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Shell Canada Energy
400 - 4th Avenue S.W.
P.O. Box 100, Station M
Calgary, Alberta T2P 2H5
Internet www.shell.ca

March 31st, 2017

Patrick Zhang, P.Eng.
Reservoir Engineer
Oil & Gas Southwest Region
Authorizations Branch
AER

Subject: **Condition 16 of APPROVAL No11837C**
InSAR Efficacy Report

Shell Canada Energy, by its managing partner, Shell Canada Limited ("Shell"), hereby submits the special report on the efficacy of InSAR as per condition 16 of the Carbon Dioxide Disposal Approval No. 11837C.

If you require more information or clarification, please contact Simon O'Brien, Quest Storage Manager, either by phone at 587-228-4454, or email at Simon.OBrien@shell.com .

Regards,

Simon O'Brien
Quest Storage Manager
Shell Canada Limited

SHELL CANADA LIMITED

Quest Carbon Capture and Storage Project

CONDITION 16 of APPROVAL No11837C

InSAR Efficacy Report

Prepared By:

Shell Canada Limited
Calgary, Alberta

March 31, 2017

1. Preface

This Special Report (the "Report") is provided in response to Condition 16 in the AER application approval referenced in the Carbon Dioxide Disposal Approval No. 11837C (the "Approval"), issued on May 12th 2015 to Shell Canada Limited ("Shell"). The filing deadline on this Report has been previously extended on application to March 31st, 2017.

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2. AER Condition

Condition 16 of the Approval states as follows:

> 16) The Approval Holder must provide a special report by July 31, 2015. This report must include the efficacy of the InSAR program. Installation of global positioning system (GPS) instruments may be required if the quality of InSAR data is too low for effective monitoring.

Note that the deadline for submission of the special report on the efficacy of the InSAR program has been extended to March 31, 2017, as provided for in an email of the AER dated February 8th, 2016:

"Your request for extension on the InSAR report is reasonable as long as data is continuously collected. The July 31, 2015 deadline date in clause 16 of Carbon Dioxide Disposal & Containment Approval No. 11837C was extended on May 27, 2015 to July 31, 2016. The deadline date is further extended to March 31, 2017."

3. Response

In response to Condition 16 of the Approval, the following work items were completed:

1. Processing of all Radarsat-2 (RSAT2) satellite images collected between 3 June 2011 and 9 December 2016 by TRE. This work is summarized in Appendix I.
2. Integration of processed RSAT2 data into a geomechanical workflow to assess efficacy of InSAR. This work is summarized in Appendix II.

Efficacy of InSAR program:

InSAR is a viable technology for assessing unexpected surface heave. Its value, however, is limited for continuous monitoring given the site specific characteristics of the Quest site. Based on the observed and modelled pressure build-up within the BCS, expected to be less than 1.5 MPa after 25 years of injection (using a two well injection scenario), dilation within the BCS storage complex will be small. The resulting surface uplift will likely fall within the noise levels of the measured ground displacement. As a result, InSAR has limited value as a continuous monitoring technology for unexpected containment issues. As injected volumes increase, it may have some value from a conformance perspective.

Installation of global positioning system (GPS) instruments:

The quality of the InSAR data is sufficient for monitoring of surface heave. There is no need to install GPS instruments. This is based on the following observations:

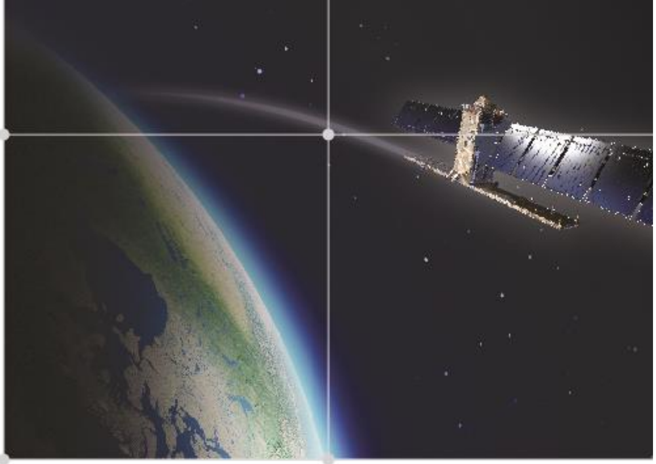
- Optical levelling and the Global Positioning System are proven alternative means of monitoring surface uplift to within 1 mm/year. Both are regretted due to poor areal and temporal sampling relative to InSAR.
- Processing of RSAT2 satellite imagery from 3 June 2011 and 9 December 2016 yielded an average precision of ground displacement measurements of ±0.5 mm/yr, corresponding to a 44% improvement compared to the 2014 processing (±0.9 mm/yr).

Proposed Action Plan:

The InSAR technology will be considered a contingency monitoring technology with a focus on the AOR (area of review) of the Quest SLA (sequestration lease area). In other words, InSAR will be used in the event of another MMV technology or observation indicating the need for further investigation.

Please refer to Appendices I and II for further details.

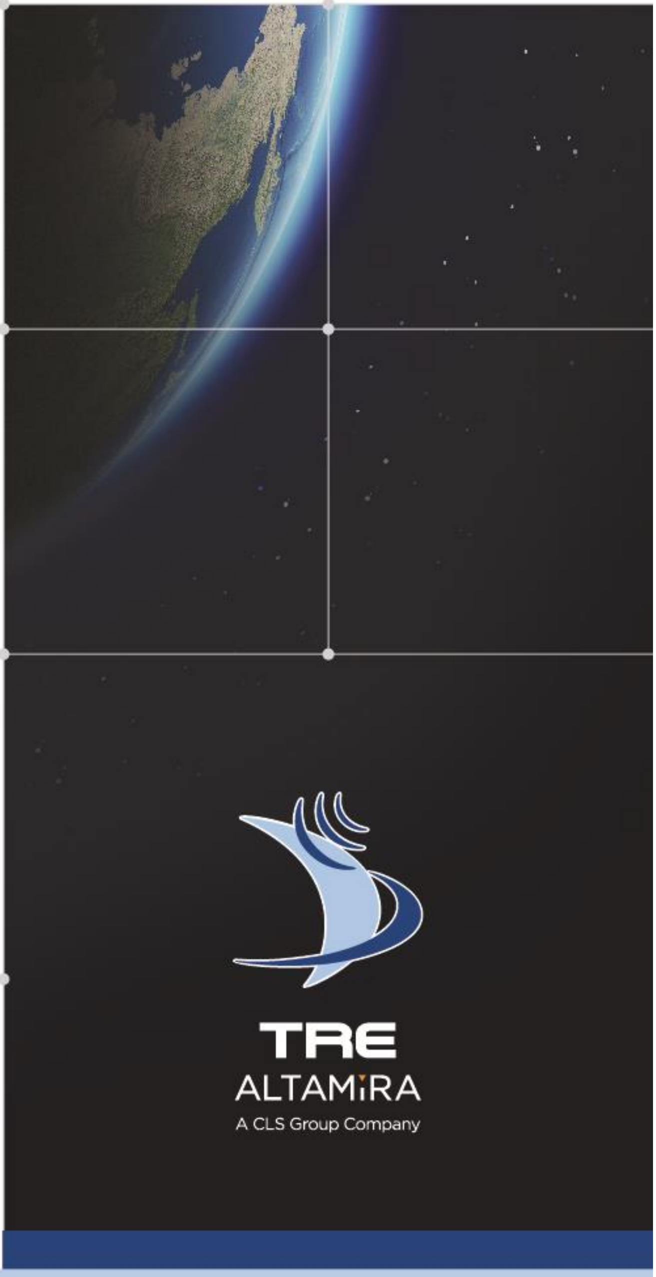
Appendix I: TRE - SqueeSAR Analysis of Ground Movement over the Quest CCS site



SqueeSAR Analysis of Ground Movement over the Quest CCS site

Technical Report

13 March 2017



TRE
ALTAMIRA
A CLS Group Company

Report specifications

Client:

Ayo Adediran
Shell Canada Energy
PO Box 1947, Station 100
Calgary, AB
T2P 2M6

Reference:

Technical Report	2016 SqueeSAR Analysis of Ground Movement over the Quest CCS site
TRE ALTAMIRA Job Order:	JO16-3012
Client Contract Number:	PO4900019663
Client Order Date:	2016/01/03

Prepared by:

TRE ALTAMIRA

Authors:	Danielle Ambs
Verified by:	Jessica Morgan
Approved by:	Giacomo Falorni
Date:	2017/03/13
Version:	1.1

Executive Summary

TRE Altamira Inc. (TRE) was contracted by Shell Canada Energy Limited (Shell) to monitor ground displacement over the Quest Carbon Capture and Storage injection site. This report describes the approach and results of the analysis carried out using TRE's proprietary SqueeSAR™ algorithm and radar satellite imagery collected between 3 June 2011 and 9 December 2016. The key findings are listed below:

- Little or no ground movement was observed over most of the area of interest (AOI), except for an area of subsidence identified in a forested portion in the north of the AOI.
- No significant changes in ground deformation have been observed since the beginning of CO_2 injection on 23 August 2015:
    - The average surface displacement rate observed over the Quest site prior to the start of CO_2 injection (from 3 June 2011 to 17 August 2015) was -0.9 mm/year.
    - The average surface displacement rate observed over the same area since the start of CO_2 injection (23 August 2015 – 9 December 2016) is -1.6 mm/year.
- Average ground displacement within 10 km of injection well pads increased from 1.0 + mm/year to -1.4 mm/year after the start of CO_2 injection. This change falls within the precision of the measurement and was also observed over inactive injector SCL 5-35.
- Measurement points with seasonal variations in the time series have been observed at specific locations. These include bridges, where changes in temperature cause thermal expansion and contraction of the structures over the course of the year. This appears unrelated to CO_2 injection activities.
- Measurement point density increased 173% over the full AOI (39.6 points/km^2) compared to the 2014 results (14.5 points/km^2). This includes an average increase of 126% in the areas surrounding the three injection sites.
- The average precision of the ground displacement measurements has reached ±0.5 mm/year for the current analysis, a 44% improvement compared to the 2014 processing (±0.9 mm/year).

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1. Radar Data

The data set used for this analysis consisted of 81 images acquired by the Canadian Space Agency Radarsat-2 (RSAT2) satellite between 3 June 2011 and 9 December 2016 on a 24-day acquisition schedule (Table 1). Images were collected in Wide Multi-Look Fine Beam Mode 3 (42.6° from vertical) in an ascending orbit. Due to the size of the Quest AOI, two adjacent RSAT2 frames on track 28 are required for complete site coverage (Figure 1). One image acquired on 8 August 2012 was excluded from processing due to excessive atmospheric noise.

