A Genetic Algorithm in Subsidence Modeling in the Cerro Prieto Geothermal Field, Baja California, Mexico

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ABSTRACT

Comparison between observed subsidence rate and 30 years of fluid extraction in the Cerro Prieto Geothermal Field (CPGF) suggests that the observed subsidence is mainly of anthropogenic origin (Glowacka *et al.*, 1999, 2000). Additionally, 8 years of continuous observations of extension at the Imperial fault and field observation of the Cerro Prieto fault indicate that most of the subsidence is bounded by these faults. In this work we use the precision leveling data obtained by CFE (Comisión Federal de Electricidad, Mexico) during 1994-1997. We choose the mathematical model of tensional cracks of Yang and Davis (1986) as the one most appropriate to represent the deformation of sediment layers produced by fluid extraction in a reservoir bounded by faults. A genetic algorithm was used to fit the crack parameters: x, y, z (center of crack), p (crack closure), c and c1 (crack dimensions), and azimuth and dip (crack orientation) by minimizing the RMS error between observed and modeled subsidence rate. The algorithm works in a stripping mode: after fitting a crack to the data, its effects are removed and new cracks are fit to the residuum. After calculating a few tens of models, we analyze the physical interpretation of the calculated parameter values and compare it with a crack model based on the known hydrological model (Sarytchikhina et al, this volume). Except for the depth of the main reservoir, the genetic solutions agree, in general, with the known structure of the reservoirs. The analysis shows that vertical data alone cannot resolve the dependency between depth and closure of the cracks, and points out the necessity to have both vertical and horizontal measurements in order to obtain unique solutions.

1. INTRODUCTION

Vertical ground deformation can be caused by natural processes or by man-induced activities like fluid extraction and injection, mining, etc. Subsidence related with geothermal fluid withdrawal has been reported, for example, in Waikarei (Allis *et al.*, 1998), Geysers (Mossop and Segall, 1997), La Mesa (Massonnet *et al.*, 1997) and Coso (Fialko and Simons, 2000) geothermal fields. Since subsidence can destroy constructions (houses, roads, irrigation channels) and wells at depth, measuring and modeling of this phenomenon can help to understand, predict and/or avoid damage.

The Cerro Prieto Geothermal Field (CPGF) is situated in a pull-apart basin created by two major strike-slip, right-lateral, step-over to the right faults: Imperial and Cerro Prieto, in the Mexicali Valley. The area is characterized by rapid geodetic deformation, high heat flow, active seismicity, and volcanism.

The CPGF is operated by the Mexican Federal Electricity Agency (Comisión Federal de Electricidad: CFE). Production of electric power began in 1973, and since then, production growth has been achieved by an increase in the number of power plants and wells, resulting in 127 operating wells in 1994, with a total fluid extraction of about $3.2m^3/s$, ranging in depth from 1500 to 3000m. Injection of the discharged fluid started in 1989 and reached 45% of the waste water (or ~20 % of the extracted fluid) in 1993. The depth range of injection is slightly shallower, between 500 and 2600m. The geothermal fluid, with a temperature of 250°- 350° C, is extracted from the gray shales, isolated from the unconsolidated rock by a layer of mudstone and brown shales which constitutes the cap-rock. A geologic cross-section of the vicinity of the CPGF (CFE, 1995) shows a thick sedimentary filled basin, with unconsolidated sediments occupying more than 2 km, and sedimentary layers of mudstone and shales lying below. Sedimentary rocks are disturbed and displaced by normal faults, and inclined as effect of local tectonics. The CPGF reservoir is characterized by having “leaky” boundaries where the hot geothermal fluids exist in dynamic equilibrium with much cooler waters (Truesdell and Lippmann, 1990). It is generally accepted that the field is recharged from the East by hot water, and from East, West and South as well as from above (Truesdell *et al.*, 1998) by colder water from shallow aquifers of the alluvial basin of the Colorado river. Figure 1 presents geographical and tectonic situation of discussed area.

