Joint Utilization of Geophysical Data Types, with Application to Monitoring of CO_2 Injection in the Skade Formation

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Large-scale CO_2 Sequestration

Rationale for geophysical monitoring

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About 12 Gt CO_2 must be stored before 2050 to meet European targets

Subsurface formation must have sufficient storage capacity

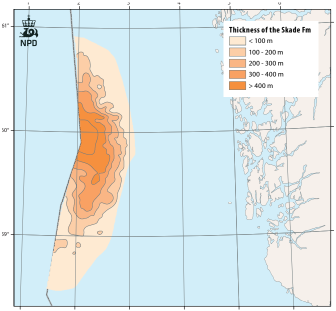
CO_2 injection will likely be performed with few wells

$\rightarrow$ High injection rates must be expected

$\rightarrow$ Assess pressure increase, in addition to CO_2 plume placement

Forward and Inverse Modelling Study

Skade formation

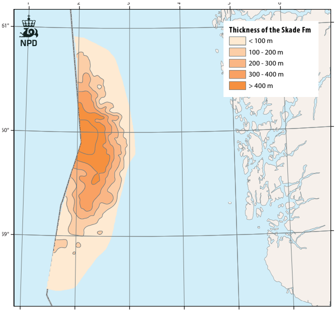


Thickness map

Storage capacity: 15 Gt

Forward and Inverse Modelling Study

Skade formation



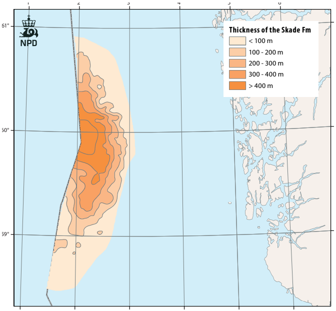
Thickness map

Storage capacity: 15 Gt

Forward: Simulate 50 years of CO_2 injection with ‘highest safe injection rates’ in three wells along East-West cross section in southern part

Forward and Inverse Modelling Study

Skade formation



Thickness map

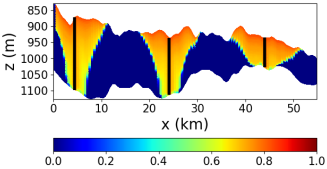
Storage capacity: 15 Gt

Forward: Simulate 50 years of CO_2 injection with 'highest safe injection rates' in three wells along East-West cross section in southern part

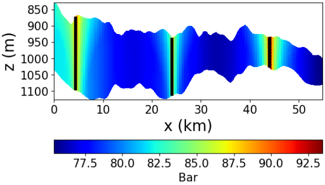
Inverse: Detect effects of simulated saturation and pressure changes by geophysical monitoring with various data types

Forward Modelling Study

Results along cross section intersecting the wells



ΔS ($\mathrm{CO_2}$ saturation change)



ΔP (Pressure change)

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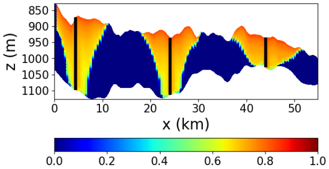
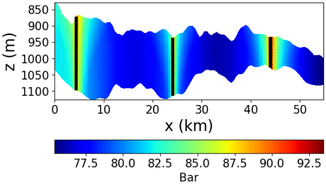


ΔS (CO_2 saturation change)

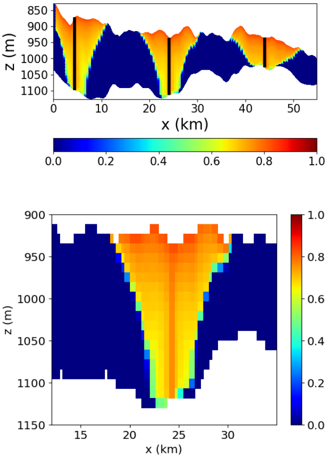


ΔP (Pressure change)

