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Ground penetrating radar (GPR) and shallow temperature survey at Orakei Korako

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Ground Penetrating Radar (GPR) and shallow temperature survey around the boardwalk at Orakei Korako geothermal field

Comparative report of 2023 and 2012 data

1.0 Executive Summary

A Ground Penetrating Radar (GPR) and downhole temperature survey, around the boardwalk at Orakei Korako geothermal field was completed in March 2023. This survey was a repeat of a 2012 survey. The purpose of the repeat survey was to image the subsurface and identify if any changes had taken place in the last 11 years.

Nine 2012 downhole temperature measurement sites and ten surface temperature measurements sites were repeated for a direct comparison with our 2023 data. Thirteen GPR sites were repeated in 2023, five 2012 GPR sites were not repeated due to inaccessibility to the site. GPR profiles from seven new sites were also collected during the 2023 survey.

Key findings include:

- Surface and subsurface temperatures have increased by 10-40 °C in the Elephant Rock area.
- The shallow subsurface immediately West of Wairiri Geyser, by the stairs going up to the viewing platform, has cooled by 10 °C but remains hot at 89 °C. The surface temperatures have also cooled by ~5 °C with maximum measured temperatures now 34 °C.
- The area north of Devil's Throat has cooled in the subsurface from 77 °C to 51 °C but has increased at the surface from 14-15 °C to 22-37 °C.
- Surface temperatures have increased in the mud pools area, along the path between the Wairiri Geyser lookout and the turn-off to the Artist's Palette lookout and by Soda Fountain.
- Surface temperatures have increased in the northern part of the boardwalk.
- GPR documented the sinter thickness at multiple locations.
- The dual technique of GPR and downhole temperature measurements tracked locations of heat in the shallow subsurface, even when there was no evidence of heat at the surface.
- Repeated GPR surveys combined with downhole temperature surveys enabled the tracking of heat migration pathways in the shallow subsurface. This is important for the evaluation of whether localised areas are heating up or cooling down.
- Currently active and historic zones of hydrothermal alteration were identified and mapped.
- The 2012 survey mapped fracture locations, and the 2023 survey confirmed if they were still present, and mapped the appearance of new fractures.

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2.0 Abstract

In 2012 a Ground Penetrating Radar (GPR) and downhole temperature measurement survey was undertaken around the boardwalk at Orakei Korako geothermal field, Taupō Volcanic Zone, New Zealand. In 2023 this survey was repeated to identify if and where changes in the subsurface had taken place over the last 11 years.

Nine 2012 downhole temperature measurement sites and ten surface temperature measurements sites were repeated for a direct comparison with our 2023 data. Downhole temperature measurements were taken at depths of 0.5 m, 1.0 m and 1.5 m where possible, using a K-type digital temperature probe with a quick response tip. Surface temperature measurements were obtained at the start and end points of each GPR transects using Digital Temperature probe with a K-type thermocouple.

Thirteen GPR sites were repeated in 2023, five 2012 GPR sites were not repeated due to inaccessibility to the site. GPR profiles from seven new sites were also collected during the 2023 survey. In 2012 we used a GSSI SIR-2000 GPR unit with a 200 MHz antenna. In 2023 a Leica DS2000 GPR unit fitted with dual frequency antennas of 250 MHz and 700 MHz was used. The 700 MHz antennae collected high resolution data from the shallow subsurface (0-3 m depth), while the 250 MHz antennae captured data from deeper layers (0-7 m) at a coarser resolution.

Our repeat survey identified areas that are heating up and cooling down, mapped migrating subsurface heat pathways, located ascending steam conduits, identified fractures, mapped zones of hydrothermal alteration, as well as imaged the thickness of the siliceous sinter terraces.

The combined techniques of GPR and temperature measurements offers an innovative method and new perspective for characterising changes that take place in the shallow subsurface over time.

3.0 Introduction

Orakei Korako is a protected geothermal system and tourist site located within the Taupō Volcanic Zone (TVZ), New Zealand (Fig. 1). The main thermal area is accessed via a short boat trip across the Waikato River at Lake Ohakuri (Fig. 1). Orakei Korako is privately owned, but open to the public, with well-formed boardwalks and paths around the geothermal field.

Thermal activity is abundant at Orakei Korako and consists of a few acid features such as mud pools, fumaroles and steaming ground, but is dominated by discharging alkali chloride hot springs and pools with expansive siliceous sinter terraces. Sinters are hot spring rocks formed as silica precipitates and accumulates from discharging alkali chloride hot spring waters (Fournier and Rowe, 1966; Fournier, 1985; Williams and Crerar, 1985). Sinters remain at the surface for thousands of years even after hot spring discharge ceases, providing ground level evidence of an alkali chloride geothermal reservoir at depth (Campbell et al., 2001; Lynne et al., 2005, 2008; Campbell et al, 2015).

Surface thermal activity is sensitive to even subtle changes in hydrology. For example, hot spring flow rates may increase or decrease or cease altogether. A decrease in reservoir pressure can be reflected at the surface by an increase of discharging steam and gases, and a decrease in hot spring flow rate. When ascending steam and hydrogen sulphide gas mix with atmospheric oxygen, acidic steam condensate is formed. Acidic steam condensate descends through the ground and/or sinter, dissolving and/or hydrothermally altering it as it migrates through permeable pathways. This process can take place below the ground surface with no evidence of heat or gas discharge at the surface.

Ground Penetrating Radar (GPR) has proven to be a useful tool to image the shallow subsurface in geothermal settings to <10 m depth. GPR can map the thickness of exposed and buried siliceous sinters (Lynne and Dougherty, 2010a, b; Dougherty and Lynne, 2010a; Foley et al., 2015; Lynne et al., 2016a), the location, orientation and connectivity of subsurface fractures (Dougherty and Lynne, 2010b; Dougherty and Lynne, 2011; Jaworowski et al., 2020), shallow hydrological changes (Lynne et al., 2016b; Lynne et al., 2018) and the occurrence of shallow steam zones and/or intensely hydrothermally altered areas (Lynne et al., 2017). When GPR is combined with downhole temperature measurements, the measured subsurface temperature confirms if hydrothermal alteration is present-day or historic (Lynne and Smith, 2014). The dual technique of GPR and downhole temperature measurements provide a useful method to track shallow changes in the subsurface over time, and are especially useful for identifying subsurface changes when there is no evidence of heat or change at the surface.

In 2012 we completed a survey around the boardwalk at Orakei Korako where we combined GPR with downhole temperature measurements taken at 0.5 m, 1.0 m and 1.5 m depth. In 2023, this survey was repeated so we could compare the results of the two surveys and identify any changes over the last 10 years.

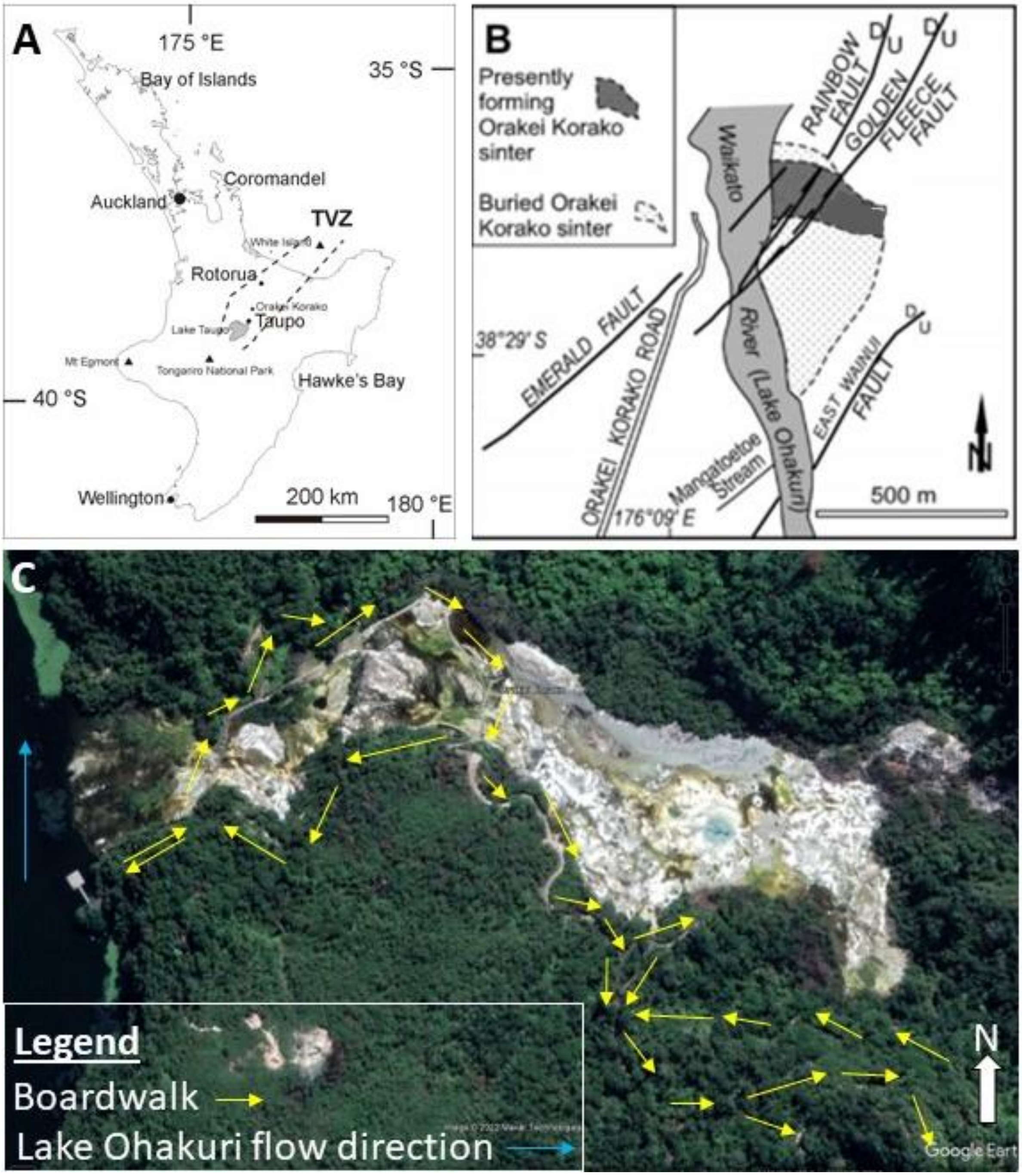

Figure 1: Location maps. (A) Taupō Volcanic Zone (TVZ) within the North Island of New Zealand. (B) Location of Orakei Korako faults and siliceous sinter terraces. (C) Photograph of the Waikato River at Lake Ohakuri, present-day sinter terrace (Emerald Terrace) and siliceous sinter covering the Emerald Terrace fault scarp.

4.0 Methods

4.1 Ground Penetrating Radar (GPR)

In 2012, the GPR unit used was a GSSI SIR-2000 with a GSSI 200 MHz antenna. Data was collected in continuous run mode at 200 ns. Topographic correction was not required as the GPR transects were along level boardwalks and ground surfaces.

In 2023, the GPR unit used was a Leica DS2000 fitted with dual frequency antennas of 250 MHz and 700 MHz. The 700 MHz antennae collected high resolution data from the shallow subsurface (0-3 m depth), while the 250 MHz antennae captured data from deeper layers (0-7 m), at a coarser resolution. At the start of the survey, data was collected using 80 ns, 150 ns and 200 ns, to compare quality of data with respect to depth. After comparison, 150 ns was chosen for this survey as an ideal compromise between depth and image resolution. Data was collected in continuous run mode at 512 samples per scan and 306 scans per meter. Topographic correction was not required for these surveys as the GPR transects were on level surfaces. The air gap between the antenna and the ground surface was removed during data processing. No gain was added during post-processing.

GPR profiles can be presented in colour or grayscale. Our 2012 images are shown in colour while our 2023 images are shown in grayscale. GPR profiles can show high, medium or low amplitude reflections (Fig. 2). The strength of the reflection depends on the dielectric properties of the subsurface rocks, hydrothermal alteration processes and the presence of fluid and or air.

Based on our previous GPR studies undertaken in geothermal settings, GPR reflections can be grouped as follows:

- Strong competent unaltered siliceous sinters produce strong, or high amplitude reflections.
- Moderately-altered rocks or siliceous sinters produce medium amplitude reflections.
- Highly-altered rocks, sinters or clays produce weak or low amplitude reflections.
- Fractures appear as offset layers.
- Subsurface steam conduits are imaged as contorted, vertical weak amplitude reflections.
- Hyperbolas are caused when the radar wave reflects off a single point round object, such as buried service pipes.

Our 2012 Orakei Korako GPR and temperature survey was ground-truthed by collecting siliceous sinter samples and analysing them using Scanning Electron Microscopy. Our 2012 survey confirmed that where GPR was collected over unaltered sinter, strong amplitude reflections were detected. Weak amplitude reflections were detected where steam was ascending and hydrothermally altering the sinter (Lynne and Smith, 2014).

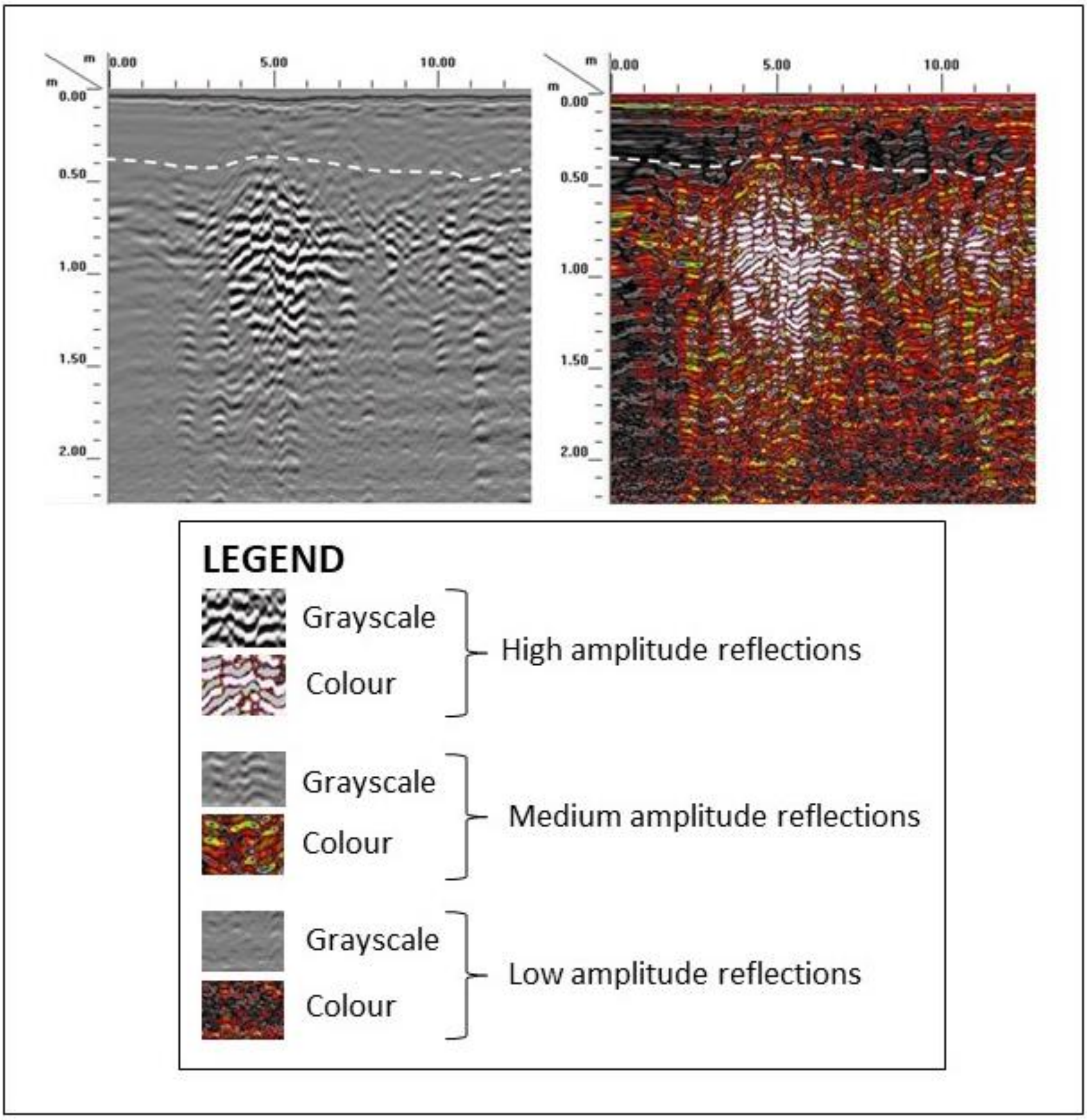

Figure 2: An example of a GPR image showing low, medium and high amplitude reflections.

4.2 Temperature Measurements

Two sets of temperature measurements were collected for these surveys.

- Downhole temperature measurements were taken at depths of 0.5 m, 1.0 m and 1.5 m using a GSI Ltd designed K-type digital temperature probe incorporating a quick response tip.
- Surface temperature measurements were obtained at the start and end points of each GPR transects using Digital Temperature probe with a K-type thermocouple.
- Ambient air temperatures in 2012 and 2023 were 10.8 °C (9 am) and 18 °C (3pm), respectively.

4.3 Site Photographs

New site photographs were only taken in 2023 where there were visual changes at the site.

5.0 Results: Temperature Measurements

5.1 Temperature Measurement Locations

The location of all the 2012 and 2023 downhole temperature measurements are shown in Figure 3. Not all the 2012 sites could be measured again in 2023 due to inaccessibility or the ground surface was too hard to penetrate with the temperature probe. However, nine downhole temperature measurements that were recorded in 2012 were repeated in 2023, for a direct comparison (Fig. 3).

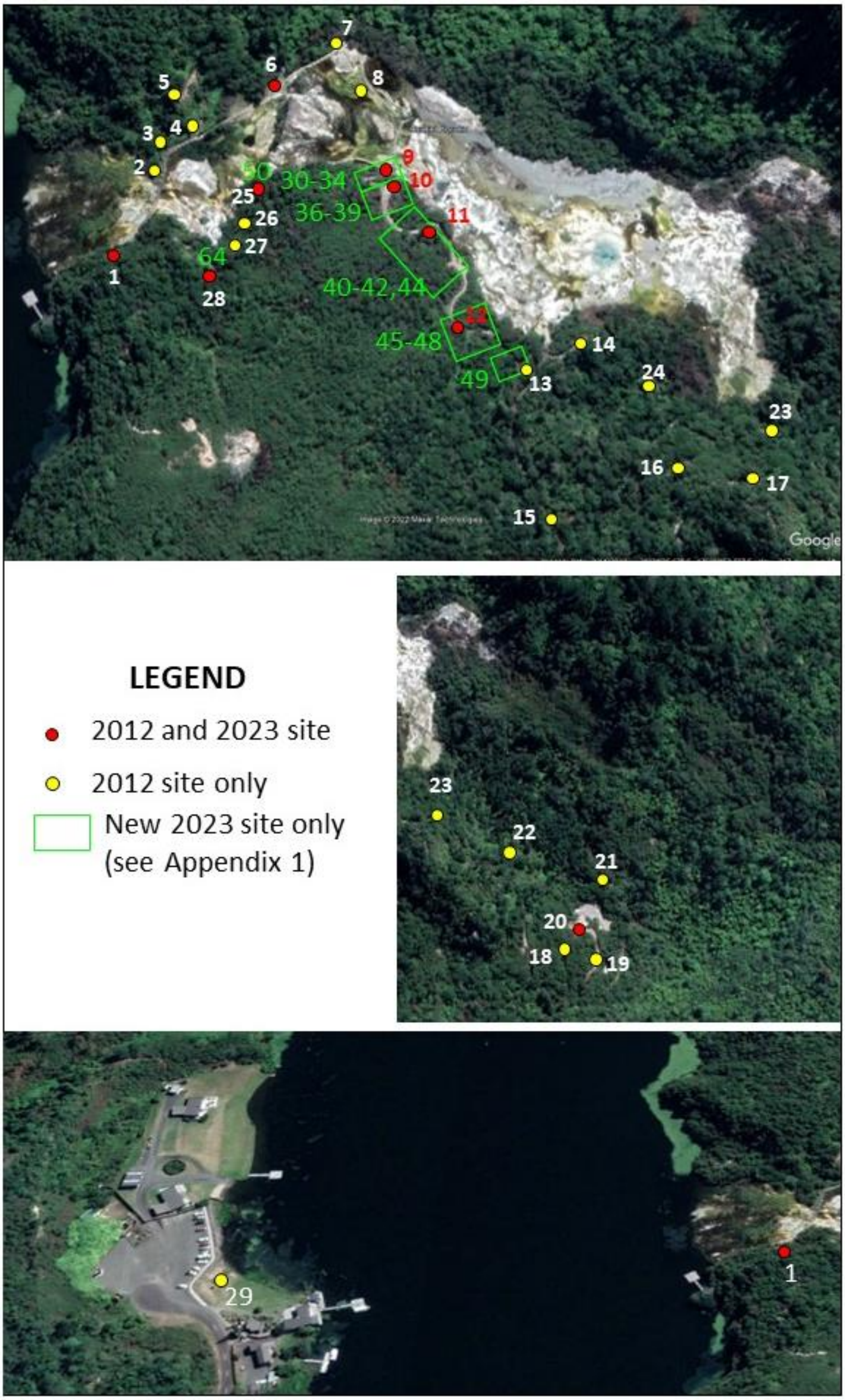

Figure 3: Location of downhole 2012 and 2023 temperature measurement sites. Refer to Appendix 1 for more details on the new 2023 site locations.

