

# Application of a reduced, composite parameter representation in combination with the ensemble Kalman Filter for facies identification

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# Outline

- 1 Reduced, composite parameter representation
  - Background and motivation
  - The main aspects of the methodology
- 2 The Ensemble Kalman Filter
  - Workflow
- 3 Facies identification
  - Hierarchical vs Vese-Chan representation
  - Channel structure

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  - Channel structure

# Reduced, composite parameter representation

## Complex facies distributions are not Gaussian

- apply a facies representation more in line with the Gaussian assumption underlying EnKF
- Truncated pluri-Gaussian representation (Liu and Oliver, 2005)
  - Gaussian mixture models (Sun et al., 2009; Dovera and Della Rossa, 2010)
  - Non-linear mapping by the use of Kernel functions (Sarma and Chen, 2009)
  - Level set representation (Moreno et al, 2008; Lorentzen et al, 2009)

# Reduced, composite parameter representation

Advantages with using the level set representation:

- Flexible with respect to which facies structures that can be estimated
- The updated fields are secured to be facies realizations
- Can be conditioned to correct facies type at well locations
- Do not involve complex modifications of the standard EnKF equations

# Reduced, composite parameter representation

Challenges with using the standard level-set representation:

- Introduce additional nonlinearity in the mapping between the data and parameter space
  - Restrictions on the ordering of the facies
  - Can lead to a large number of unknowns especially in cases with multiple facies
- ⇒ For practical implementations with limited data and a restricted ensemble size the level-set representation can lead to instabilities

# The main aspects of the methodology

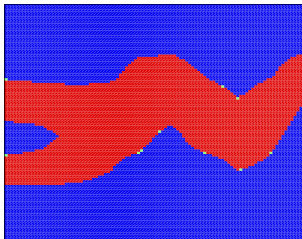


Illustration of channel structure

# The main aspects of the methodology

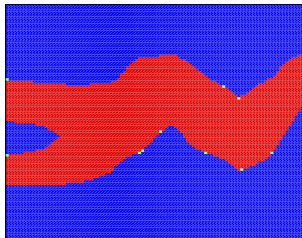
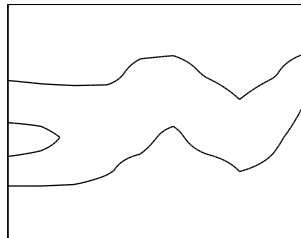


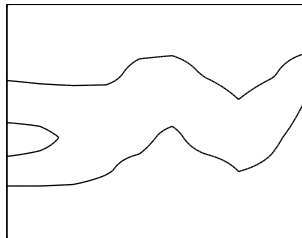
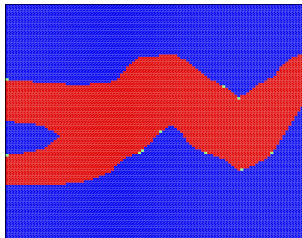
Illustration of channel structure



Channel boundaries

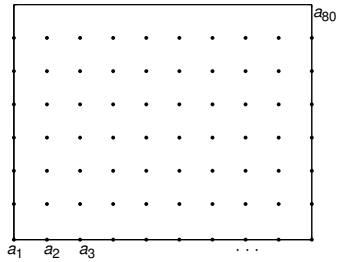
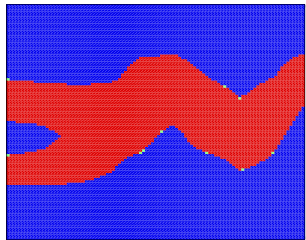


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Representing structure:

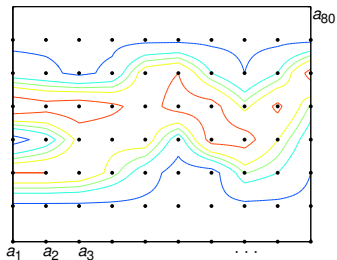
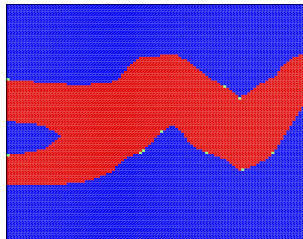
# The main aspects of the methodology



Representing structure:

a - values

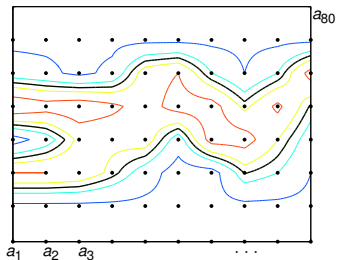
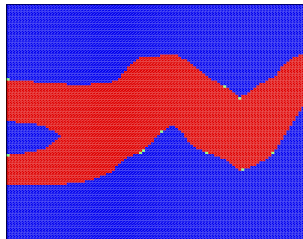
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Representing structure:

$\mathbf{a}$  - values  $\Rightarrow I(\mathbf{x}; \mathbf{a})$

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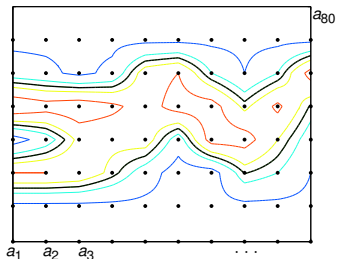
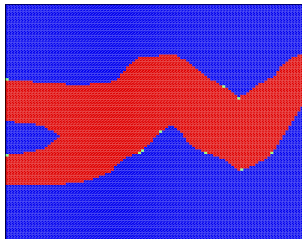


