FAULT NETWORK UNCERTAINTY ASSESSMENT WITH A GENERATIVE GRAPH-BASED ALGORITHM

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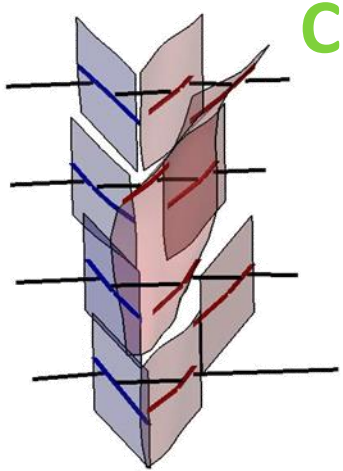
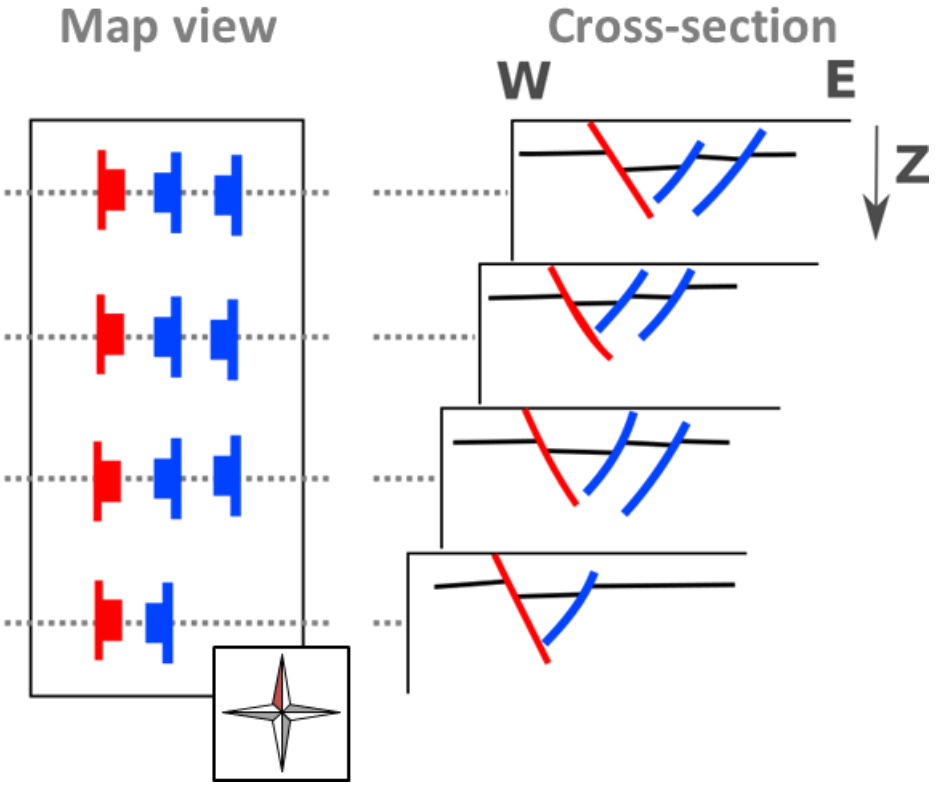
CURRENT STATUS AND PERSPECTIVES



EGU General Assembly 2020

Guillaume Caumon, Gabriel Godefroy, Paul Marchal

Fault association problem

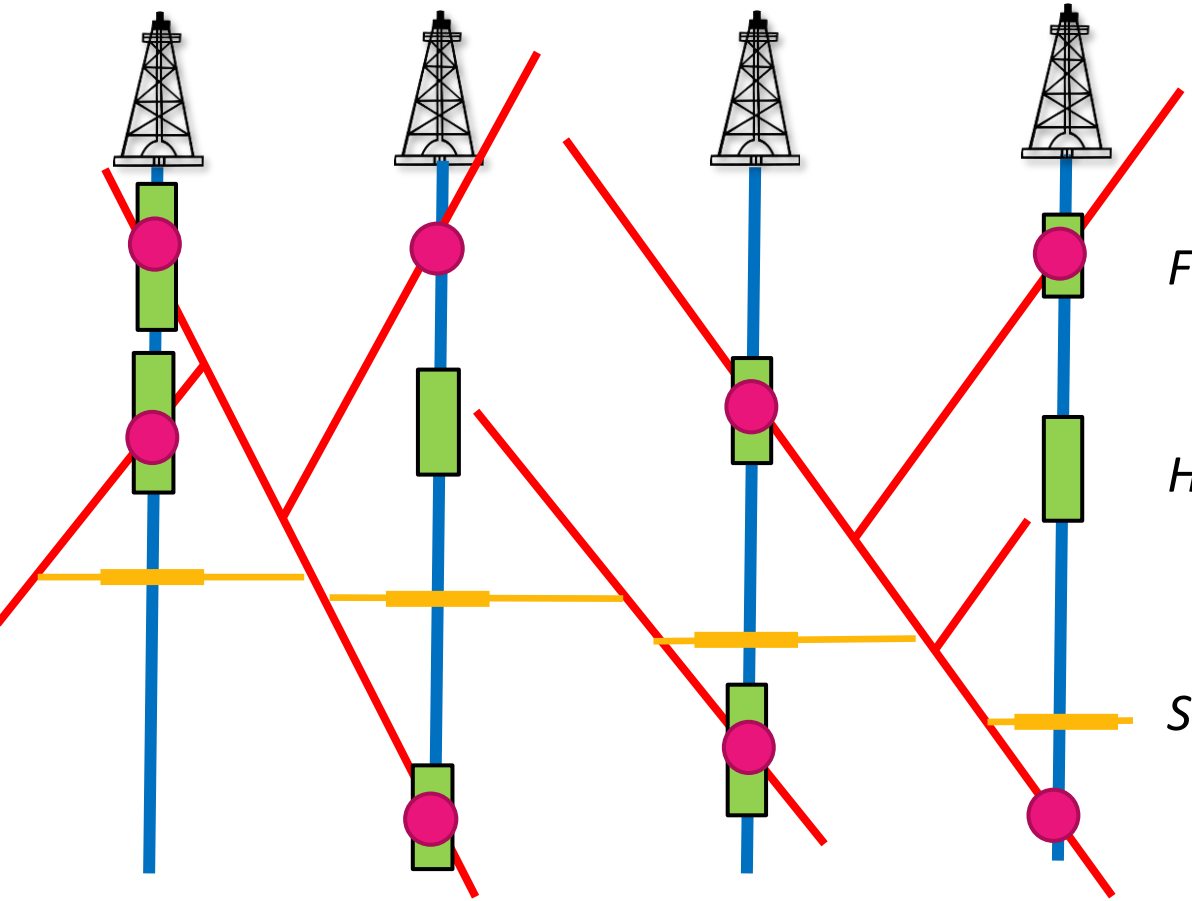


"Find the simplest and most likely explanation for your data"

- Anonymous teacher -

[Modified from Freeman et al., *First Break* 1990]

