UNIVERSITY OF CALGARY

CREWES

CMC Containment & Monitoring Institute

# The seismic interpretability of a 4D data, a case study: The FRS project

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Don Lawton

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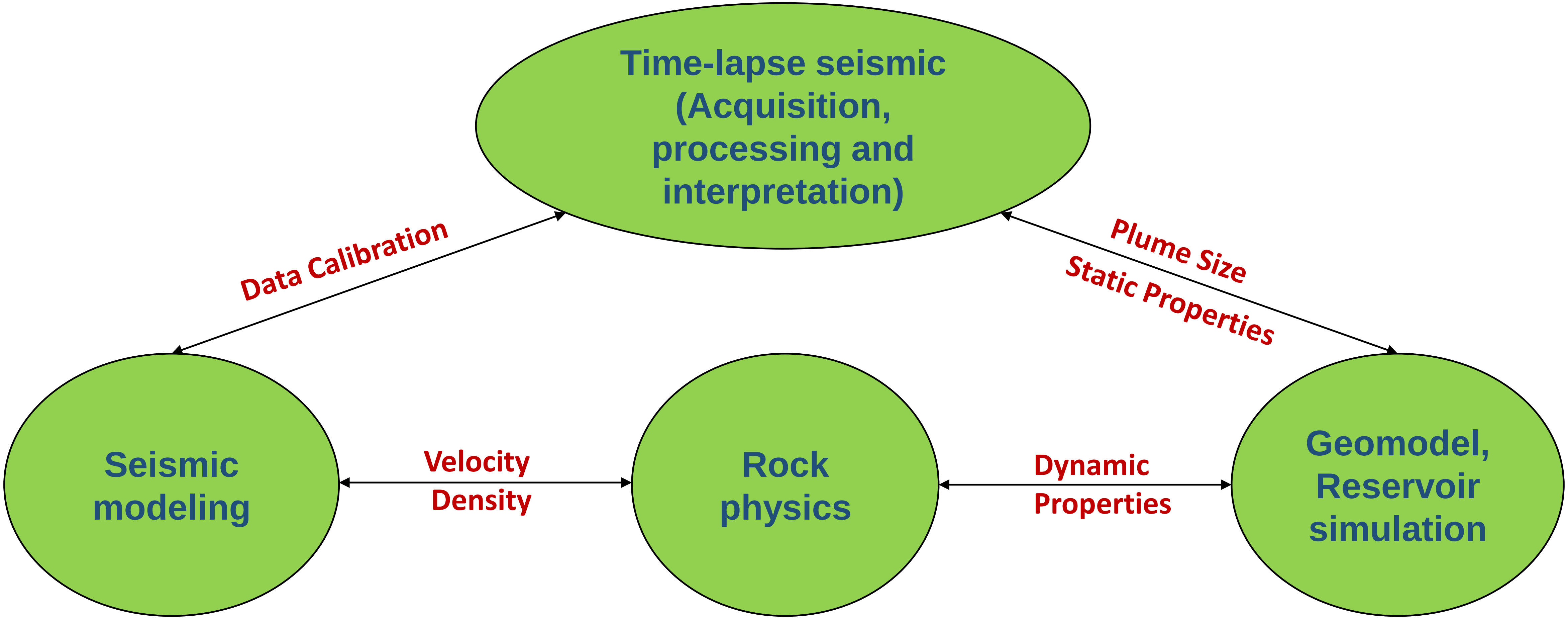
# Outline

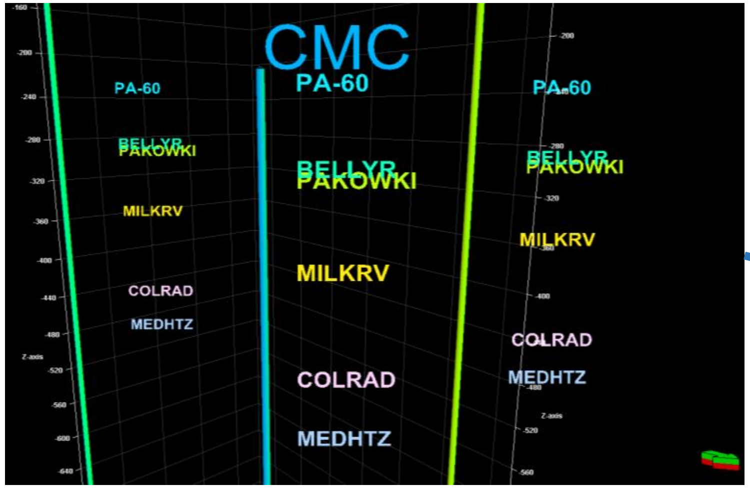
- Introduction
- Reservoir simulation
- Rock physics and fluid substitution
- Velocity perturbation models
  - Solid
  - Diffusive
- Full waveform analysis and imaging (acoustic)
- Saturation and plume size influences in the seismic response
- Conclusions and acknowledgments