Representing structure:

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$I(\mathbf{x}; \mathbf{a}) = 0$  represents the facies boundary

# The main aspects of the methodology

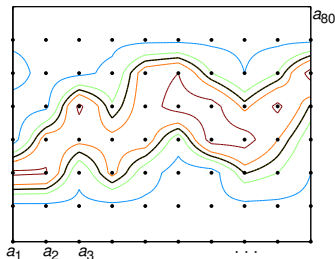
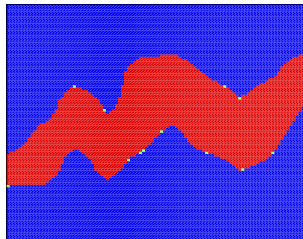


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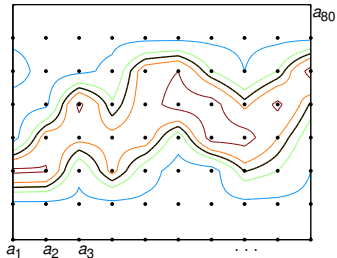
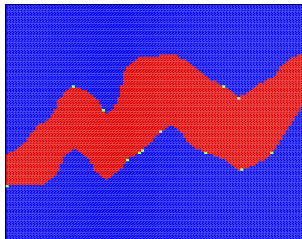
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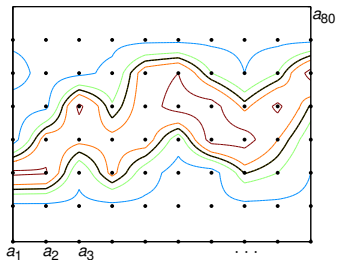
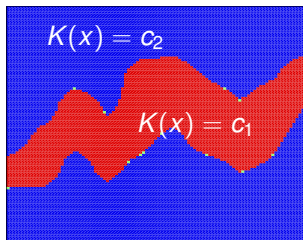
$\rightarrow$  update facies geometry by changing  $a$ -values

# The main aspects of the methodology



Representing magnitude:

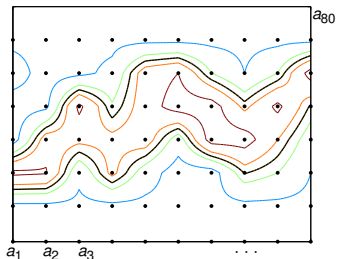
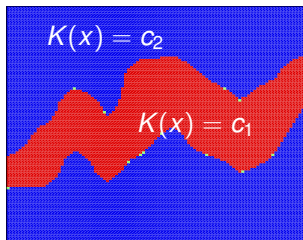
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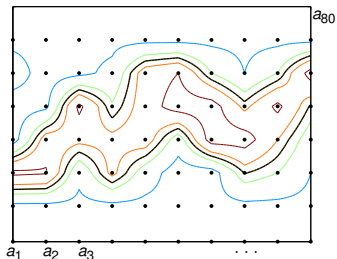
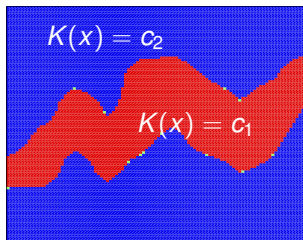
# The main aspects of the methodology



Representing magnitude:

c - values

# The main aspects of the methodology

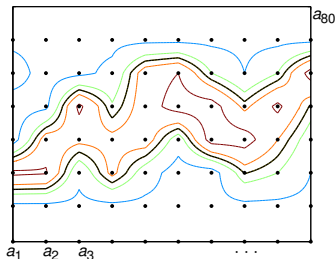
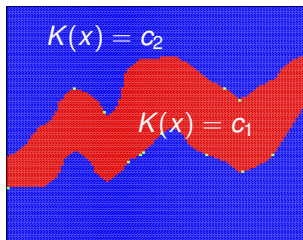


Representing magnitude:

c - values

$$K(\mathbf{x}) = c_1 E(I(\mathbf{x}; \mathbf{a})) + c_2 (1 - E(I(\mathbf{x}; \mathbf{a})))$$

# The main aspects of the methodology



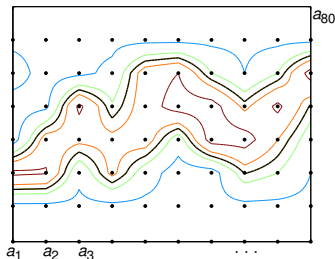
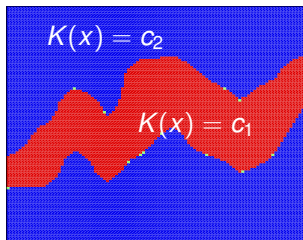
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$$E(I(\mathbf{x}; \mathbf{a})) = 0 \vee 1$$