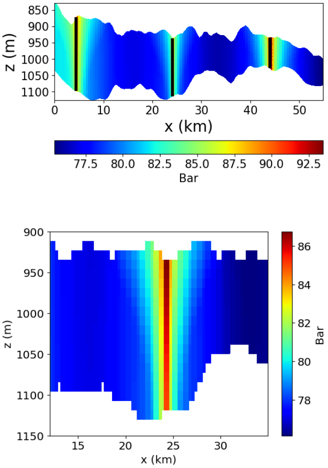
Select region around middle well for Inverse Modelling Study

Forward Modelling Study

Results along cross section intersecting the wells – around middle well



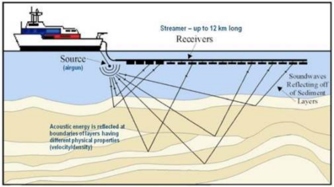
ΔS



ΔP

Inverse Modeling Study

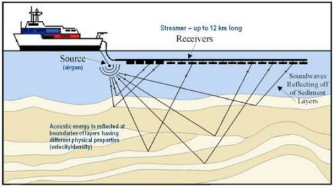
Seismic data



Seismic survey

Inverse Modeling Study

Seismic data



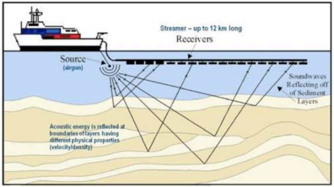
Seismic survey

Data $\rightarrow$ velocity

$$d_s \rightarrow V$$

Inverse Modeling Study

Seismic data



Seismic survey

Data $\rightarrow$ velocity

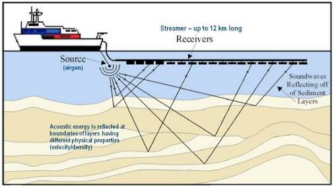
$$d_s \rightarrow V(\Delta S, \Delta P)$$

$$V(\Delta S, \Delta P) = V_0(1 - k\Delta S - l\Delta P - m(\Delta P)^2) \quad \text{(Landrø 2001)}$$

(We assume that V_0 is known)

Inverse Modeling Study

Seismic data



Seismic survey

Data $\rightarrow$ velocity

$$d_s \rightarrow V(\Delta S, \Delta P)$$

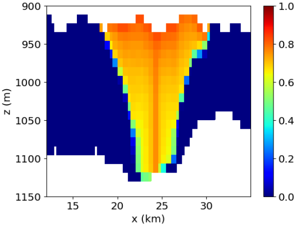
Aim to estimate $V(\Delta S, \Delta P)$. Will not attempt to estimate ΔS and/or ΔP

$$V(\Delta S, \Delta P) = V_0(1 - k\Delta S - l\Delta P - m(\Delta P)^2) \quad \text{(Landrø 2001)}$$

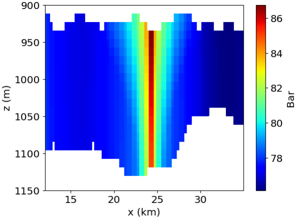
(We assume that V_0 is known)

Seismic Velocity

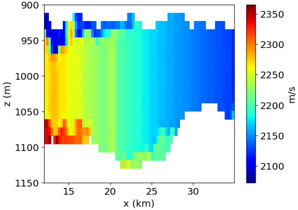
Dependence on ΔS and ΔP (and V_0)



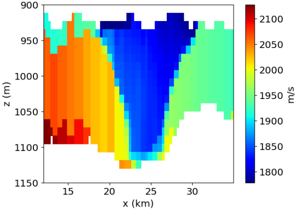
ΔS



ΔP



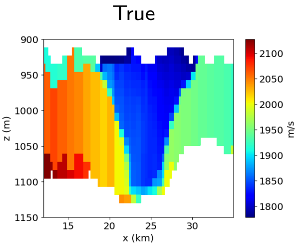
V_0



Simulated $V(\Delta S, \Delta P)$

Assimilation Results for V

Seismic data



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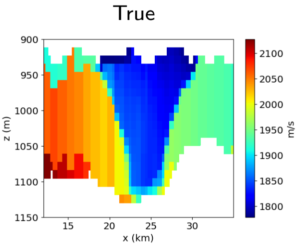