Geodetic studies in the Mexicali Valley began in the sixties and continued with varying space and time frequency until the 90’s. Analyzing the time and spatial distribution of the results of local leveling measurements in Mexicali Valley and the fact that the subsidence rate increases after every large fluid production increase, Glowacka *et al.* (1999) concluded that the observed subsidence rate, of about 12 cm/year for years 1994-1997 (Fig.1), is mainly induced by geothermal fluid extraction. Subsidence at CPGF was also measured by SAR (Synthetic Aperture Radar) interferometry by Carnec and Fabriol (1999) and Hanssen (2001) and was interpreted as being produced by geothermal fluid extraction. Modeling done by Sarychikhina *et al.* (this volume) confirm that man-induced subsidence accounts for ~96% of observed subsidence.

2. ROLE OF FAULTS

The trace of the Imperial fault has been recognized since the 1940 El Centro earthquake. The surface rupture of the 1940 earthquake spanned almost 62 km, from Brawley (California) to Canal Solfatara (Richter, 1958), located 13 km north of the CPGF. In 1977 a local earthquake with a 4.2 magnitude produced a vertical rupture of the paved road in Ejido Saltillo (González, 1990). This rupture was reactivated during following earthquakes and has continued to grow and at present it can be observed crossing through paved roads, concrete channels and abandoned fields. The observed rupture was mainly vertical, always west side down. Studies done during 1989-1996 (González, 1990, González *et al.*, 1998) show that the rupture zone is about 8 km long in the southernmost segment.

In 1996 continuous vertical movement measurements across the Imperial fault started in Ejido Saltillo using a crackmeter installed in a vertical position (Glowacka *et al.*, 2000). Since then the 6cm/year vertical displacement across the fault (along the 3 meters span of extensometer) was observed. Amplitude, extension and time behavior of the displacement of the southern part of Imperial fault points the conclusion that Imperial fault is an eastern boundary of the subsided area and a groundwater barrier (Glowacka *et al.*, 1999, 2000).

The Cerro Prieto fault, which crosses the CPGF area in a series of small scarps and cracks, was surveyed by CFE between 1995 and 1998, and 4cm/year east side down displacement was observed for this period (Lira, 1999). This suggests that the Cerro Prieto fault is a groundwater barrier too.

The role of faults located in the extraction zone was analyzed by Lippmann at al. (1991). According to these authors, faults H and L (Fig.1) are used as a conduct for hot and cold water recharging and as a boundaries between reservoirs α, β and γ.

3. MODELING

To evaluate the elastic deformation caused by volume extraction, mathematical models used for vulcanology and hydrofracturing can be applied. The one most commonly used is the Mogi (1958) model of a spherical source with hydrostatic pressure inbeded in an elastic half-space. This model was used by Mossop and Segall (1997) to model subsidence in the Geysers geothermal field, and by Carnec and Fabriol (1999) and Hansen (2001) to model subsidence in the CPGF. The model of deflation of a triaxial ellipsoidal cavity in an elastic half-space (Davis, 1986) was used for subsidence modeling in the Coso geothermal field (Fialko and Simons, 2000). The subsidence induced by fluid extraction was evaluated by Segall (1989) using a poroelastic model of an axisimetric reservoir. All those models have some kind of symmetry: 3 or 2 dimensional. Because the CPGF reservoirs are located in sedimentary layers and bounded by faults, we decided to use the mathematical model of a rectangular tension crack (Yang and Davis, 1986) as the one which better represents the geometry of reservoirs.

Each crack is characterized by the parameters: x, y, z (center of crack), p (crack closure), c and c1 (crack length and width half-dimensions), and azimuth and dip (crack orientation). A genetic algorithm was used to fit the crack parameters by minimizing the RMS error between observed and modeled subsidence rate. In the first step, *n* cracks (parents) are created by random distribution in a parameter space defined a priori. Then, *m* children are generated for every parent, by random variations of all parameters using normal distributions centered at the parent parameter, and having a standard deviation calculated from the parent population. In the next step the best *n* solutions (those with the smallest errors) are chosen form both parents and children, to become the next parent generation. The process iterates until a threshold RMS error value is attained or further changes are insignificant. The algorithm works in a stripping mode: after fitting a crack to the data, its effects are removed and new cracks are fit to the residuum.