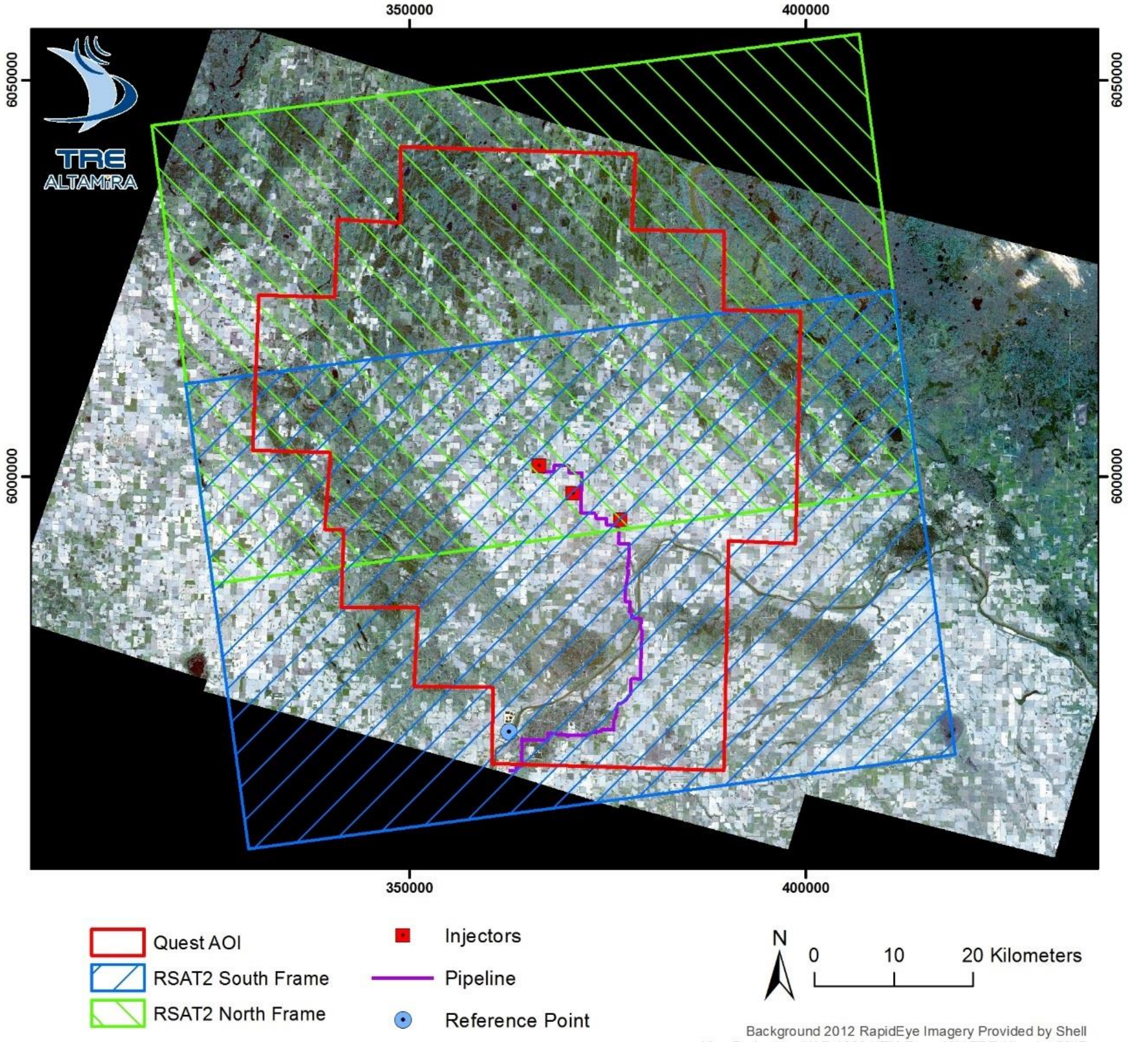
Initial 2012 Baseline Archive									
1	03/06/2011	**6**	01/10/2011	**11**	29/01/2012	**16**	21/06/2012	**20**	19/10/2012
2	27/06/2011	**7**	25/10/2011	**12**	22/02/2012	**17**	15/07/2012	**21**	12/11/2012
3	21/07/2011	**8**	18/11/2011	**13**	10/04/2012		08/08/2012	**22**	06/12/2012
4	14/08/2011	**9**	12/12/2011	**14**	04/05/2012	**18**	01/09/2012		
5	07/09/2011	**10**	05/01/2012	**15**	28/05/2012	**19**	25/09/2012		
2014 Monitoring Report Archive									
23	23/01/2013	**28**	23/05/2013	**33**	20/09/2013	**38**	18/01/2014	**43**	18/05/2014
24	16/02/2013	**29**	16/06/2013	**34**	14/10/2013	**39**	11/02/2014	**44**	11/06/2014
25	12/03/2013	**30**	10/07/2013	**35**	07/11/2013	**40**	07/03/2014	**45**	05/07/2014
26	05/04/2013	**31**	03/08/2013	**36**	01/12/2013	**41**	31/03/2014		
27	29/04/2013	**32**	27/08/2013	**37**	25/12/2013	**42**	24/04/2014		
2016 Monitoring Report Archive									
46	29/07/2014	**54**	02/03/2015	**62**	10/09/2015	**70**	20/03/2016	**78**	28/09/2016
47	22/08/2014	**55**	26/03/2015	**63**	04/10/2015	**71**	13/04/2016	**79**	22/10/2016
48	15/09/2014	**56**	19/04/2015	**64**	28/10/2015	**72**	07/05/2016	**80**	15/11/2016
49	02/11/2014	**57**	13/05/2015	**65**	21/11/2015	**73**	31/05/2016	**81**	09/12/2016
50	26/11/2014	**58**	06/06/2015	**66**	15/12/2015	**74**	24/06/2016		
51	20/12/2014	**59**	30/06/2015	**67**	08/01/2016	**75**	18/07/2016		
52	13/01/2015	**60**	24/07/2015	**68**	01/02/2016	**76**	11/08/2016		
53	06/02/2015	**61**	17/08/2015	**69**	25/02/2016	**77**	04/09/2016		

Table 1: Dates of the RSAT2 archive images. The date highlighted in red corresponds to the image which was excluded from processing due to excessive atmospheric noise.

2. Data Processing

2.1. Area of Interest

The Quest area of interest (AOI), as indicated by Shell, can be seen below in Figure 1. The Quest site is located approximately 80 km northeast of Edmonton, Alberta. The 3790.9 km^2 enclosed by the AOI is dominated by agriculture and forested areas and has little topographic variation. Sparse man-made structures present within this area include small towns, roads and other infrastructure. The AOI is located in an area with a humid, continental climate and encounters a high amount of precipitation annually, including snow cover (which can limit radar reflectivity) for up to six months of the year.



Background 2012 RapidEye Imagery Provided by Shell
Map Projection: NAD 1983 UTM Zone 12N TRE Altamira 2017

Figure 1: The area of interest (AOI) and RSAT2 frame footprints for Quest data processed using imagery dated 3 June 2011 to 9 December 2016.

2.2. Injection site locations

Detailed information regarding the location of the injection sites is indicated in Table 2.

Injection Well Full Name	Injection Well Short Name	X Coordinate (m)	Y Coordinate (m)
102-05-35-059-21Q4-00	SCL 5-35*	366,359.88	6,001,418.03
103-07-11-059-20W4-00	SCL 7-11	376,614.76	5,994,645.58
100-08-19-059-20W4-00	SCL 8-19	370,645.70	5,997,974.82

Table 2: Locations of drilled injection well sites on the Quest site.
**No injection occurred at SCL 5-35 during the time period covered by this analysis.*

2.3. Large area processing

In all prior analyses, it had been necessary to divide the radar imagery into separate tiles to be processed individually. Due to the continued increases in the computational capacity of TRE Altamira's data processing centre, increased experience with the surface characteristics of the Quest site, as well as advances in the SqueeSAR algorithm, it is now possible to analyze the full AOI in one processing. A single reference point was therefore used for the entire AOI, instead of the multiple reference points required previously. All points identified within the SqueeSAR analysis have undergone TRE's ISO-certified quality management procedures.

3. Results

3.1. Cumulative displacement

Cumulative surface displacement between 3 June 2011 and 9 December 2016 is shown in Figure 2. Surface displacement values across the full AOI measured from 3 June 2011 to 9 December 2016 range from +115.2 to -283.7 mm (increased from +75.9 to -68.0 mm in 2014). The largest values are associated with very localized movement on individual structures (e.g. buildings) that are not related to the regional ground deformation that would be expected from injection operations at depth. Eighty percent of the measurement points fall within one standard deviation (*-21.0 to +7.0 mm)* and 96% fall within 2 standard deviations of the average cumulative displacement (*-35.0 to +21.0 mm*). The distribution of cumulative displacement data can be seen in Figure 3. A similar data distribution was obtained with the 2014 results. No discernible change has been observed since the start of CO_2 injection.

Each measurement point corresponds to a Permanent Scatterer (PS) or Distributed Scatterer (DS), and is color-coded according to the magnitude of total movement. Surface displacement is measured along the line-of-sight (LOS) of the satellite and is represented in metric measurement units in the figures below. Negative values (red) indicate surface displacement away from the satellite (e.g. subsidence), while positive values (blue) indicate surface displacement towards the satellite (e.g. uplift).

