Advanced Time-lapse InSar for Reservoir Management*

Giacomo Falorni[1], Andy Higgs[1], Jessica Morgan[1], Andrea Tamburini[2], and Marco Minini[2]

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[1]TRE Canada, Vancouver, BC, Canada (giacomo.falorni@trecanada.com)
[2]TRE Europa, Milan, Italy

Abstract

Surface deformation data is increasingly being used to actively manage reservoirs and optimize production. One of the techniques capable of providing a dense network of precise ground displacement data over large areas is InSAR. Recent improvements in data-processing algorithms and in radar satellite characteristics have increased the quantity and quality of surface deformation measurements.

The most advanced InSAR techniques process a large number of radar images to determine displacement of naturally occurring or man-made targets. The use of multiple images allows sophisticated statistical calculations of atmospheric noise, which can then be removed from the displacement readings, increasing measurement precision to millimeter scale. SqueeSAR™, a recently released algorithm, in addition to making measurements from point targets, has introduced the capability also to extract information from spatially distributed targets, thereby greatly increasing the density of measurement points in areas that were traditionally challenging for InSAR.

Recently launched radar satellites have lower revisiting times (i.e., the interval between subsequent radar images), which is now less than 8 days in some cases, and spatial resolution is close to 1 m^2. Furthermore, the optimization of algorithms and powerful parallel processors now allow data to be processed in near-real-time.

Volumetric changes in reservoirs due to fluid extraction or injection can induce either subsidence or uplift of the ground surface. The magnitude of surface displacement depends on reservoir depth and on the reservoir/overburden characteristics. It has been shown that even reservoirs located at great depth can induce deformation of the ground surface.

Measurement of surface displacement can help in understanding the dynamic behavior of a reservoir, and inversion techniques can lead to estimates of reservoir volume changes through time. Accurate assessments and detailed understanding of reservoir properties (e.g., the

location of flow barriers or of areas of enhanced permeability) require repeated, high density measurements over large areas and with millimeter precision.

Surface deformation measurements are valuable in EOR, water flooding and SAGD activities as they can provide indirect observation of subsurface fluid movement. We show here case studies in which SqueeSAR™ data is used for the characterization of reservoirs, the delineation of active faults and for the observation of fluid flow behavior.

References

Chambers, K.T., W.S. Hallager, C.S. Kabir, and R.A. Garber, 1997, Characterization of a Carbonate Reservoir with Pressure-Transient Tests and Production Logs: Tengiz Field, Kazakhstan: SPE #38657-MS, 16 p.

Klemm, H., I. Quseimi, F. Novali, A. Ferretti, and A. Tamburini, 2010, Monitoring horizontal and vertical surface deformation over a hydrocarbon reservoir by PSInSAR: EAGE First Break, v. 28, p. 29-37.

Ringrose, P., M. Atbi, D. Mason, M. Espinassous, O. Myhrer, M. Iding, A. Mathieson, and I. Wright, 2009, Plume development around well KB-502 at the In Salah CO_2 storage site: First Break, v. 27, p. 85-89.

Vasco, D.W., A. Rucci, A. Ferretti, F. Novali, R.C. Bissell, P.S. Ringrose, A. Mathieson, and I.W. Wright, 2010, Satellite-based measurements of surface deformation reveal fluid flow associated with the geological storage of carbon dioxide: Geophysical Research Letters, v. 37/3, 5 p.

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Advanced Time-lapse InSAR for Reservoir Management

AAPG 2012 Annual
Convention & Exhibition

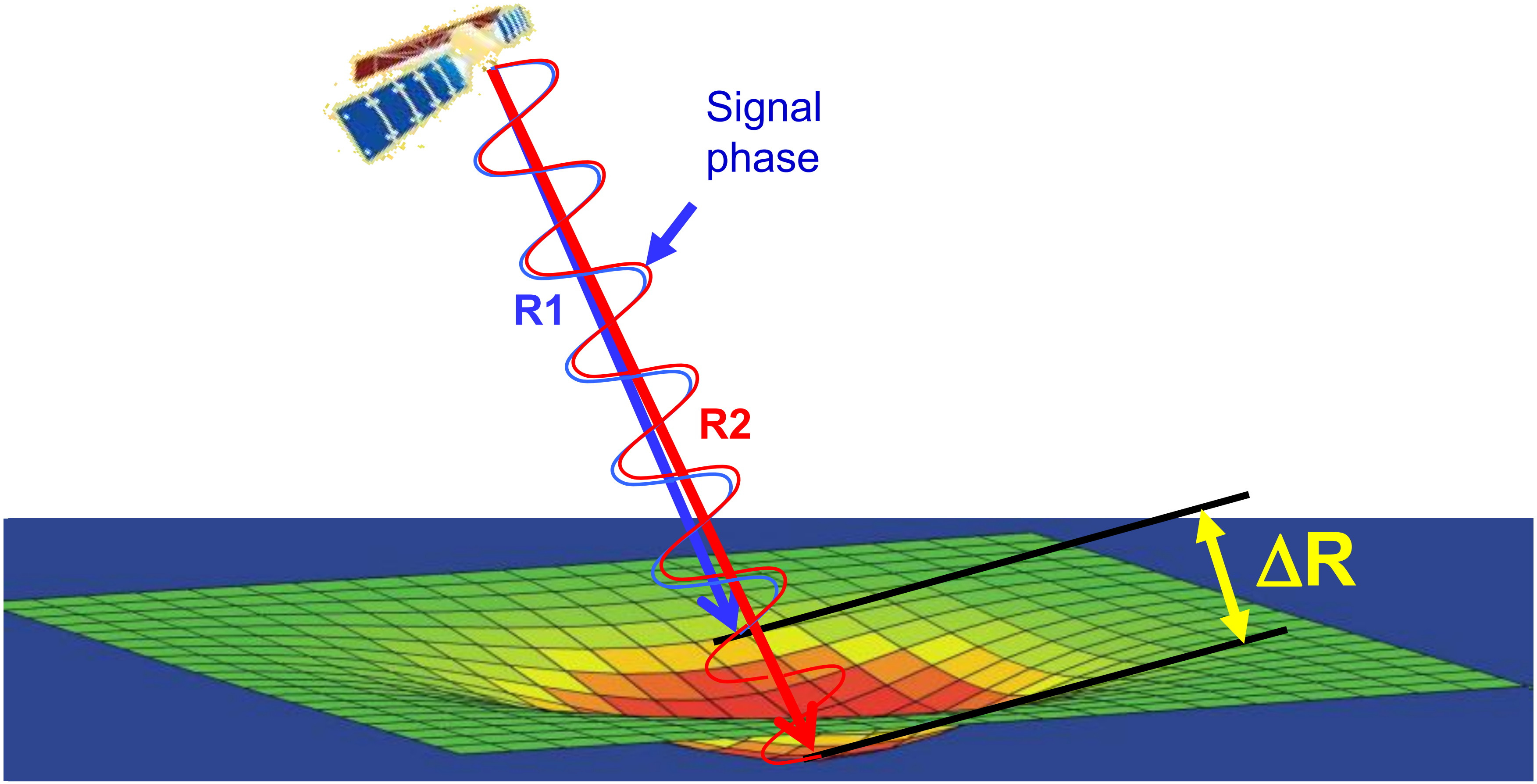
Giacomo Falorni[1]
Andy Higgs[1]
Jessica Morgan[1]
Andrea Tamburini[2]
Marco Minini[2]

[1] TRE Canada [2] TRE Europa

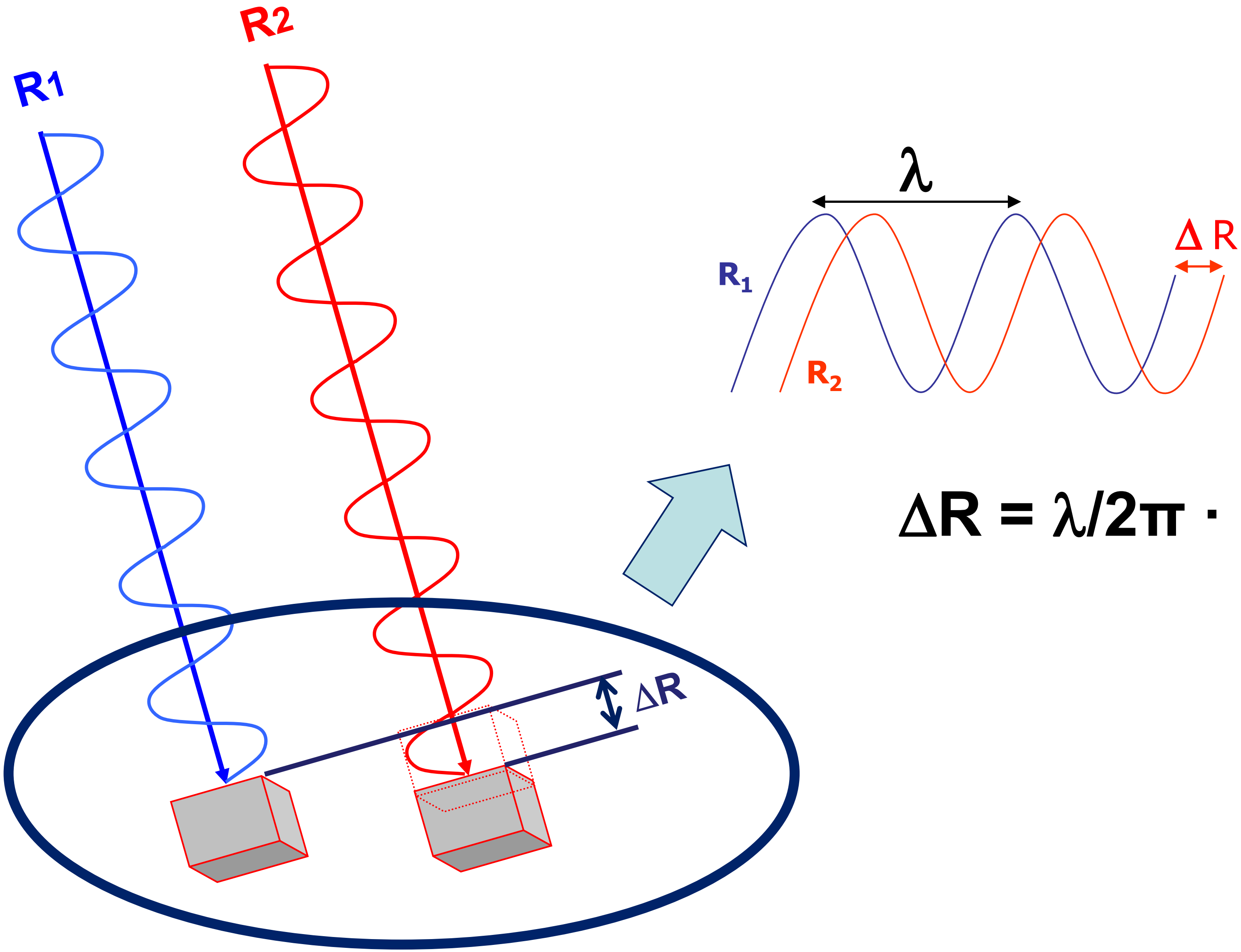
Introduction

- InSAR has always been a time-lapse technique…

InSAR principle



InSAR (radar interferometry): shifts in signal phase are used to measure ground movement

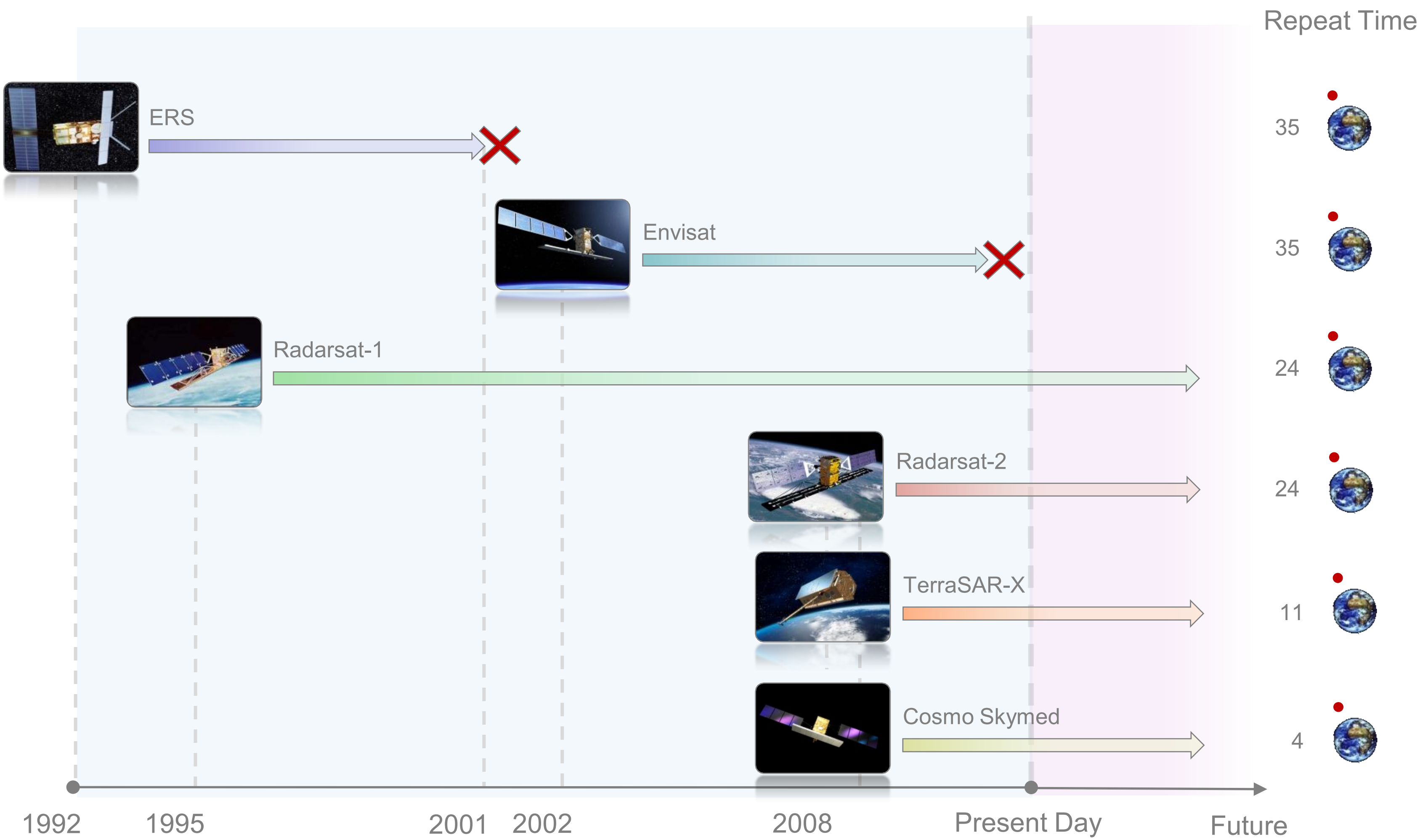


$$\Delta R = \lambda / 2\pi \cdot \Delta\phi$$

Introduction

- InSAR has always been a time-lapse technique…
- So what has changed?