5.2 Subsurface Temperatures

The downhole subsurface temperature measurements are given in Tables 1, 2 and 3.

- Table 1 presents the 2012 downhole temperature measurement data.
- Table 2 presents the 2023 downhole temperatures taken at the same locations as in 2012.
- Table 3 presents the new 2023 downhole temperature locations. These were collected near 2012 sites. Refer to Appendix 1 for site photographs of these new locations.

Figure 4 shows the location of downhole temperatures sites measured in 2023, with their associated temperatures.

Figure 5 shows the location of downhole temperatures sites measured in 2012 that match sites measured in 2023. Associated temperatures for each site is given.

Table 1: 2012 measured downhole temperatures at 0.5 m, 1.0 m and 1.5 m depth at 29 sites at Orakei Korako. Refer to Figure 3 for sample locations.

Location #	Nearest feature	GPS Coordinates (NZMG)	Temperature (°C) </= 0.5 m depth	Temperature (°C) at 1.0 m depth	Temperature (°C) at 1.5 m depth
1	Diamond Geyser	E2784618 N6298506	51.8	N/A	N/A
2	Hydrothermal Eruption Crater	E2784637 N6298544	23.2	37.2	46.9
3	Map of Africa	E2784686 N6298563	20.8	33.1	36.6
4	Lookout (North)	E2784654 N6298565	68.6	74.4	73.8
5	Lookout (Mudpool)	E2784688 N6298589	55.3	76.8	86.6
6	Devil's Throat	E2784697 N6298563	66.7	74.3	77.1
7	End of Eastern Boardwalk	E2784737 N6298584	24.8	62.2	69.6
8	Western side of Fred and Maggie's	E2784734 N6298561	38.5	69.5	92.1
9	West Boardwalk - Fossilised outcrop	E2784731 N6298521	100	N/A	N/A
10	VPWG	E2784743 N6298514	30.1	32	34.5
11	Elephant Rock	E2784752 N6298489	41.2	44.2	N/A
12	EW Steaming Ground Area	E2784769 N6298474	58	59	N/A
13	1655 - Opposite mudpool	E2784786 N6298439	96.5	99.3	99.2
14	Lookout over Artists Palette	E2784820 N6298431	24.1	28.1	31.2
15	Turutu Signal 1	E2784804 N6298343	13.6	18.7	30
16	Turutu Signal 2	E2784859 N6298394	16	19.9	19.7
17	Lookout bend	E2784872 N6298367	15.1	19	21
18	Palm tree curve to the left	E2784911 N6298351	13.3	15	16.4
19	Before mud pool	E2784963 N6298351	33.2	48.8	62.9
20	Apex mud pool	E2784993 N6298266	46.2	59.7	73.3
21	East of mud pool	E2784985 N6298300	54.3	79.6	94.2
22	Corner 90° curve to the left	E2785009 N6298325	25.3	36.2	43
23	Ponga signal	E2784972 N6298385	20	28.3	37
24	Between Ponga and bridge	E2784933 N6298401	19.1	26.2	29.6
25	Before soda fountain	E2784676 N6298502	99.4	99.2	99.7

26	Before soda fountain	E2784674 N6298512	29.5	43	53.3
27	Before soda fountain	E2784667 N6298499	72.9	75	80.1
28	Soda fountain	E2784661 N6298488	45	51.7	N/A
29	In front of reception grounds	E2784329 N6298480	100	100	100

Table 2: 2023 measured downhole temperatures taken at the same locations as in 2012. Refer to Figure 3 for sample locations. Grey highlighted lines are data from 2012. Comparison of the 2023 and 2012 temperatures data, highlights areas that have heated up, cooling down or showed minimal change.

2012	Dec 2022 or March 2023						
Sample number	**Sample number**	**Location notes**	**Temperature (°C)**	**Depth (m)**	**Easting**	**Northing**	
1		Beside Diamond Geyser	51.8	<0.5	E2784618	N6298506	
	1	Beside Diamond Geyser. Hard sinter could not penetrate deeper than 0.1 m.	20.4	0.1	E2784618	N6298506	
6		Temperature profile taken in 2012 was at 25 m mark	77.1	1.5	E2784697	N6298563	
	6	Grass area beside Devil's Throat at 10 m mark on GPR profile G3.	50.8	1.5			[blue]
		21 m long GPR that started at the 4 m mark of the 2012 GPR profile					
9		West boardwalk fossilised outcrop	100	<0.5	E2784731	N6298521	
	31	3rd step going up by fossilised outcrop	89.6	0.05	E2784736	N6298520	[blue]
10		Viewing platform overlooking Wairiri Geyser	30.1	<0.5	E2784743	N6298514	
	10	Viewing platform overlooking Wairiri Geyser. At 2 m mark along GPR profile SW16	68	0.2			[red]
		At small steam vent near 3.8 m mark along GPR profile SW16	90	surface			
11		Elephant rock	41.2	<0.5	E2784751	N6298490	
	11	Elephant rock	44.8	0.3	E2784751	N6298490	[red]
12		EW Steaming ground area	58	<0.5	E2784769	N6298474	
	44	EW steaming ground area. Right side of boardwalk.	78	surface	E2784769	N6298474	[red]
20		Mud pools GPR profile G19. Temperature at 8 m mark	73.3	1.5	E2784963	N6298280	
	20	Mud pools GPR profile G19. Temperature at 8 m mark	99.8	1.2	E2784963	N6298280	[red]
25		Little cave on left side of boardwalk on way out. Before Soda Fountain	99.4	<0.5	E2784676	N6298502	
	50	Little cave on left side of boardwalk on way out. Before Soda Fountain	99.6	0.5	E2784677	N6298504	[green]
28		Right side of boardwalk immediateley before Soda Fountain.	45	<0.5	E2784651	N6298488	
	64	Right side of boardwalk immediateley before Soda Fountain.	41.1	0.2	E2784650	N6298491	[blue]

Key	
[red]	Heating up
[blue]	Cooling down
[green]	Minimal change

Table 3: 2023 new measured downhole temperatures taken near 2012 sites. Refer to Appendix 1 for site photographs and Figure 3 for site locations.

Near 2012 site number	Dec 2022 or March 2023 Sample number	Location notes	Temperature (°C)	Depth (m)	Easting	Northing
9	30	Base of fossilised outcrop	35.9	0.25	E2784741	N6298522
9	30	Base of fossilised outcrop	42.9	0.6	E2784741	N6298522
9	31	Base of fossilised outcrop	89.6	0.05	E2784740	N6298521
9	32	6th step on right going up by fossilised outcrop	33.4	0.05	E2784736	N6298519
9	34	6th step on left going up by fossilised outcrop	72.9	0.75	E2784738	N6298514
Between 9 and 10	36	Between planks and inline with post on left just before steps	84.4	surface	E2784746	N6298510
	37	Approx 2 m from 36 on right side of boardwalk just before steps	73.1	0.2	E2784738	N6298508
	38	Left side of boardwalk going towards Artist's Palette	97.4	0.15	E2784740	N6298507
	39	Right side of boardwalk going towards Artist's Palette	99.7	0.35	E2784740	N6298503
10	SW17	On viewing platform overlooking Wairiri Geyser.	68	0.2		
		At the 3 m mark on the GPR profile or the 2 m mark on SW16.				
11	40	Left side of boardwalk before Elephant Rock	83.2	0.5	E2784748	N6298495
	42	Right side of boardwalk going up towards Artist's Palette	99.7	0.8	E2784765	N6298486
		Small vent at surface 0.3 m away form measurement site = 99.5 °C				
Between 11 and 13	45	New water feature just before large mud pool	91	surface	E2784770	N6298443
	46	Right side of boardwalk going towards Artist's Palette	38.9	0.3	E2784786	N6298441
	47	Going towards Artist's Palette	71.2	0.4	E2784784	N6298441
	48	Going towards Artist's Palette	89.7	0.5	E2784781	N6298447
	48	Going towards Artist's Palette	92.2	0.8	E2784781	N6298447
12	SW20	At 7.5 m mark on GPR profile SW20. New boardwalk.	65.5	1		
13	49	Going towards Artist's Palette	28.6	0.5	E2784794	N6298433

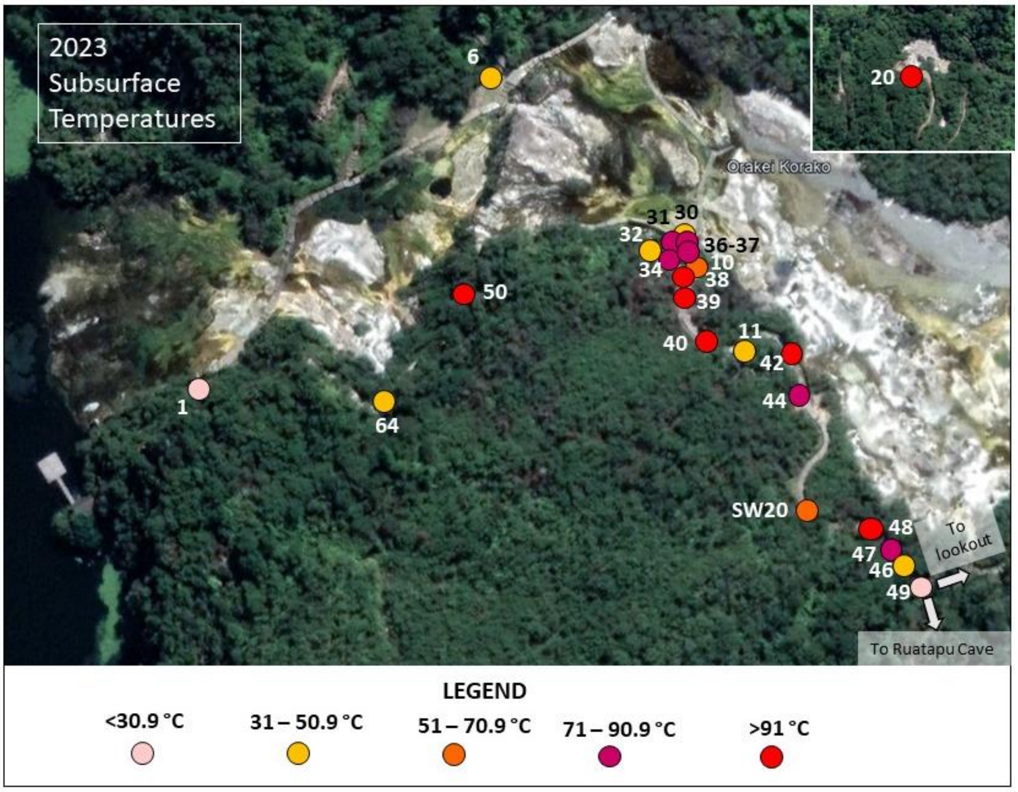

Figure 4: 2023 downhole temperatures measurement sites with corresponding temperature groups shown. Refer to Tables 2 and 3 for depth of measurements and Appendix 1 for site photographs. Insert: Site 20 by the mud pools.

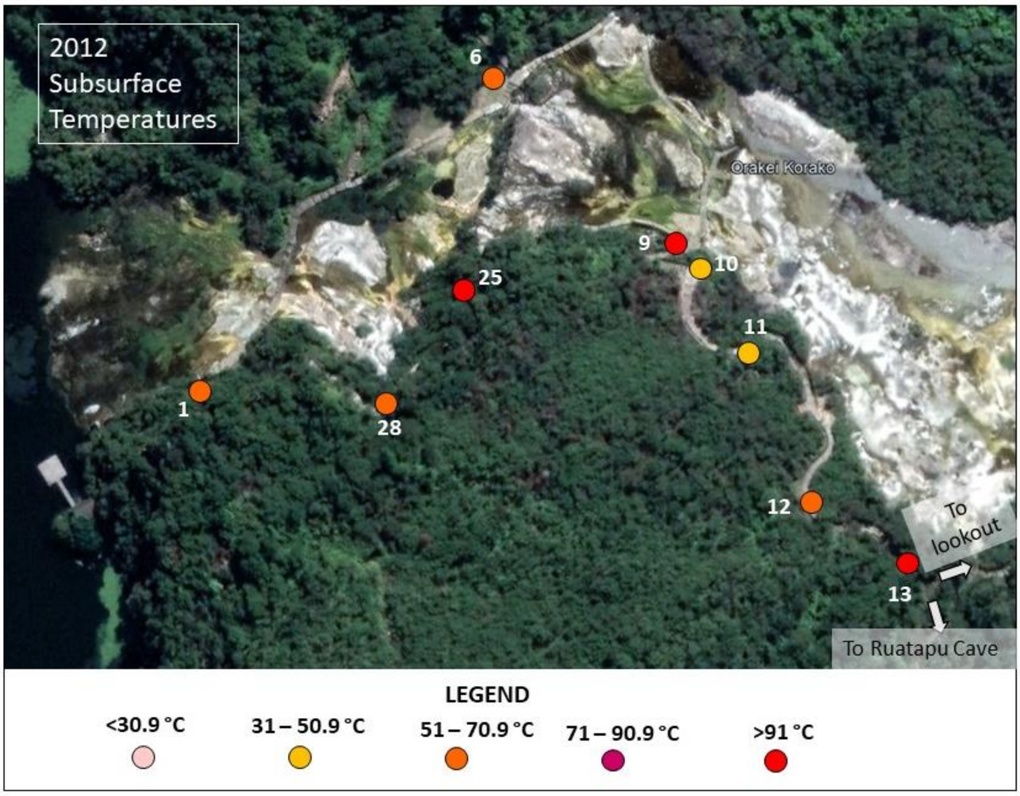

Figure 5: 2012 downhole temperatures sites that match the 2023 downhole temperature measurement sites, with corresponding temperature groups shown. Refer to Table 1 for depth of measurements.

Figure 6 shows the areas where the shallow subsurface downhole measured temperatures have increased, decreased or revealed minimal change in temperature, since 2012.

Key finding are summarised below:

- One area shows minimal temperature change
  - Little cave before Soda Fountain on way out (site 25 on Fig. 6)
- Three areas have decreased in temperature
  - Corner of boardwalk by Diamond Geyser (site 1 on Fig. 6)
  - Grassed area by Devil's Throat (site 6, on Fig. 6)
  - Boardwalk west of fossilised outcrop by Wairiri Geyser (site 9 on Fig. 6)
- Five areas have increased in temperature
  - Three areas between the viewing platform overlooking Wairiri Geyser and the turn off to Artist's Palette viewing platform (sites 10-12 on Fig. 6)
  - Mud pools (site 20 on Fig. 6)
  - Soda Fountain area (site 28 on Fig. 6)

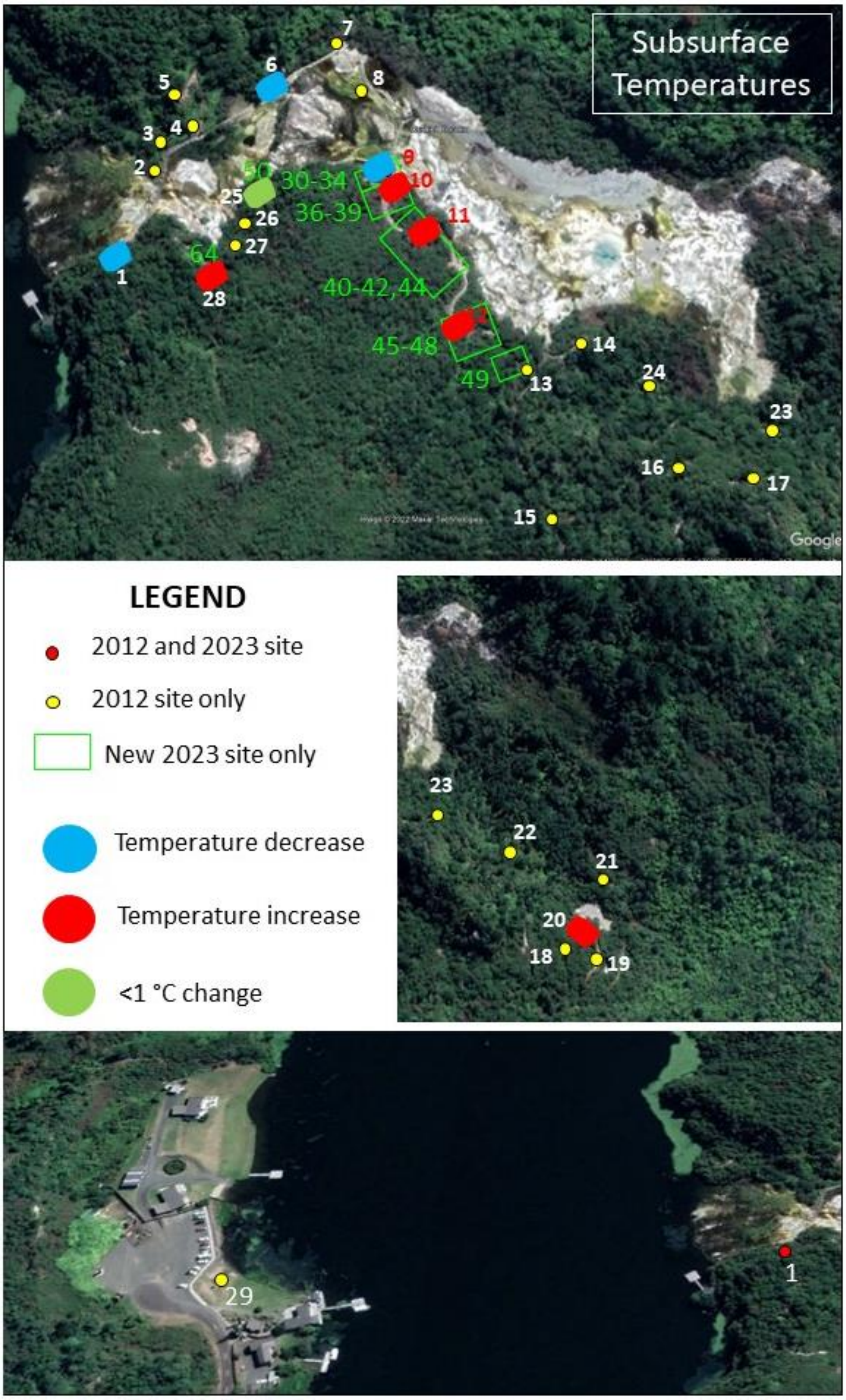

Figure 6: Map showing where and how the shallow subsurface temperatures have changed between 2012 and 2023 at the nine sites where their locations could be matched.

5.3 Surface Temperatures

Surface temperatures were collected at the start and end of each GPR transect line in 2012 and in 2023. A comparison of the surface temperatures is given in Table 4. Our results show that some sites have increased, while other sites have decreased in temperature over the last 11 years (Fig. 7).

Key findings are summarised below:

- Eight areas show an increase in surface temperature.
    - Boardwalk across Emerald/Rainbow Terrace (G2 on Fig. 7)
    - Northern lookout (G4 on Fig. 7)
    - Two areas on northern side of Devil's Throat (G3, G5-7 on Fig. 7)
    - Elephant Rock (G14 on Fig. 7)
    - Entrance to Ruatapu Cave (G18 on Fig. 7)

- Two areas reveal surface temperatures have decreased.
    - Boardwalk by Diamond Geyser (G1 on Fig. 7)
    - New boardwalk west of Wairiri Geyser (G9 on Fig. 7)

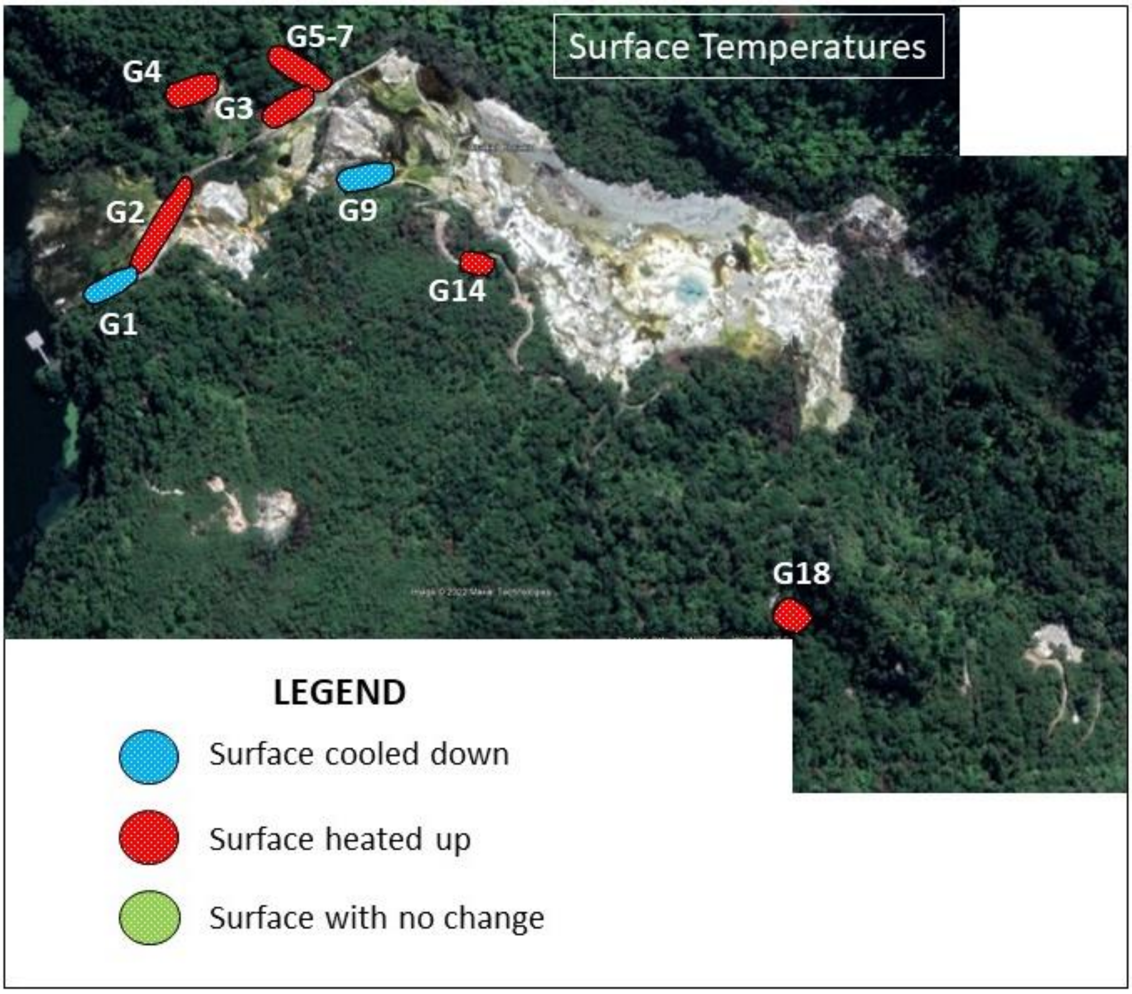

Figure 7: Map showing locations where the surface temperature has either increased, decreased or remained unchanged between 2012 and 2023.