# The main aspects of the methodology



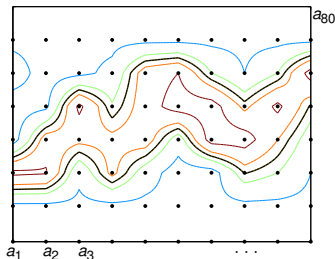
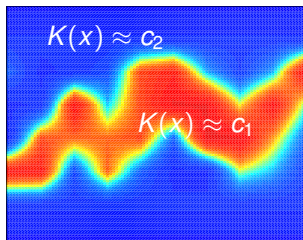
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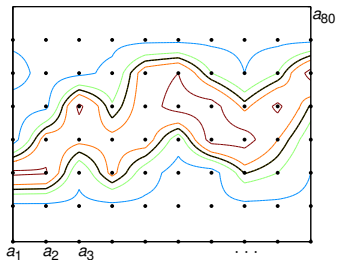
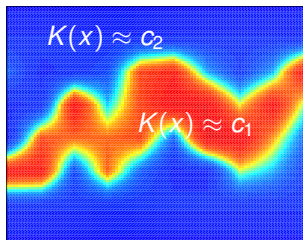
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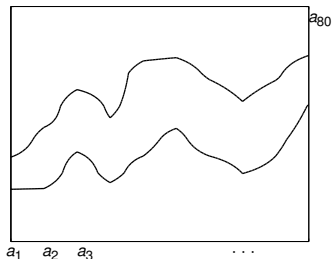
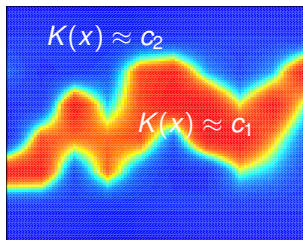
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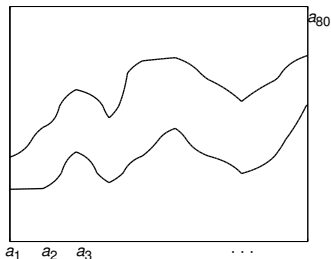
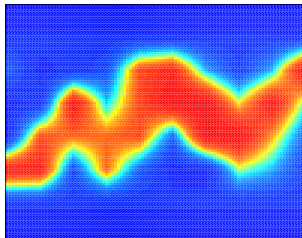
Identification of multiple facies:

# The main aspects of the methodology



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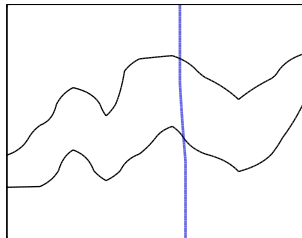
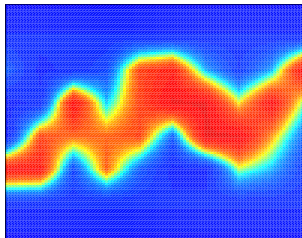


Identification of multiple facies:

Vese-Chan representation



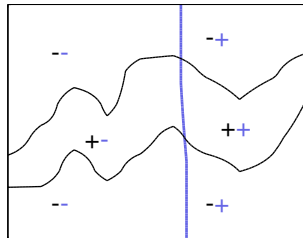
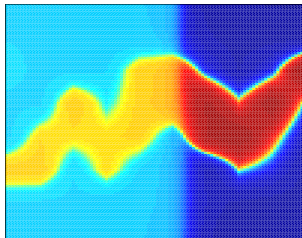
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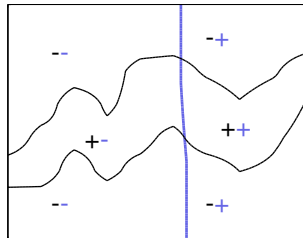
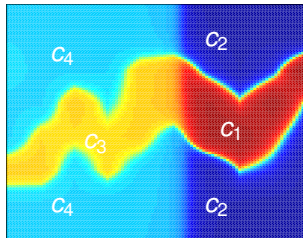
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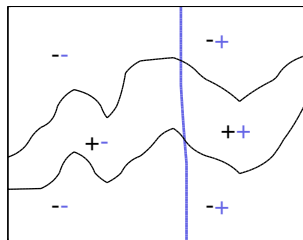
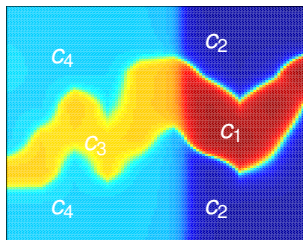
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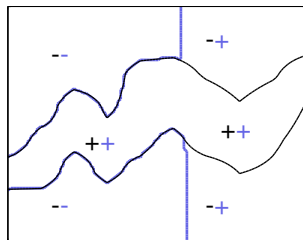
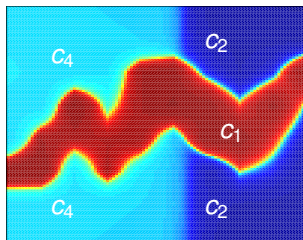


Identification of multiple facies:

Vese-Chan representation:  $N_f \rightarrow 2^{N_f}$  facies

$$K = c_1 E(I_1) E(I_2) + c_2 (1 - E(I_1)) E(I_2) + c_3 E(I_1) (1 - E(I_2)) + c_4 (1 - E(I_1)) (1 - E(I_2))$$

# The main aspects of the methodology

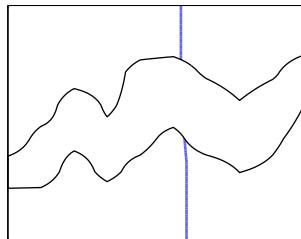
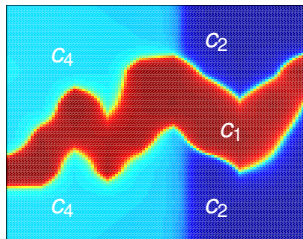


