Combining time lapse seismic and gravity to estimate CO_2 saturation changes at Sleipner

ROSE meeting 2015

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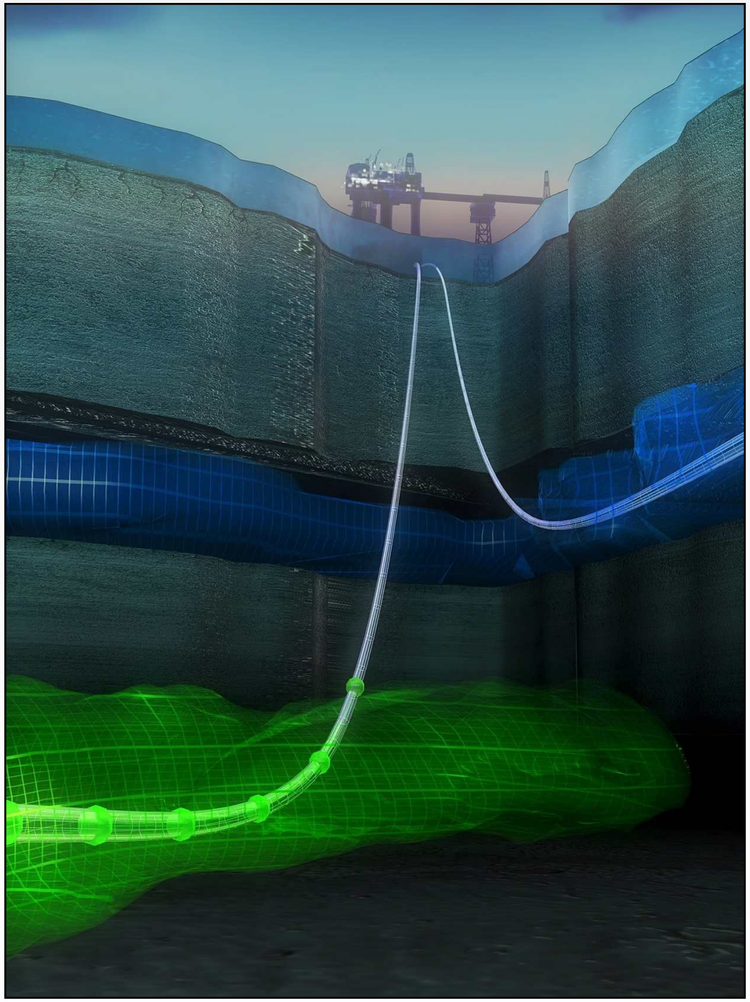
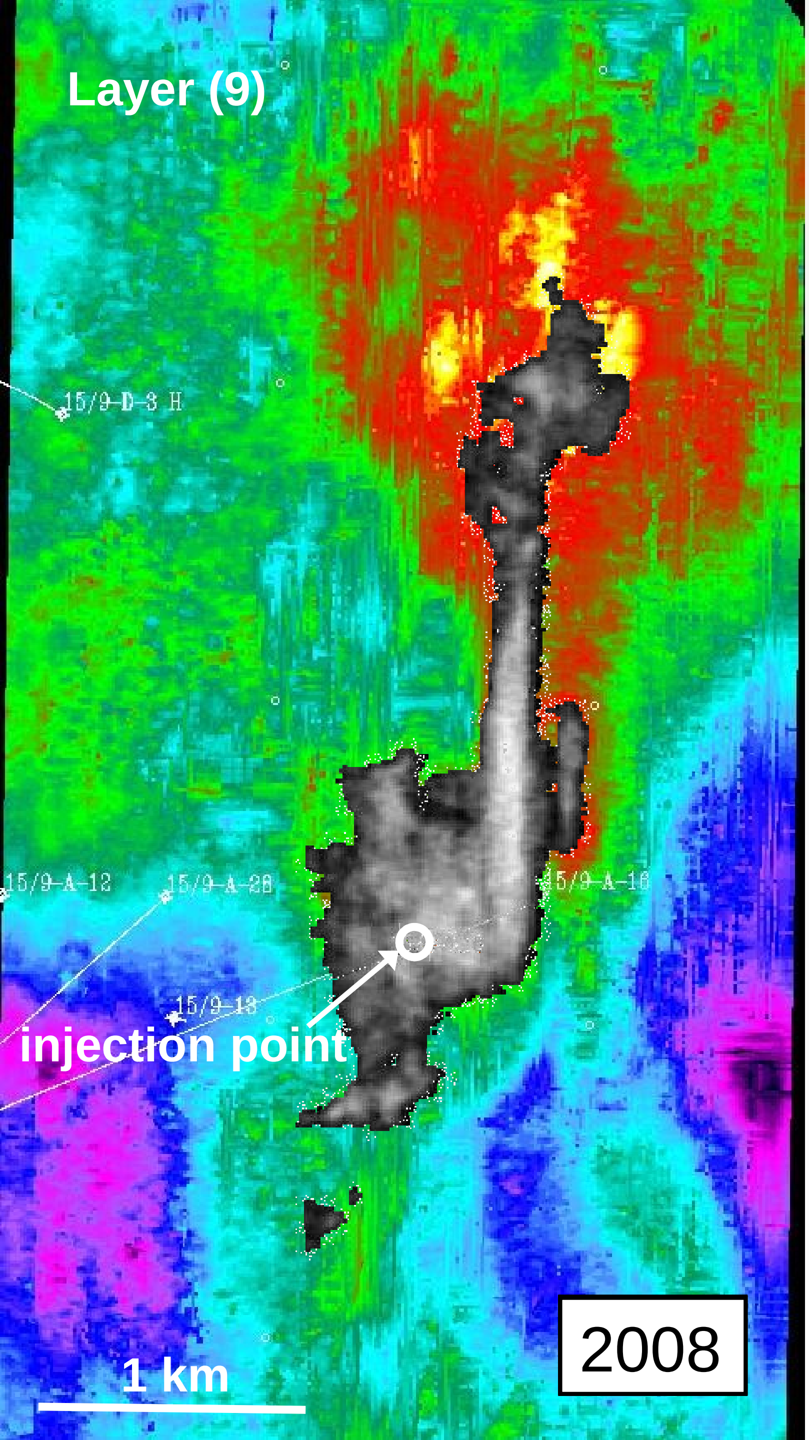
Sleipner CO_2 storage

- Reservoir unit at 800-1100 m depth
- One CO_2 injector
- Over 12 Million tons CO_2 have been injected
- Norway can store 50 Gtons offshore (NPD)
- Yearly global emission was 32 Gtons in 2010 and 40 Gtons in 2014…

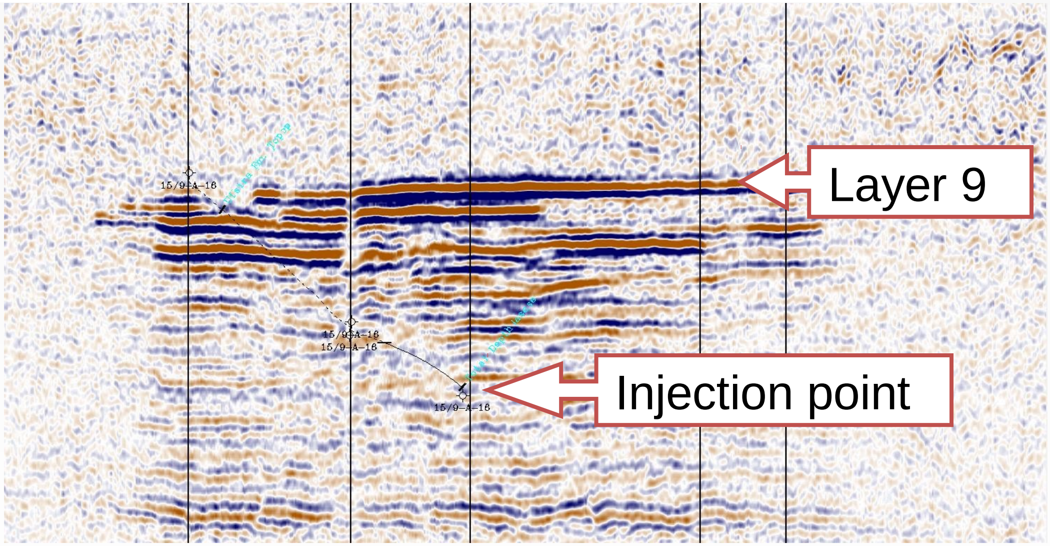




Sleipner CO_2 monitoring

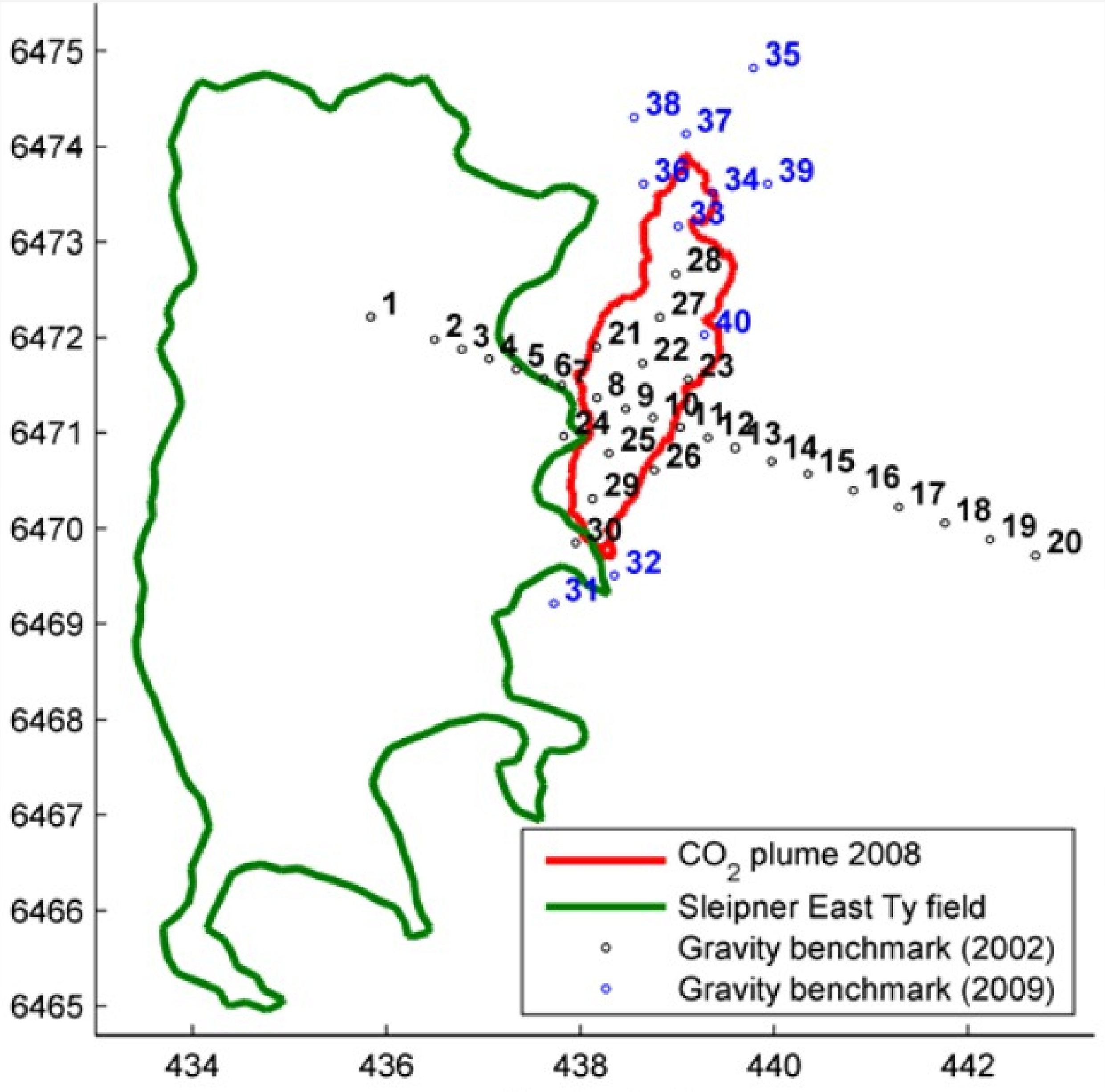
- Seismic monitoring data indicates a northerly extension to the plume, especially in the uppermost layer 9

