Next-generation Geological Model Updating and Ranking for Improved Oil Recovery*

Marko Maucec[1], Gustavo Carvajal[2], Ajay Singh[2], and Seyed Mirzadeh[2]

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[1]HALLIBURTON, Consulting & Project Management, Kuala Lumpur, Malaysia (marko.maucec@halliburton.com)
[2] HALLIBURTON, Consulting & Project Management, Houston, TX

Abstract

The conventional oil production practices recover, on average, approximately one third of the original oil in place with estimated remaining mobile oil. To increase the overall production, large investments are made in Improved Oil Recovery (IOR) of which success greatly depends on the ability to estimate volumes and locations of bypassed oil from available historical data using History Matching techniques. We present a new approach with the potential to more accurately capture uncertainty of the inherent geological model, facilitate accurate description of reservoir heterogeneities and honor the conceptual depositional model.

The novelty lies in direct interfacing between Next-generation geological modeling and forward simulator. Efficient model parameterization that enables rapid generation of model updates in wave-number domain is used to characterize the main features of geologic uncertainty space: structural, stratigraphic, facies and petrophysical properties. Model inversion workflow is based on multi-step Bayesian Markov chain Monte Carlo (MCMC). Traditional MCMC methods provide most rigorous sampling of posterior distribution but suffer from high computational cost. We implement an approach where proxy model is guided by streamline-based sensitivities, dispensing with the need to run forward simulation for every model realization, thus significantly reducing the computation time. An ensemble of sufficiently diverse model realizations is generated at the high-resolution geological scale that secures more accurate results by obeying known geostatistics and well constraints.

The workflow is validated on a case-study combining geological model with ~1M cells, four different depositional environments and 30 wells with 10-year water-flood history. A history match indicates significant reduction in the misfit between observed and simulated water-cut curves, even for producers with difficult non-monotonic behavior.

Finally, the method is described to rank dynamically the reconciled model realizations for identifying the highest potential, to capture bypassed oil and implement IOR solutions. The main features include use of fast streamline simulations to calculate dynamic model responses (e.g. recovery factors), evaluate their dissimilarity with pattern-recognition techniques and assigning of a few realizations, representative for production forecasting, to full-physics simulation.

References

Alpak, F.O., M.D. Barton, F.F. van der Vlugt, C. Pirmez, B.E. Prather, and S.H. Tennant, 2010, Simplified modeling of turbidite channel reservoirs: SPE Journal, v. 15/2, p, 480-494.

Scheidt, C., and J. Caers, 2009, Uncertainty quantification in reservoir performance using distances and Kernel methods; application to a West Africa deep-water turbidite reservoir: SPE Journal, v. 14/4, p. 680-692.

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Marko Maučec

Gustavo Carvajal

Ajay Singh

Seyed Mirzadeh

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Outline

- **O**bjective…
- **U**ncertainty in Geological Models
- **H**istory Matching and Uncertainty Management
- **N**ext-generation Geological Modeling
- **M**odel Parameterization and Reduction
- **M**odel Inversion:
    - Multi-stage Markov chain Monte Carlo…
    - Validation
- **D**ynamic Model Ranking
    - Validation
- **S**ummary & Conclusions

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Objective…

Coupling Geo-modeling, Reservoir modeling, Wells and Surface Network Models in…

All-in-one
Uncertainty Quantification Workflow
fully integrated on a unified database

- Minimum or no model up-scaling,
- Include multiple types/scales of data and 1st order effects,
- Capture full range of outcomes,
- Reduce analysis & decision time.

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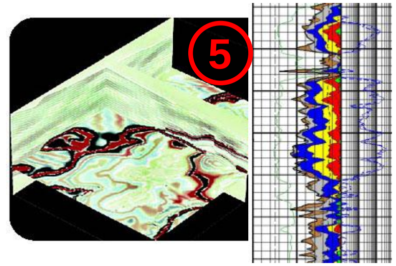
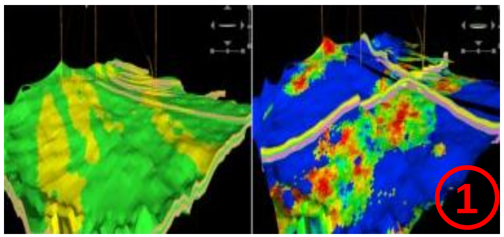
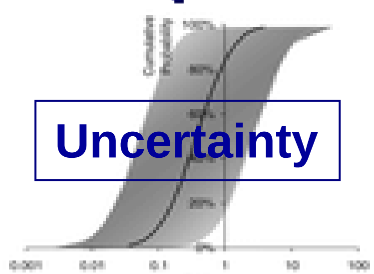
… Big-loop Reservoir Management



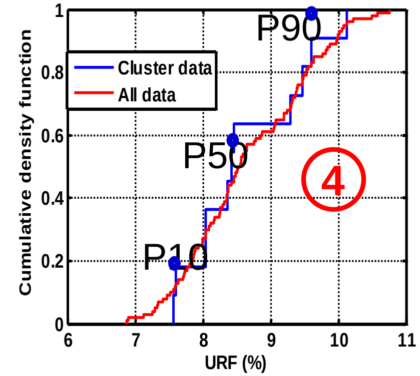
Updates:
production data, 4D seismic, logs…

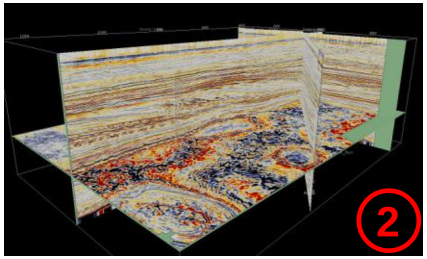
Geo-cellular model



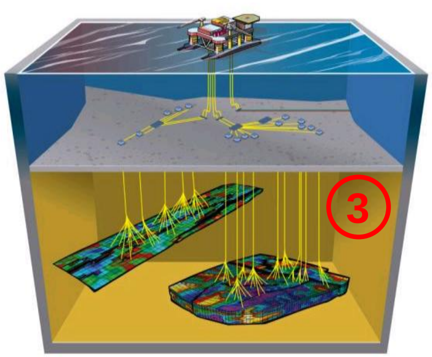


Ranking,
decisions,
actions



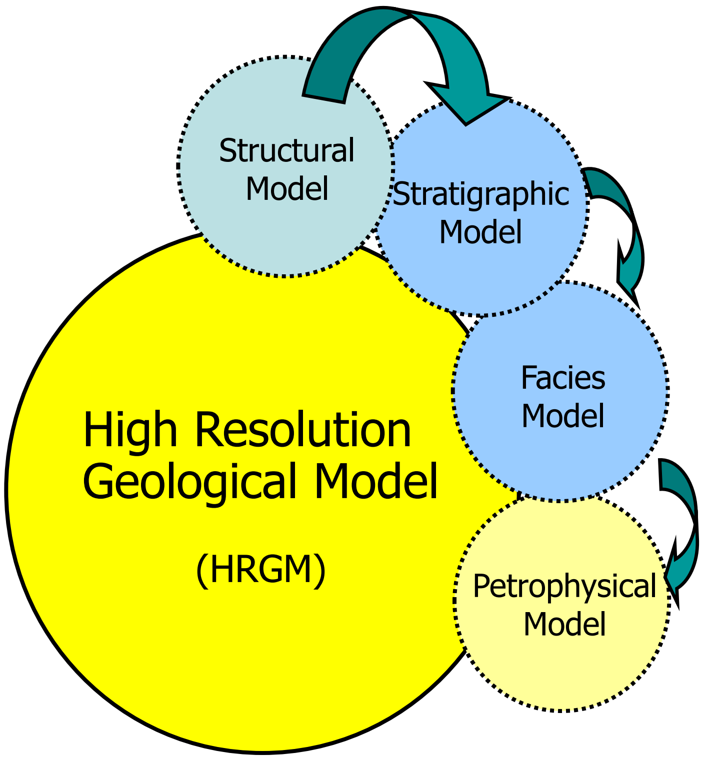


Seismic constraints



Dynamic data:
reservoir, wells, facilities…

Uncertainty in Geological Models



Structural model
defines gross volumes

Stratigraphic model
layering controls lateral connectivity
variogram range controls vertical connectivity

