Towards a Better Description of Subsurface Heterogeneities.

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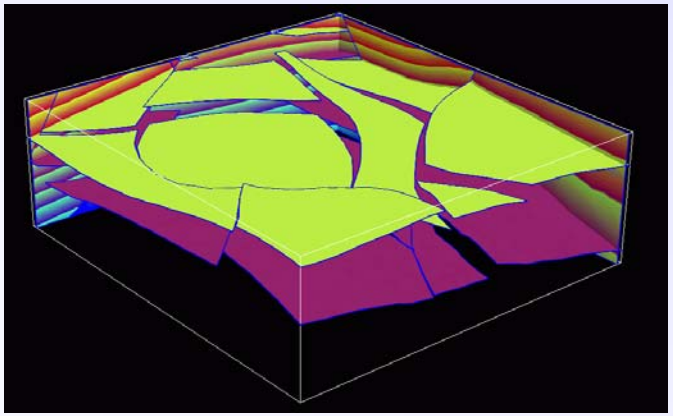
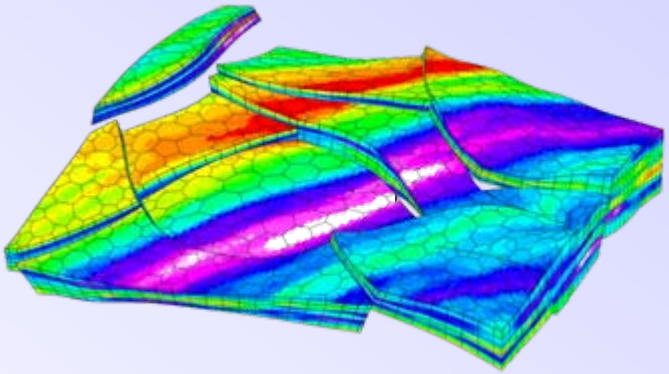
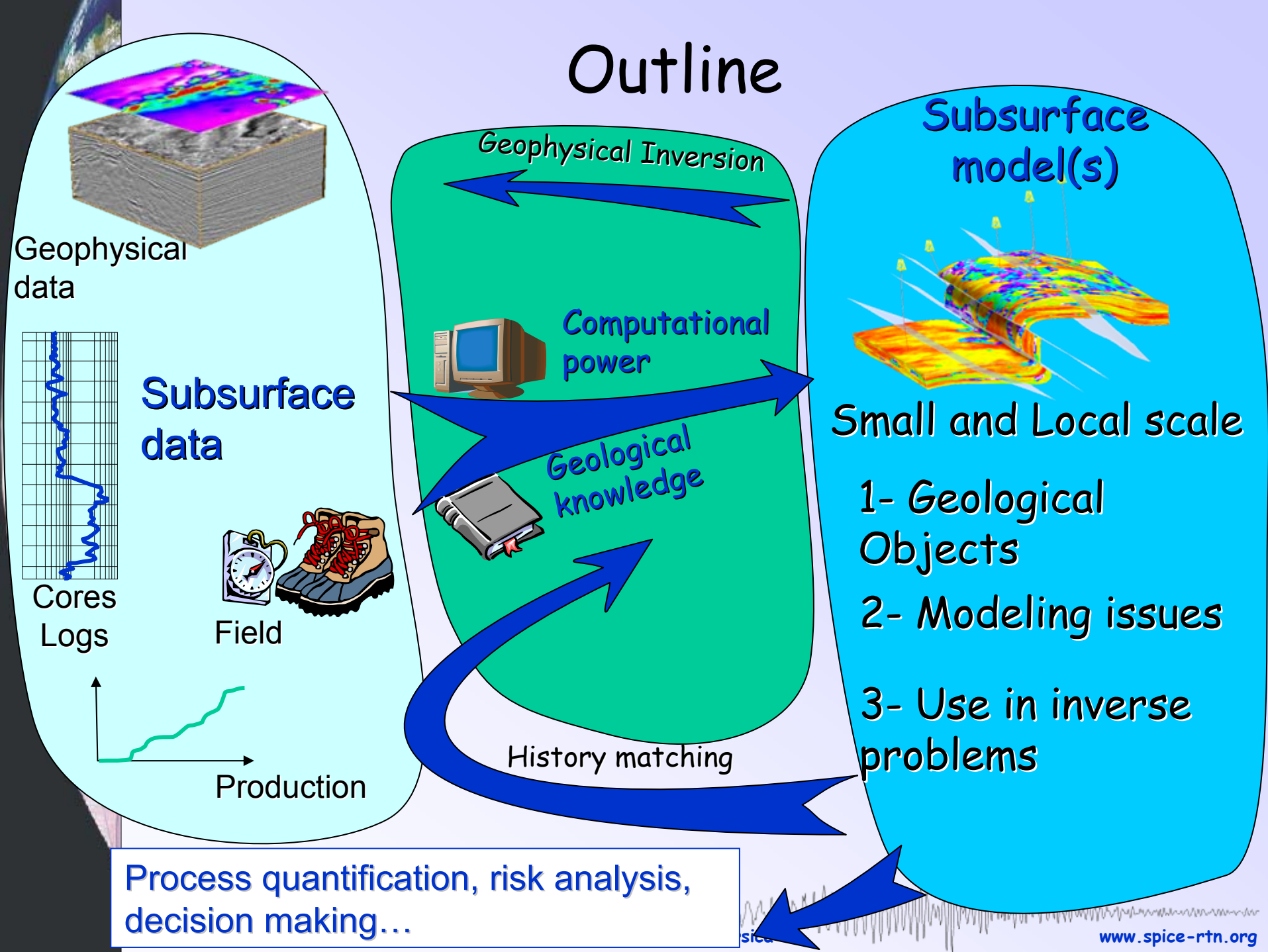
GOCAD
CRPG

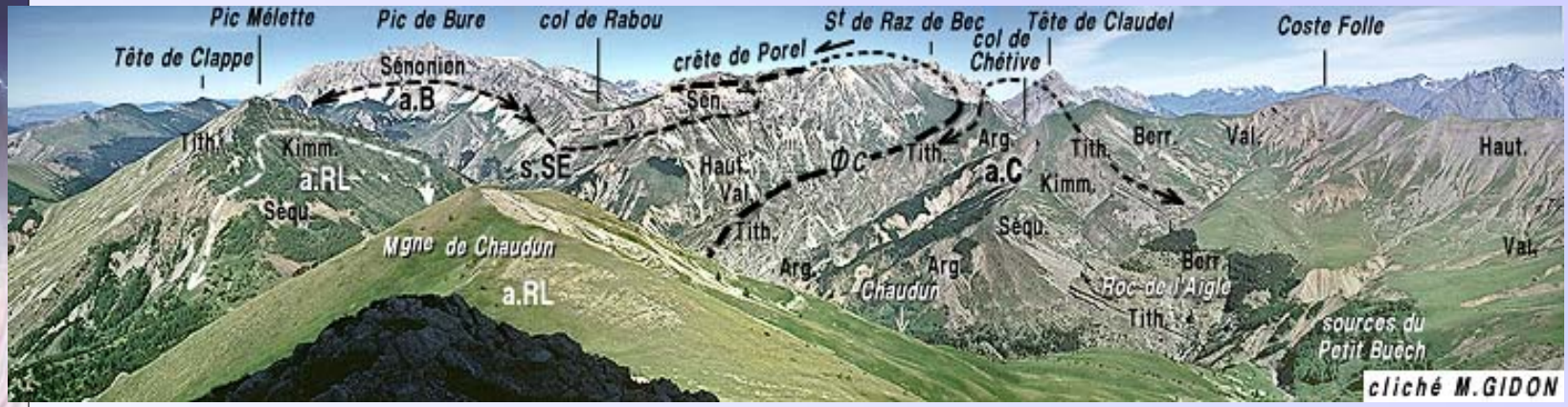




Outline

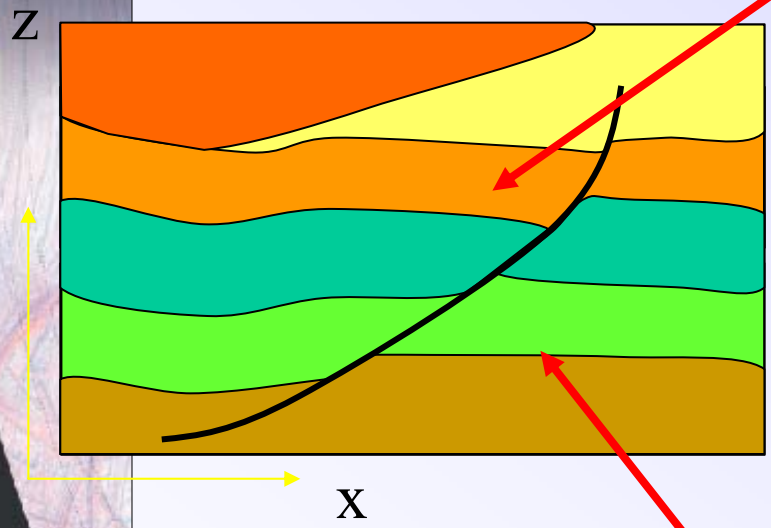

Geophysical data
Subsurface data
Cores
Logs
Field
Production
Geophysical Inversion
Computational power
Geological knowledge
History matching
Subsurface model(s)
Small and Local scale
1- Geological Objects
2- Modeling issues
3- Use in inverse problems
Process quantification, risk analysis, decision making…

1. Geological Objects



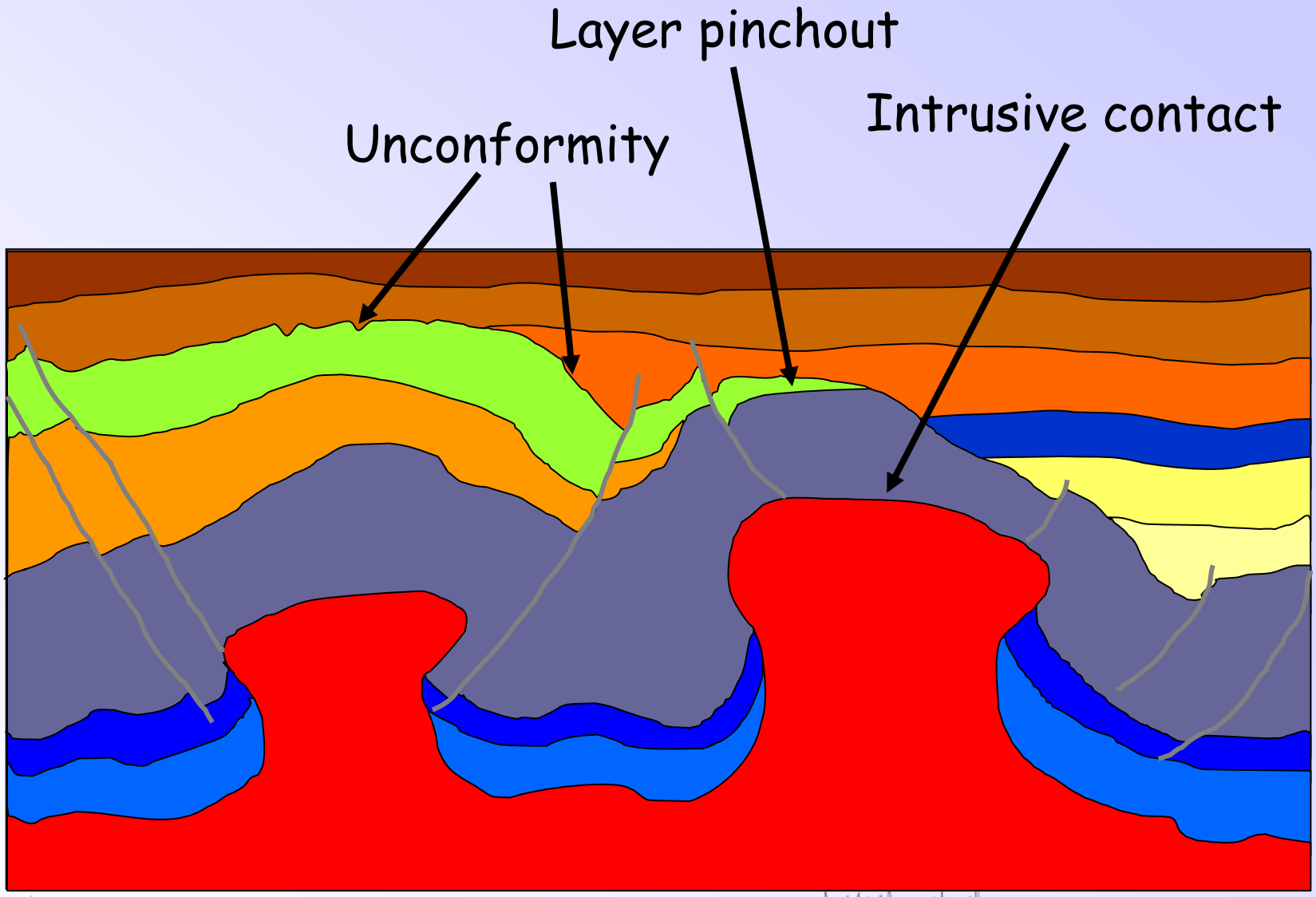
Stratigraphic Objects

Sedimentary Unit = layer

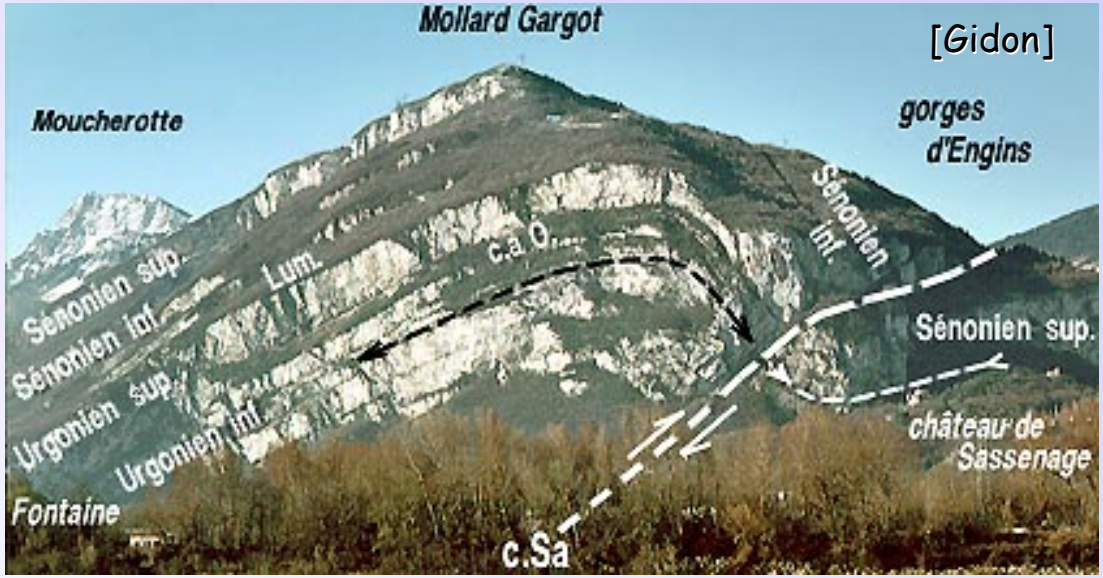


Interface = Horizon

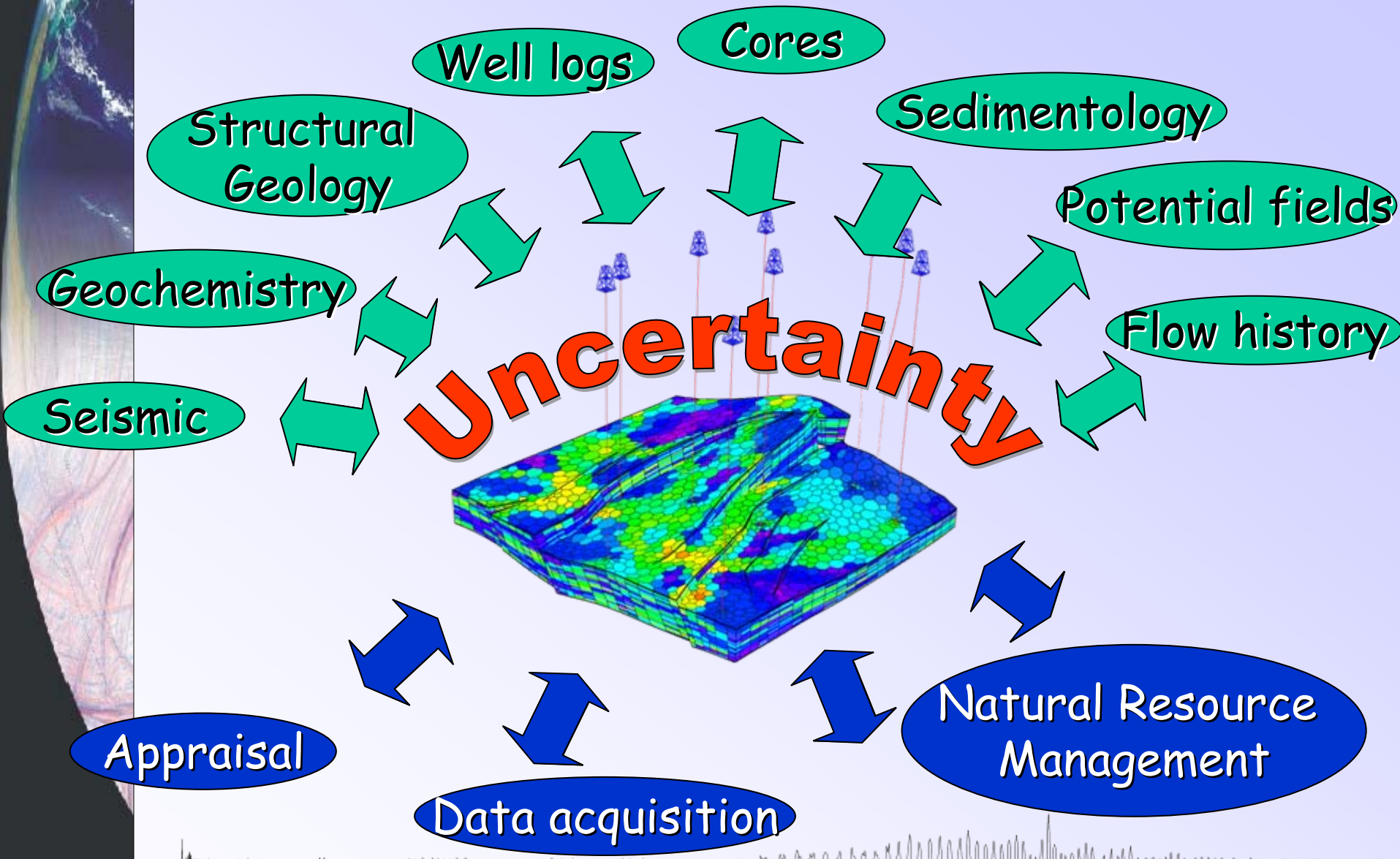
Unconformities



Tectonic Structures : Folds and Faults



2 Shared Earth Modeling



Software

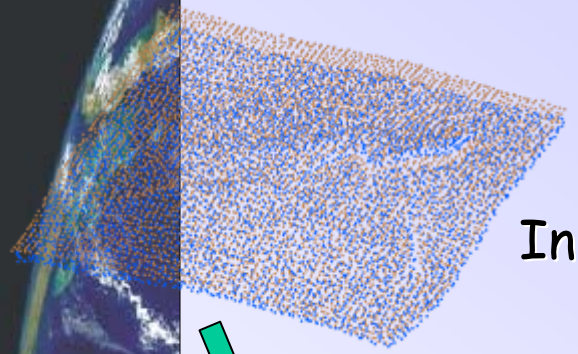
- Gocad / Earth Decision Suite – Paradigm Geophysical
- Petrel - Schlumberger
- Power Model – Landmark Graphics
- RMS - Roxar
- Earth Vision – DGI
- Jewel Suite – JOA

