XVI SIMPOSIO INTERNACIONAL SELPER 2014

La Geoinformación al Servicio de la Sociedad

Memorias

Sociedad Latinoamericana en Percepción Remota y Sistemas de Información Espacial Capítulo Colombia

30 AÑOS

Medellín, Colombia
29 de Septiembre al 3 de Octubre de 2014

Title: InSAR observations of surface heave induced by enhanced oil recovery in northern Alberta, Canada

Título: Observaciones del levantamiento de la superficie en los campos de petróleo en Alberta Canada, usando interferometría de radar

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Abstract

Interferometric Synthetic Aperture Radar (InSAR) observations over northern Alberta, Canada show persistent surface uplift occurring at rates of 1-4 cm/year, localized at sites where the Steam-Assisted Gravity Drainage (SAGD) technique is currently used to extract bitumen from the Athabasca oil sands. We find that uplift rates above the horizontal injector wells are strongly correlated with rates of steam injection, even though there is a net fluid loss from the reservoir pore space as oil and water are withdrawn through the production wells. In combination with available steam injection and bitumen production data at four sites, we use reservoir flow models to explain how the thermal and geomechanical effects of steam injection on an oil sand reservoir can generate uplift at the surface. Results of our numerical experiments show that persistent surface heave consistent with observed rates can be driven by stress changes in the reservoir due to porous flow and thermal expansion.

Resumen

Observaciones por interferometría de radar (InSAR) en el norte de Alberta, Canada, muestra un levantamiento continuo de la superficie con velocidades entre 1 y 4 cm por año, localizado en sitios donde el proceso de inyección de vapor (SAGD) es usado para extraer el petróleo de la arena en los campos de petroleo en Athabasca. Las velocidades de levantamiento encima de los pozos de injección tienen fuertes correlaciones con las tasas de injeccion de vapor, a pesar de que hay una perdida neta de fluidos de los poros del embalse, pues el petróleo y el agua es extraída continuamente por los pozos de producción. Usando los datos de inyección de vapor y producción de betún en 4 sitios, desarollamos modelos de flujo en los embalses para explicar como los efectos térmicos y geomecánicos causan levantamiento de la superficie. Nuestros experimentos numéricos muestran que el levantamiento persistente observado por medio de la interferometría de radar puede ser explicado por los cambios de estrés en el embalse causados por el flujo en los poros y la expansión térmica.

Keywords

InSAR, surface deformation, Alberta oil sands, numerical models

Palabras Clave

Interfermetría de radar, deformación de la superficie, campos de petroleo de Alberta, modelos numéricos

Introduction

Alberta's oil sands contain one of the world's largest deposits of crude oil, in the form of viscous bitumen embedded within uncemented sand (Mossop*,* 1980; Mossop and Flach, 1983). The oil sands differ from other crude oil deposits in that they are heavier and have a viscous tar-like consistency, so they are unable to flow under reservoir conditions and must be recovered using unconventional methods. A common thermal method is steam-assisted gravity drainage (SAGD), in which groups of horizontal wells are drilled into the reservoir side by side, maximizing contact between injected steam and the reservoir. The wells are drilled in pairs, with a production well sitting below a steam injection well to collect the heated bitumen, which flows into it by gravity drainage and is pumped to the surface (Butler, 1994; 1998; 2001).

Withdrawal or injection of material into the subsurface is known to cause deformation at the surface; the wavelength, shape and rate of the deformation depend on a variety of factors including the depth and rate of the injection or withdrawal, temperature and pressure of injected material, properties of the reservoir and overburden, and local geology. InSAR is a satellite-based remote sensing technique capable of measuring surface deformation measurements with sub-millimeter precision (Massonet and Feigl, 1998; Burgmann *et al.*, 2000; Singhroy, 2009). An interferometric phase image (interferogram) represents the phase differences between the backscatter signals in two or more radar images obtained from similar positions in space. Once the topographic phase is removed, the phase differences between two repeat-pass images are the result of changes in the line-of-sight (LOS) distance between the surface and the satellite due to displacement of the surface as well as changes in the atmospheric conditions between scenes.

