InSAR and GPS of the Acoculco and Los Humeros geothermal fields

D5.7

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Version 1.0

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[1] The content of this report reflects only the authors' view. The Innovation and Networks Executive Agency (INEA) is not responsible for any use that may be made of the information it contains.

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Executive summary

In order to understand both the resource amount and the reservoir sustainability, it is mandatory to know as accurately as possible the structure of a geothermal field, the limits of the reservoir, and its change with time. One of the key technologies the reservoir dynamics is to unravel the vertical motions at surface related to reservoir production is by acquisition and analysis of INSAR and GPS data. This task has been defined to perform this INSAR and GPS acquisition and analysis of the geothermal fields of Acoculco and Los Humeros, and has been subdivided in three different subtasks (in brackets the subtask numbers of the GEMEX workplan):

1. inSAR data aquisition and analysis (Los Humeros and Acoculco) (5.3.2a)
2. Modelling of inSAR derived motions in the Los Humeros Field due to production and analysis and modelling of inSAR derived motions during the M4.2 event in 2008 (5.3.2c).
3. GPS data acquisition and analysis in Acoculco and Los Humeros field (5.3.2b)

We present surface movements at the Los Humeros Geothermal Field (LHGF) inferred from InSAR. We also processed satellite images acquired at Acoculco, but we could not detect and reliable deformation there. This is mainly due to the combination of lack of coherence of the area caused by vegetation and presumably very small deformation signal which cannot be detected by InSAR.

Deformation at the Los Humeros was mapped through PS-InSAR (Persistent Scatterer by Synthetic Aperture Radar Interferometry) time-series between April 2003 – March 2007. We attribute the observed deformation to field operations, since volcano-tectonic movements are only expected with magnitudes below the resolution of the InSAR data. The area of maximum subsidence is relatively small, located at the northern part of the geothermal field. The subsidence pattern with movemenents up to 8 mm/y, indicates that the geothermal field is controlled by sealing faults separating the reservoir into several blocks. We related surface movements with volume changes in the reservoir through analytical solutions for different types of nuclei of strain.

Furthermore, we analysed and inverted for fault source scenarios the inSAR derived motions during the M4.2 event in 2008.. The event occurred after a sharp increase in the injection rate at the Los Humeros Geothermal Field and it was recorded by the seismic monitoring network of the power plant. Despite the inaccuracy of the fault models, all our models locate the activation of the fault at shallow depth: no activation was predicted below ~1200m depth. This implies that the earthquake most likely originated in the top of the reservoir.

For performing GPS we have used a measurement procedure called DGPS (Differential GPS) in which two or more GPS receivers are employed. GPS data acquisition was performed by Mexican partners. The data collection is done every six months and will be done for four years (three campaigns have been carried out at the present). It was fortunate that during the first and second monitoring there was a large earthquake that affected the study area and whose effects are showing a more solid displacement vector. As preliminary results, we have obtained motion vectors that act on the regional structures, with horizontal displacements (σminH) of up to 3 cm in NW-SE direction. This means that both calderas are in a tectonically active zone. where the faults and the blocks present relative movements, ideal characteristic for the reopening of fractures and faults previously sealed and for the mobility of fluids in the geothermal systems.

The observation deformation rates are well in accordance with similar geothermal fields in Iceland.

1 Introduction

1.1 Objective of the task

In order to understand both the resource amount and the reservoir sustainability, it is mandatory to know as accurately as possible the structure of a geothermal field, the limits of the reservoir, and its change with time. One of the key technologies the reservoir dynamics is to unravel the vertical motions at surface related to reservoir production is by acquisition and analysis of INSAR and GPS data. This task has been defined to perform this INSAR and GPS acquisition and analysis of the geothermal fields of Acoculco and Los Humeros.

1.2 Limitations of the report

This task has been performed in collaboration with our Mexican partners from Michoàcan University (Morelia) and UNAM (Mexico-city). The industrial partner CFE provided very valuable information for us to evaluate the validity of our results. However, the timeframe of the counter-part project in Mexico was not in good alignment with the European project time line, and therefore the usage of both inSAR (acquired mostly by European partners) and GPS data (acquired mostly by the Mexican partners) was not well aligned. Consequently, we give the description of the results to the INSAR and GPS data acquisition and analysis of observed vertical motions, and deal separately with modelling of the reservoir and geodynamic/mechanical mechanisms underlying the observed motions based on INSAR data only.