SAR Satellites

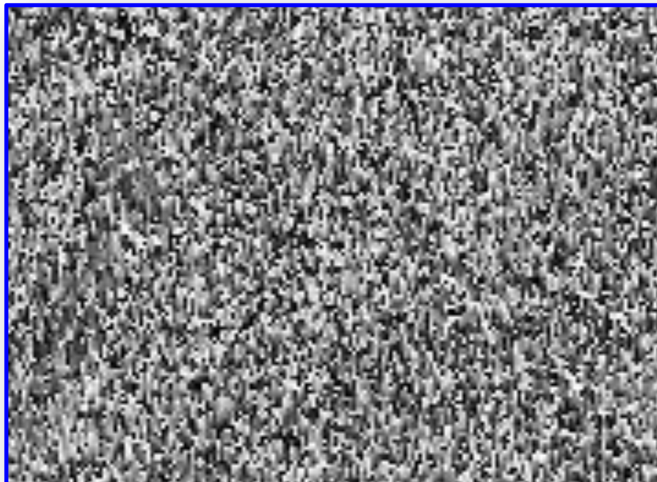


Types of InSAR

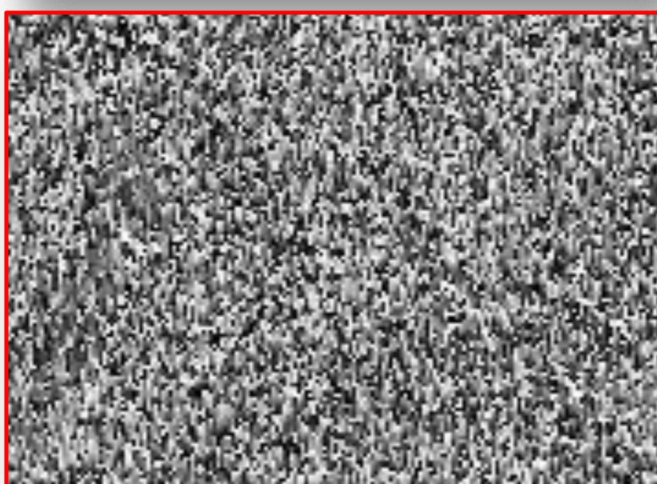
Type	Principle	Product	Precision
DInSAR (Differential InSAR)	Compare 2 radar images	Deformation map	Centimetric
SqueeSAR (Advanced time lapse InSAR)	Measure deformation from **stack of radar images**	Point cloud of deformation with time history of motion for each point	Millimetric

DInSAR

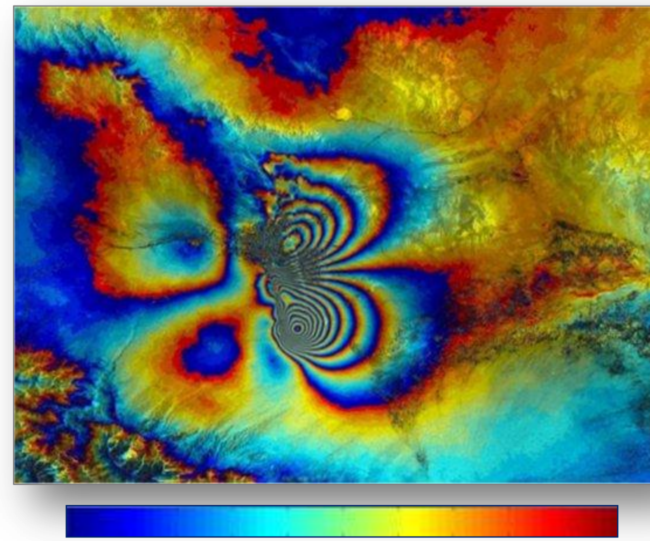
Satellite Image 1



Satellite Image 2



Interferogram

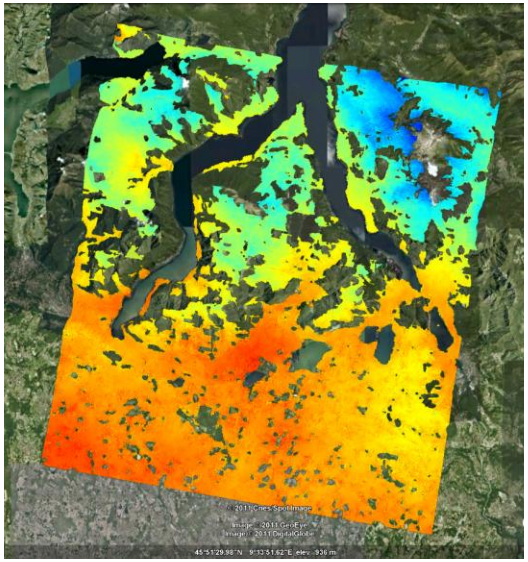


Phase shift (Δθ)

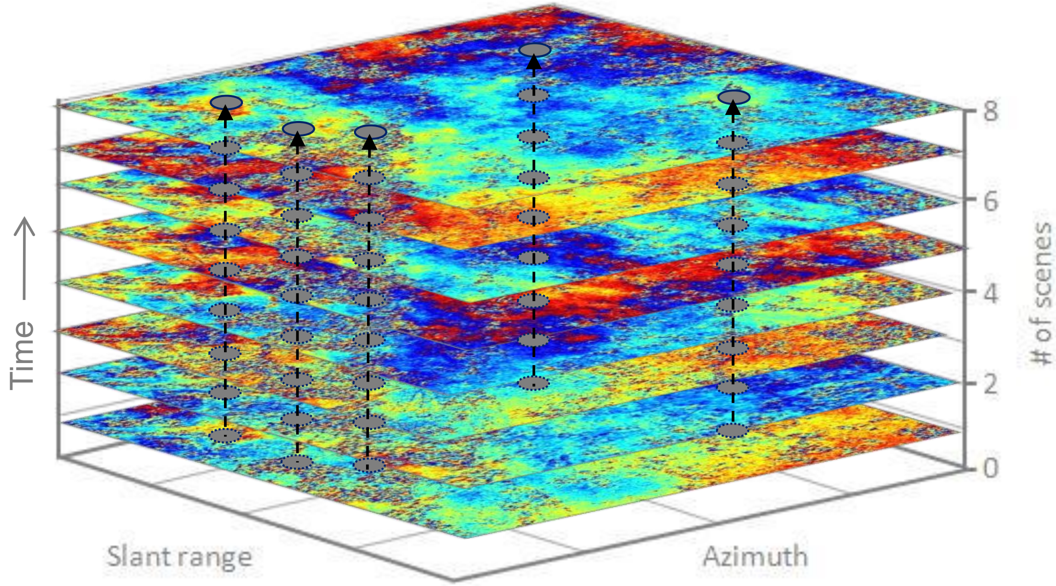
Phase Values

DInSAR

- Quick, straightforward method for viewing deformation between 2 moments in time
- If coherence is high, provides complete map of ground deformation
- If coherence is low, can have large areas with no data
  - Ask your providers how they handle no data areas!
- Cannot account for atmospheric effects
  - Precision is in cm range

