Acta Geophysica
https://doi.org/10.1007/s11600-018-0173-7

RESEARCH ARTICLE - APPLIED GEOPHYSICS

Near-surface study of a hot spring site in Fiji

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Received: 13 July 2017 / Accepted: 14 June 2018

Abstract

A geophysical investigation of a hot spring system located in Rabulu, Fiji, was carried out from October 2014 to March 2015. The investigation covered a survey area of 6075 m^2. Self-potential (SP), ground temperature and soil carbon dioxide (CO_2) concentrations were measured and investigated for their distribution characteristics and inter-linkages. Results indicated obvious anomalous zone at the hot spring discharge site. The SP profile analysis highlighted thermal water upwelling zones and elevation-driven subsurface groundwater pathways. Measurement of subsurface temperatures up to 1 m depths revealed increasing temperatures, indicating potentially high thermal gradients in the area. Surface soil CO_2 distributions also agreed with SP and ground temperature results. The overall result of the study demonstrated that synchronised measurements of SP, ground temperature and soil CO_2 can be instrumental in identifying anomalous zones near the hot spring sites. Other parameters such as spring water temperature, discharge rate and energy flux estimates from the spring were calculated and analysed. The high-dense multi-parameter data coverage allowed interpretation of geothermal features at a scale never conducted in Fiji before. The near-surface investigations reported in this study corroborate previously suggested steady geothermal activity in the region, deserving further detailed investigation.

Keywords Near-surface · Geophysical investigation · Self-potential · Spatial distribution · High thermal gradient · Geothermal activity

Introduction

Constantly growing demand for energy and predictable scarcity of fossil fuels in immediate future has put impetus on exploring renewable energy resources worldwide (Coyle and Simmons 2014). Geothermal sources are one such renewable energy resources which are being utilised for energy production. Geothermal energy is renewable and environmental friendly; thus, it has serious advantages over other energy sources. Holm et al. (2012) reported that geothermal energy is a crucial energy source, which is well positioned to play a vital role in alleviating global climate change issues, increasing national energy security and safeguarding public health. At the 21st Conference of the Parties (COP 21) held in December 2015, 195 partaking countries accepted the universal climate deal. The deal provides a global action framework for countries to work together in trying to combat climate change issues by limiting global warming to below 2 °C (Kinley 2017). Asia and the Pacific are highly susceptible to climate change and yet considered as biggest contributor to greenhouse gas emissions. Immediate actions are needed to stop strong global challenges posed by climate change. Fiji has pledged to tackle climate change in many possible ways and affirmed to only use renewable energy by 2020 (Hourçourigaray et al. 2014). To achieve its affirmation, Fiji can utilise available geothermal energy resources. In Fiji, geothermal reservoirs in the form of hot springs are widely scattered over the islands. There is an urgent need of classifying these high-temperature hot spring systems into potential geothermal energy source sites. Hence, in this paper, we present the results of an integrated geophysical survey carried out at the Rabulu hot spring site, located in the Western part of Viti Levu, Fiji's biggest island. This study is a continuation of the work reported in Lal et al. (2015) and the primary objective of the investigation was to use self-potential (SP), ground temperature

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(GT) and soil carbon dioxide (CO_2) concentration results to establish their distribution characteristics and quantify their inter-linkages at the study area. Also, based on the geophysical data obtained, the secondary objective was to classify the site as a realistic area for future developments in terms of feasibility and energy potential.

Hot springs are common surface manifestation of geothermal systems and are described as discharge of heated groundwater from subsurface to its surface. According to Lewicki and Oldenburg (2008), most commercial geothermal projects have been developed in or near areas of hot springs, geysers and fumaroles. In the most simplest of form, geothermal energy refers to the thermal (heat) energy contained within the earth (Saemundsson et al. 2009). Geothermal energy originates from the earth and flows naturally up into the atmosphere through hot springs, geysers and volcanoes (Halfhide et al. 2009). In Fiji, the conceptualisation and utilisation of geothermal energy are at the development stage. Despite the occurrences of high-temperature hot spring systems in Fiji, characterisation and/or developments on these sites are very rare. This can be attributed to lack of research, funds and skilled professionals. To address this issue and open possibilities for further research, a small-scale near-surface geophysical investigation was undertaken to characterise the Rabulu hot spring site utilising SP, GT and soil CO_2 concentration methods.

The SP method was successfully featured in many geothermal exploration studies around the world (Bedrosian et al. 2007; Byrdina et al. 2009; Maucourant et al. 2014; Richards et al. 2010). SP method is a passive electrical method which measures the potential difference between any two points on the ground due to variations in naturally occurring current beneath the Earth's surface (Mauri et al. 2012). SP anomalies are produced by differences in electrical resistivity, fluid flow in response to pressure gradient, heat and ion accumulations in the earth's interior (Apostolopoulos et al. 1997; Drahor and Berge 2006). Corwin (1990) stated that hot fluid circulation takes place along faults, and SP investigations have proved to be useful in locating and delineating features associated with fluid motions. In geothermal areas, SP anomalies are most likely to be electrokinetic potential produced by hydrothermal fluid circulation (Ishido et al. 1989). Hence, SP method has become a popular tool for characterising subsurface hydrology at geothermal areas. SP data interpretation is mainly done quantitatively. A positive SP anomaly indicates fluids' up-flow zones, while a negative SP anomaly indicates a down-flow zone (Ishido et al. 1989). For the present study, the qualitative approach is exploited.