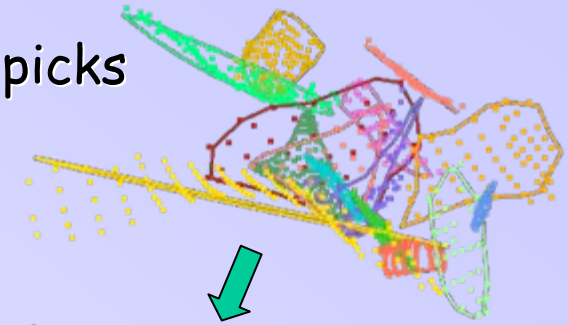
⇒ Integrated 3D modeling software

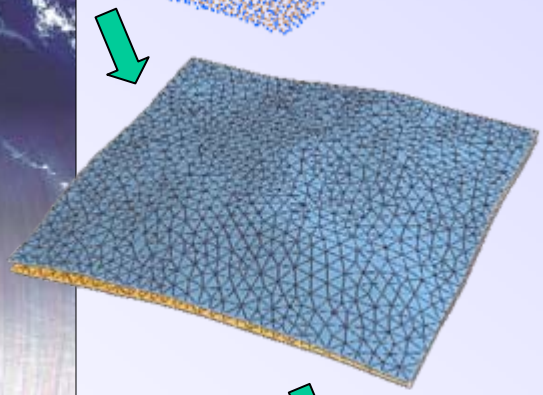
⇒ Data transfer issues

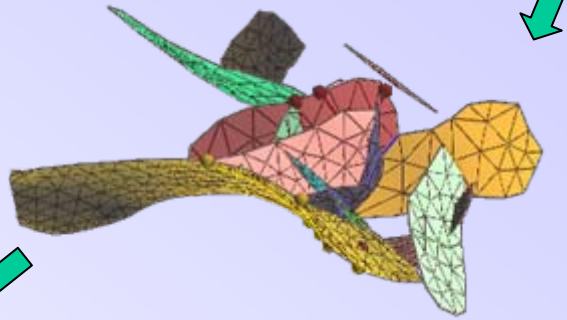
2.1 Structural Model building

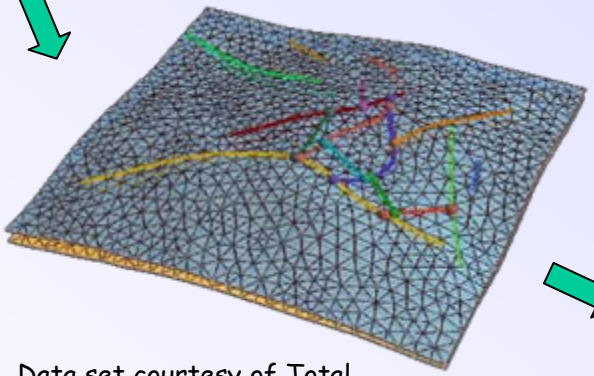
Input: Outcrop, wells, or seismic picks





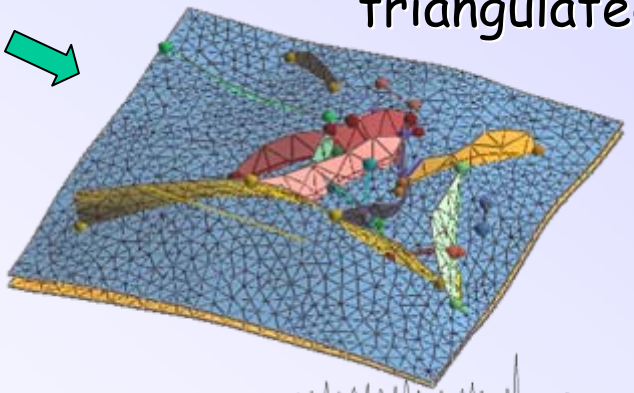




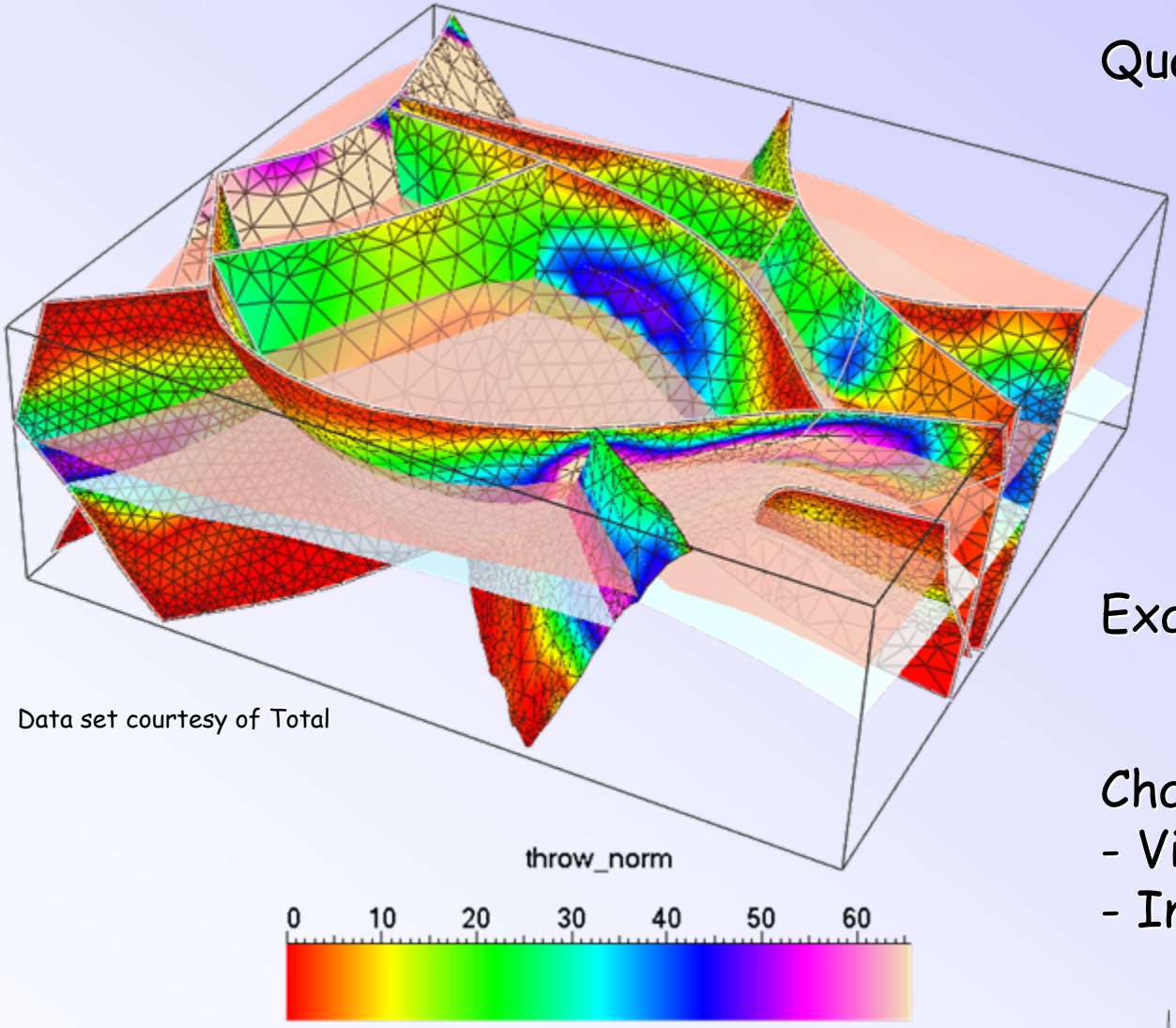


Data set courtesy of Total

Output: set of triangulated interfaces



Structural Model: QC



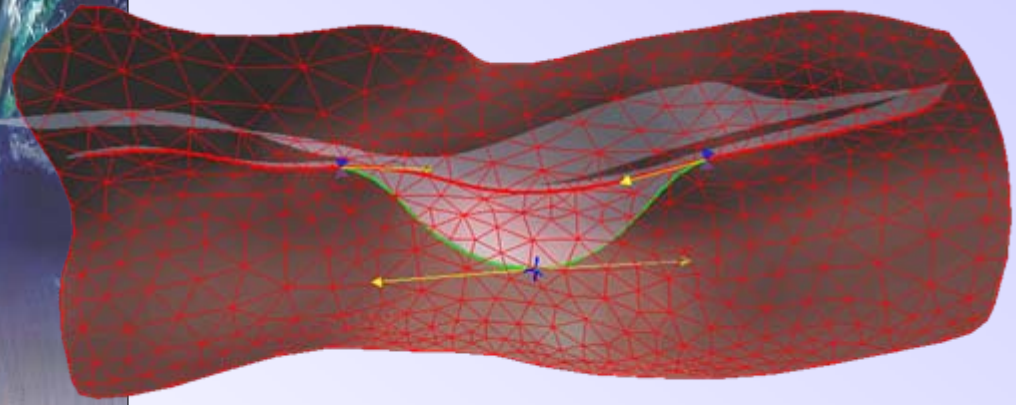
Data set courtesy of Total

Qualitative QC

Example: fault slip

Challenges:
- Visualization
- Interactive editing

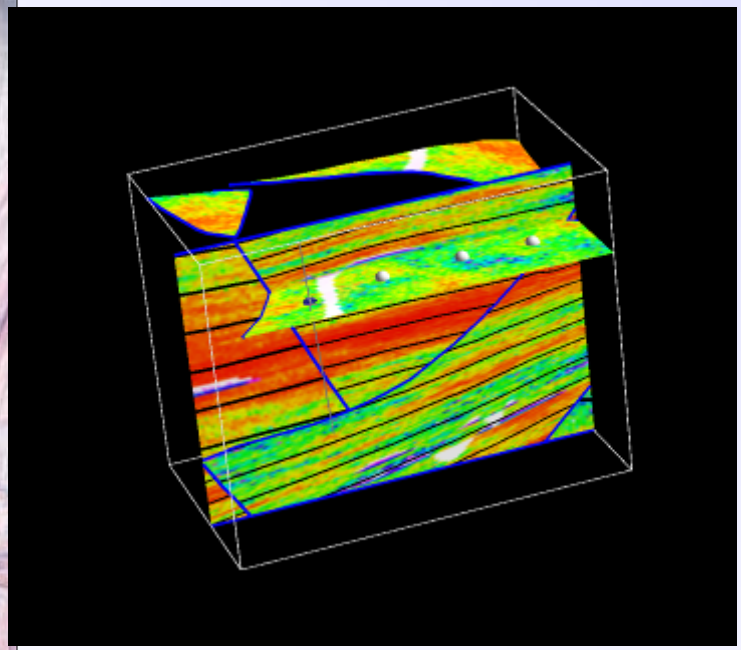
Editing a structural model



Interactive contact editing on explicit interfaces

[Caumon et al, 2004]

Controlled topological changes
Local remeshing issues



Interactive editing on implicit interfaces

[Frank & Mallet 2005]

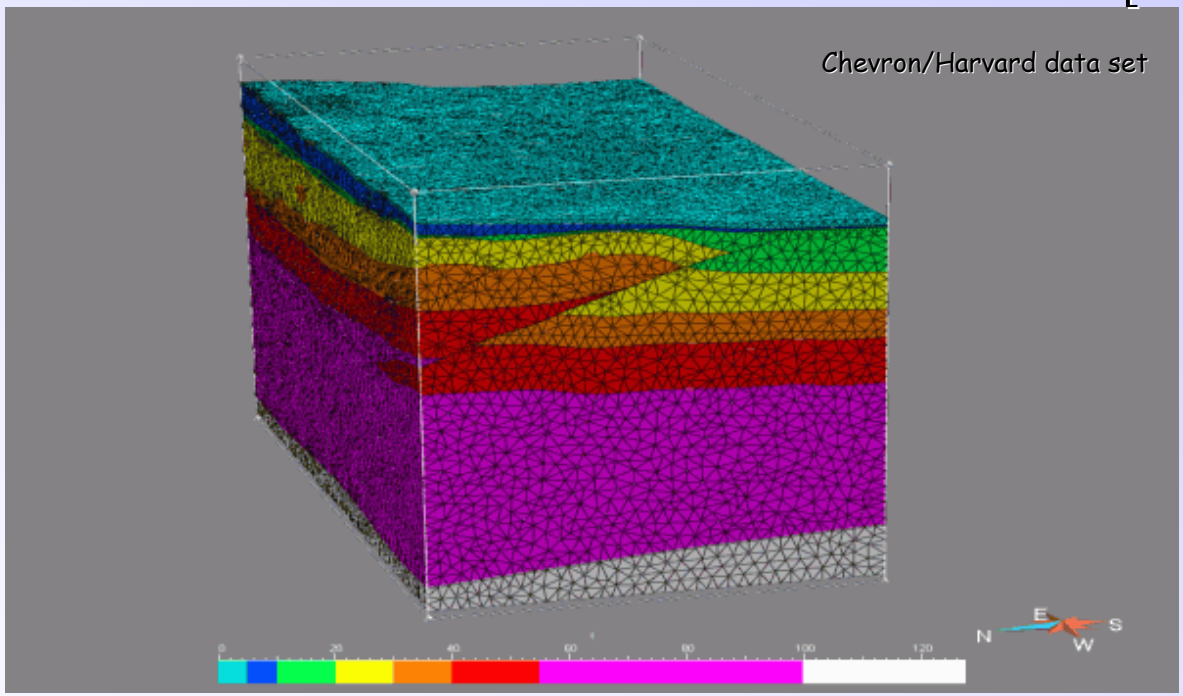
Editing of the implicit function
No remeshing needed

Fault editing in a tetrahedral mesh

[Tertois&Frank, 2005]

Quantitative QC: structural restoration

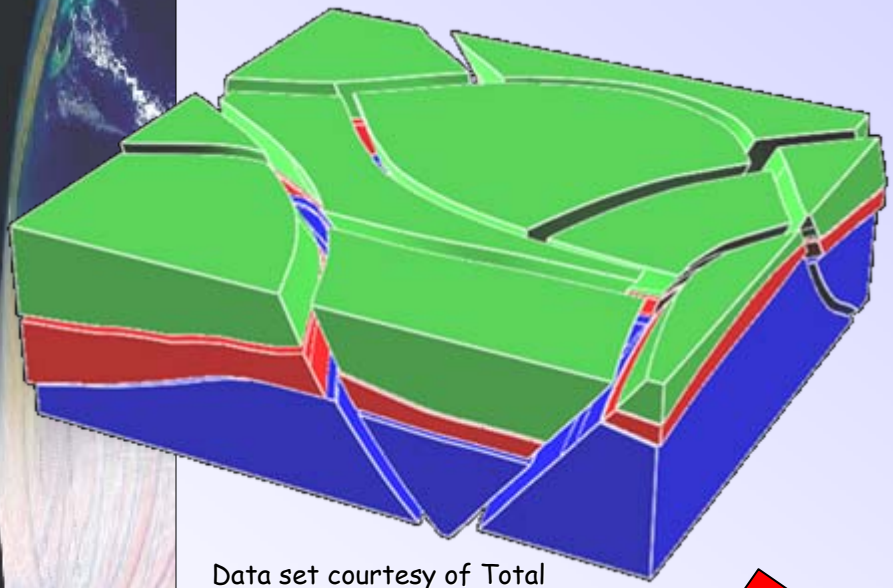
[Muron et al, 2005]



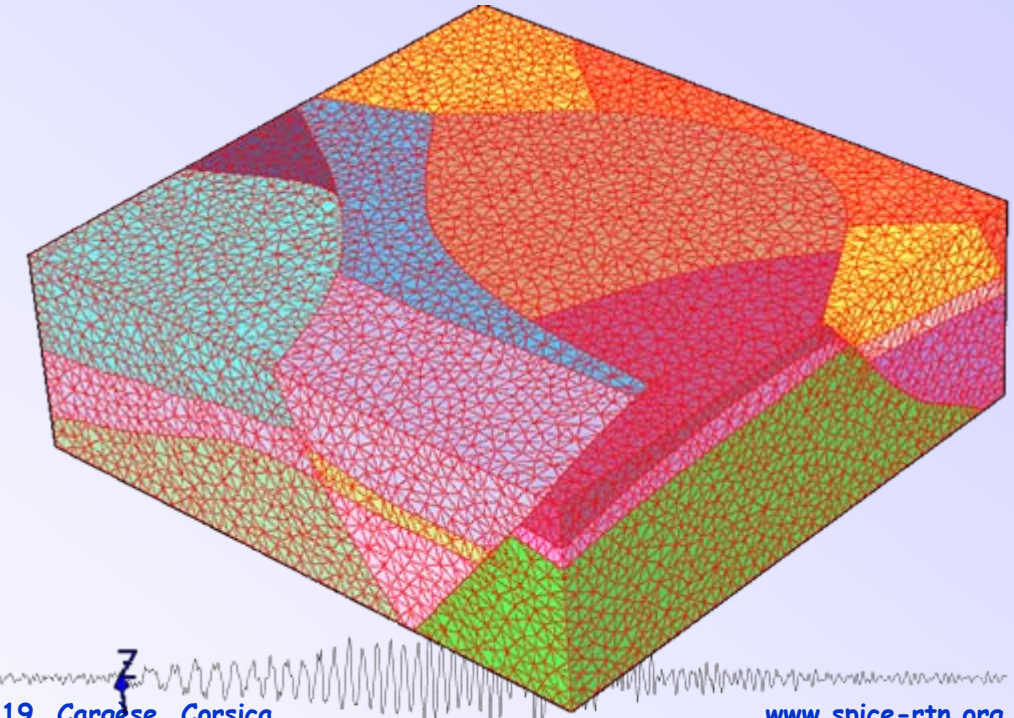
Restoration of volumes
(FE linear elastic model, with dynamic relaxation or static analysis to handle faults)

Tetrahedral gridding

[Lepage, 2003]

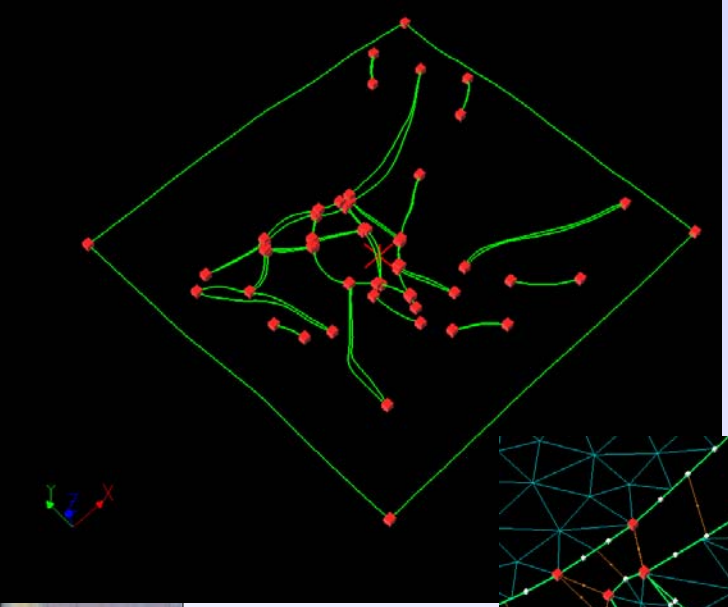


Data set courtesy of Total

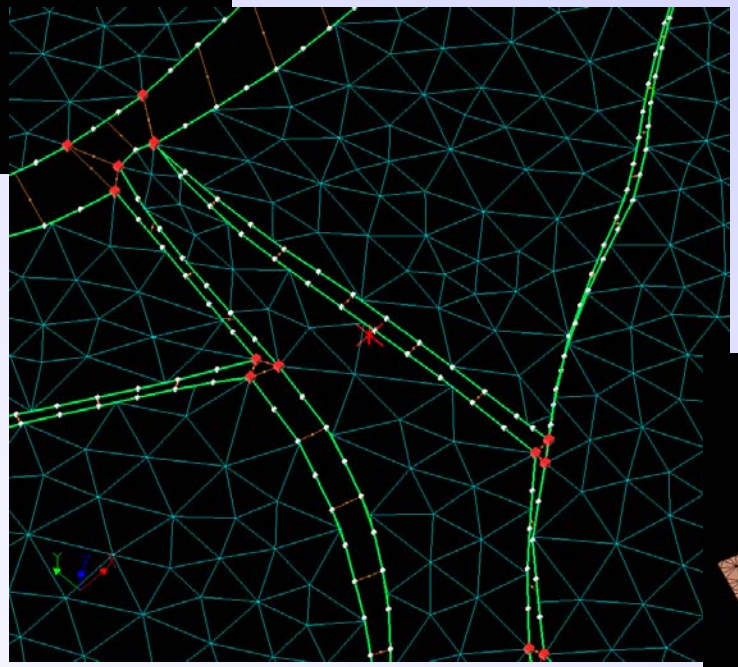


Tetrahedral gridding

[Lepage, 2003]

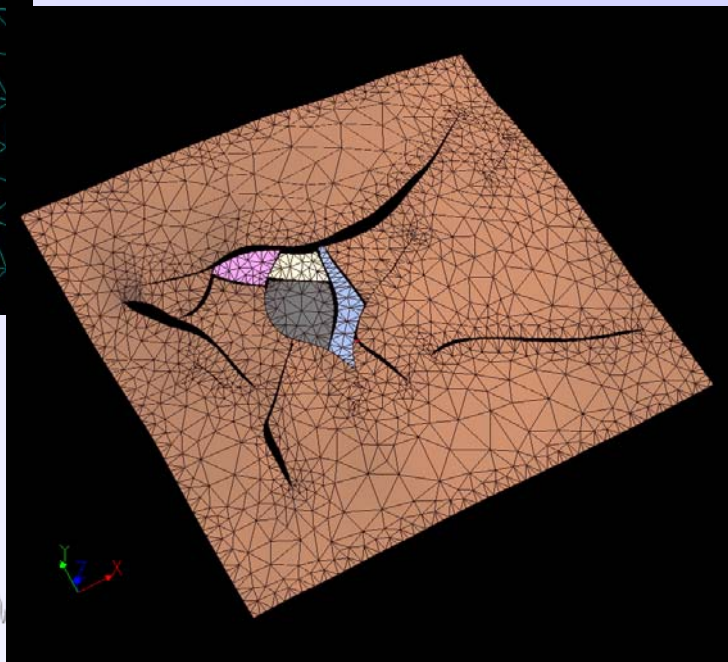


1- Extraction of contacts



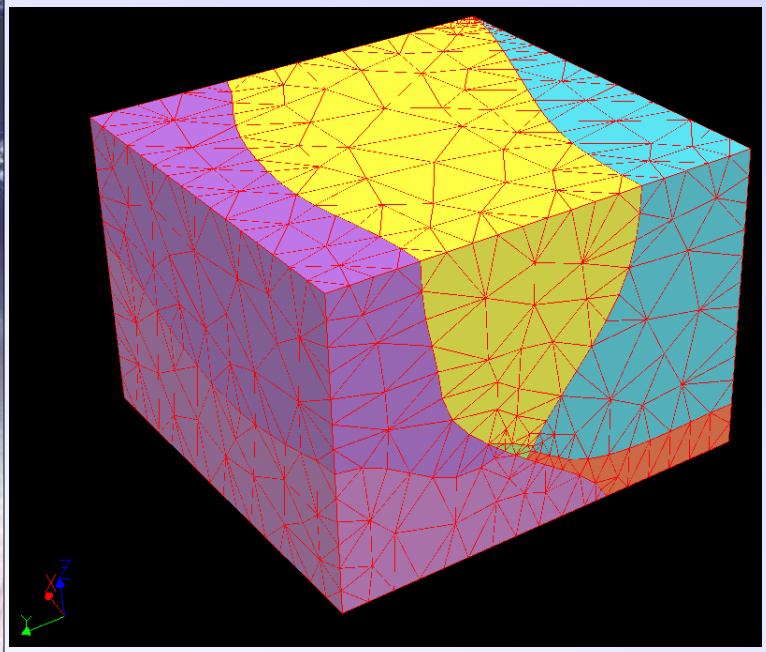
2- Uniform resampling

3- Surface re-meshing



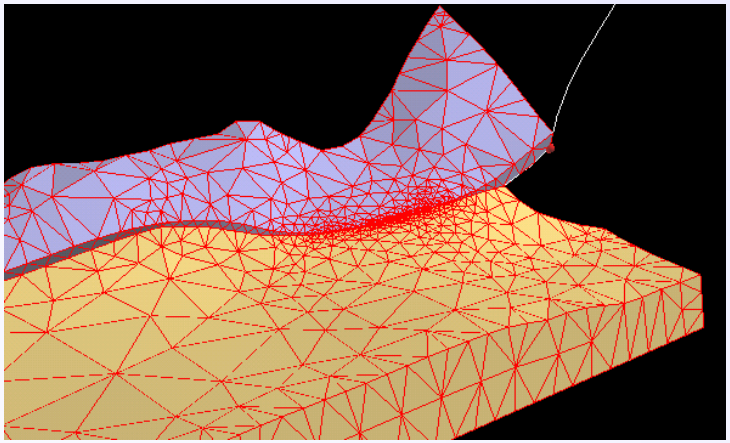
Tetrahedral gridding

[Lepage, 2003]



4- Conforming tetrahedral meshing

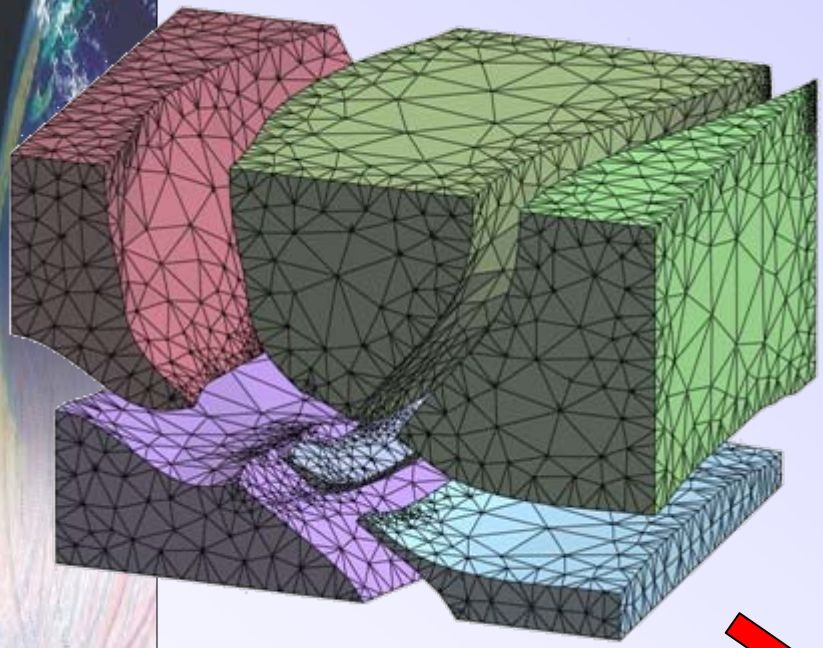
Insertion of points so as to:
- Maximize mesh quality
- Honor constraints (Faults, horizons)