Table 4: Comparison of surface temperatures collected at the start and end of each GPR profile in 2012 and 2023. Refer to figure 9 for GPR transect locations.

2012 Profile name	2023 Swath number (SW)	GPR Total length in meters	2023 Temperature on surface at start of GPR (°C)	2023 Temperature on surface at end of GPR (°C)	2012 Temperature on surface at start of GPR (°C)	2012 Temperature on surface at end of GPR (°C)	Temperature change
G1	SW6	10	18.5	18.4	33.4	18.2	
G1 repeat	SW7	10					
G2	SW8	12	23.5	32.3 in water	21.7		
G3	SW9	21	21.9	36.9	15.2	14.5	
G4	SW11	5	22.3	22.8	15.6	22.2	
G5	SW10	5	24.2	24.6	16.4	20.6	
G6	SW12	10	18	22.5	18.2	13.9	
G7	SW13	10	18	20.8	15.3	11.6	
G8		5			15	15.8	
G8 new site	SW14	6.1	29.4	28.4			
G9	SW15	13	33.8	21.8	39.1	31	
New	SW16	3.7	37	90			
New	SW17	3	55.8	68			
New	SW18	4.8	64.2	44.1			
G14	SW19	18.4	27.7	37.2	20	17.9	
G15	SW20	12			14.8	13.7	
New	SW21	7.8	20	25.1			
G19	SW22	16.2			18.5	16.1	
G18	SW24	10	19	16	9.6		
	SW23						
G26	SW4	38	29.9	28.5			
G26 repeat	SW5	38	29.9	28.5			

Key	
	Heating up
	Cooling down
	Minimal change

5.4 Temperature Survey Conclusions

This study highlights the areas at Orakei Korako that have shown a temperature change in the last 11 years (Fig. 8). Nine 2012-2023 downhole temperature sites can be directly compared for temperature changes (Table 2). Ten 2012-2023 surface temperature measurements can be directly compared (Table 4).

2012-2023 temperature survey, surface and subsurface direct comparison key findings

Elephant Rock area

- Temperatures have increased in the Elephant Rock area. Subsurface temperatures have increased from 30 to 68 °C (site 10, Fig. 8), 41 to 44 °C (site 11, Fig. 8) and 58 to 78 °C (site 12, Fig. 8). Surface temperatures have also increased from 18-20 °C to 27-37 °C (G14 on Fig. 8).

West of Wairiri Geyser

- The area West of Wairiri Geyser and North of the fossilised outcrop by the stairs going up to the viewing platform, has cooled in the subsurface from 100 °C to 89 °C. (site 9 on Fig. 8). It has also cooled at the surface from 31-39 °C to 22-34 °C (site G9 on Fig.8). This area now has three new vents that were exposed in 2019. A new boardwalk has been constructed around the new vents. Exposure and reactivation of the vents may be allowing the area to cool.

Devil's Throat area

- The area north of Devil's Throat has cooled in the subsurface from 77 °C to 51 °C (site 6 on Fig. 8) but has increased at the surface from 14-15 °C to 22-37 °C (G3 on Fig. 8).

2012-2023 surface temperature survey, key findings

- Surface temperatures have increased at sites G2 to G7 (Fig. 8). These locations are in the northern part of the boardwalk.
- Surface temperatures at the entrance to Ruatapu Cave have increased from 9 to 19 °C (G18 on Fig. 8). The ambient temperature in 2023 at this site was 18 °C, so this increased heat is likely to be solar heat and not geothermally heated ground.
- Surface temperatures under the boardwalk by Diamond Geyser have cooled from 18-33 °C to 18 °C (G1 on Fig. 8). The 2023 temperatures were measured in water flowing under the boardwalk. It is not known if the 2012 temperature recorded were measured in water.

2012-2023 subsurface temperature survey, key findings

- Subsurface temperatures have increased in; (1) the mud pools area (20 on Fig. 8), (2) along the path between the Wairiri Geyser lookout and the turn-off to the Artist's Palette lookout (10-12 on Fig. 8), and (3) by Soda Fountain (28 on Fig. 8).

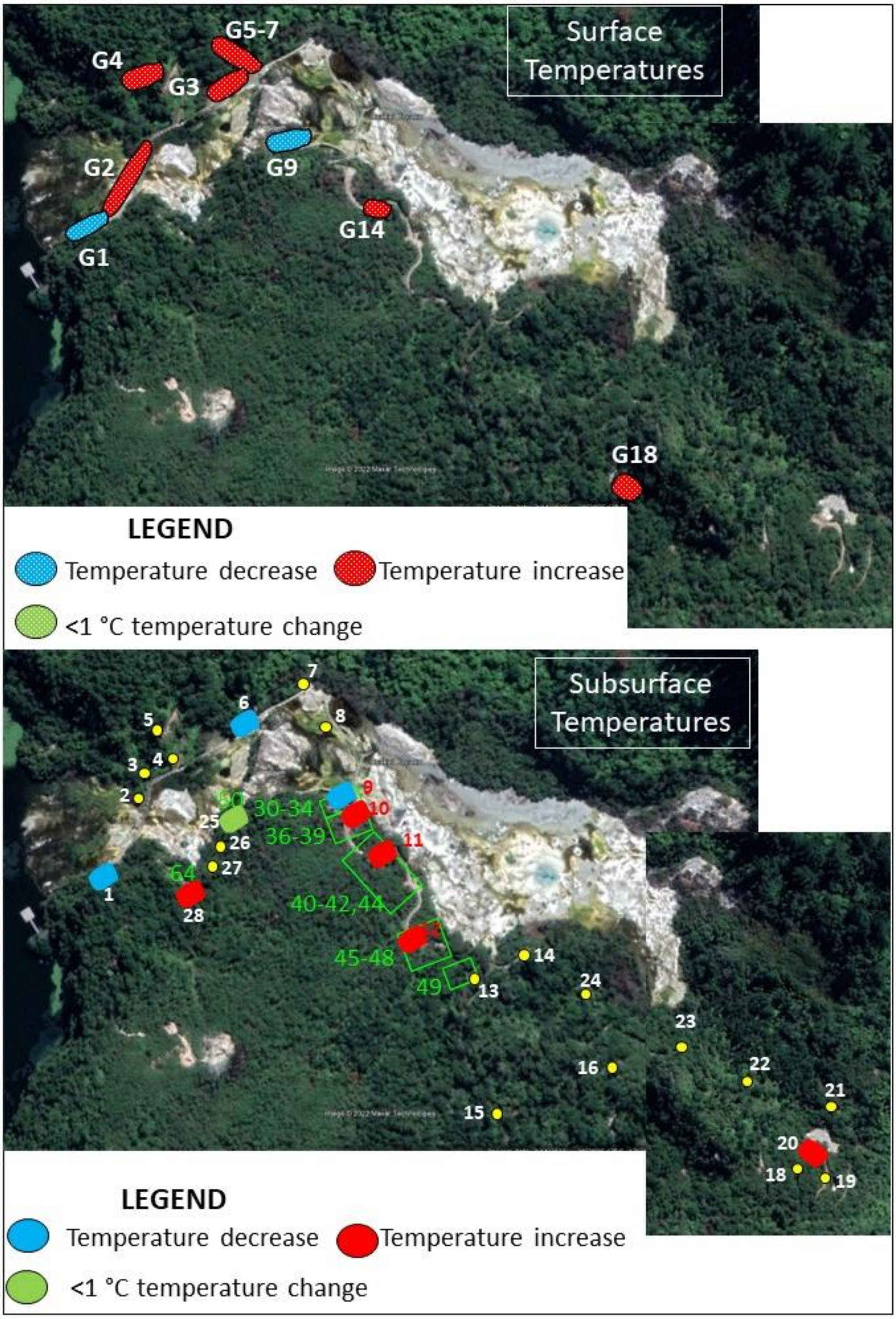

Figure 8: Location map showing shallow subsurface areas and surface areas that have heated up, cooled down or showed minimal temperature change between 2012 and 2023.

6.0 Results: Ground Penetrating Radar

6.1. Ground Penetrating Radar Sites

The location of the 2012 and 2023 GPR sites are presented in Figure 9, with the direction of the GPR data collection indicated by the line from the square. Thirteen sites were repeated in 2023, five sites were not repeated due to inaccessibility to the site in 2023. GPR profiles from seven new sites were collected in 2023. For all GPR profiles repeated in 2023 the preface (G) is given to the profile name. For the new GPR profiles collected in 2023 the preface (SW) is assigned to the profile name. GPR transect lengths, names and comments about their location are presented in Tables 5 and 6.

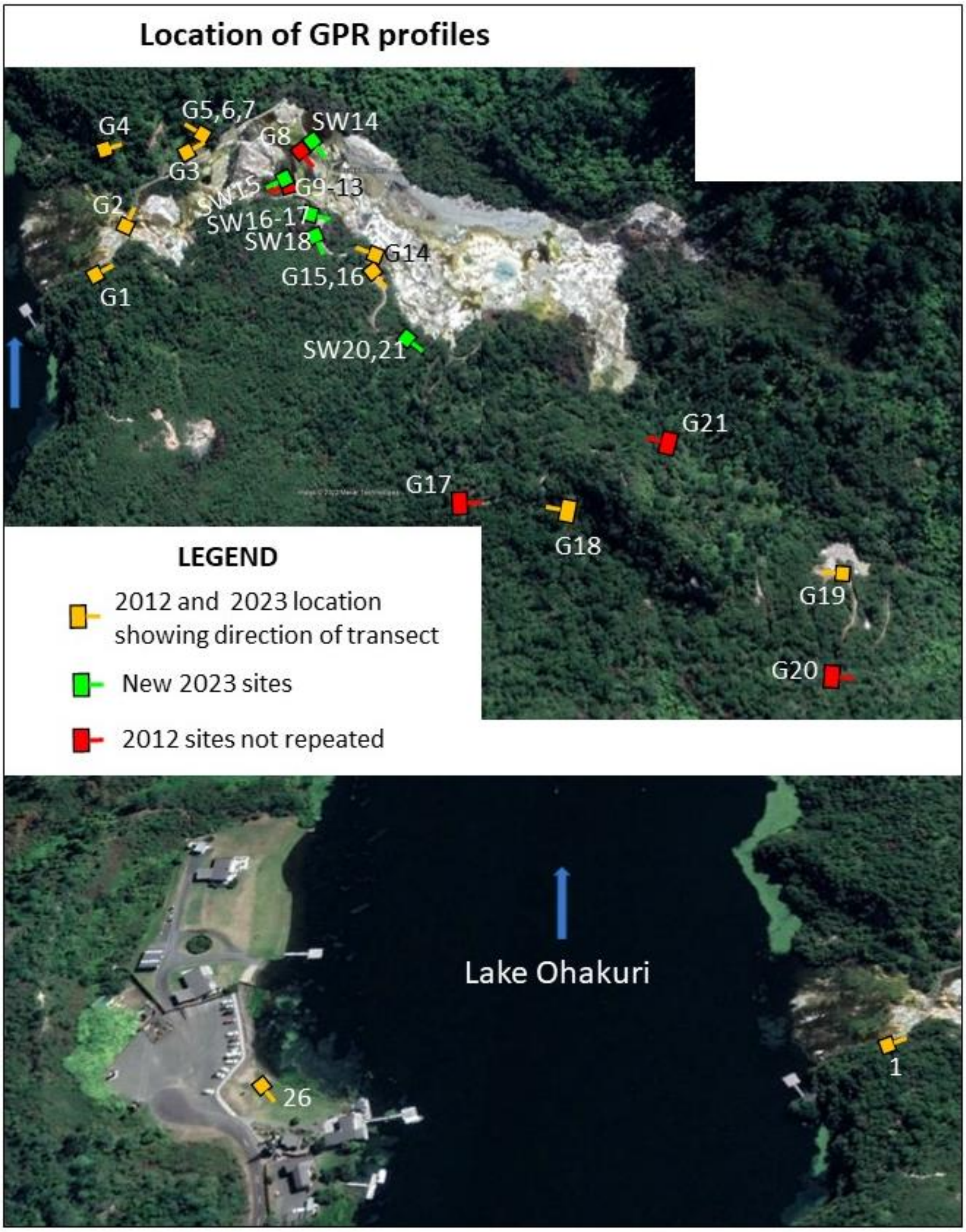

Figure 9: Map showing the location of the 2023 and 2012 GPR sites. Blue arrow indicates the flow direction of the Waikato River at Lake Ohakuri.

Table 5: GPR transect locations, length and orientation of the 2012 GPR transect lines. Transects with a * were not repeated in 2023.

Date (2012)	GPR Transect	Temper-ature site	Length (m)	Location Description	GPS Co. (NZMG)	Orientation Of transect
27/06	G1	1	10	Diamond Geyser.	E2784619 N6298507	Along boardwalk.
	G2	2	12	In front of Sapphire Geyser.	E2784633 N6298524	Along boardwalk.
	G3	3	25	Map of Africa (on the way to little mud pool).	E2784686 N6298582	320°
	G4	4	5	Lookout for Rainbow Terrace.	E2784650 N6298568	45°
	G5	5	5	Lookout mud pool.	E2784684 N6298591	320°
	G6	-	10	On the way to Devil's throat (off boardwalk).	E2784674 N6298557	260°
	G7	6	10	Devil's throat.	E2784704 N6298565	320°
	G8*	8	5	Western side Fred and Maggies (off boardwalk).	E2784734 N6298559	160°
	G9*	9		West of Wairiri Geyser- fossilised outcrop.	E2784728 N6298526	270°
	G10*	-	6.5	Further West of Wairiri Geyser.	E2784713 N6298529	270°
	G11*	-	5	8 m from G10.	E2784704 N6298529	270°
	G12*	-	7	5 m from G11 towards Soda fountain past the "Do not cross sign".	E2784689 N6298530	210°
	G13*	-	10	10 cm away from G12 (off boardwalk).	E2784685 N6298519	200°
	G14	11	15	Curved path around Elephant Rock.	E2784765 N6298496	0-6m: 330° 6-18m: 270°
	G15	12	6	EW steaming ground area. 12 m from G14 past Elephant Rock.	E2784756 N6298502	150°
	G16	-	4	Short run between G14 and G15.	-	150°
	G17*	15	6	Turutu signal 1. Path to Ruatapu Cave (off boardwalk).	E2784802 N6298351	120°
	G18	16	10	Turutu signal 2. Ruatapu Cave entrance, beside rest point.	E2784860 N6298330	Along boardwalk
	G19	20,21	18	Mud pool (off boardwalk).	E2784989 N6298299	300°
	G20*	-	8	Corner 90°, curve to the left.	E2784991 N6298259	255°
	G21*	24	11	Between ponga and bridge (off boardwalk).	E2784939 N6298399	272°
	G22*	25	3.5	Path to Soda Fountain.	E2784675 N6298505	245°
	G23*	27	8	Path to Soda Fountain, 5 m from G22.	E2784670 N6298501	242°
	G24*	28	4	Hypotenuse transect at Soda Fountain (off boardwalk).	E2784662 N6298492	224°
	G25*		5	L-shaped transect at Soda Fountain (off boardwalk).	E2784662 N6298492	-

	G26	29	37	In front of reception ground parallel to car park. On ground.	E2784325 N6298488	105°
	G27*		17	In front of reception ground transect cut G26 at right angle at 10 m.	E2784327 N6298475	15°

Table 6: New 2023 GPR profile names, locations and lengths.

GPR profile	Length (m)	Location description
SW14	6.1	On boardwalk parallel to 2012 site G8.
SW15	13.2	Adjacent to 2012 sites G9-12. New vents and boardwalk in this area so sites G9-12 no longer accessible.
SW16	3.8	Viewing platform above Wairiri Geyser.
SW17	3	Viewing platform above Wairiri Geyser. Perpendicular to SW16.
SW18	4.8	On boardwalk.
SW20	12	On new boardwalk after Elephant Rock and before path up to Artist's Palette.
SW21	7.8	After Elephant Rock, on boardwalk, beside acid pool

6.2 Individual Ground Penetrating Radar Profiles

2012 G1 and 2023 SW7

A site photograph and GPR profiles are presented in Figure 10.

The 2023 GPR transect was located at the same location as the 2012 GPR transect line.

Significant changes

- A fracture was identified in 2012, at the 5 m mark along the transect. This fracture is still clearly visible in the 2023 GPR data. The 2012 image shows the fracture extends to 2 m depth but the 2023 GPR image reveals it extends to at least 4 m depth.
- The area of near-surface weak reflections imaged in 2012, have now become either moderate or strong reflections. Between 8 and 10 m along the 2023 transect line, the microbial mat covering the sinter surface is almost level with the boardwalk. The 2023 strong lateral reflections indicate the sinter is at least 2 m thick.

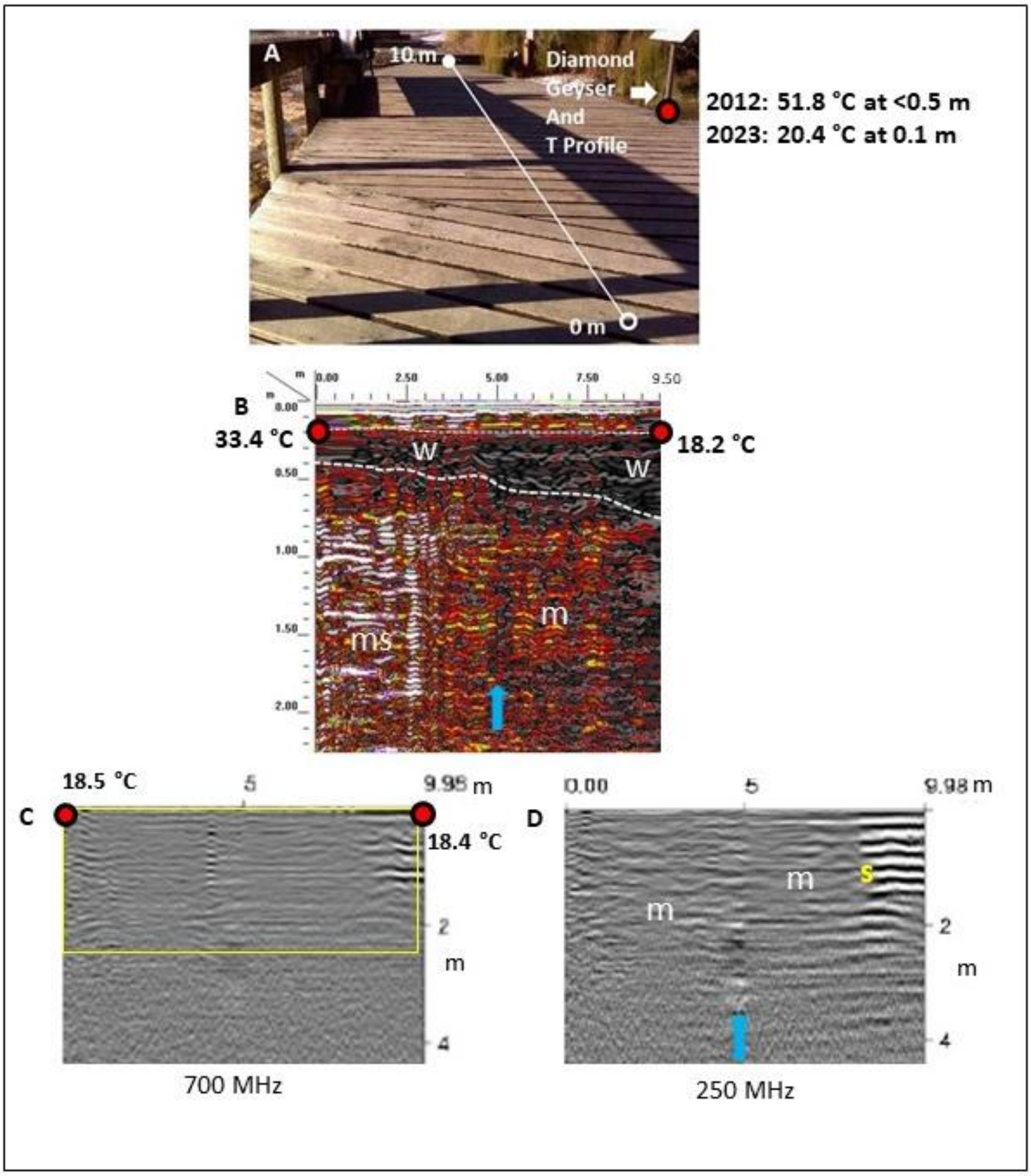

Figure 10: GPR site G1/SW7. (A) 2012 site photograph. (B) 2012 GPR image. Weak reflections (w) dominate the near-surface along the entire profile. Below the weak reflections are moderately-strong reflections (ms) and moderate reflections (m). Fracture at 5 m (arrow). (C-D) 2023 GPR images. Yellow box indicates area of 2012 GPR image. Moderate (m) reflections dominate the area with strong reflections (s) between 8 to 10 m. Arrow indicates a fracture at 5 m. (B-C) Surface temperatures at start and end of transect lines.