Thermal method is another geophysical technique commonly used for geothermal exploration purpose. Thermal methods directly measure temperature and heat which is of substantial importance while investigating a geothermal site. In the assessment of any geothermal prospect, subsurface temperature is the initial parameter that needs to be measured and interpreted. According to Gray et al. (2012), the measurement of subsurface temperatures at a geothermal field is the fundamental observation that is used to determine and constrain models of other thermal parameters such as geothermal gradient, heat flow and total heat accessibility. Busby et al. (2011) specified that direct measurements of temperature remain the most precise method for defining a geothermal system. Thermal method has been widely used as a geothermal exploration tool all around the world (Dawson and Fisher 1964; Hakanson 2011; Mwawongo 2013; Wanjohi 2014). For the present study, subsurface ground temperature measurements were carried out to characterise the geothermal field and establish a subsurface groundwater temperature distribution map of the investigation site.

Soil CO_2 flux measurements have also proven to be a useful in delineating subsurface features during the early stages of geothermal exploration (Harvey and Harvey 2015). The work of Fridriksson (2009) emphasised that CO_2 is the most common gas in geothermal fluids and measurements of the diffuse flow of CO_2 through soil in geothermal fields can be useful for the purpose of outlining structures that direct flow of fluids in the geothermal reservoir. In addition, the work of Bloomberg et al. (2012) stated that numerous studies have utilised soil CO_2 concentration results as a proxy for heat and mass flow in volcanic hydrothermal systems, which has greatly improved our understanding on heat and mass transfers from high-temperature reservoirs. Similarly, Shimoike et al. (2002) also highlighted that variations in diffuse output of CO_2 correlate with changes in the geothermal activity in the area, and therefore, CO_2 flux measurements can be used as an important tool in monitoring such activities. Recently, increasing number of researchers has conducted soil CO_2 surveys for geothermal exploration purpose (Bloomberg et al. 2012; Brombach et al. 2001; Chiodini et al. 2005; Rissmann et al. 2012). The work of Harvey and Harvey (2015) identified over 20 case studies, which incorporated soil CO_2 gas flux investigations for geothermal exploration. The successful application of soil CO_2 measurements in many studies worldwide suggested that soil CO_2 measurement is an important tool needed for initial investigation of the Rabulu hot spring site.

In several studies, a combination of geophysical methods has been successfully used for exploring geothermal systems (Bruno et al. 2000; Daud et al. 2000; Lagios and Apostolopoulos 1995; Wanjohi 2014). A similar approach is used in this study in which SP, GT and soil CO_2 concentration data is gathered and interpreted to characterise subsurface features near the hot spring site. Additional important parameter measurements, such as hot spring discharge rate, hot spring discharge water temperature, and estimated energy flux, are calculated to provide further insight into the present study. This study was motivated by the need to demonstrate that there is scope for further detailed geothermal investigations at the Rabulu hot spring site, which can be beneficial for the local isolated communities near Rabulu.

Study area

Fiji is located in the South Pacific Ocean between 177°E–178°W and 16°S–20°S. Fiji is an island nation, of which Viti Levu and Vanua Levu are the two main islands (Fig. 1). The Fiji group comprises 332 islands and has a total land area of 18,333 km^2 (Ledua 1995). Viti Levu (land area of 10,642 km^2 and 57% of the nation's land area) and Vanua Levu (land area of 5807 km^2) are the two main islands of Fiji group. Prominent feature in both the islands is mountains with peaks rising to 1300 m.

The geology of Fiji has been summarised by Adams et al. (1979), Foye (1918), Kroenke and Rodda (1984) and more recently by (Rodda 1994). The islands making up the Fiji group lie in a tectonically complex area at the boundary of the Pacific and Australian plates in the Southwest Pacific (Fig. 1a). Fiji is surrounded by island nations and its geologic history provides some realistic hypotheses as to faunal origins. The complicated geology of Fiji can be attributed to repeated volcanism and tectonic activity, combined with uplift and erosion (Evenhuis and Bickel 2005) (Fig. 1b). The Rabulu hot spring site is situated on the Northern part of Viti Levu, which mainly consists of volcanic landforms and comprises of volcanic and basalt rocks (Ollier and Terry 1999). A detailed geology of Rabulu, which falls in the district of Tavua, has been extensively documented (Blatchford 1953; Cohen 1962; Setterfield et al. 1991). The hot spring system is located in the Eastern rim of the Tavua caldera. Tavua is approximately 186.70 km north-west of Suva, the capital of Fiji. It comprises many village settlements and the hot spring system investigated in this study is situated in the Rabulu settlement. The location of the hot spring site is given in Fig. 2. The topography of the study site consists of an area of gentle slope and irregular low hills separated by wide valleys. The study site was approximately 17 m above sea level and characterised by dry farmlands surrounded by trees and forests.