Seismic amplitude difference (2008-1994)



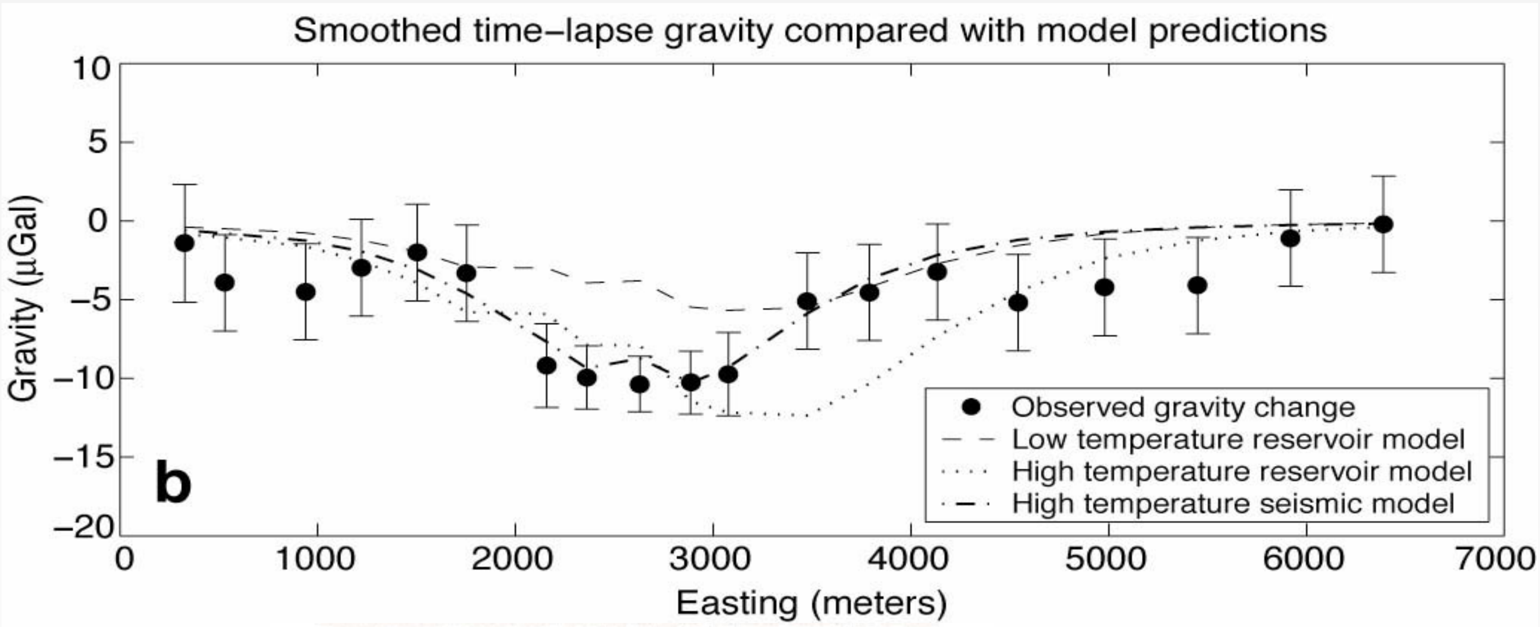
Data courtesy of Stato

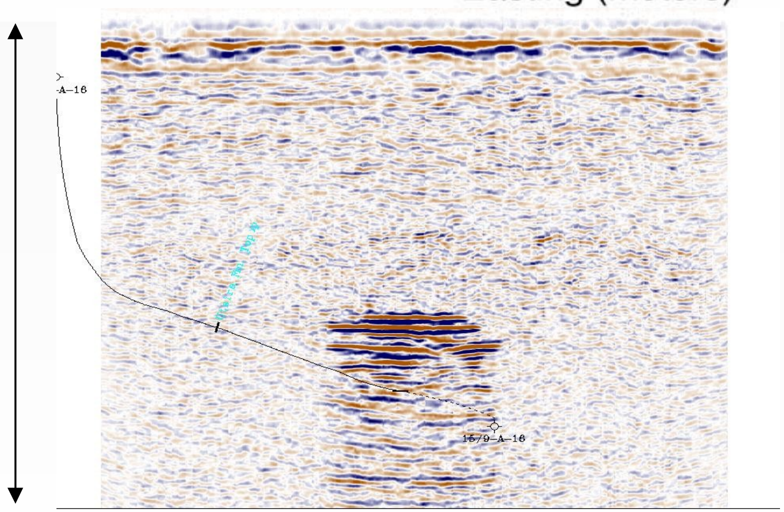
ravity data: 30 repeated gravity measurement



Source: Alnes et al., 201

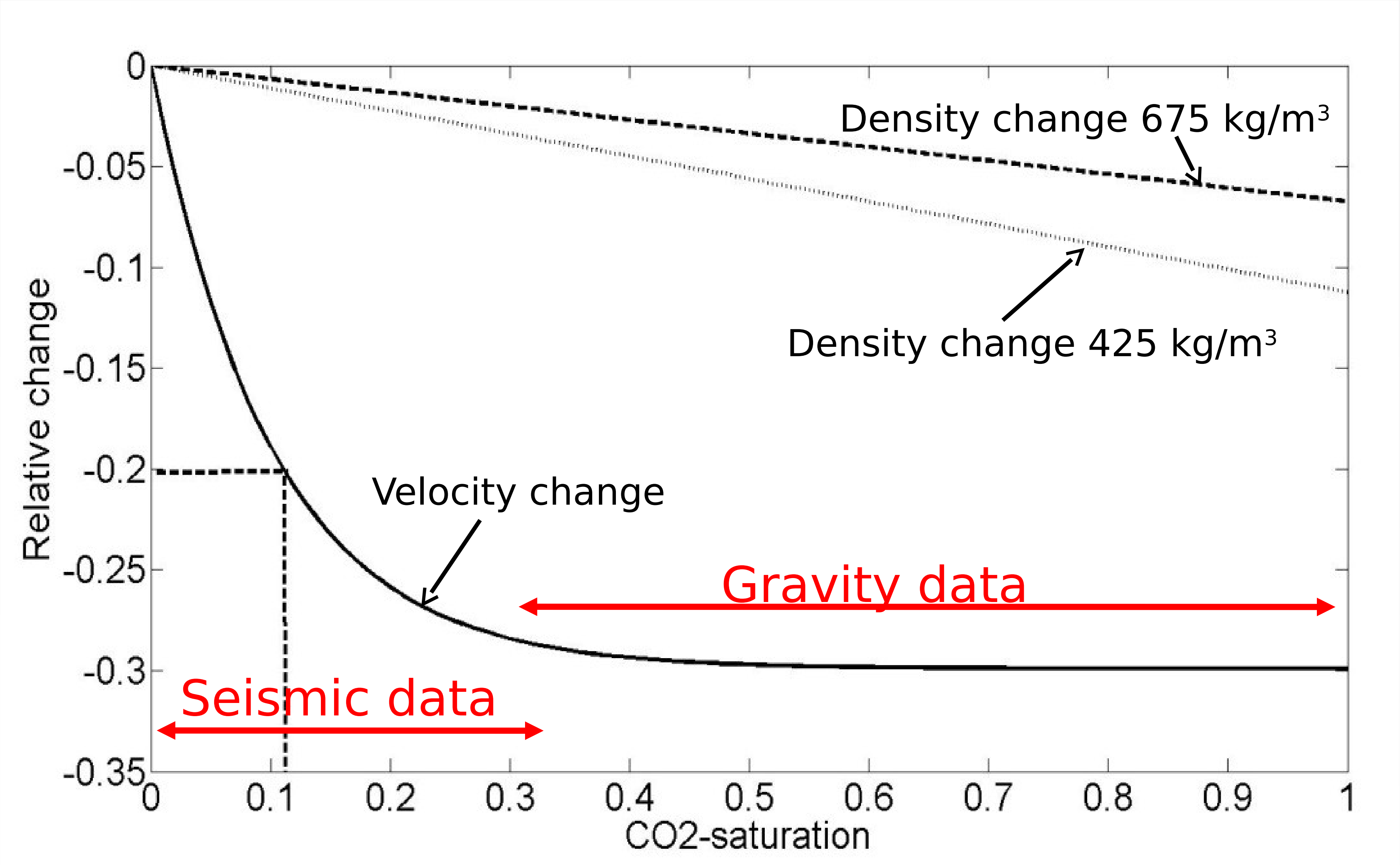
Time lapse gravity – Sleipner CO_2 plume





by H. Alnes, O. Eiken, S. Nooner, G. Sasagawa, T. Stenvold and M. Zumb

nple rock physics model for Sleipner CO_2-injec



gy for how to combine time lapse seismic and

	CO_2-saturation 0-0.3	CO_2-saturation 0.3-1	Spatial resolution
Seismic			
Gravity			

Spatial resolution is most important =>

1. Use time lapse seismic to estimate saturation changes up to 0.3
2. Use time lapse gravity in areas where seismic estimates are above 0.3 or where there is a seismic

e lapse AVO for density and velocity estimatio

$$\Delta R = \frac{1}{2}\left(\frac{\Delta\rho}{\rho} + \frac{\Delta\alpha}{\alpha}\right) + \frac{\Delta\alpha}{2\alpha}\tan^2\theta$$

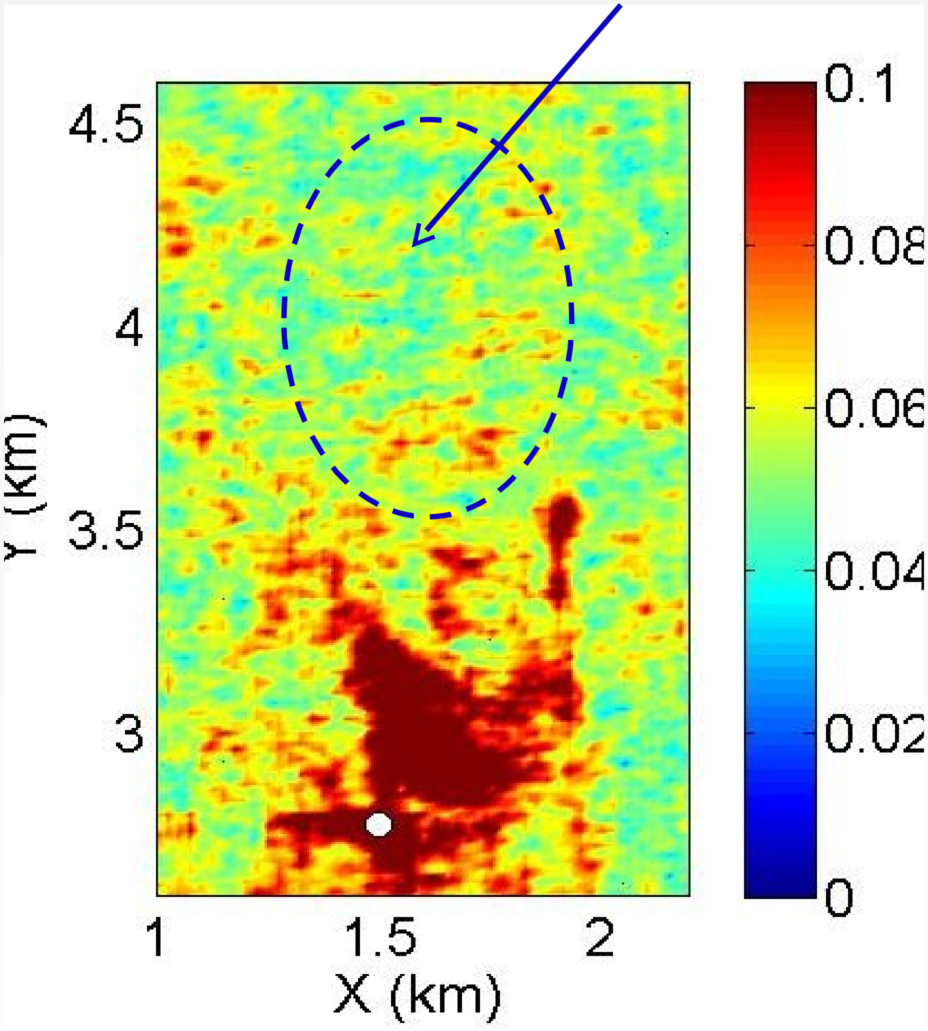
Landrø, Geophysics, 2001

$$\Delta N = \frac{1}{2}\left(\frac{\Delta\rho}{\rho} + \frac{\Delta\alpha}{\alpha}\right) + \frac{\Delta\alpha}{2\alpha}\tan^2\theta_N \quad \Delta F = \frac{1}{2}\left(\frac{\Delta\rho}{\rho} + \frac{\Delta\alpha}{\alpha}\right) + \frac{\Delta\alpha}{2\alpha}\tan^2\theta_F$$

$$\frac{\Delta\alpha}{\alpha} = \frac{2(\Delta F - \Delta N)}{\tan^2\theta_F - \tan^2\theta_N} \qquad \frac{\Delta\rho}{\rho} = 2\Delta N - 2\frac{(\Delta F - \Delta N)}{\tan^2\theta_F - \tan^2\theta_N}\left(1 + \tan^2\theta_N\right)$$

