Preliminary Results of a Surface Deformation Study, Using Differential InSAR Technique at the Cerro Prieto Geothermal Field, B.C., Mexico

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ABSTRACT

The Cerro Prieto geothermal field, located in the Mexicali Valley, B.C., Mexico, has been exploited for energy production since 1973. Geodetic and geotechnical measurements have revealed subsidence likely due to a combination of fluid extraction and tectonic movement in this active tectonic area.

This paper reports preliminary results of an ongoing project in which satellite radar (ERS 1/2 and ENVISAT C-band) data is used to map the deformation in this region via interferometric processing. The project objective is to use Differential Interferometric Synthetic Aperture Radar (DInSAR) together with geodetic (leveling surveys) and geotechnical (tiltmeters and extensometers) techniques to monitor the spatio-temporal evolution of the surface deformation in the study area and to distinguish among several possible causes (tectonics and fluid extraction) and mechanisms (aseismic and seismic slip).

1. Introduction

Surface deformation is an expected consequence of the production of geothermal fluids and steam. Surface subsidence rates up to dozens of centimeters per year have been measured across several major geothermal fields (e.g., Wairakei, New Zealand (Allis, 2000), Geysers, USA (Mossop and Segal, 1997)). Deformation is observed even in kilometer deep reservoirs isolated from shallow groundwater.

Historically, deformation monitoring in geothermal fields has been carried out using geodetic methods such as precise leveling and geotechnical instruments such as tiltmeters. In the last two decades, GPS campaigns and continuous GPS have also become widely used. These methods measure deformation at specific points on the Earth's surface, therefore the spatial coverage of such monitoring techniques is very limited. Leveling surveys are generally too expensive to repeat over time, which limits the temporal resolution. In order to measure the ground deformation over large areas at a high spatial resolution, it is possible to use Interferometric Synthetic Aperture Radar (InSAR). InSAR is a technique that is potentially capable of measuring deformation over large areas (~100×100 km), with high spatial resolution (~25m), and with high accuracy (~1cm).

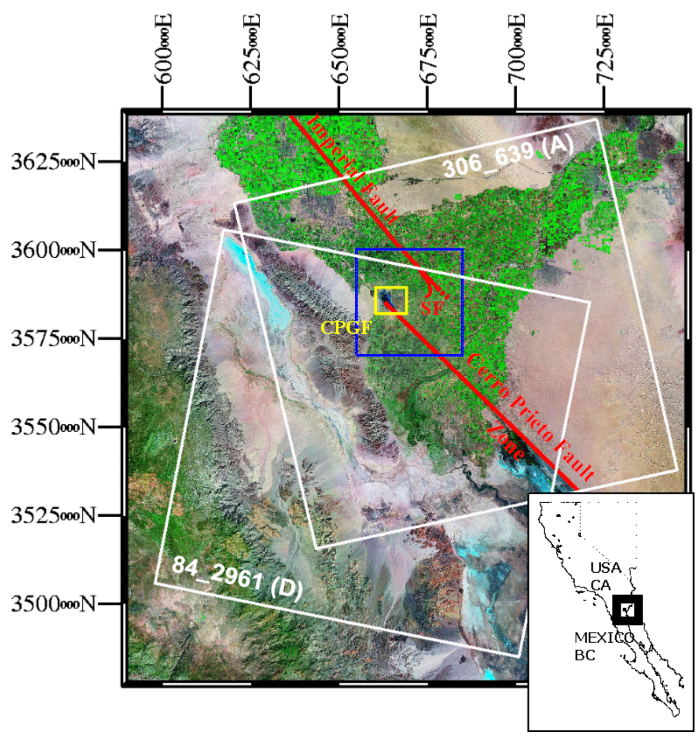

Figure 1. Regional map of study area. Landsat image is used as a background. Large white rectangles indicate the spatial coverage of the ERS1/2 and ENVISAT tracks along which SAR data were collected. A and D indicates respectively ascending and descending tracks. Blue rectangle represents study area. Yellow rectangle marks the Cerro Prieto Geothermal Field. SF denotes Saltillo Fault.

The objective of the present work is to use two-pass Differential Interferometric Synthetic Aperture Radar (DInSAR) together with geodetic and geotechnical techniques to monitor the spatio-temporal evolution of the surface deformation in the Cerro Prieto area, an area which is influenced by a variety of ongoing tectonic, hydrothermal, and anthropogenically induced processes.