We use InSAR observation coupled with petroleum production data and numerical modelling to study surface deformation driven by the SAGD process. We collected 5 years of InSAR observations from the Canadian satellite RADARSAT-2 at four active sites within the Athabasca oil sands, as well as steaming and production rates for the well pairs, and used these data to constrain numerical models that simulate porous flow, phase changes and heat transfer in the reservoir.

Methodology

We chose four test sites in the Athabasca oil sands for InSAR observation and analysis, labelled in Figure 1. All four sites contain SAGD operations with active steaming and production throughout 2008-2013. We analyzed a large catalogue of SAR scenes from RADARSAT-2 in Ultrafine, Multilook Fine and Ultrafine Wide beams. Interferograms were computed using the GAMMA Remote Sensing software (Wegmuller and Werner, 1997), using 5-meter resolution LiDAR digital elevation models for topographic correction. InSAR time series and linear deformation rate maps for each scene were computed from the set of highly coherent unwrapped interferograms using a linear least-squares inversion technique based on a small-baseline subset algorithm (Samsonov *et al.,* 2011).

Figure 2 (a-d) shows the average surface deformation rates at each of the four sites. The geometries of active horizontal SAGD wells are plotted over the average deformation maps to demonstrate the association between well locations and surface deformation. Despite the low coherence of the InSAR in some places, we see uplift associated with active horizontal steaming wells at all four sites, in some cases with rates of up to almost 4 cm/year (in the satellite line of site).

Figure 3 shows cumulative LOS deformation from the InSAR time series for the chosen points at each site (red circles from Figure 2) plotted together with the time series of cumulative volume of steam injected, averaged over all wells within the corresponding well cluster. Steaming data was purchased from IHS, a commercial oil and gas database. LOS displacement (in cm) is plotted on the left y-axis, and injected steam volume (in m^3) on the right y-axis. In all cases we see that cumulative surface deformation is correlated with cumulative steam injection volumes.

This persistence of the surface heave with continued steam injection is counterintuitive given that in a mature active SAGD reservoir, both oil and water are continuously produced from the lower well in each pair as steam is injected into the upper well, so that net fluid volume in the reservoir is decreasing with time. This suggests that the observed surface heave must result from geomechanical and thermal effects of the SAGD process rather than a net change in volume of pore fluids in the reservoir.

We present a series of simple numerical models showing how thermal effects of the SAGD process can generate surface heave at rates comparable to what is observed in the InSAR dataset. Although geomechanical models aimed at understanding SAGD and optimizing production have already been developed (e.g. Dusseault and Rothenburg (2002); Dusseault, (2007); Yin et al., (2009), Azad and Chalaturnyk (2011)), the mechanisms leading to deformation within the reservoir and the overburden are still not very well understood. We use forward modelling to estimate how much surface deformation can be generated by porous flow and thermal expansion in a typical SAGD operation.

In this study, we use the finite element method (FEM) and finite difference method (FDM) to explain the observed heave from the perspective of reservoir geomechanics.

We experiment with three different model configurations with different combinations of overburden thickness and elastic properties to gauge the relative impact of these parameters on surface deformation. These models are designed to represent typical SAGD conditions, based on available information on the Long Lake and Surmont sites.

In SAGD operations, high temperature steam (> 200 Celsius) is injected into the reservoir through the upper well, and heat conduction into the oil sand decreases the viscosity of the bitumen. As the bitumen melts it flows out of the sandstone, allowing the steam to flow into the vacated pore space. Thus heat flow and steam chamber growth within the reservoir are driven primarily by advection through the pore spaces in the sandstone, creating an envelope of hot fluid that expands out into the reservoir. We use Computer Modelling Group's commercial software, CMG-STARS, to simulate the porous flow and thermal expansion of the reservoir and the induced overburden deformation. It uses FDM for reservoir flow modeling and FEM for geomechanical modeling.

The CMG-STARS reservoir flow simulation module accounts for porous flow as well as phase changes of bitumen and water, both of which lead to changes in effective stress (and thus localized volume changes within the reservoir). It also calculates heat flow and temperature field of steam chamber. The reservoir sandstone and overburden are treated as purely elastic, so the simulation does not consider volume changes due to plasticity, failure, creep and consolidation. We separate the SAGD site into 3 layers: overburden, reservoir and underburden. Three horizontal wells are placed in the center of the reservoir layer with a horizontal spacing of 50 m.

