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Integrating Geologic and Geophysical Data in Geostatistical Inversion

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Summary

Modern exploration requires a Team approach wherein disparate pieces of information from different disciplines need to be integrated toward the estimation of reservoir properties and facies of interest. We show haw this can be accomplished within the framework of Bayesian geostatistics, the ultimate end products being of critical interest to Engineers.

Introduction

One of the essential requirements for building useful quantitative 3D reservoir models of subsurface properties is to properly integrate disparate data sources with multi-disciplinary prior information into a realistic stratigraphic grid, sufficiently detailed to capture reservoir heterogeneity and flow characteristics. This integration is of particular importance in facies modeling, since facies generally dominate rock properties like porosity and permeability which in turn, govern the overall static character and dynamic behavior of reservoir models. Seismic reflection data can contribute meaningful additional information regarding the spatial distribution of facies away from well control but should be interpreted in a geologic context. Optimum estimation of reservoir properties are achieved when

- The seismic, well and geological constraints are applied simultaneously
- The seismic and reservoir properties are related through a predictive rock physics model
- The facies definitions are meaningful and related across all domains: elastic, reservoir and geologic.

We show how geostatistical inversion can be used to integrate partial stack 3D seismic with well logs and prior geological beliefs to simultaneously produce useful, realistic and highly detailed 3D models of facies and reservoir properties of interest. The geostatistical algorithm is outlined and then various important features are discussed that will be highlighted by examples.

Geostatistical Inversion Method

The geostatistical inversion algorithm represents each piece of known information such as partial-stack seismic, well logs and geological expectation as a probabilistic density function (pdf) . These are then combined into a single global pdf using a Bayesian framework which describes the distributions of the desired outcomes. A customized Markov Chain Monte Carlo sampling scheme is subsequently applied to obtain realizations from that pdf. For example, a realization could consist of a 3D volume of each inverted elastic property (e.g. Zp, Zs, Rho), a 3D volume of the each desired petrophysical property (e.g. phi, Vclay, k) and a 3D volume of the corresponding facies model (e.g. brine sand, oil sand, shale). The typical inputs and outputs are illustrated schematically in Figure 1.