2. Study Area

The Cerro Prieto Geothermal Field (CPGF) is situated in Mexicali Valley, in the southern part of the Salton Trough, and at the tectonic boundary between the Pacific and North American Plates (Figure1). The CPGF is characterized by rapid geodetic deformation, high heat flow, active seismicity and young volcanism, and is located between two major right-lateral strike-slip faults, the Imperial and Cerro Prieto Faults.

The CPGF is the world's second largest geothermal field and is operated by the Mexican Federal Electricity Commission (Comisión Federal de Electricidad – CFE). The field has been studied since the 1950's when the first deep (>1000 m) exploratory wells were drilled. Fluid extraction for electricity production began in 1973 at 1500–3000 m depth. Since then, production growth has been achieved by increase in the number of power plants and wells. The last increase in production is related to the development of a new power plant (CP IV) to the northeast of existing plants. Injection of the discharged fluid began in 1989 at 500-2600 m depth.

The subsidence history at the CPGF area has been well documented. Geodetic studies in the Mexicali Valley began in the 60's. Ground deformation in the studied area has been monitored by repeat ground surveys with precise leveling and GPS (mainly conducted by the CFE) and is currently monitored by quasi continuous records of geotechnical instruments network (tiltmeters and extensometers) maintained by CICESE and CONACYT. The measurements from these ground surveys have revealed subsidence, which is likely due to fluid extraction combined with tectonic effects (Glowacka *et al*., 1999; Glowacka *et al*., 2005). The geometry of the subsidence area is controlled by faults. The geotechnical instruments measurements suggest mainly aseismic creep in the form of vertical (6cm/yr) and horizontal (2cm/yr) movements in the southern branch of the Imperial Fault (Saltillo Fault) and a vertical (3cm/yr) movement in the northern end of the Cerro Prieto Fault. Subsidence modeling has been done using precise leveling data (Sarychikhina *et al.*, 2005; Glowacka *et al.*, 2005). The results show that tectonic subsidence explains only ~4% of the measured subsidence. Anthropogenically induced subsidence was evaluated using a model of rectangular tensional cracks, based on the hydrological model of CPGF proposed by Lippmann *et al*. (1991), together with the Coulomb 2.0 software (King *et al.*, 1994; Toda *et al.*, 1998). The final model consists of five (5) tensional rectangular cracks which represent three (3) geothermal reservoirs, located in the CPGF production zone (p), superficial recharge aquifer that covers a wide zone between two major faults and a local recharge aquifer located between the CPGF production zone and the Saltillo Fault (recharge zone - r) (Figure 2 a1-a2, Figure 3 a1-a2).