1.3 Structure of the report

This report is based on the description of work given by the proposal and project GEMEX. In order to reach the objectives described in the main text of the proposal, we divided our task in three main tasks concerning the field under investigation and the method of analysis.

1. First, overview of relevant inSAR data aquisition and analysis (Los Humeros and Acoculco);
2. Second modelling of inSAR derived motions in the Los Humeros Field due to production and analysis and modelling of inSAR derived motions during the M4.2 event in 2008.
3. GPS data acquisition and analysis in Acoculco and Los Humeros field

The first deals with task 5.3.2a of the GEMexproject workplan and is described in chapter 2. The second is presented in chapter 3 and deals with task 5.3.2c: Analysis of crustal deformation by use of InSAR and high precision GPS data to identify reservoir compartmentalisation and sort out background vertical motions related to magmatism. This also includes a comparison to similar results in superhot systems in Iceland. The last deals wth task 5.3.2b of the GEMex project.

InSAR data acquisition and Analysis in Acoculco and the los Humeros field

1.4 Los Humeros Field

1.4.1 Introduction

The deployment of DInSAR (Differential Interferometric Synthetic Aperture Radar) allows to detect small movements on the Earth's surface (Hanssen, 2001, Ferretti, 2014). It utilizes the phase difference between two SAR images to estimate displacement along the satellite line-of-sight (LOS). Better temporal resolution can be achieved using several SAR images and performing a time-series analysis. This facilitates the monitoring of gradual changes in ground movements using multiple interferograms, while increasing the performance of the phase unwrapping.

Here we present surface movements at the Los Humeros Geothermal Field (LHGF) inferred from InSAR. We also processed satellite images acquired at Acoculco, but we could not detect and reliable deformation there. This is mainly due to the combination of lack of coherence of the area caused by vegetation and presumably very small deformation signal which cannot be detected by InSAR.

Deformation at the Los Humeros was mapped through PS-InSAR (Persistent Scatterer by Synthetic Aperture Radar Interferometry) time-series between April 2003 – March 2007. Additionally, we related the observed surface movements with volume changes in the reservoir through analytical solutions for different types of nuclei of strain.

1.4.2 Satellite data

We performed PS-InSAR (Persistent Scatterer by Synthetic Aperture Radar Interferometry) time series analysis over the eastern sector of the Trans-Mexican Volcanic Belt with main focus on the Los Humeros and Acoculco geothermal fields. We used Single Look Complex (SLC) Envisat ASAR images acquired on C-band. Acquisitions are available on ascending and descending satellite passes. On the other hand, not all acquisitions were suitable for processing due to the limited number of images with the same footprint. Data considered as applicable for the time series analysis are listed in Table 1. Note that the ascending images covering Acoculco were excluded due to the very small deformation signal observed on the PS results of the descending orbit.

Satellite	Orbit	Study Area	Coverage	Number of Images	Track	Processed
Envisat	Descending	LH	20030308-20070313	22 (13 used)	212	Yes
Envisat	Descending	AC	20030216-20091206	31 (16 used)	484	Yes
Envisat	Ascending	AC	200302-201004	34	148	No

Table 1 Data selected for PS-InSAR time series analysis. LH and AC stand for the images covering the Los Humeros and Acoculco geothermal fields, respectively.

Additionally, we processed Sentinal-1 radar images acquired in wide-swath mode to map the coseismic deformation due to the 8 February 2016, Mw 4.2 earthquake at the LHGF. We used images with dates 29 January 2016 and 10 February 2016 for the ascending interferogram. The descending interferogram was retrieved from data acquired on 7 February 2016 and on 19 February 2016.