In the simulation process, steam is injected into the reservoir at a rate of approximately 325 m^3/day through each well. The temperature of the injected steam is set to be 245 Celsius, and once bitumen has begun to flow out of the reservoir, heat transfer is mainly driven by advection of steam into the vacated pore space. The simulation was run for 10 years. We use three combinations of overburden thickness and overburden elasticity in this experiment. For configuration 1, we use an overburden thickness of 180 m, which is close to the depth to the top of the reservoir at Long Lake area. Young's modulus is set to be 1 GPa. Configuration 2 uses the same overburden thickness but harder rock, with a Young's modulus of 2 GPa. Finally, for Configuration 3 we tested an overburden thickness of 400 m (which is close to the depth of the reservoir at the Surmont site) and a Young's modulus of 1 Gpa for the overburden. Possion's ratio is assumed to be constant at 0.3 for all three cases. The sandstone reservoir is assumed to be elastic with a Young's modulus of 0.5 Gpa and Poisson's ratio of 0.3 in all three configurations. Further details of the modelling can be seen in *Pearse et al*., 2014.

Results

Figure 4 (a) shows the deformation from Configuration 1 in the 10^{th} year of the operation. The maximum heave is observed in the center of the model with a magnitude of 0.065m. Figure 4 (b) shows the deformation of the three configurations as a function of time at the maximum deformation point shown at Figure 4 (a). Configuration 2, with the thinnest overburden and Young's modulus of 2 GPa, shows the strongest deformation. Configuration 1, which has the same overburden thickness as configuration 1 but with weaker rock (a Young's modulus of 1 Gpa), starts to show slightly less deformation than Configuration 2 after about 3.5 years. The most influential parameter is overburden thickness: increasing the depth-to-top of the reservoir from 180 m to 400 m reduces the magnitude of surface deformation by about a factor of 3 (Configuration 3).

Discussion of results

Our reservoir models tend to somewhat under-predict surface deformation, when compared with the peak rates in the InSAR deformation rate maps. In the case of model configuration 2 (based on the Long Lake site) our models estimate about 2 cm/year of uplift within the first 3 years, which gradually tapers off and eventually subsides, whereas InSAR shows rates as high as 3.5-4 cm/year at Long Lake (though this varies from well group to well group) throughout the span of the observations.

The fact that the models do not produce an exact fit to the shape and rates of heave observations at each individual site is a result both of limitations in the data available (such as uncertainty in rock parameters), and of several simplifying assumptions we make in the modelling. Real oilsand reservoirs have irregular shapes, heterogeneous material properties, and spatially varying depth-to-top of the reservoirs. The complexity of the well configurations, the limited availability of information on the day-to-day operations, reservoir geometries, and overburden properties, and the short timespan of the InSAR observations made it impossible to produce a fully realistic model of any particular reservoir.

Conclusions

We completed a multi-year InSAR surface deformation survey of a broad region within the Alberta oil sands which includes four separate active SAGD operations. Our data show that surface heave between about 1.5 cm/year and 4 cm/year is associated with active steam injection at all the sampled sites, and that rates of uplift are well-correlated with rates of steam injection despite a net loss of total reservoir fluids with time. Numerical reservoir models using coupled finite-difference and finite-element methods demonstrate that surface heave at rates consistent with observation can be generated by the stress fields created within the reservoir by porous flow of steam and bitumen, as well as thermal expansion of reservoir rock produced by the introduction of hot steam. We found that by far the most influential parameter in determining magnitude of surface deformation was the depth to the top of the reservoir.

Our study highlights the importance of using InSAR observations coupled with production data and increasingly sophisticated modelling to monitor and predict the surficial effects of SAGD production and their potential relevance to safety, integrity of reservoir caprock, and effects on local infrastructure. Future studies should focus on observing new SAGD operations throughout their lifespans to capture both the transient effects of the initiation of production and any long-term surficial changes following the cessation of production. Current efforts are underway to improve reservoir modelling techniques (see for example Shen *et al.,* 2014). Such studies will provide better constraints on the material properties of oilsand reservoirs and improve our understanding of the mechanics and surficial effects of enhanced oil recovery techniques, including the long-term response of reservoirs to the SAGD process.

