Journal of Volcanology and Geothermal Research 356 (2018) 175–182

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Seasonal patterns of seismicity and deformation at the Alutu geothermal reservoir, Ethiopia, induced by hydrological loading

Yelebe Birhanu [a], Matthew Wilks [a,b], Juliet Biggs [a,*], J-Michael Kendall [a], Atalay Ayele [c], Elias Lewi [c]

[a] School of Earth Sciences, University of Bristol, Queens Road, Bristol BS8 1RJ, United Kingdom
[b] Norsar, Gunner Randers vei 15, Kjeller 2007, Norway
[c] Institute of Geophysics, Space Science and Astronomy, Addis Ababa University, Addis Ababa, Ethiopia

ARTICLE INFO

Article history:
Received 17 November 2017
Received in revised form 16 February 2018
Accepted 12 March 2018
Available online 13 March 2018

Keywords:
Seasonal seismicity
Vertical GPS
Hydrologic loading
Pore-fluid pressure
Critically stressed reservoirs
Geothermal power

ABSTRACT

Seasonal variations in the seismicity of volcanic and geothermal reservoirs are usually attributed to the hydrological cycle. Here, we focus on the Aluto-Langano geothermal system, Ethiopia, where the climate is monsoonal and there is abundant shallow seismicity. We deployed temporary networks of seismometers and GPS receivers to understand the drivers of unrest. First, we show that a statistically significant peak in seismicity occurred 2–3 months after the main rainy season, with a second, smaller peak of variable timing. Seasonal seismicity is commonly attributed to variations in either surface loading or reservoir pore pressure. As loading will cause subsidence and overpressure will cause uplift, comparing seismicity rates with continuous GPS, enables us to distinguish between mechanisms. At Aluto, the major peak in seismicity is coincident with the high stand of nearby lakes and maximum subsidence, indicating that it is driven by surface loading. The magnitude of loading is insufficient to trigger widespread crustal seismicity but the geothermal reservoir at Aluto is likely sensitive to small perturbations in the stress field. Thus we demonstrate that monsoonal loading can produce seismicity in geothermal reservoirs, and the likelihood of both triggered and induced seismicity varies seasonally.

1. Introduction

Induced or triggered seismicity can be caused by transient changes in reservoir stress conditions. Induced seismicity is associated with anthropogenic fluid injection at geothermal and hydrocarbon reservoirs (e.g. Ellsworth, 2013; Gaucher et al., 2015; Grünthal, 2014; Verdon, 2014), or surface loading such as water impoundment (e.g. Simpson et al., 1988; Talwani et al., 2007). Natural processes, such as ice sheet unloading (e.g. Stewart et al., 2000), dynamic stresses from large, distant earthquakes (e.g. Prejean et al., 2004), or magmatic overpressure (e.g. Ebmeier et al., 2016) can also trigger seismicity in critically stress reservoirs.

Seasonal variations in the number of small ($M < 4$) and shallow (<5 km) seismic events have been observed at a range of settings including, at volcanoes (e.g. Christiansen et al., 2005; Saar and Manga, 2003; Wolf et al., 1997), faults (Bettinelli et al., 2008; Christiansen et al., 2007; Hainzl et al., 2006) and intraplate settings (Costain and Bollinger, 2010; Costain et al., 1987). Two hydrological mechanisms have been proposed to account for these observations 1) loading due to seasonal changes in surface and near-surface water storage, and 2) increased pore-pressure along faults within the reservoir due to subsurface recharge (Saar and Manga, 2003). The time delay between peak surface runoff and peak seismicity varies from days to months and is attributed to the timescale of groundwater recharge, governed by pore-fluid pressure diffusion (Hainzl et al., 2006; Lee and Wolf, 1998; Saar and Manga, 2003).

Hydrological processes also cause seasonal patterns in vertical displacements and these can be measured by the Global Positioning System (GPS). GPS-derived estimates of ground-water storage correspond well with those made by the Gravity Recovery and Climate Experiment (GRACE) (Fu et al., 2015). Surface loading causes subsidence, with snowfall causing an instantaneous elastic response (Argus et al., 2014) and monsoonal loading causes delayed subsidence with the delay attributed to the timescale of ground-water recharge (Birhanu and Bendick, 2015). In contrast, fluid injection into reservoirs is typically associated with uplift (Vasco et al., 2010; Vasco et al., 2013) and extraction with subsidence (Fialko and Simons, 2000; Parker et al., 2017).