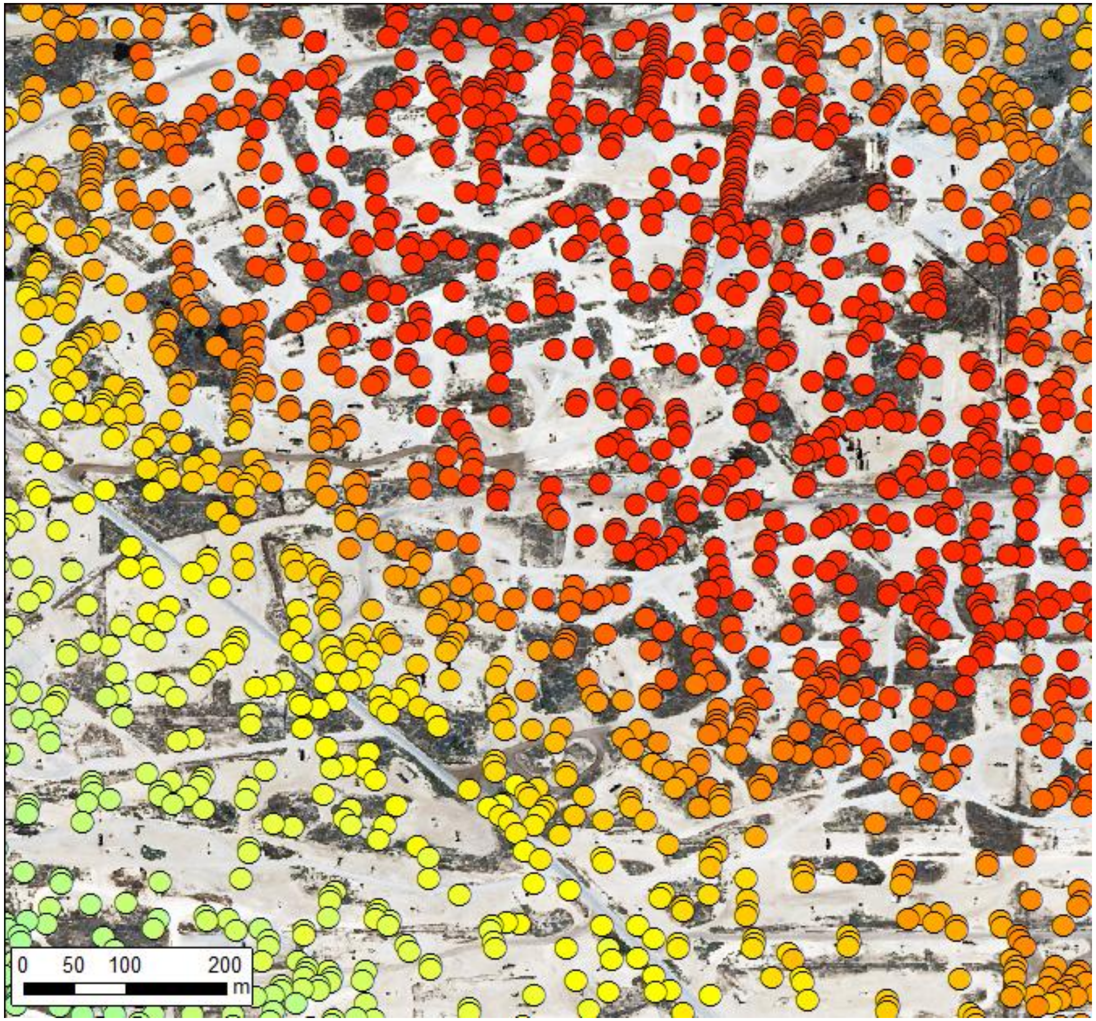


Multi-interferogram InSAR
e.g. PSInSAR™, SqueeSAR™

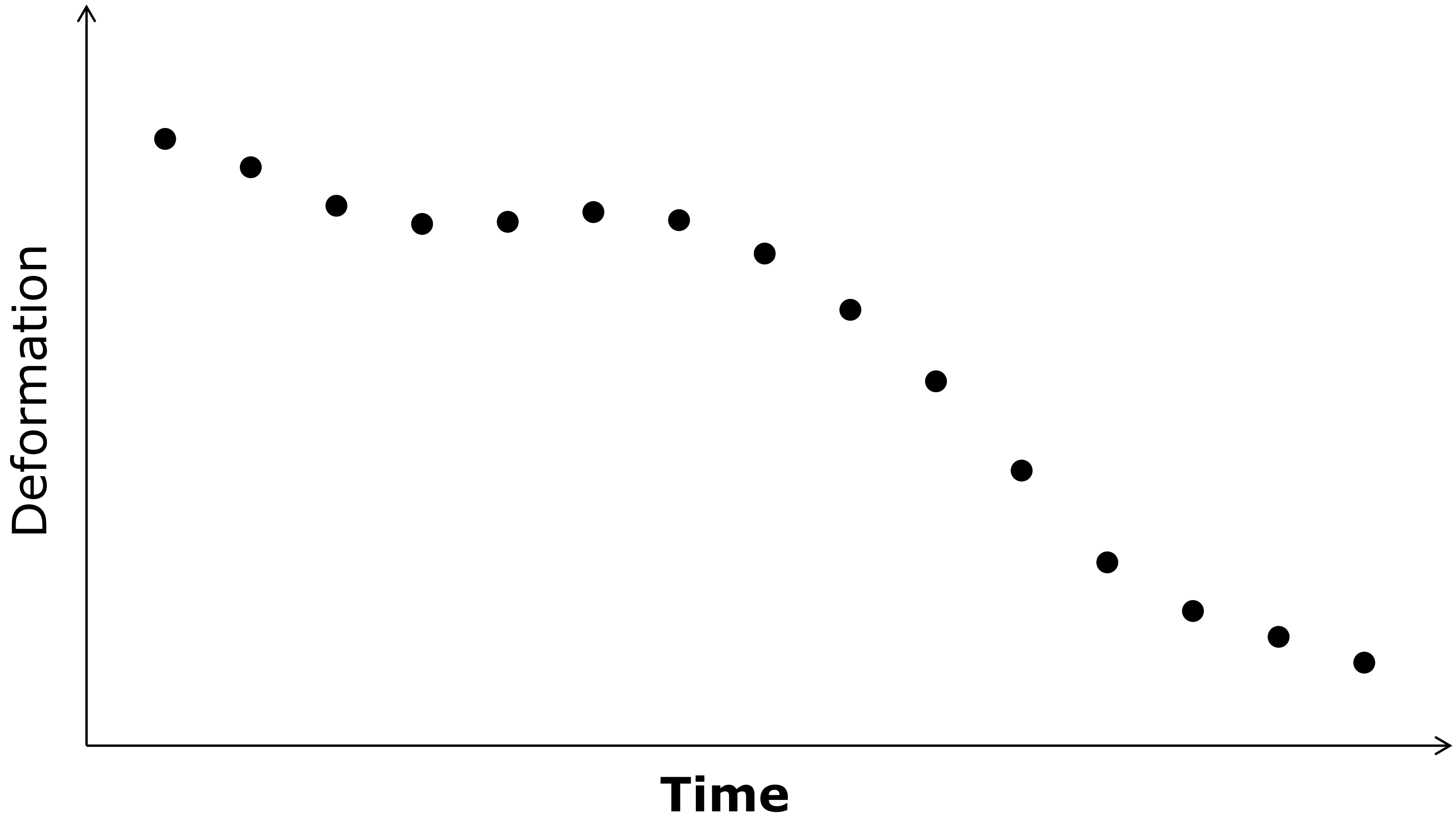


Interferogram stack

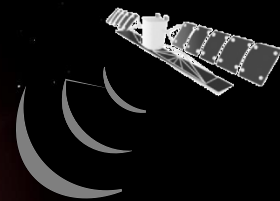
SqueeSAR



SqueeSAR



- Point cloud showing ground deformation over time
  - Possible to interpolate to obtain continuous map
- Time history of motion
- Atmospheric contribution is removed
  - mm precision



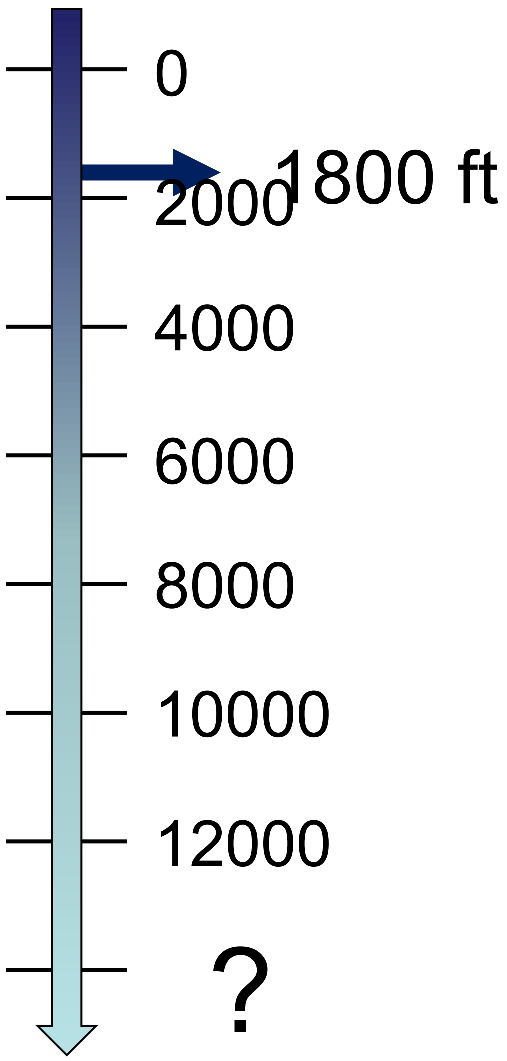
Applications

Applications

- To what depth do reservoirs continue to cause surface deformation?

- How is time lapse InSAR useful for managing reservoirs?

Surface deformation vs reservoir depth



How deep is too deep to cause surface deformation?

Surface deformation vs reservoir depth

1800 ft

EOR
Salt Creek
Wyoming

EOR – Salt Creek

Area = 95 sq. mi (245 km^2)

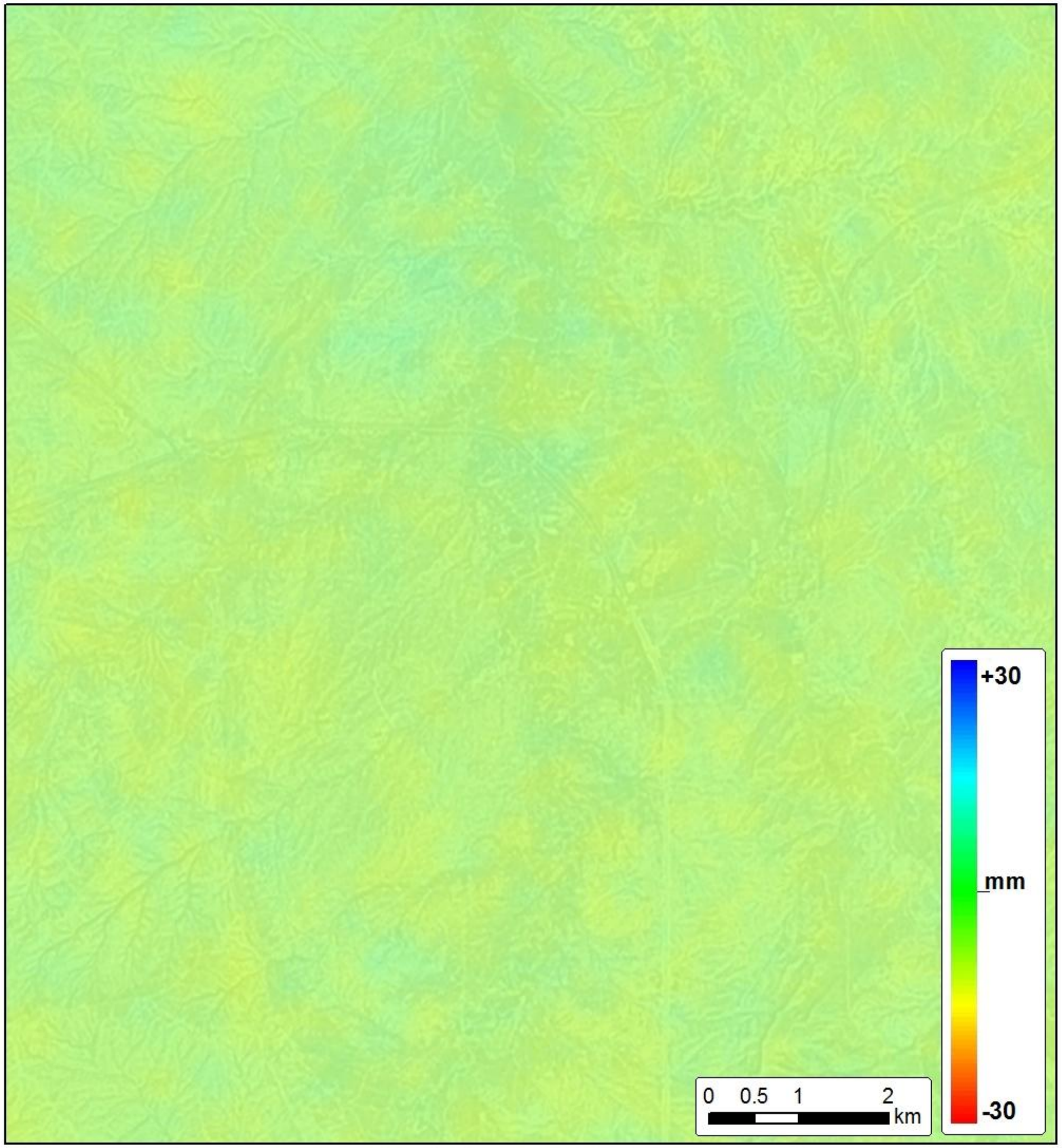
Period: 1 July 2004 – 1 May 2008

Reservoir depth: 1800 ft

Measurement point density:

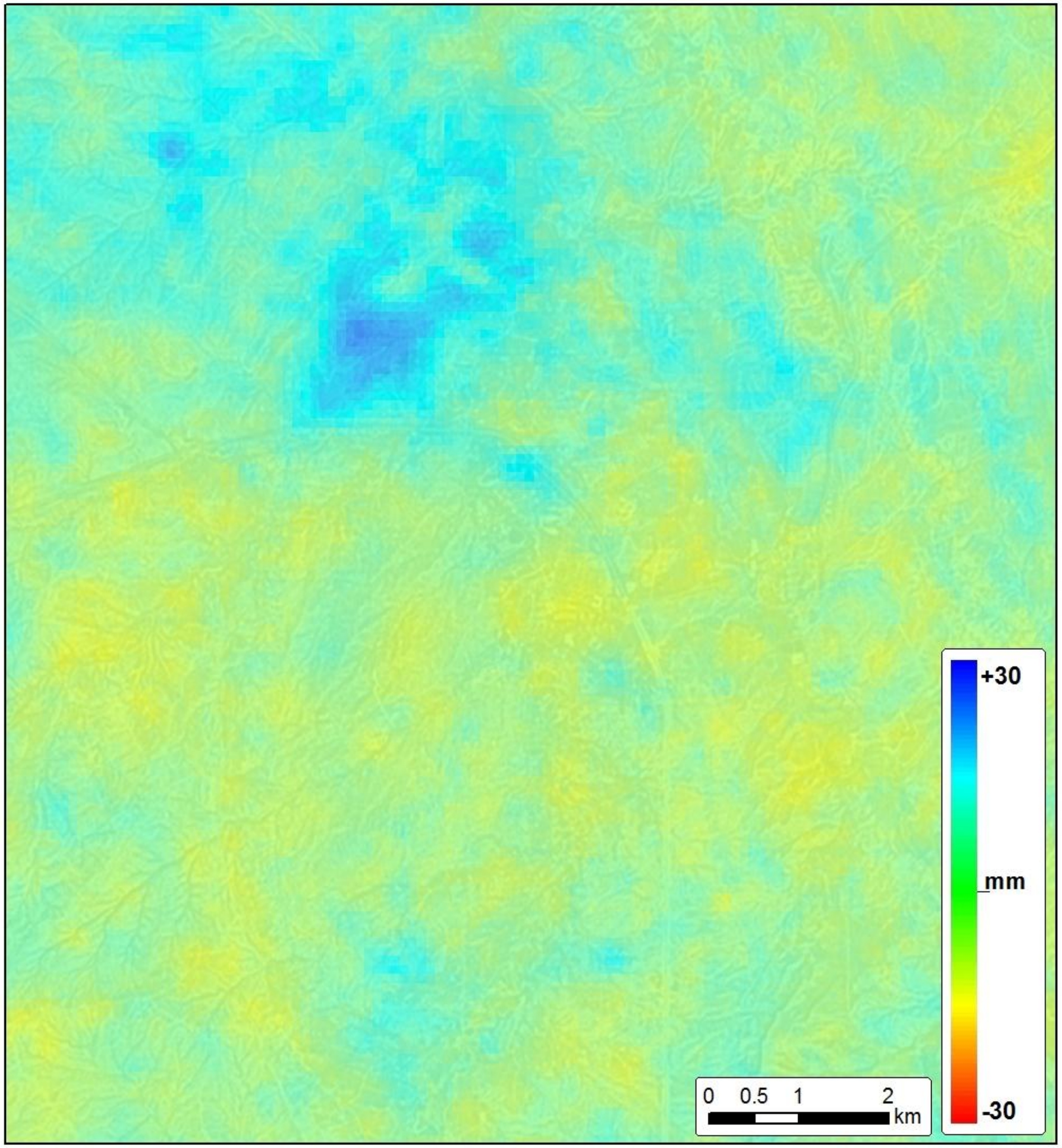
1142 points / sq. mi.