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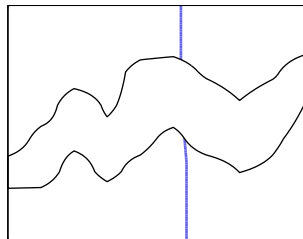
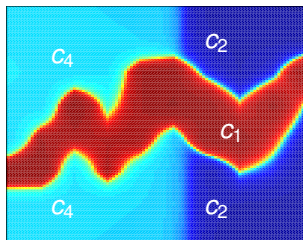
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Identification of multiple facies:

Hierarchical representation

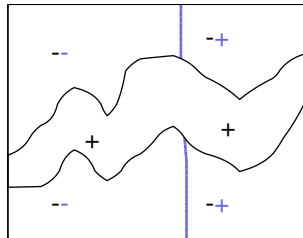
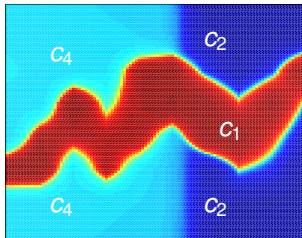
# The main aspects of the methodology



Identification of multiple facies:

$$\text{Hierarchical representation: } K = c_1 E(I) + c_2 (1 - E(I))$$

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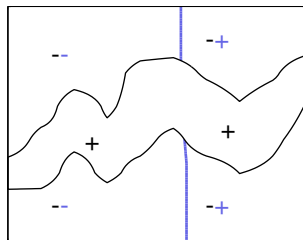
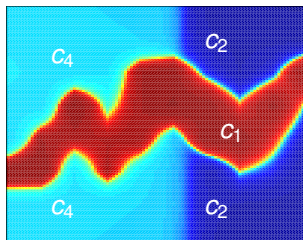
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$c_2 = c_2 E(I_2(\mathbf{x}; \mathbf{a})) + c_4 (1 - E(I_2(\mathbf{x}; \mathbf{a})))$



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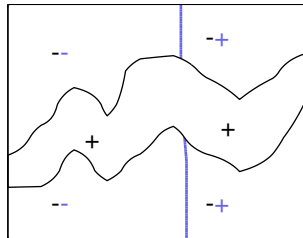
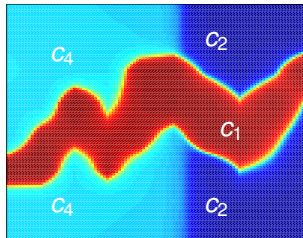
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# The main aspects of the methodology



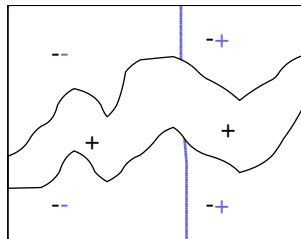
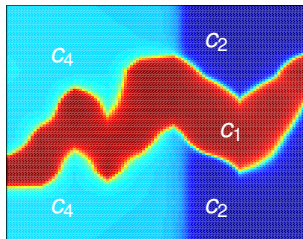
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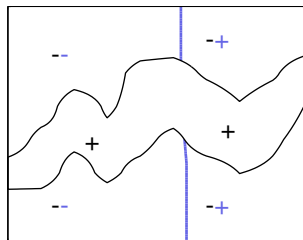
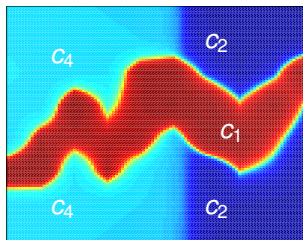
$$c_4 = c_4 E(I_3(\mathbf{x}; \mathbf{a})) + c_5 (1 - E(I_3(\mathbf{x}; \mathbf{a})))$$

# The main aspects of the methodology



Compared to standard level-set representation:

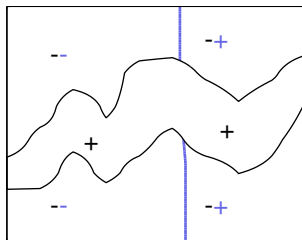
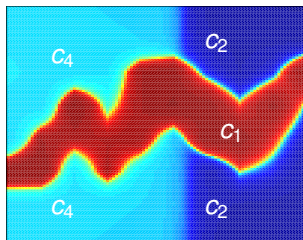
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Compared to standard level-set representation:

Smoothed representation with reduced non-linearity

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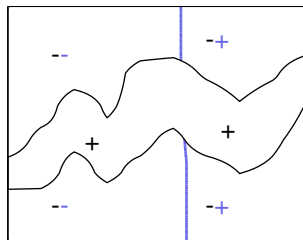
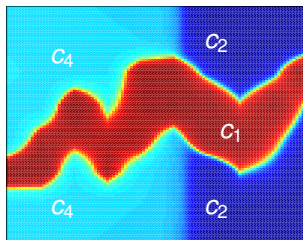


Compared to standard level-set representation:

Smoothed representation with reduced non-linearity

Less unknowns (160 a-values and 3 c-values in this case)

## The main aspects of the methodology



Compared to standard level-set representation:

Smoothed representation with reduced non-linearity

Less unknowns (160 a-values and 3 c-values in this case)

No restrictions on the facies ordering

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# Workflow for data assimilation

↓  $t = 0$

Ensemble of state vectors

$$\mathbf{x}_{t,j}^a = [\mathbf{a}_i, \mathbf{c}_i, \mathbf{y}_{t,i}, \tilde{\mathbf{d}}_{t,i}]^T$$