Fault association problem



Faults

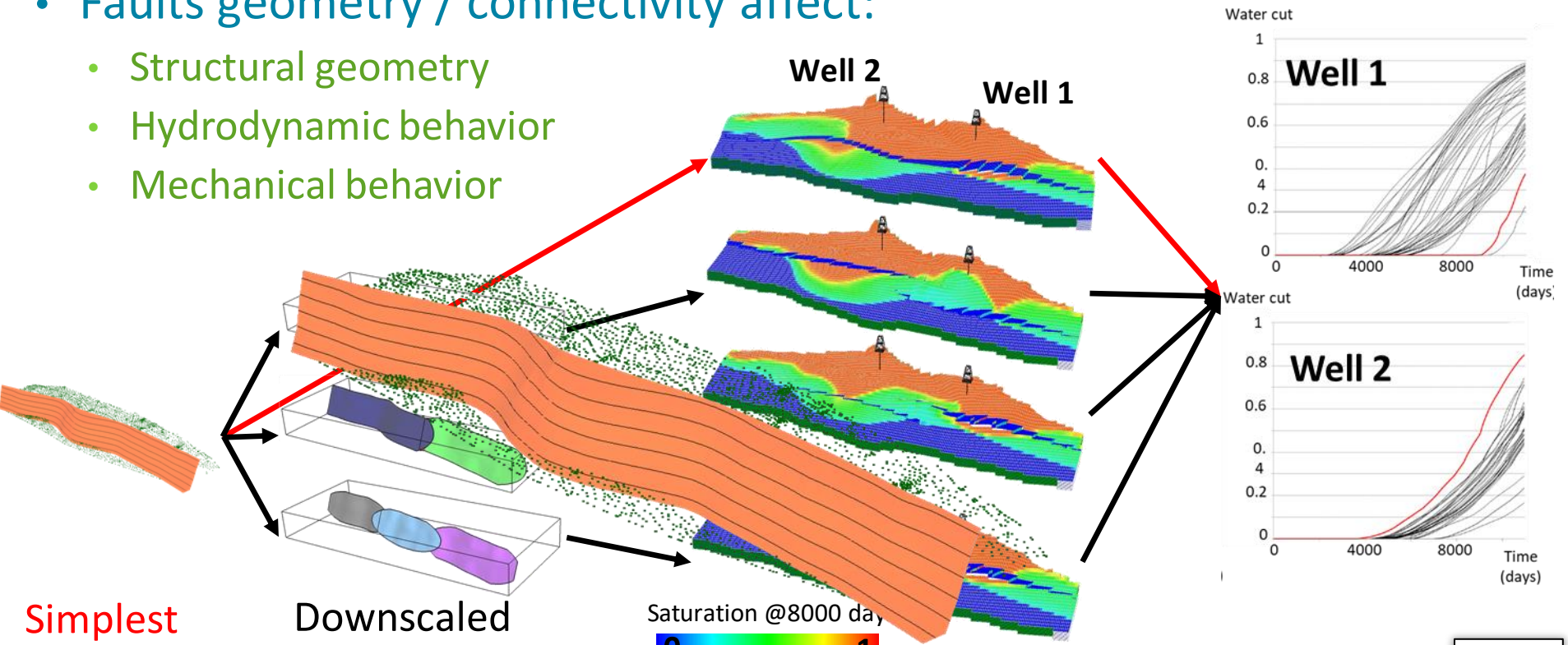
Hydrothermal alteration

Stratigraphic horizon

Fault uncertainty: Should we care ?

- Depends on the model purpose
- Faults geometry / connectivity affect:
  - Structural geometry
  - Hydrodynamic behavior
  - Mechanical behavior

[Julio et al, *Interp* 2015]



Motivation

"In developing the multiple hypotheses, the effort is to bring up into view every rational explanation of the phenomenon in hand [...]

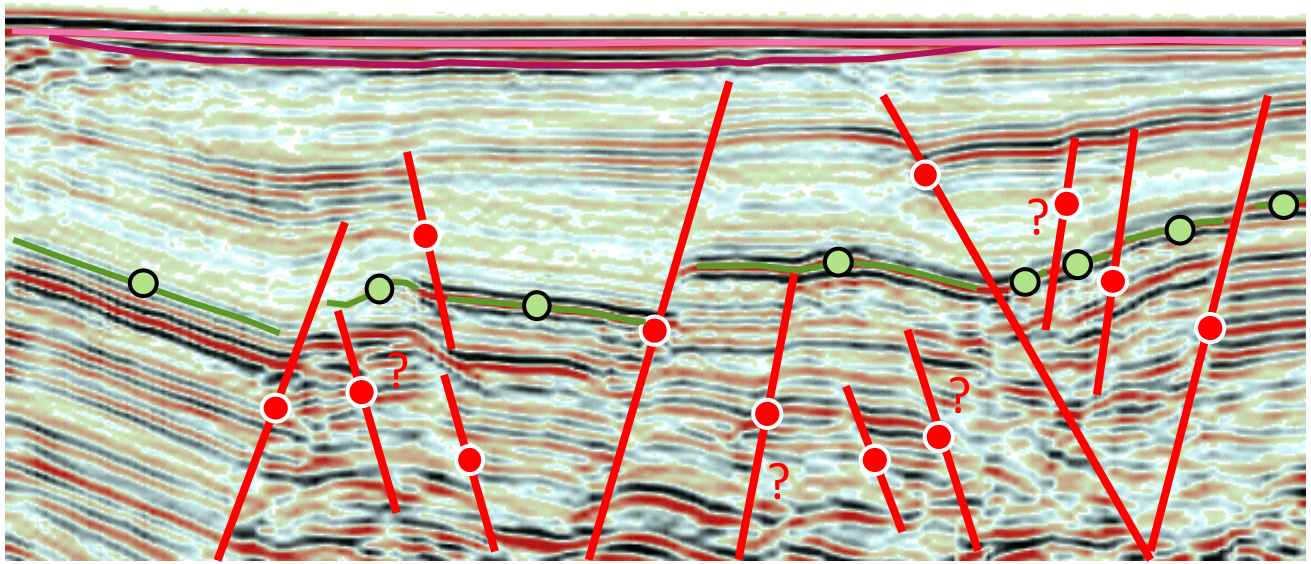
The chief danger that springs from affection is counteracted"

T.C. Chamberlin, *The method of Multiple working hypotheses, 1897*

Approaches [Wellmann & Caumon, *Adv Geophys* 2018]:

- Data perturbation [Wellmann et al, 2010; Lindsay et al 2013; Giraud et al 2019]
- Model perturbation [Abrahamsen 1992; Lecour et al, 2001]
- Expert-based [Bond et al 2007; Schaaf & Bond, 2019]
- Expert-based + Model perturbation [Suzuki et al, 2008; Scheidt et al, 2018]
- Iterative fault simulation [Cherpeau et al, 2010; 2012; 2015; Julio et al, 2015]
- Stochastic processes [Holden et al, 2003; Aydin and Caers, 2017]