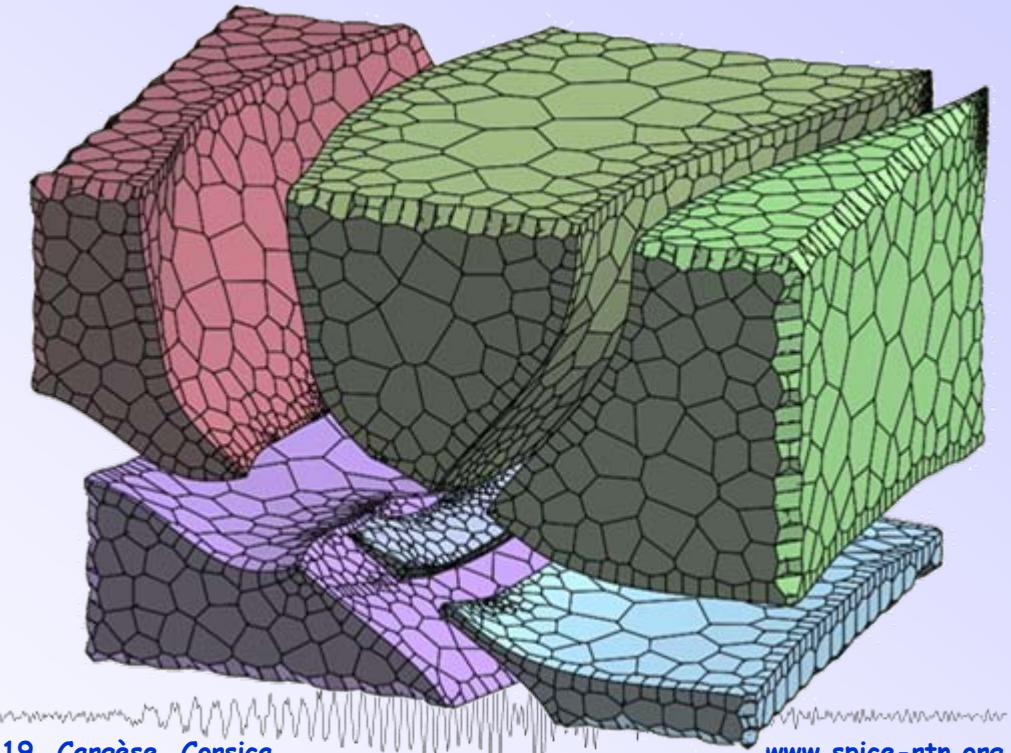


Consequence: high tetra density close to neighboring contacts

Voronoi gridding

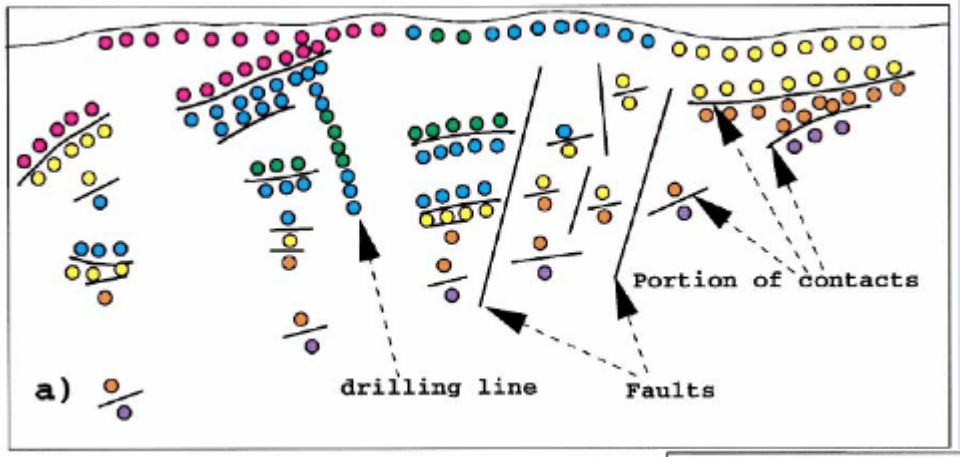
[Conreaux, 2001; Lepage, 2003]





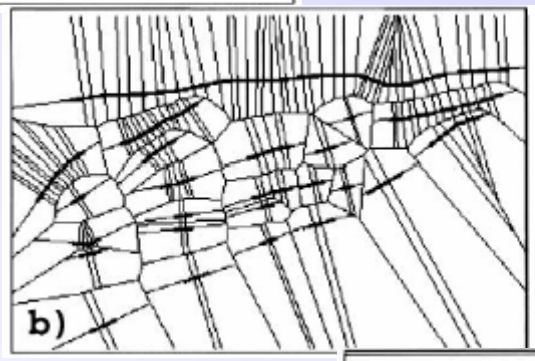
Direct Voronoi-based gridding

[Courrioux et al., 2001]
[Nullans et al, 1998]



Input (field) data

Voronoi diagram

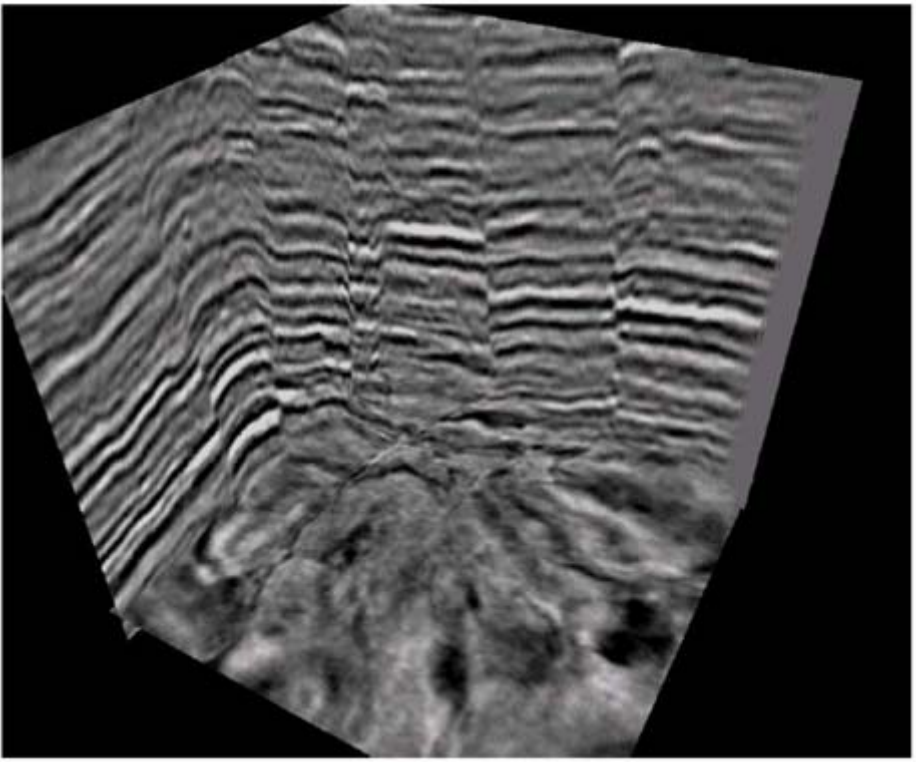


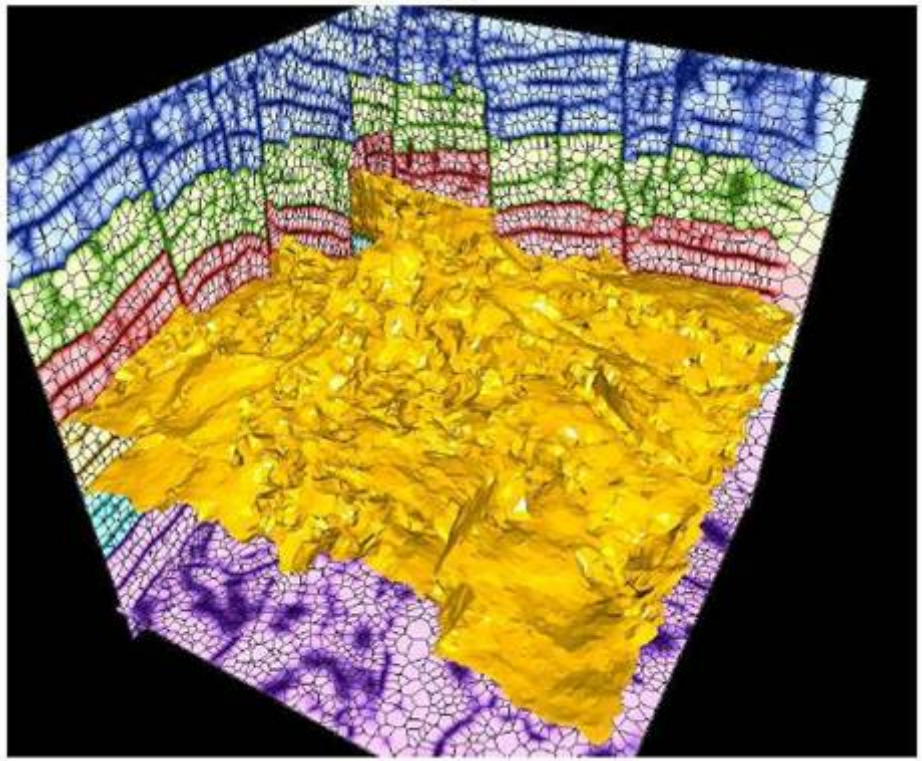
Smoothed Voronoi diagram

Direct construction from migrated seismic data

[Hale and Emmanuel, 2002]

"Atomic Meshes"

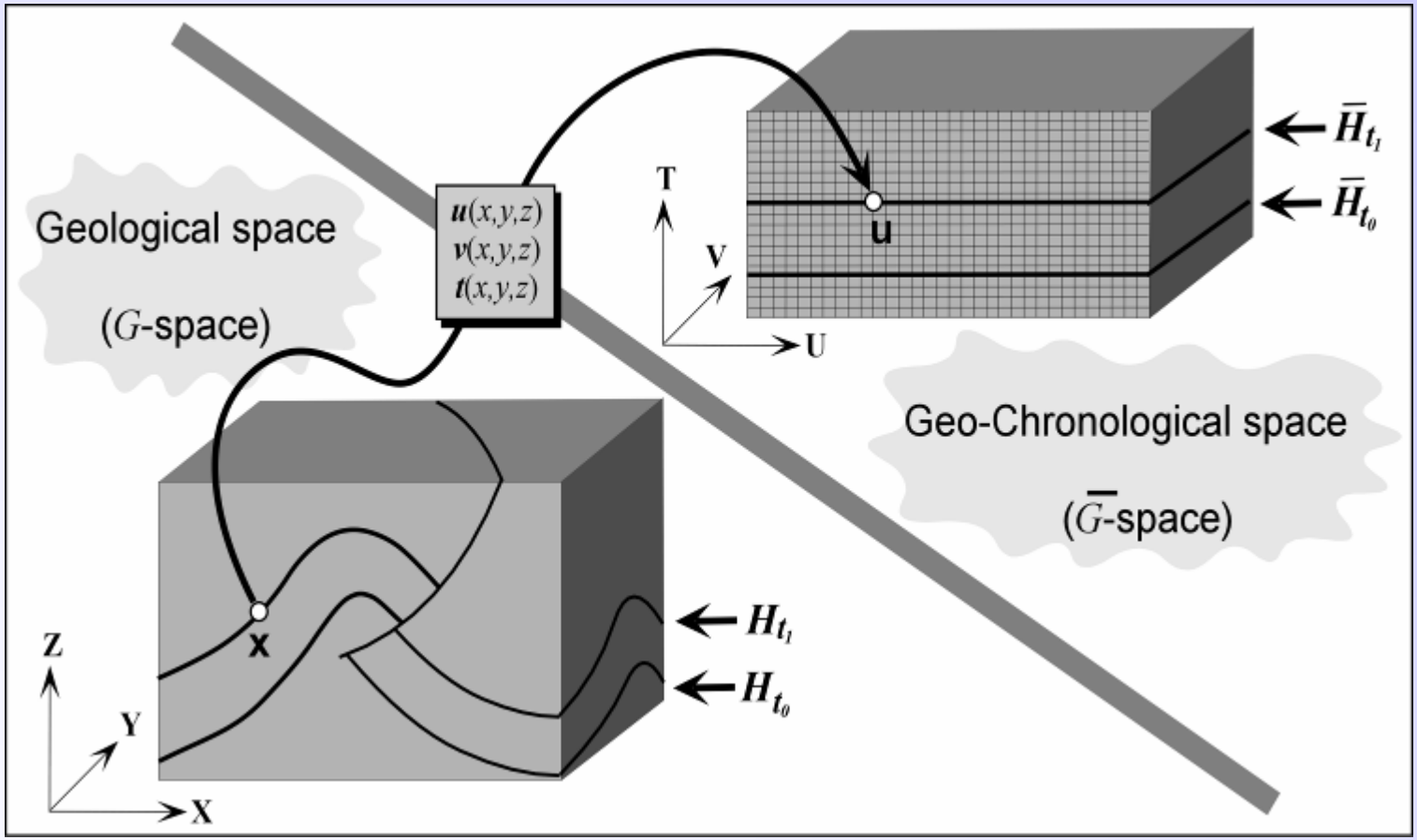




Both automatic approaches are appealing,
but take no geological input, hence obtained models lack realism

2.2 Petrophysical Modeling

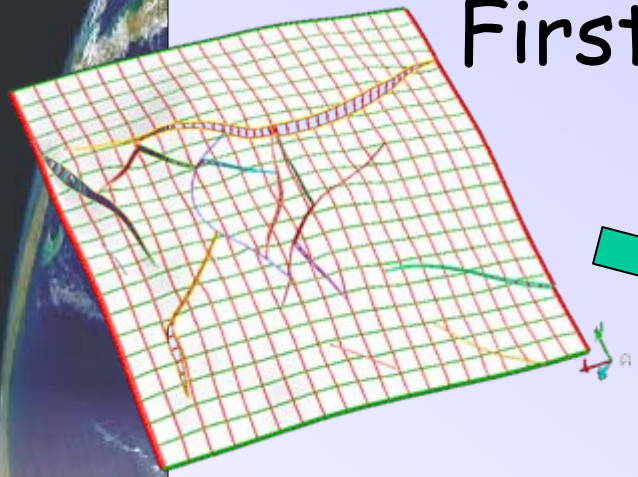
[Mallet, 2004]

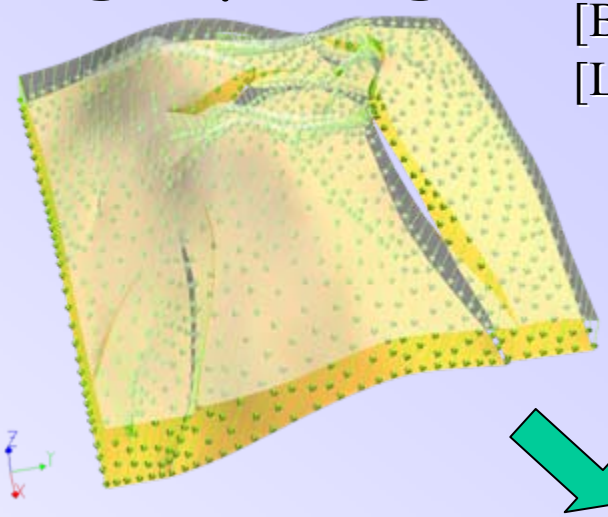


Mapping into the Geo-Chronological space

First Geochron Implementation: Stratigraphic gridding

[Bombarde & Mallet 96]
[Levy & Mallet 98]



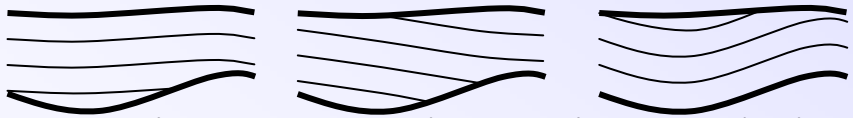


Compute curvilinear (u,v) Coordinates on the horizon: 2D Quad gridding

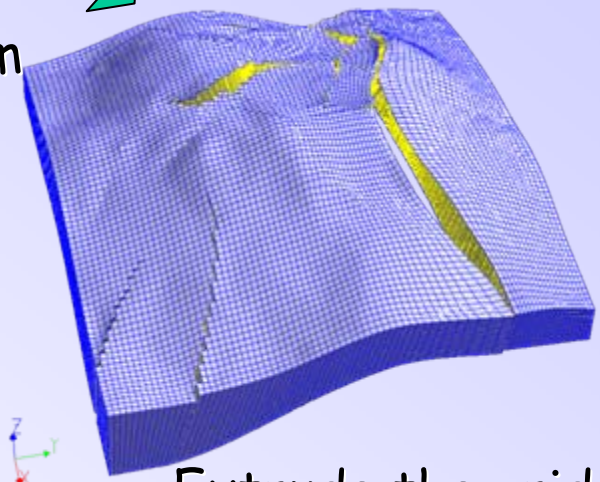
Associate top and bottom

Compute thickness maps

Conforming



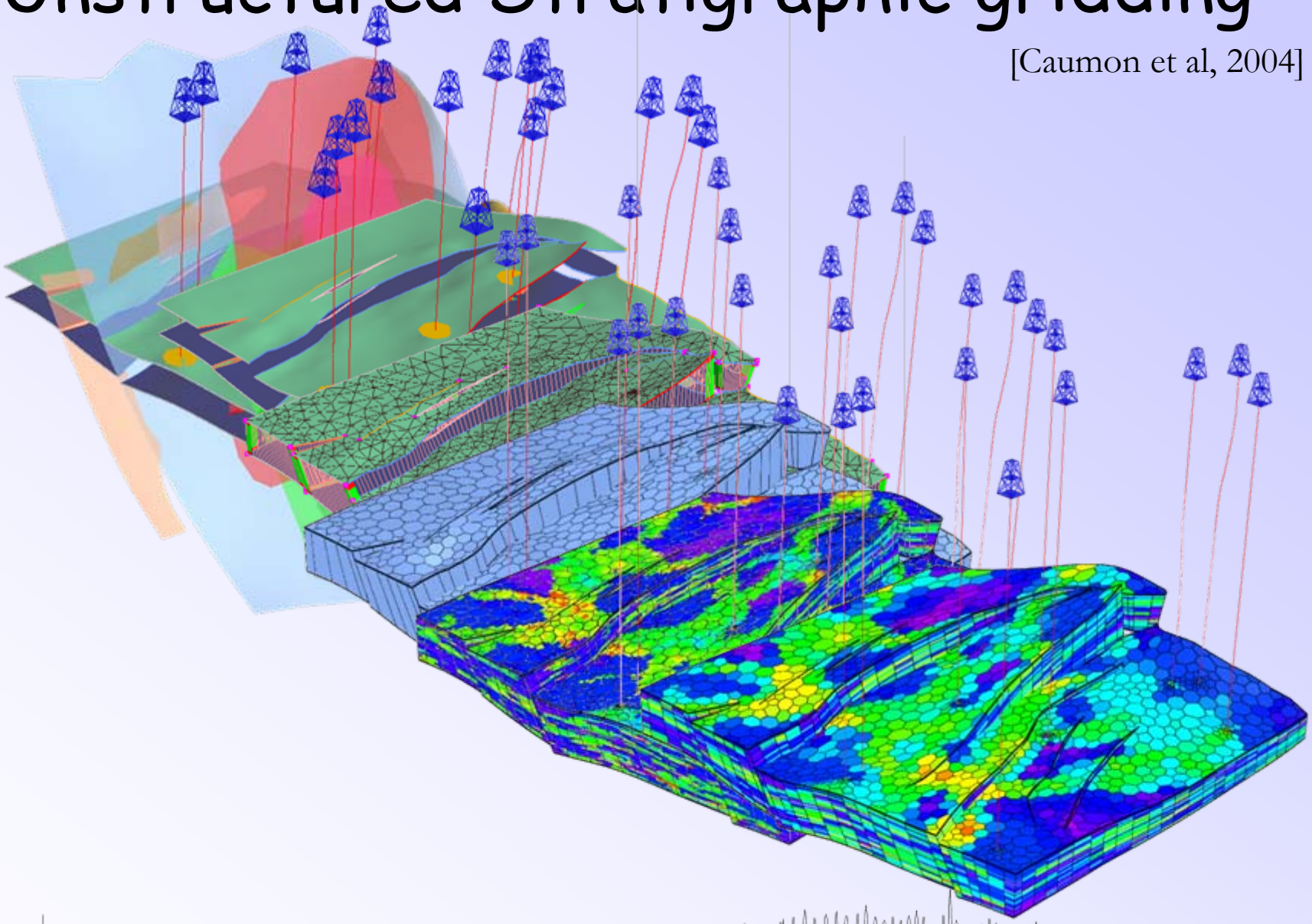
Baselap Progradational Eroded



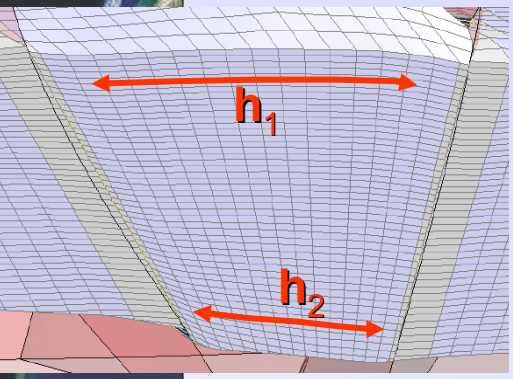
Extrude the grid

Unstructured Stratigraphic gridding

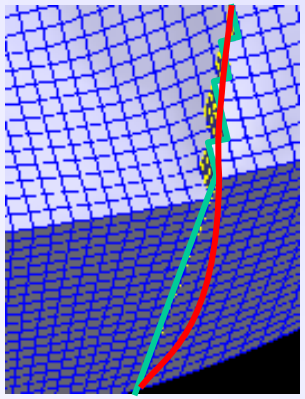
[Caumon et al, 2004]



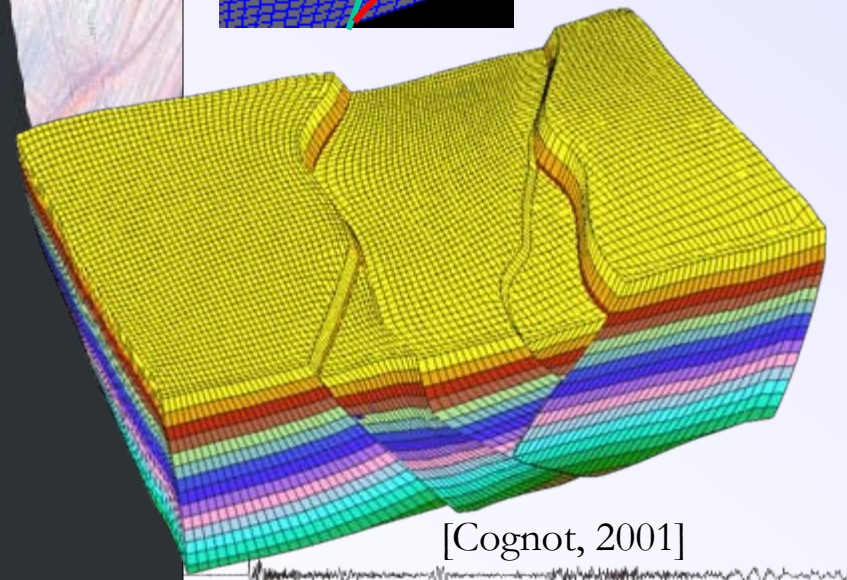
Stratigraphic Gridding: problems



- Distortions



- Simplification of fault geometries



[Cognot, 2001]

More generally: a structured hexahedral mesh cannot conform to all geometries encountered in nature

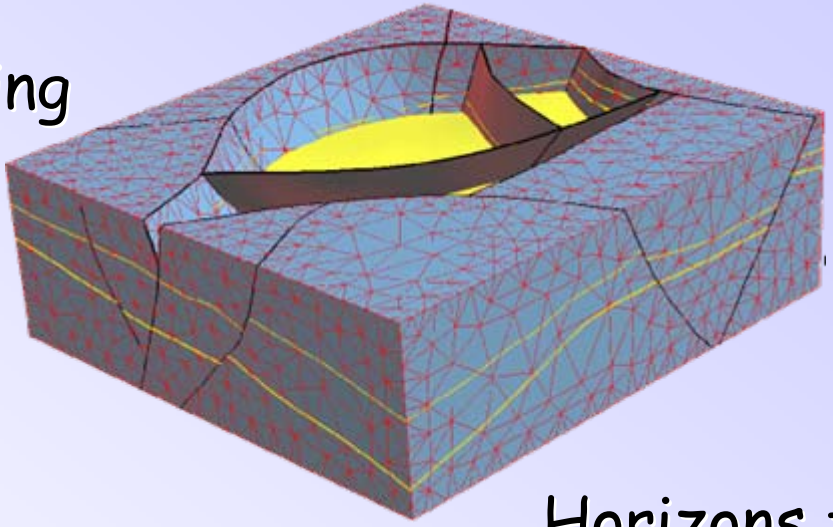
Second Geochron Implementation

[Moyen & Mallet 2004]