↓

Petrophysical parameters

$$\mathbf{a}_i, \mathbf{c}_i \rightarrow K(\mathbf{x}), \phi(\mathbf{x})$$

↓

$t = t+1$   
←

EnKF assimilation step

$$\mathbf{x}_{t+1,i}^a = \mathbf{x}_{t+1,i}^f + \mathbf{K} (\mathbf{d}_{t+1,i} - \tilde{\mathbf{d}}_{t+1,i})$$

↑

Facies parameters

$$\mathbf{x}_{t+1,i}^f = [\mathbf{a}_i, \mathbf{c}_i, \mathbf{y}_{t+1,i}, \tilde{\mathbf{d}}_{t+1,i}]^T$$

↑

Forward step

$$\mathbf{x}_{t+1,i}^f = f(\mathbf{x}_{t=0,i}^a)$$

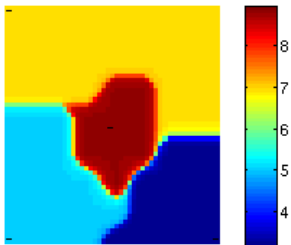
↑  $t+1 = T$



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# Vese-Chan representation

$K^{true}$

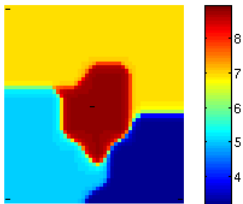


Example setup:

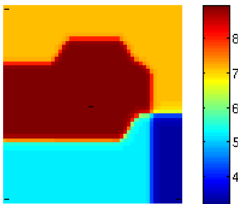
- $N_t^d = 18, t = 1, \dots, 15$
- $N^e = 100$
- $N^g = 2500$
- $N^{a,VC} = 81 + 81 = 162$
- $N^c = 4$

# Vese-Chan representation

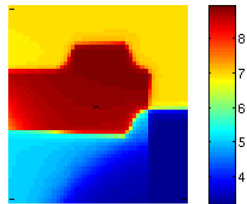
$K^{true}$



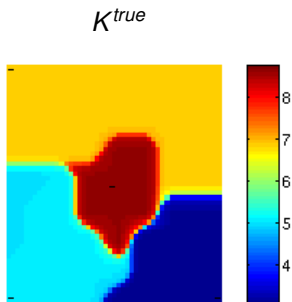
$K^{init}$



$K^{final}$



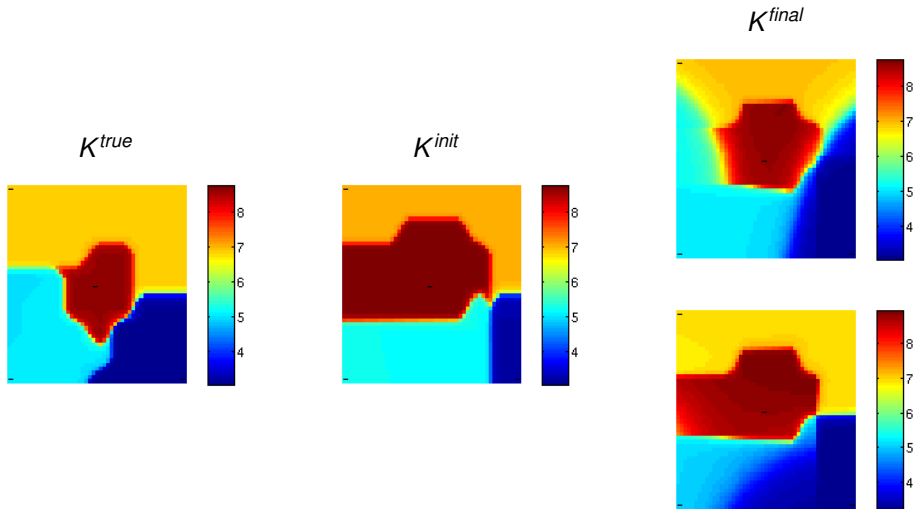
# Hierarchical representation



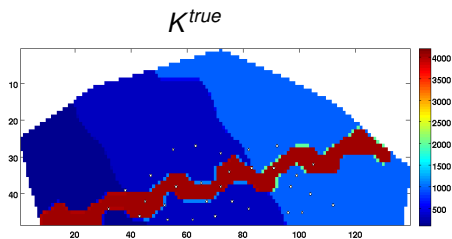
Example setup:

- $N_t^d = 18, t = 1, \dots, 15$
- $N^e = 100$
- $N^g = 2500$
- $N^{a,H} = 81 + 81 + 81 = 243$
- $N^c = 4$

# Hierarchical representation



# Modified Brugge example

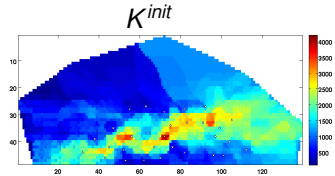
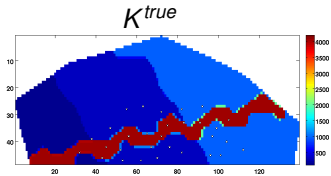


[Lorentzen et al. 2011]

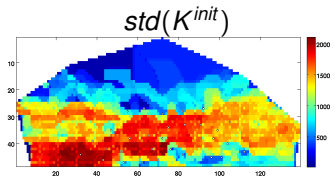
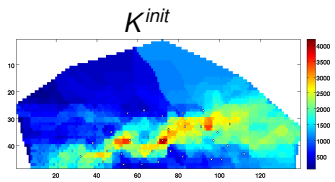
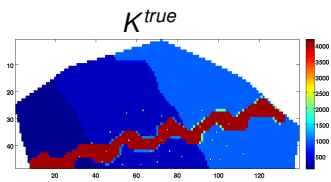
- $N_t^d = 100, t = 1, \dots, 30$
- $N^e = 150$

