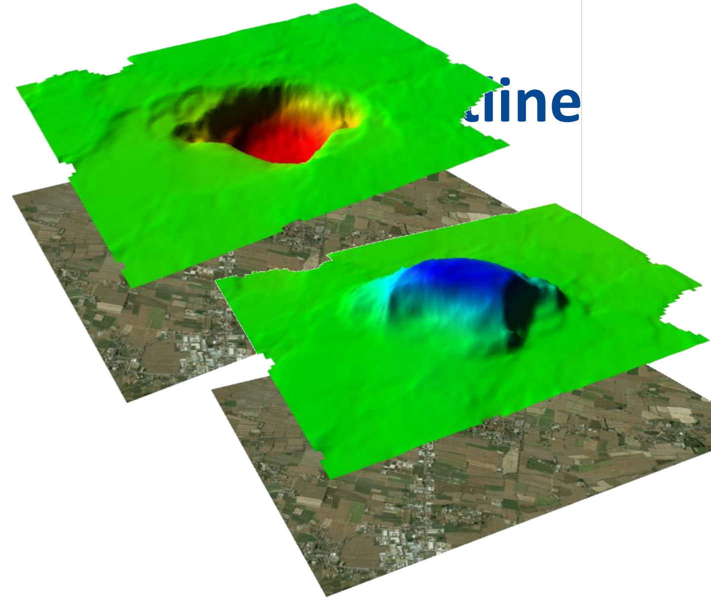
TRE ALTAMIRA
A CLS Group Company

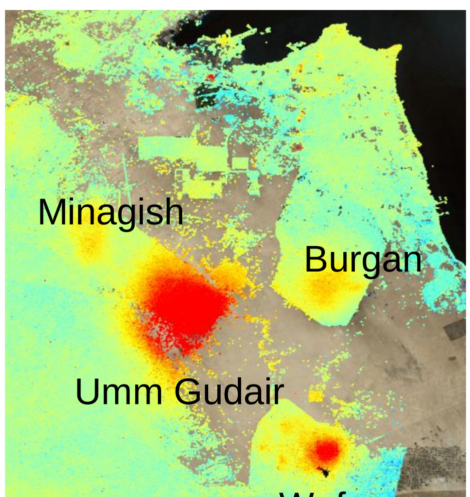
InSAR for reservoir geomechanical analysis
A. Rucci

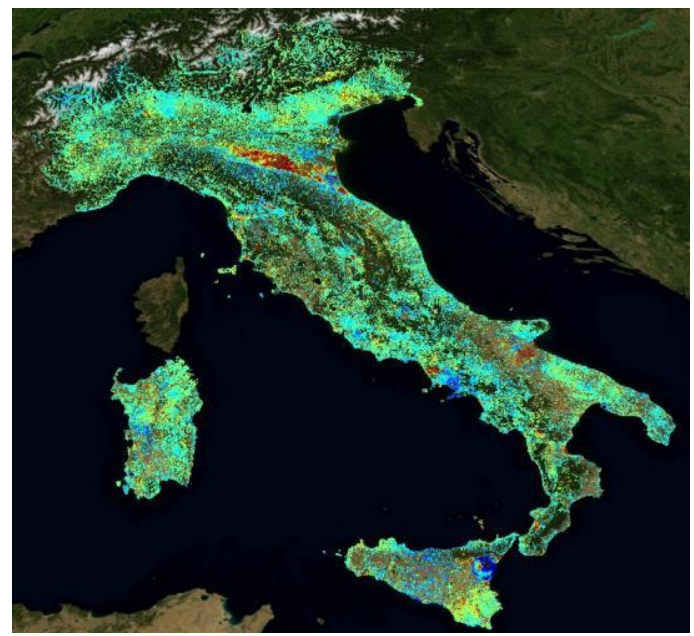
INFORMATION FROM SPACE

Alessio Rucci
MDIS, 2019



- Why InSAR in oil&gas?
- InSAR for reservoir monitoring and modelling
- Application on real case scenarios
- Conclusions



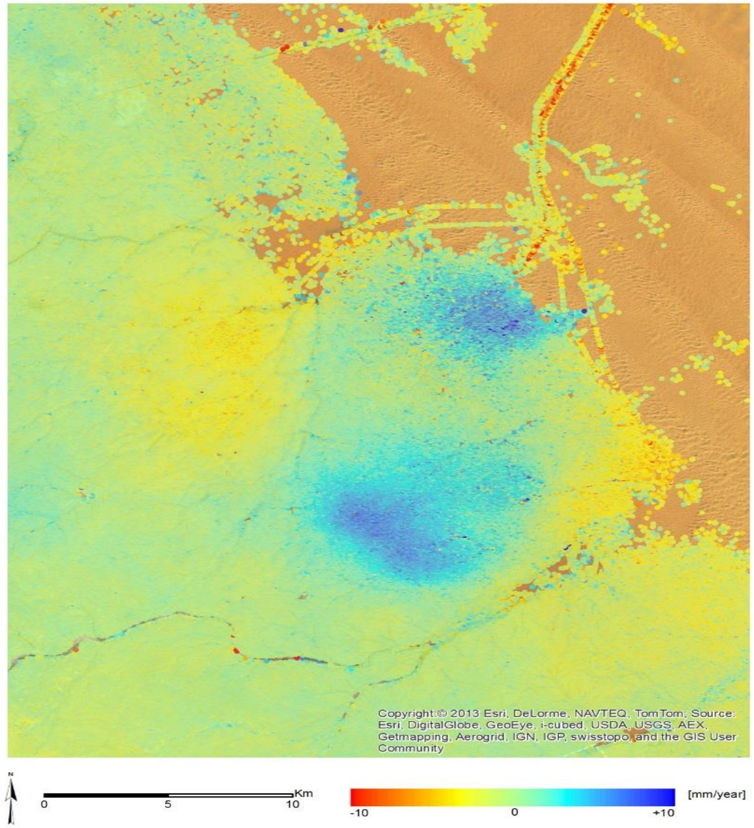


Why InSAR for oil&gas?

» At the beginning InSAR was considered an imortant tool to provide ground displacement information over large areas for building safety assesement and environmental monitoring

» In the last 10 years it has been recognised the value of this layer of information for reservoir monitoring and medeling

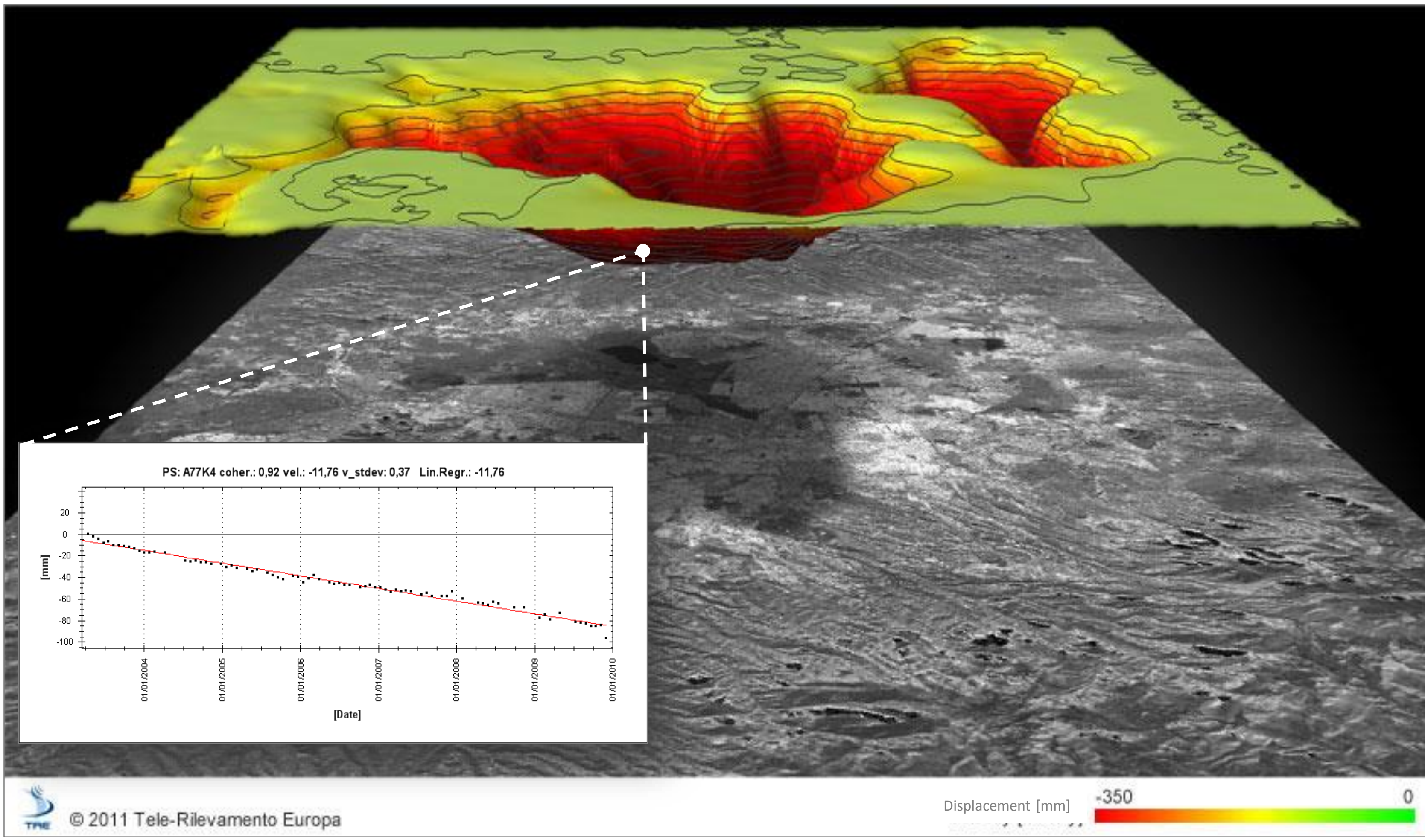
» Especially in secondary recovery phase when lot of unknowns play a role in defining the best preduction strategy



SAR interferometry evolution

Type	Principle	Product	Precision
DInSAR (‘90s)	comparison of 2 images, interferometry	Deformation map	Centimetric
PSInSAR™ (1999)	stack of radar images (min 20), multi interferometry	- Permanent Scatterers (PS) with time series of displacement for each point	Millimetric
SqueeSAR™ (2010 – 2012)	stack of radar images (min 20), multi interferometry	- Permanent Scatterers (PS) - Distributed Scatterers (DS) with time series of displacement for each point Maps of: - Average Displ. Rate - Elevation	**Millimetric**

A Typical Result

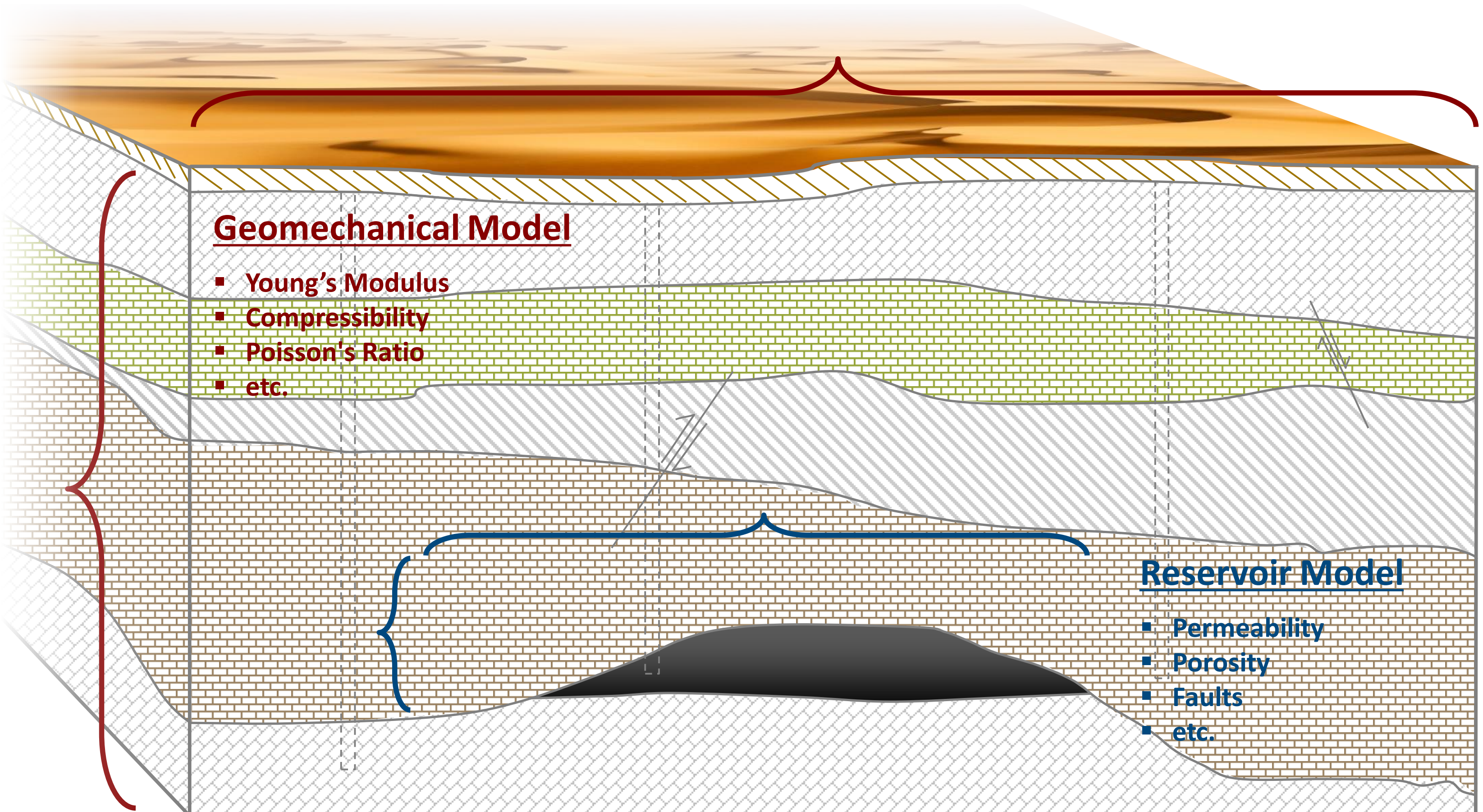


Cumulative displacement March 2003 – October 2007

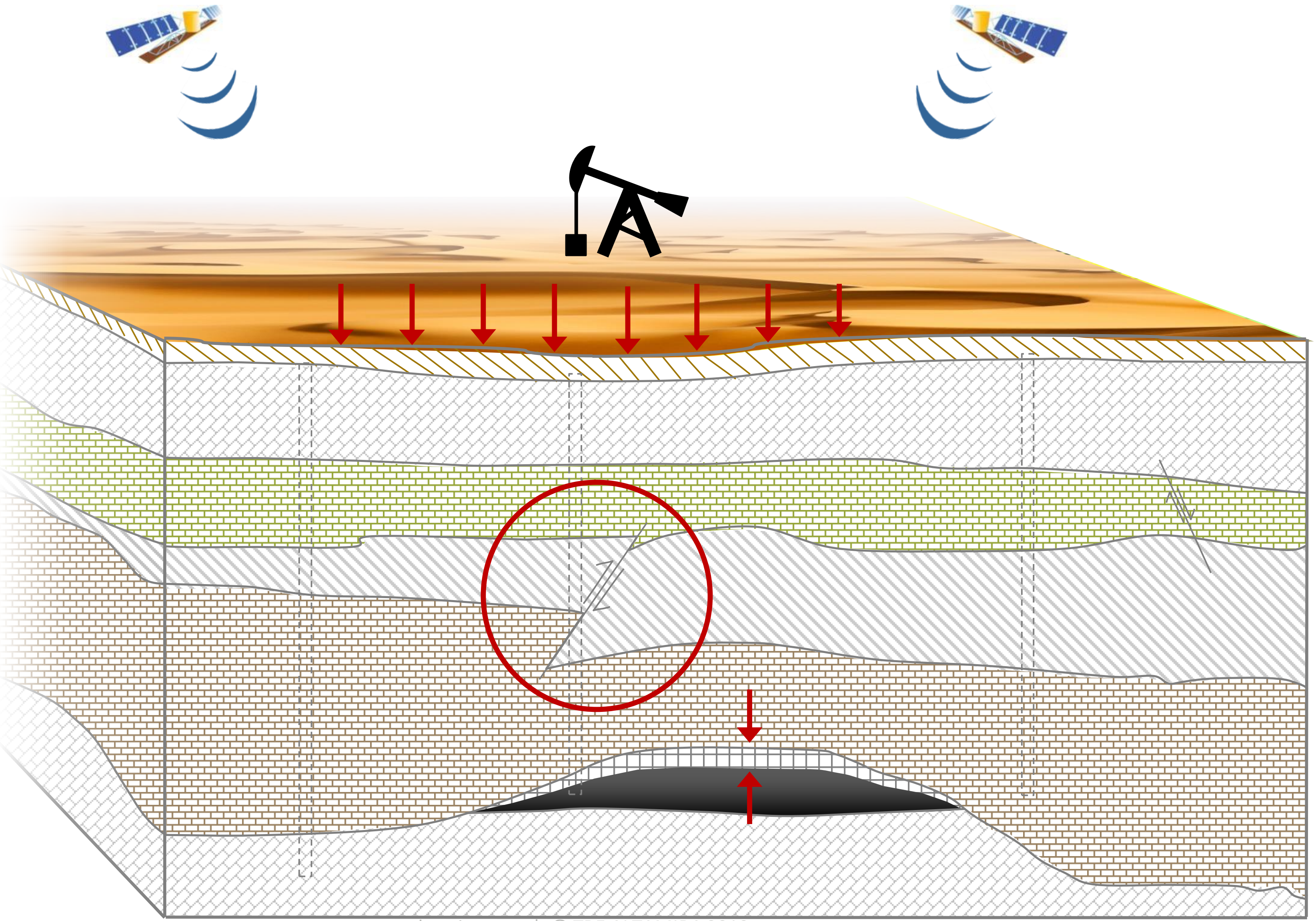
Reservoir Monitoring and modeling

- Surface displacement data can provide valuable information about reservoir geomechanics behaviour
- Different information can be extracted
  - Reservoir pressure-volume changes
  - Identification of fault-fracture reactivation
  - Elastic model calibration

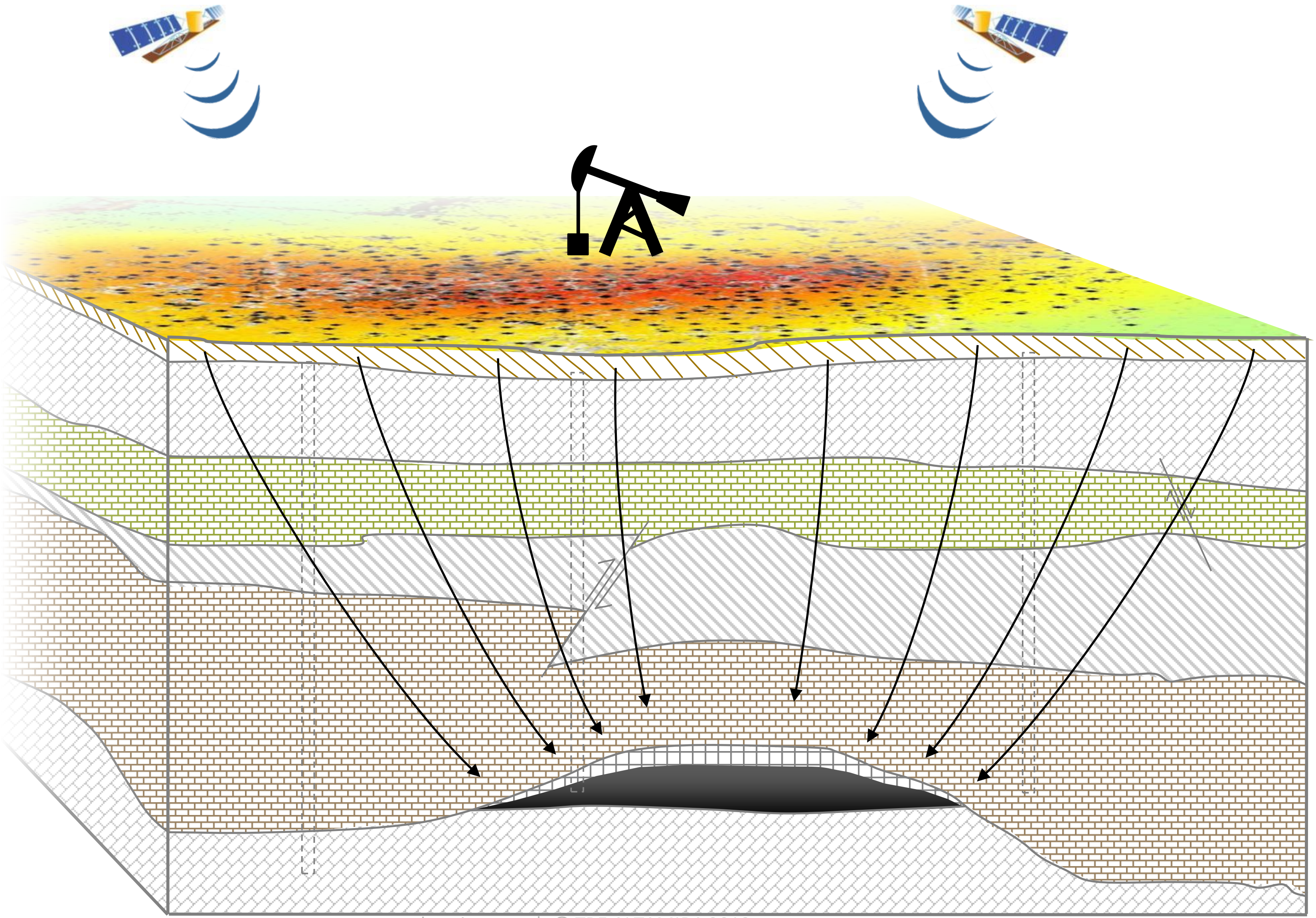
From Reservoir to Surface



From Reservoir to Surface



From Reservoir to Surface



Volume/Pressure changes estimation

Producing Reservoir Characterization

»Following this methodology we can infer volume/pressure changes and then the relative permeability

