When Geostatistical Reservoir Models Become Unfit for Purpose

(…and ways to avoid this)

Michael Pyrcz and Richard Sech

Modified from the original key note talk from the

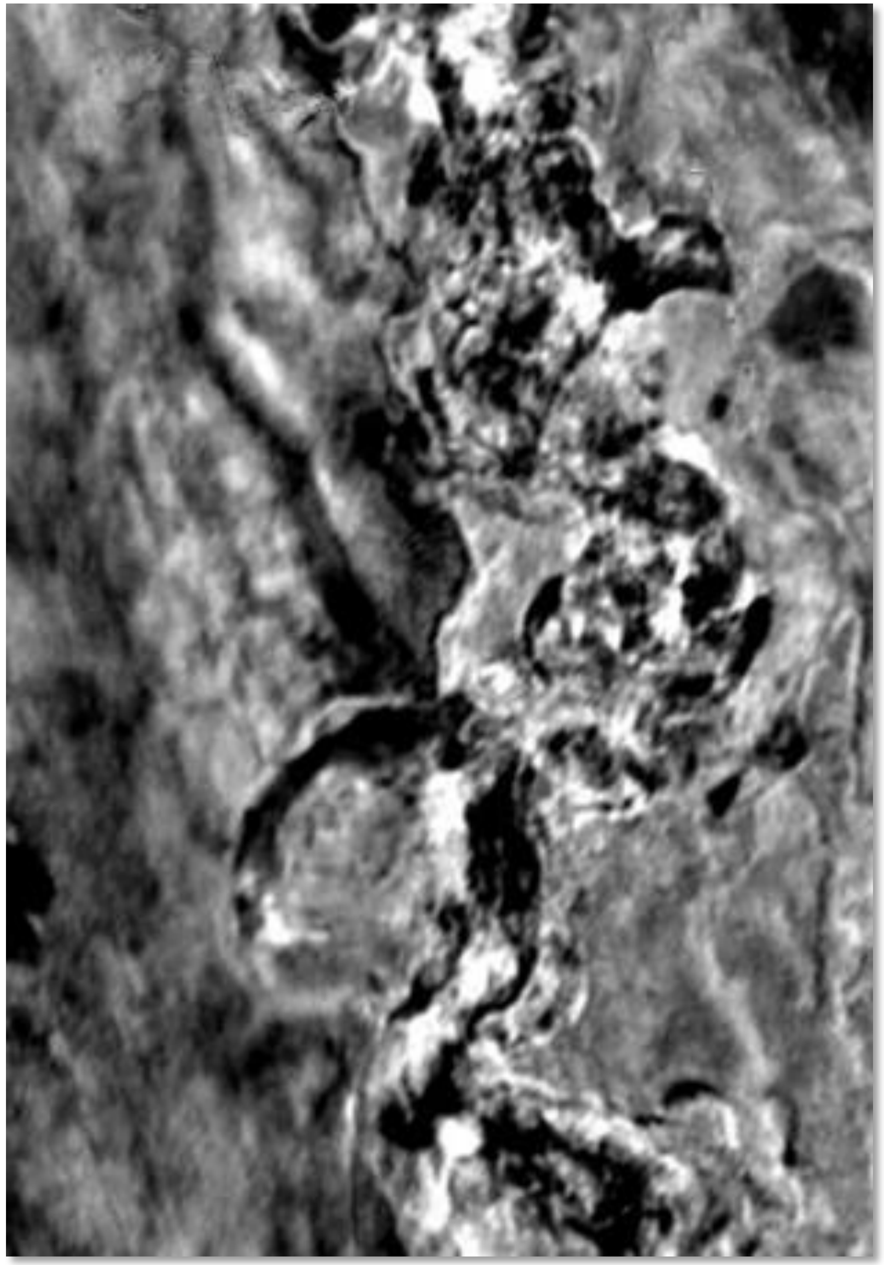
Geological Society of London
Reservoir Modeling Conference, 2015

Pyrcz, M.J., and Sech, R., 2015, When Geostatistical Reservoir Models Become Unfit for Purpose (And Ways to Avoid This): Geological Society of London, Reservoir modeling Conference at University of Aberdeen, March 4-5.

Introduction

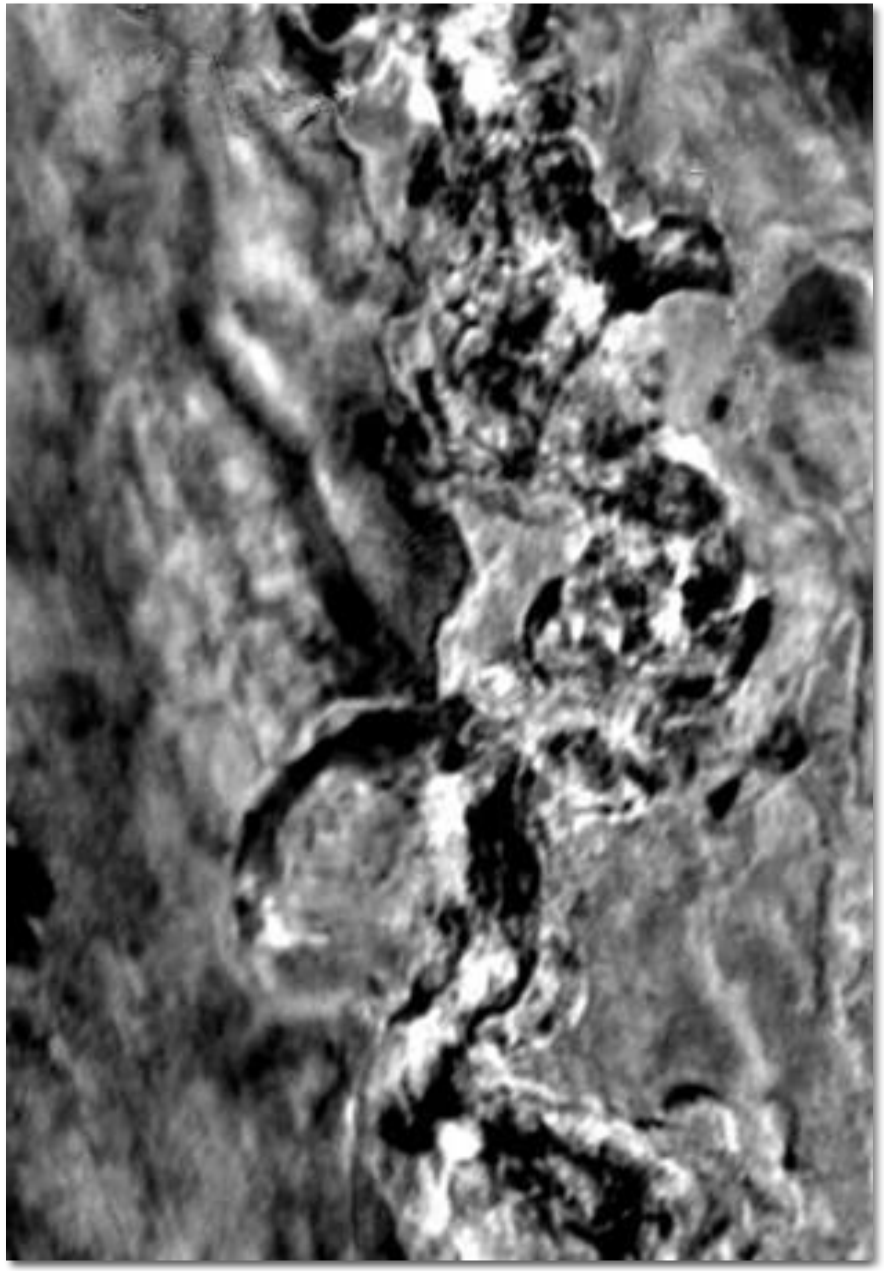
- Characterizing the spatial distribution of reservoir properties to support billion dollar investment decisions is a major challenge in the presence of typical subsurface datasets

- Sample datasets are limited across all of the scales that are represented in reservoir models



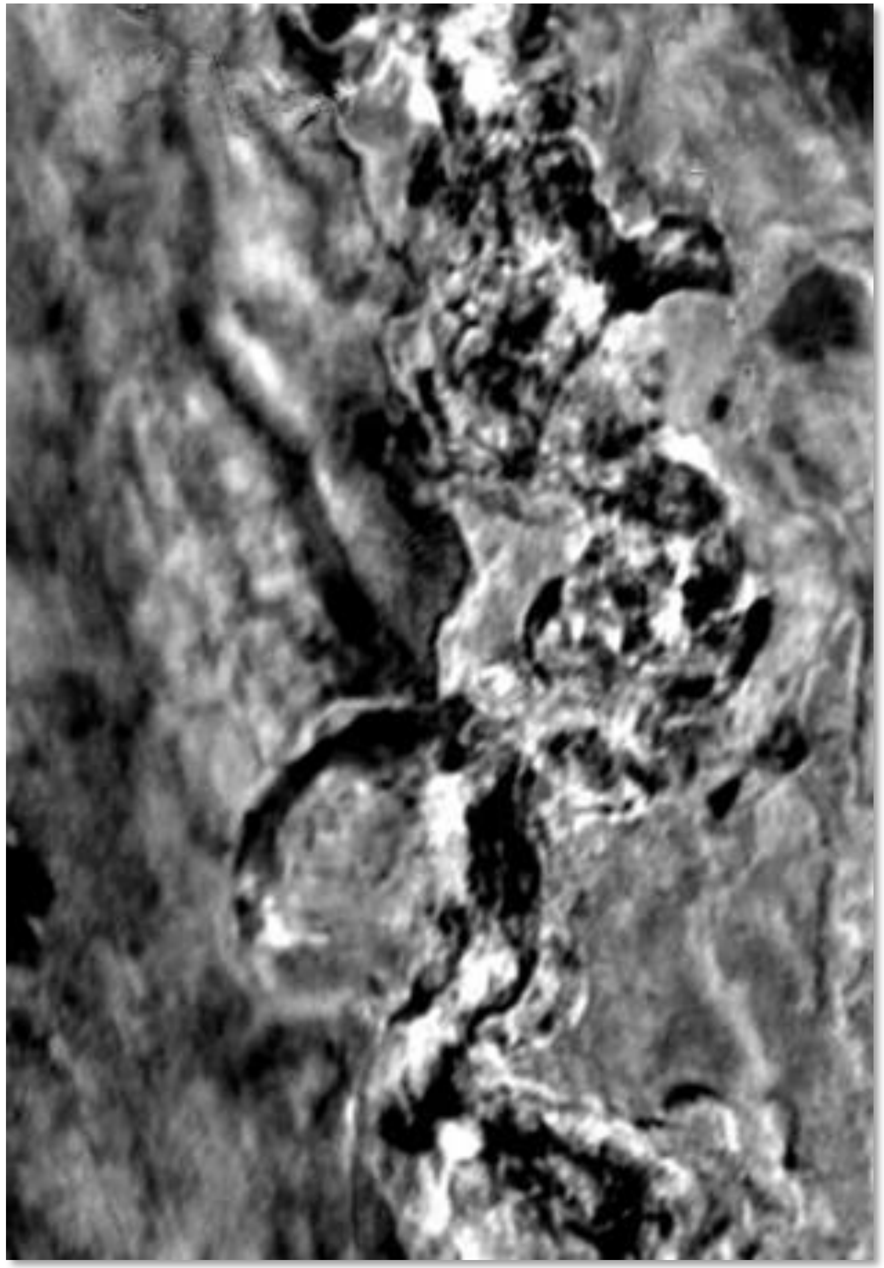
Introduction

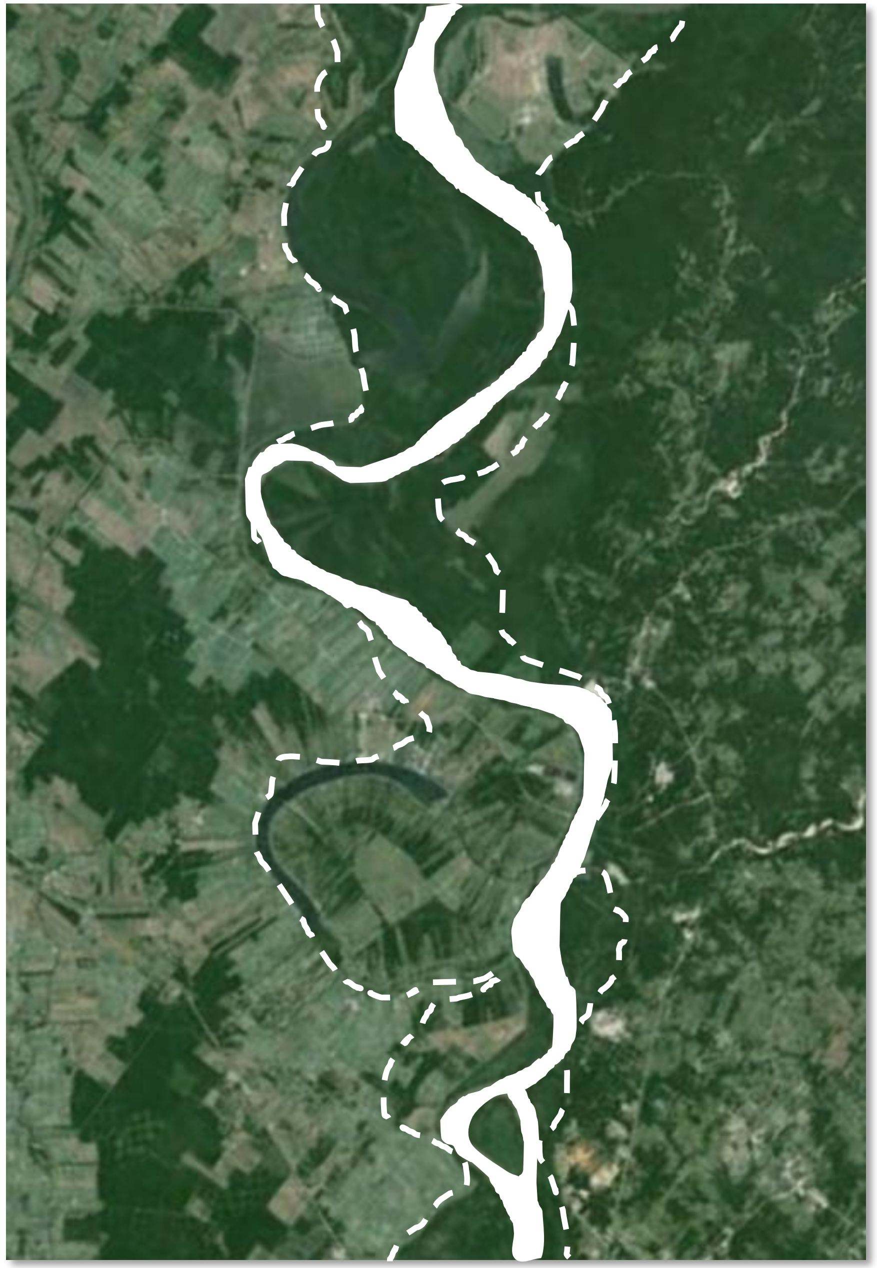
- We consider analogues to identify attributes of the reservoir which cannot be determined from seismic, well, or production data