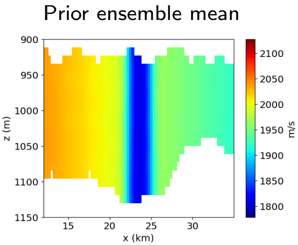

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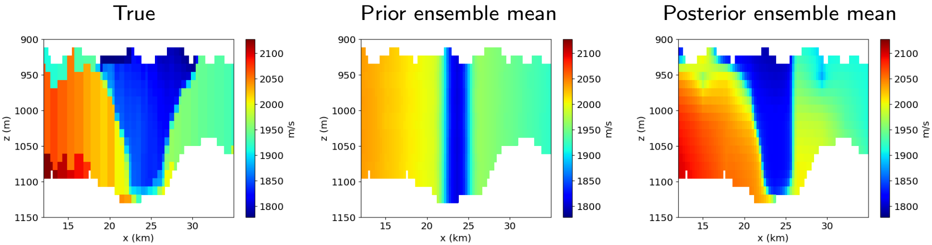

Geophysical Data

Seismic, gravimetric and electromagnetic

Seismic: $d_s \to V(\Delta S, \Delta P)$

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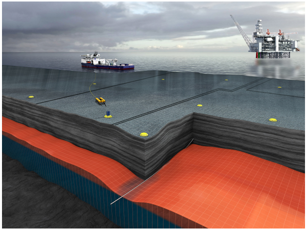
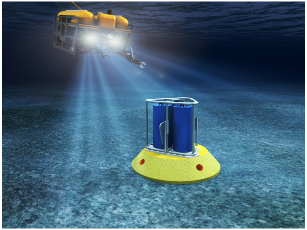
Gravimetric:

Gravimetric Data

Acquisition – overview

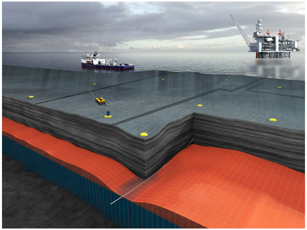


Acquisition – detail

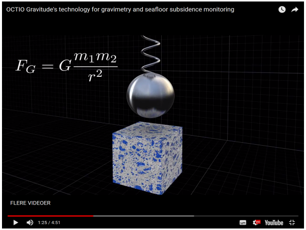


Gravimetric Data

Acquisition – overview



Brine-saturated subsurface



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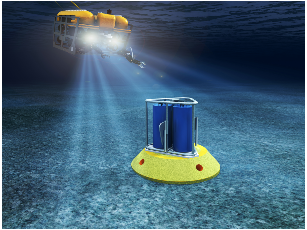
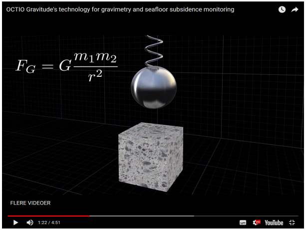


CO_2-saturated subsurface



Geophysical Data

Seismic, gravimetric and electromagnetic

Seismic: $d_s \to V(\Delta S, \Delta P)$

Gravimetric: $d_g \to \rho(\Delta S, \Delta P)$ (ρ: density)

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Electromagnetic:

Electromagnetic Data

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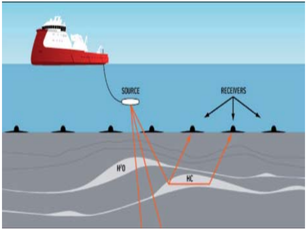

