Groundwater level changes in a deep well in response to a magma intrusion event on Kilauea Volcano, Hawai'i

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[1] On May 21, 2001, an abrupt inflation of Kilauea Volcano's summit induced a rapid and large increase in compressional strain, with a maximum of 2 μstrain recorded by a borehole dilatometer. Water level (pressure) simultaneously dropped by 6 cm. This mode of water level change (drop) is in contrast to that expected for compressional strain from poroelastic theory, and therefore it is proposed that the stress applied by the intrusion has caused opening of fractures or interflows that drained water out of the well. Upon relaxation of the stress recorded by the dilatometer, water levels have recovered at a similar rate. The proposed model has implications for the analysis of ground surface deformation and for mechanisms that trigger phreatomagmatic eruptions. *INDEX TERMS:* 5104 Physical Properties of Rocks: Fracture and flow; 8045 Structural Geology: Role of fluids; 8494 Volcanology: Instruments and techniques; 8424 Volcanology: Hydrothermal systems (8135); 8160 Tectonophysics: Rheology—general. **Citation:** Hurwitz, S., and M. J. S. Johnston, Groundwater level changes in a deep well in response to a magma intrusion event on Kilauea Volcano, Hawai'i, *Geophys. Res. Lett.*, *30*(22), 2173, doi:10.1029/2003GL018676, 2003.

1. Introduction

[2] It has long been observed that groundwater levels in wells tapping confined aquifers change in response to volumetric strain induced by earth tides and barometric pressure changes [e.g., *Rojstaczer*, 1988], fault creep [*Roeloffs et al.*, 1989], and seismic waves [e.g., *Cooper et al.*, 1965; *Montgomery and Manga*, 2003]. Poroelastic theory implies that in a homogeneous and isotropic aquifer, a rapid change of the static volumetric strain field should result in a step like response of the groundwater level, rising or falling depending whether the well site contracts or expands. The size of the water level change should be proportional to the amplitude of the static strain field [*Roeloffs*, 1996]. Nevertheless, in several studies it has been reported that the sign of the water level change was in the opposite direction expected from theory [*Roeloffs*, 1998; *Brodsky et al.*, 2003; *Segall et al.*, 2003], suggesting that in some cases the response may not be poroelastic.

[3] Several examples of pre-eruptive groundwater pressure changes on volcanoes indicate that water-level measurements can be a valuable tool for detecting volcanic unrest. For example, fluid-pressure changes that preceded volcanic eruptions at Mount Usu, Japan, in 2000 [*Shibata and Akita*, 2001] are believed to indicate dike intrusion. Groundwater pressure records from wells on active volcanoes may also enable examination of hypotheses linking water pressure transients to phreatic eruptions, long period earthquakes, flank stability and ground surface deformation.

[4] Because deep wells on or near volcano summits are scarce, only a few continuous water level (water pressure) records are currently available. In this study, we analyze the groundwater pressure response in a deep well (NSF well or the "Keller Well") on the summit of Kilauea Volcano (Figure 1) induced by an intrusion event on May 21, 2001. This is one of the first studies to analyze water level transient in conjunction with strain data from a dilatometer installed in the same well.

2. Kilauea Volcano

[5] Magma rises from the mantle through a conduit located below Kilauea summit to a plexus of magma storage reservoirs at depths of roughly 2–7 km beneath the summit [*Ryan et al.*, 1981]. Recent studies indicate that parts of these reservoirs may be as shallow as ~1 km beneath the northeast edge of Halemaumau pit crater [*Dawson et al.*, 1999]. Magma is partitioned from the shallow reservoir either upward to feed summit eruptions, or laterally outward to feed the conduit systems of the east and southwest rift zones (Figure 1a). Volcanic activity is monitored by a network of continuously recording geodetic instruments, including a seismic network, global positioning system, tilt meters, and strain meters operated by the Hawaiian Volcano Observatory of the U.S. Geological Survey.