Facies model
controls depositional continuity

Petrophysical model
defines property distribution

Uncertainty impact

Higher

Lower

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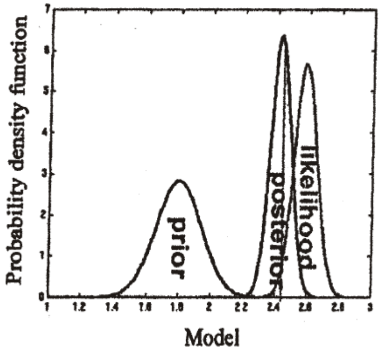
Bayesian inference: assessing parameter uncertainty

Gaussian form of likelihood term

$$p_{d|m}(\mathbf{d}\,|\,\mathbf{m}) \propto exp\left[-\frac{1}{2}(\mathbf{d}-\mathbf{g}(\mathbf{m}))^T C_d^{-1}(\mathbf{d}-\mathbf{g}(\mathbf{m}))\right]$$

Gaussian form of prior term

$$p_m(\mathbf{m}) \propto \; exp\left[-\frac{1}{2}\left(m-m^0\right)^T C_M^{-1}\left(m-m^0\right)\right]$$



$$\boxed{p_{m|d}(\mathbf{m}\,|\,\mathbf{d}) = \frac{p_{d|m}(\mathbf{d}\,|\,\mathbf{m})\,p_m(\mathbf{m})}{p_d(\mathbf{d})}}$$

BAYESIAN MODEL

m = model **d** = data **g** = simulator

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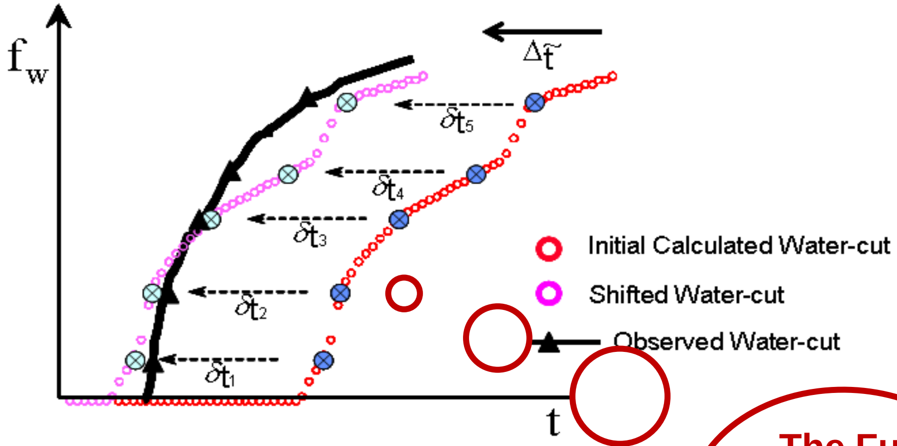
History Matching in a nutshell…

… a systematic procedure of altering a reservoir simulation model to reproduce the dynamic field response by honoring geological constraints!
… **OBJECTIVE:** Minimize the error between measured and simulated response!



DATA USED:

- Production data
- Pressure data
- Other (temp profiles, saturation distribution…)

The Future of AHM

- Intelligent and intensive use of cluster computing.
- Ensemble-based methods to capture model uncertainty.
- Hierarchical ranking of model uncertainties.
- Optimal model resolution.

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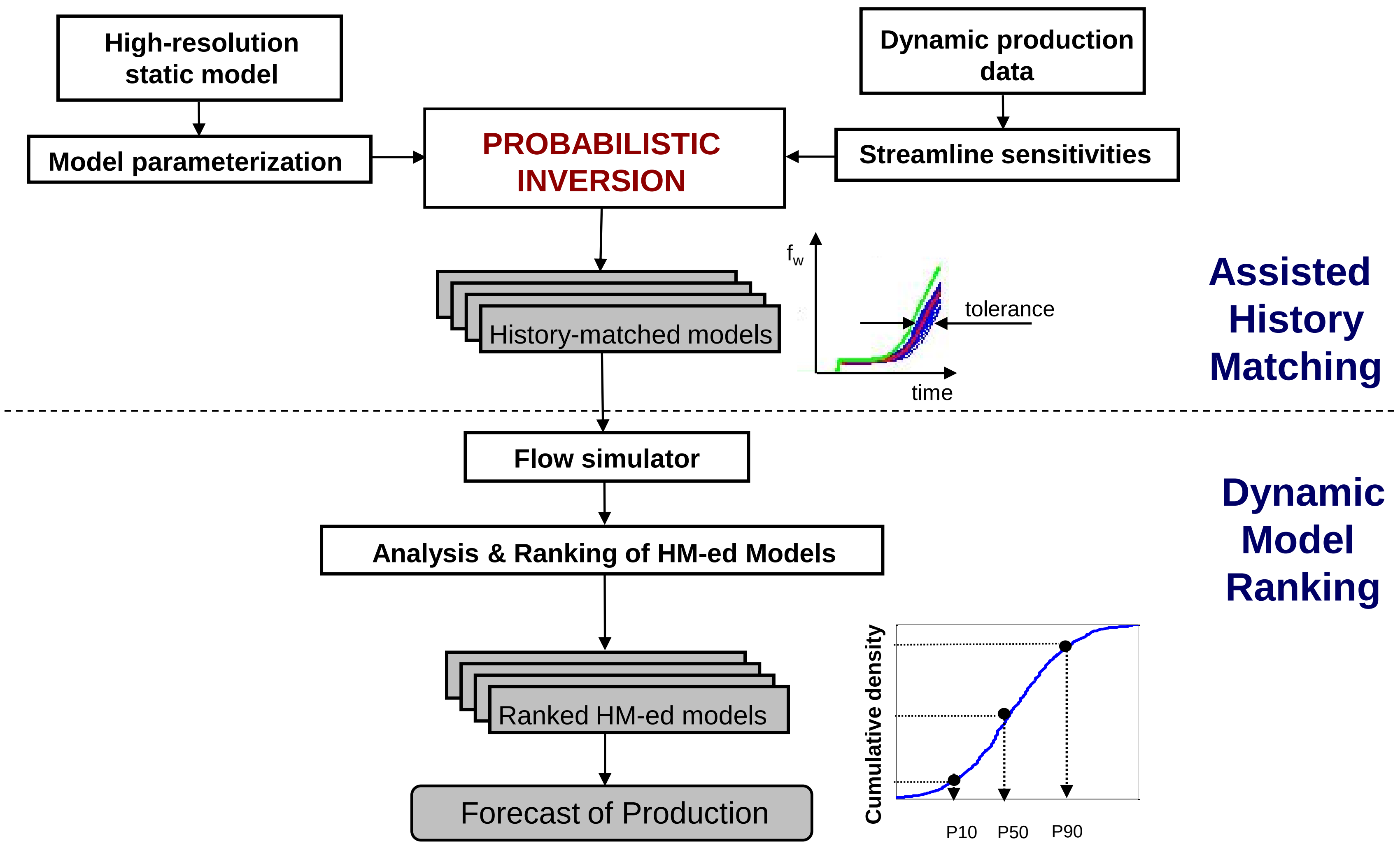
Quantitative Uncertainty Management



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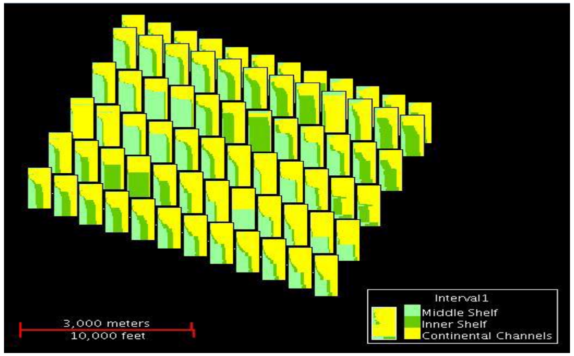
Next-generation Geological Modeling

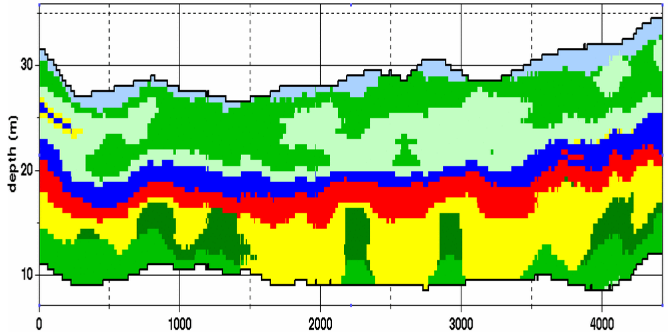
Stratigraphic modeling

- Lithotype proportions: accurate and efficient representation of geological non-stationarity (trends)