EOR monitoring



August 2004

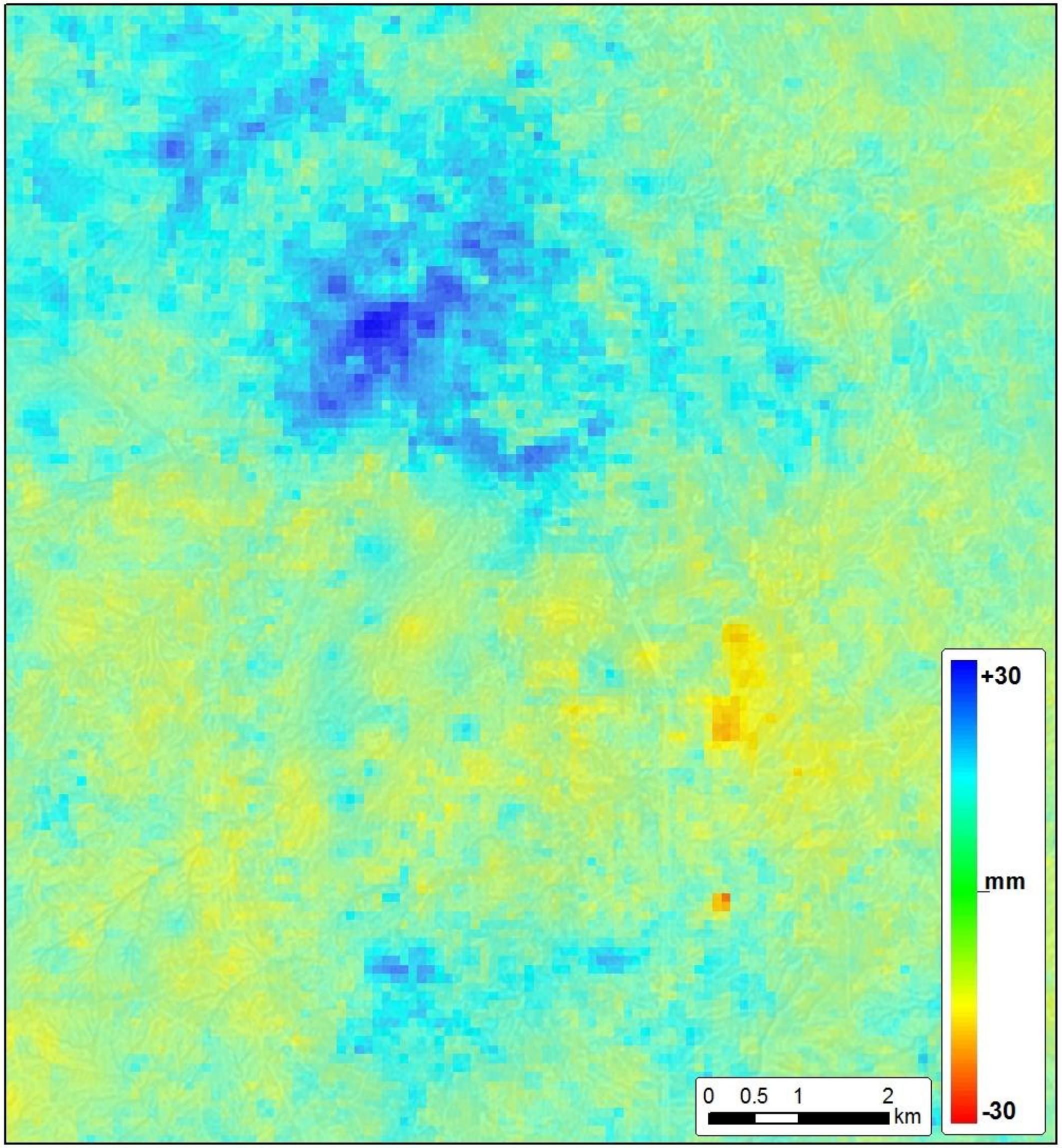
EOR monitoring



August 2004

June 2005

EOR monitoring

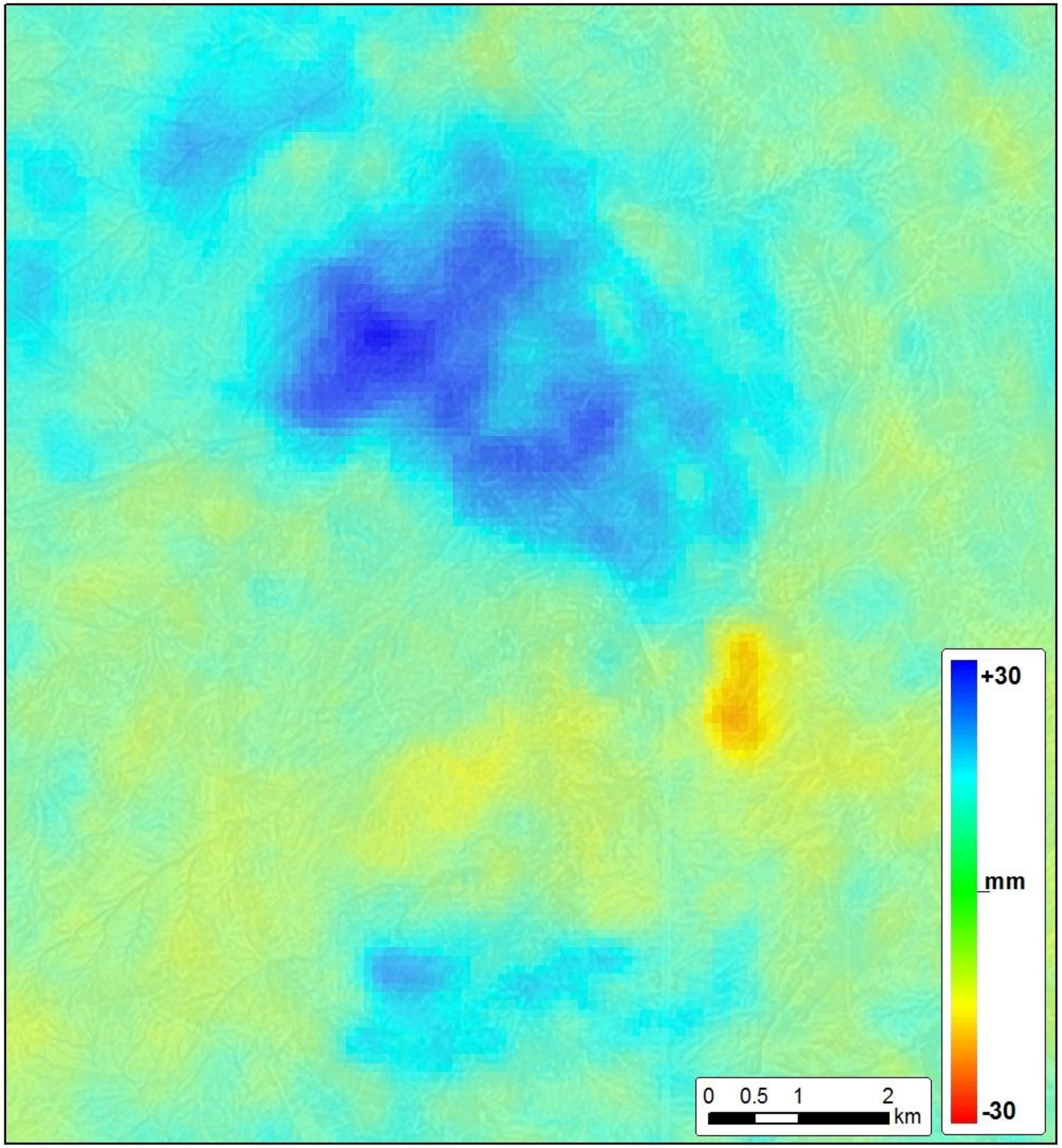


August 2004

June 2005

June 2006

EOR monitoring



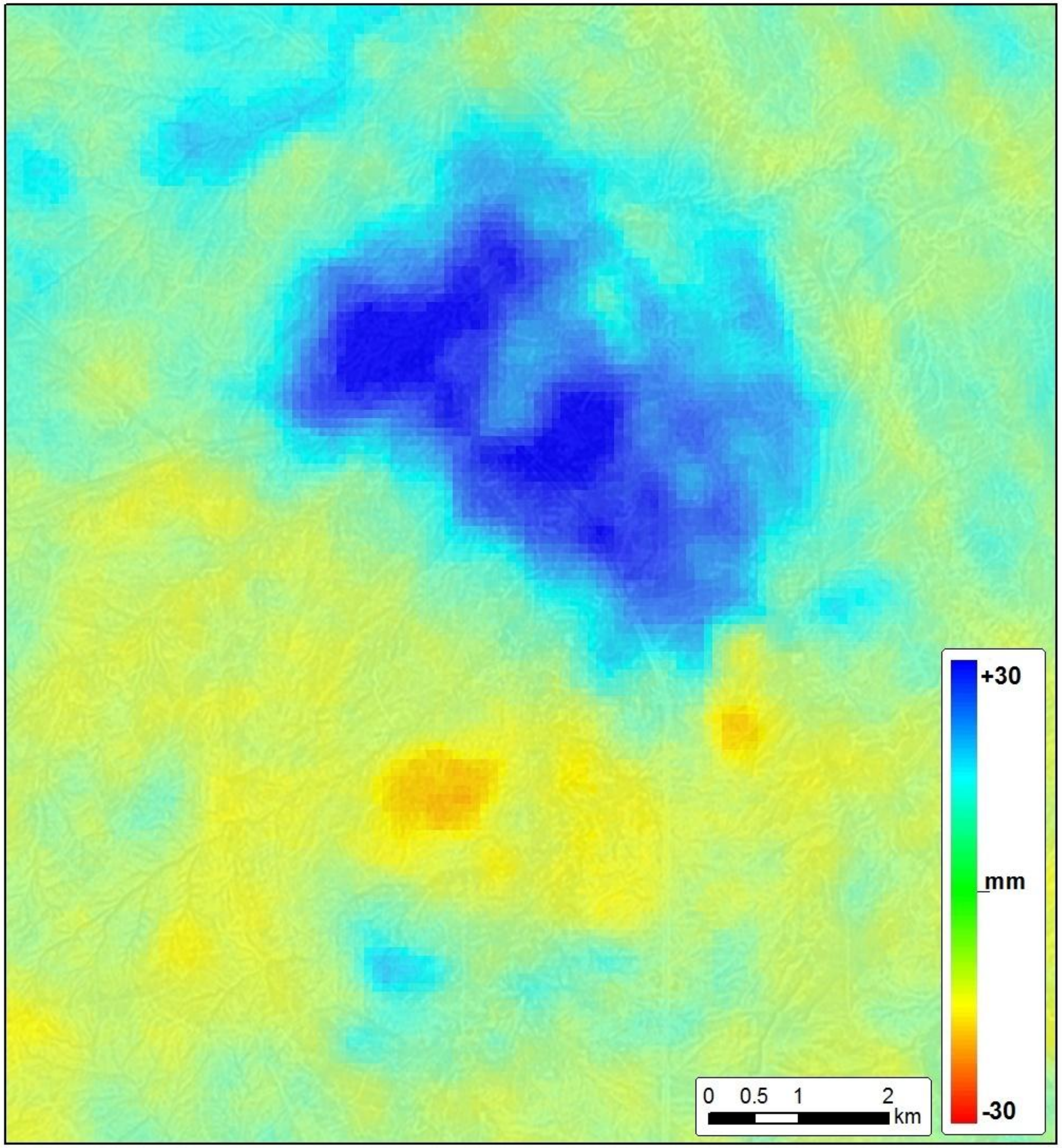
August 2004

June 2005

June 2006

June 2007

EOR monitoring



August 2004

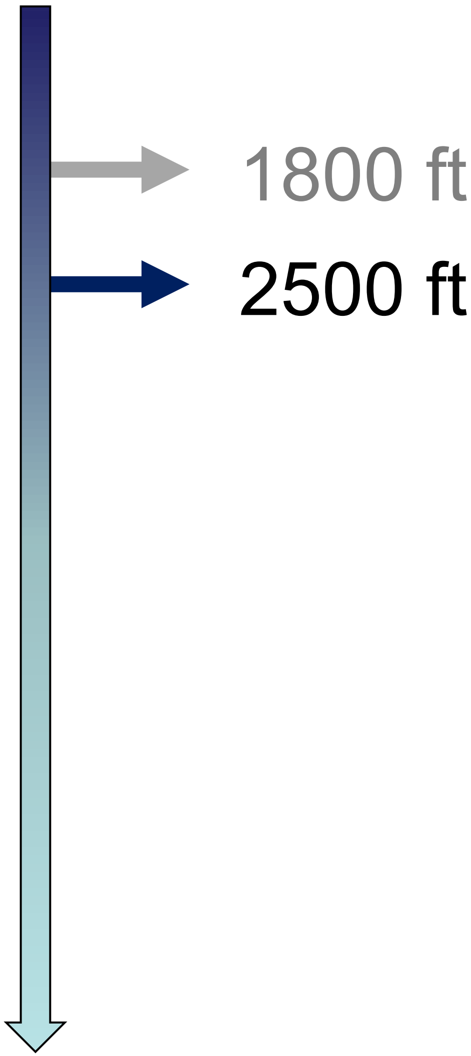
June 2005

June 2006

June 2007

May 2008

Surface deformation vs reservoir depth



IOR
Middle East

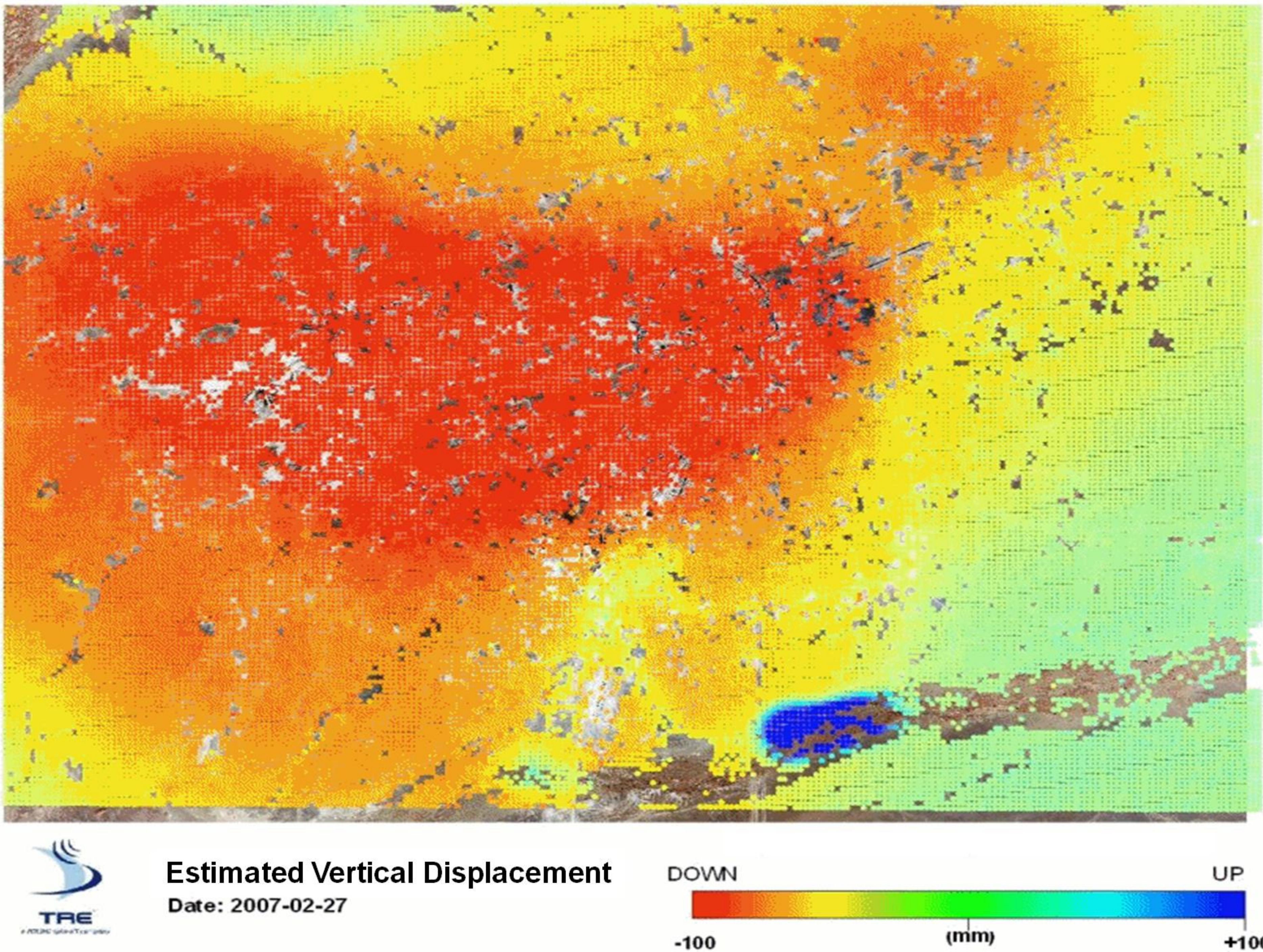
