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.
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
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.