Analysis of enhanced permeability using 4D seismic data and locally refined simulation models

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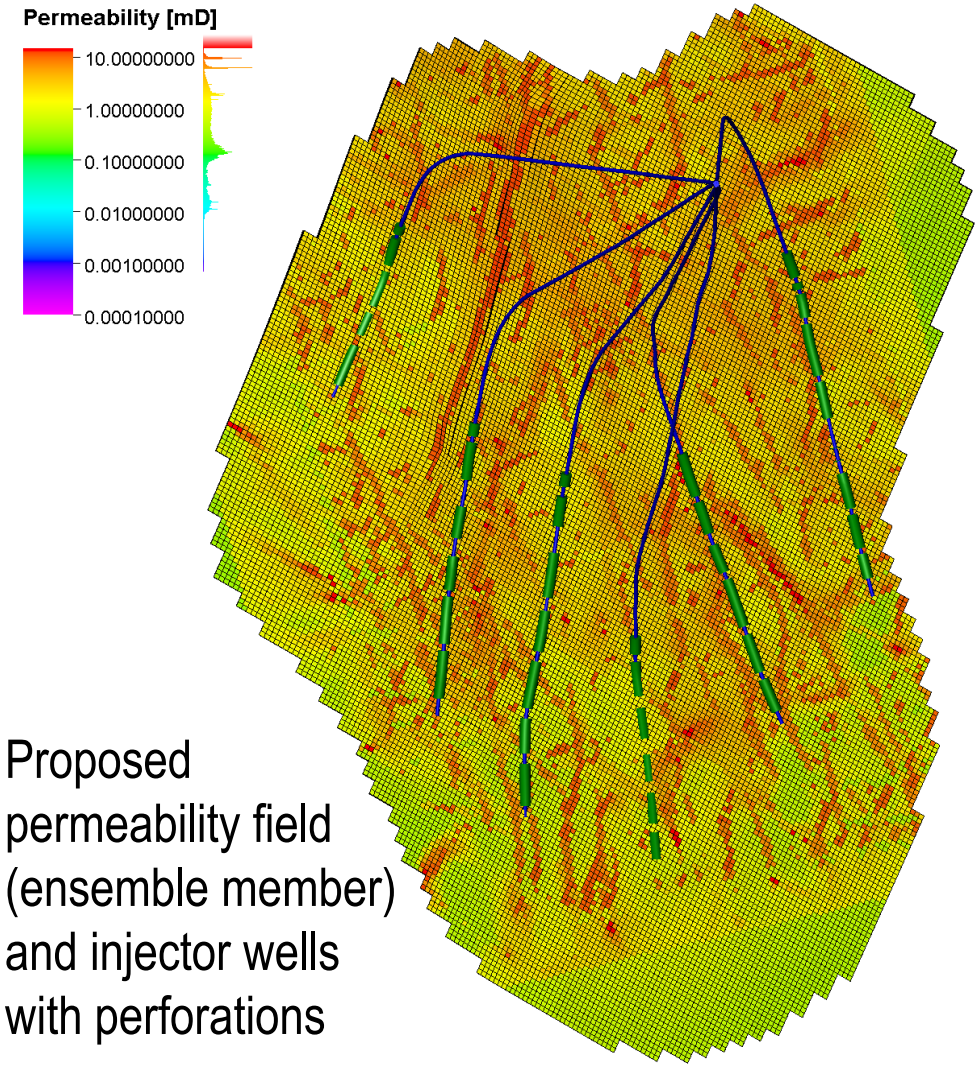
Motivation and objectives

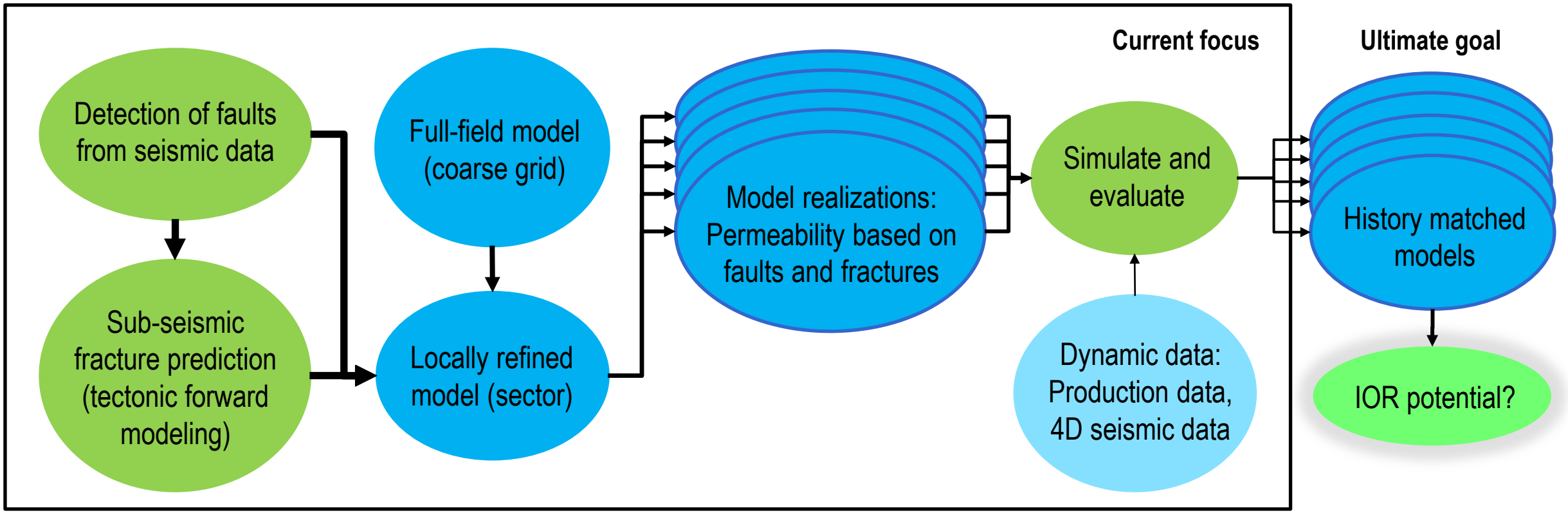


Proposed permeability field (ensemble member) and injector wells with perforations

- For optimal **sweep efficiency**, we need to understand and control zones of enhanced permeability (thief zones)
- Case study: naturally fractured chalk
  - Seismic **fault detection** and sub-seismic **fracture prediction from tectonic modeling** used as input to **locally refined** reservoir simulation model
  - **Ensemble of models** evaluated against production data and 4D seismic data
  - Analysis limited to sector in the south of the field

Key elements in workflow

- **Automation** in seismic interpretation, tectonic modeling and reservoir simulation
- Tight **integration** between seismic data and **locally refined simulation models**
- **Ensemble of models** consistent with detected faults and predicted fractures



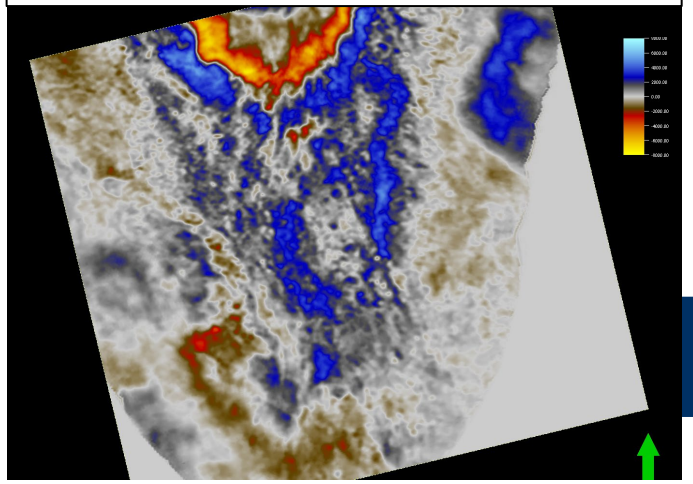
Outline

- **Detection and characterization of faults** from seismic data
- **Fracture prediction** by forward modeling of detected faults, constrained by well data
- **Local grid refinement** to capture fault and fracture characteristics in simulation grid

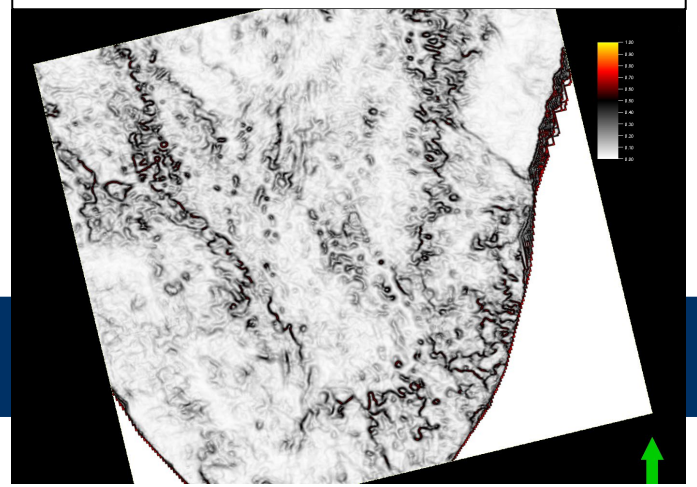
- **Ensemble of models** with different permeability characteristics
- **Production data and 4D seismic data** used to evaluate ensemble members

Automated fault detection workflow – Medium to large scale

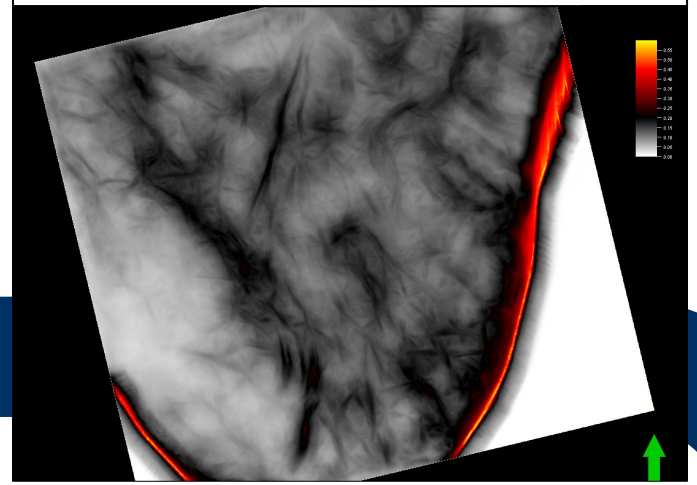
Input [Seismic]



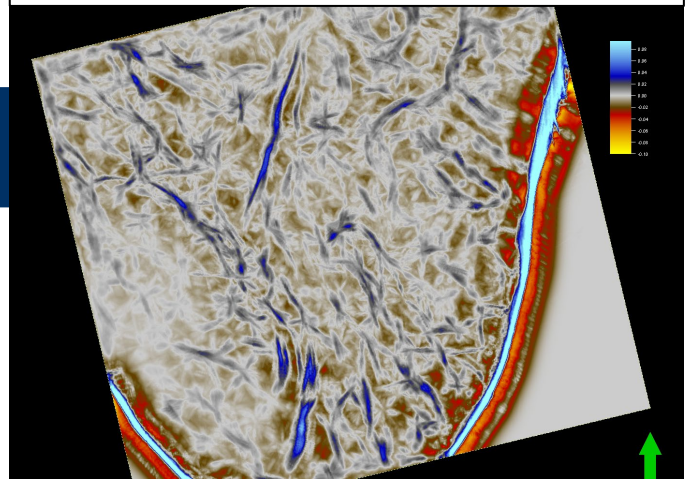
Edge Detection [Amplitude Contrast]



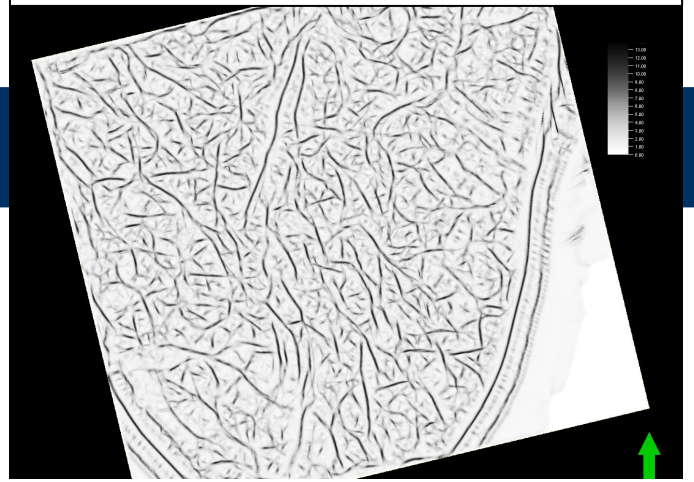
Edge Enhancement I [EOF]



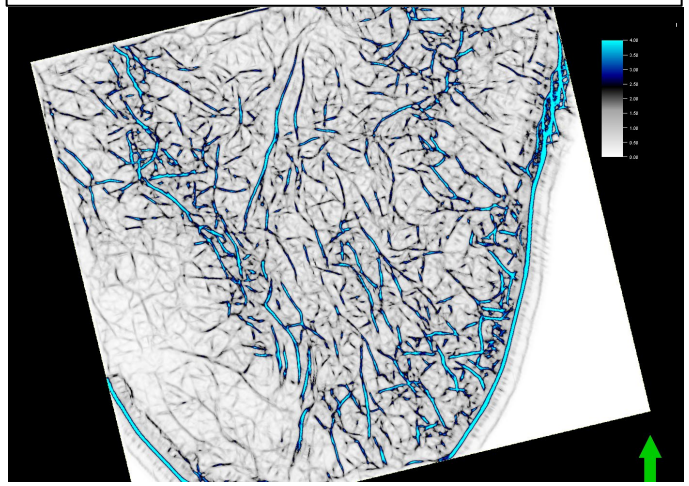
Edge Enhancement II [Pseudo Gauss]