IOR – Middle East

- Stacked carbonate reservoir
- Mature gas field at 2500 ft
- Oil reservoir at 3800 ft produced by water flood

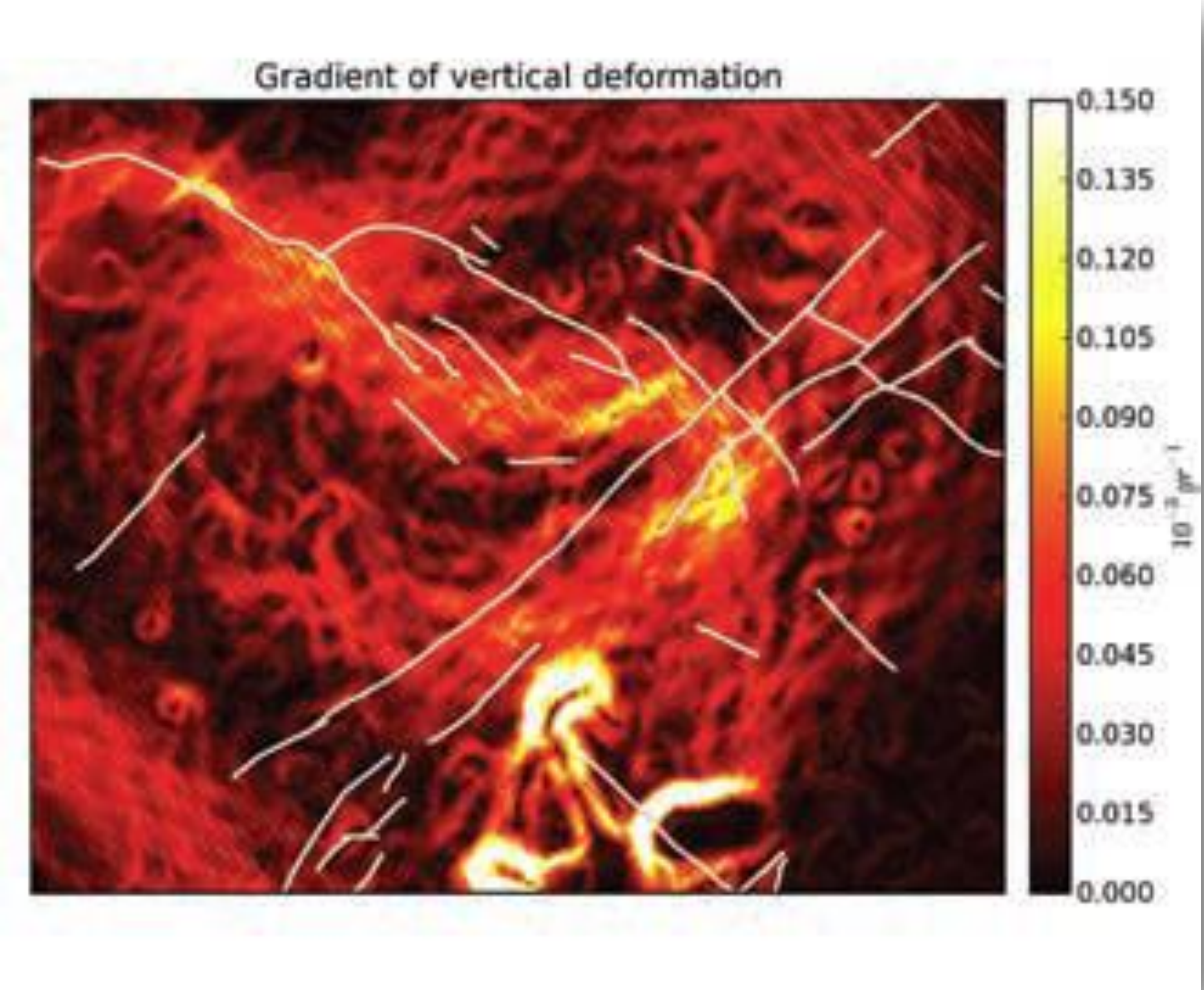
Surface deformation info was used to:

- Constrain geomechanical models
- Detect fault reactivation
- Mitigate well failures
- Aid with field management

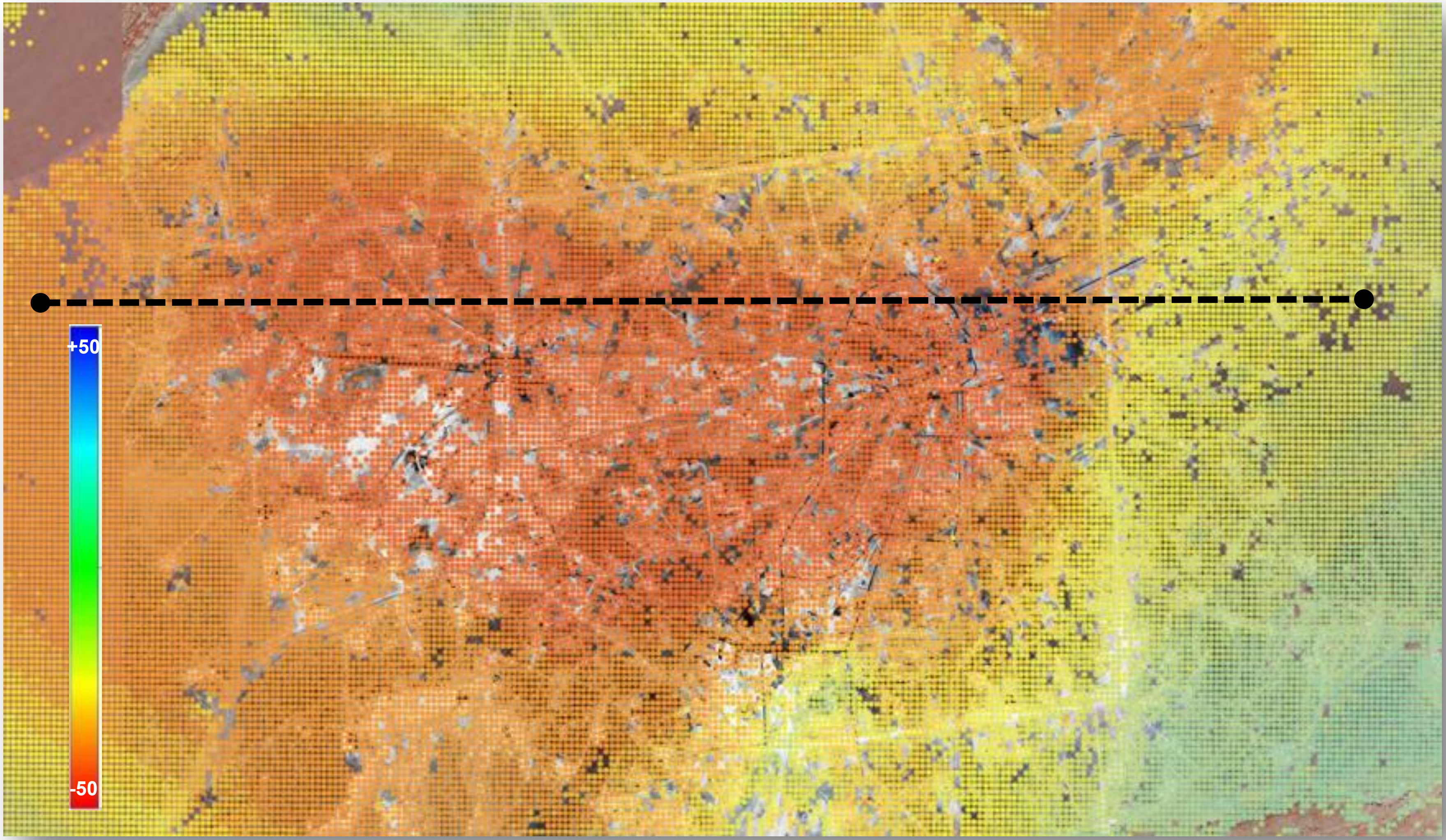
More info:
Klemm et al, "Monitoring horizontal and vertical surface deformation over a hydrocarbon reservoir by PSInSAR", First Break, Vol 28, 2009