Acquisition – receiver

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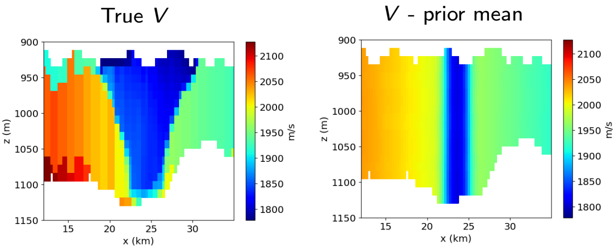
$\to$ Utilize results from assimilation of electromagnetic or gravimetric data to improve prior model for V in inversion of seismic data

Joint Utilization of Geophysical Data

Example with electromagnetics and seismics



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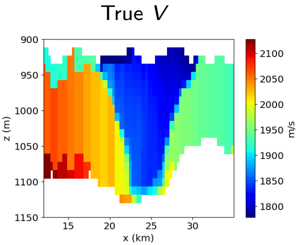
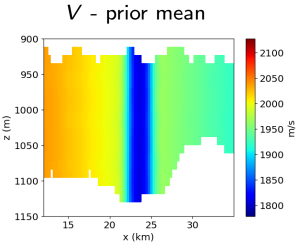
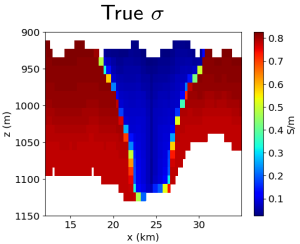
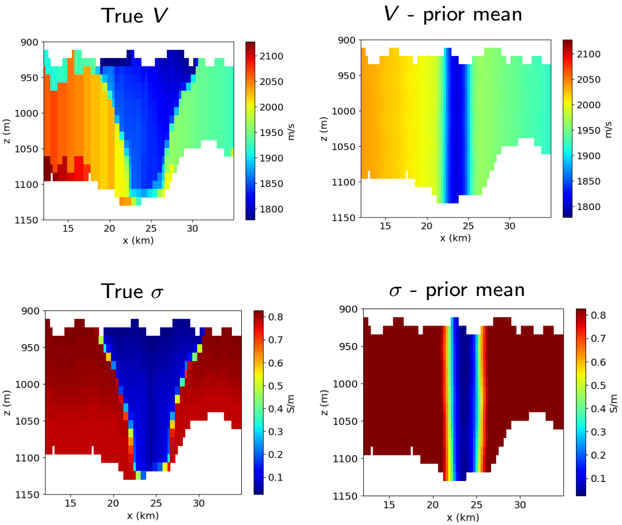






Joint Utilization of Geophysical Data

Example with electromagnetics and seismics



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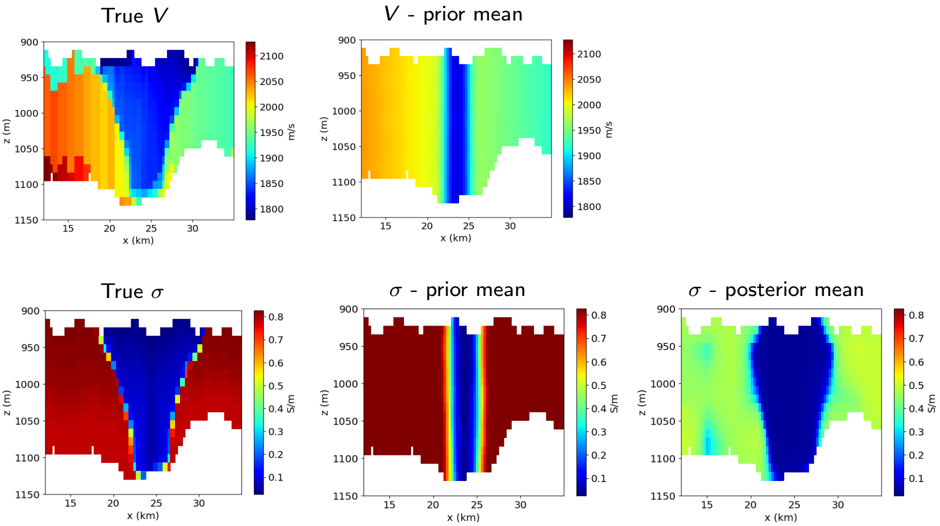