METHODOLOGY

1 From the surface deformation we estimate the volume changes in the reservoir

2 Volume changes are converted into pressure changes

3 The inferred pressure filed can, then, be used to get information about premeability

Volume change estimates

We construct a linear equation system relating volume changes $\mathbf{v}(t)$ to deformation observations $\mathbf{u}(t)$

$$\mathbf{u}(t,\mathbf{x}) = \mathbf{\Psi}\mathbf{v}(t,\mathbf{y})$$

$$\boxed{\begin{array}{c}\mathbf{v}(t,\mathbf{y}) \leq 0 \\ \text{With inequality constraints}\end{array}}$$

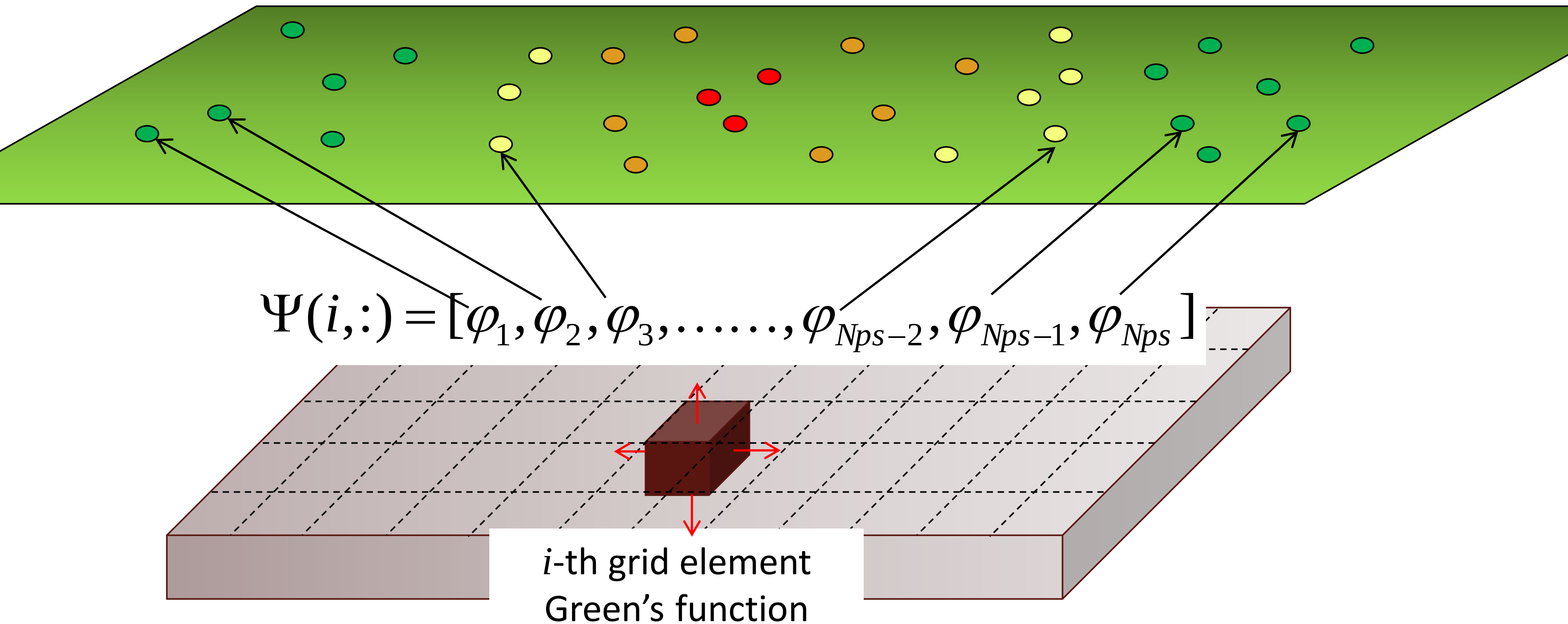
Where the coefficients of the matrix Ψ represent the Green's function relating surface deformation at location $\mathbf{x}$ to volume changes at location $\mathbf{y}$.

This Green's function depends on the geometry of the reservoir and on the Poisson's ratio of the medium, in particular:

$$\Psi \propto \upsilon$$

Reservoir discretization

» It is assumed that the reservoir volume has been discretized into a 3D configuration of grid blocks. Each grid block within the reservoir can undergo a fractional volume change due to changes in fluid pressure induced by production.



From volume changes to pressure changes

$\boxed{\text{direct elastic relationship}}$

$$\delta\mathbf{p}(t) = \beta\,\mathbf{v}(t)$$

Where β is the compressibility

Methodology validation

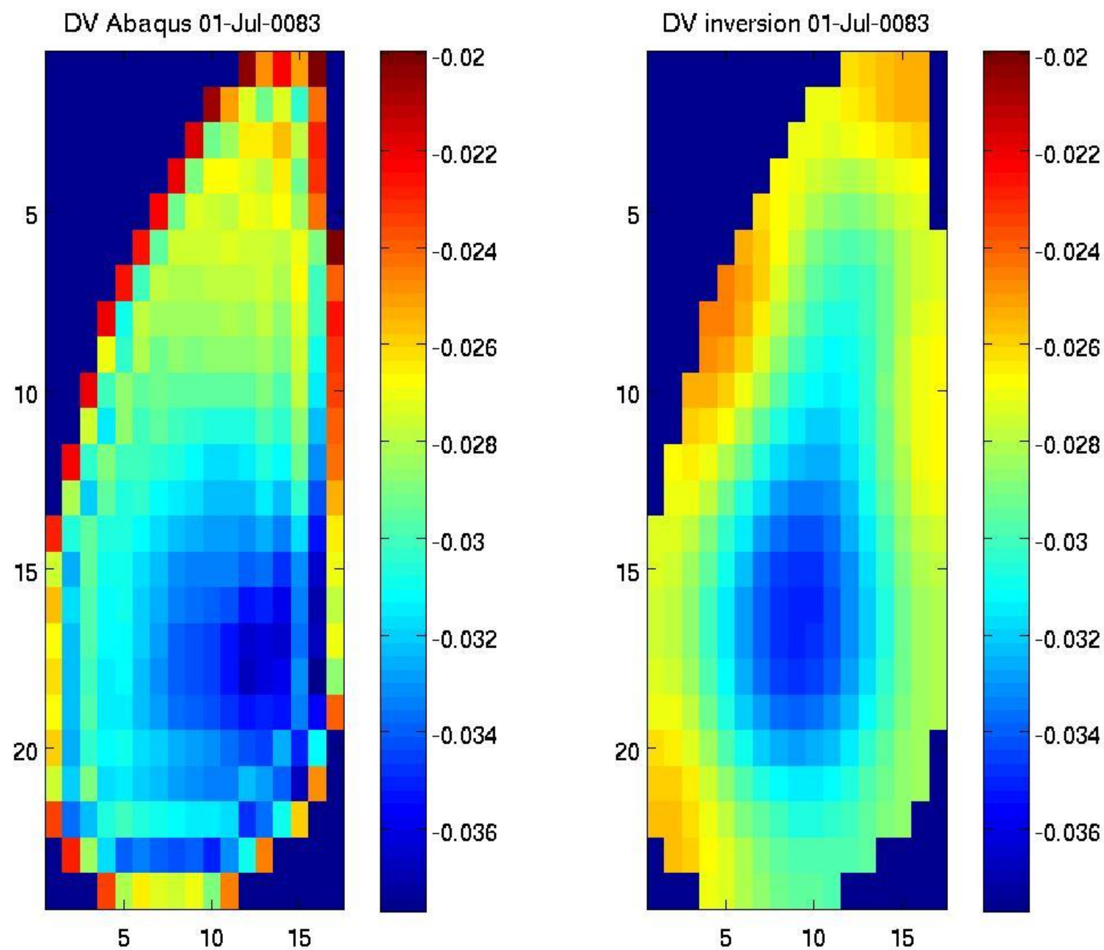
» To validate the suggested methodology a synthetic test has been performed

- Eclipse has been used to infer the space/time evolution of the pressure filed at the reservoir layer which is 1500 m depth

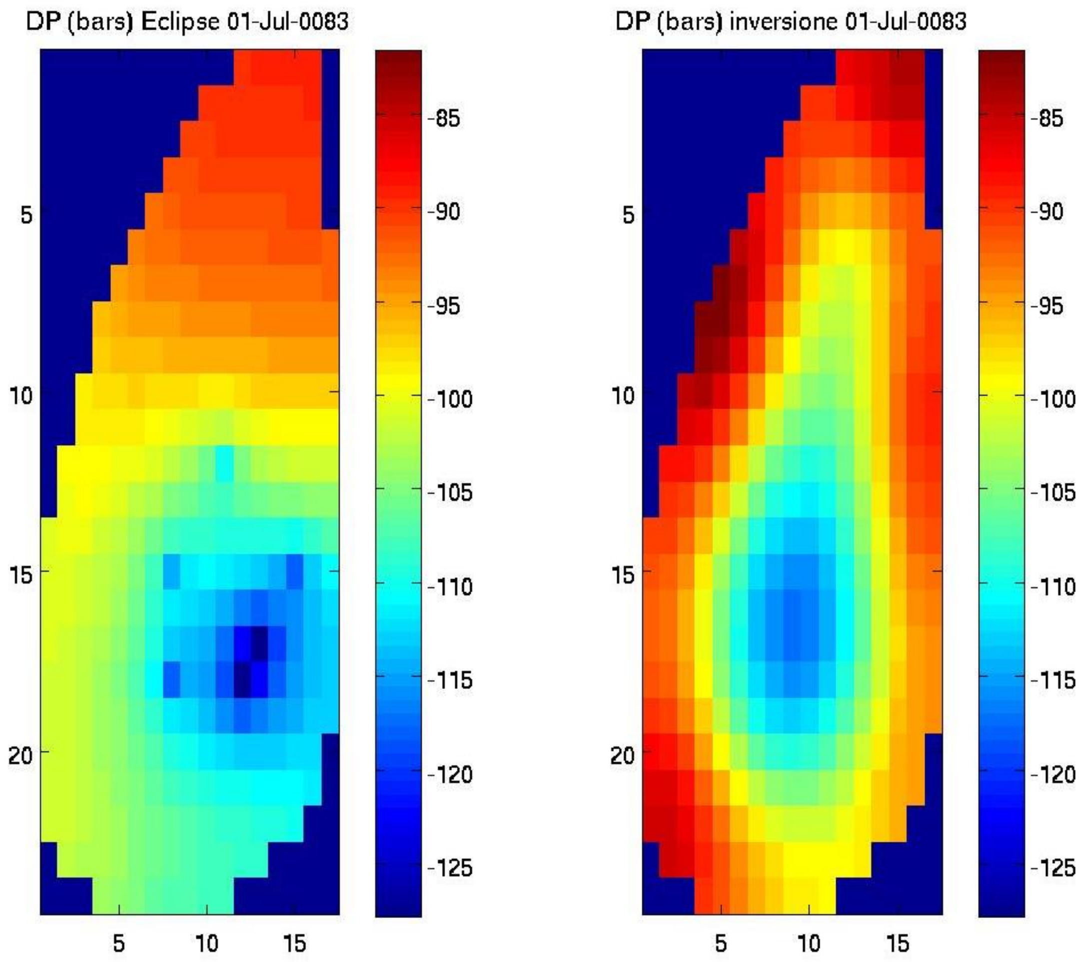
- The pressure model has been used as input for Abaqus to generate the surface displacement field

- Displacements have been inverted into volume/pressure changes at the reservoir layer

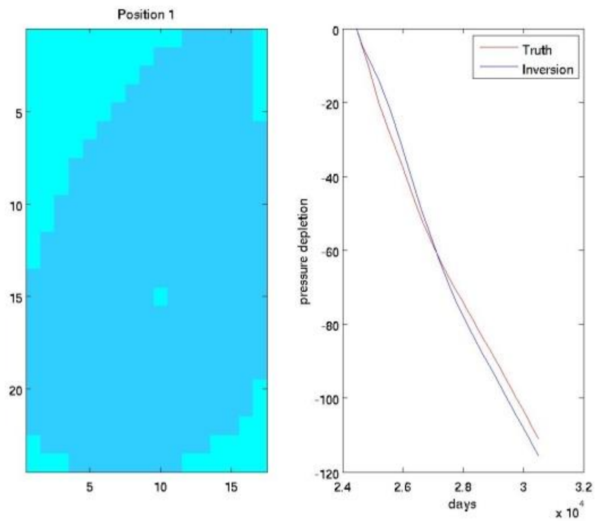
Volume changes comparison

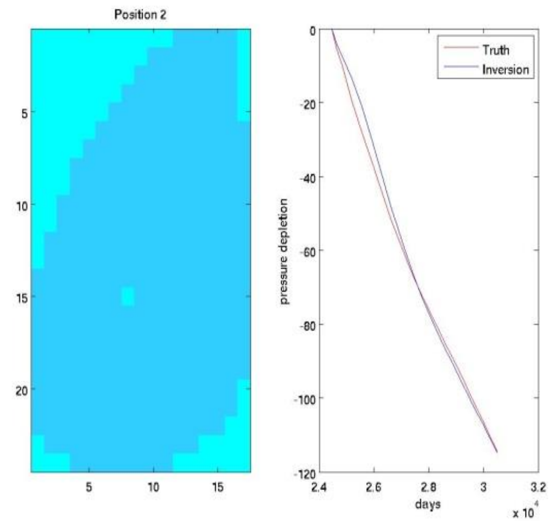


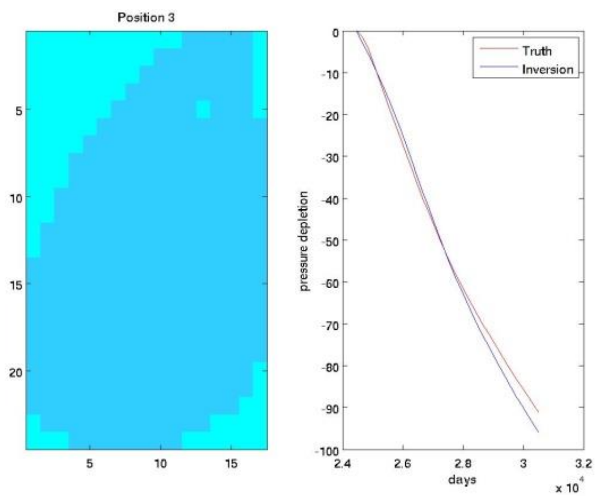
Pressure changes comparison

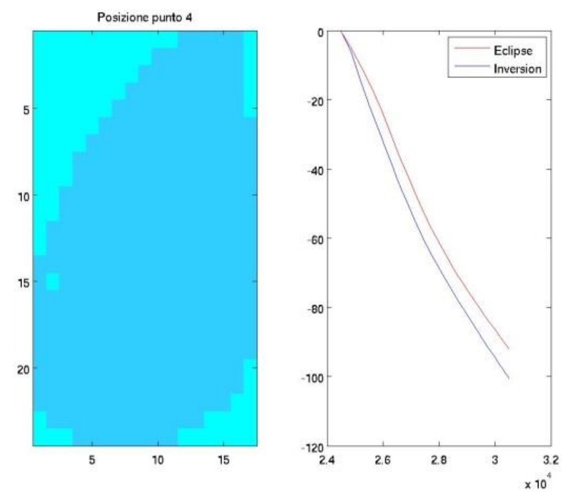


Pressure changes comparison (2)