2012 G2 and 2023 SW8

A site photograph and the GPR profiles are presented in Figure 11.

The 2023 GPR transect was located at the same location as the 2012 GPR transect line.

Significant changes

- The cluster of strong reflections between 3 and 7 m on the 2012 GPR image extends down to ~1.5 m depth. The 2023 images show this extends to ~3.5 m depth.
- On the 2023 GPR image, at the 7 m mark, there is a well-defined vertical boundary marking a change from strong to moderately-strong reflections. In 2012 this was a gradational boundary.
- The area of strong reflections suggests unaltered sinter, which is up to 3 m thick.
- The surface temperature has increased at this site from 21 to 23 °C between 2012 and 2023. The grass immediately adjacent to the end of the 2023 transect measured 25.5 °C. A measured temperature of 32.3 °C at the end of the 2023 GPR transect was taken in thermal water.

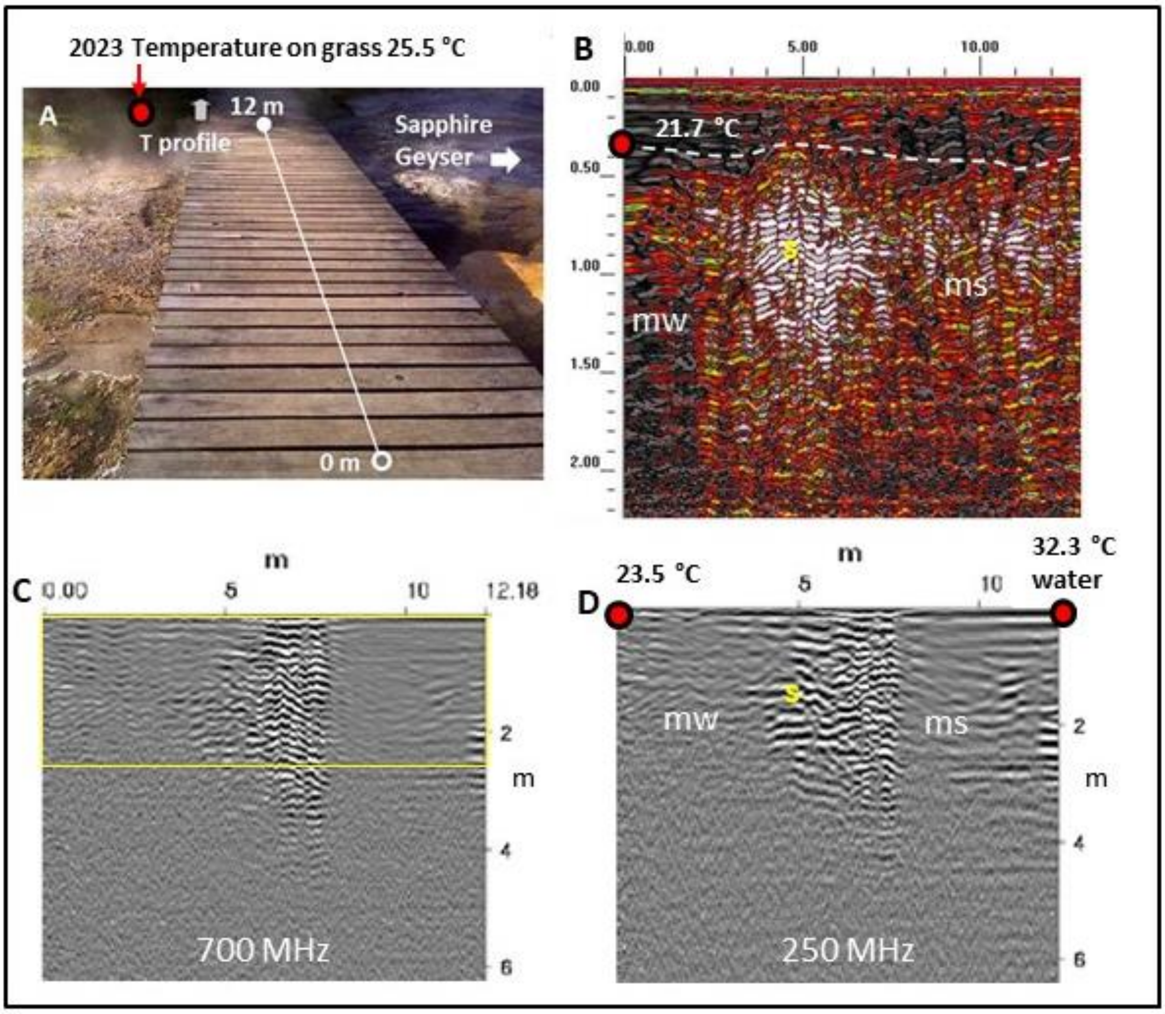

Figure 11: GPR site G2/SW8 (A) 2012 site photograph. (B) 2012 GPR image shows a cluster of strong reflections (s) surrounded by moderately-weak (mw) and moderately-strong (ms) reflections. 2023 surface temperature measured on grass beside GPR transect line. White dotted line is the top of the sinter surface, below the boardwalk. (C-D) 2023 GPR images shows strong (s), moderately-weak (mw) and moderately-strong (ms) reflections. Yellow box indicates area shown (B). (B and D) Surface temperatures at start and end of transect lines.

2012 G3 and 2023 SW9

A site photograph and the GPR profiles are presented in Figure 12.

The 2012 and 2023 GPR transect lines are not in the exact same location but are parallel to each other and separated by several meters.

Significant observations

- Main differences between the 2012 and 2023 data are:
  - The area of strong amplitude reflections in 2012 are not present in 2023. These strong reflections are immediately adjacent to the sinter terrace and are likely to be a continuation of the sinter terrace under the grassed area.
  - Although the temperature measurements are not in the exact same location as 2012 measurements, they are very close to the 2012 measurement sites. The 2023 temperature survey shows that the surface temperatures have increased but the subsurface temperatures have decreased. This suggests that while less heat is in the subsurface, more heat is escaping at the surface.
  - Several fracture pathways visible in the 2012 data, were not detected 2023. The 2023 transect line is located several meters north of the 2012 transect line indicating these fractures are isolated at specific locations and not continuous over this area.

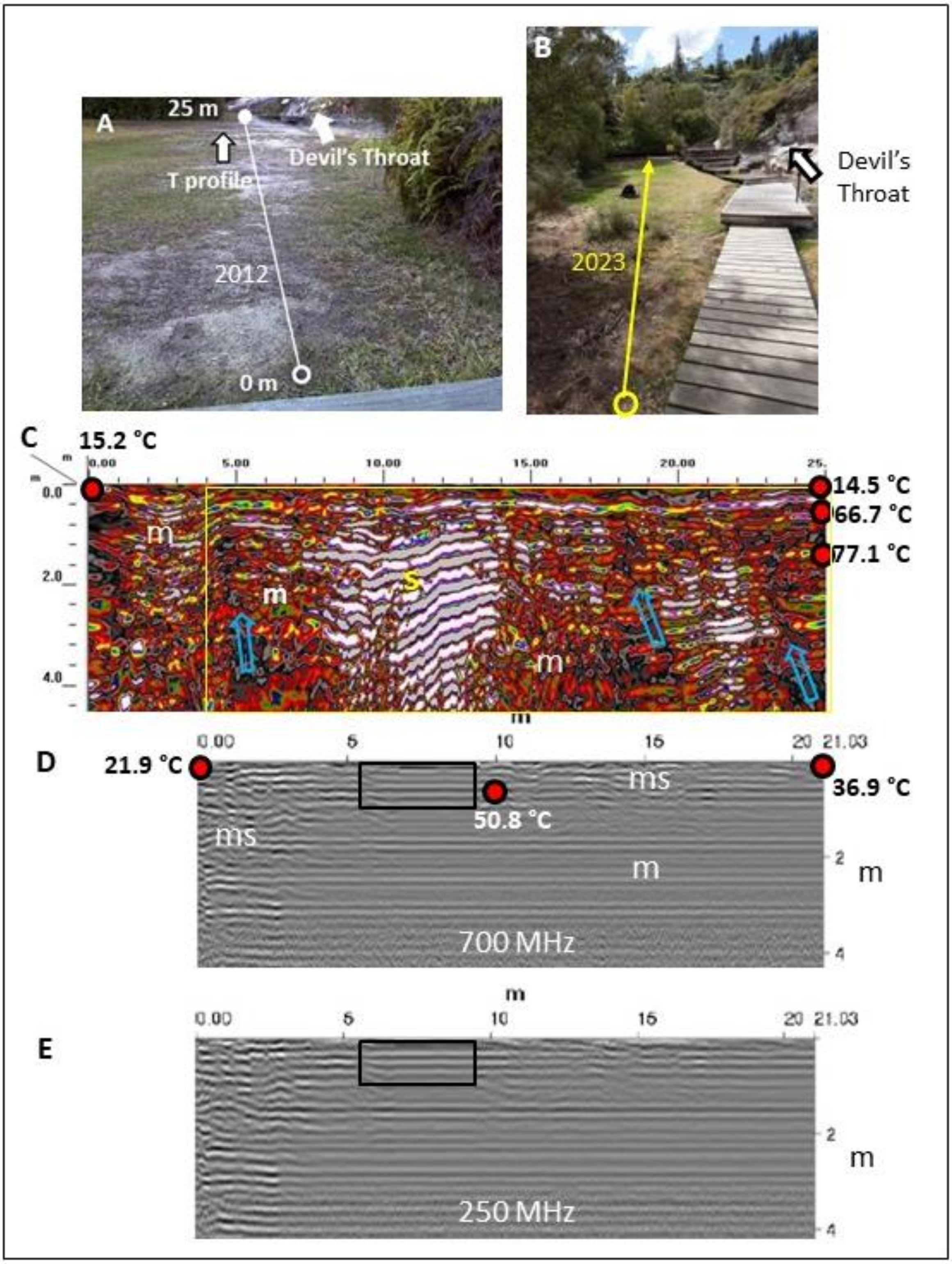

Figure 12: GPR site G3/SW9. (A) 2012 site photograph with 2012 and 2023 transect lines shown. (C) 2012 GPR image with a central cluster of strong amplitude reflections (s) surrounded by moderate reflections (m). Fractures (arrows) show weak reflections (w). Yellow box shows area imaged by GPR in 2023. (D-E) 2023 GPR images 2023 GPR data collection started at the 4 m mark of the 2012 GPR profile. Black box is where the GPR antennae was slightly off the ground due to tree branches covering the surface. (B-D) Temperature measurements shown.

2012 G4 and 2023 SW11

A site photograph and the GPR profiles are presented in Figure 13.

The 2023 GPR transect was located at the same location as the 2012 GPR transect line.

Significant changes

- In 2012 the entire GPR image shows weak reflections, while in 2023 there are several narrow vertical bands of strong reflections separated by weak reflections.

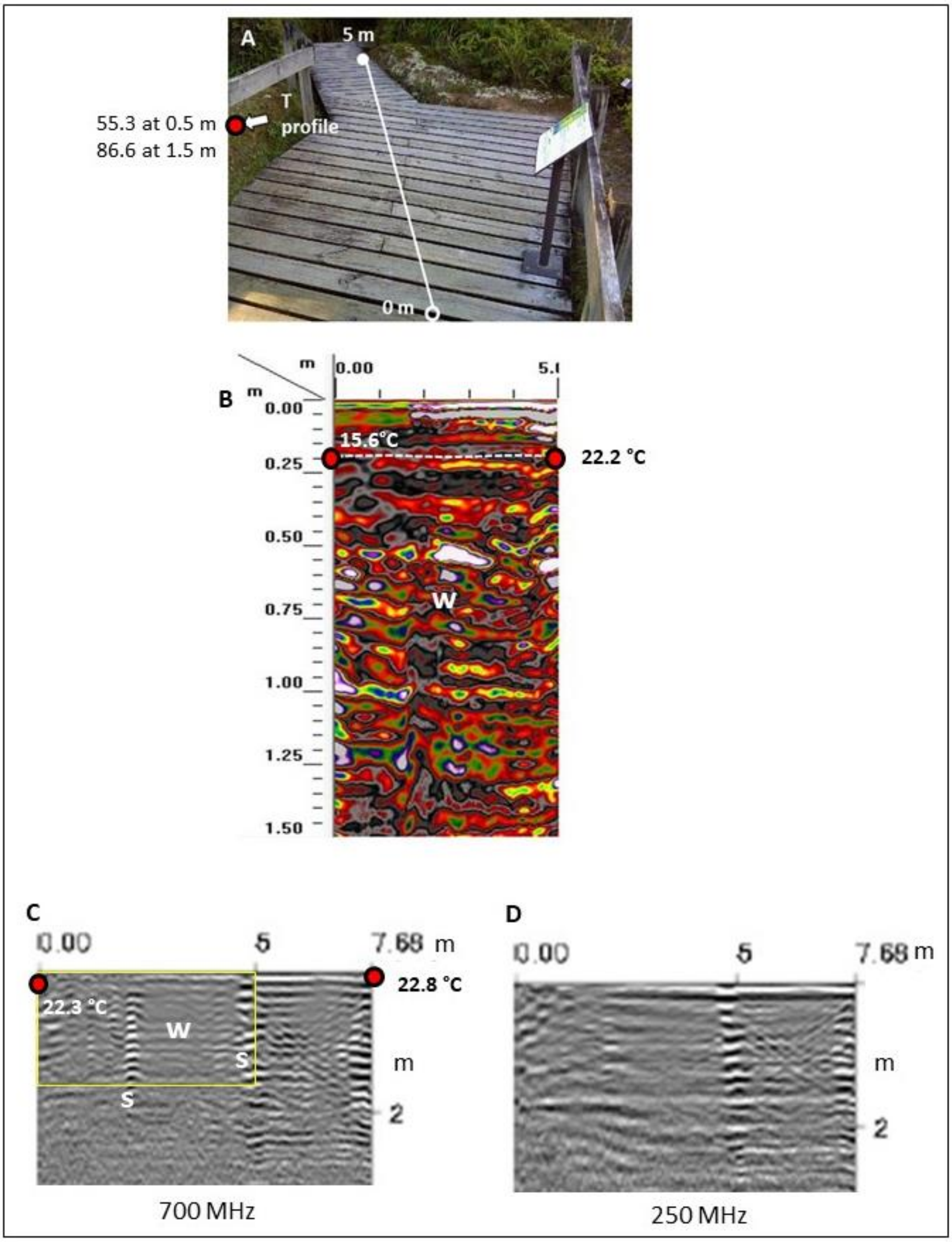

Figure 13: GPR site G4/SW11. (A) 2012 site photograph with 2012 downhole temperature profile site on side of boardwalk. (B) 2012 GPR image shows weak reflections (w). White dotted line is the ground surface underneath the boardwalk. (B-C) Surface temperature measurements shown. (C) Yellow box represents area of 2012 GPR profile. Several vertical bands of strong reflections (s) separated by weak reflections (w).

<u>2012 G5 and 2023 SW10</u>

A site photograph and the GPR profiles are presented in Figure 14.

The 2023 GPR transect was located at the same location as the 2012 GPR transect line.

Significant changes

- No significant change between the 2012 and 2023 GPR images.
- At 4 m along the transect line, a stream now flows underneath the boardwalk. The strong amplitude reflections directly underneath the stream, may be due to silica depositing from the thermal water.

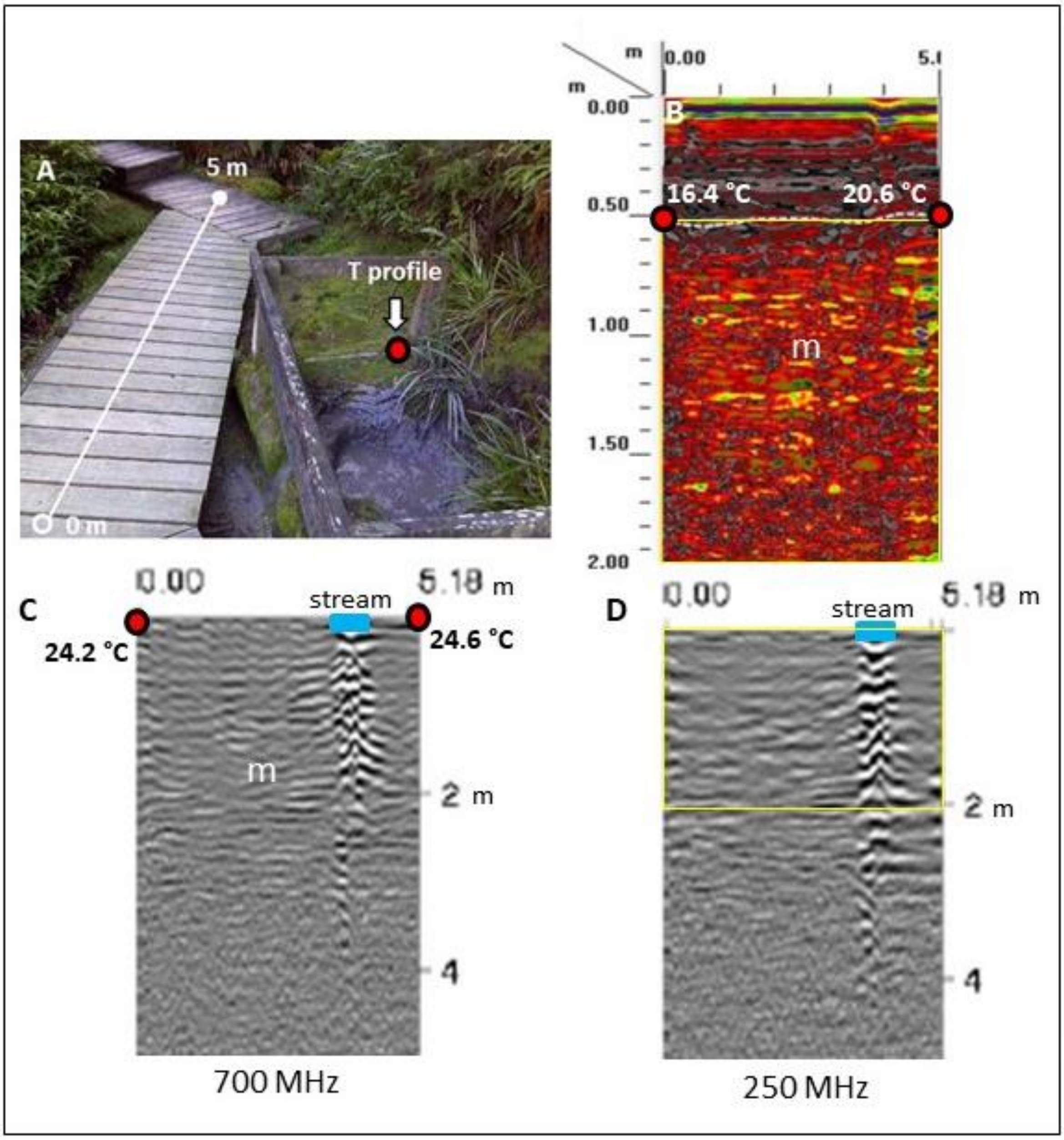

Figure 14: GPR site G5/SW10. (A) 2012 site photograph. (B) 2012 GPR image showing moderate reflections. White dotted line is the ground surface below the boardwalk. (C-D) 2023 GPR images show moderate reflections (m) but a vertical zone of strong reflections where a stream was flowing underneath the

boardwalk. Surface temperature measurement shown. Yellow boxes match the length and depth of the 2012 GPR image to the 2023 image.

2012 G6 and 2023 SW12

A site photograph and the GPR profiles are presented in Figure 15.

The 2023 GPR transect was located at the same location as the 2012 GPR transect line.

Significant changes

- A stream now flows underneath the boardwalk along the entire length of the boardwalk. The thermal stream may be the cause of the increased measured surface temperatures.
- The 2023 GPR scan penetrated to 4 m depth compared 1.5 m in 2012.
- In 2012 there was a zone of strong, moderate and weak reflections. In 2023 the area consists of moderate reflections.

