GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 7, PAGES 1307-1310, APRIL 1, 2001

Linking Oil Production to Surface Subsidence from Satellite Radar Interferometry

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Abstract. Land subsidence over the Belridge and Lost Hills oil fields, Southern California, was measured using spaceborne interferometric synthetic aperture radar (InSAR). During the 105-day period between 11/5/95 and 2/17/96, the subsidence in the center of the Lost Hills field reached 15 cm. We assume that this surface subsidence resulted from the vertical shrinkage of the reservoir, which in turn was due to oil production and the resulting pore pressure drop. We model this mechanical effect using an elastic deformation theoretical solution with input constants taken from relevant experiments. The modeled surface deformation matches the InSAR measured values. This result indicates that it is possible, in principle, to monitor hydrocarbon production using satellite-based measurements of earth deformation.

1. Introduction

Land subsidence above compacting oil and gas reservoirs has been observed worldwide and has significant, and often negative, effect on the field infrastructure and management. A few of the well-known cases are subsidence at Wilmington oil field, California; Groningen gas field, the Netherlands; Bolivar Coastal oil fields, Venezuela; Po Delta gas field, Italy [*Barends et al.*, 1995]. Another example is Belridge and Lost Hills oil fields, central California. In those two fields, oil production from the shallow, thick, very soft diatomite reservoirs has led to substantial surface subsidence and well failure [*Bruno and Bòvberg*, 1992; *Bowersox and Shore*, 1990; *Dale et al.*, 1996]. Efforts to mitigate the effect of subsidence (e.g., via water injection) have been only partly successful because well failure persisted [*Wallace and Pugh*, 1993; *Fast et al.*, 1993].

In all these cases worldwide, subsidence coincides with hydrocarbon production. It is fair to assume that this subsidence is the surface imprint of the vertical shrinkage of the reservoir due to hydrocarbon withdrawal. This reservoir shrinkage may result from the increased effective stress due to pore pressure drop associated with production.

The new InSAR technique provides massive, high-precision, and real-time data of surface deformation. If this deformation is due to hydrocarbon production, the InSAR technique gives us an opportunity to monitor this production in time and space. Such monitoring is important for oil field development and management.

In this paper we show, using the Belridge and Lost Hills field example, that such monitoring is in principle possible.

Paper number 2000GL012483.
0094-8276/01/2000GL012483$05.00

2. Subsidence from InSAR

Differential Synthetic Aperture Radar Interferometry (InSAR) is a newly emerged technique that allows for high-precision (a centimeter range) surface deformation over large areas [*Massonet et al.*, 1993; *Massonet and Feigl*, 1998; *Zebker et al.*, 1994; *Gabriel et al.*, 1989; *Amelung et al.*, 1999]. We use two synthetic aperture radar (SAR) images acquired by the European Earth Remote-Sensing (ERS) satellites with a temporal separation of 105 days to form a change interferogram (see the description of this procedure in, e.g., *Massonet and Feigl*, 1998).

The change interferogram represents the phase change between two signals reflected from the same point on the surface but at different time. The more the subsidence the larger the phase change. The radar wavelength of ERS satellites is 56 mm and, therefore, one cycle of phase corresponds to 28 mm (half wavelength) of radar line-of-sight displacement. The look angle of the ERS satellites is 23°. As a result, the vertical ground displacement that corresponds to a cycle is 30.4 mm (28 mm / $\cos 23°$).

Because the phase is periodical (2π), the change interferogram requires unwrapping to obtain the absolute surface deformation occurring between the two points in time. In this study we used a new unwrapping algorithm [*Chen and Zebker*, 2000], which gave improved results as compared to previous studies of the same area [*Fielding et al.*, 1998; *van der Kooij et al.*, 1997].

The interferogram corresponding to the 105-day period under examination is shown in Figure 1. The fringes form bowl-shaped patterns over Lost Hills and Belridge fields. One bowl-shaped fringe in this figure corresponds to 2π of the phase and 30.4 mm vertical surface displacement. The number of the fringes over the Lost Hills field is between 4 and 5 and the resulting maximum subsidence is between 122 and 152 mm.

The unwrapped interferogram is given in Figure 2 where the subsidence is color-coded. The first panel of Figure 3 zooms on the Lost Hills field. The maximum subsidence in the center of this field is about 15 cm – a dramatic value for the short period of 105 days.

3. Subsidence from Oil Production

Reservoir deformation due to pore fluid withdrawal and pore pressure drop is a complicated poroelastic/plastic process that often involves faulting and micro-earthquakes [e.g., *Segall et. al*, 1994]. To model this deformation and the resulting surface subsidence, one needs detailed information about the poroelastic and plastic properties of the reservoir and overlaying rock. Also, implementing the full system of equations describing the process requires involved numerical simulation [e.g., *Settari and Mourits*, 1998; *Lewis and Shrefler*, 1998].