- $N^g = 13344$
- $N^a = 48 + 48 + 640 = 732$
- $N^c = 4$

# Modified Brugge example

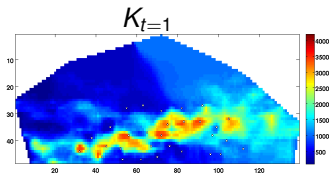
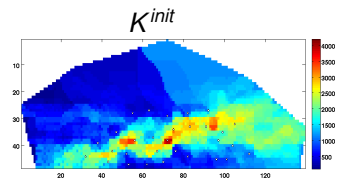
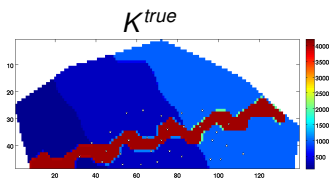


# Modified Brugge example

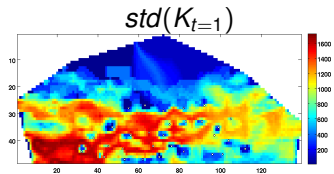
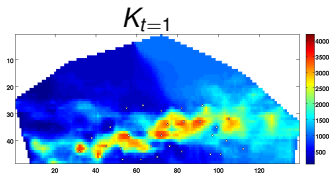
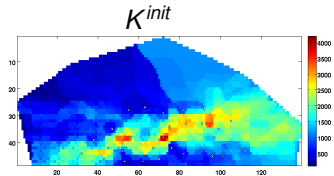
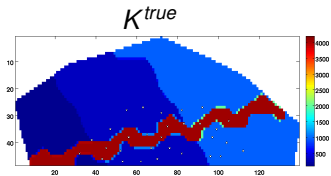




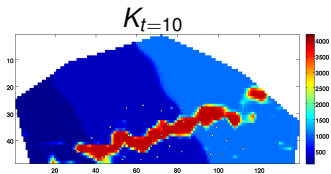
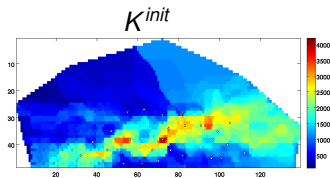
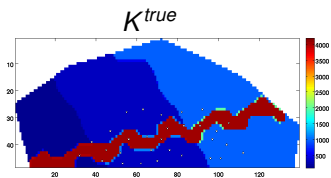
# Modified Brugge example



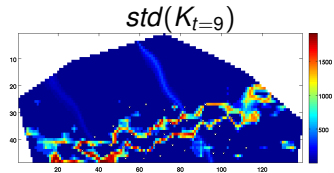
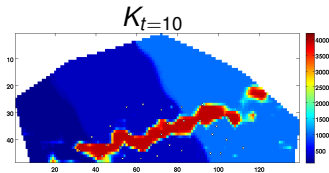
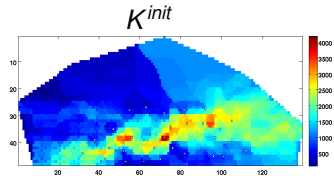
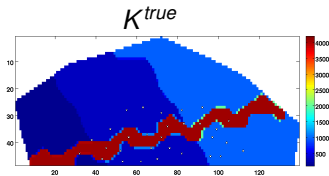
# Modified Brugge example



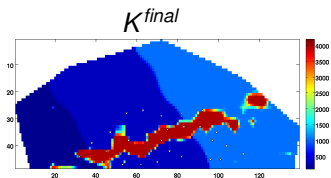
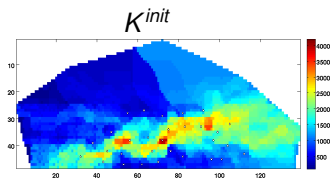
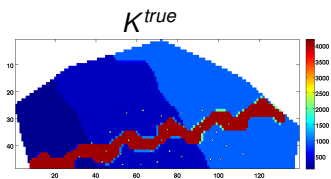
# Modified Brugge example; Localisation on static well data



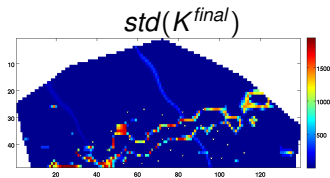
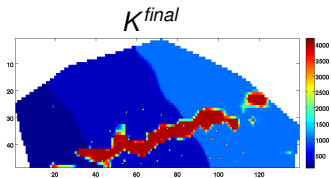
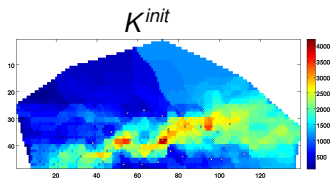
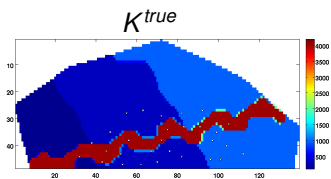
# Modified Brugge example; Localisation on static well data



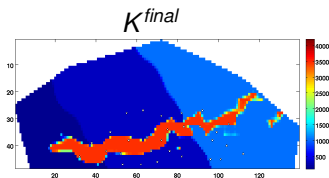
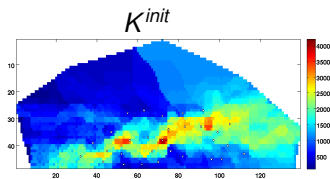
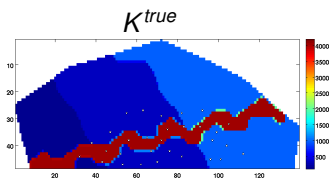
# Modified Brugge example; Localisation on static well data



