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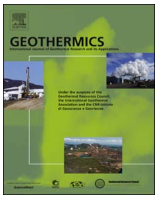

Geodetic measurements and numerical models of transient deformation at Raft River geothermal field, Idaho, USA

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ABSTRACT

We perform synthetic aperture radar interferometry using data acquired between 2004 and 2016 by the Envisat, and ALOS-2 satellite missions to measure transient deformation at the Raft River geothermal field in Cassia County in Southern Idaho where geothermal production began in late 2007. Time-series analysis of multiple interferometric pairs indicates uplift at an exponentially decaying rate, over an ~8 km-by-5 km area centered near three injection wells that recycle produced brine. Similarly, subsidence at an exponentially decaying rate is observed in a 4 km-by-4 km area west of the production wells. These two signatures remain in the same location in all of the well-correlated Envisat interferometric pairs spanning the time interval between 2007 and 2010. The boundary separating the uplifting and subsiding areas is associated with the steeply dipping Bridge fault zone. Using two-dimensional numerical models, we explore first-order, bi-directional coupling between hydrological and mechanical processes. Our results suggest that: (i) most of the deformation occurs due to pore pressure changes following the start of geothermal production, (ii) the rate of deformation decays to zero over a time scale on the order of ~5 years as the system reaches steady state, and (iii) a reservoir-scale permeability of the order of ~1E–14 m^2 is required to explain the transient deformation.

1. Introduction

Interferometric Synthetic Aperture Radar (InSAR) is a geodetic technique for measuring crustal deformation that provides very good precision, unsurpassed spatial sampling, and a useful observation cadence (e.g., Massonnet and Feigl, 1998). It has been used to monitor anthropogenic deformation at a number of geothermal fields (Ali et al., 2016 and references therein). However, the geodetic observations have rarely been combined with reservoir models incorporating appropriate physics (e.g., Vasco et al., 2013). By analyzing the temporal evolution and spatial pattern of deformation, and combining them with physics-based numerical models, we can gain insight into the associated subsurface processes, as well as the geometry and material properties of the reservoir. In this article, we demonstrate that transient deformation at Raft River is driven by hydro-mechanical processes associated with geothermal production.

The Raft River geothermal field is located in Southern Idaho at the southern periphery of the Snake River plain, within the north-south trending Raft River valley. The valley is filled with ~1.5 km of Pleistocene and Tertiary sediments, conglomerates and volcanic rocks, i.e., the Raft River, and Salt Lake formations, that overlie the Precambrian, eastward-dipping basement. A ~13 MW power plant has been operational at Raft River since November 2007. The primary production reservoir is within the ~150 m-thick Elba quartzite, a fine-grained, metamorphosed, quartz-rich sandstone located just below the contact between the sedimentary layers and the basement, at depths of 1400–1800 m, and is fracture-controlled (Ayling and Moore, 2013, and references therein). Four producing wells extract hot fluids with an average temperature of ~140 °C from depths of ~1500–1900 m. Following generation of electricity, the cooled fluids are reinjected back via three injection wells located in the southeast corner of the field at a pressure of ~1.9 MPa (Fig. 1). The injection wells are 1200–1900 m deep, and cased to a depth of at least 500 m (DiPippo, 2012). The rates of production and reinjection have each been roughly constant at