[6] The NSF well on Kilauea summit was drilled in 1973 to a total depth of 1262 m from an elevation of 1103 m above msl [*Keller et al.*, 1979]. The well is located on the southwest rim of the caldera, 1.2 km south of Halemaumau crater (Figure 1b). Casing in the well extends from the ground surface to a depth of 315 m, and the water table was encountered at a depth of 488 m. The temperature near the water table is 92°C, and it increases to 137°C at total depth [*Keller et al.*, 1979; *Hurwitz et al.*, 2002]. Manual measurements between May 2000 and June 2003 indicate water-table depths of 489–493 below the ground surface, similar to the depth following completion in 1973.

[7] Between February and June 2001, water level (pressure) in the well was measured with a gas line that consists of a chamber attached to the lower end of a 500 m coaxial tube. The chamber was kept full of gas by a slow flow of nitrogen down the annulus of the coaxial tube. The controlled flow of nitrogen emerges as occasional bubbles from orifices at the bottom of the chamber, maintaining a gas-water interface where pressure is sensed. The pressure at the interface was transmitted to two transducers at the ground surface through

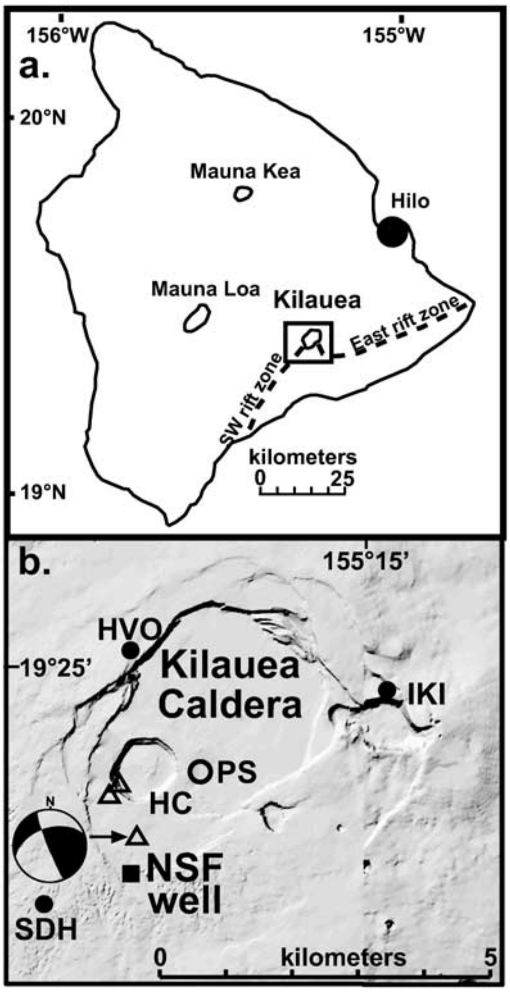

Figure 1. (a) Map of the Island of Hawaii showing Kilauea caldera and two rift zones. (b) Inset map showing Kilauea caldera, the Halemaumau pit crater (HC), the location of the NSF well, the location of the summit tiltmeters (SDH, HVO, IKI), the location of the pressure source that produced the summit inflation described in the text (PS) [*Cervelli and Miklius*, 2003], the location of the three summit earthquakes that occurred during the intrusion event, and the focal mechanism for the M_L 3.5 (D = 3.3 km) earthquake.

the inner part of the tube. The first transducer has a resolution of 0.05 cm and sampled every 5 minutes and the other transducer has a resolution of 0.03 cm and sampled every 10 minutes. The data from the two transducers was similar. We used the data from the first transducer for the analysis.

[8] In July 2000, a Sacks-Evertson dilatometer was installed in the unsaturated part of the well at a depth of 366 m below the ground surface. Sampling rate of the dilatometer in 2001 was every 10 minutes and was later increased.