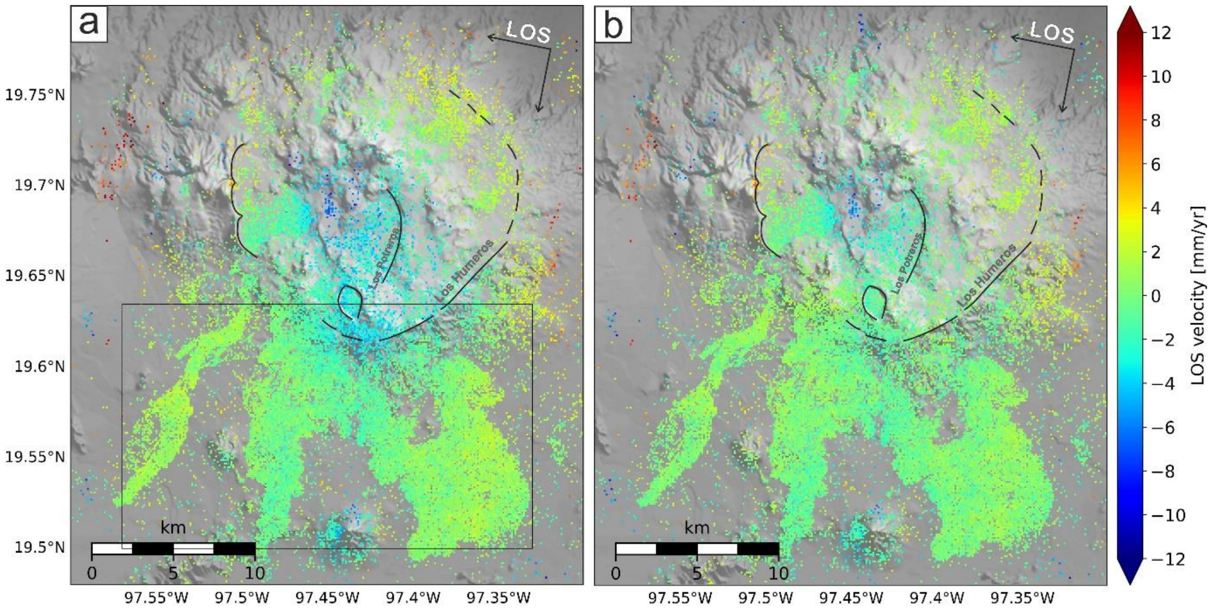

Figure 1 Deformation maps showing the mean velocities in the satellite line of sight (LOS) in mm/year (a) without tropospheric correction, (b) corrected for topography-related tropospheric phase delays. Movements are relative to the mean of the whole area. Negative values indicate movement away from the satellite (~subsidence) and positive values indicate movement towards the satellite (~uplift). The black rectangle in figure (a) highlights the region used for tropospheric correction (from Bekesi et al., 2019, under revision).

1.5 Acoculco Field

We performed for Acoculco a similar data collection and analysis as in Los Humeros (Figure 2). At Acoculco we could not detect a reliable deformation signal. This is mainly due to the combination of low coherence of the area caused by vegetation and presumably very small deformation which cannot be detected by InSAR. Local anomalies with significant deformation can be observed (b), but these phase jumps are most likely due to unwrapping errors caused by the combination of steep topography and lack of coherence.