# The research workflow

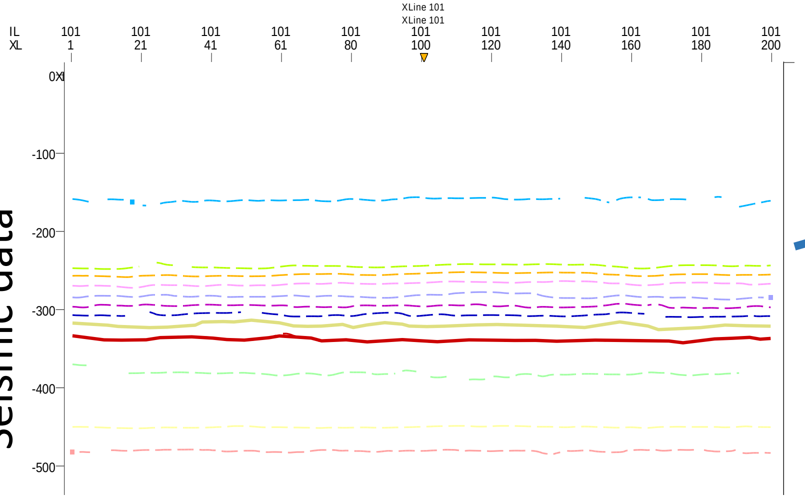


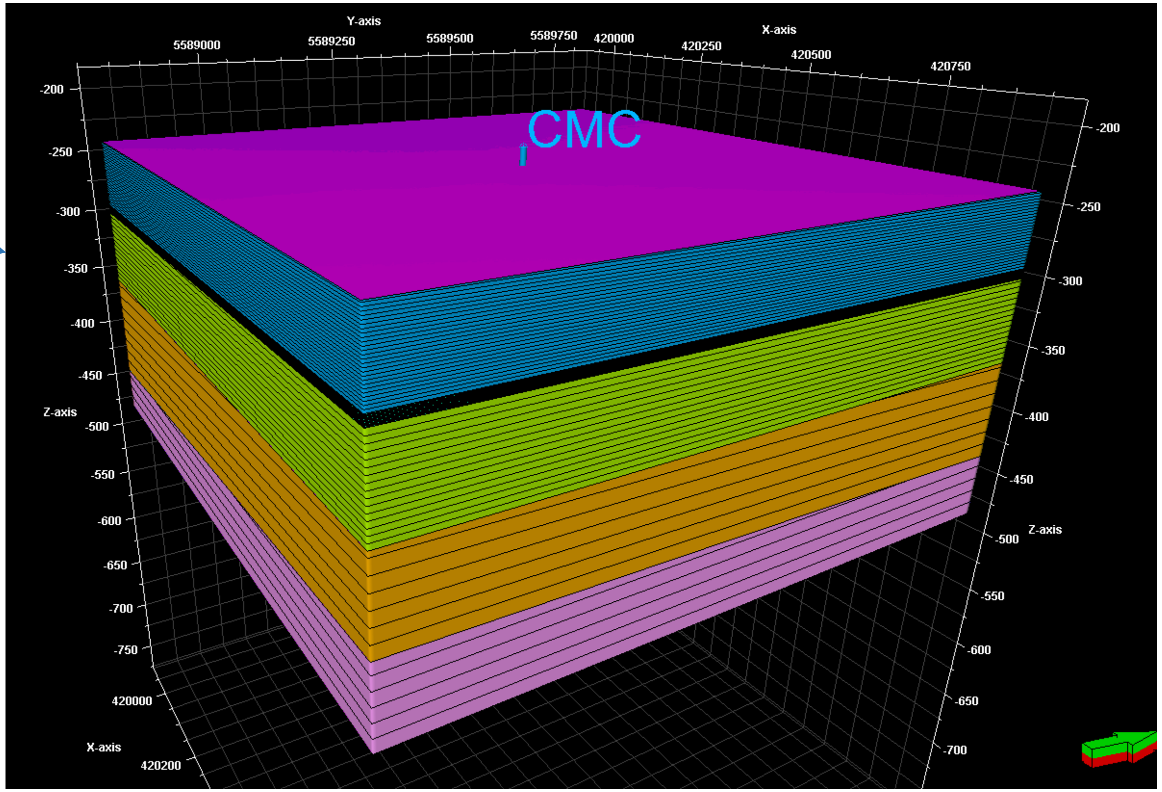
# The geometry of the formations

Well tops

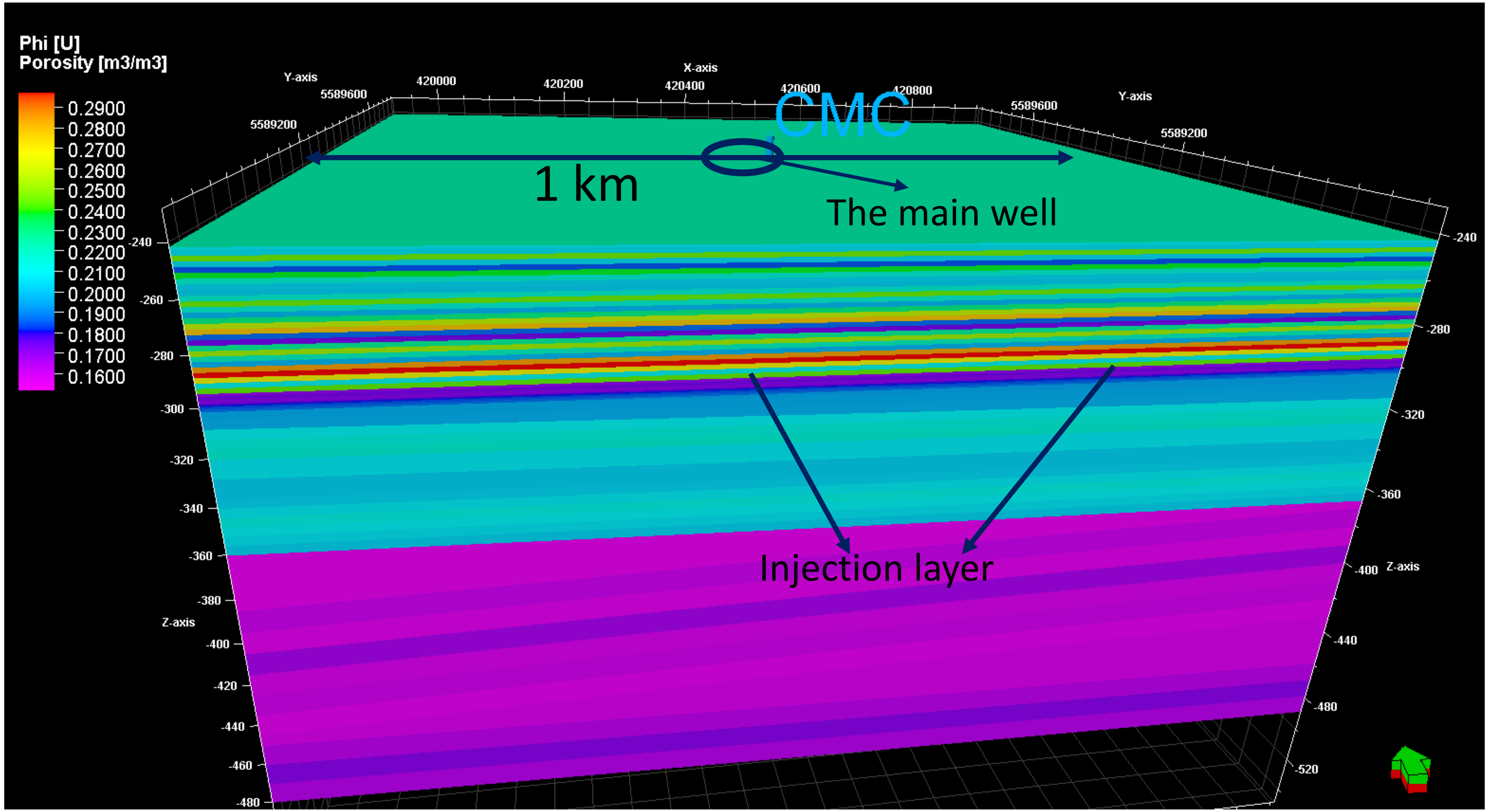



Seismic data

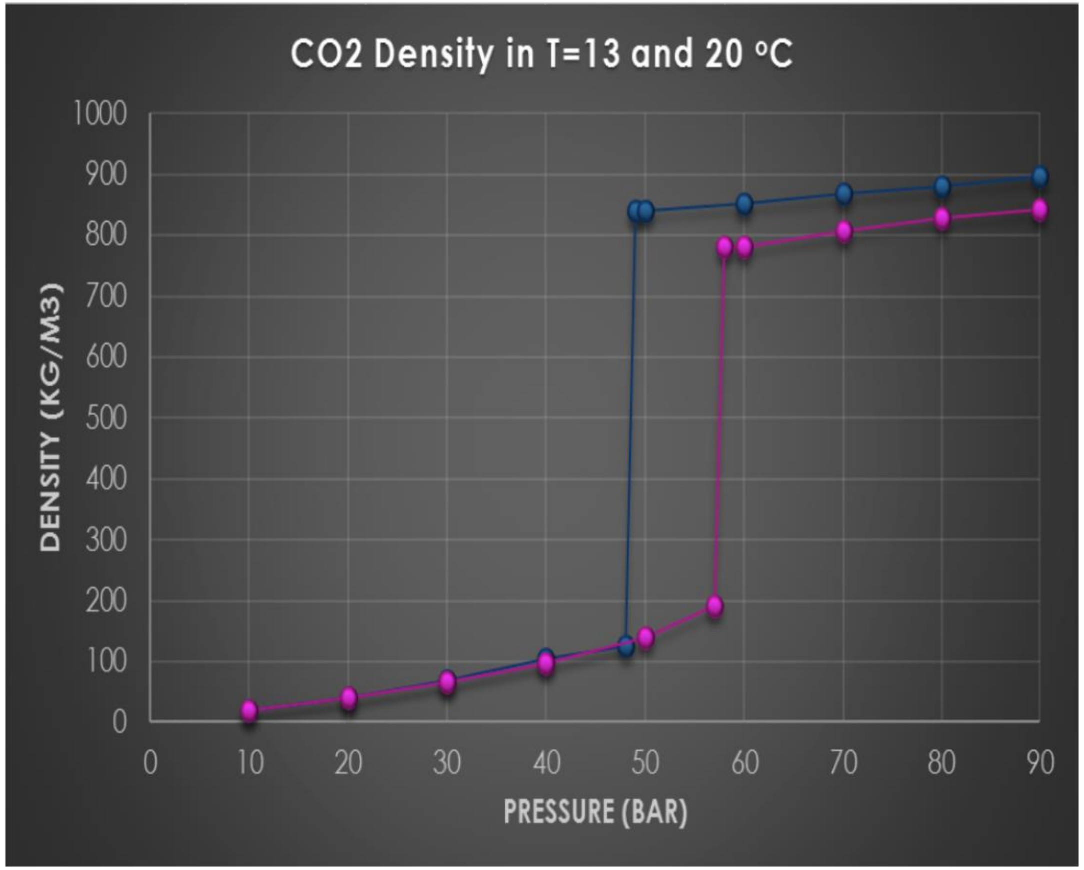


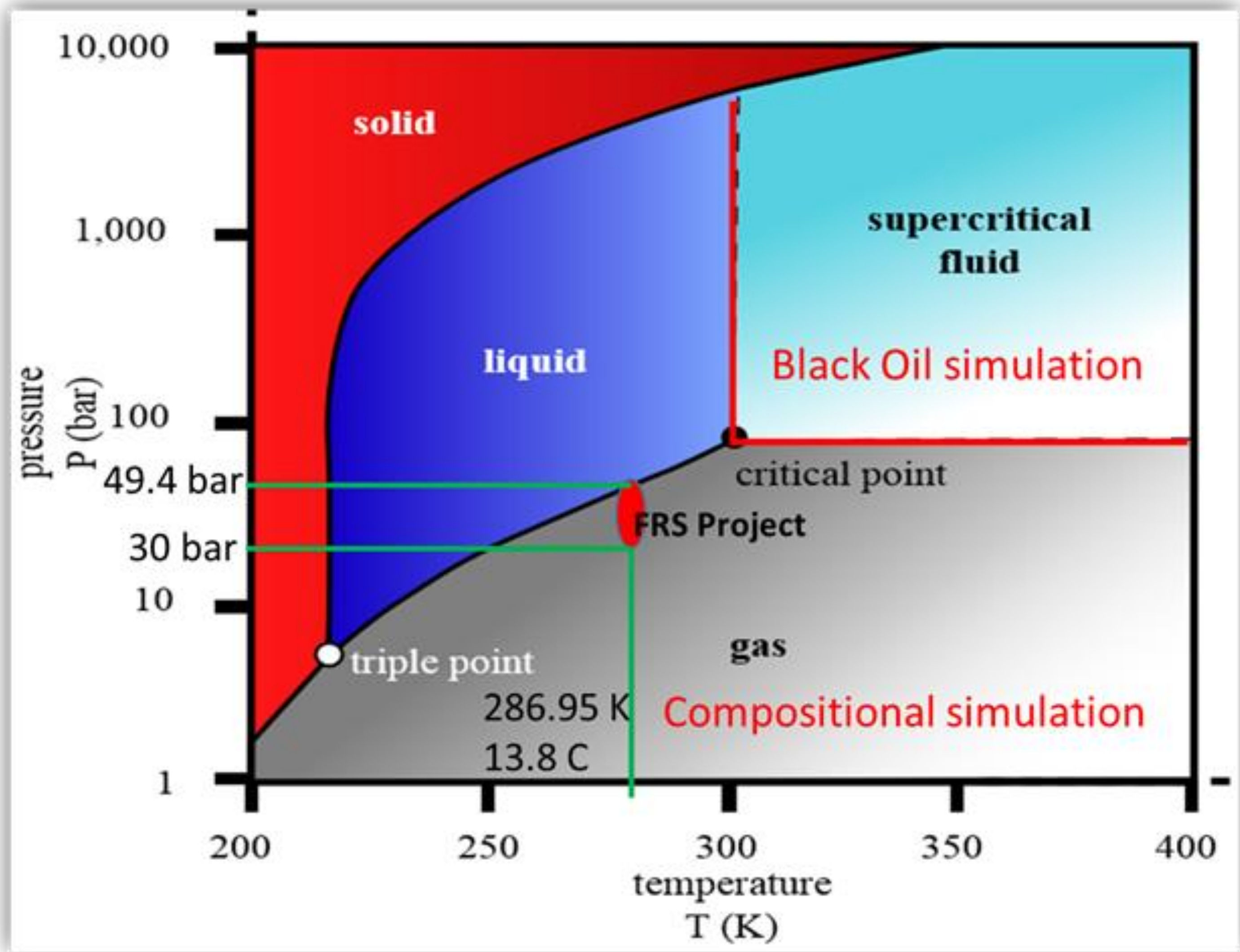



# Porosity geomodel

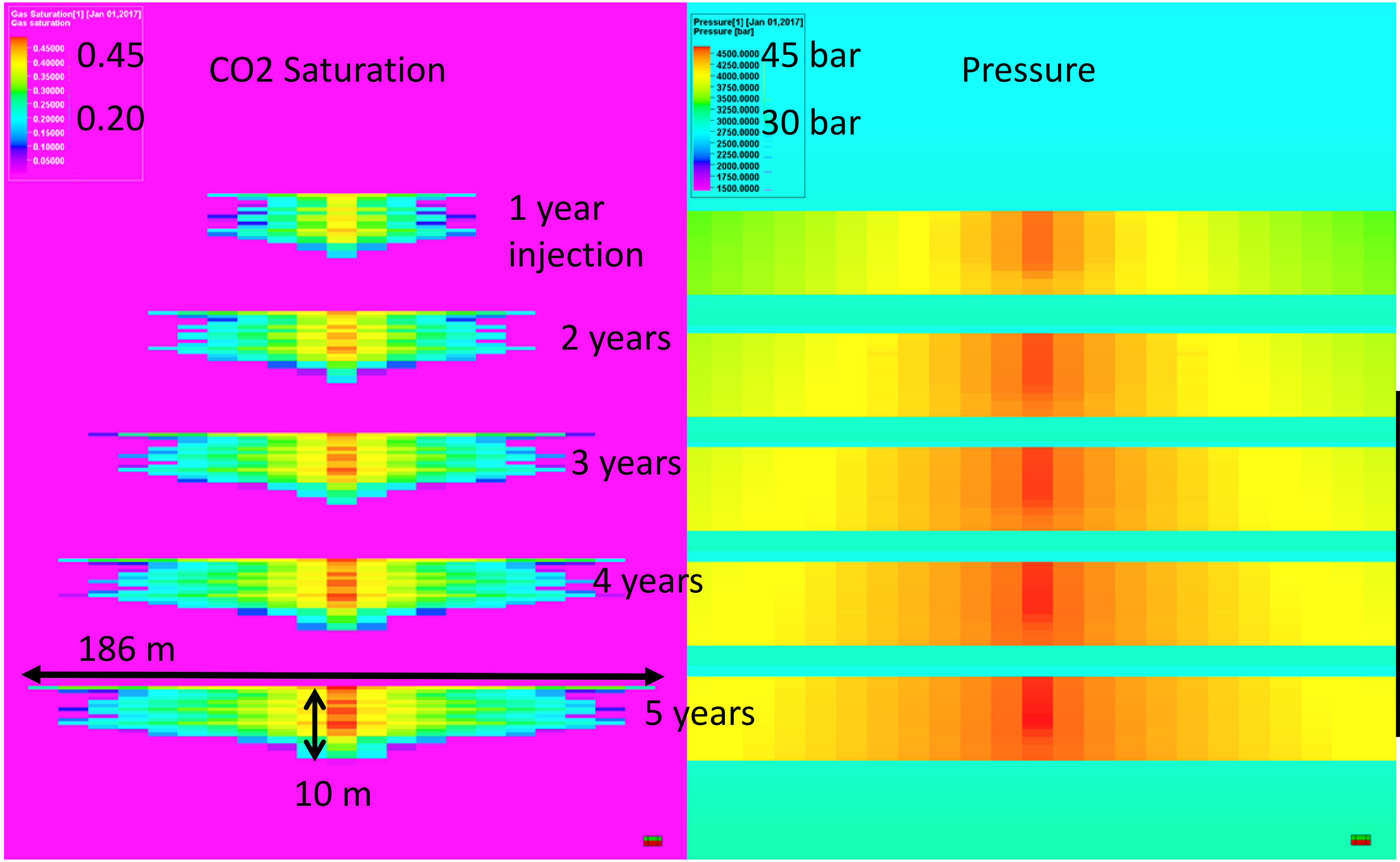


# $CO_2$ phase diagram



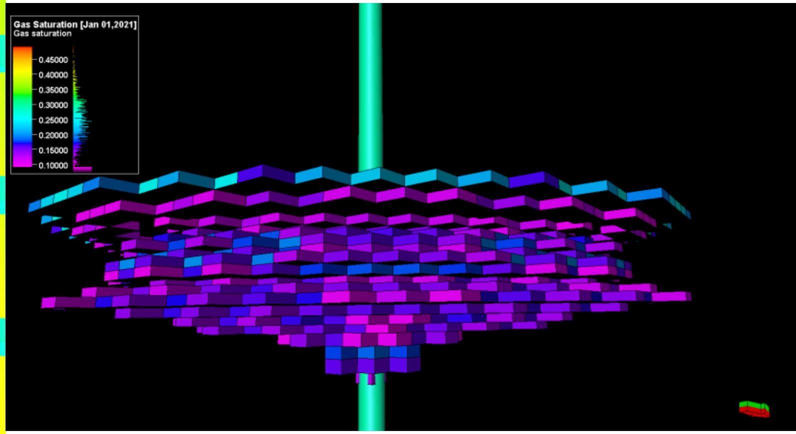



# The fluid simulation result

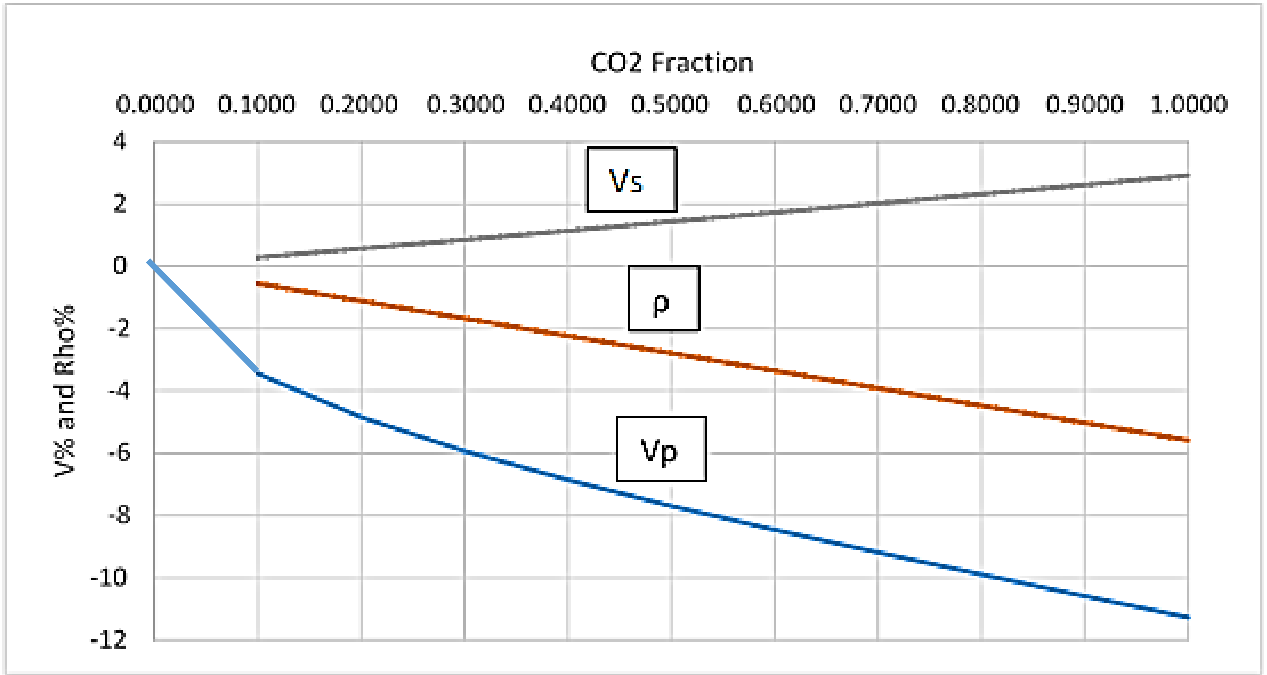



**Compositional simulator**
**Unlimited boundaries condition**

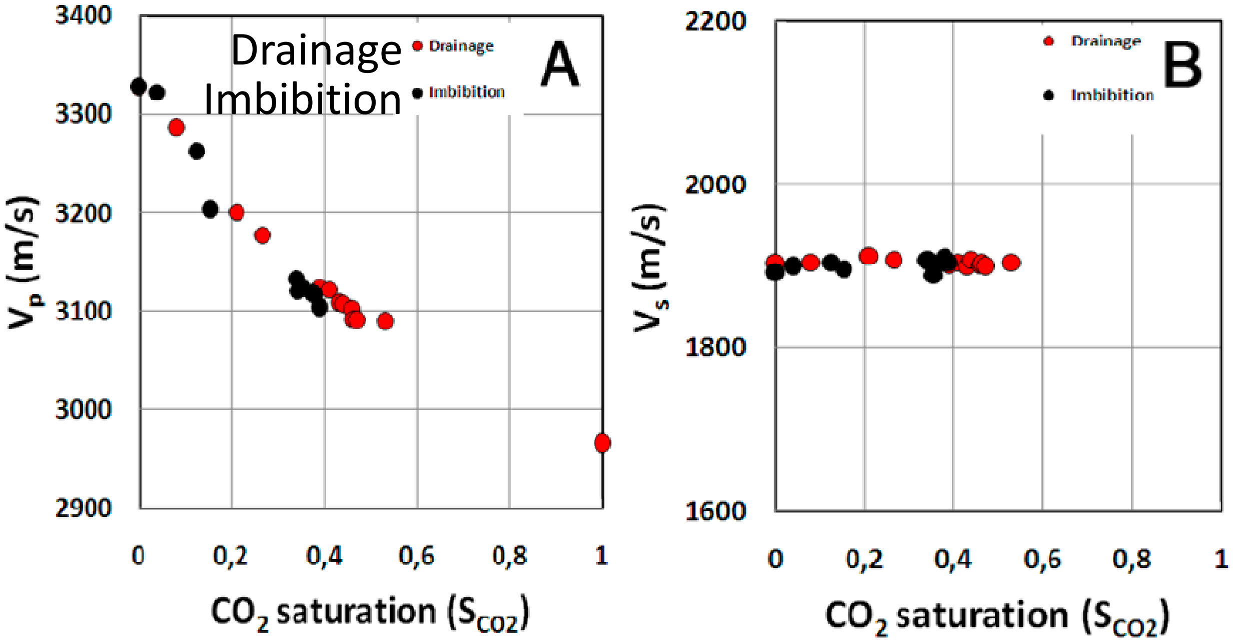
**Injection strategy:**
**Five years injection**
**Constant BHP=49.4 bar**