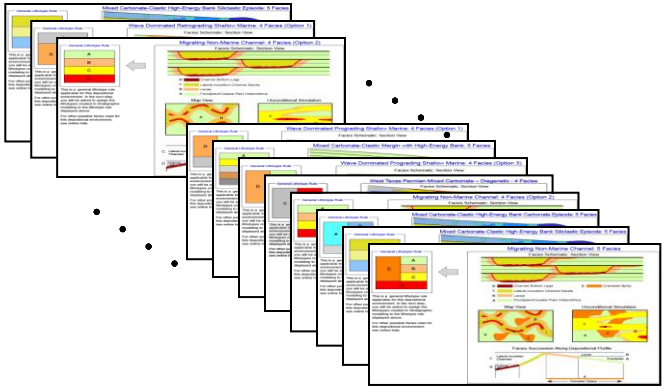
Facies simulation

- *Geologically driven*: ultra sophisticated, simple to use, combine different variagram model types, each exhibiting different anisotropic conditions.

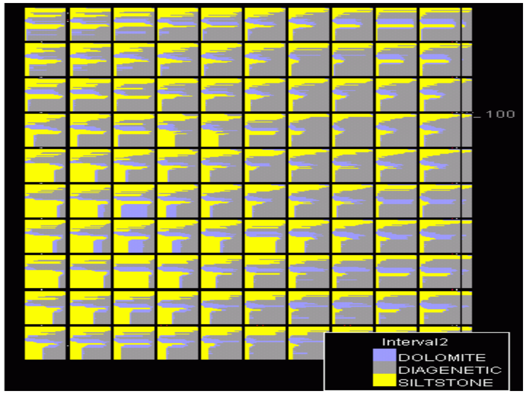


Facies modeling

- Lithotype rules



- Vertical Proportion Matrices: define how the facies behave vertically over the area of the reservoir



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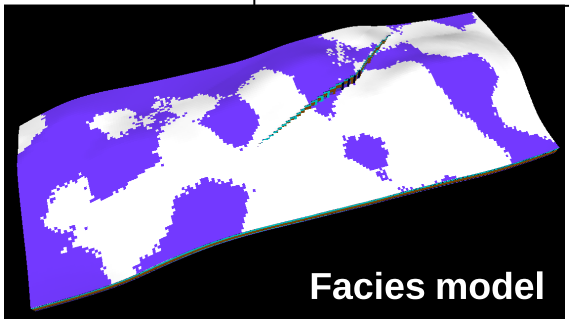
Generation of Geo-model Realizations

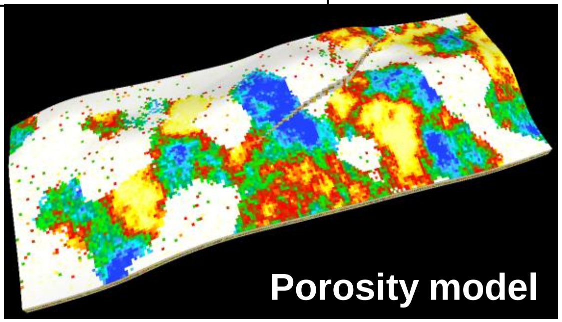
Statigraphic grid

Rules for Facies Simulation

Rules for PP Simulation

Next-generation Geo Modeling API


Facies model


Porosity model

Challenges for AHM workflow

- Preserve realism of high-resolution model.
- Retain distribution of main features that have control over depositional connectivity, *i.e.* facies.
- Perform **FAST** model updating.

Model parameterization

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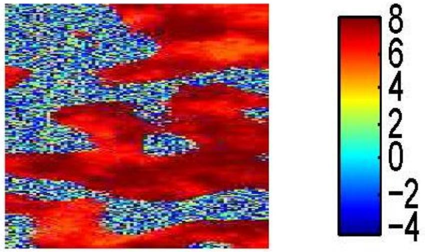
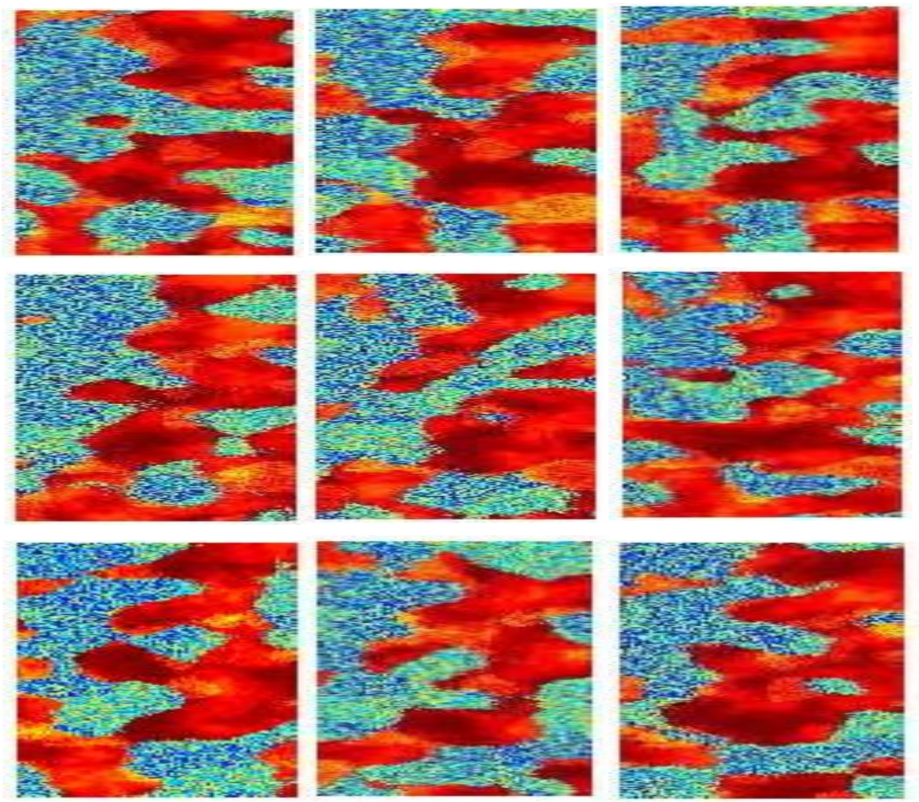
Model Parameterization

Initial log-perm model





Log-perm maps, Brugge fluvial, top-layer, 9 realizations

HIGHLIGHTS

- **Speed:** wave-number approach eliminates the need for prior Cov matrix inversion
- **Geological realism:** adheres to the geological detail of the initial static model.
- **Versatility:** preserves low frequency moments of the image, which correspond to large features, *e.g.* facies
- **Statistical soundness:** produces statistically unbiased prior model realization.
- **Flexibility:** fully applicable to multi-million-sized models.

