GeoNeurale

DETERMINISTIC CONSTRAINTS IN SEISMIC INVERSION, STATIC MODELING AND FWI

In seismic inversion, FWI and static modeling there are two main problems.
Filling the 3D volume with parameters where measurements are not available and screening higher resolution where measurements do not allow higher resolutions.
An additional problem is the positioning of the property values within the volume assuming that the difficult process of a proper velocity modeling and migration (construction of the reflector structure, assignment of each reflection event to the proper bin) have been successfully implemented.

Regions of the subsurface where the joint variographic / spatial-covariance function for seismic impedance or attributes parameters lays within stable tolerance limits (meaning relative constant values) can be called “**Uniform Regions** for seismic impedance or for a specific attribute”.
This will usually mark a specific lithological formation or subdivision within the same formation into different fluid/gas saturation, texture or mineral compartments.
In the seismic impedance domain the joint variographic parameters would be velocity and density which would constrain themselves and their product within the limits typical for the formation or compartment under consideration.

Outside uniform regions, the general variability trend from a region to the next offer further instruments of discriminating trends (isotropy and anisotropy).
A variogram model can be calculated on 360° or solid angle directions, which will produce different variograms for every directions. After determination of Sill, Range, Nugget Effect for each variogram, the spatial data can be screened for homogeneous, heterogeneous, isotropic or anisotropic behaviour.
If the values of Sill, Range, Nugget Effect are constant in all directions, then we will have full isotropic behaviour otherwise, anisotropic behavior and the significance of each specific parameter defining the variogram geometry will have to be studied in the context of interscale and regional variability.

REV (REPRESENTATIVE ELEMENTARY VOLUME)

In reservoir engineering scale is a synonym of system dimension.
Scales are classified as micro (pore scale), macro (core scale), mega (3D seismic scale), giga (regional geology to reservoir architecture) (Haldorsen and Lake 1989, Fanchi 2001).
Therefore the pore scale will be classified as a low scale while regional geology will be a higher scale.
Resolution is the power of a tool to discriminate the smallest details in the formation, therefore petrophysical measurements have higher resolution that 3D seismic.
REV is the resolution domain of the measuring system, measuring a specific "average" of the various components in the volume.
Below this, the measurement can not catch the lower scale variability (linear spatial variability /heterogeneity, azimuthal spatial variability / anisotropy) of the system.
Within the REV a tool with higher resolution could catch the variability at a lower scale.

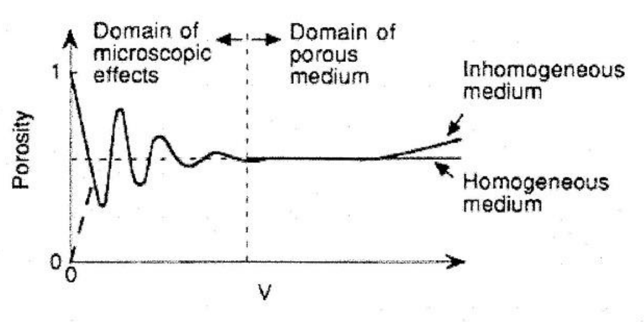

Fig. 1
REV example of property (porosity) variability within the volume of investigation resolution.
Cy: Bear (1972), L.W. Lake (2002). Reservoir Characterization from the laboratory to the field (SPE 2002)

In petrophysics the REV is related to the volume of investigation for a specific tool.
Within this volume measurements "averages" can be calculated with convenient rock physics algorithms and these correspons to the tool reading.

A REV with constant parameters is a subdomain of a uniform region and the volume to be investigated consists of many uniform regions with different parameters.
The concept recalls the cells functions of a static model where the petrophysical properties are upscaled with the most convenient algorithm into each cell in order to provide a new model for the next steps of dymanic simulation. As a consequence, cells of constant values or values constrained within specific limits can be grouped into a uniform region.

Above and below each REV or measurement systems there are indetermination areas called gaps. New tools (NMR, electromagnetic resisitivity) and measurements combination methods are continuously developed to try and fill scale gaps.
Role of the integration between measurement systems / scales is the determination of variability/ies and properties in each gap.

One of the main roles of geostatistics is to fill interspatial gaps at specific actual REV scales but also interscale gaps within the same uniform region (measurements combination). Conventional estimation techniques of linear or non-linear kriging but also Markow chain processes and multipoint histogram techniques are mainly concentrated to fill spatial gaps in regions without available measurements, but recent developments allow discrimination below an actual REV resolution.
Stochastic inversion takes advantage of geostatistical techniques like sequential gaussian simulation (SGS), simulated annealing and derivated algorithms to calculate unknown points at a specific empty data location. This functions both as spatial gap and scale gap screening. However ,as in the case of SGS, the uncertainty will propagate when statistically calculated points will be used as measurements to calculate the next point in the next empty location.