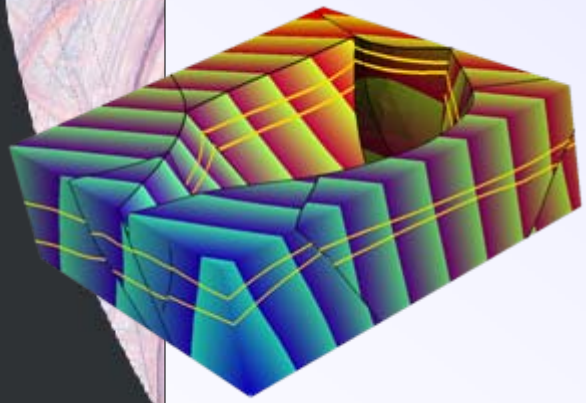
(u,v,t) coordinates on a Tetrahedral mesh

Mesh conforming to faults only

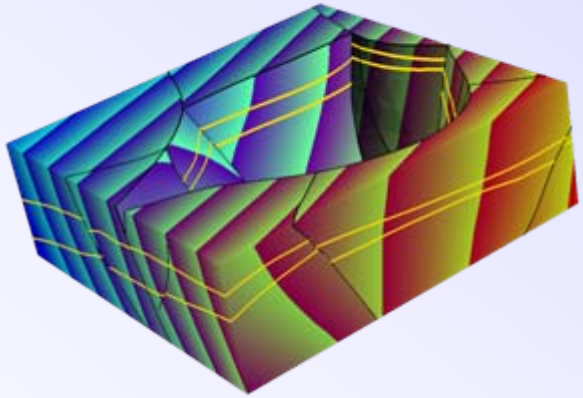
[Lepage, 2003]



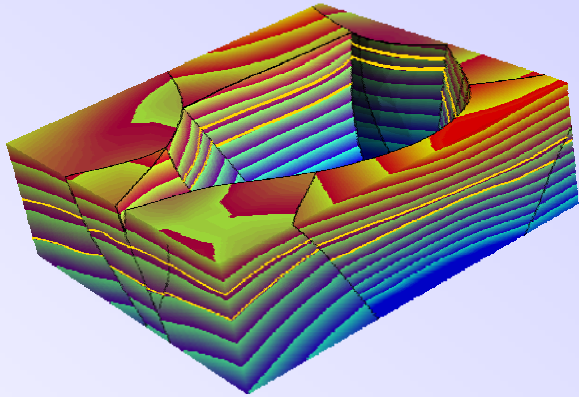
Horizons = isovalues of t



u



v



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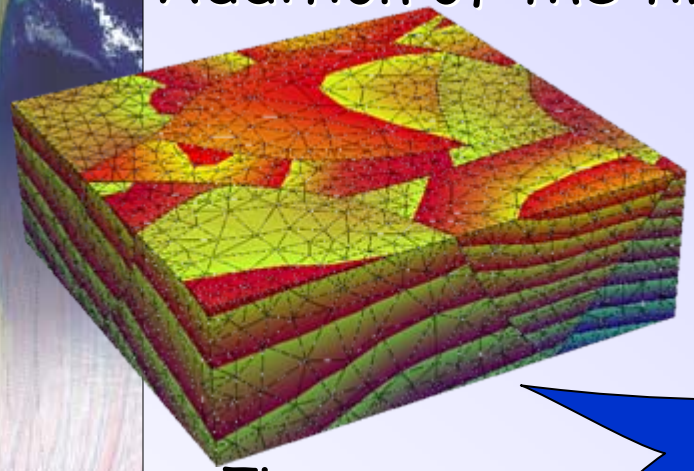
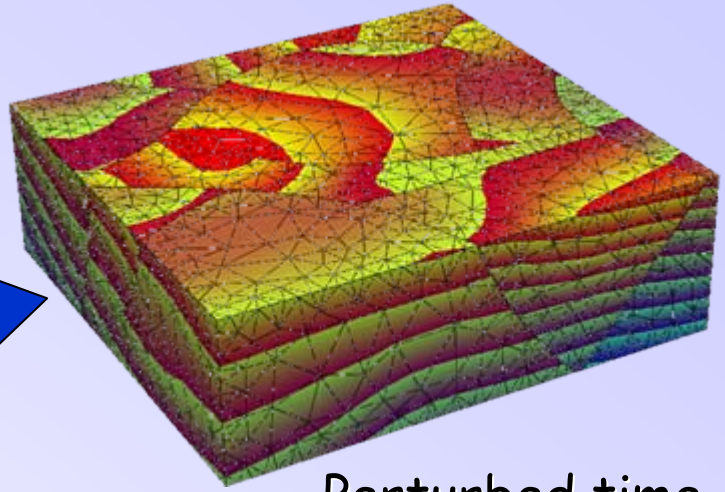
Stratigraphic Uncertainty

[Caumon et al. 2006]

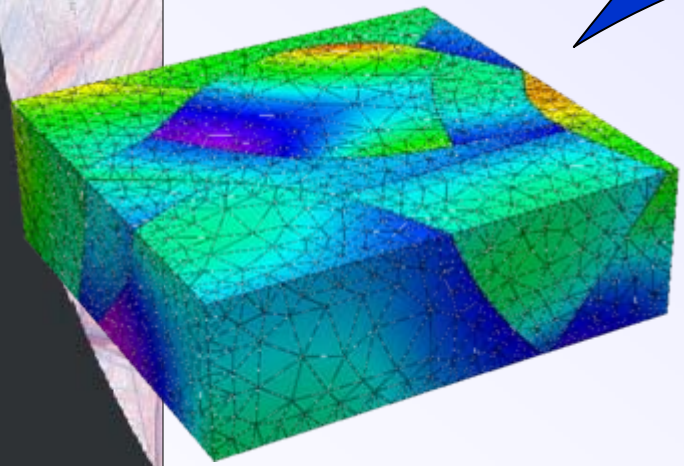
Addition of the time coordinate with 3D random fields



Time



Perturbed time



Perturbation

Horizontal γ range ~ wavelength
Vertical γ range ~ Δ Thichness

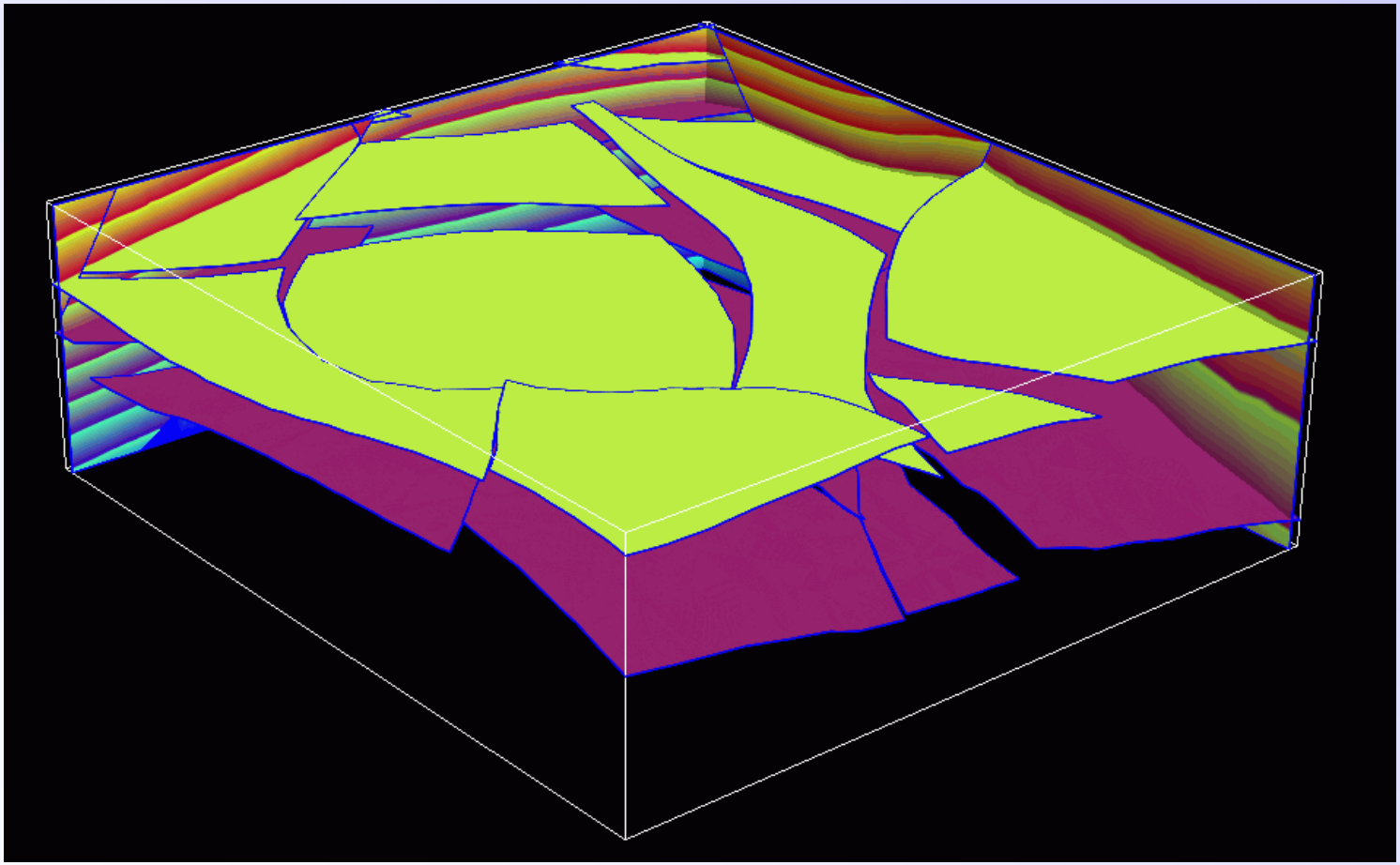
Random field may be generated either:

- in Geochron space (fault throw fixed)
- in Geological space (fault throw variable)

Stratigraphic Uncertainty

[Caumon et al. 2006]

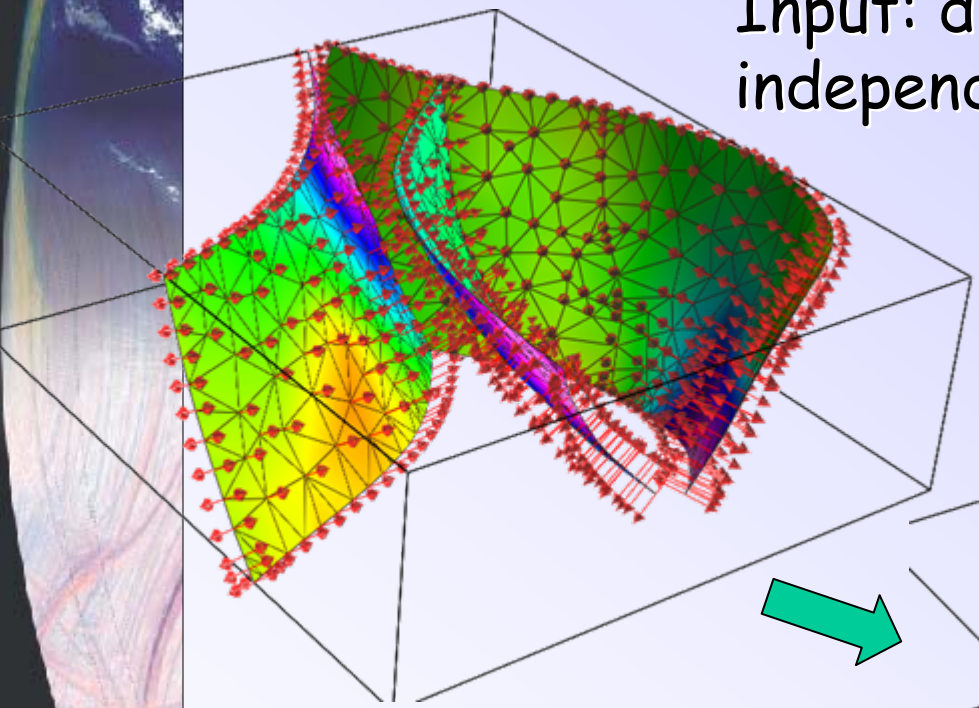
Addition of the time coordinate with 3D random fields



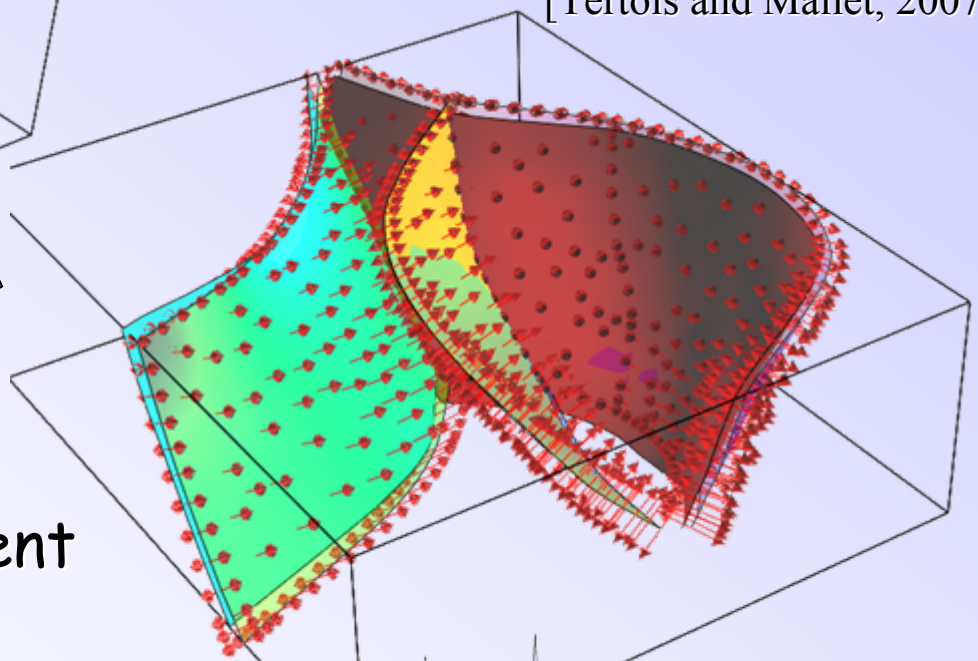
Uncertainty about Fault Geometry

[Zhang & Caumon, 2006]
[Caumon et al, 2007]

Input: displacement vectors computed independently on faults [Thore et al 2002]

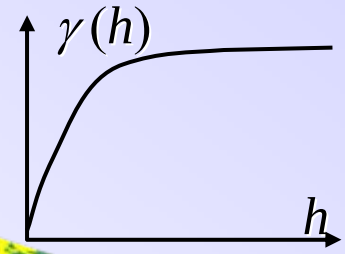


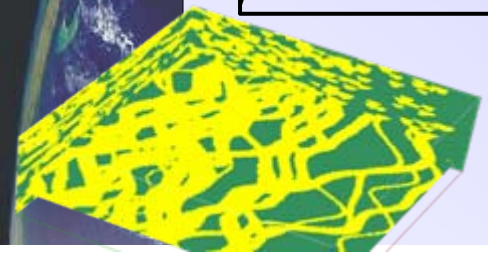
Mesh Deformation
[Tertois and Mallet, 2007]



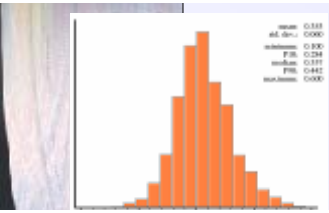
Output:
consistent displacement vectors everywhere

Petrophysical modeling: Object and MP Geostats



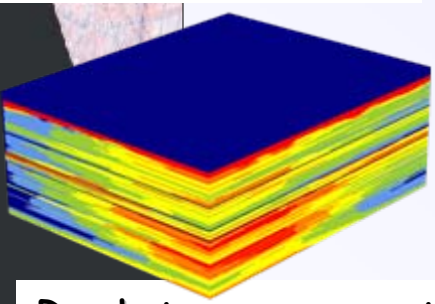


Spatial Variability model :
(Variogram / training image)

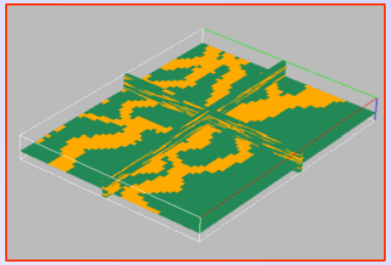


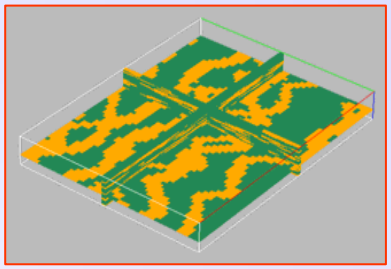
Univariate stats

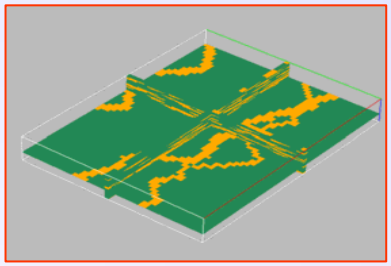
Hard data (wells)



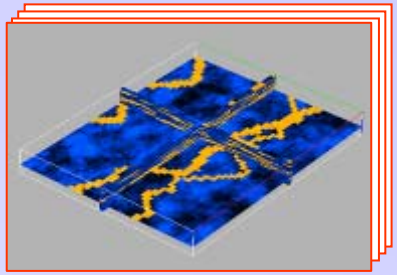
Rock type proportion cube

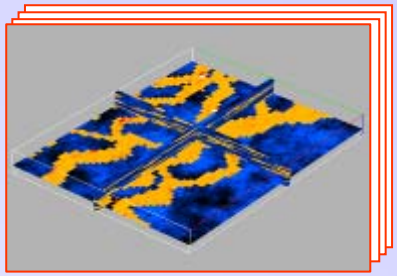


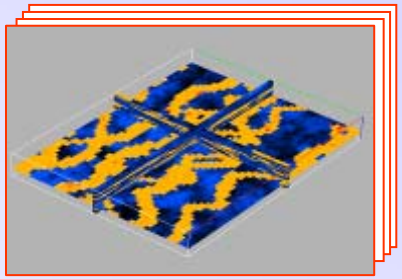




N Facies realizations

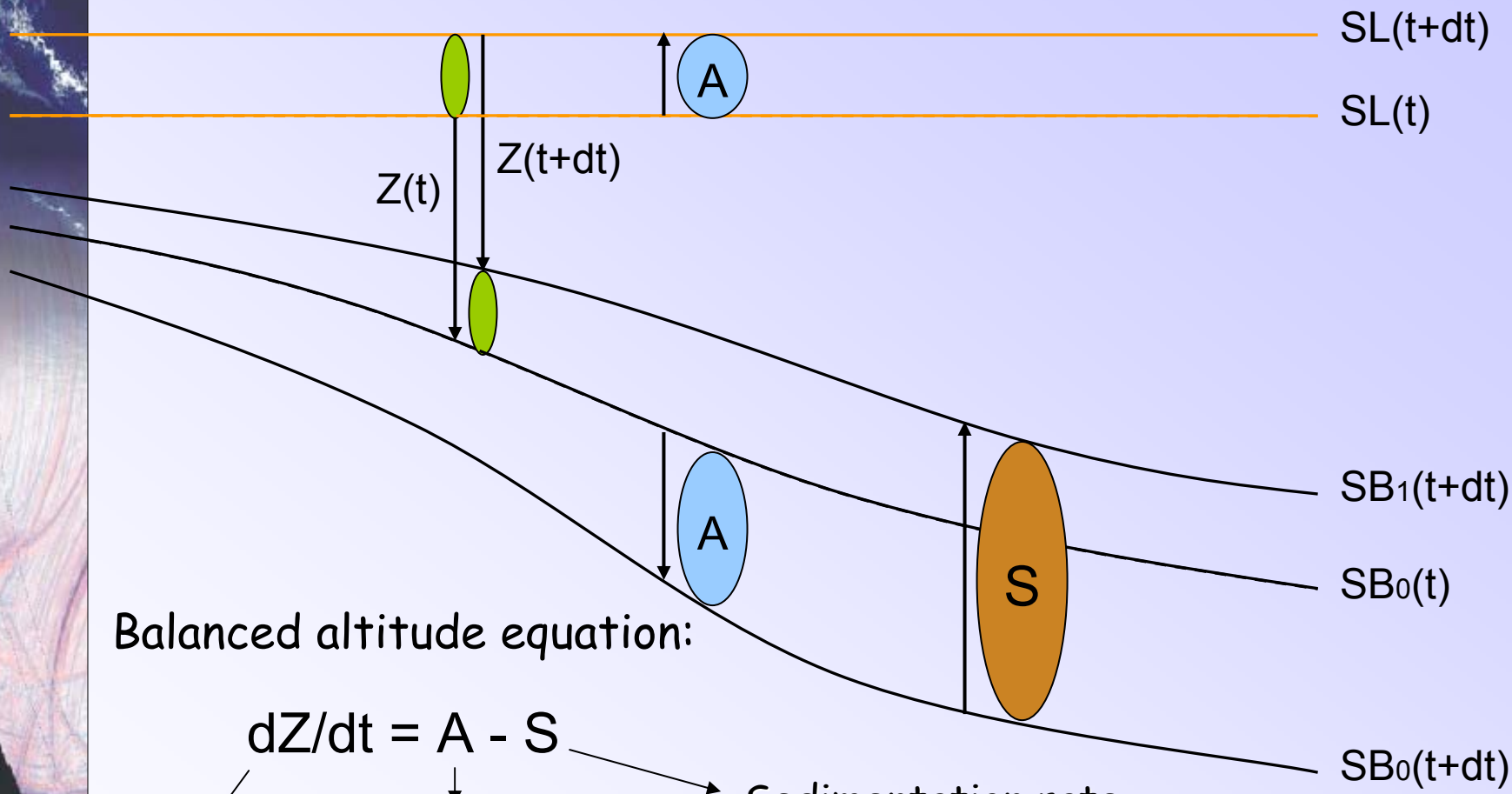






NK Petrophysical models

balanced altitude equation



Balanced altitude equation:

$$dZ/dt = A - S$$

Variation of Bathymetry

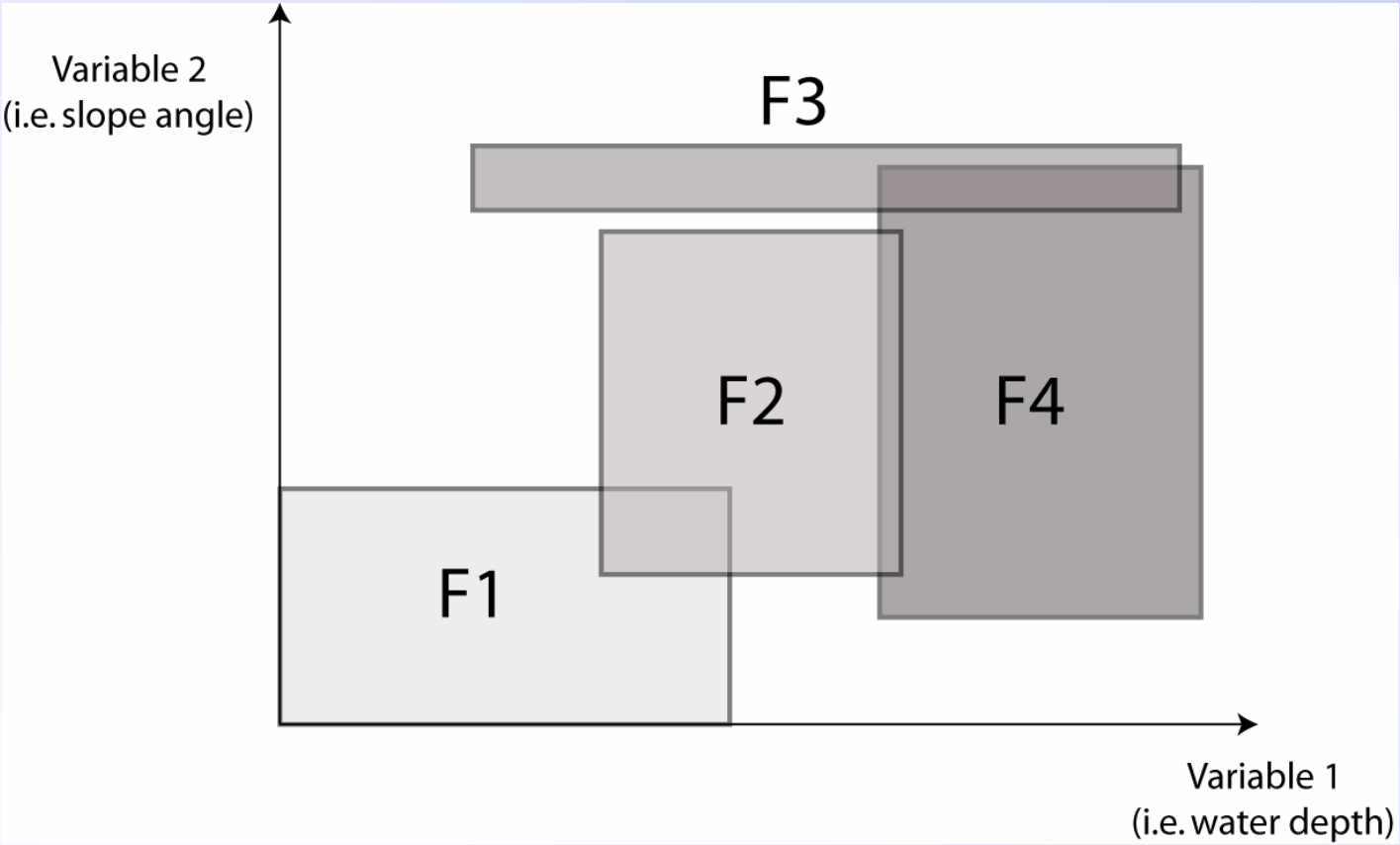
Variation of Accomodation (available space)

