GROUND PENETRATING RADAR IMAGING OF OLD FAITHFUL GEYSER VENT, YELLOWSTONE NATIONAL PARK, USA

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ABSTRACT

In April 2015, Ground Penetrating Radar (GPR) was used to characterise the shallow subsurface (0-5 m depth) of the western sinter slope, immediately adjacent to Old Faithful geyser and directly above an inferred, deep, geyser chamber. A series of time sequence images were collected between two eruptive events. Each set of time sequence GPR recordings consisted of four transects aligned at approximately 90° to each other, to enable coverage over the location of the inferred, deep, geyser chamber. Seven time sequence events were collected over a 48 minute interval to image changes in the near-surface, as well as pre- and post-eruptive cycles. No fractures were visible at the surface but the time sequence GPR images revealed a series of micro-fractures at 0-5 m depth that fill and drain repetitively, immediately after an eruption and prior to the main eruptive event. No large cavity was observed, but this could be present at depths greater than those possible to image using GPR.

1. INTRODUCTION

Ground Penetrating Radar (GPR) has been used as a non-invasive method to study the shallow subsurface geologic structures, stratigraphy, hydrothermal alteration and hydrologic conditions at Old Faithful geyser and surrounding hydrothermal features in Yellowstone National Park, Wyoming, USA (Fig. 1). This study follows successful applications of GPR in hydrothermal areas elsewhere around the world (Dougherty and Lynne, 2011; Lynne and Sim, 2012; Lynne and Smith, 2013). The preliminary results of this study were reported by Foley et al. (2015).

Previous studies at Old Faithful primarily have emphasized the patterns of eruptive behaviour (e.g., Hurwitz et al., 2008), seismic activity (e.g., Vandemeulebrouck et al., 2013), vent characteristics (e.g., Hutchinson et al., 1997), eruptive behaviour (e.g., O'Hara and Esawi, 2013), or fluid chemistry (e.g., Hurwitz et al., 2012). Identification of shallow fractures, sinter thickness, feeder vents, pre-eruption changes in water or vapor saturation of the shallow subsurface, assessment of altered zones and details of sinter morphology were not part of these previous studies.

The Old Faithful area has been the focus of numerous remote sensing investigations since the sensor tests of the 1960's. Satellite, fixed-wing, and helicopter platforms have provided both visible and thermal infrared imagery at different spatial resolution and at different times of day or year. Recent fixed-wing, night thermal infrared work by Jaworowski and others (2010, 2012) have provided a time-sequence of changing hydrothermal activity for the Upper Geyser Basin hydrothermal system, including the Old Faithful area.

A previous GPR study in Yellowstone (Speece and Joss, 1999) described using GPR in the travertine areas at Mammoth Hot Springs, but did not include any sinter areas. Price et al. (2015) studied the use of shallow seismic refraction, but not GPR, in an area in the Lower Geyser Basin, to identify shallow hydrologic conditions near hot springs.

Figure 1: Location maps of Old Faithful geyser, Yellowstone National Park, USA.

2. METHODS

A series of GPR transects were taken on the western slope of the sinter apron around Old Faithful geyser on April 11th 2015 (Fig. 2), in order to determine any changes during the filling of the proposed subsurface geyser chamber. A GSSI 200 MHz antenna with a GSSI Sir 4000 controller was used to collect GPR data. Raw data were processed using Radan 7 software.

GPR transects were collected at five to ten minute intervals for approximately one hour prior to an eruption of Old Faithful geyser (Table 1). Based on the regularity of the approximate 91-minute eruptive cycle and the previous eruption time of 10:39 am, the next eruption was expected at 12.10 pm. However, Old Faithful geyser did not erupt until 12.20 pm. Seven GPR runs were completed before the 12.20 pm eruption. Each GPR run consisted of GPR data collection along lines 1, 2, 3 and 4 (Fig. 2). For example, run 1 included GPR numbers 6, 7, 8 and 9 and run 2 included GPR numbers 10, 11, 12 and 13 as shown on Figure 2. Between 11.55 am and 12.20 pm there were significant pre-play eruptions which made working on the cone unsafe.