With recent methods in multiattributes analysis many techniques have been introduced to solve for empty spaces with calculated parameters in the 3D volume but also to distribute higher resolution measurements with the aid of combined seismic attributes.
However this processes are always statistic. They can be subdivided into two main cathegories: linear and non-linear multiattribute analysis.
The linear multiattributes analysis is generally realized through multivariate linear regression methods with algorithmic improvements (es. convolutional operators).
The non-linear multiattribute analysis is mainly implemented through logistic regression and neural networks (NN).
Non-linear methods perform higher efficiency and precision in the simulation and distribution of lower scale properties into the 3D volume.
Both methods for property volume distributions are performed in supervised mode, where a training correlation and validation process precedes a simulation/distribution phase .
Parameters like porosity, density, P waves and S waves velocity, water saturation, gamma ray have been distributed with a certain efficiency in the seismic volume mainly through NN algorithms.

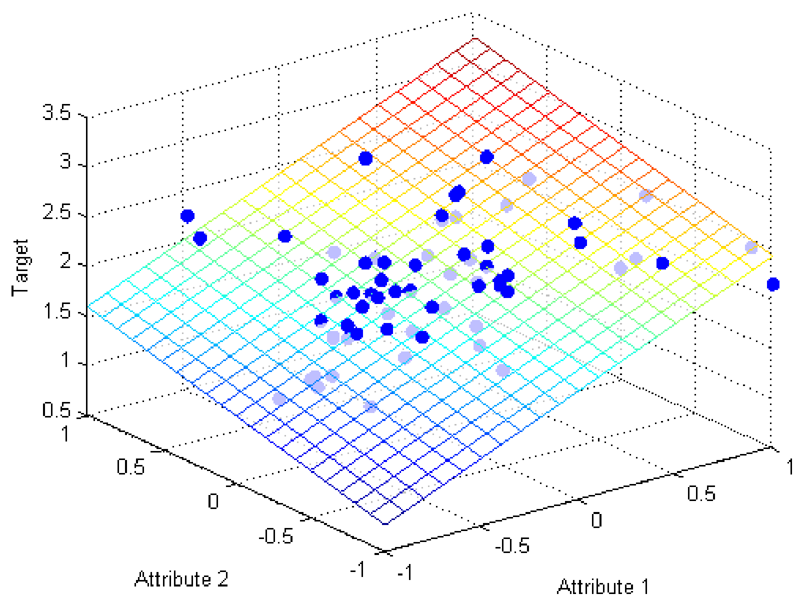

Fig. 2

Linear regression geometry: multivariate linear regression with two training attributes and one target
Cy: Hampson-Russel 2013

DETERMINISTIC CONSTRAINTS PRODUCE HIGHEST RESOLUTION

In the search for higher resolution it can be an advantage if we look for physical relationships to input higher resolution (lower scale properties) into higher scale uniform regions. GeoNeurale research introduced new deterministic constraint which have been produced to correlate seismic impedance and resistivity attributes (Piasentin 2013).
Apparently these two kinds of parameters could seem to be one another uncorrelated .
The algorithm can be successfully used for studies in carbonate as well as clastic formations introducing constraints into uniform regions and distributing higher resolution parameters into the seismic volume. Resistivity attributes are introduced into the elastic domain through the porosity exponent [Pexp].
The Porosity exponent contains petrophysical paremeters, Sw , Rw. Rt , m that can be distributed into the seismic volume as subdomains of a seismic attributes and within a seismic attribute spatial location.

$$R_p(0) = \frac{\Delta V_{p\text{-seis}}}{V_{Pave\text{-seis}}} + \frac{\left[\, \rho_{ma} + (\rho_f - \rho_{ma})\, e^{[Pexp]} \,\right]_2 - \left[\, \rho_{ma} + (\rho_f - \rho_{ma})\, e^{[Pexp]} \,\right]_1}{\dfrac{\left[\, \rho_{ma} + (\rho_f - \rho_{ma})\, e^{[Pexp]} \,\right]_2 + \left[\, \rho_{ma} + (\rho_f - \rho_{ma})\, e^{[Pexp]} \,\right]_1}{2}}$$

(8)

and:

(9)

$$R_s(0) = \frac{\Delta V_{s\text{-seis}}}{V_{Save\text{-seis}}} + \frac{\left[\, \rho_{ma} + (\rho_f - \rho_{ma})\, e^{[Pexp]} \,\right]_2 - \left[\, \rho_{ma} + (\rho_f - \rho_{ma})\, e^{[Pexp]} \,\right]_1}{\dfrac{\left[\, \rho_{ma} + (\rho_f - \rho_{ma})\, e^{[Pexp]} \,\right]_2 + \left[\, \rho_{ma} + (\rho_f - \rho_{ma})\, e^{[Pexp]} \,\right]_1}{2}}$$

After correlation of sonic velocities with interval velocities, and seismic and petrophysical densities, the zero offset reflectivity can be transformed into seismic impedances.
Alternative methods for direct calculation of seismic impedances have been also developed.
Integrating microproperties with seismic macroproperties we can talk about corresponding property systems: “Geomicrosystems” and “Geomacrosystems” . Within these systems each property is in a scale dependent correlation.
Eq. 8 to 13 represent deterministic relationships between petrophysical and seismic properties.