Introduction

- Those attributes can be analysed at varying degrees of complexity

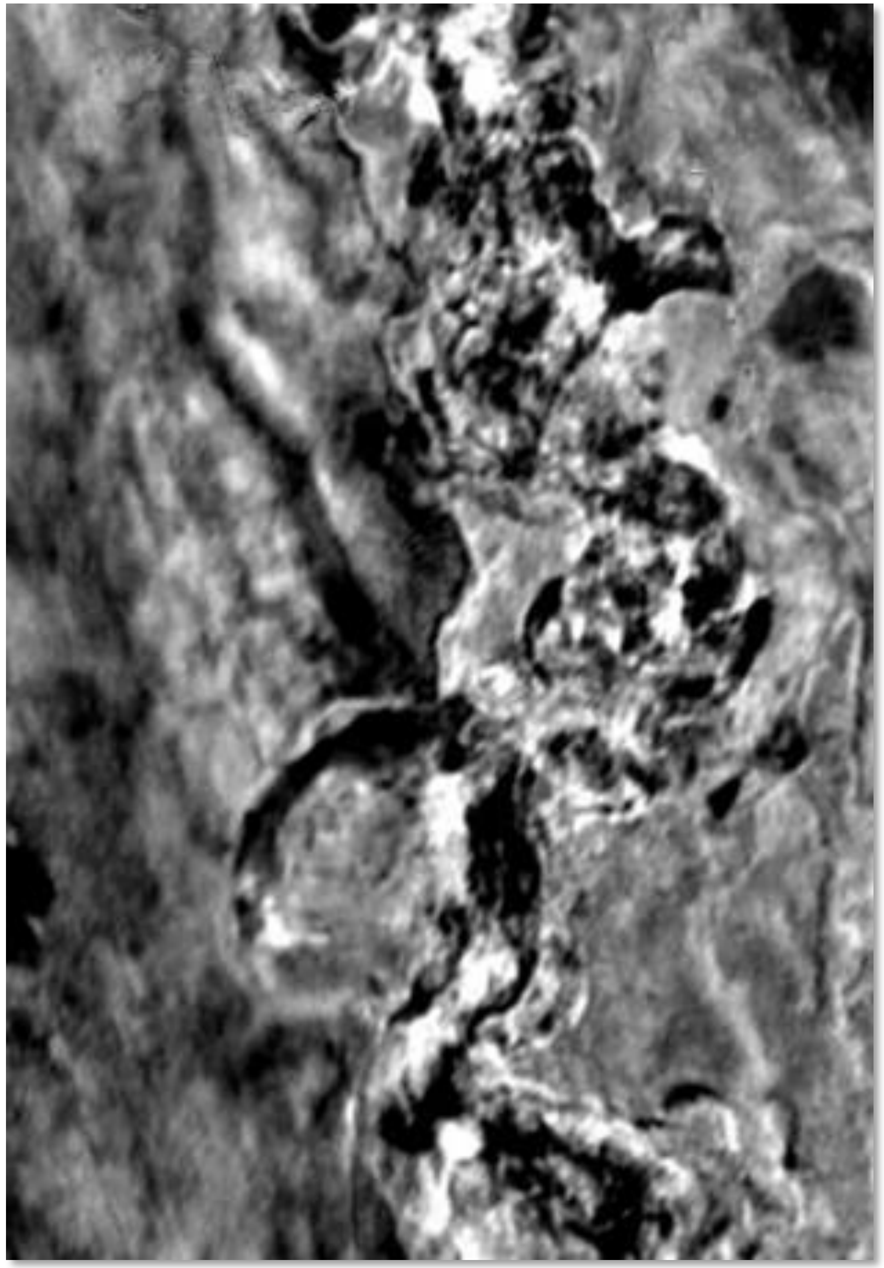




(Google Earth)

Introduction

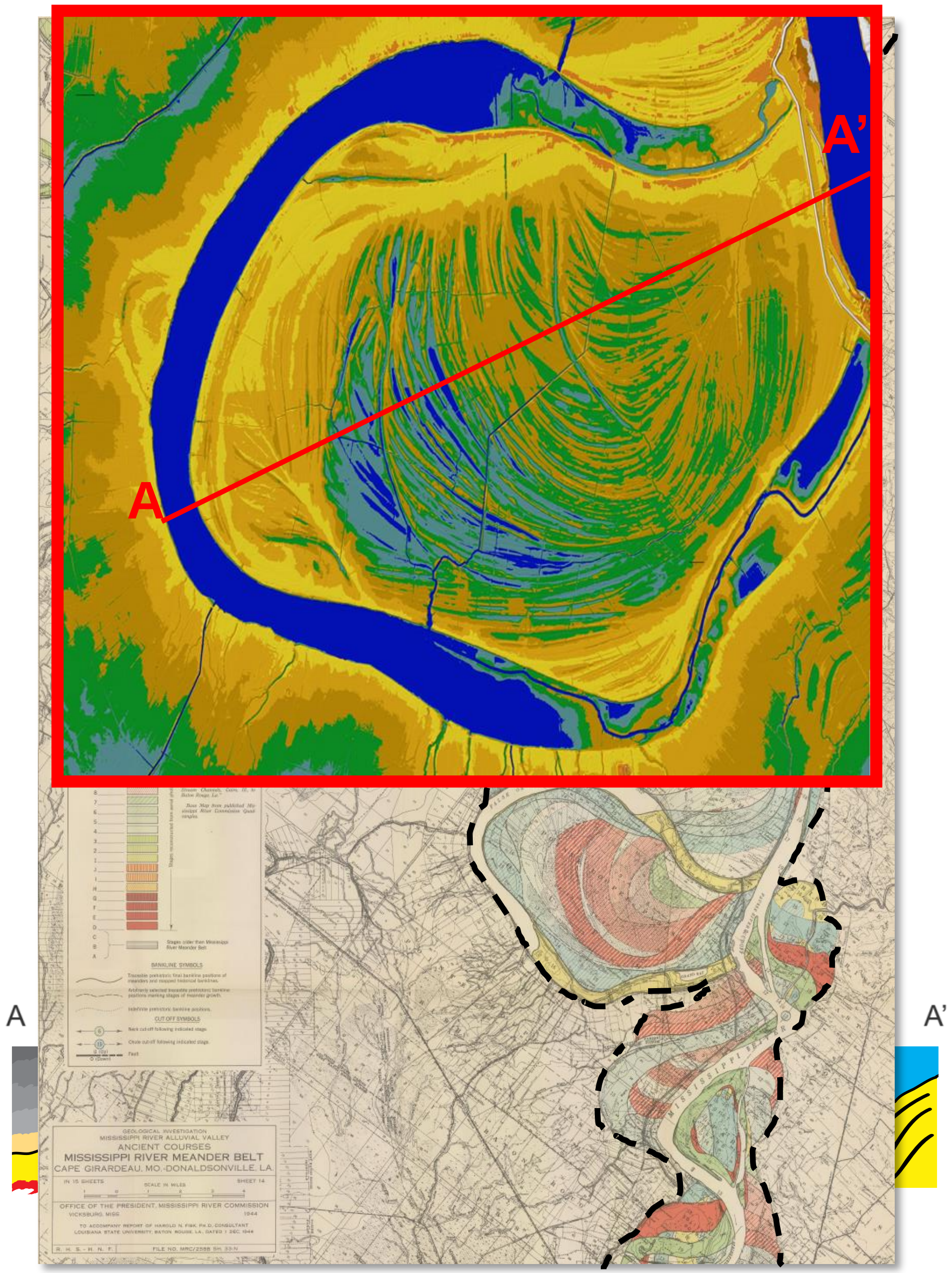
- Each feature of the preserved sandbody is the result of the interaction of various processes at various scales of time and space



(*Fisk, 1944,* Mississippi River Commission Report)

Introduction

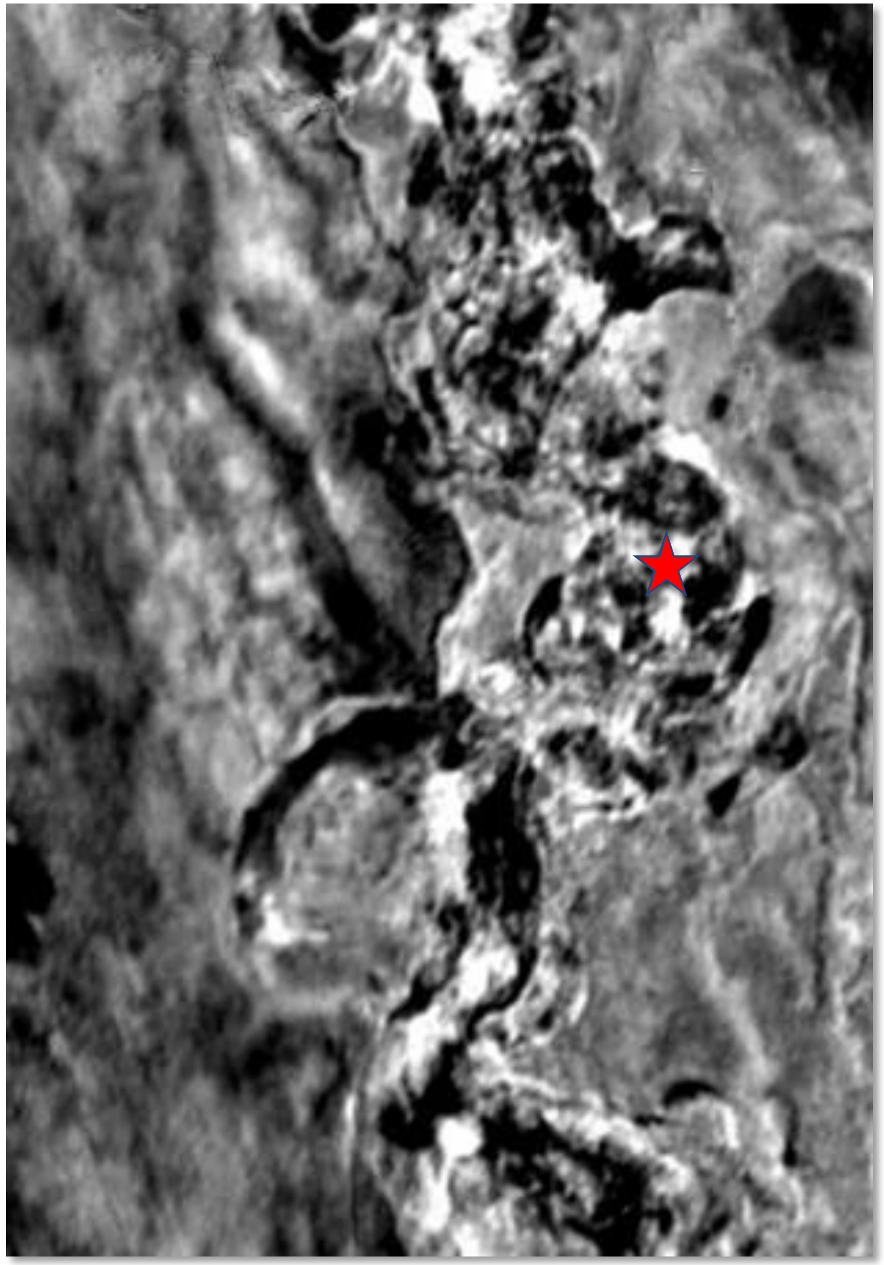
- So, we have complex spatial distributions of properties which are sparsely sampled and which are the product of processes we don't fully understand



(*Fisk, 1944,* Mississippi River Commission Report)

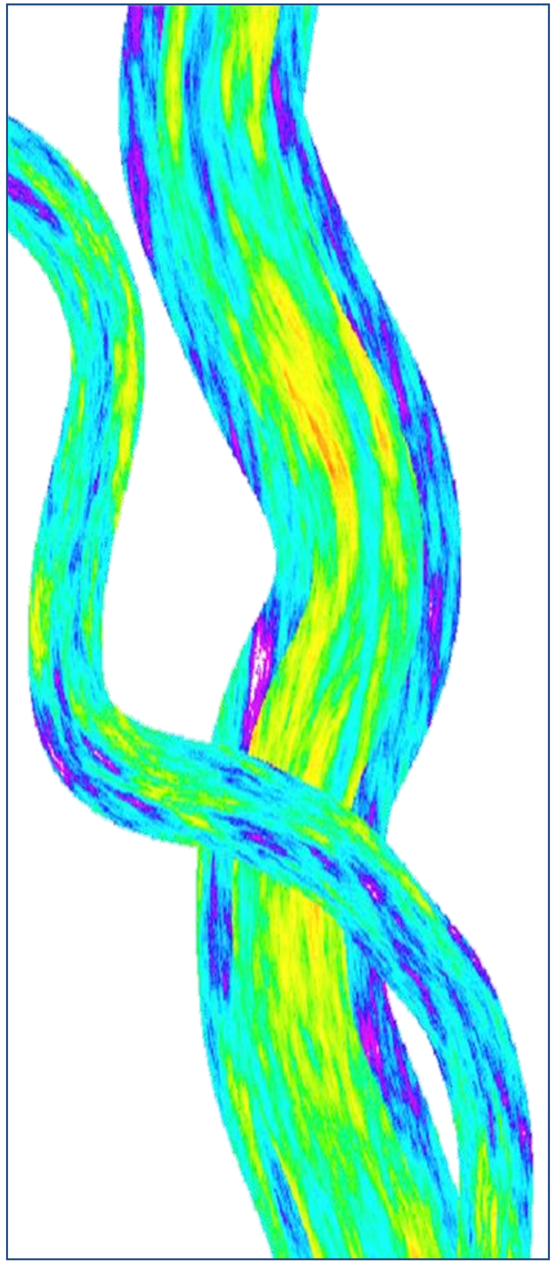
Introduction

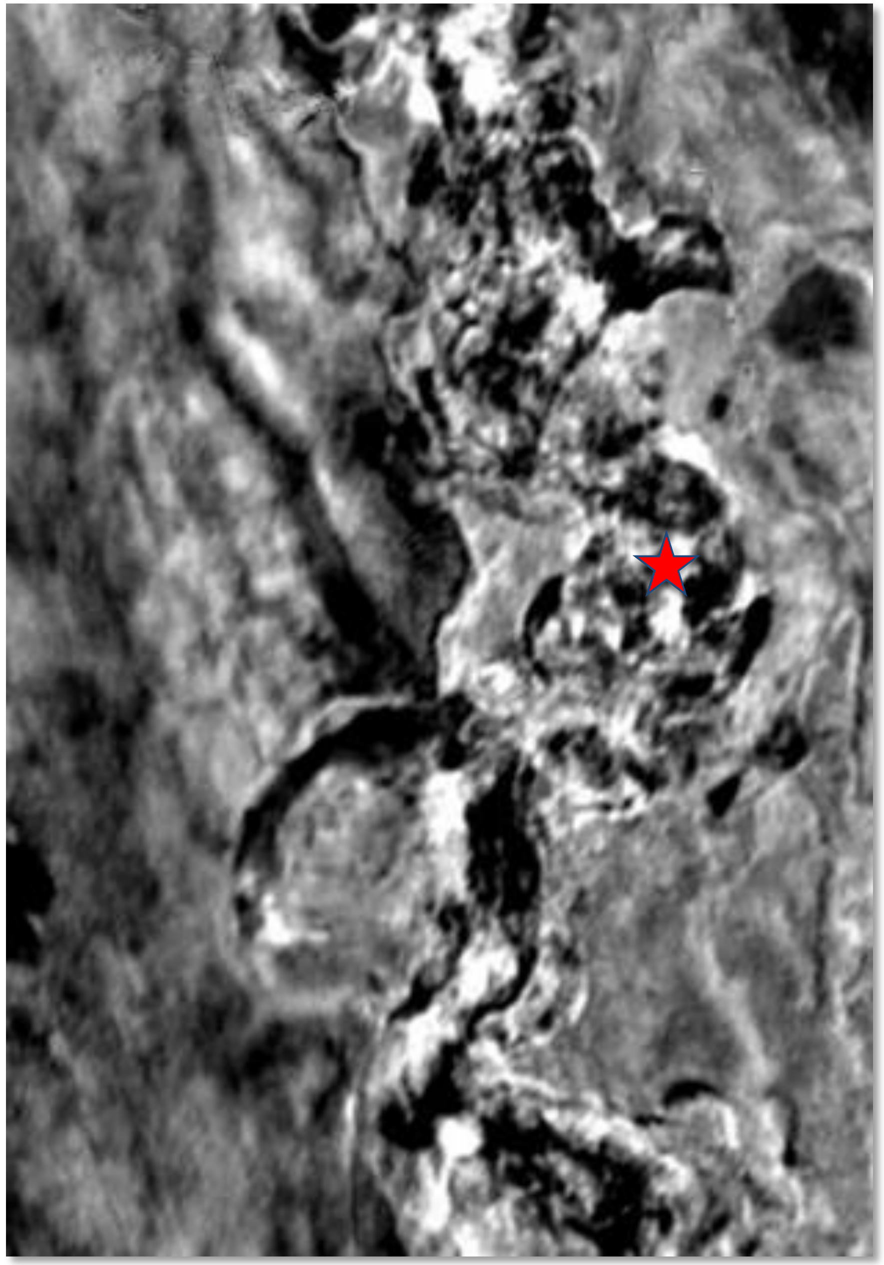
- Improved reservoir characterization can have a tangible impact on field economics
- For example, the cost of drilling a well in the setting shown here is $300 million
- Further, the development plan for this field assumes no water handling capability



Introduction

- A typical reservoir model for this EoD might depict the permeability distribution like this:
- The model offers a fine reproduction of the data statistics…but is it an acceptable representation of the geology…and does that matter?