3. Strain, Tilt and Earthquake Data

[9] On May 21, 2001 between 02:10 and 02:20 (GMT) a rapid and large increase in volumetric strain (compression) was observed on three borehole dilatometers coincident with a change in tilt on five tiltmeters on Kilauea and Mauna Loa summit. On Kilauea summit, the NSF well dilatometer reached a maximum strain of 2 μstrain while tilts on the three nearby tiltmeters reached 5 μradians (Figures 2 and 3). Inversion of these data indicated a shallow pressure source ((PS) just east of Halemaumau pit crater (Figure 1b) [*Cervelli and Miklius*, 2003], which followed a gradual deflation event with a much deeper source [*Johnston et al.*, 2001] (Figures 2 and 3). Strain started decreasing at 03:30, and tilt reversal appears only 10 minutes later. This apparent non-synchronous response probably could results from either the higher resolution of the strainmeters or different data sampling times. Strain and tilt began to decline, and after approximately six hours stabilized at slightly higher than pre-intrusion levels. The strain and tilt data were calibrated using ocean-load corrected earth tides. Also, spurious small once-per-day steps in the strain data, likely due to solar charging, were removed.

[10] On May 21, seismicity was higher than normal in Kilauea's vicinity, and nine earthquakes with local magnitudes (M_L) smaller than 2.0 occurred in the 12 hours preceding the step-like strain and tilt increase. Eight of these earthquakes were in the depth (D) range of 5–14 km. Three shallow (<3.3 km) earthquakes with M_L = 3.1–3.5 occurred within the compressional phase (Figure 1b), and eleven additional earthquakes (M_L = 0.7–1.4; D = 9.9–18.3 km) occurred during the recovery period.

4. Water Level Data

[11] Water level in the well was analyzed for its response to barometric pressure and earth tides for the period between 24 February and 30 May 2001. The barometric pressure was obtained from an on site instrument sampling

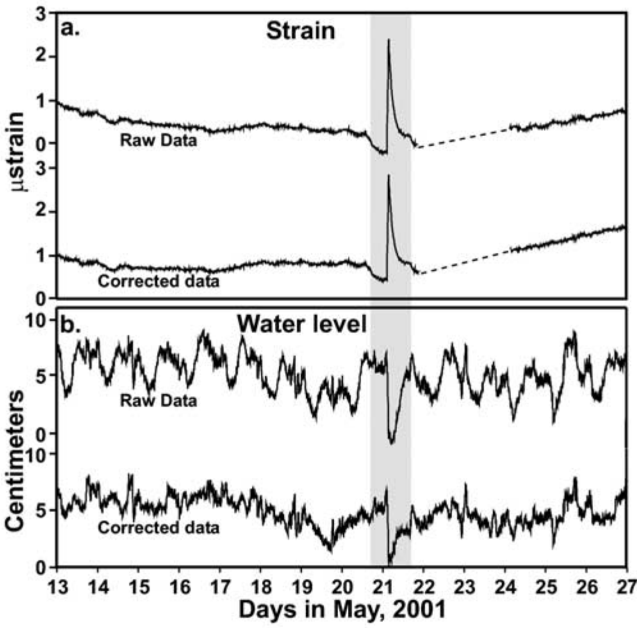

Figure 2. Raw strain data (a) and water-level data (b) before and after correction for earth tides and barometric pressure loading from the NSF well during the two-week p Positive strain indicates compression. Dashed section of the strain data represents lost data, but not lost strain reference. Grey shading represents the time interval shown in Figure 3.