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Figures

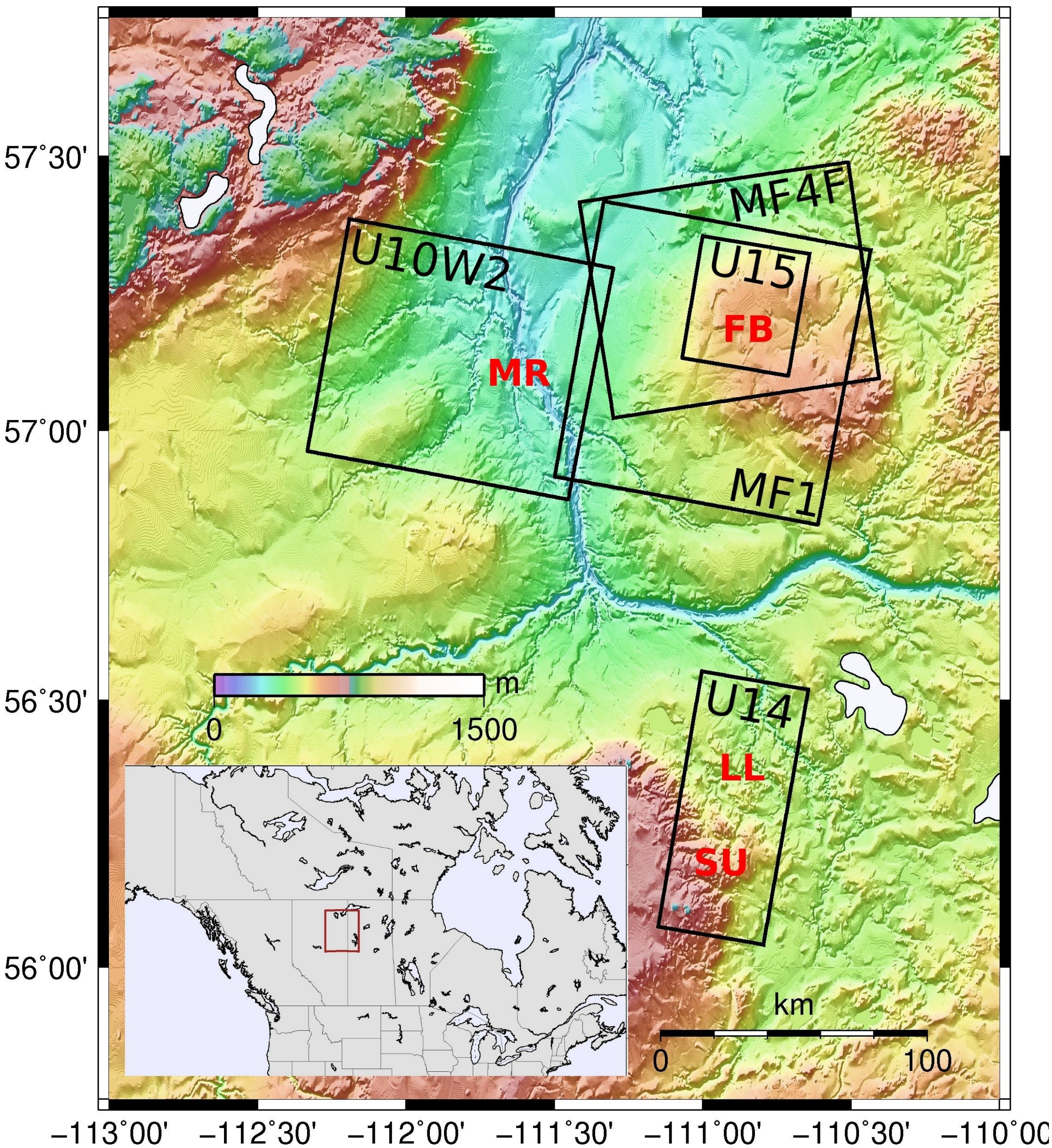

Figure 1: Coverage of Alberta's oil sand regions by RADARSAT-2 InSAR scenes. The location of the chosen SAGD sites are labelled as LL (Long Lake), SU (Surmont), MR (MacKay River) and FB (Firebag). Inset: map of Alberta showing location of the study area.