Introducing petrophysical constraints into the porosity exponent, a distribution of saturation, cementation exponent and electrical properties within the volume is possible after correlation of seismic impedance and secondarily Pexp and Sw with seismic attributes (single or combined intensity of low frequency spectral decomposition, statistical texture attributes, complex signal strength amplitude, real amplitude and real amplitude Hilbert transform, instantaneous phase and frequency and AVO attributes).

$$V_{Pe} = \frac{\dfrac{1}{\left[\tau_{ma} + (\tau_f - \tau_{ma})\ e^{[Pexp]}\right]_2} + \dfrac{1}{\left[\tau_{ma} + (\tau_f - \tau_{ma})\ e^{[Pexp]}\right]_1}}{2} \qquad (10)$$

$$\Delta V_{Pe} = \frac{1}{\left[\tau_{ma} + (\tau_f - \tau_{ma})\ e^{[Pexp]}\right]_2} - \frac{1}{\left[\tau_{ma} + (\tau_f - \tau_{ma})\ e^{[Pexp]}\right]_1} \qquad (11)$$

$$V_{Se} = \frac{\dfrac{1}{\left[\tau_{Sma} + (\tau_{Sf\text{-}app} - \tau_{Sma})\ e^{[Pexp]}\right]_2} + \dfrac{1}{\left[\tau_{Sma} + (\tau_{Sf\text{-}app} - \tau_{Sma})\ e^{[Pexp]}\right]_1}}{2} \qquad (12)$$

$$\Delta V_{Se} = \frac{1}{\left[\tau_{Sma} + (\tau_{Sf\text{-}app} - \tau_{Sma})\ e^{[Pexp]}\right]_2} - \frac{1}{\left[\tau_{Sma} + (\tau_{Sf\text{-}app} - \tau_{Sma})\ e^{[Pexp]}\right]_1} \qquad (13)$$

VALIDITY AND CONSTRAINTS

The model is valid for water saturated or partial water/gas saturated formations, for partial water/oil saturated formations this model must be upgraded with new constraints. The model has to be labor calibrated and classified for texture and lithology.

This will also introduce correlation between Compressibility **K** and Rigidity μ .
A correction term have to be introduced for each step of overburden pressure increment. Therefore a single model is only valid into the own overburden pressure definition limits.

A specific note has to be addressed concerning S-waves slowness for the fluid component τ_f that appear in the petrophysics theory for calculation of bulk slowness and porosity through the sonic tool. Whereas Vs in fluid is considered to be equal to zero, the experimental fluid slowness in the bulk slowness calculation is a finite value due to the bound water and structural water components.

This model is integrated into the AVO theory, it can be calibrated in the lab and in the field for different wavelengths and reflection angles, it allows the introduction of new geo-microsystems attributes such as **Sw** , **Rw**, **Rt** , **m**, texture and mineral component with transition between uniform regions adding additional data to the uncertainty volume and increasing resolution into an inversion volume. Furthermore reservoir characterization based on cementation exponent **m** provide answers to critical issues like texture and genetic / classification systems in carbonates.

NOTATIONS

$R_p(\theta)$ = Reflectivity of P waves with angle of incidence θ

$R_p(0)$ = Zero Offset Reflectivity P waves
$R_s(0)$ = Zero Offset Reflectivity S waves

V_P = Velocity P wave
V_S = Velocity S wave

Difference between velocities at the lower and upper layer
$\Delta V_p = V_{P2} - V_{P1}$
$\Delta V_s = V_{S2} - V_{S1}$
$\Delta V_\rho = V_{\rho 2} - V_{\rho 1}$

e = Euler number (2,71..)

ρ_{be} = Electro bulk density
ρ_{ma} = matrix density
ρ_f = fluid density

τ_{Pbe} = Elektro-Slowness P waves
τ_{ma} = Matrix Slowness P waves
τ_f = Fluid Slowness P waves

$R_p(0)$ = Zero Offset Reflectivity

$V_p = 1 / \tau_{Pbe}$

[Pexp] : Porosity exponent

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