Assessing deformation and fracturation with volumic balanced restoration

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Abstract

This poster illustrates a methodology to characterize fracturation and assess induced permeability based on connectivity analysis. Fractures parameters (density, size, aperture...) are stochastically generated from well data. Secondary information (soft data) is an analogue parameter that integrates all available indirect information on fractures (seismic attributes, strain, stress, curvatures...). Multivariate statistics are used to find the best non-linear combination of indirect parameters that fits observed parameters on wells.

Strain related information (tensor, principal strain direction and elongations) can be easily computed over all a defined volume using 3D balanced unfolding based on tetrahedral meshes. It may enhance greatly the quality of the analogue fracture parameter. A new methodology derived from mechanics of continuum media allows to estimate the restored geometry and a static strain associated with the folding / faulting process.

Introduction and goals

Sub-seismic scale fracture characterization is a key issue for the assessment of equivalent permeability in reservoirs. This is commonly achieved by stochastic modeling.

- Fracture parameters (mainly density and orientation) are directly available on wells (e.g. FMI) and thus remains spatially clustered. Other parameters (seismic attributes, rock types, curvatures...) are indirectly related to fractures, available over all the volume and must be taken into account.
- Selecting an appropriate set and combination of indirect parameters is critical to properly provide soft data for stochastic modeling. It needs to be automated, optimized and validated against well data by statistical analysis (part V).
- The range and quality of secondary data (from seismic attributes to curvatures) could be greatly enhanced by a geologically meaningful parameter such as rock strains. This methodology proposes, for example, to use the strain tensor computed from volumic structural restoration (parts I to IV)

I 3D balanced unfolding methodology

The goal of 3D balanced unfolding is to restore a stack of sedimentary layers in such a way that the upper bounding horizon H[1] is transformed into an unfolded and unfaulted horizon H[0] and that the underlying layers follow this transformation in a piecewise continuous way (Figure 1).

A so-called restoration vector is computed for each particle α embedded in the considered layers. To actually balance the volume and ensure geological meaning of the restored state, the field of restoration vectors honors two general weighted constraints.

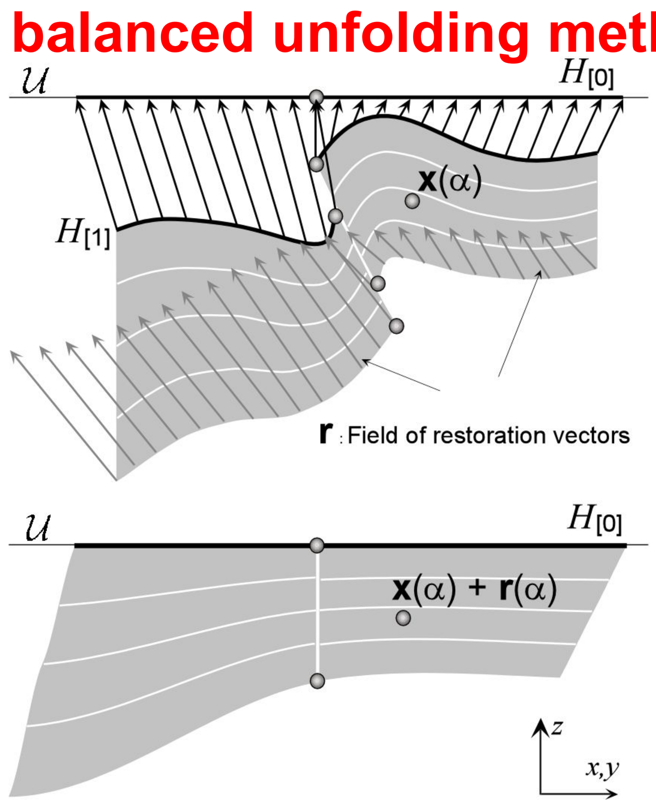


Figure 1 [Mallet, 2001, modified]

Geometry based techniques
Algorithmic & computational geometry

Interpolation techniques
Analogy to M.C.M.
Discrete Smooth Interpolation (least-square solver)