The observed subsidence was corrected by subtracting the modeled tectonic subsidence (Sarychikhina *et al.*, this volume). Based on the known physical parameters of the CPGF reservoirs and geotectonics, the following range of parameters was allowed: p: 0.01 – 1.0 m, z: 0.2 – 10 km, x, y –analyzed area, azimuth: 0-180^o, dip: 0 – 20^o. Parameters c and c1 were given fixed values between 2 and 7 km for each trial. There were 25 trials, every time with 4 cracks. All trials gave similar results, with similar RMS values of about 1cm/yr, for an estimated observed subsidence rate uncertainty of 0.34 cm/yr (Sarychikhina, 2003). The centers of the resulting cracks are presented as points in Figure 2. Very deep cracks with small p are considered insignificant and not shown in the figure. The crack centers are concentrated in four groups. Figure 3 presents an example of a trial, with four cracks projected above the observed subsidence; the resulting residuals are shown in Figure 4.

A comparison of the calculated parameter values with those of a model based on the known hydrology (Sarytchikhina et al, this volume) is as follows. Model crack group 1 has depths between 4.5 and 8 km, and other crack groups have depths between 0.5 and 1.5 km; while the depths of cracks in the hydrology based model are between 1.0 and 2.5 km, close to the depths of extraction wells. The *p* parameter ranges between 0.3 and 1.0 m for the first group, and is about 0.1 for others. Except for the depth of the main reservoir, the locations of genetic solutions agree, in general, with the known structure of the reservoirs. Crack 1 in Fig.3 belongs to group 1 of fig.2, and models the subsidence caused by extraction from reservoir β. Crack 2 in figure 3 is a member of group 2 and models the subsidence caused by (horizontal) fluid recharge from an unexploited reservoir located to the east of CPGF (proposed by Glowacka *et al.*, 1999). Crack 3 in figure 3 belongs to group 3 and models the subsidence caused by extraction from reservoir α. The azimuths are mainly N-S for group 1, NE-SW, for group 2, and N-S for group 3, and do not correspond to the azimuth of known faults.

4. DISCUSSION AND CONCLUSIONS

As is well known, the inverse problem of subsidence sources, like many other inverse problems in geophysics, has no unique solution. Additionally, the final results depend heavily on the limits imposed on the parameter set.

A better agreement (smaller RMS error) between the observed and calculated subsidence rate can be achieved by adding more cracks, but this will merely eliminate very local, small, residuals and hence will not contribute to our knowledge about the reservoir.

The horizontal location of the modeled cracks agrees with that of reservoirs α and β, while depths do not agree.

Contrary to the expectation, the orientation of the cracks is not related to the fault azimuth, because for a deep source the deformation on the surface has almost no dependence on the azimuth of the crack.

Compared to the depth of extraction, the first crack is too deep, while the others are too shallow. There is no crack which could represent the recharge from a shallow and wide reservoir. This is an effect of stripping mode used by the program, since on its first attempt the program is finding the crack that minimizes the overall RMS, so it chooses a deep source in order to remove as much of the subsidence as possible. This effect can be counteracted by defining limits for every stripping step; this scheme results in lower RMS (0.87) and a source depth agreeing with the extraction depth, but it gave no possibility to distinguish sources equivalent to the α, β and γ reservoirs (Sarychikhina, 2003). The possibility that the source of subsidence is, in fact, deep and equivalent to a natural (volcanic) source, should be rejected, since the subsidence rate agrees with the extraction changes, which can not be a case in the natural subsidence.

Since the relation between source parameters and deformation is different for vertical and horizontal components there is a need to have both vertical and horizontal measurements in order to obtain unique solutions. Only GPS measurements can fulfill this necessity. It should be also pointed that to understand the dynamics of subsidence as a function of extraction, the measurements should be done at least once per year and in the area considerably larger than the field itself.

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REFERENCES

Allis, R. G., X. Zhan and A. Clotworthy: Predicting Future Subsidence at Wairakei Field, New Zealand, *Geothermal Resources Council Trans.*, **22**, (1998), 43 – 47.

Carnec, C. and H. Fabriol: Monitoring and modeling land subsidence at the Cerro Prieto geothermal field, Baja California, Mexico, using SAR interferometry, *Geophysical Research Letters*, **26**, **9**, (1999), 1211 – 1214.

Comisión Federal de Electricidad (CFE): Campo Geotérmico Cerro Prieto, (1995).

Davis P. M.: Surface deformation due to inflation of an arbitrary oriented triaxial ellipsoidal cavity in an elastic half-space, with references to Kilauea Volcano, Hawaii, *Journal of Geophys. Research*, **91**, **B7**, (1986), 7429-7438.