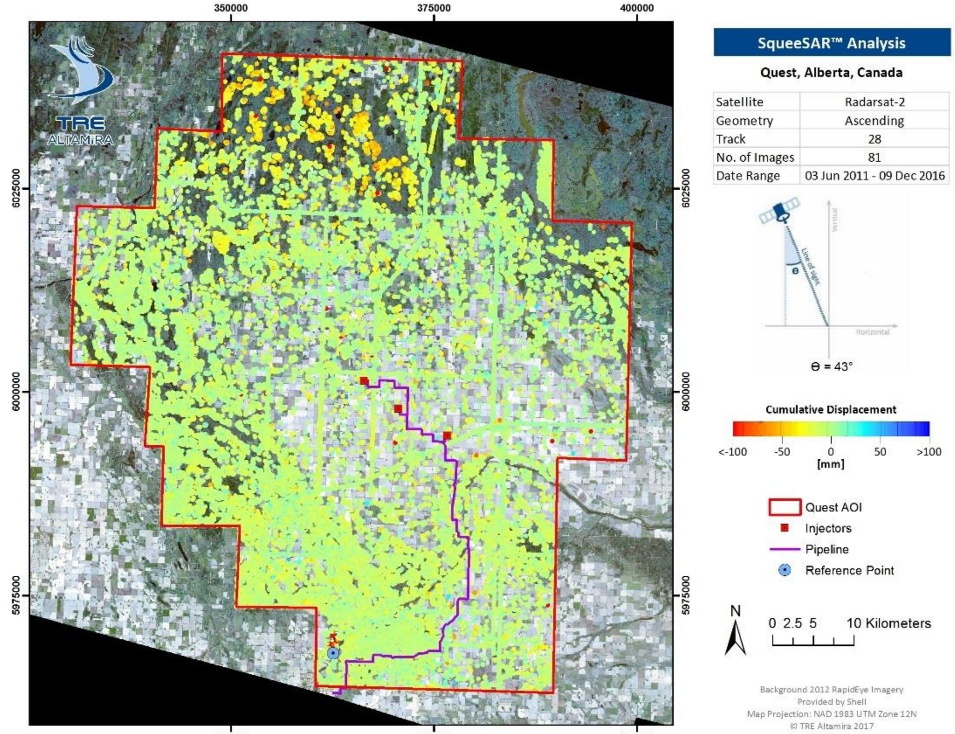


Figure 2: Cumulative deformation measured between 3 June 2011 and 9 December 2016.

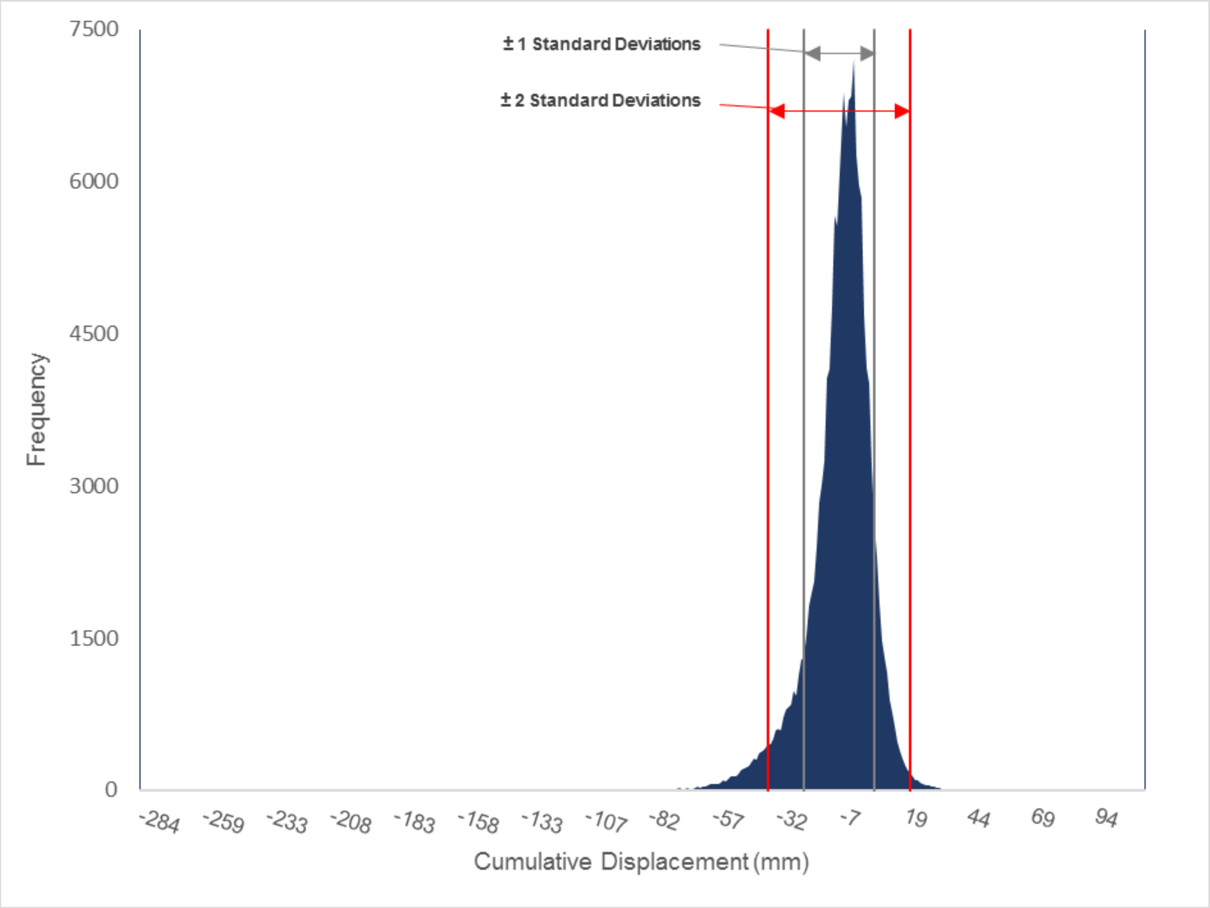
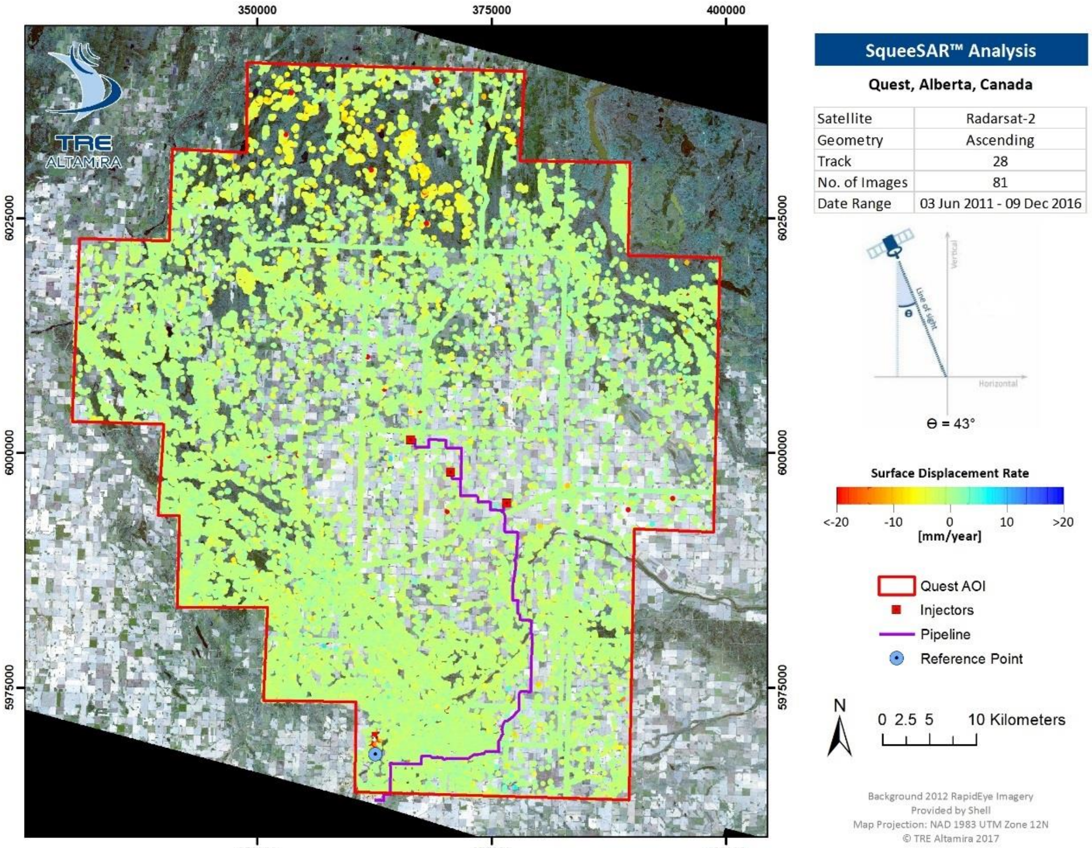


Figure 3: Distribution of cumulative deformation results.

3.2. Displacement rate

The line-of-sight (LOS) displacement rates are calculated from a linear regression of the ground movement measured over the entire time period covered by the acquired satellite images. An average annual surface displacement rate of -1.0 ± 0.5 mm/year was identified during this data processing, compared to -0.2 ± 0.9 mm/year measured in 2014. (Figure 4). The values are statistically similar and indicate little or no effect of CO_2 injection on ground displacement. This can also be seen within 1 km of the well pads, where the average annual displacement rate is -1.8 mm/year since the start of injection compared to -1.4 mm/year prior to injection operations. Further analysis of the annual displacement rates near the CO_2 injectors is outlined in Section 4.3.



Satellite	Radarsat-2
Geometry	Ascending
Track	28
No. of Images	81
Date Range	03 Jun 2011 - 09 Dec 2016

Figure 4: Annual surface displacement rates.

3.3. Displacement rate standard deviation

The average standard deviation of all measurement points identified within the AOI is ± 0.5 mm/year (Figure 5) and continues to improve (e.g. was ±0.9 mm/year in 2014).

The standard deviation of the surface displacement data characterizes the error associated with the measurements of surface displacement. The displacement for a given point should be read as Displacement Rate ± Standard Deviation. Areas impacted by higher standard deviation values indicate greater variability in measured displacement and are helpful in identifying surface features with rapid or inconsistent movement patterns. On average, standard deviation values increase with distance from the reference point. In the case of Quest the northernmost measurement points have the highest standard deviation values as they are the farthest from the reference point (Figure 5).