Geomechanics techniques
Finite Elements Methods

Data requirements - Computation time

II Constraints on the restoration vectors field

Minimum infinitesimal strain

- *Isotropic*

$$\varepsilon_{[1]\mathbf{x}^i\mathbf{x}^j}(\alpha) \approx -\frac{1}{2}\cdot\left\{\frac{\partial \mathbf{r}^i_{[1]}}{\partial \mathbf{x}^j} + \frac{\partial \mathbf{r}^j_{[1]}}{\partial \mathbf{x}^i}\right\} \approx 0, \quad \forall i,j \in \{1,2,3\}$$

- *Anisotropic* : minimization along specified direction(s) **W(α)**

$$\Delta(\mathbf{W}_\alpha) = \mathbf{W}_\alpha{}^t \cdot \varepsilon \cdot \mathbf{W}_\alpha \approx 0$$

Volume preservation

"Equation of continuity" + $\left.\frac{\partial \mathbf{x}_{[t]}(\alpha)}{\partial t}\right|_{t=1} \approx -\mathbf{r}(\mathbf{x}_{[1]}(\alpha))$

$$div\{\mathbf{r}(\mathbf{x}_{[1]}(\alpha))\} = \sum_{i\in\{1,2,3\}} \frac{\partial \mathbf{r}^i_{[1]}}{\partial \mathbf{x}^i} \approx 0$$

Particle α modeled as a tetrahedron

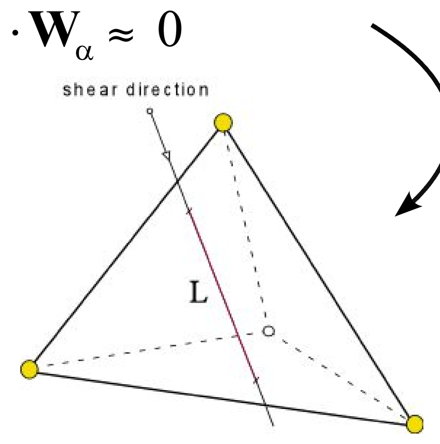


Figure 2 : For an **inclined shear deformation style**, directions are chosen accordingly to the local shear directions at the location of particle α.

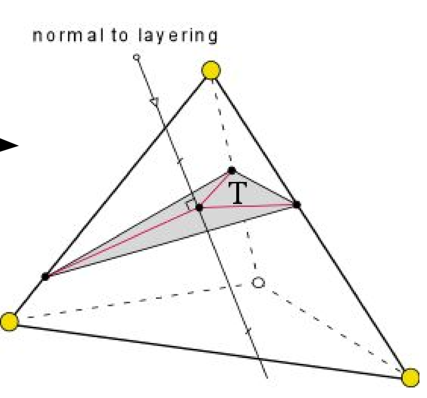
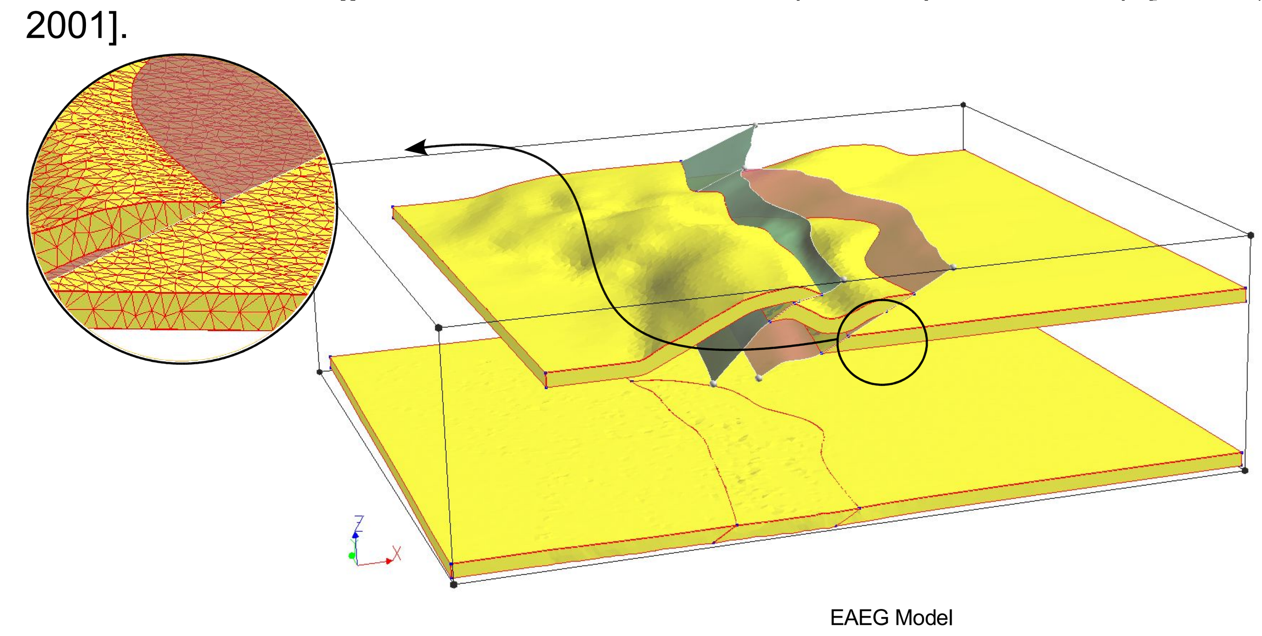