TRE
Estimated Vertical Displacement
Date: 2007-02-27
DOWN
UP
-100
(mm)
+100

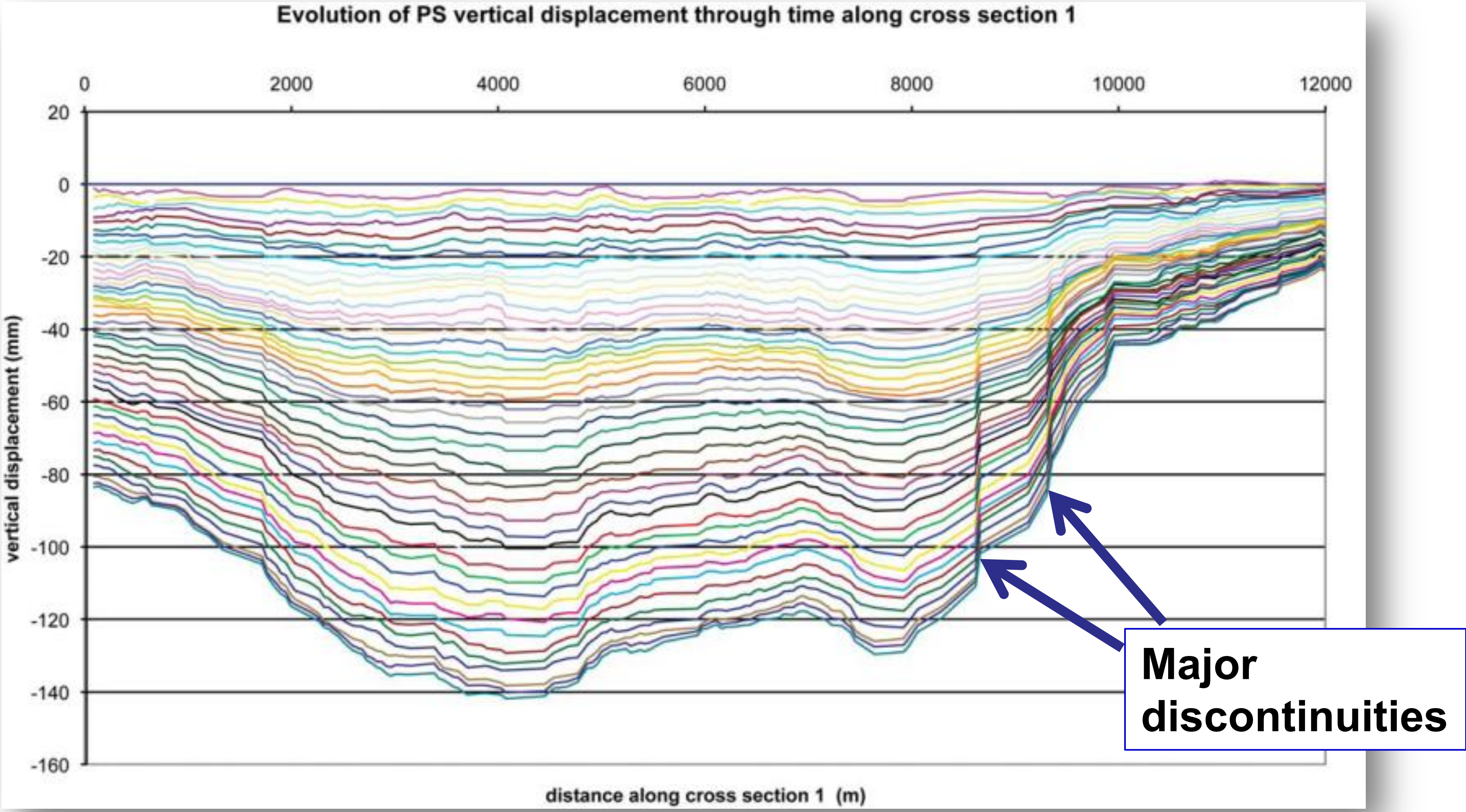
Gradient map vs mapped faults



Surface profile evolution



Surface profile evolution



Surface deformation vs reservoir depth

1800 ft

2500 ft

5700 ft

CCS
In Salah, Algeria

CCS – In Salah

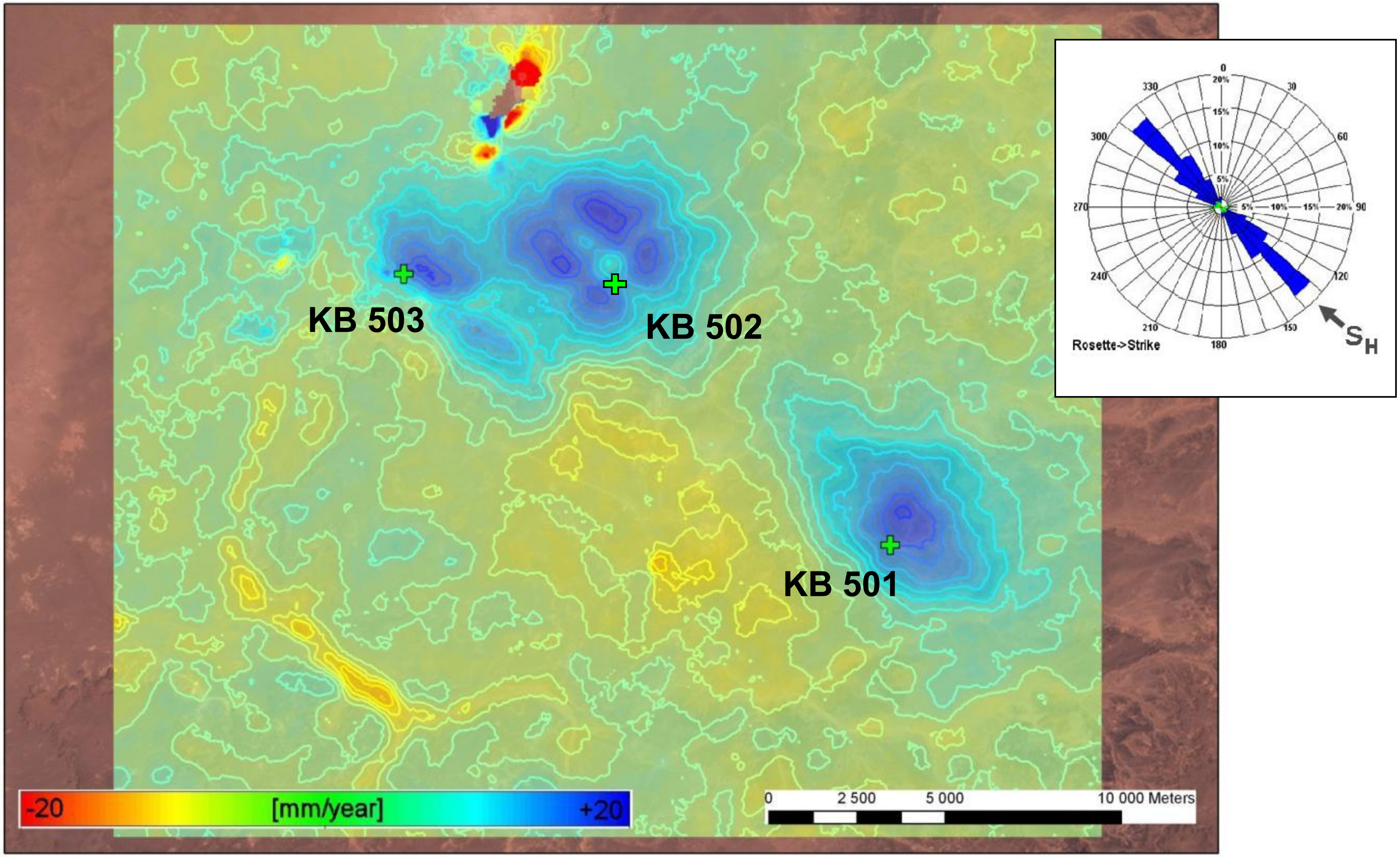
- CO_2 injected at 5700 ft into saline aquifer via three 1500 m horizontal wells
- Aquifer is thin (20 m) sandstone with 15% porosity and 10 mD permeability
- Injection pressure is 175 bars and temperature is 200°F
- Mudstone/siltstone overburden with minor fractures and faults

More info:

Ringrose et al, "Plume development around well KB-502 at the In Salah CO^2 storage site", First Break, 2009

Vasco D. W., et al., "Satellite-based measurements of surface deformation reveal fluid flow associated with the geological storage of carbon dioxide". Geophysical Research Letters, Vol. 37, Feb. 2010

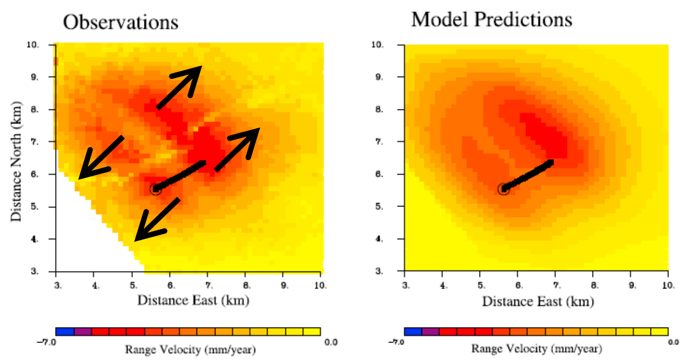
Surface deformation - In Salah



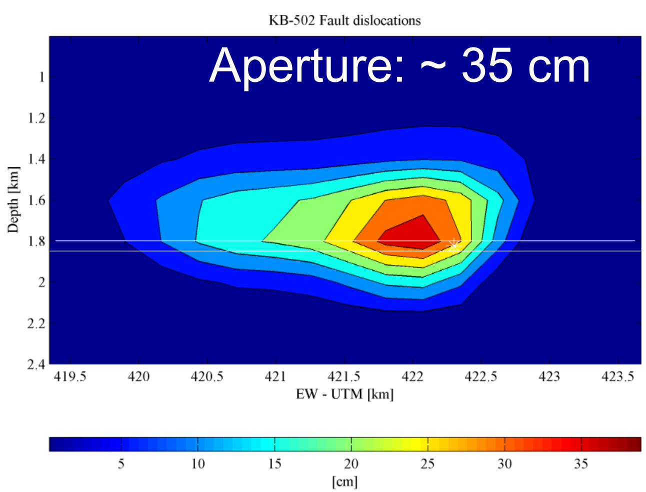
ENVISAT data (2004-2007)