Calibration step 1

erage value of 0.06 obtained by multiplication with 0.02



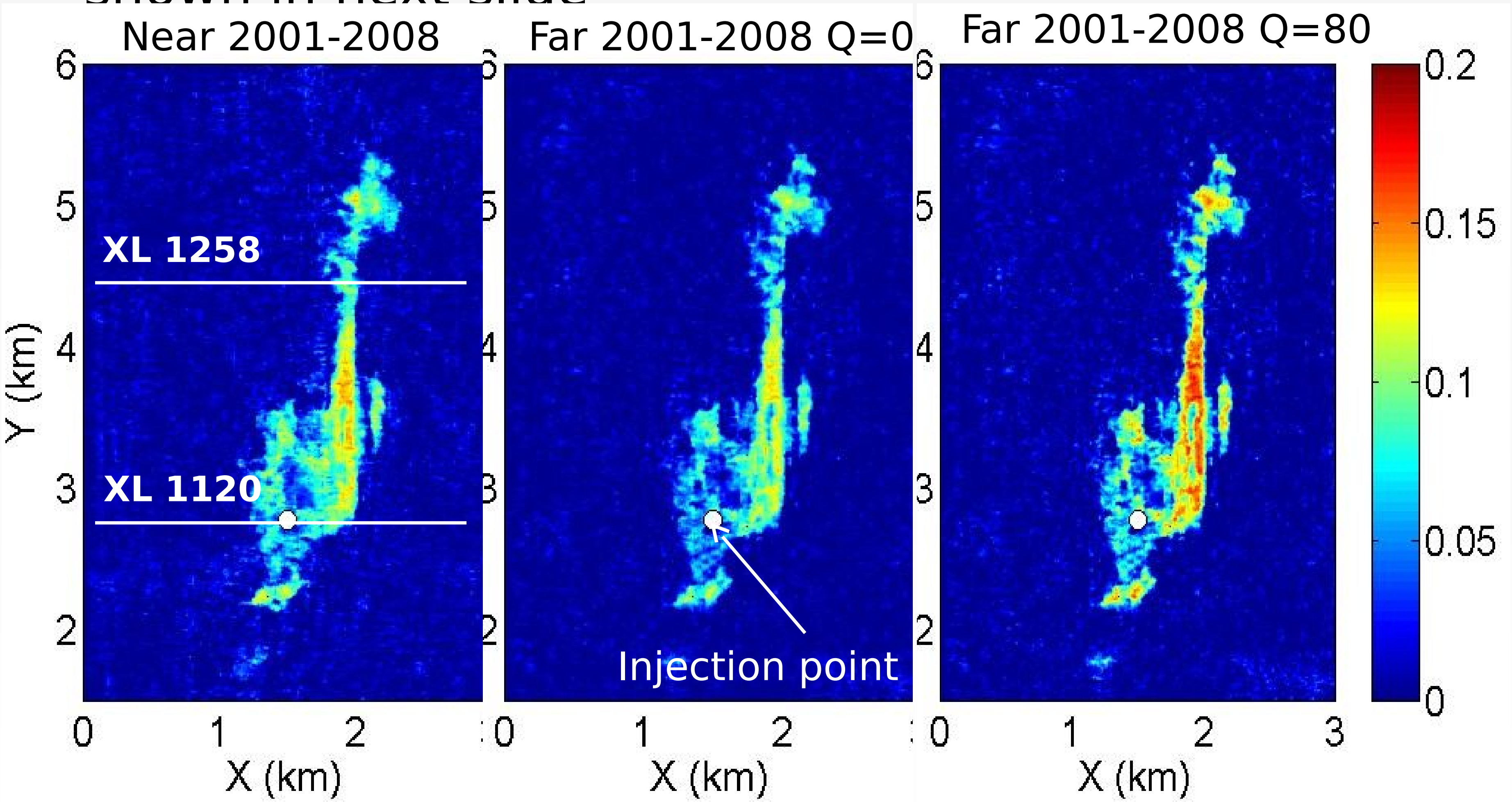
2001 RMS near offset amplitude map (26 ms window covering the top reservoir interface)

Modeled zero offset response from well log input: -0.06

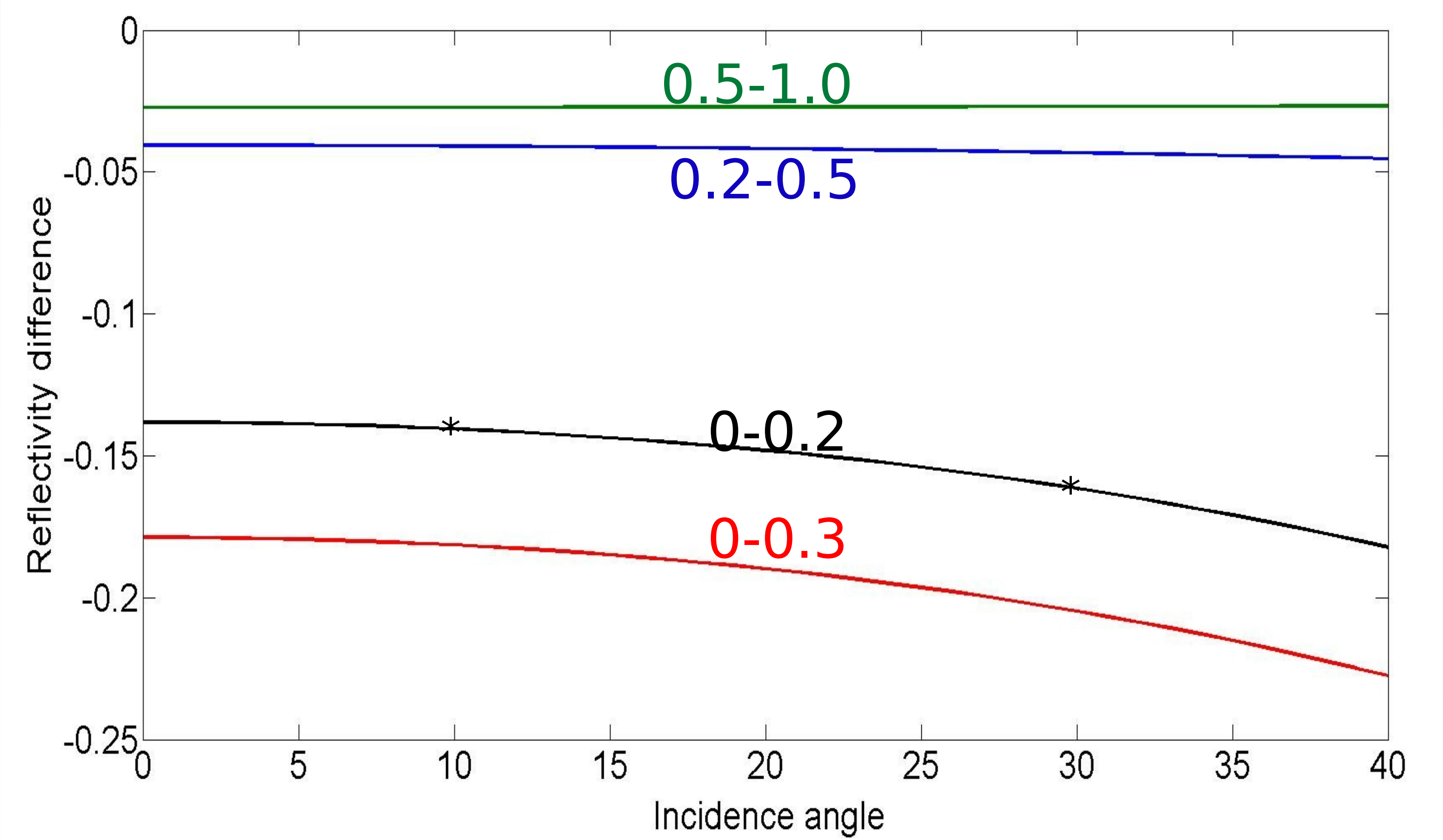
=> Use a global scalar of 0.02 to achieve this

Far offset calibration (step 2)

Q-value fitted by trial and error until a good match with modeled AVO-response is obtained – shown in next slide



Calibration of seismic data – determining Q



Notice: Q=80 will fit both 0-0.2 and 0-0.3 scenario

Estimating the 1999-2001 saturation change

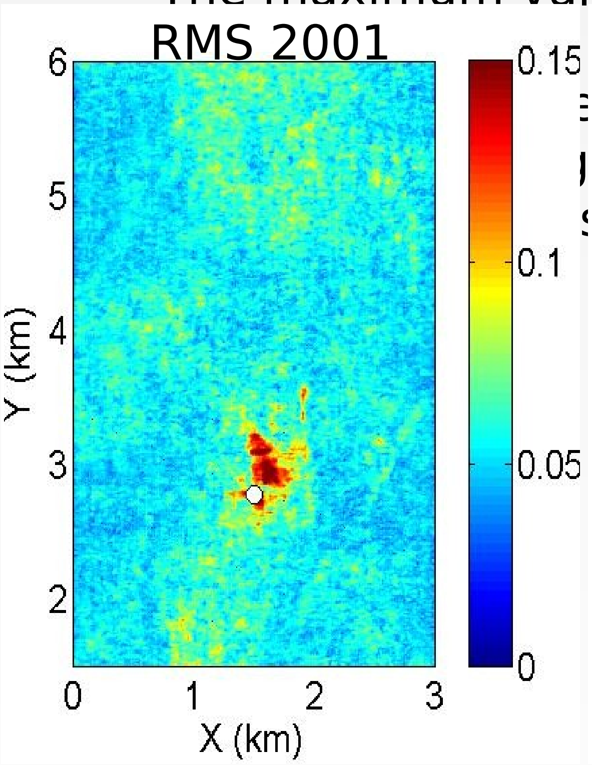
The maximum value for this difference is 0.1, which corresponds to