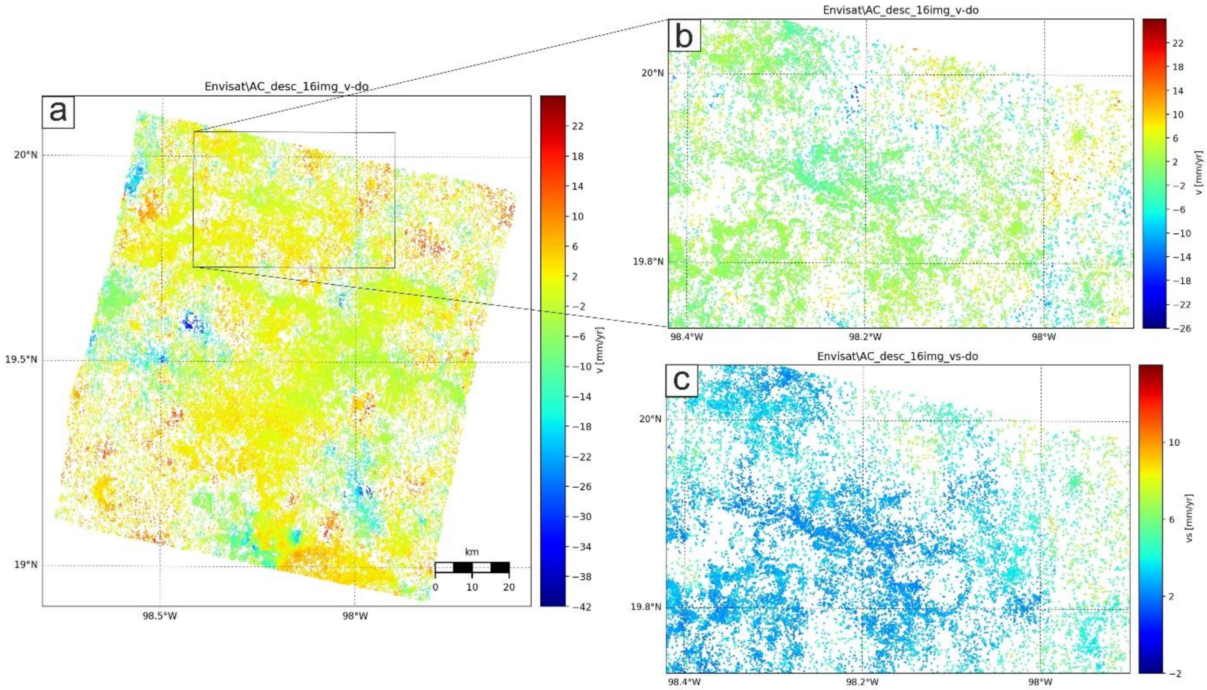

Figure 2 Mean PS velocities in the LOS direction for the entire footprint of the Envisat image (a) and a subset covering the regional model of Acoculco (b). Negative LOS velocities indicate movement away from the satellite (~subsidence) and positive values indicate movement towards the satellite (~uplift). The standard deviations of the velocity estimates at Acoculco are shown in (c).

1.6 Data availability

The radar images we processed to arrive to the findings of this study are freely accessible by the European Space Agency via EOLI-SA upon registration for the (A)SAR On The Fly Service.

2 Modelling of inSAR derived motions in the Los Humeros Field

This section reports two major studies of subtask 5.3.2: Analysis of crustal deformation by use of InSAR and high precision GPS data to identify reservoir compartmentalisation and sort out background vertical motions related to magmatism.

The first presented in section 3.1 deals with Inversion of ground deformation at the Los Humeros Geothermal Field based on PS-InSAR. The second in section 3.2 deals with Inversion of coseismic deformation due to the 8th February 2016, Mw 4.2 earthquake at Los Humeros (Mexico) inferred from DInSAR. The described results in this chapter are more fully documented in a peer reviewed paper under revision for geofluids special issue on GEMEX and a paper submitted to the EGC 2019.

2.1 Inversion of ground deformation at the Los Humeros Geothermal Field based on PS-InSAR

Main goal of this subtask activity has been to reveal the pressure distribution in the reservoir and to identify reservoir compartmentalization for inSAR data, which can be important aspects for optimizing production of the field. The reported results are a summary of the peer reviewed paper which is under review[2] The result of the PS-InSAR (Persistent Scatterer by Synthetic Aperture Radar Interferometry) analysis shows that the subsidence at the LHGF was up to 8 mm/year between April 2003 - March 2007, which is small relative to the produced volume (Figure 3). The subsidence pattern also indicates that the geothermal field is controlled by sealing faults separating the reservoir into several blocks. We related surface movements with volume changes in the reservoir through analytical solutions for different types of nuclei of strain. We constrained our models with the movements of the PS points as target observations.

We attribute the observed deformation to field operations, since volcano-tectonic movements are only expected with magnitudes below the resolution of the InSAR data. The area of maximum subsidence is relatively small, located at the northern part of the geothermal field. This area appears to be isolated from the injection wells that were operational during the period of the InSAR analysis. This isolation is supported by the epicenters of the induced earthquakes, most of which are located west from the injectors, suggesting that the majority of the injected fluids are directed westwards. No clear subsidence signal is observed in the southern and western part of the field, although large numbers of production wells have been drilled in these areas. This indicates a significant pressure support of that area that might originate from deep recharge. Pressure drop in the reservoir is most likely restricted below the clearly subsiding area. As regular pressure measurements from the wells are not available to support these findings, this conclusion demonstrates the versatility of the use of surface movement data combined with inversion.

Our models imply small volume changes in the reservoir and the different nuclei of strain solutions differ only slightly. These findings suggest that the pressure within the reservoir is well supported and that reservoir recharge is taking place.