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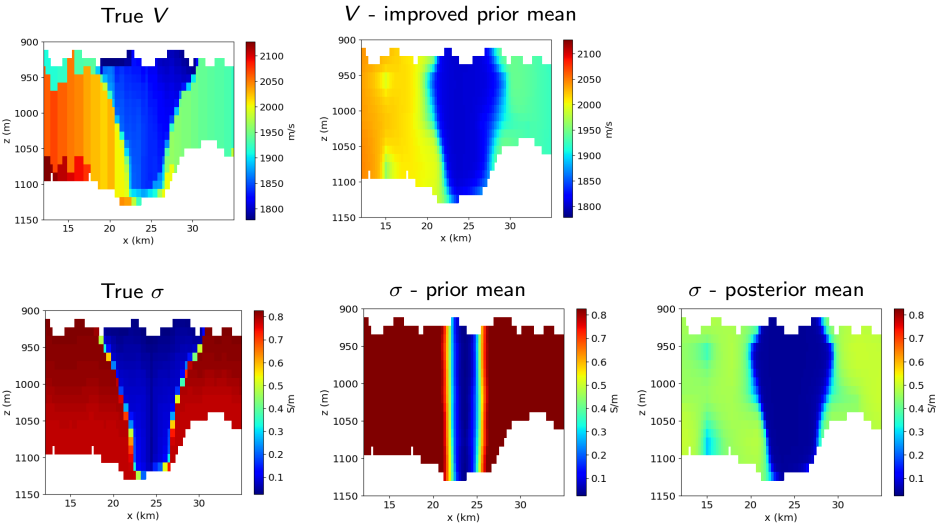

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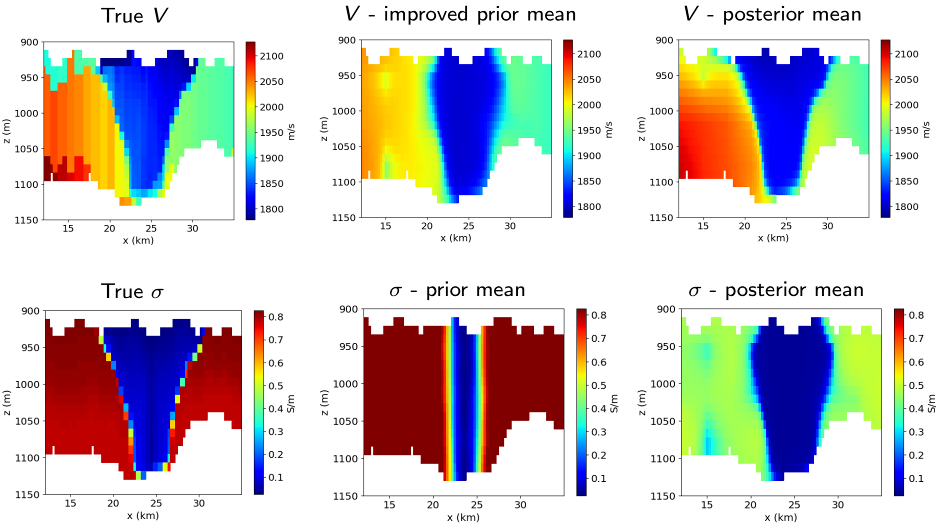
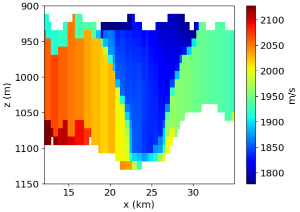