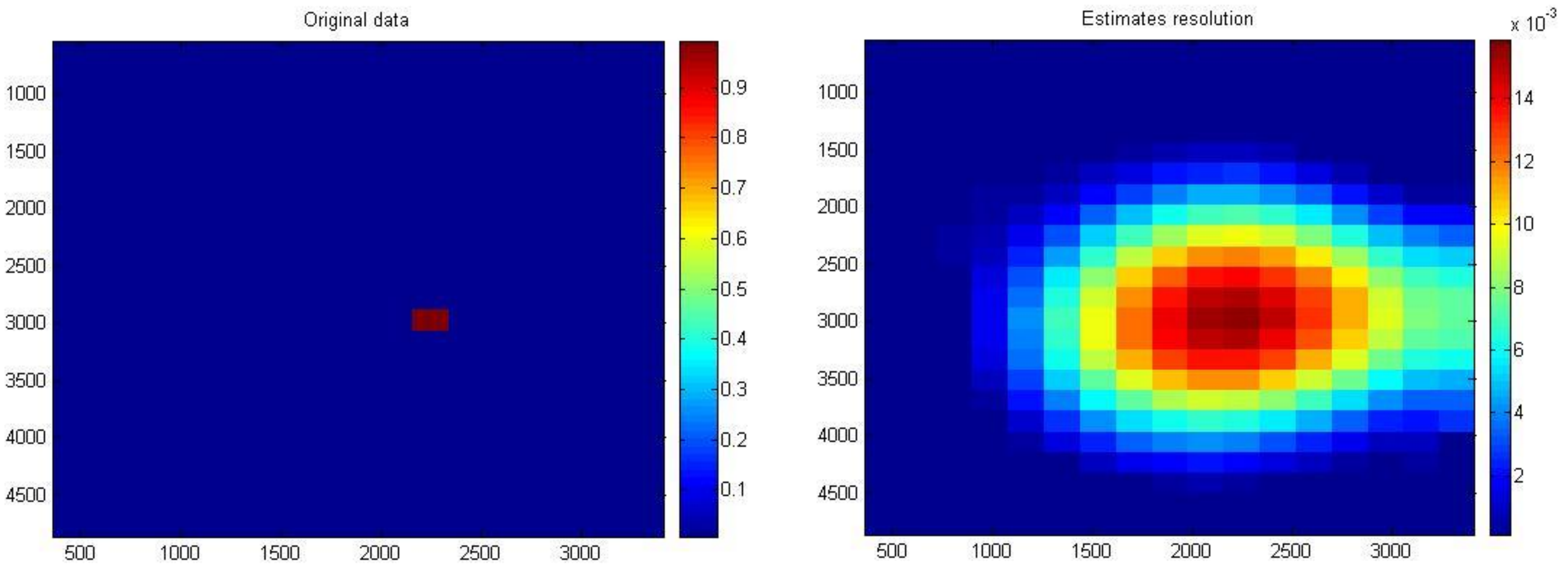




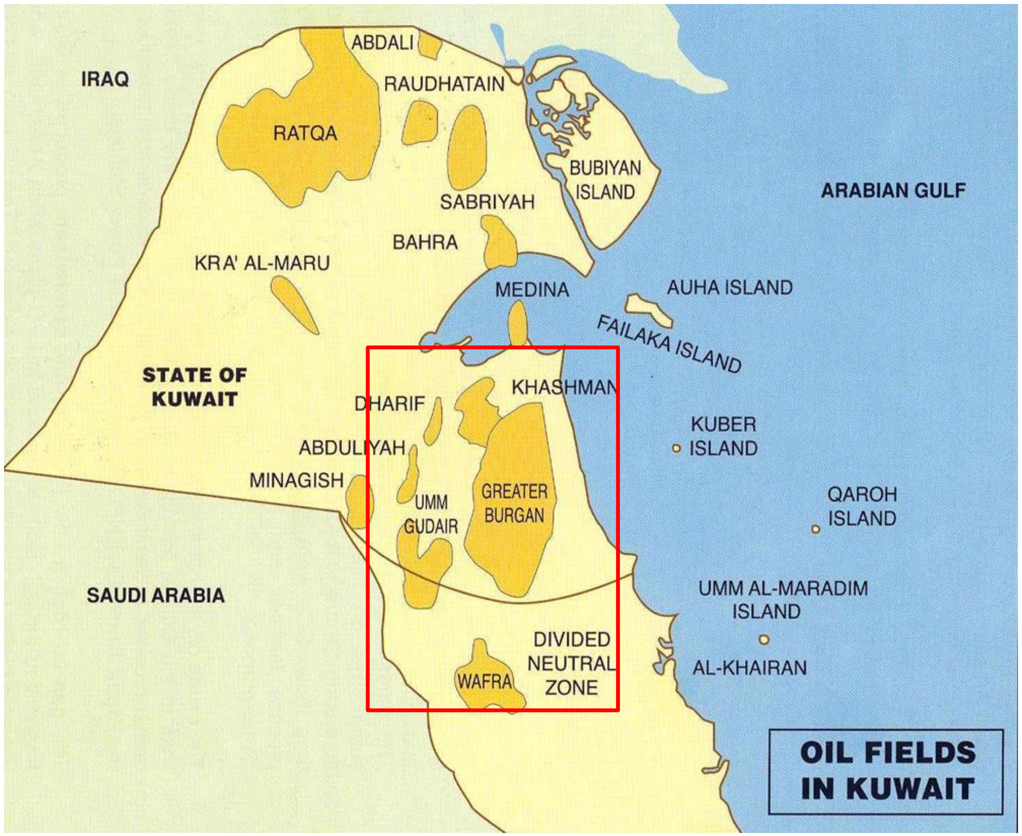




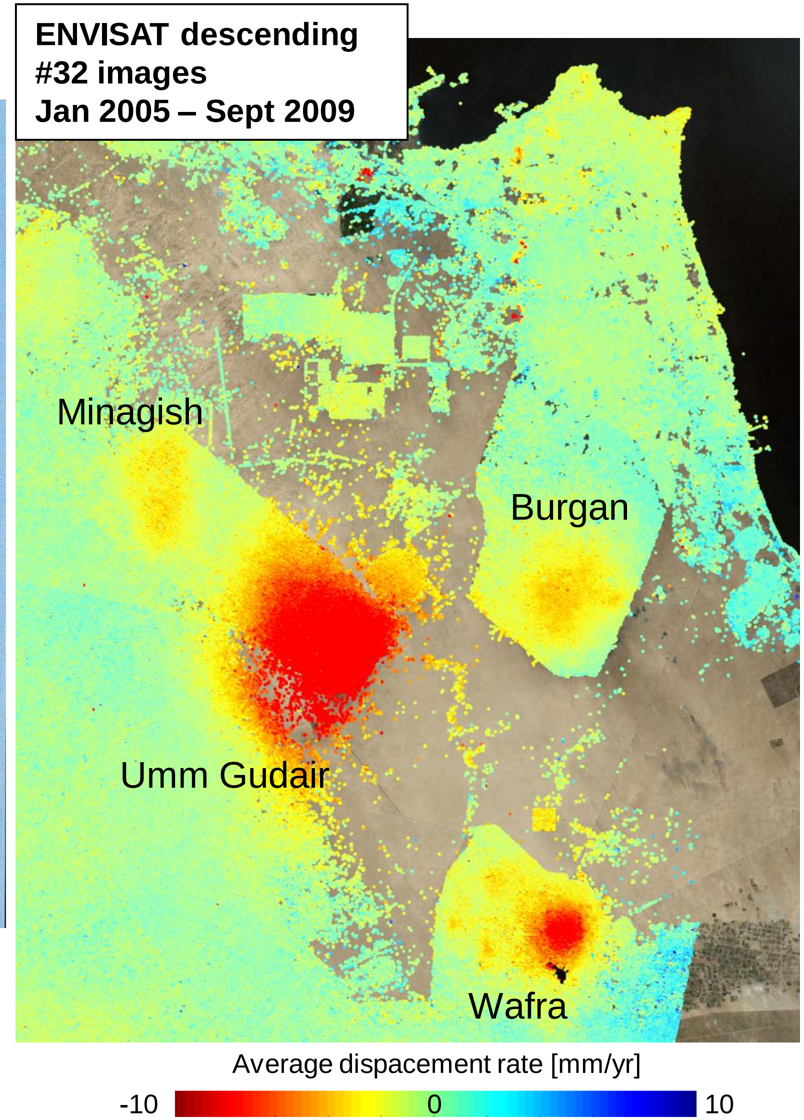
Estimates Resolution



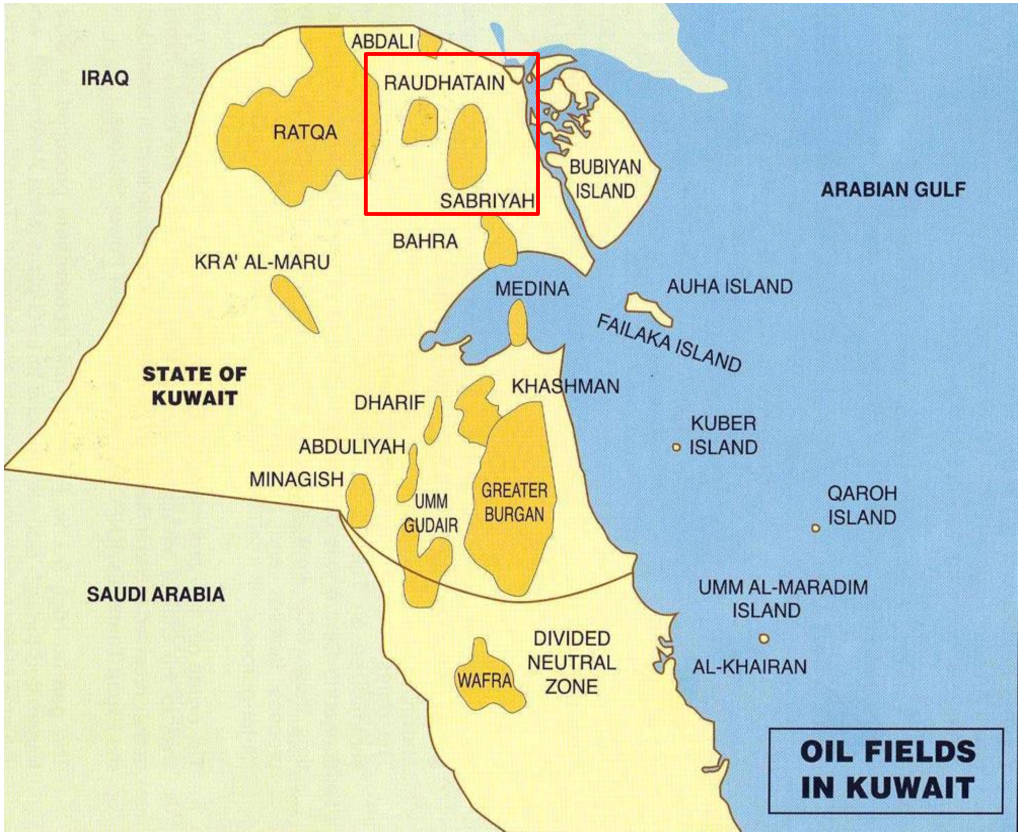
Kuwait



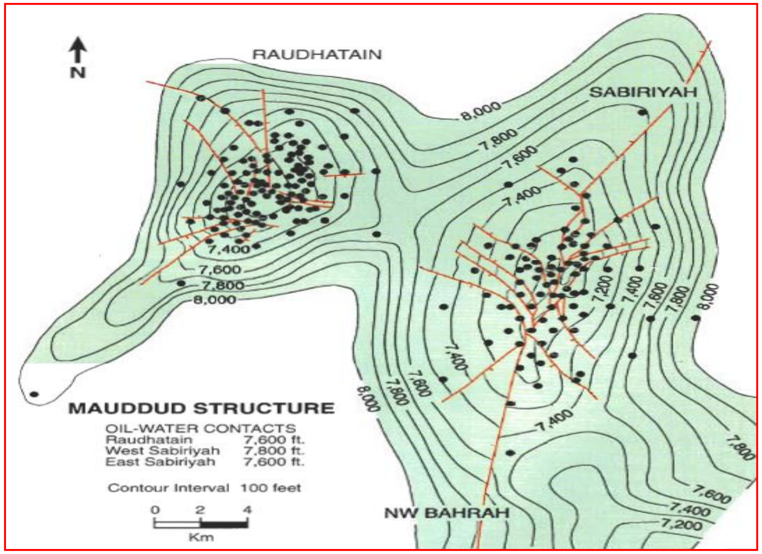
http://www.moo.gov.kw



Raudhatain and Sabiriyah Field



http://www.moo.gov.kw

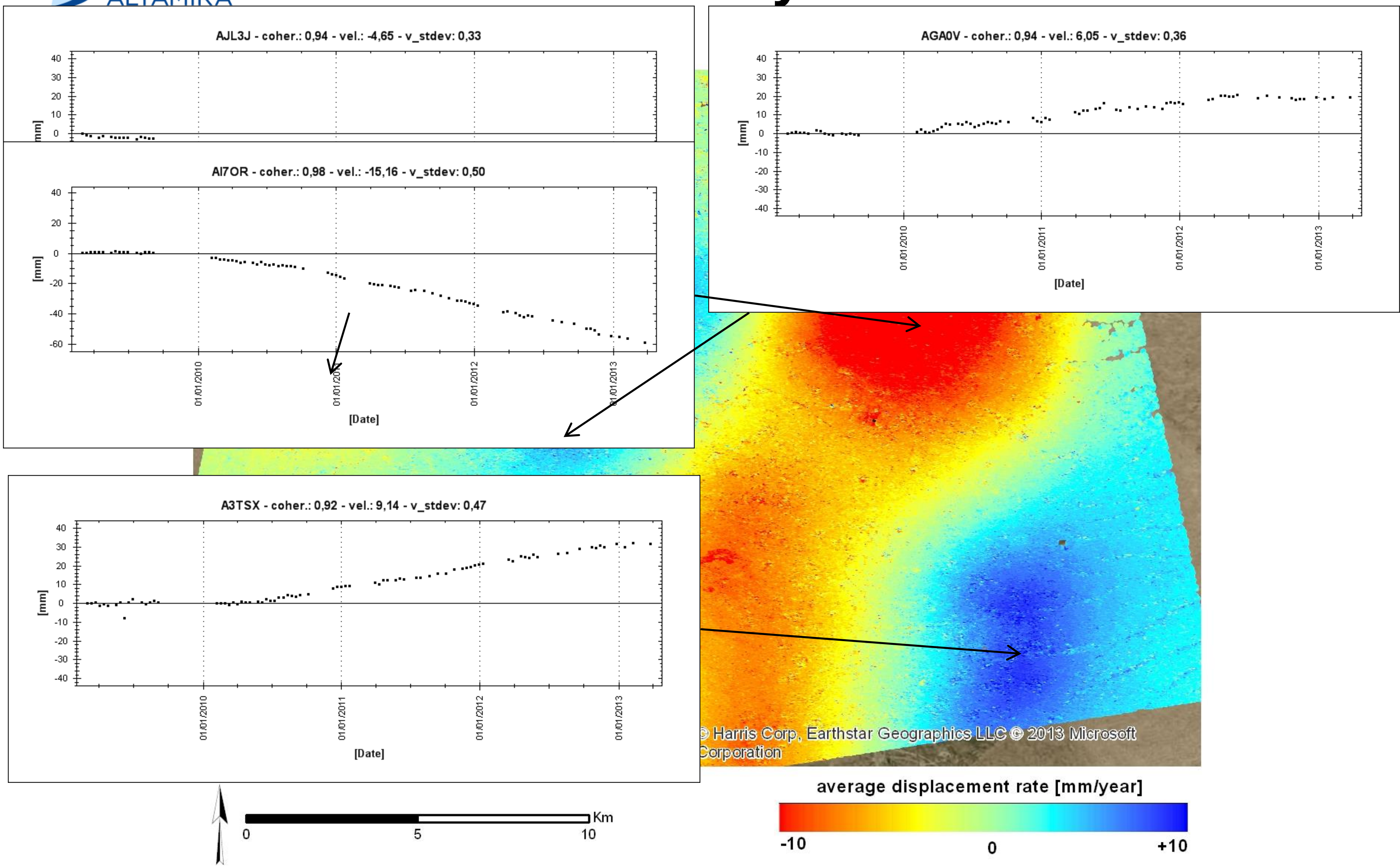


Carman J., 1996

<u>Mauddud Reservoir</u>:

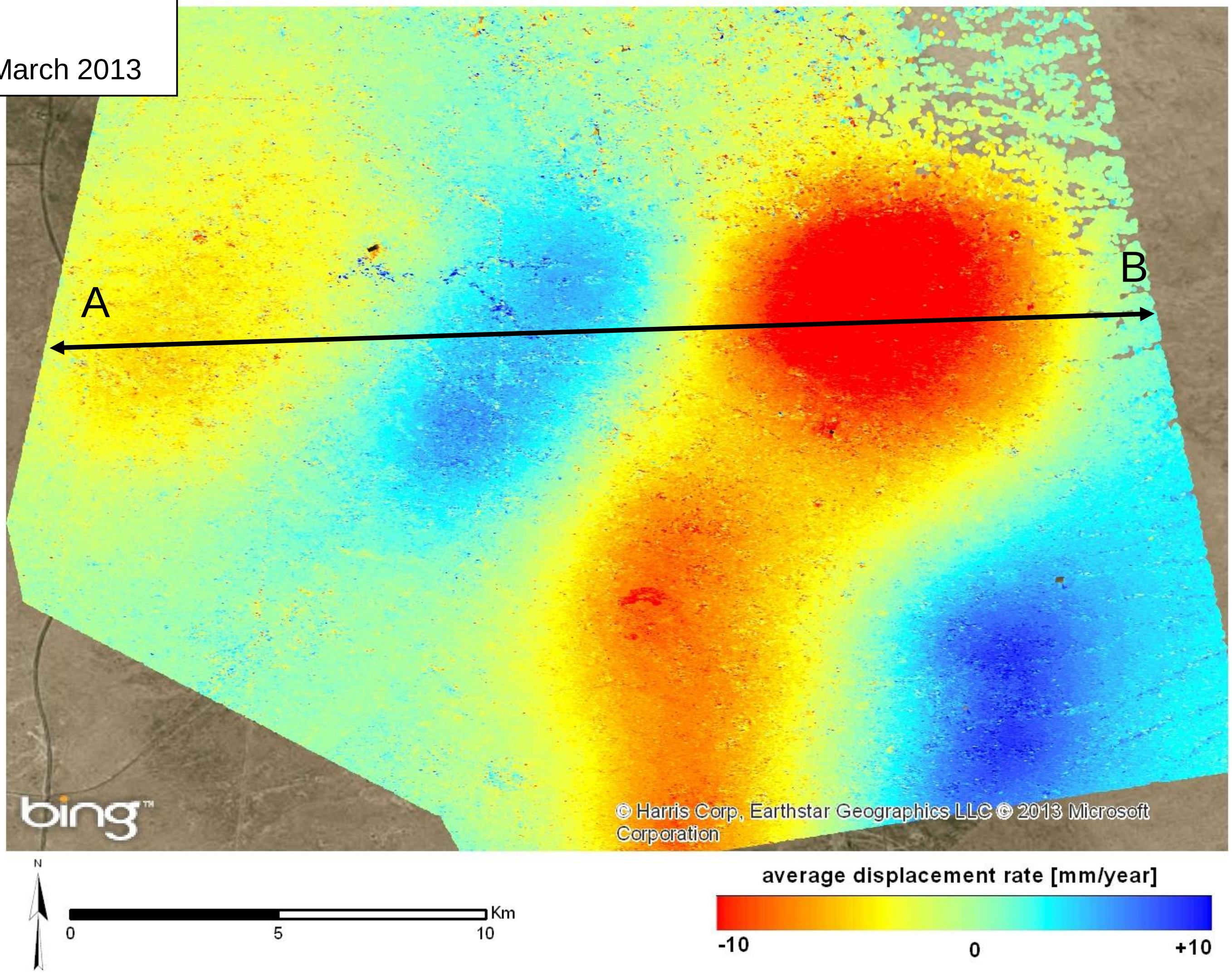
- Carbonate oil reservoir
- Depht: 2195 m
- Domal anticlines crossed by strike-slip related faults.
- Lateral and vertical heterogeneity
- They have been under water injection since 2000, to provide pressure support .