[2] Békési, E., Fokker, P.A., Martins, J.E., Limberger, J., Bonté, D., and Van Wees, J.D., 2019. Inversion of ground deformation at the Los Humeros Geothermal Field based on PS-InSAR, Geofluids special issue on GEMEX, under review.

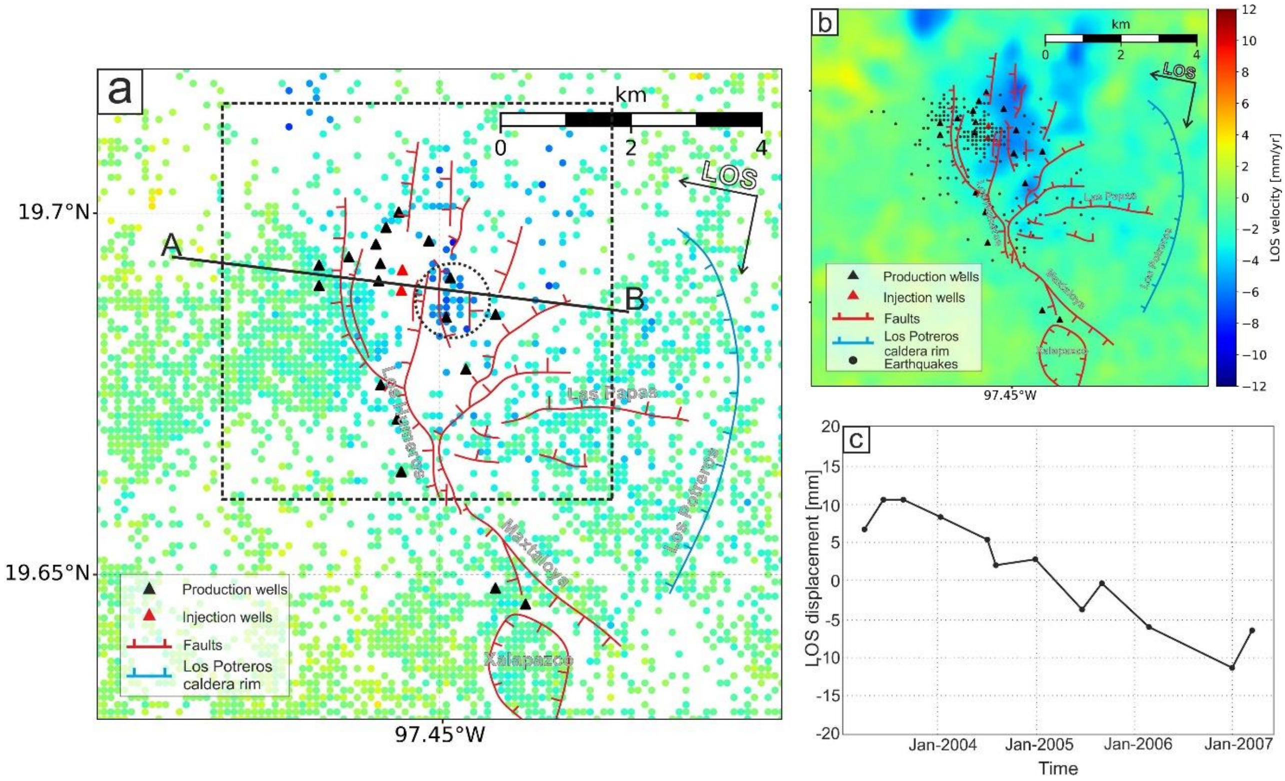

Figure 3 Mean (a) and interpolated (b) PS velocities in the LOS direction at the LHGF. Negative LOS velocities indicate movement away from the satellite (~subsidence) and positive values indicate movement towards the satellite (~uplift). The main structures after Norini et al. [10] and Carrasco-Núñez et al. [11] and the wells operating during the period of the InSAR are shown in both figures. The black dashed rectangle marks the outline of the area selected for modeling. The epicenters of induced earthquakes between December 1997 to October 2008 after Urban and Lermo [14] are plotted in (b). The time series of the mean LOS velocities from the area where the largest subsidence is observed (highlighted in (a) with dotted circle) is shown in (c). from Bekesi et al., 2019.