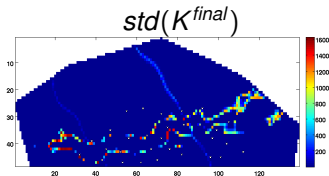
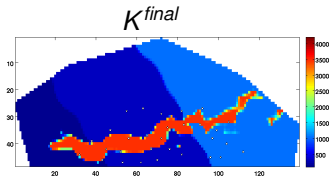
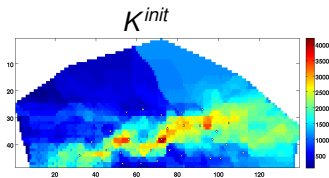
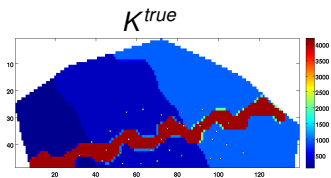
# Modified Brugge example; Localisation on static well data



# Modified Brugge example; No localisation

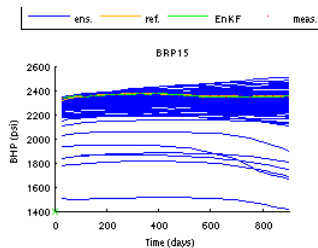


# Modified Brugge example; No localisation

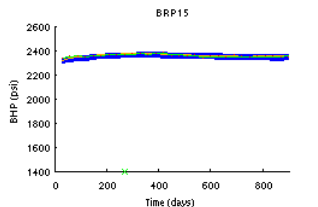
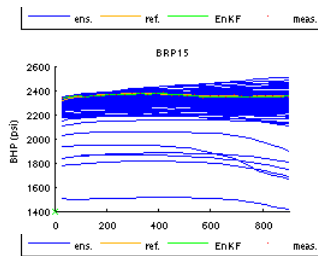




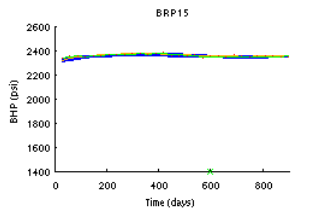
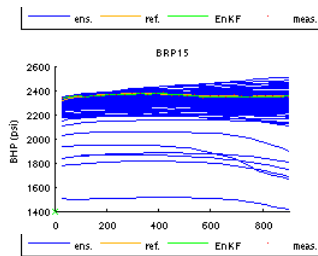
# Modified Brugge example



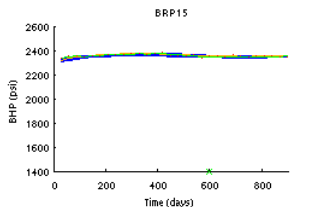
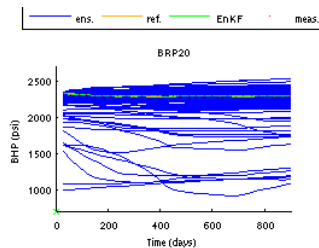
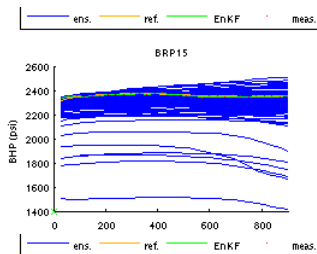
# Modified Brugge example



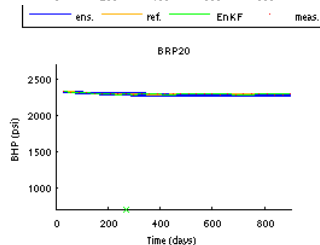
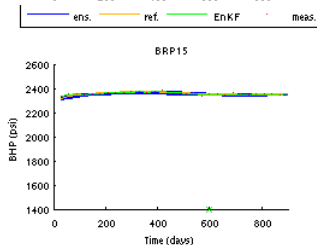
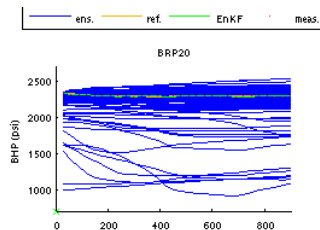
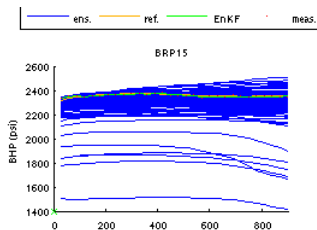
# Modified Brugge example



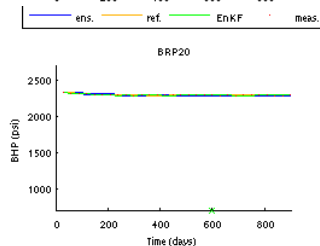
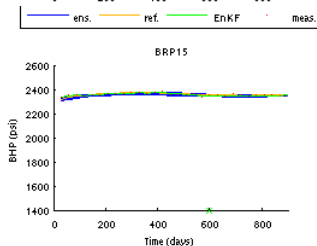
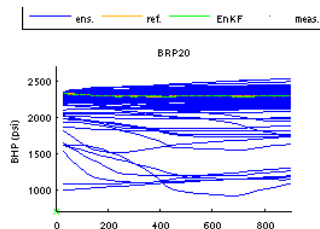
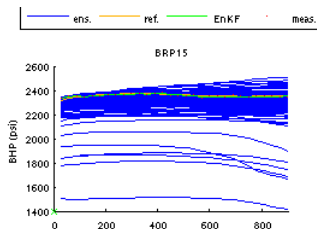
# Modified Brugge example