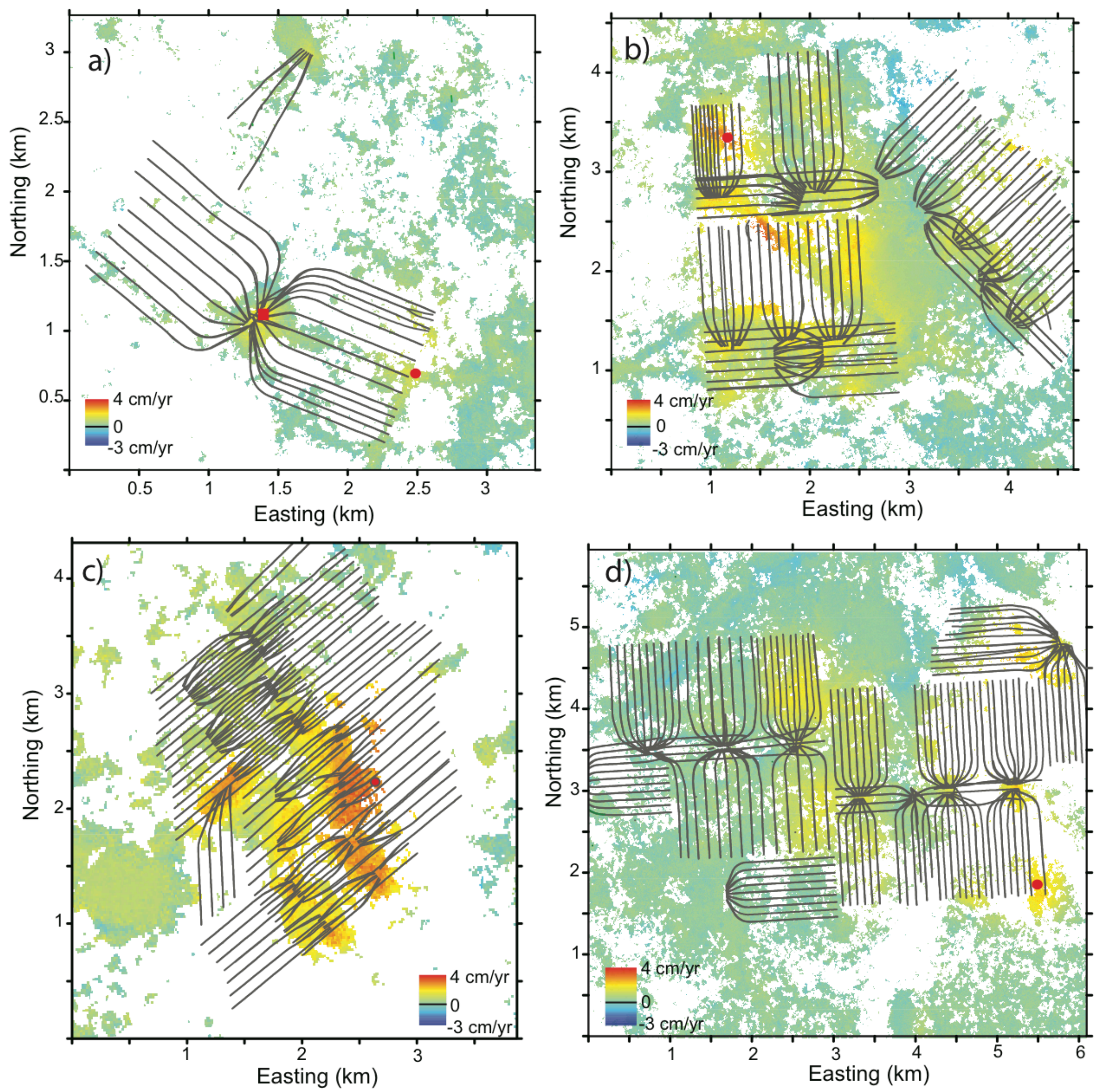

Figure 2: Images of average rate of line-of-sight surface deformation in cm/year four SAGD sites: (a) Surmont; (b) Long Lake; (c) MacKay River; and (d) Firebag. The local

horizontal SAGD well geometries are plotted in grey. The solid red circles indicate locations chosen for plotting InSAR time series.