Raudhatain and Sabiriyah 2009 - 2013

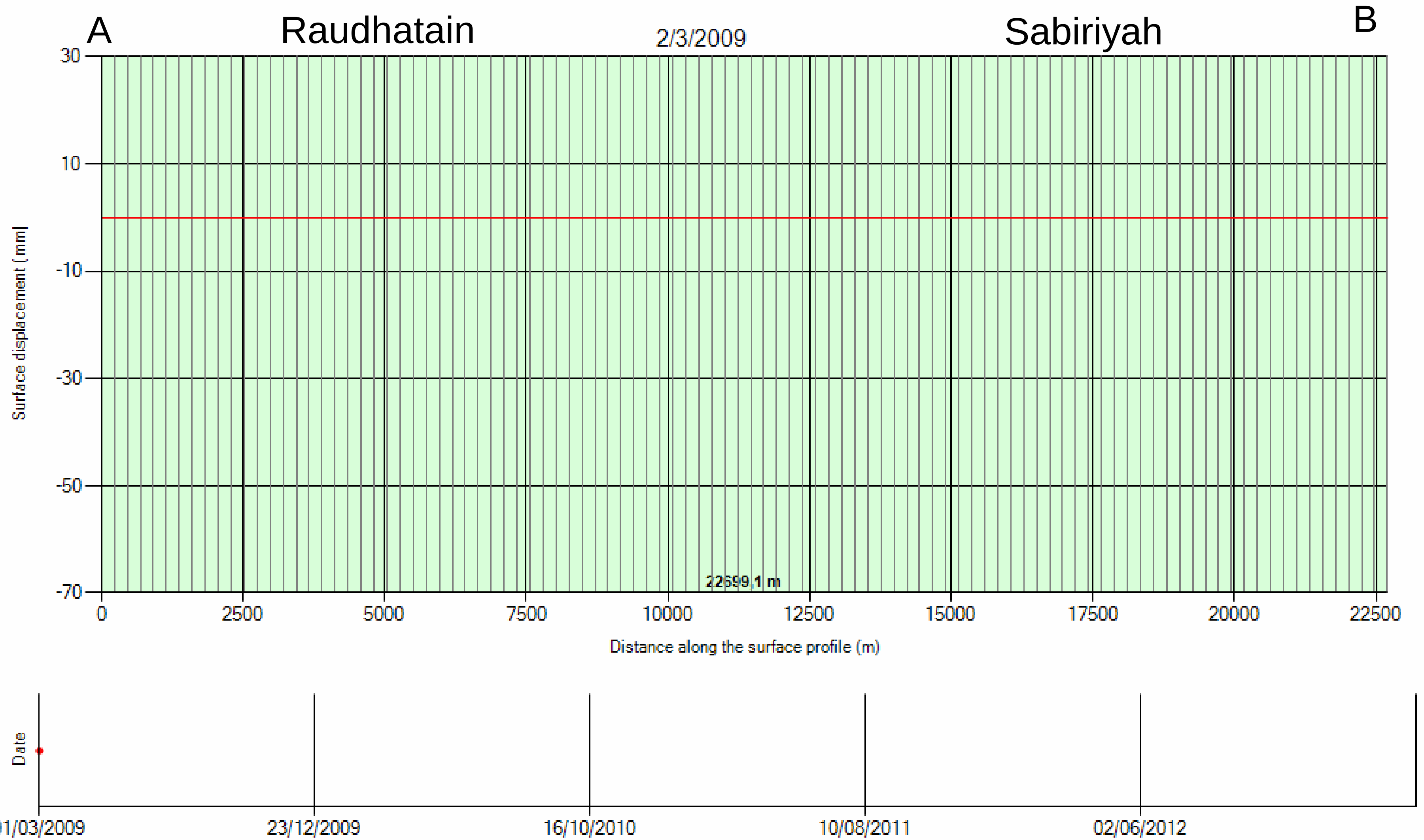


Raudhatain and Sabiriyah Field

TSX ascending
#78 images
March 2009 – March 2013



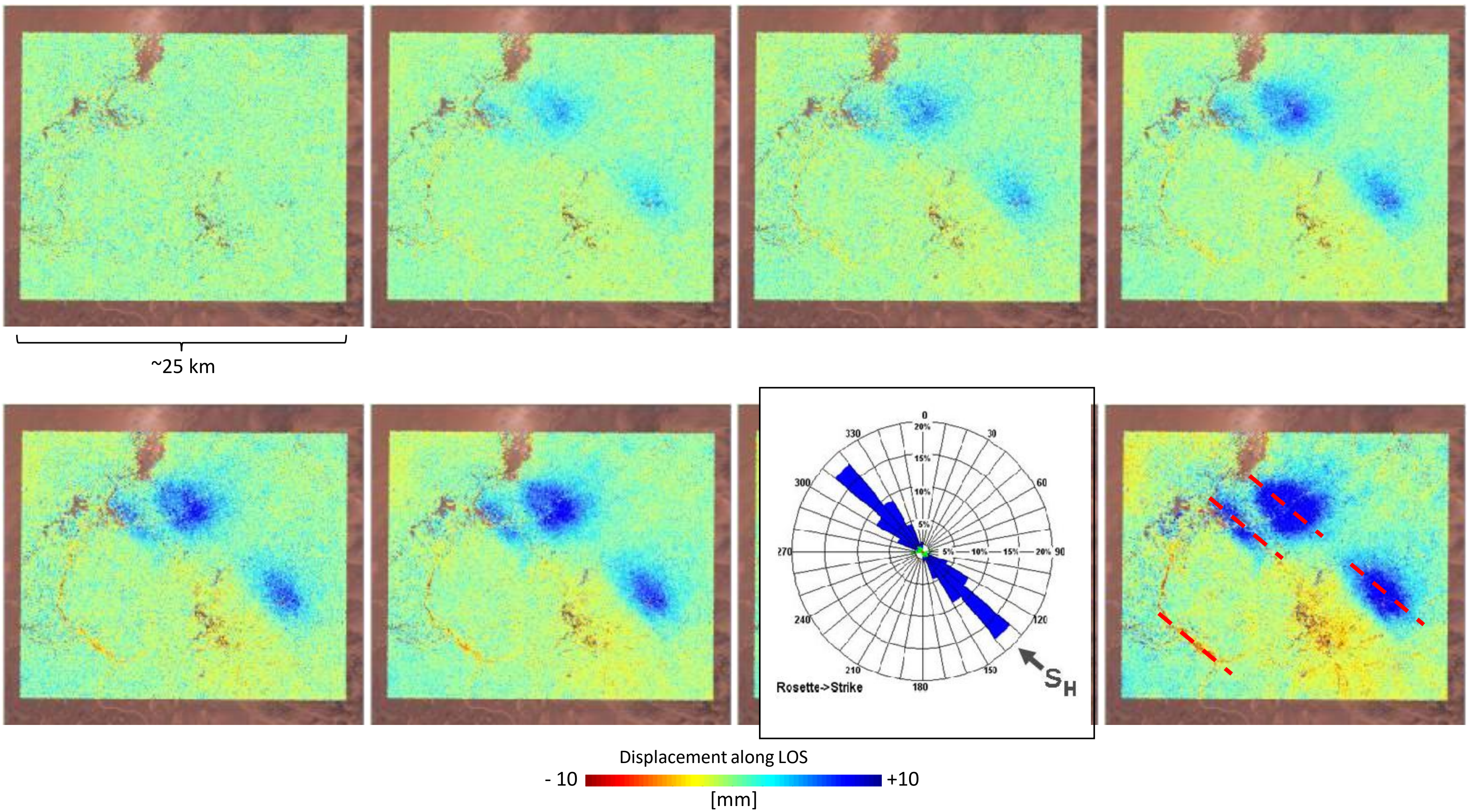
Cross Section – Displacement evolution



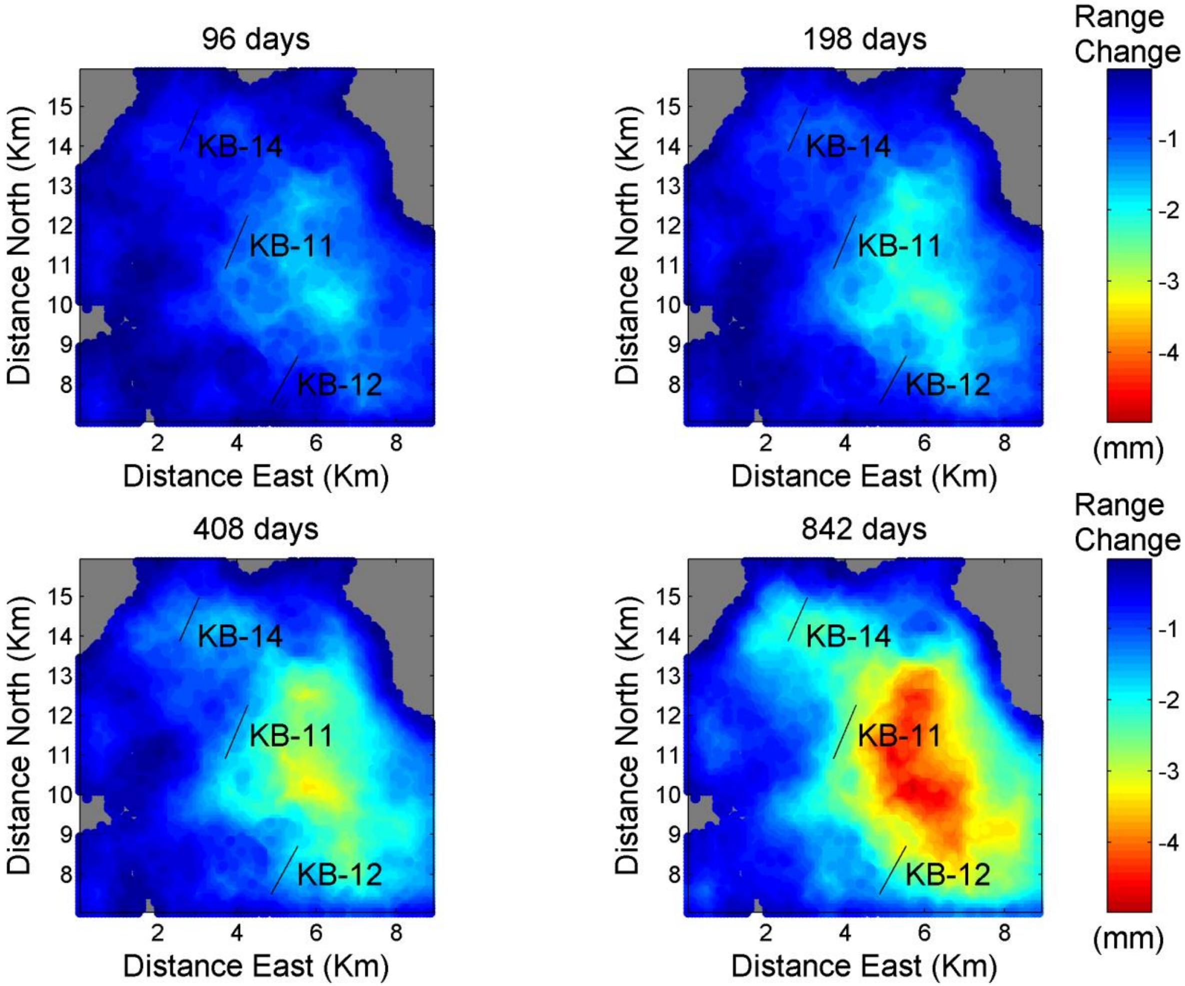
CO2 Sequestration - In Salah, Algeria

- In Salah gas storage is JIP of Sonatrach, BP and Statoil Hydro
- Field produces gas with up to 10% CO_2
- 1 million tons CO_2 captured from gas and injected annually
- ~ 3 million tons CO_2 injected by end of 2008

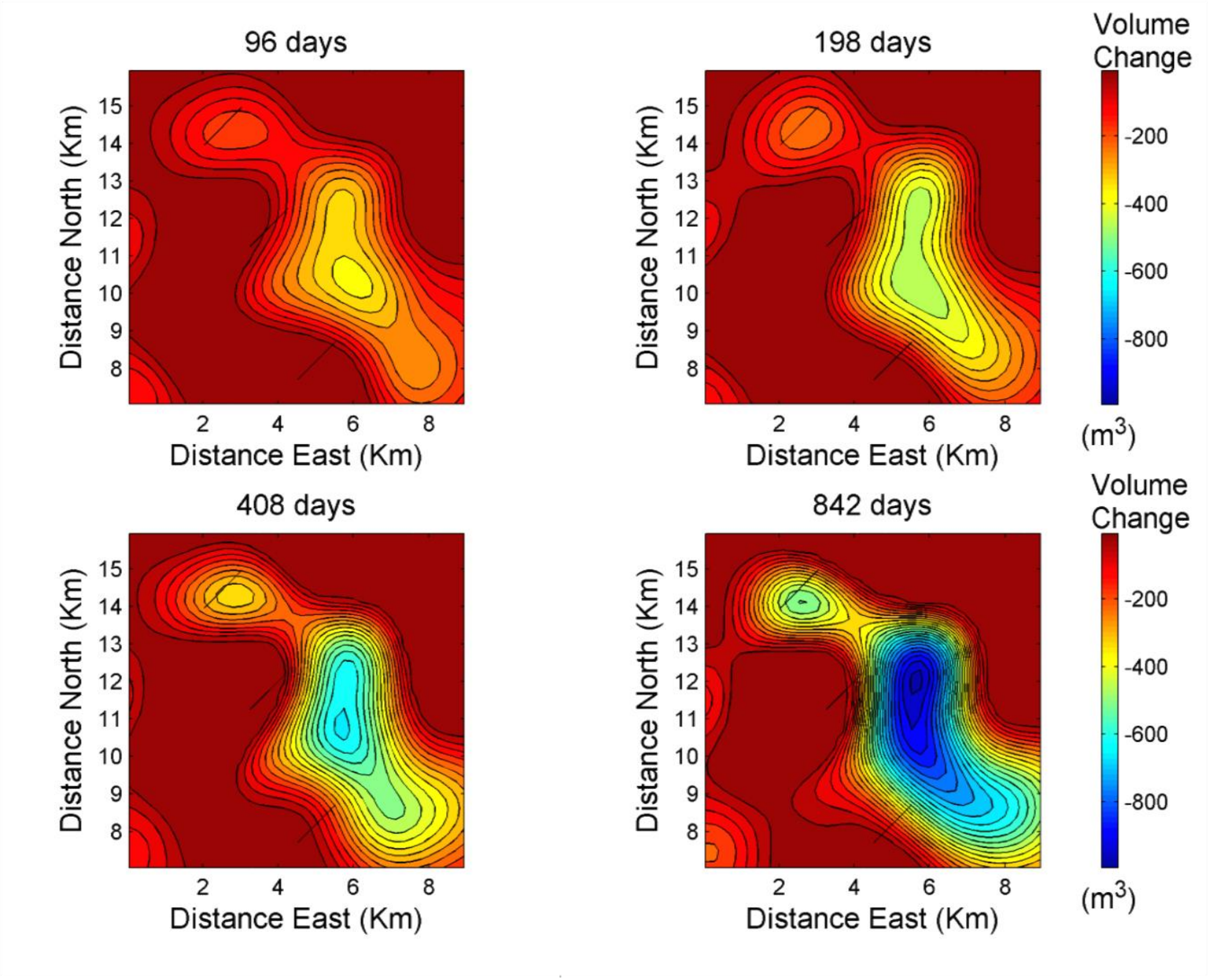
Time lapse analysis of surface displacement



Case study: Krechba field velocity map

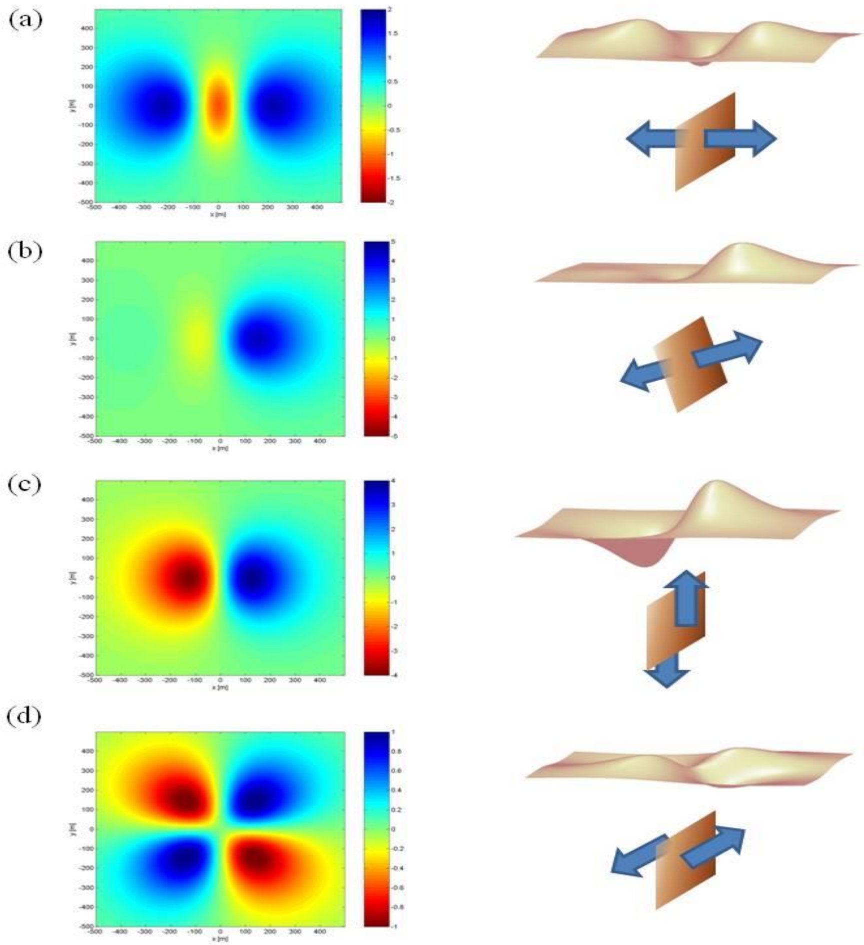


Volume change estimates

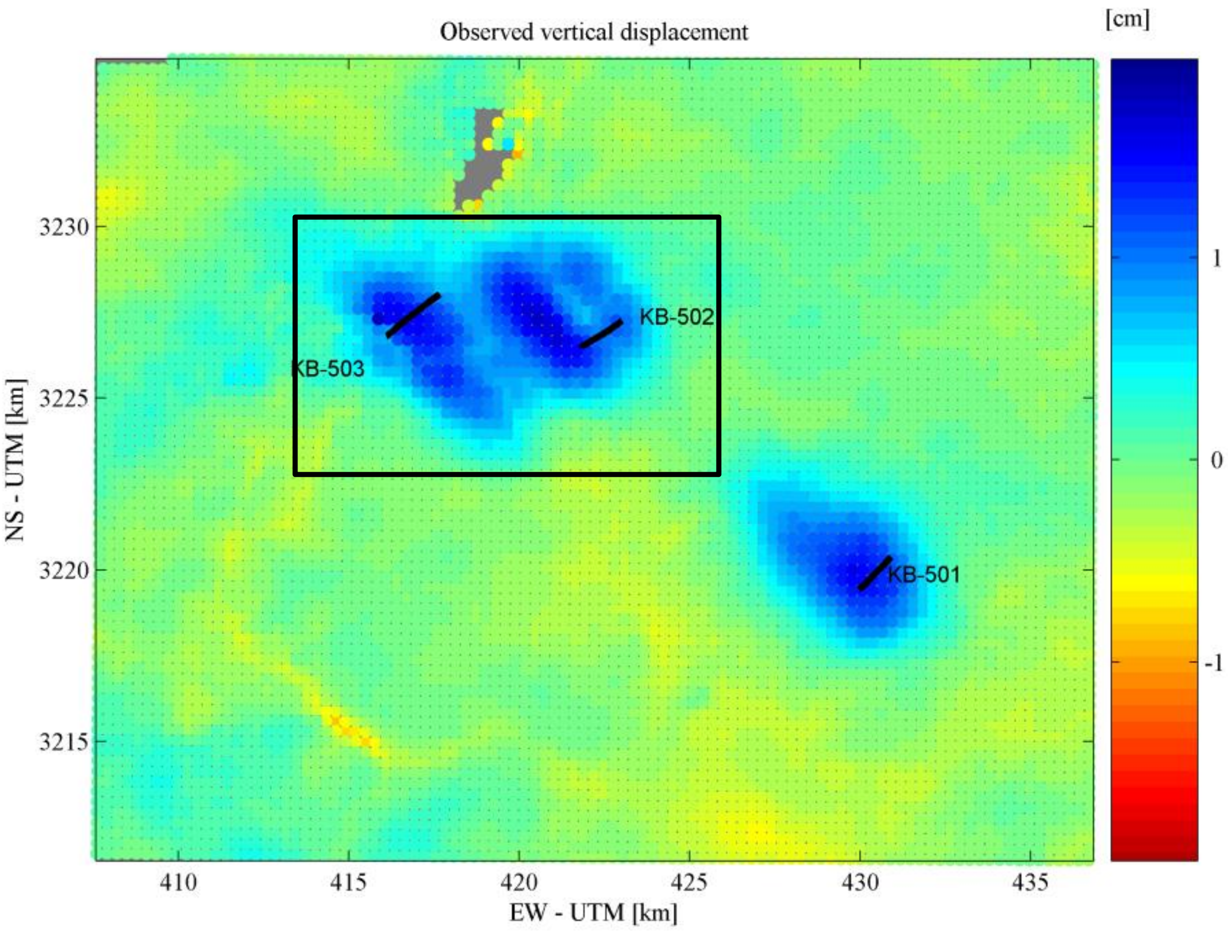


Fault fracture reactivation

Fault characterization from surface deformation



KB-502 & KB-503 analysis

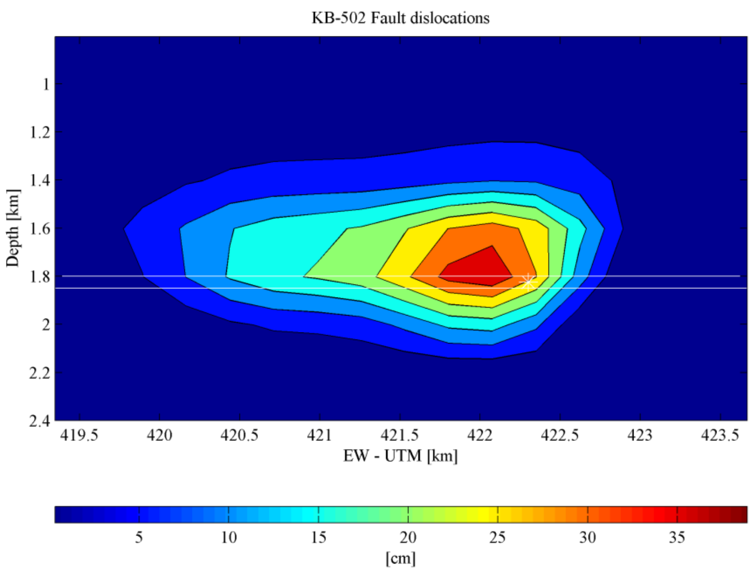


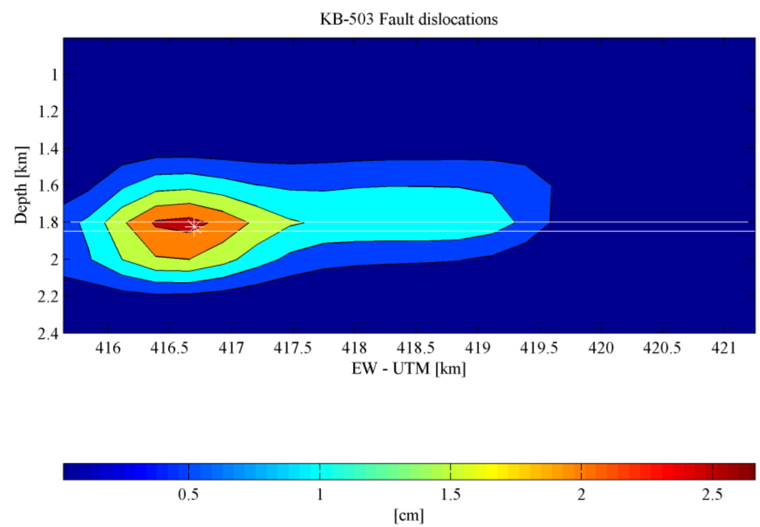
Dislocations along a fault plane – KB502 & KB50

» Average demage zome dislocations for KB502 and KB503

Observed verical displacement

[cm]

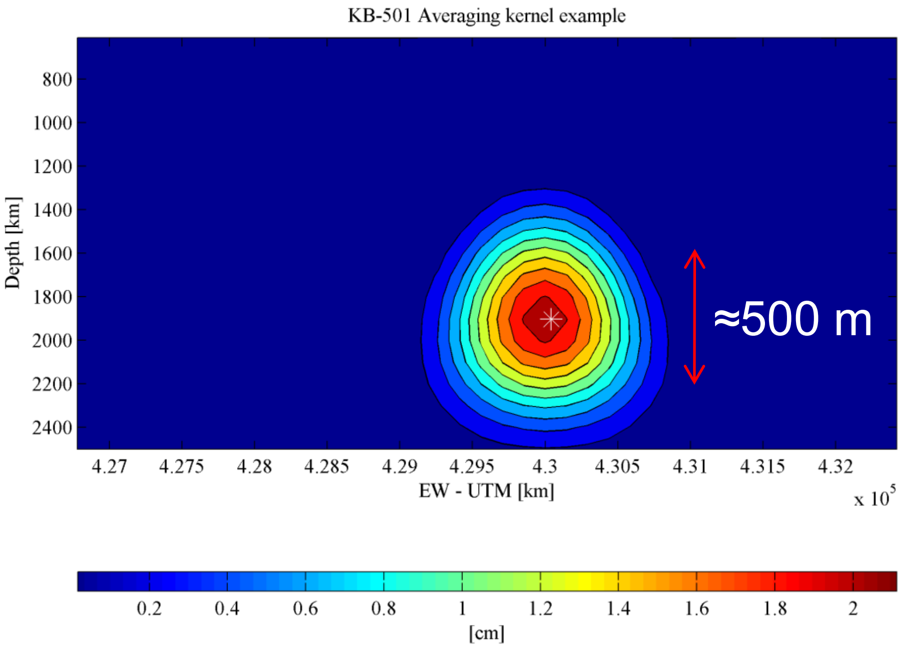




EW - UTM [km]