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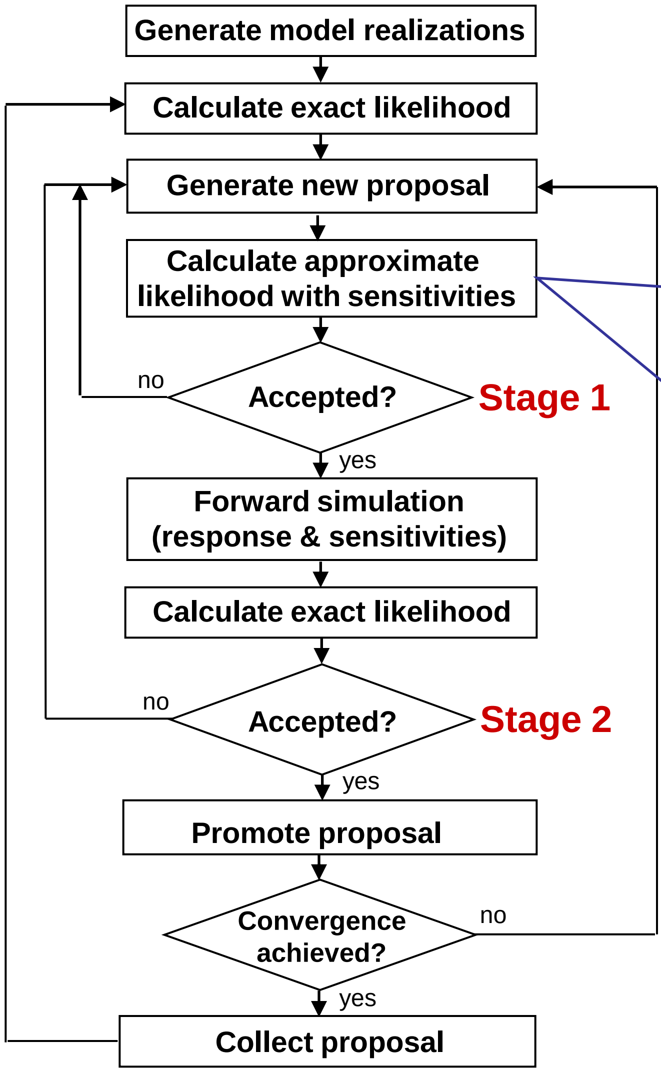
Multi-stage Markov chain Monte Carlo (MCMC) - I



Proxy Likelihood Model

For a proposed transition

$$\boldsymbol{\delta}\mathbf{m} = \mathbf{m}^{*} - \mathbf{m}^{i}$$

the change in model parameters to the change in forward model response is related via **streamline sensitivity matrix S**:

$$\boldsymbol{\delta}\mathbf{d} = S\delta\mathbf{m}$$

Streamline Sensitivities: derivatives of a streamline travel time with respect to model parameters *e.g.* permeability, porosity, BHP, fluid saturation…

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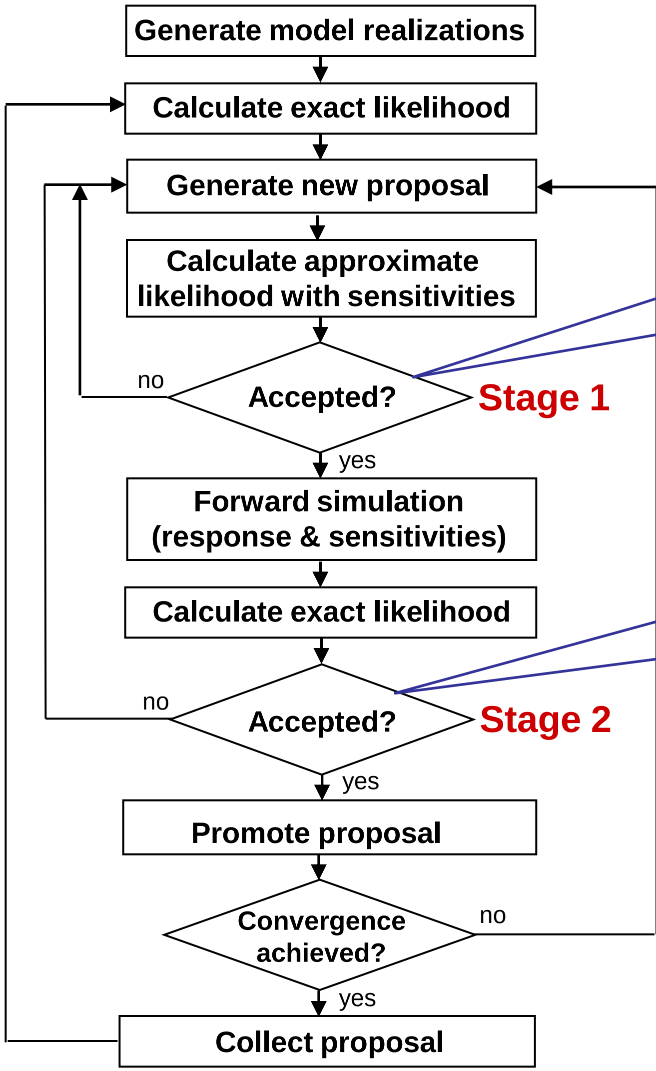
Multi-stage Markov chain Monte Carlo (MCMC) - II



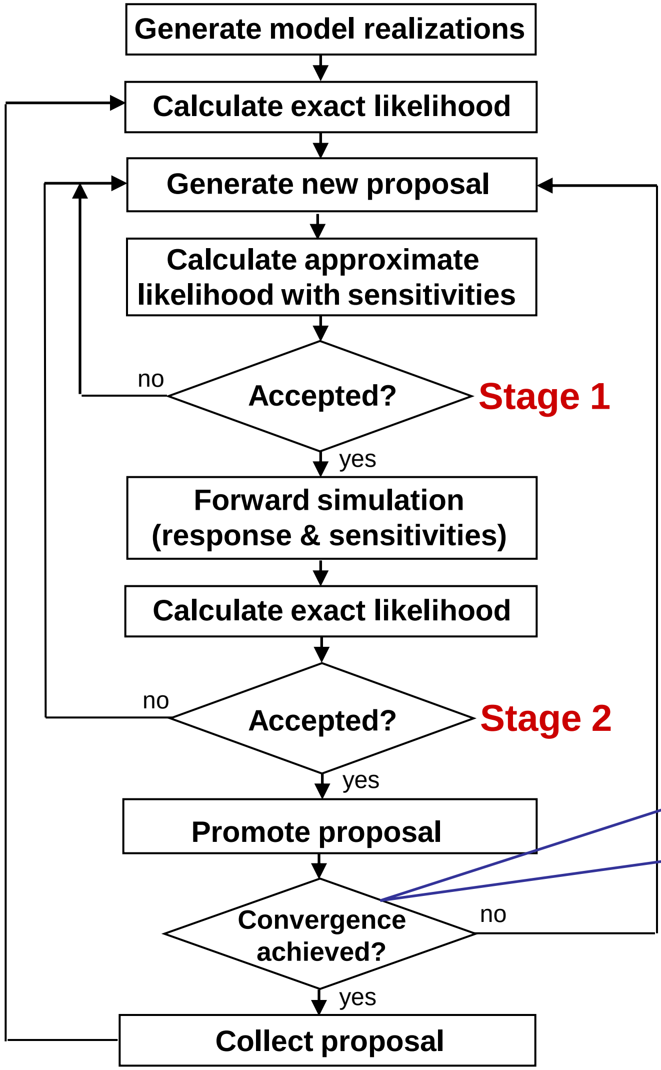
Acceptance Criterion – Stage 1

Standard Metropolis - Hastings

Acceptance Criterion – Stage 2

Standard Metropolis - Hastings

Multi-stage Markov chain Monte Carlo (MCMC) - III



Convergence diagnostics

Entropy, S

$$S = -\left\langle p_{\mathbf{m}|\mathbf{d}} \log(p_{\mathbf{m}|\mathbf{d}}(\mathbf{m} \mid \mathbf{d})\right\rangle$$