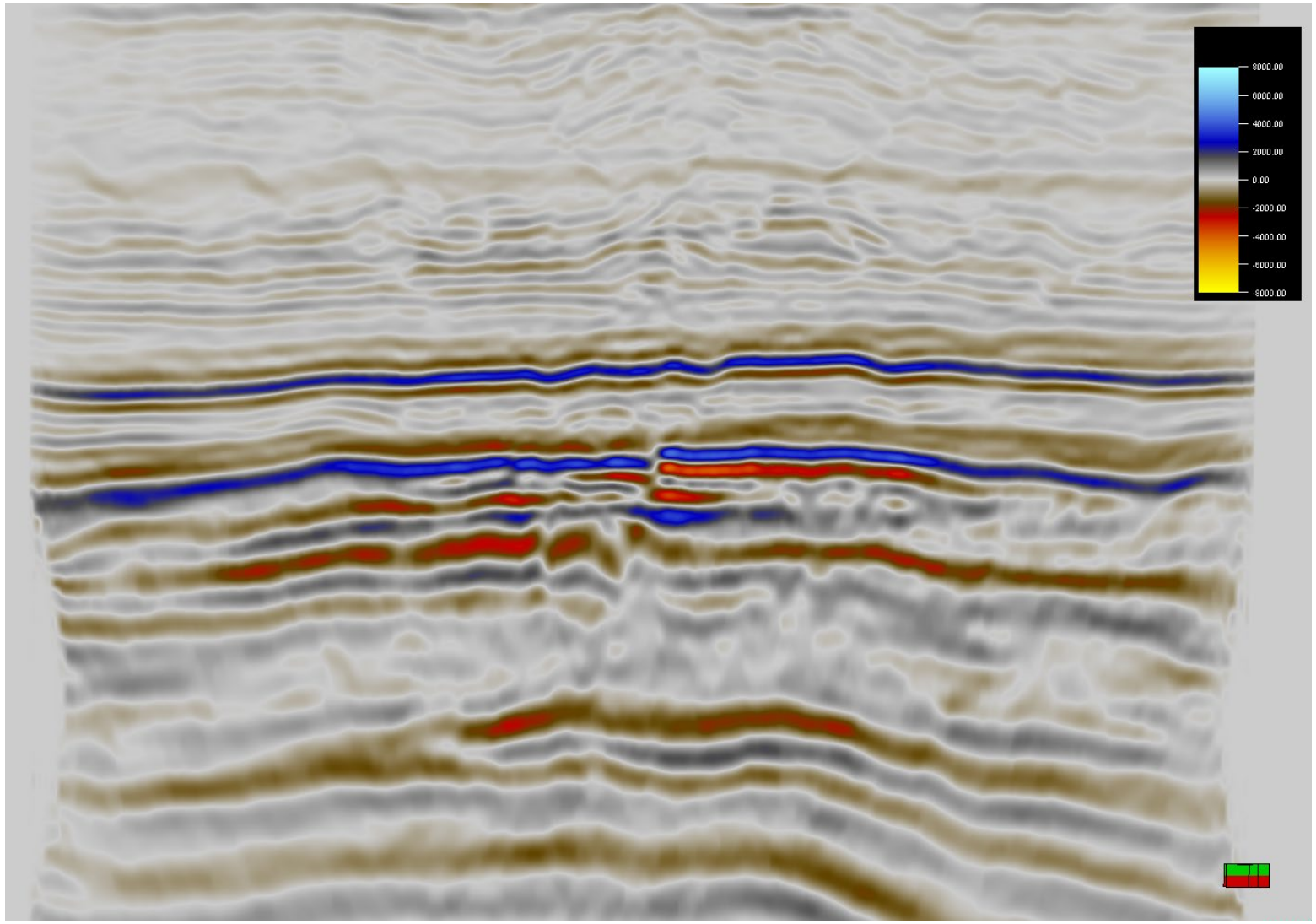
Edge Enhancement III [Edge Evidence]



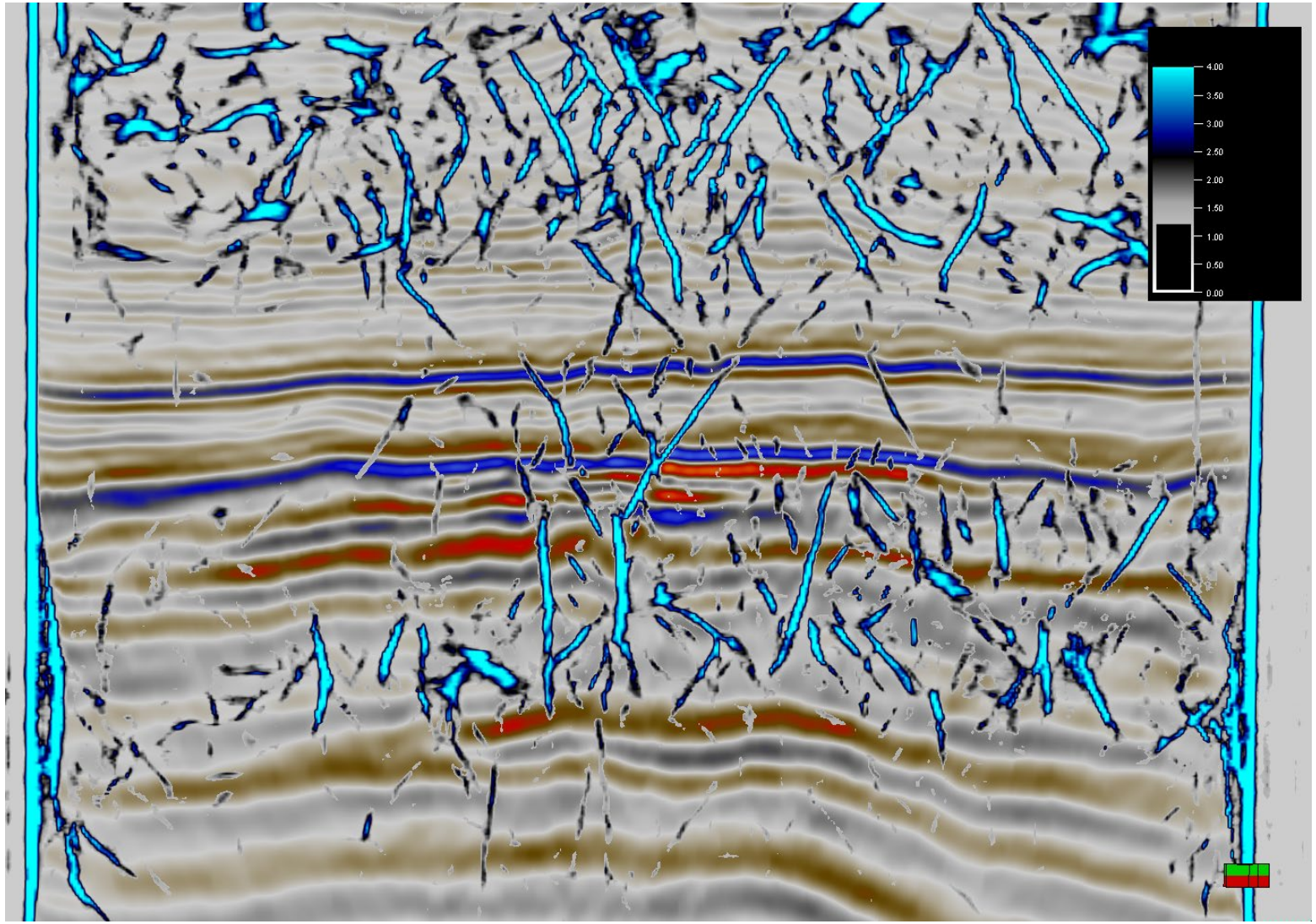
Output [Fault cube]



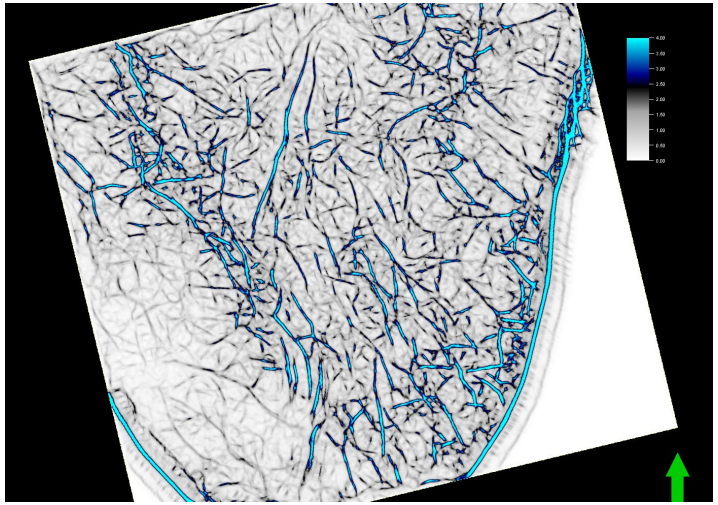
Automated fault detection workflow – Medium to large scale



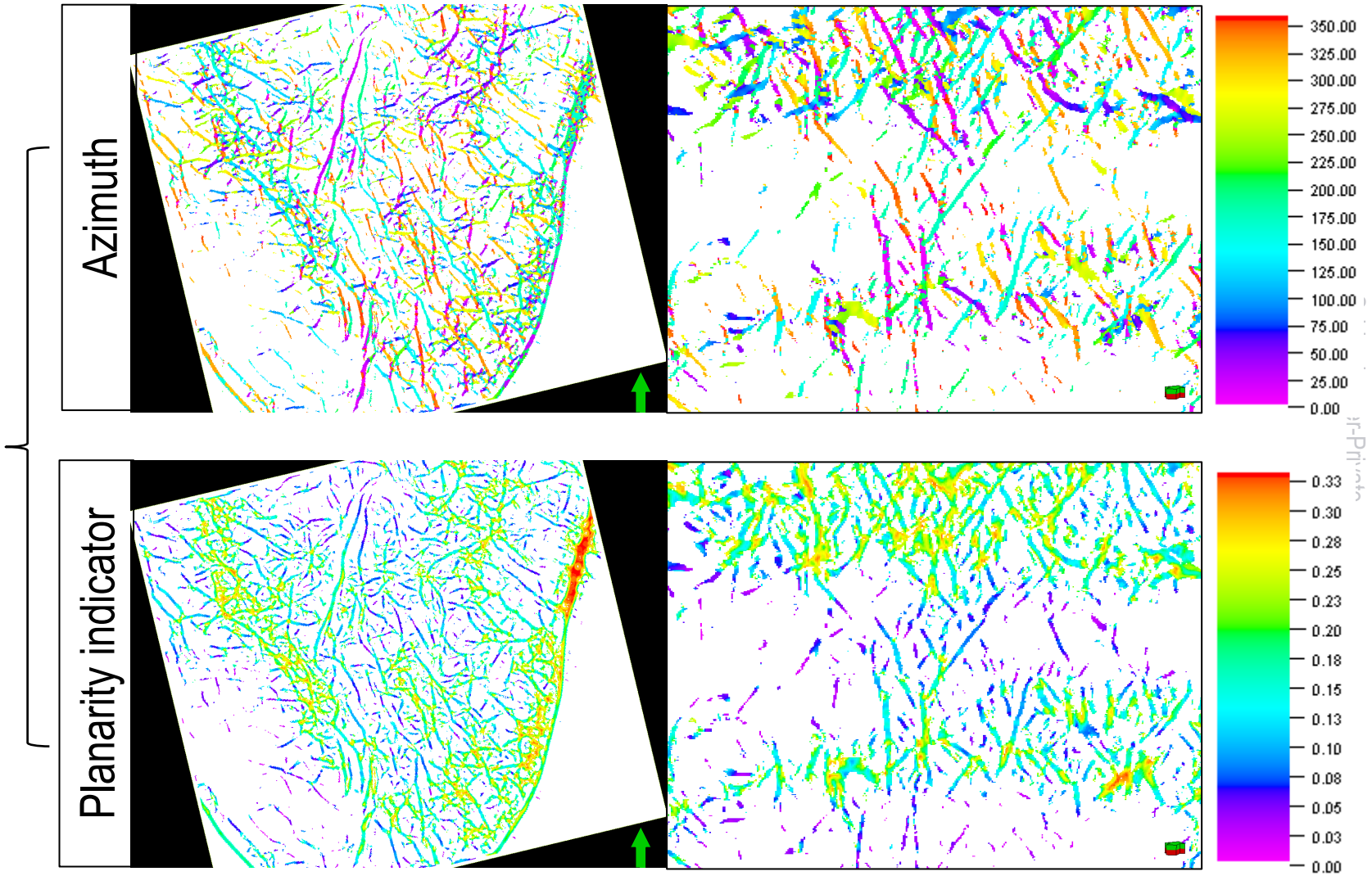
Automated fault detection workflow – Medium to large scale