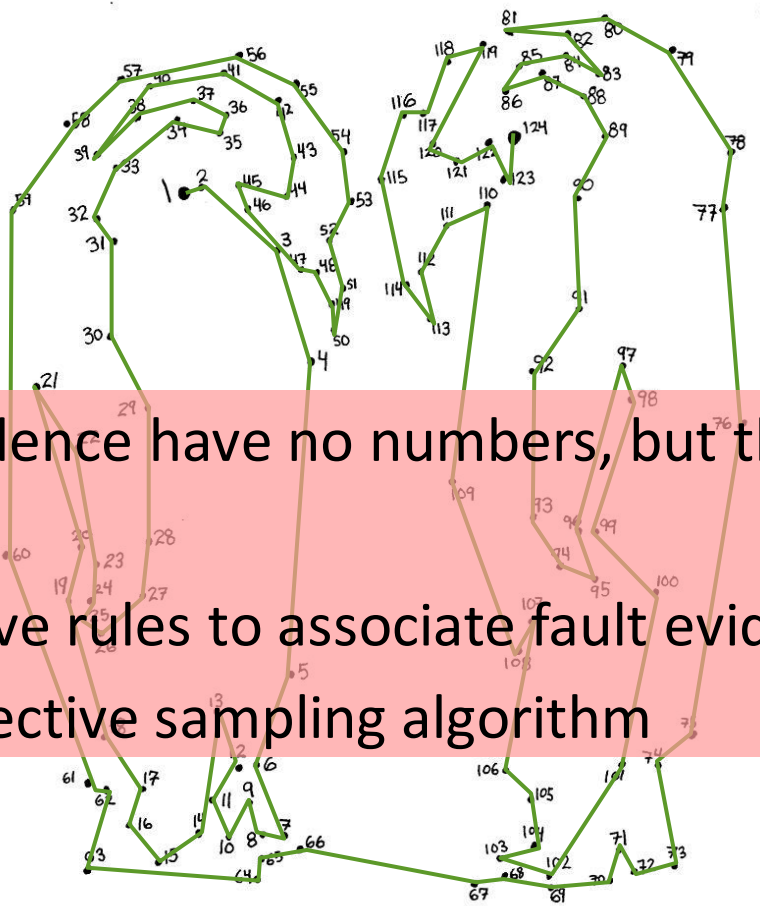
Fault uncertainty: components



[Data: Taylor et al, *GJI* 2010]

1. Identifying evidence
2. Associating evidence
3. Modeling & QC

Joining the dots…



Rule: increment number

Strategy : search locally

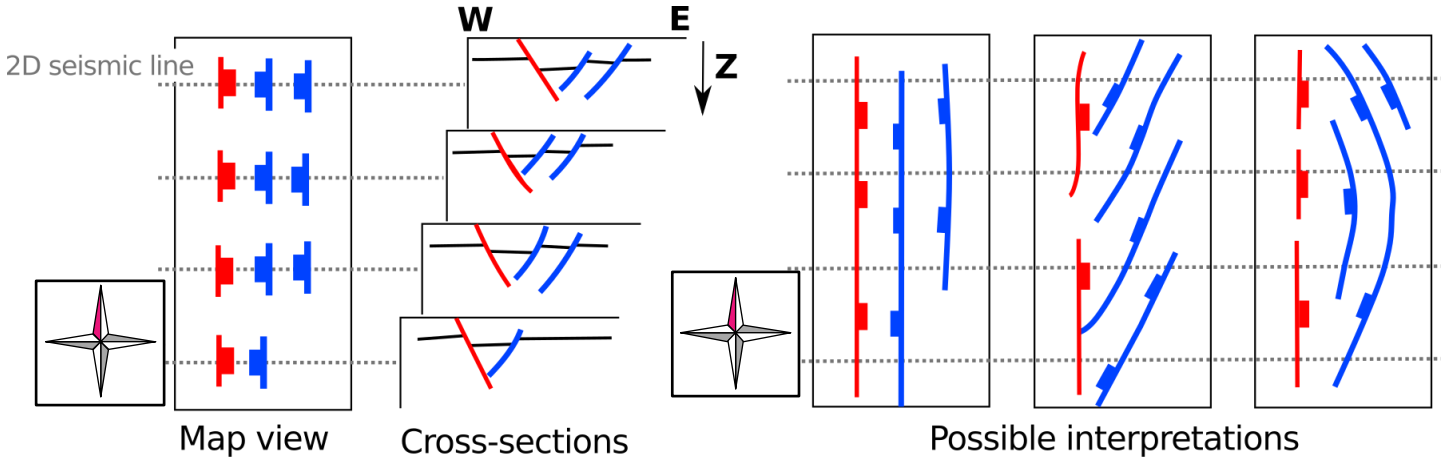
Fault evidence have no numbers, but they carry information!

Need for:

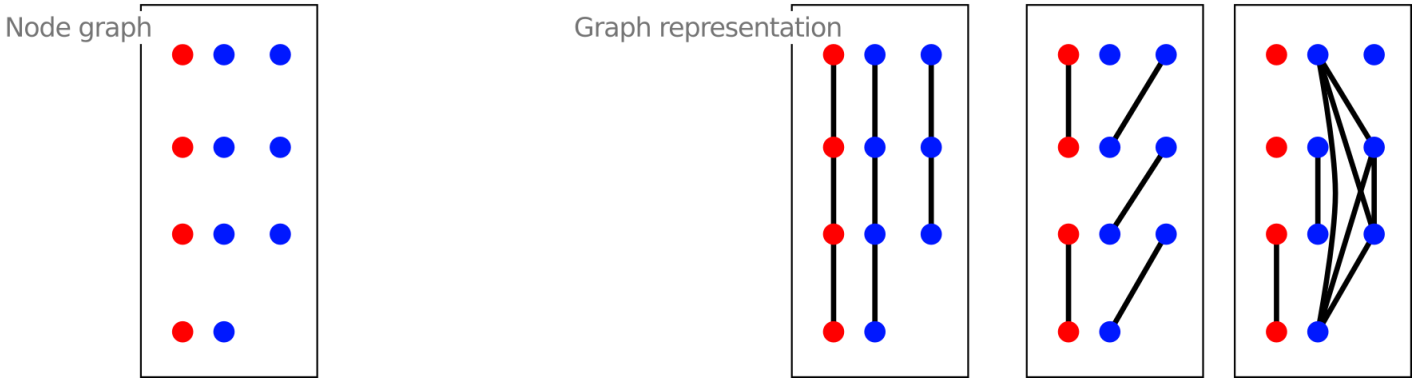
- Effective rules to associate fault evidence
- An effective sampling algorithm

By whitney waller - connect-the-dots, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=45762268

Fault association as a graph creation problem

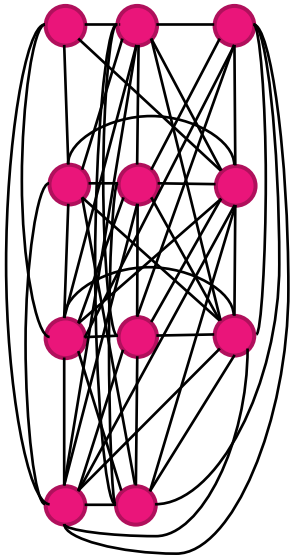


[Modified from Freeman et al., *First Break*, 1990]



[Godefroy et al, *Math Geosci*, 2019]

The possibility graph



Each node = piece of fault evidence

Point, line, surface

[+ location uncertainty]

Each edge :

Likelihood that the endpoints belong to the same fault surface

n = 11 nodes

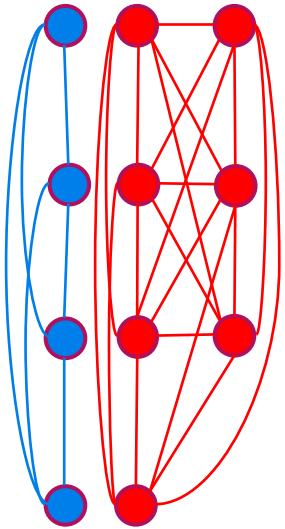
11×10/2 = 55 edges

Max number of scenarios (Bell number):