Spatial resolution of the estimates

- Due to preconditioning used in the inversion, the resolution of the estimates is downgraded
- To measure the effective resolution we can look at the averaging kernels of the resolution matrix, as they measure the resolution of each unknown parameter

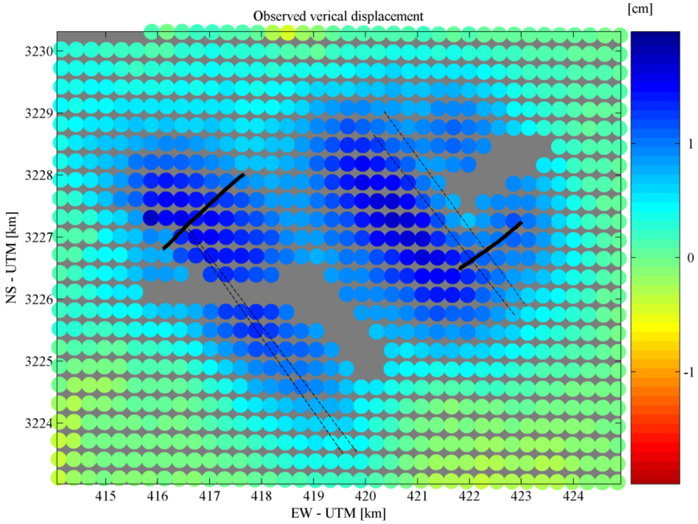


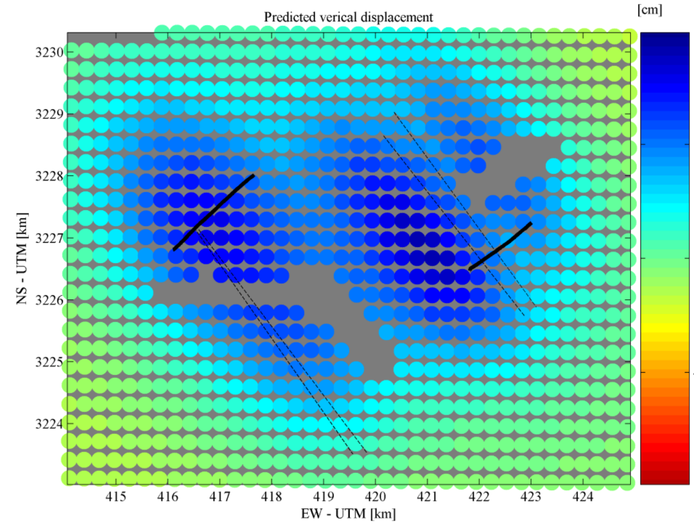
Vertical displacement component comparison

Observed

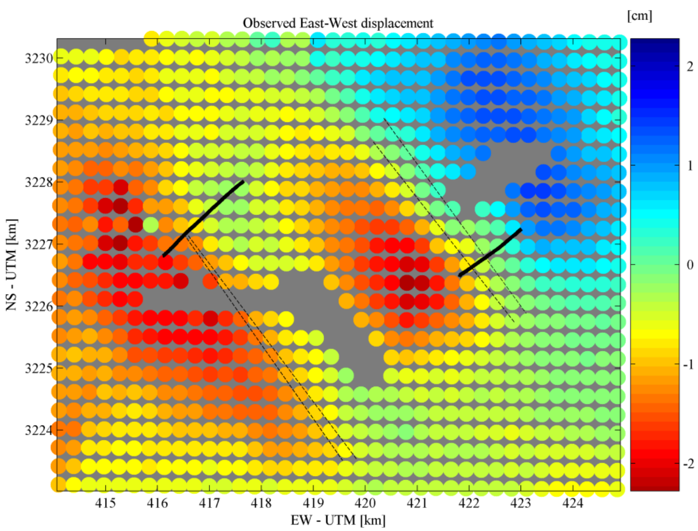
Vertical

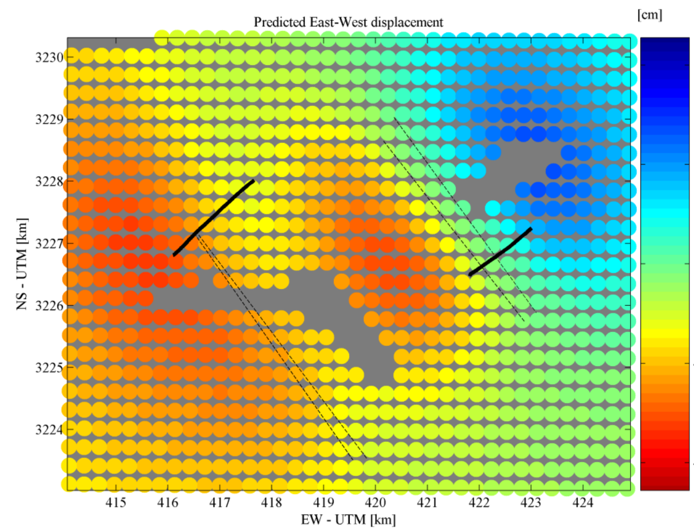
Predicted



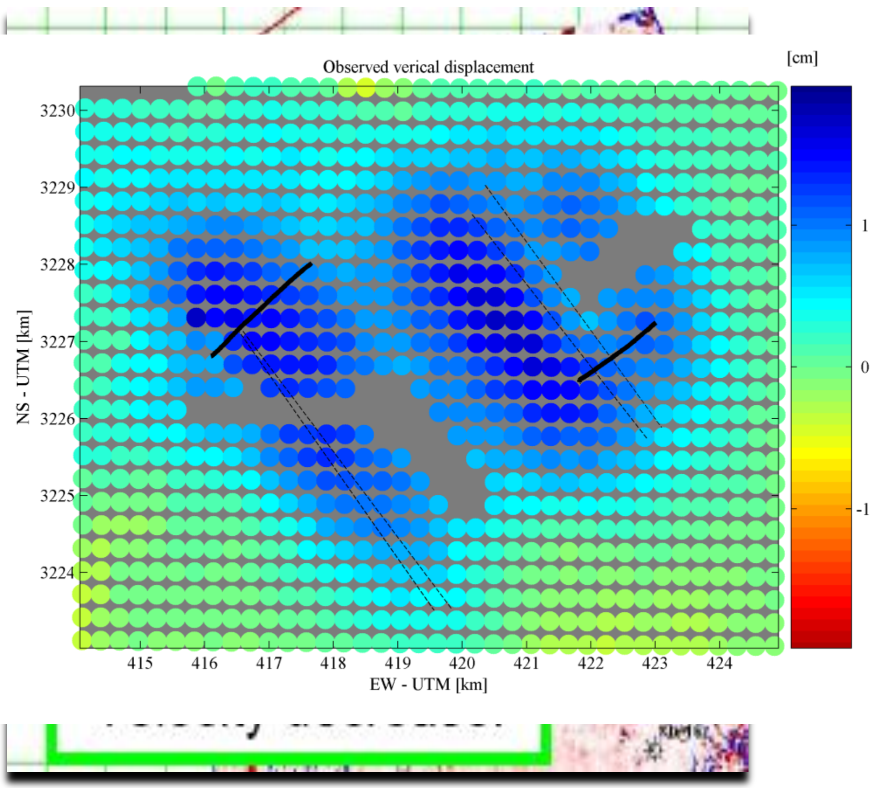


EW





- Velocity variations have been identified mainly along the two faults crossing wells KB502 and KB503

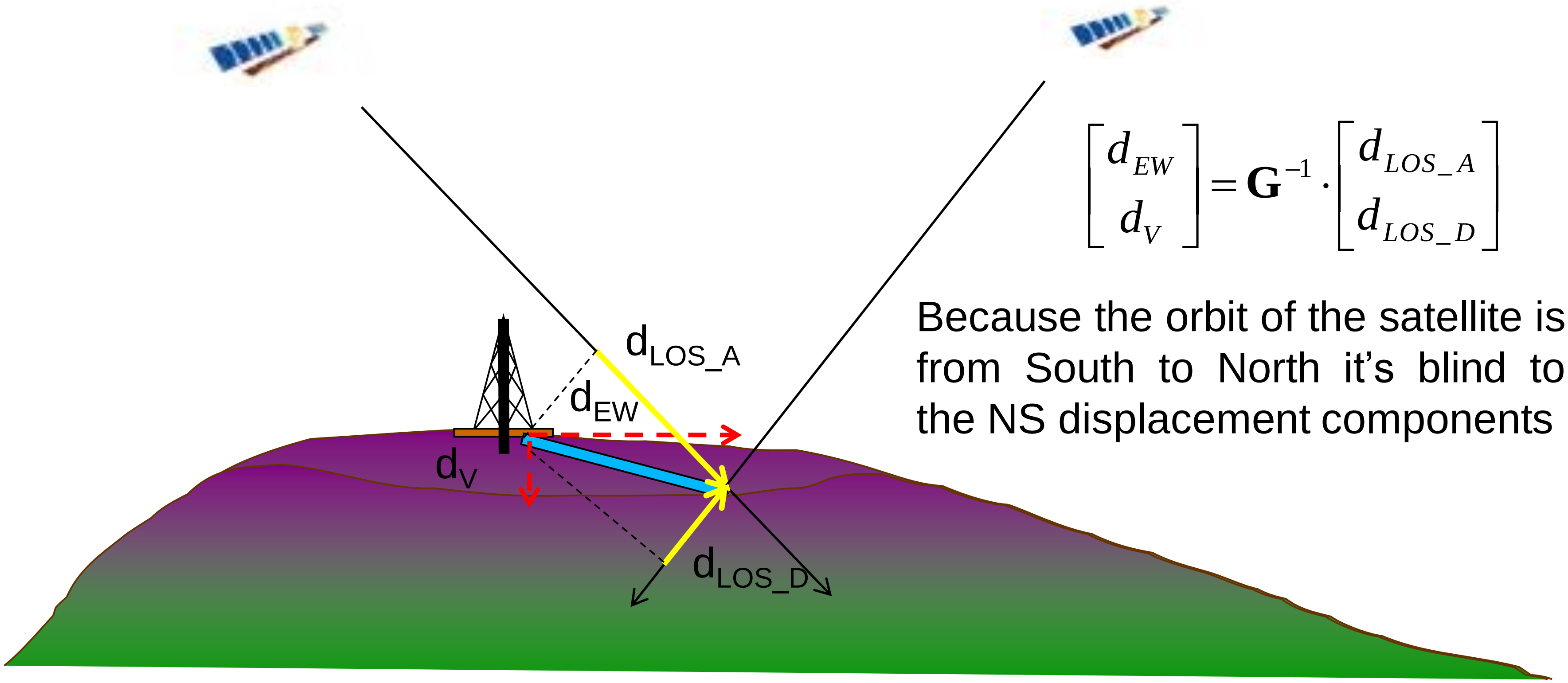


Importance of 2D components

2D Surface displacement monitoring

SAR satellites measures the Line of Sight (LOS) component of displacement

We can use multi-geometries SAR data to extract the East-West and Vertical components of displacement



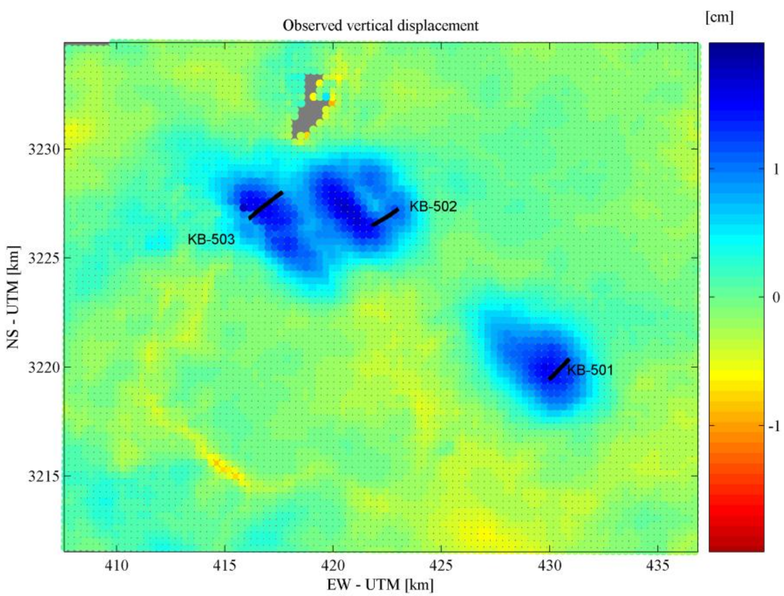
$$\begin{bmatrix} d_{EW} \\ d_V \end{bmatrix} = \mathbf{G}^{-1} \cdot \begin{bmatrix} d_{LOS\_A} \\ d_{LOS\_D} \end{bmatrix}$$

Because the orbit of the satellite is from South to North it's blind to the NS displacement components

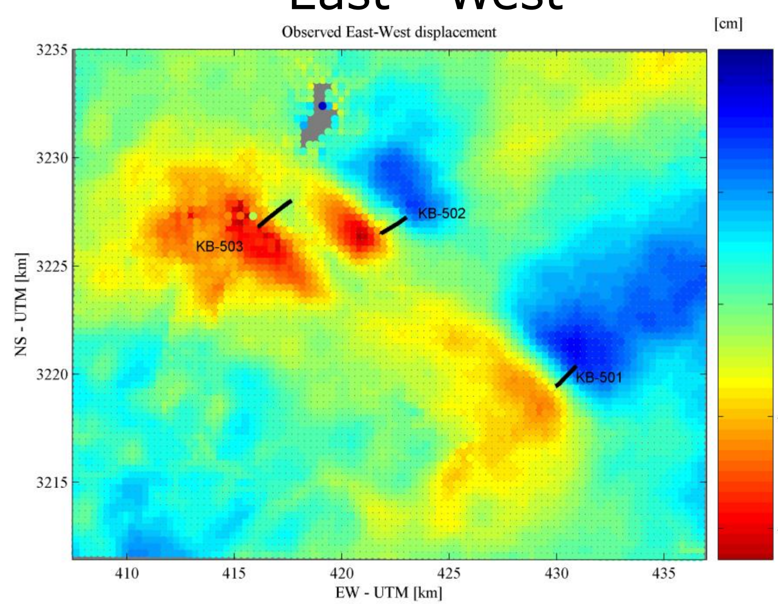
2D surface displacement components

- To obtain the 2D displacement field they have been processed:
  - One Descending geometry, processed applying SqueeSAR
  - One Ascending interferogram where no atmospheric compensations were feasible