Statement of the problem

- Geostatistical modeling is a fundamental tool for reservoir characterisation. However, we identify limitations to the use of geostatistics for the specific purpose of reservoir modeling owing to the following reasons:
  - **Using it wrong!** abuse, misuse, and misunderstanding of the fundamental principles of geostatistics
  - **Unreasonable expectations**! arising from inadequate appreciation of the limitations of the technology
  - **Instead of geology**! ignorance to the requirement for the integration of conceptual geological knowledge into the reservoir modeling process
- This talk will address why these issues arise, how they can be mitigated, and what directions research in geostatistical reservoir modeling is taking

Geostatistical reservoir modeling - talk outline

1. Supported uses
2. Common abuses
3. Misunderstandings
4. Fit for purpose
5. Future research directions

Geostatistical reservoir modeling - talk outline

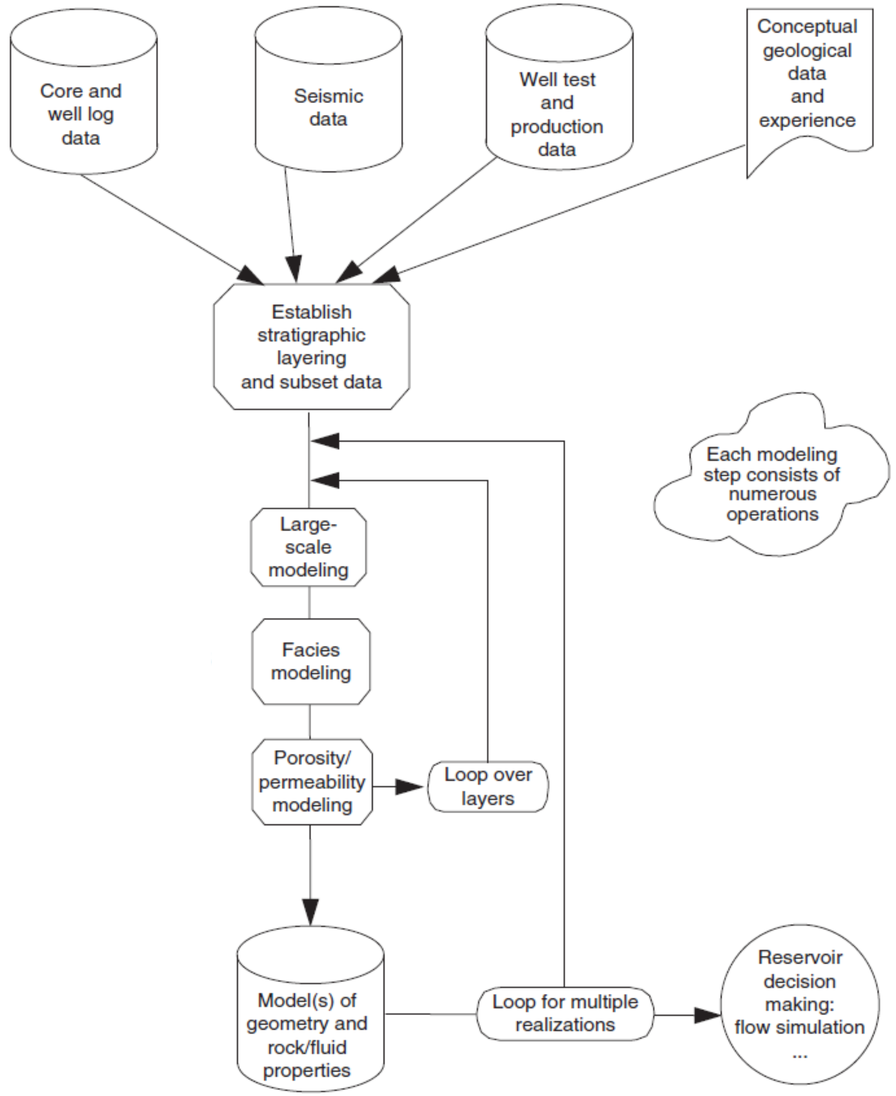
1. **Supported uses**
2. Common abuses
3. Misunderstandings
4. Fit for purpose
5. Future research directions

- Numerical description of heterogeneity consistent with measured data
- Integration multiple data sources
- Accounting for scale
- Multiple realizations to model uncertainty
- Objectivity: repeatable, measurable
- Robust treatment of probability
- Practical: user friendly, intuitive, tractable

Geostatistical reservoir modeling is *the* practical choice for subsurface geological characterization

- Intuitive, transparent, repeatable
- Flexible, conditional heterogeneity
- Widely available in vendor and academic software
- Taught in various academic institutions and recognized in industry
- A wealth of published workflows and results
- Supports optimum decision making
- Better way? Add it to the tool box…

(Pyrcz and Deutsch, 2014)



Practical approach with theoretical underpinnings and demonstrated track record.

Geostatistical methods can account for scale variability in input data

Accounting for Scale

- All statistical inputs have implicit volume support

  Dispersion variance is a generalized volume-based variance

$$D^2(v,V) = \overline{\gamma}(V,V) - \overline{\gamma}(v,v)$$

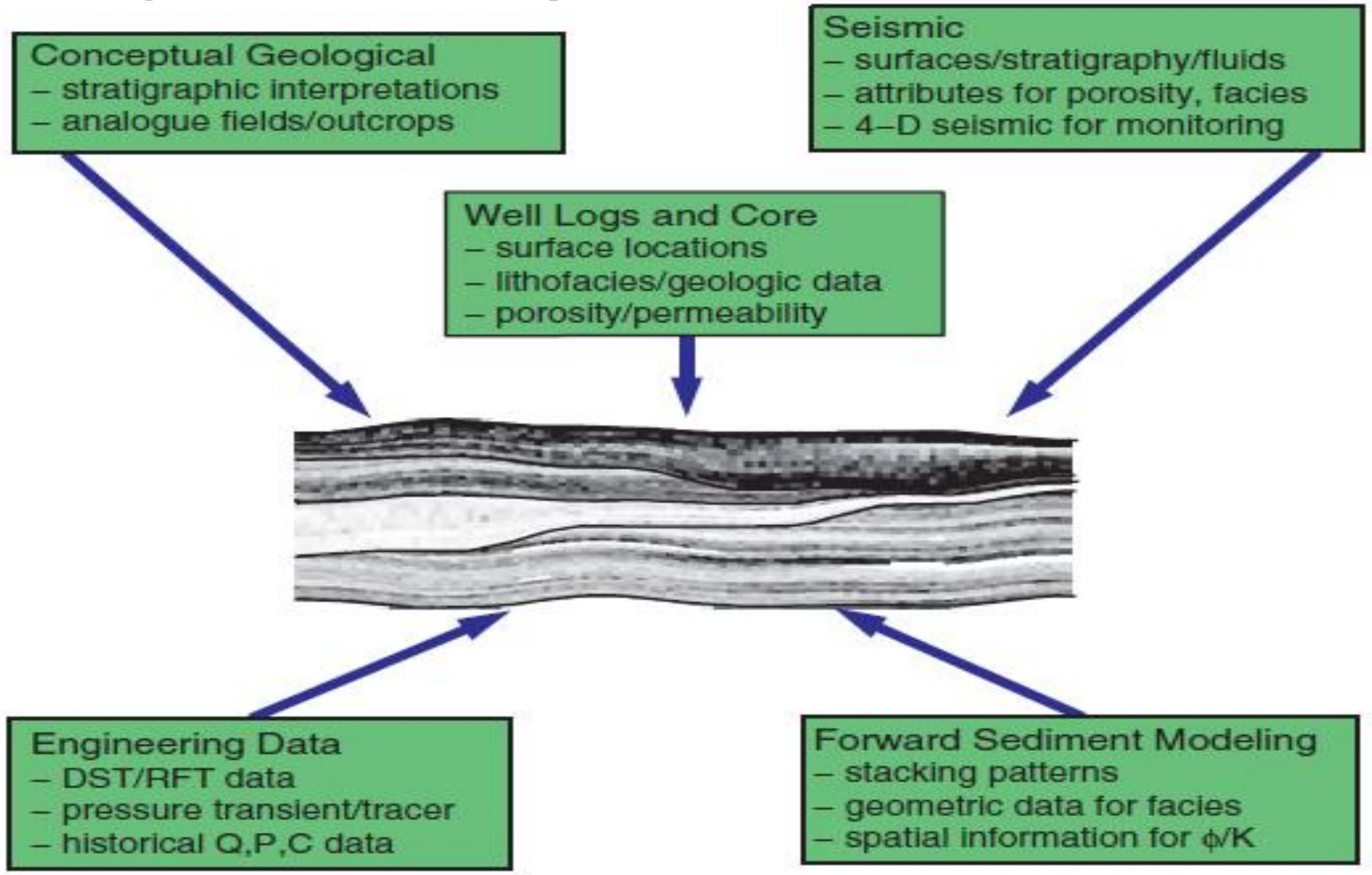
- Kriging system is general, supports volume integrated variograms (gamma bar)

  Gamma bars may be applied directly

$$\overline{\gamma}\left(v(\mathbf{u}), V(\mathbf{u}')\right) = \frac{1}{v \cdot V} \int_{v(\mathbf{u})} \int_{V(\mathbf{u}')} \gamma(y - y')\, dy dy'$$

Many of the estimation and simulation routines are general – support any scale.

Geostatistics can integrate multiple data sources



Various types of data that may be integrated into reservoir models (Pyrcz and Deutsch, 2014)

– Enablers: Conditional to soft and hard data, Bayesian approaches, multivariate relationships, hierarchical, explicit scale, inversion workflows

Various updating, combination, merging and soft data approaches are available.

Geostatistics allows for a quantitative description of geology

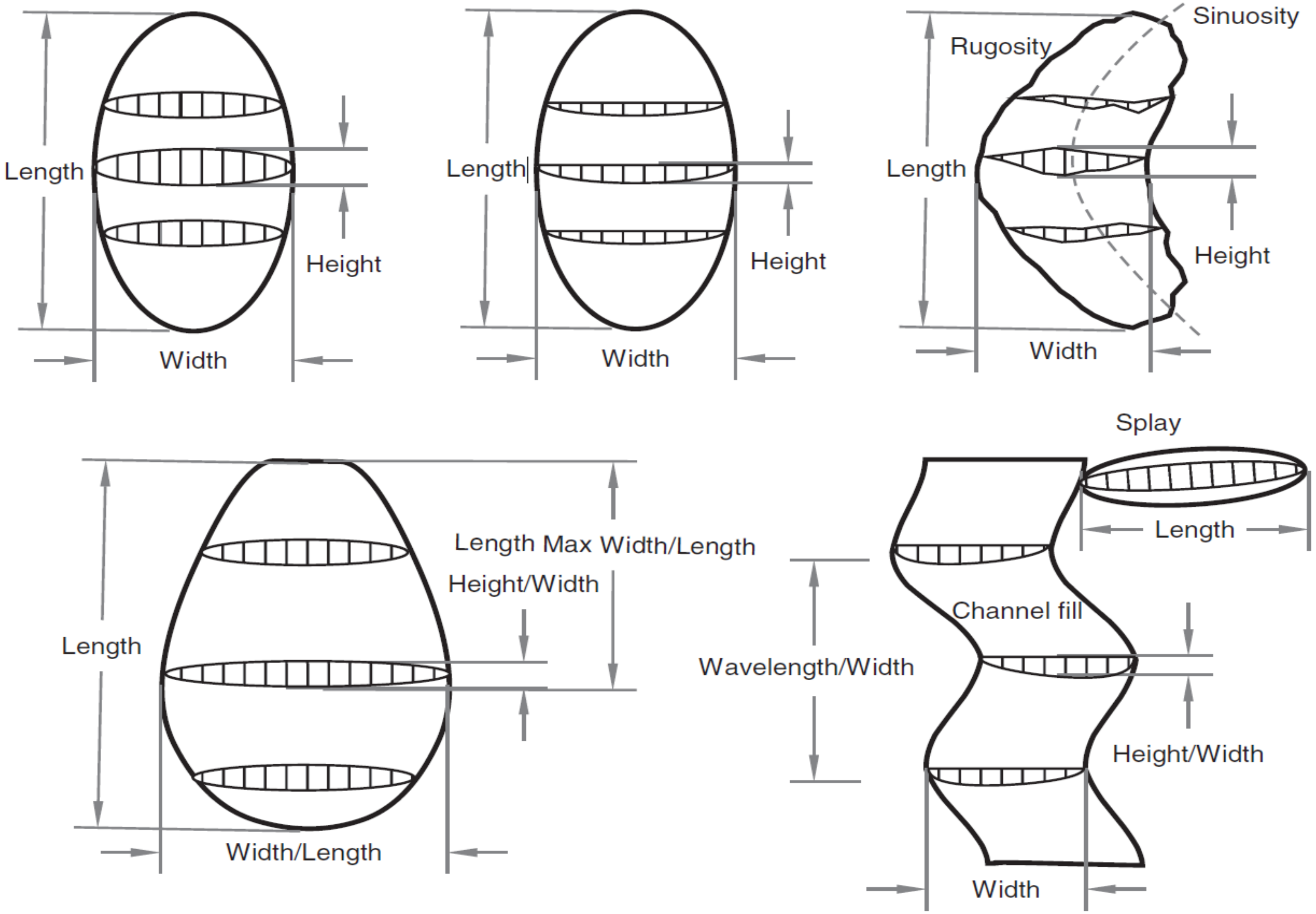
Quantitative Geology Workflow

- Repeatable
- Transparent
- Defendable

Characterization

↓

Reproduction



Various examples of object-based geometric parameterization (Pyrcz and Deutsch, 2014)

Explicit decision to parameterize (abstract) geology and then we can test significance.