Fialko Y. and Simons M.: Deformation and seismicity in the Coso geothermal area, Inyo County, California, Observations and modeling using satellite radar interferometry. *Journal of Geophys. Research*, **105**, **B9**, (2000), 21781-21793.

Glowacka, E., J. J. Gonzalez and H. Fabriol: 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**, (1999), 591 - 614.

Glowacka E., Gonzalez J. and Nava A.: Subsidence in the Cerro Prieto Geothermal Field, Baja California, Mexico, *Proceedings*, World Geothermal Congress (2000), 591-596.

González J. J.: La falla Imperial en el Valle de Mexicali, a 50 años del temblor Imperial, magnitud Richter 7.0 del 18 de mayo de 1940, *Comunicaciones Académicas*, CICESE, CISIT9003, Ensenada, B. C. México (1990).

González, J. J., E. Glowacka, F. Suárez, G. Quiñónez, M. Guzmán, J. M. Castro, F. Riviera, and M. G. Felix, 1998, Movimiento reciente de la falla Imperial, Mexicali, B. C., *Divulgare, Ciencia para todos*, Mexicali, B. C, **6**, **22**, (1998), 4 - 15.

Hanssen, R. F.: Radar Interferometry, Kluwer Academic Publisher, Netherlands (2001).

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

Lira H.: Resultados del monitoreo de desplazamiento de la falla Cerro Prieto en 1998, *Informe Técnico RE05/99*, CFE (1999).

Massonnet D., Holzer T. and Vadon H.: Land subsidence caused by the East Mesa Geothermal Field, California, observed using SAR interferometry, *Geophys. Res. Letters.*, **22**, (1997), 1537-1540.

Mogi K.: Relations between the eruptions of various volcanoes and the deformation of the ground surface around them, *Bull. Earthquake Res. Inst. Univ. Tokyo*, **36**, (1958), 99 - 134.

Mossop A. P. and P. Segall: Subsidence at the Geysers geothermal field, N. California from comparison of GPS and leveling surveys, *Gephysical Res. Letters*, **24**, (1997), 1839-1842.

Richter, Ch. F.: Elementary Seismology, Freeman and Company (1958).

Sarychikhina, O.: Modelación de subsidencia en el campo geotérmico Cerro Prieto, *Tesis de Maestría*, CICESE, México (2003).

Sarychikhina O., Glowacka E., Nava A., Romo J.:Modeling of Subsidence in the CerroPrieto geothermal Field, B. C., Mexico, (2004) This volume.

Segall, P.: Earthquakes triggered by fluid extraction, *Geology*, **139**, (1989), 535 – 560.

Truesdell, A. H. and M. J. Lippmann: Interaction of cold-water aquifers with exploited reservoirs of the Cerro Prieto Geothermal system, Geothermal Resources Council Trans. 14, (1990), 735 – 741.

Truesdell, A. H., M. J. Lippmann, H. Gutiérrez P. and J. de León V.: The Importance of Natural Fluid Recharge to the Sustainability of the Cerro Prieto Resource, *Geothermal Resources Council Trans.*, **22**, (1998), 529-536

Yang, X. and P. M. Davis: Deformation due to a rectangular tensional crack in an elastic half-space, *Bulletin of the Seismological Society of America*, **76**, **3**, (1986), 865 - 881.