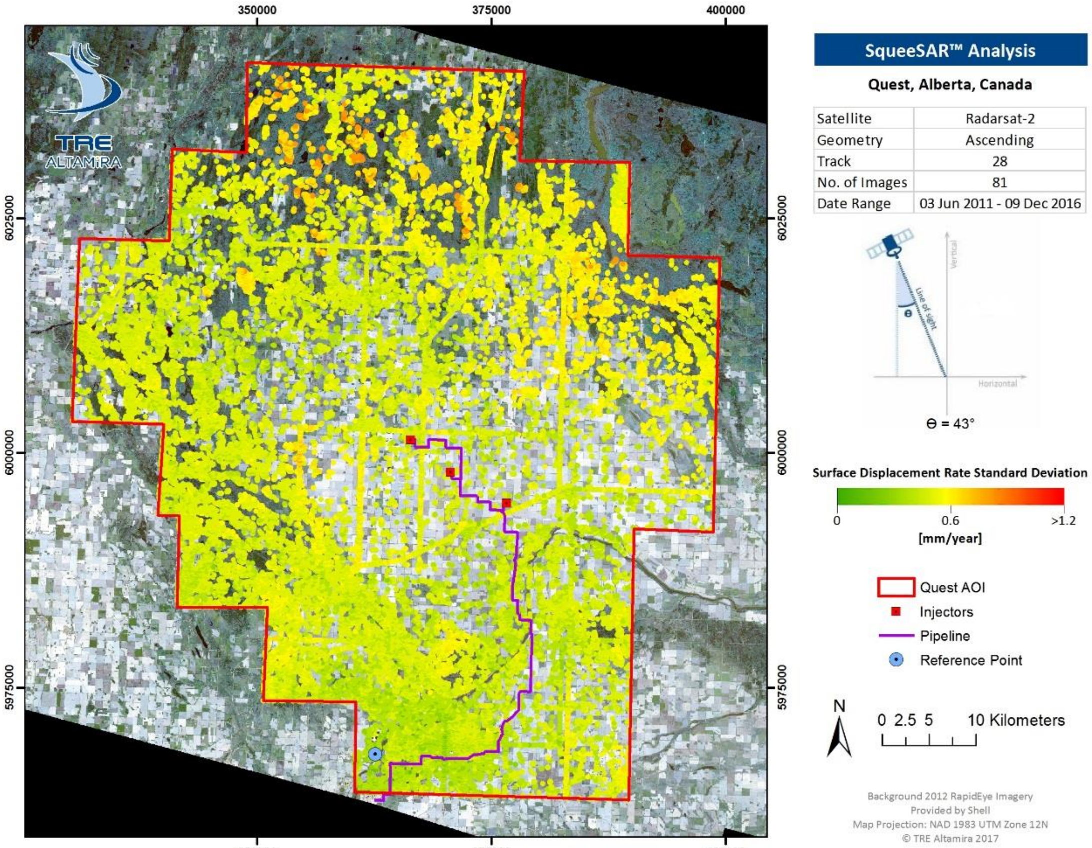


Figure 5: Standard deviation values of the annual displacement rates.

3.4. Acceleration

Acceleration rates can be used to identify non-linear trends in the deformation time series and areas where the deformation rate is increasing or decreasing over time. Negative accelerations, marked in red, indicate either an increase in downward displacement rates, or a decrease in uplift rates. Positive accelerations, marked in blue, indicate either an increase in upward movement or a decrease in subsidence.

Acceleration rates within the area of interest are low to null. No relevant acceleration is observed in the area of the injection well pads. Slight increases in subsidence rates are observed in the forested areas in the north of the AOI that appear unrelated to injection activities (Figure 6).

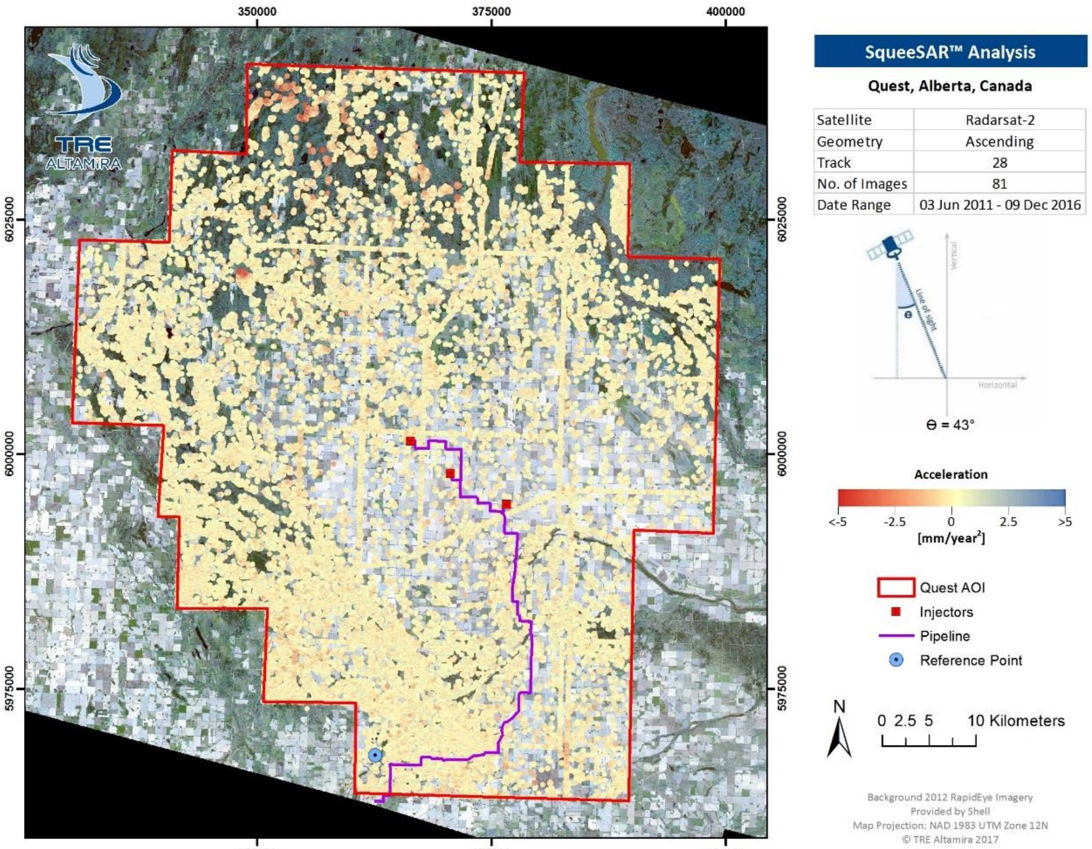


Figure 6: Measurement point acceleration rates.

4. Observations

4.1. Overview of ground deformation

Ground deformation over the area of interest is dominated by large regions of slow movement (-1.0 mm/year on average), particularly in the northern forested region of the area of interest (Figure 8). Areas surrounding Shell operations appear mainly stable with small areas of slight subsidence. Mild seasonal variations in surface displacement are observed in the northern forested areas away from Shell operations. Such variations may be related to seasonal phenomena such as freeze/thaw cycles, groundwater recharge due to precipitation and snow/ice melt, changes in temperature and annual variations in soil moisture content. In general, the seasonal variations do not alter the underlying long-term deformation trend but simply introduce fluctuations of the displacement values on an annual cycle (Figure 7).

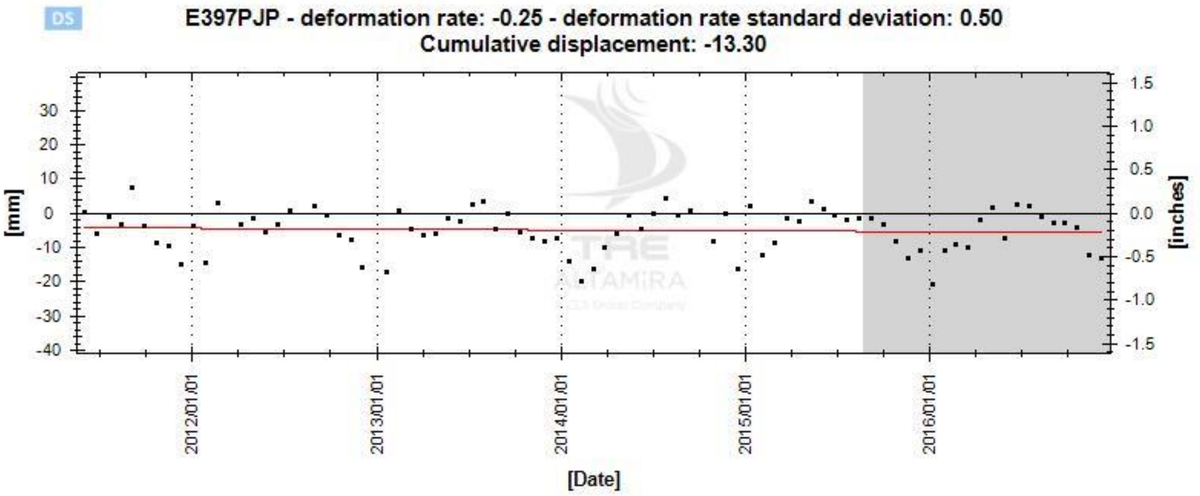
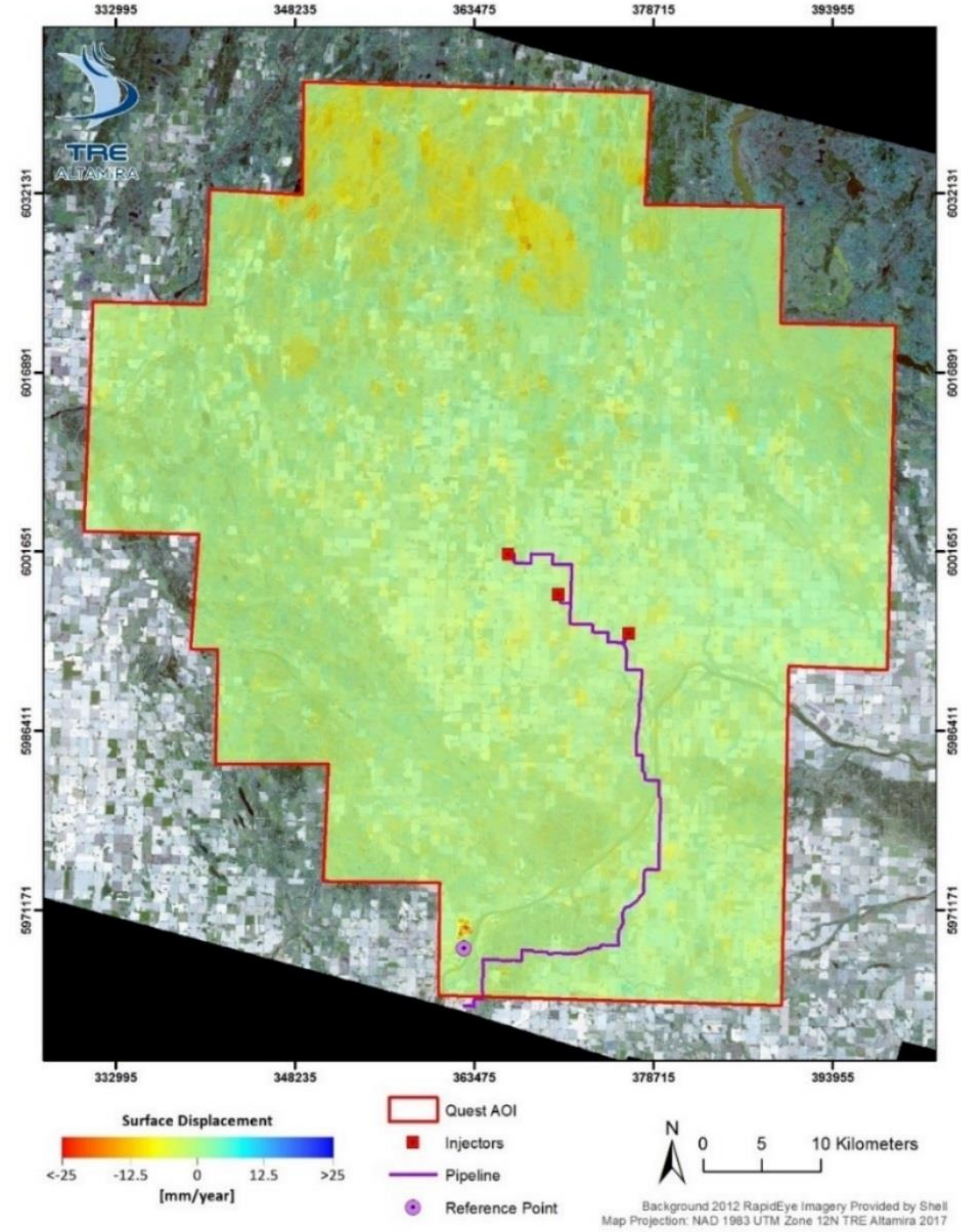


Figure 7: Example of a time series of a measurement point affected by seasonal fluctuations. This point is located on a bridge crossing the North Saskatchewan River approximately 25 km south of injection well pads. The period of time during which injection has taken place is indicated by the shaded area.