Geostatistics provides a robust treatment of probability

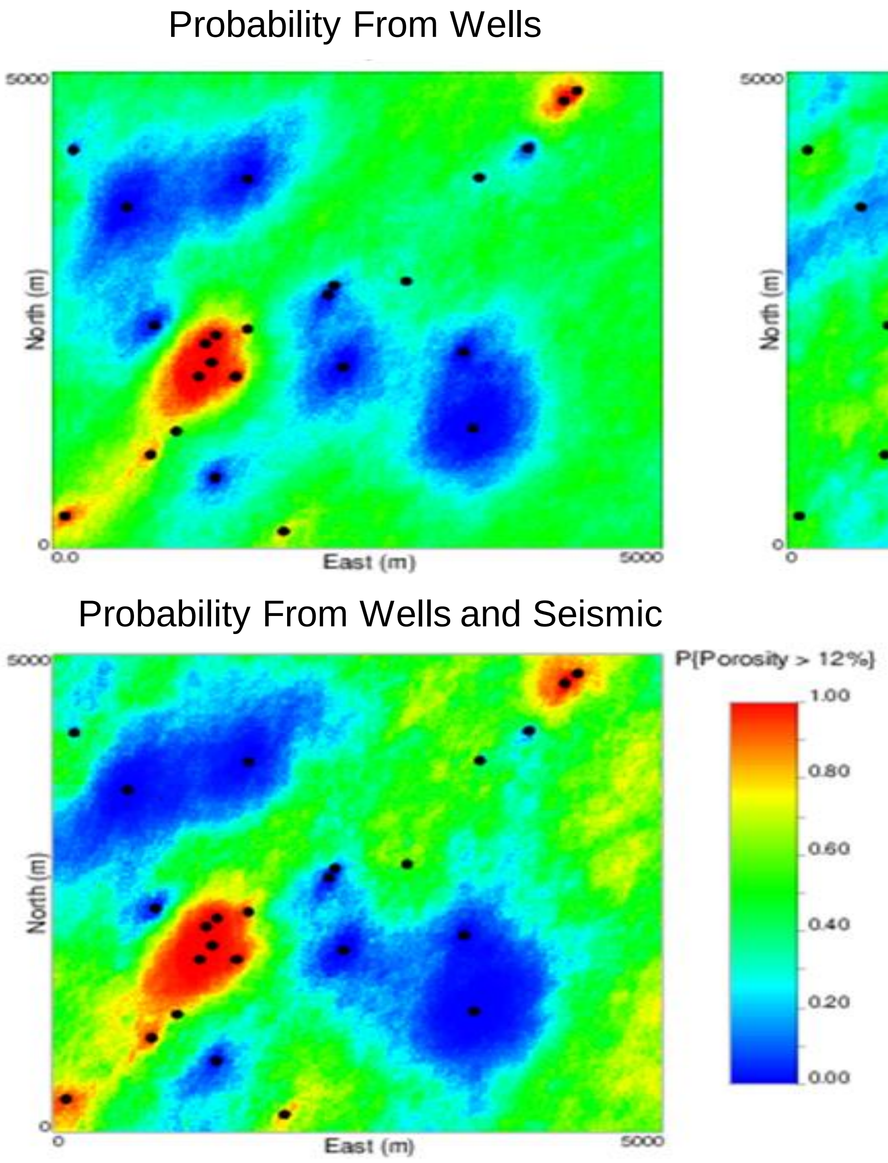
Robust Treatment of Probability

- Methods to calculate the required probabilities
- Probability-based workflows

Probability Aggregation

Bayesian Updating

Probability Combination



Probability combination for well and seismic derived information
(Pyrcz and White, in press)

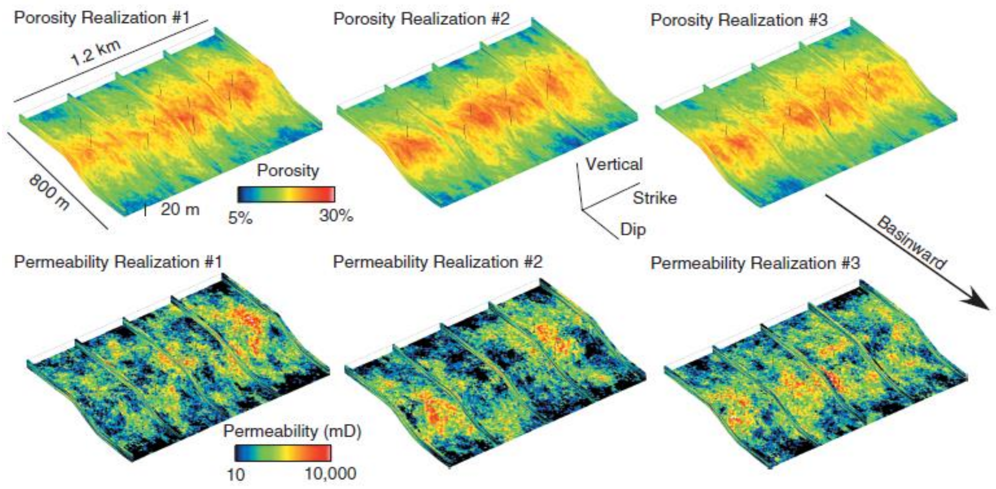
Tools for calculating the required probability distributions.

Geostatistics provides an uncertainty model

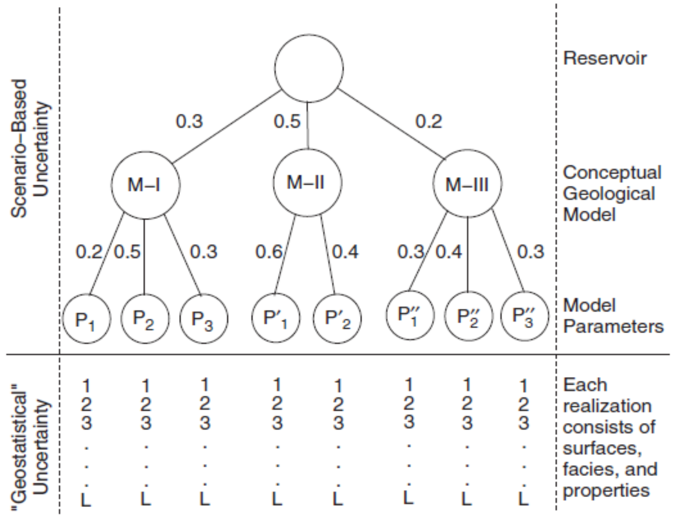
Multiple Realizations to Account for Uncertainty

– Efficient calculation of scenarios and realizations

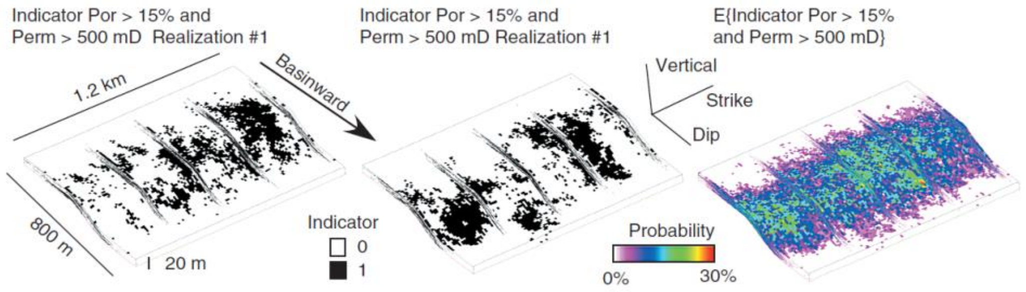
Summarization, post-processing, transfer functions



Multiple porosity and permeability realizations (Pyrcz and Deutsch, 2014)



Uncertainty model through scenarios and realizations (Pyrcz and Deutsch, 2014)



Local uncertainty model based on multiple realizations (Pyrcz and Deutsch, 2014)

Efficient **exploration of uncertainty through scenarios and realizations.**

Supported Uses Conclusions

- The bar is high for expectation / fundamental pillars of geostatistics
  1. Conditional
  2. Heterogeneity
  3. Uncertainty
- Inevitable compromises
- If you have you got something better?
  – Can you handle all of this practically?
  – If it does – you are one of us!
  – We’ll make space in the tool box.
  – Optimization-based, indicator-based, multiple point-based, process-mimicking

Geostatistical reservoir modeling - talk outline

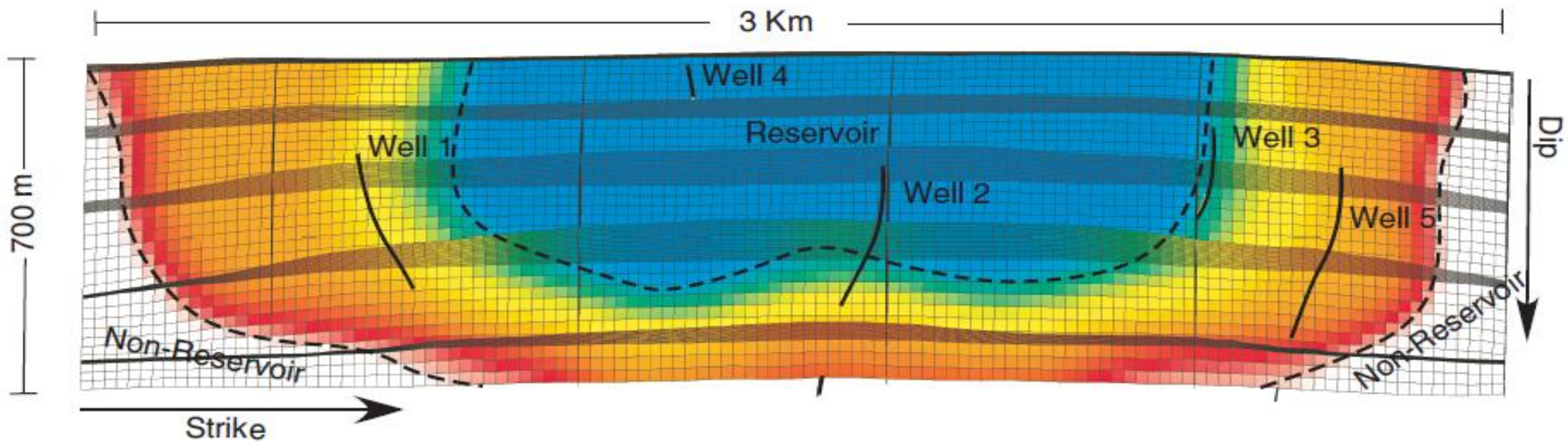
1. Supported uses
2. **Common abuses**
3. Misunderstandings
4. Fit for purpose
5. Future research directions

- Geologist in a box
- Statistical representativity
- Precisely honor inputs
- Fully geologic realism – limited statistics, limited constraints, temporal
- Complete geologic realism
- Complete uncertainty

Geostatistics does not create geologic knowledge

Cannot Replace Geologic Interpretation

- Slavishly honors inferred statistics and trends
- Reproduces data integrations at data locations
- **Worst Practice**: conduct reservoir modeling as a statistical data fitting study
- **Best Practice**: focus on expert geologic mapping



Geological concept driven trend model to constraint reservoir quality away from well data (Pyrcz and Deutsch, 2014).

Model assumes stationarity except data conditioning, secondary information and trends.

Geostatistics will propagate sampling bias unless corrected

Correct for Biased, Non-representative Sampling

- Slavishly honors inferred statistics and trends
- **Worst practice** is to use poorly chosen regions to for inference and modeling with inferred statistics
- **Best practice** is to use geologic and engineering constraints to segment the subsurface into unique populations for investigation
- **Worst practice** is to rely on naïve data statistics
- **Best practice** is to model the input statistics
- **Worst practice** is to rely on a stationary statistical model
- **Best practice** is to constraint the statistical model with geological concept driven trends

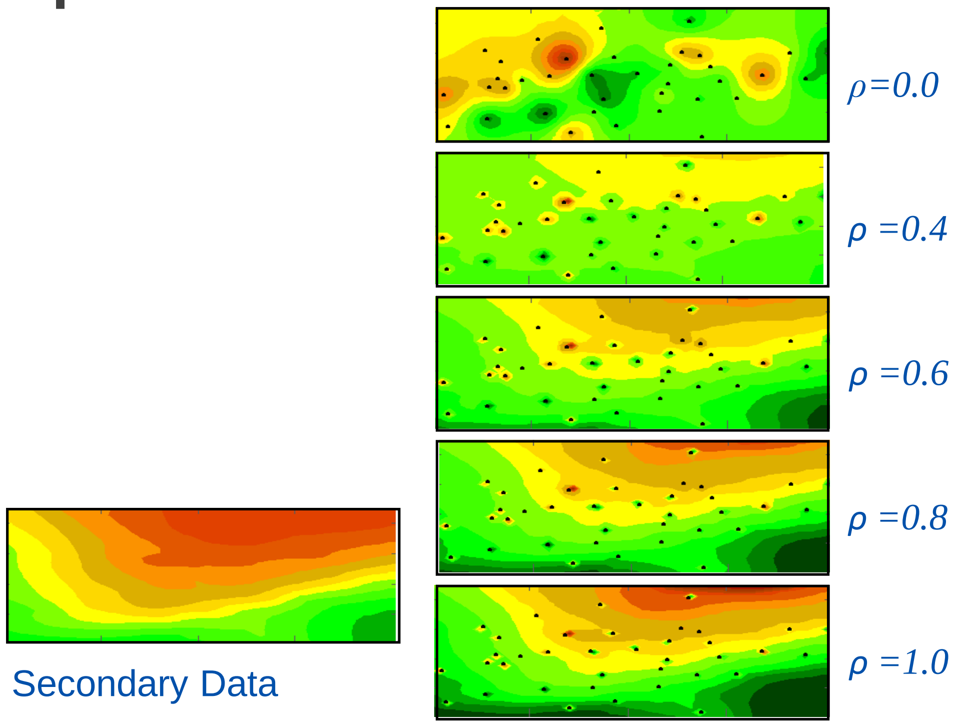
Must model and take ownership the inputs.

Geostatistics may not perfectly honor the input statistics

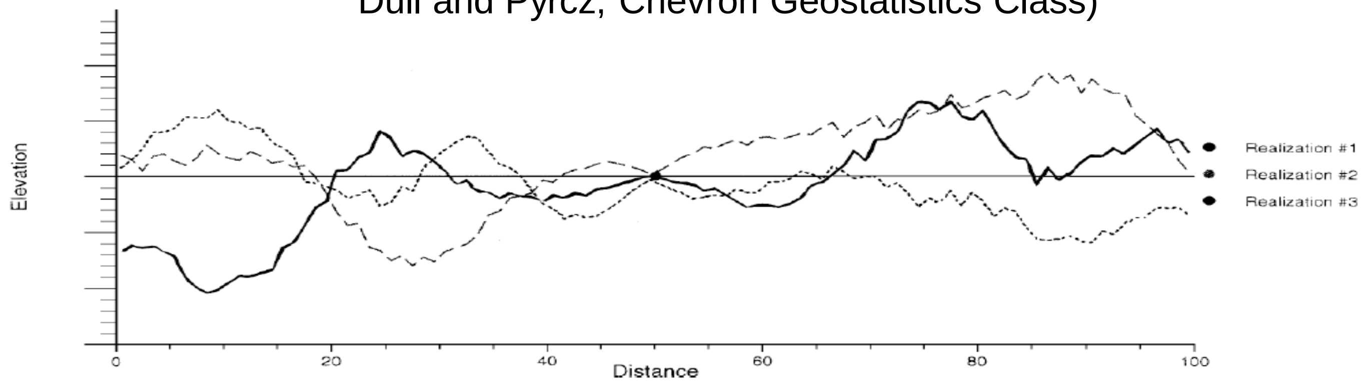
Limits to Precisely Honoring of Input Statistics

- Ergodic Fluctuations
  - Input statistics fluctuate, can be predicted
- Contradictions
  - Ability to honor various inputs
  - No explicit check for contradictions
  - Conditioning priority is implicit
- Artifacts
  - Some known artifacts e.g. P-field, collocated cokriging etc.

Expert judgment is critical



Impact of contradiction between primary, secondary and cross spatial relationships. (Meddaugh, Dull and Pyrcz, Chevron Geostatistics Class)



P-field simulation honors data as local minima or maxima. (Pyrcz and Deutsch, 2001)

You need to understand what is happening under the hood.

Geostatistics will not always provide complete geologic realism

Complete Geologic Realism

– Level of required realism depends on the modeling question / modeling purpose
– Use of a limited set of input statistics

Abstraction

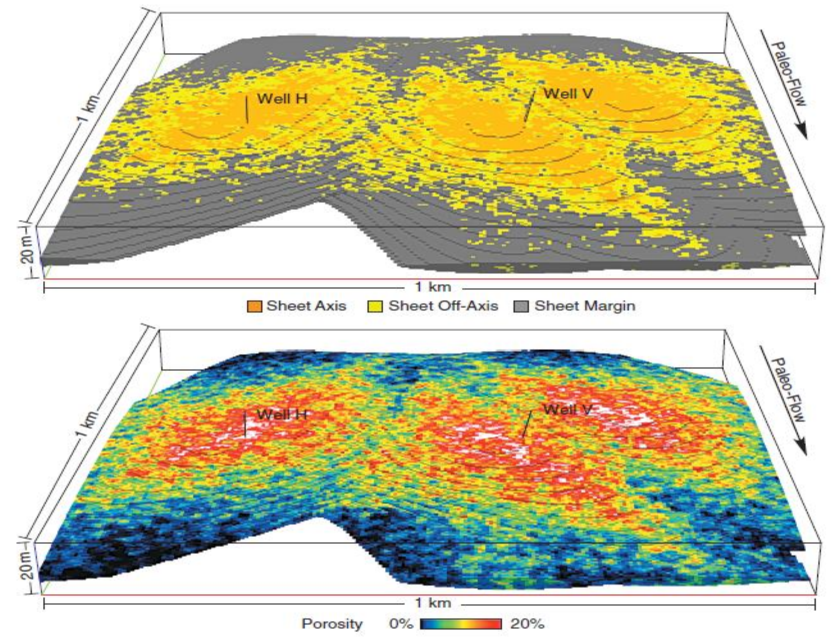
Stationarity

Transparent, defendable – objectivity?