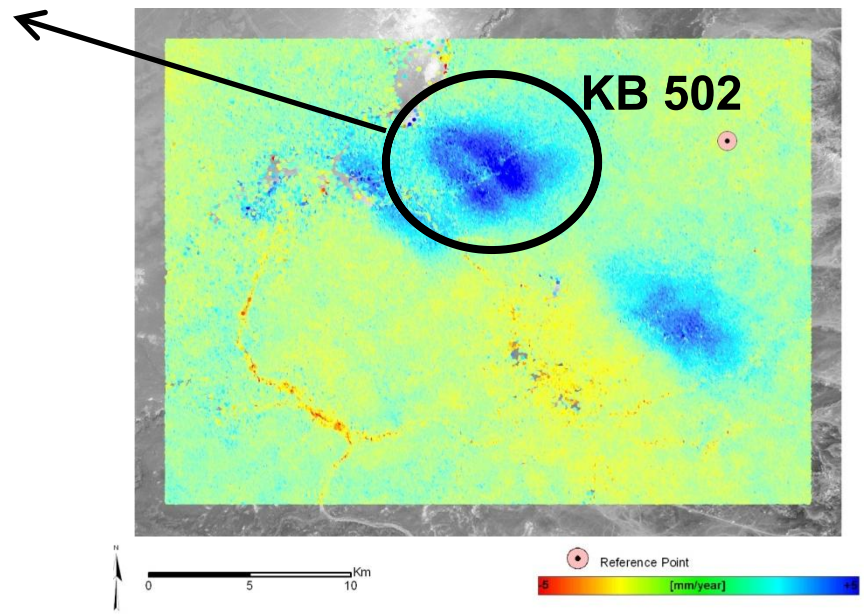
Fault reactivation – In Salah

Geomechanical model calibration

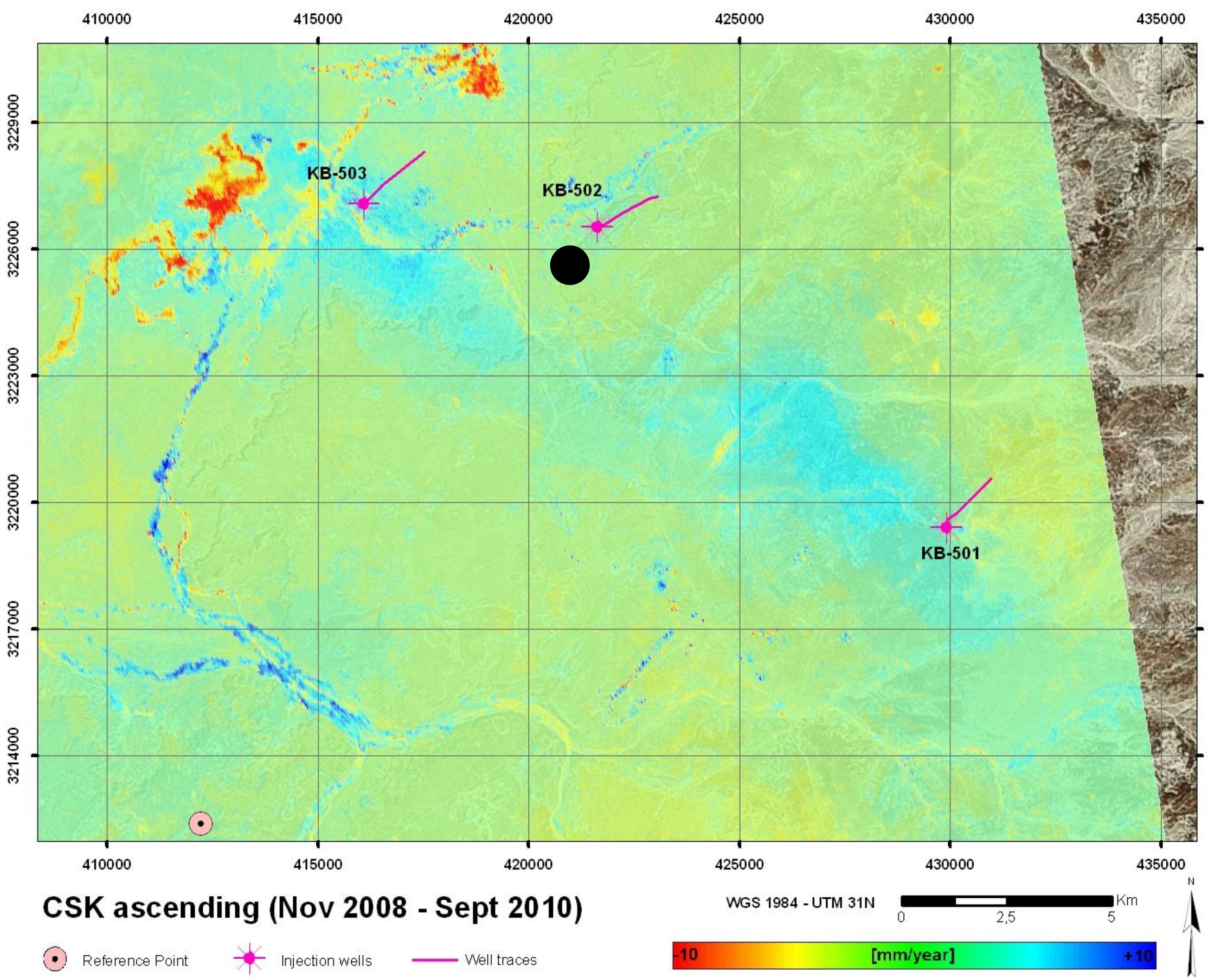


Fault opening estimation



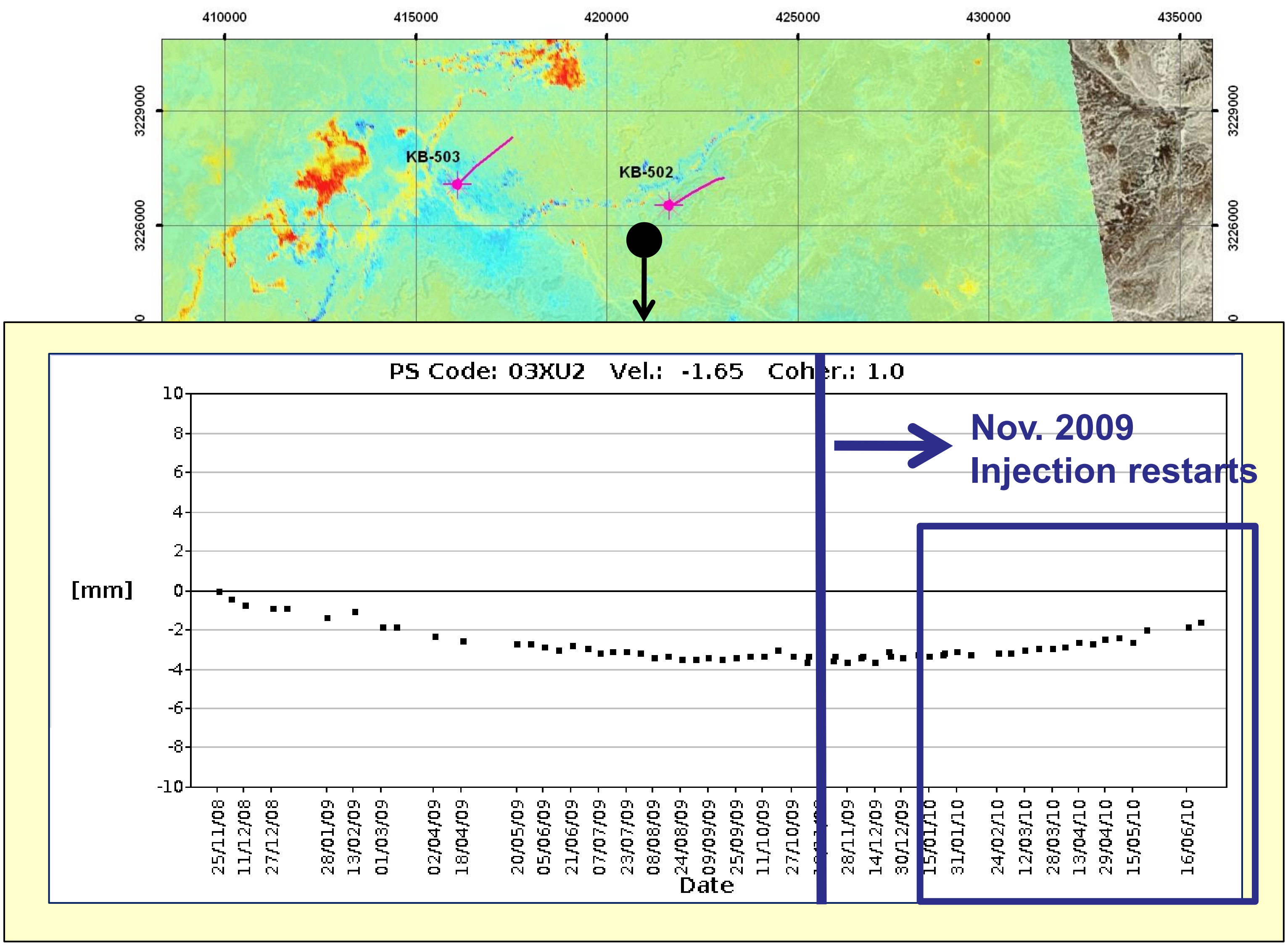


Measurement precision – In Salah

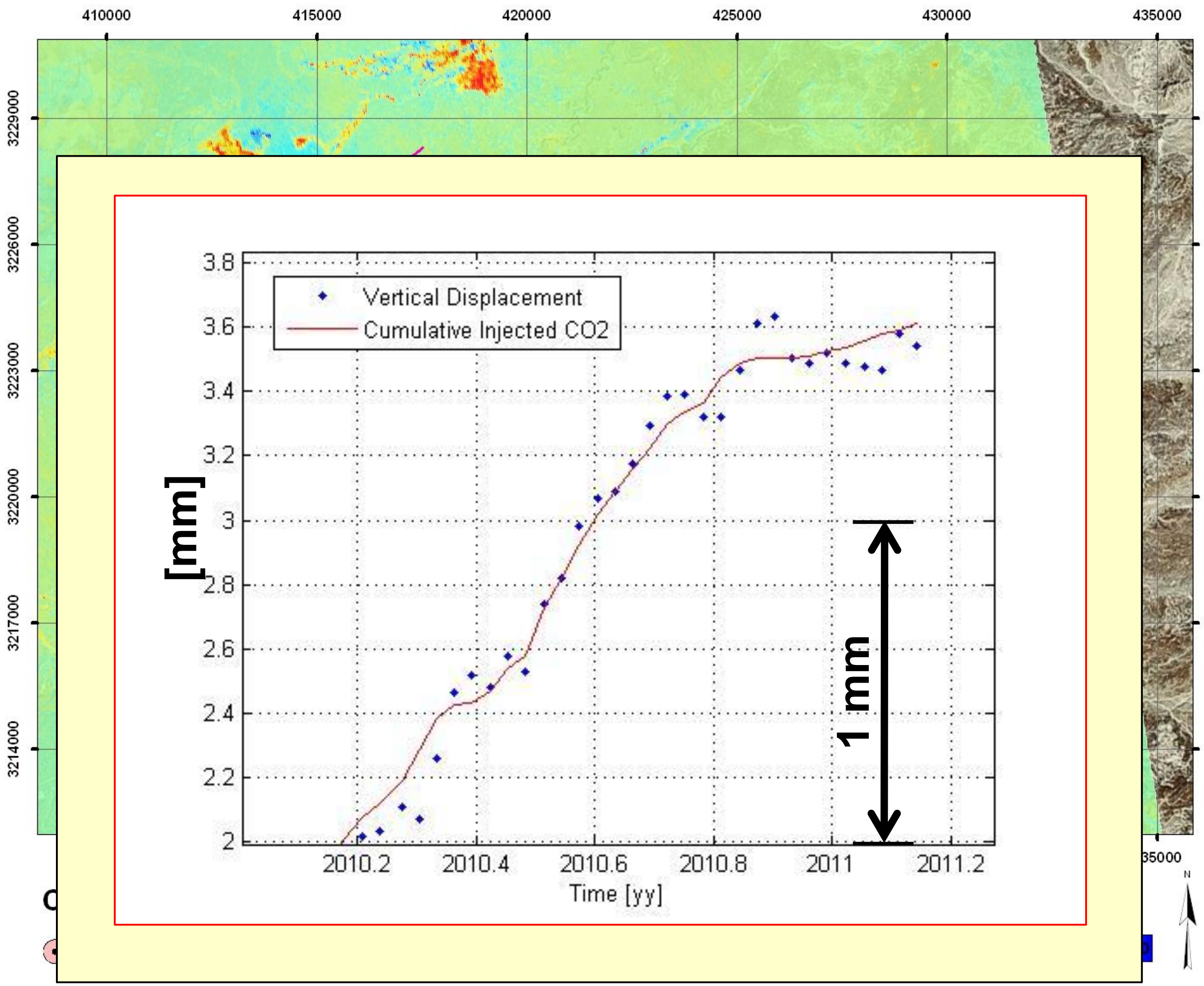


CSK ascending (Nov 2008 - Sept 2010)

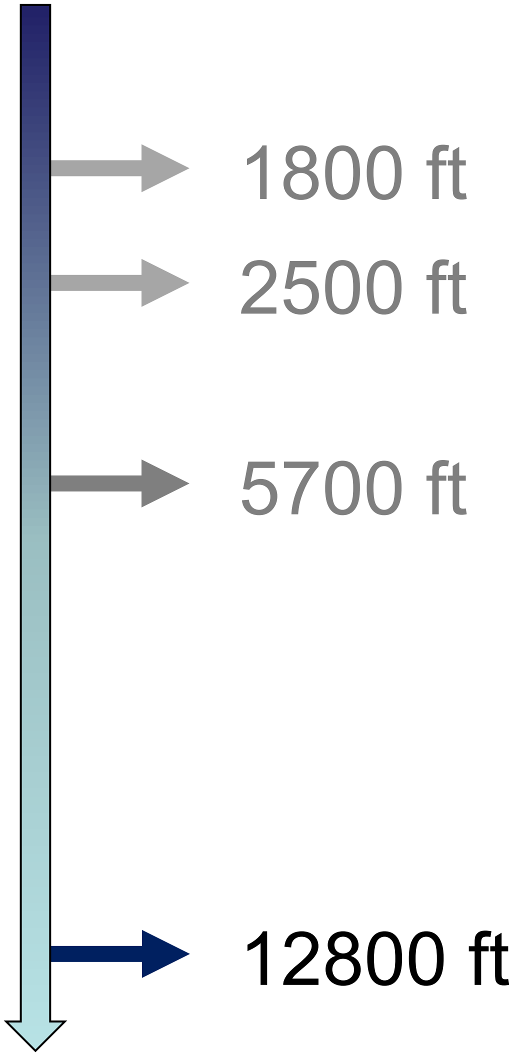
Measurement precision – In Salah



History matching - In Salah



Surface deformation vs reservoir depth



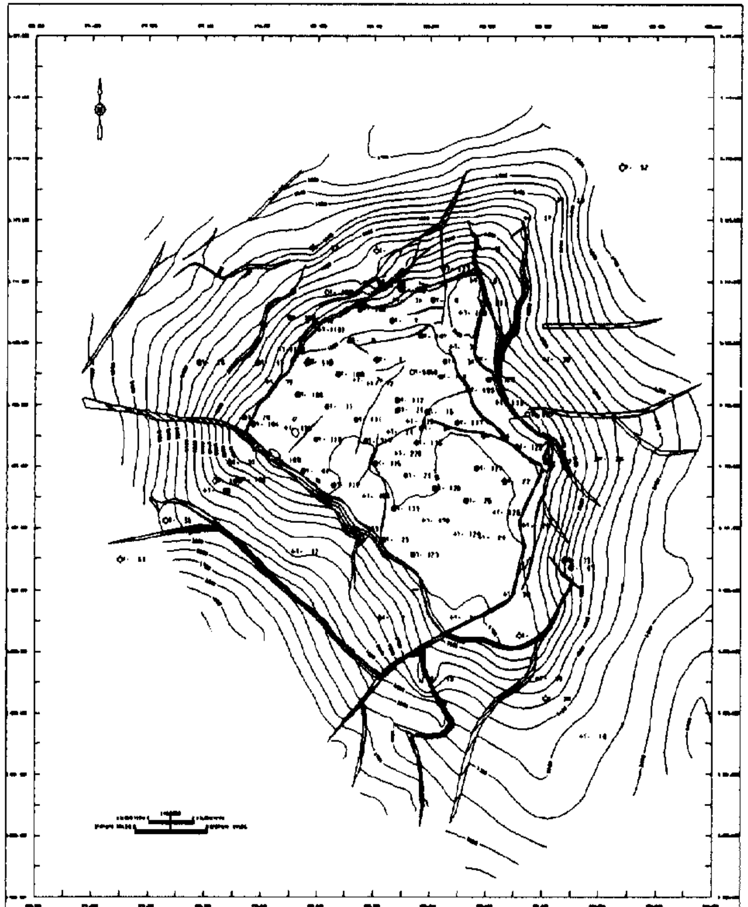
**Tengiz oil field,
Kazakhstan**

Tengiz

- The Tengiz field is located in the southern part of the North Caspian Basin
- Depth > 12,800 ft
- Structure is an irregular flat-topped dome with steep flank dips (up to 30°)
- Evaporite seal