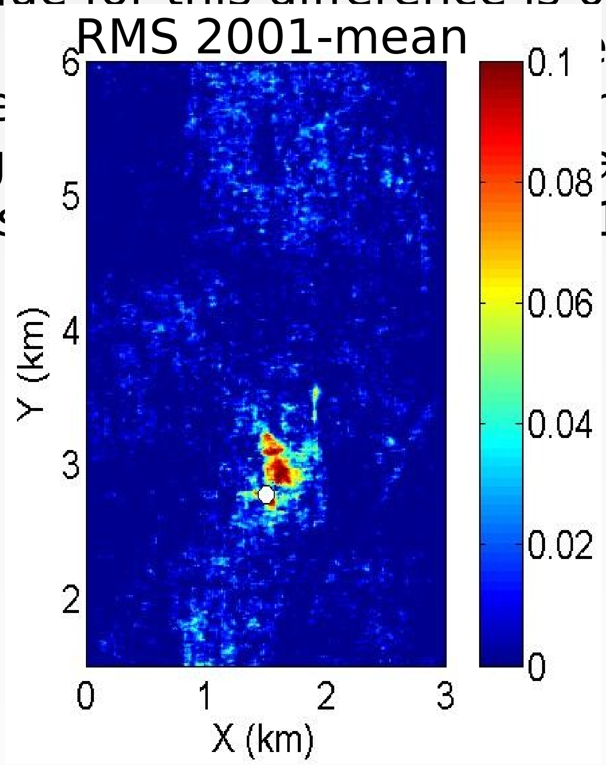
esponding saturation

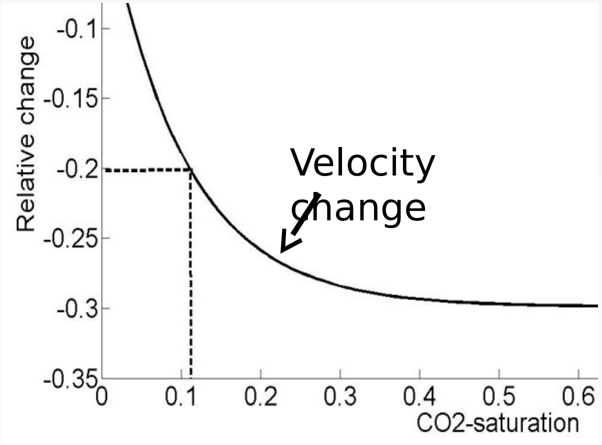
roximately 0.1. This

as an initial guess for the

1, without further



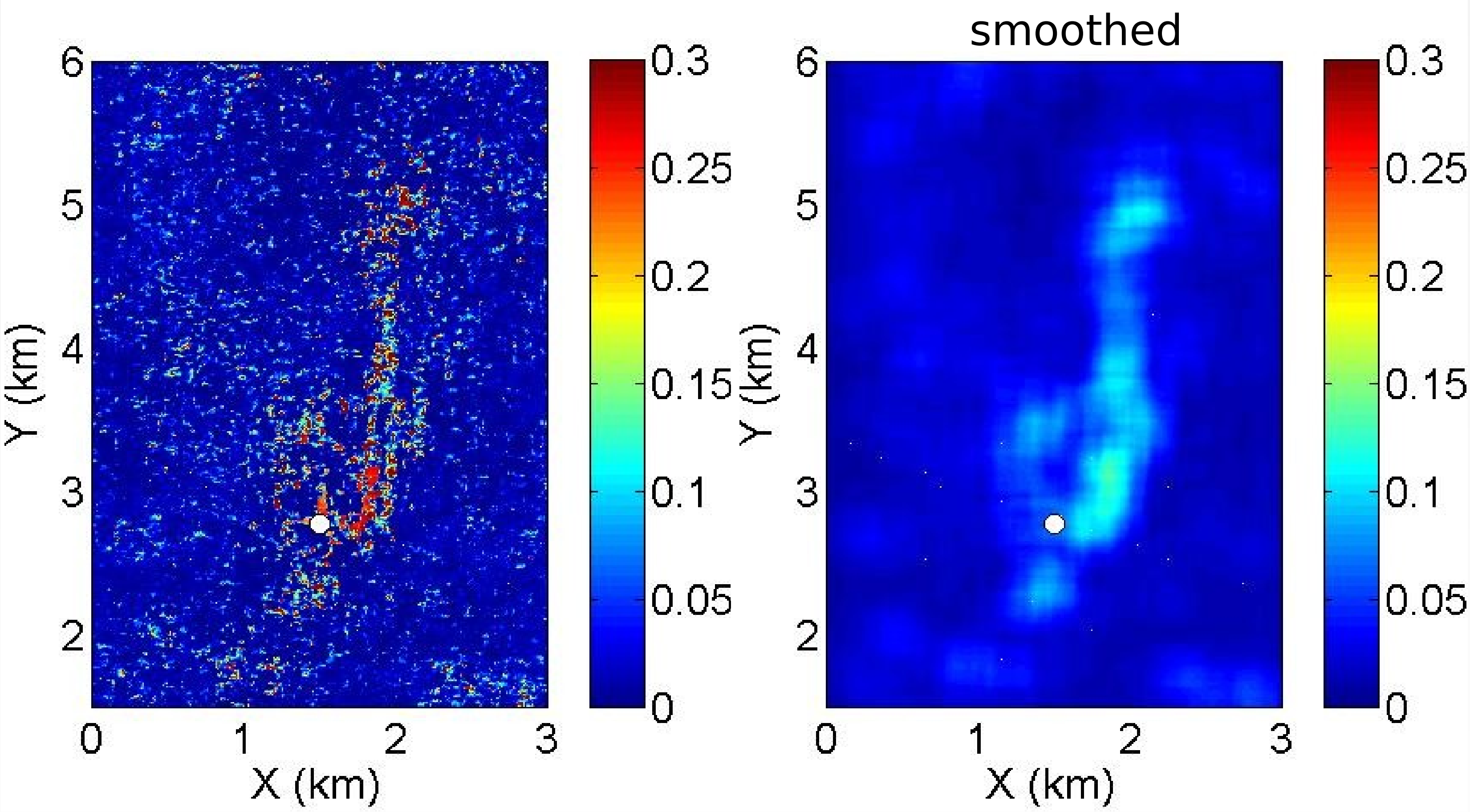




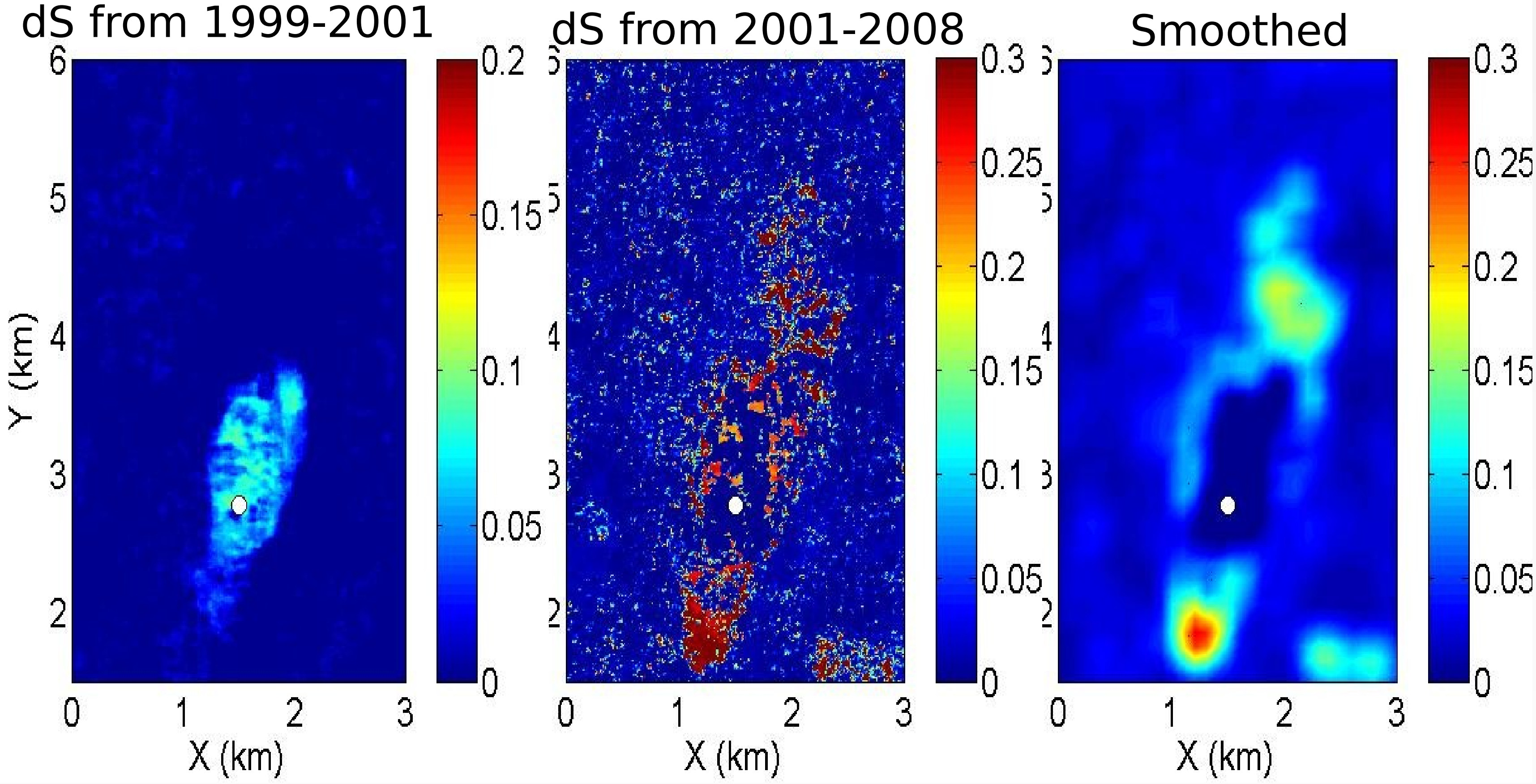
$$\Delta R \approx -0.1 \approx \frac{\Delta\alpha}{2\alpha} => \frac{\Delta\alpha}{\alpha} \approx -0.2 \quad => \quad \Delta S_{CO2} = 0.1$$

scaling factor is 1, and the RMS 2001-mean = ΔS_{CO2}

Saturation changes for the upper layer 2001-2008



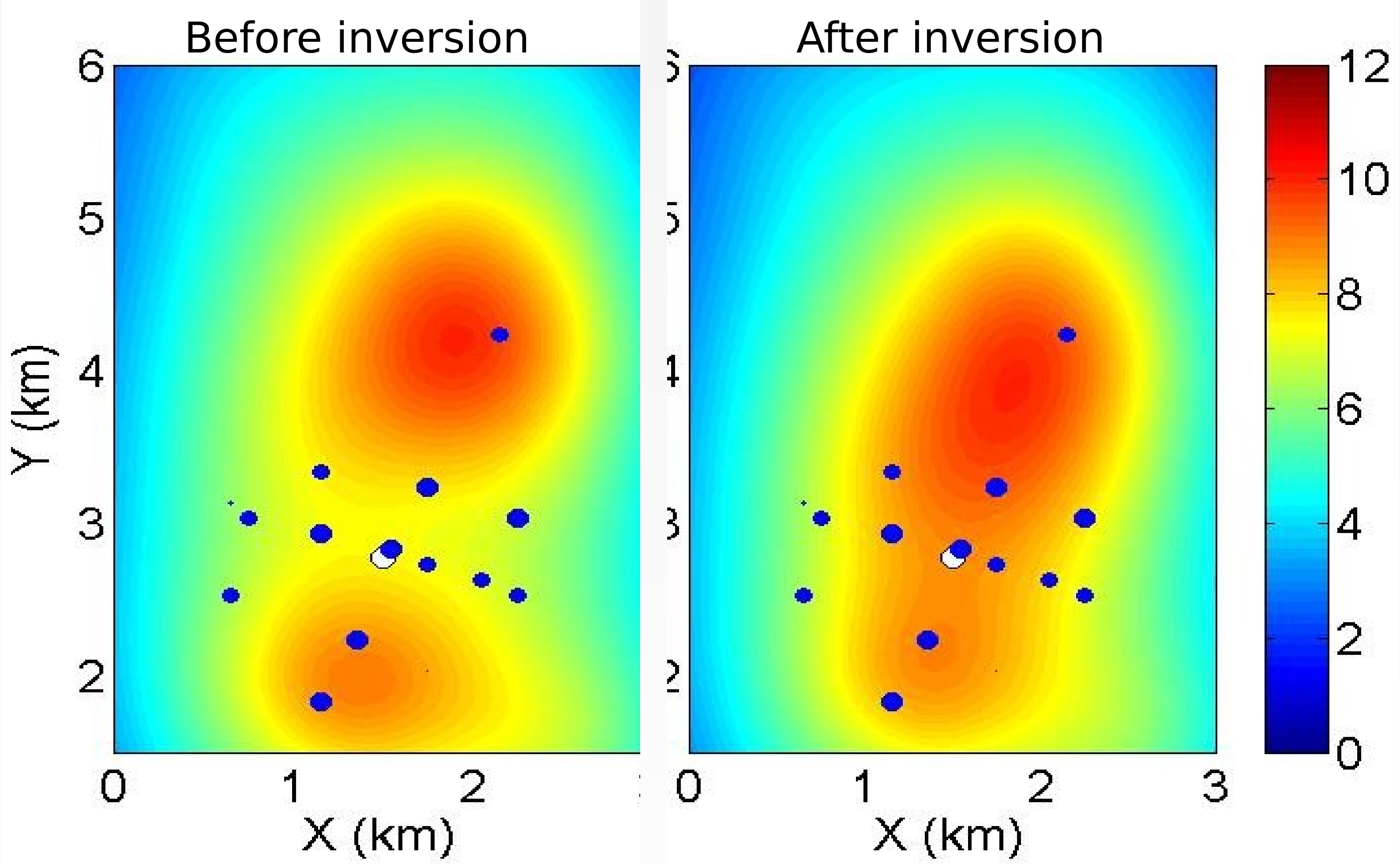
Using a thick RMS window: 850-1100 ms



Note: A new global scalar was determined (0.06), and the Q kept constant at 80

m: NO SIGNAL BELOW PLUME IN 2001 – shadow effect and the 0.