Experimental design and methodology

Measurements were conducted at the hot spring site from October 2014 to March 2015. The investigation was conducted during the dry season of the year (ambient temperature varied between ∼ 28 and ∼ 32 °C) and when the study location was absent from the usual agricultural activity. SP, GT and soil CO$_2$ measurements were conducted in profiles directly transecting the hot spring discharge zone. These measurements were conducted during November 2014. The 680 m profile was oriented in the West–East direction and the origin was chosen to be at the highest elevated area. This line consisted of 68 measurement stations separated by 10 m. At each station the elevation, longitude and latitude were also measured using a hand held GPS device.

Profile measurements

Non-polarisable Cu/CuSO$_4$ electrodes, pre-calibrated under laboratory conditions in a strong brine solution, were used for SP measurements in the field. Calibration results suggested a mean drift of < 1 mV/sec amongst the electrodes, with maximum drifts of ± 5 mV/sec, which is a common for the Cu/CuSO$_4$ electrodes (Butler 2005). To carry out SP measurement, a 10-cm hole was dug and drenched with a strong brine solution. The strong brine solution improves the electrical contact between the electrode and the ground surface (Bhattacharya and Shalivahan 2016; Deo 2013). This also eliminated any heterogeneous contact potentials from both electrodes due to surface irregularities. The potential gradient method was utilised for SP measurements along a profile. GT measurements were carried out using a temperature probe (K-type chrome-aluminium probe) which had an accuracy of ∼ ±0.2 °C. These measurements were carried out at a depth of (30 ± 5) cm at the same location coinciding with SP and CO$_2$ measurements. To ensure equilibrium conditions, measurements were conducted after 2 min. Temperature measurements were recorded between 10 a.m. to 2 p.m. to avoid huge diurnal temperature variations and these measurements were verified with early morning and afternoon readings. Soil CO$_2$ concentration measurements were taken by placing the Vernier CO$_2$ gas sensor ∼ 5 cm deep into the soil surface. This sensor was interfaced to the Logger Pro device, and the CO$_2$ levels were recorded in ppm. To detect and control any drift of the device calibration, atmospheric CO$_2$ concentration was measured at the beginning and at the end of a profile. The SP, GT and CO$_2$ measurements were taken at the same locations along the profiles. However, each measurement was taken after a time span of few days; i.e., SP, GT and soil CO$_2$ concentration