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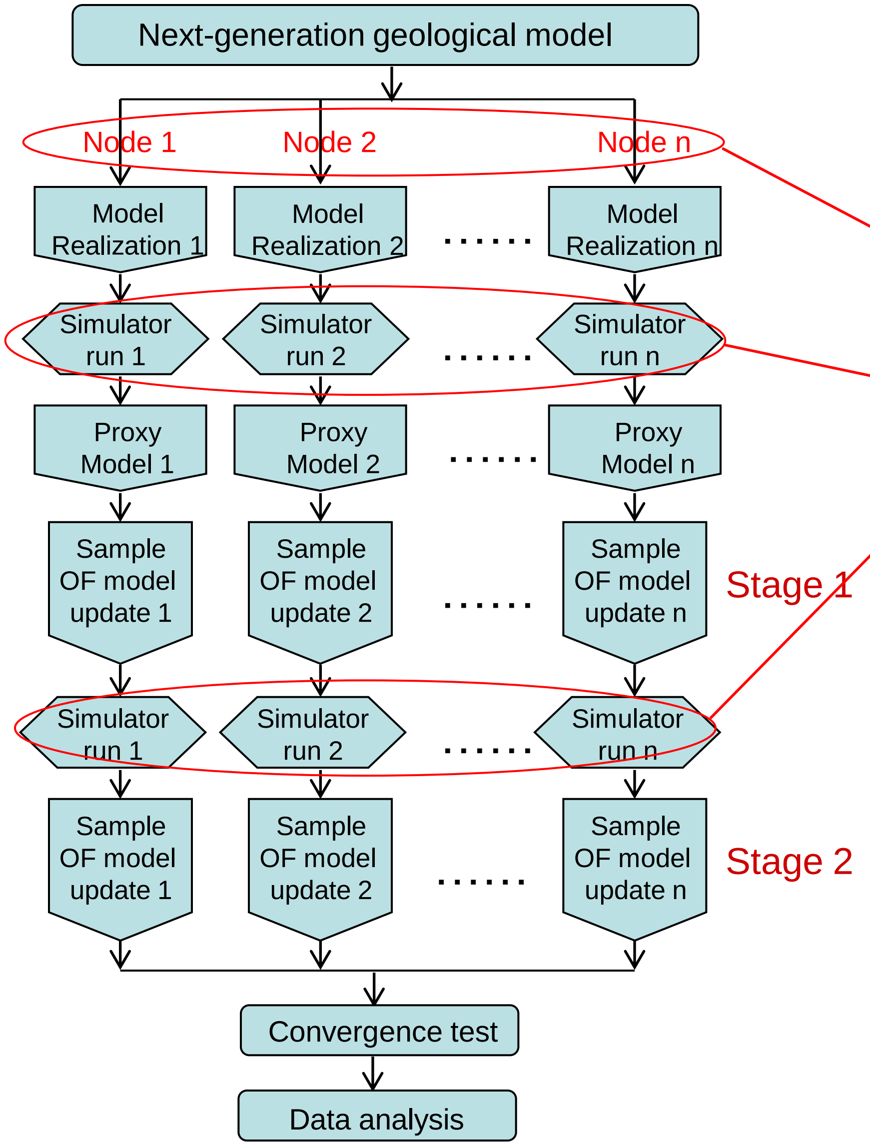
Interfacing Geological Modeling and Simulator



Reservoir (forward) simulation is most time consuming step!

- Use of cluster and parallel CPU computation is imperative!
- Considerable gains in effective computation time!
- Example simulation: ~3h /w 1 Quad; ~45 min /w 4 Quads.

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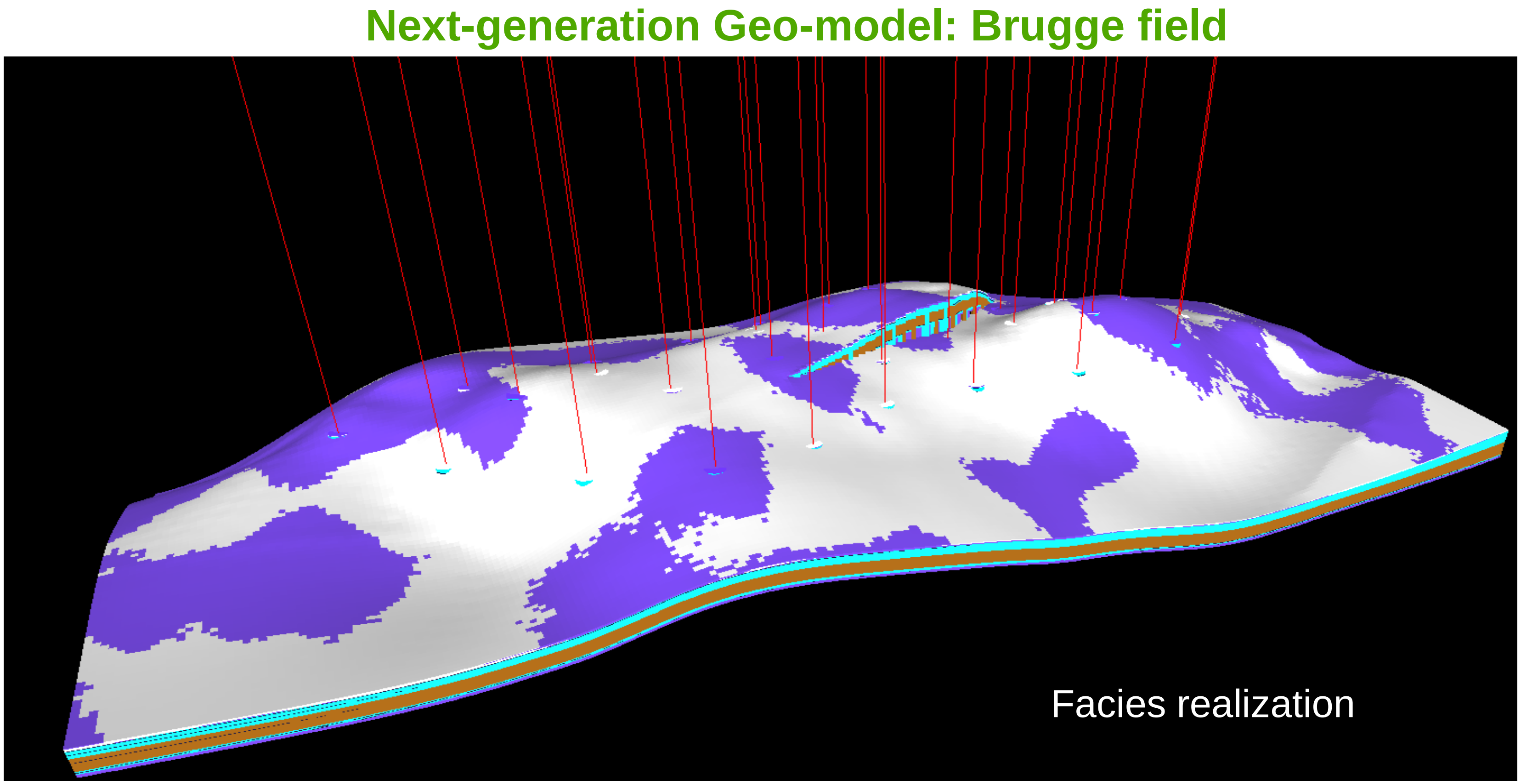
Validation: benchmark model



- 4 depositional systems,1 fault
- Grid: 211 x 76 x 56 ➔ ~900k cells
- 20 producers, 10 injectors: all vertical, perforating through all 56 layers