In this paper, we use a network of continuous GPS (cGPS) and seismometers at Aluto-Langano geothermal reservoir, Ethiopia to study seasonal patterns of deformation and seismicity. Aluto volcano is known to be actively deforming and experiences a monsoonal climate, while the geothermal system generates significant seismicity. In theory, increased loading due to lake level rise will cause subsidence, while increased pore pressure within the reservoir would cause uplift. Thus we

* Corresponding author.
E-mail address: juliet.biggs@bristol.ac.uk (J. Biggs).

https://doi.org/10.1016/j.jvolgeores.2018.03.008

investigate the relationship between seismicity, deformation, precipitation and lake level to better understand the stress state of geothermal reservoirs.

2. Background

The Aluto-Langano system lies in the Main Ethiopian Rift, between Lake Ziway to the north and Lake Langano to the south (Fig. 1). The Main Ethiopian Rift divides the Nubian and Somalian plates at a rate of ~5–6 mm/year (Bendick et al., 2006; Bilham et al., 1999). Magmatic segments in the rift floor accommodated ~80% of the strain (Birhanu et al., 2016; Kogan et al., 2012) and most of the seismicity (Ayele and Kulhánek, 1997; Keir et al., 2006; Mazzarini et al., 2013). At Aluto, large ignimbrite forming eruptions took place at ~316 ka and 306 ka (Hutchison et al., 2016c), with post-caldera, edifice building volcanism consisting of highly-evolved peralkaline rhyolite lavas, ignimbrites and pumice fall deposits starting at ~55 ka (Hutchison et al., 2016a). The most recent eruption has been dated at ~400 years ago (Hutchison et al., 2016a). Magnetotelluric studies show a highly conductive clay cap in the upper 2 km, but no evidence for a deeper magmatic system (Samrock et al., 2015).

A two-year seismic deployment detected 1361 earthquakes in a 15 km radius area around Aluto, ranging in magnitude from −0.4 to 3.0 (Wilks et al., 2017). The majority of events (760 of 1361) were located within the geothermal reservoir (Fig. 2), defined as 1) 2 km from the surface (above sea level), and b) within 15 km from the centre of the caldera (defined as seismic station A01E). Applying a Gutenberg-Richter relationship to this subset, gives a b-value of 2.55 ± 0.55 and high seismicity rate ($a = 5.64$), consistent with other volcanic environments where circulation of fluids means strain is preferentially released by numerous small events (Wilks et al., 2017). Fault plane solutions for a subset of the deeper and off-edifice events show ~NNE-SSW normal faults, consistent with the current direction of extension. No fault plane solutions are available for the shallow events.

Surface deformation measurements from satellite InSAR have shown two pulses of uplift in 2004 and 2008 (>15 cm) separated by periods of slow (~3 mm/year) subsidence (Biggs et al., 2011; Hutchison et al., 2016b). It is not possible to discriminate between magmatic and hydrothermal processes using deformation alone, but the uplift episodes at Aluto are interpreted to represent the repeated injection of magmatic fluids to shallow (<5 km) depths causing inflation, whereas the cooling and flow of hydrothermal fluids causes the subsequent subsidence (Hutchison et al., 2016b).

Pathways for fluids are controlled by shallow structures including the NNE-SSW Artu Jawe Fault Zone (AJFZ) which crosscuts the volcanic edifice and a caldera ring fault (Braddock et al., 2017; Hutchison et al., 2015). The majority of geothermal fluids are derived from precipitation on the rift flanks, with <10% from nearby lakes (mainly from lake Ziway) (Darling et al., 1996). Although there is no long-term ground-based monitoring, the distribution and the fumaroles can be mapped using a 12 year archive of thermal infrared images from the ASTER satellite. The temperature and extent of the fumaroles show no relation to the surface deformation, but the Bobesa fumaroles, located along the caldera ring fault in the east, show a delayed response to rainfall (Braddock et al., 2017). Geothermal development at Aluto-Langano began in 1981 (Hochstein et al., 2017) and continue at the present time. The plant was only operational for a small fraction of the experiment (14th January 2012 until 4th July 2012) with power production ranging from 10-35MWh during this period.