Background 2012 RapidEye Imagery Provided by Shell
Map Projection: NAD 1983 UTM Zone 12N TRE Altamira 2017

Figure 8: Interpolated surface displacement rates based on the point data observed in Figure 4, providing an overview of ground deformation over the full processed area.

4.2. Comparison to previous analysis

This analysis identified a total of 149,942 measurement points for a point density of 39.6 points/km^2, a 173% increase in point density compared to the analysis in 2014 (14.5 points/km^2). The distribution of points is now fairly homogeneous across the full AOI (Figure 9).

Measurement precision is primarily assessed through the standard deviation of displacement rates and coherence values. This analysis identified an average precision of ±0.5 mm/year (a 44% improvement from ±0.9 mm/year in 2014). The large number of images now contained within the data stack (81 images) is a strong contributor to the large increase in point density and increased precision.

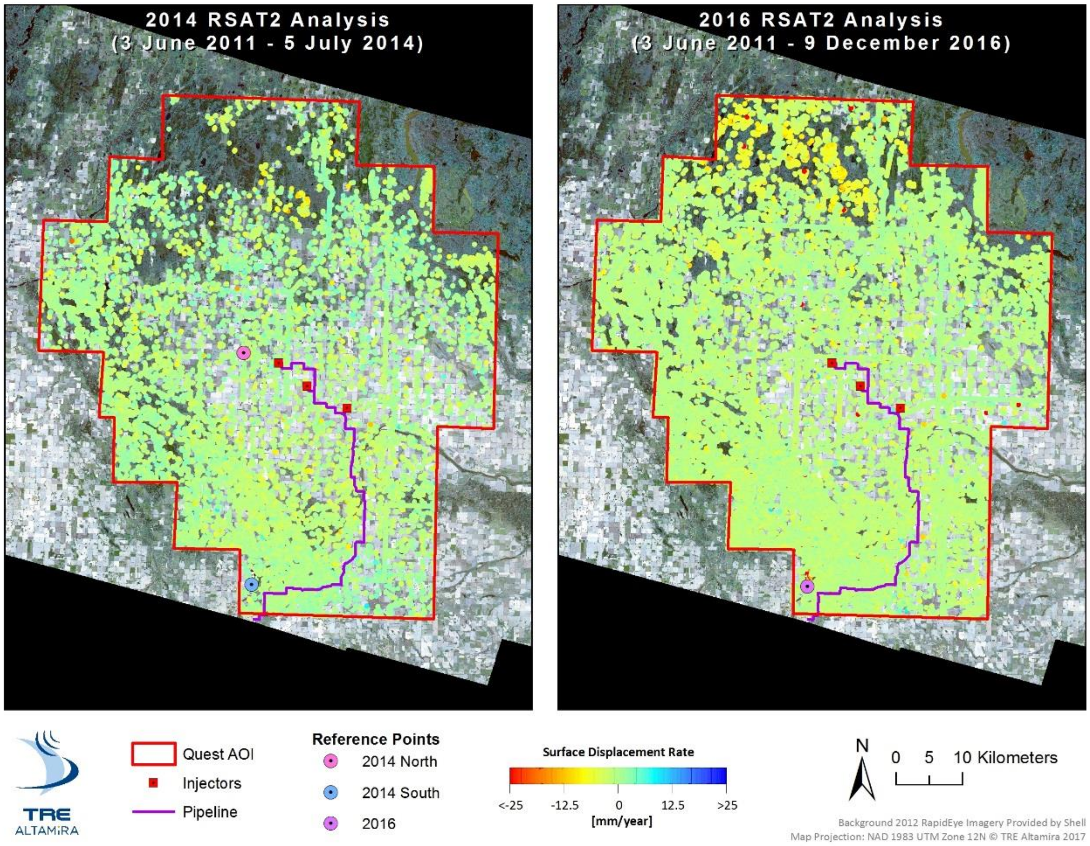


Figure 9: Left panel: Surface displacement results from the 2014 processing.
Right panel: Surface displacement results from the current processing.

A summary of the statistics of each SqueeSAR analysis over the Quest site are shown below in Table 3.

Attribute	Radarsat-2 Analysis 2011 – 2012	Radarsat-2 Analysis 2011 – 2014	Radarsat-2 Analysis 2011 – Dec 2016
No. of Images Processed	22	45	81
Time period covered (years)	1.5	3	5.5
No. of PS	17,753	30,892	74,482
No. of DS	22,145	23,375	75,460
Total No. of Measured Points (PS and DS)	39,898	54,267	149,942
Average PS and DS (per km^2)	10.6	14.5	39.6
Average Displacement Rate (mm/year)	0.3	-0.2	-1.0
Average Displacement Standard Deviation (mm/year)	2.0	0.9	0.5

Table 3: Statistics of the previous and current SqueeSAR analyses conducted over the Quest site.

4.3. Ground Deformation Before and After the Start of Injection

Injection of CO_2 began at SCL 7-11 and SCL 8-19 on 23 August 2015, as indicated by Shell. A summary of changes in average annual surface displacement rates within a 10-km buffer around each injector before (3 June 2011 – 17 August 2015) and since the start (10 September 2015 – 9 December 2016) of injection are summarized in Table 4. Results indicate that the displacement rate changed from -1.0 mm/year to -1.4 mm/year. The change in displacement rate falls within the precision tolerance. The change in displacement rate was also observed around injector SCL 5-35, which is inactive.

Injector	Average Displacement Rates Pre-Injection (mm/year)	Average Displacement Rates Since Injection Start (mm/year)	Change in Average Displacement Rates (mm/year)
SCL 5-35	-1.1	-1.5	-0.4
SCL 7-11	-0.8	-1.2	-0.4
SCL 8-19	-1.1	-1.5	-0.4
Average	**-1.0**	**-1.4**	**-0.4**

Table 4: Changes in average annual surface displacement rates of measurement points within a 10-km buffer of each injector before and after injection began on 23 August 2015. Injector SCL 5-35 is currently inactive.

4.4. Point Distribution and Density around Injection Sites

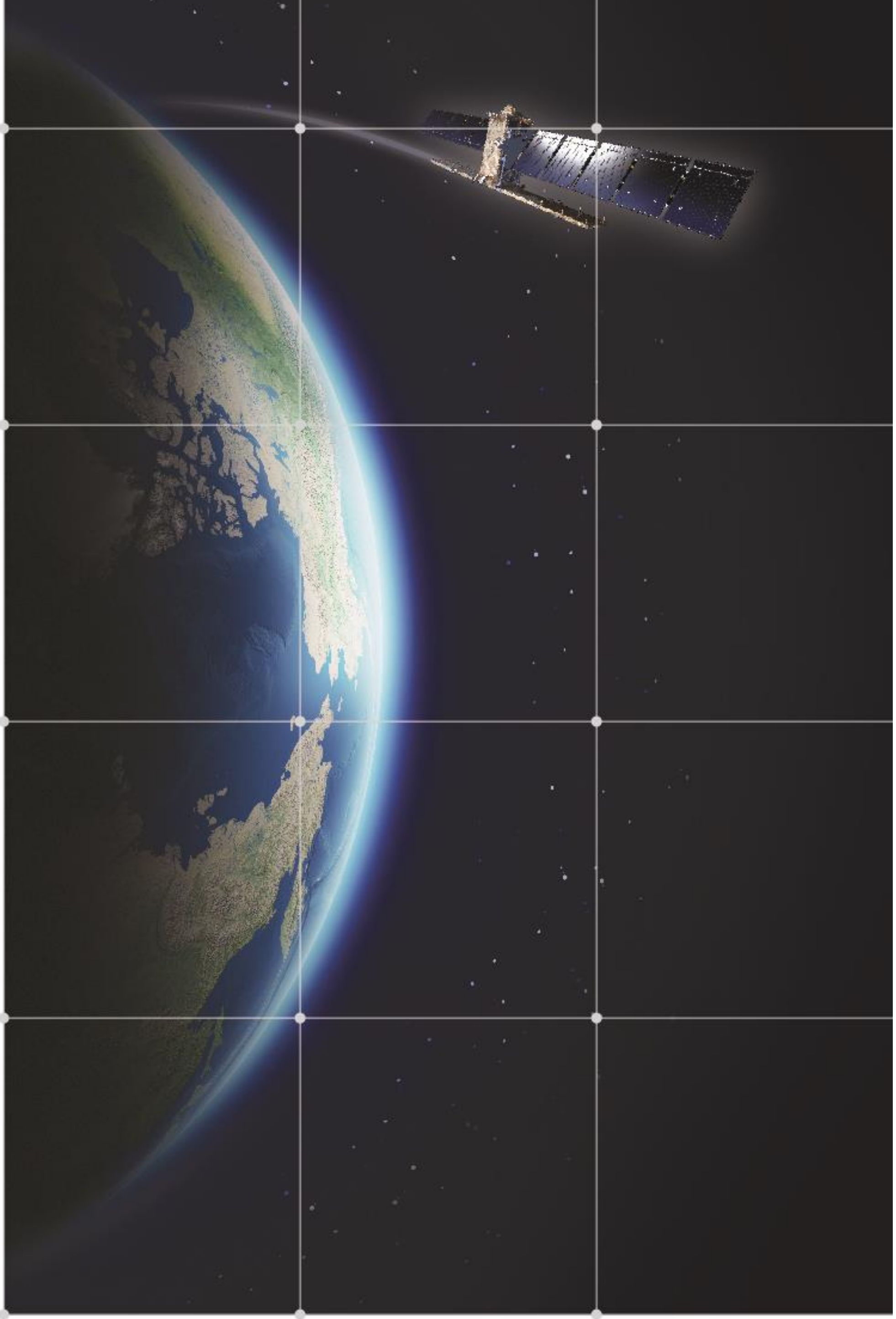
An analysis of measurement point distribution and density near the injector well pads was carried out to assess data coverage around the operational zone. Point density has increased 173% from 2014 and is considered satisfactory for this type of terrain, particularly considering the vegetative cover, lack of man-made structures and presence of snow. As comparison, over SAGD operations in similar settings where corner reflectors (CRs) have been installed, typical densities reach up to 16 CR/km^2.