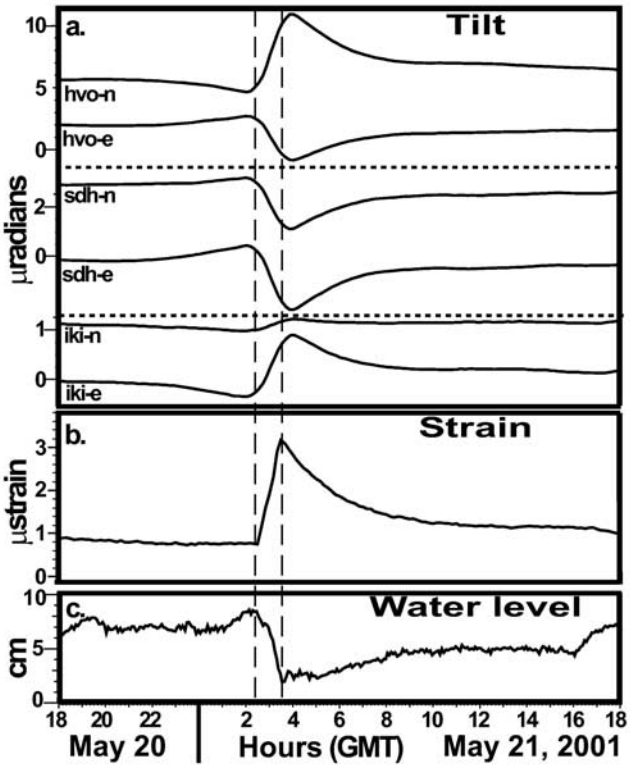

Figure 3. One day (gray shading in Figure 2) of tilt, strain and water-level data covering the 21 May, 2001 intrusion event on the summit of Kilauea. a. Tilt data from three tiltmeters on the caldera boundary (station locations in Figure 1b). Changes in tilt are expressed as orthogonal components, and the letter following the station name refers to the north-south (n) and east-west (e) components of the tiltmeters. b. Strain data from the dilatometer in the NSF well. Positive strain indicates compression. c. Water-level data from the NSF well. All the data are corrected for barometric pressure and Earth tides.

every 10 minutes, and earth tides were obtained by least square fitting of a 16-harmonic earth tidal time series to the data. After trends and some outliers were removed from the raw data, the amplitude of water level changes in response to barometric pressure and the O_1 and M_2 tidal components was calculated. Tidal responses are 0.04 (O_1) and 0.005 (M_2) cm per nanostrain. Considering the theoretical ocean-tide corrected amplitudes, it would appear that the O_1 component was affected by temperature variations in the gas line, and is therefore less reliable. Water level responded to barometric pressure changes only at high frequencies, where it equaled 0.28 cm/mbar at periods of about 2 days. These changes are extremely small, implying that either the open hole is within an unconfined aquifer with a large specific yield, or that there is poor communication between the well bore and the surrounding formation, consistent with the concept of low permeability in the vicinity of the well [*Hurwitz et al.*, 2002]. After removing the barometric pressure and Earth tide effects from the data, some unresolved high frequency and low amplitude (<1 cm) signals remain in the data.

[12] Following three days of an overall water level drop of about 3 cm, water level increased by 1.5 cm between the afternoon of May 19 and 20:00 on May 20. Water level was then constant until 01:00 May 21 and increased by 1.5 cm at 02:20 (Figure 2). Between 02:20 and 03:30, water level dropped by 6 cm, coincident with the step like strain and tilt increase (Figure 3). The water level drop occurred within the 5-minute sampling interval, which followed the strain and tilt changes. Within the resolution of sampling (5 minutes for water level and 10 minutes for geodetic measurements) we cannot rule out the possibility that water level drop preceded surface deformation induced by the intrusion. As with the strain and tilt, water level gradually recovered, and stabilized at lower than pre-intrusion levels after six hours. A two cm water level increase 14 hours after the onset of the event (Figure 2c) remains unexplained.

5. Discussion and Conclusions

[13] The abrupt water level drop on May 2001 is coincident with the compressional strain and tilt transients in the summit region, and therefore is probably associated with magma intrusion that caused inflation of the summit region. The amplitude of the water level drop was significantly larger than the amplitudes associated with either barometric pressure or earth tides, but much smaller than that expected from the measured strain. Poroelasticity dictates that a water level rise on the order of 1 m is expected from a compression of 2 µstrain [*Roeloffs*, 1996]. The unexpected sign of the water level transient (drop), suggests that the response was not controlled by poroelastic deformation or by thermal pressurization of fluids in the host rock surrounding the dike, which would cause pressure diffusion towards the well [*Delaney*, 1982]. In both cases water level increase would be expected.

[14] We propose a mechanism to account for the simultaneous water level drop and compressional strain in which fractures or mechanically weak layers that transect the well open instantaneously due to the applied stress (Figure 4).