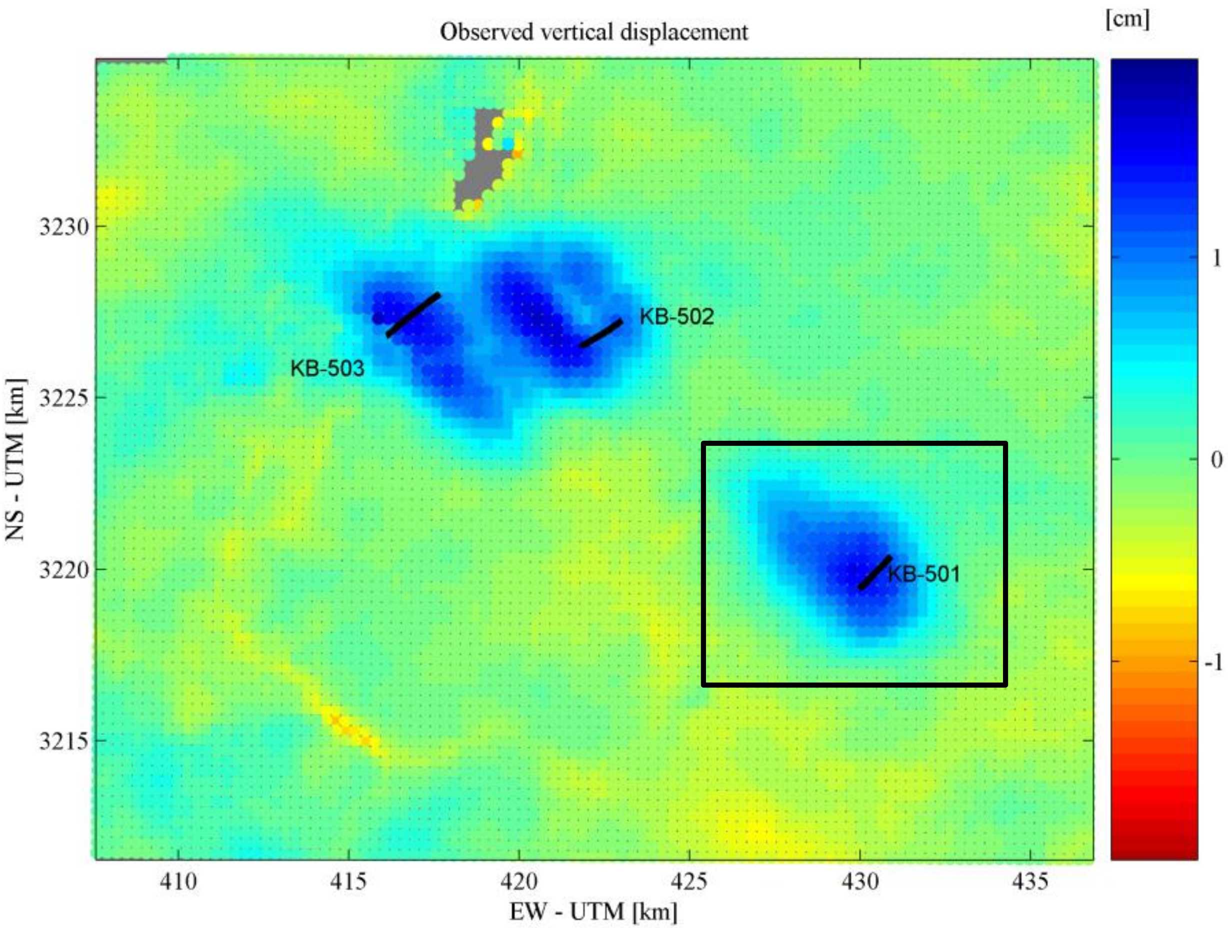
Vertical



East - West

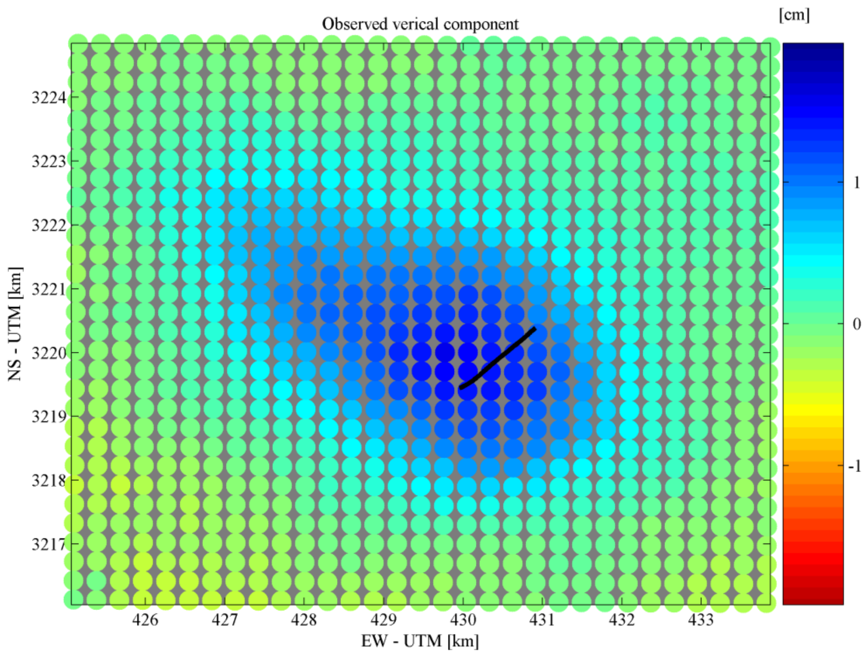


KB-501 analysis

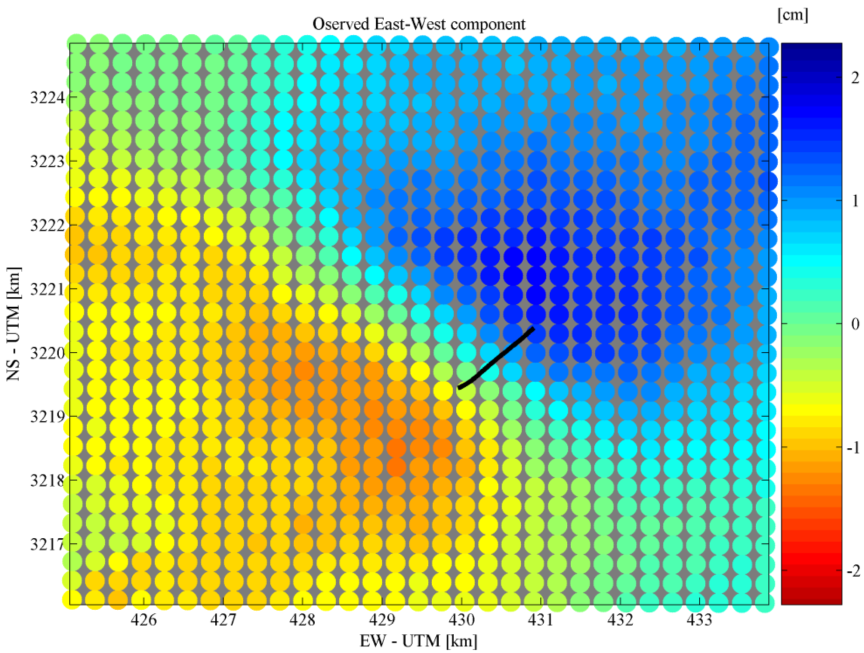


2D surface displacement close-up on KB - 501

Vertical



East - West



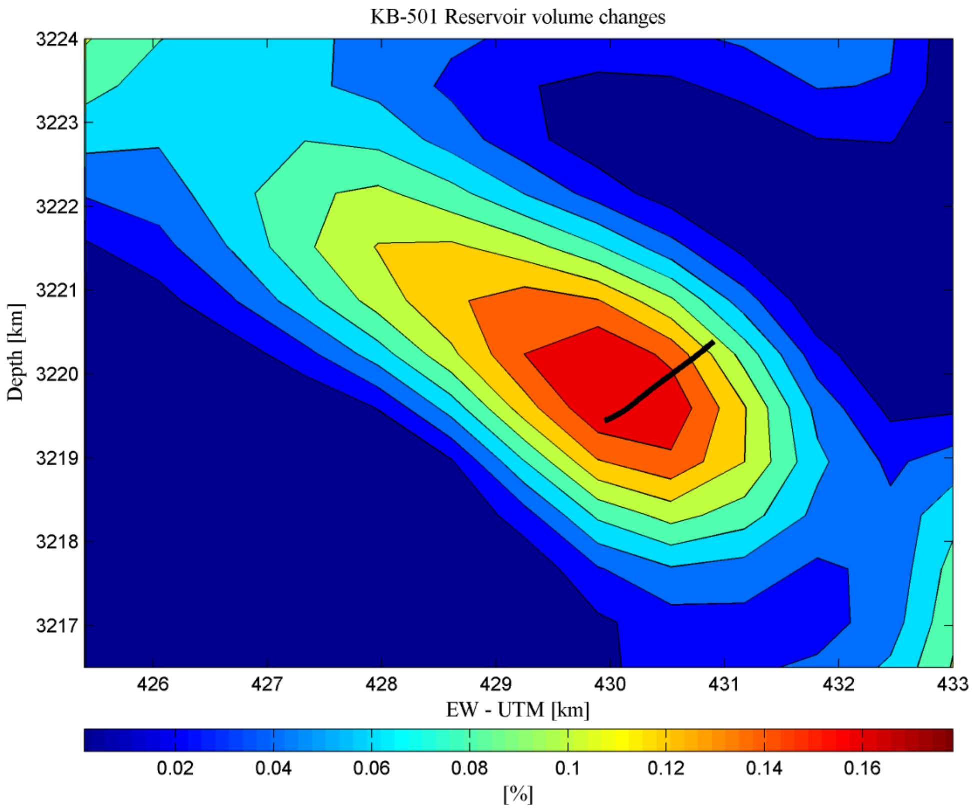
Model used for the inversion

- The two components of displacement have been inverted into flow-related processes at depth
- We considered two different models:

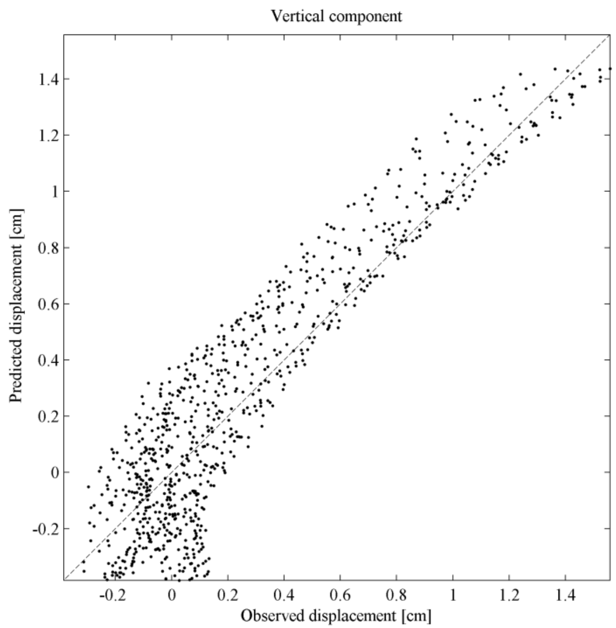
1. Only volume changes at the reservoir layer are allowed
2. Volume changes and dislocations along a fault are allowed

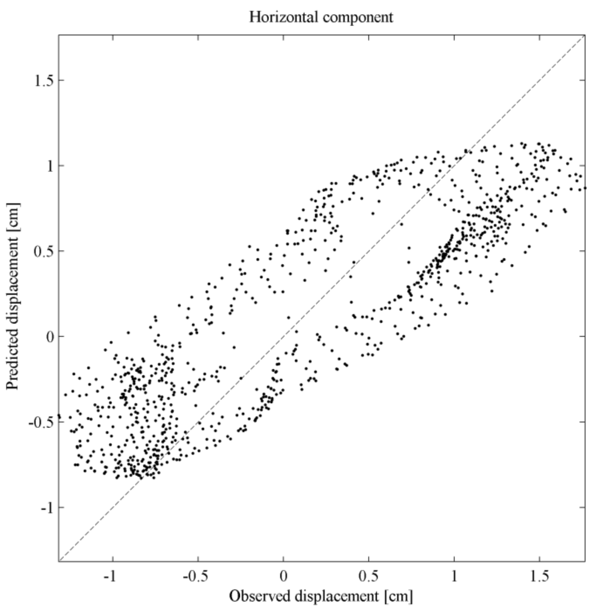
Volume changes at the reservoir layer (1)

- Volume changes estimated from the 2 displacement components



Volume changes at the reservoir layer (1)



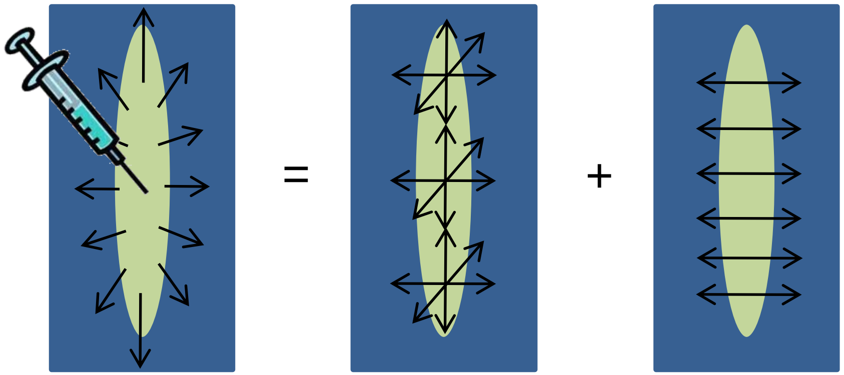


Volume changes and dislocations along fault plane

» 4D seismic reveals that for KB502 and KB503 velocity anomalies were detected mainly along fault plane or damage zone

» In case of liquid intrusion in a dyke the surface displacement is due to two sources:

- Dilatation sources (Volume changes)
- Tensile force (Dislocations)



» We used the same model for the injection of CO_2 in a fault plane/damage zone

Geomechanical parameters inversion

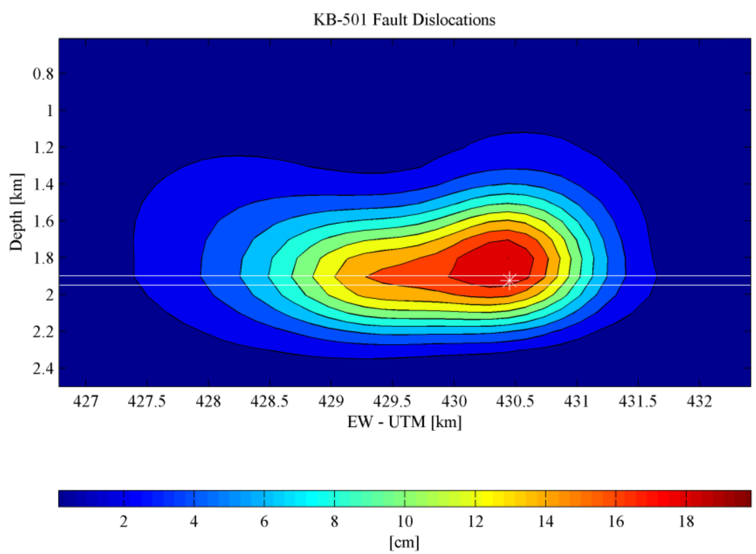
» As the model consist in an opening fracture with volume changes along it, through a non-linear optimization we estimate:

- The dip angle of the fault
- The strike angle
- The position
- The ratio between tensile and dilations forces

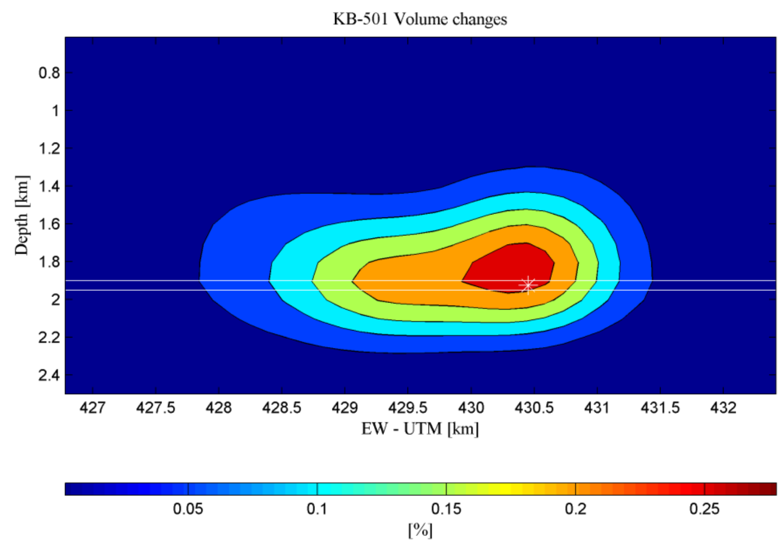
- Then inequality constraints are included in the inversion under the assumption that CO2 injection can lead only to positive opening of the fault

Volume changes and dislocations along a fault (1)

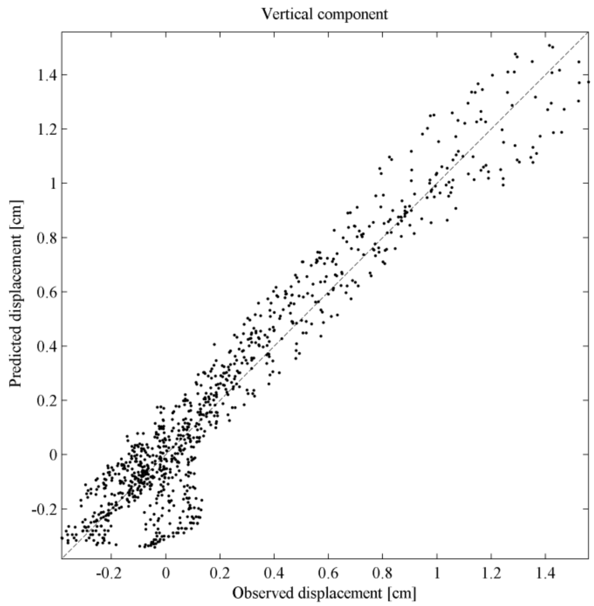
Dislocations

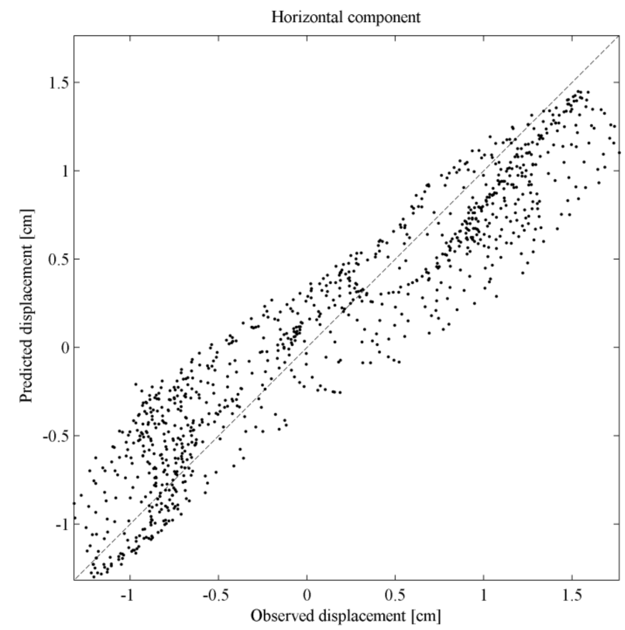


Volume changes



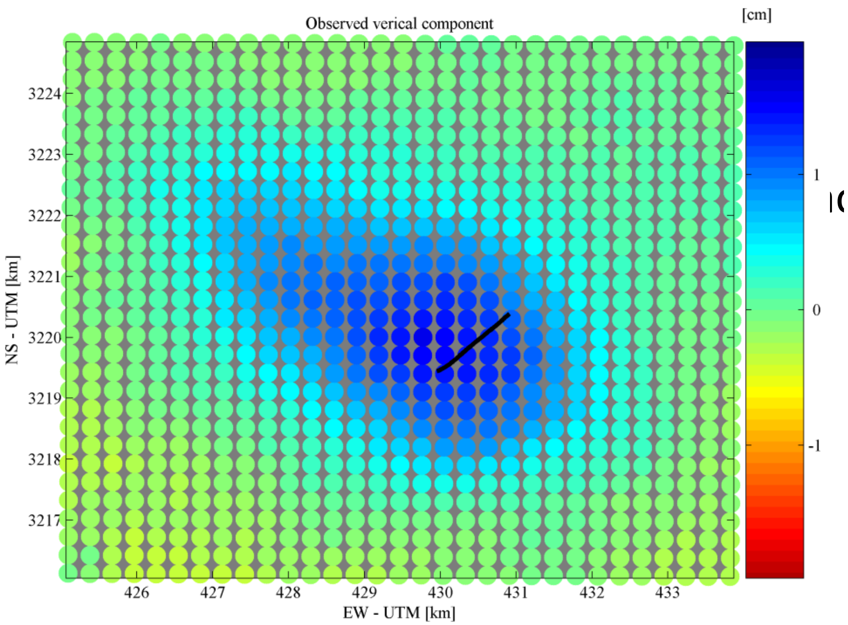
Volume changes and dislocations along a fault (2)



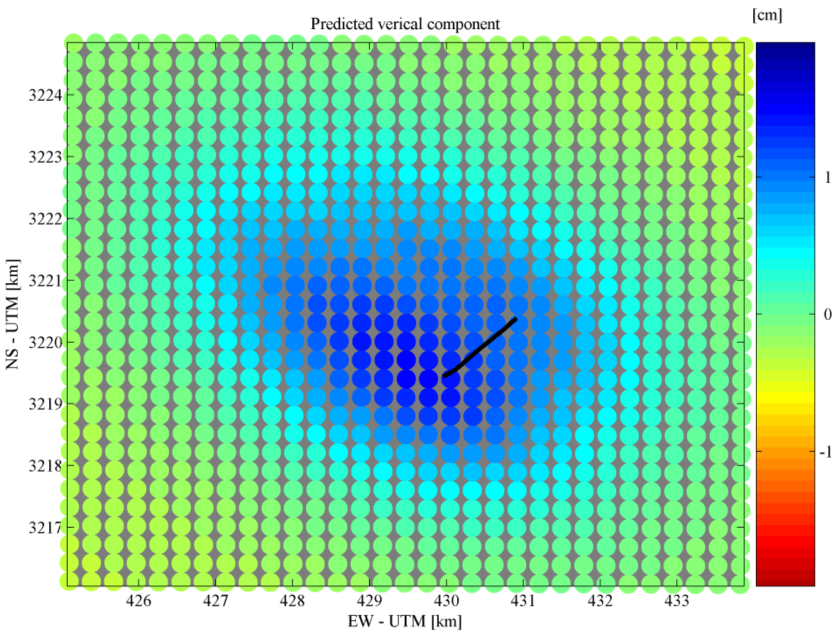


Volume changes and dislocations along a fault (3)

Observed

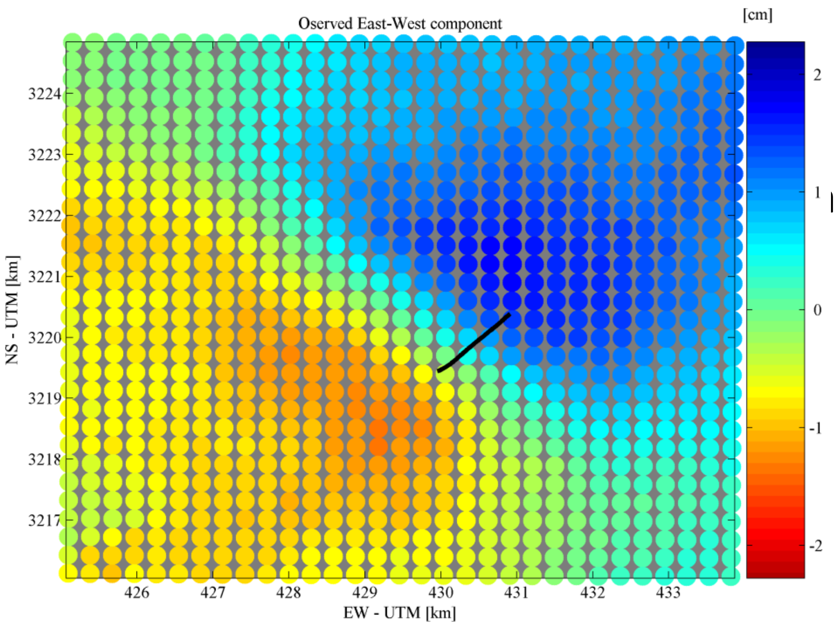


Predicted

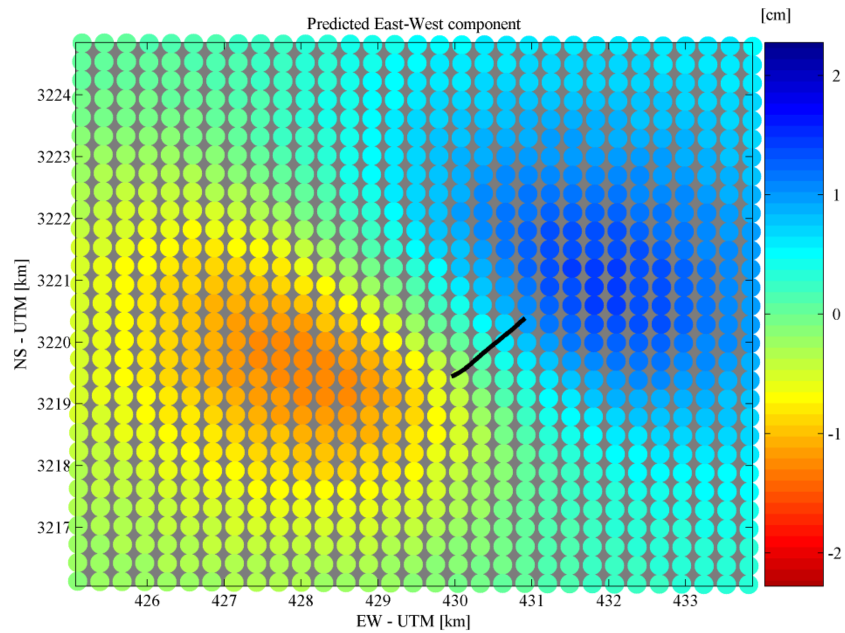


Volume changes and dislocations along a fault (4)