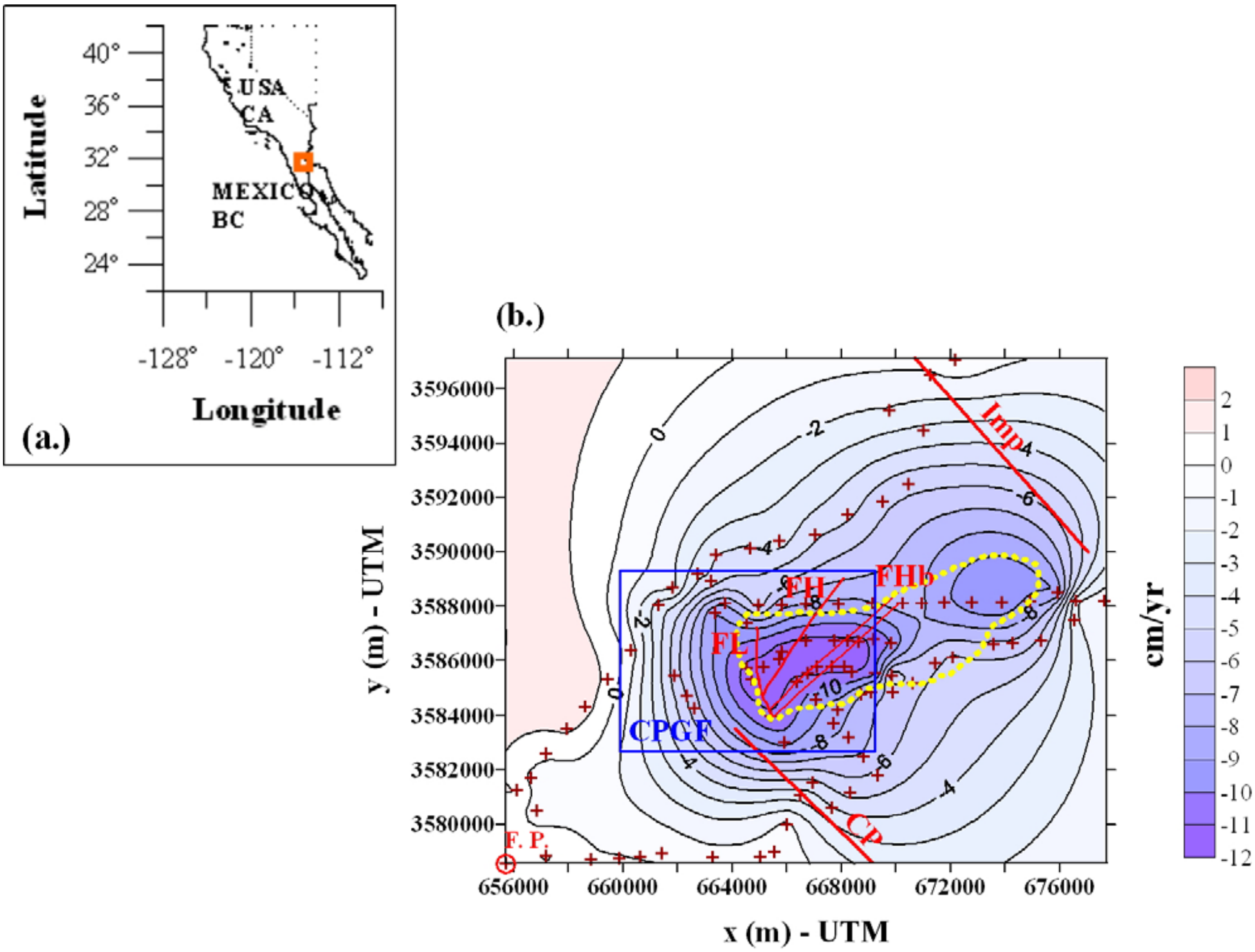

Figure 1. Geographical Situation: (a.) Location map. (b.) Observed subsidence rate (1994 - 1997) in cm/yr. CPGF - Cerro Prieto Geothermal Field (blue rectangle), Imp - Imperial fault, CP - Cerro Prieto fault, FH ─ surface projection of H fault, FHb ─ intersection of H fault with the top of the β reservoir, FL ─ L fault. Dotted yellow line ─ T ≥ 300° isotherm. Brown crosses ─ leveling points, F. P. ─ fixed point.