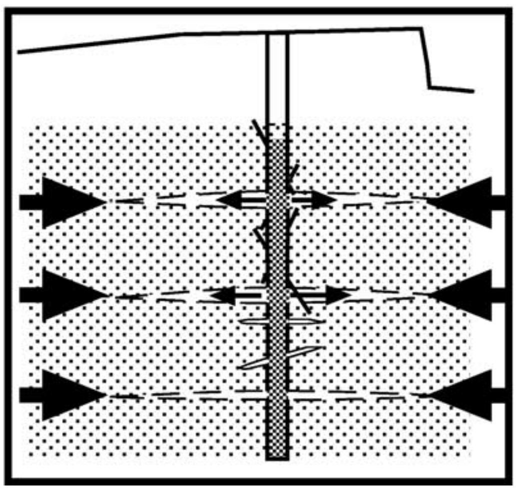

Figure 4. Proposed conceptual model: the saturated zone (dotted area) penetrated by the well is of low permeability, and is transected by fractures, ash layers, and inter-layers of basalt flows. During intrusion, the surrounding rocks are compressed leading to opening of horizontal and subhorizontal fractures and drainage of water from the open hole.

The top of the pressure source that produced the summit inflation and compressional strain in the NSF well dilatometer was at a depth of 300 m below the surface, approximately 2 km northeast from the NSF well (PS in Figure 1b) [*Johnston et al.*, 2001; *Cervelli and Miklius*, 2003]. The depth of the water table and the dilatometer in the NSF well are 490 and 366 m, respectively, implying that the principal stress component at the NSF well location during the intrusion episode was sub-horizontal. Following the analysis of *Jaeger and Cook* [1976; p. 267], the volume of (sub) horizontal ellipsoid cavities should increase when (sub) horizontal compressional stress is applied. The volume increase in the cavity depends on the magnitude of the stress, the ellipsoid's aspect ratio, and its orientation relative to the principal stress. Plausible cavities within the rather compact basalt are fractures and/or ash and clinker layers. The initial pressure within the dilating cracks is smaller than pressure in the open hole, causing drainage of water out of the well, and a subsequent water level drop. The volume of water drained out of the NSF well (6 cm of water level drop times the well cross section) is approximately 1.5 liters. This volume can be accommodated by a single 1 m^2 crack with a dilatation of 1.5 mm.

[15] Water level recovery time following the abrupt drop is similar to that of the strain and tilt (Figure 3), and therefore it is proposed that stress relaxation and closure of the fractures and/or weak layers was the control (Figure 4). We must also consider the possibility that a fraction of the water level increase was caused by groundwater flow induced by thermal pressurization along the dike-host rock contact. The time scale for pressure diffusion is given by $t = x^2/4c$, where x is distance and c is the hydraulic diffusivity of the host rock, $c = k/\phi\mu\beta$, where k is permeability, ϕ is porosity, μ is the dynamic viscosity of water and β is host rock compressibility. For a distance of 2 km between the tip of the dike and the well and a large fault zone hydraulic diffusivity of 30 m^2/sec [*Cervelli et al.*, 2002] the pressure pulse would result in 9.2 hours. If pressure propagated through a homogeneous porous media with perhaps more realistic parameters of $\phi = 0.01$, $\beta = 10^{-10}$ Pa^{-1} and $k = 10^{-16}$ m^2 – which is an upper bound for the low permeability rocks – then the time would be approximately 2,800 hours (almost 4 months).

[16] Several studies have proposed that pore pressure diffusion following intrusive activity may account for the observed patterns of volcano or caldera inflation/deflation cycles [e.g., *Bonafede*, 1991]. The lack of poroelastic response following magma intrusion on May 21, 2001 together with the inferred low permeability in the saturated zone of the NSF well ($<10^{16}$ m^2) [*Hurwitz et al.*, 2002] suggests that, in Kilauea, surface deformation triggered by pressurization of the hydrothermal system is unlikely. Most intrusions impose large-amplitude compression in the summit area for hours to several days, and the time to transport large quantities of water is much longer.

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References

Bonafede, M., Hot fluid migration; an efficient source of ground deformation; application to the 1982–1985 crisis at Campi Flegrei-Italy, *J. Volcanol. Geotherm. Res.*, *48*, 187–198, 1991.