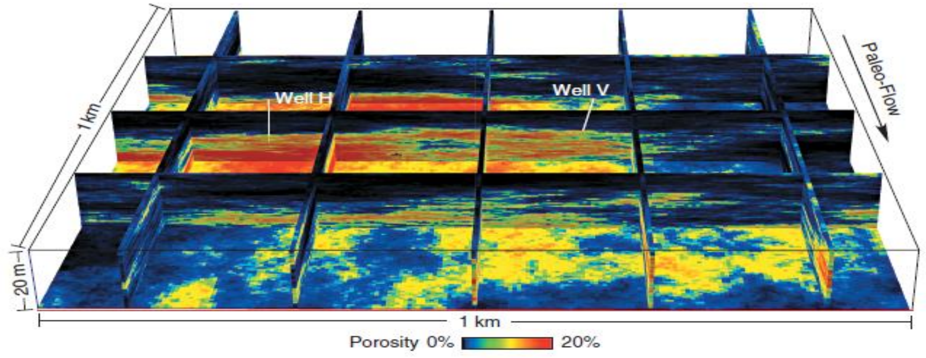
Characterization from data and concepts → Reproduction in model → Decision Making

– Features beyond the imposed statistics approach maximum entropy

Un-conservative flow response.



Deepwater lobe reservoir model with geometries, facies and trends. (Pyrcz and Deutsch, 20014)



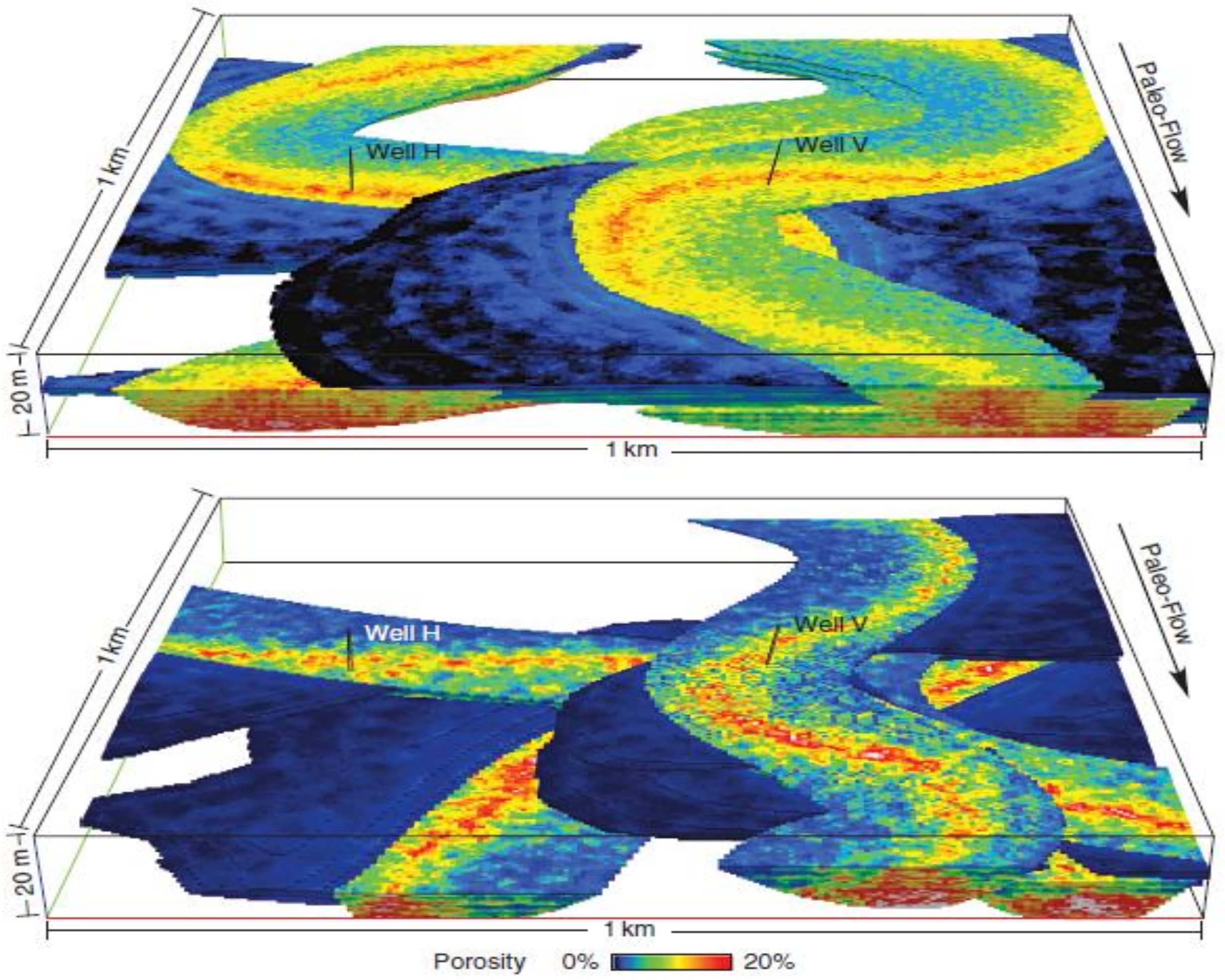
Stationary variogram-based model. (Pyrcz and Deutsch, 20014)

Statistical characterization and reproduction within geologic framework is powerful.

Geostatistics cannot capture all possible uncertainties

Complete Uncertainty Model

- Level of subjectivity in estimation and uncertainty modeling
  - Geologic mapping and concepts are central
- Geologic concept uncertainty must be explicitly defined
  - Scenarios of framework, reservoir types, trends
- Practical decision to limit investigation of uncertainty sources
  - Focus on those assessed to be most important
  - Uncertainty in the uncertainty is not useful
- Uncertainty is a model
  - Cannot predict black swans



Deepwater channel reservoir model with 2 realizations from the with various uncertianties.
(Pyrcz and Deutsch, 20014)

There is no “true” uncertainty.

Common Abuses Conclusions

- Sound geology is fundamental
- Inexperienced / black box use is dangerous
- Compromises must be understood
- Must know when to stop

Geostatistical reservoir modeling - talk outline

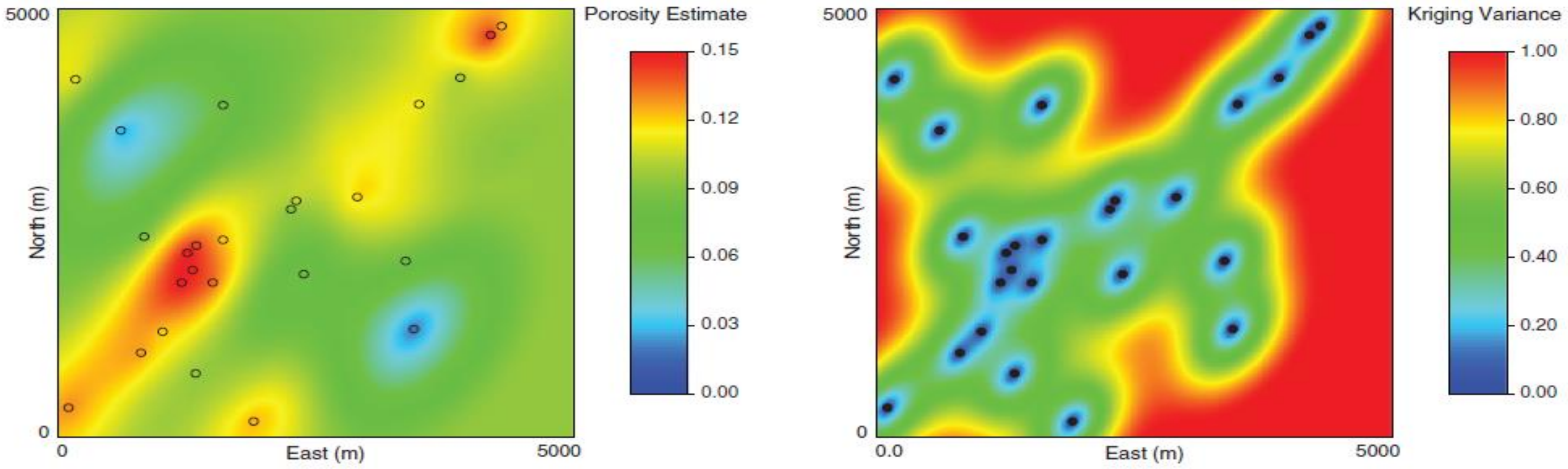
1. Supported uses
2. Common abuses
3. **Misunderstandings**
4. Fit for purpose
5. Future research directions

- Reserves – potential issues / different drivers
- Avoid Making Decisions
- Use of a Single Realization
- Misuse of Ranking
- Models are Frozen

Geostatistics may not be the right method for reserves

Reserves

- The case for geometric criteria for resources and reserves classification
  - Deutsch and others (2007), understandable by the public, driven by experience
- Modeling decisions within a purely geostatistical approach may have significant, unexpected impact on results
  - Nugget effect is important and hard to infer
- Could use concepts of spatial continuity to calibrate geometric approaches
  - Concept of kriging estimates and estimation variance



Kriging estimates and standardized kriging variance for porosity (Pyrcz and White, 2014).

Geostatistics may be used to support a geometric reserves method.

Geostatistical model decisions cannot be avoided

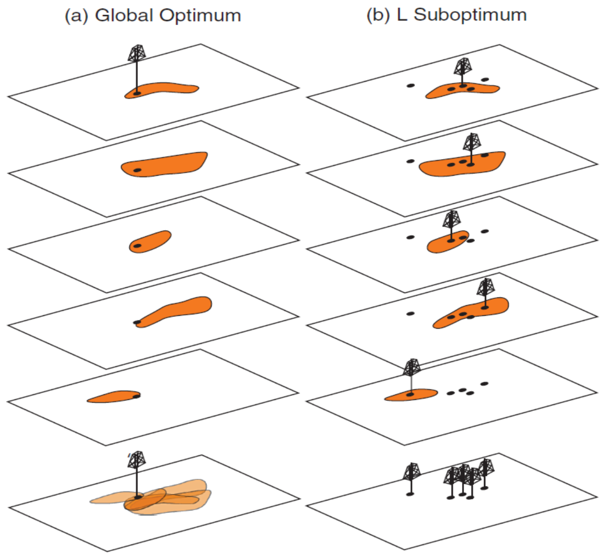
Avoiding Making Decisions

- Often the null choice is a strong decision – we must always make a choice
  - No Trend -> good quality reservoir away from wells fills the AOI
  - No Training Image -> 2 point continuity and maximum entropy with optimistic flow
  - No Reference Distribution -> preferentially sampled wells provide representative statistics
  - No Facies -> porosity and permeability mixing throughout AOI
  - No Correlation -> porosity and permeability are potentially independent
- Better to make a decision then document and defend
- Than to:
  - rely on a default
  - rely on an implicit model assumption
  - rely on a very general stationarity assumption

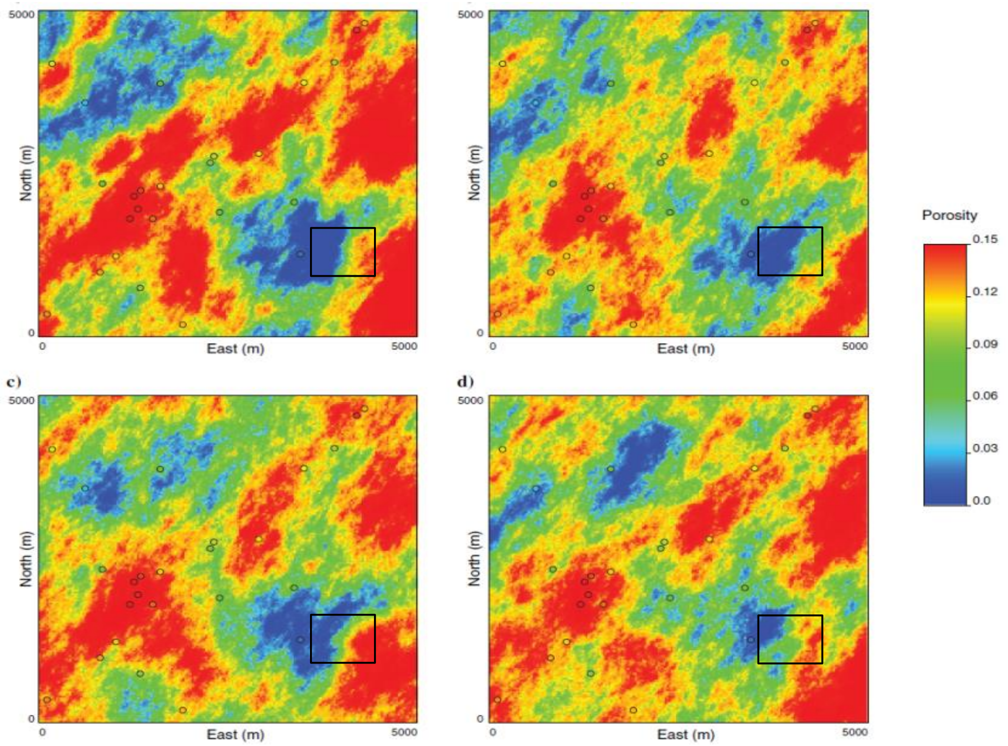
Explicitly make and document choices and integrate uncertainty if needed.

Geostatistical uncertainty requires consideration of multiple realizations

- Use of a Single (or Too Few Realizations)
  - Must consider scenarios and realizations jointly
    - Stochastic islands
    - Sufficient models for local distributions of uncertainty (more than H, M, L)



Well site selection with single and multiple realizations (Pyrcz and Deutsch, 2014).



Multiple porosity realizations (Pyrcz and White, 2015).

  - Integration of multiple realizations to evaluate joint uncertainty model
    - Results in global optimum vs. “L” suboptimal results

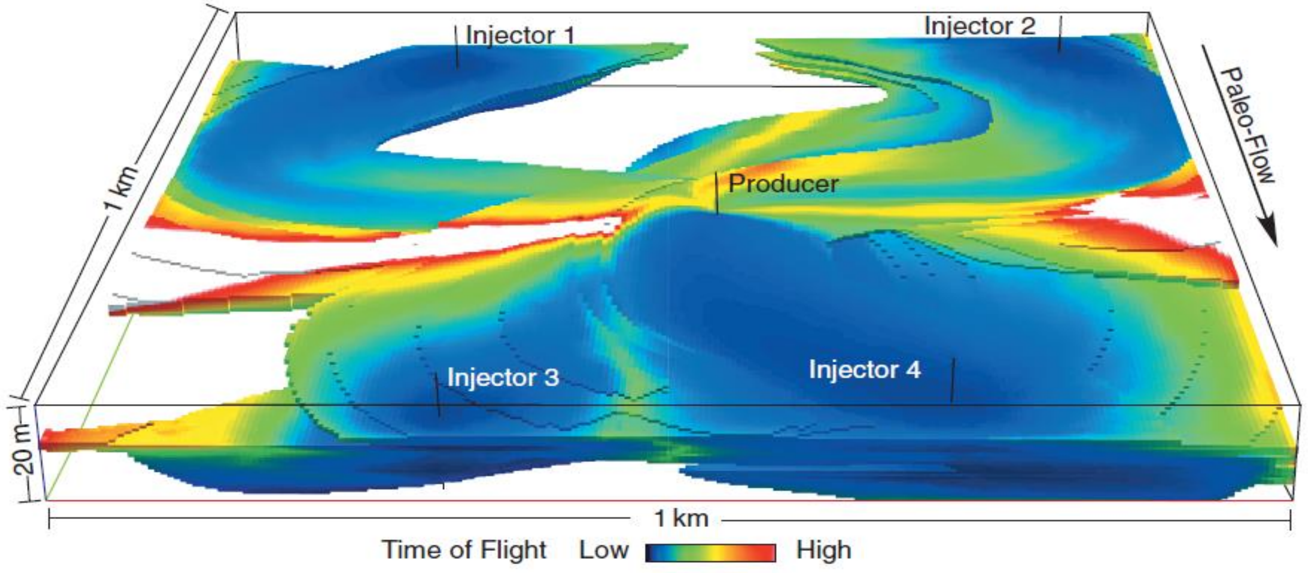
Evaluate uncertainty and optimize decision making jointly over realizations.