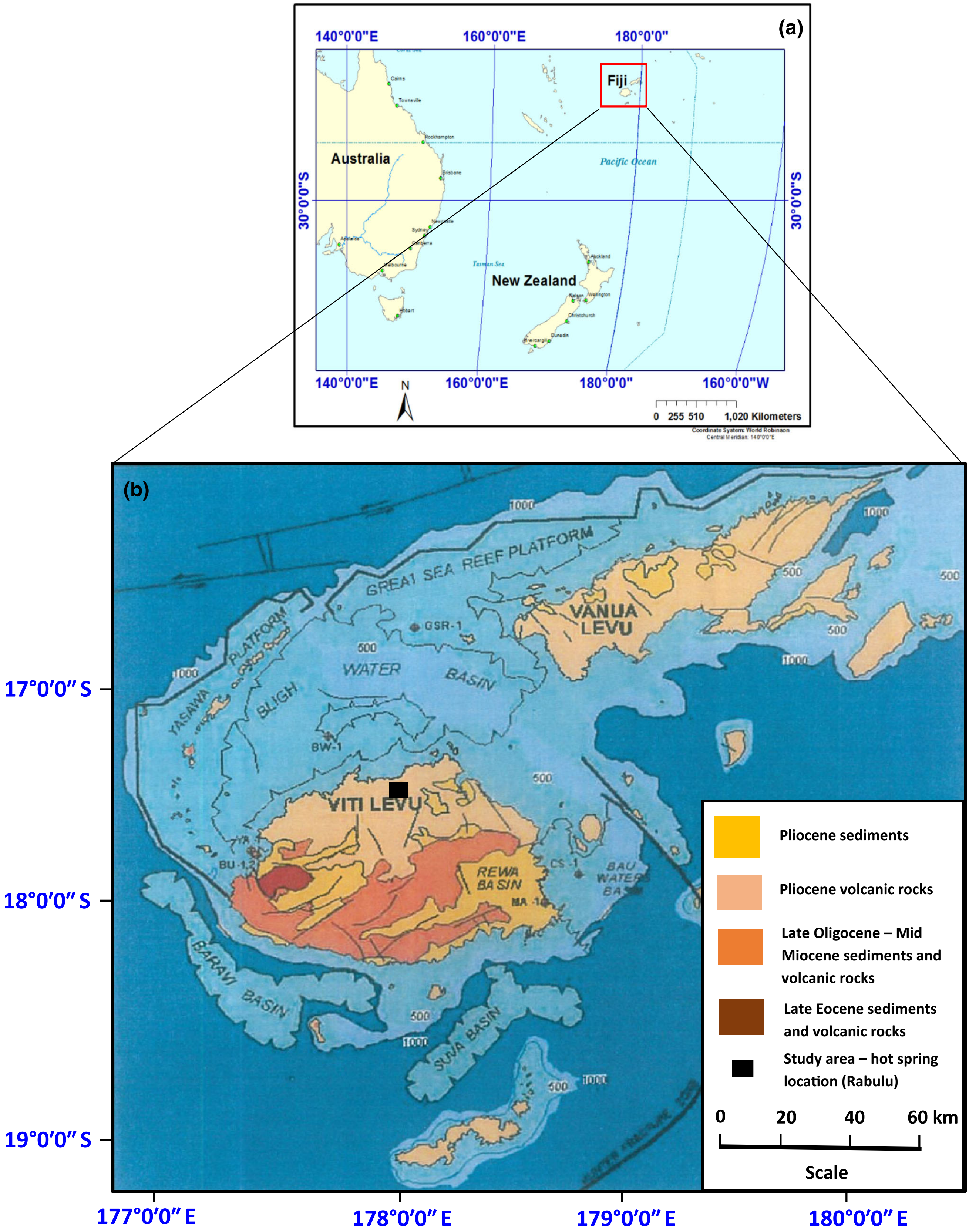


Fig. 1 **a** Location of Fiji in the Oceania region and **b** geological map of the Fiji Islands *Source*: Mineral Resources Department, Fiji

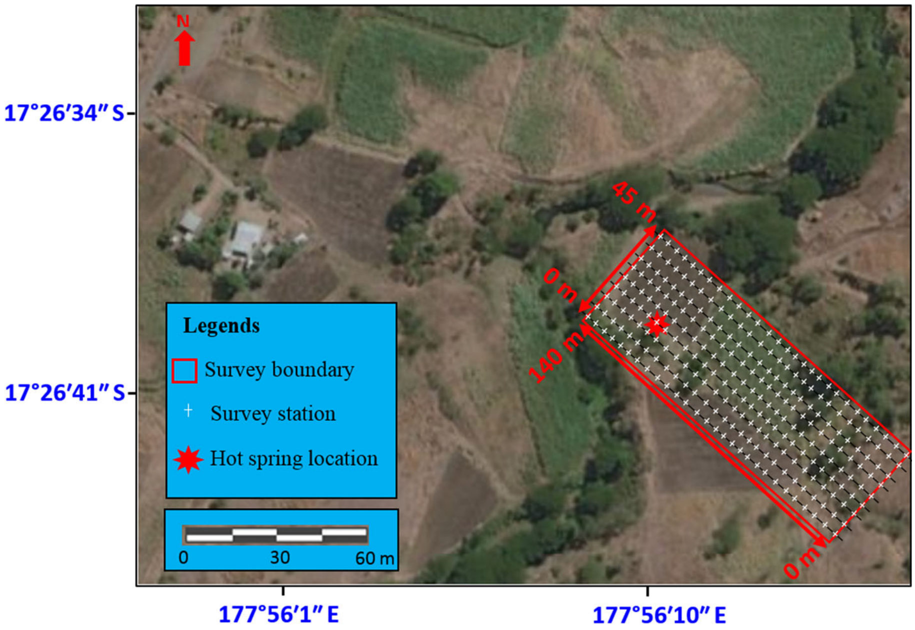


Fig. 2 Location of the study area with a schematic of the study area boundary and survey stations *Source*: Google Earth

measurements were not simultaneously taken. This was done to ensure that digging and wetting does not alter the natural condition of the soil.

Gridded area measurements

For spatial distribution mapping, the investigation was carried out in an area of approximately 6300 m^2 surrounding the hot spring site. SP and GT measurements were conducted in multiple profiles covering this area. A total of 9 profiles' measurement (maintaining equal separation between profiles) was conducted during the survey. On average, each profile comprised of 28 measurement stations at 5 m intervals between stations (Fig. 2). To ensure reliable GT measurement and to avoid diurnal GT variation, GT measurements were recorded at a depth of 0.3 m due to poor thermal conduction of soil (Mauri et al. 2012). The parameter distribution map was obtained using licensed Surfer software by exploiting Kriging interpolation technique.

Ground temperature-depth profile measurements

Observed changes in GT at a geothermal field narrate the natural variability of the underlying geothermal systems (Heasler et al. 2009). Georgsson (2009) suggested that temperature data from deeper levels is essential as it provides information on geothermal gradients and possibly the depth to the exploitable geothermal resources. To investigate temperature variations with depth, GT data was acquired using thermal probes. Each thermal probe consisted of seven *K*-type thermocouples located at seven different intervals (Fig. 3) ensuring GT measurements at 0.05, 0.10, 0.15, 0.30, 0.50, 0.75 and 1 m. A 1-m-deep hole was dug at the site, and the thermal probes were installed. After installation, the soil was compactly packed and the probes were given few hours to stabilize before temperature data was recorded. The thermocouples from each probe were connected to the data logger which logged the temperatures for 24 h period, storing 10 min average data in its internal memory.