2.2 Inversion of coseismic deformation due to the 8th February 2016, Mw 4.2 earthquake at Los Humeros (Mexico) inferred from DInSAR

On the 8th of February 2016, a Mw 4.2 earthquake was detected inside the Los Humeros caldera. The event occurred after a sharp increase in the injection rate at the Los Humeros Geothermal Field and it was recorded by the seismic monitoring network of the power plant. The earthquake was felt by the local population and it caused damage in the power plant infrastructure. The focal mechanism solution of a previous study based on seismological data shows a reverse movement with a minor left-lateral component: Mw=4.2, depth=1500m, strike=169°, dip=61°, rake=42°.

We have performed a geodetic and geomechanical analysis of the seismic source event based on ground deformation inferred from DInSAR. The results below have been extensively described in an extended abstract summited to the EGC2019[3]. Here we present a summary of the results. We used ascending and descending

[3] Békési, E., Fokker, P.A., Martins, J.E., Van Wees, J.D., 2019. Inversion of coseismic deformation due to the 8th February 2016, Mw 4.2 earthquake at Los Humeros (Mexico) inferred from DInSAR. European Geothermal Congress extended abstract, submitted

Sentinel-1 differential interferograms to retrieve the horizontal and vertical components of the co-seismic deformation. Subsequently, we inverted the estimated deformation to obtain the solution of an activated fault using the Okada model (Figure 4). These results shed light on the geomechanical aspects of the event and can help to understand the effects of field operations interacting with pre-existing structural features and active tectonic processes in the Los Humeros caldera.