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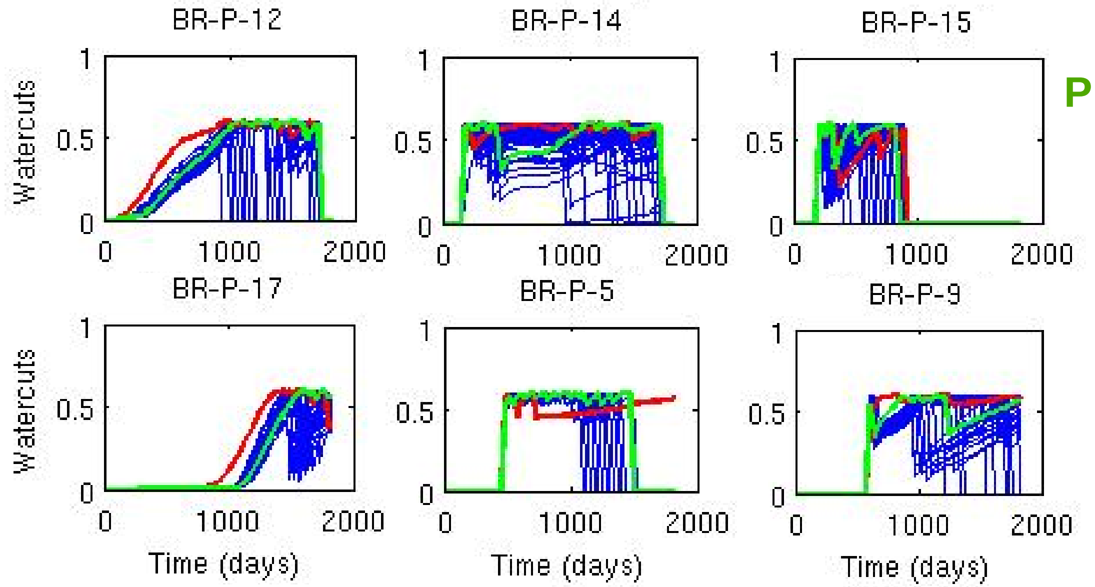
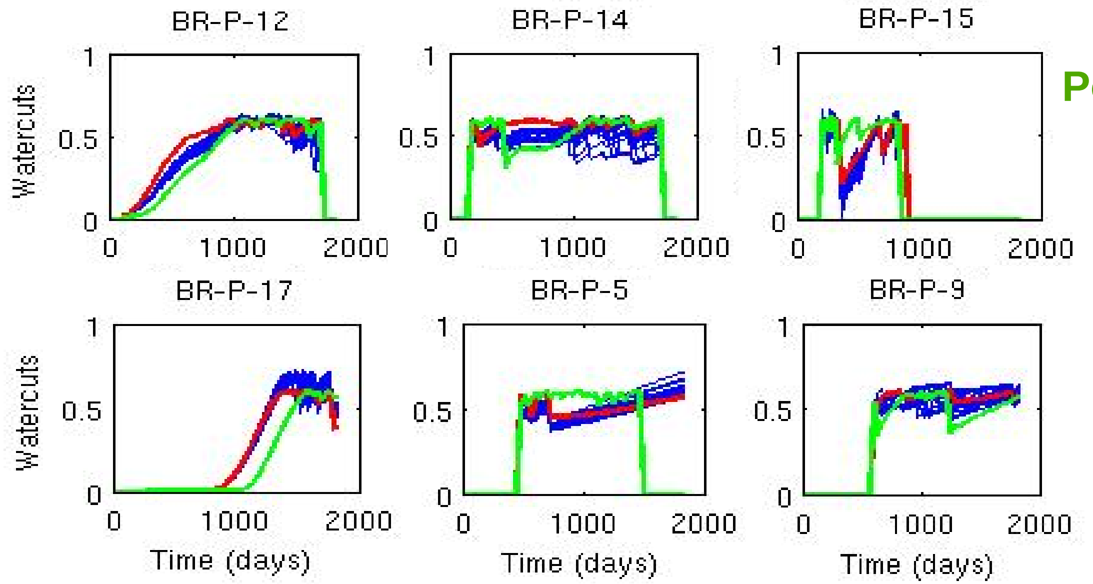
Water-cut Curves



Prior model realizations



Posterior model realizations

prior / posterior model

observed data

initial model

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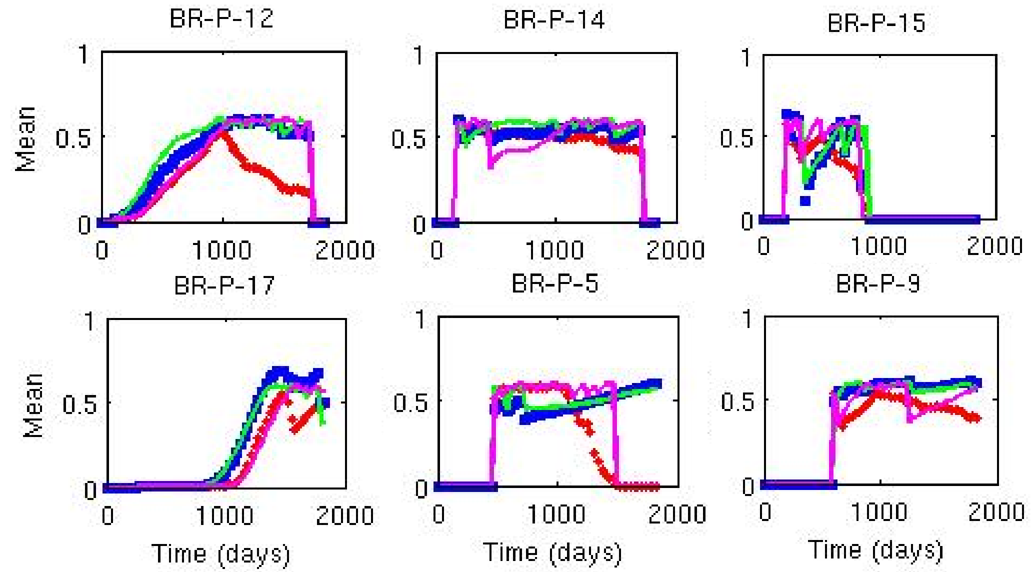
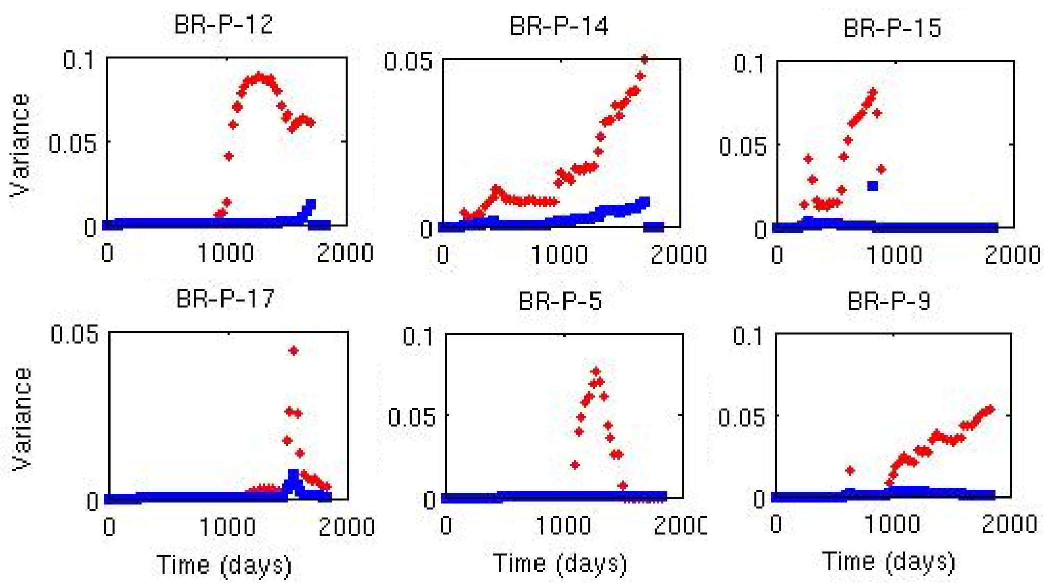
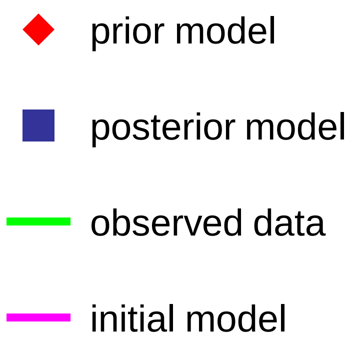
Water-cut Curves: mean & variance



Mean



Variance



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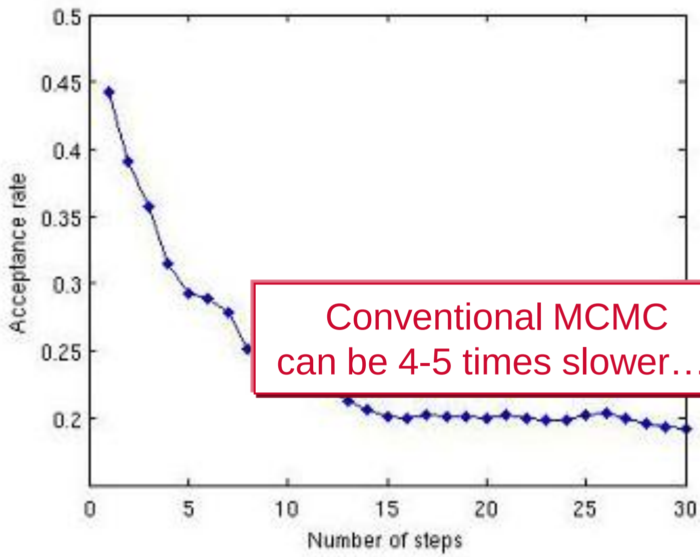
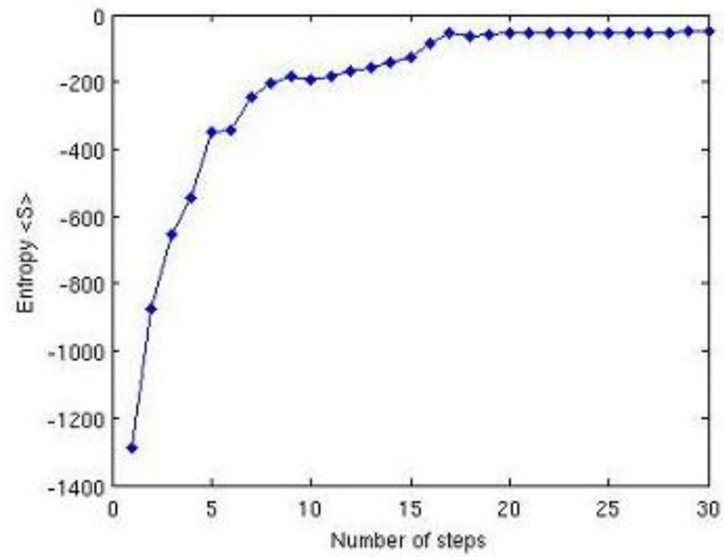
Convergence Diagnostics



