Investigating the relation between geothermal reservoir compaction, geometry and production rates from a ten-year InSAR ground displacement history at the Bradys and Desert Peak fields: Assessing the potential of retrospective InSAR monitoring to assist reservoir management and expansion over fields without previously documented subsidence

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ABSTRACT

Knowledge of a geothermal reservoir's hydro-thermal-mechanical response to production is critical to sustaining and/or expanding its production capacity. We propose investigating the relation between geothermal reservoir compaction (or bulk porosity loss), geometry and production rates by recovering a ten-year InSAR ground displacement history at the Bradys and Desert Peak fields, in west central Nevada. Our objectives are to 1) Demonstrate the recover and application of retrospective InSAR annual histories for geothermal fields lacking documented subsidence; 2) Identify specific reservoir structural controls through integration of the subsidence patterns with mapped geological and geophysical data; 3) Chart measures of each reservoir's subsidence vs. production sensitivity over time to define its progression toward sustainability. The work will lead to increased utilization of geothermal resources in the Western United States by providing basic measurements and interpretations that will directly assist reservoir management and expansion at Bradys and Desert Peak. Knowledge of the reservoir's subsidence geometry and response to production will immediately assist in defining preferred locations for new production and recharge wells that can improve reservoir performance. The project's publication of the case histories and observation data sets will inform the geothermal community and inspire broader applications. The method's low cost, available data and processing tools encourage its wide application.

INTRODUCTION

Surface deformation is an expected consequence of the production of geothermal fluids and steam even if the reservoir is kilometers deep and is isolated from shallow groundwater. Reservoir deformation is driven largely by pressure reduction (*underpressure*) which reduces the reservoir's compressive strength and allows subsidence of the overlying rocks into the reservoir. Reservoir volume loss is achieved largely at the expense of its bulk porosity through compression of pore and fracture space which has the effect of restoring strength, hence halting further deformation. Contraction due to cooling is also a factor in reservoir compaction. Although geothermal production subsidence rates are expected to vary dramatically between fields depending on geologic and hydrologic conditions, a geothermal system advancing toward steady state recharge might be expected to show annual reductions in reservoir compaction. Complete production-recharge equilibrium would theoretically be indicated by cessation of volume loss and subsidence with a constant reservoir *underpressure* - a condition that probably never exists in producing fields.

Surface subsidence rates of several centimeters per year have been measured across several major geothermal fields beginning at least as early as the mid 1970's using optical leveling techniques. Owing to the leveling method's cost and speed, spatial and temporal data density remained limited. The availability of GPS in the early 1990s fostered expanded research into geothermal production related subsidence with data sets of improved spatial and temporal density (Antony, 1997). By the mid 1990's satellite InSAR began to demonstrate its potential for providing map-like images of subsidence around producing fields at resolutions of 30 meters. (Fialko, 2000). In addition to high spatial resolution, the InSAR method offers a capability beyond GPS or optical leveling: It can generally be applied in retrospective subsidence rate studies by using its 10 year archive of ERS1/2 scenes. Presently, InSAR's potential has been applied only to a few major geothermal fields. The results are improving our understanding of geothermal reservoir compaction processes and have also allowed recognition of superimposed signatures of fluid flow related to shallow crustal magnetism (Wicks 2001). InSAR investigations at the Coso, California geothermal field have shown that surface deformation resulting from one year's production can be measured reliably (Wicks 2001). While the InSAR methods ability to monitor geothermal field subsidence effects has been well established on the largest fields, the method has not been applied and evaluated for its reservoir management value at mid-capacity geothermal fields. Consequently, its value remains an unknown. Specialized reservoir management models which relate surface deformation observations to reservoir production characteristics are available or being developed by Schlumberger, Lawrence Livermore National Laboratory and others (Vasco, 2001a,b). The evolution and application of these reservoir management tools depends in large part on the availability of observation data sets.