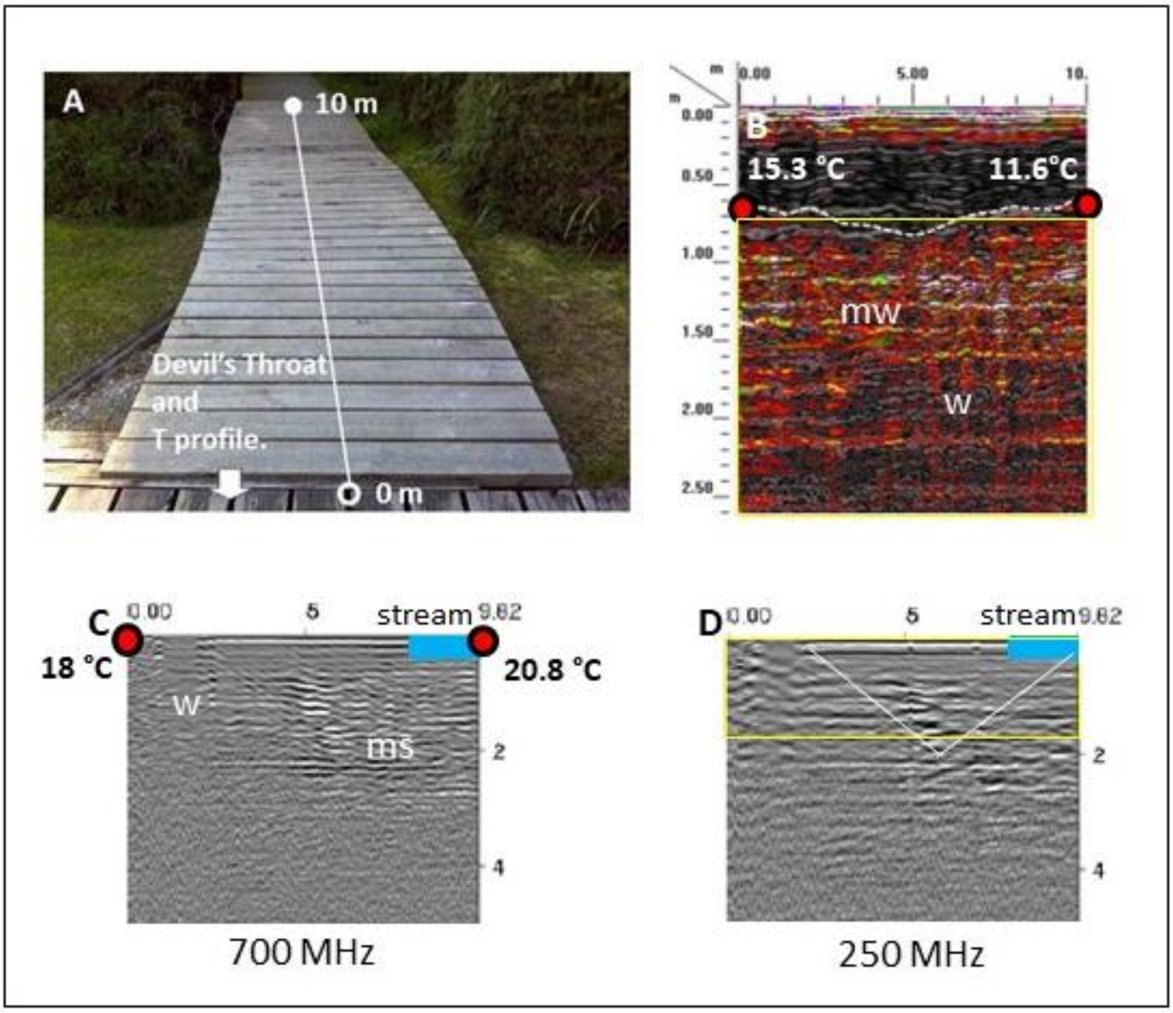

Figure 15: GPR site G6/SW12. (A) 2012 site photograph. (B) 2012 GPR image showing strong (s), moderate (m) and weak (w) reflections. White dotted line is the ground surface below the boardwalk. (B-C) Surface temperature measurement given. (C-D) 2023 GPR images show moderate reflections (m). A stream was flowing underneath the entire boardwalk. Yellow boxes match the length and depth of the 2012 GPR image to the 2023 image.

2012 G7 and 2023 SW13

A site photograph and the GPR profiles are presented in Figure 16.

The 2023 GPR transect was located at the same location as the 2012 GPR transect line.

Significant changes

- No significant change observed between the 2012 and 2023 GPR images.
- A possible paleo-channel has been detected in 2023 that is not visible in the 2012 image. This may be the result of different GPR units used for the two surveys.
- The temperature increase in 2023, at the 10 m mark, may be due to thermal water flowing underneath the boardwalk, which was not present in 2012.

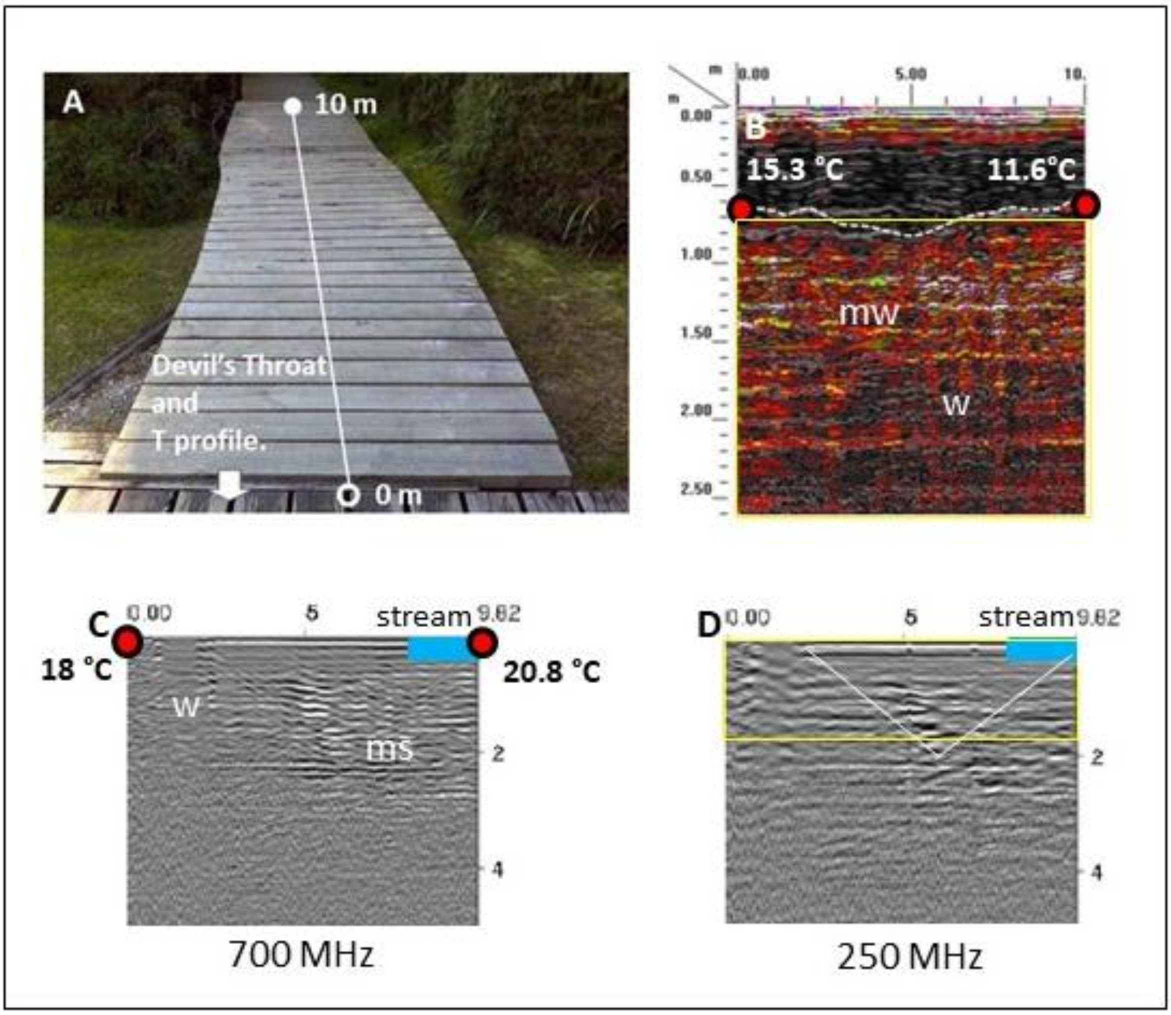

Figure 16: GPR site G7/SW13. (A) 2012 site photograph. (B) 2012 GPR image showing moderately-weak (mw) and weak (w) reflections. White dotted line is the ground surface below the boardwalk. (B-C) Surface temperature measurement given. (C-D) 2023 GPR images show zones of moderately-strong (ms) and weak (w) reflections. A stream was flowing underneath the boardwalk from 8.5 to 10 m. Yellow boxes match the length and depth of the 2012 GPR image to the 2023 image.

2012 G8 and 2023 SW14

A site photograph and the GPR profiles are presented in Figures 17 to 19.

The 2023 GPR profile (SW14) is located ~5 m East of the 2012 GPR profile (G8). The 2012 GPR site could not be repeated as that area is now covered in microbial mats. SW14 is located on the boardwalk. The 2023 GPR transect line runs parallel to the 2012 GPR transect.

Figure 17: Location of the 2012 and 2023 GPR profiles for sample site G8 (2012) and SW14 (2023).

While no direct comparison can be made between the 2012 and 2023 GPR data, we can infer the following:

Significant observations

- In 2012, the GPR image shows three vertical bands of weak reflections separated by moderate reflections, to a depth of 3 m. One of the vertical bands correlated to measured temperatures of 92.1 °C at 1.5 m depth, confirming heat in the subsurface. These vertical conduits represent pathways (possibly fractures) where steam is ascending and hydrothermal alteration of the sinter is actively taking place, resulting in weak reflections.
- In 2023 along a parallel transect to the 2012 transect, two of the vertical bands of weak reflections present in 2012, are no longer visible. The third vertical band of weak reflections present in 2012 at the 4-5 m mark, does show a change from strong to moderately-strong reflections in 2023, suggesting a vertical conduit at this location may still exist.
- Although the 2012 and 2023 GPR transects are 5 m apart, there may be a fracture between the 4 m marks on both GPR transect lines, as at the 4 m mark on both profiles there is evidence of a vertical conduit. However, the 2012 GPR profile shows significantly higher temperatures than the 2023 GPR profile.
- No strong reflections were observed in 2012, but are visible in 2023, from 3-5 m, down to 2 m depth, indicating unaltered sinter with a thickness of 2 m.
- In 2012 surface temperature measurements (~15 °C) were lower than those recorded in 2023 (~29 °C).
- A possible fracture occurs at ~5.8 m along the 2023 GPR transect. This area was not imaged in 2012.

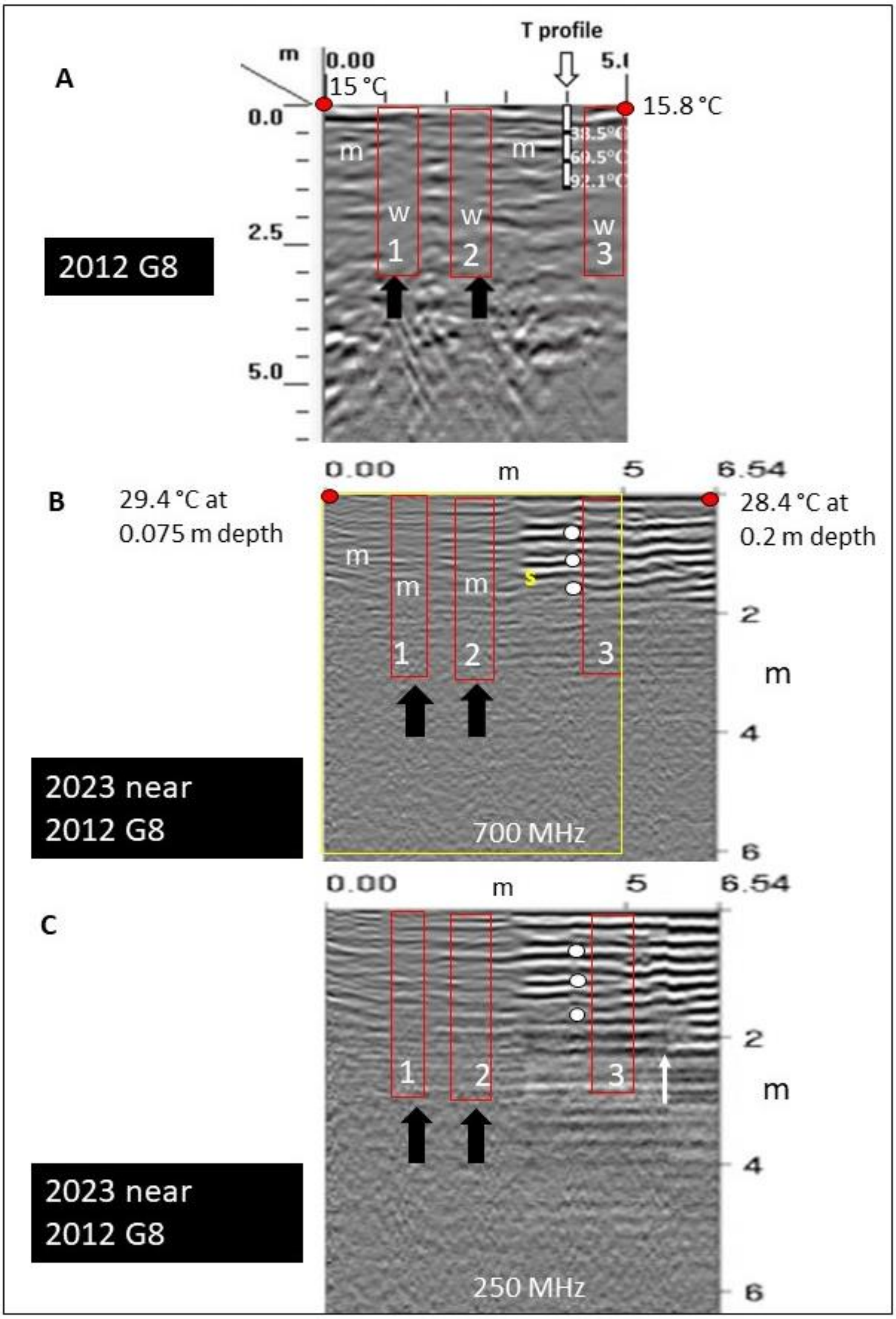

Figure 18: GPR profiles for G8 taken in 2012 and 2023. (A) 2012 GPR image. Red boxes show change in strength of reflections from moderate (m) to weak (w) at 1 to 1.5 m, 2 to 2.5 m and 4 to 5 m, along the transect. Surface and downhole temperatures shown. (B-C) 2023 GPR images. Red boxes 1-3 correlate to the red boxes in (A), where moderate (m) reflections visible inside the boxes 1 and 2. The 2012 moderate reflections inside box 3 have been replaced by moderately-strong reflections in 2023. White circles on the 2023 images indicate corresponding depths and locations of the 2012 downhole temperature measurements (although 5 m to the East of the 2012 image). Possible fracture (arrow) at ~5.8 m along the transect. Measured temperatures at both ends of the transect are shown. Yellow box represents area scanned in 2012.

Figure 19 shows the relationship between the 2012 and 2023 GPR profiles.

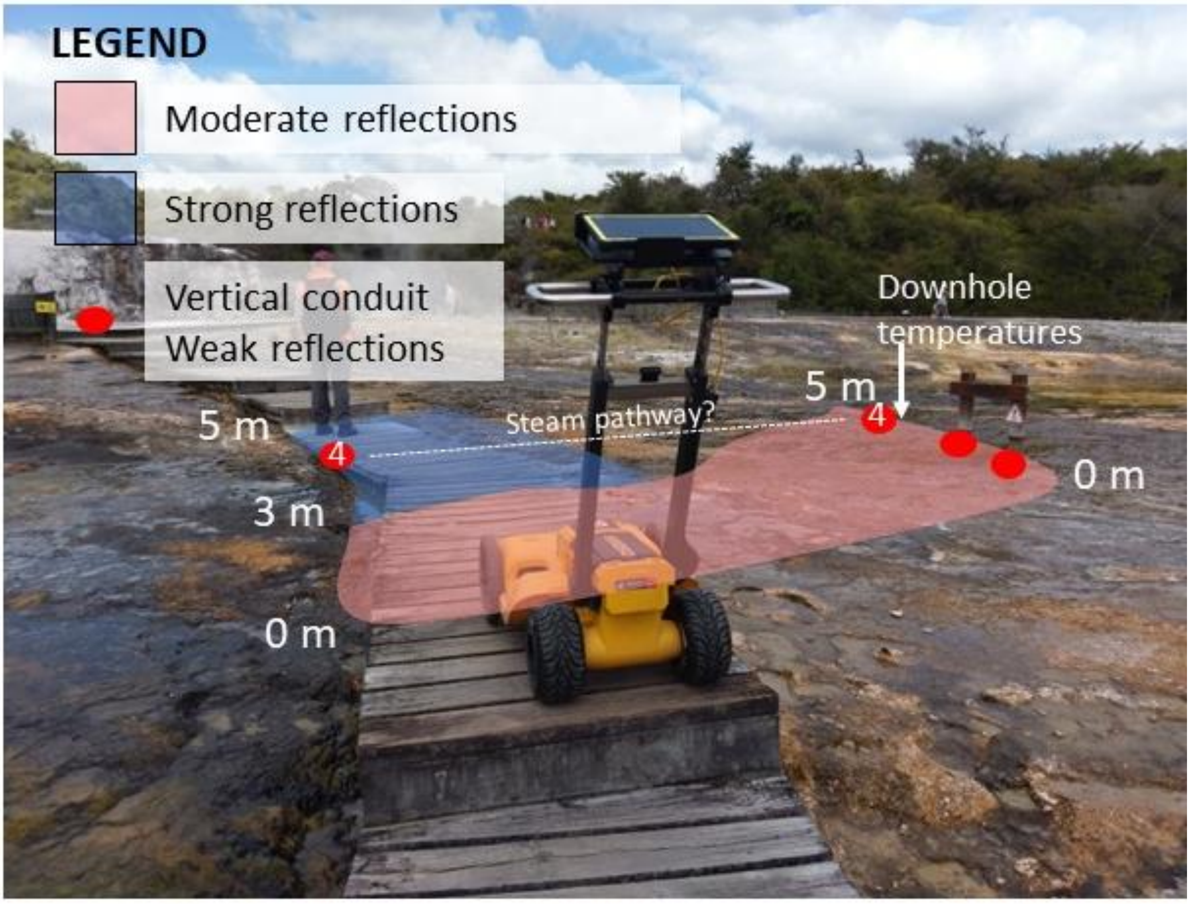

Figure 19: Overview showing how the vertical conduits, weak, moderate, strong reflections can be interpolated between the 2012 and 2023 GPR data.

SW15 (2012 G9)

A site photograph and the GPR profiles are presented in Figures 20 and 21.

The 2012 GPR profile could not be repeated as the boardwalk has been moved several meters to the north, due to the appearance of three vents, in 2019. The 2023 GPR profile runs parallel to the 2012 GPR profile, along the new boardwalk.

Figure 20: Sites G9 (2012) and SW15 (2023). (A) Overview of the 2012 site G9. (B) The new vents in 2019 and the new boardwalk. (C) Relationship between 2012 and 2023 GPR profiles shown.

Significant observations:

- Distinctive vertical conduits of weak amplitude reflections are visible in the 2023 GPR image, below the new vents, but several meters to the north of the vents.
- Strong reflections are visible in the 2023 images that line up with the sides of the vents, but several meters to the north of the vents.

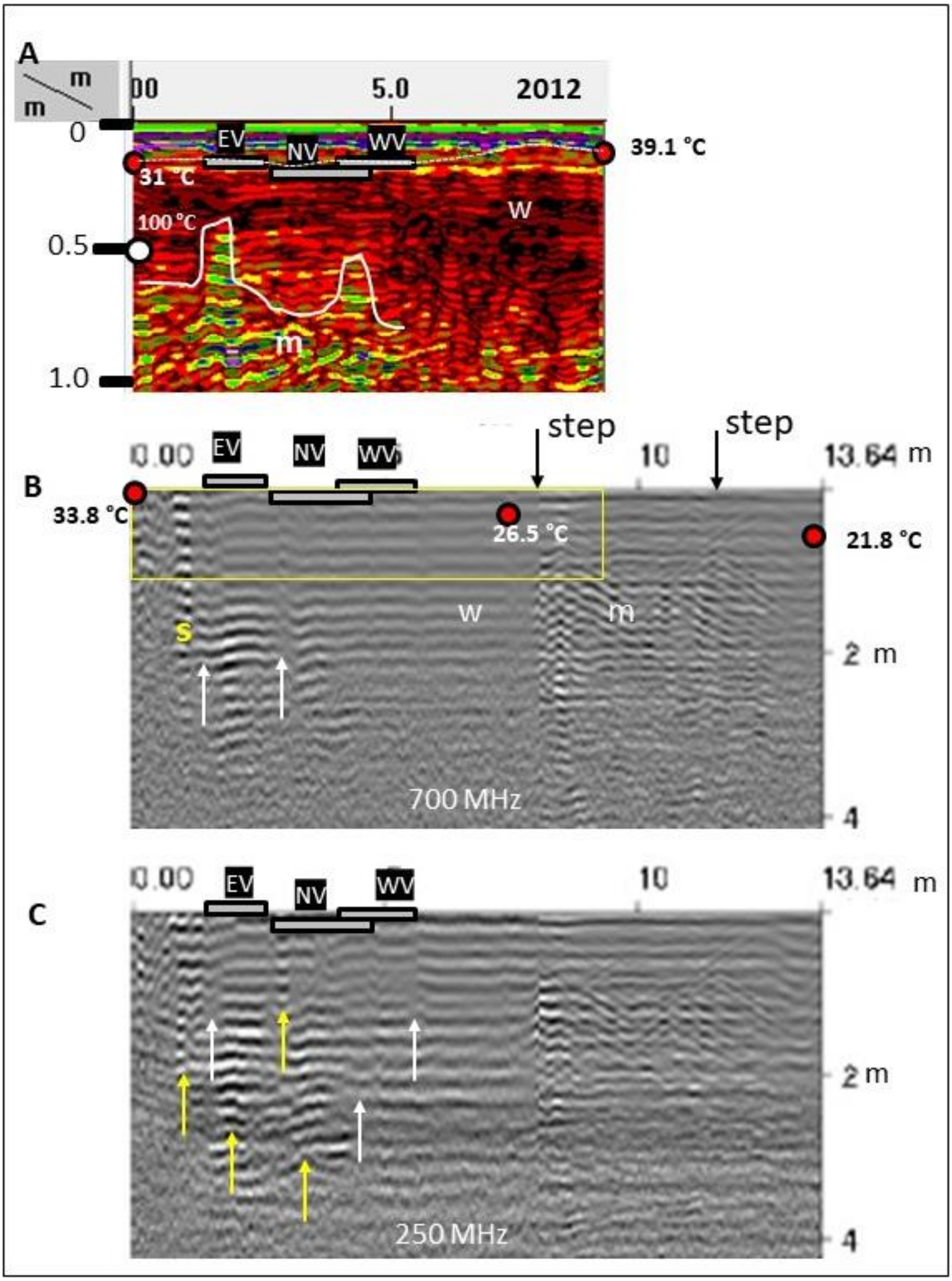

Figure 21: GPR profiles of the 2012, G9 site, and the 2023, SW15 site. Location of the East vent (EV), North vent (MV) and West vent (WV) are shown. (A) 2012 GPR image with areas of moderate (m) and weak (w) reflections. Sinter surface below boardwalk shown as white dotted line. Measured temperatures at both ends of the transects are shown. (B-C) 2023 GPR images show vertical bands of strong reflections parallel (yellow arrows) to the sides and beneath the East and North vents. White arrows indicate vertical zones of weak reflections that line up with the three vents, although several meters to the North. Yellow box in (B) indicates area scanned in 2012.