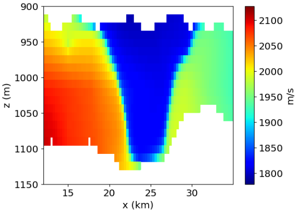
Joint Utilization of Geophysical Data

Summary of results for posterior mean of V

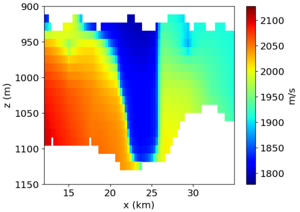
True



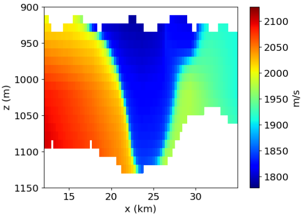
Utilizing d_e and d_s



Utilizing d_s

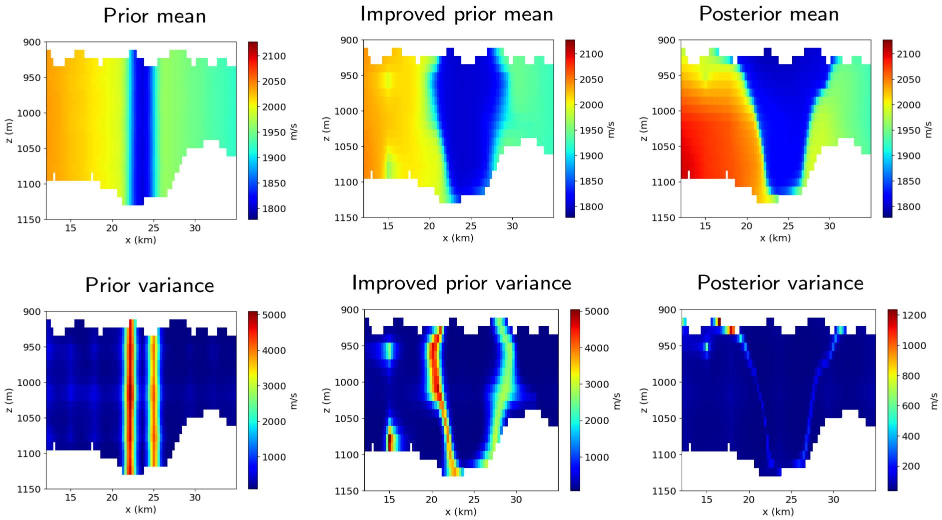


Utilizing d_g and d_s



Joint Utilization of Electromagnetic and Seismic Data

Development of estimate for V



Parameterization

The true V is characterized by large regions with slow (unknown) variation, sharp boundaries between regions, and unknown region shapes

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Part of each state vector, y, will contain parameters, a, controlling region-boundary positions, b; $b = f(a)$.

$$y^T = [a_1 \dots a_A$$

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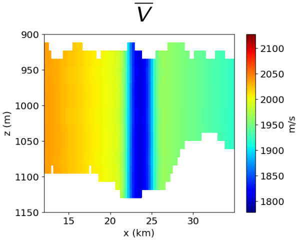
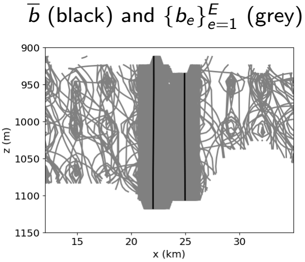
Part of each state vector, y, will contain parameters, a, controlling region-boundary positions, b; $b = f(a)$.
Other parts will contain parameters controlling spatial variation within each region.

$$y^T = [a_1 \ldots a_A | m_1 \ldots m_M | q_1 \ldots q_Q]$$

Illustration of Parameterization—Prior Model for V

Mean of V, mean of region boundaries, and region-boundaries ensemble



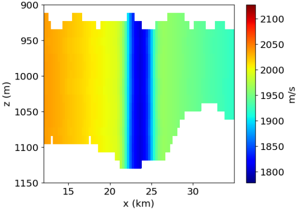


Joint Utilization of Electromagnetic and Seismic Data

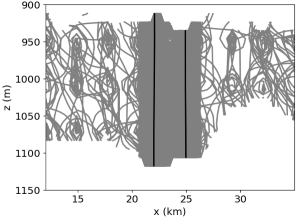
Development of mean of V, mean of region boundaries, and region-boundaries ensemble