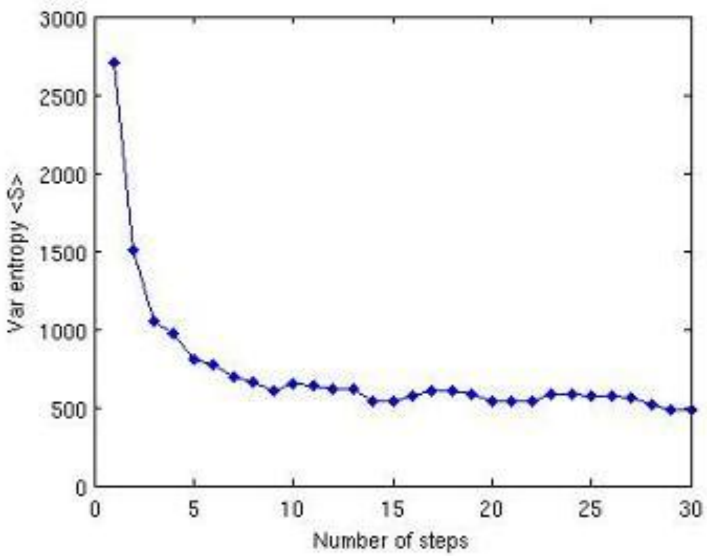
Conventional MCMC
can be 4-5 times slower…!

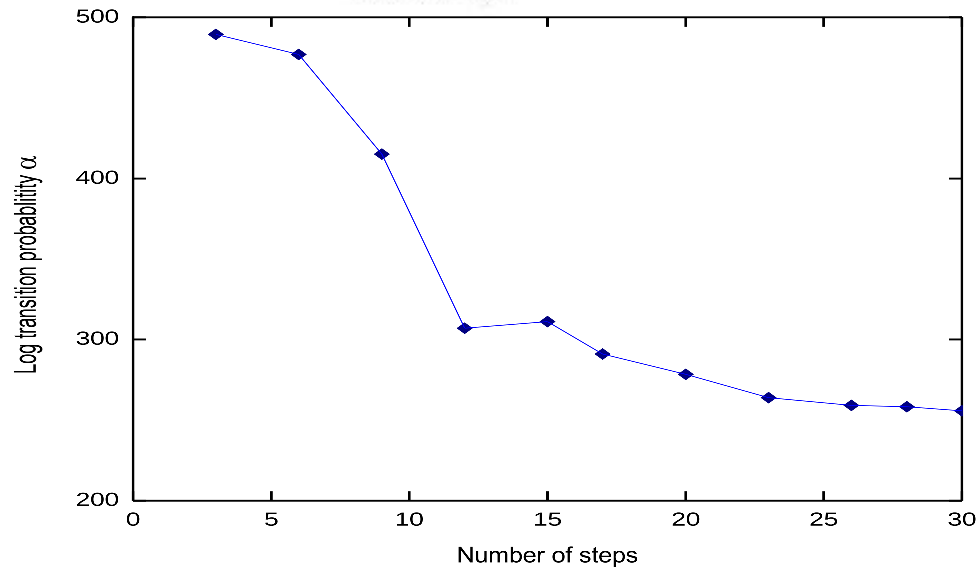


Sample size (1500)

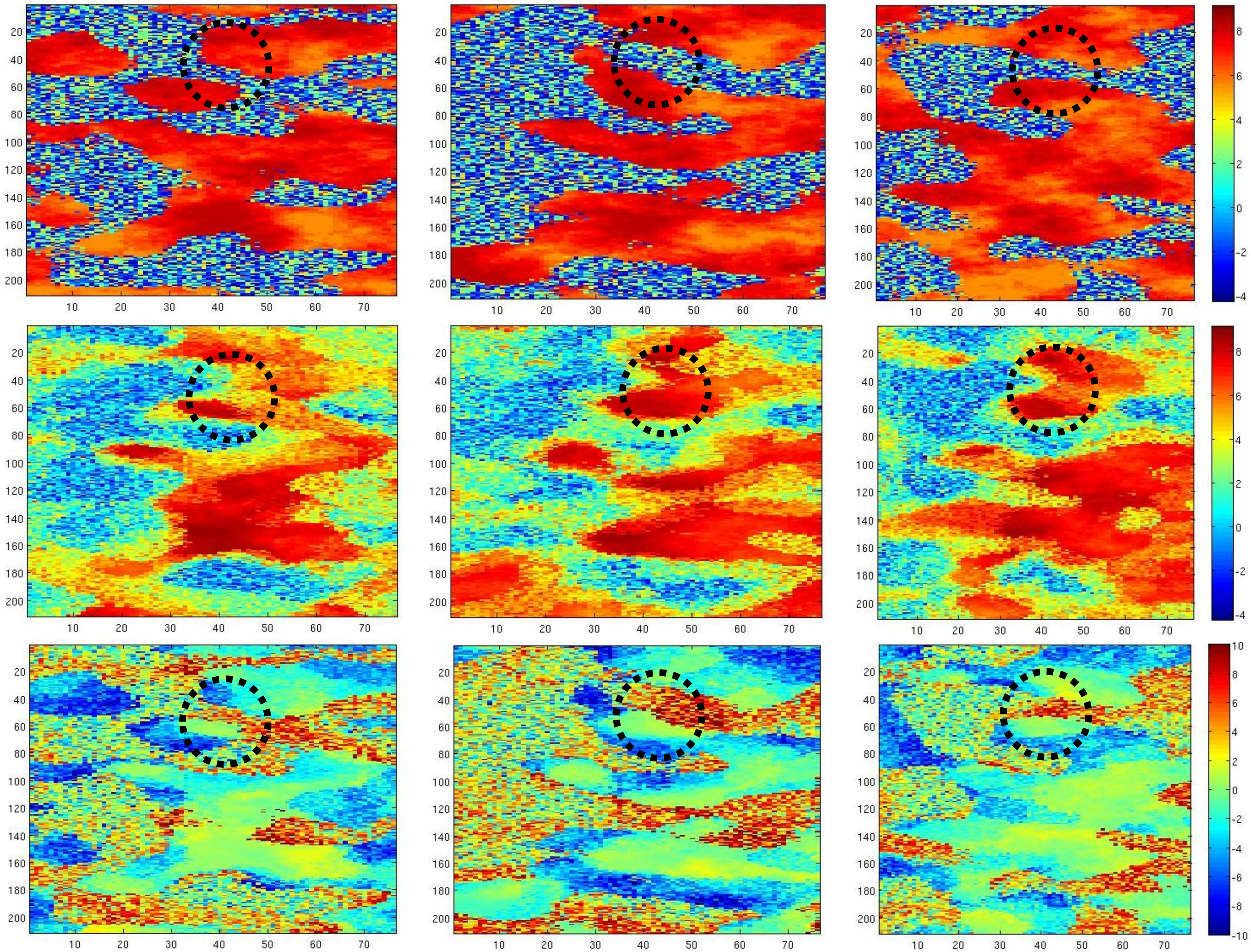
⇓

Number of steps (30)
X
Ensemble size (50)





History-matched Permeability Models



Prior model realization

Posterior model realization

Difference: posterior-prior

Layer 1 of three model realizations (log-perm scale).