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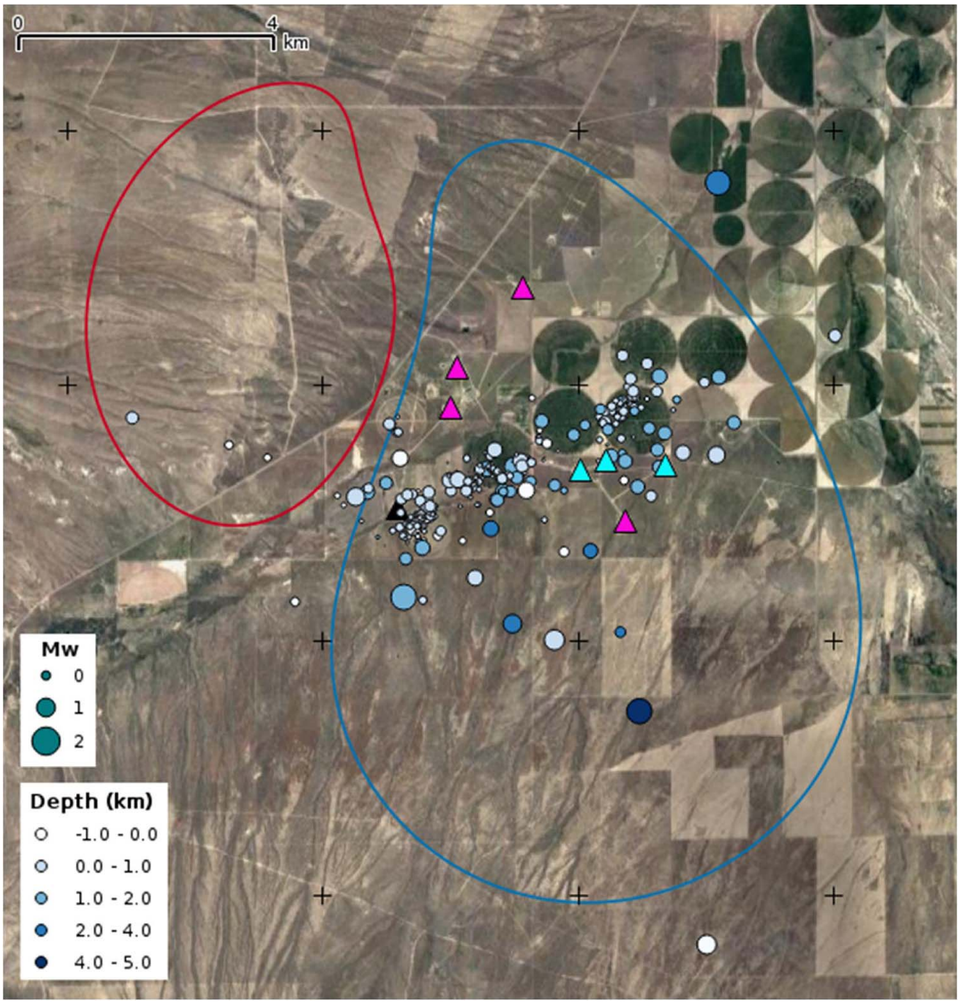

Fig. 1. Seismicity beneath Raft River geothermal field. Injection and production wells are represented by cyan and magenta triangles, respectively. Red and blue lines represent contours of range change rate, derived from Fig. 2(c), at intervals of 1 and −1 mm/year, respectively, and indicate areas where subsidence and uplift are observed following start of geothermal production. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

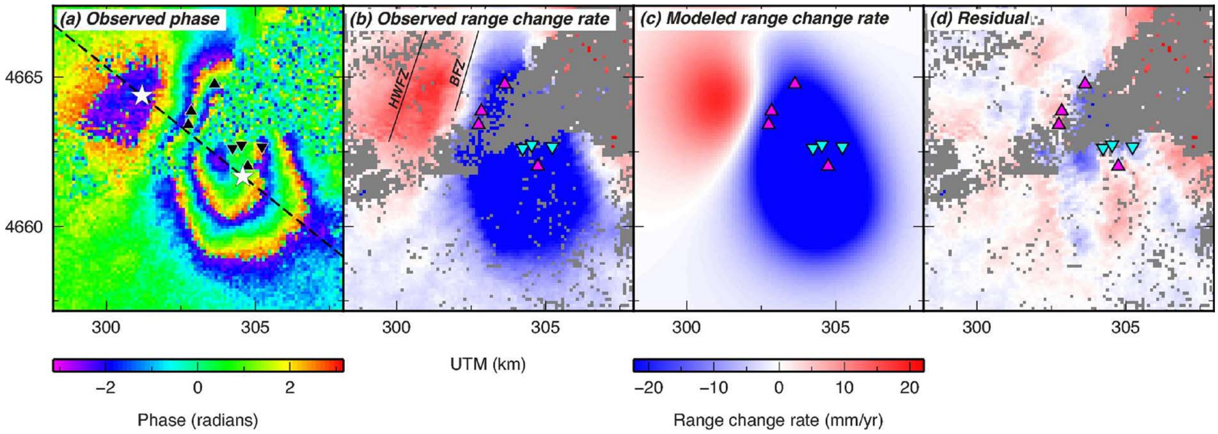

Fig. 2. (a) Observed wrapped phase change values (in radians) over a 350 day interval between July 29, 2007 and July 13, 2008. One colored fringe corresponds to 28 mm of range change, towards or away from the satellite. (b) Range change rate in mm/year, calculated after unwrapping the observed wrapped phase shown in (a). Blue color indicates decreasing range between the ground and the satellite, and therefore represents uplift, whereas red color indicates increasing range, and represents subsidence. (c) Modeled range change rate in mm/year calculated using an elastostatic model containing rectangular, opening or closing tensile dislocations, buried in a half-space. (d) Residual range change rate, calculated by subtracting the observed values from the modeled values. Injection wells are represented by downward pointing black or cyan triangles, and production wells by upward pointing black or magenta triangles. White stars in (a) represent the two locations at which uplift, and subsidence are plotted over time in Figs. 4 and 6(b). Labels HWFZ and BFZ in (b) represent the Horse Wells and Bridge fault zones, respectively. Coordinates are kilometers in easting and northing of the Universal Transverse Mercator projection (Zone 12). Look vector between satellite and ground is [−0.38168, −0.083011, 0.92020]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)