Structural properties – Azimuth, planarity indicator

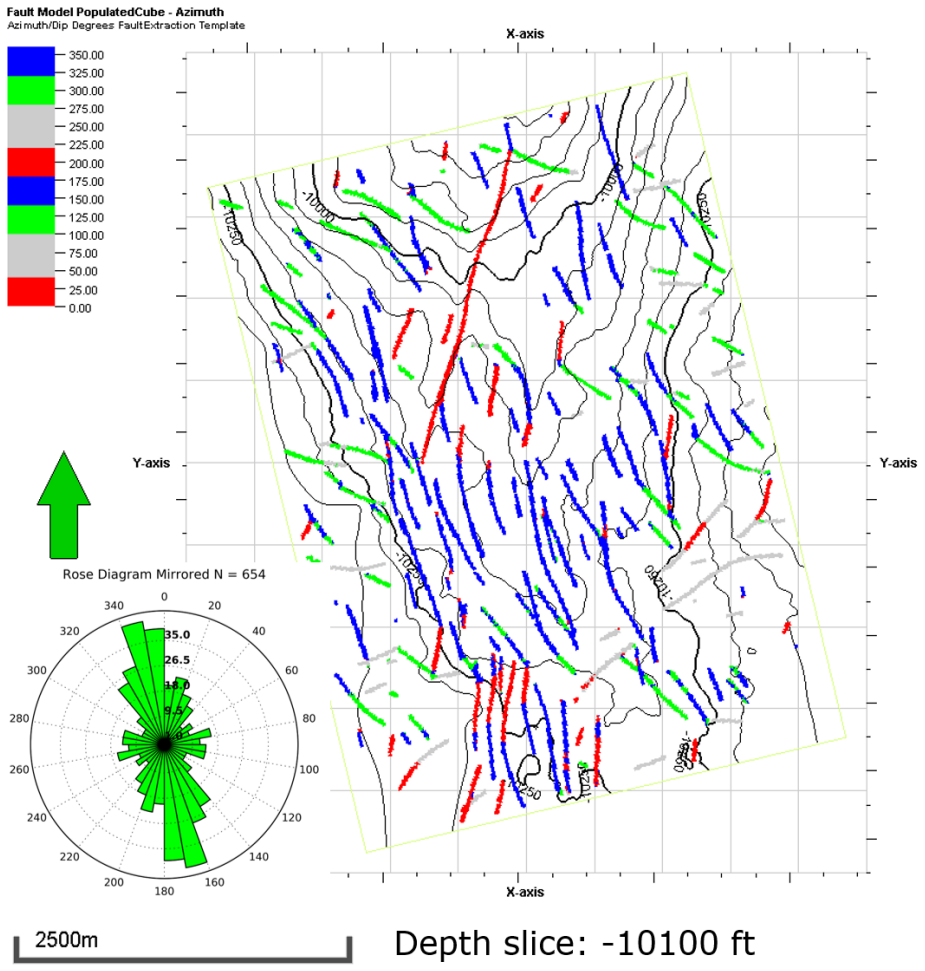


- Input to tectonic modeling
- Basis for permeability parametrization

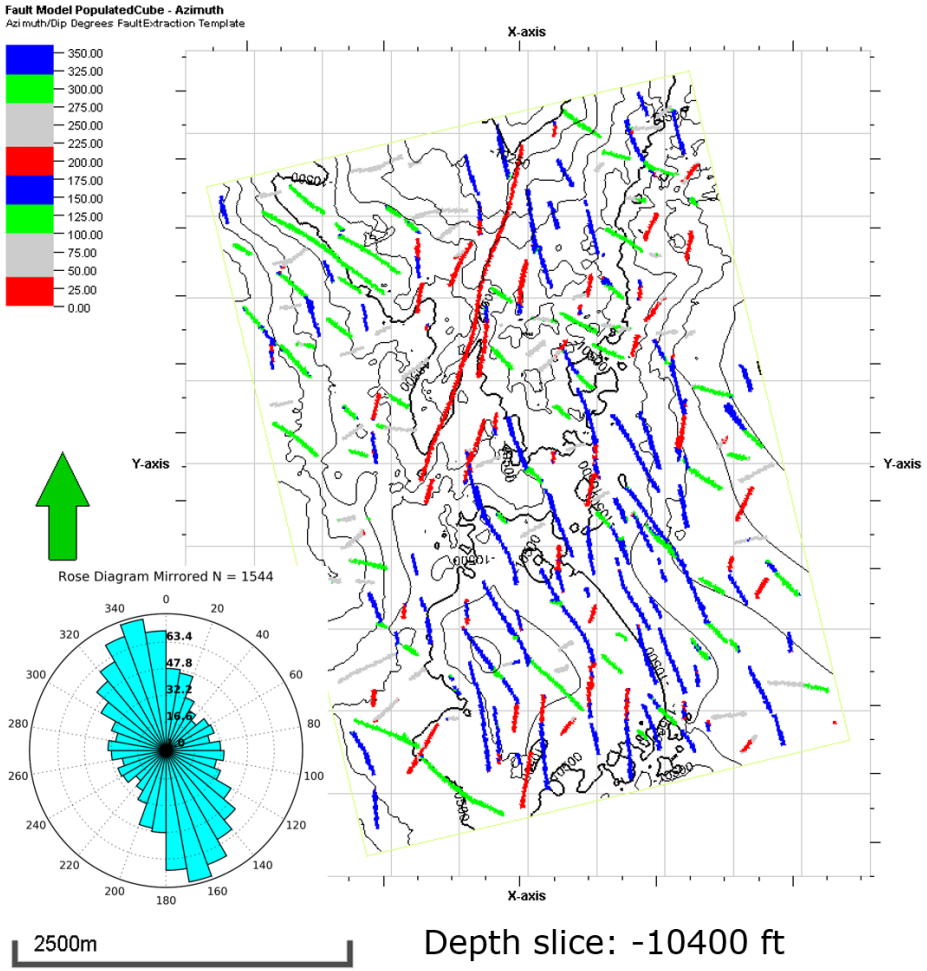


Tectonic forward modeling to predict sub-seismic fractures

4 fault groups considered, based on tectonic history and well observations. Minor faults excluded.



Depth slice: -10100 ft



Depth slice: -10400 ft

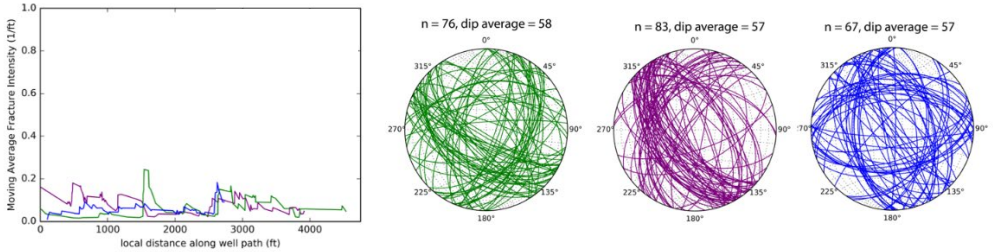
Number of faults: 2198

- WNW – ESE
- NNW – SSE
- ENE – WSW
- NNE – SSW

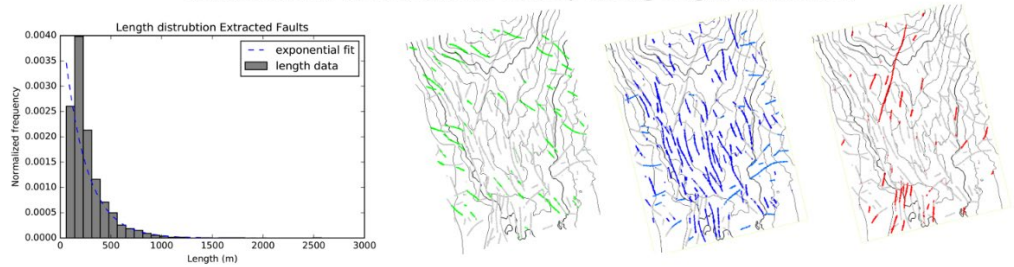
Input and output data

NFP Modelling workflow (Input Data)

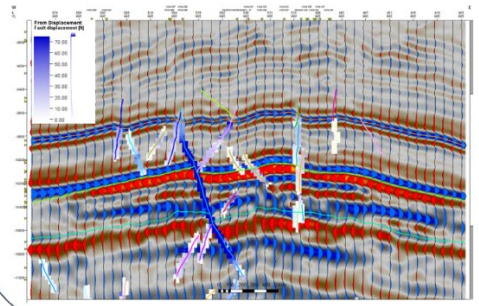
Statistical Fracture/Fault data from wells (used for calibration)



Extracted fault model and the corresponding length distribution



Tectonic Stress (calibrated by faults and fault displacement)



$$\frac{\sigma_z}{\sigma_z} = 1.0$$

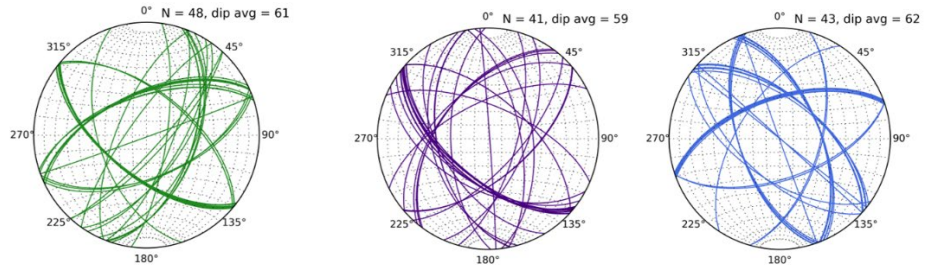
$$\frac{\sigma_H}{\sigma_z} = 0.667$$

$$\frac{\sigma_h}{\sigma_z} = 0.334$$

$\sigma_{H\,tect1} = 130°$
$\sigma_{H\,tect2.1} = 160°$
$\sigma_{H\,tect2.2} = 70°$
$\sigma_{H\,tect3} = 200°$

NFP Modelling workflow (Output)

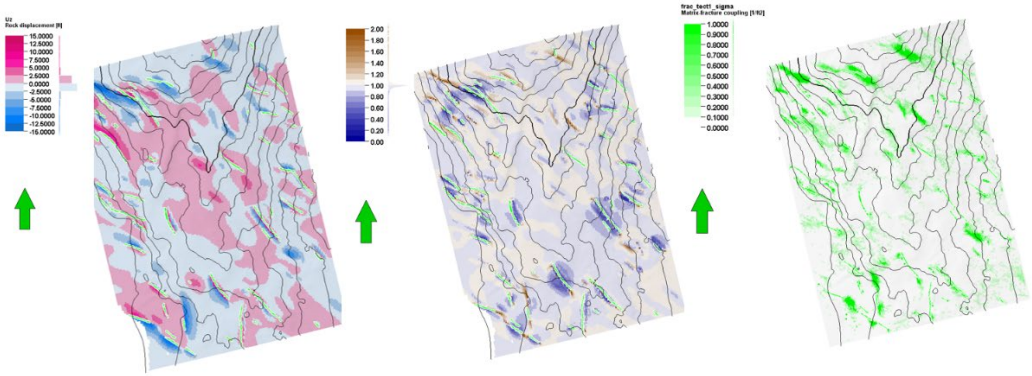
1) Modelled Fractures for each implemented well



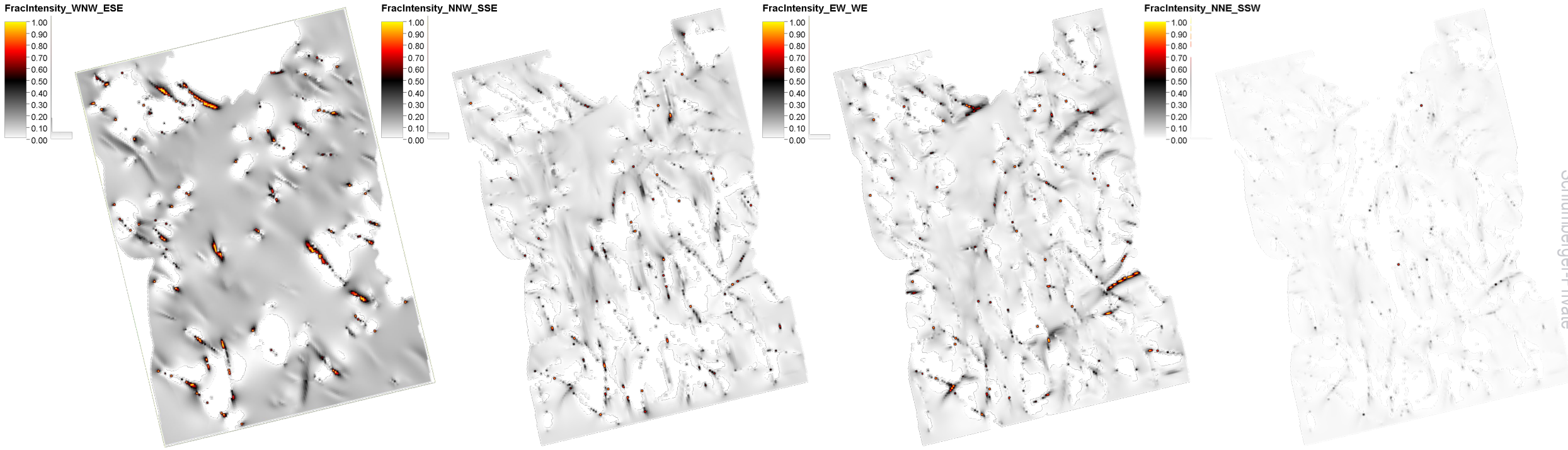
2) Local rock displacement

3) Normalized differential stress

4) Local Fracture Intensity



Output: Fracture intensities associated with each event (3D grids)



WNW – ESE

NNW – SSE

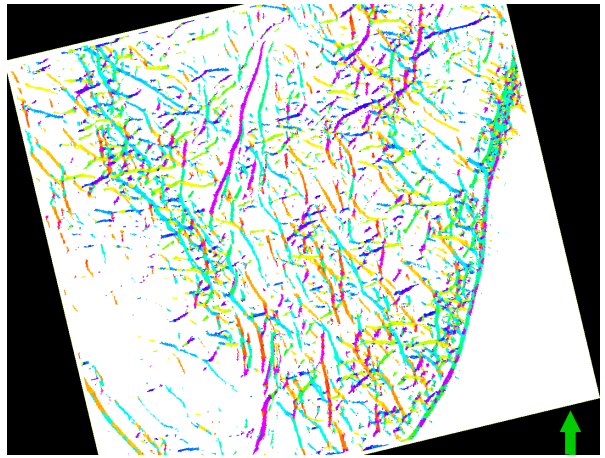
ENE – WSW

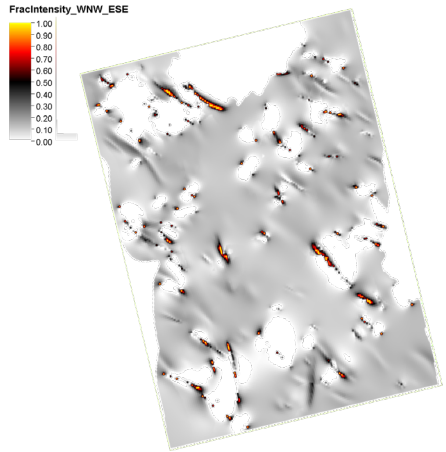
NNE – SSW

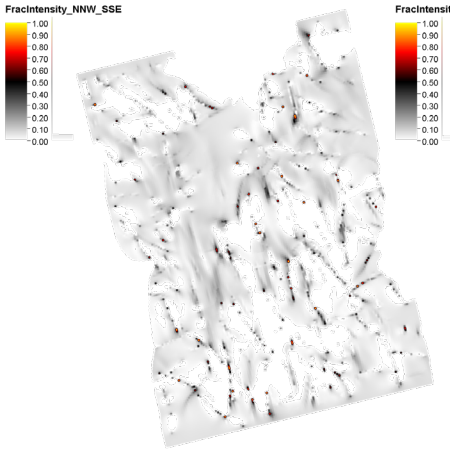
Fracture intensities constrained by well data. Directions parallel to well trajectory tend to be underestimated.