Gravity data and constrained inversion

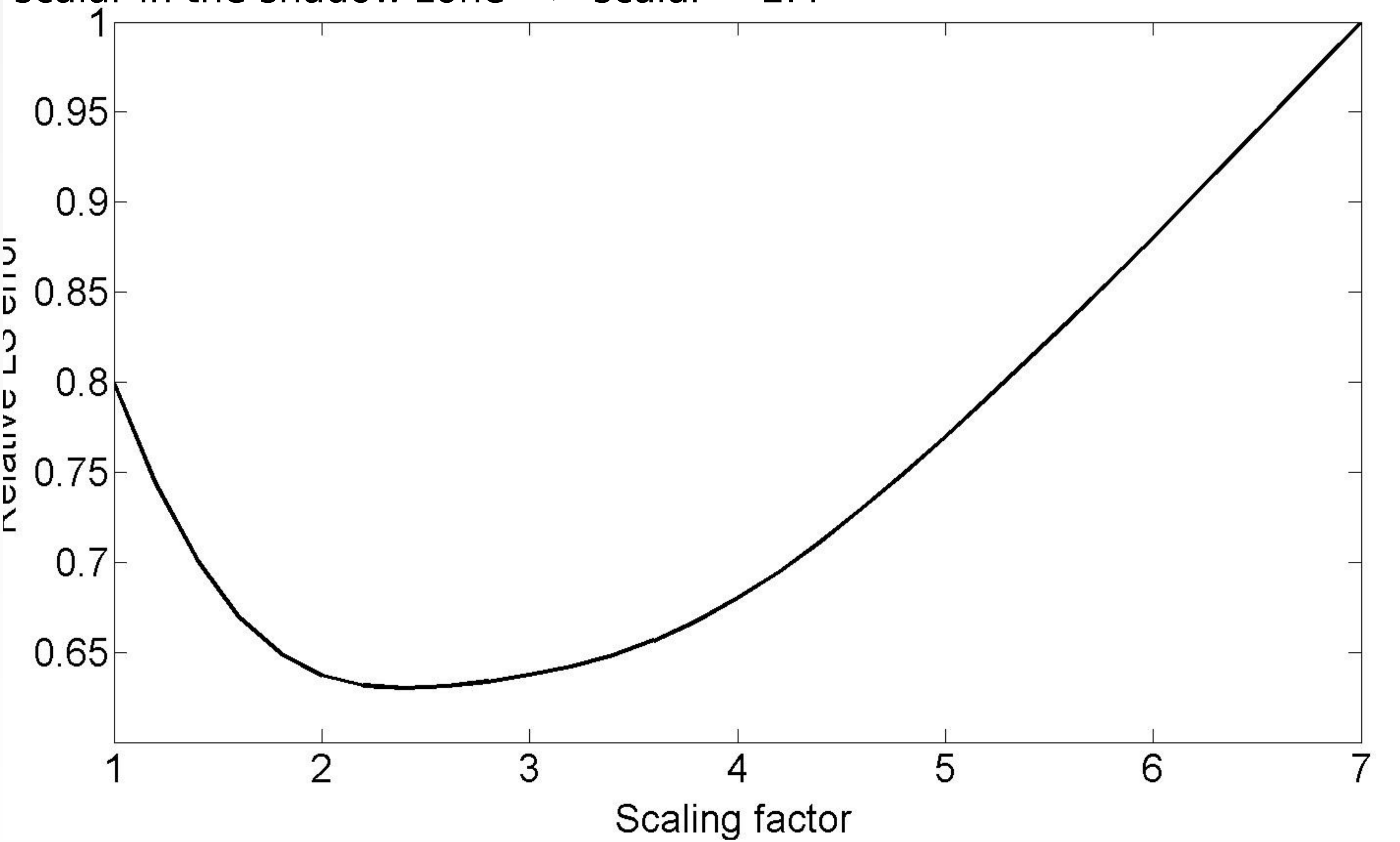


circles are gravity measurements – size proportional to gravity change
ground color map represents MODELED responses from estimated saturation cha

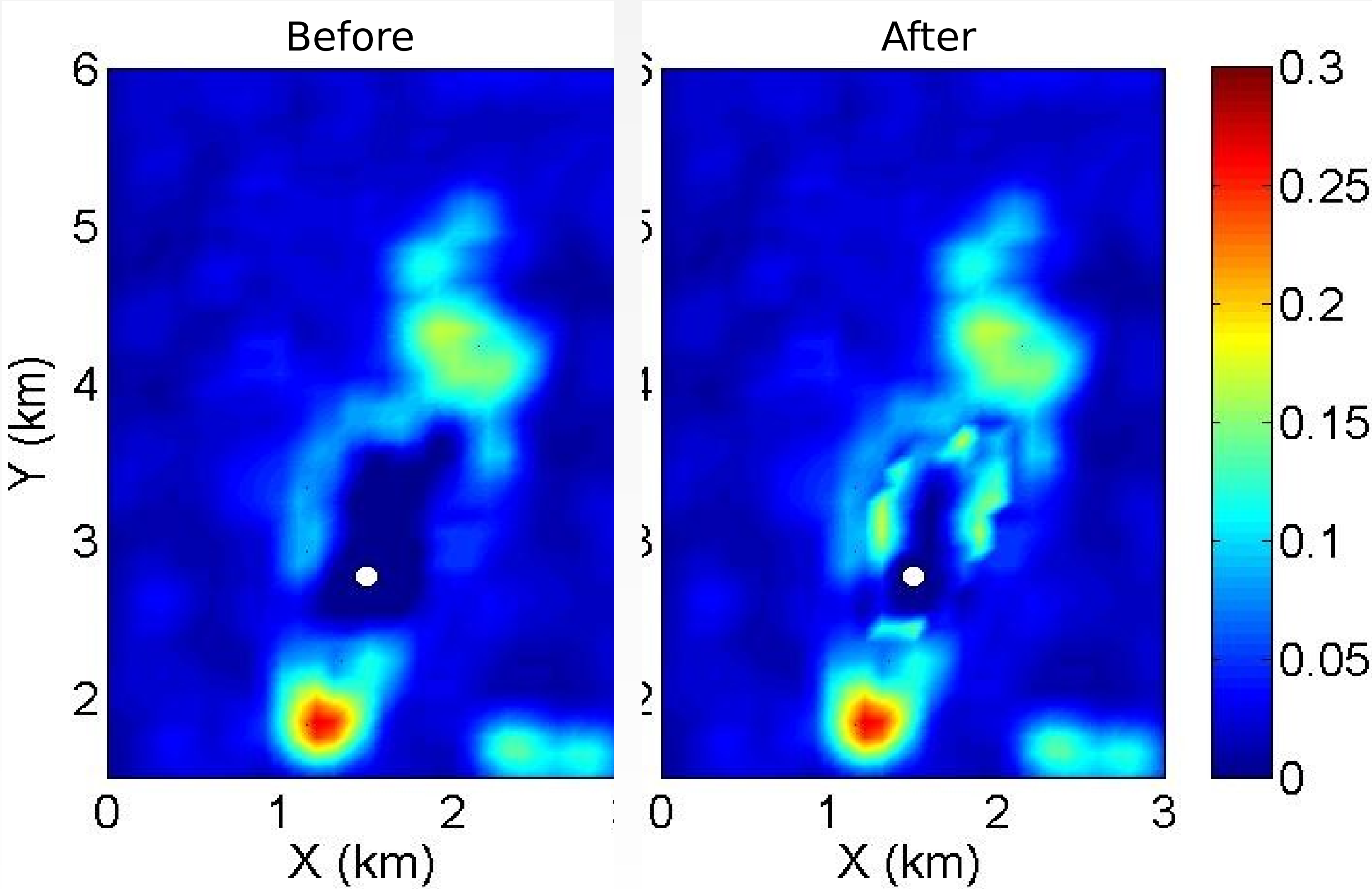
strained inversion gives a better fit to the measured gravity dat

Inversion – LS error

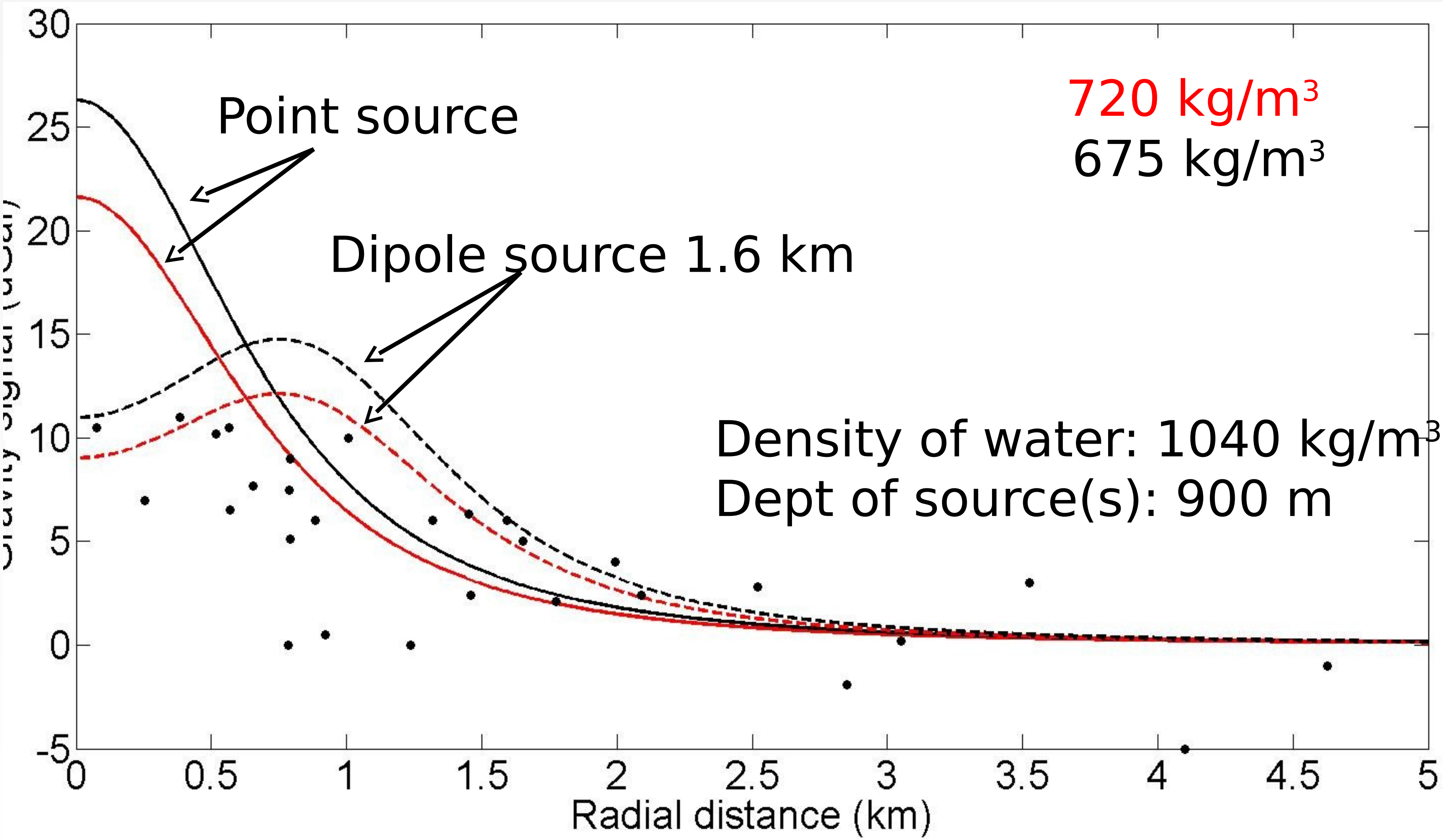
Assume that the spatial distribution suggested by the time lapse seismic inversion is OK, and simply scale this distribution by one single scalar in the shadow zone => scalar = 2.4