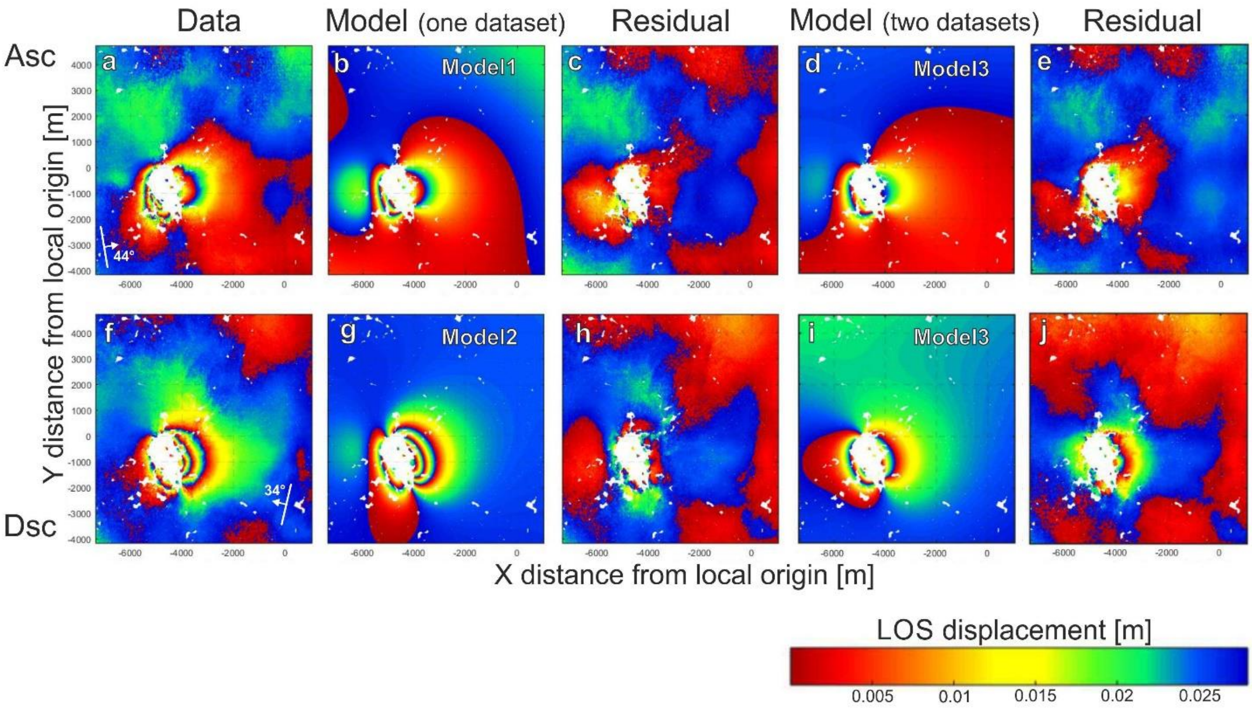

Figure 4 Observed (a, f), modeled (b, d, g, i), and residual (c, e, h, j) displacements in the LOS direction for ascending (top) and descending (bottom) satellite passes, mapping the coseismic deformation of the 8 February 2016 earthquake. Arrows in a and f indicate the flight direction of the satellite and the look direction with the corresponding incidence angles. Model 1 and Model 2 are obtained by the inversion of the ascending and descending interferograms separately. For Model 3 the two interferograms were used simultaneously. From Bekesi et al., 2019.

We inverted the interferograms for an activated fault solution using the datasets separately (Model 1 and Model 2) and jointly (Model 3). Our models yielded significantly different source parameters, especially when the descending dataset is used (Model 2). This leads to the conclusion that using either ascending or descending data can yield misleadingly good fits and misleadingly well-constrained parameter estimates. The combination of the data sets provides for essential additional information.

Our model calibrated jointly with the two interferograms (Model 3) shows misfits up to 30 mm with the descending data. These misfits suggest that the models are inaccurate. We think the source of the inaccuracy is in the assumption of a single fault plane with uniform slip. Despite the inaccuracy, however, all models locate the activation of the fault at shallow depth: no activation was predicted below ~1200m depth. This implies that the earthquake most likely originated in the top of the reservoir. Additionally, all models predict a reverse movement along the trace of the Los Humeros fault. This fault was previously mapped as a normal fault associated with the resurgence of the caldera floor east of the fault (e.g. Norini et al. 2015), suggesting reactivation with opposite kinematics. This reactivation may imply the cessation of resurgence processes inside the caldera or alternatively the tilting of a trapdoor block (e.g. Acocella 2007).

2.3 Comparison to similar results in superhot systems in Iceland

In Iceland six geothermal power plants are currently in operation: Hellisheiði and Nesjavellir both part of the Hengill geothermal area, Reykjanes, Svartsengi, Krafla and Theistareykir. They can all be classified as superhot geothermal systems, many with borehole temperatures up to 330 °C and higher.

In recent years, multiple studies on these Icelandic geothermal fields show a link between geothermal harvesting and ground displacement rates, constrained by InSAR and GPS data. Due to the complexity of the geological settings in Iceland, modelling of ground deformation in geothermal fields must be co-modelled with the regional tectonic and volcanic deformation as the signals are overlapping. The modelled depths of these geothermal areas are all shallow, between 0.6 and 3 km depth (e.g. Juncu et al., 2017; Juncu et al., 2018; Parks et al., 2018).

At Krafla volcano, north Iceland, Drouin et al., 2017, attribute the subsidence rate of ~5 mm/y over a 5 km wide area to geothermal utilization. They associate thermal contraction of the bedrock as the main cause of the deformation. At Hellisheiði and Nesjavellir, south-west Iceland plate-triple junction, local deformation has been explained by the extraction of geothermal fluids, i.e. pressure drawdown within the geothermal reservoir (Juncu et al., 2017).

At Reykjanes, southern tip of the Reykjanes peninsula, local deformation was observed shortly after a new geothermal powerplant was opened there in 2006, operating with 4-5 times higher extraction rates than in the previous decades (Parks et al., 2018). They investigate the period 2003-2016 using InSAR time series analysis and find that during the 2005–2008 period the main area of deformation was 4 km long by 2.5 km wide, aligned along the Reykjanes fissure swarm, but in the period 2009–2016 it is more circular in shape and ~2 km wide. They find the maximum value for the whole-time period 2005–2016 to be −0.26 m (subsidence). During the first 2–3 years after the onset of production at a new power plant, LOS displacement rates were higher with a broader deformation signal. However, since the beginning of 2009, when the reinjection started, LOS displacement has continued steadily at a slightly lower rate.

Another less well studied example of local subsidence in an Icelandic geothermal field is observed at Svartsengi located on the Reykjanes peninsula (Parks et al., 2018). The signal in this region corresponds to the Svartsengi injection site. Contrastingly, the detailed study of Juncu et al., 2018 observe slight inflation at the Hellisheiði injection area, Húsmúli, during the period 2011-2012, which is attributed to increased pore-pressure.