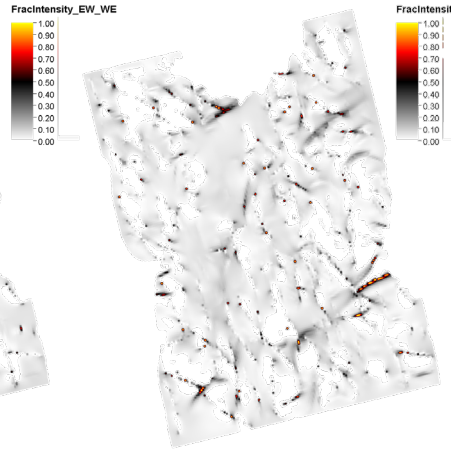
Integrating faults and fractures in reservoir simulation model

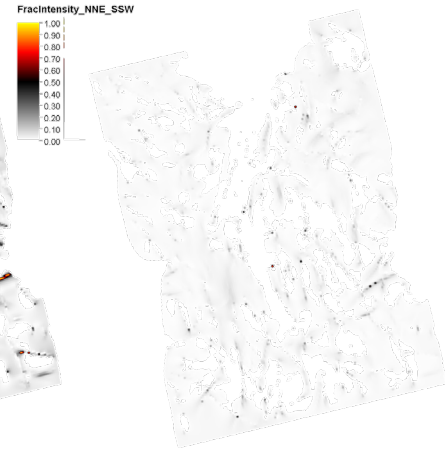
- Model repository
  - Fault groups with azimuth and planarity
  - Fracture intensity for each group
  - 3D properties at seismic grid resolution, 12.5 m x 12.5 m
- Full-field simulation model has grid dimensions of ~ 100 m x 100 m
- Refinement / upscaling needed





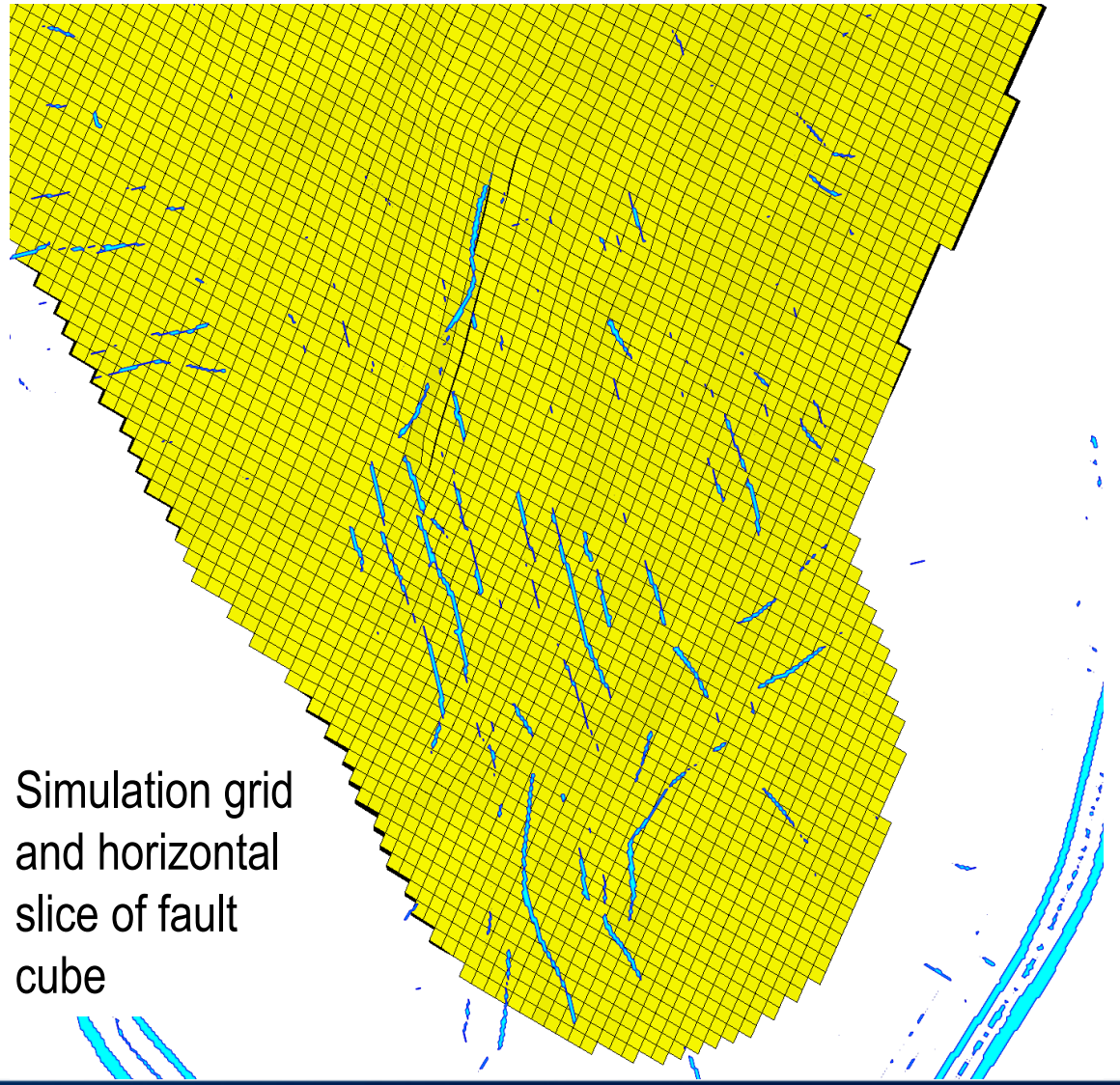






Refinement / upscaling

- Objectives:
  - Discretize faults – preserve connectivity
  - Keep simulation run time acceptable
- Current solution:
  - Refinement of **sector** of full-field model, refined grid dimensions around 25 m
  - Relative permeability curves still include mix of matrix and fracture characteristics



Simulation grid and horizontal slice of fault cube

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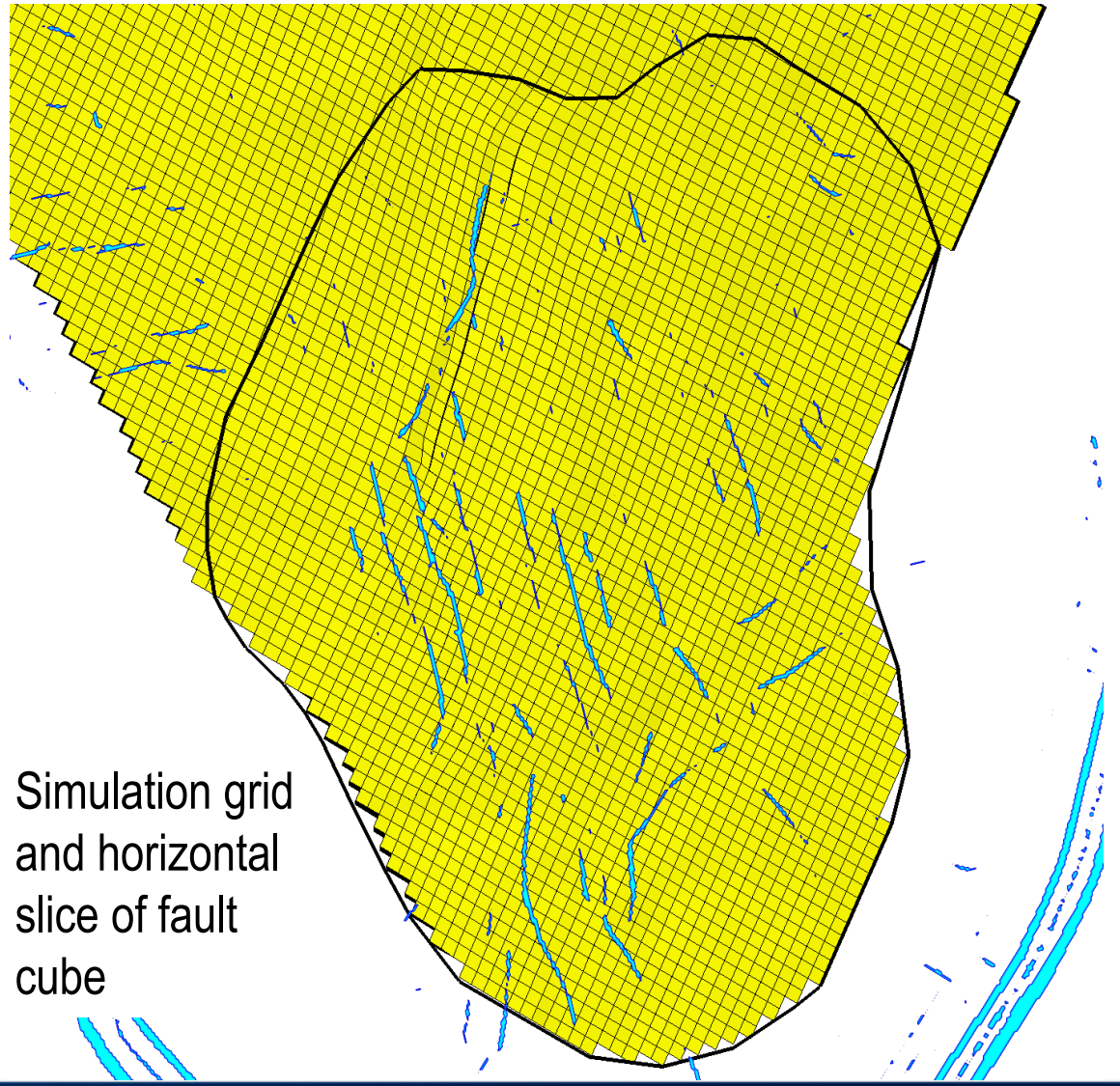

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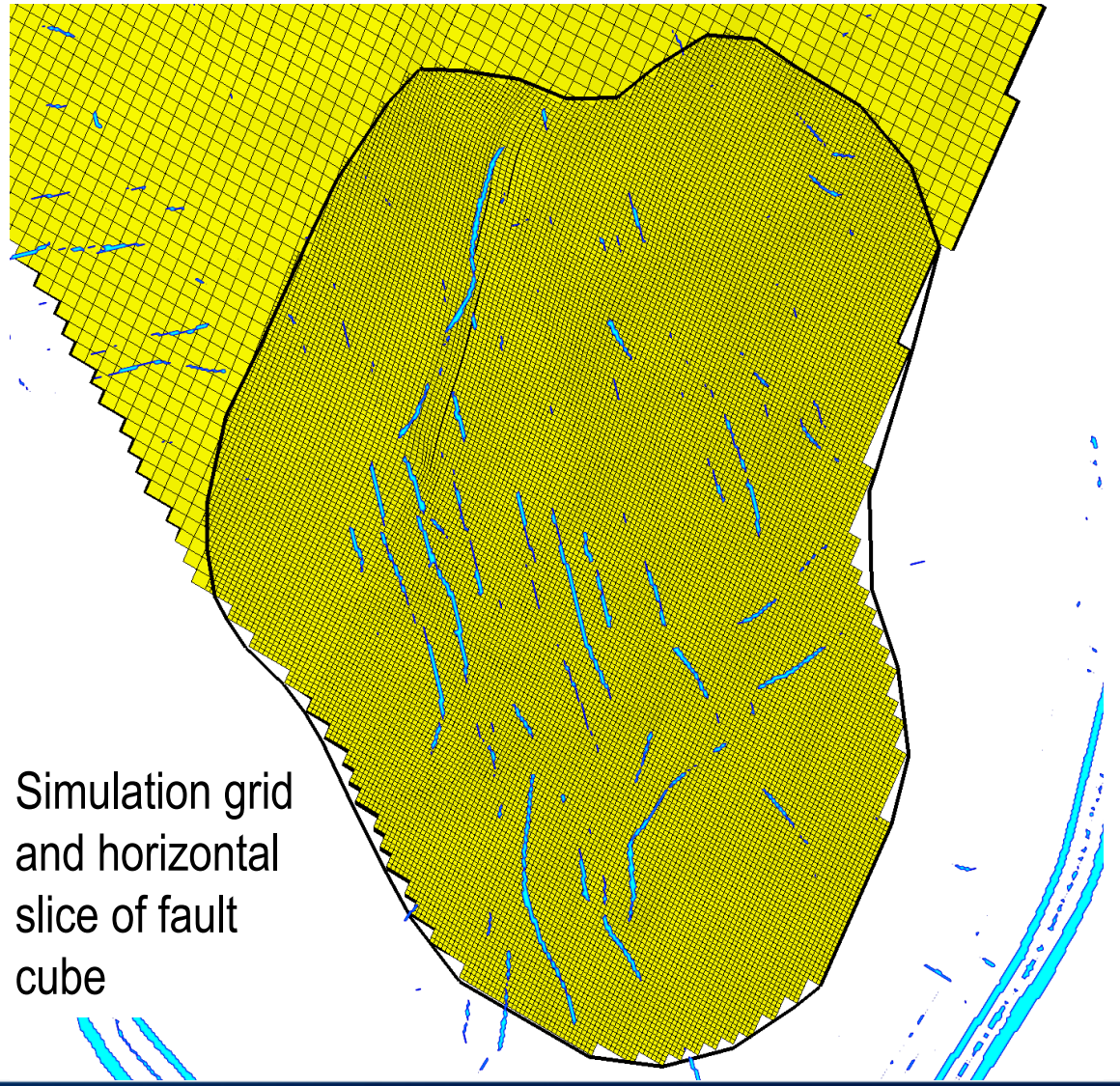
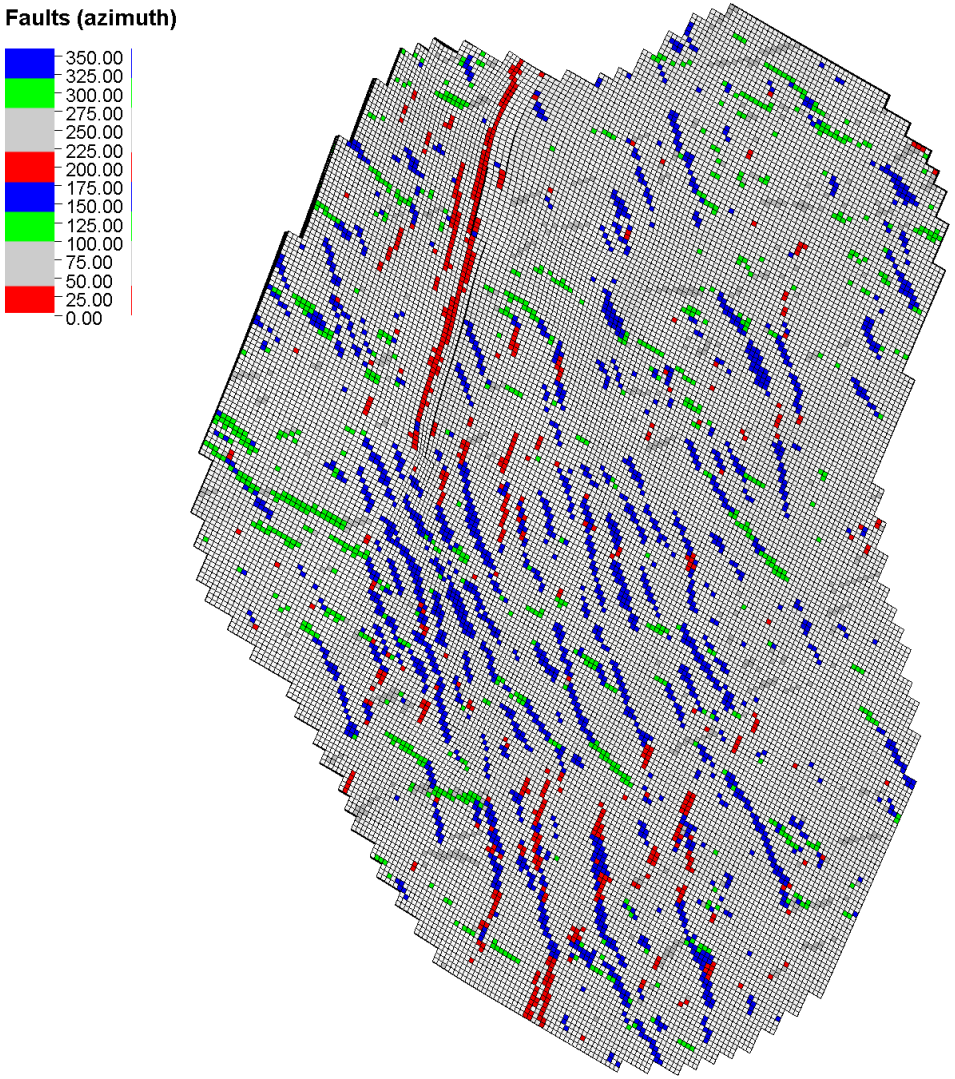
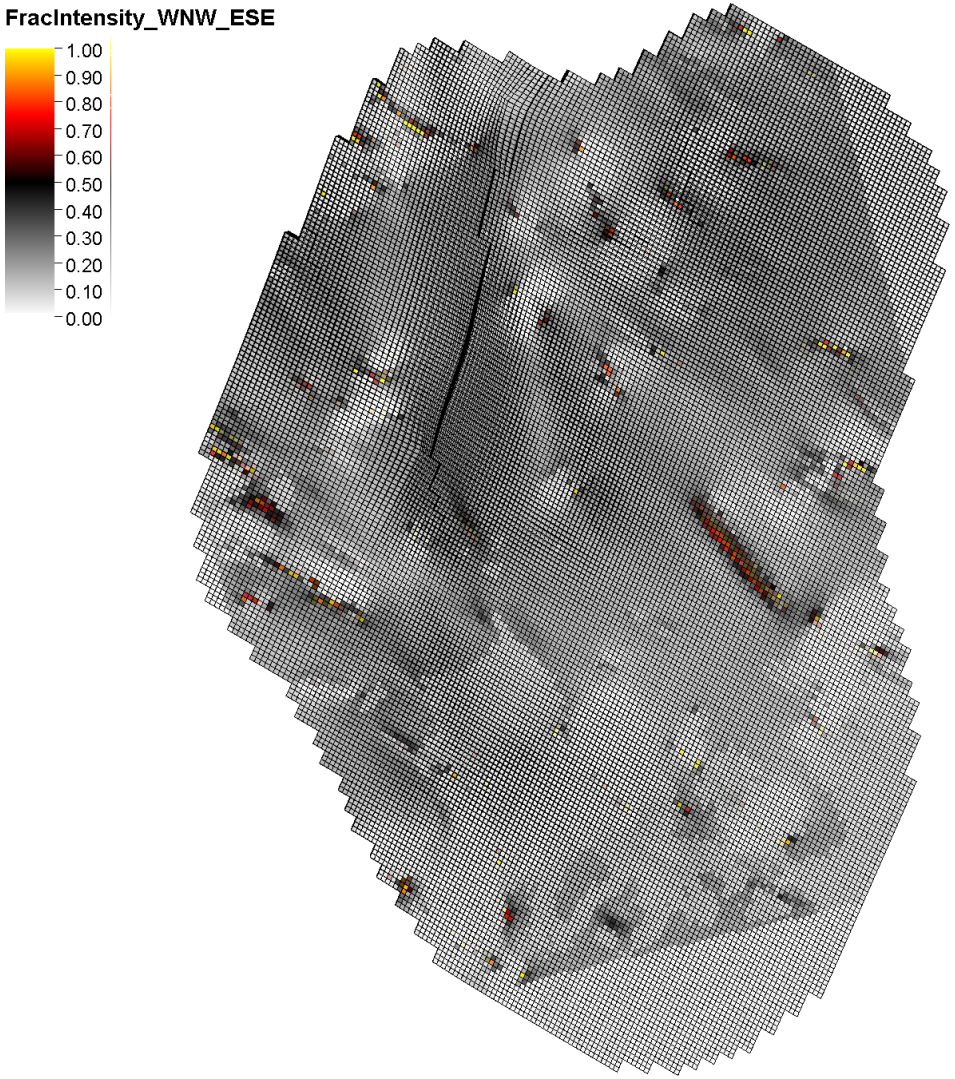