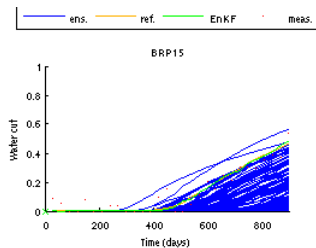
# Modified Brugge example



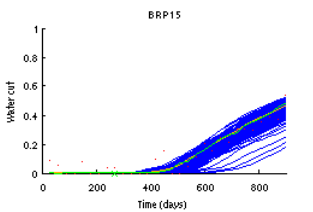
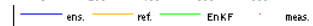
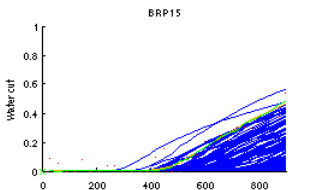
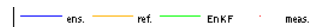
# Modified Brugge example



# Modified Brugge example

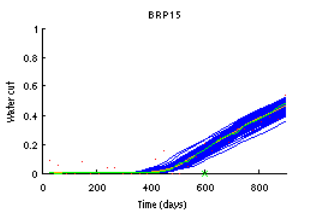
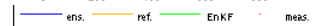
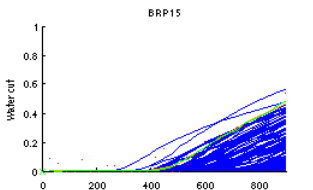
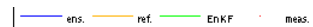


# Modified Brugge example

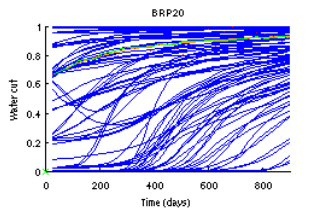
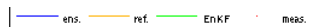
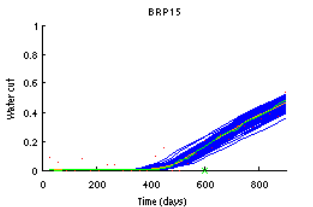
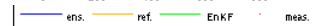
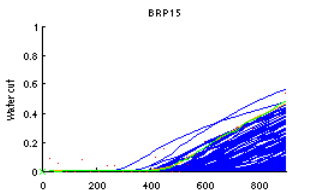
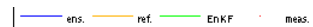




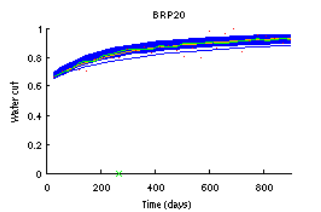
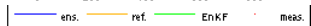
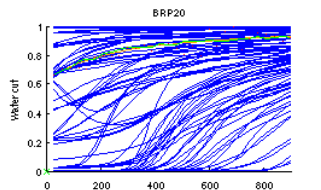
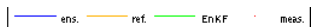
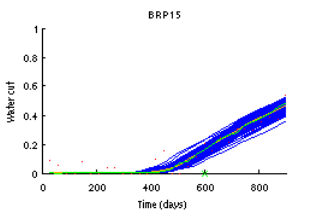
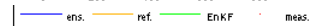
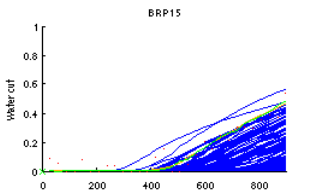
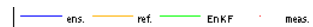
# Modified Brugge example



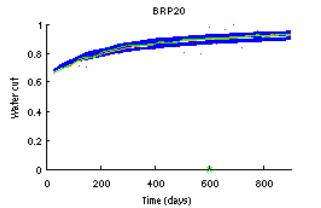
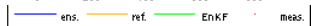
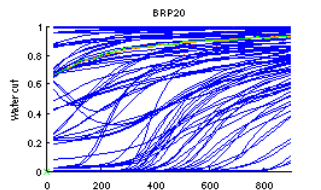
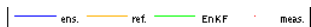
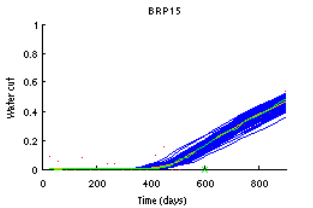
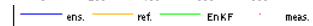
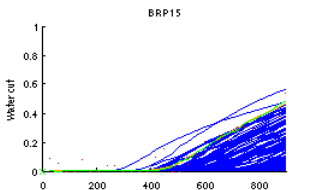
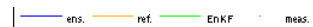
# Modified Brugge example



# Modified Brugge example



# Modified Brugge example



# Summary

- Method for facies identification
- Reduced, composite parameter representation
  - Flexible w.r.t. geological variability
  - Stabilise assimilation
- Further work:
  - Multilevel assimilation
  - Localisation
  - Shape priors

# Acknowledgements

Support is provided by the IRIS/CIPR cooperative research project "Integrated Workflow and Realistic Geology", which is funded by industry partners ConocoPhillips, Eni, Petrobras, Statoil, and Total, as well as the Research Council of Norway (PETROMAKS).