Geostatistical ranking should be avoided or used with care

Misuse Ranking

- Model ranking is the use of an efficient proxy to order realizations and to select realizations for the complete transfer function
- Ranking precision is variable
- Model ranking is only valid for the specific ranking criteria

  Ranks are “sticky” and abused
- Ranking criteria must be documented with rank scores
- Ranking must be repeated for a new question
- When transfer function is “fast enough” apply all models



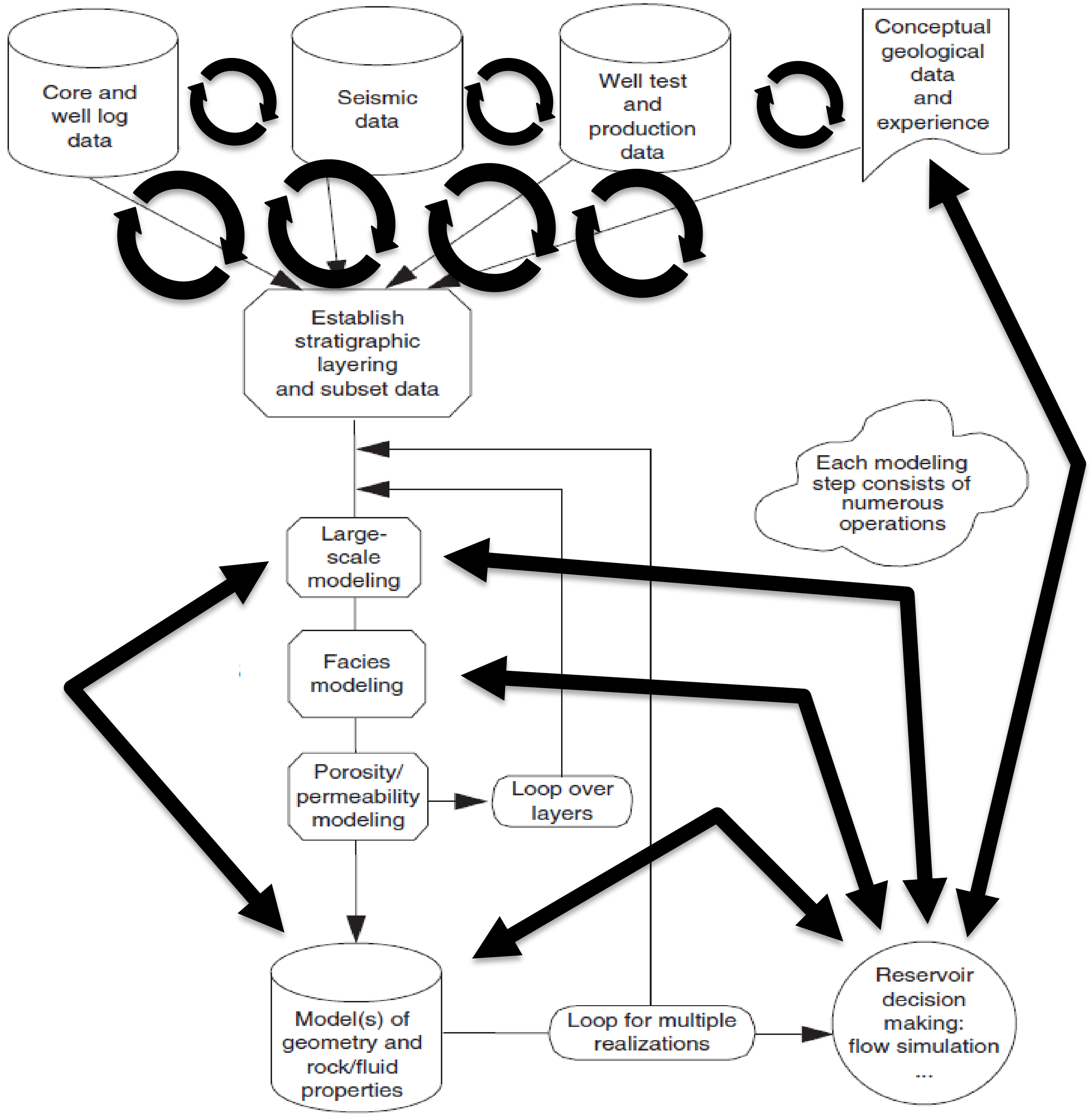
Time of flight based on streamline simulator for model ranking (Pyrcz and Deutsch, 2014).

When possible use all realizations and calculate uncertainty on-the-fly.

Geostatistical models are living assessments of reservoir

Models Should Either be *Disposable* or *Evergreen*

- Cannot freeze the reservoir model
  - New information
  - New Project Objectives / Questions
- Modeling is empirical
  - A *lens* to help understand the reservoir
  - Top-down, fit for purpose approaches
- The reservoir model is not often the final product
  - *Decision support* is the product
- Workflows must support the concept of the evergreen model.



The geostatistical model is primarily a tool for decision support.

Misunderstandings Conclusions

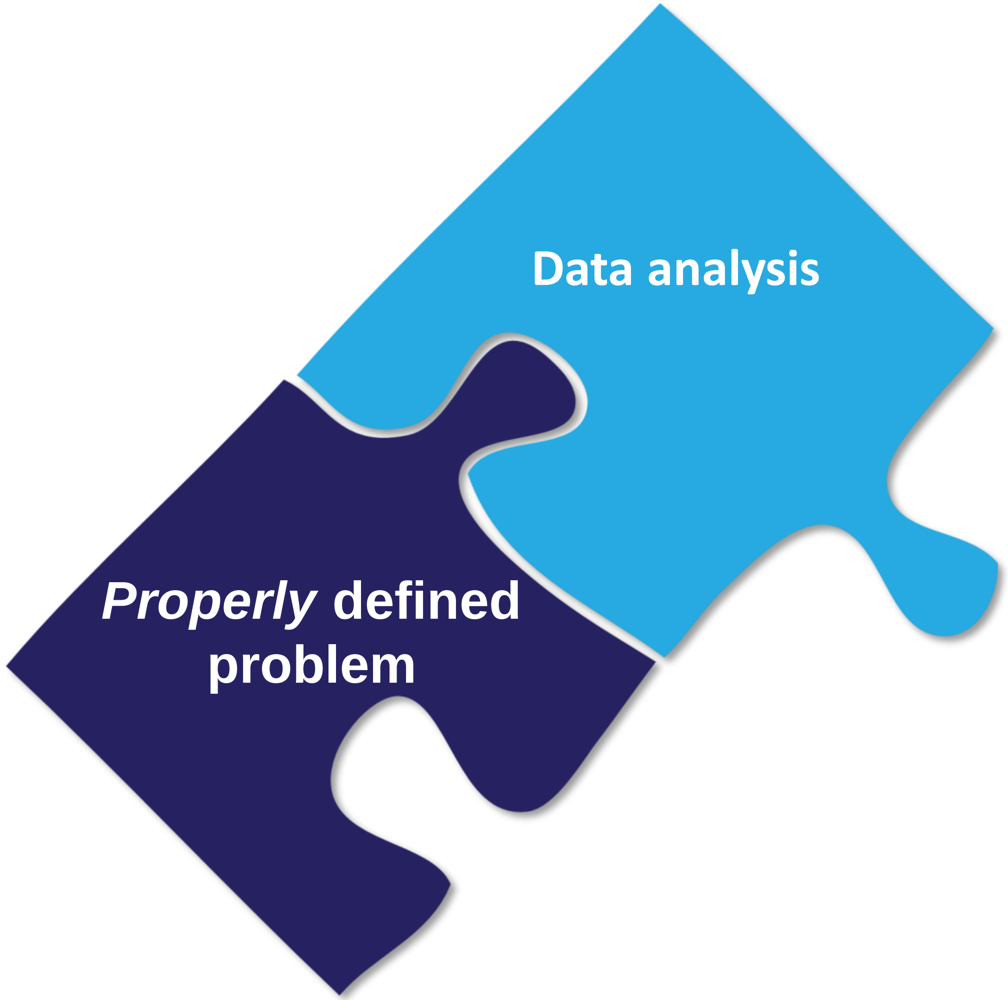
- Reserves have different drivers
- Cannot avoid decisions
- Uncertainty through multiple realizations
- Don’t fall in love with your model

Geostatistical reservoir modeling - talk outline

1. Supported uses
2. Common abuses
3. Misunderstandings
4. **Fit for purpose**
5. Future research directions

- Fitness has to be tested
- Purpose has to be specified
- Lack of fitness can be identified

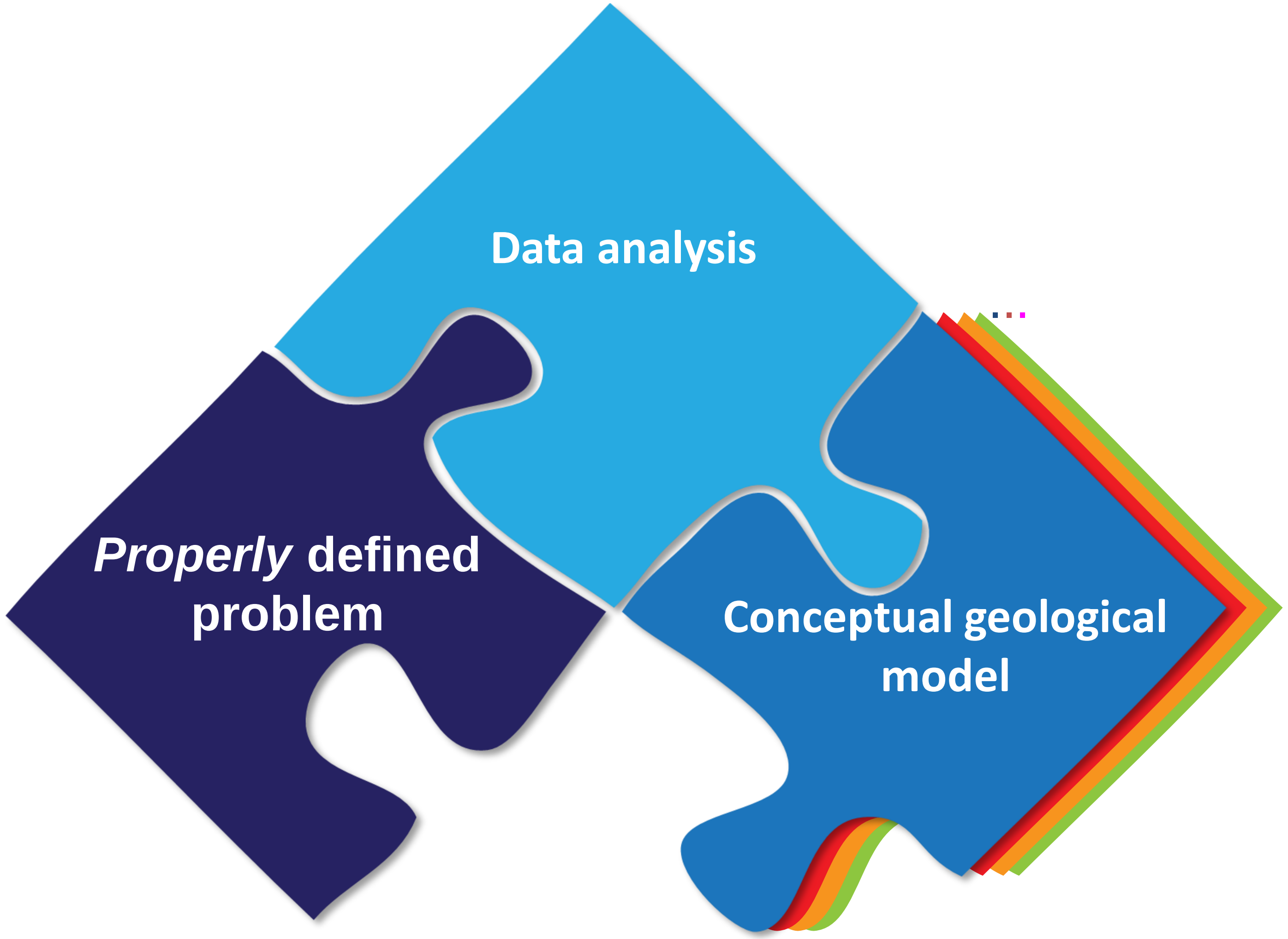
Geostatistical Reservoir Modeling – how is fitness obtained?



1. Linking the problem to the data available
   - establish a plan, strategy and tactics
   - establish expectations
   - specify the uncertainties and identify gaps
   - anticipate changes (to the problem and/or to the data)

this defines what actions should be taken and sets the criteria against which results from the final model products can be judged

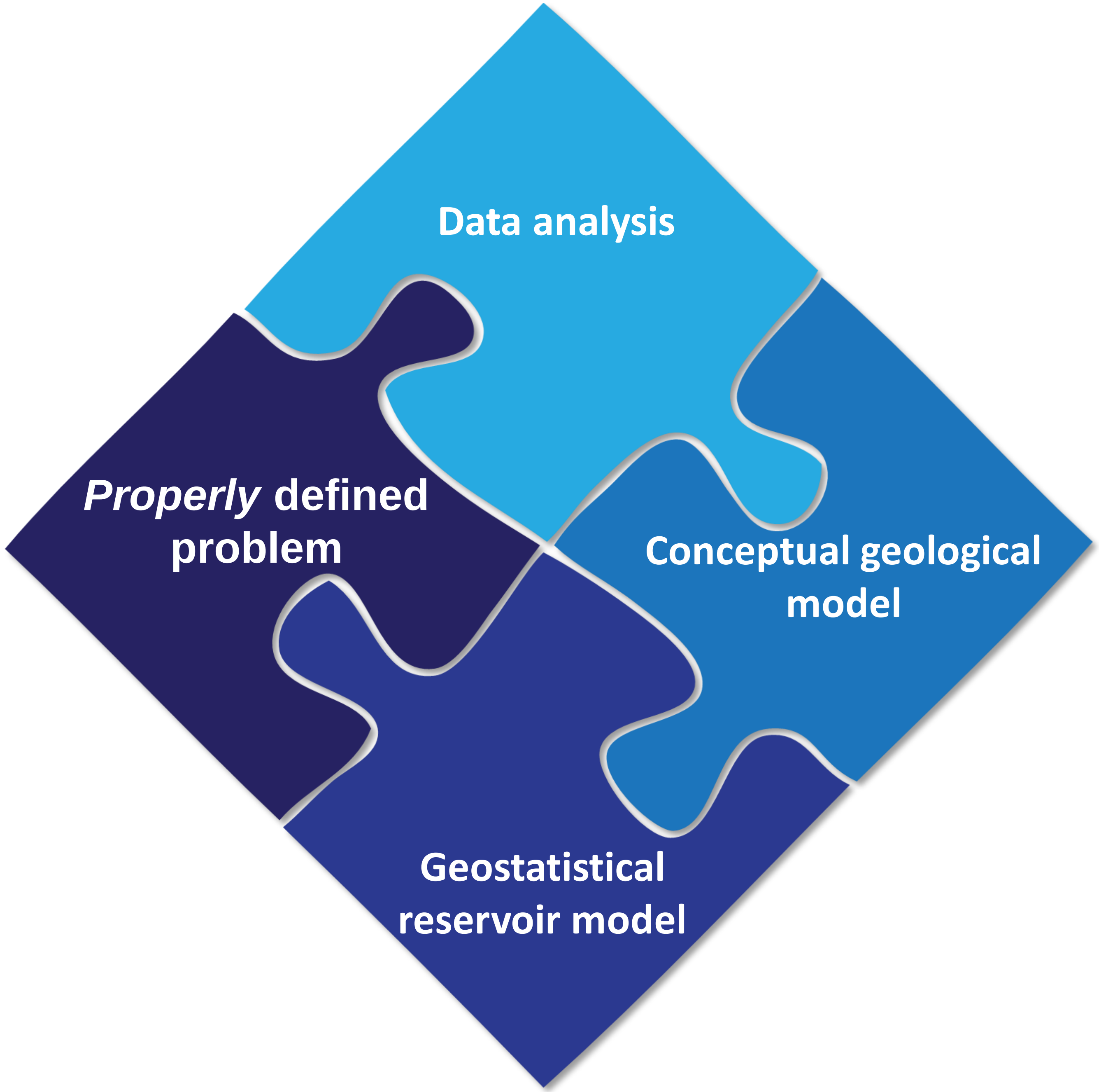
Geostatistical Reservoir Modeling – how is fitness obtained?