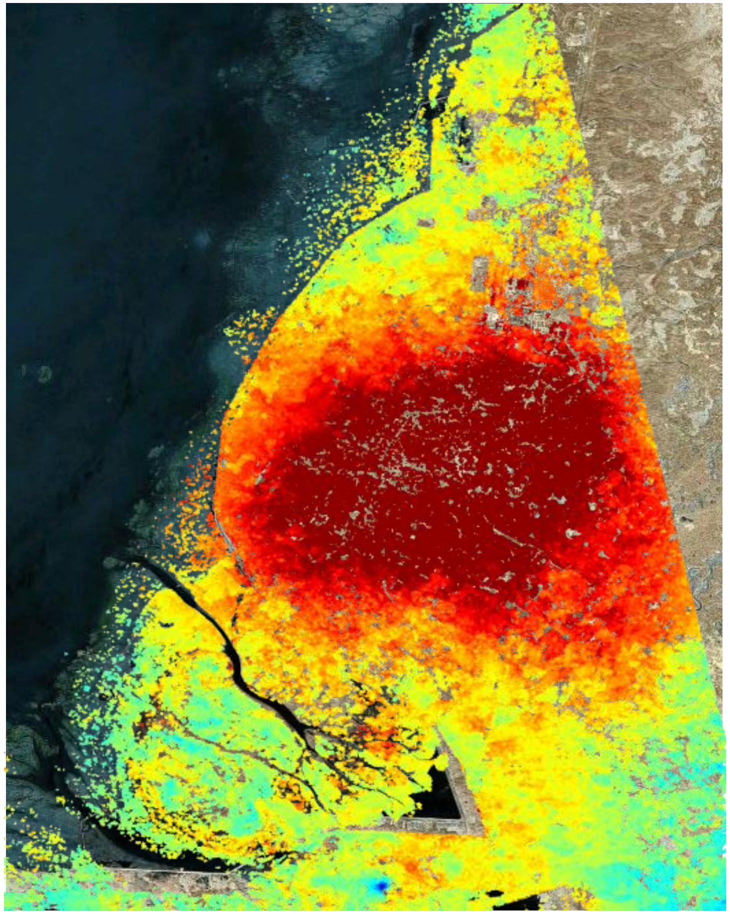
Tengiz

- Faulting is largely confined to the flanks
- Fractures are mainly subvertical

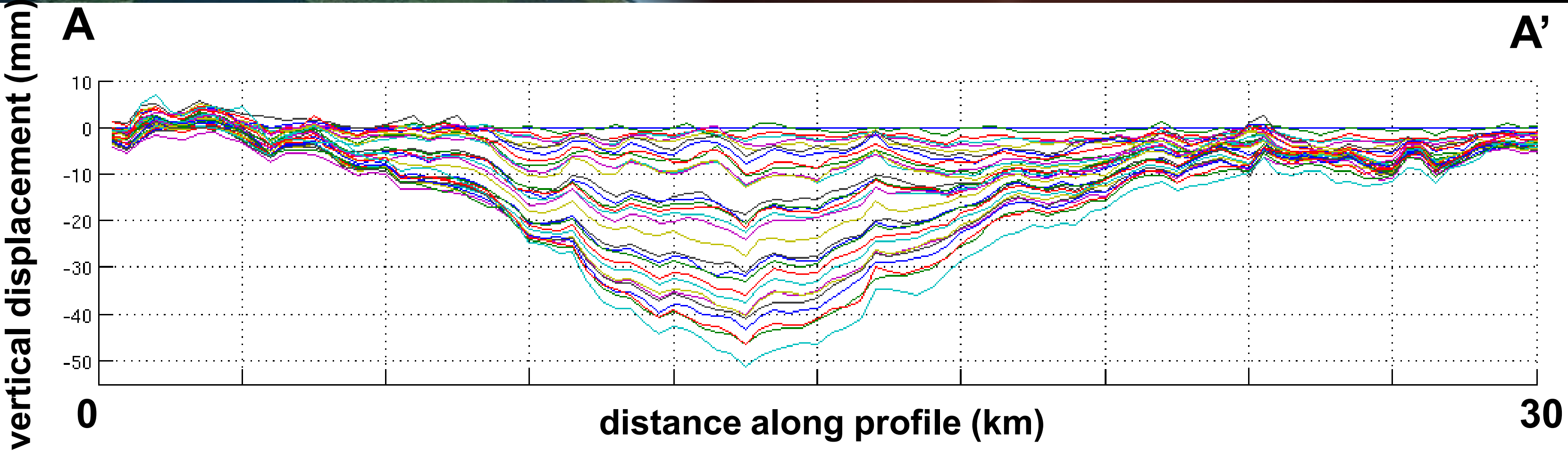


From Chambers et al., 1997

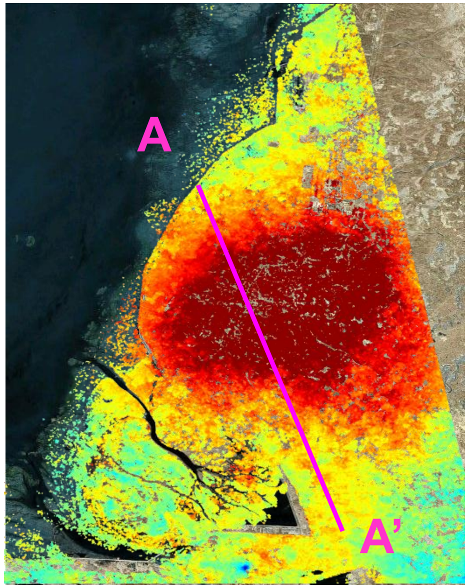
Tengiz – surface deformation



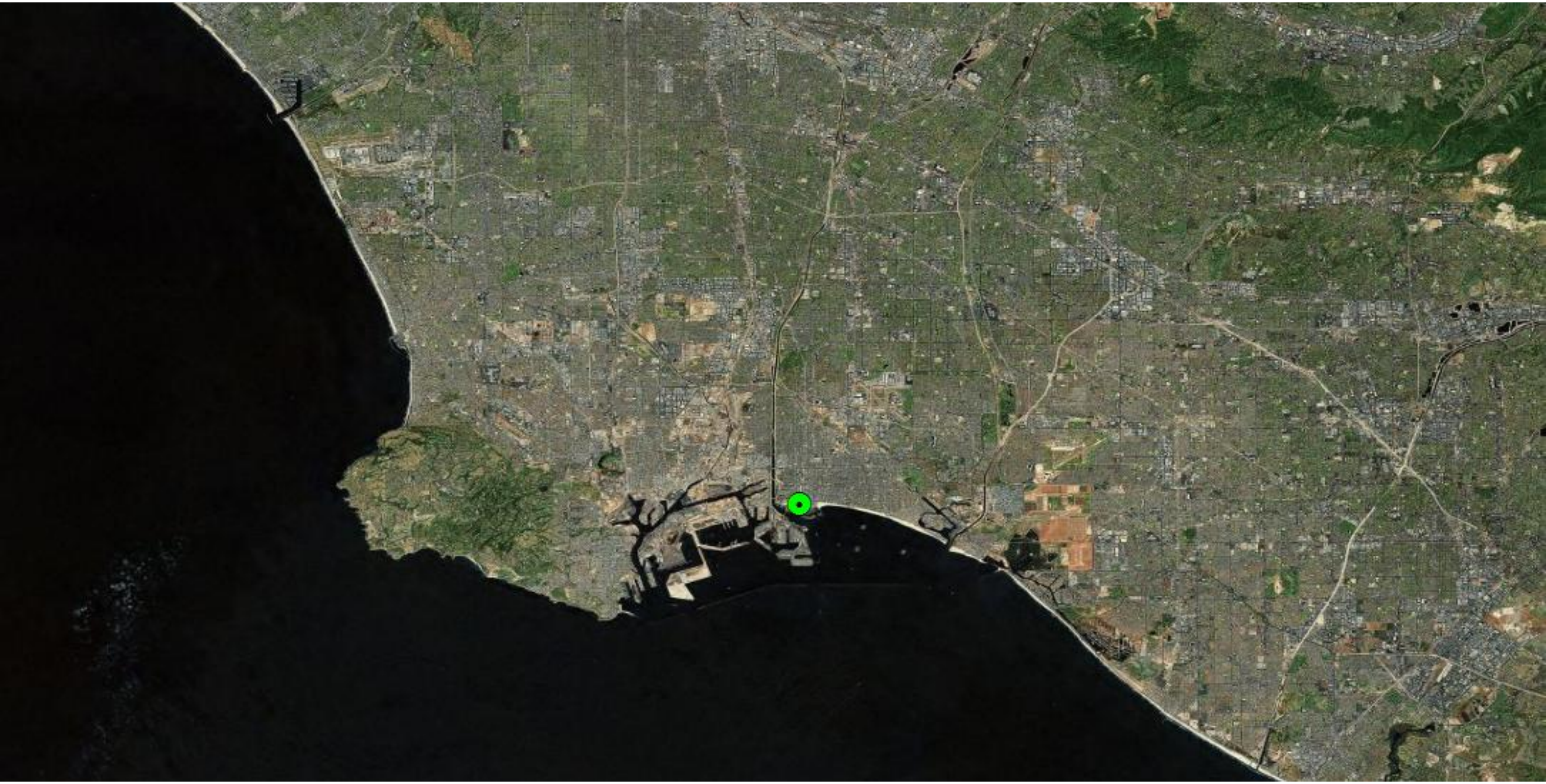
Tengiz – surface profiles



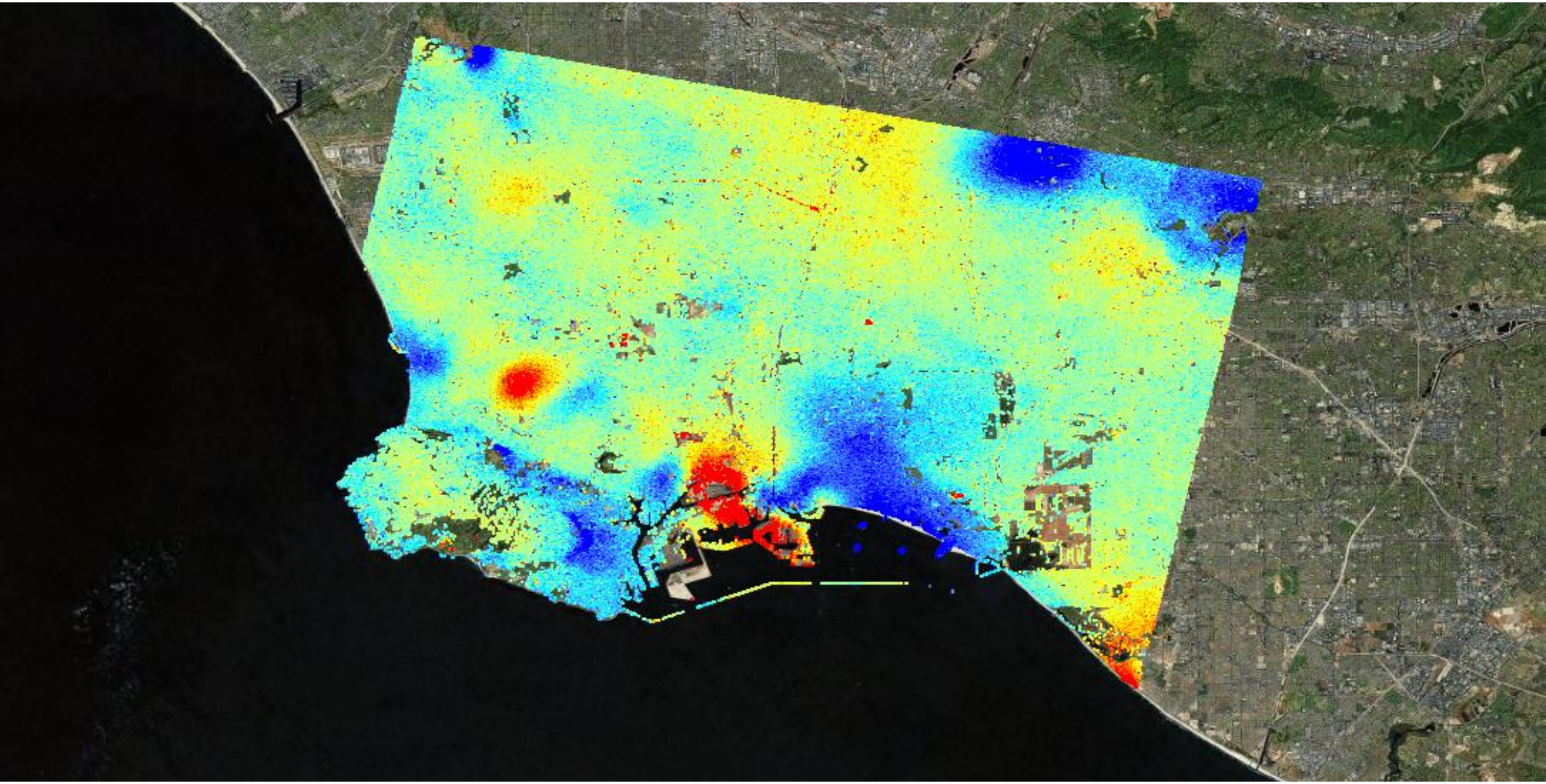
- Presence of high displacement gradients, corresponding to flanks
- Probable smoothing effect on displacement profiles related to plastic behavior of evaporite seal



Long Beach, CA



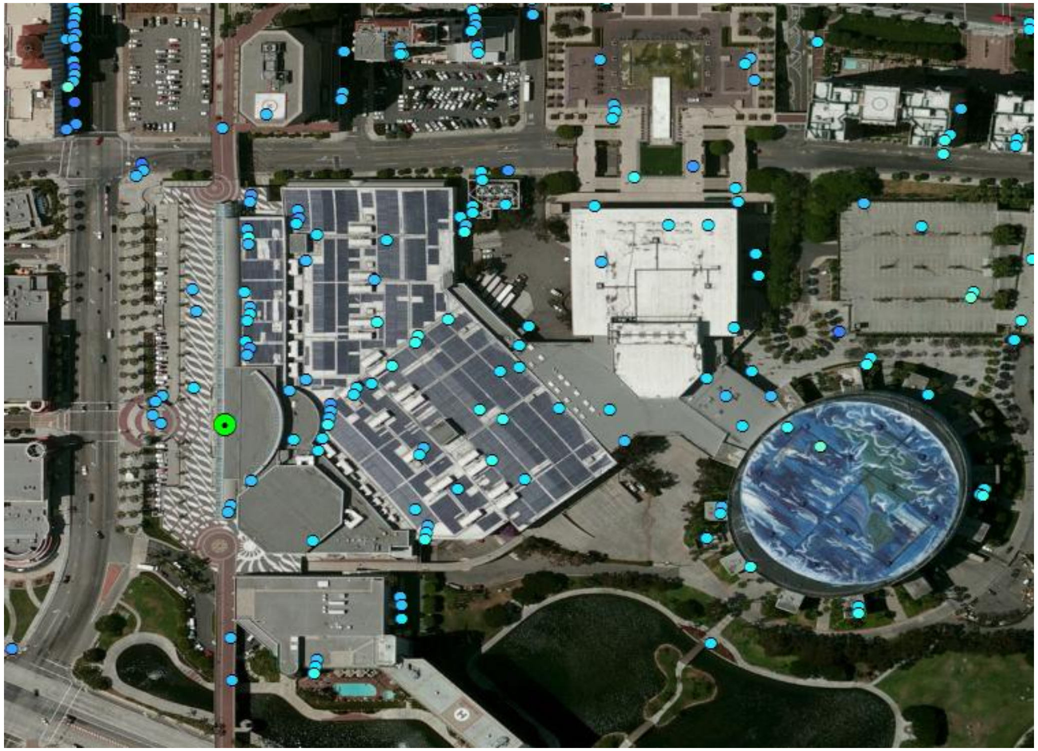
Are we moving?



Are we moving?

Def. rate ~ 4 mm/yr

20 min ~ 0.000152 mm



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Thank you

giacomo.falorni@trecanada.com