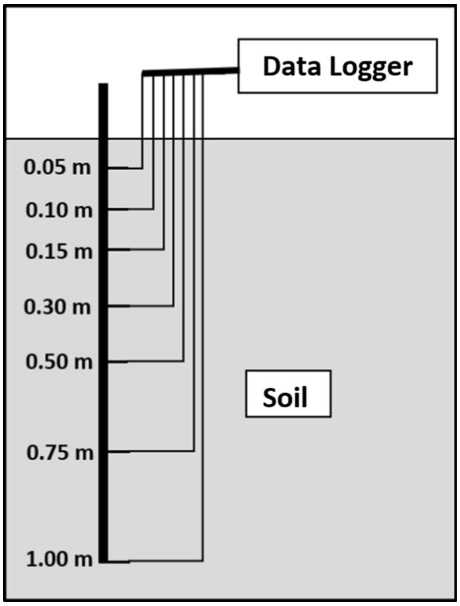


Fig. 3 Schematic of the thermal probe used for temperature-depth profile measurements

Additional measurements of the spring

To gather additional information, hot spring discharge rate, the discharge water temperature and the ambient temperature measurements were carried out hourly for a 24 h period. The volumetric discharge estimation (VDE) was calculated in L/s using the volume vs time relationship. The hot spring discharge was channelled into a known volume container and the time to fill was measured. In addition, hot spring water samples were collected every hour over a 24 h period on 20 December 2015 and analysed for chloride (Cl^-) and calcium (Ca^{2+}) concentrations using respective ion-selective electrodes in the laboratory. In addition, hot spring discharge rate, hot spring water temperature and water at ambient temperature were also monitored for a period of 6 months at monthly interval.

Results and discussion

Self-potential, ground temperature and soil carbon dioxide profile measurement results

The SP, GT and soil CO_2 concentration profiles (Fig. 4) were constructed from measurements at the hot spring site where the origin (0 m) was taken at the highest elevation.

A prominent anomaly (refer Fig. 4) is visible on the profiles at the hot spring discharge region. The patterns observed in the profiles presented in Fig. 4 are comparatively similar. Peak values in SP, GT and soil CO_2 concentration are observed at the hot spring discharge zone. The SP profile shows a maximum peak of about 120 mV while GT reveals a peak value of 39.2 °C near the hot spring. Likewise, soil CO_2 concentration attains a maximum value of 674 ppm. The GT and CO_2 concentrations measured across the profile ranged from 30.0 to 39.2 °C and 508 to 674 ppm, respectively. The SP signals remain nearly constant with little variations at the elevated region where no hot spring discharge was observed. However, the SP signals displayed high peak with positive values of SP near the hot spring discharge area. Similar patterns were exhibited by GT and CO_2 concentration profiles. Soil CO_2 concentration also oscillated between the two segments. A significant peak in soil CO_2 concentration profile can be distinguished at the hot spring discharge zone. The average CO_2 value along the profile was approximately 548.26 ppm. Such values of CO_2 concentration on geothermal fields were reported by Maucourant et al. (2014) and Shen et al. (2011) at geothermal systems in Italy and Tibet, and China respectively.

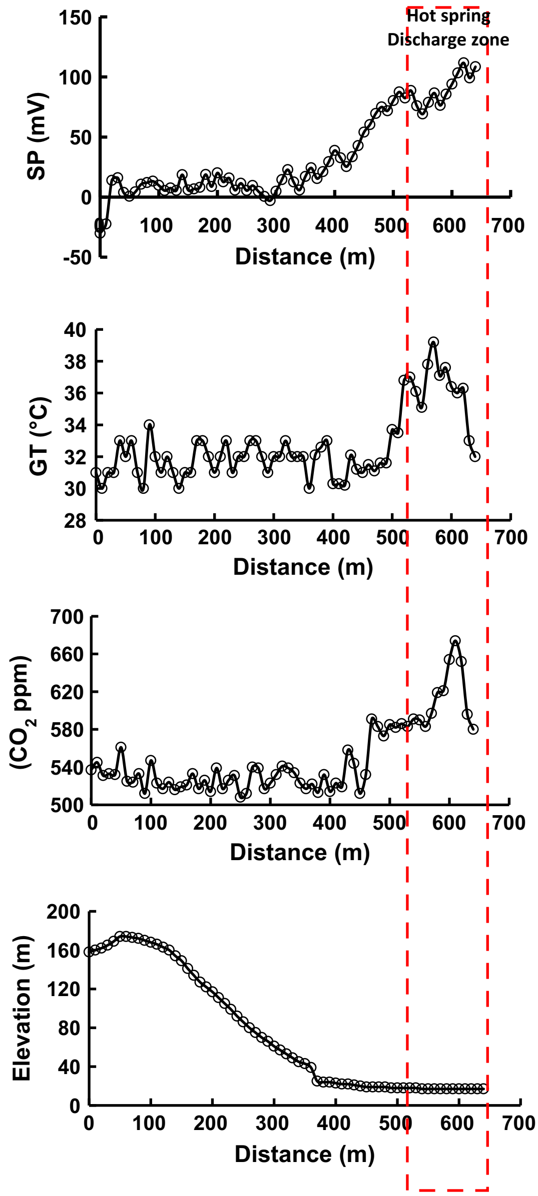


Fig. 4 SP, GT, soil CO_2 concentration and elevation profiles at the hot spring site