Figure 3 : For a **flexural slip deformation style**, the metric properties of layers are preserved by choosing three non-colinear directions embedded in the layering at the location of particle α.

III Spatial discretization and Interpolation

A volumic boundary representation is computed from the structural model of the region of interest and tessellated with tetrahedra [Lepage, 2003]. Displacement boundary conditions as well as main constraints (strain minimization and volume preservation) are expressed as a linear combination of restoration vectors at mesh nodes. A linear system is built and solved in the generic D.S.I. Framework (least-square solver) [Mallet, 2001].



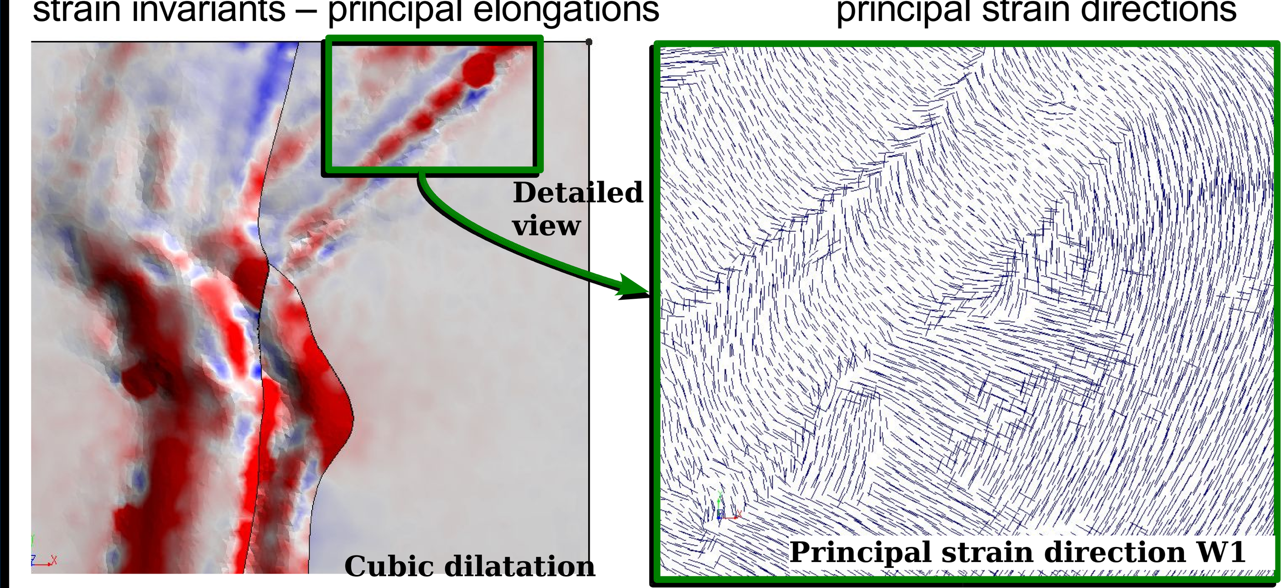
EAEG Model
130 000 tetrahedra
Computation time ~ 3 min (on PIV 2 Ghz)