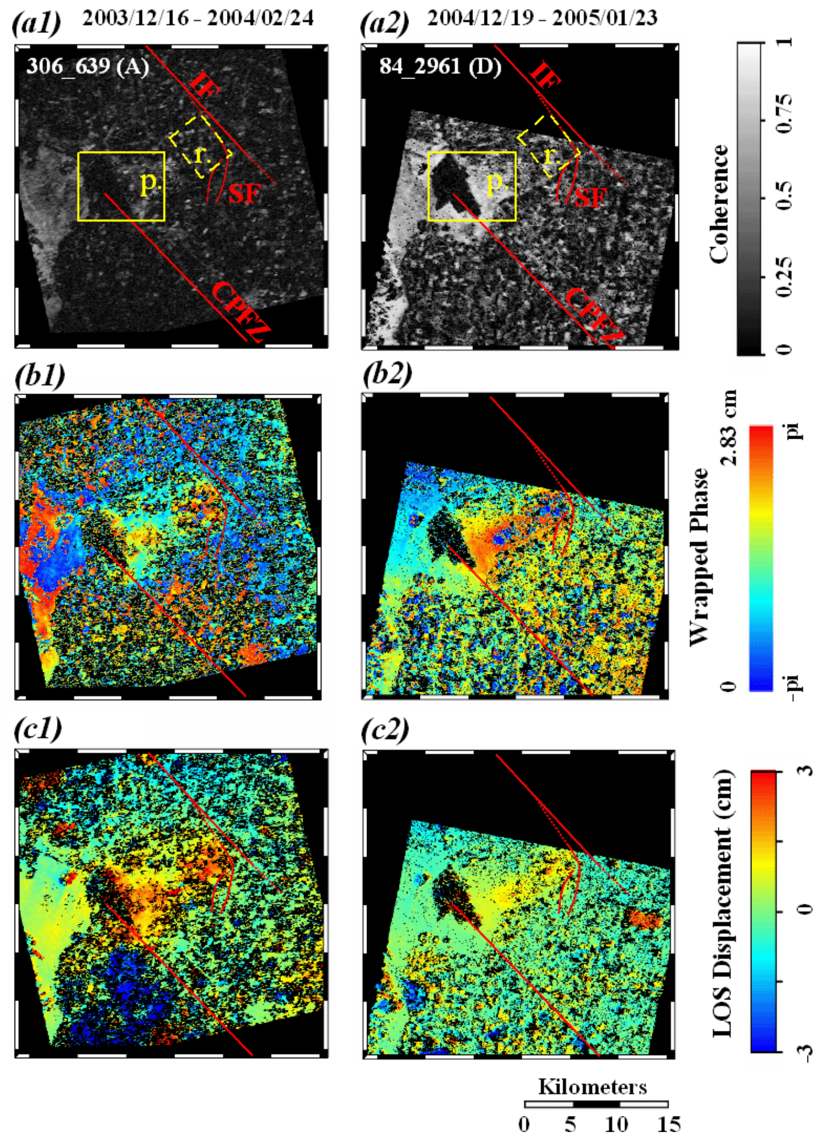

Figure 2. InSAR results from interferometric pairs 1 and 2 from Table 1. (a1-a2) geocoded coherence images; (b1-b2) wrapped phase interferograms; (c1-c2) surface displacements away from the satellite along the radar line of sight (LOS). CPFZ denotes Cerro Prieto Fault Zone, IF the Imperial Fault, SF the Saltillo Fault. Yellow solid rectangle (p) marks the CPGF area, same as in Figure 1. Yellow dashed outline (r) shows the surface projection of the recharge aquifer (Glowacka *et al.*, 2005).

Subsidence in the study area was studied using InSAR by Carnec and Fabriol (1999) and Hanssen (2001) using ERS1/2 images acquired in the periods 1993 – 1997 and 1995-1997, respectively. A significant local subsidence has been detected. Due to the high degree of temporal and spatial decorrelation, reliable data was obtained only over the mainly desert area of CPGF. Although agricultural activity in the area limited the investigation, interferometric monitoring revealed that the ground deformation is associated with the withdrawal of