Self-potential and ground temperature spatial distribution

The SP and GT distributions (Fig. 5) compare well with other similar study reported by Richards et al. (2010). The SP signals (Fig. 5a) are within range of what are typically seen at geothermal sites (Corwin and Hoover 1979). A positive SP anomaly (> 30 mV) is mapped along the hot spring location. This anomaly extends south-east of the hot spring area. Both positive and negative SP signals are observed in the SP spatial distribution map. Higher SP values are seen at the hot water upwelling area. There also exist some anomalies towards the North end of the spatial

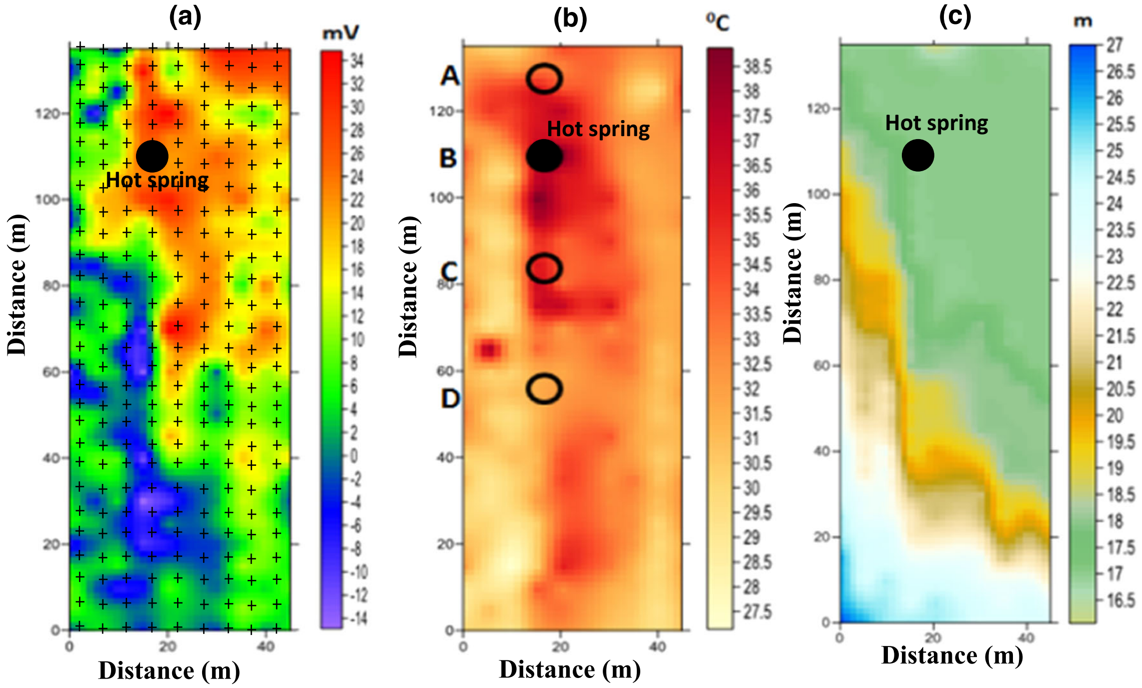


Fig. 5 **a** SP distributions, **b** GT at 0.3 m depth with locations of the four thermal probes denoted by circles and hot spring discharge zone denoted by square and **c** elevation distribution at the hot spring site

distribution map as seen by high SP values. GT spatial distribution map (Fig. 5) shows ground temperatures ranging from 27.5 to 38.5 °C. Highest GT of ~ 38.5 °C is observed at the thermal water discharge zone. Minor anomalies also occur in the southern and eastern part of the study area with different intensities depending on the parameters being measured.

Ground temperature-depth profile

With an aim to assess temperature distribution within the geothermal field, ground temperature-depth profile analysis was carried out. It is understood that shallow wells are not adequate to get reliable values. However, it was necessary to get an indication of the GT at the investigated site with its variation pattern. Ground temperature-depth profile measurements were conducted to quantify the expected increase of temperature with depths. Thermal probes were installed in areas where thermal anomalies were seen as illustrated by the ground temperature spatial distribution map (Fig. 5b). Ground temperature-depth profile (Fig. 6) shows distinctive GT variations with increasing depth.

All four thermal probes installed show similar variations, and the hottest temperatures (32.7 ± 0.2 °C) were recorded at PROBE B installed at the hot spring discharge location (Fig. 5). It was observed that the temperatures increased with depth for all the probes. The strongest temperature gradient was observed at PROBE B. In addition, the 10-min GT data of PROBE B recorded at respective depths over a period of 24 h (starting at 1500 h) is given in Fig. 7. The GT result for PROBE B demonstrated that after 0.3 m, the ground temperatures at respective depths remained constant with little variations (Fig. 7). GT temperatures above 0.3 m showed diurnal variations.