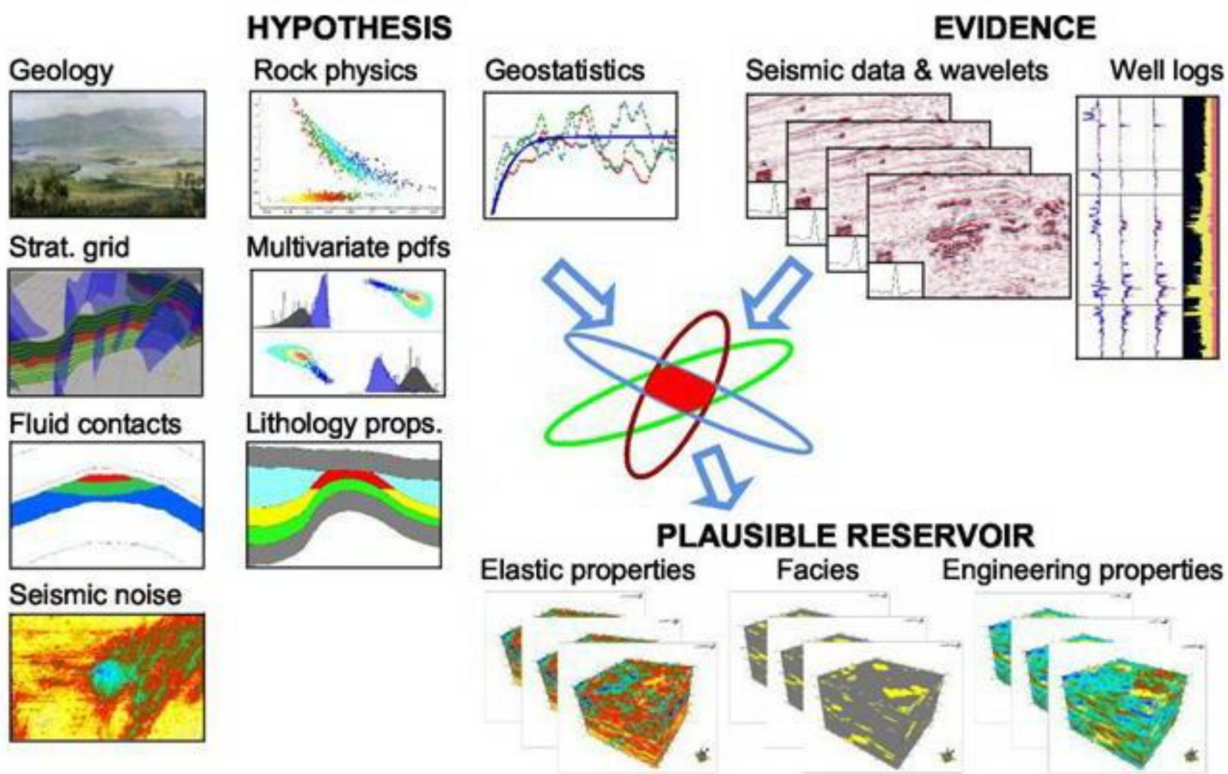

Figure 1: A Bayesian geostatistical inversion framework to integrate various data types and scales to create detailed 3D volumes of facies, elastic properties (Ip, Vp/Vs, Rho) and engineering properties (k, Sw, ϕ).

The inversion begins by building a representative stratigraphic grid of the reservoir and then generating facies-dependent multivariate pdfs of all continuous elastic and petrophysical properties of interest at the proper stratigraphic scale for each geologic zone. For each facies and each continuous property in each zone, a 3D geostatistical variogram is also specified to reflect its degree of spatial continuity. The facies is itself expressed with multiple 3D variograms in a pluri-gaussian or truncated Gaussian form (or a mixture of the two), depending on local geological expectations. Next, a pdf is built for each angle or offset seismic stack and each well log in order to reflect the inherent uncertainties of the measured data. The pdfs of the elastic properties are linked directly to the pdf of the seismic data using the Knott Zoeppritz or Aki-Richards convolutional models and a set of either constant or spatially varying wavelets for each seismic stack. A customized Markov Chain Monte Carlo algorithm is then applied to the global pdf to generate highly detailed volumes of facies and continuous properties that honor all known information about the reservoir. This information can extend beyond the seismic band.

The Bayesian framework within which this geostatistical inversion is carried out provides great flexibility to address a wide range of scenarios:

- A trend can be added to each continuous property type within each facies. For example, it becomes possible to explicitly capture effects such as a compaction trend that might have a different spatial impact on velocities in sands and shales.
- The pdf of each facies is the prior probability and can be expressed as a 3D volume, thus providing an essential entry point for including geological information such as fluid contacts, depositional trends and regional drift into the inversion itself.
- Any property can be modeled as an expression of another property. For example, it becomes possible to include any desired saturation height method into the workflow for computing

hydrocarbon volumes.

- Petrophysical properties can be linked to elastic properties via either geostatistical co-simulation or from rock physics models. For example, if there is a strong correlation between porosity and p-velocity and s-velocity, co-simulation can be used to compute it; otherwise, a rock physics model can be used.
- The stratigraphic grids on which the reservoir properties are generated can be in either depth or time. If the grid is in depth, all facies and continuous properties are generated directly in depth and the elastic properties are internally converted to time before being convolved with the appropriate wavelets.

A critical component of the algorithm is the simultaneous estimation of facies. When facies are inverted simultaneously with continuous properties, there are several advantages:

- Simulations are constrained to directly honor the measured seismic data, the measured well logs and the inferred geological trends
- Model scan have a facies-dependent rock physics model linked to elastic properties
- Sharp boundaries in the modeled properties can be achieved
- Different levels of heterogeneity which exist inter- and intra-facies as different spatial constraints can be applied to different facies and to the properties corresponding to each one.
- Continuous property trends, such as compaction trends, that differ vertically and laterally between facies can be included.

Geostatistical inversion also makes it possible to directly account for the inherent uncertainty associated with each input source of data. Together with the ability to produce multiple representations of the reservoir, it is thus possible to gain valuable insight into the underlying uncertainties. The success of the method has been demonstrated by several authors. See, for example, Merletti and Torres-Verdin, 2010 and Sams et al., 2011

Conclusions

The key to building highly detailed, realistic and useful 3D reservoir models of facies and petrophysical properties lies in the integration of disparate data sources such as seismic data, well logs and prior geological expectations. This level of integration is at best difficult with conventional methods based on various forms of well log interpolation and/or deterministic seismic inversion. This is because all such methods rely on a sequential determination of facies and elastic/petrophysical properties. Examples were shown in this paper to illustrate how simultaneous inversion of facies and elastic properties within a geological context is made possible by using a geostatistical inversion algorithm in a Bayesian framework. Such an integrated approach leads to more robust facies models that have the expected level of fine scale heterogeneity

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