Sedimentation rate

[Massonnat, 1999]

[Kedzierski & Mallet, 2006]

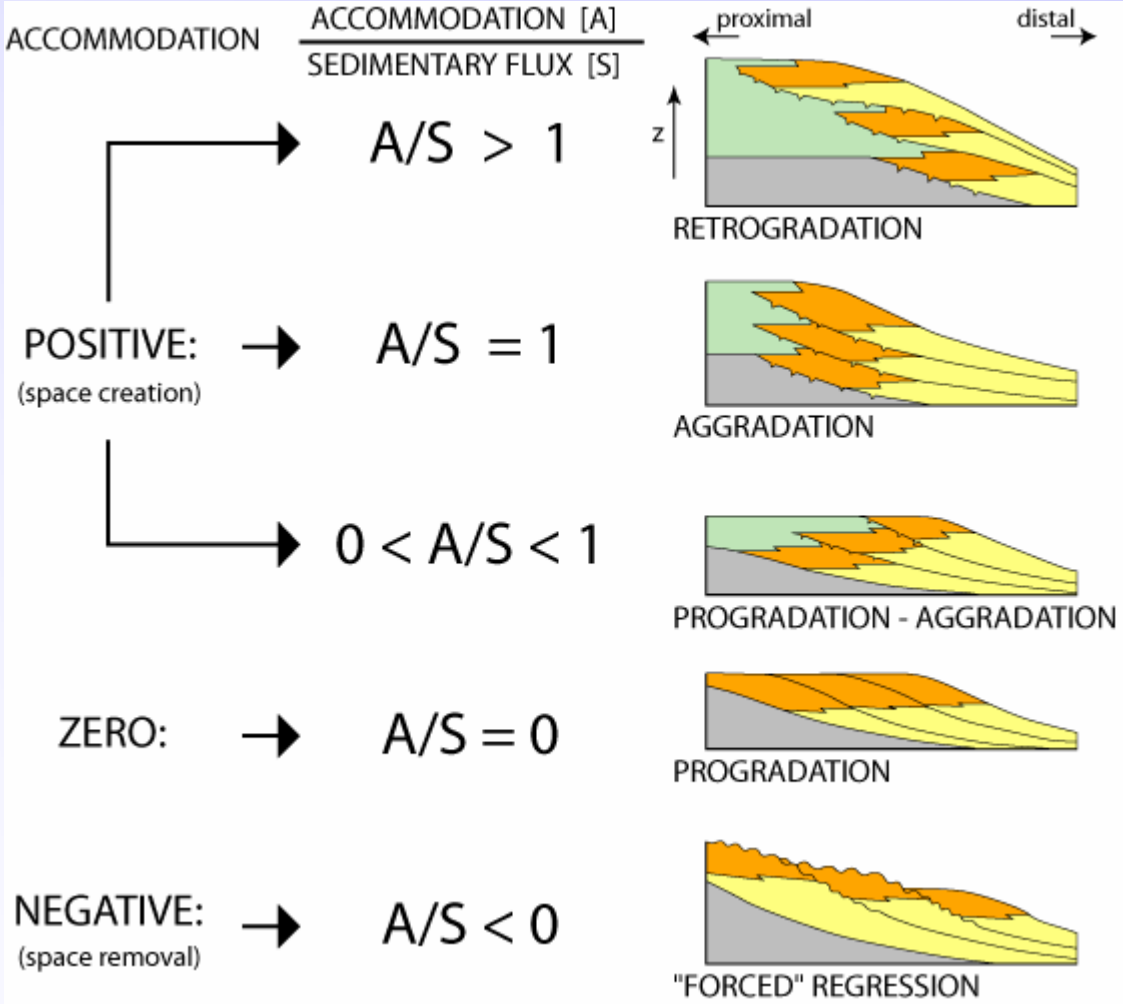
Sedimentological knowledge



(Kedzierski & Mallet, 2006)

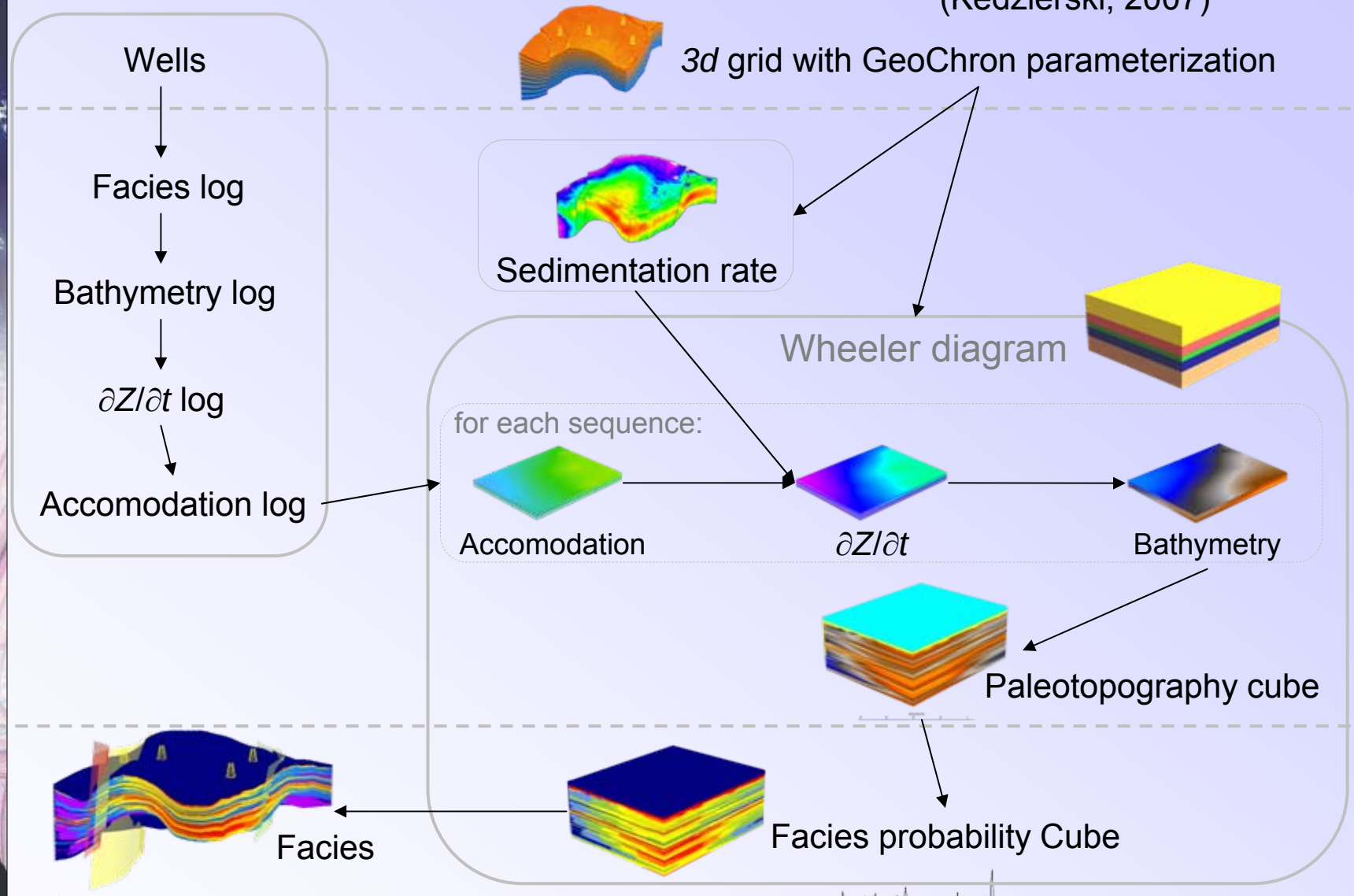
stratigraphic architecture control

(Homewood et al.,1999)



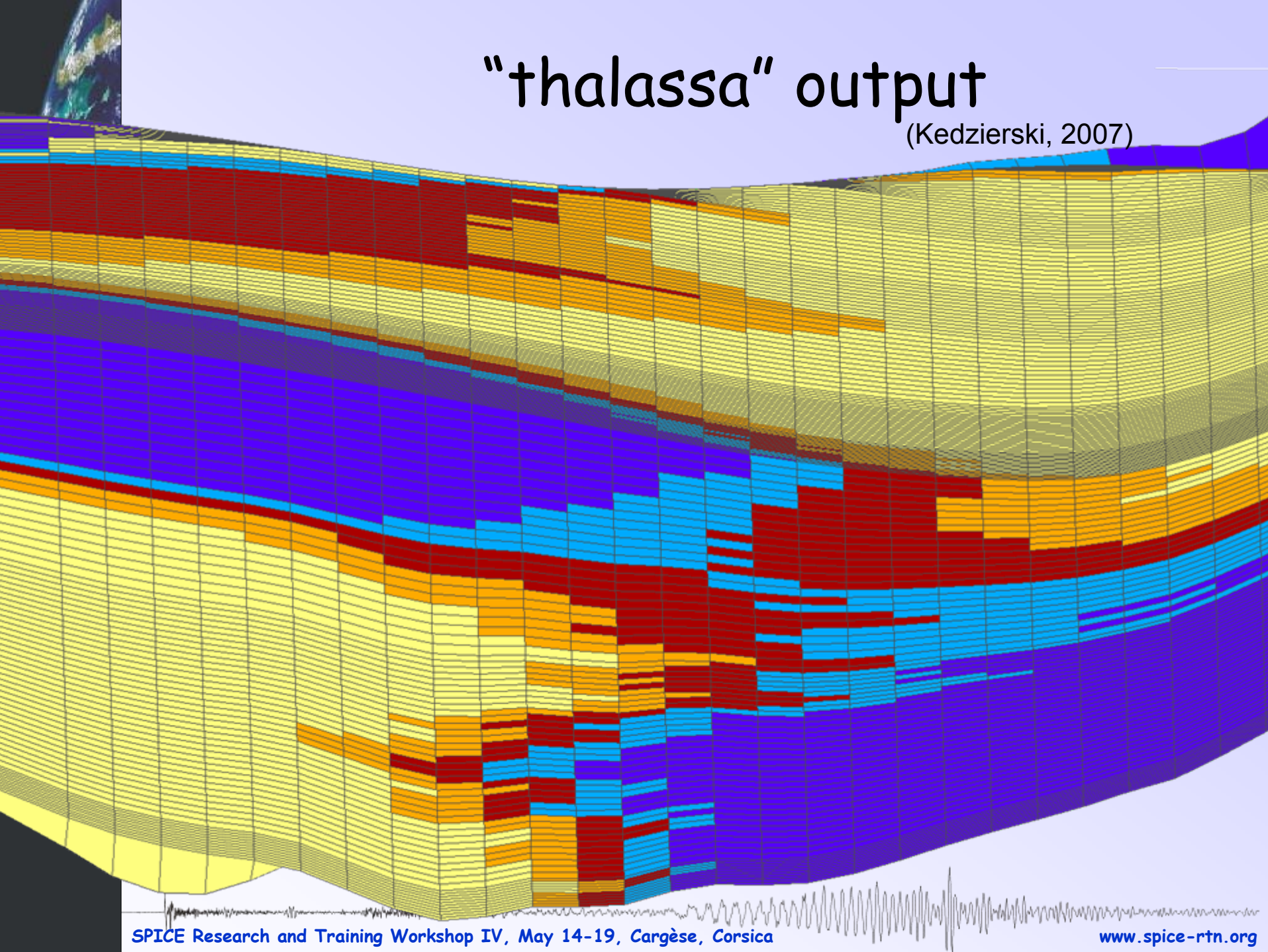
"thalassa" workflow

(Kedzierski, 2007)



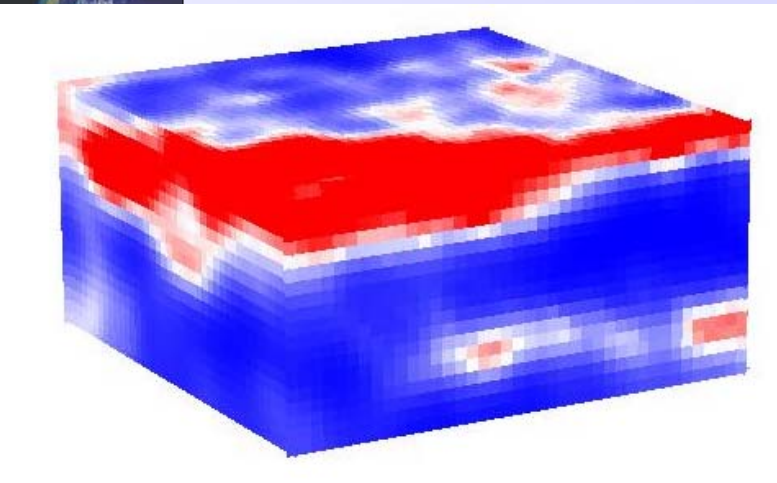
“thalassa” output

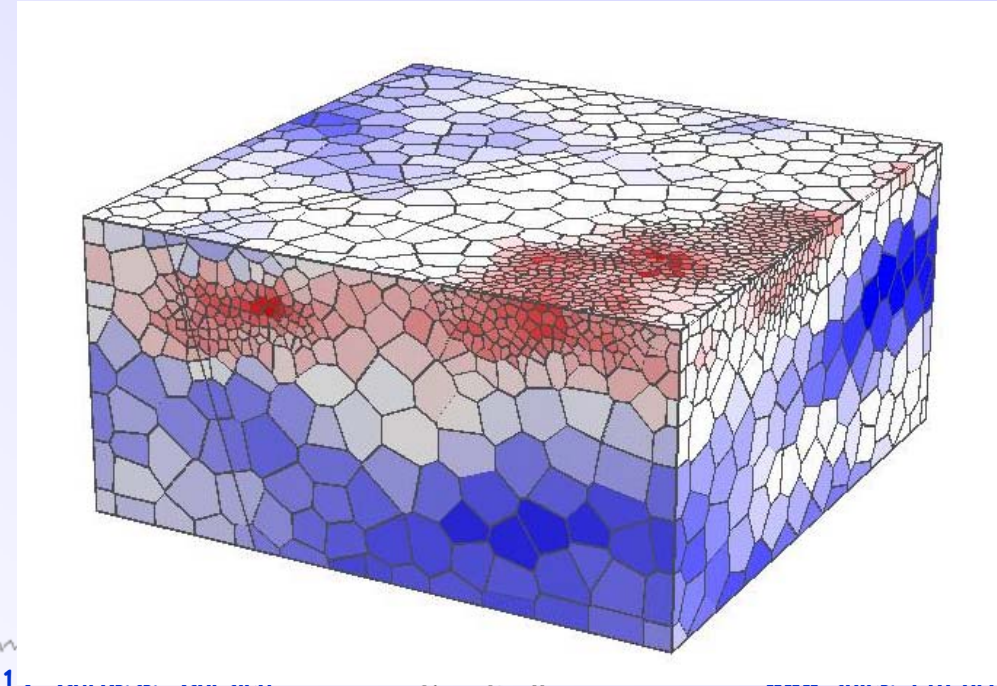
(Kedzierski, 2007)



Unstructured Grid Upscaling

[Prevost et al., 2005]





3. Applications to inverse problems

3.1- Inverting fault slip using surface restoration

[Caumon and Muron, 2006]

3.2- Response surfaces in reservoir engineering

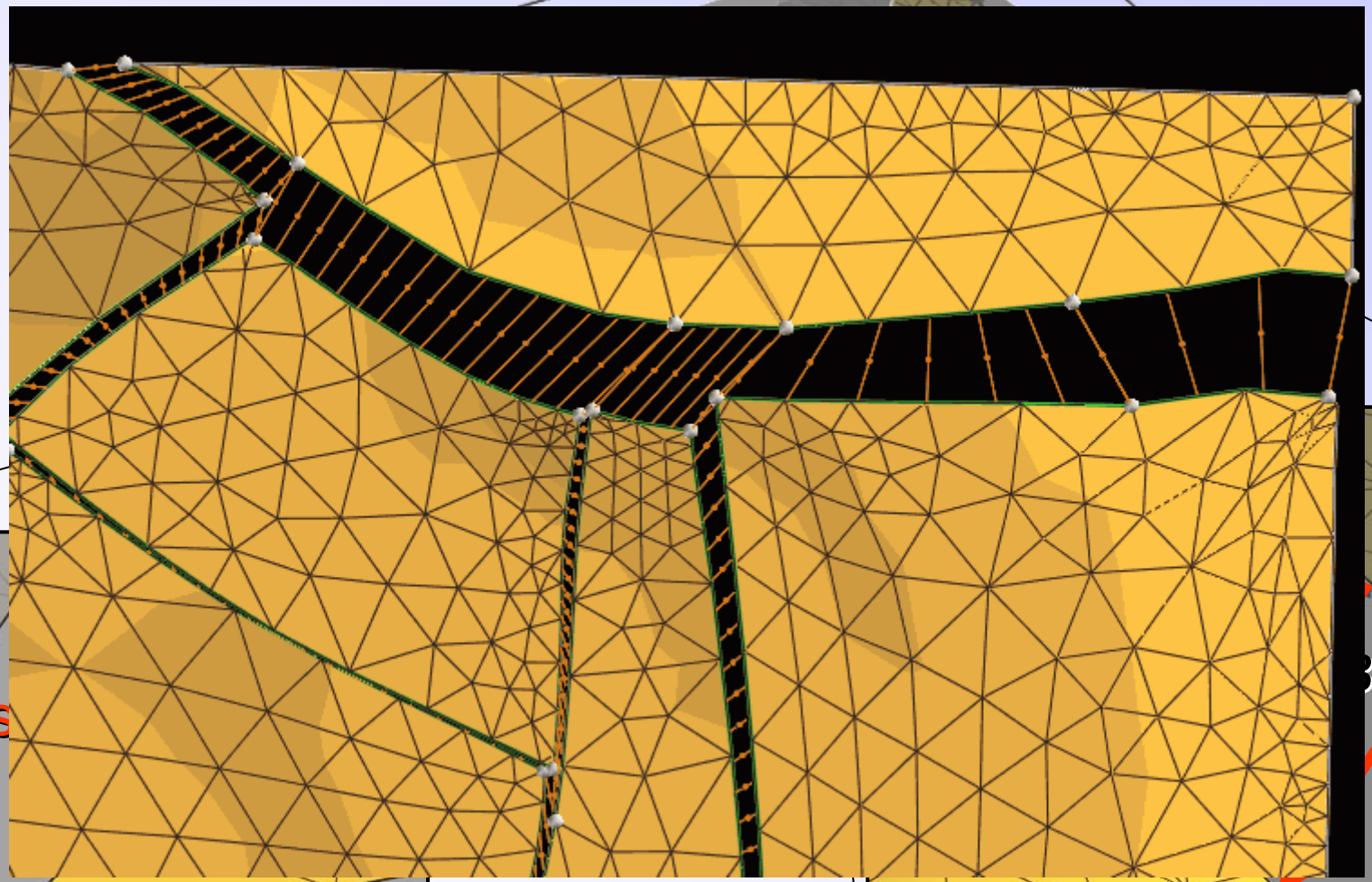
[Fetel et al, 2006]

3.3- Inverting reservoir geometry using production data

[Suzuki et al, 2006]

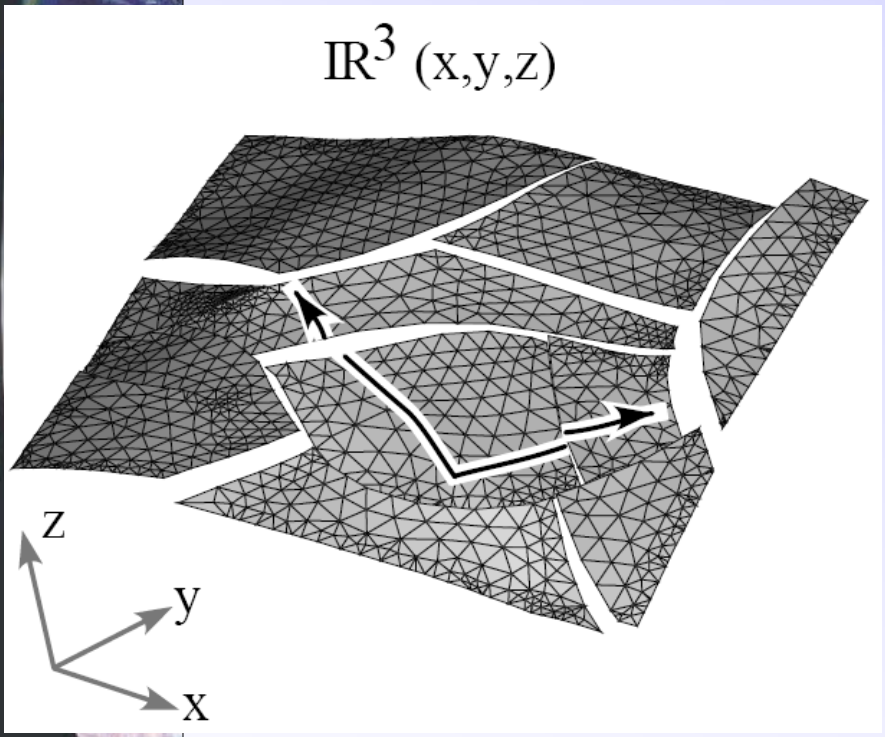
Problem

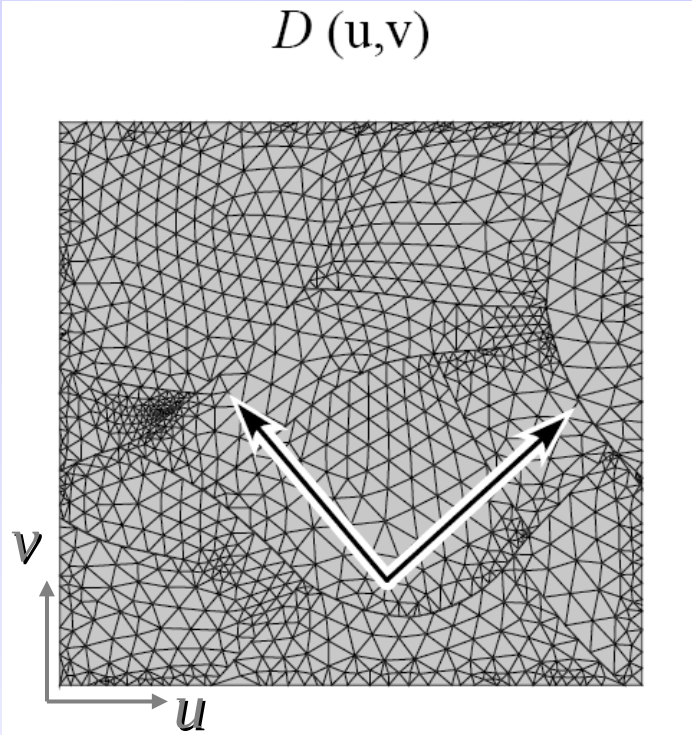
Fault throw is not unique for a given model geometry