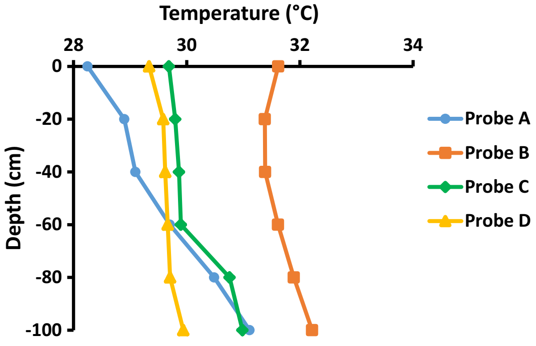


Fig. 6 Ground temperature variations with depth

Other key hot spring parameter estimation results

The hot spring water temperature was found to be constant (~ 45.4 °C) throughout the 24 h period (Fig. 8a). However, the ambient water temperature showed significant variations (Fig. 8b). This variation was attributed to diurnal

Fig. 7 Ground temperature-depth profile variation over 24 h period

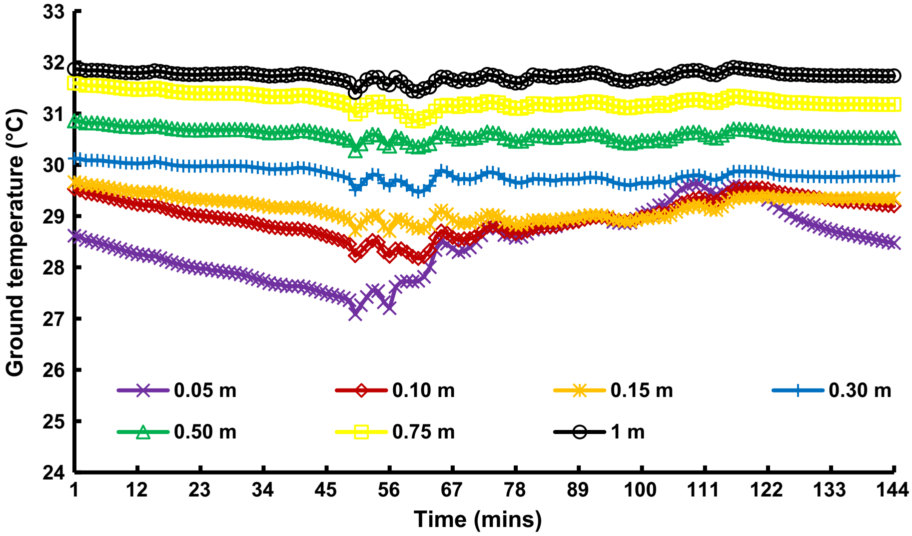
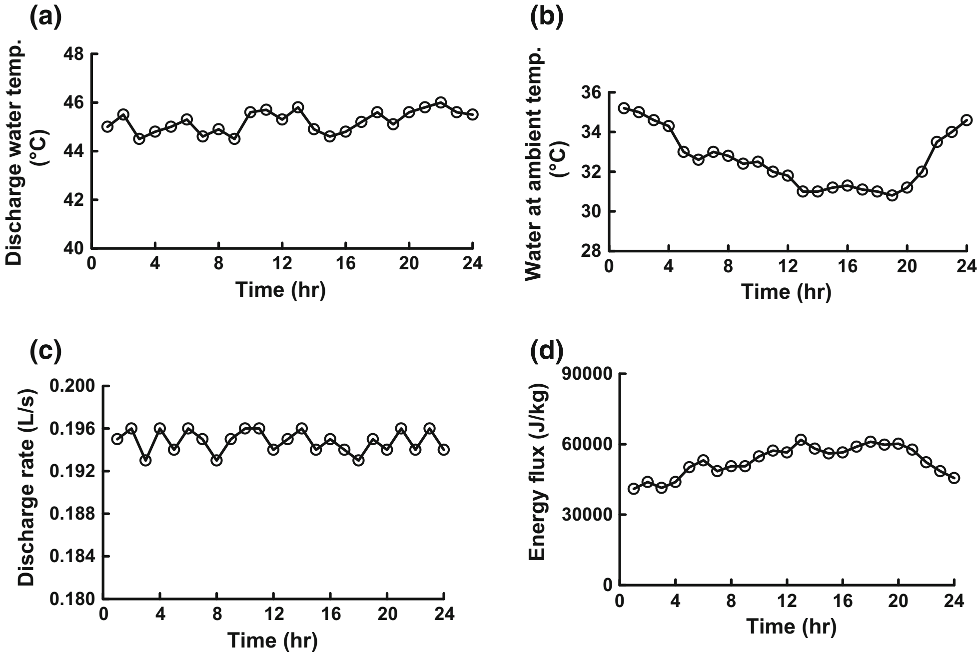


Fig. 8 **a** Hot spring water temperature variations, **b** water at ambient temperature variations, **c** discharge rate variations and **d** estimated energy flux of the hot spring system for a 24 h period



weather conditions. High air temperature during the day matched with an increase in ambient water temperature, while a lower ambient water temperature was recorded for the night time. The estimated volumetric discharge rate was calculated to be 0.2 L/s. It was also observed that the discharge rate (Fig. 8c) was fairly constant throughout the day. Furthermore, based on the data, the estimated average energy flux of the system was ~ 60.4 kJ/kg. Over a 24 h period, the estimated energy flux showed minor variation (Fig. 8d), which was again largely due to variations in the ambient water temperature during the day. In addition to hourly measurements, some of these parameters were also monitored over a 6-month period (Fig. 9). Hot spring water temperature showed no major variation during the 6-month period. As a result, no major difference was achieved in the estimated energy flux.