$B(n) = 678570$

[Godefroy et al, *Math Geosci*, 2019]

The possibility graph



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Point, line, surface

[+ location uncertainty]

Each edge :

Likelihood that the endpoints belong to the same fault surface

Family marks (inducing subgraphs) 

4 + 7 nodes

6 + 21 edges

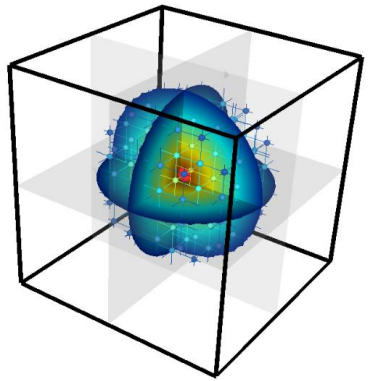
Max number of scenarios:

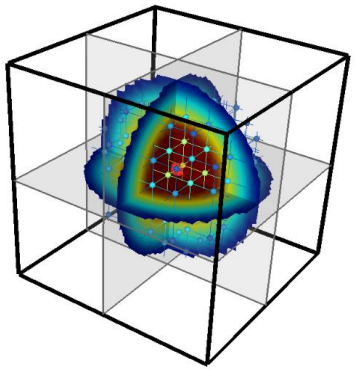
$B(4) + B(7) = 15 + 877$

[Godefroy et al, *Math Geosci*, 2019]

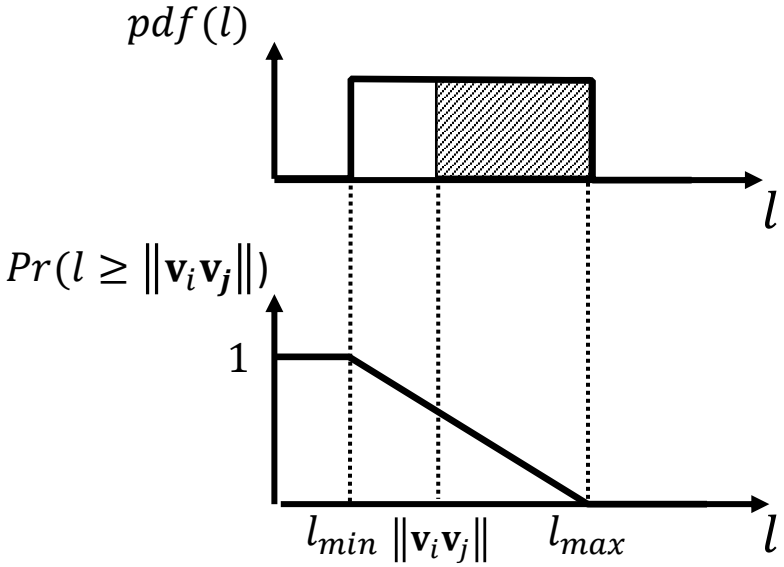
Simple association likelihood: distance

[Godefroy et al, *Math Geosci*, 2019]





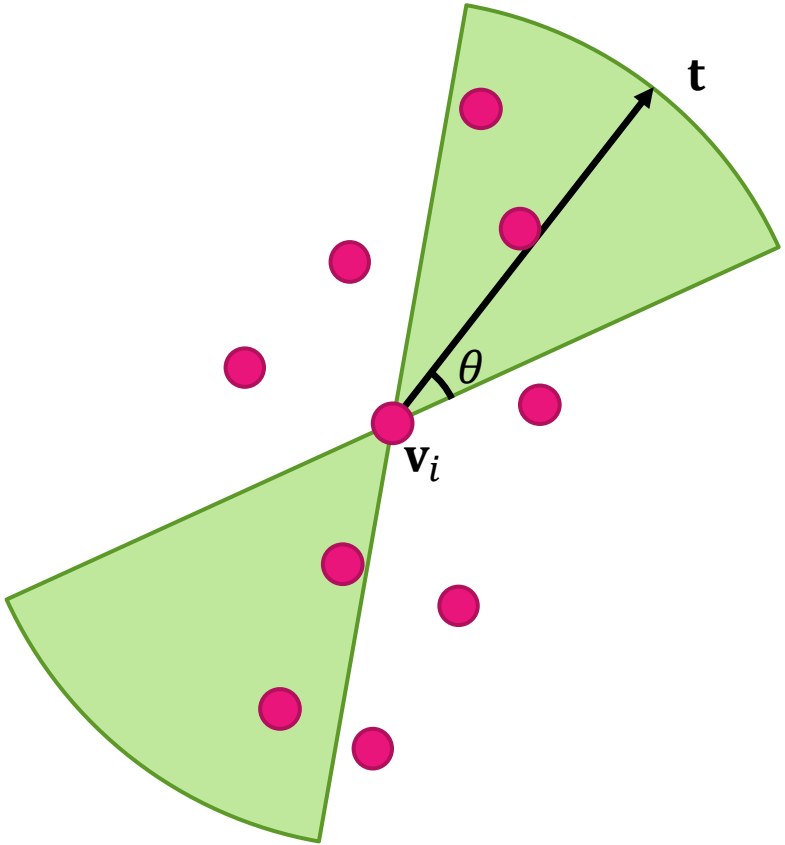
Example: uniform distribution



$$L_d(\mathbf{v}_1 \leftrightarrow \mathbf{v}_2) = \frac{l_{max} - \|\mathbf{v}_i\mathbf{v}_j\|}{l_{max} - l_{min}}$$

Simple association likelihood: orientation

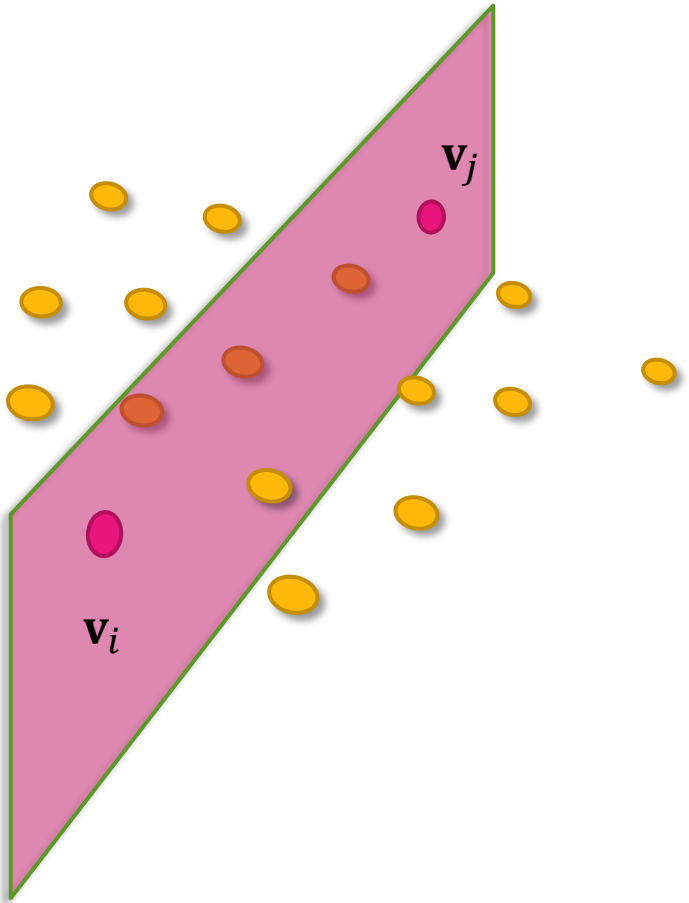
[Godefroy et al, *submitted*]