Simulation grid and horizontal slice of fault cube

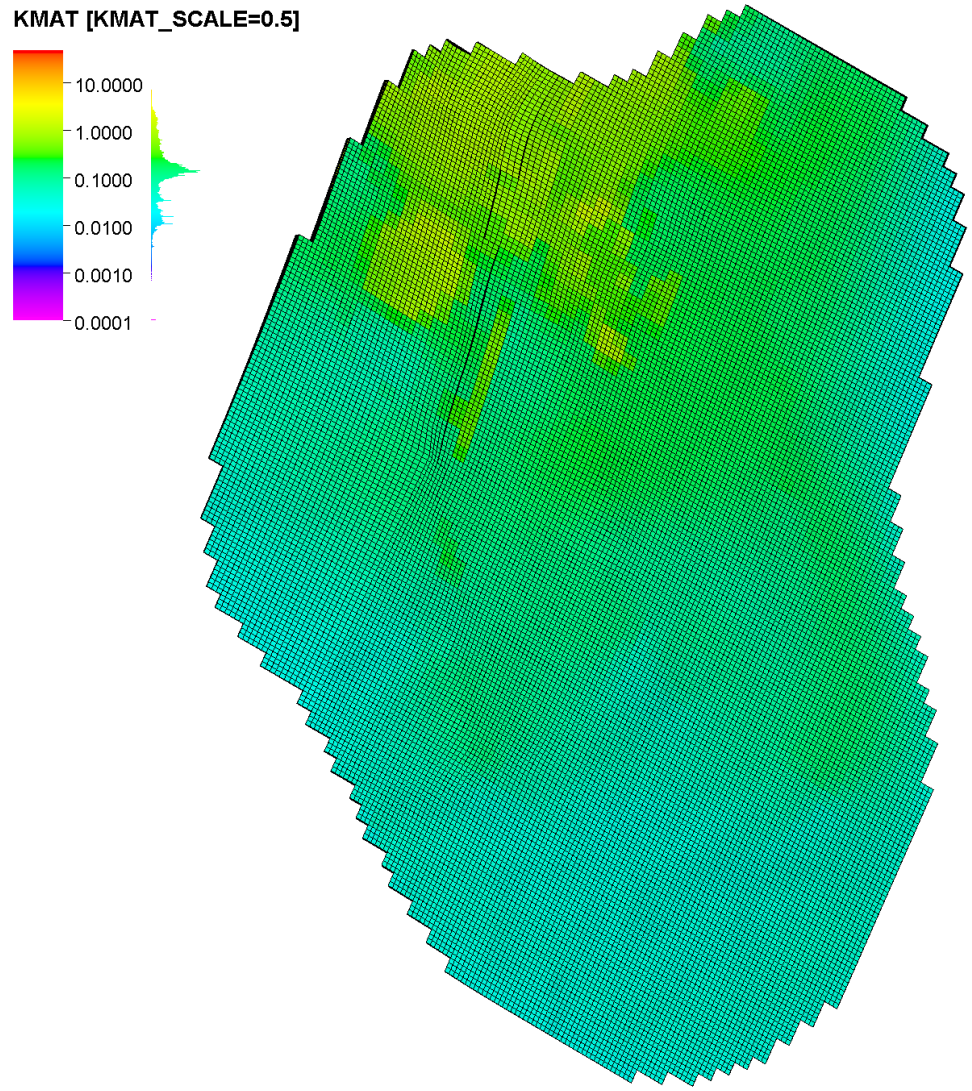
Fault groups and fracture intensities mapped into refined grid





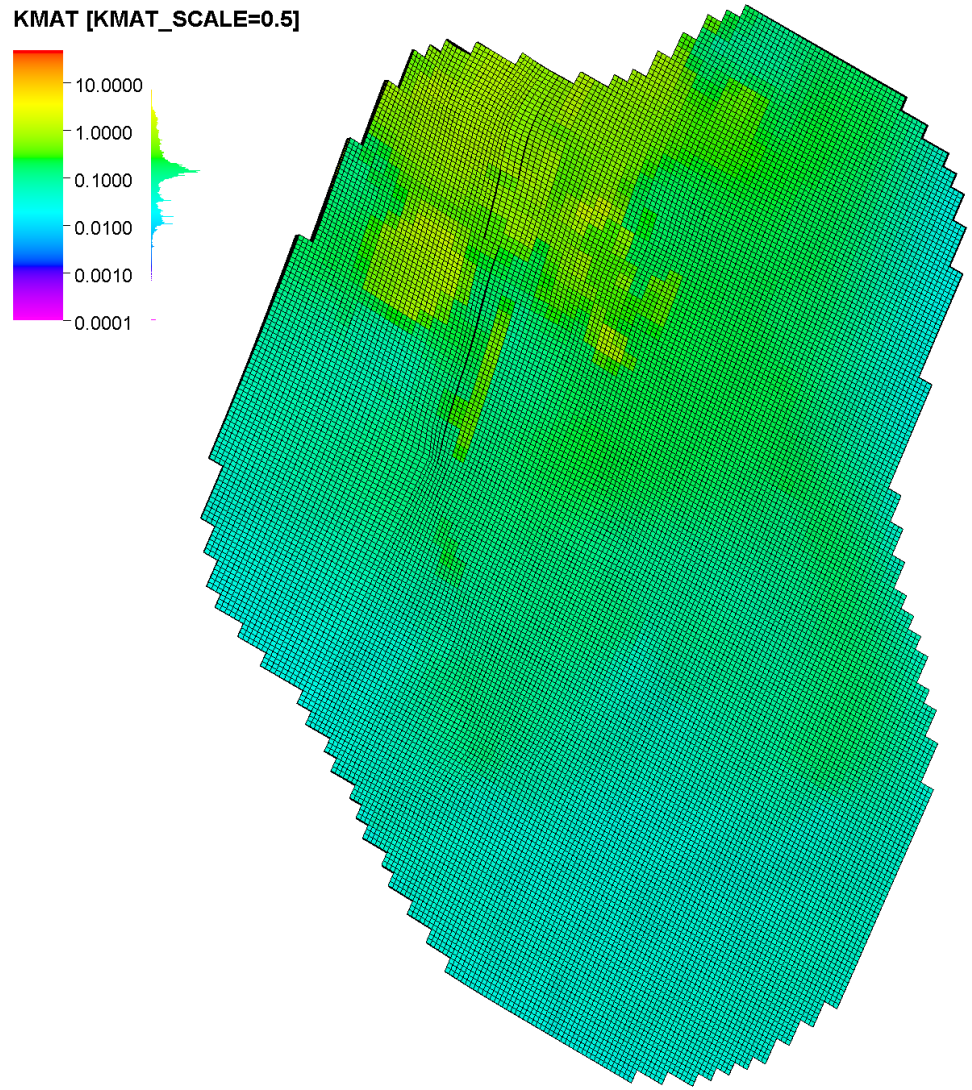
Permeability parametrization – Combining matrix, faults and fractures

- Matrix permeability (porosity correlation)
  - Scaling factor <KMAT_SCALE>



Permeability parametrization – Combining matrix, faults and fractures

- Matrix permeability (porosity correlation)
  - Scaling factor <KMAT_SCALE>
- Fault permeability – per group
  - WNW-ESE, NNW-SSE, ENE-WSW, NNE-SSW
  - Permeability: <KG1>, <KG2>, <KG3>, <KG4>



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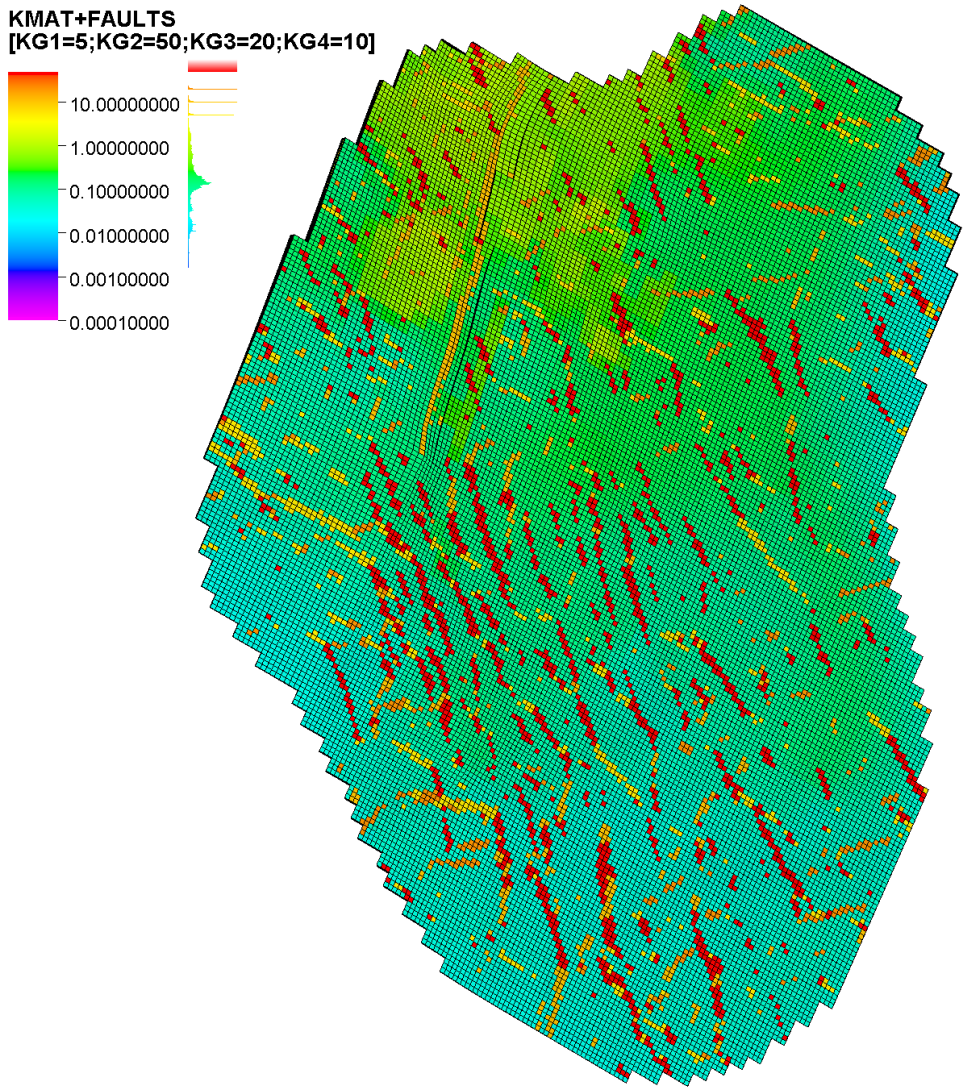