2. Integrating the data with underlying geological concepts
   - are observations consistent with expectations?
   - how many degrees of freedom?
   - analogue examples?
   - known knowns…known unknowns…

this constrains the reservoir model with our understanding of the geology and the engineering scenarios we're dealing with

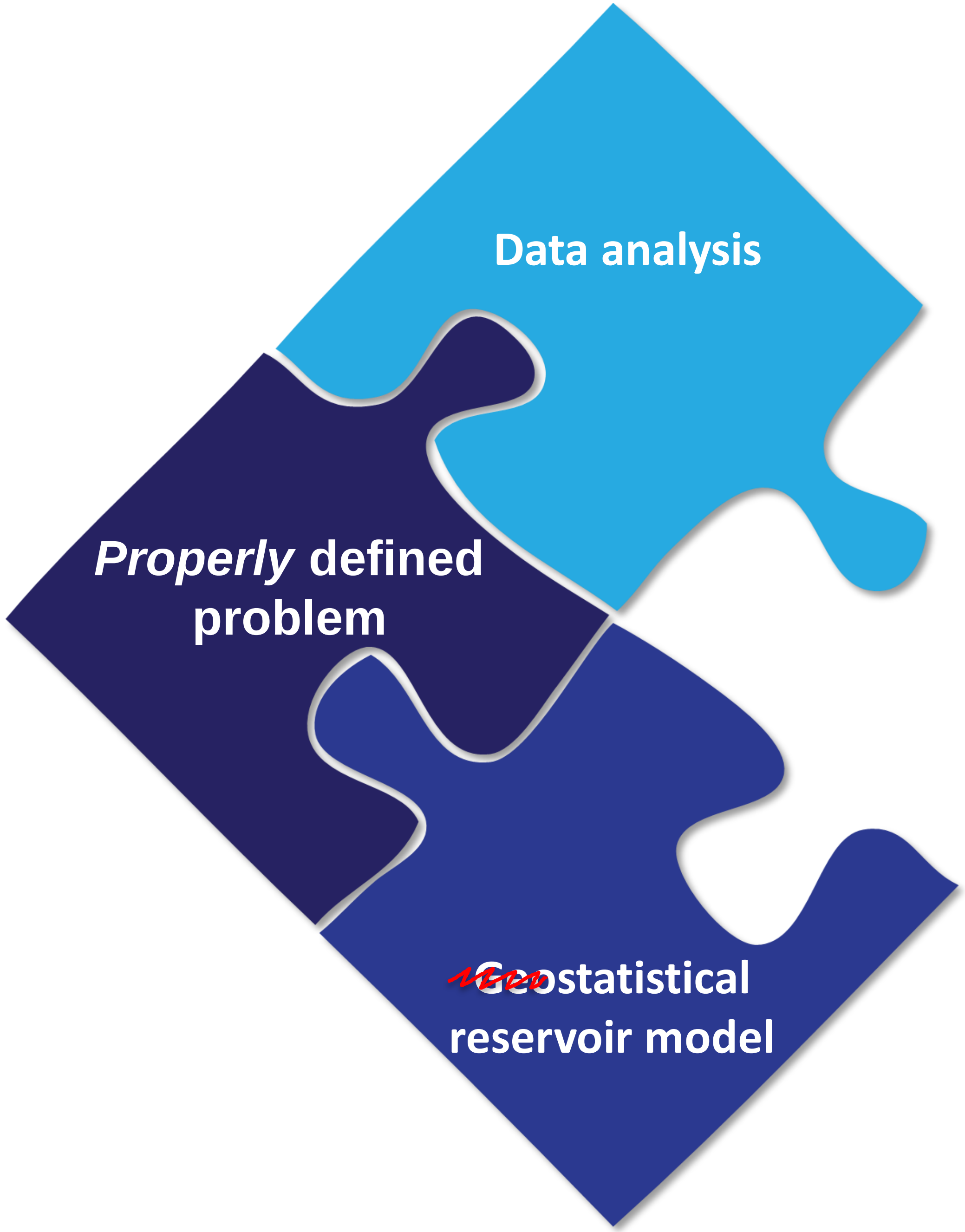
Geostatistical Reservoir Modeling – how is fitness obtained?



3. Exploring parameter space through geostatistical reservoir modeling
   - can we satisfy the input conditions?
   - where are compromises made or expected?
   - can a response be measured to impact the problem?

this integrates our knowledge of the data with our view of the uncertainty space and helps us navigate towards solutions that are underpinned by science

Geostatistical Reservoir Modeling – how is fitness lost?



1. Decoupling the model from the geology
   - statistics from data alone is not sufficient
   - quest for objectivity is alluring but misleading
   - regions and trends from geologic mapping are often critical
   - data driven extrapolation is not typically possible
   - statistics alone is not sufficient …even though we may be convinced otherwise by the colourful patterns we’re able to produce

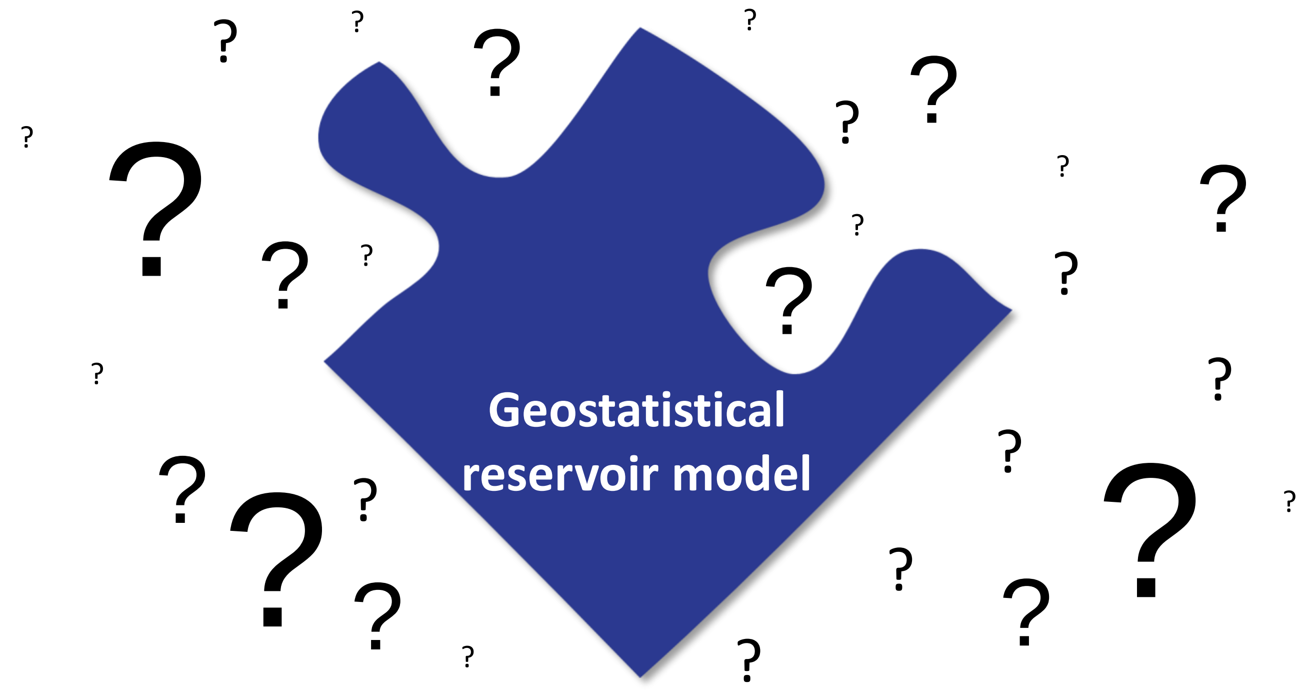
Geostatistical Reservoir Modeling – how is fitness lost?

2. Losing sight of the goal
   - …or never having a view of it in the first place
   - modeling choices all rely on understanding of the goal

Recognising the limits of reservoir modeling…do we?

Where Are Our Examples, and Why Are They So Difficult to Come By?

- Train wrecks happen, but where are the loop backs?
- Limitations in documentation and corporate memory, and success culture?
- Causes are often traced back to (1) fundamental model inputs (inference) and (2) flow heterogeneity (reproduction).



- *we think we know the cure, but we're not very good at self-diagnosis*

Fit for Purpose Conclusions

- Modeling linked to data and projects goals+
- Driven by conceptual geologic model
- Constrained by limitations of modeling methods
- Keep an eye on the goal

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2. Common abuses
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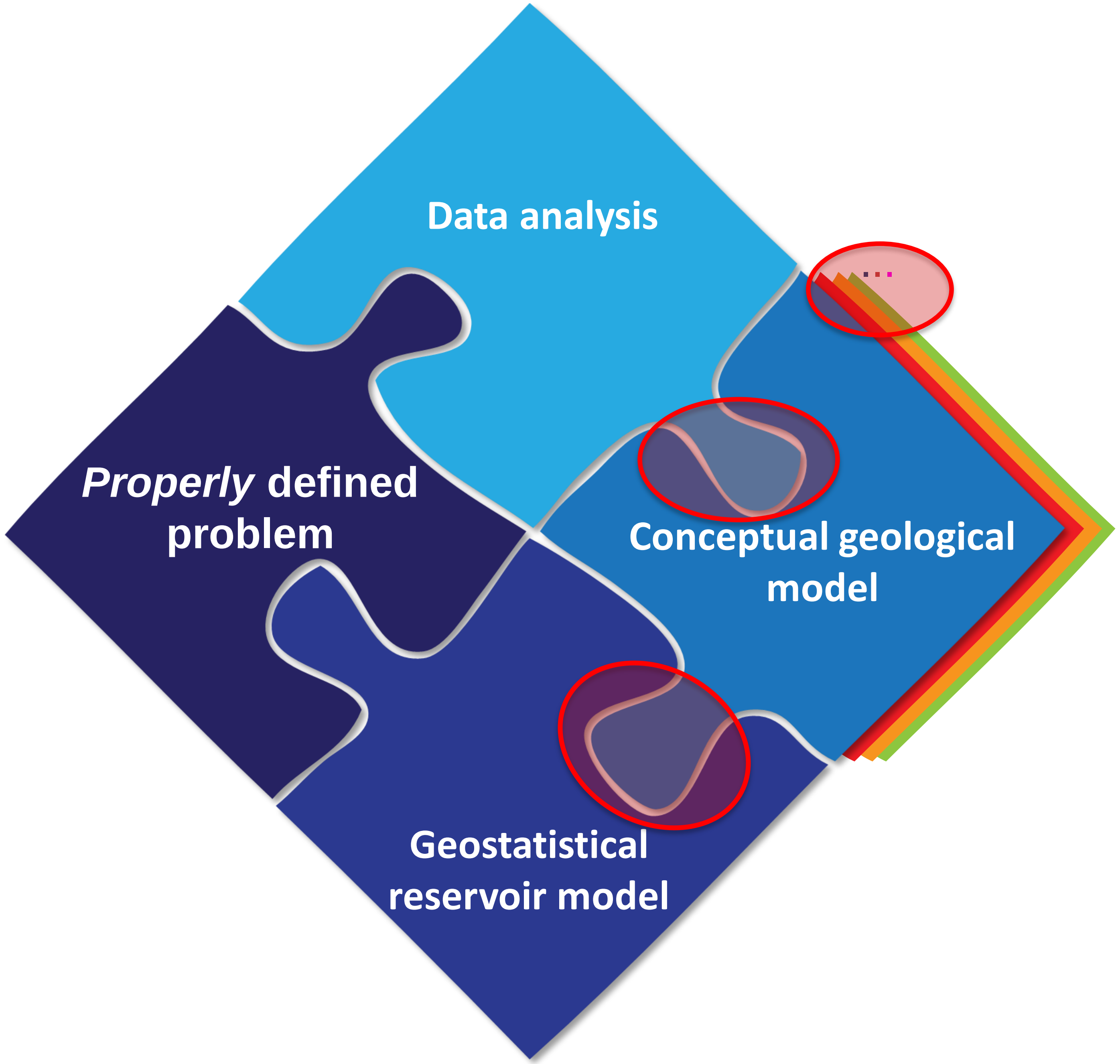
5. **Future research directions**

- More geologic realism
- More empiricism
- Advanced integration
- Improved Uncertainty Modeling

Future research directions

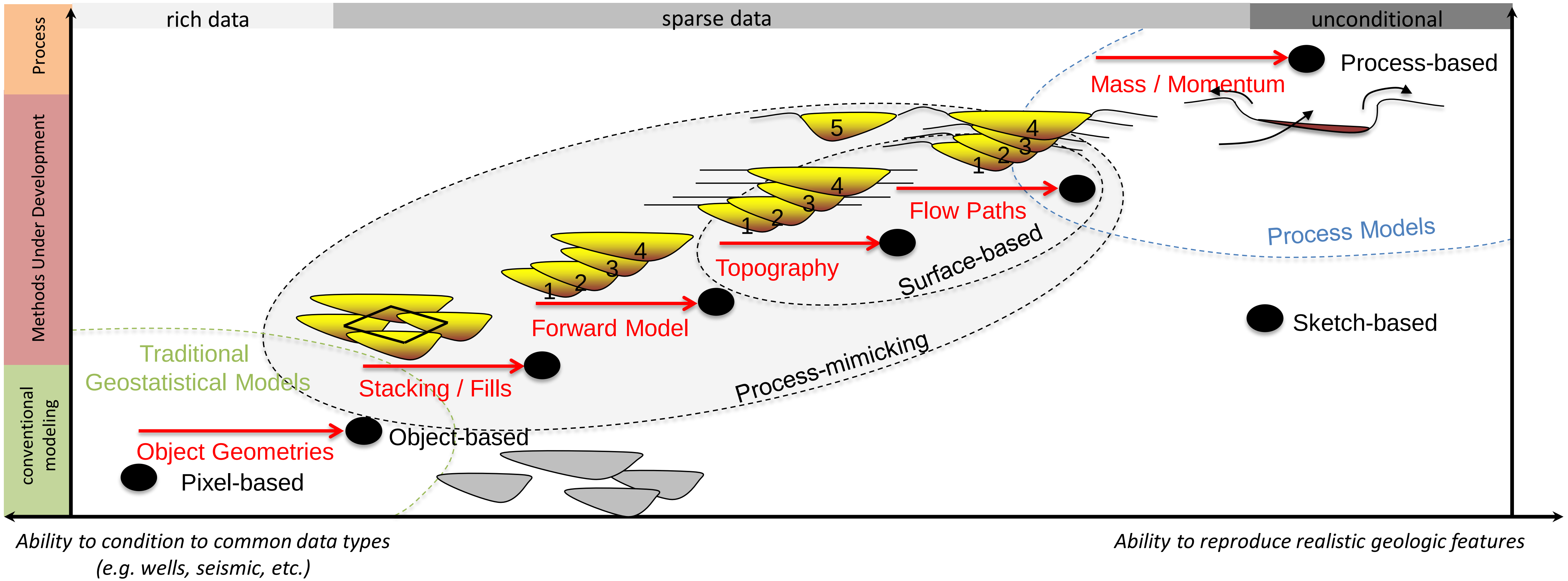
There is active research in order to improve reservoir modelling processes



Geostatistical models can incorporate process information

More Geologically Realistic

– Opportunities through the improved integration of geological process information