# Fluid substitution, $CO_2$ effect on the velocity

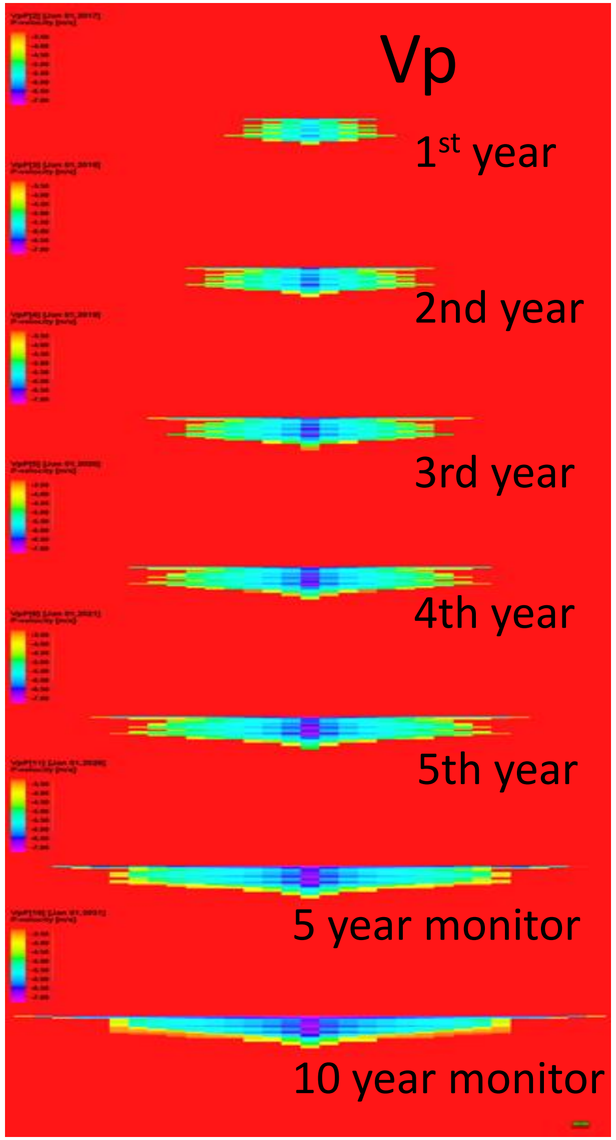


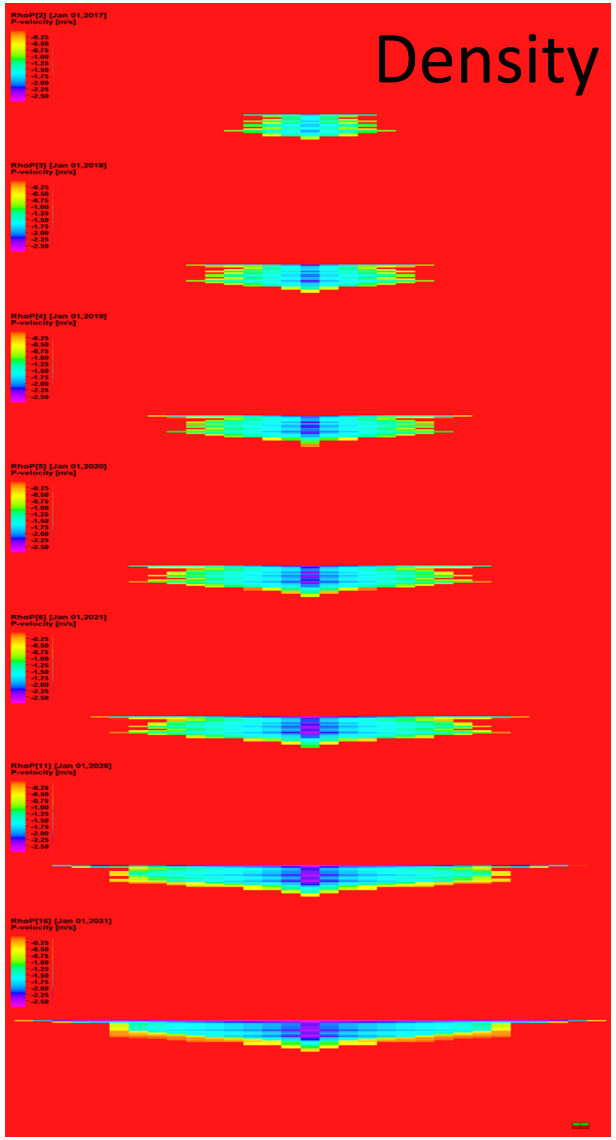

Fluid substitution effect

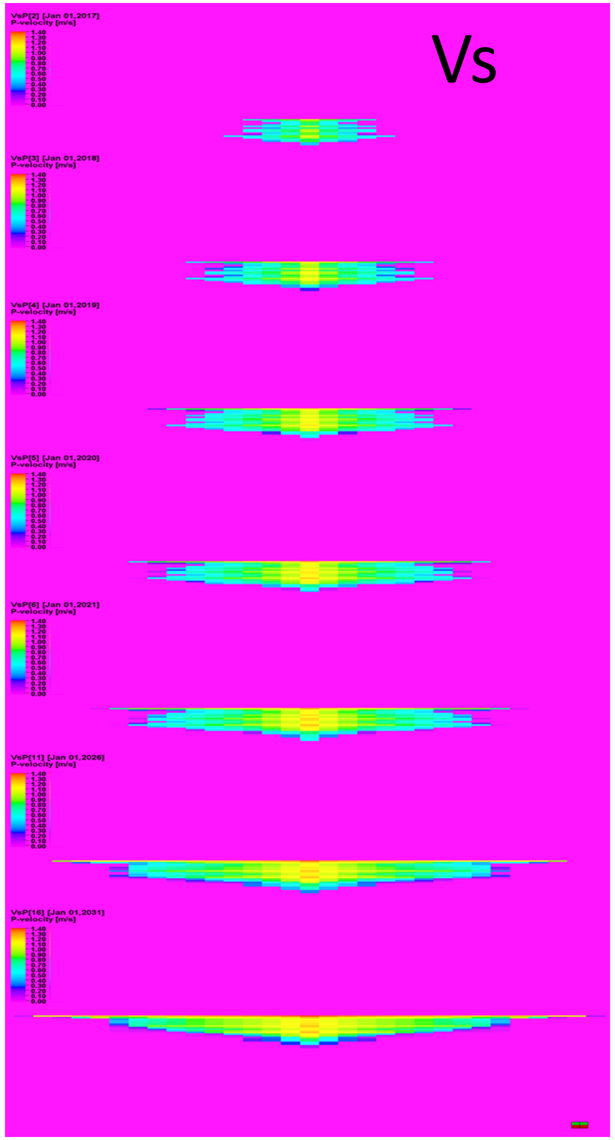



Lab test result for the $CO_2$ injection into the Sandstone (B.Alemo et al., 2011 )

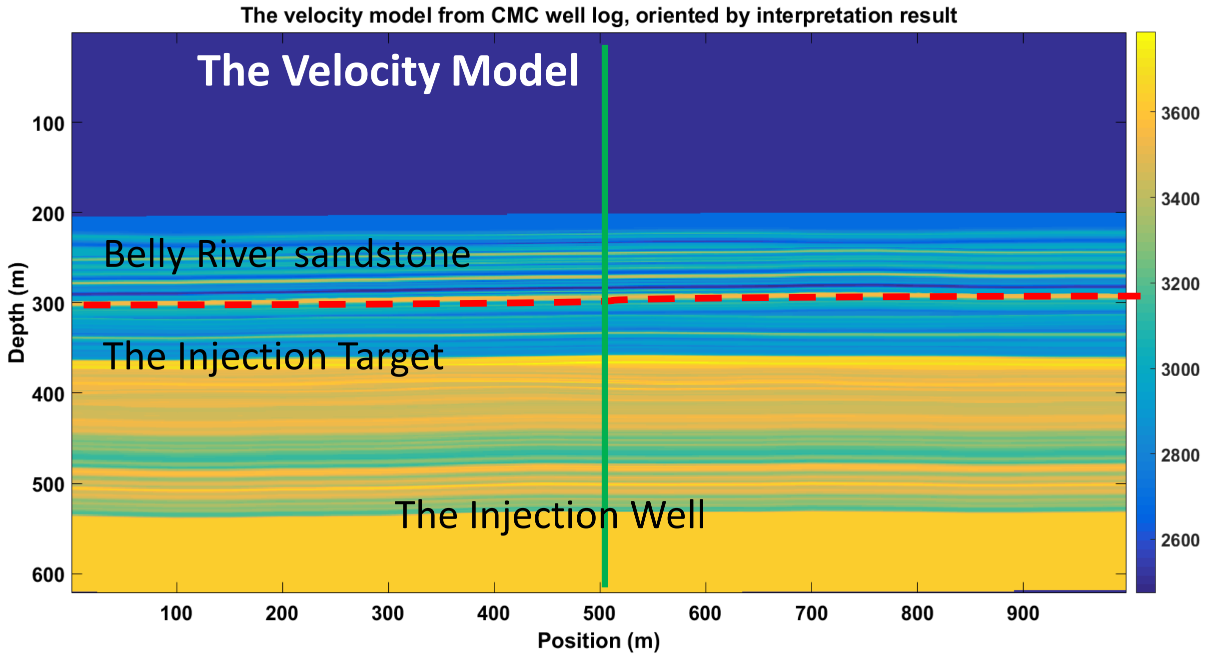
# Vp, density and Vs in the reservoir during injection

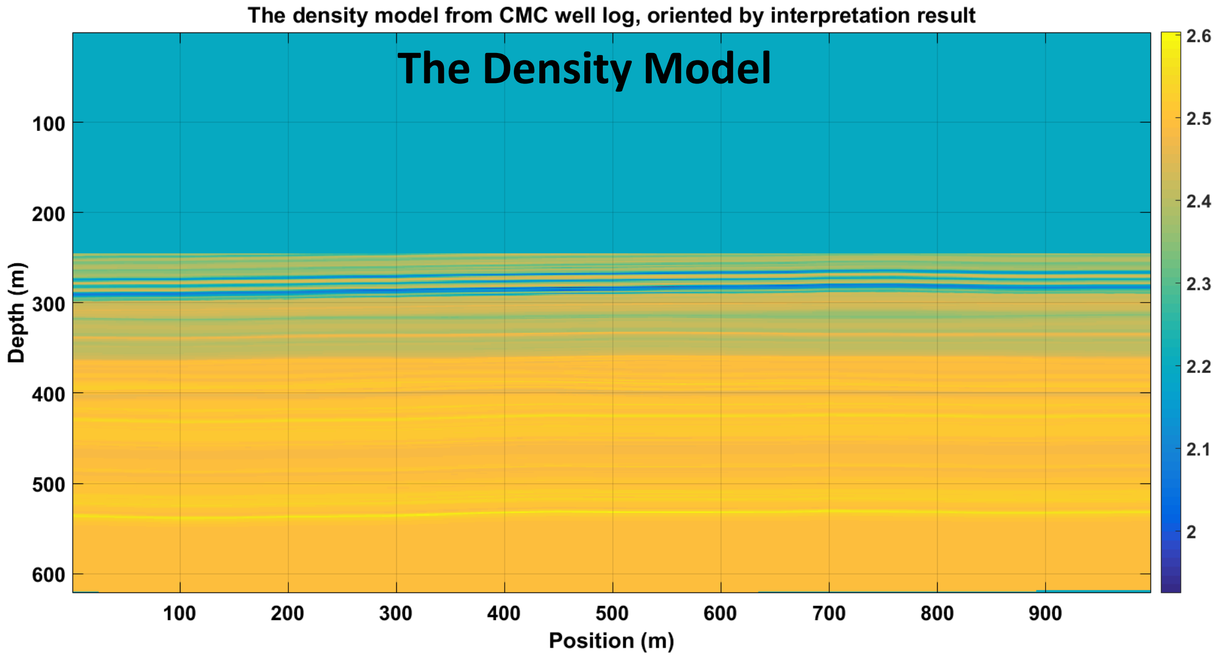


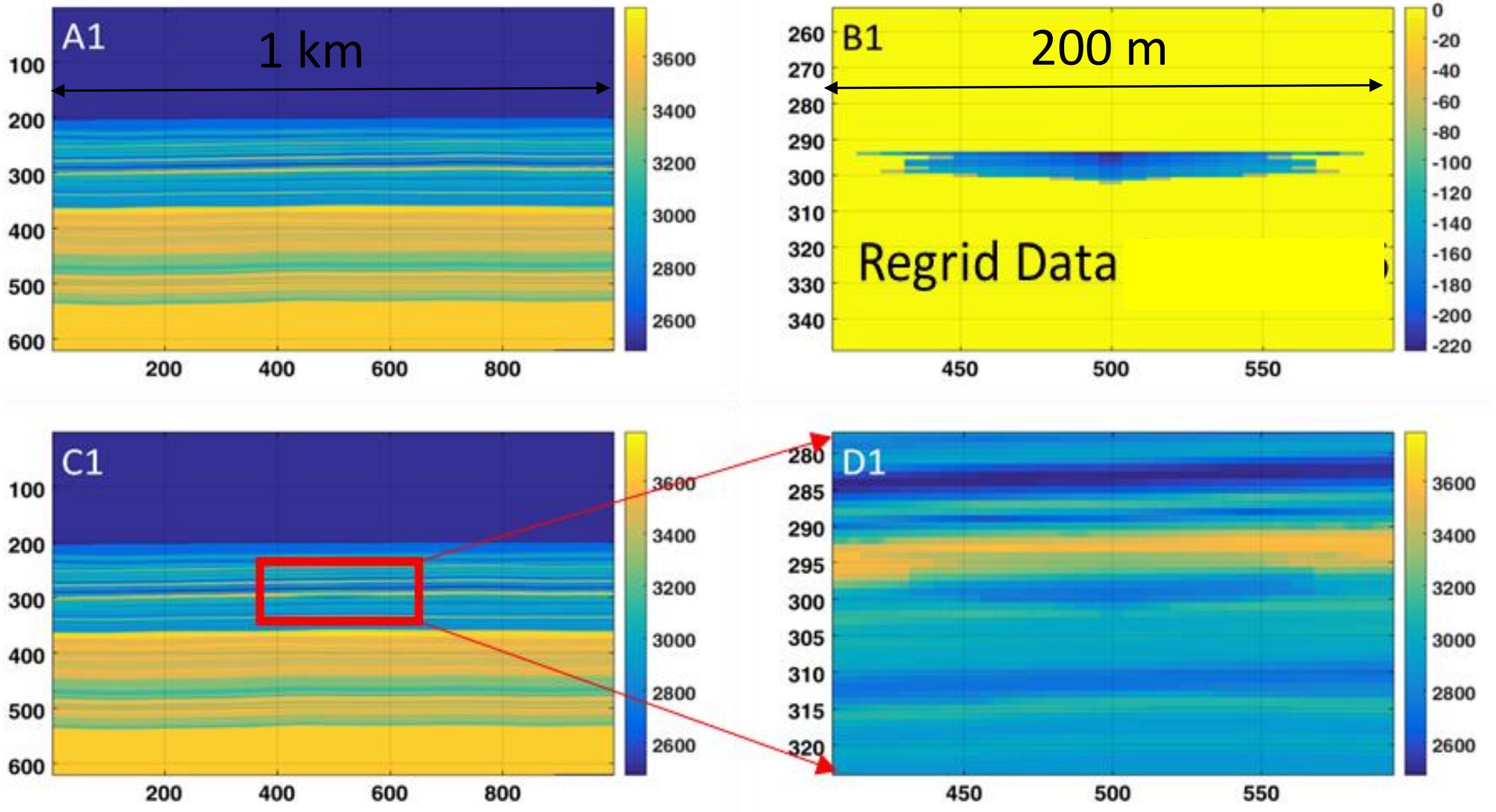
# The velocity and density models



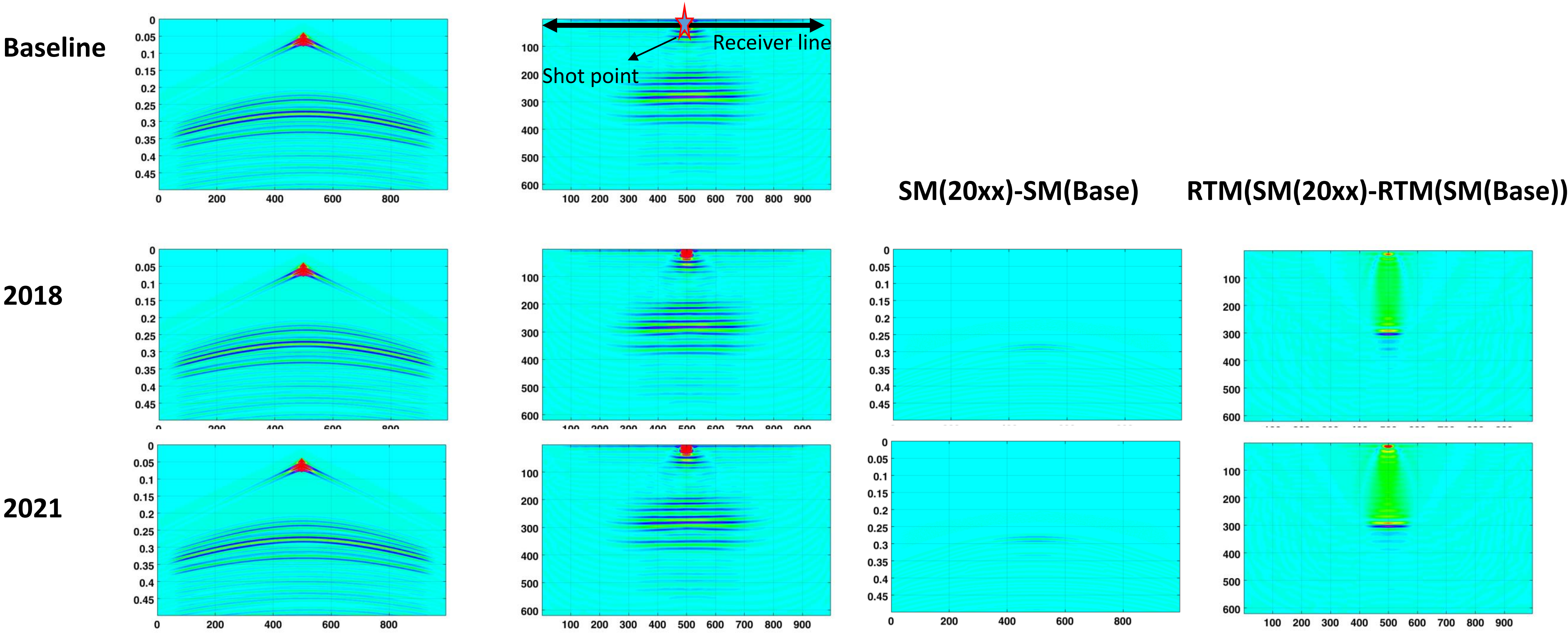




Layers geometry is based on seismic interpretation result
The velocity and density are from CMC main well log data
Model has 1*1m cell size and geomodel made in Petrel