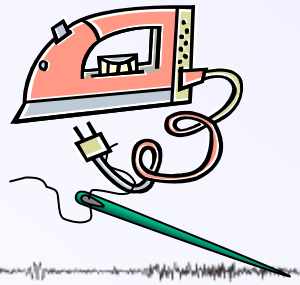


2D Restoration

[Gratier et al 91, Rouby et al. 93, Léger et al 97, Rouby et al 00, Mallet 02, Massot 02, Dunbar & Cook 03, Thibert 05, Moretti et al 06]





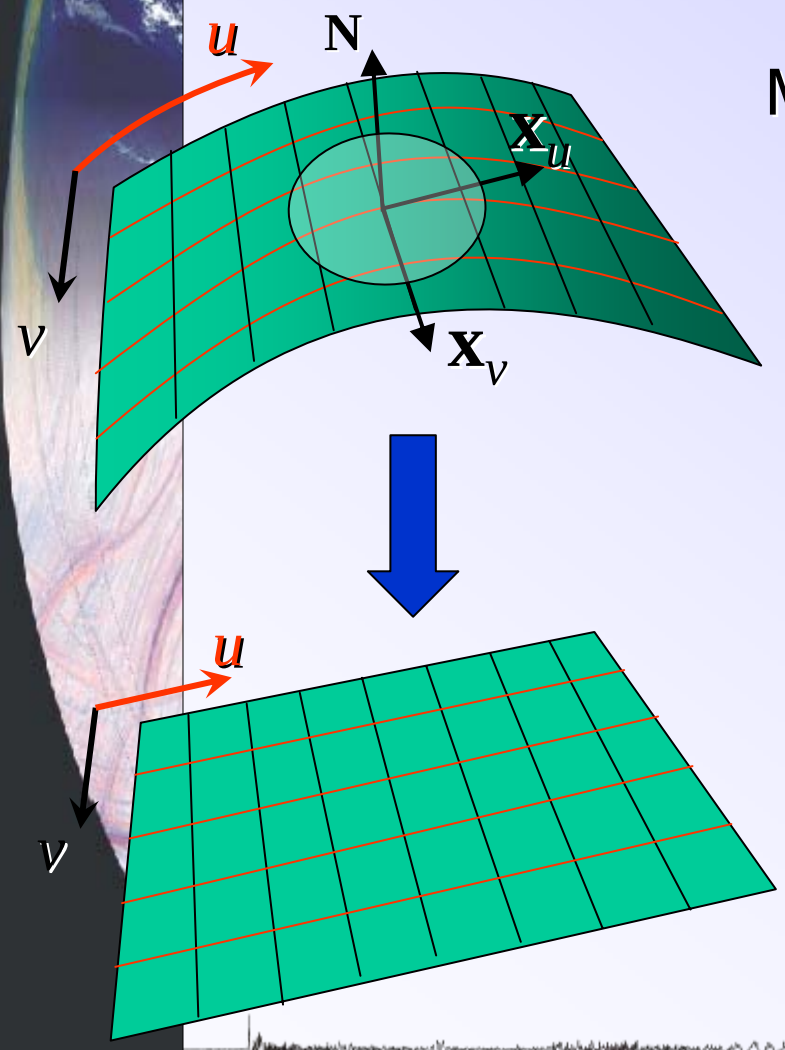


1/ “Iron” geological surfaces

2/ “Sew” Fault gaps

1/ Flattening the horizons

Amounts to parameterize the surface [Levy et al 98, Levy 01]



Minimizing strain $\varepsilon = \frac{1}{2}(\mathbf{G}_1 - \mathbf{G}_0)$ entails :

Minimum elongation
(conservation of distances)

$$\| \text{grad } u \| = \| \text{grad } v \| = 1$$

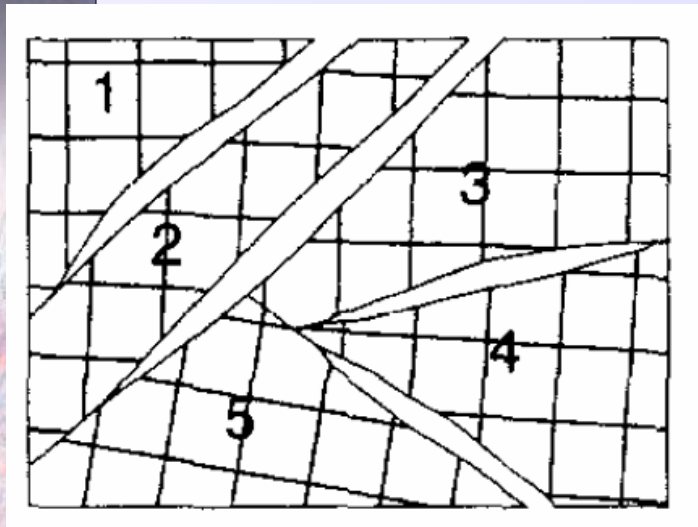
Minimum distorsion
(conservation of angles)

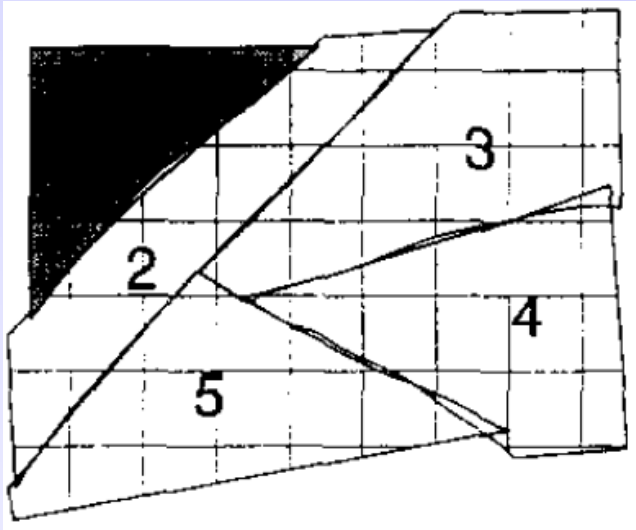
$$\text{grad } u \cdot \text{grad } v = 0$$

2/ Bridging fault gaps

Rigid blocks hypothesis
$\Rightarrow$ block packing

[Rouby et al 93]





Unfolded blocks

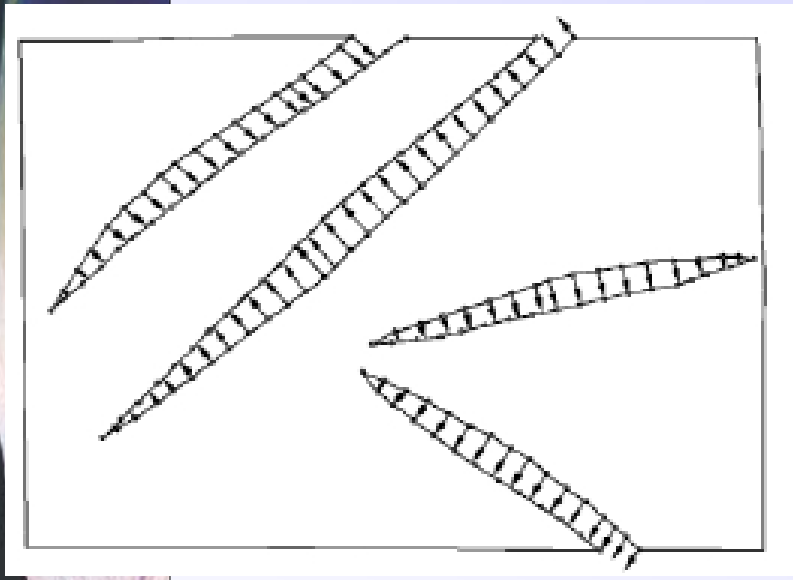
Restored model

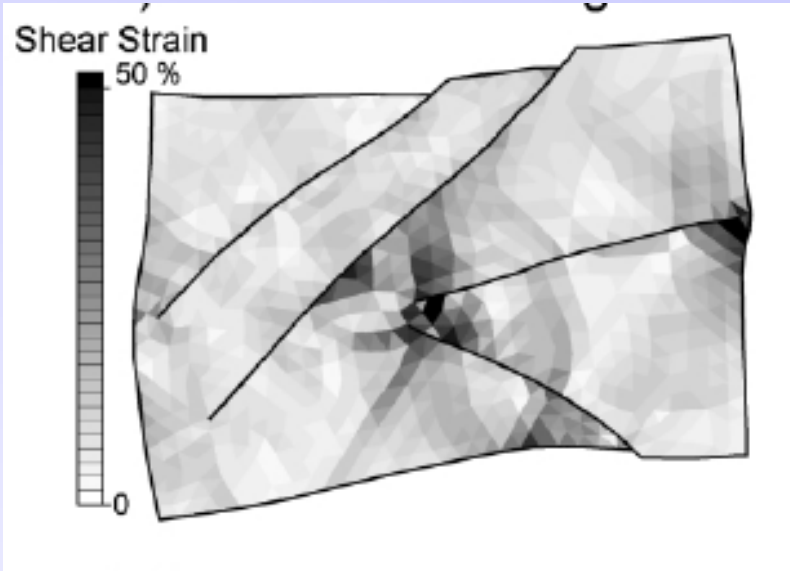
Blocks may not be rigid

2/ Bridging fault gaps

Thin plate analogy

[Dunbar &Cook 03]





Initial throw definition

Restored model

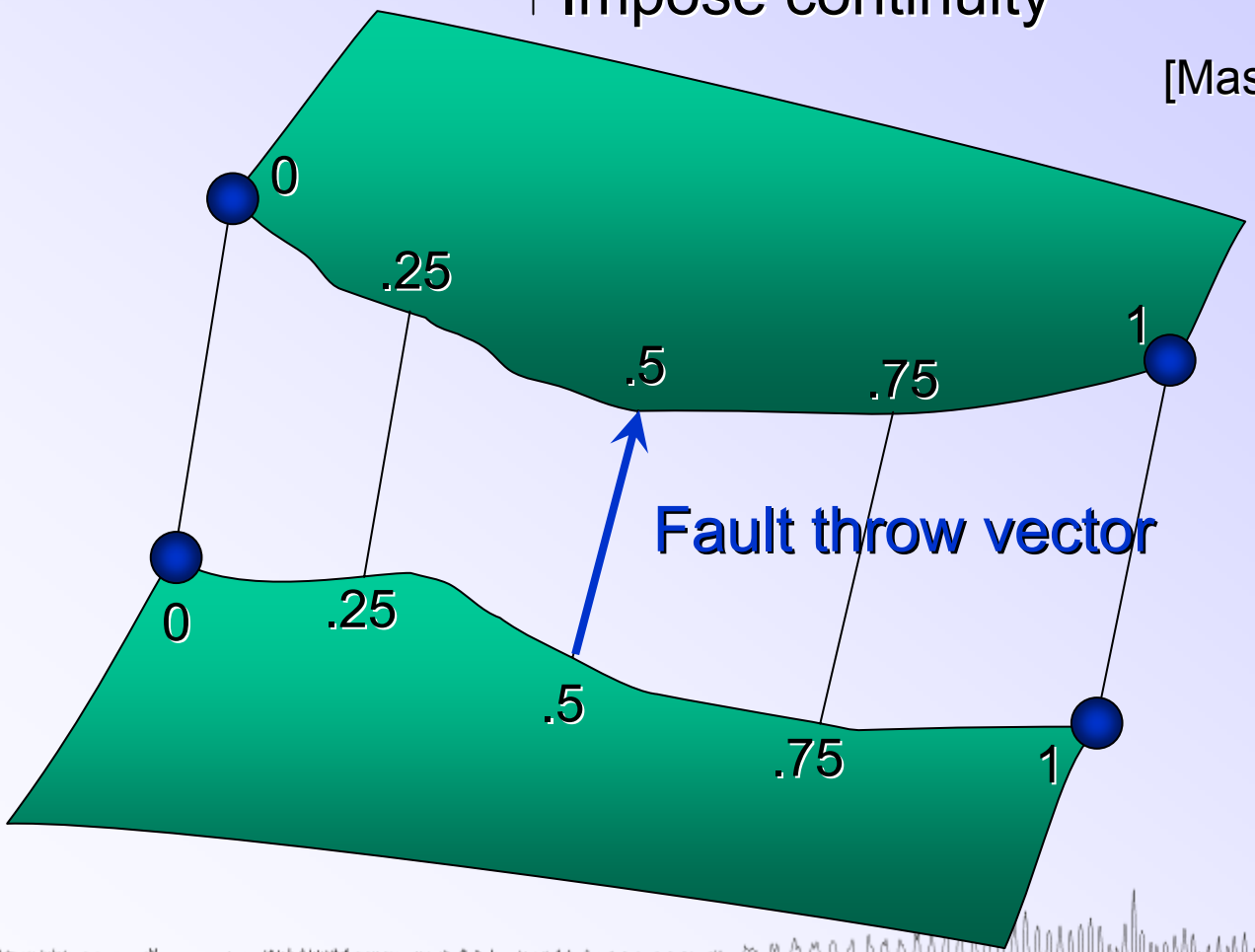
Throw is optimized in the process

Mechanical approach interesting, but questionable in 2D

2/ Bridging fault gaps

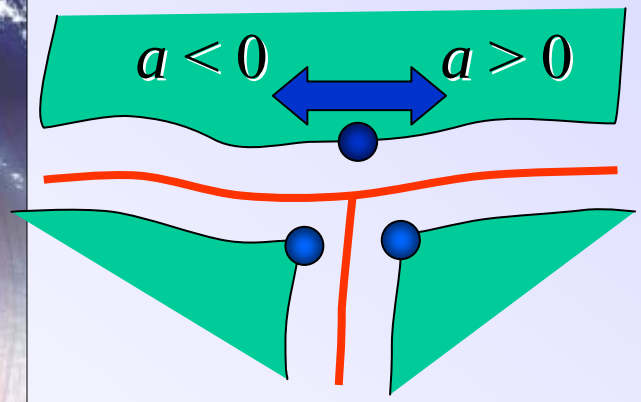
- Use curvilinear coordinates (u,v)
- Impose continuity

[Massot & Mallet 02]

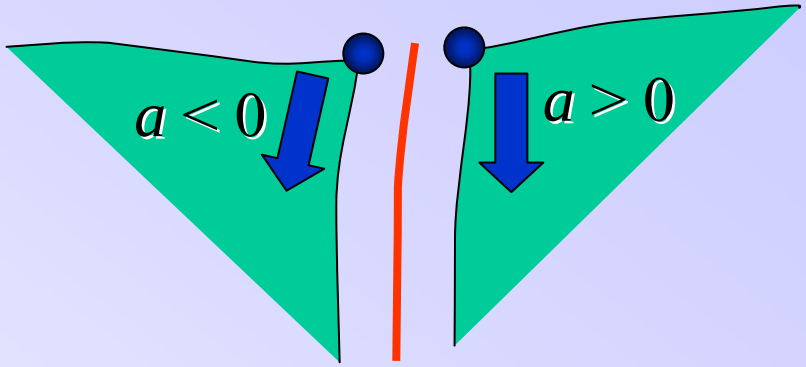


Fault throw perturbation

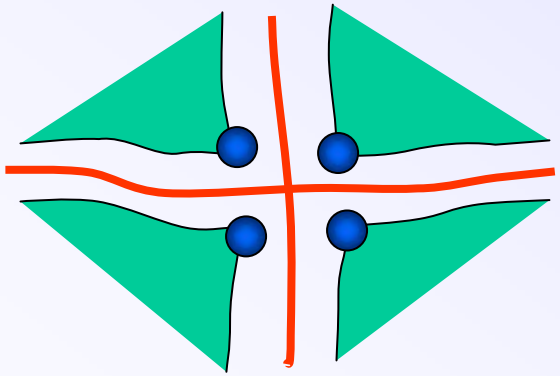
Displace border extremities ● by some curvilinear abscissa a, relative to the reference position



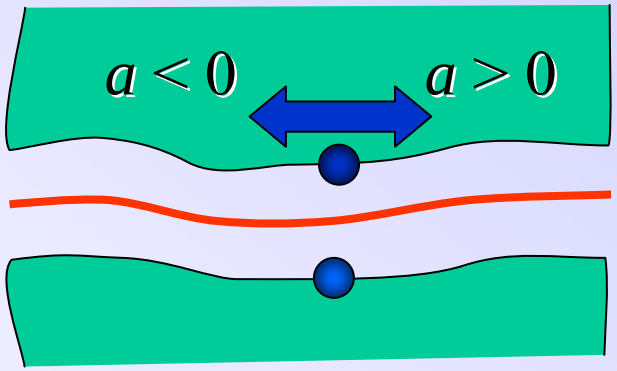
Main and Branching fault ⊥⊥



Fault and external border ⊥⊥



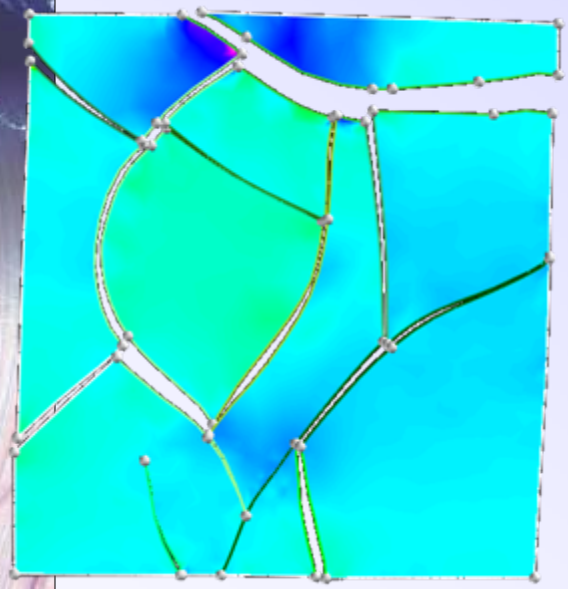
Multiple (frozen) ╬



Internal ═

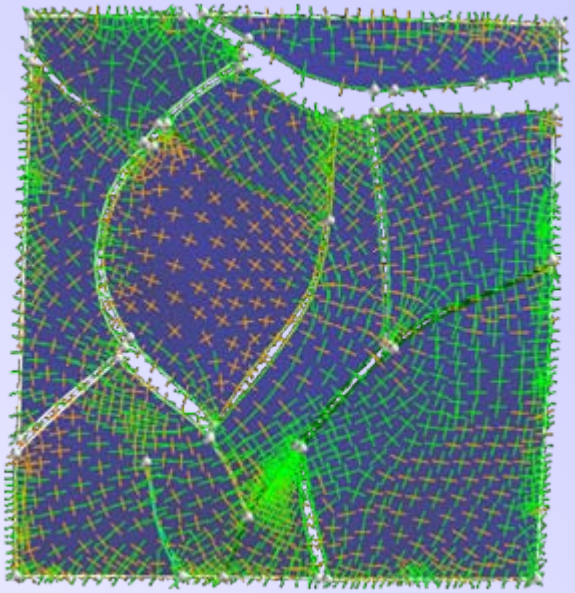
Fault Slip validation: 2D strain analysis

strain $\varepsilon = \frac{1}{2}(\mathbf{G}_1 - \mathbf{G}_0)$



Dilatation

Should close to 0



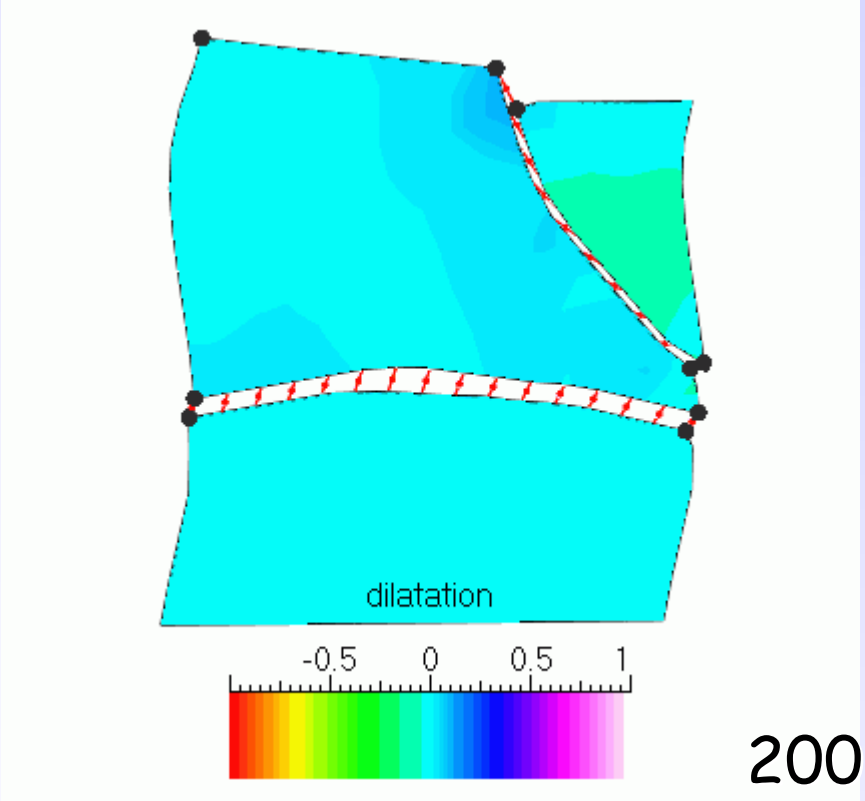
Principal strain directions

Should be ~isotropic

→ More valuable than curvature

Simple application

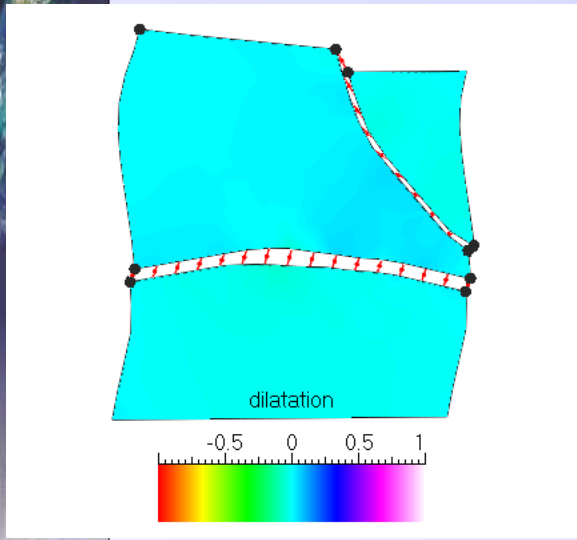
3 flattened fault blocks (deformation due only to faults)
Prior uncertainty : 20% of fault trace length
MCMC sampling