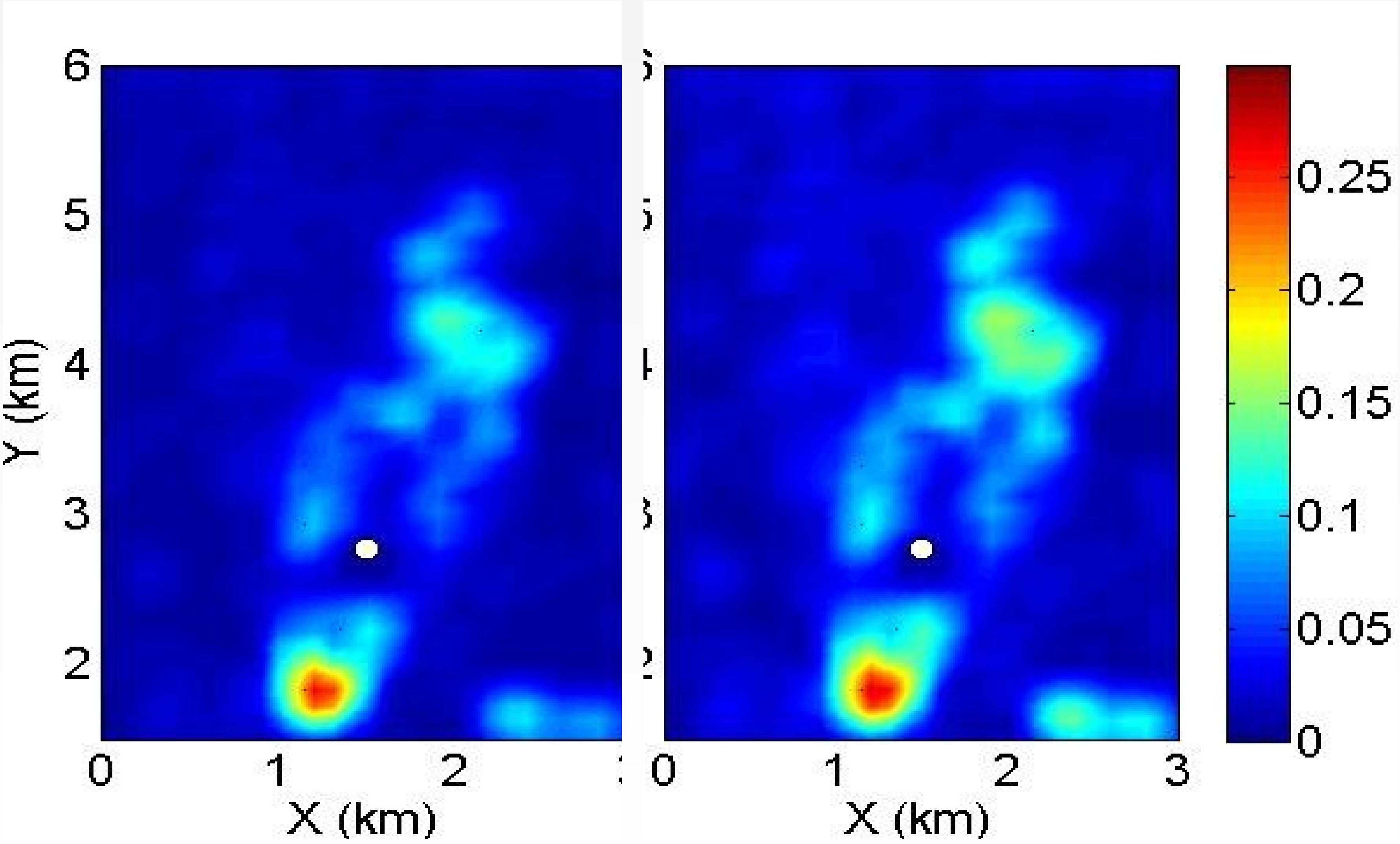
Before and after using gravity data



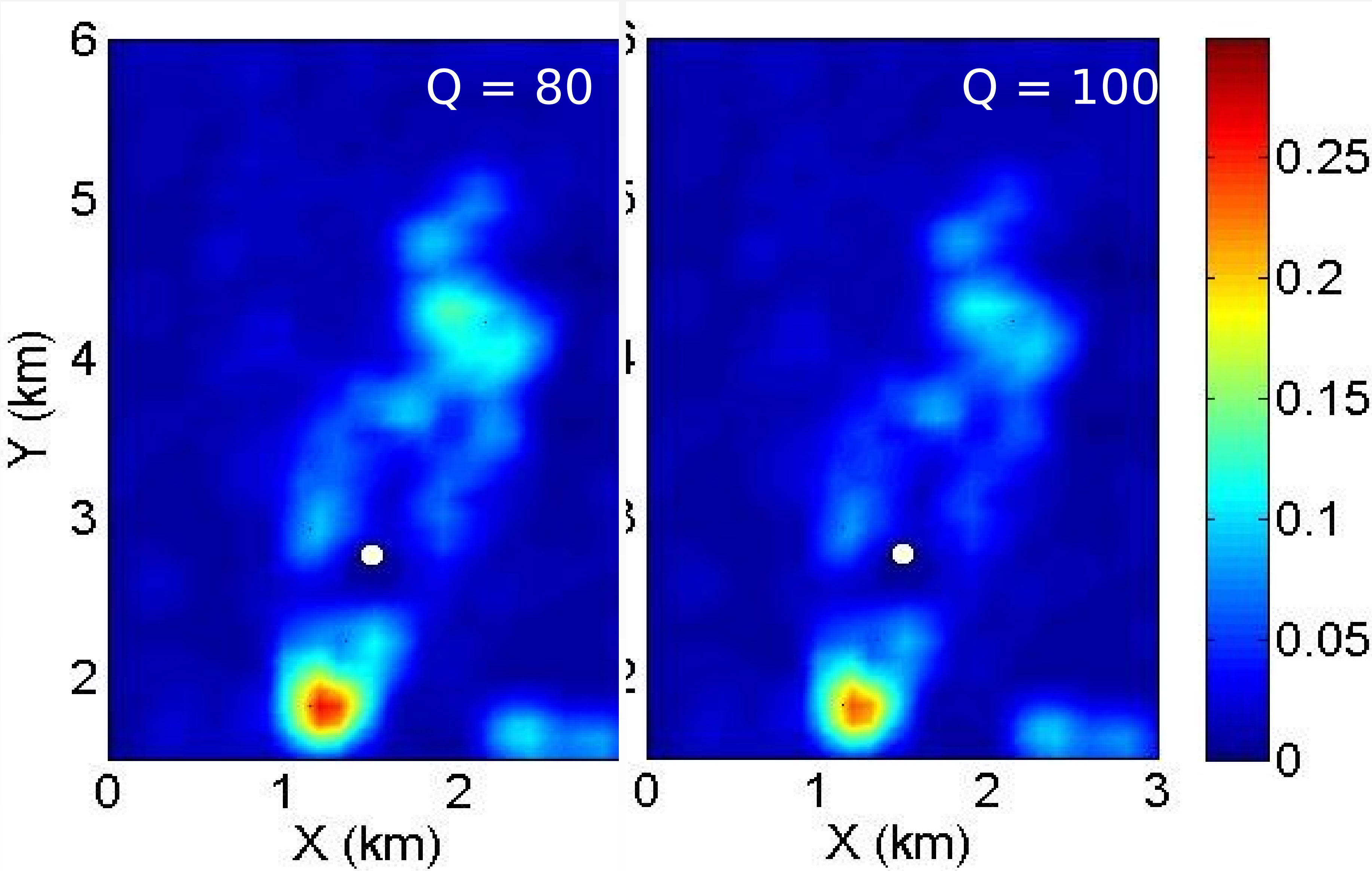
Gravity change (2002-2008) versus radial distance from the injection point compared to modeled results (5.88 Mtons injected)