# The velocity perturbation due to the reservoir



# The seismic response of the reservoir

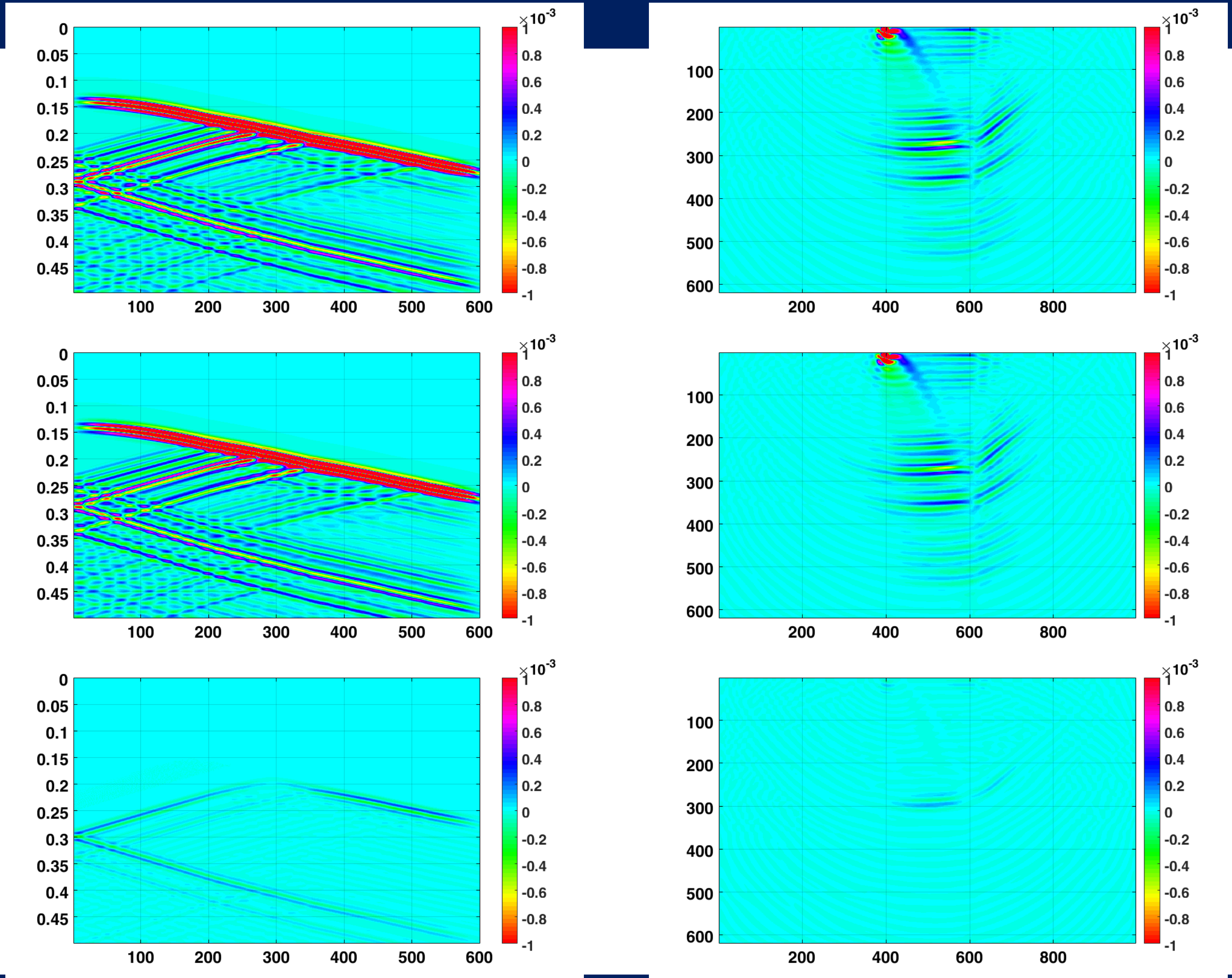


# VSP models

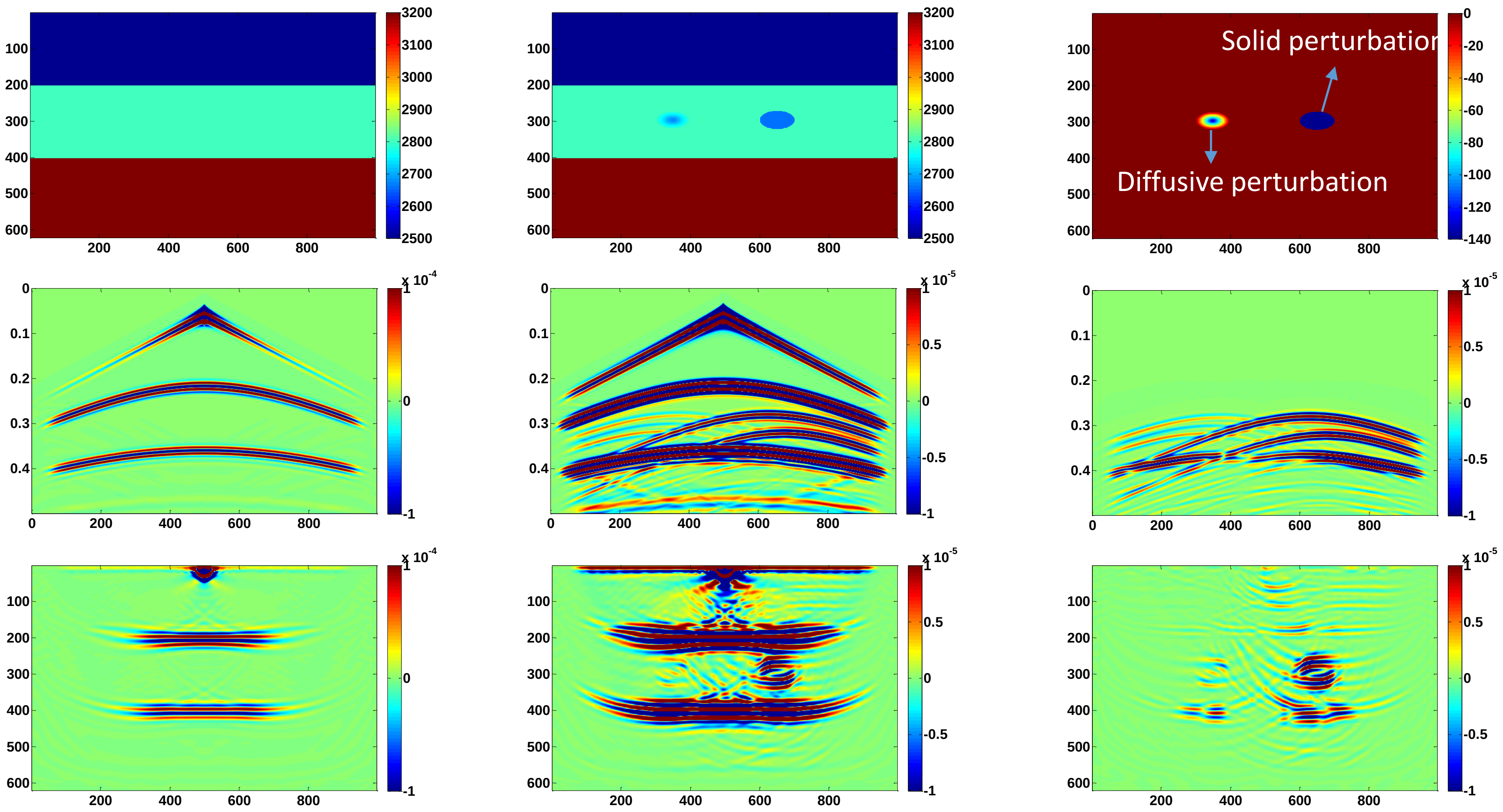
**Baseline**

**2021 (5-year injection)**

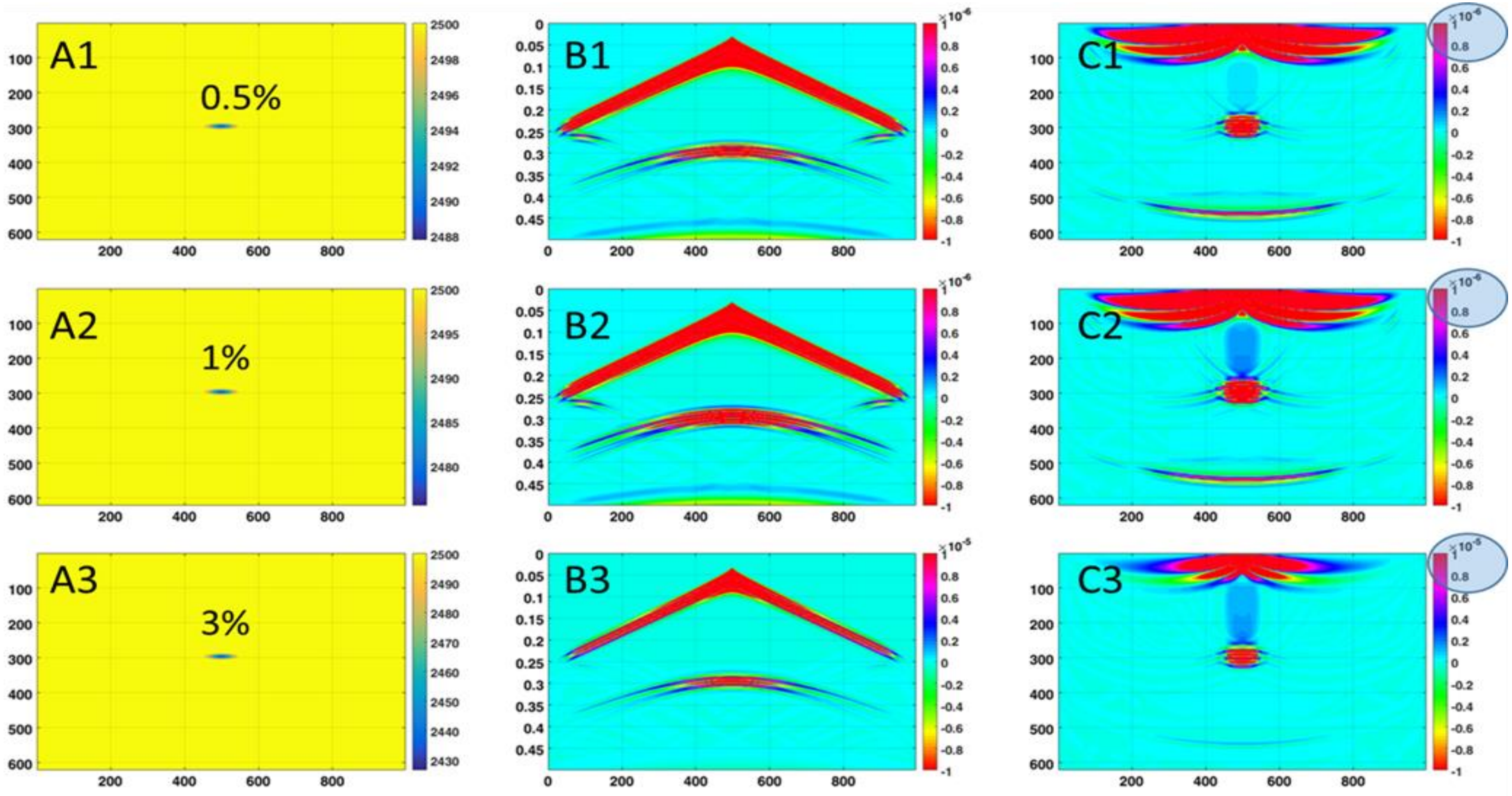
**Difference**



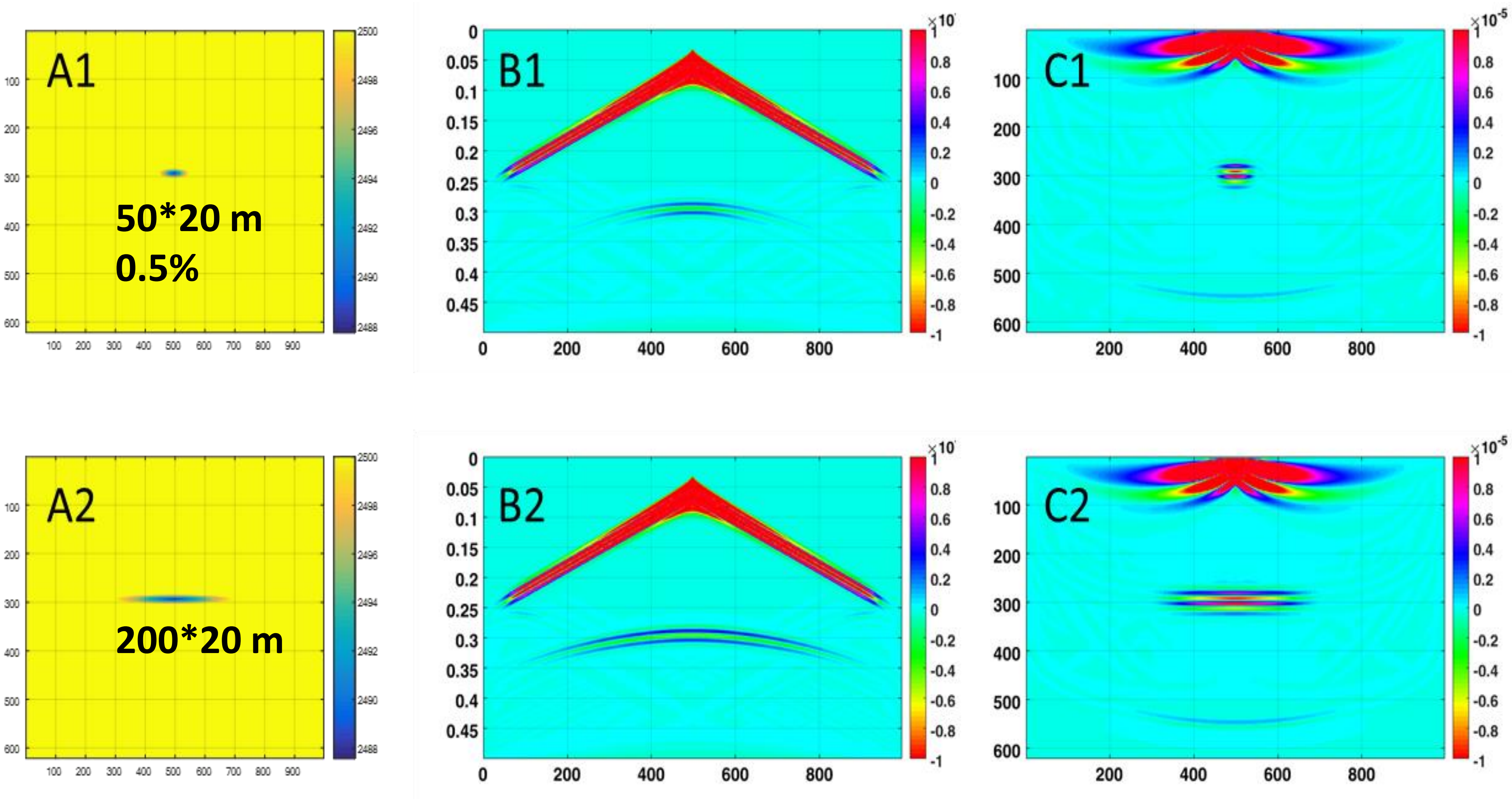
# Seismic response for solid and diffusive velocity