2023 SW16 and SW17

A site photograph and the GPR profiles are presented in Figures 22 to 24.

These are new 2023 GPR sites but in 2009 a 2 m long GPR transect was collected here.

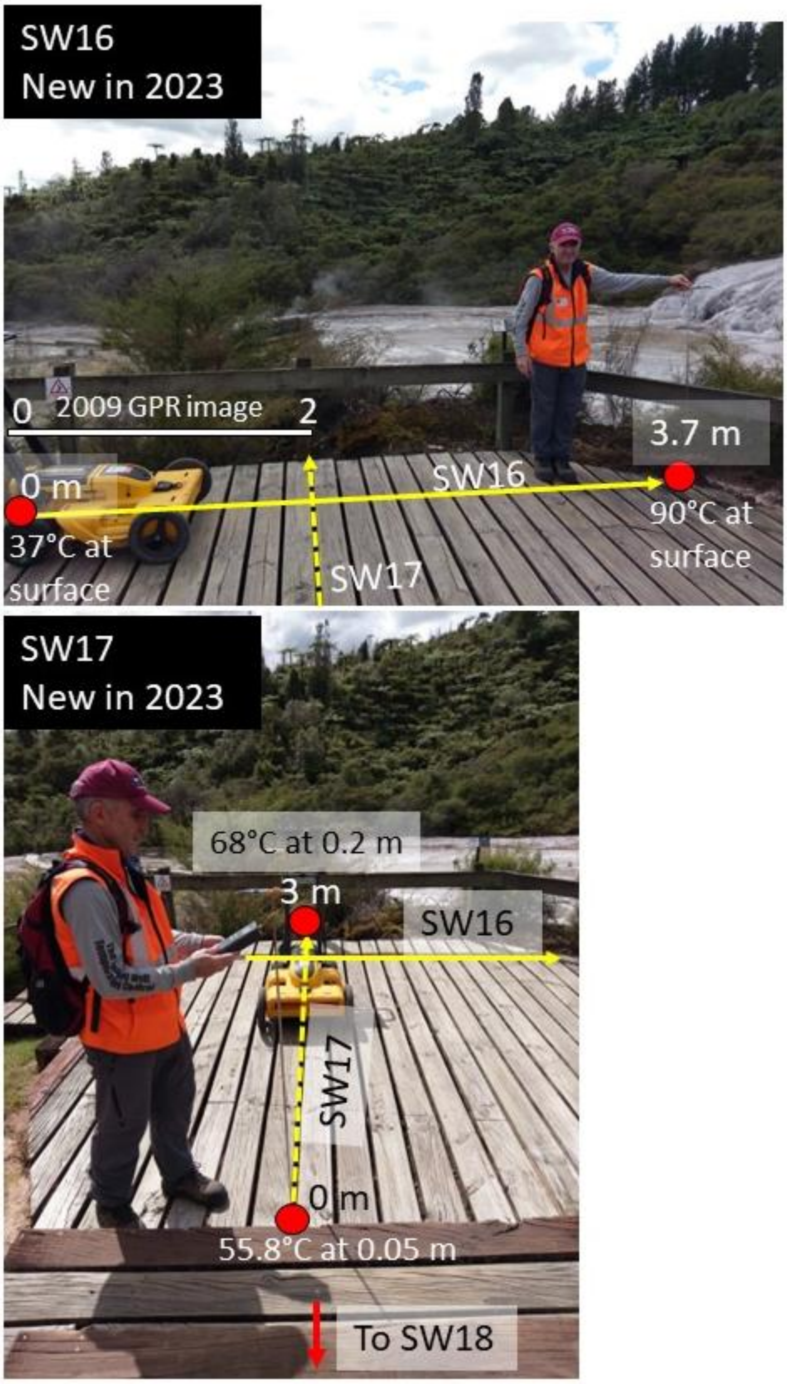

Figure 22: Photographs of GPR sites SW16 and SW17 and the 2009 GPR profile. Surface temperature measurements shown.

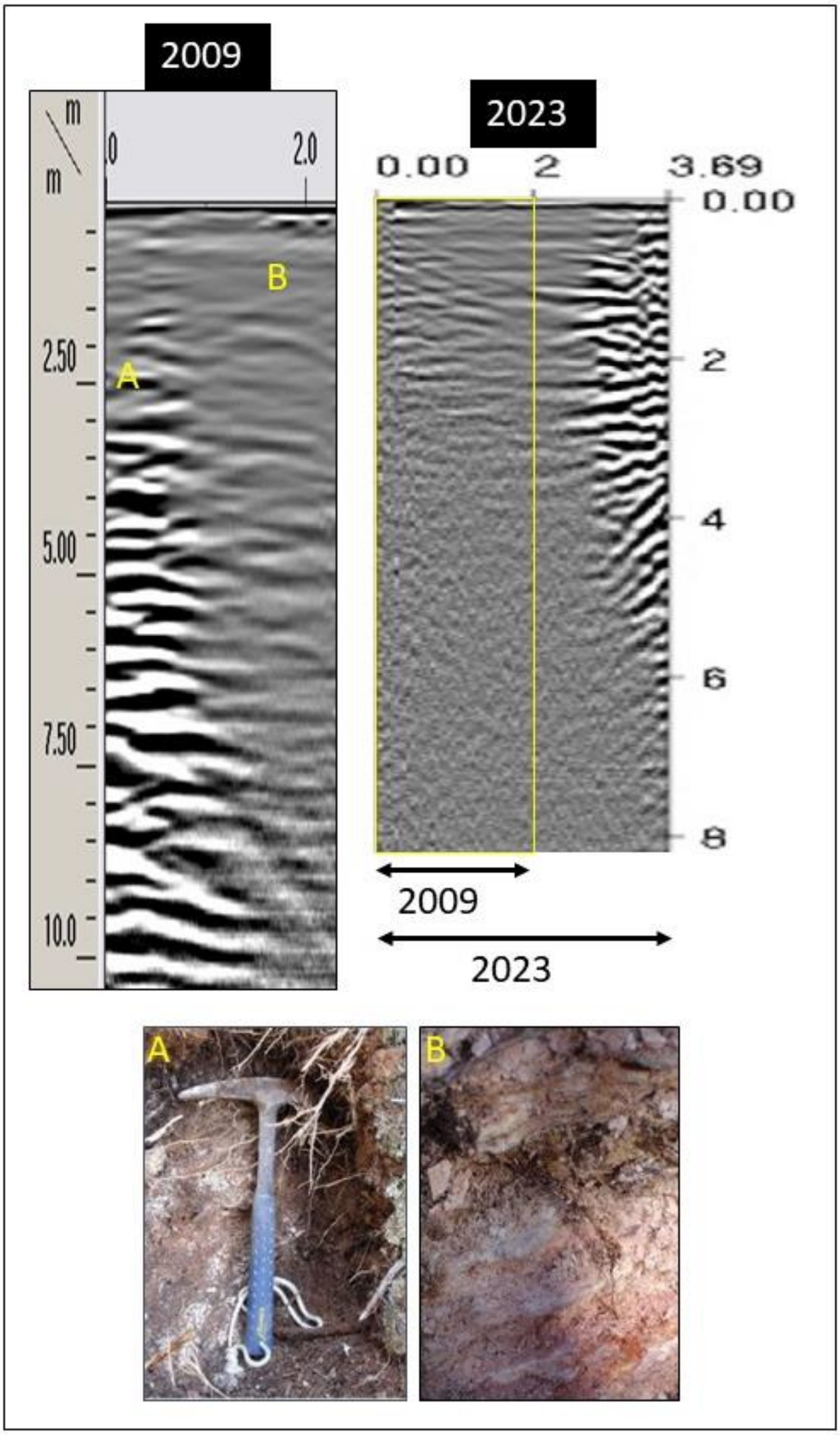

Figure 23: GPR profiles collected in 2009 and 2023 on the edge of the viewing platform overlooking Wairiri Geyser. Photographs of sinter sampled in 2009 from sites A and B shown on 2009 GPR profile. Yellow box indicates the area of the 2009 GPR image.

2009 GPR observations (Fig. 23)

In 2009, a GPR profile was collected at the same sites as SW16 (Fig. 22). The 2009 GPR profile was ground-truthed, as a sinter outcrop was accessible directly below this GPR transect line.

- In 2009 and at 2.5 m deep and below the 0 m mark on the GPR profile, a sinter sample was collected and analysed confirming an unaltered sinter represents the strong amplitude reflections (Fig. 23).
- In 2009, at 1 m deep and below the 1.8 m mark on the GPR profile, a sinter sample was collected and analysed confirming a highly-altered sinter represents the weak amplitude reflections (Fig. 23).

Comparison of 2009 and 2023 GPR images (Fig. 23)

- The area of strong amplitude reflections shown in 2009 were not detected in 2023. This area now reveals weak amplitude reflections suggesting significant hydrothermal alteration of the sinter has occurred in the last 14 years. Elevated surface temperatures confirm hydrothermal alteration is presently altering the sinter (Fig. 24).

SW16 GPR observations (Fig. 24)

- At the start of the transect, the surface temperature was 37 °C which correlates to moderately-weak reflections. At the 2 m mark, the temperature increased to 68 °C and this area shows weak reflections. The decrease in the GPR signal strength correlates to an increase in temperature. Increase in subsurface temperature would be responsible for hydrothermally altering the sinter, resulting in weaker amplitude reflections than those detected in 2009.
- At the 3.7 m mark, the surface temperature measured 90 °C, directly over a small vent. Temperatures surrounding the vent were between 70-80°C. The 90 °C vent is above the strong amplitude reflections suggesting either: (1) This area is newly-heated and the underlying sinter has not had enough time to become sufficiently altered, which would produce weak reflections; or (2) The unaltered sinter (strong reflections) are creating a barrier and the steam is ascending alongside the strong amplitude reflection area.
- Strong reflections are detected to 6 m depth suggesting the sinter here is 6 m thick. Sinter exposed in the outcrop beneath this GPR transect line is 2.5 m thick.

SW17 GPR observations (Fig. 24)

- Vertical bands of weak amplitude reflections and the elevated temperatures measured at the surface, suggests these weak reflection bands are vertical conduits of ascending steam.

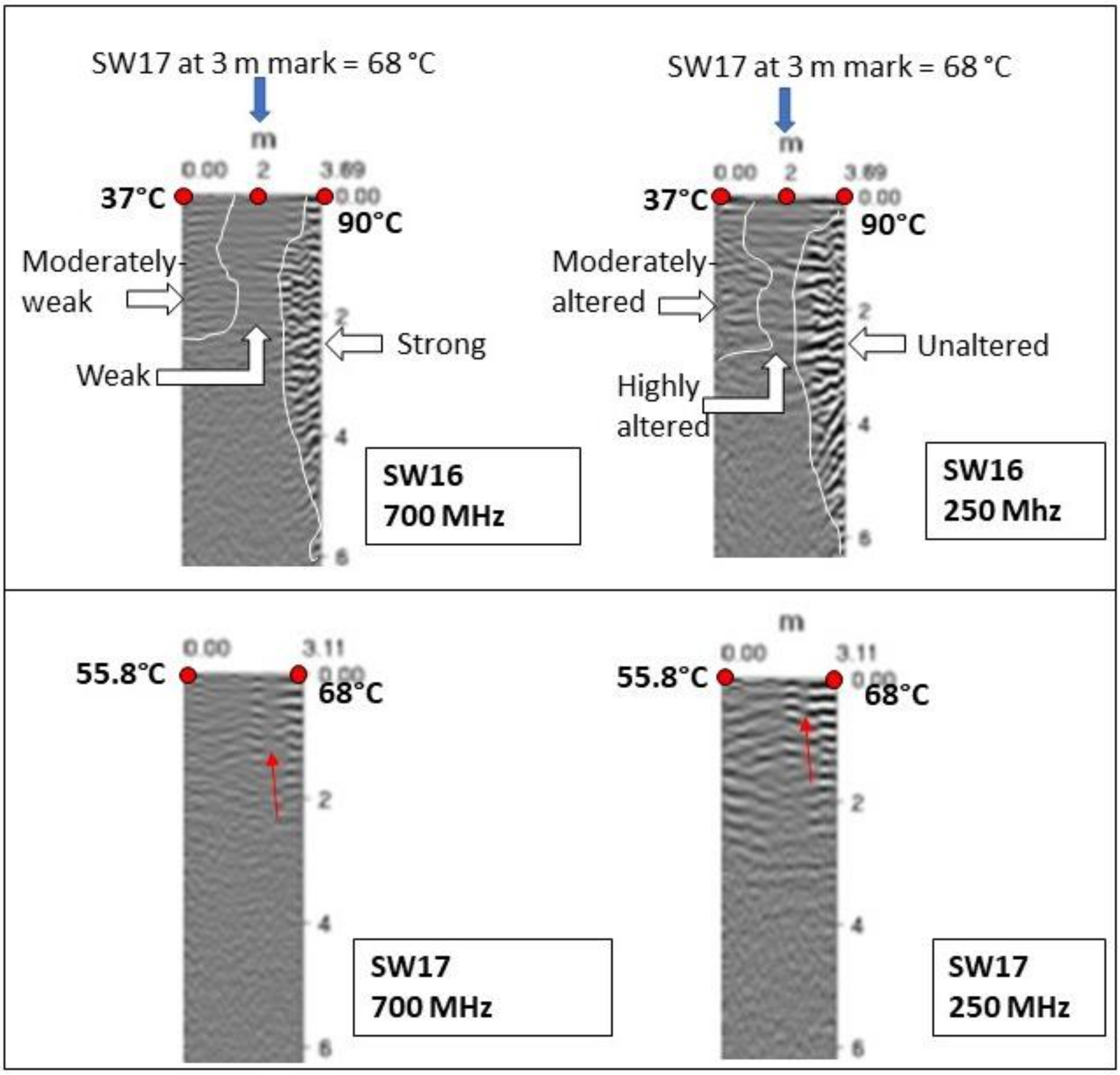

Figure 24: GPR profiles for SW16 and SW17. Temperature measurements given. For SW16, areas of moderately-weak reflections occur between 0 and 1.5 m. From 1.5 to 3 m the reflections are weak. A band of strong reflections to 6 m depth occurs between 2.8 and 3.6 m. For the SW17 profile vertical conduits of weak reflections (red arrows) are separated by moderate and strong reflections.

2023 SW 18

A site photograph and the GPR profiles are presented in Figure 25.

This is a new 2023 GPR site.

Significant observations

- This GPR image is dominated by weak and moderately-weak reflections. Measured surface temperatures of 44 to 64 °C indicate present-day heat in the shallow subsurface which favours active hydrothermal alteration. Clays can be seen around the boardwalk.
- A possible fracture or steam conduit can be seen at the 2 m mark, where reflection offsets are visible.
- A paleo-surface sloping at approximately 45 ° may be present.

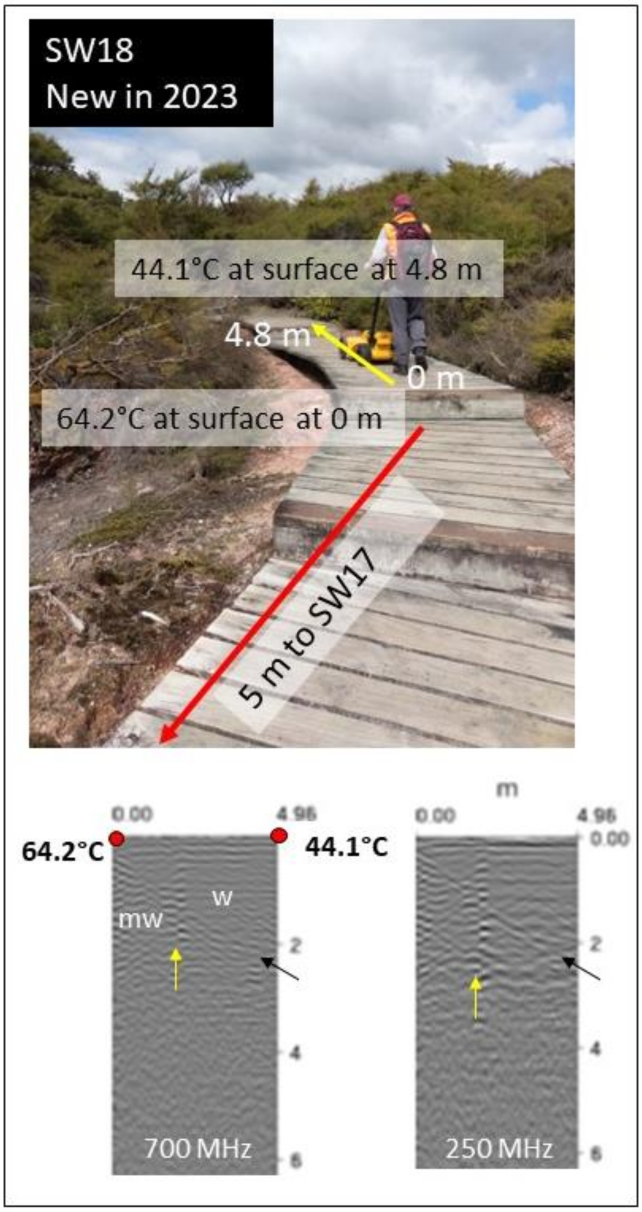

Figure 25: GPR site photograph and profile for new 2023 site, SW18. Weak (w) and moderately-weak (mw) reflections, paleo-surface (black arrows) and a fracture (yellow arrows) are visible. Surface temperatures are shown.

2012 G14 and 2023 SW19

A site photograph and the GPR profiles are presented in Figure 26.

The 2023 GPR transect was located at the same location as the 2012 GPR transect line.

Significant changes

- The surface temperatures and the downhole measured temperatures have increased since 2012.
- The zone of strong amplitude reflections in the 2012 image, between 13 and 18 m, have been replaced with moderate reflections in 2023. The elevated surface temperatures of up to 37 °C which are higher than the 2012 surface temperatures of 20 °C, may indicated hydrothermal alteration of the subsurface, resulting in a weakening of the GPR reflections.
- Strong amplitude reflections between 5 and 13 m in 2012, remain similar in 2023.
- An area of moderate reflections from 0 to 3 m in 2012, have been replaced in 2023 by weak reflections between 0 and 2 m.