Prior

$\overline{V}$



$\overline{b}$ (black) and $\{b_e\}_{e=1}^{E}$ (grey)



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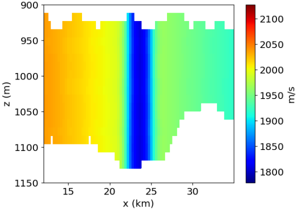
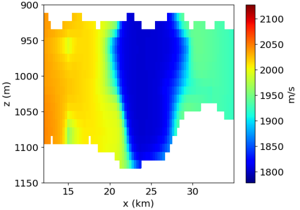
Prior

Improved prior

$\overline{V}$



$\overline{V}$



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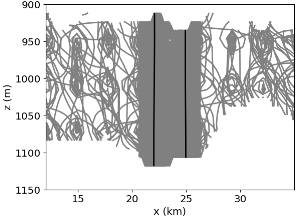

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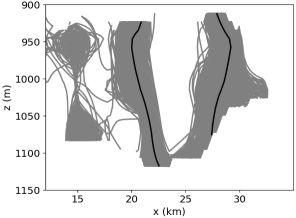

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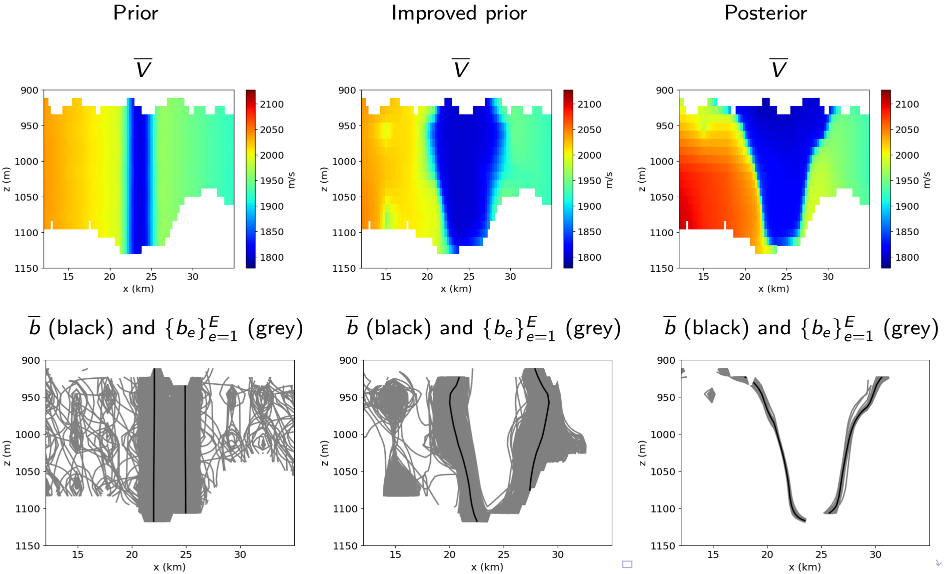

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Joint utilization of different geophysical data types, advanced parameterization techniques, and ensemble-based data assimilation, are key elements in the methodology

Improved estimates of seismic velocity were obtained when electromagnetic or gravimetric data were utilized to improve the prior model for seismic velocity before inversion of the seismic data

Acknowledgements

Partial financial support was provided by the SUCCESS project, funded by ConocoPhillips, DEA, DONG, Octio, Statoil, Store Norske Spitsbergen Kullkompani, and the Research Council of Norway (RCN) (Climit). Partial financial support was also provided by the PROTECT project, funded by DEA, Total, and RCN (Climit)