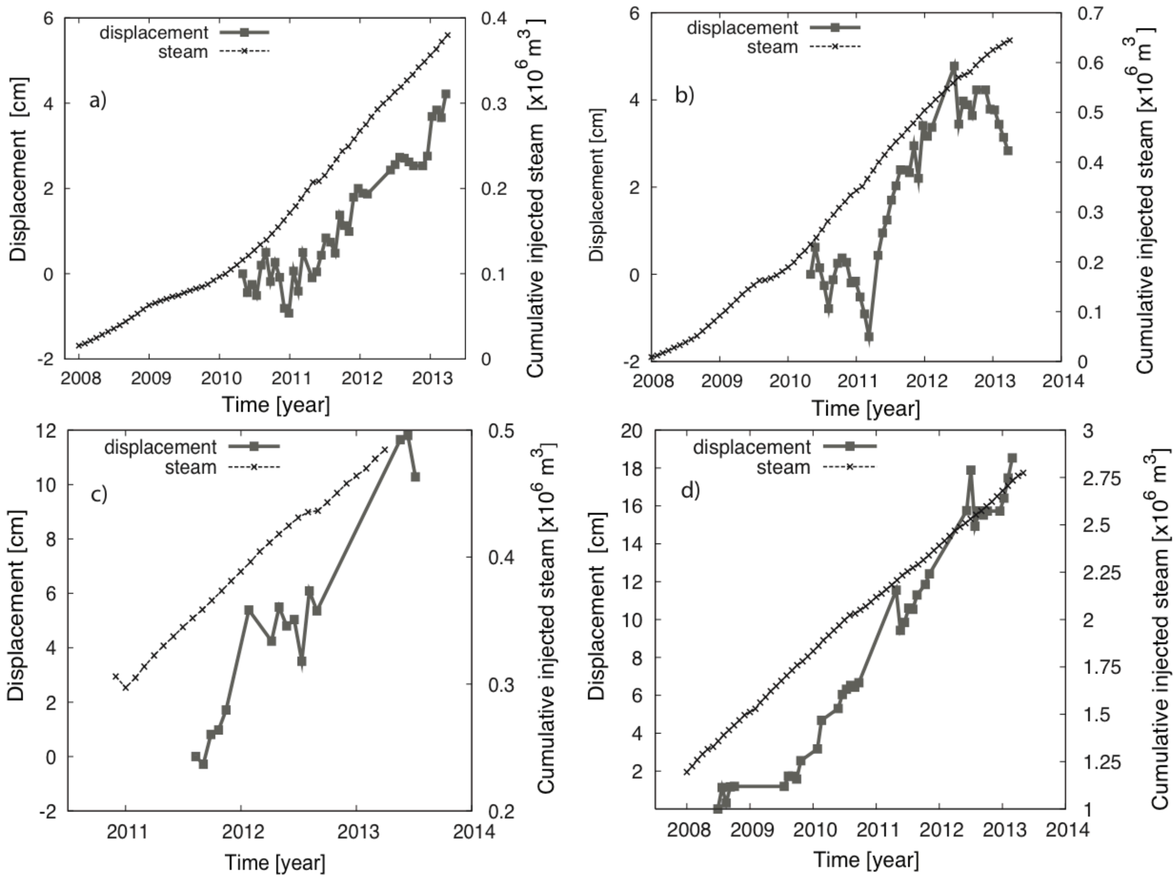

Figure 3: Time series of cumulative surface deformation plotted along with cumulative injected steam volume for (a) Surmont, (b) Long Lake, (c) MacKay River and (d) Firebag. The time series are for points marked by the red circles in Figure 2 (a-d).