5. Discussion

TRE Altamira carried out a new analysis over the Quest site with the SqueeSAR algorithm to measure ground deformation with the maximum possible density of measurement points. The study spans the period 3 June 2011 – 9 December 2016 and uses 81 RSAT2 images to cover the 3,790.9 km^2 area in northern Alberta. The site is mainly agricultural or forested and is typically considered a difficult area from an InSAR standpoint. The analysis identified 149,942 measurement points for an average density of 39.6 points/km^2, a 173% increase from the processing carried out in 2014 (14.5 points/km^2) and point distribution has become more homogenous across the full AOI. Measurement density in the area of the injector well pads has also increased. Algorithm optimizations and increased computational capabilities have allowed the site to be processed as a single tile for the first time (one reference point for the full AOI).

No surface uplift has been observed in the area of the well pads since the start of CO_2 injection on 23 August 2015. The deformation rates indicate a slight increase in subsidence over injectors SCL 7-11 and 8-19 (-0.8 to -1.2 mm/year and -1.1 to -1.5 mm/year, respectively). However, this same change was observed over inactive injector SCL 5-35 (-1.1 to -1.5 mm/year) and is within measurement precision. Across the entire AOI, surface displacement rates have also become more negative as they have changed from -0.2 ± 0.9 mm/year in 2014 to -1.0 ± 0.5 mm/year for this processing, indicating a general subsidence trend in the area. In any case, the variation should be considered within the measurement tolerance.

The average standard deviation value of the surface displacement rates for all measurement points was ±0.5 mm/year, a 44% improvement from the 2014 processing (± 0.9 mm/year). The large number of images (81) is a strong contributor to the increased point density and higher precision of the current results.



TRE
ALTAMIRA
A CLS Group Company

MILAN

Ripa di Porta Ticinese, 79
20143 Milano - Italy
Tel. +39.02.4343.121
Fax +39.02.4343.1230

BARCELONA

C/ Corsega, 381-387
E-08037 Barcelona Spain
Tel.: +34 93 183 57 50
Fax: +34 93 183 57 59

VANCOUVER

410 - 475 West Georgia Street
Vancouver, BC V6B 4M9 - Canada
Tel. +1.604.331.2512
Fax +1.604.331.2513

tre-altamira.com

Appendix II: Technical Feasibility of InSAR for CO_2 Storage Monitoring and Leak Detection at the Quest CCS project - 2017 Update

Technical Feasibility of InSAR for CO2 Storage Monitoring and Leak Detection at the Quest CCS project - 2017 Update

by

M.V. Cid Alfaro (GSNL-PTI/RC)
S. Das (PTIIN-PTI/CT)
M. Dean (GSNL-PT/RC)

Executive summary

The purpose of this report is to review the efficacy of Interferometric Synthetic Aperture Radar (InSAR) monitoring for the Quest CCS project given the newest available data. InSAR is a space-borne remote sensing technique for measuring displacements of the Earth's surface. This work provides an update on the predicted surface deformation based on pressure predictions obtained from the most recent dynamic reservoir model (GEN-5) and reviews if those predicted displacements can be monitored by means of the InSAR technology.

The Quest Carbon Capture and Storage Project proposes to inject 1.08 million tonnes/annum of CO2 into the BCS storage complex at a depth of about 2 km below the surface for a period of up to 25 years. This storage process creates a temporary build-up of pore fluid pressure inside the storage complex that will dissipate after the end of the injection period. During the injection period, these increased pressures are expected to induce a distribution of surface uplift that increases smoothly to a maximum of up to 3.5 millimetres near the centre of the storage site after 25 years. This small, slow, smooth accumulation of reversible surface uplift will be imperceptible to residents and will have no effect on groundwater resources.

As a result of initial injection performance and reservoir response, the GEN-5 model predicts a pressure increase, which is lower than the high case used in the previous study performed in 2015. In turn, the surface uplift forecasted by the geomechanical model is also lower than in the previous study. This poses a great challenge for the monitoring of ground deformations since such small displacements may fall within the noise levels of the measured ground displacements. To date, very little ground movement has been observed over the Quest Sequestration Lease area (SLA), based on the analysis carried out by TRE Altamira using their proprietary SqueeSAR algorithm and radar satellite imagery collected between 3 June 2011 and 9 December 2016. Measurements show an overall trend of subsidence across the SLA. No significant anomalous change in the ground deformation has been observed at any of the injection well pads since the beginning of the CO2 injection on 23 August 2015, and the observed changes in ground displacement fall within the precision of the measurements. The reason for the regional subsidence has not been investigated, but it is not considered to be related to Quest activities.

In summary, based on the observed and modelled pressure build-up within the BCS, expected to be less than 1.5 MPa after 25 years of injection (using a two well injection scenario), dilation within the BCS storage complex will be small. The resulting surface uplift will likely fall within the noise levels of the measured ground displacement. As a result, InSAR has limited value as a continuous monitoring technology for unexpected containment issues. As injected volumes increase, it may have some value from a conformance perspective. Hence, InSAR will be considered a contingency monitoring technology in the event of another MMV technology or observation indicating the need for further investigation.

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1. Introduction

This report summarizes work done in response to Condition 16 in the AER Approval No. 11837C to assess the efficacy of the Interferometric Synthetic Aperture Radar (InSAR) program for the Quest CCS project and the potential requirement for other related monitoring technology, such as GPS instrumentation.

To address these goals, the study generated an update on the predicted surface deformations using geomechancial modelling (with Shell's proprietary Finite Element software GEOMEC) based on pressure predictions obtained from the most recent dynamic reservoir model (GEN-5) from Quest. The modelled changes at the surface were then compared with the most recently processed InSAR data provided by TRE Altamira. Further, a statistical analysis of the InSAR data was performed to identify any changes in the data after CO2 injection commencement.

2. Method

2.1. Geomechancial Model

As a consequence of the CO2 injection, the volume in the aquifer will change depending on the pressure changes computed in response to the CO2 injection and the compressibility of the aquifer. The aquifer dilation will induce deformation on the surrounding rock mass as a mechanical response; the dilated aquifer pushes outwards in all directions inducing horizontal and vertical displacements.

Observed deformations of the Earth's surface due to small volume changes associated with fluid injection or extraction from subsurface reservoirs can be well represented by simple continuum models of a homogeneous linear elastic subsurface. In this study, surface uplift and aquifer dilation due to pressure build-up in the BCS and LMS formations as a result of CO2 injection was estimated by means of a geomechanical model using the Shell proprietary Finite Element (FE) software GEOMEC. The simplified geology consists of the following four formations:

- Overburden (comprising all formations above LMS)
- LMS (subdivided into 2 layers)
- BCS (subdivided into 2 layers)
- Pre-Cambrian basement

The FE mesh was built using hexahedral elements (circa 316 thousand cells). The size of the elements (in plane) is 1000m x 1000m in the outer rim of the model. The zone covering the SLA in which the injection operations take place and hence the pressure changes are expected to occur, is discretized using 500m x 500m size elements. The mesh refinement is done with the purpose of improving the accuracy of the model results.

The rock properties (Section 2.1.1), the subsurface geometry (Section 2.1.2) and the pressure build-up associated with CO2 injection (Section 2.1.3) are the main input to the geomechanical FE model.

2.1.1. Rock properties

The rock properties used for the Quest geomechanical model are summarized in Table 2.1 giving the range of rock properties measured for the BCS and the overlying Lower Marine Sand Formation (LMS).

Table 2.1: The range rock properties for the BCS and LMS formations as computed from core and log measurements.

Formation	Case	Formation Compressibility [1/MPa]	Porosity [-]	Bulk Compressibility [1/MPa]	Bulk Modulus [MPa]	Poisson's Ratio [-]	Young's Modulus [MPa]	Shear Modulus [GPa]
BCS	Low	4.E-05	0.15	8.E-06	130.E03	0.18	250.E03	106.E03
	High	4.E-04	0.15	8.E-05	13.E03	0.18	25.E03	11.E03
LMS	Low	1.E-04	0.1	1.E-05	69.E03	0.25	103.E3	41.E03
	High	1.E-03	0.1	1.E-04	7.E03	0.25	10.E3	4.E03

2.1.2. Depth and Thickness maps

The most recent Quest Petrel static model was used to extract the horizons to build the geomechanical model. In the original 2011 study, the formations were considered to have a constant depth and thickness. However, in the present work, the actual thickness and burial depth of the individual layers was considered in order to honour as much as possible the geometry of the real subsurface.

2.1.3. Pressure build-up during CO2 injection

Reservoir simulations indicate the LMS Formation is expected to accommodate pressure just like the BCS. As both the BCS and LMS are expected to experience increased fluid pressure, both will undergo dilation (1-10 mm/MPa) and contribute to surface uplift. Pressure increases greater than 3 MPa inside the BCS storage complex are of particular importance because this is the minimum pressure required to lift BCS brine to above the base of groundwater protection through a permeable pathway should one exist. This corresponds to an increase in the combined thickness of the BCS and LMS of 3 to 30 mm. This would be expected to induce surface uplift above these locations which is expected to be detectable by InSAR.

The injection rates and amount of CO2 injected are used by the reservoir dynamic model (Gen-5) to estimate the pressure build-up for 1, 5, 10, and 25 years after the initiation of injection. Pressure predictions were made considering the scenario where only two of the three available wells are used for the CO2 injection. The maximum estimated pressure change per layer after 1, 1.3 and 25 years of injection is shown in Table 2.2.

Table 2.2: Maximum estimated pressure build-up in storage formations.