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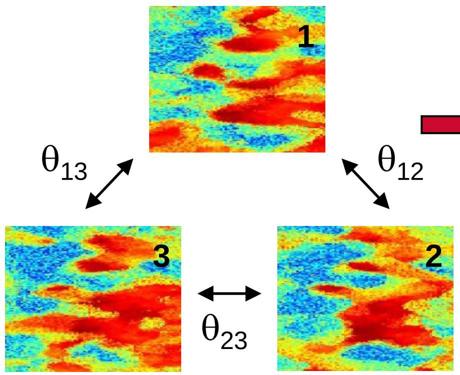
Dynamic Model Ranking - I

… Assisted History Matching is inherently ill-posed and can generate non-geological realizations. Such models are **NOT** suitable for production forecasting!

Fast flow simulations on models



Connectivity-distance matrix

	1	2	3
1	θ_{11}	θ_{12}	θ_{13}
2	θ_{21}	θ_{22}	θ_{23}
3	θ_{31}	θ_{32}	θ_{33}

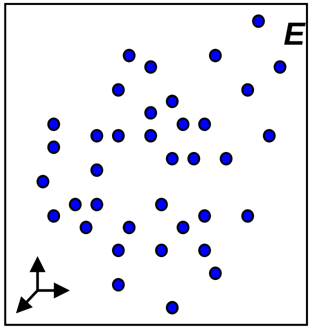
$$\theta_{kl} = \sqrt{\sum_{t \in T} (RF_k - RF_l)^2}$$

MDS

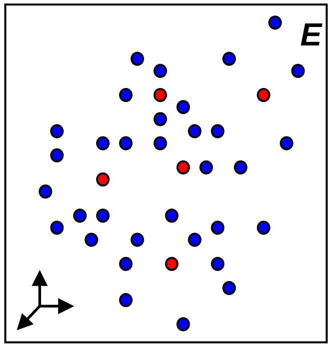
Post-MDS matrix with data-point map in Euclidean domain

	1	2	3
1	T_{11}	T_{12}	T_{13}
2	T_{21}	T_{22}	T_{23}
3	T_{31}	T_{32}	T_{33}

Non-linear Euclidean domain

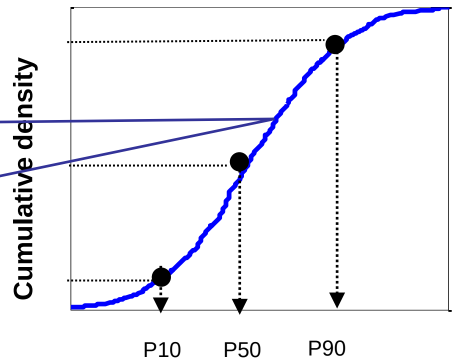


Kernel K-means Clustering



= cluster centroids

Full-physics simulation



Only model responses closest to cluster centroids in *E* domain are simulated with full-physics simulator to construct the URF cdf!

Modified from:
Scheidt & Caers, 2009;
Alpak et al., 2010.

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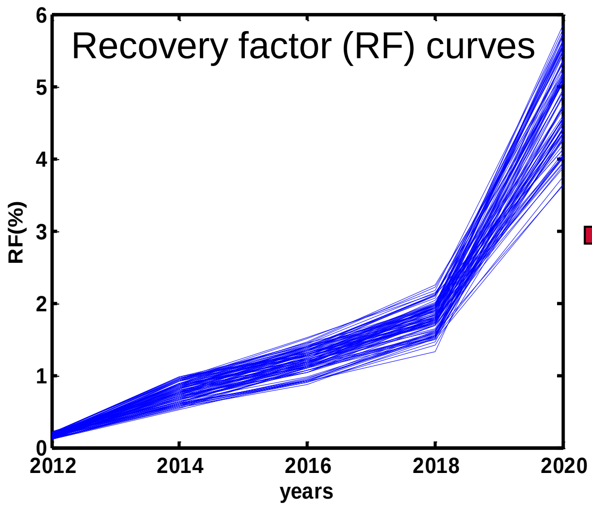
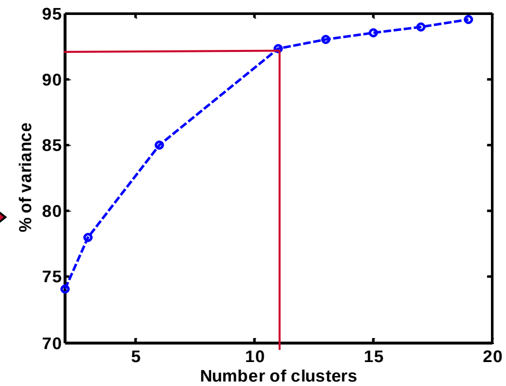
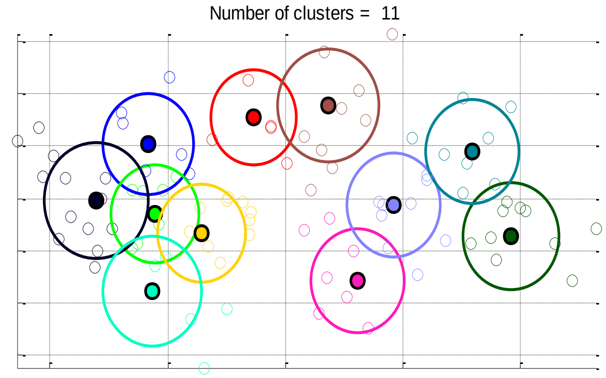
Dynamic Model Ranking - II

Validation: arbitrary “synthetic” dataset, with 100 recovery factor curves…

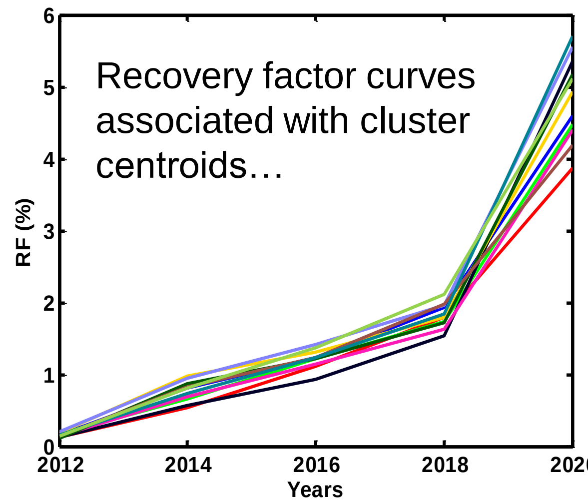


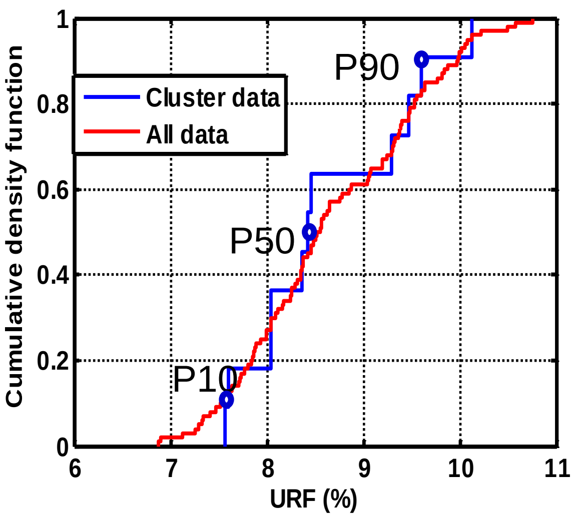


…optimal number of clusters



…selected clusters with centroids





…generated URF cdf with simulated cluster centroid RF data…

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Summary and Conclusions

- **Quantifying** and **ranking the impact** of uncertainty in underlying geological models is of fundamental importance when reconciling with dynamic data!
- Workflow introduces novel aspects to quantification of uncertainty for **Integrated Asset Management** and **Production Forecasting**:

  a) Integrates and dynamically interfaces reservoir simulator with next-generation Geological modeling. Future development will consider multi-level approach to history-match reservoir pressures and define/update pore scale features – followed by well-by-well HM.

  b) History-matching of well production data interfaces high-resolution subsurface models and robust model parameterization and updating, with great adherence to geological detail!

  c) Fully automated, parallel and load-distributed, without compromising statistical rigor – applicable to large-scale, real-time projects!

  d) Uncertainty ranking of history-matched models to intelligently select an optimal geological model that secures the **best (most likely) response for production forecasting**!

- The workflow is currently being developed and implemented in collaboration with the Middle East partner.

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