Observed

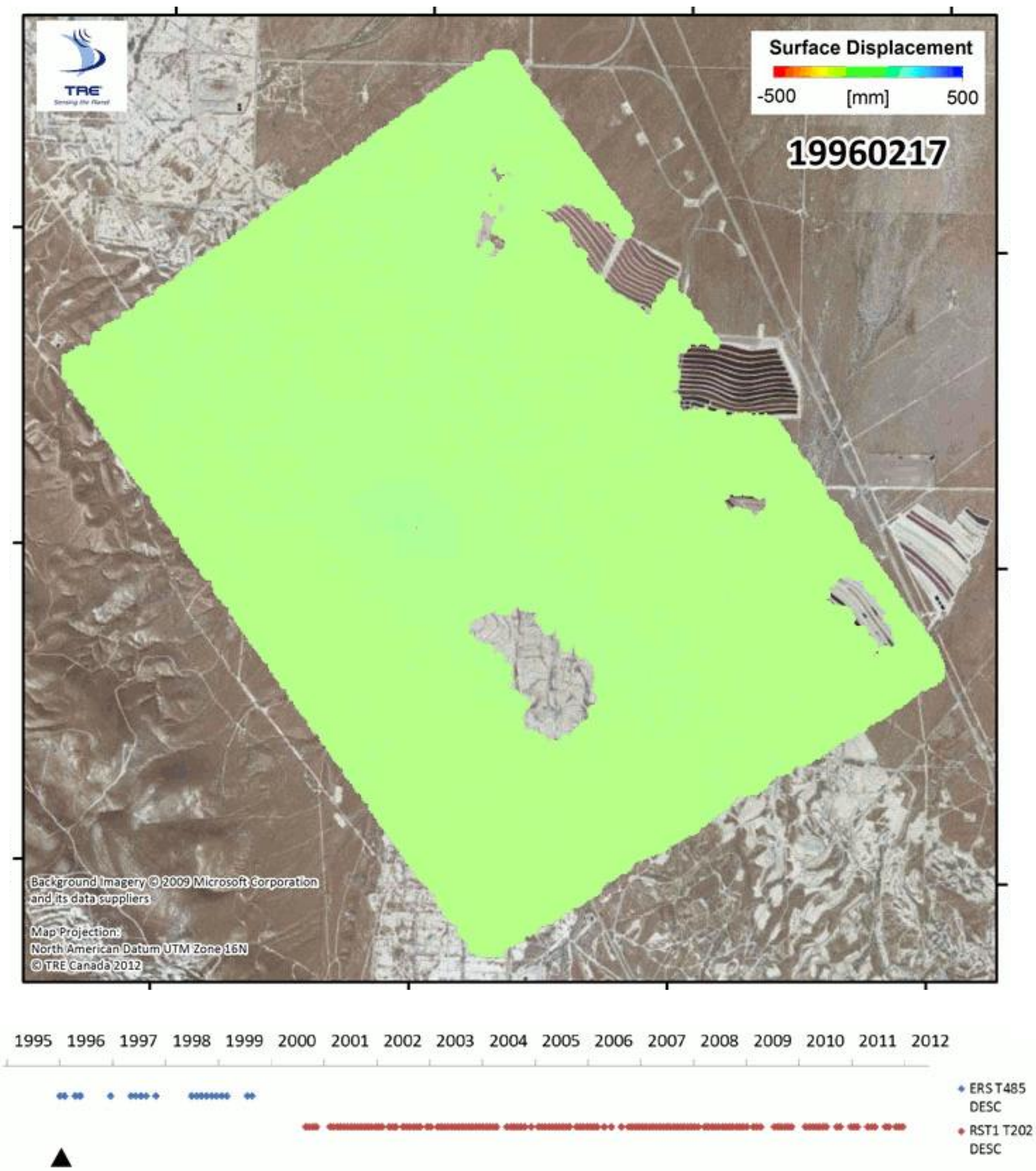


Predicted



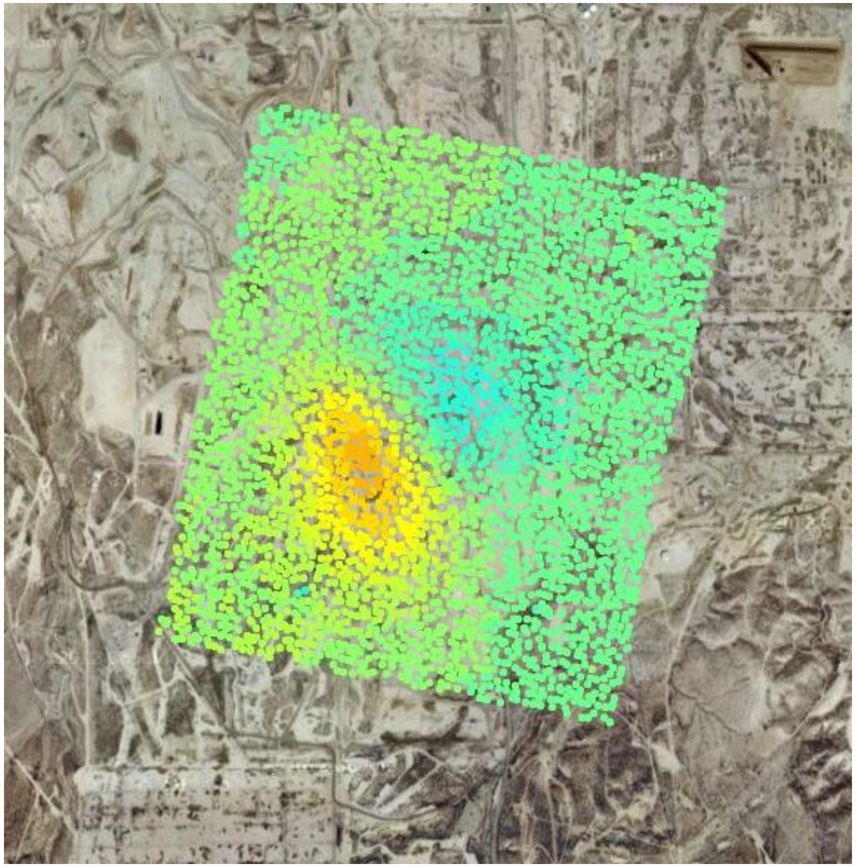
Heavy oil
In California

EOR – Steam injection



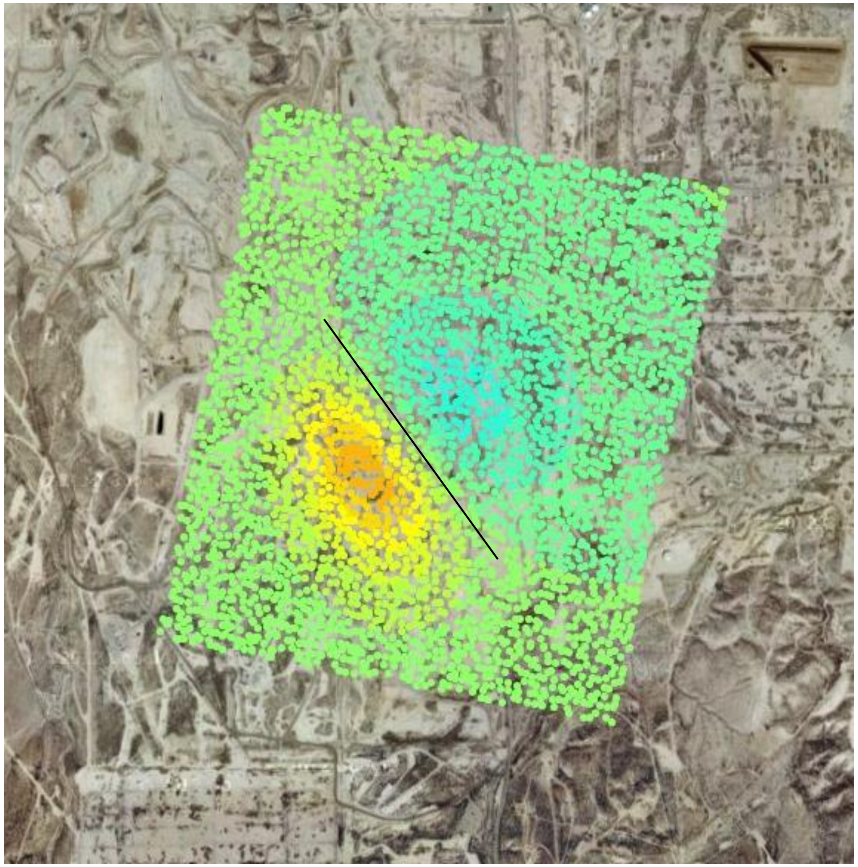
LOS displacement close-up between 20040117 - 20040210

- Possible dip-slip fault reactivation due to steam injection activity

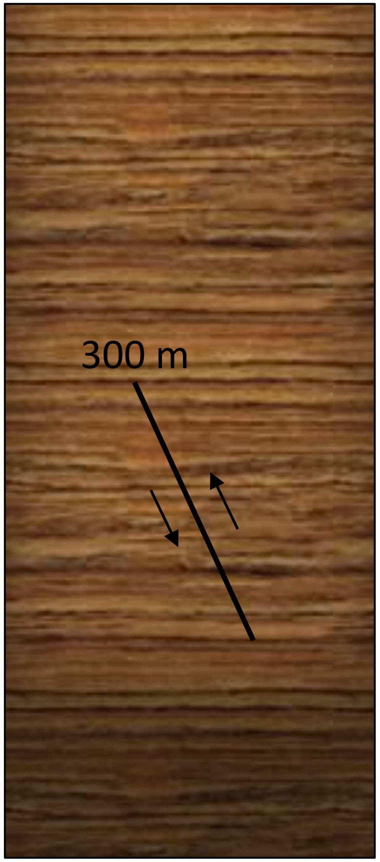


Displacement predicted by the model

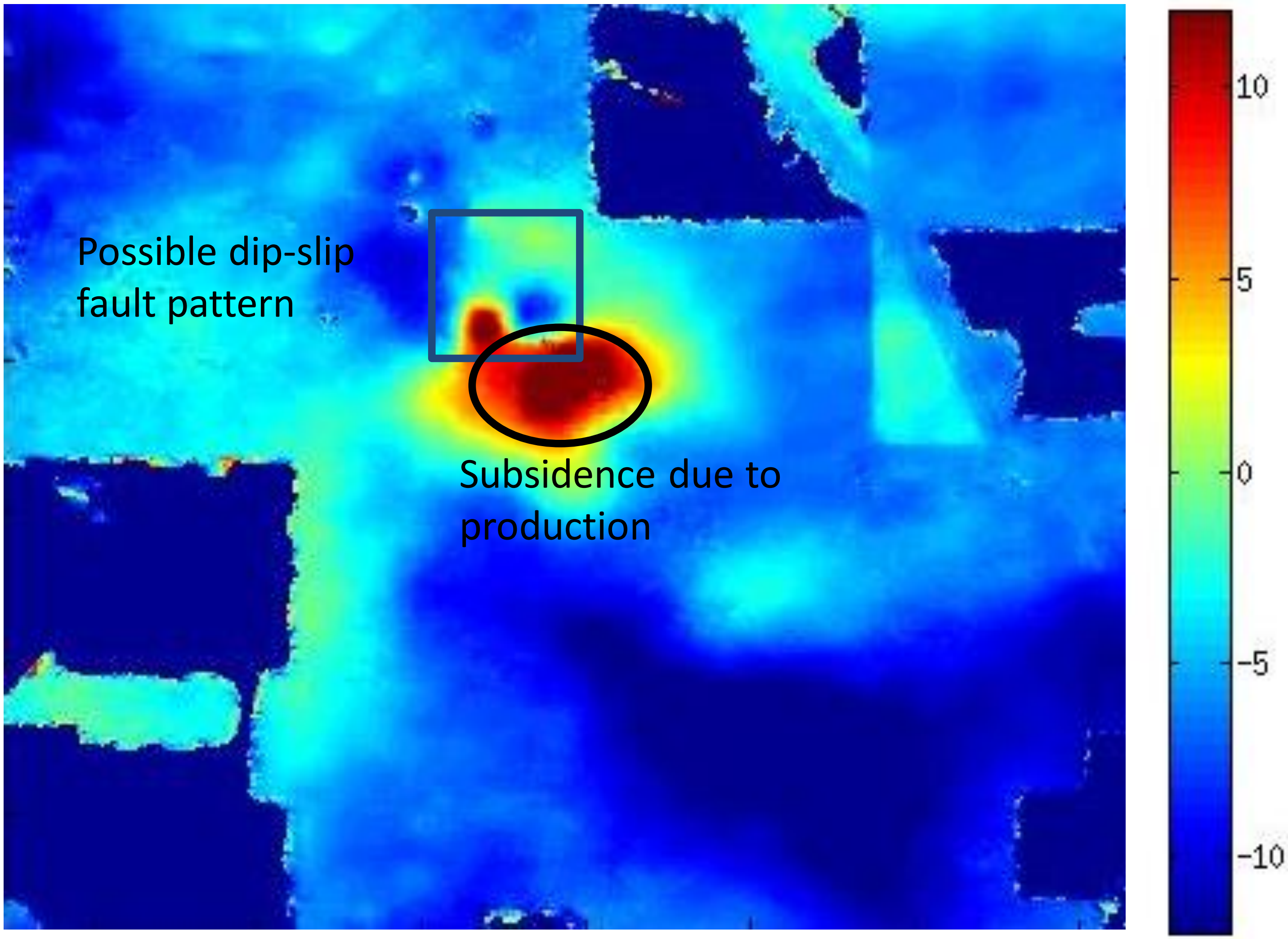
- The fitting inferred a dip-slip dislocation at 300 meters depth with a 70° dip angle



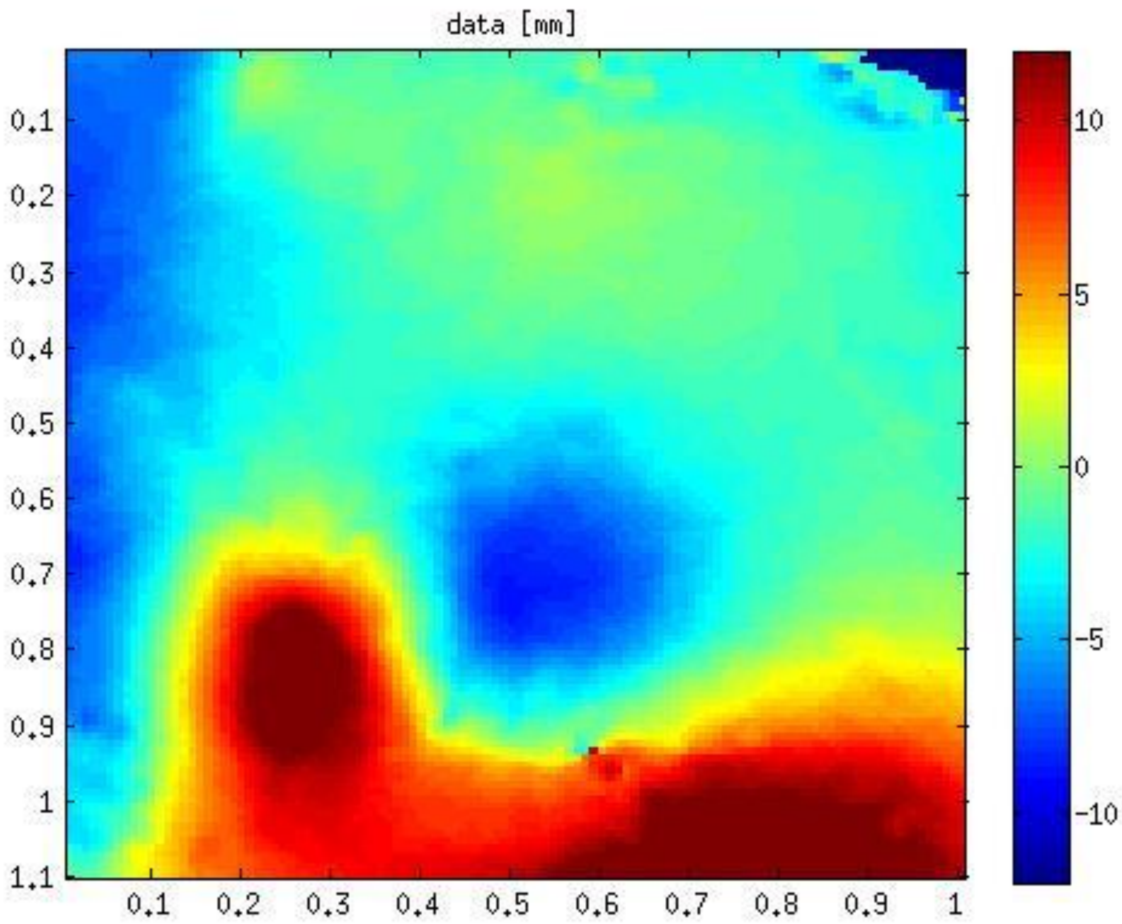
ground



LOS displacement observed between 4 Feb 2014 and 28 March 2014



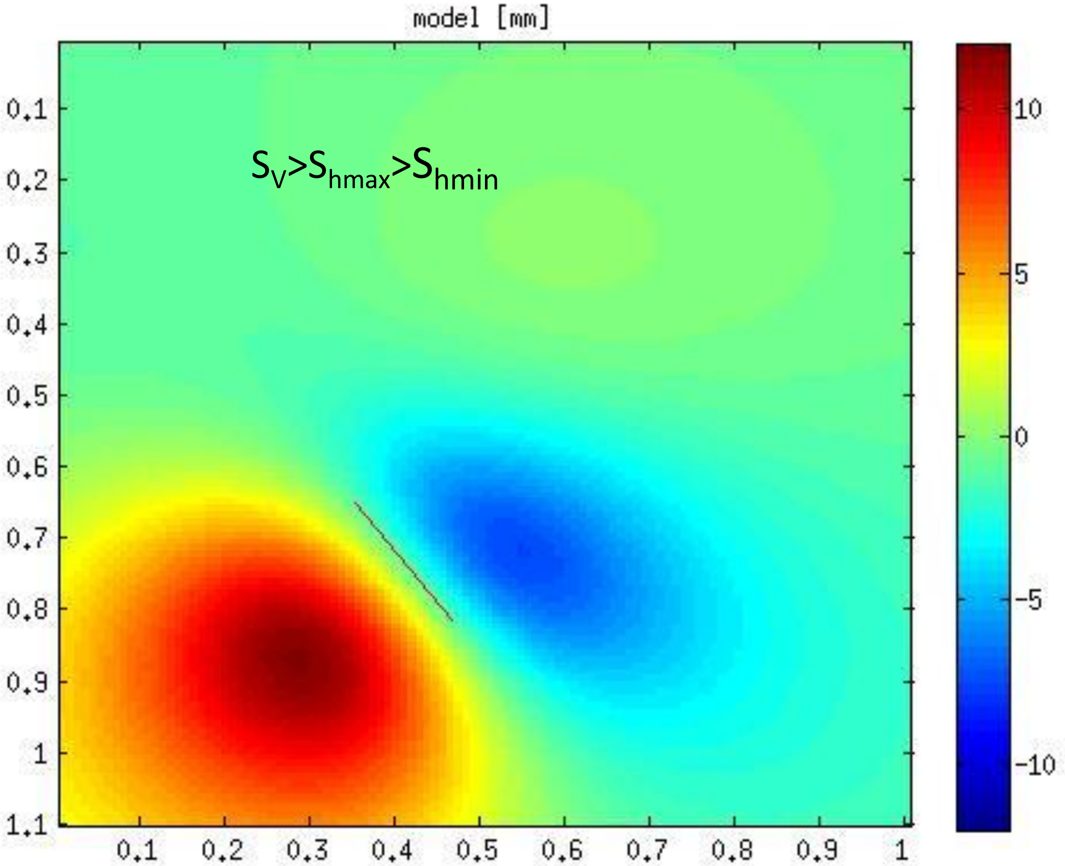
Close-up



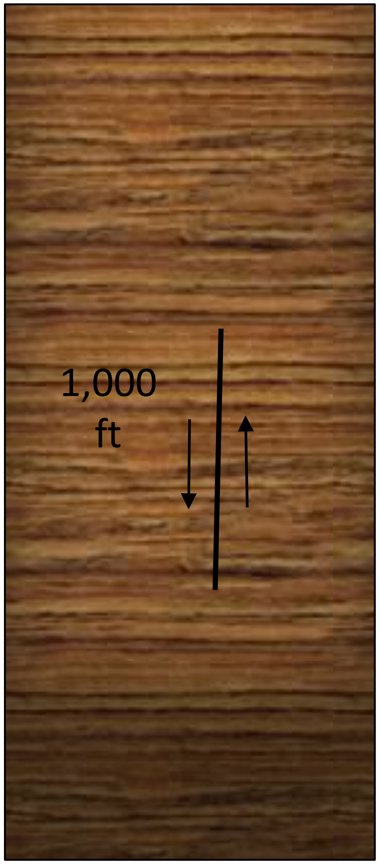
data [mm]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10
5
0
-5
-10