Lake Ziway is the largest volume fresh water lake in the Main Ethiopian Rift with surface area 440 km^2 and maximum depth of 8.9 m and is the only source of fresh water to the town of Ziway and nearby villages

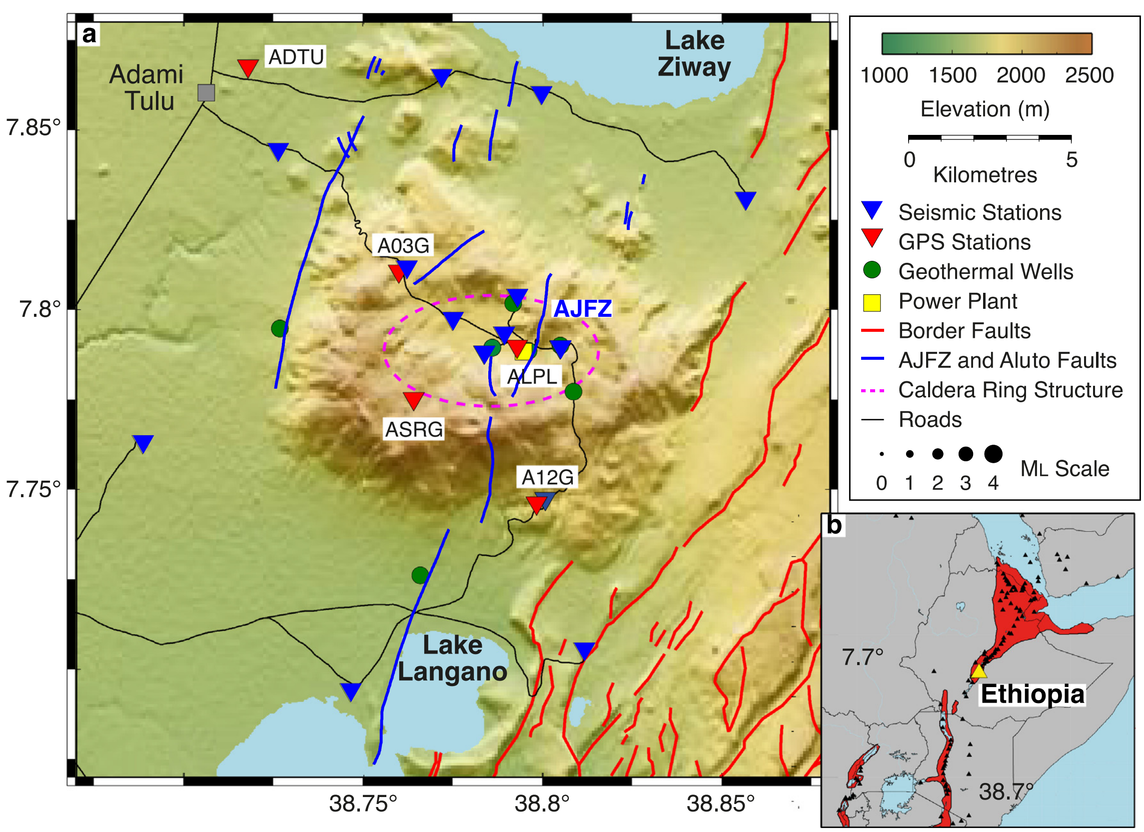

Fig. 1. a) Topographic map of Aluto volcano showing the seismic and GPS network, the Aluto-Langano Geothermal Power Plant and geothermal wells. Border faults are red (Agostini et al., 2011) while the Artu Jawa fault zone (AJFZ) and other faults of the Aluto volcanic complex are blue (Kebede et al., 1985; Hutchison et al., 2015). b) Location of Aluto volcano. Modified from Wilks et al. (2017).