Effect of increasing the global scalar by 30 %

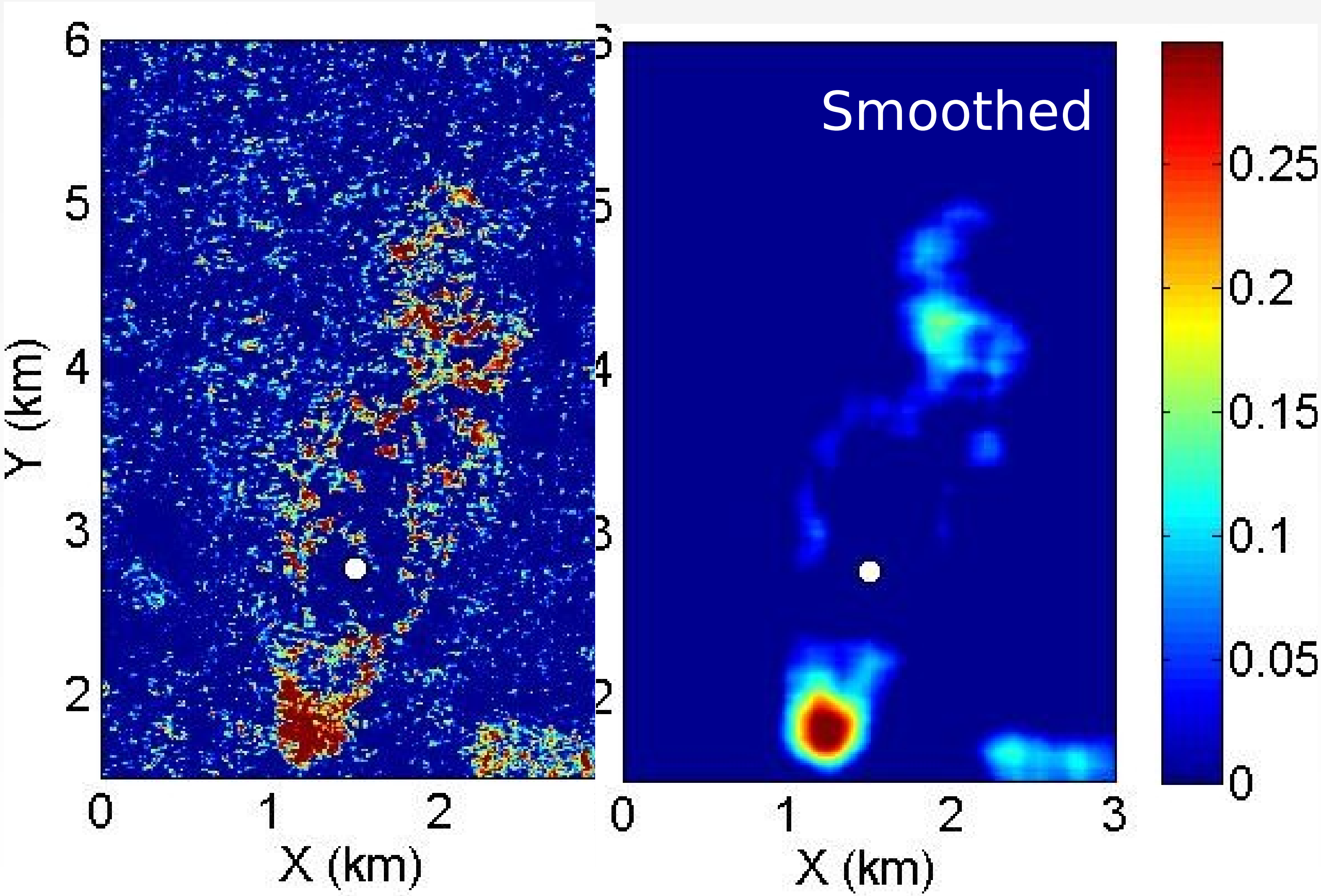


Effect of increasin Q from 80 to 100



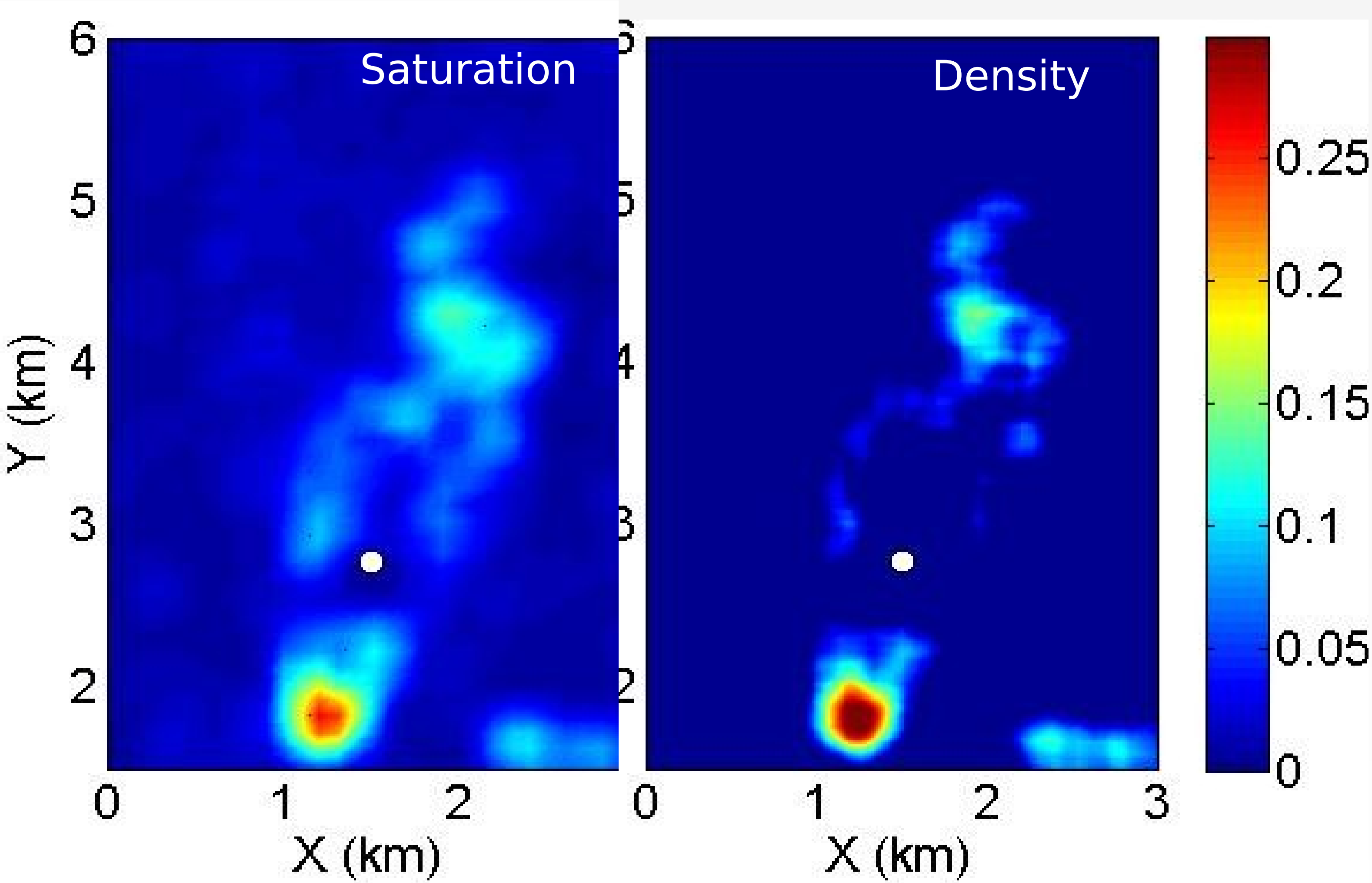
Estimated density changes

$$\frac{\Delta\rho}{\rho} = 2\Delta N - 2\frac{\left(\Delta F - \Delta N\right)}{\sin^2\theta_F - \sin^2\theta_N}\left(1+\sin^2\theta_N\right)$$



Saturation changes and density changes - compared

$$d\rho = \left(\rho_W - \rho_{CO2}\right) \cdot dS$$



Almost proportional…

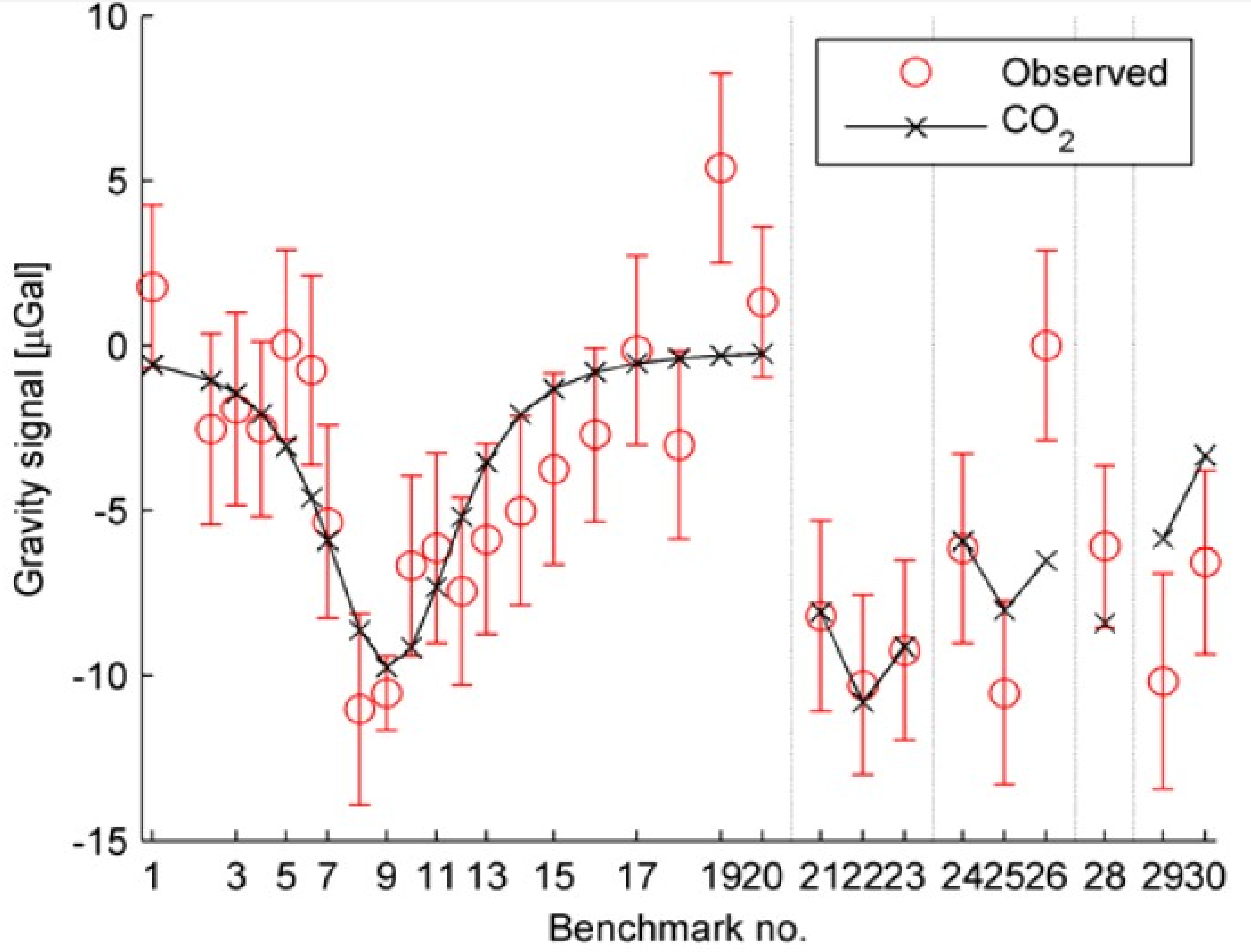
Conclusions

- **Stacked layers of CO2 represents a huge challenge for quantitative saturation estimation from 4D AVO**
- **Top layer analysis gives reasonable results**
- **Practically no change in seismic data for saturation changes above 0.3**
- **A constrained gravity-seismic inversion is used to improve results in the seismic shadow zone**
- **The LS error between initial (seismically derived saturation changes) and final saturation change**

Acknowledgments

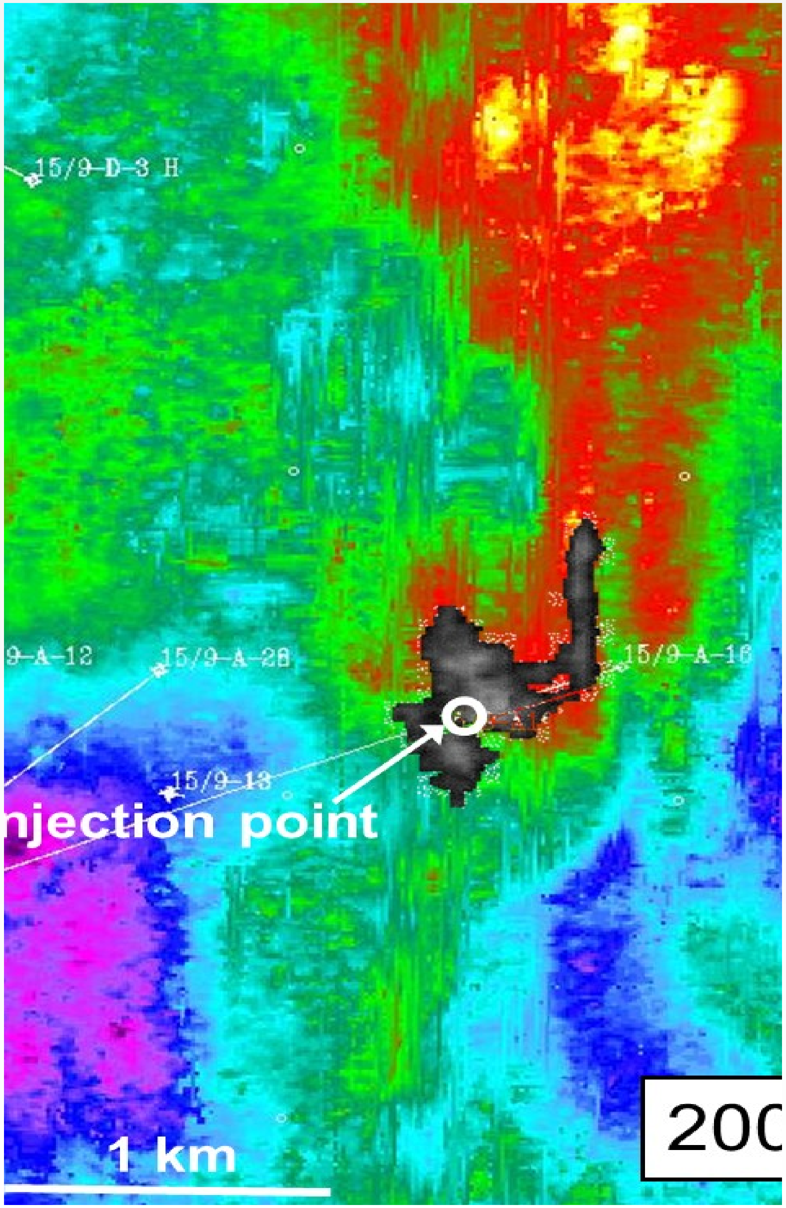
- **Statoil and the Sleipner license partners ExxonMobil and Total for permission to use the data**
- **Anne-Kari Furre and Ola Eiken for support and discussions**
- **Alistair Harding and Matthew Dzieciuch for help and assistance**
- **Scripps for hosting me and the Norwegian Research Council for financial support**