Example: uniform distribution around direction $\mathbf{t}$

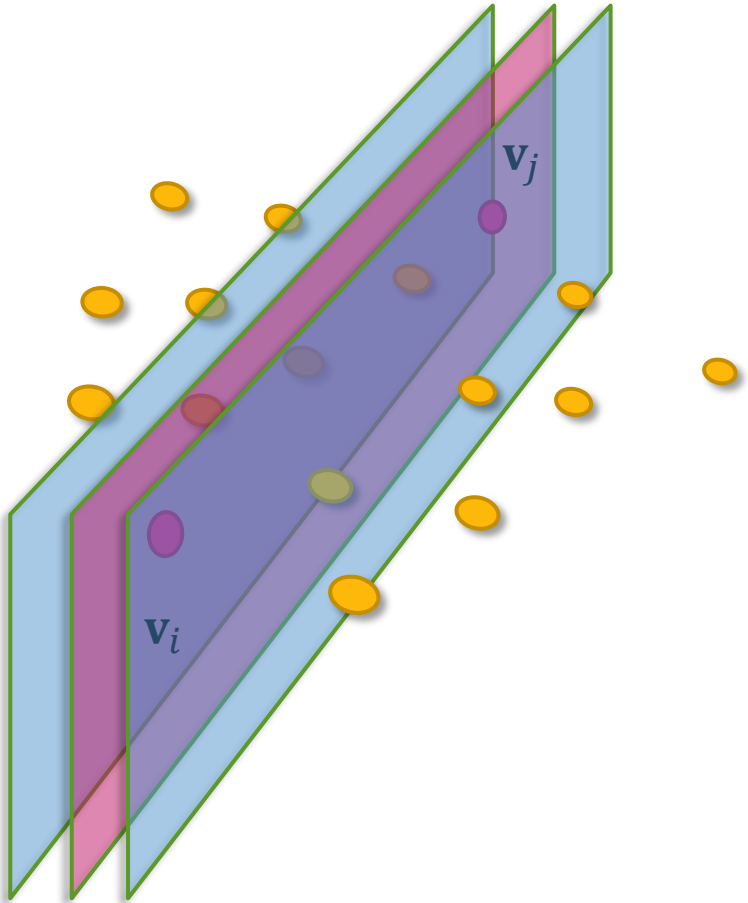
$$L_o(\mathbf{v}_i \leftrightarrow \mathbf{v}_j) = \begin{cases} 1 \text{ if } \operatorname{acos}\left(\dfrac{\mathbf{v}_i\mathbf{v}_j}{\|\mathbf{v}_i\mathbf{v}_j\|} \cdot \dfrac{\mathbf{t}}{\|\mathbf{t}\|}\right) < \theta \\ 0 \text{ if not} \end{cases}$$

Simple association likelihood: stratigraphic offset



Create a test surface from the fault data

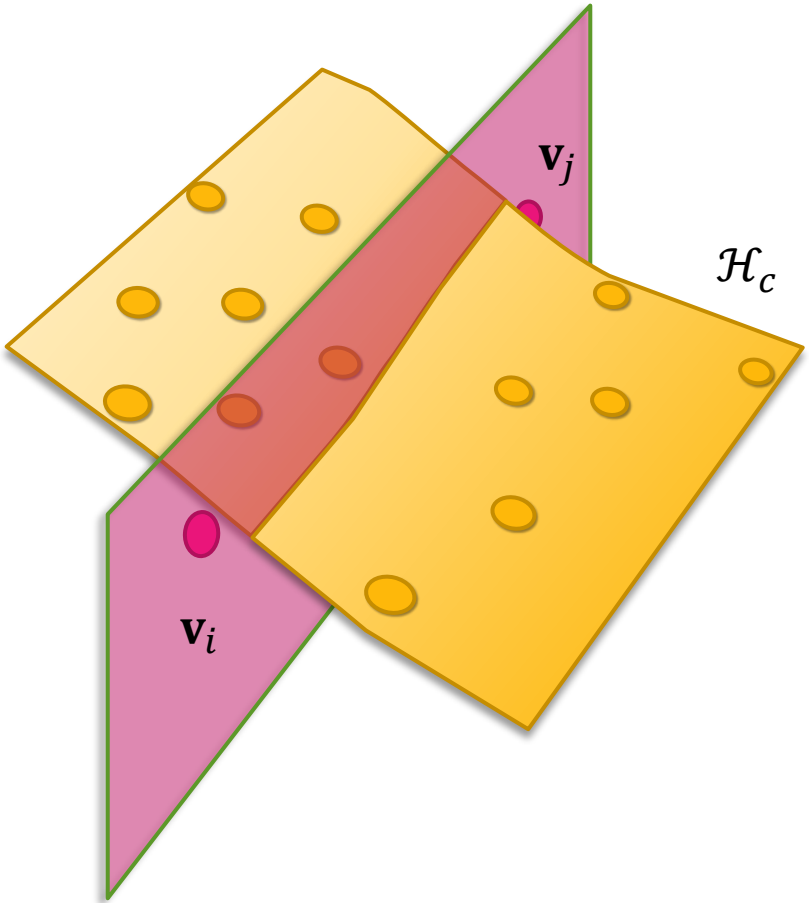
Simple association likelihood: stratigraphic offset