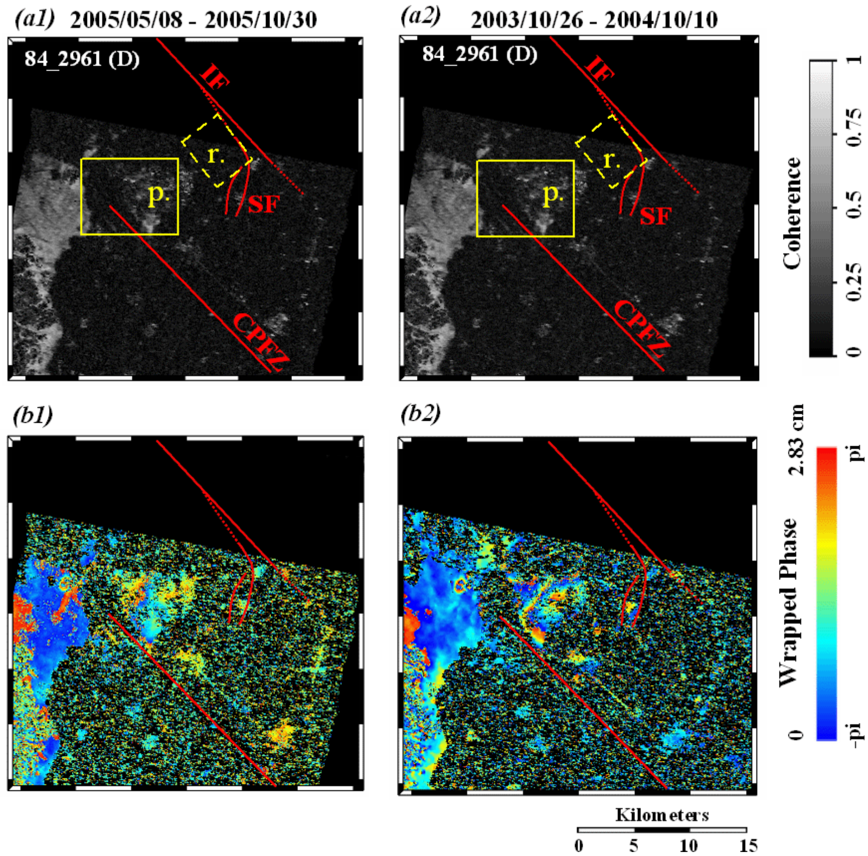

Figure 3. InSAR results from interferometric pairs 1 and 2 from Table 1. (a1-a2) geocoded coherence images (a1-a2); (b1-b2) wrapped phase interferograms. Annotation as in Figure 2.

geothermal fluid and agreed with the leveling data. Modeling of the subsidence was carried out assuming elastic deformation in a half-space from simple point sources, of which five were necessary to reproduce the fringe patterns observed on the interferograms (Carnec and Fabriol, 1999). The depths and locations of three of the sources are compatible with the location of the known reservoir.

3. Processing Software and Data Set

SAR images (single-look complex) were acquired from ESA and interferogram processing was conducted using the DORIS and SNAPHU software (Kampes, 1999; Chen et al., 2001), Delft orbits (Scharroo *et al.*, 1998), and SRTM elevation data.

In this paper we present analysis of four ENVISAT interferograms which were selected based on good correlation and lack of obvious atmospheric artifacts. Details are listed in Table 1. These include both ascending (track 306, frame 639) and descending (track 84, frame 2961) data. Figure 1 shows their spatial coverage.

4. Preliminary Results Analysis

Figure 2 shows interferometric results (coherence, wrapped phase and surface displacement away from the satellite along the radar line of sight (LOS)) for the interferometric pairs 1 and 2 (Table 1), with temporal baselines of 70 and 35 days, respectively. The interferograms have a good coherence at the CPGF area and the surrounding areas. The deformation pattern is clearly visible. The dominant feature that shows the highest deformation rate is a NE-SW elliptical area with two subsidence bowls. The maximum subsidence rate is ~1.5 cm/month and is located in the recharge zone (r) (Figure 2 b1-b2, c1-c2). A second centre of subsidence is located below the CPGF production zone (p) and has a subsidence rate ~ 1 cm/month. These results are in good agreement with the latest leveling data.

A relatively strong subsidence gradient is observed to the south of an evaporation lagoon, near the northern end of the Cerro Prieto Fault and in the eastern part of the study area, near the Saltillo Fault. The high subsidence gradient to the south of the evaporation lagoon was reported previously by Hanssen (2001); however the other strong subsidence gradient is detected for the first time here. Interferograms 1 and 2 (03/12/16-04/02/24 and 04/12/19-05/01/23) show that the ground deformation area is bounded in the east by the Saltillo Fault and in the west by the more diffuse (~ 2km) Cerro Prieto Fault Zone (Figure 2 b1-b2, c1-c2).

A vertical creep event of 1.2 cm observed by a vertical extensometer installed on the Saltillo Fault falls in the time spanned by the first (03/12/16-04/02/24) interferogram.

Figure 3 shows the interferometric results (coherence and wrapped phase) for the interferometric pairs 3 and 4 (Table 1), with temporal baselines of 175 and 350 days, respectively. These interferograms show higher decorrelation, but a good signal is still observed in the desert area near the CPGF. Although the data consist of isolated patches, it is still possible to follow the main fringes visually. The contours of the fringes show an elliptic subsidence bowl bellow the CPGF production zone (p). The maximum subsidence rate occurs near the eastern boundary of the CPGF where the production in the newest power plant (CP IV) has started in 2000. This production development may be accompanied by changes in the ground deformation pattern, but there is little in-situ information available to confirm or reject this assumption. In addition, the last leveling data also suggests the migration of the maximum of subsidence in the production zone to the eastern border of the field. However, there is a span of ~ 9

Table 1. Interferometric pairs used in this study. A and D indicate ascending and descending tracks, respectively.