# Saturation and velocity change effect

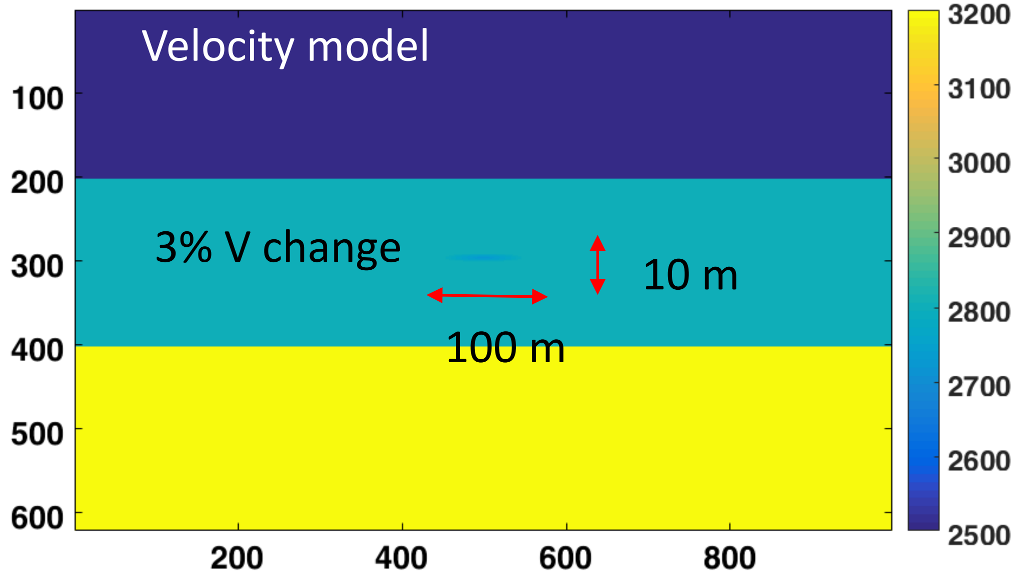


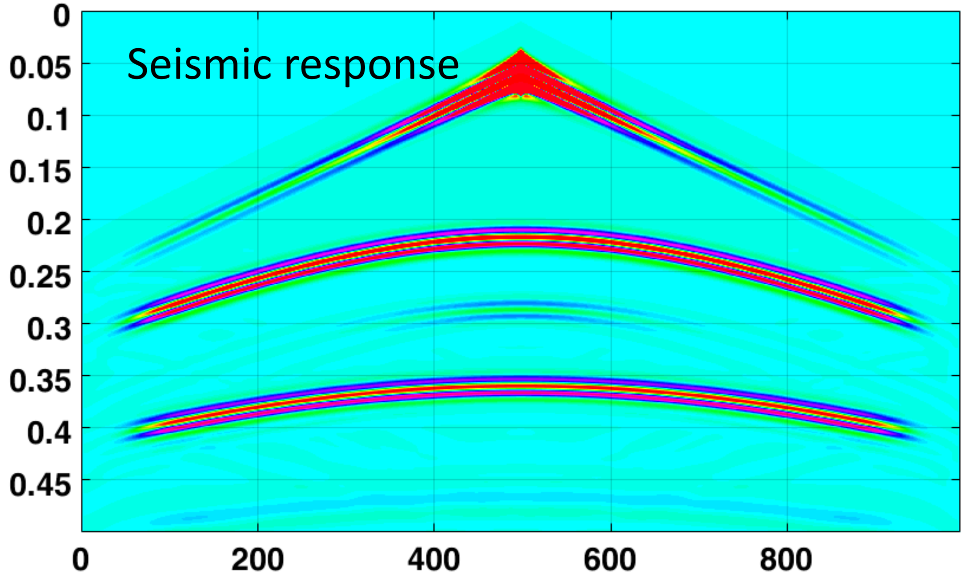
# The plume size effect

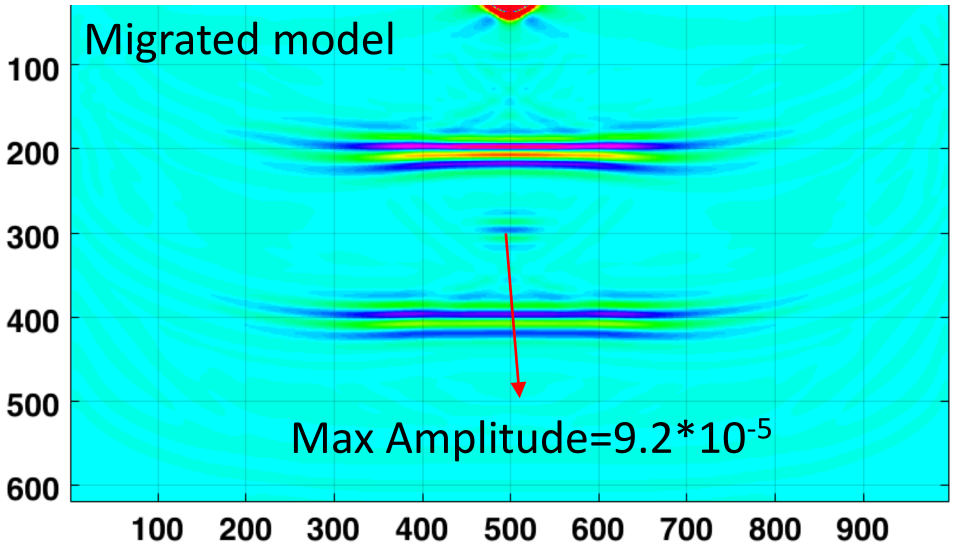


# 3-layer model with diffusive velocity

100*10 m – 3%

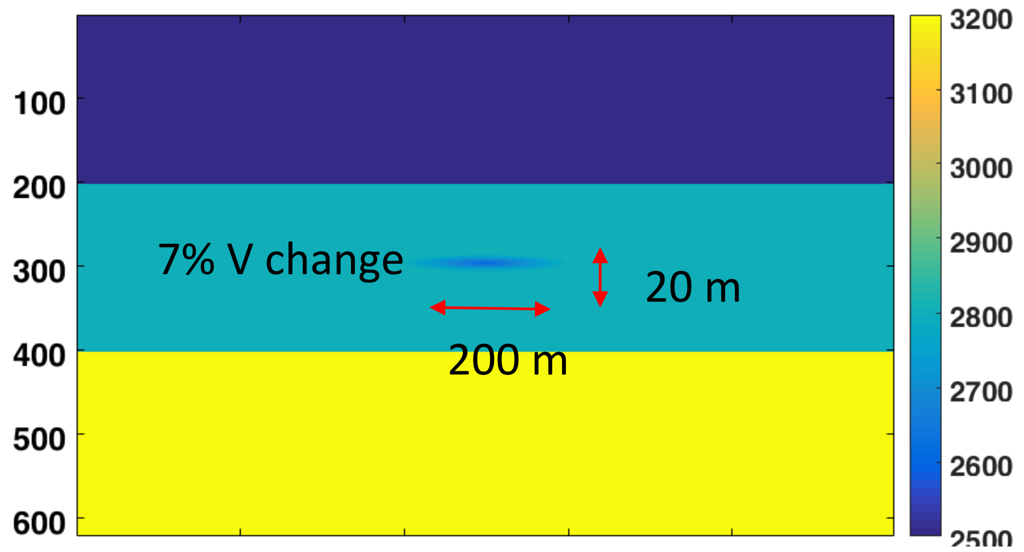


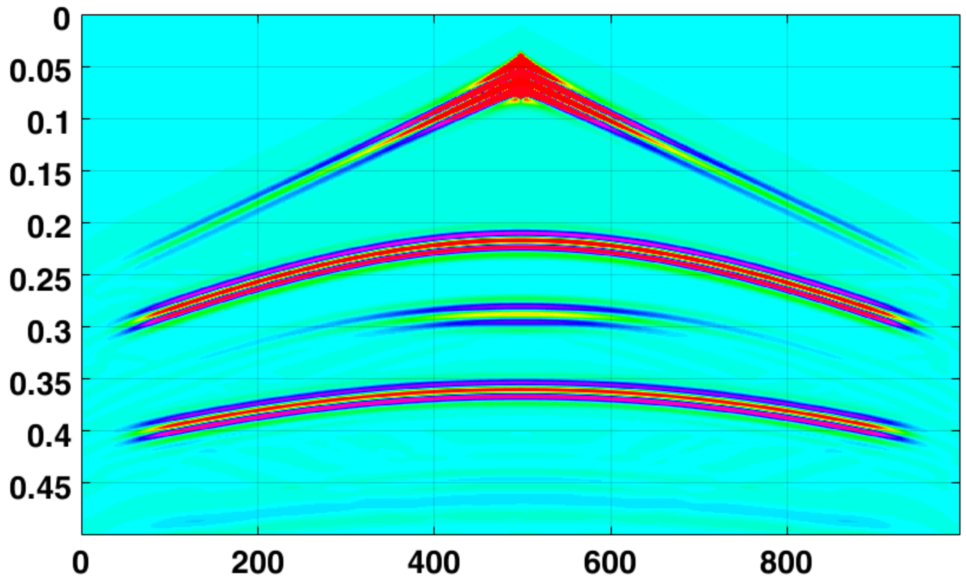



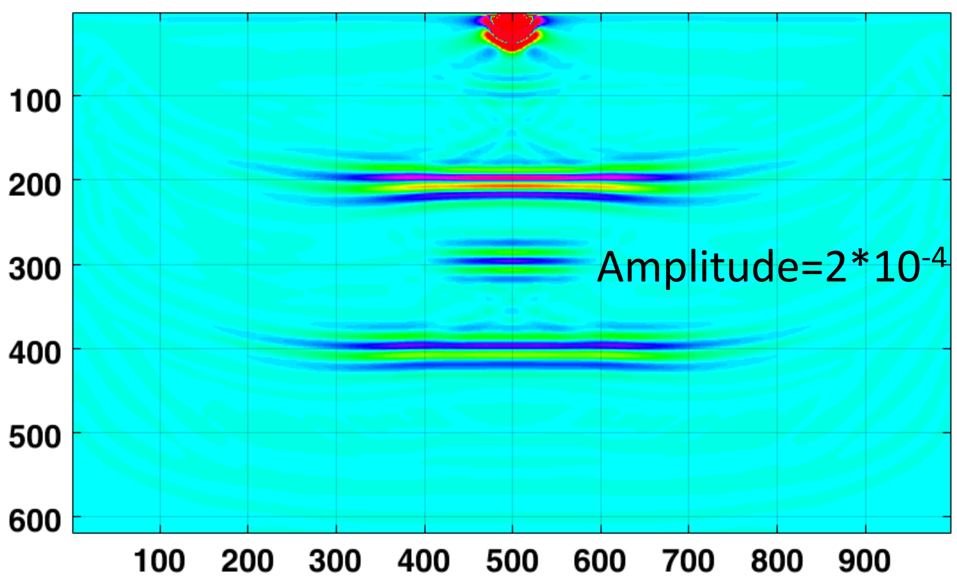



# 3-layer model with diffusive velocity

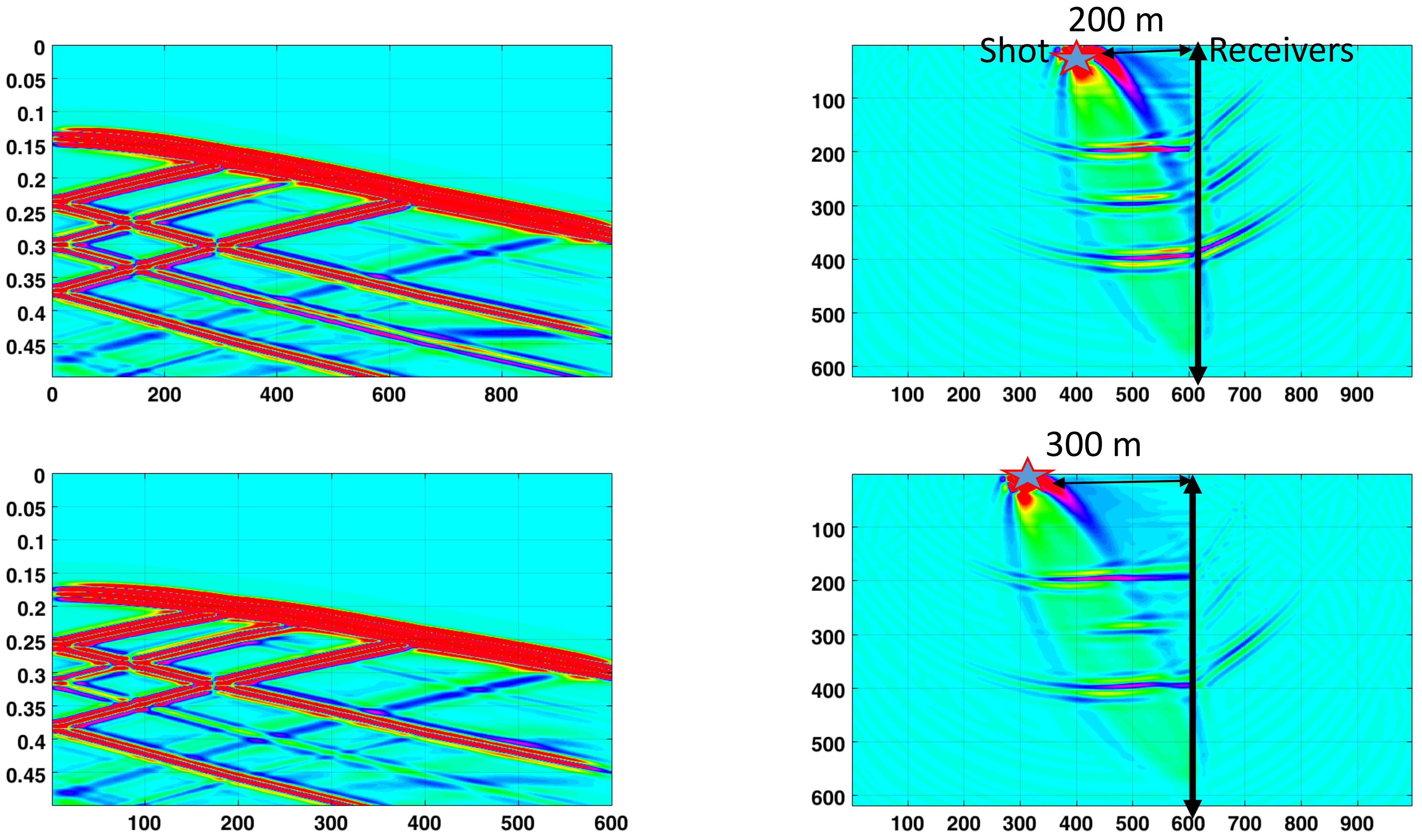
200*20 m – 7%



# Narrow vs wide offset VSP models



# Conclusions

- The time-lapse seismic response of diffusive zone shows small changes in the amplitude compared to similar solid block changes.
- Because of velocity decrease in the reservoir , a time delay effect was detected in reflectors below the reservoir, so we should consider the changes in travel time of transmitted waveforms as an alternative framework for a full waveform study.
- Surface seismic acquisition is a suitable method for the shape estimation of the plume, but well seismic data has better amplitude and frequency content, so VSP are most useful for the small changes of fluid saturation.
- The Migrated data has a better amplitude condition , so interpretation is possible with the full migrated data.