IV 3D static strain tensor from displacement

$\left.\varepsilon_{[1]\mathbf{x}^i\mathbf{x}^j}\right|_T$ Infinitesimal (and finite) strain **Tensors**

Scalars
strain invariants – principal elongations

3d directions
principal strain directions

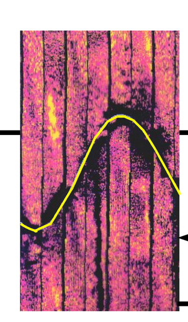


V Fracture Characterization

1. Data

1D hard data

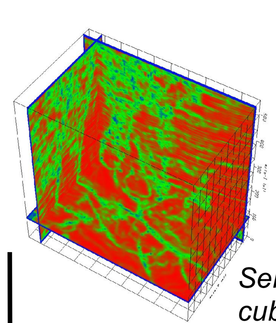
Well Borehole Images



OFP

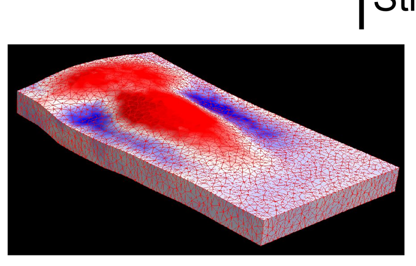
Calibration Q.C.

Seismic Attributes

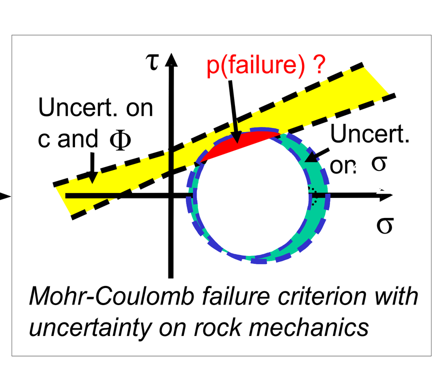


Porosity Estimate
Curvature Analysis
Deformation → Dilatation, Strain

3D soft data



Hook's law → Stress



Failure Criterion

Fracture Drivers

Distance to failure

2. Fracture Parameters

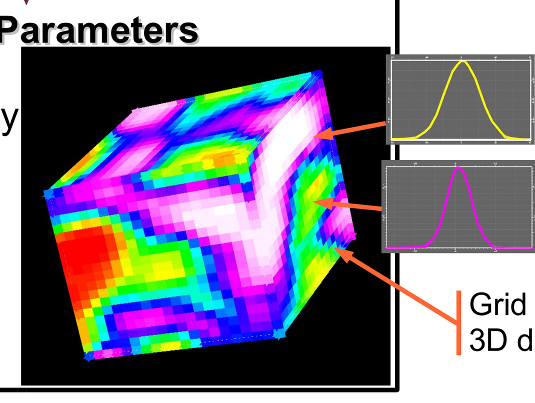
Non linear Multi-Regression (per facies)
Along well path, find α_i, φ_i such that:
$\alpha_1.\varphi_1(P_1) + ... + \alpha_n.\varphi_n(P_n)$ = EFP≈OFP