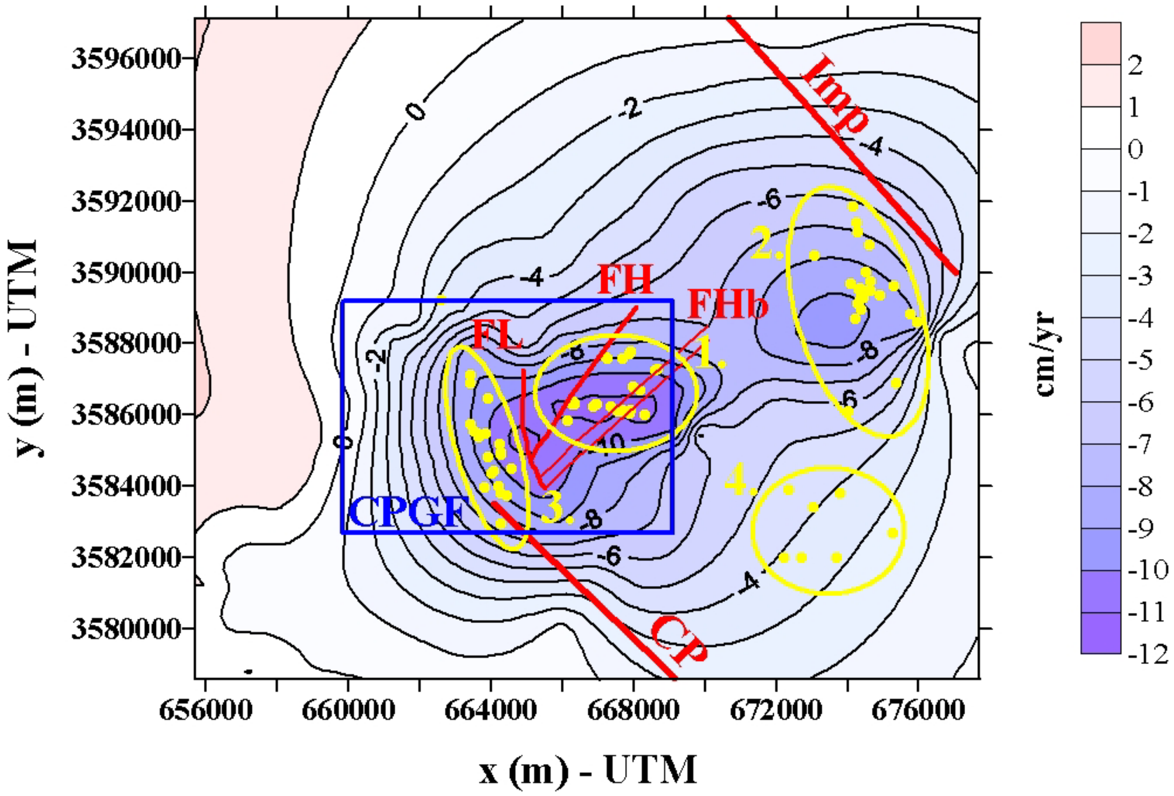

Figure 2. Surface projection of cracks centers (yellow dots). Isolines are observed subsidence rate (minus tectonic component).