Displacement predicted by the model

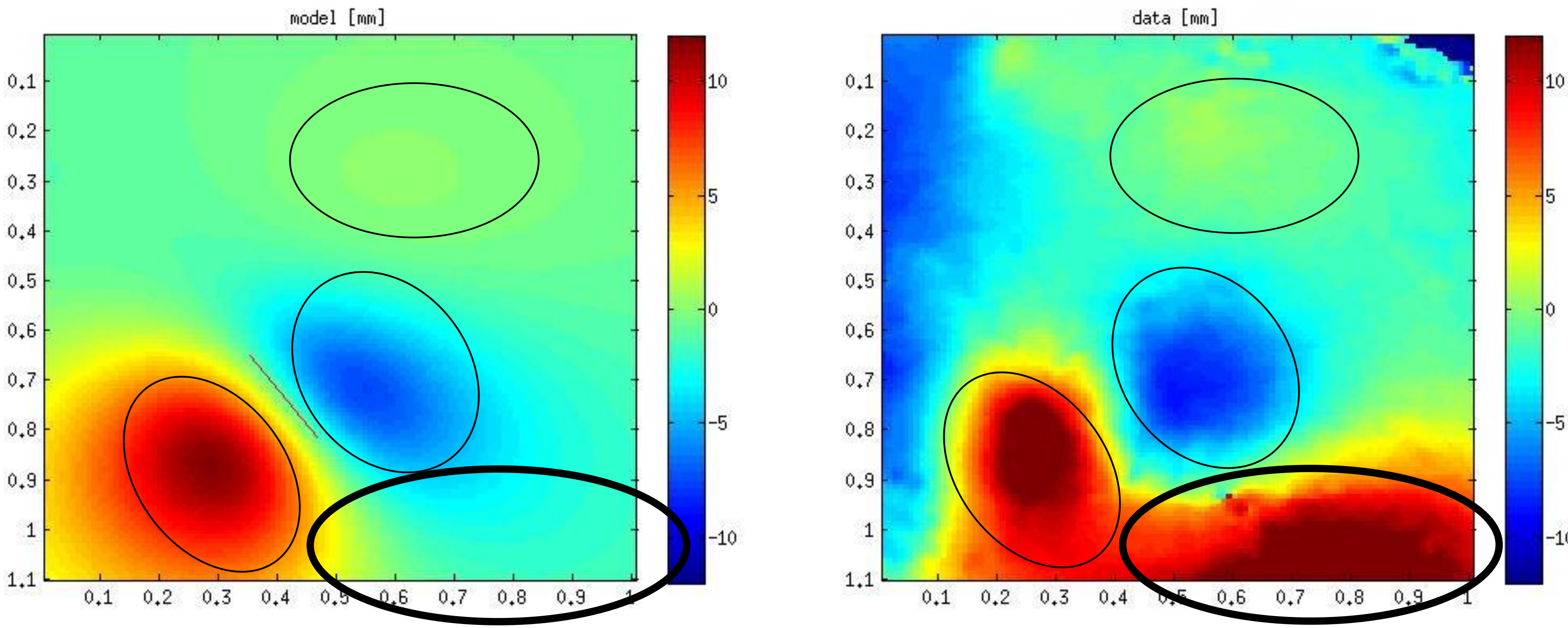
The model fitting inferred the presence of a dip-slip dislocation at a depth of 1,000 feet, with an estimated 90° dip angle



Surface



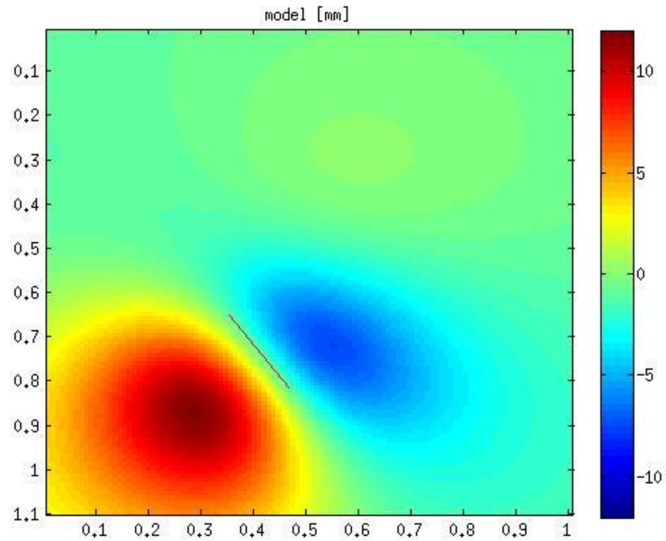
Measured vs Predicted displacement



Subsidence due to production not included in the model

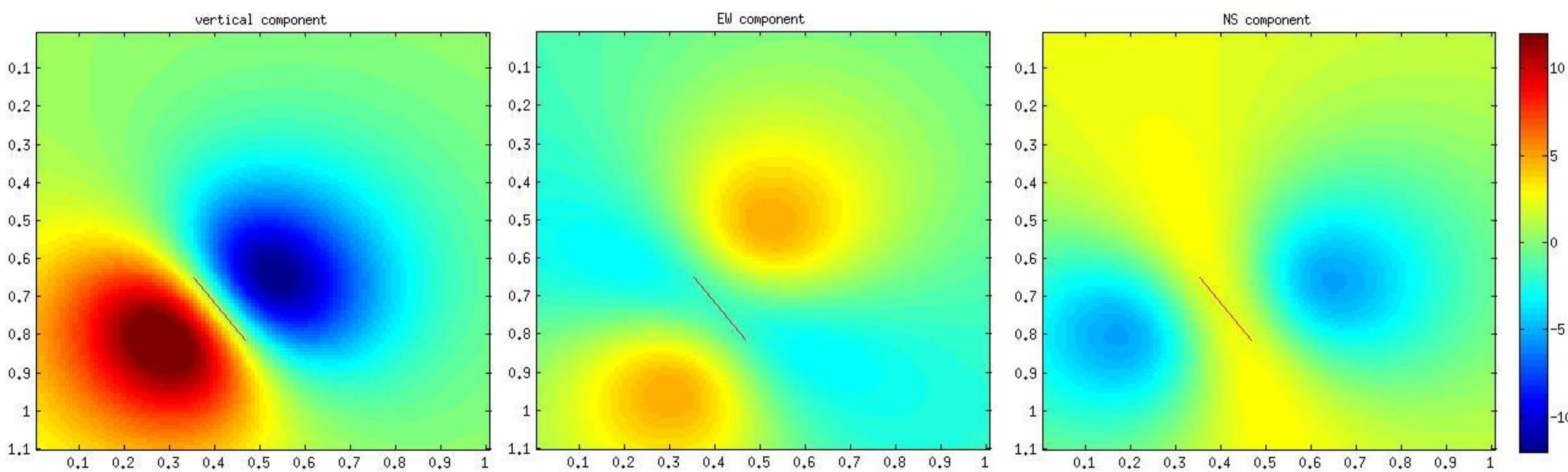
Subsidence due to production

From LOS component to 3D



LOS=0.68*vert + 0.717*EW -0.136*NS

Based on the fault dislocation geomechanical model it is possible to decompose the LOS components into the 3D displacement field



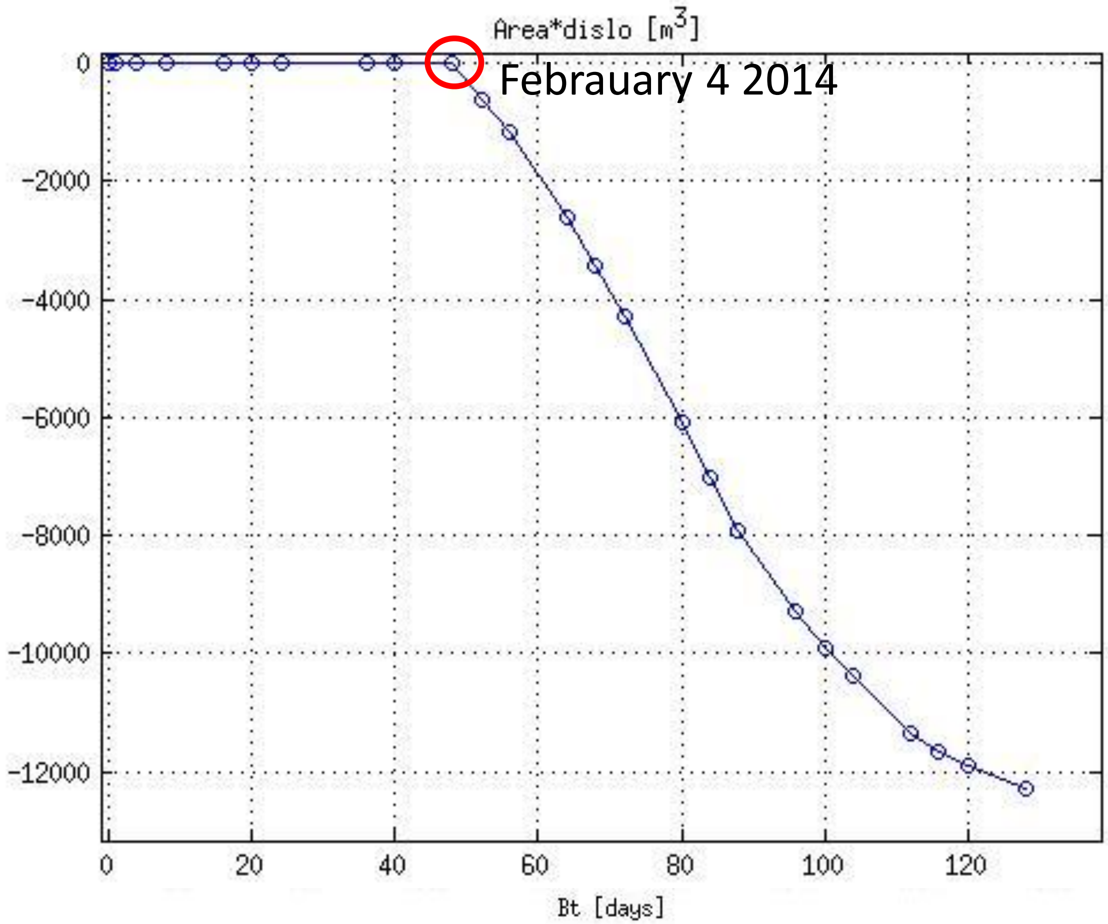
Uncertainties

As the dimension of the fault plane is unknown it has to be inferred from SAR data leading to a trade-off between the area of the fault plane and the amount of slip

If it is not available any fault geometry model from SAR data it will be possible to provide a reliable estimate of the fault moment (M) which is equal to:

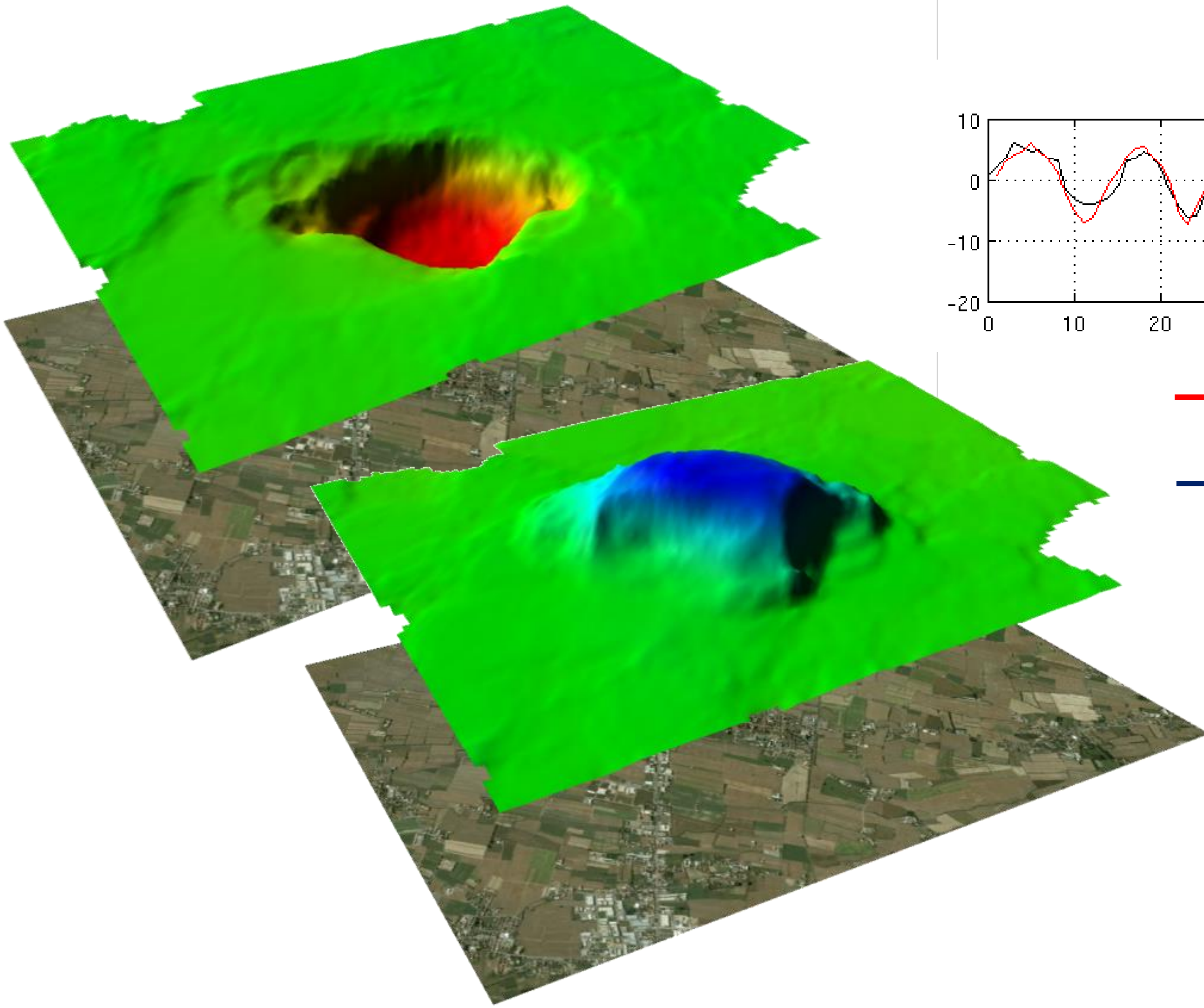
$$M = Area * dislo$$

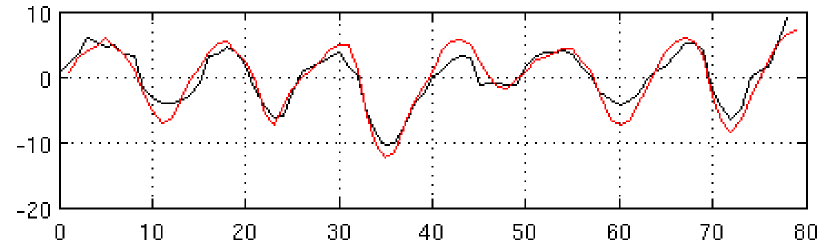
Temporal evolution of M



Goemechanical model calibration

Underground Gas Storage Modeling & Monitoring

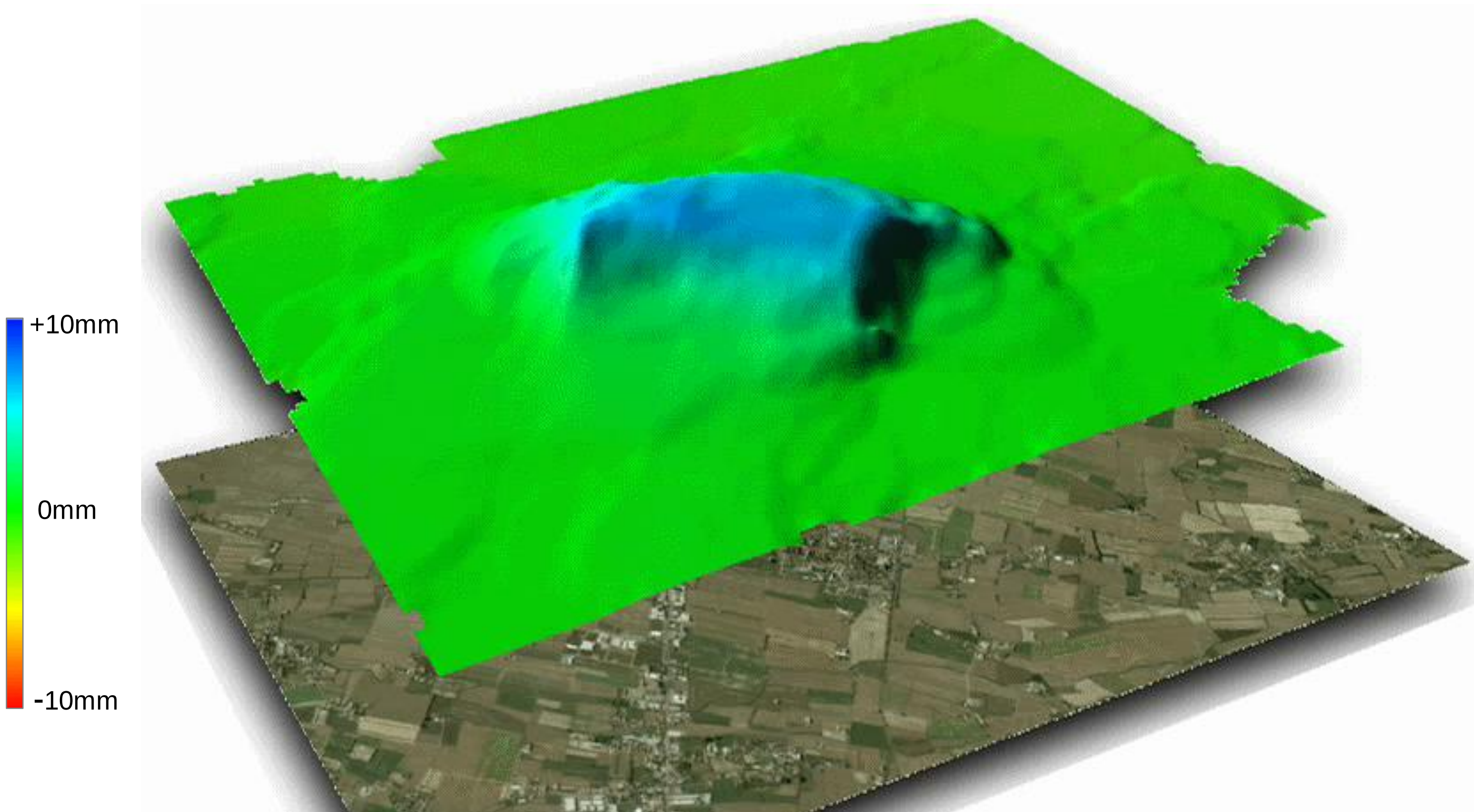


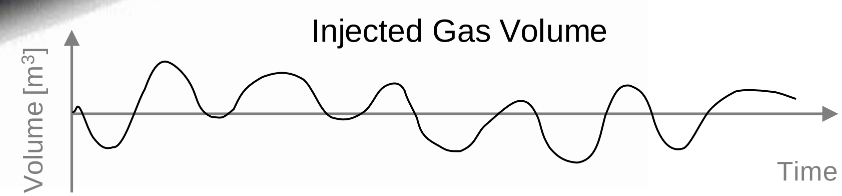


Injected/extracted volume

Surface displacement

Underground Gas Storage - Monitoring





Vertical surface displacement of a gas field with related injected and extracted gas volumes

Elastic model calibration

- To relate injected/extracted gas time series to surface displacement it is necessary to consider two forward models:
  - Fluido-dynamic model: it relates injected/extracted gas time series to reservoir pressure changes
  - Geomechanical model: it relates reservoir pressure changes to surface displacement

1. Based on a history matching applied to pressure and production measurements it is possible to calibrate the reservoir fluido-dynamics parameters (conductivity). These parameters can be used to run a fluido-dynamic model in order to infer the reservoir pressure field
2. Once the reservoir pressure field is available it is possible to calibrate the overburden elastic parameters using as input data the pressure field and the surface displacement parameters
3. Using the calibrated elastic parameters surface displacement can be predicted as a function of the reservoir pressure changes

Model application

	Original	Present	Scenario 1	Scenario 2
Pressure	p_i	$103\%p_i$	$107\%p_i$	$120\%p_i$
Displacement		10mm	15mm	25mm
Volume			**+65%**	**+180%**

» Results show that there is a **negligible impact** on the ground surface with deformation gradients that remain well **below the most restrictive admissible limits** for the civil structures and infrastructures

Teatini et al. (2011) - *Geomechanical response to seasonal gas storage in depleted reservoirs: A case study in Po River basin, Italy.* Journal of Geophysical Research, Vol. 116.

Conclusions

- InSAR data are becoming more and more important for reservoir monitoring, especially for EOR and CCS projects.

- The possibility to provide measurement of surface displacement with millimeter accuracy over hundreds of square kilometers make it possible to track the reservoir pressure field and to monitor possible fault-fracture reactivation.

- In history-matching InSAR data can provide a valuable input of information, provided that a sensitivity analysis has been carried out to infer which parameters can be tuned

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