Pairs	Satellite	Track_ Frame	Master Image (yy/mm/dd)	Slave Image (yy/mm/dd)	B⊥ (m)	B_{temp} (days)
1	ENVISAT	306_639 (A)	2003/12/16	2004/02/24	157	70
2	ENVISAT	84_2961 (D)	2004/12/19	2005/01/23	77	35
3	ENVISAT	84_2961 (D)	2005/05/08	2005/10/30	160	175
4	ENVISAT	84_2961 (D)	2003/10/26	2004/10/10	147	350

years between the two last leveling measurements, therefore the time resolution is very low. Our InSAR results show the possibility of improving the temporal resolution of monitoring this phenomenon.

5. Concluding Remarks

This paper presents preliminary results from the InSAR monitoring of the CPGF. For this purpose, ENVISAT data were used and more accurate estimates of the rate of subsidence over time were achieved. The interferograms clearly show a deformation signal with a time span of up to 1 year. However, the temporal decorrelation increases considerably for the interferometric pairs that span more than three months in the areas covered by agricultural fields around the CPGF. In our next step, we hope to construct time series of deformation. The interferograms with temporal baselines of 35 and 70 days generated from ENVISAT data show the existence of deformation in an area to the east of the CPGF production zone, which is recharge zone. These data allow the estimation of the recharge zone extension.

The combination of InSAR with the available ground truth data (leveling and geotechnical instruments) is powerful and has already yielded useful results. We are currently in the process of modeling of the deformation signals observed by InSAR, geodetic and geotechnical techniques.

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7. References

1. Allis, R. G., 2000. "Review of subsidence at Wairakei field, New Zealand". Geothermics, 29 (4-5), 455-478.

2. Carnec, C. and H. Fabriol, 1999. "Monitoring and Modeling Land Subsidence at the Cerro Prieto Geothermal Field, Baja California, Mexico, Using SAR Interferometry". Geophysical Research Letters, 26 (9), 1211 – 1214.

3. Chen, C. W. and H. A. Zebker, 2001. "Two-dimensional phase unwrapping with use of statistical models for cost functions in nonlinear optimization". Journal of the Optical Society of America A., 18, 338-351.

4. Glowacka, E., J. J. Gonzalez, and H. Fabriol, 1999. "Recent Vertical deformation in Mexicali Valley and its Relationship with Tectonics, Seismicity and Fluid Operation in the Cerro Prieto Geothermal Field". Pure and Applied Geophysics, 156, 591 – 614.

5. Glowacka, E., O. Sarychikhina, and F. A. Nava, 2005. "Subsidence and stress change in the Cerro Prieto geothermal field, B.C., México". Pure and Applied Geophysics, 162, 2095-2110.

6. Hanssen, R.F., 2001. "Radar Interferometry; Data Interpretation and Error Analysis". Kluwer Academic Publisher, Dordrecht, Netherlands.

7. Kampes, B., 1999. "Delft Object-oriented Radar Interferometric Software User's manual, Delft University of Technology", Nederlanden.

8. King, G. C. P., R. S. Stein, and J. Lin, 1994. "Static Stress Changes and the Triggering of Earthquakes". Bulletin of the Seismological Society of America, 84 (3), 935 – 953.

9. Lippmann, M. J., A. H. Truesdell, A. M. Mañón, and S. E. Halfman, 1991. "A review of the hydrogeologic-geochemical model for Cerro Prieto". Geothermics, 20, 39 – 52.

10. Mossop, A.P. and P. Segall, 1997, "Subsidence at the Geysers Geothermal Field, N. California from a Comparison of GPS and Leveling Surveys". Geophysical Research Letters, 24, 1839–1842.

11. Sarychikhina, O., E. Glowacka, F. A. Nava Pichardo, and J. M. Romo Jones. 2005. "Modeling of subsidence in the Cerro Prieto Geothermal Field, B.C., Mexico". Proceedings World Geothermal Congress 2005,Antalya, Turkey, paper no.1189.

12. Scharroo, R., P. N. A. Visser, and G. J. Mets, 1998. "Precise orbit determination and gravity field improvement for the ERS satellites". Journal of Geophysical Research, 103 (C4), 8113-8127.

13. Toda, S., R. S. Stein, P. A. Reasenberg, and J. H. Dieterich, 1998. "Stress transferred by the Mw=6.9 Kobe, Japan, shock: Effect on aftershocks and future earthquake probabilities". Journal of Geophysical Research, 103, 24543 – 24565.