Create a test surface from the fault data

Deactivate stratigraphic information in a buffer zone

Simple association likelihood: stratigraphic offset

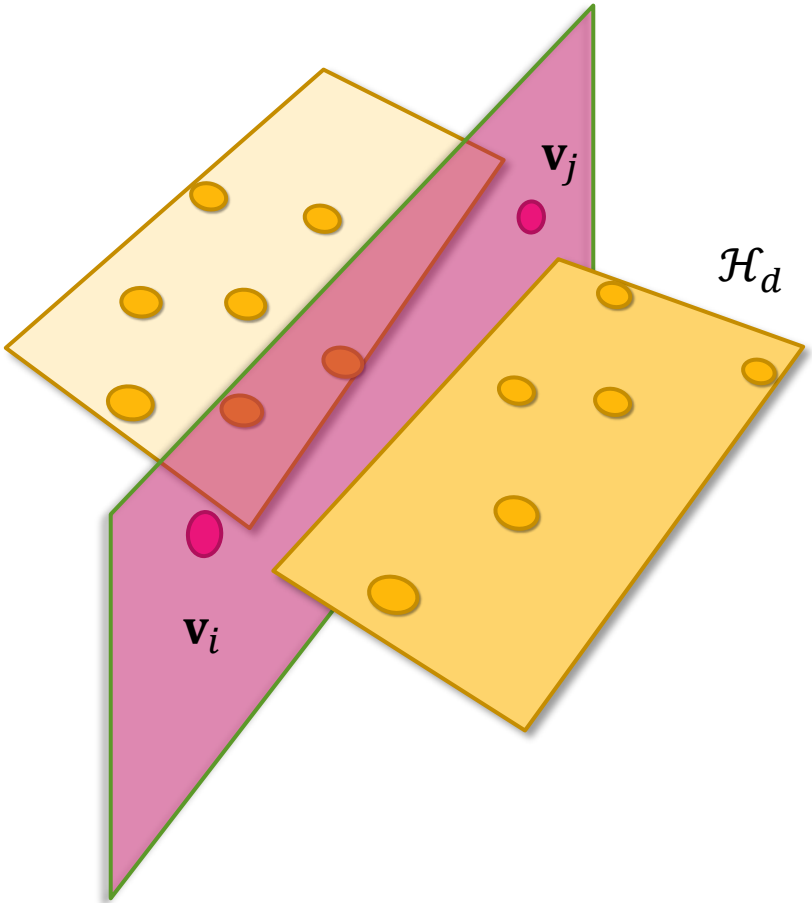


Create a test surface from the fault data

Deactivate stratigraphic information in a buffer zone

Compute a continuous horizon $\mathcal{H}_d$ by LS

Simple association likelihood: stratigraphic offset



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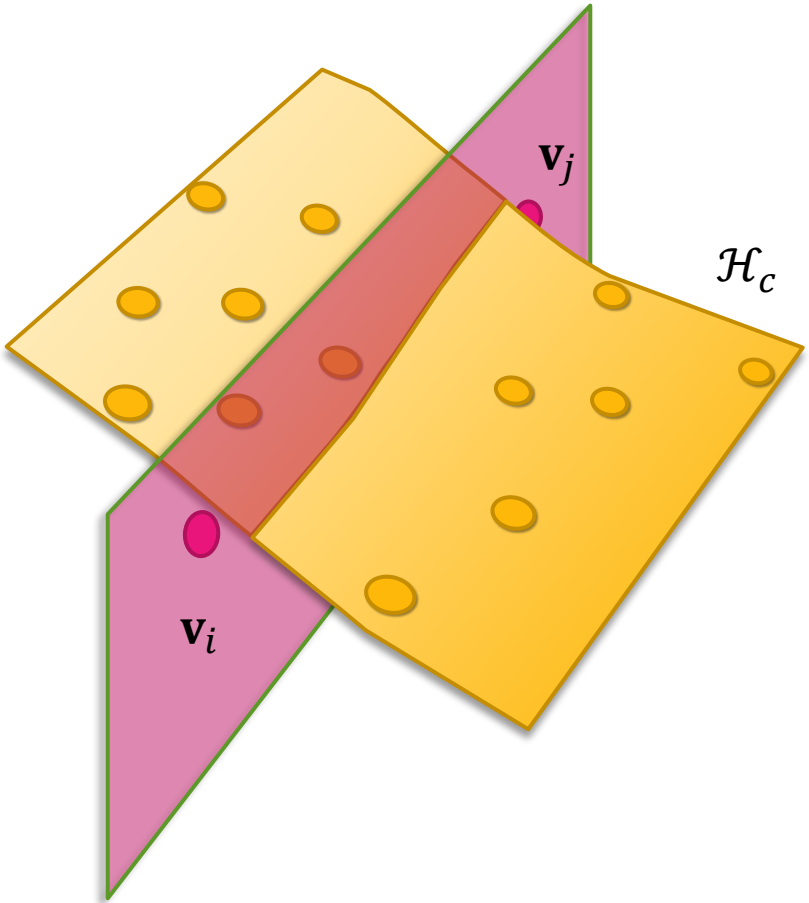
Compute a discontinuous horizon $\mathcal{H}_d$ by LS

$$L_o(\mathbf{v}_i \leftrightarrow \mathbf{v}_j) = \frac{\|\mathcal{H}_c - \mathcal{H}_d\|}{RMS(\mathcal{H}_c) + RMS(\mathcal{H}_d)}$$

Simple association likelihood: stratigraphic offset



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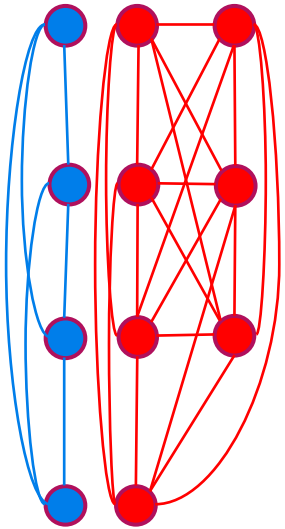
Aggregating association likelihoods

[Godefroy et al, *Math Geosci*, 2019]

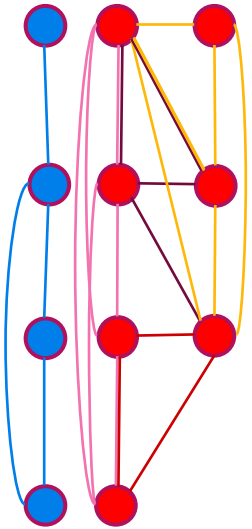


$$L(\mathbf{v}_i \leftrightarrow \mathbf{v}_j) = \prod_{\alpha} L_{\alpha}(\mathbf{v}_i \leftrightarrow \mathbf{v}_j)$$

Remove edges with zero (or very small) likelihood from the possibility graph

Identify possible largest faults

[Godefroy et al, *Math Geosci*, 2019]



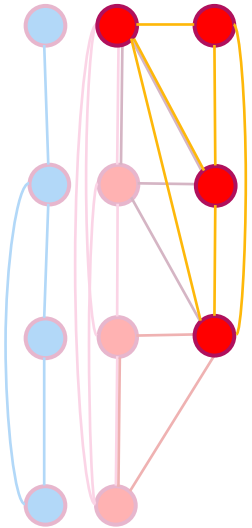
Faults : cliques of the possibility graph

Large faults : maximal cliques of the possibility graph

[Bron Kerbosh 1979]

Sequential Fault Sampling

[Godefroy et al, *submitted*]



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[Bron Kerbosh 1979]

Randomly sample a maximal clique $\mathbb{F}$

$$P_{draw\ struct}(\mathbb{F}) = \frac{\overline{L_{\varphi}^{\mathbf{all}}(\mathbb{F})}\ |\mathbb{F}|^{\alpha_{draw}}}{\sum_{\mathbb{F}}^{\mathbf{all\ cliques}} \overline{L_{\varphi}^{\mathbf{all}}(\mathbb{F})}\ |\mathbb{F}|^{\alpha_{draw}}}$$

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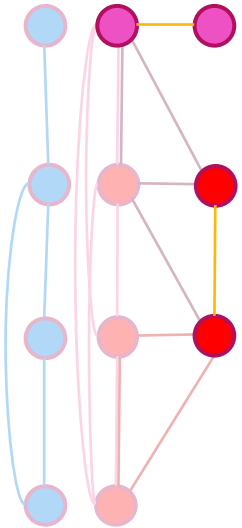

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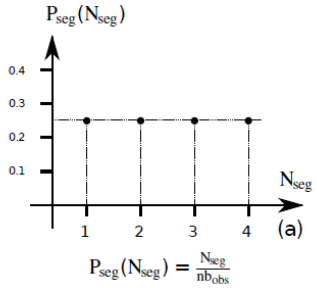
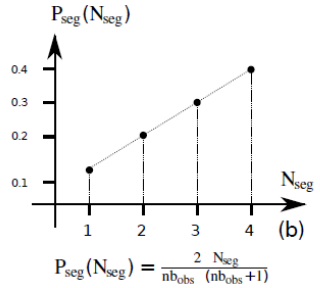
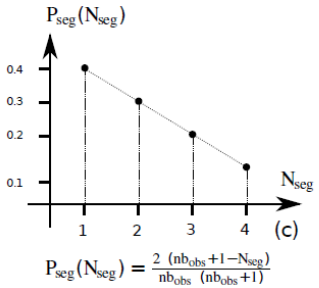
Optional: downscale