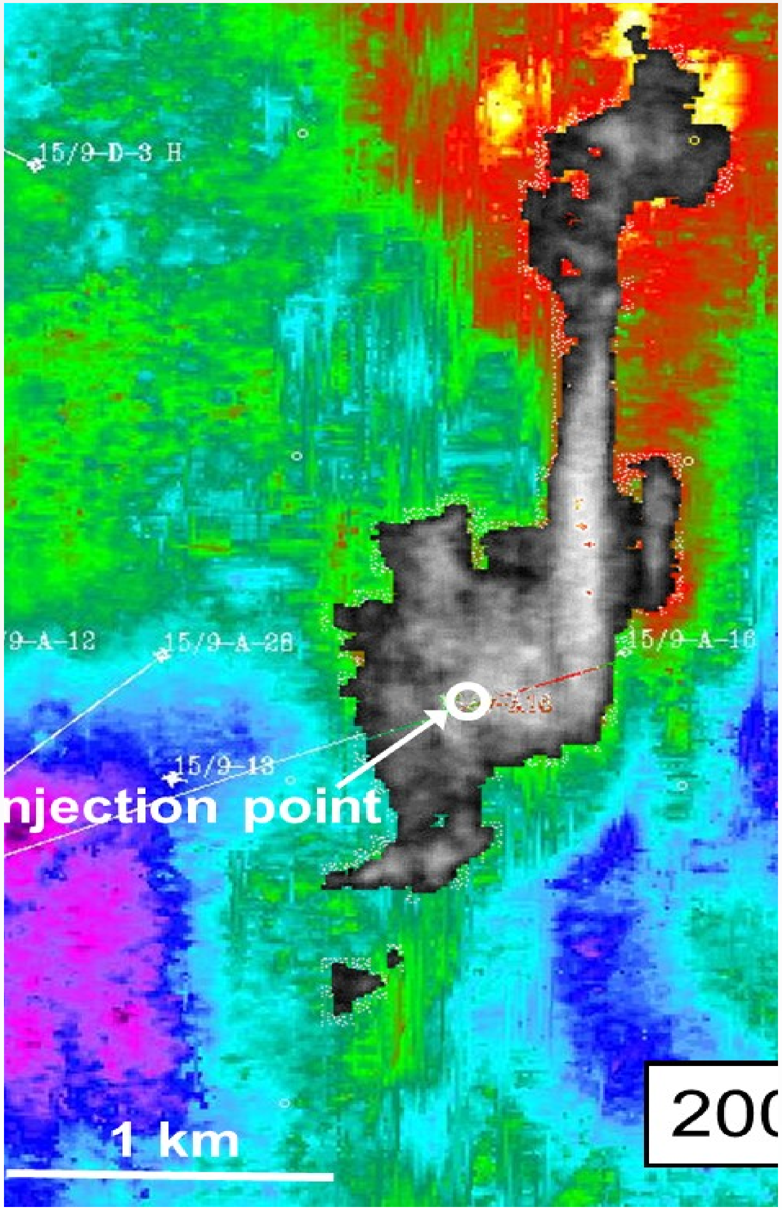
Time lapse gravity results



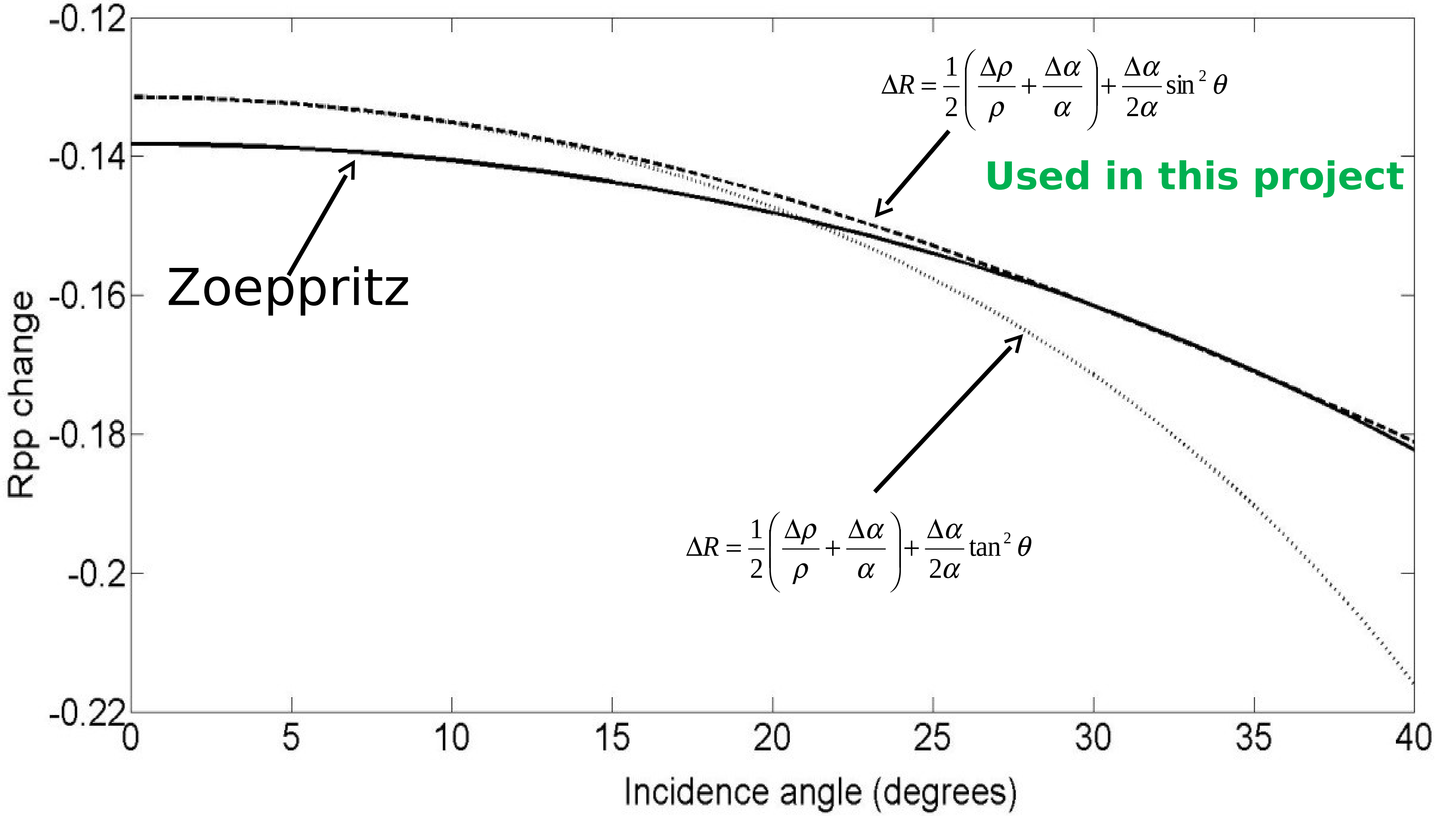
Source: Alnes et al., 201

eismic data sets used: 3D from 2001 and 2008

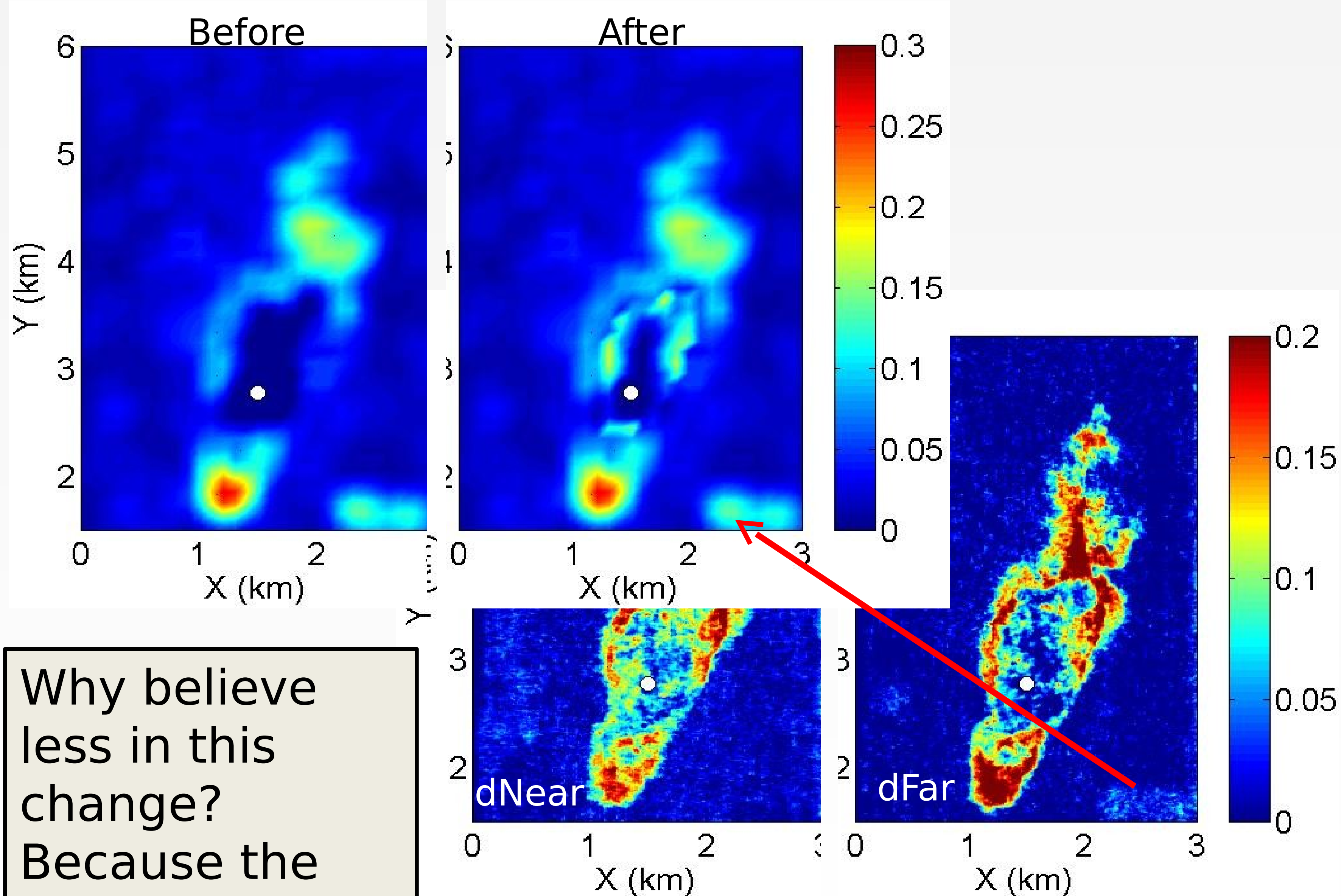




Testing approximations



The anomaly in the lower right corner..



Why believe less in this change? Because the near difference