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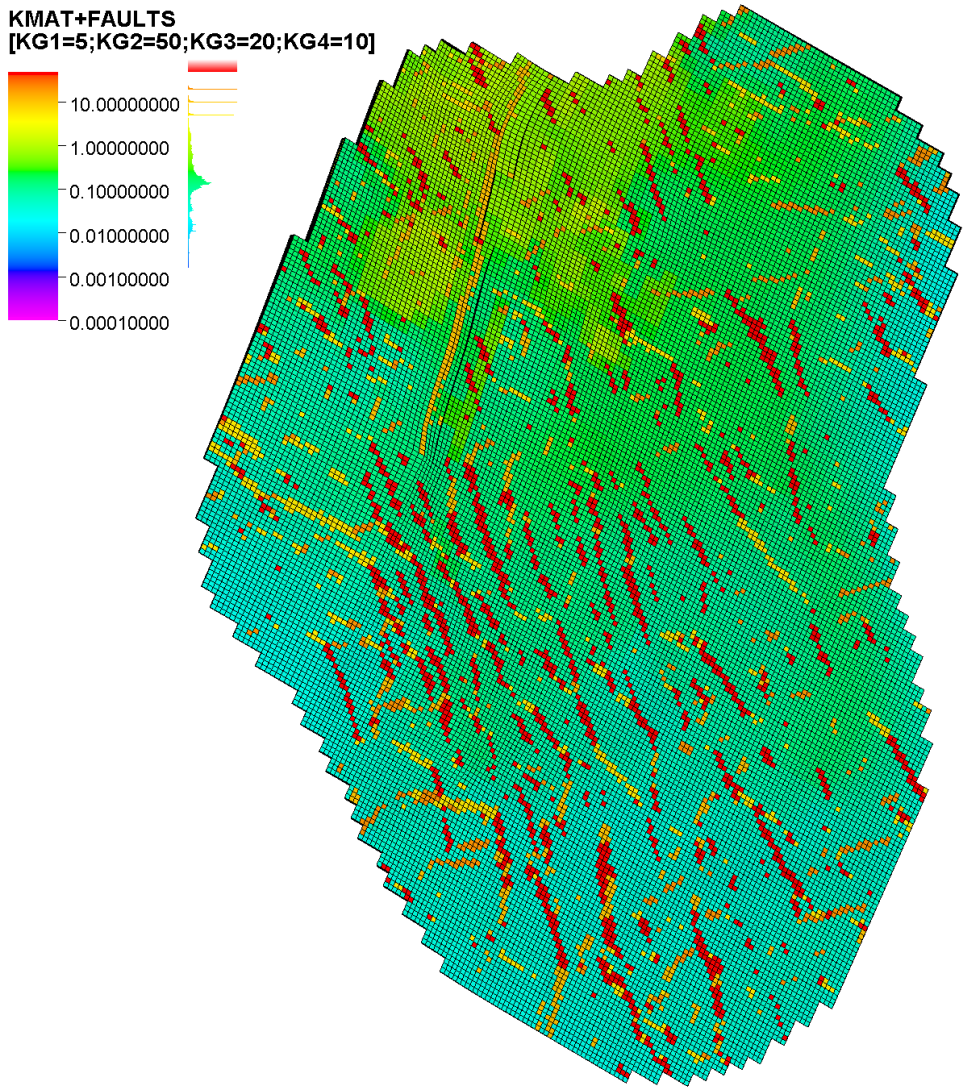
  - WNW-ESE, NNW-SSE, ENE-WSW, NNE-SSW
  - Permeability: <KG1>, <KG2>, <KG3>, <KG4>
- Fracture permeability – per group
  - Fracture intensities mapped to (0,<KG1>), (0,<KG2>), (0,<KG3>), (0,<KG4>)
  - Mapping options: linear, quadratic, cubic
  - All contributions added to effective permeability



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- Fault permeability – per group
  - WNW-ESE, NNW-SSE, ENE-WSW, NNE-SSW
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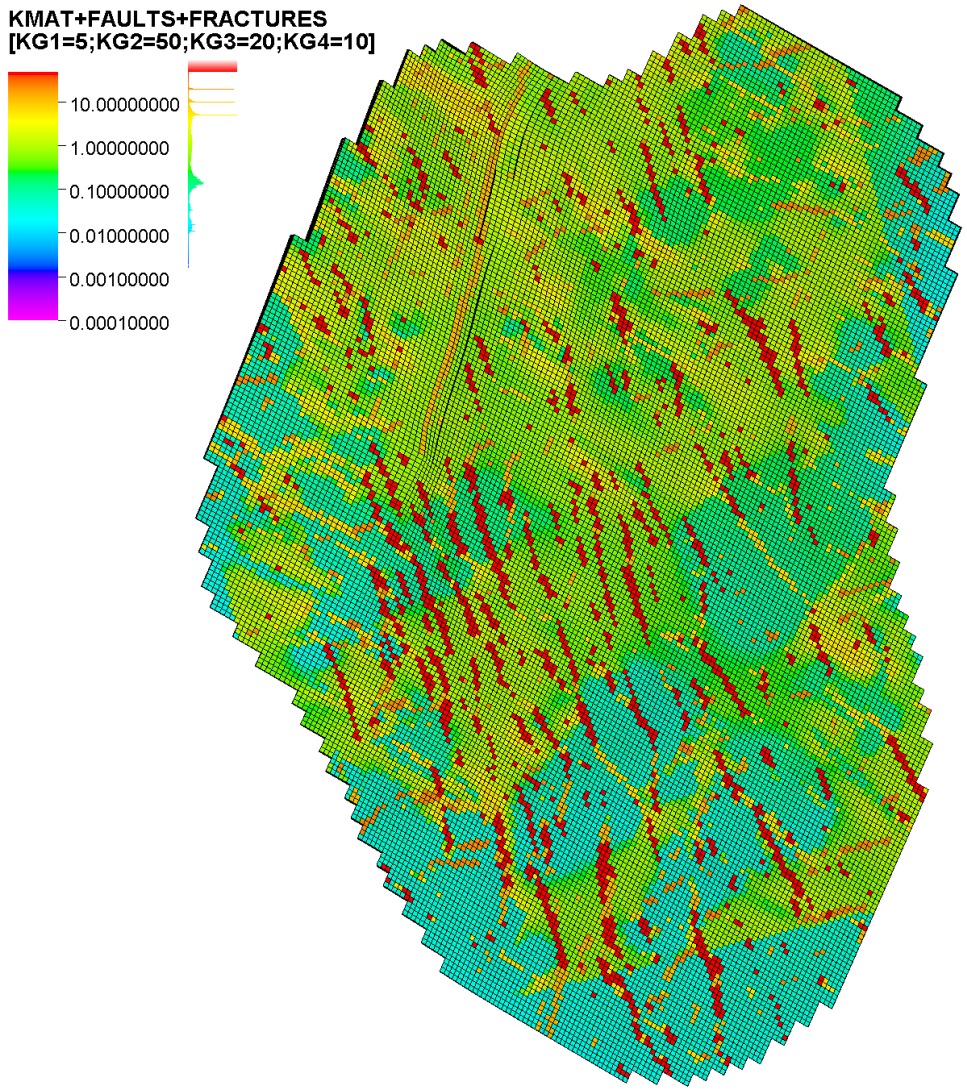
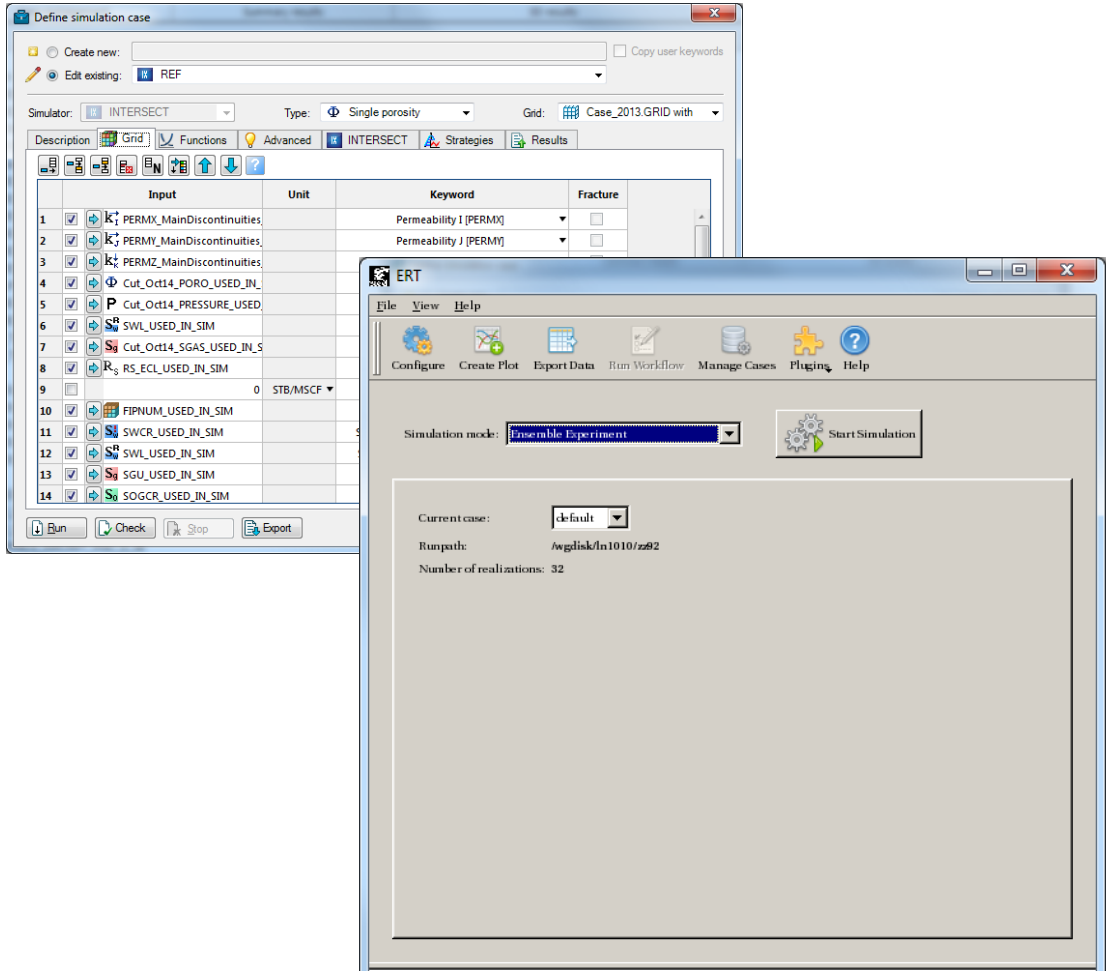
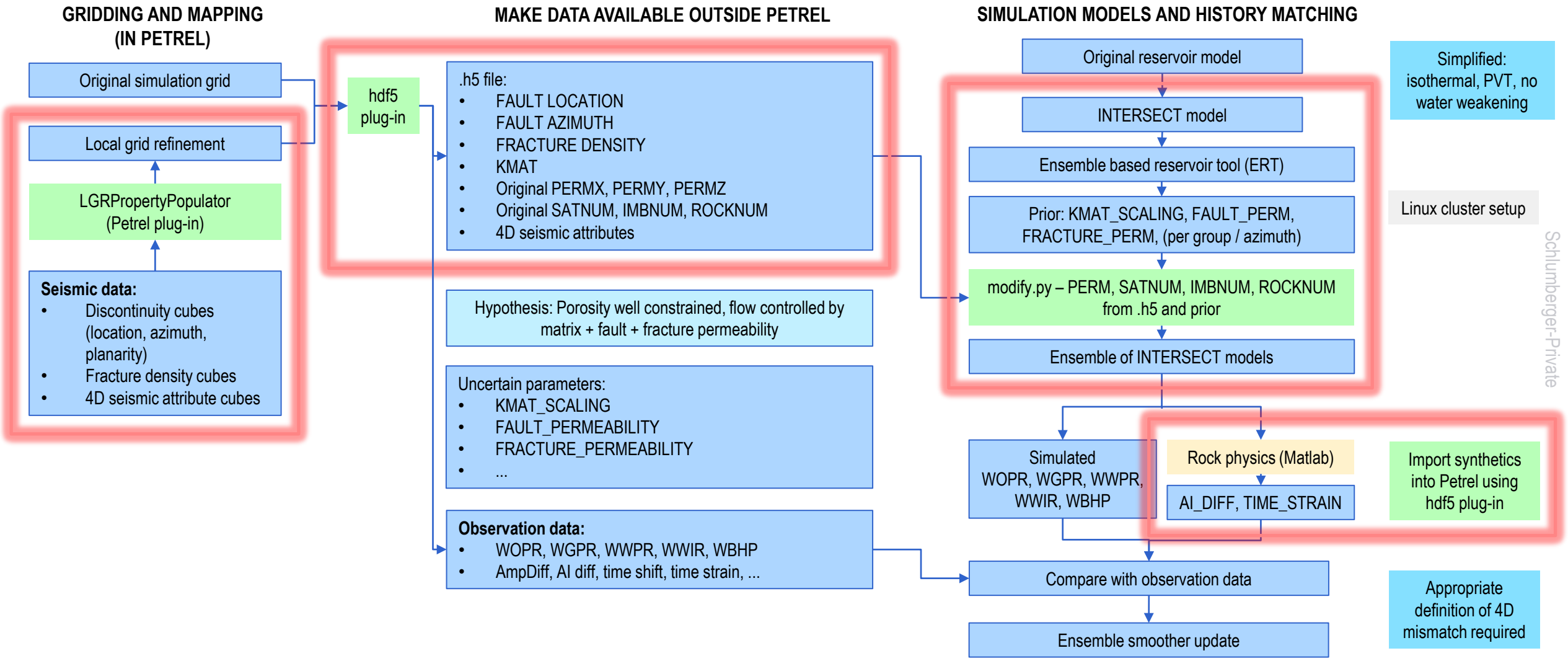


Ensemble experiment – Setup

- Base case: modified from original model
  - INTERSECT isothermal, black-oil
  - Compaction by depletion only (no water weakening)
  - Full-field model + local grid refinement
    - Original coarse grid 436480 cells + 847745 local grid cells
  - Ensemble of models for sector only
- Ensemble based reservoir tool (ERT)
  - Open source, Statoil / Norwegian Computing Centre
- Initial ensemble:
  - <KMAT_SCALE> UNIFORM 0.5 1.5 (unit-less)
  - <KG1> UNIFORM 0 50 (mD)
  - <KG2> UNIFORM 0 50 (mD)
  - <KG3> UNIFORM 0 50 (mD)
  - <KG4> UNIFORM 0 50 (mD)