$P_1...P_n$: input data
$\varphi_1...\varphi_n$: log, √, ², ...
$\alpha_1...\alpha_n$: coefficients
OFP: Observed Fracture Parameters
EFP: Estimated Fracture Parameters

max(|EFP - OFP|) ↔ uncertainty

Fracture Parameters

EFP: Fracture Density, Orientation, Size, Aperture

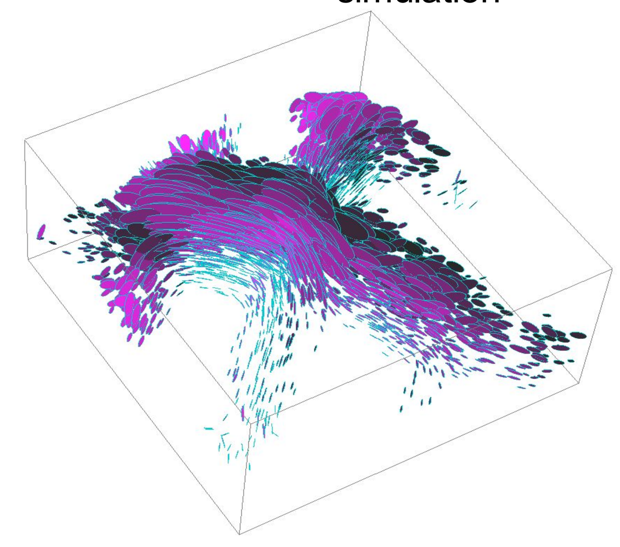


Grid property representing 3D distribution of probability laws

3. Stochastic Simulation

Fracture Centers → Non homogeneous Poisson point process

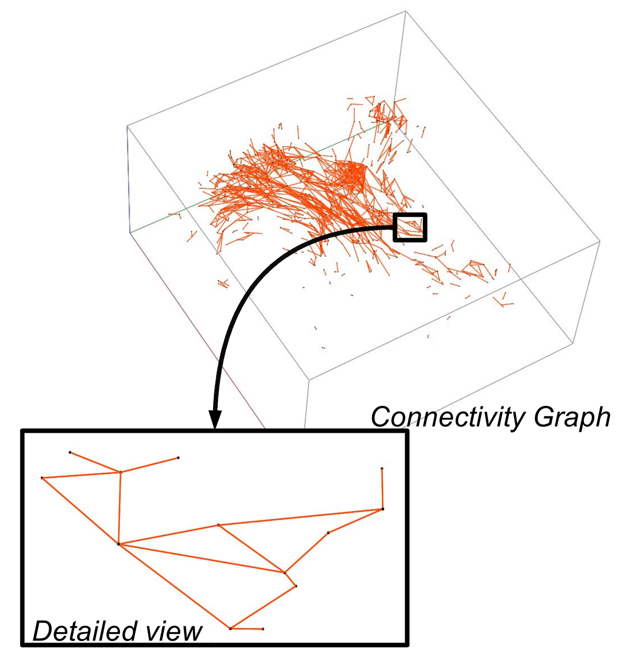
Other Parameters → Monte Carlo simulation



Discrete Fracture Network

4. Connectivity and Permeability

Fast Connectivity estimate using Octree



5. Perspectives

Equivalent permeability estimate

Conclusions

- The 3D balanced unfoldind brings valuable volumic information while requiring a minimum a priori knowledge and computation time. It can be used indirectly in the fracture characterization workflow.
- Fracture characterization and fracture permeability quantification are divided into three distinct steps :
  - Estimate first 3D distributions of each parameter describing the fracture network. Uncertainty on rock mechanic parameters such as Lame coefficients, cohesion and friction angle are taken into account ;
  - Obtain 3D Discrete Fracture Networks through stochastic simulation ;
  - Compute equivalent fracture permeability.
- Methodology validation needs to be performed on real fractures well data sets using cross-validation.

References

- **Lepage F. (2003)** – Génération de maillages tridimensionnels pour la simulation des phénomènes physiques en géosciences. - These de l'Institut National Polytechnique de Lorraine (Nancy, France)
- **Mallet J.L. (2001)** – Geomodeling. – Oxford University Press