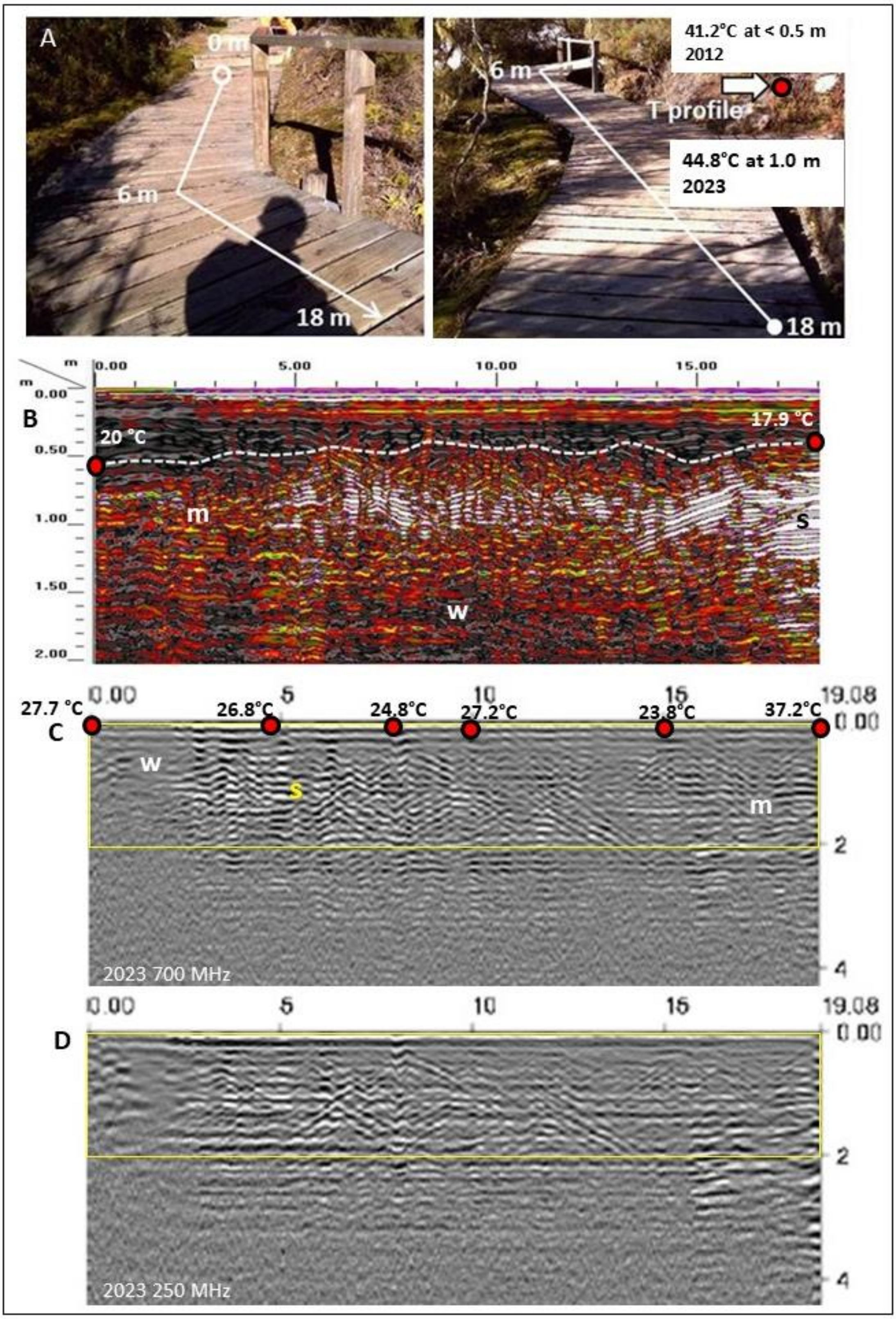

Figure 26: GPR site G14/SW19. (A) 2012 site photograph with temperature measurements shown. (B) 2012 GPR image. A 0.4 m thick band of undulating, strong reflections from 5 to 18 m along the transect line at ~0.5 m depth, that increase in thickness from 15 to 18 m. Moderate (m) and weak (w) reflections are observed in the rest of the profile. White dotted line is the ground surface below the boardwalk. (C-D) 2023 GPR images. Strong (s), moderate (m) and weak (w) reflections observed. Yellow boxes match the length and depth of the 2012 GPR image to the 2023 image. Temperature measurement given.

2012 G15 and 2023 SW20

A site photograph and the GPR profiles are presented in Figure 27.

No direct comparison can be made as a new boardwalk has been constructed and moved a few meters to the south-west of the 2012 boardwalk.

Significant observations

- Several vertical zones of weak reflections can be seen in the 2023 images suggesting zones of heat. This is supported by the 65.5 °C temperature measured on the edge of one of the weak reflection areas.

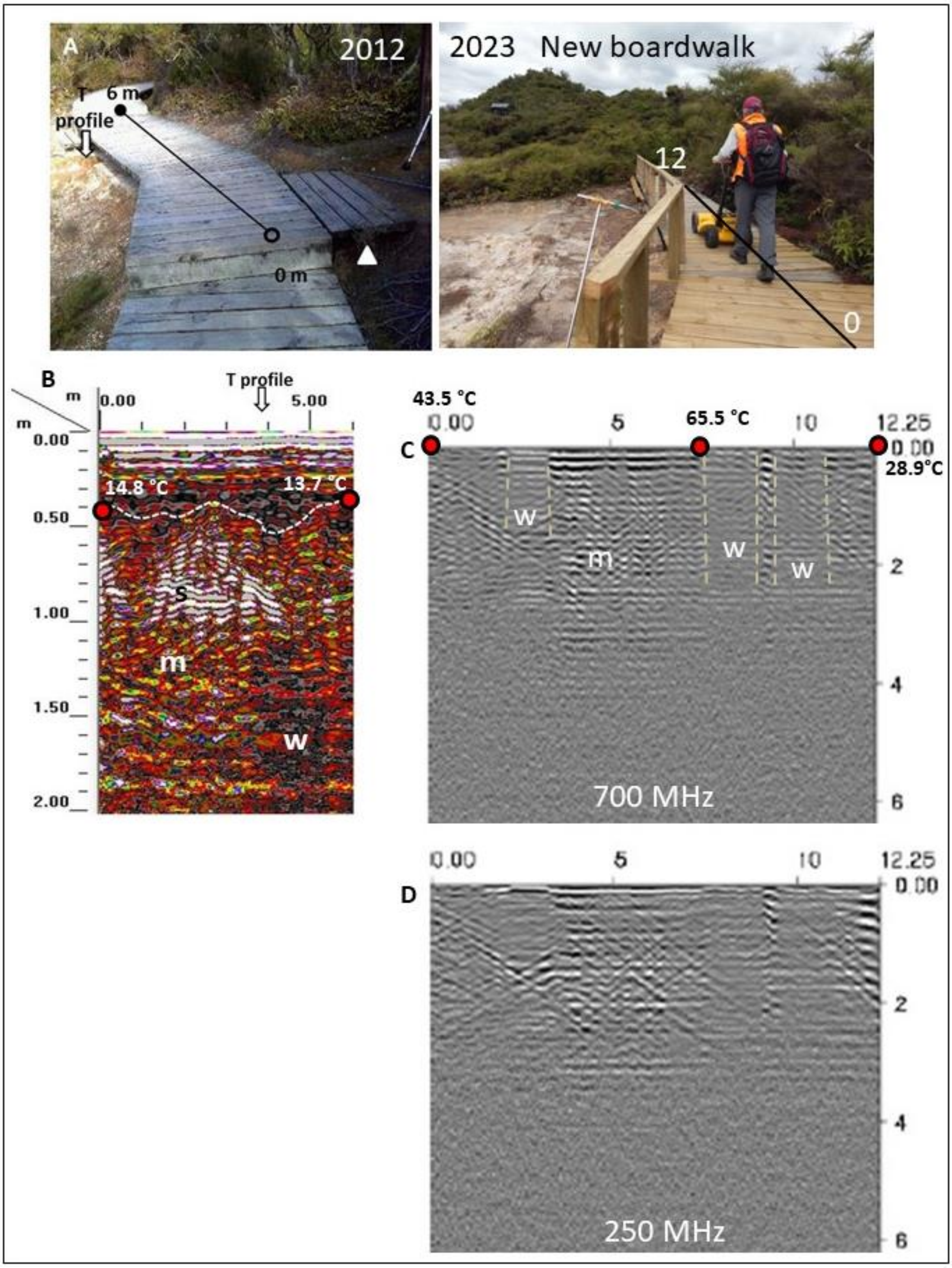

Figure 27: GPR site G15/SW20. (A) 2012 and 2023 site photographs. (B) 2012 GPR image with strong (s), moderate (m) and weak (w) reflections. White dotted line is the ground surface below the boardwalk. (B-C) Surface temperature measurement shown. (C-D) 2023 GPR images. Moderate (m) and three vertical conduits of weak reflections (w) are shown.

SW21

A site photograph and the GPR profiles are presented in Figure 28.

This is a new GPR site imaged in 2023.

Significant observations

- Changes in GPR signal strength in the shallow subsurface may be highlighting areas where some hydrothermal alteration is taking place.

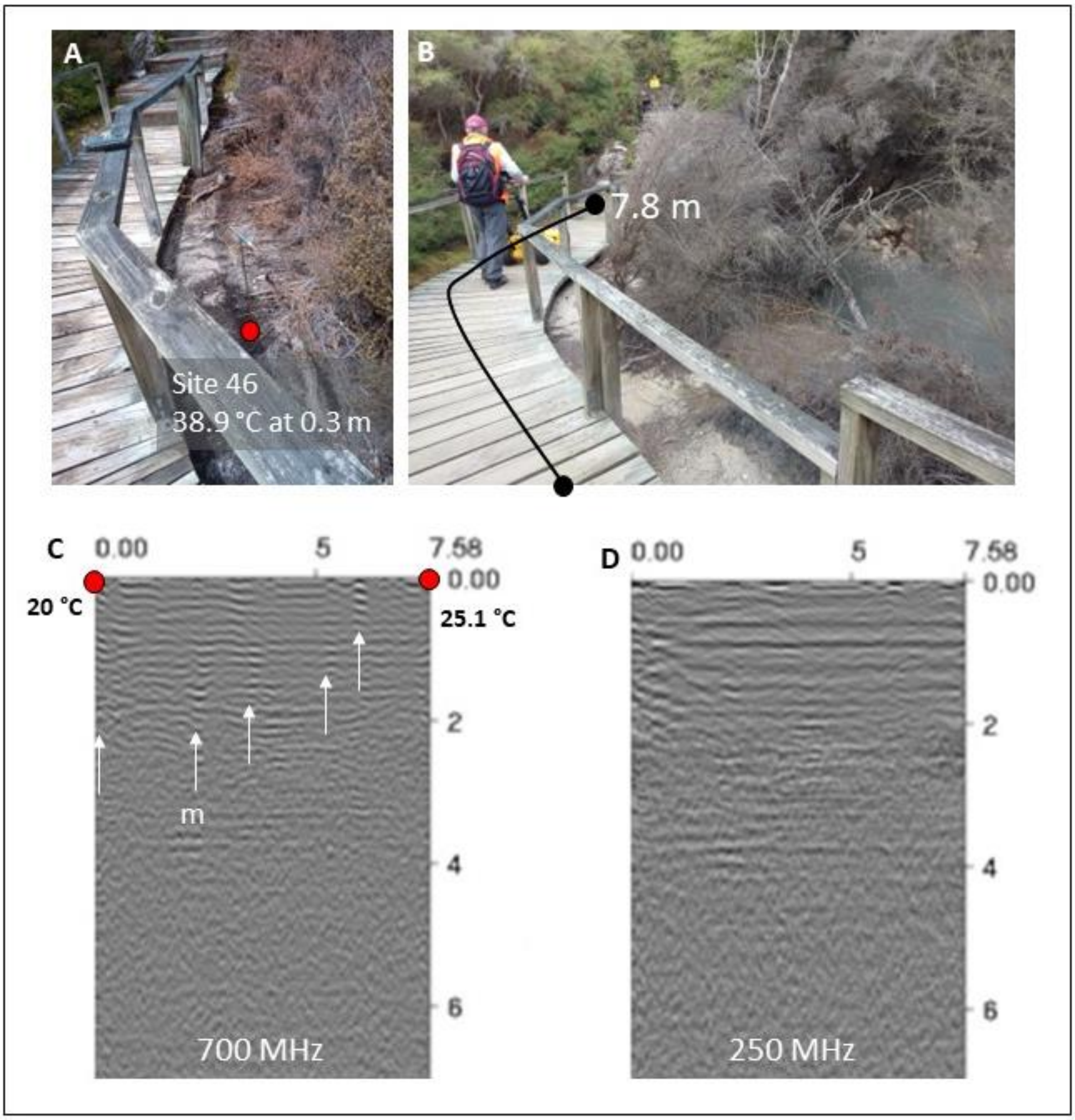

Figure 28: New GPR site SW21. (A-B) 2023 site photographs. (C-D) GPR images. The 700 MHz image with the higher resolution at shallow depths shows multiple vertical bands of moderate reflections (m and arrows), separated by weaker reflections. Temperature measurements shown.

2012 G18 and 2023 SW24

A site photograph and the GPR profiles are presented in Figure 29.

The 2023 GPR transect was located at the same location as the 2012 GPR transect line.

Significant changes

- No significant changes between 2012 and 2023.

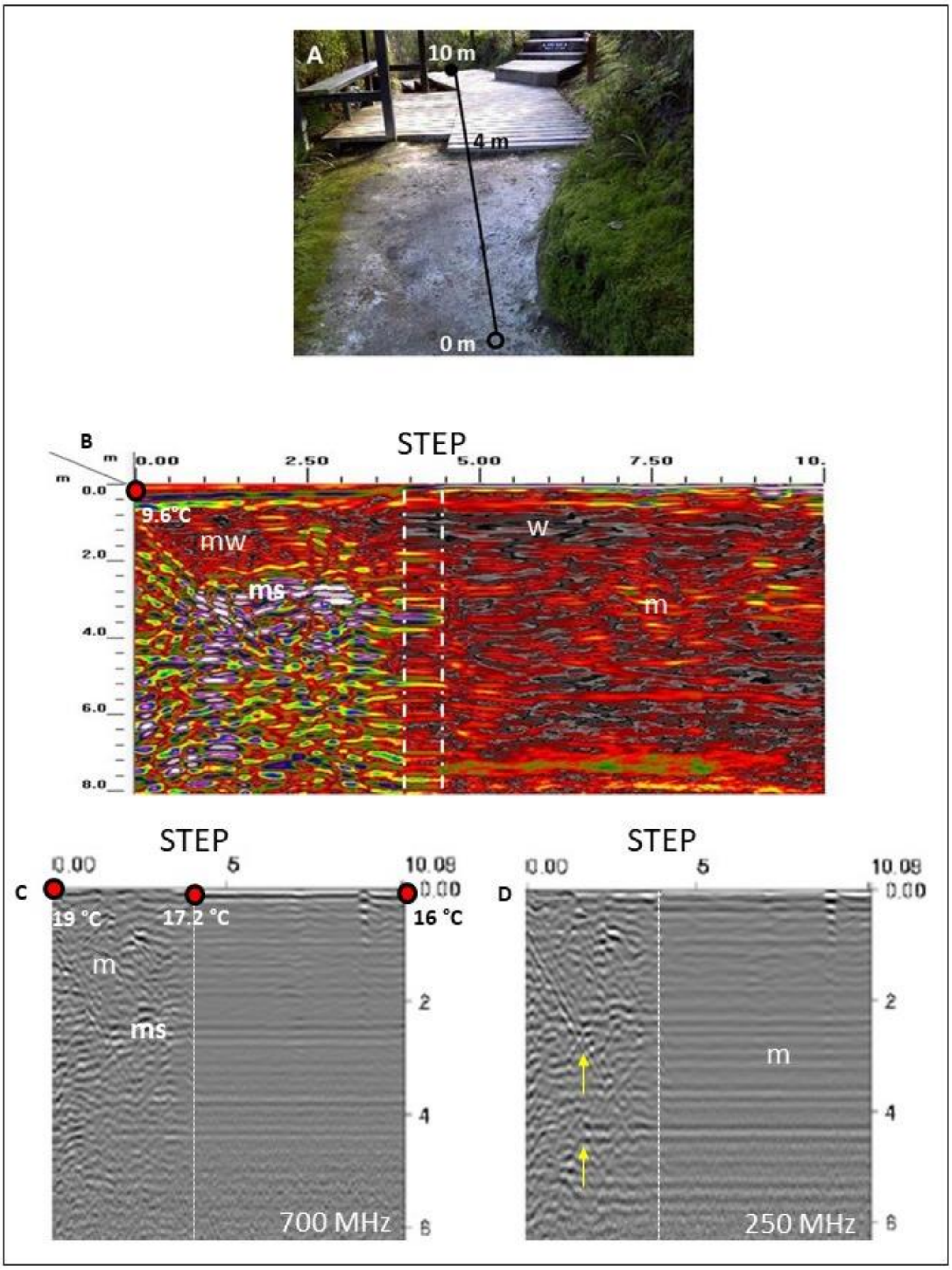

Figure 29: GPR site G18/SW24. (A) 2012 site photograph. (B-D) GPR image showing moderately-strong (ms) and moderate (m) reflections. (B) 2012 GPR image. (C-D) 2023 GPR images. Multiple hyperbolas (arrows).

2012 G19 and 2023 SW22

A site photograph and the GPR profiles are presented in Figure 30.

The 2023 GPR transect was located at the same location as the 2012 GPR transect line.

Significant changes

- The 2012 GPR images shows a thin band of near-surface strong reflections, which have imaged as moderate reflections in 2023. Subsurface temperatures have also increased from 73 to 99 °C. The increased temperatures and the weakening of the GPR signal suggests active hydrothermal alteration in the shallow subsurface.

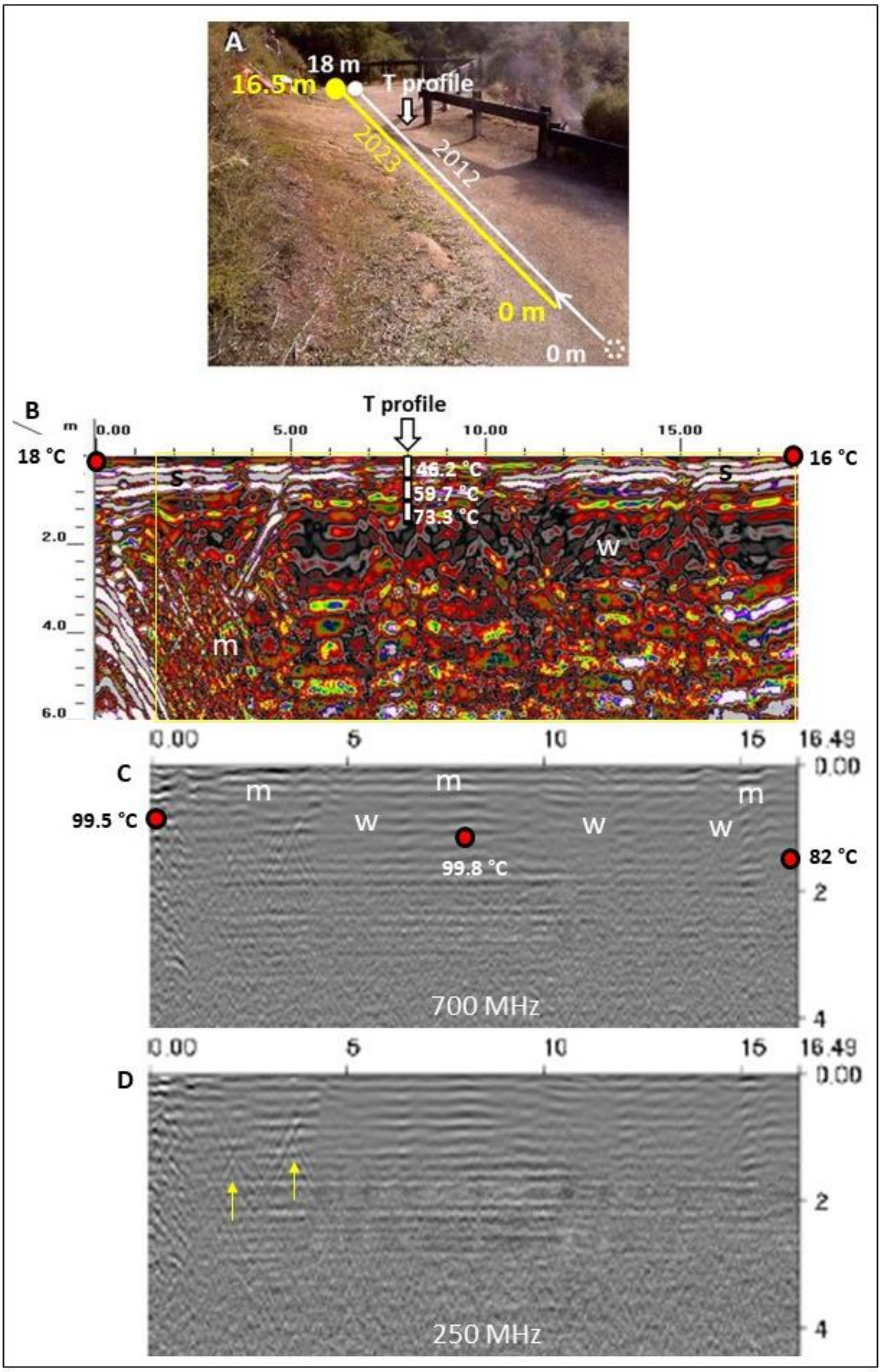

Figure 30: GPR site G19/SW22. (A) 2012 site photograph. (B) 2012 GPR image showing strong (s), moderate (m) and weak (w) reflections. Downhole temperature measurements shown. Yellow box matches the area re-surveyed in 2023. (C-D) 2023 GPR images show zones of moderate (m) and weak (w) reflections, and hyperbolas (arrows). Downhole temperature measurements given.

<u>2012 G26 and 2023 SW5 profile</u>

A site photograph and the GPR profiles are presented in Figure 31.

Significant changes

- An undulating zone of weak amplitude reflections present in 2012 from 1 to 4 m depth between the 4 and 16 m marks has been partly replaced by moderate reflections.
- A zone of strong reflections in 2012 at the 23 to 25 m marks has been replaced in 2023 by weak reflections.
- Multiple hyperbolas were imaged in both 2012 and 2023. These are likely underground services.