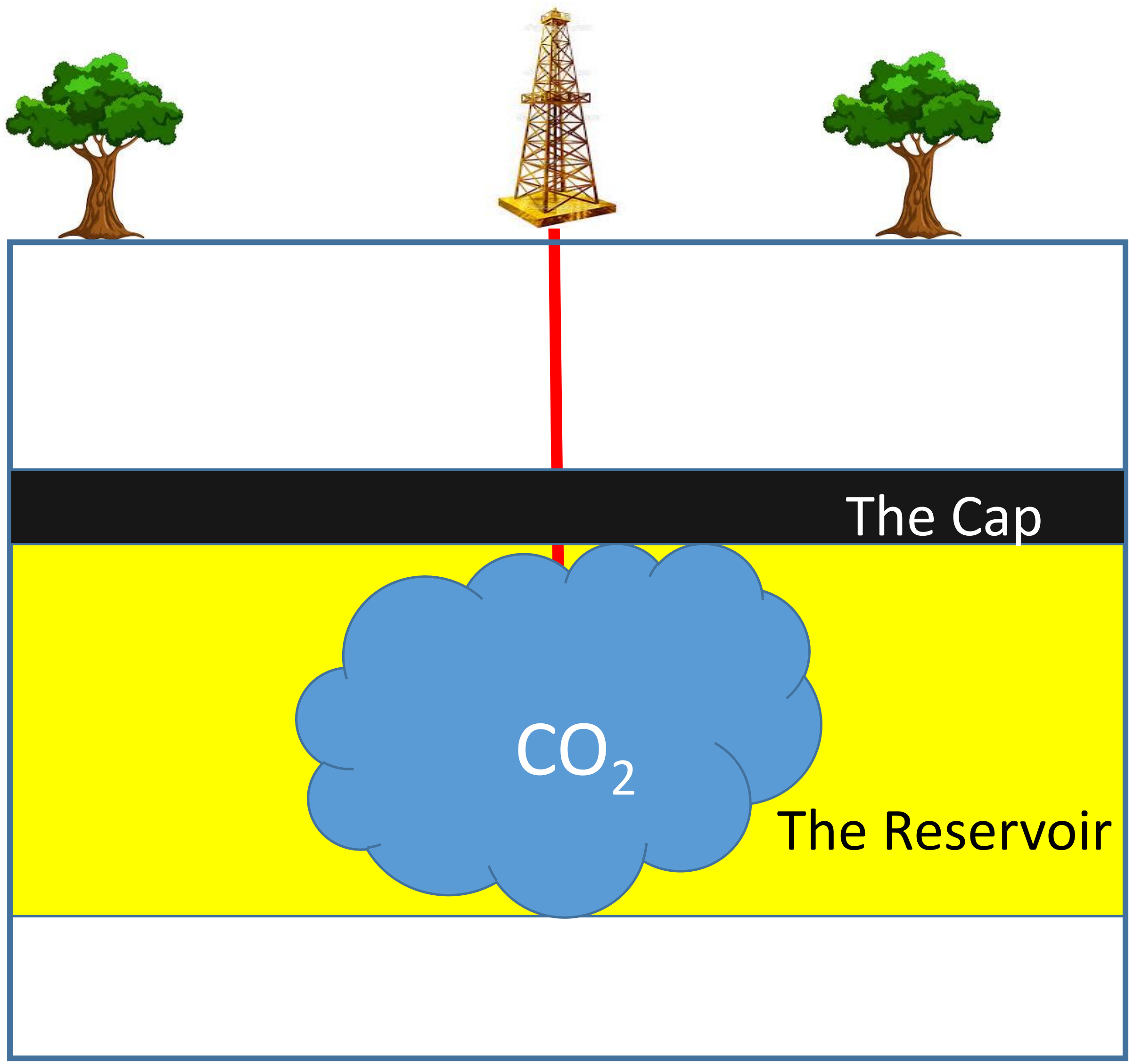
# Acknowledgments


- Industrial sponsors who support CREWES
- CMC Research Institutes, Inc.
- NSERC Grant
- CREWES team and students
- Helen Isaac for the seismic data processing

# Full Waveform Inversion and plume model

- The basic equations used in this study is the acoustic velocity-stress wave equation approach.
- Wave equation are solved by Finite Difference Time Domain in an explicit scheme. $2^{nd}$ order in time and $4^{th}$ order in space, staggered grid in a leap frog scheme

# Reservoir Geophysics

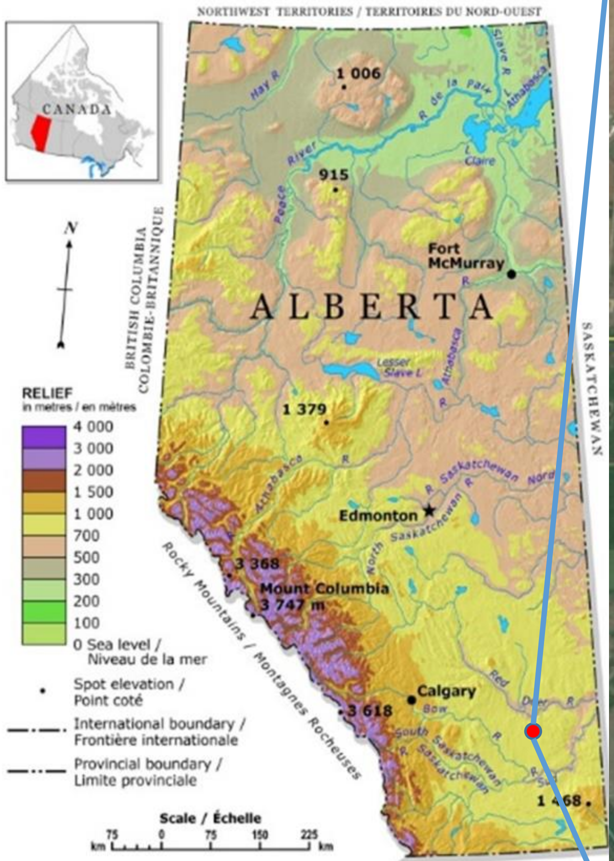


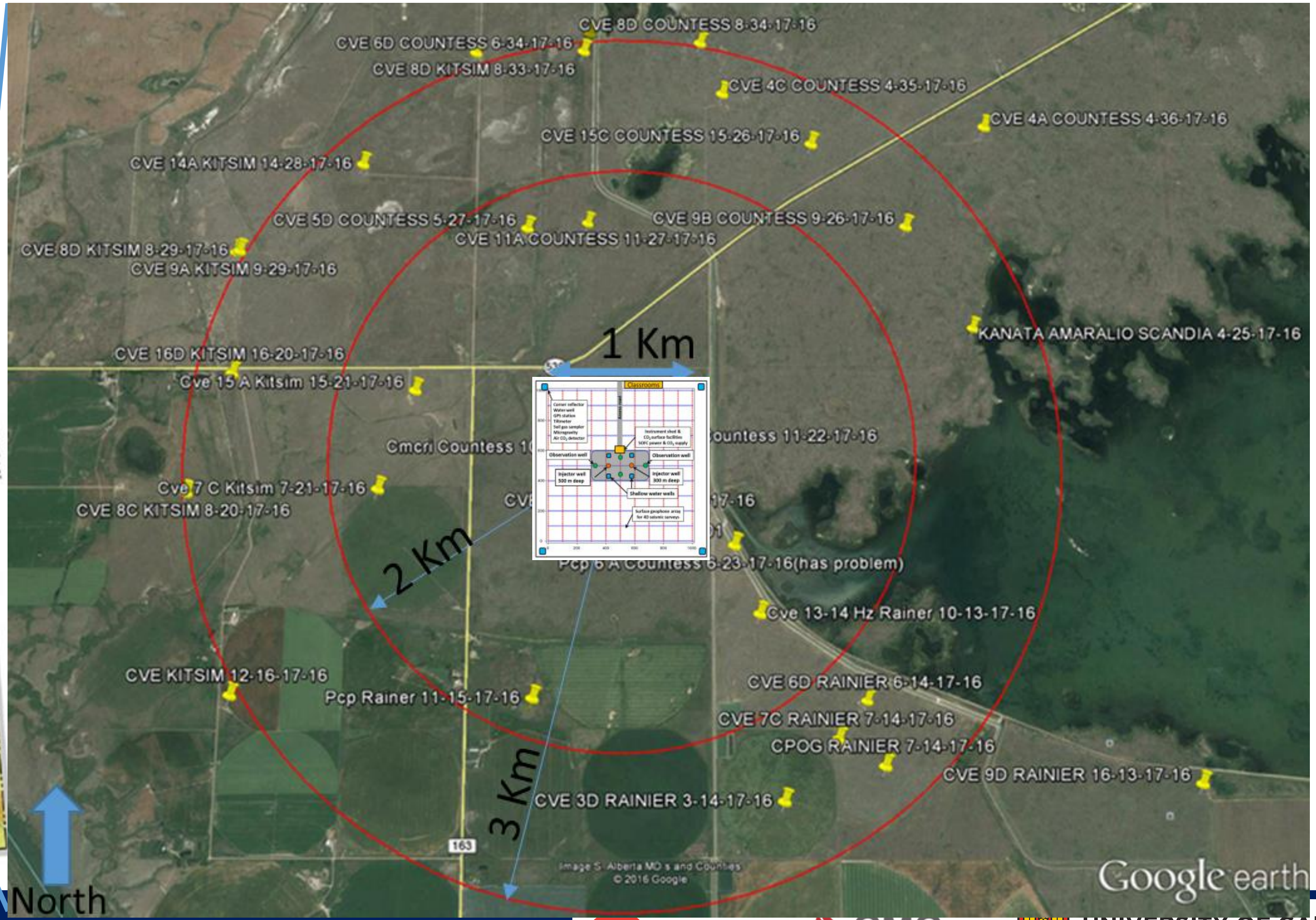

**Plume Shape ~ f(k,ϕ,Injection rate)**

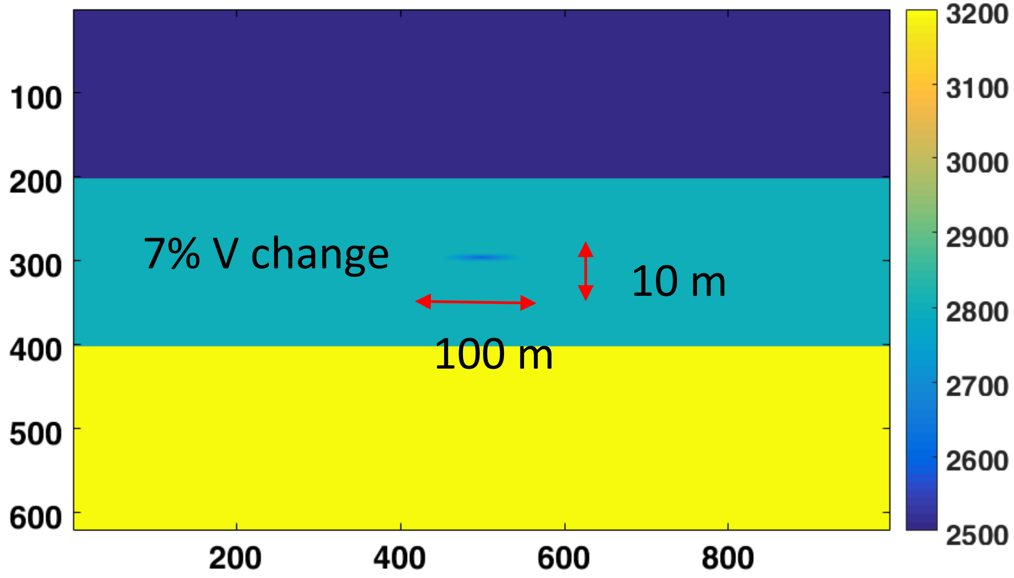
**Velocity and density change**

**V ~ f(Km,Kf1,Kf2,Kd, ϕ,k)**

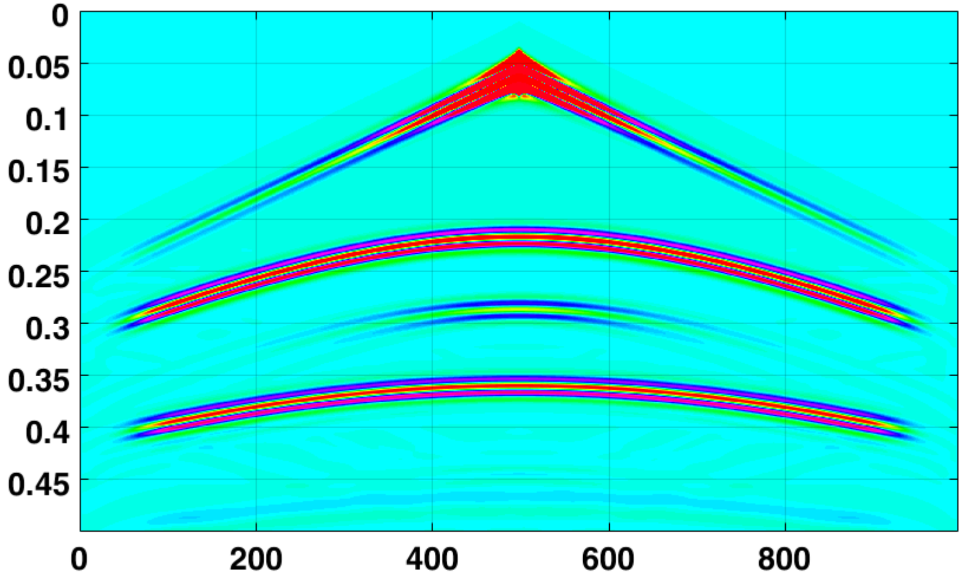
**Density ~ f(ρm,ρf1,ρf2,ϕ)**


NORTHWEST TERRITORIES / TERRITOIRES DU NORD-OUEST
CANADA
BRITISH COLUMBIA
COLOMBIE-BRITANNIQUE
SASKATCHEWAN
ALBERTA
N
1 006
915
Fort McMurray
1 379
Edmonton
3 368
Mount Columbia
3 747 m
Calgary
3 618
1 468
Peace River
Hay R.
Athabasca
Slave R.
Lesser Slave L.
North Saskatchewan
South Saskatchewan
Red Deer R.
Bow
Rocky Mountains / Montagnes Rocheuses
RELIEF
in metres / en mètres
4 000
3 000
2 000
1 500
1 000
700
500
300
200
100
0 Sea level / Niveau de la mer
Spot elevation / Point coté
International boundary / Frontière internationale
Provincial boundary / Limite provinciale
Scale / Échelle
75 0 75 150 225
km

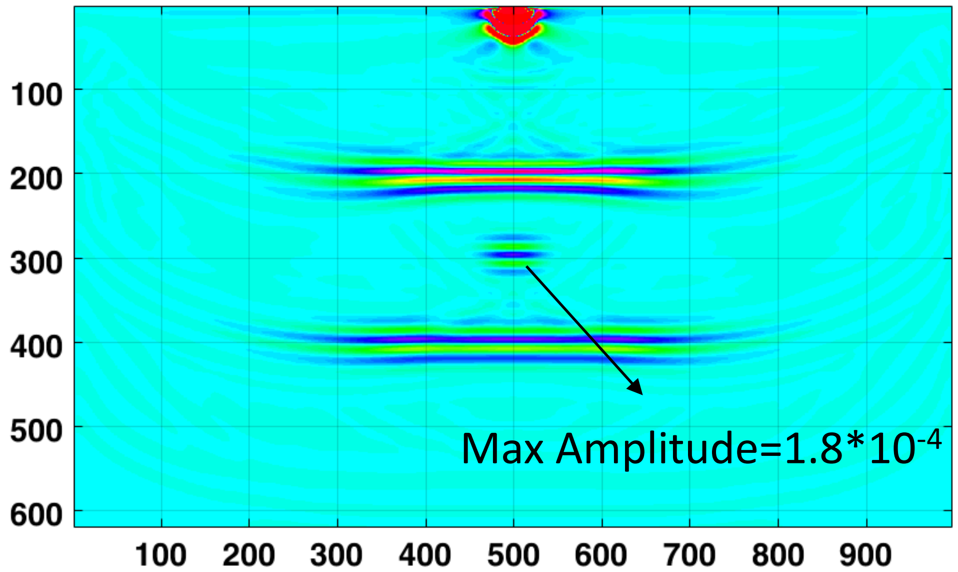

CVE 8D COUNTESS 8-34-17-16
CVE 6D COUNTESS 6-34-17-16
CVE 8D KITSIM 8-33-17-16
CVE 4C COUNTESS 4-35-17-16
CVE 4A COUNTESS 4-36-17-16
CVE 15C COUNTESS 15-26-17-16
CVE 14A KITSIM 14-28-17-16
CVE 5D COUNTESS 5-27-17-16
CVE 9B COUNTESS 9-26-17-16
CVE 11A COUNTESS 11-27-17-16
CVE 8D KITSIM 8-29-17-16
CVE 9A KITSIM 9-29-17-16
KANATA AMARALIO SCANDIA 4-25-17-16
1 Km
CVE 16D KITSIM 16-20-17-16
Cve 15 A Kitsim 15-21-17-16
Cmcri Countess 1
ountess 11-22-17-16
Cve 7 C Kitsim 7-21-17-16
CVE 8C KITSIM 8-20-17-16
2 Km
Pcp 6 A Countess 6-23-17-16(has problem)
Cve 13-14 Hz Rainer 10-13-17-16
CVE KITSIM 12-16-17-16
Pcp Rainer 11-15-17-16
CVE 6D RAINIER 6-14-17-16
CVE 7C RAINIER 7-14-17-16
CPOG RAINIER 7-14-17-16
CVE 9D RAINIER 16-13-17-16
CVE 3D RAINIER 3-14-17-16
3 Km
163
North
Image S. Alberta MD s and Counties
© 2016 Google
Google earth