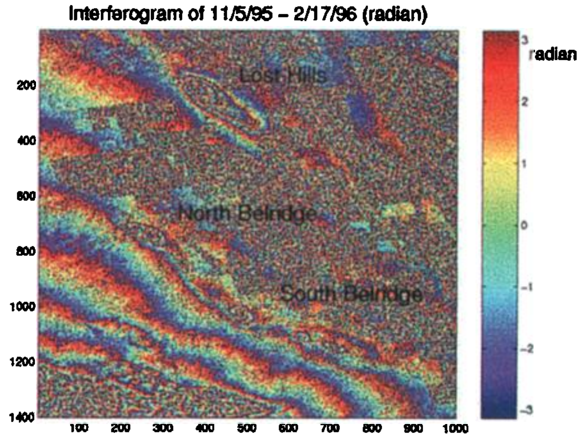

Figure 1. Interferograms of Belridge and Lost Hills oil field. The time lapse is 105 days (11/5/99 – 2/17/96). The perpendicular baseline is 227 meters, hence the image includes both deformation and topography information. Most noticeably, the large fringes to the bottom left are topography effects, while the "bowl" shaped fringes in the image are resulting from deformation.

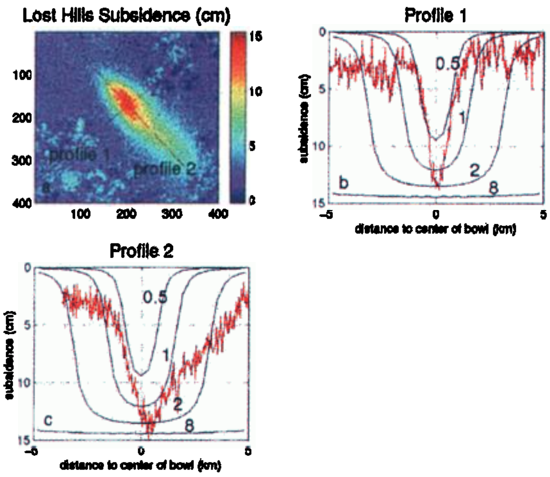

Figure 3. (a) InSAR observed subsidence in Lost Hills oil field occurred between 11/5/99 – 2/17/96 (105days). The dark lines show the locations of profile 1 and 2. The scale is in centimeters. (b). InSAR observed subsidence and theoretical subsidence along profile 1 for assumed reservoir radius of 0.5, 1, 2, and 8 miles, in Lost Hills field for the same period. (c) InSAR observed subsidence and theoretical subsidence along profile 2 for assumed reservoir radius of 0.5, 1, 2, and 8 miles, in Lost Hills field for the same period.

In this study we use a simple model of surface deformation due to the shrinkage of a reservoir, which still allows us to highlight the principal features of the subsidence process. The model [*Geertsma*, 1973] assumes that the reservoir is a circular disk of radius R and height h buried parallel to the flat earth surface at depth D. The elastic earth is treated as an elastic half-space with Poisson's ratio ν. Then the vertical component of the displacement of the surface u is

$$u(r) = (2\nu - 2)\Delta hR\int_0^\infty e^{-D\alpha}J_1(\alpha R)J_0(\alpha r)d\alpha \quad (1)$$

Where r is the radial coordinate along the surface with the origin above the center of the reservoir; Δh is the reduction of the height of the reservoir due to its compaction; and α is the integration variable.

To determine the vertical deformation of the disk-shaped reservoir Δh, we assume that deformation is proportional to the change in the differential pressure acting on the reservoir, where the differential pressure is the difference between the overburden and pore pressure. The overburden pressure remains constant and, as a result, the reservoir's compaction is proportional to the pore pressure change ΔP.

The next assumption is that the reservoir's vertical deformation Δh is inversely proportional to the "static" Young's modulus E of the reservoir rock, which comes from laboratory high-strain deformation load-frame measurements. As a result,

$$\Delta h = h\Delta P / E. \quad (2)$$

Rouffignac et al. [1995] present stress-strain curves for diatomite reservoir rock samples from South Belridge that are

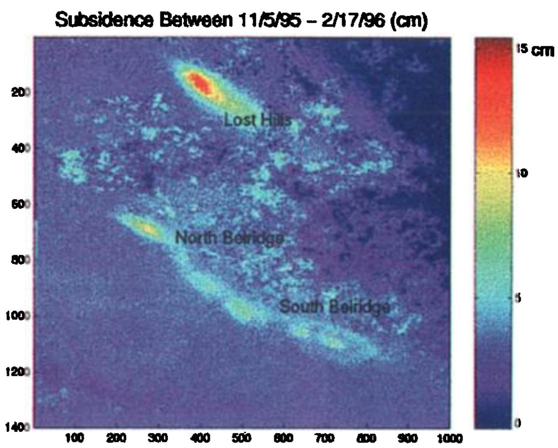

Figure 2. Unwrapped interferogram showing the subsidence in Belridge and Lost Hills oil fields occurred between 11/5/99 – 2/17/96(105days). The scale is in centimeters. The maximum subsidence reached 15 cm at the center of Lost Hills field