STUDY AREA

The Desert Peak-Brady geothermal field lies in the Hot Springs Mountains of west central Nevada, about 80 km east-northeast of Reno. Although located within 6 km of one another, isothermal maps suggest that the Brady and Desert Peak production are associated with independent thermal features (Benoit et al., 1982). Desert Peak is distinguished as a blind geothermal resource lacking current and paleo hydrothermal surface manifestations. The Hot Springs Mountains are composed of Tertiary volcanic and sedimentary rocks that rest directly on Mesozoic metamorphic basement that forms the reservoir systems. The Brady 21.1-MW dual-flash geothermal plant produces from 6 production wells with an average depth of 3,057 feet and average fluid temperature of ~312 F. The plant has eight injection wells with an average injection fluid temperature of ~238 F. The Brady plant also supplies geothermal fluid to the Brady Hot Springs onion dehydration plant. The Desert Peak 9.9 -MW dual-flash geothermal plant produces from two production wells with an average depth of 3,683 feet and fluid temperature of ~312 F. Desert Peak has two injection wells with an average depth of 4,000 feet and injection temperature of ~198 F. (Hess 2001), (Snow, J., Nevada Division of Minerals, 2002). Poorly defined geothermal reservoirs boundaries at Bradys Hot Springs and Desert Peak systems pose problems for their further development.

PROPOSED RESEARCH

We propose investigating the relation between geothermal reservoir bulk porosity loss, geometry and production rates by recovering a ten-year InSAR ground displacement history at the Bradys and Desert Peak fields, in west central Nevada. Our objectives are to 1) Demonstrate the recover and application of retrospective InSAR annual histories for geothermal fields lacking documented subsidence; 2) Identify specific reservoir structural controls through integration of the subsidence patterns with mapped geological and geophysical data; 3) Chart measures of each reservoir's subsidence vs. production sensitivity over time to define its progression toward sustainability.

InSAR data. We have identified 18 European Space Agency (ESA) ERS 1/2 (European Radar Satellites 1 & 2) scenes in Track 256 Frame 2799 which are suitable for interferometric image generation covering the interval between March 1992 and September 2002. These scenes form four groups that have internal base-lines of 100 meters or less and Doppler frequency variations less than 300 Hz. The largest unsubdivided time step between InSAR forming scene pairs is 23 months (November 1993 and October 1995). The scenes were selected with a criterion of a minimum of 11 months between InSAR scene pairs. Four of the needed scenes are available from the WinSAR archives leaving 14 to be purchased. UNR is a member of the WinSAR (W estern North America In terferometric S ynthetic A perature R adar) satellite radar research consortium.

Methods. We will use the 18 ERS 1/2 satellite radar scenes covering March 1992 through September 2002 to measure deformation in the Hot Springs Range study area by preparing multiple interferograms combinations using JPL ROI_PAC processing software which is currently installed on a dedicated Sun Blade workstation in the Arthur Brant Laboratory for Exploration Geophysics at UNR. The topographic models for InSAR processing will be created from a 10 meter U. S. Geological Survey (USGS) digital elevation model (DEM) refined with 350 GPS control points from a recent gravity survey. Interferograms will be generated from all compatible scene pairs with time spans from 11 months to nine years. The differential ground height changes inferred from each InSAR scene pair will be used to construct a best fitting apparent ground deformation time-series. InSAR deformation rates will be validated by eight hour GPS occupations of six National Geodetic Survey (NGS) first order vertical control monuments that cross the Bradys production area along the I-80 highway. The NGS defined these with differential leveling in 1991 as part of a Nevada leveling network. To facilitate millimeter level conversions between the existing leveling heights and new GPS ellipsoidal heights we will produce a new 300 meter resolution local geoid model for the entire study area from our recent gravity investigation. If suitable leveling control is identified over the Desert Peak reservoir it will be similarly utilized. If these are not identified, precision GPS heights will be measured at six control monuments in the Desert Peak field to facilitate future subsidence work. Geothermal production summaries will be compiled with monitoring well level data to define the spatial and temporal ground water inputs to the reservoir and overlying aquifer. Available surface geology, and gravity defined basin geometries and structures from recent studies in the Bradys Desert Peak area will be combined with production data in a Geographic Information System (GIS) for inter-comparison with derived InSAR patterns. The InSAR measured ground deformations and production summaries will be used to compute annual reservoir compaction factors to track each reservoirs development.

Some Analysis Questions

- How different are the ground deformation responses over the Bradys and Desert Peak systems. Do known geological differences provide an explanation?

- Is the annual reservoir compaction factor decreasing over time?

- Is a long-term time constant apparent in the reservoir compaction factor.

- How robust are the surface deformation volume estimates obtained over intervals of one year, and two years?

- How do the reservoir ground deformation patterns relate to the known or suspected faults that feed and bound the reservoir?

- Are the reservoir ground deformation patterns indicative of fluid production from a narrow structural zone or a large volume? Is deformation asymmetric relative to the production center?