The localised ~8mm/y subsidence observed in Los Humeros it therefore in broad agreement with the localised deformation rates observed in geothermal production fields in Iceland. In both Mexico and Iceland, the deformation sources are modelled at very shallow depths.

3 GPS data acquisition and analysis in Acoculco and Los Humeros field

The main goal of the GPS monitoring is to know how the actual stress field affect the regional structures and comparing this data with the structural geology, seismically monitoring and InSAR works of the GEMex project in the Acoculco and Los Humeros calderas.

For performing these activities we have used a measurement procedure called DGPS (Differential GPS) in which two or more GPS receivers are employed. In this modality, there is a reference receiver and it is called the base station, which occupies a point and of which the precise coordinates are known, which will allow to calculate the errors with reference to this or to several receivers called "rovers" that are in the point or points in which we want to obtain the precise coordinates. The great advantage of this method is that the positioning errors, very similar in both points, are eliminated for the most part. The monitoring network consists of 14 control points, strategically distributed along fault structures that affect the Acoculco and Los Humeros calderas, the major's structures have NW-SE and NE-SW orientations. The data collection is done every six months and will be done for four years (three campaigns have been carried out at the present). It was fortunate that during the first and second monitoring there was a large earthquake that affected the study area and whose effects are showing a more solid displacement vector.

As preliminary results, we have obtained motion vectors that act on the regional structures, with horizontal displacements (σminH) of up to 3 cm in NW-SE direction. This means that both calderas are in a tectonically active zone. where the faults and the blocks present relative movements, ideal characteristic for the reopening of fractures and faults previously sealed and for the mobility of fluids in the geothermal systems.

Surely, this data should be compared with the seismic monitoring performed by GEMEx. For example, the partial data of focal mechanisms already show in Los Humeros tensors of deformation similar to the results of GPS. However, there is not enough data to corroborate the findings with InSAR, where it is clear vertical movements along the main structures with NNW-SSE tendencies.

4 Conclusion

4.1 Main results achieved – milestones of the task

The main results of the task are the collection and analysis of inSAR data in the Los Humeros and Acoculco Fields. In Acoculco we did not expect a pronounced deformation as the resource is not yet developed. This has been confirmed by the data which does not evidence a reliable deformation signal. In Los Humeros the data clearly evidences subsidence up to 8 mm/y related to production. The subsidence pattern also indicates that the geothermal field is controlled by sealing faults separating the reservoir into several blocks.

We have performed a geodetic and geomechanical analysis of the seismic source of the Mw=4.2 event, in the Los Humeros Field which occurred in 2016, based on ground deformation inferred from DInSAR. All our models locate the activation of the fault at shallow depth: no activation was predicted below ~1200m depth. This implies that the earthquake most likely originated in the top of the reservoir and can be associated by injection. Additionally, all models predict a reverse movement along the trace of the Los Humeros fault.

Milestones	Due date /data of achievement	Status
M5.4 inSAR data collected	01.04.2018	MS reached succesfully

Table 2: List of Milestones

4.2 Scientific knowledge increased

The InSAR data together with the modeling results suggest two reservoir characteristics. First, they indicate that the pressure within the reservoir is well supported suggesting that recharge is taking place. Second, they imply that the Los Humeros geothermal field is controlled by sealing faults that separate the reservoir into several blocks. However, additional subsurface data, for instance regular pressure measurements from the wells, are needed to improve our modelling results. This would also allow us to study fault sealing behaviour that controls reservoir compartmentalization. Still, our results make clear that based on the subsidence pattern we have obtained a better understanding of the pressure conditions within the reservoir and potential local recharge zones. This will facilitate better quality decisions on well planning and operations.

The joint deployment of ascending and descending InSAR data has shown that further research, taking into account the complexity in the subsurface, is crucial for a quantitative understanding of unravelling source mechanisms for induced events such as the Mw=4.2 event which occurred in 2016 in the Los Humerois Field. The present study has given a good estimate of the reactivated fault orientation and rake, and it has set the direction in which to search to reveal the other source parameters. Such understanding can then be used to develop understanding and quantification of the connection between geothermal operations and induced seismicity.

5 Acknowledgments

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