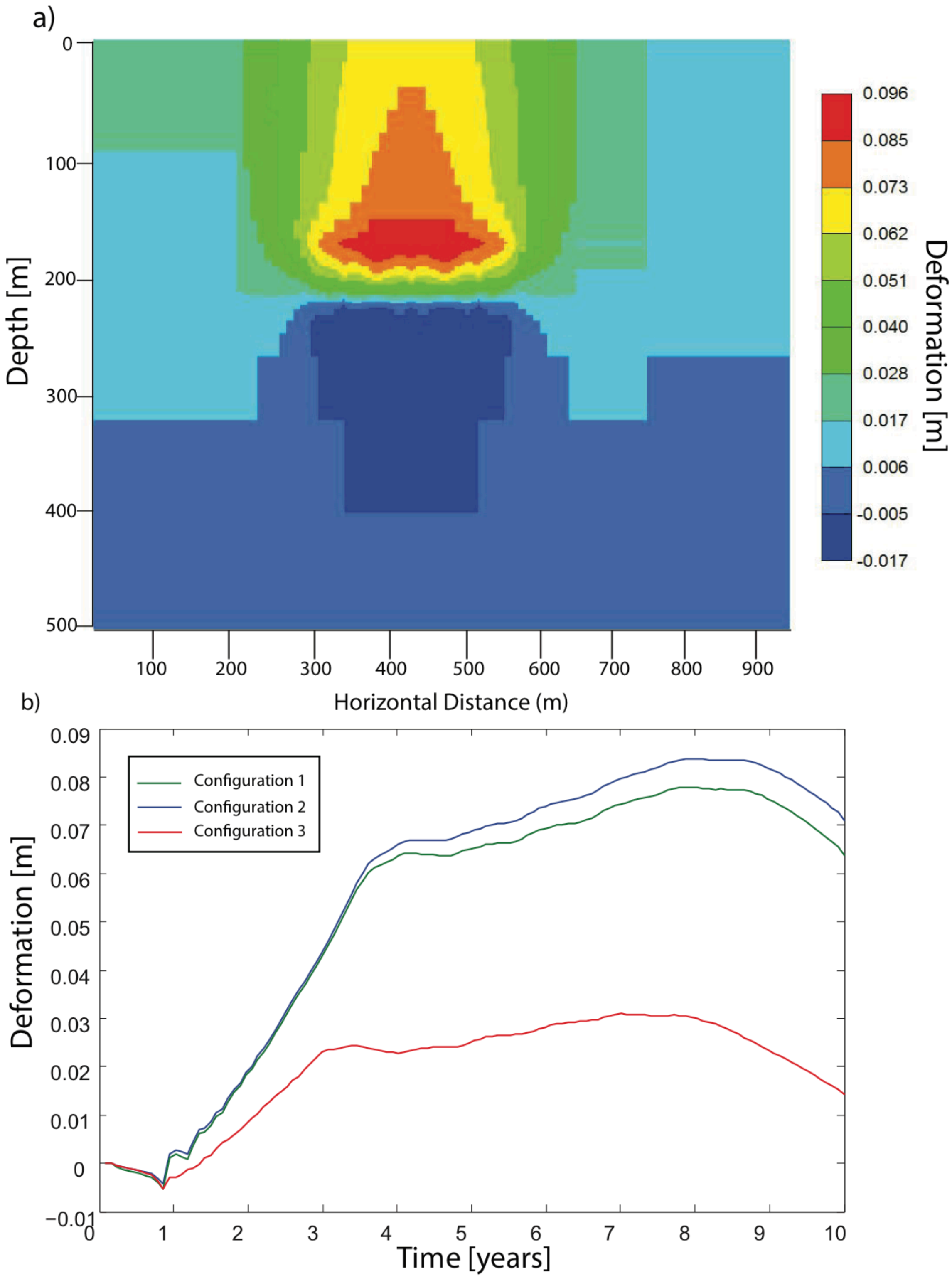
a)
Depth [m]
0
100
200
300
400
500
100
200
300
400
500
600
700
800
900
Horizontal Distance (m)
Deformation [m]
0.096
0.085
0.073
0.062
0.051
0.040
0.028
0.017
0.006
-0.005
-0.017
b)
Deformation [m]
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−0.01
Configuration 1
Configuration 2
Configuration 3
0
1
2
3
4
5
6
7
8
9
10
Time [years]

Figure 4: Deformation induced by injection of steam and extraction of bitumen. The duration of the simulation is ~10 years starting from the installation of heaters: a) Vertical deformation of the model configuration 2. This configuration has reservoir depth similar to that of Long Lake. The strongest deformation is observed in the center of the model, which shows 0.07 m of vertical deformation at the surface; b) time series of deformation at the maximally deformed point in three configurations.