Equipment and Resources. UNR has all of the specialized equipment and software required to complete this project including three Trimble 4000Ssi geodetic receivers. Radar interferograms will be processed and analyzed on our SUN Blade 1000 workstation using JPL ROI_PAC software maintained in the Arthur Brant Laboratory for Exploration Geophysics at UNR and also at LLNL. GPS data will be processed using JPL's GIPSY software also on our SUN workstation.

Personnel. Dr. Gary Oppliger, Associate Research Professor, in addition to leading the project, administering resources and reporting, will be responsible for the ERS 1/2 Radar scene ordering, InSAR processing, geodetic GPS data collection and processing and elevation and geoid model development. Dr. Oppliger will maintain a project web page, present results at a conference and take the lead the publication of results.

Mark Coolbaugh, Assistant Research Professor, will be responsible for integration of the InSAR and production results with existing geology and geophysics data. He will collect and compile Brady and Desert Peak well production records and develop an analysis of the integrated results as they may impact geothermal production and exploration.

Dr. William Foxall, an InSAR researcher at LLNL, will be an unfunded collaborator on this project. Dr. Foxall will advise on InSAR usage and processing and contribute to the analysis and publication of the results.

RESULTS AND RELEVANCE

The proposed work is possibly the first to investigate the recoverability and utility of annual InSAR histories over geothermal fields lacking previously documented subsidence. Our objectives are to 1) Demonstrate the feasibility of the recovery and application of retrospective InSAR annual histories to define the production related subsidence responses over mid-capacity geothermal fields lacking documented subsidence; 2) Identify specific reservoir structural controls through integration of the subsidence patterns with mapped geological and geophysical data; 3) Chart measures of each reservoir's subsidence vs. production sensitivity over time to define its progression toward sustainability. The work will lead to increased utilization of geothermal resources in the Western United States by developing basic measurements and interpretations that will directly assist reservoir management and expansion at Bradys and Desert Peak and will provide valuable case examples. Knowledge of the reservoir's subsidence geometry and response to production will immediately assist in defining preferred locations for new production and recharge wells that can improve reservoir performance. Because the application of this method is relatively inexpensive and uses widely available data and processing tools the method has the potential for rapid commercialization.

This project is directly relevant to two of the *applied research areas* in the Great Basin Center for Geothermal Energy Research Program, including (1) *Geothermal Reservoir Management - Assessment of reservoir properties* (Part 2A in request for proposals [RFP]), (2) *Geothermal Resource Assessment - geophysical imaging* (Part 1D in RFP).

SCHEDULE AND DELIVERABLES

Start of project work: July 1, 03

1st Interim deliverable: September 30, 2003

Project web page created.
Table of InSAR scenes that have been ordered.
Table of existing vertical survey control monuments.

2nd Interim deliverable: September 30, 2004

- Project web page updated.
- Preliminary report on web.
- Preliminary map of time progression of surface deformation at Bradys and Desert Peak Fields showing inferred reservoir boundaries.
- Preliminary chart of annual cumulative volumetric change associated with the two geothermal fields.
- Preliminary results submitted for presentations at GSA, AGU or GRC annual meeting.

Final Deliverables before September 30, 2005

- Map showing time progression of surface deformation at Bradys and Desert Peak Fields showing inferred reservoir boundaries.
- Chart of annual and cumulative observed ground displacement for each group of closely associated production wells.
- Chart of annual and cumulative volumetric change associated with the two geothermal fields.
- Project web page finalized.
- Deformation time series grids published on web.
- Final technical report with results and analysis.
- Publication to submitted journal.

Quarterly reports

Fiscal year annual reports

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MILESTONES

Task	Description	Start mo/yr	Complete by mo/yr	Responsibility
1	SAR order	7/01/03	12/31/03	PI
2	SAR process	8/30/03	8/30/04	PI
3	GPS survey	9/01/04	9/30/04	PI
4	GPS process	9/30/04	10/30/04	PI
5	Geothermal production data	8/01/03	4/31/04	M.C
6	Project web page Initial Preliminary Final	 8/30/03 8/30/04 5/30/05	 9/30/03 9/30/04 6/30/05	PI
7	Elevation model	8/01/03	6/30/04	PI
8	Geoid model	9/01/03	9/30/04	PI
9	GIS integration	6/30/04	6/30/05	M.C.
10	Preliminary technical report	6/30/04	9/30/04	PI, M.C.
11	Prepare and submit presentation	5/30/04	8/30/04	PI, M.C.
12	Prepare and submit publication	5/30/04	8/30/05	PI, M.C.
13	Final technical report	5/30/05	8/30/05	PI, M.C.