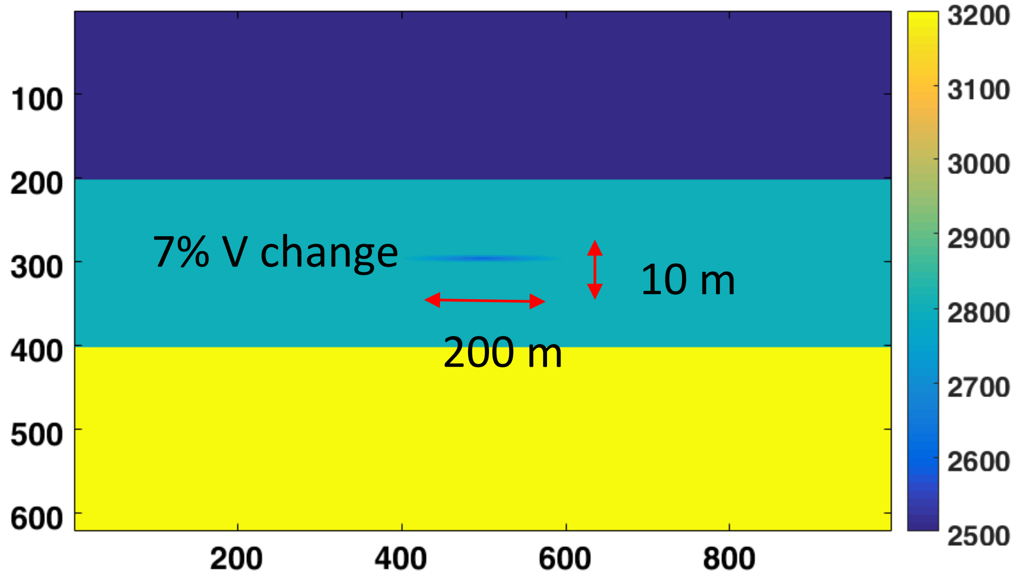
100
200
300
400
500
600
200
400
600
800
3200
3100
3000
2900
2800
2700
2600
2500
7% V change
10 m
100 m

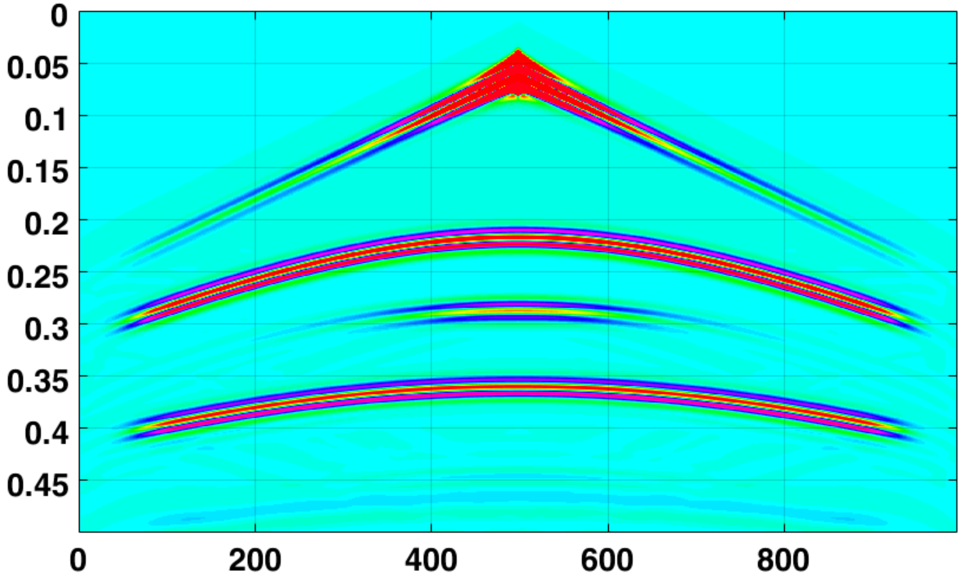



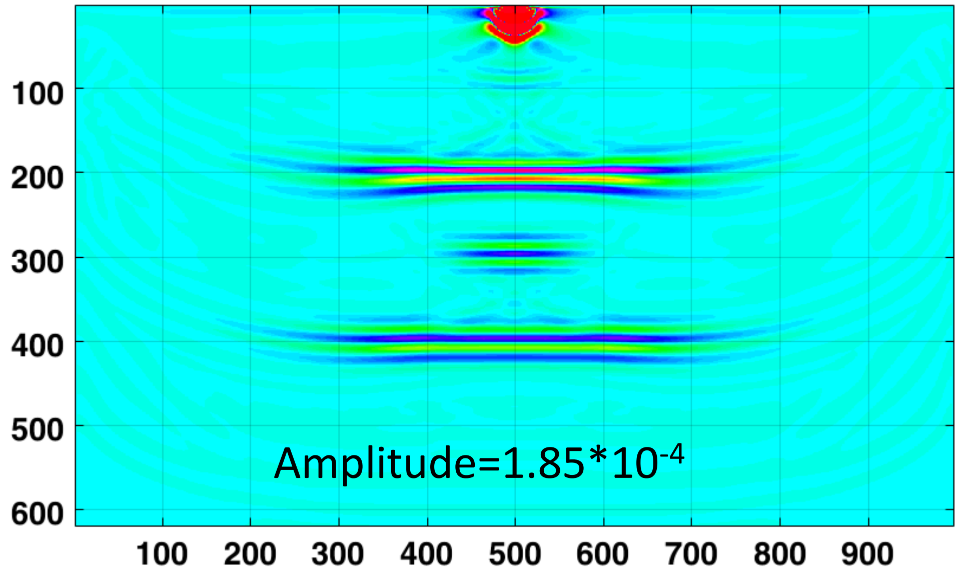
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0
200
400
600
800

100
200
300
400
500
600
100
200
300
400
500
600
700
800
900
Max Amplitude=1.8*10-4


7% V change
10 m
200 m
100
200
300
400
500
600
200
400
600
800
3200
3100
3000
2900
2800
2700
2600
2500


0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0
200
400
600
800


Amplitude=1.85*10-4
100
200
300
400
500
600
100
200
300
400
500
600
700
800
900

# Theory of modeling and imaging

2D Acoustic approximation of wave propagation

$$\left.\begin{aligned}\frac{\partial u}{\partial t} &= -\frac{1}{\rho}\frac{\partial p}{\partial x},\\ \frac{\partial v}{\partial t} &= -\frac{1}{\rho}\frac{\partial p}{\partial z},\end{aligned}\right\} \quad \textit{Euler}$$

$$\frac{\partial p}{\partial t} = -\rho v_P{}^2\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial z}\right), \quad \textit{Continuity}$$

Migration and inversion framework

$$I_u(\vec{x}) = \int_0^{T_{\max}} S_u(t,\vec{x})\, r_u(t,\overleftarrow{x})\, dt,$$

$$I_v(\vec{x}) = \int_0^{T_{\max}} S_v(t,\vec{x})\, r_v(t,\overleftarrow{x})\, dt,$$

$$I_p(\vec{x}) = \int_0^{T_{\max}} S_p(t,\vec{x})\, r_p(t,\overleftarrow{x})\, dt,$$

***where,***

$I(x)$ ***is the migrated*** image in subsurface coordinate

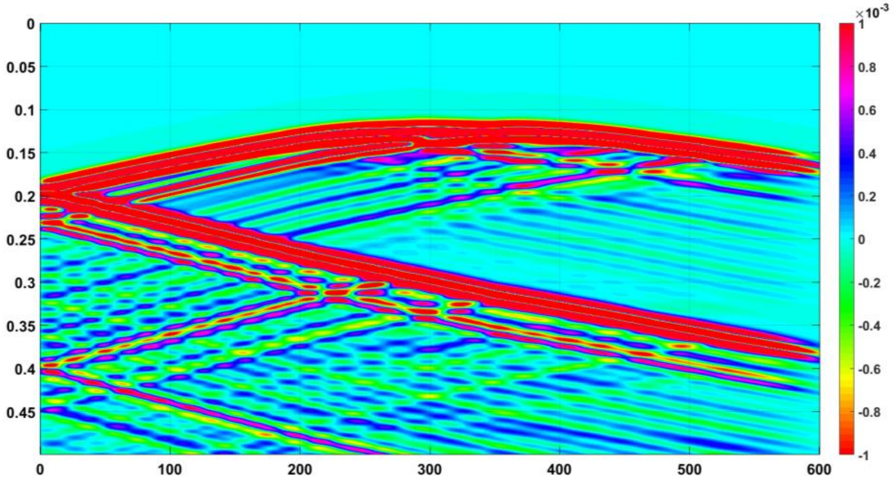
$\vec{x} = (x,z)$

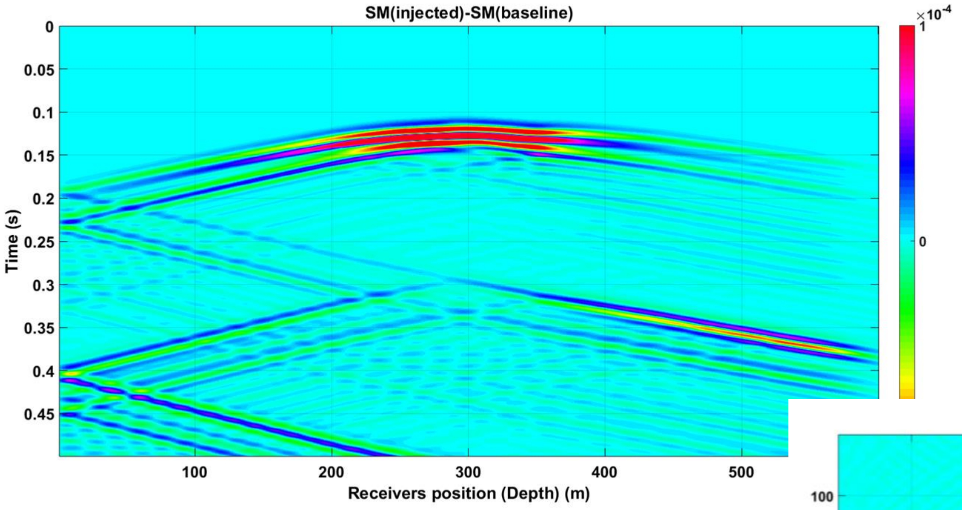
$T_{max}$, is maximum recorded time,

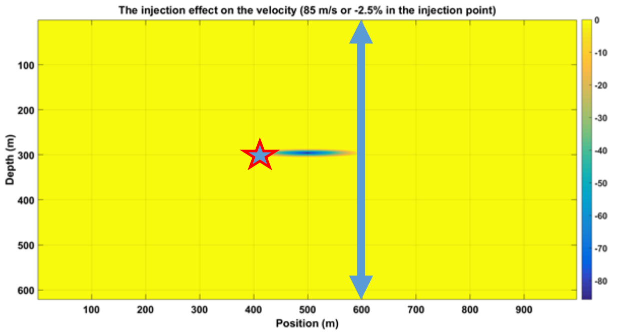
$S(t,\vec{x})$ ***is forward propagated source and***

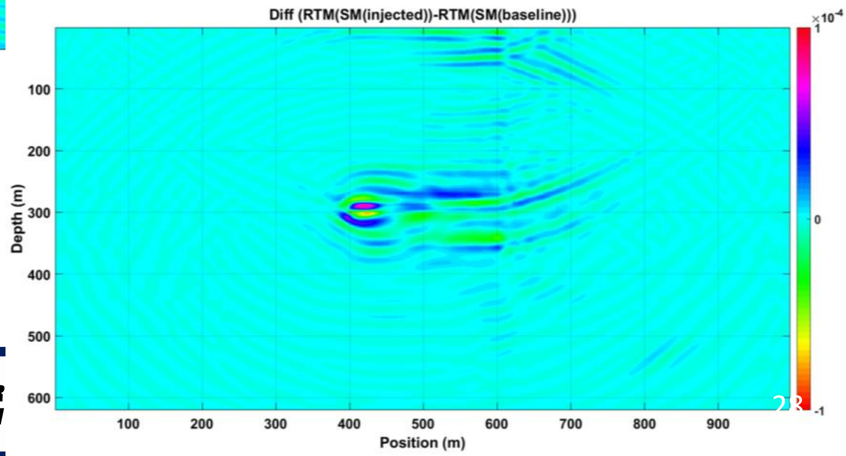
$r(t,\overleftarrow{x})$ ***is the backward propagated receivers.*** The subscripts $p$, $u$ and $v$ correspond to ***three images for pressure and displacements obtained by imaging conditions.***