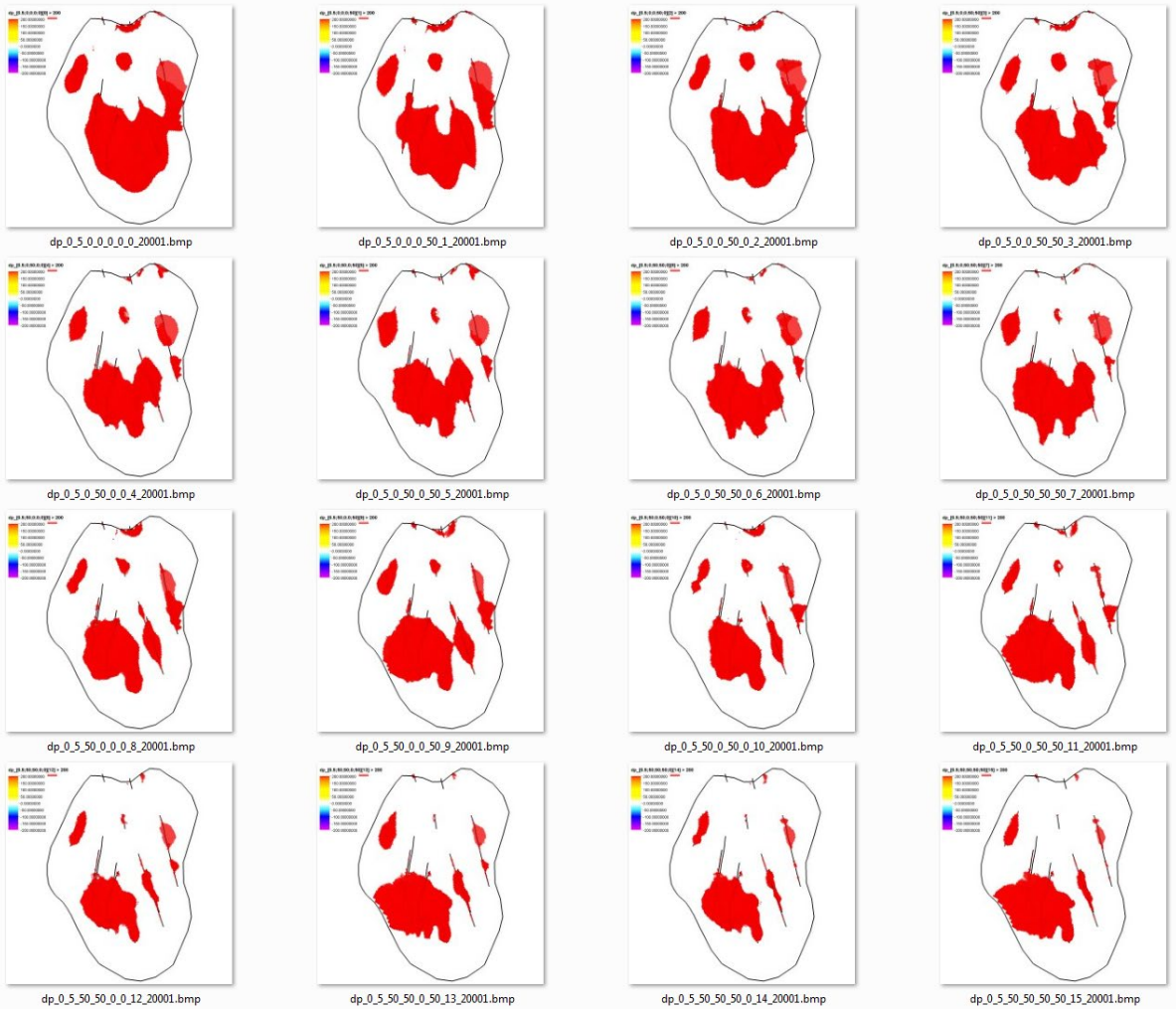


Ensemble experiment – Automation



Ensemble experiment – Automation

- Realizations generated automatically from prior and posterior distributions of <KG1>, <KG2>, <KG3>, <KG4>, <KMAT_SCALE>
- Simulations run in parallel (cluster)
- Processing of simulation results
  - Extract relevant time lapse changes
  - Run rock physics script
- Bitmaps of simulation results

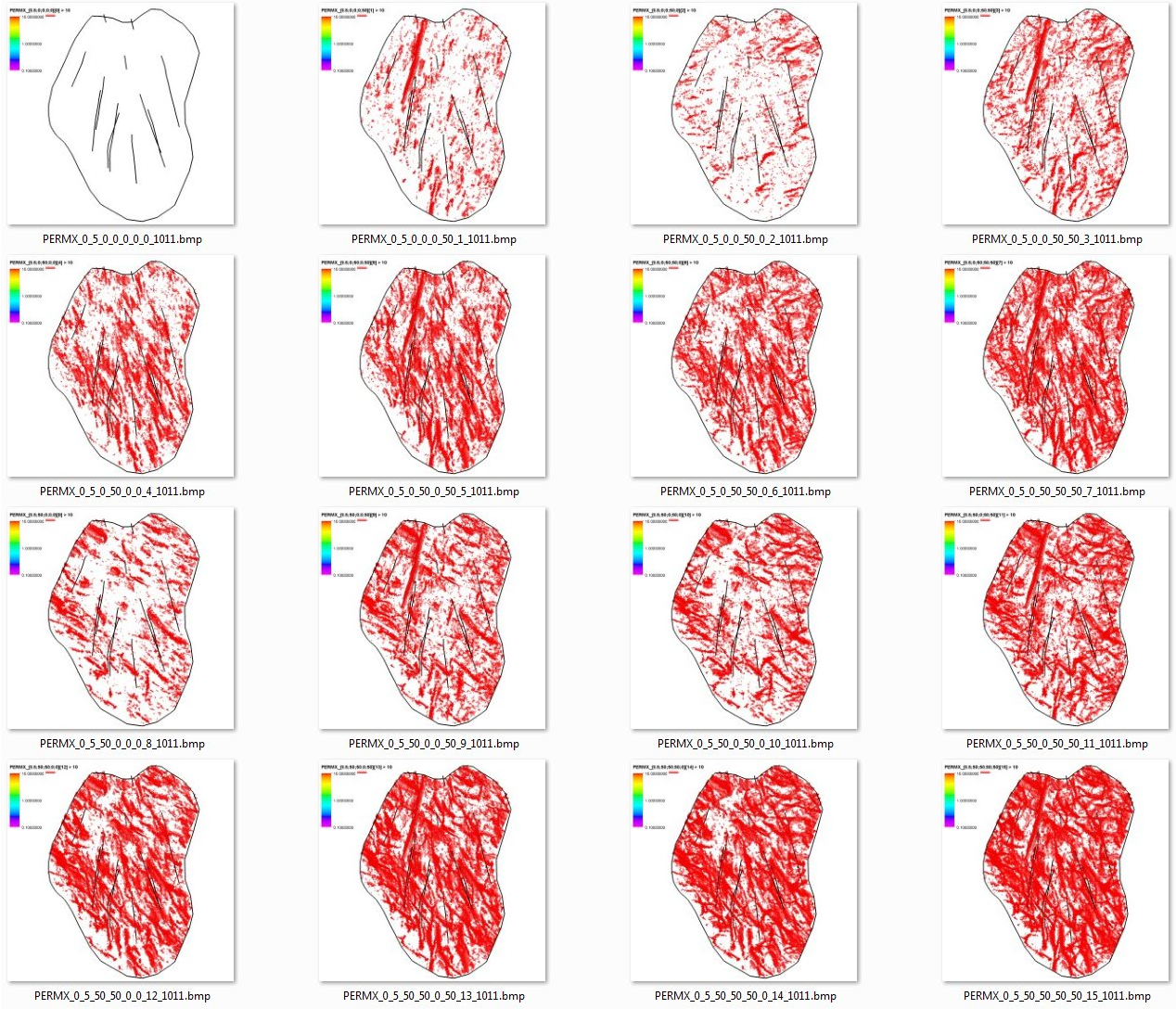


Simulation results exported as bitmaps (here: pressure fronts)

Example: Ensemble end members

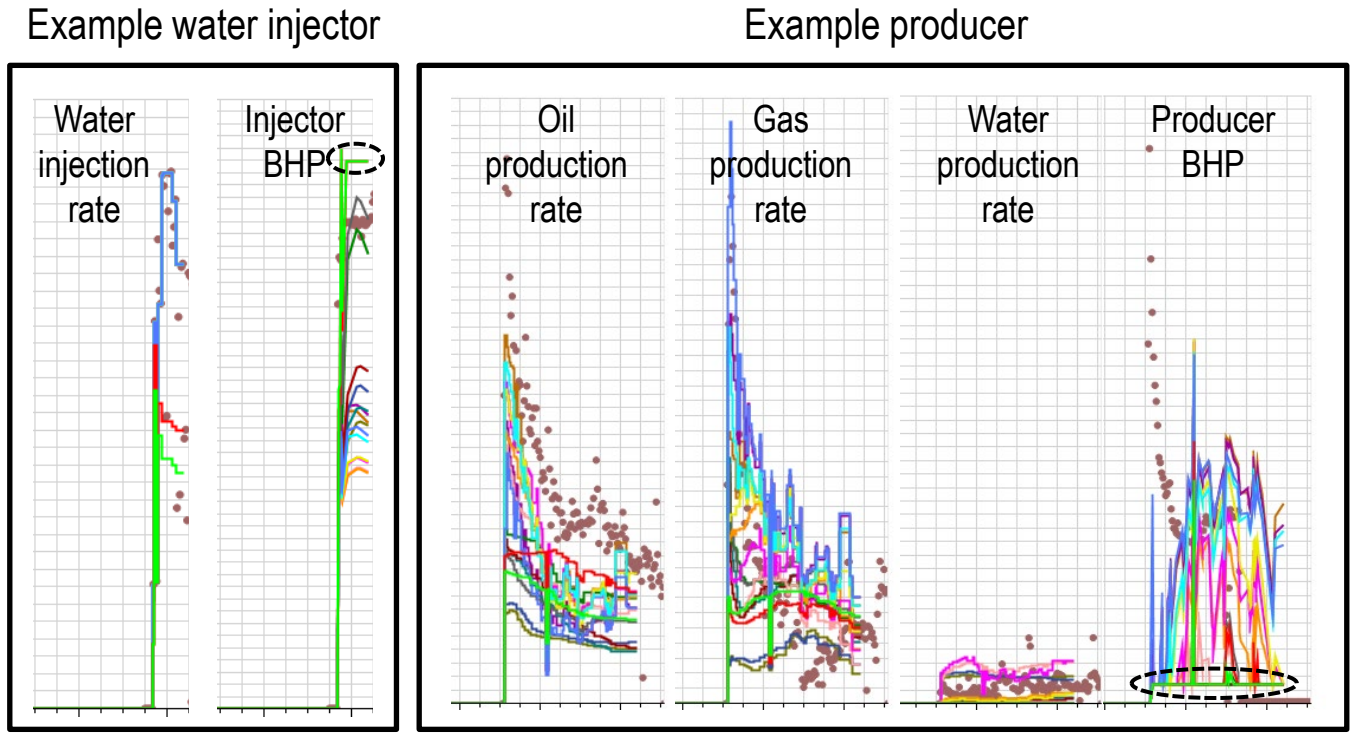
- Enhanced permeability of up to 50 mD for no groups, one group, two groups, three groups or all four groups
- => 16 ensemble end members
  - KG1 = 0, KG2 = 0, KG3 = 0, KG4 = 0
  - KG1 = 0, KG2 = 0, KG3 = 0, KG4 = 50
  - ...
  - KG1 = 50, KG2 = 50, KG3 = 50, KG4 = 50

PERMX
(filter: > 10 mD)
Black lines: injectors



Evaluation: Production data

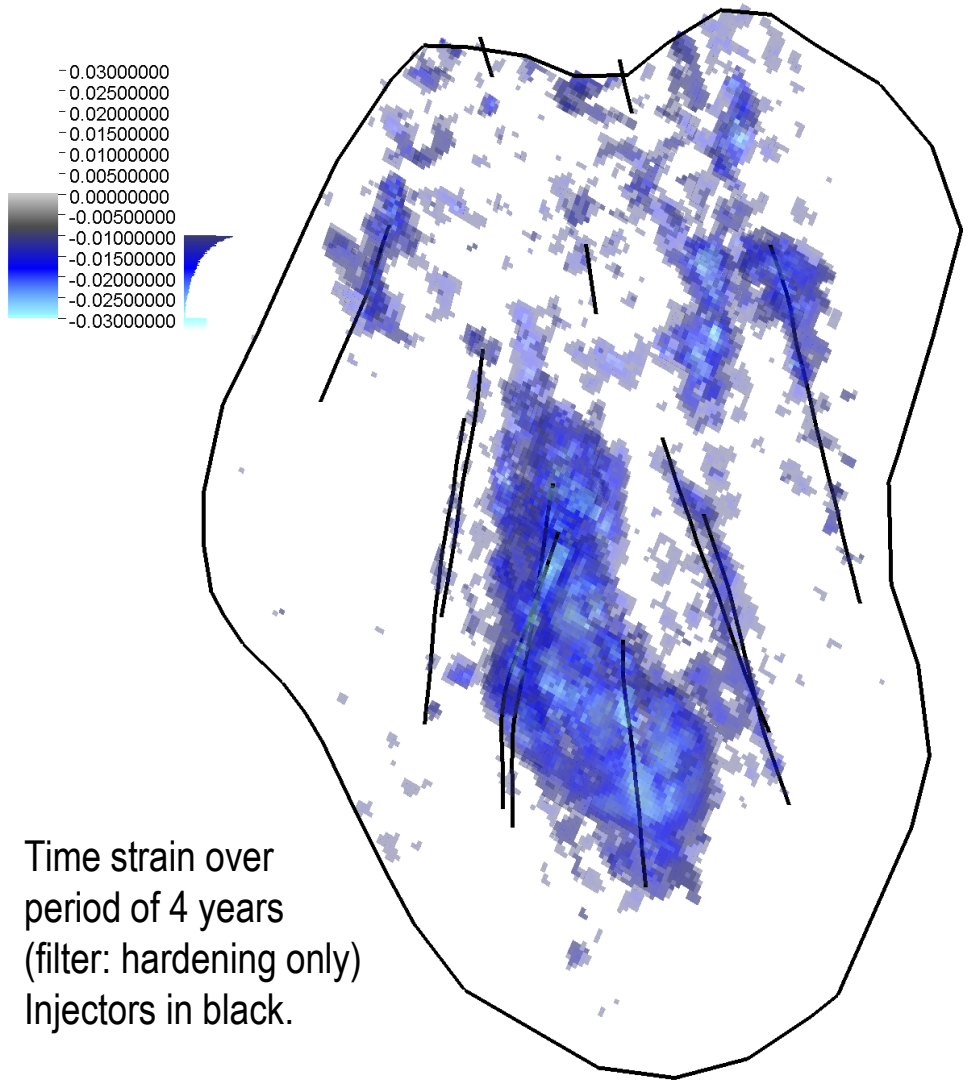
- Well deliverability check
  - Need enough permeability around wells to inject / produce specified amount without violating bottom hole pressure constraints
- Rate and pressure mismatch
  - Oil, gas and water production rates
  - Bottom hole pressures



Ensemble end member simulation results (lines) versus observed data (dots)
For some of the simulated cases, well deliverability fails because of bottom hole pressure constraints.
Note in particular the **green line**, which represents the case of **matrix permeability only**.
For the other cases, mismatch analysis of bottom hole pressures and production rates is feasible.