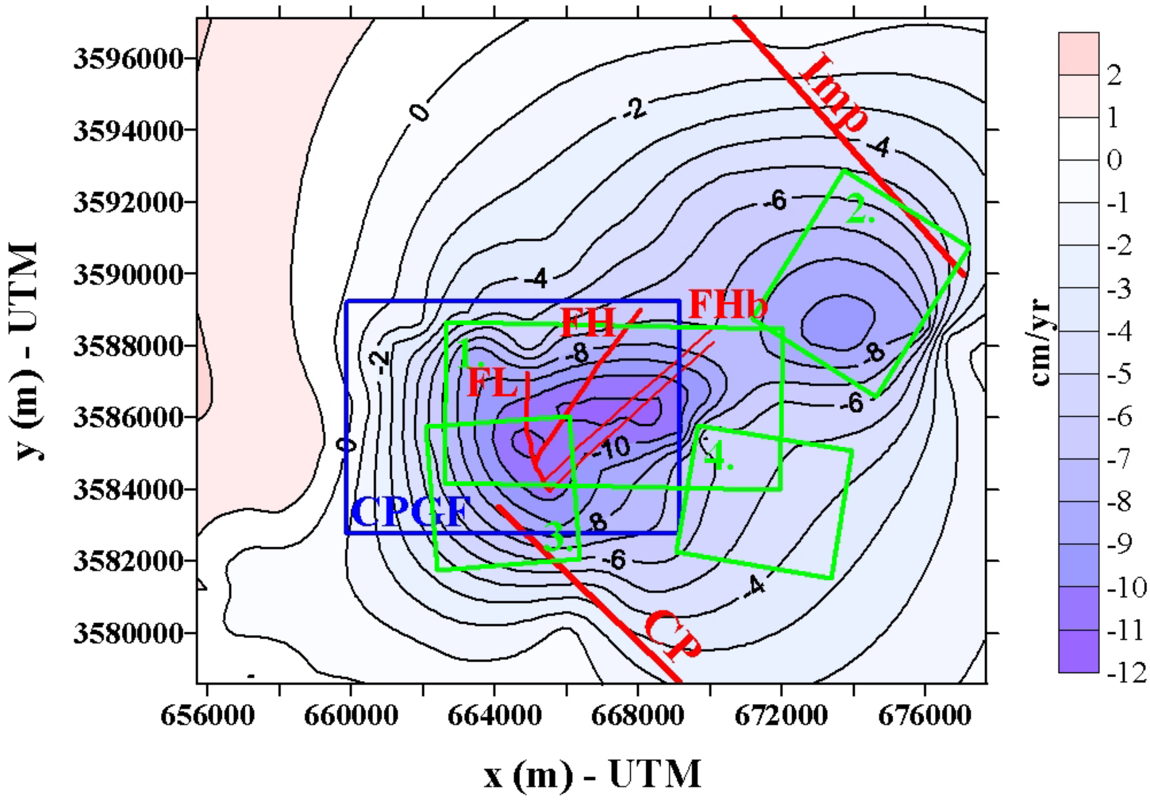

Figure 3. Surface projection of cracks (green rectangles) . Isolines are observed subsidence rate (minus tectonic component).

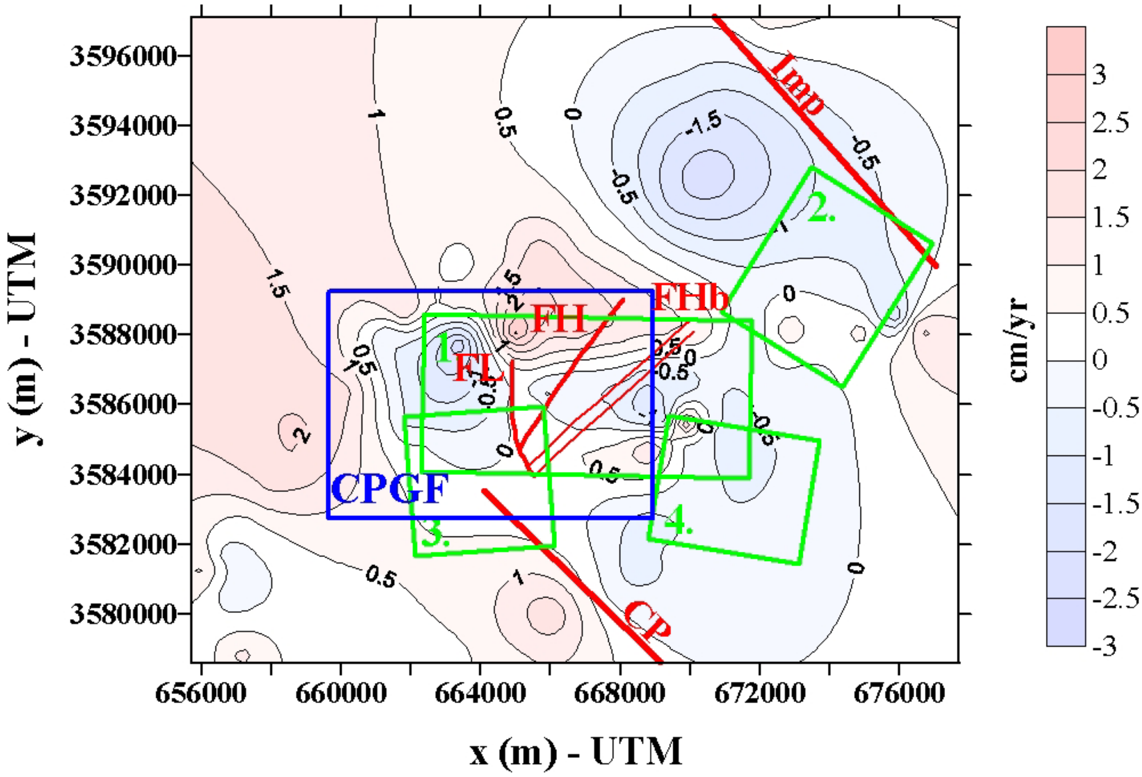

Figure 4. Surface projection of cracks (green rectangles) and residual (cm/yr).