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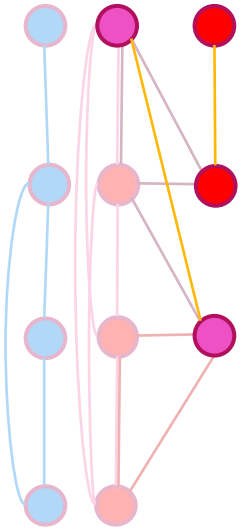

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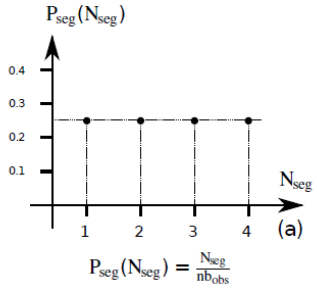

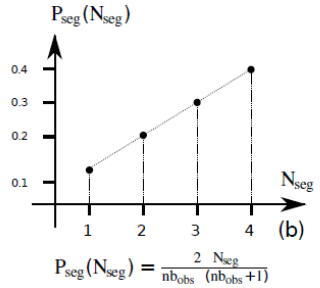

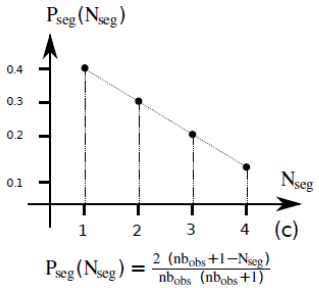

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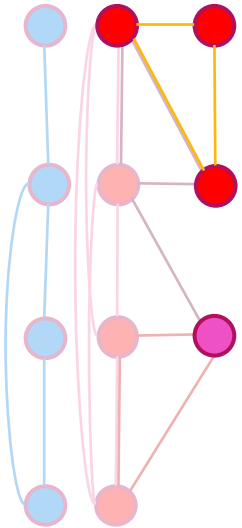

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[Bron Kerbosh 1979]

Randomly sample a maximal clique $\mathbb{F}$

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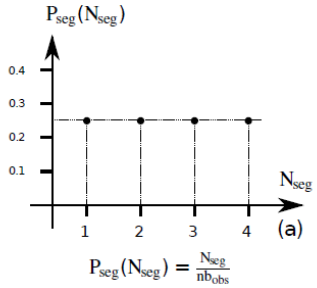

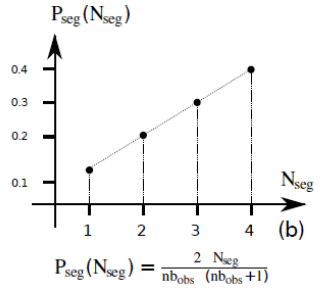

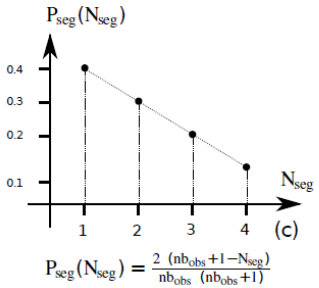

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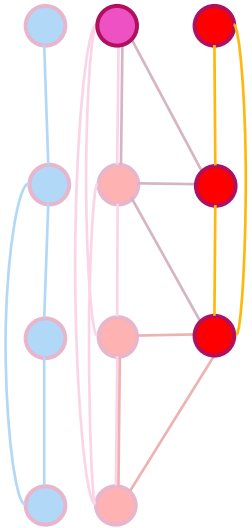

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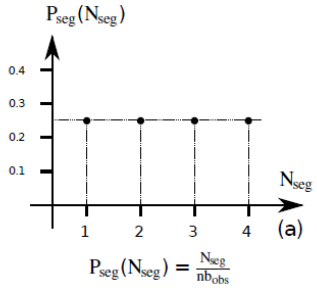

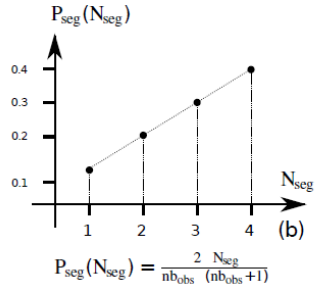

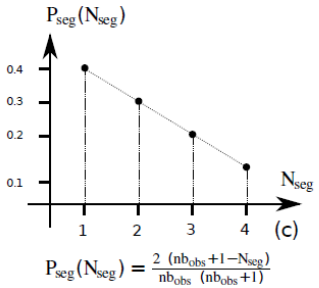

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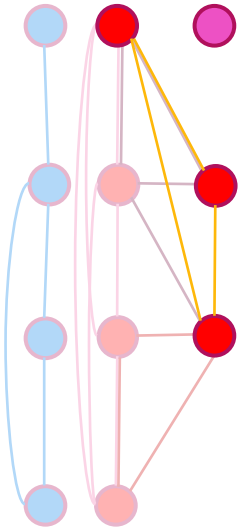

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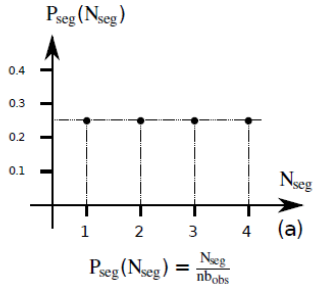

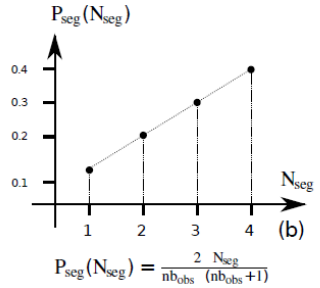

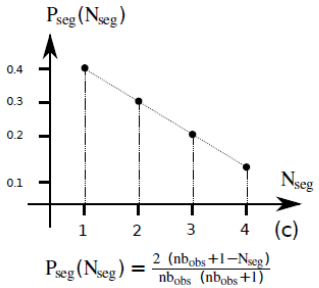

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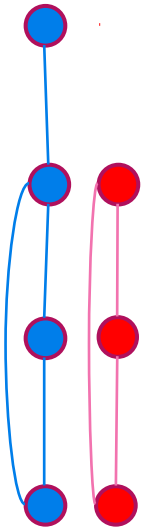

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Large faults : maximal cliques of the possibility graph

[Bron Kerbosh 1979]