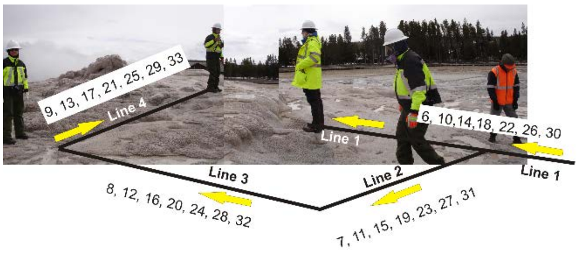

Figure 2: Four time sequence transect lines (Lines 1 to 4) located on western slope of Old Faithful geyser. Seven GPR runs were performed along the four lines at different time intervals (see Table 2). Numbers represent each GPR run.

Time (am)	GPR transect number	Minutes after previous eruption	Minutes before next eruption
11.07	6 to 9	28	73
11.10	10 to 13	31	70
11.20	14 to 17	41	60
11.30	18 to 21	51	50
11.40	22 to 25	61	40
11.50	26 to 29	71	30
11.55	30 to 33	76	25

Table 1: Time sequence data for GPR transects prior to the 12.20 pm geyser eruption on April 11th, 2015.

3. RESULTS

3.1 Overview of time sequence GPR profiles for Lines 1 to 4

GPR data was collected seven times over the same four transect lines (Lines 1 to 4 on Fig. 2) to observe changes in the subsurface during the build up to an eruption. Significant changes were identified during this time sequence imaging.

Figure 3 summarises the GPR images in 3D at 70, 40 and 25 minutes prior to the 12.20 pm eruption. Table 2 describes the features shown in Figure 3 and the associated interpretation.

	Grayscale	Colour	Associated feature
High amplitude reflections	Black and white stripes	Grey and white stripes	Sinter
Moderate amplitude reflections	Grey and white stripes	Pink, blue, green yellow	Saturated sinter
Low amplitude reflections	Pale grey with faint lines	Red and black	Water or steam
Low amplitude reflections	Pale grey with no lines	Black	Fracture networks or vents

Table 2: Features shown in Figure 3 and associated interpretation.

At 70 minutes prior to the 12.20 eruption, lines 1 to 3 are dominated by strong amplitude reflections indicating a non-saturated sinter. Line 4 also reveals a small zone of non-saturated sinter (strong amplitude reflections) but most of this area consists of moderate amplitude reflections suggesting a semi-saturated state. All four lines showed an increase in high amplitude reflections between 73 to 70 minutes prior to the eruption suggesting the area is draining.

By 40 minutes prior to the 12.20 pm eruption, line 1 shows moderate and low amplitude reflections suggesting a partially saturated subsurface. However, the saturation of the subsurface along line 1 increases as you approach Old Faithful geyser vent. Line 2 reveals higher amplitude reflections than all other lines suggesting it is less saturated than the other three lines. Line 3 is dominated by moderate amplitude reflections inferring partial saturation. Line 4, dominated by low amplitude reflections appears to be the most saturated area at this time interval.

By 25 minutes prior to the 12.20 pm eruption, line 1 shows much of the subsurface consists of low amplitude reflections, but the zone at the start of the transect line (furthest from the vent) is dominated by moderate amplitude reflections. This suggests an increase in subsurface permeability as you approach the vent. A similar pattern is also visible along line 2, where there is a decrease in amplitude as you move along the transect line, indicating an increase in saturation towards the middle and end of line 2. Line 3 is dominated by both moderate and low amplitude reflections indicating it is semi-saturated. Line 4 shows mostly low amplitude reflections suggesting it is a highly saturated subsurface.

The GPR data clearly shows that significant changes take place in the shallow subsurface of Old Faithful geyser during the build up to an eruption.