# The base seismic and difference after injection (XW)

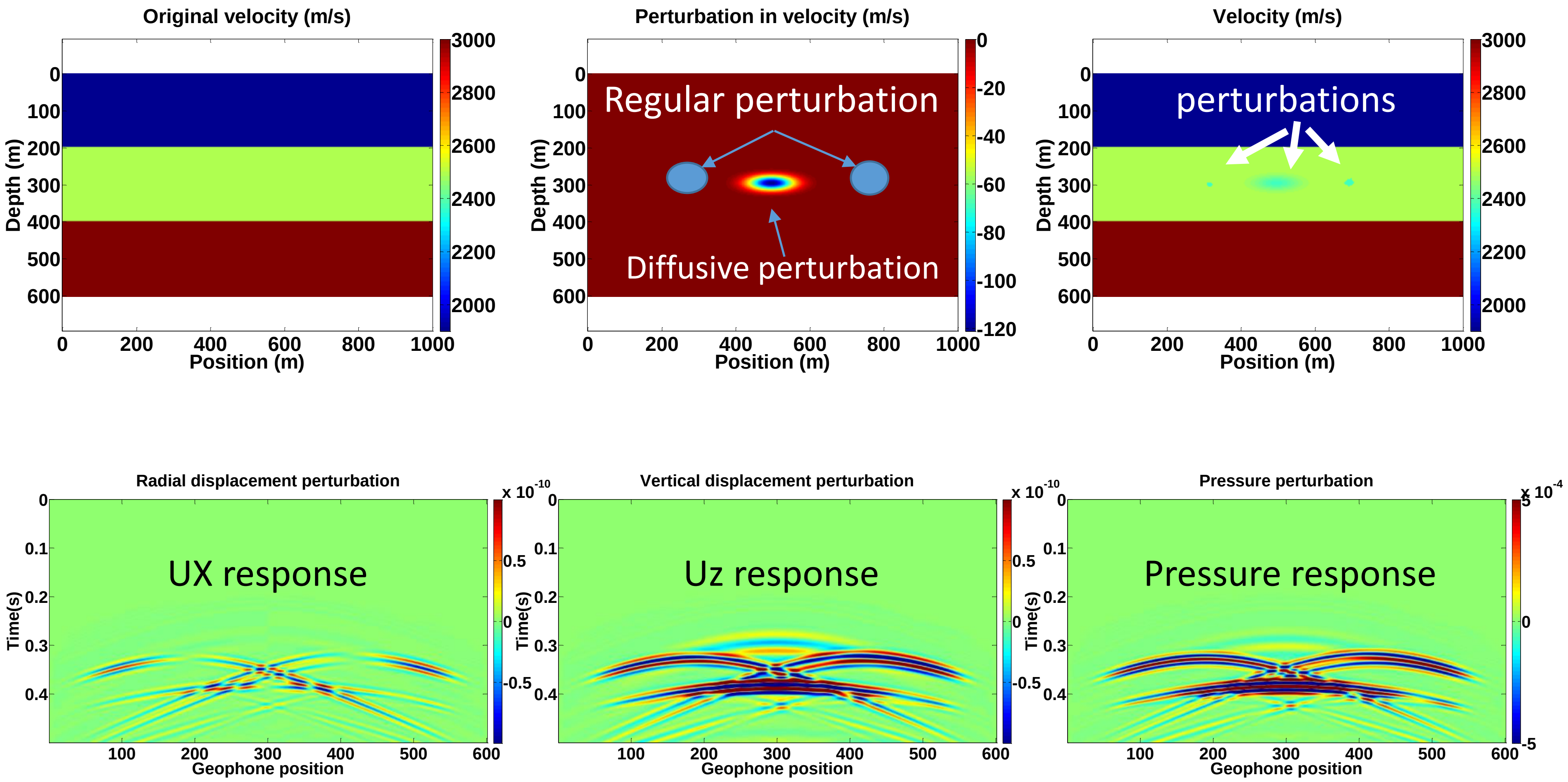


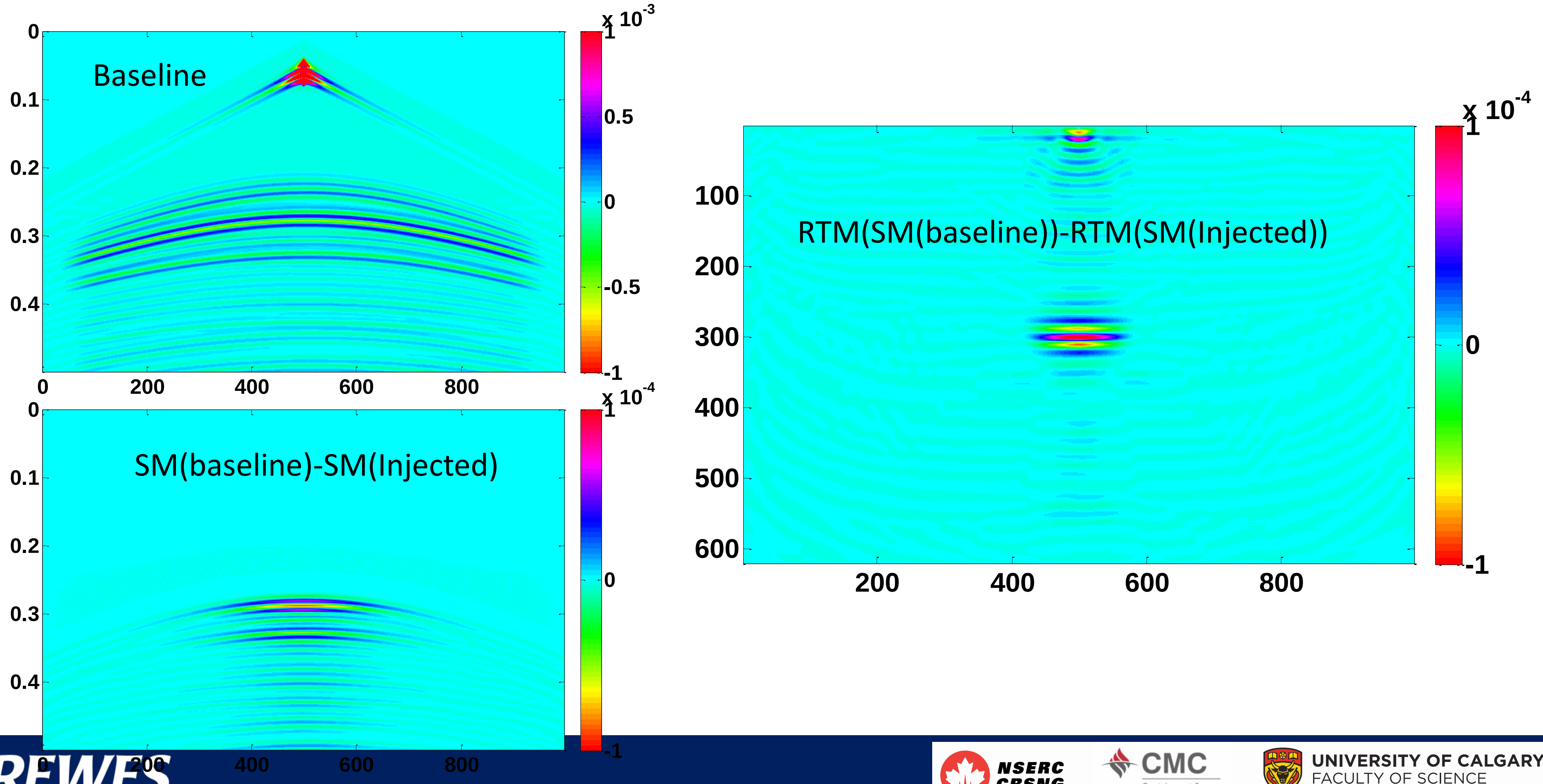



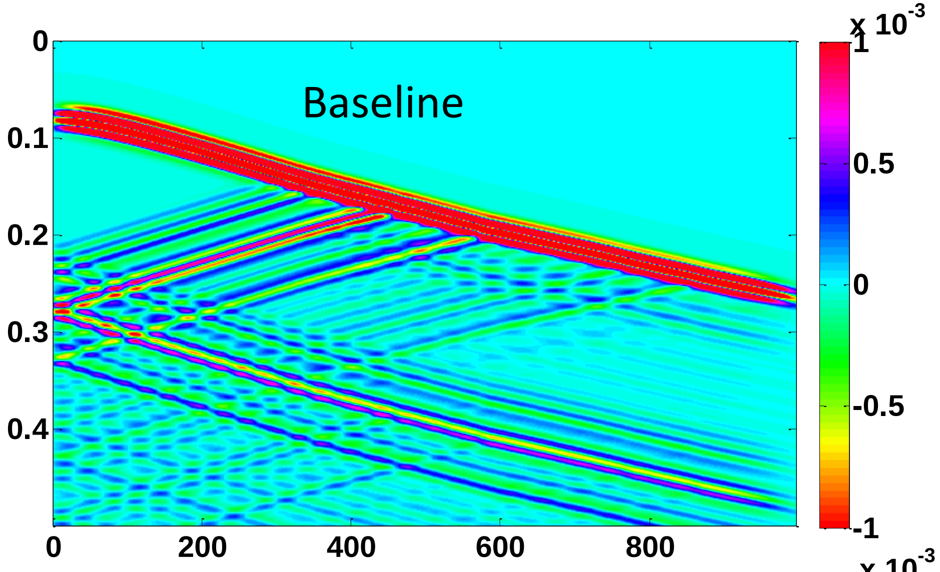



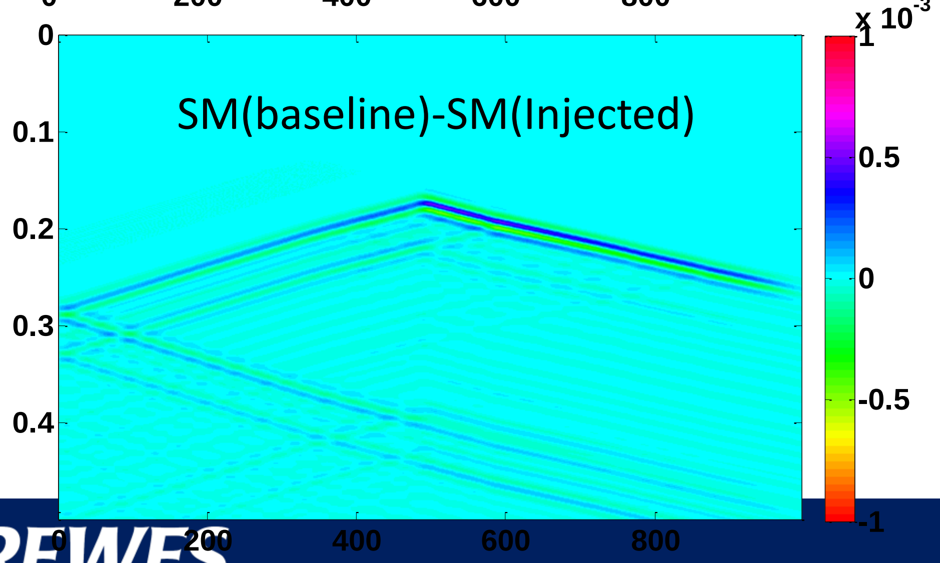
# Model set up and seismic response

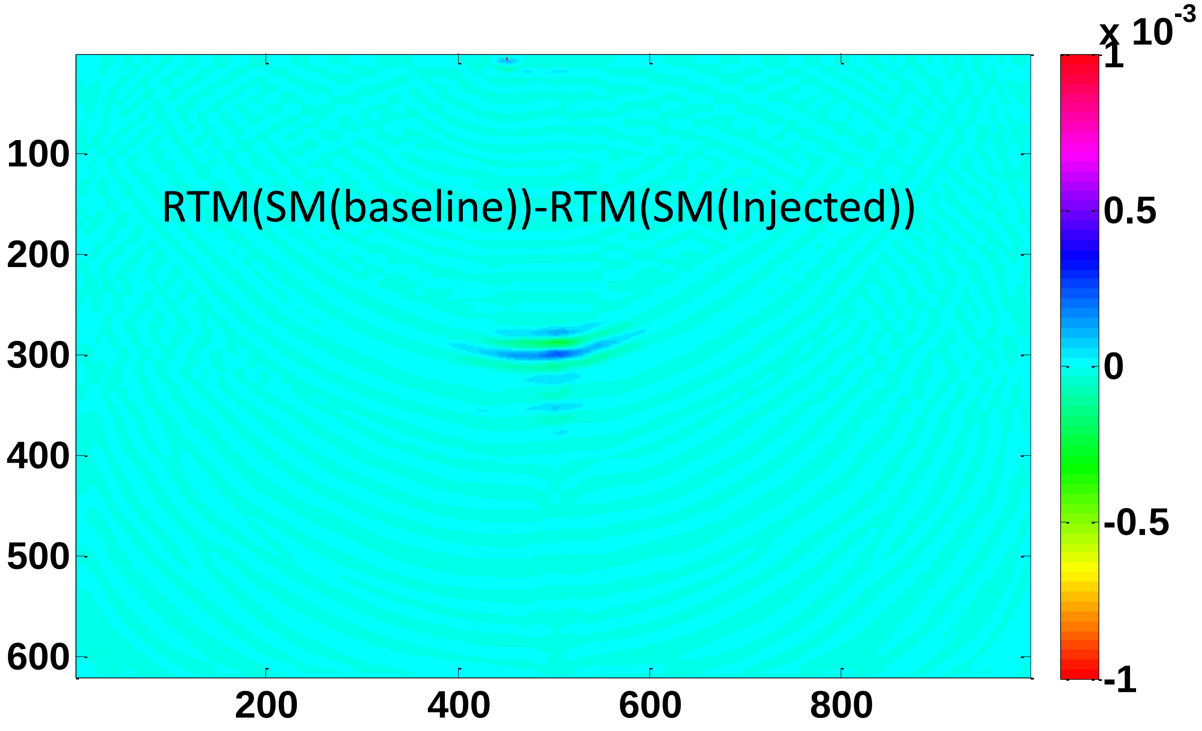





CREWES NSERC CRSNG CMC Containment & Monitoring Institute UNIVERSITY OF CALGARY FACULTY OF SCIENCE Department of Geoscience


Baseline
0
0.1
0.2
0.3
0.4
0
200
400
600
800
x 10^-3
1
0.5
0
-0.5
-1

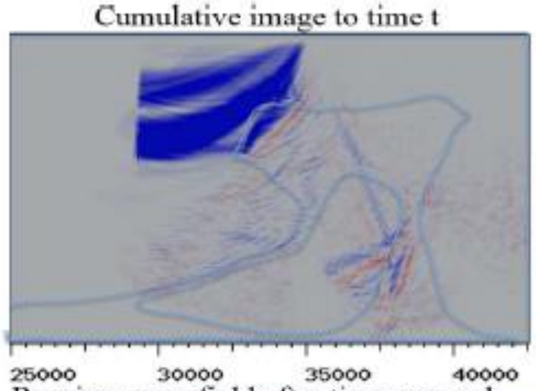

SM(baseline)-SM(Injected)
0
0.1
0.2
0.3
0.4
0
200
400
600
800
x 10^-3
1
0.5
0
-0.5
-1

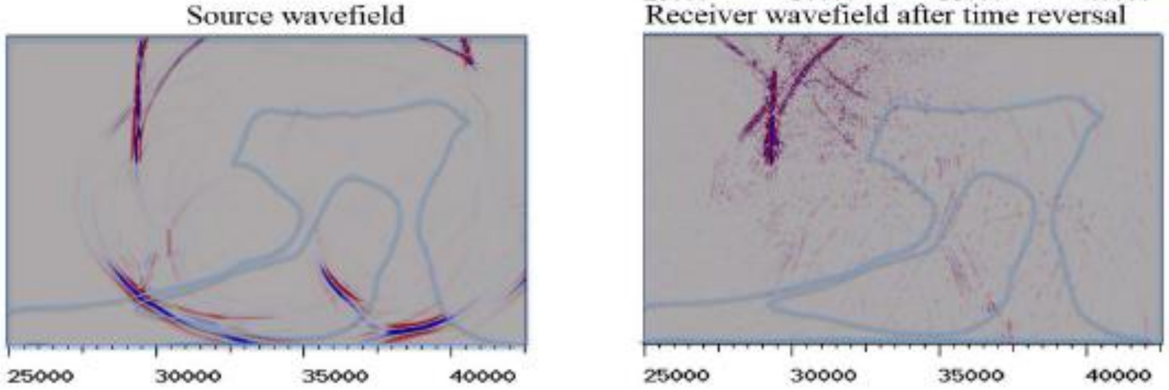

RTM(SM(baseline))-RTM(SM(Injected))
100
200
300
400
500
600
200
400
600
800
x 10^-3
1
0.5
0
-0.5
-1

# Cross correlation: The simplest RTM imaging condition

$$I(\mathbf{x}) = \frac{1}{A(\mathbf{x})}\int S(\mathbf{x},t)R(\mathbf{x},T-t)dt \quad \mathbf{x}=(x,y,z)$$

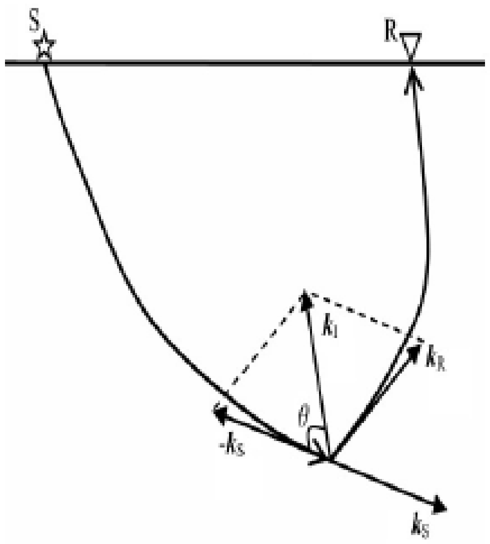
- After time reversal of the receiver wavefield, the artifacts of the rtm occur where the two wavefields are traveling **in the same direction**
- Note the accumulating low wavenumber noise through time




(After Whitmore et al., 2012)

# Laplacian filter for low wavenumber noise reduction




$$\nabla^2 \to -\left(k_x^2 + k_y^2 + k_z^2\right) = -\left|\vec{k}_I\right|^2;$$

$$\vec{k}_I = \vec{k}_R - \vec{k}_S$$

$$\left|\vec{k}_I\right|^2 = \left|\vec{k}_R\right|^2 + \left|\vec{k}_S\right|^2 - 2\left|\vec{k}_R\right|^2\left|\vec{k}_S\right|^2 \cos(\pi - 2\theta) = \frac{4\omega^2}{v^2}\cos^2\theta$$

$\omega$ = angular frequency;
v= velocity;
$k_R$ = Receiver wavenumber;
$k_S$ = Source wavenumber;
$k_I$ = Image wavenumber;
$k_x$ = spatial wavenumber in x;
$k_y$ = spatial wavenumber in y;
$k_z$ = spatial wavenumber in z;
$\theta$ = Incidence angle.

(After Liu et al., 2010)

## Full Waveform Inversion (FWI) - Concept