Randomly sample a maximal clique $\mathbb{F}$

Optional: downscale

Update possibility graph and cliques and start again

From fault graphs to geometric structures

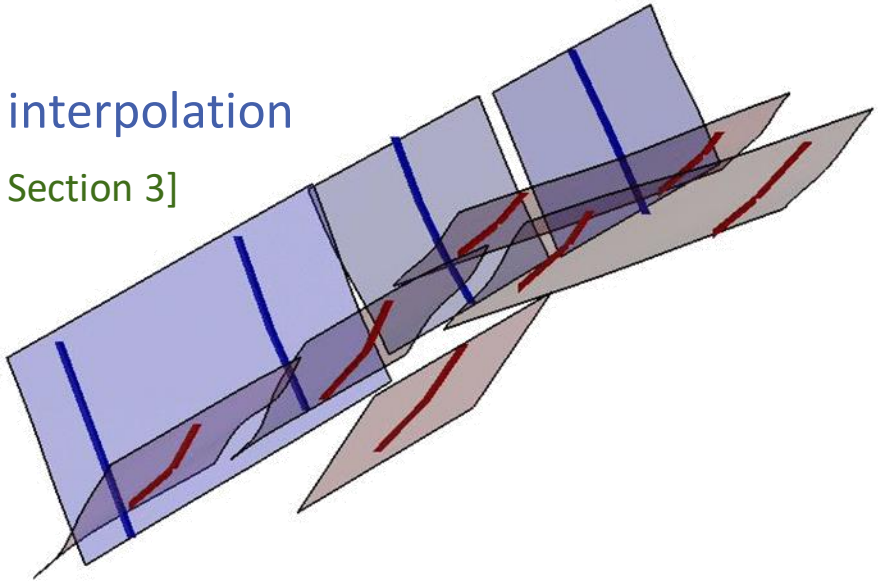
[Godefroy et al, *submitted*]

For each association scenario :

- For each fault
  - Determine outline
  - Create surface by least-squares interpolation

    [e.g., Wellmann & Caumon 2018, Section 3]

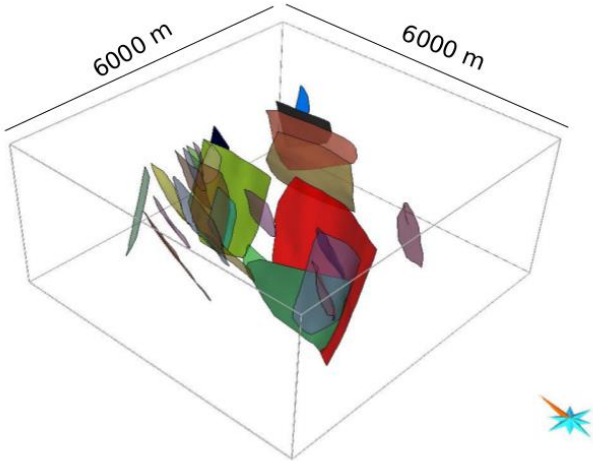
Example obtained with SKUA structure & stratigraphy



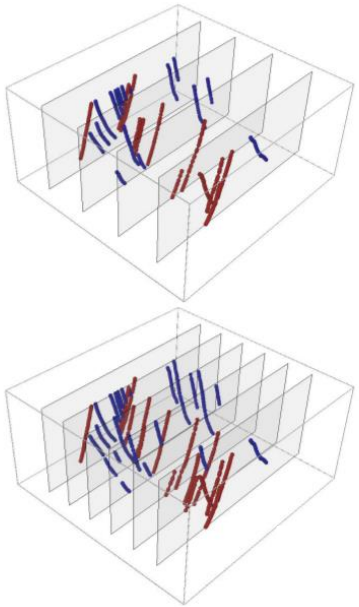
Example: Santos Basin

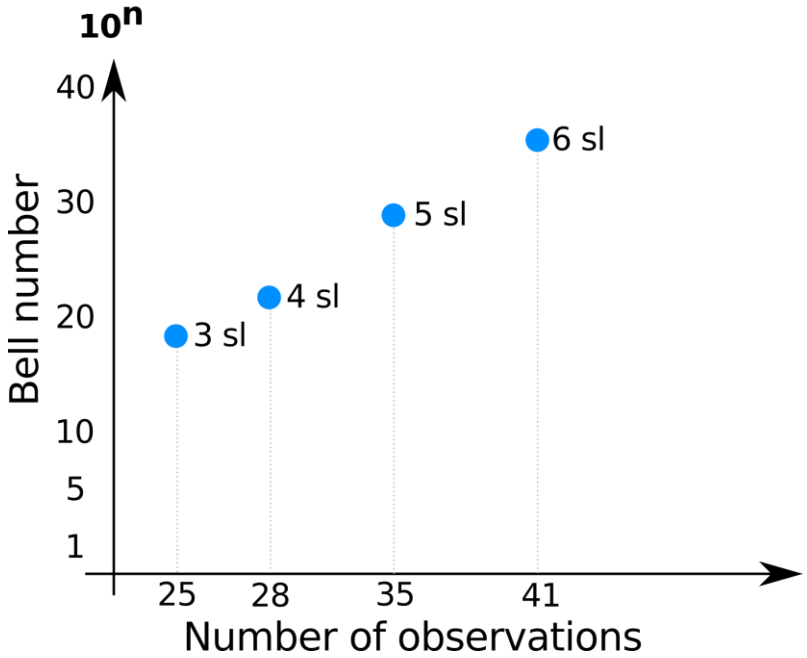
Data: doi:10.17605/OSF.IO/MP97W [Godefroy et al, *submitted*]

Visualization: https://gabrielgodefroy.github.io/StochasticInterpData/README.html



Seismic data courtesy of PGS

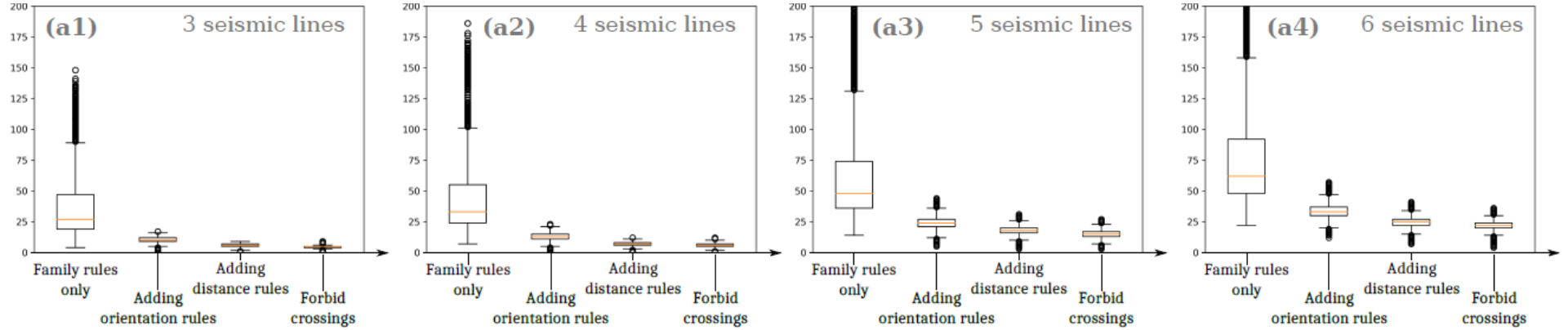




Example: Santos Basin

Data: doi:10.17605/OSF.IO/MP97W [Godefroy et al, *submitted*]

Visualization: https://gabrielgodefroy.github.io/StochasticInterpData/README.html



- SFS is consistent: As more informative rules are used,
  - Average models gets closer to the reference
  - Uncertainty decreases
- Adding data makes the problem harder !

Wrapping up

- Sequential fault sampling
  - Interesting level of abstraction (AI-compatible)
  - Parsimonious
  - Easily extensible to classify realizations
- Simple two-point rules
  - Not objective, but reproducible
  - Need for multiple-point interactions
  - Global a posteriori realism assessment [Caumon, 2010; de la Varga & Wellmann, 2018]
- Philosophical questions
  - Can we harness the curse of dimensionality (visualization, processing)?
  - Can we hope to capture interpretive process in mathematical terms?
  - Ethical use of technology

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