4. DISCUSSION

Geyser plumbing systems and formation mechanisms for controlling geyser eruptions are complex and not fully understood (Fig. 4). The more traditional explanation is that geyser eruptions result from the sudden flashing of superheated water to steam within a vertical conduit plumbing system (Wang and Manga, 2009). However, other mechanisms for geyser eruptions are also reported. Vandemeulebrouck et al. (2013) proposed the plumbing system of Old Faithful geyser to consist of a 20 m wide, oval chamber at 15 to 30 m depth, based on seismic soundings. They propose the oval chamber is connected to a narrow conduit that extends to the surface with several small horizontal cavities connected to the main vertical conduit (Fig. 4A). An alternate geyser mechanism proposed by Belousov et al. (2013) is based on video recordings of four geysers in Kamchatka, Russia. In these geysers, pressurized steam gradually accumulates in underground cavities (or bubble traps) and periodically erupts through a water-filled, highly contorted conduit (Fig. 4B). Furthermore, Munoz-Saez et al. (2015) document the eruptive cycle of El Jefe geyser at El Tatio in Chile. They concluded eruptions are triggered by the episodic addition of steam from depth, and that the eruption mechanisms are dominated by both geometrical and thermodynamic complexities in the conduit and reservoir (Fig. 4C).

Our GPR results show the upper part of Old Faithful geyser (0 to 5 m depth), consists of a complex system of interconnected voids and fractures that repeatedly drain and fill during non-eruptive intervals. This is similar to the highly-contorted, water-filled bubble traps, proposed for the Kamchatka geysers. Due to limitations on the GPR unit in our study, we could not image to 15 m depth. Therefore, a deep, hollow chamber is still plausible. It may be that the Old Faithful geyser eruptive mechanism is a combination of several processes; (1) complex, interconnected cavities from 0-5 m depth that periodically fill and drain during non-eruptive periods; and (2) a hollow chamber at >15 m depth, or (3) eruption mechanisms are dominated by both geometrical and thermodynamic complexities in the conduit and reservoir.