Formation	Max pressure build-up after **1 year** of injection MPa	Max pressure build-up after **16 months** of injection (Dec-2016) MPa	Max pressure build-up after **25 years** of injection MPa
Upper LMS	0.0014	0.0018	0.12
Lower LMS	0.045	0.1	0.75
Upper BCS	0.73	0.83	1.4
Lower BCS	0.83	0.95	1.35

3. Discussion

3.1. Forward Modelling Results

Figure 3.1 shows the computed surface displacements corresponding to the pressure scenarios discussed above using the high case rock properties listed in Table 2.1. Dilation inside the BCS storage complex intuitively induces surface uplift, but perhaps less intuitively also induces horizontal displacements oriented away from the centre of uplift and are largest on the flanks of the uplifted region (Figure 3.1 (centre). This occurs because the dilated aquifer pushes outwards in all directions including pushing the sides away which in turn induces horizontal displacements at the surface. The magnitude of lateral variation in horizontal and vertical displacements are similar at the surface.

Computed vertical and horizontal displacements are used to estimate the line-of-sight (LOS) displacement expected to be measured by the acquired satellite images (InSAR), see Figure 3.1. InSAR-based approaches measure surface displacement on a one-dimensional plane, along the satellite line-of-sight. The LOS angle varies depending on the satellite and on the acquisition parameters. The images for the present project were acquired from an ascending orbit (satellite travelling from south to north and imaging to the east). The symbol θ represents the angle the LOS forms with the vertical and δ the angle formed with the geographic north. The values of the angles used in this study are: $\theta = 42.63°$ and $\delta = 7.64°$.

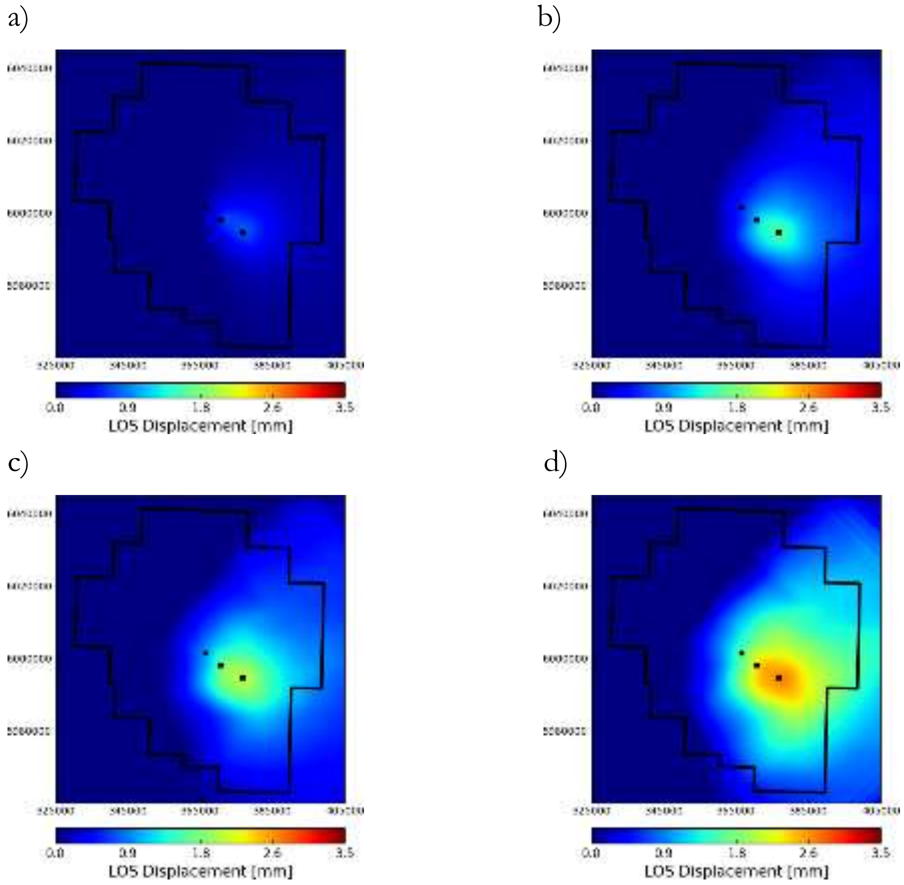

Figure 3.1: Estimated surface uplift as LOS displacement; a) after 1 year, b) after 5 years, c) after 10 years, d) after 25 years.

Surface displacements computed through time indicate how the lateral migration of the surface displacements away from the injectors mirrors the lateral migration of pressure build-up inside the aquifer. In addition, as shown in Figure 3.2, surface displacements increase monotonically through time during injection. The early phase of rapid surface uplift is driven by the early rapid advance of the pressure front away from the injectors. Subsequently, the pressure front advances more slowly and exerts less influence on the maximum surface displacement as it extends further away from the point of maximum surface uplift above the injectors. Once the lateral extent of the pressured region greatly exceeds the overburden thickness, the magnitude of maximum surface uplift depends less on the average amount of reservoir dilation within the central region and not on its lateral extent. This situation arises after about 5 years of injection given the current reservoir modelling forecast.

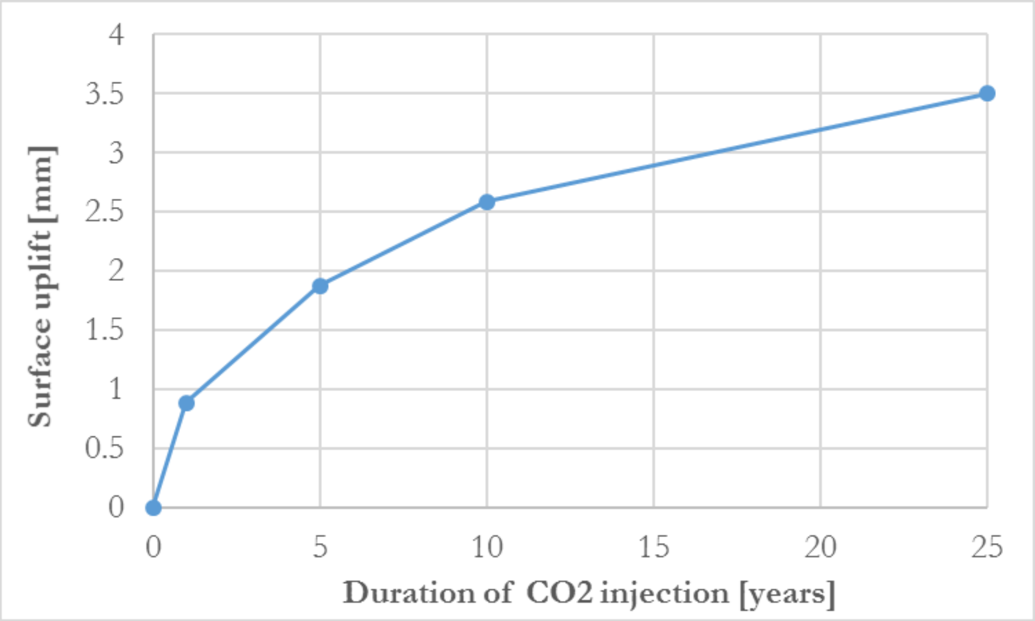

Figure 3.2: Maximum surface uplift calculated in response of CO2 injection into the BCS complex. Assuming the high case rock properties listed in Table 2.1.

Given all assumptions, the maximum surface uplift computed is 0.9 mm after 1 year of injection and 3.5 mm after 25 years of CO2 injection, see Figure 3.1 (left) and Table 3.1. Note that the computed LOS displacements are smaller in magnitude than the computed vertical displacements. As expected, as shown in Table 3.1, the magnitude of vertical displacement at top reservoir is slightly higher than the computed uplift at the ground surface. Because displacements of the surrounding rock mass are directed away from the source of volume increase, the deformations spread-out and diminish with distance from the source (aquifer). In all cases some surface displacements are also modelled outside the SLA (Fig. 3.1). These displacements are so small as to constitute no threat to groundwater availability. The maximum surface uplift at the sequestration lease boundary is about 1.8 mm after 25 years.

Table 3.1: Computed maximum vertical displacement at ground surface and top LMS and BCS.

Formation	Max vertical displacement after **1 year** of injection (mm)	Max vertical displacement after **16 months** of injection (Dec-2016) (mm)	Max vertical displacement after **25 years** of injection (mm)
Ground surface	0.9	1.3	3.5
Top LMS	1.2	1.4	3.8
Top BCS	1.2	1.3	1.9

3.2. Measured Surface Deformations – InSAR Data

InSAR technology was selected as a feasible candidate to monitor conformance and containment over the Quest injection site. According to the technical specifications provided by TRE Altamira this technology can measure changes in displacement rates as small as 1mm/year. The results of the analysis of radar satellite imagery collected between 3 June 2011 and 9 December 2016 showed that little to no ground movement was observed over most of the Quest AOI, except for an area of subsidence in a forested portion in the north of the SLA, Figure 3.3. In addition, no significant change in ground deformation have been observed since the beginning of injection on 23 August 2015.

TRE Altamira analysis also shows that little ground deformation appears to be occurring near the injector wells. No uplift is observed and there was slight subsidence in the area, even in the area around the inactive injector well, see Figure 3.4. Results shown in Figure 3.3 and Figure 3.4 are consistent with the findings from the statistical analysis of the InSAR data briefly summarized below. The reason for this behaviour has not been investigated, but it is not considered to be related to Quest activities.

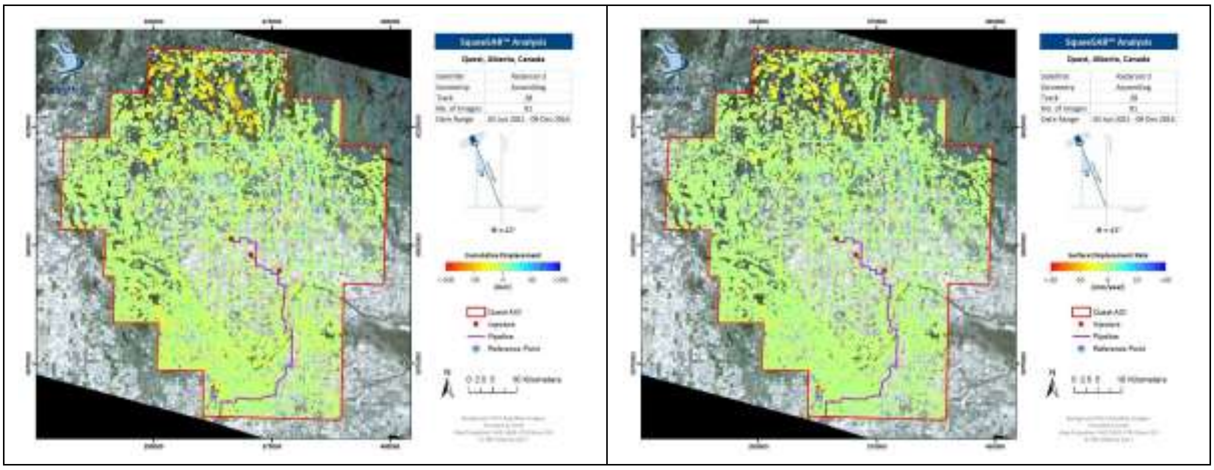

Figure 3.3: Cumulative deformation measured between 3 June 2011 and 9 December 2016 (left) and annual displacement rates (right). (source: TRE Altamira[14]).