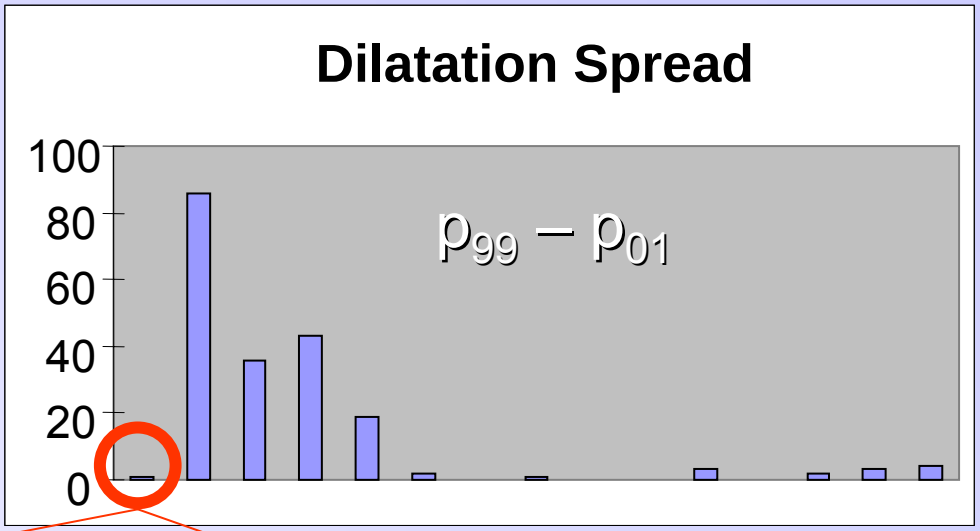
200 realizations, ~3 min

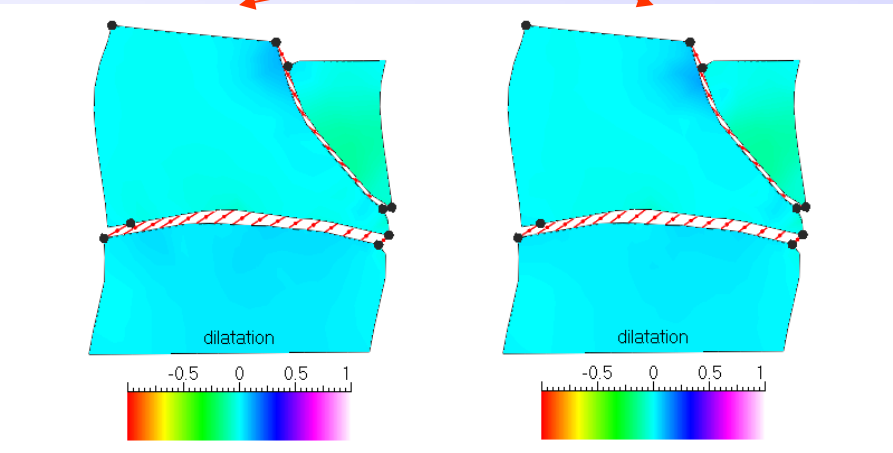
Objective function: $p_{99} - p_{01}$ of the dilatation

Results



Reference model





MCMC: Computationally expensive (optimizations in progress)
Choice of the objective function difficult

3. Applications to inverse problems

3.1- Inverting fault slip using surface restoration

[Caumon and Muron, 2006]

3.2- Response surfaces in reservoir engineering

[Fetel et al, 2006]

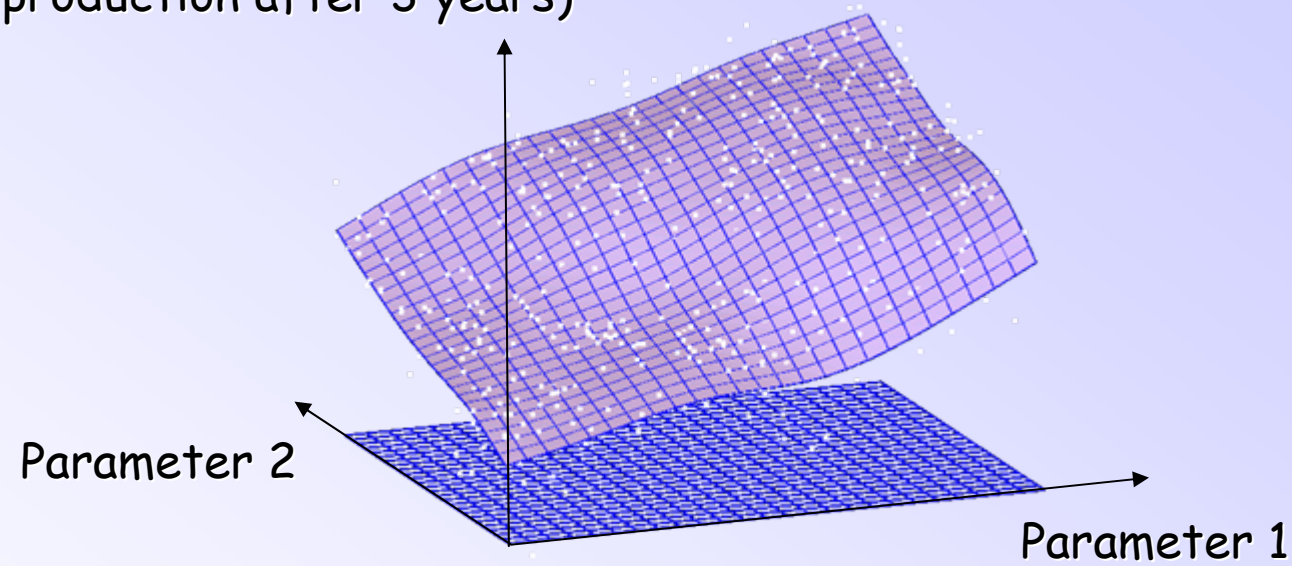
3.3- Inverting reservoir geometry using production data

[Suzuki et al, 2006]

Another approach to explore uncertainty: response surfaces

[Fetel, 2006]

Response obtained by FD flow simulation
(e.g., production after 3 years)



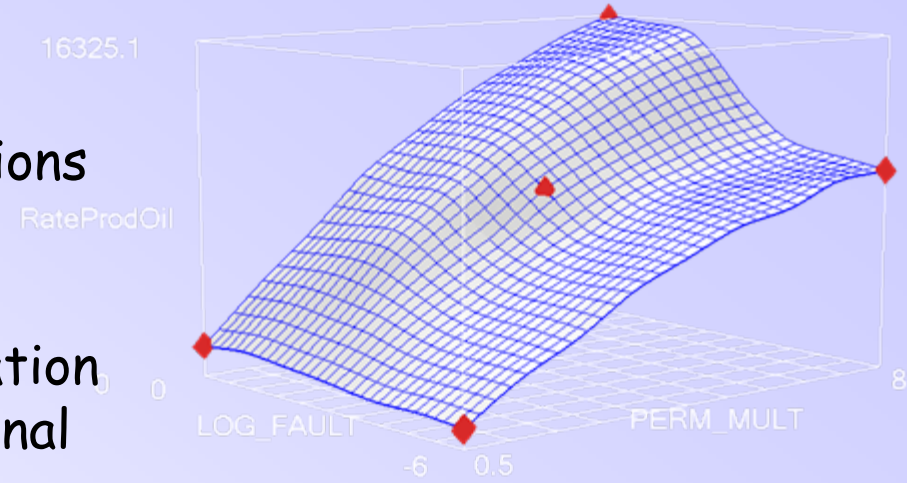
Sampling with experimental design

2 problems:

- Computationally expensive
- handling discrete parameters ?

Taking into Account Secondary Data

[Fetel 2006]



Combination of

- Complete flow simulations
- TOF swept volume estimations

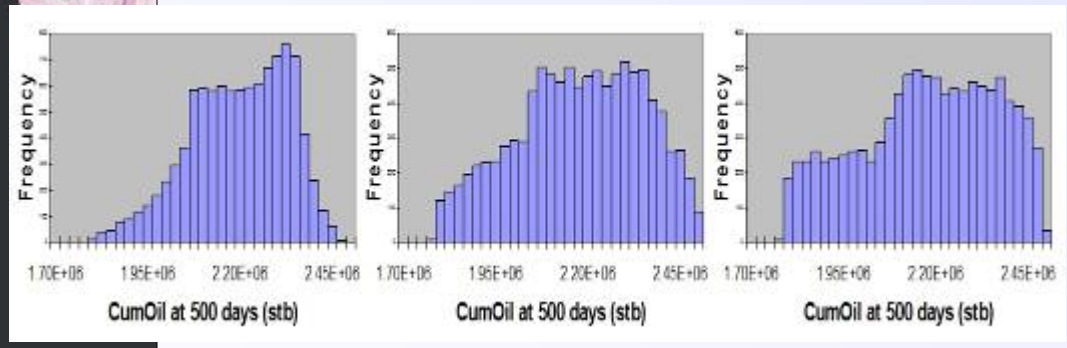
Algorithms

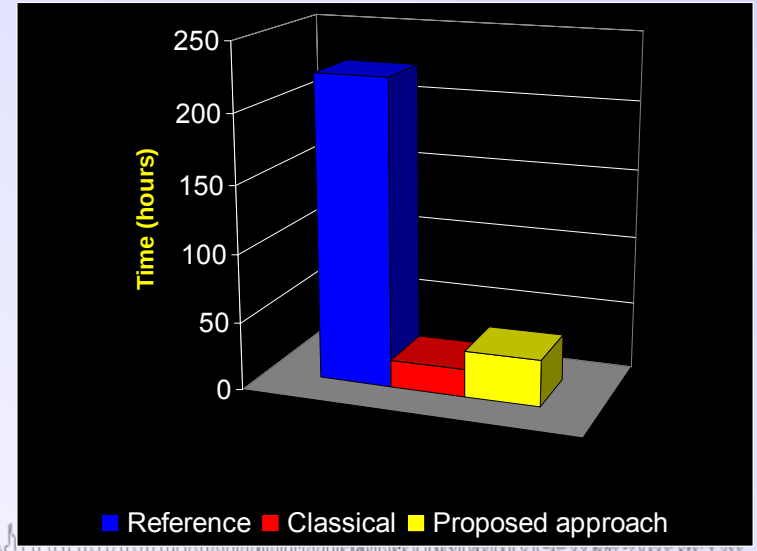
- Discrete Smooth Interpolation
- Dual Kriging With an External Drift

Without secondary data

DSI

Reference

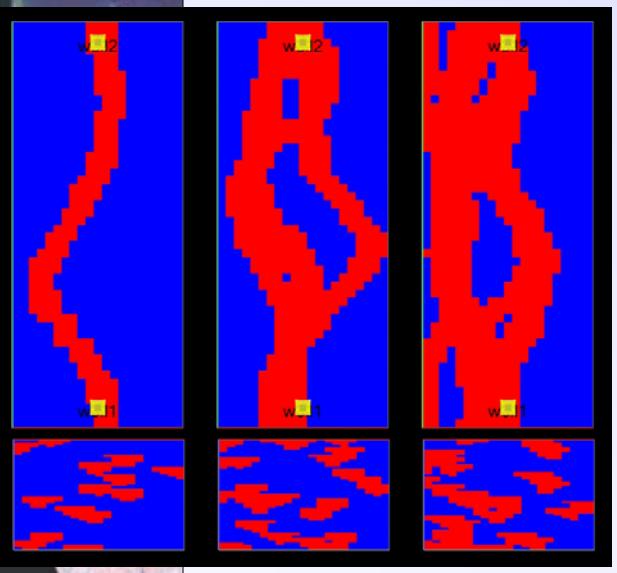




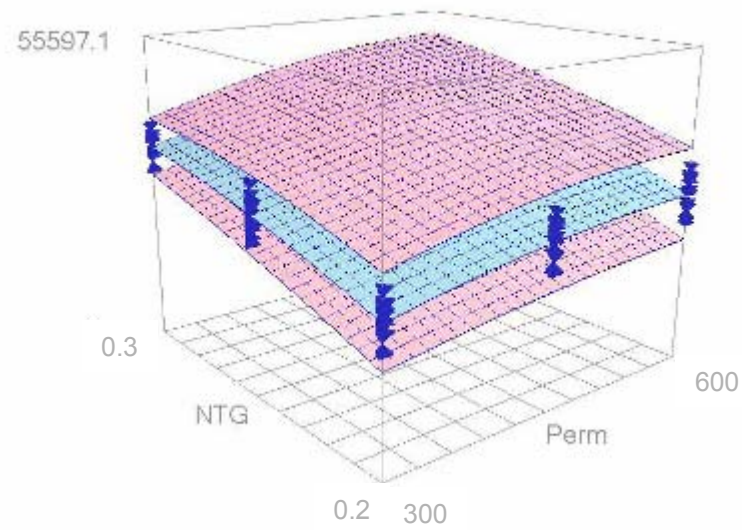
Managing Stochastic Uncertainty

[Fetel 2006]

Discrete parameters represented as dispersion of the response surface (Gaussian model)



Production at 400 days



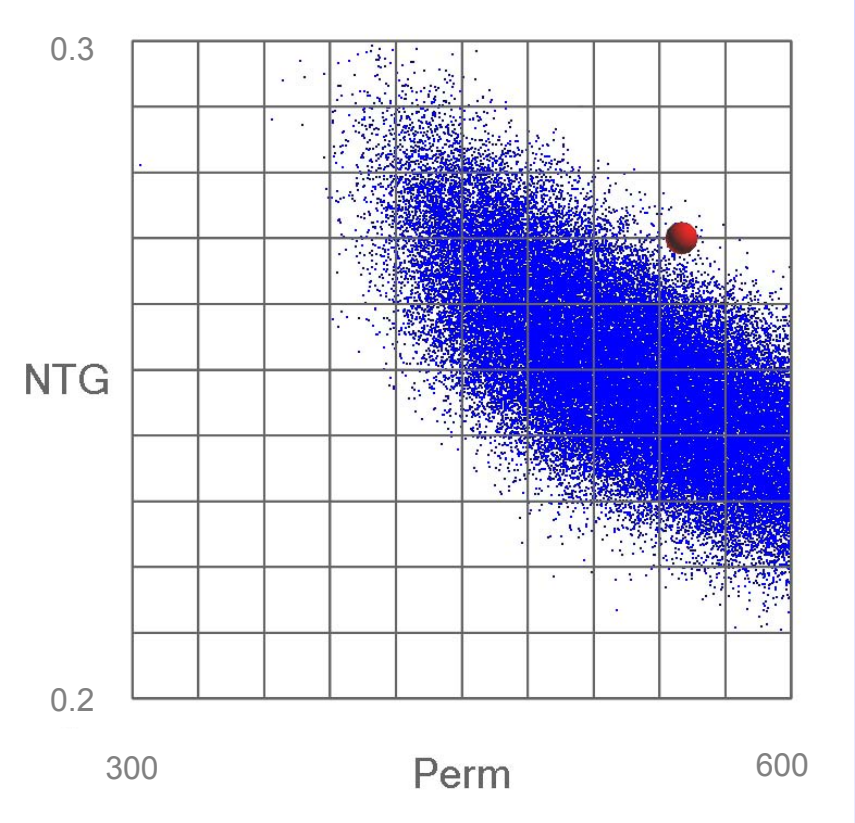
Possible to use MC sampling *à la* Tarantola to get posterior parameter distribution

Stochastic Response surfaces and Bayesian inversion

[Fetel 2006]

When production data are available,
Monte Carlo sampling *à la* Tarantola provides posterior parameter distribution

$$p(m \mid d = d_0) = k\, p_0(x)\, \theta(d = d_0 \mid m)$$



3. Applications to inverse problems

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[Caumon and Muron, 2006]

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[Fetel et al, 2006]

3.3- Inverting reservoir geometry using production data

[Suzuki et al, 2006]

Goal

[Suzuki et al, 2006]

Multiple prior structural models = search space

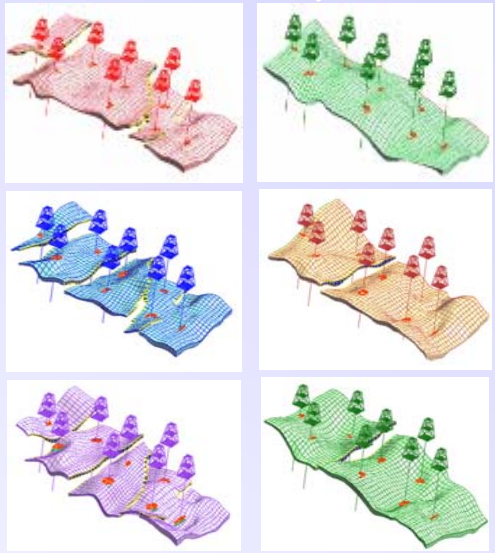
Posterior structural models

Sensitivity on migration parameters

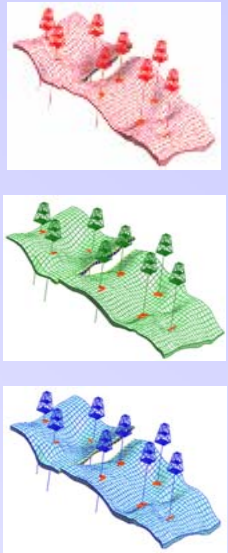
Structural scenarii

Structural interpretation

Stochastic Perturbation



History matching

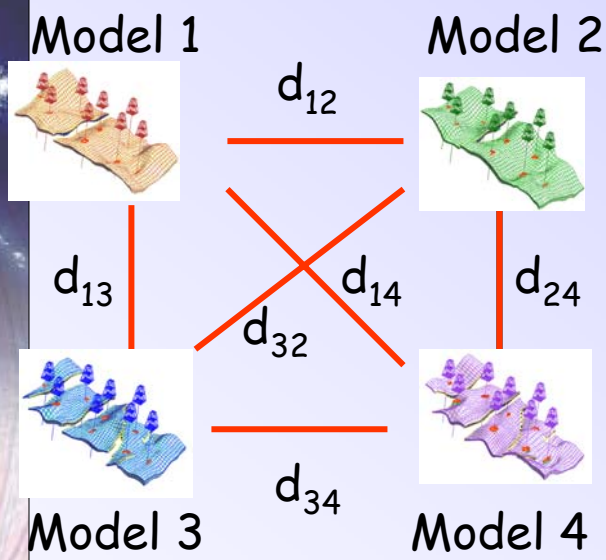


[Samson et al 1996]
[Charles et al 2001]
[Thore et al 2002]
[Zhang & Caumon 2006]

Discrete search, using neighborhood algorithm

1/ Define a distance between models

[Suzuki et al, 2006]



d_{ij}: similarity distance

Similarity distance matrix

	1	2	3	4
1	0	d_{12}	d_{13}	d_{14}
2	d_{12}	0	d_{23}	d_{24}
3	d_{13}	d_{23}	0	d_{34}
4	d_{14}	d_{24}	d_{34}	0

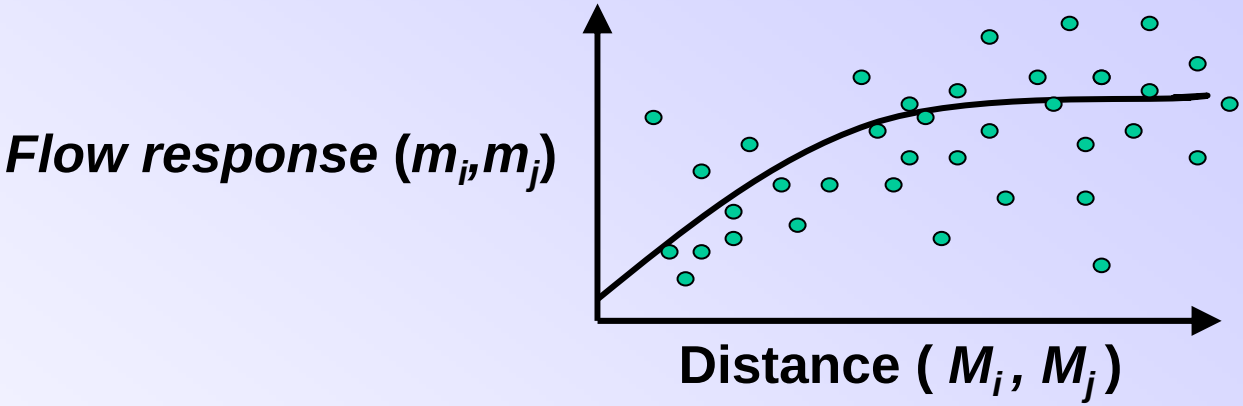
Hausdorff Distance :

$$d_H(M_i, M_j) = \mathrm{MAX}\Big|_{\mathbf{p}_i \in M_i} \{ \mathrm{MIN}\Big|_{\mathbf{p}_j \in M_j} \{\mathbf{p}_i, \mathbf{p}_j\} \}$$

2/ Hypothesis

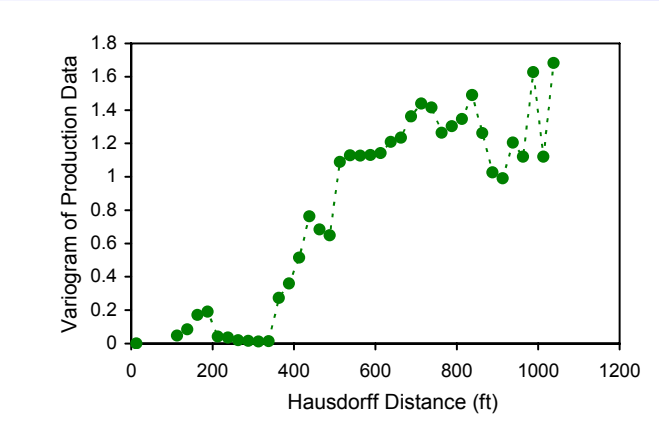
[Suzuki et al, 2006]

Small distance ~ similar flow response

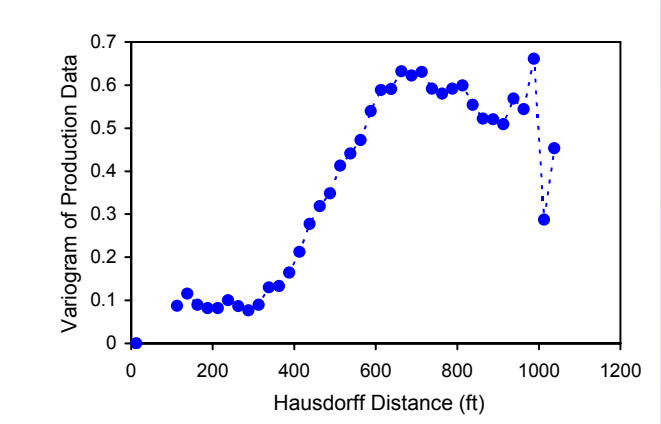


Experimental "production" variograms on 400 models:

Pressure



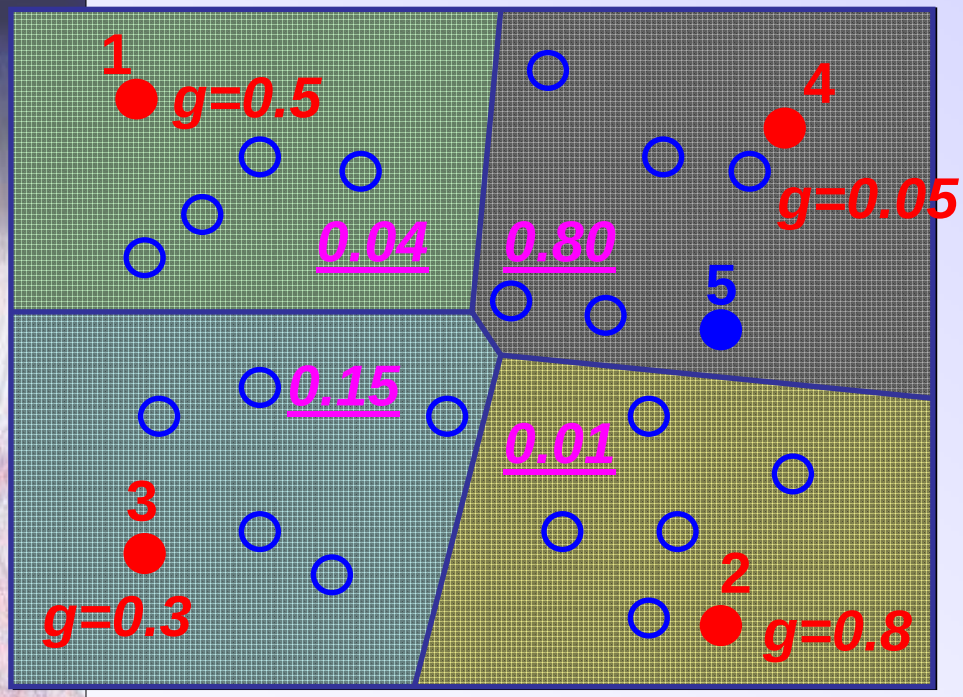
Water cut



Neighborhood Algorithm

[Sambridge 1995]