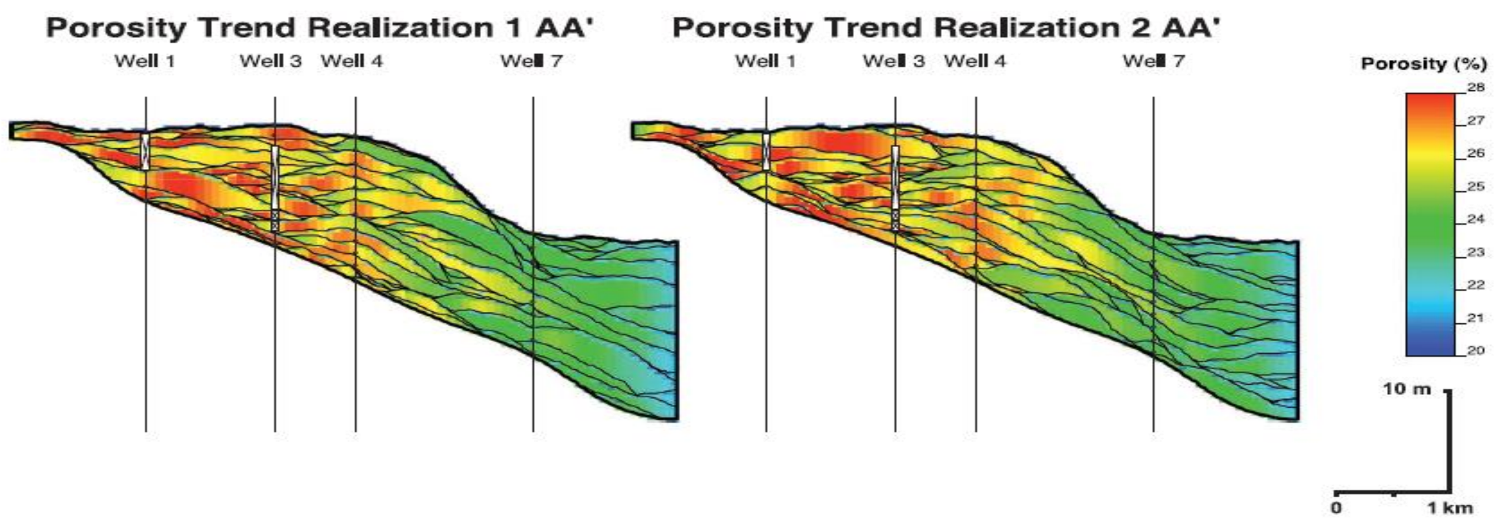
Continuum of geological process-based modeling (Pyrcz et al., in press)

There is a continuum of opportunities to improve geologic realism.

Geostatistical modeling with event-based / process-mimicking

More Geologically Realistic

- Capturing geologic rules in a “forward geostatistical modeling method”, object and surface-based methods
  - Hybrid modeling, event-based modeling, process-mimicking
- Rules are intuitive
- Significant increase in geological realism
  - Conditioning limitations similar to object-based methods



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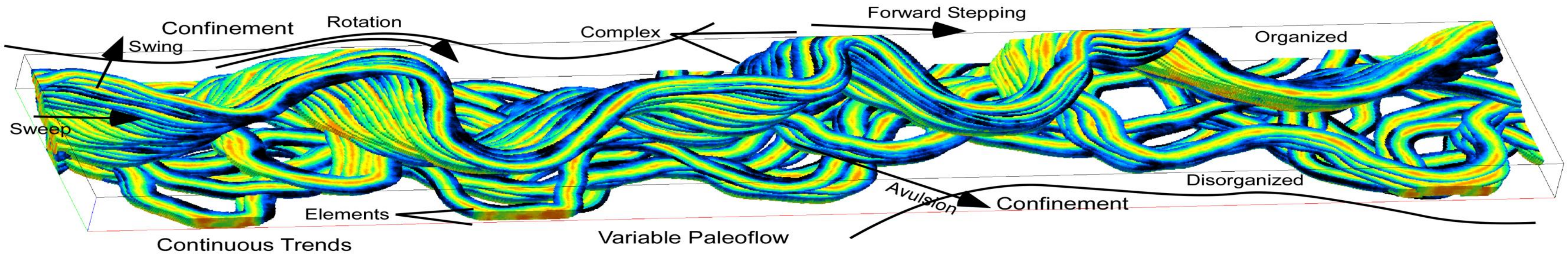
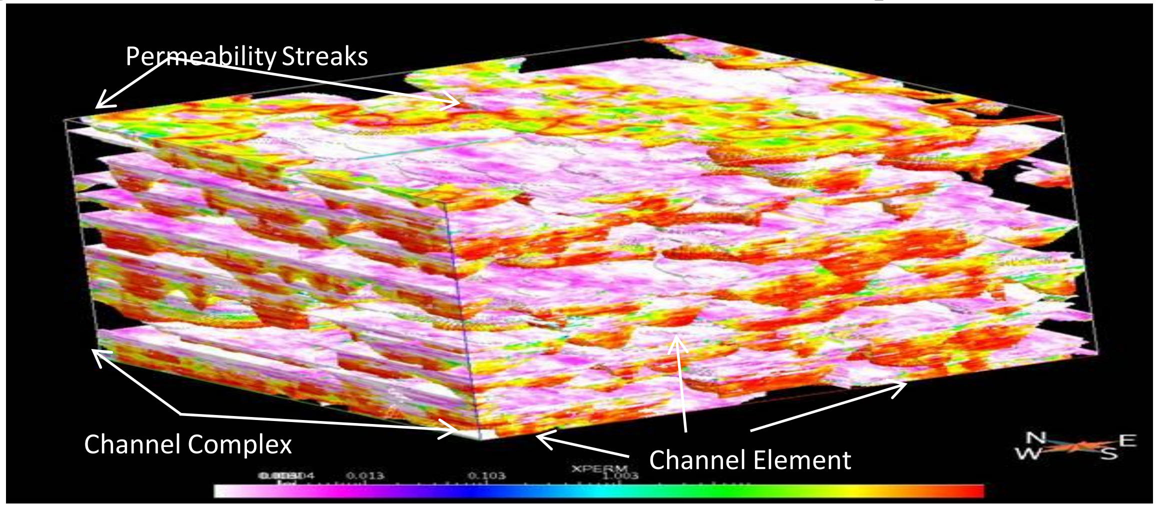


Example of Process-mimicking Deepwater Slope Valley Model (Pyrcz et al., 2012)

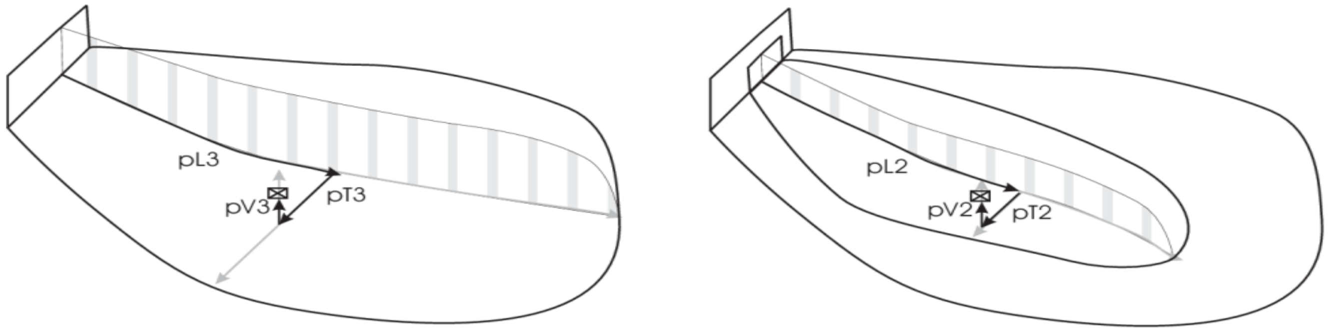
Geostatistical workflows can rely on a greater degree of empiricism

More Empiricism

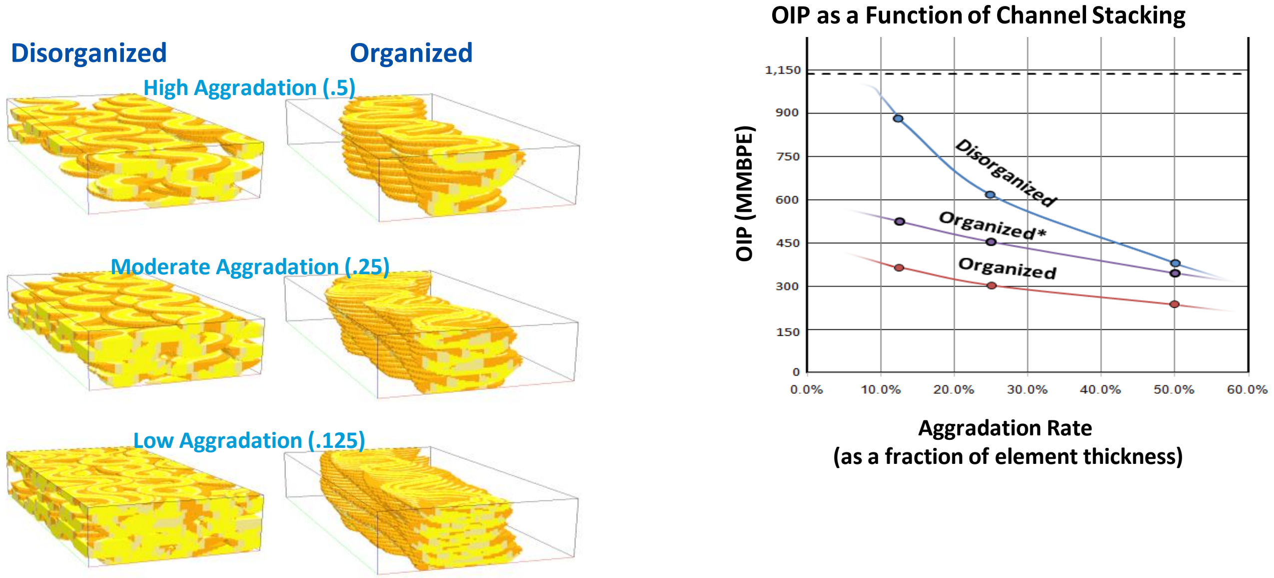
- Testing, mitigation in presence of heterogeneity / connectivity risk
- Top-down modeling
  - Incrementally add details from large scale to small scale
  - Determine require level of complexity to meet project objectives



Permeability model from a deepwater disorganized channel complex set.



Depositional coordinates for 2 orders of deepwater lobes (Pyrcz et al., 2005)



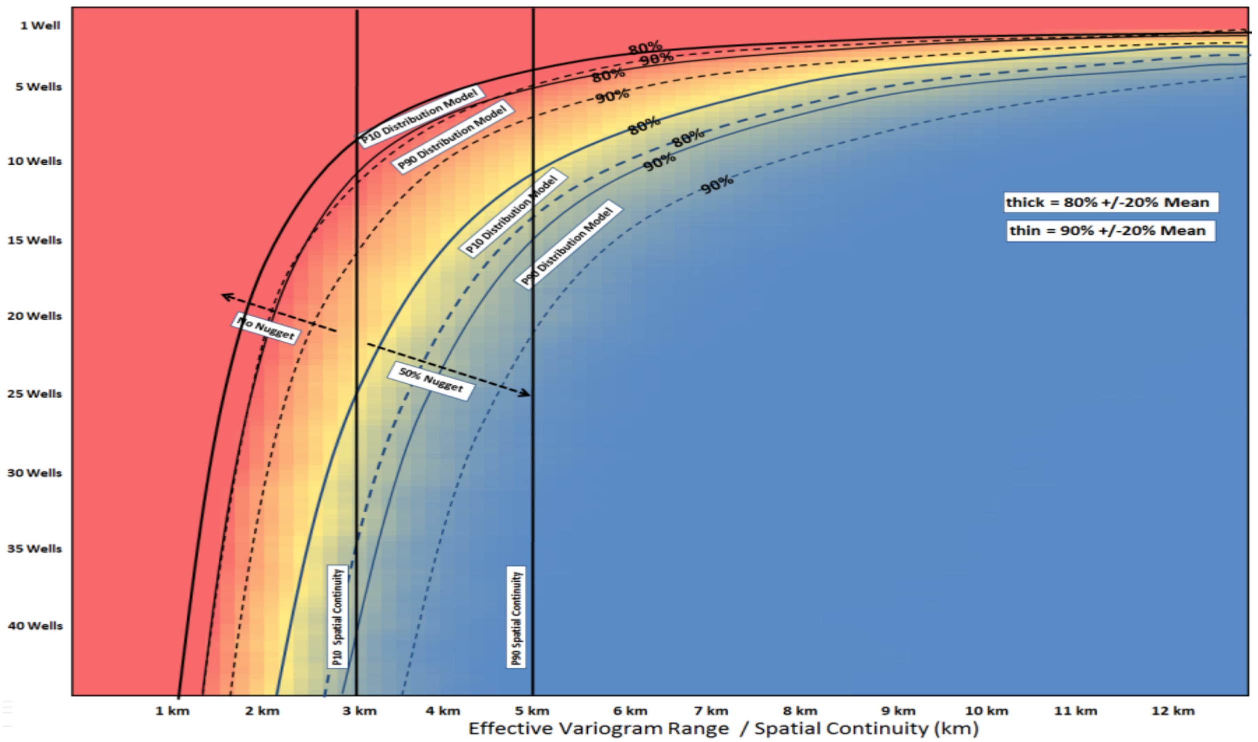
Empirical study on the impact of DW channel type on OIP.

Methods to explore models and learn from them.

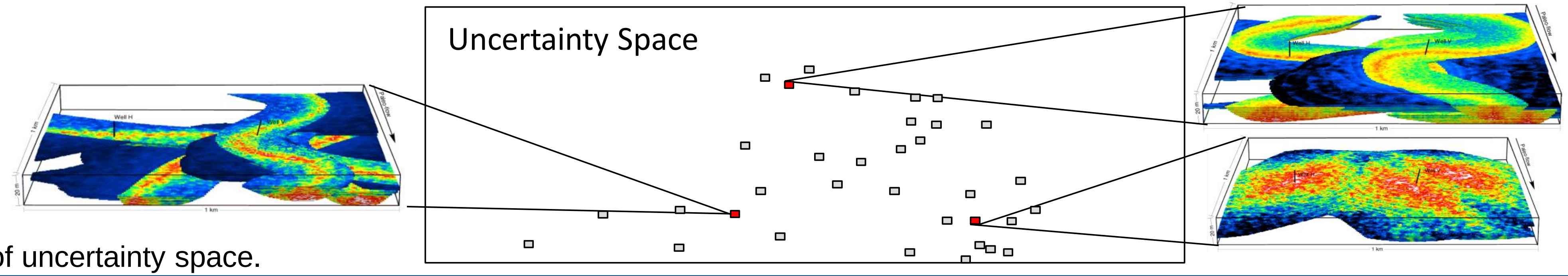
Geostatistical approaches with improved uncertainty models

Improved Uncertainty Models / Uncertainty Space Visualization

- Quantitative methods to determine parameter uncertainty
  - Spatial bootstrap, conditional finite domain etc.
- Reduced dimensionality visualization of model similarity (Caers, 2014)
  - Enables analysis of the uncertainty space, clustering, ranking



Response surface for block uncertainty (Pyrcz, 2012)



Schematic illustration of uncertainty space.

Learning from the uncertainty space.

Future Research Directions Conclusions

- Models could be more realistic and integrate more information
- More could be asked of the models
- We will discuss more data analytics and machine learning for subsurface modeling
- But the fundamental pillars remain
  - Conditioning to data
  - Heterogeneity reproduction based on quantification
  - Uncertainty modeling through multiple scenarios and realizations

Conclusions

- We are optimists.
  - Yes, there is misuse.
  - Yes, more could be done.
  - Yes, there are new opportunities.
- Suggest evolution, not a revolution
  - Geostatistics is a practical approach that latter obtained theoretical underpinnings
  - And if you go something better – add it to the tool box