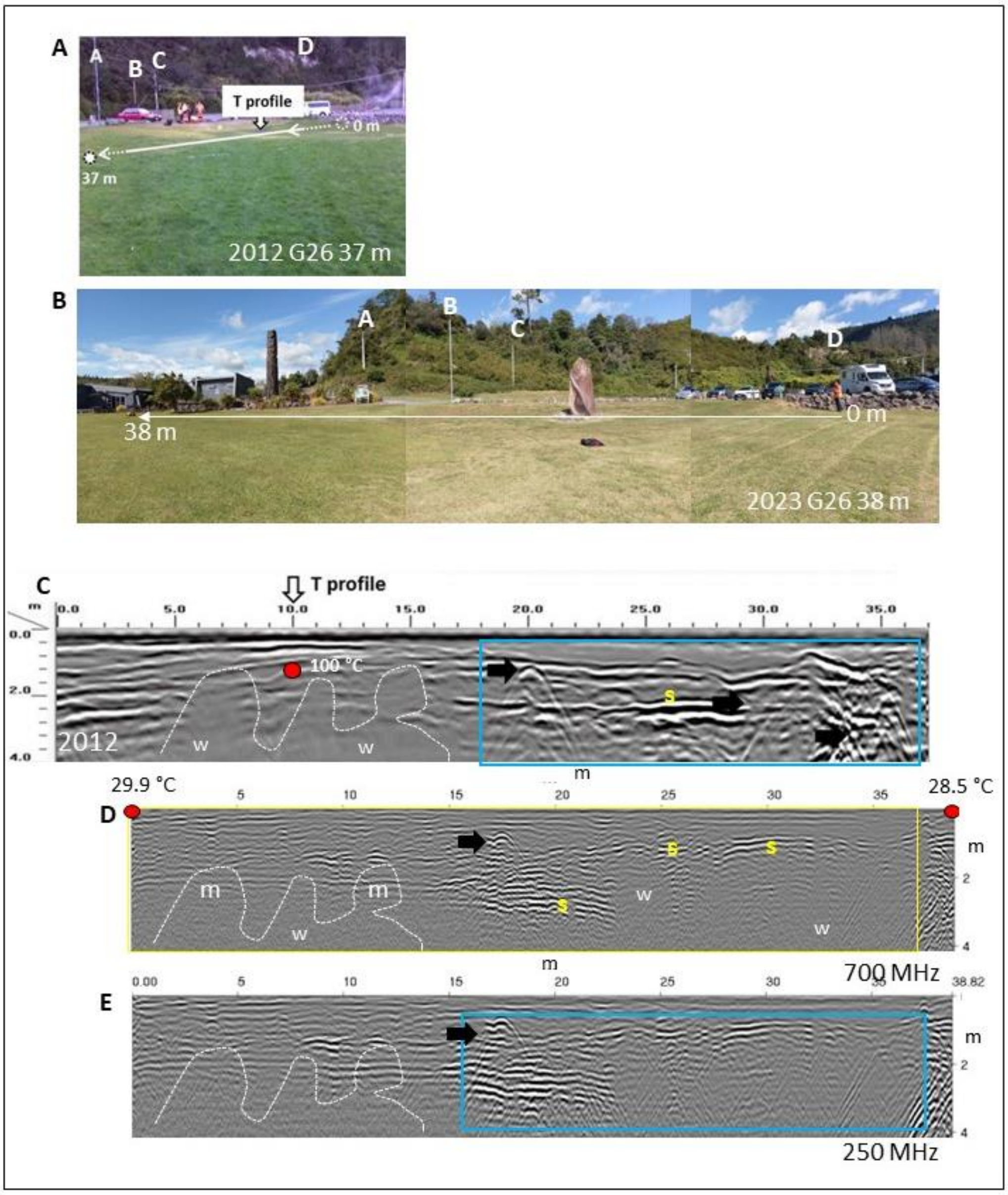

Figure 31: 2012 and 2023 GPR profiles. (A-B) Site photographs. (C) 2012 GPR profile. (D-E) 2023 GPR profiles. (C-E) Multiple hyperbolas (blue boxes and arrows) detected in both 2012 and 2023. Zone of weak amplitude reflections (w) in 2012 partly replaced by moderate reflections (m) in 2023. Zones of strong amplitude reflections (s) in 2012 replaced by weak reflections (w). Surface and subsurface temperatures shown.

7.0 Ground Penetrating Radar Survey Conclusions

For a direct comparison of GPR results, 13 sites imaged in 2012 were repeated in 2023. Five sites were inaccessible in 2023, so were not repeated. Seven new GPR sites were imaged in 2023.

Key findings:

- GPR is useful in estimating sinter thickness.
- The dual technique of GPR and downhole temperature measurements tracked locations of heat in the shallow subsurface, even when there was no evidence of heat at the surface.
- Repeated GPR surveys combined with downhole temperature surveys enabled the tracking of heat migration pathways in the shallow subsurface. This is important for the evaluation of whether localised areas are heating up or cooling down.
- Currently active and historic zones of hydrothermal alteration were identified and mapped.
- The 2012 survey mapped fracture locations, and the 2023 survey confirmed if they were still present, and mapped the appearance of new fractures.

8.0 Recommendations

1. Based on information from this survey and other previous work completed at Orakei Korako, it would be useful to create a sinter thickness and distribution map. Several sinter samples have already been dated at locations where GPR transects were undertaken. This would establish the thermal flow history of Orakei Korako.
2. Geothermal fields naturally change over time, so it would be of interest to correlate the temperatures measured in the last 11 years, with those previously reported from the 1960's to 2012, including records held by Waikato Regional Council.
3. Compare the changes determined in the last 11 years with production data from the Ngatamariki power station, changes in water levels at Lake Ohakuri and seismic events.
4. GPR over the top of Ruatapu Cave as changes in the cave have been observed, such as water level changes in the pool at the base of the cave, and the amount of gas and steam discharging. Access to the pool at the bottom of the cave is no longer permitted.
5. With a focus on eruptive hot springs and geysers at Orakei Korako, undertake a time-series GPR study to map the subsurface hydrology pre- and post-eruptive events. We successfully undertook a study to do this around Old Faithful Geyser in Yellowstone National Park, and determined the subsurface hydrology. We imaged water filling permeable sinter layers pre-eruption and the draining of sinter layers post-eruption. This was undertaken to assess anthropological versus natural controls on behavioural changes observed in geysers with time.
6. Repeat GPR and downhole temperature surveys are of value for monitoring changes in the shallow subsurface, even before changes are observed at the surface. There are a number of other Taupō Volcanic Zone geothermal areas where these surveys were completed between 2010 and 2014. It may be of value to consider doing repeat surveys at more geothermal areas.

9.0 Acknowledgements

We would like to acknowledge Nik Gibson for allowing access to Orakei Korako and Waikato Regional Council for supporting this project.

10.0 Appendix 1: Photographs of New 2023 Downhole Temperature Sites

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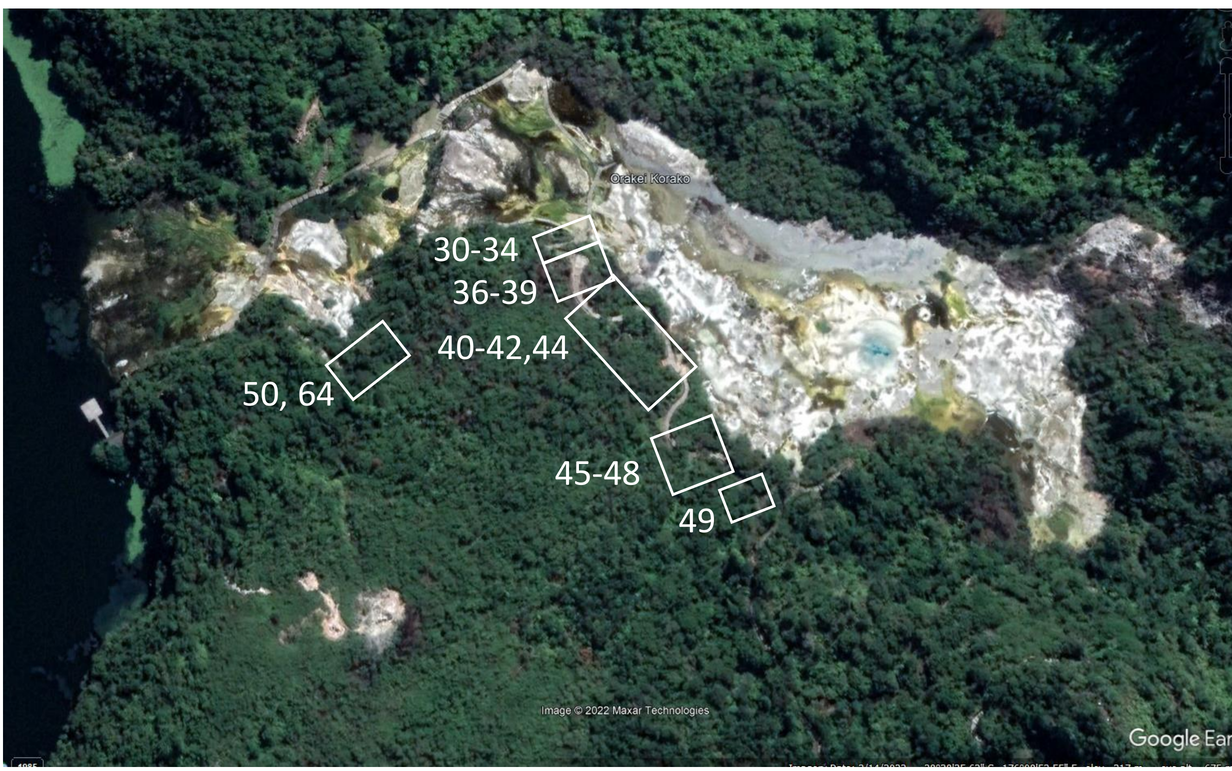
APPENDIX 1

2023 DOWNHOLE TEMPERATURES MEASUREMENT SITES

Overview of 2023 downhole temperature measurement sites

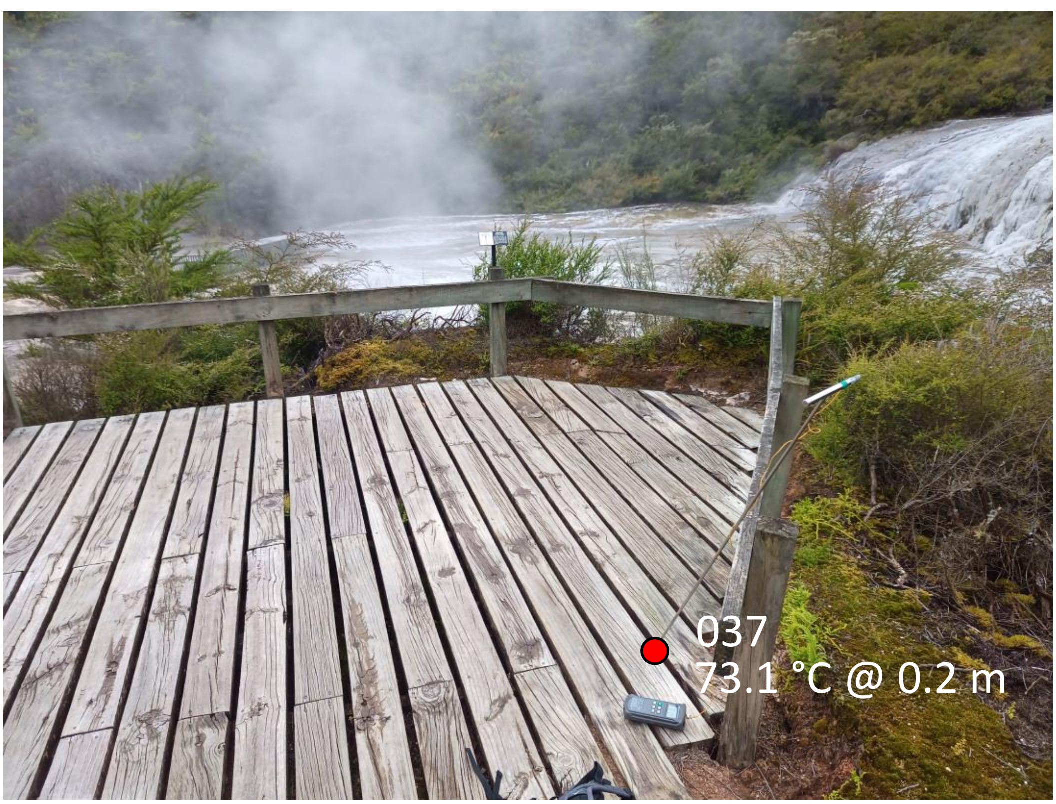


Location of 2023 downhole temperature measurement sites

Site photographs

Fossilised outcrop
034
72.9°C @ 0.75m

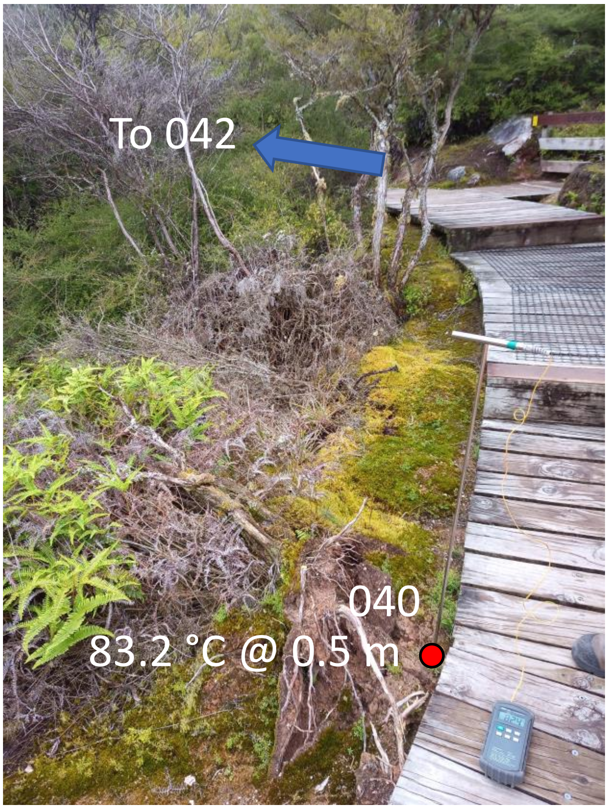

Fossilised outcrop
036
84.4 °C @ surface


037
73.1 °C @ 0.2 m


039
99.7 °C @ 0.35 m
038
97.4 °C @ 0.15 m
037
73.1 °C @ 0.2 m


038


039



Elephant Rock

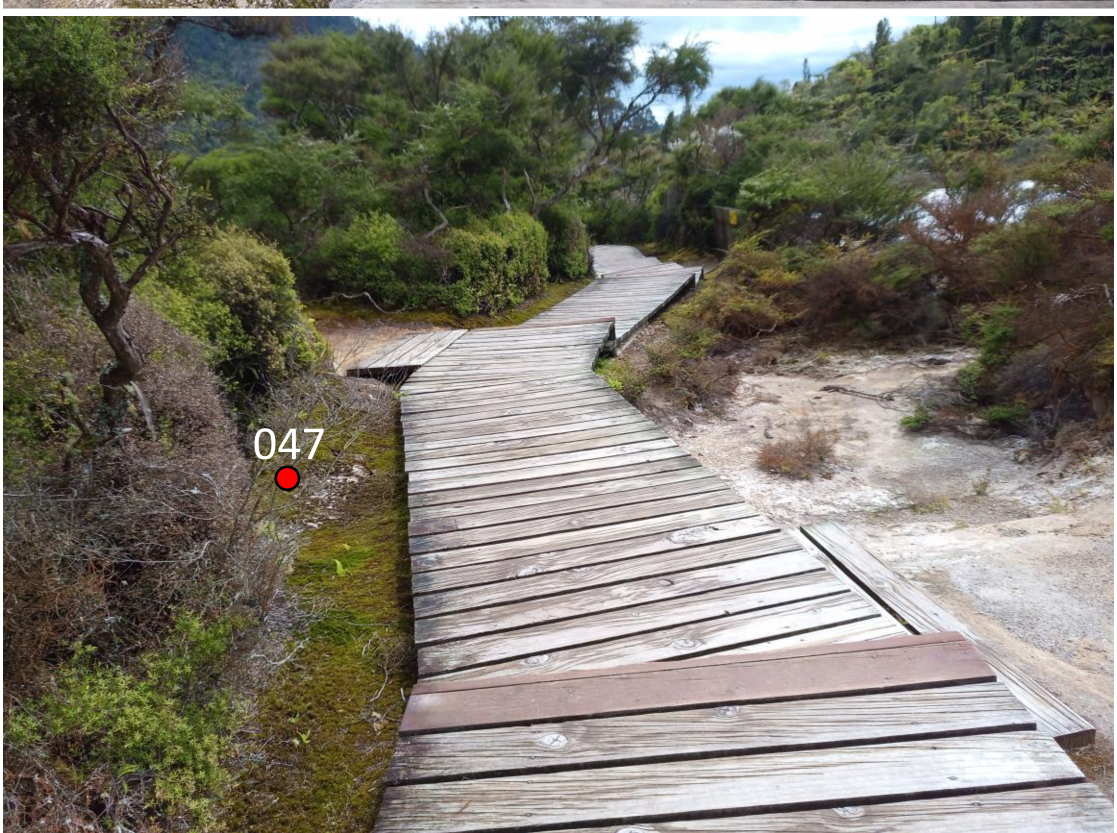
Small vent beside boardwalk

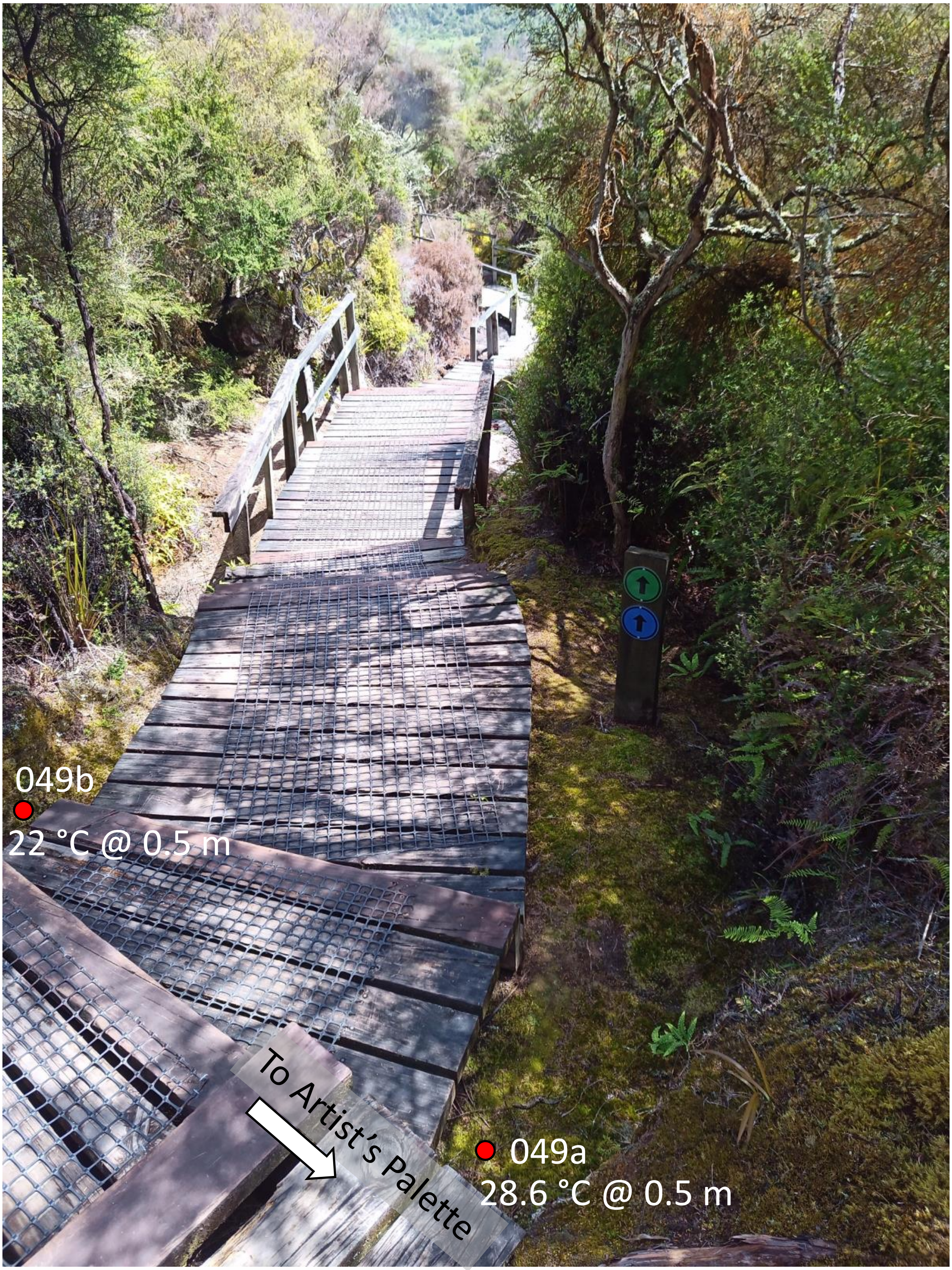
Vent with moss


Mud on
vegetation from
recent eruption
To Mud Pool
048
89.7°C @ 0.5 m
92.2°C @ 0.8 m


DANGER
046
38.9°C @ 0.3 m
Silica residue on surface


047
71.2°C @ 0.4 m


047


049b
22 °C @ 0.5 m
To Artist's Palette
049a
28.6 °C @ 0.5 m