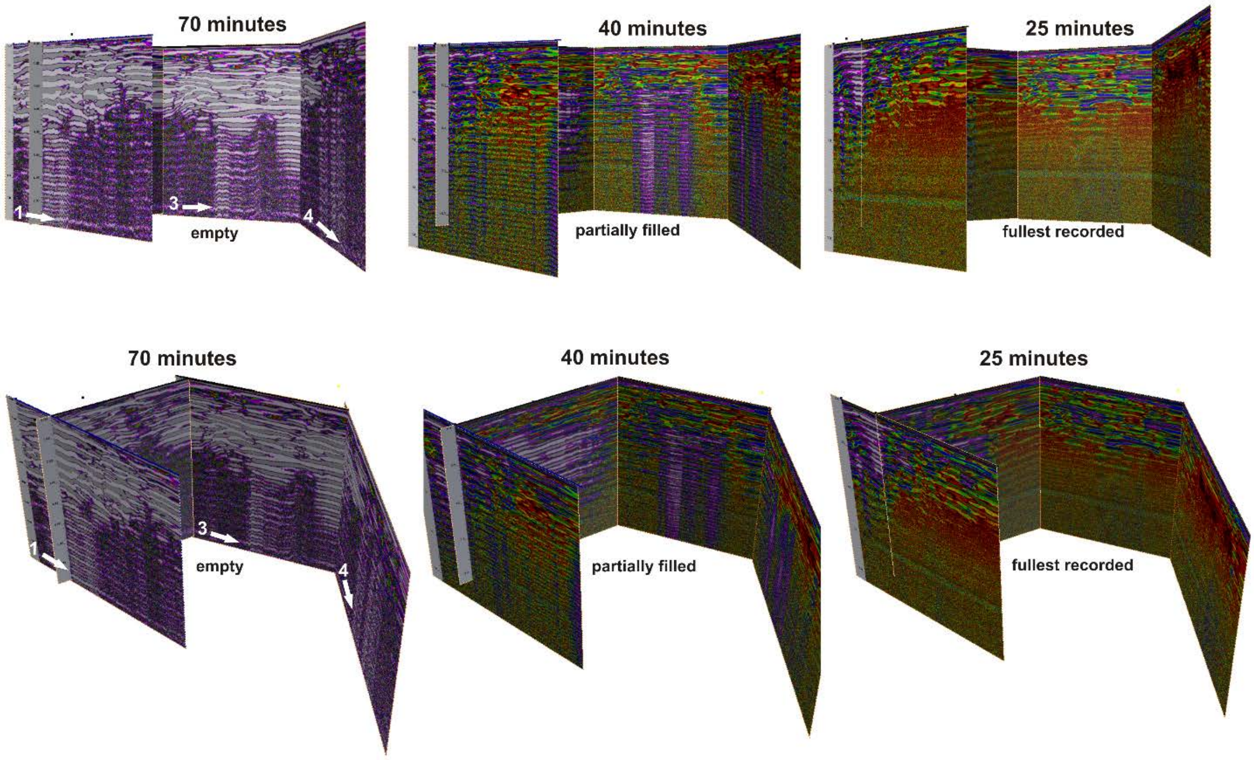

Figure 3: Two different orientations of the time sequence profile lines 1 to 4, at 70, 40 and 25 minutes prior to the 12.20 pm eruption. The 3D GPR images show the subsurface area empty of water/steam (left), semi-saturated with water/steam (middle) and at the time when the subsurface appeared to be highly saturated with water/steam (right). Refer to Table 2 for interpretation of colours.

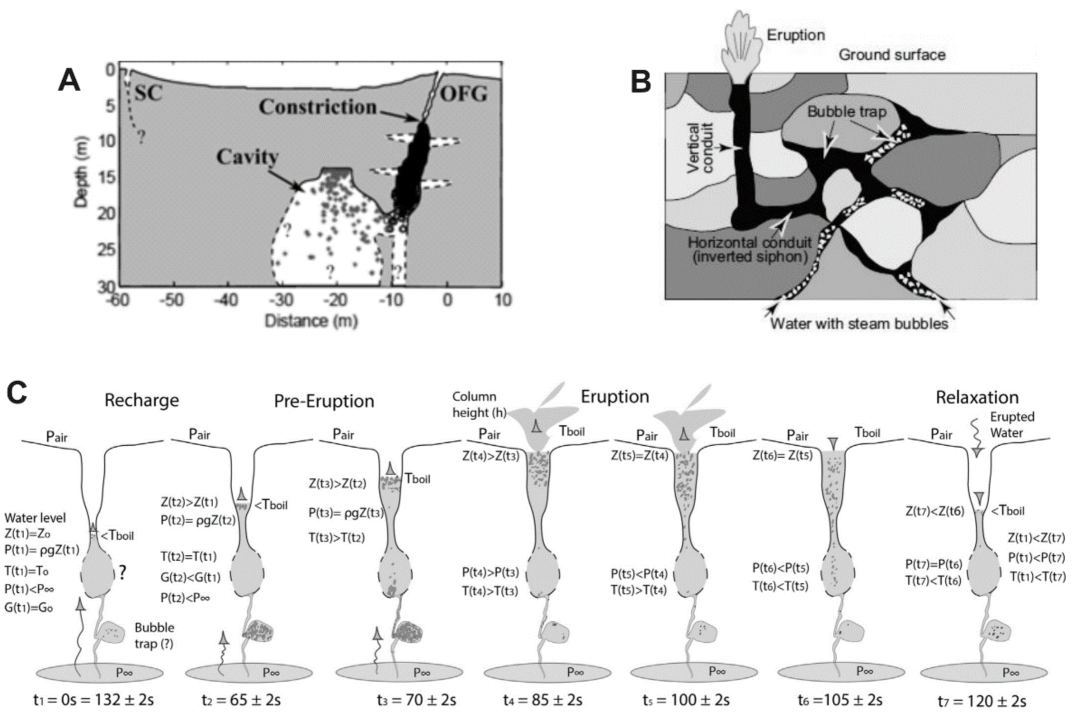

Figure 4: Conceptual models proposed for geyser plumbing configurations and eruption mechanisms. (A) Old Faithful geyser model with hollow chamber at 15-30 m depth (Vandemeulebrouck et al. 2013). (B) Kamchatka geyser model with complex subsurface cavities or bubble traps that fill with water and steam, followed by discharge along a narrow horizontal and then vertical conduit (Belousov et al. 2015). (C) El Jefe Geyser model, El Tatio, showing recharge, pre-eruption, eruption and relaxation cycles. Vent architecture consists of a vertical conduit with a narrow restriction above an oval chamber at depth (Munoz-Saez et al. 2015).

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