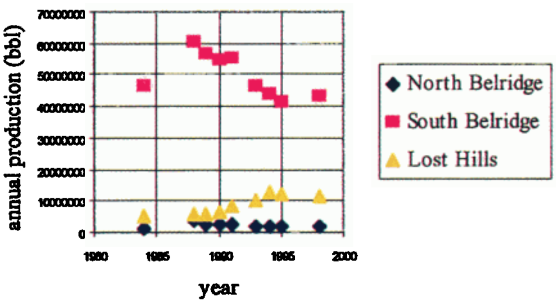

Figure 4. Annual production volume of the Belridge (north and south) and Lost Hills oil fields in barrels.

approximately linear in loading. The resulting average value of the static Young's modulus is about 0.046 GPa, which indicates that diatomite is extremely soft rock. We use the same E value for Lost Hills.

The same authors present production-data-based reservoir simulation results for South Belridge. From these results we estimate the approximate pore pressure drop over a 105-day period as 2.5 psi (160 psi of pore pressure drop for 20 years).

Next, we assume that the average reservoir thickness in Lost Hills is 300 m, according to *The California division of oil, gas and geothermal resources* [1984-1998]. Then the resulting Δh is 11 cm.

It is clear from Figure 2 that the Lost Hills reservoir is not circular but rather elliptical. Still, we will use the circular reservoir approximation and vary the reservoir radius to bound the estimate. Specifically, we use Equation (1) for R = 0.5; 1; 2; and 8 miles. We choose these values because the Lost Hills reservoir is 1 to 1.5 miles wide and about 16 miles long. Also, we use D = 100 m for the depth of burial of the Lost Hills reservoir [*The California division of oil, gas and geothermal resources*, 1984-1998]. We also choose $\nu = 0.3$ as an average Poisson's ratio in the shallow subsurface.

The surface vertical displacement profiles for R = 0.5; 1; 2; and 8 miles are plotted versus the radial coordinate in Figure 3b and 3c. These displacement curves are superimposed on the subsidence profiles along the short (Figure 3b) and long (Figure 3c) axes of the elliptical subsidence bowl calculated from InSAR data.

The theoretical R = 1 and 2 mile profiles are close to the observed subsidence values. The R = 8 mile profile matches the peak of the observed subsidence. We conclude that, in general, the theoretical subsidence calculated from the production data is consistent with the InSAR data.

4. Discussions and Conclusions

The estimate given in the previous section shows that hydrocarbon production and surface subsidence can be quantitatively linked to each other. Therefore, it is possible, in principle, to monitor hydrocarbon production, and, in general, pore-fluid-related changes in the subsurface using InSAR data. Still, it is important to include additional and detailed production, and reservoir and rock property data into consideration.

Consider Figure 4 that shows the annual production in the Belridge (north and south) and Lost Hills oil fields compiled from various publications of *the California division of oil, gas and geothermal resources* [1984-1998]. It is apparent that Lost Hills field produced oil at a much slower rate than South Belridge field. Logically, it would be reasonable that more subsidence should occur in Belridge than in Lost Hills. However, Figure 2 shows the opposite effects. This effect can be explained by the fact that Lost Hills has similar size as South Belridge, similar porosity, but is shallower, thicker, has higher permeability, and contains oil of lower viscosity. In addition, South Belridge produces only about 20% of its total production from soft diatomite [*Bowersox,* 1990], while most of the production in Lost Hills comes from diatomite. It is hence understandable why a significantly smaller production rate in Lost Hills caused subsidence comparable to or even larger than the subsidence in South Belridge. We can see that reservoir properties such as rock compressibility, permeability, fluid viscosity, are essential factors in forming the final pattern of surface subsidence. Therefore, it may be possible to infer those important reservoir properties from high resolution InSAR data.

The above case study shows that applying physical modeling to the interpretation of InSAR data help determine important reservoir properties as well as fluid movement in the subsurface. Therefore, InSAR measurements can be an alternative or supplement to 4-D seismic reservoir monitoring, which is expensive and time-consuming.

Acknowledgments. Howard Zebker helped obtain SAR data and provided help for InSAR data processing; Curtis Chen provided software for phase unwrapping; Mamta Sinha helped with data processing. We thank Shana Shi for assistance with preparing the manuscript. Comments made by an anonymous reviewer improved the manuscript.

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(Received October 09, 2000; revised January 16, 2001; accepted January 18, 2001)