- Simulate flow on a few models far away from each other
  ➔ evaluate objective function *g(t,m)*



○ **Prior model**

g(t,m) = Production mismatch

Selection probability

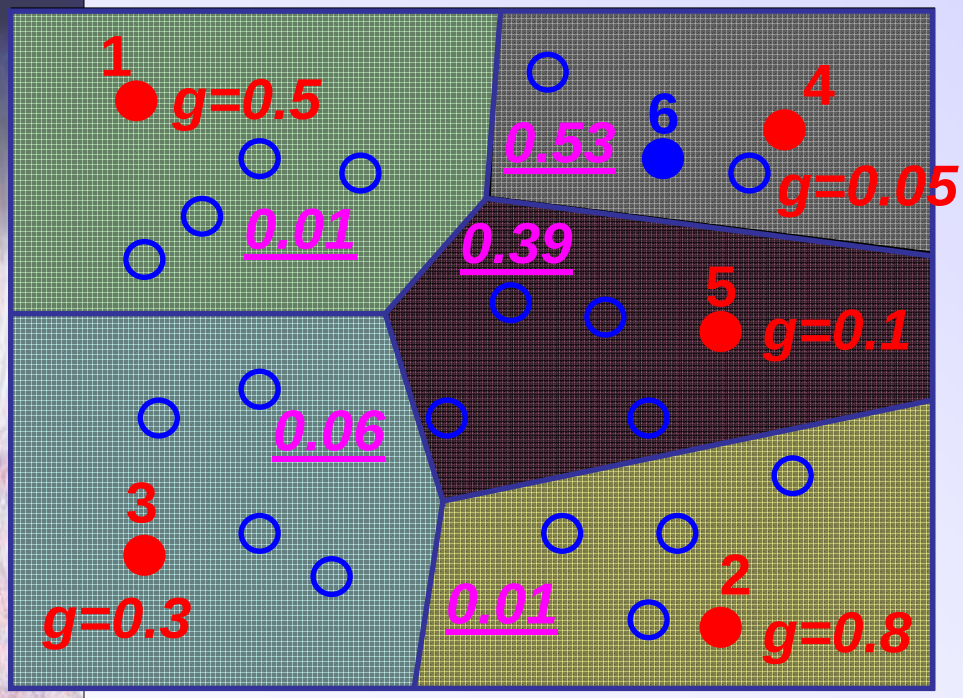
$$p(m_i) = \exp\left\{-\frac{1}{T}\frac{g(m_t, m_i)}{M}\right\}$$

- Define clusters in model space
- Assign selection probability and randomly draw next model ➔ 5

Neighborhood Algorithm

[Sambridge 1995]

- Simulate flow on model 5 ➔ evaluate objective function *g(t,m)*



○ **Prior model**

g(t,m) = Production mismatch

Selection probability

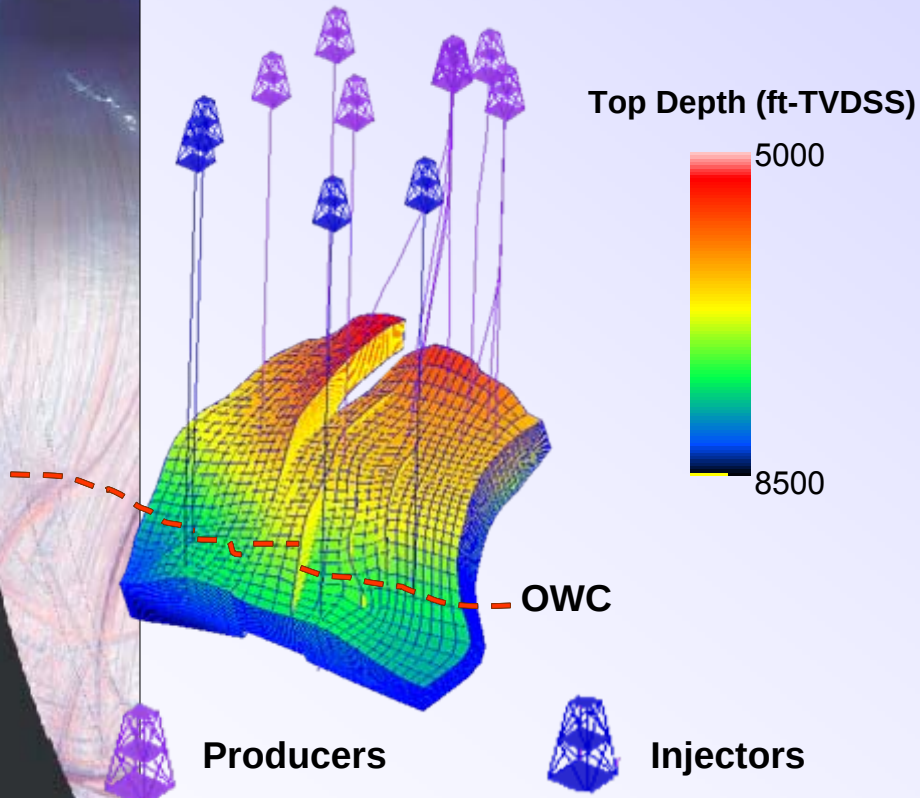
$$p(m_i) = \exp\left\{-\frac{1}{T}\frac{g(m_t, m_i)}{M}\right\}$$

- Update clusters in model space
- Recompute selection probabilities and repeat

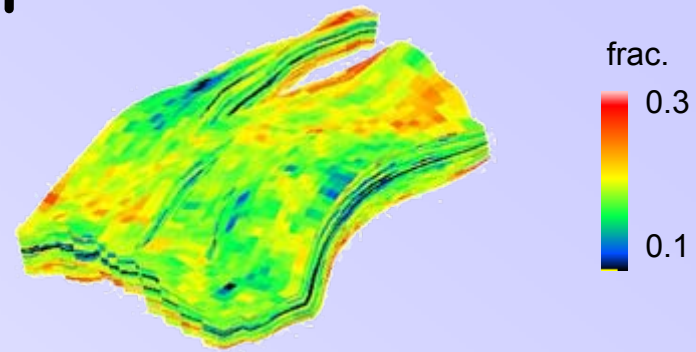
[Suzuki et al, 2006]

Example

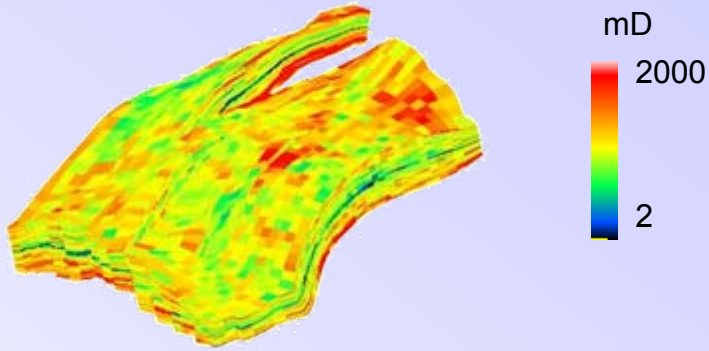
- ‘True’ reservoir



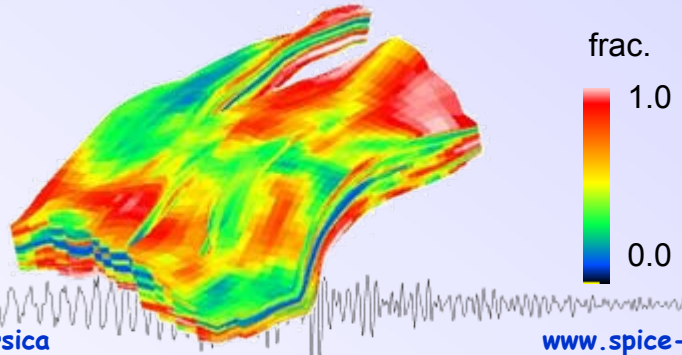
Porosity



Permeability



NTG



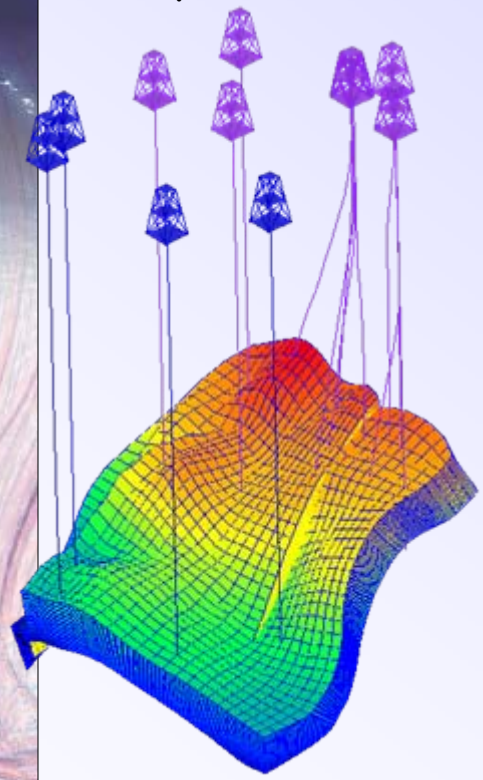
10 producers & 4 injectors

[Suzuki et al, 2006]

Prior structural uncertainty

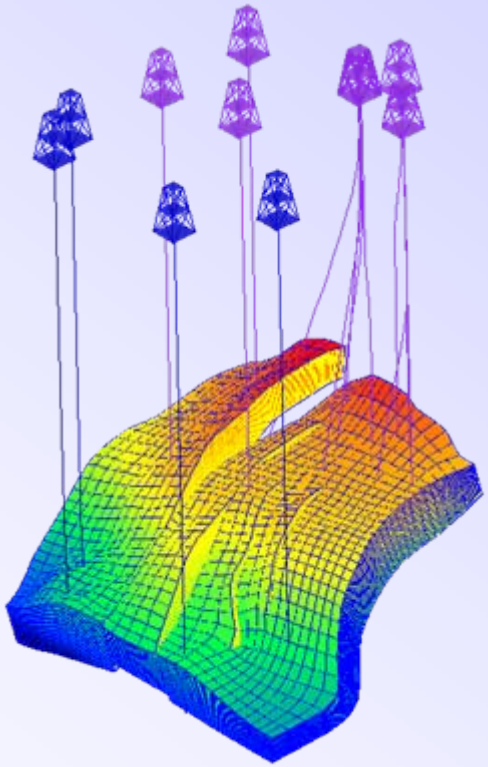
3 interpretations

Interpretation 1



2 faults

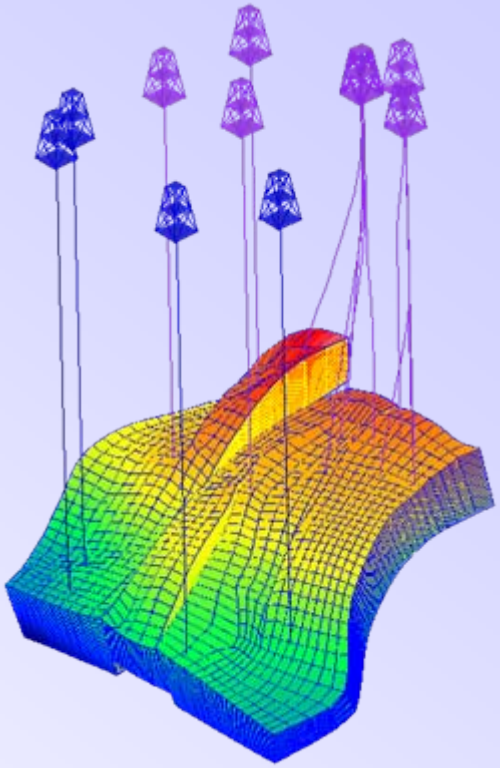
Interpretation 2



4 faults

Reference :
excluded from the search

Interpretation 3

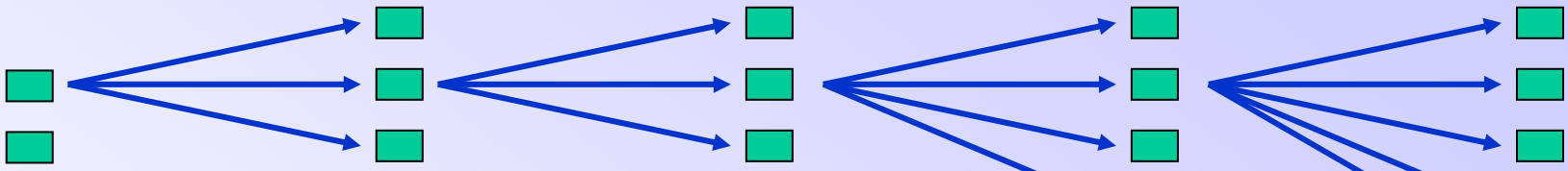


5 faults

[Suzuki et al, 2006]

Prior structural uncertainty

Stochastic perturbation of horizons/faults



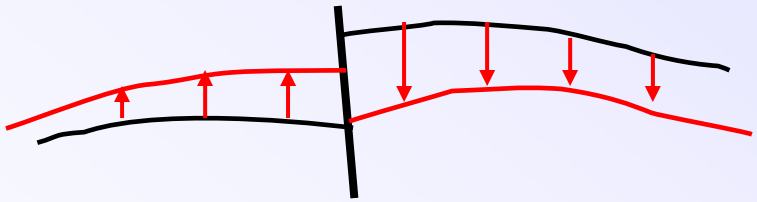
2 Interpretations

Perturb top depth (horizon position)

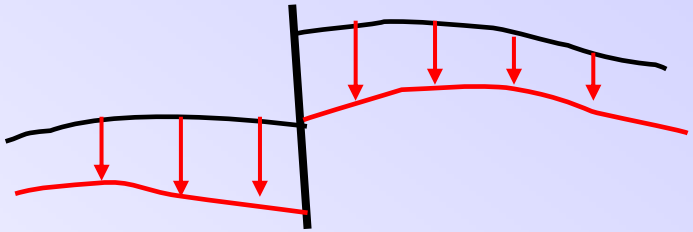
Perturb gross H

Perturb faults

Perturb top depth (fault throw)



discontinuous perturbation across a fault



continuous perturbation across a fault

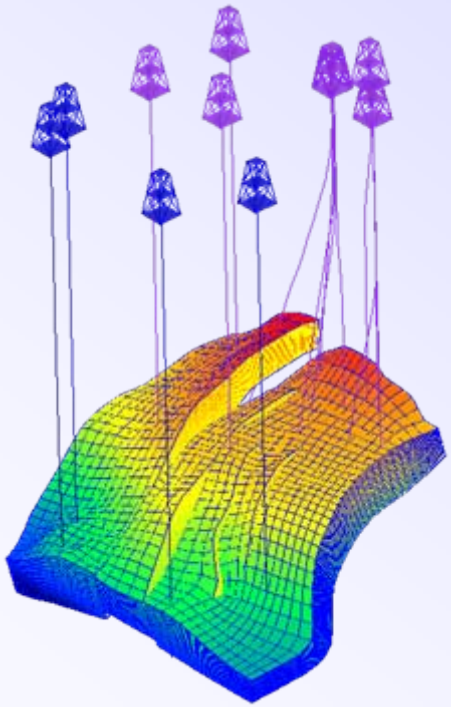
Total of 432 structural models

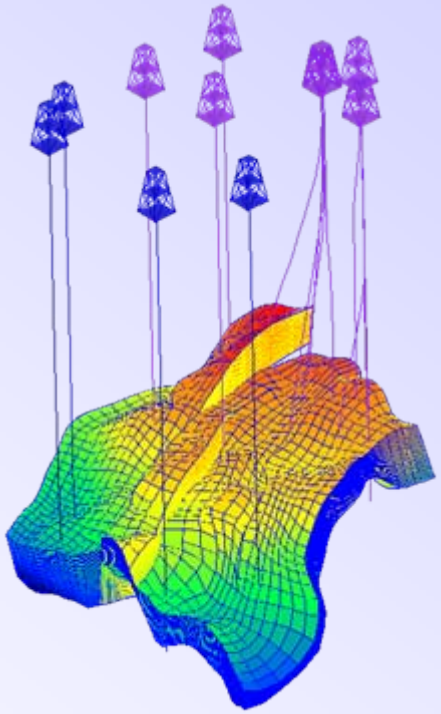
[Suzuki et al, 2006]

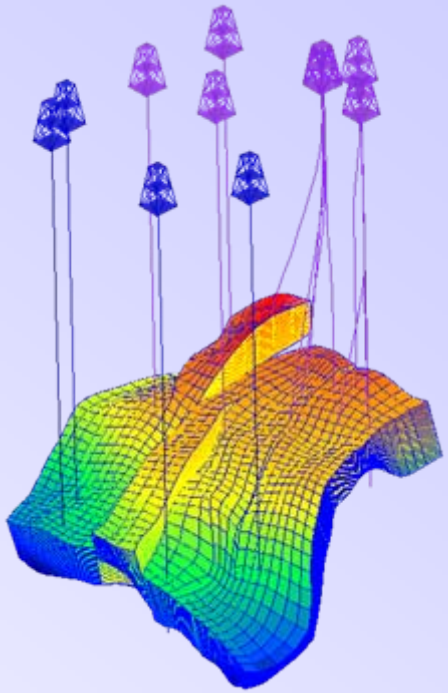
Results

Reference structure

Two history matched models



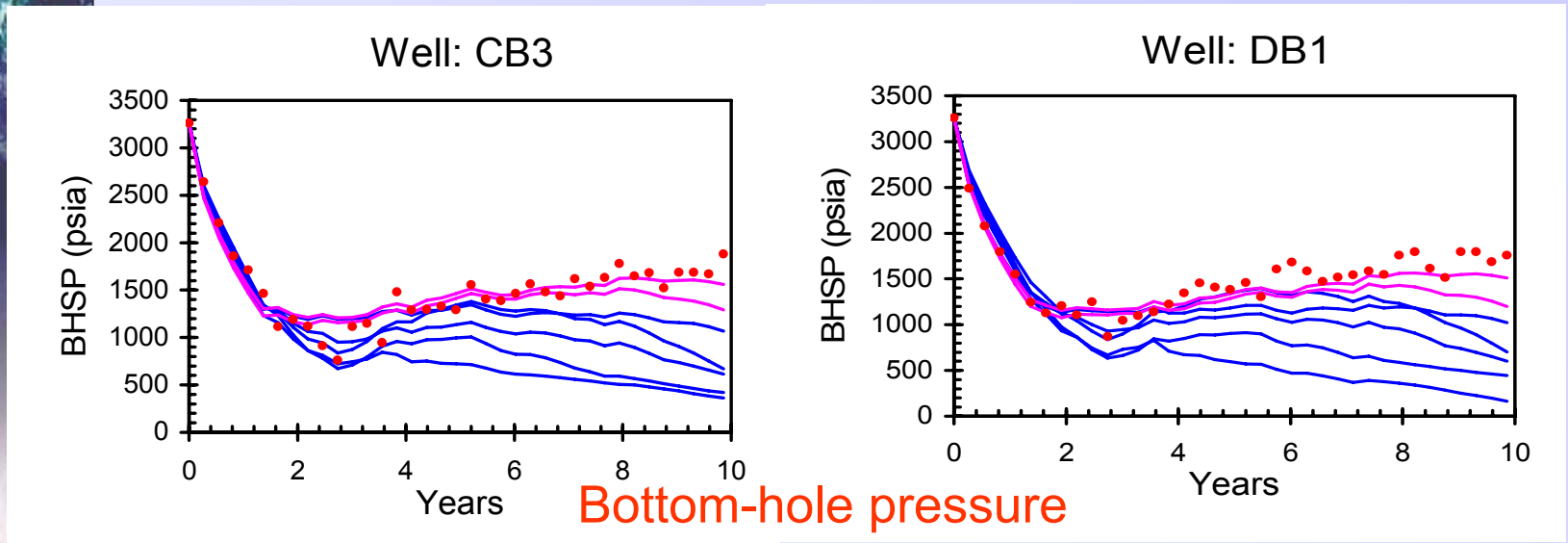


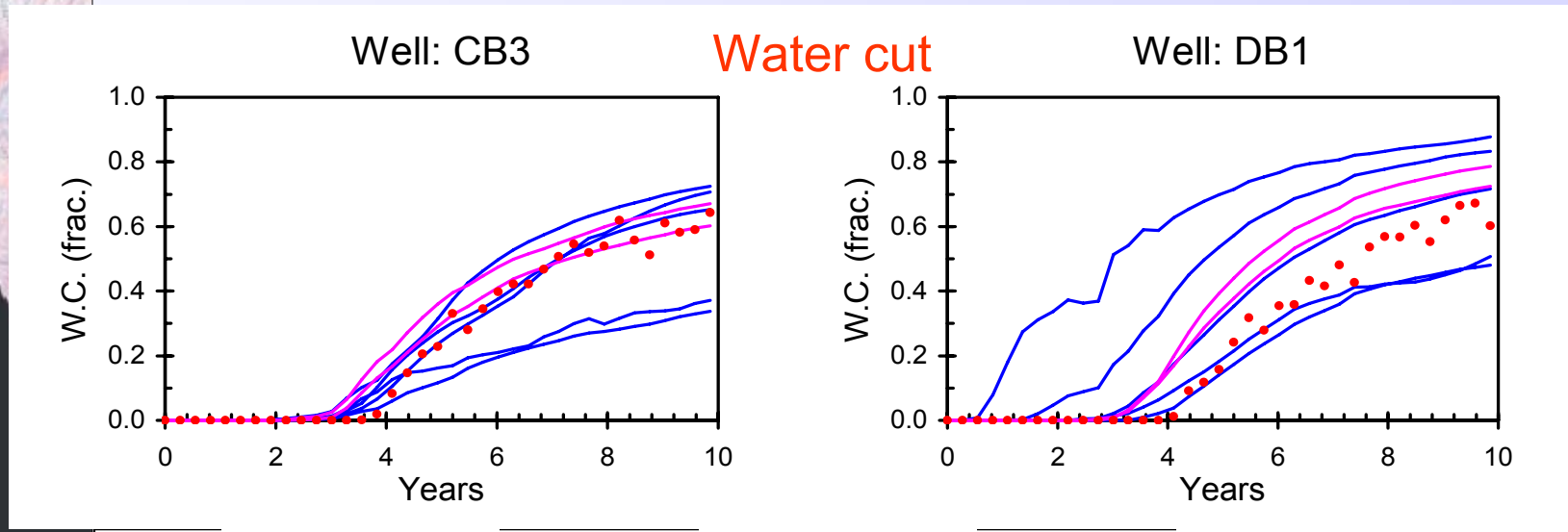


47 flow simulations
(23.5 / HM model)

[Suzuki et al, 2006]

Results





Field data — Initial runs — History matched

Conclusions & Challenges

- Ill-posed inverse problem
- Need for:
  - Efficient optimization / sampling algorithms
  - Representing uncertainty to study risks
  - Quantitative Geology
  - Confronting all information from different disciplines
- Key issue: finding a good model parameterization
  - At small and local scales: Geological parameters
- Are "details" important ?
  - Case-specific answer
  - Parsimony principle to be rethought when modeling uncertainties
  - Upscaling techniques may provide a sound answer

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