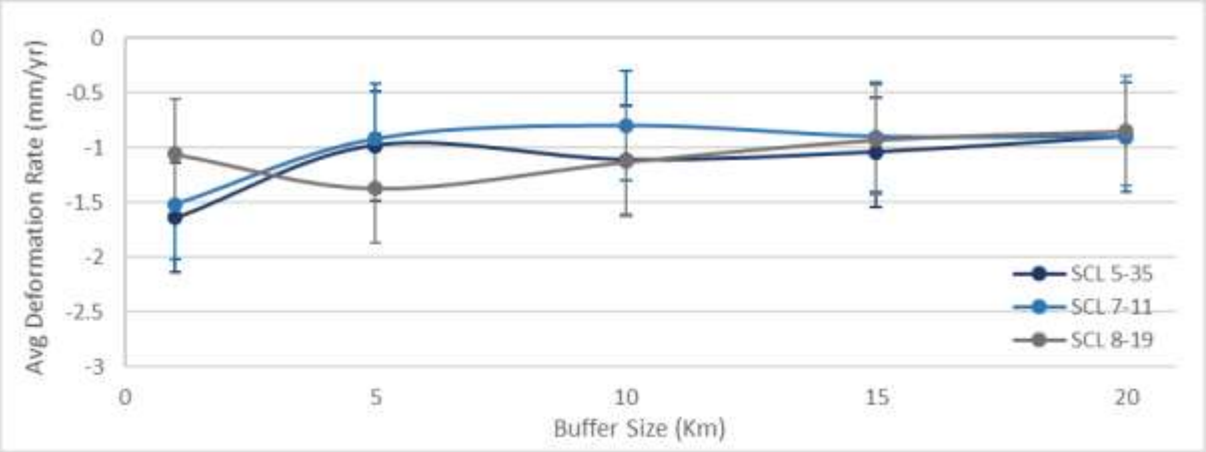

Figure 3.4: Change in average deformation rates with increasing distance from injection sites (negative values indicate subsidence) (source: TRE Altamira[14]).

In summary, the analysis of the InSAR data performed by TRE Altamira shows no uplift across the Quest SLA. Measurements show that the area is subsiding with an average rate of -0.9 mm/year prior to the start of CO2 injection and -1.6 mm/year since the start of injection.

3.3. Statistical Analysis of InSAR Data

A statistical analysis of the InSAR data was performed using 81 surface deformation maps provided by TRE Altamira. The central objective was to find out whether there is any observable or measurable change in the Quest field surface due to CO2 injection. It is assumed that if there are changes in surface deformation due to CO2 injection, then the highest impact will be near the active wells. In order to understand the impact near the wells, three circular zones of 5km radius were identified (Figure 3.5.): Zone 1 located at the north of the field, centred at location (363475, 6024891); Zone 2 centred at well SCL 8_19 and Zone 3 located at the south of the field, centred at location (363475, 5978411). For the analysis, it is fair to assume that the pressure build-up due to injection will have very low or even no impact at Zone 1 and Zone 3.

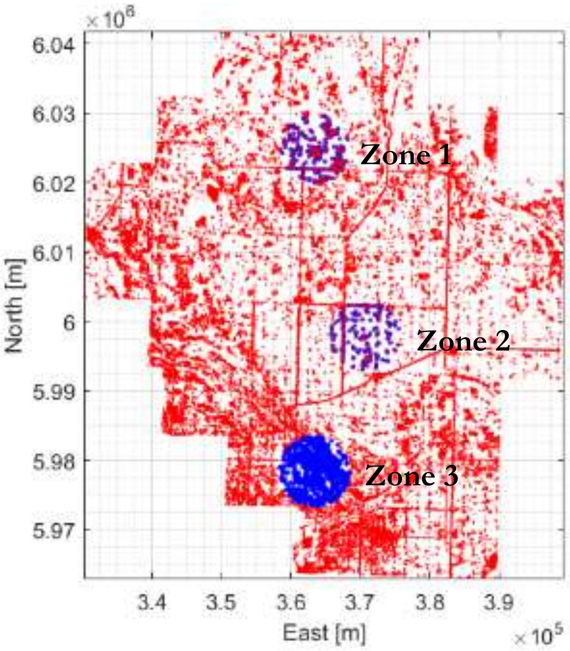

Figure 3.5: Three zones of analysis with 5km radius.

3.3.1. Principal Component Analysis

Principal component analysis (PCA) is a statistical procedure that uses an orthogonal transformation to convert variables in such a way that the largest principal component accounts for as much variability in the data as possible. In other words, the largest principal component shows the dominant trend in the data. PCA is routinely used for the analysis of spatiotemporal data, like temperature over a certain station in a region over an interval of time or air quality at stations over a period of time. Principal components along the temporal and spatial direction are estimated from spatiotemporal data. The temporal principal components represent the gross trend over time.

PCA is done using singular value decomposition of the data matrix. In this context the data matrix is formed by placing each spatial frame of displacement as a column. Each row of the matrix represents the time series of displacement of a particular location of the field. The left and the right singular vectors represent the spatial principal components and the temporal principal components, respectively. The singular vectors are normalized and thus the Euclidian norm is always 1. Note that the temporal principal components should only be used for understanding the change in trend and compare trend across different zones. These are not absolute values representing the magnitude of the displacement. In other words, principal components are more about understanding the dominant direction of a set of vectors and not the magnitude.

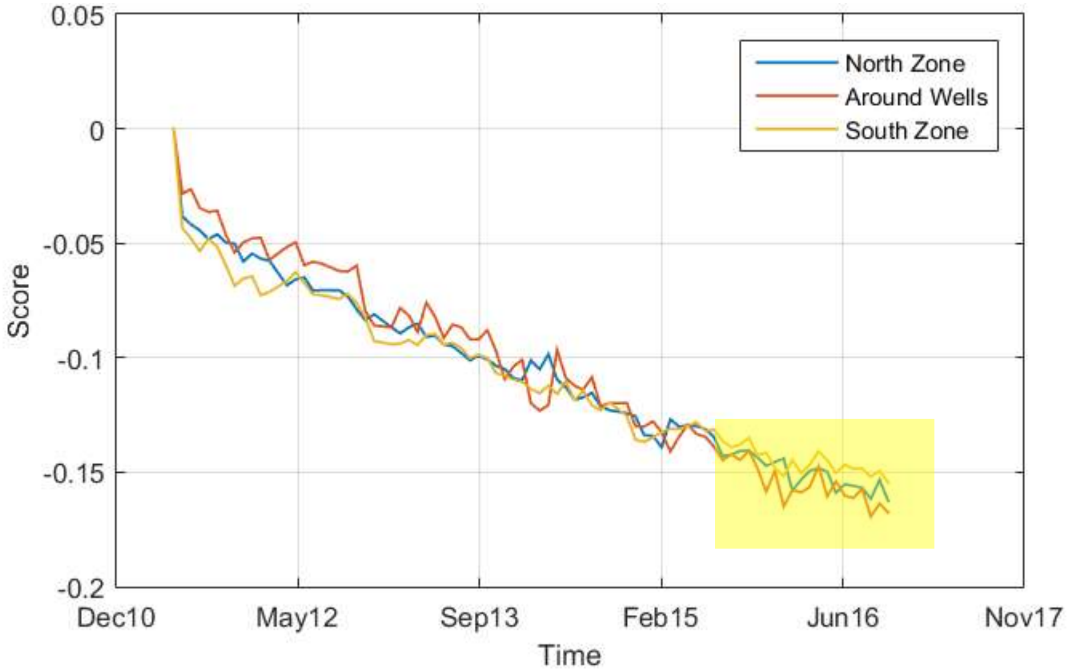

Figure 3.6: Scores of the temporal principal components north of the wells, around the wells and south of the wells.

The scores of the principal components are shown in Figure 3.6. Subsidence, i.e. movement away from the satellite is observed throughout the field. The temporal rate in all the three zones is very similar. Though not significant, a slowdown in subsidence is observed over the last 1 year. Note that this slowdown is observed across the entire SLA, i.e. north zone, around the wells and south zone.

4. Related Monitoring Technology

Optical levelling and the Global Positioning System are proven others means of monitoring surface uplift to within 1 mm/year. Both are regretted due to poor areal and temporal sampling relative to InSAR. Both optical levelling and GPS require establishment of a network of geodetic-quality survey monuments with a 1-2 km spacing and that are surveyed annually. More frequent surveys of more survey monuments are technically possible, but this increases costs and operational exposure to levels substantially greater than required for InSAR. In addition, it does not add value compared to the resolution provided by the InSAR technology (see section 3.2).

5. Conclusions

TRE Altamira carried out an analysis over the Quest site applying their SqeeSAR algorithm to measure ground deformation. The study spans a period starting from 3 June 2011 until 9 December 2016 using 81 satellite images. The site is considered challenging for InSAR since it is mainly agricultural or forested. However, previous studies by TRE Altamira confirmed that there are sufficient persistent scatterers over the Quest SLA.

According to the 2017 TRE Altamira technical report, InSAR is sensitive to a deformation rate of 1 mm/year with a precision of ±0.5 mm/year. The analysis performed by TRE Altamira also showed that no surface uplift has been observed since the start of CO2 injection on 23 August 2015. The rates over the field indicate an overall trend of subsidence across the SLA. The underlying cause of subsidence over the field has not been investigated.

To conclude, InSAR is a viable technology for assessing unexpected surface heave. Its value, however, is limited for continuous monitoring given the site specific characteristics of the Quest site. Based on the observed and modelled pressure build-up within the BCS, expected to be less than 1.5 MPa after 25 years of injection (using a two well injection scenario), dilation within the BCS storage complex will be small. The resulting surface uplift will likely fall within the noise levels of the measured ground displacement. As a result, InSAR has limited value as a continuous monitoring technology for unexpected containment issues. As injected volumes increase, it may have some value from a conformance perspective. The InSAR technology will be considered a contingency monitoring technology with a focus on the AOR (area of review) of the Quest SLA (sequestration lease area). In other words, InSAR will be used in the event of another MMV technology or observation indicating the need for further investigation.