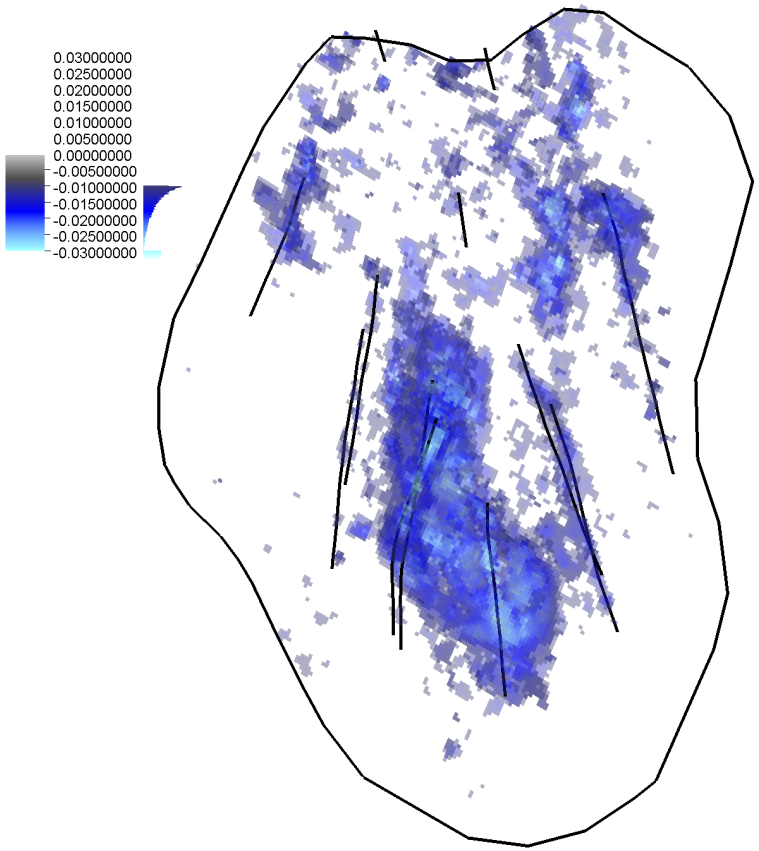
Evaluation: 4D seismic data

- Focus on time strain around injectors
  - Hardening (blue)
    - Water saturation increase
    - Gas back into solution (pressure increase)
    - Rock compaction
    - Pressure reduction
  - Softening (red)
    - Gas out of solution (pressure reduction)
    - Rock dilation (rock compaction below)
    - Pressure increase
- Mapped into simulation grid for comparison with simulation results

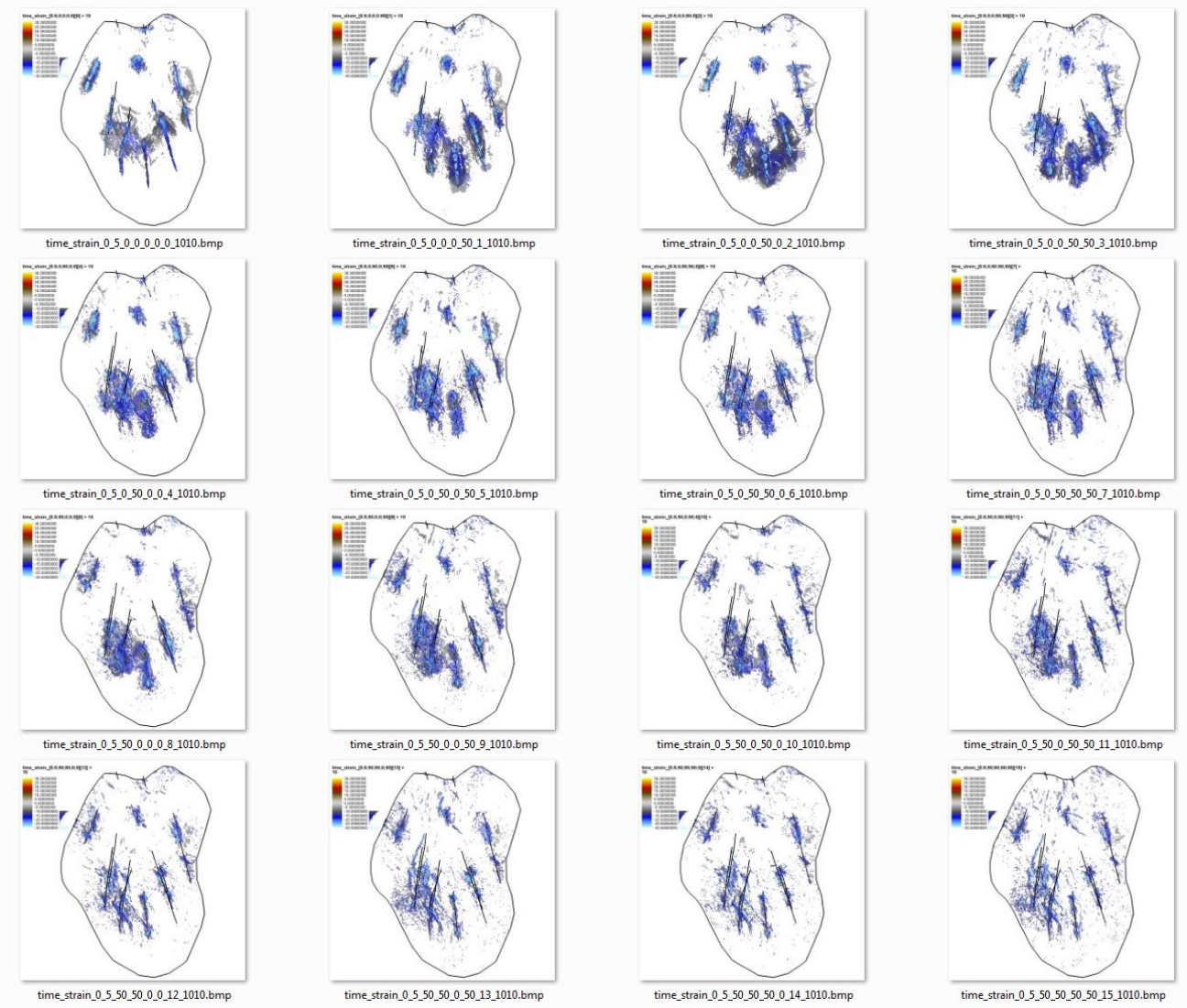


Time strain over period of 4 years (filter: hardening only) Injectors in black.

Evaluation: 4D seismic data versus simulation results

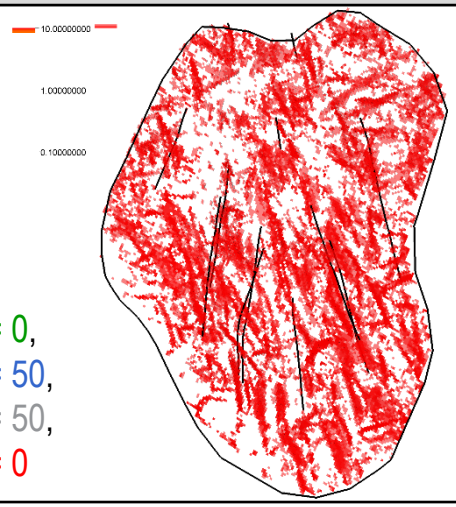


Observed versus simulated time strain over time period of 4 years (filter: hardening only)



Evaluation: Flow model and rock physics model

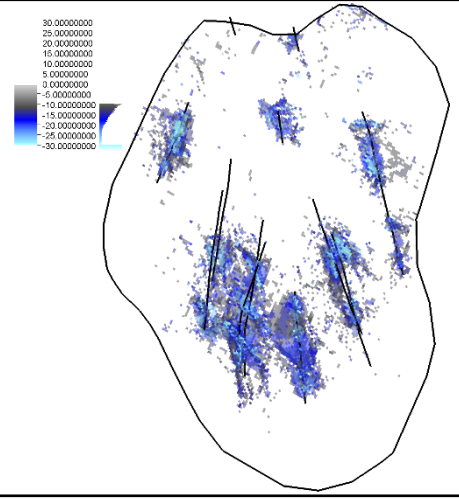
Flow model: PERMX (filter: > 10 mD)



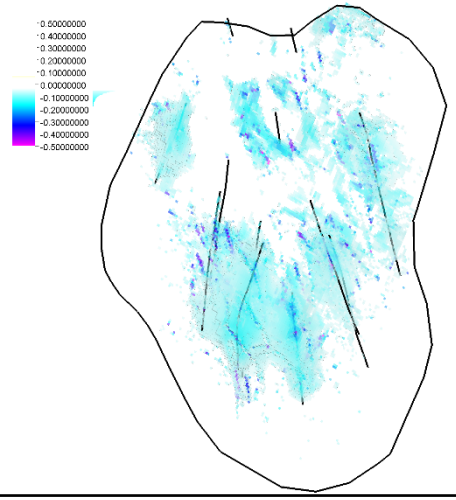
KG1 = 0,
KG2 = 50,
KG3 = 50,
KG4 = 0

Flow model: pressure increase (filter: > 200 psi)

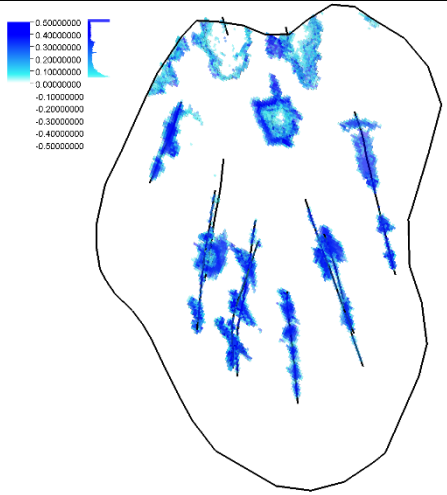
RPM: time strain > 1 % (filter: hardening only)



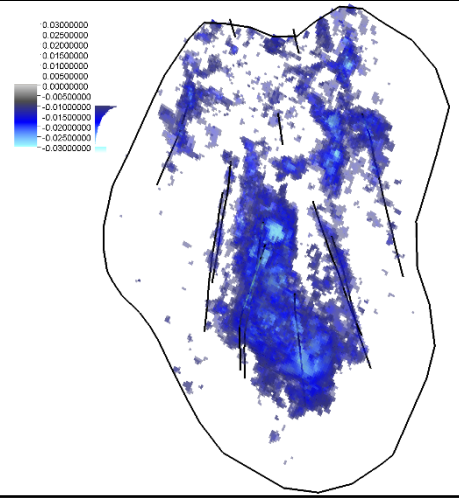
Flow model: gas saturation reduction (filter: > 5 %)



Flow model: water saturation increase (filter: > 5 %)



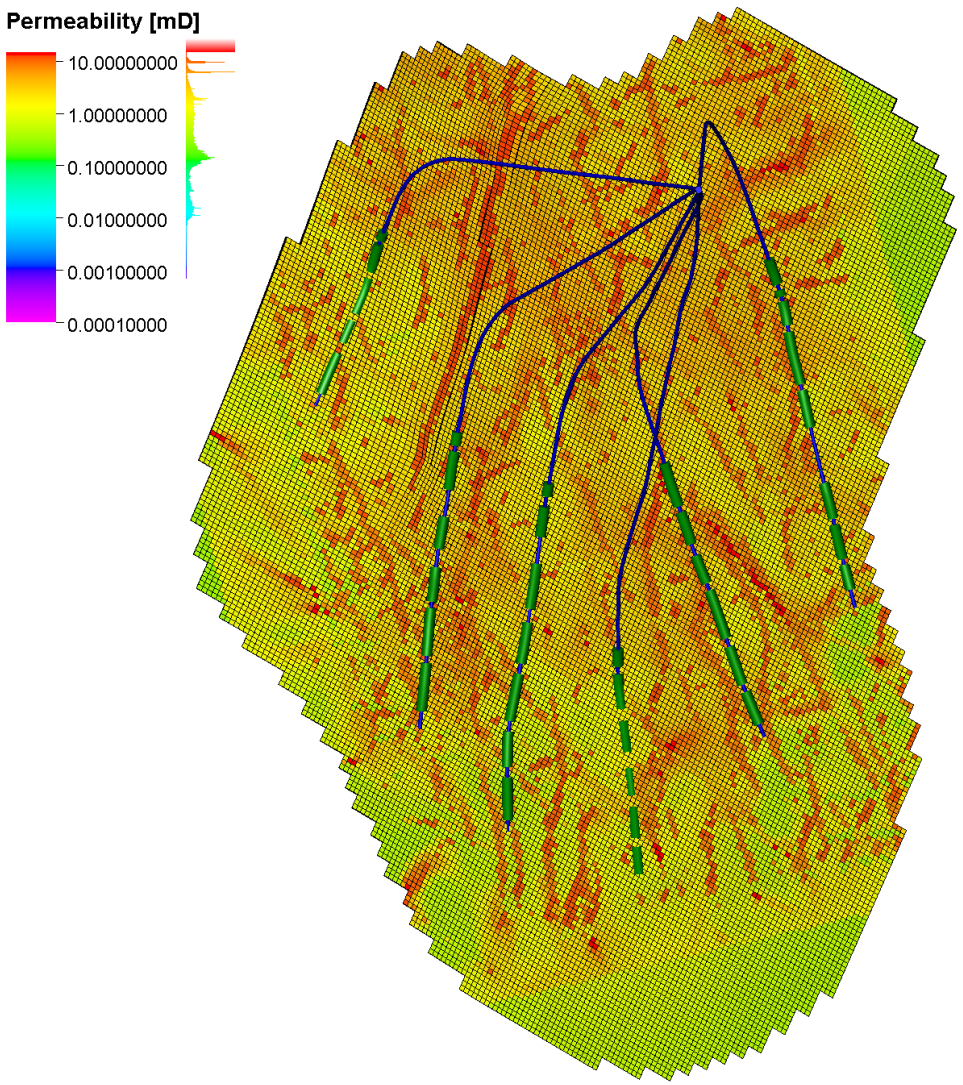
Observation: time strain > 1 % (filter: hardening only)



Summary and further work

- Seismic **fault detection** and sub-seismic **fracture prediction from tectonic modeling** used as input to **locally refined** reservoir simulation model
- **Permeability model**: Matrix + faults + fractures
- **Ensemble of models** evaluated against **production data** and **4D seismic data**

- **Further work:**
  - Ensemble smoother update, including rates, pressures and time strain in misfit term
  - Quantitative time strain mismatch might require further analysis and calibration of rock physics parameters



Acknowledgements

- The authors acknowledge the Research Council of Norway and the industry partners, ConocoPhillips Skandinavia AS, Aker BP ASA, Eni Norge AS, Maersk Oil, a company by Total, Statoil Petroleum AS, Neptune Energy Norge AS, Lundin Norway AS, Halliburton AS, Schlumberger Norge AS, Wintershall Norge AS, and DEA Norge AS, of The National IOR Centre of Norway for support.
- The authors thank ConocoPhillips Skandinavia AS, Total E&P Norge AS, Eni Norge AS, Statoil Petroleum AS and Petoro AS for permission to present the results of the case study.

Questions

Thank You!

Key elements in workflow

- **Automation** in seismic interpretation, tectonic modeling and reservoir simulation
- Tight **integration** between seismic data and **locally refined simulation models**
- **Ensemble of models** consistent with detected faults and predicted fractures