Brodsky, E. E., E. Roeloffs, D. Woodcock, I. Gall, and M. Manga, 2003, A Mechanism for Sustained Ground Water Changes Induced by Distant Earthquakes, *J. Geophys. Res.*, *108*(B8), 2390, doi:10.1029/2002JB002321, 2003.

Cervelli, P., P. Segall, K. Johnson, M. Lisowski, and A. Miklius, Sudden aseismic fault slip on the south flank of Kilauea Volcano, *Nature*, *415*, 1014–1018, 2002.

Cervelli, P. F., and A. Miklius, The shallow magmatic system of Kilauea Volcano, in *The Pu'u 'O'o-Kupaianaha eruption of Kilauea Volcano, Hawai'i; the first 20 years*, edited by C. Heliker, D. A. Swanson, and T. J. Takahashi, U.S. Geological Survey Professional Paper, P1676, 149–163, 2003.

Cooper, H. H., J. D. Bredehoeft, I. S. Papadopulos, and R. R. Bennett, The response of well-aquifer systems to seismic waves, *J. Geophys. Res.*, *70*, 3915–3926, 1965.

Dawson, P. B., B. A. Chouet, P. G. Okubo, A. Villasenor, and H. M. Benz, Three-dimensional velocity structure of the Kilauea caldera, Hawaii, *Geophys. Res. Lett.*, *26*, 2805–2808, 1999.

Delaney, P. T., Rapid intrusion of magma into wet rock: Groundwater flow due to pore pressure increases, *J. Geophys. Res.*, *87*, 7739–7756, 1982.

Hurwitz, S., S. E. Ingebritsen, and M. L. Sorey, Episodic thermal perturbations associated with groundwater flow: Example from Kilauea Volcano, Hawaii, *J. Geophys. Res.*, *107*, 2297, doi:10.1029/2001JB001654, 2002.

Jaeger, J. C., and N. G. W. Cook, *Fundamentals of rock mechanics*, 2nd edition, Chapman and Hall Ltd., London, 1976.

Johnston, M. J. S., M. Lisowski, D. P. Hill, and J. Power, Mechanics of volcanic activity in Long Valley and Kilauea/Mauna Loa volcanic areas from multi-parameter borehole measurements, *Trans. Am. Geophys. Un.*, *82*, F1309, 2001.

Keller, G. V., L. T. Grose, J. C. Murray, and C. K. Skokan, Results of an experimental drill hole at the summit of Kilauea volcano, Hawaii, *J. Volcanol. Geotherm. Res.*, *5*, 345–385, 1979.

Montgomery, D. R., and M. Manga, Streamflow and Water Well Responses to Earthquakes, *Science*, *27*(300), 2047–2049, 2003.

Roeloffs, E. A., Poroelastic methods in the study of earthquake-related hydrologic phenomena, in Advances in Geophysics, edited by R. Dmowska, pp. 135–195, Academic, San Diego, 1996.

Roeloffs, E. A., Persistent water level changes in a well near Parkfield, California, due to local and distant earthquakes, *J. Geophys. Res.*, *103*, 869–889, 1998.

Roeloffs, E. A., S. Schulz-Burford, F. S. Riley, and A. W. Records, Hydrologic effects on water level changes associated with episodic fault creep near Parkfield, California, *J. Geophys. Res.*, *94*, 12,387–12,402, 1989.

Rojstaczer, S. A., Intermediate period response of water levels in wells to crustal strain; sensitivity and noise level, *J. Geophys. Res.*, *93*, 13,619–13,634, 1988.

Ryan, M. P., R. Y. Koyanagi, and R. S. Fiske, Modeling the three-dimensional structure of macroscopic magma transport systems: Application to Kilauea Volcano, Hawaii, *J. Geophys. Res.*, *86*, 7111–7129, 1981.

Segall, P., S. Jónsson, and K. Ágústsson, When is the strain in the meter the same as the strain in the rock?, *Geophys. Res. Lett.*, *30*, doi:10.1029/2003GL017995, 2003.

Shibata, T., and F. Akita, Precursory changes in well water level prior to the March 2000 eruption of Usu volcano, Japan, *Geophys. Res. Lett.*, *28*, 1799–1802, 2001.

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