According to Yoshiike (2003), Cl^- and Ca^{2+} are the major dissolved solids present in thermal waters. Thus, Cl^- and Ca^{2+} content in the thermal waters were measured on an hourly basis for 24 h. The results (Fig. 10a) showed minimum variations in Cl^- and Ca^{2+} concentration in the sampled thermal waters. The average calcium and chlorine content of the thermal water were 41.1 and 144.0 mg/L, respectively (Fig. 10b). High chloride content in the hot spring water correlated well with similar results reported by Petrescu-Mag et al. (2009).

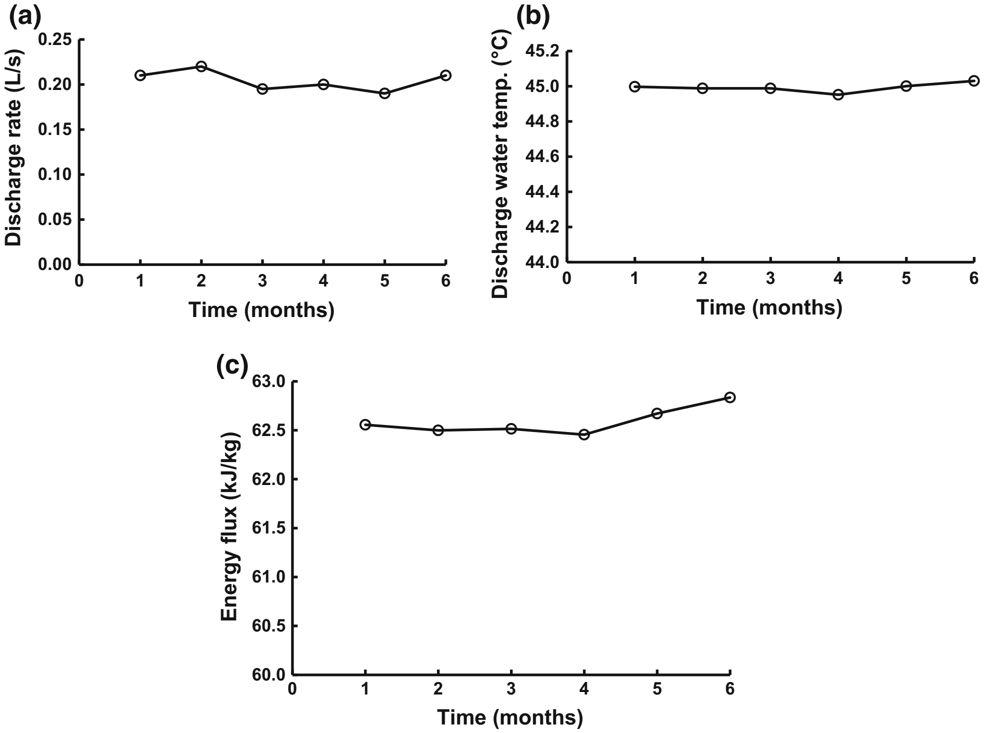
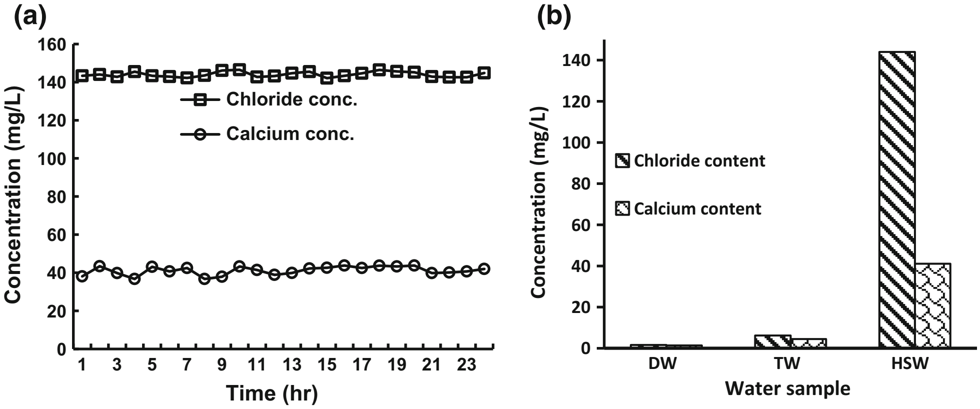


Fig. 9 **a** Discharge rate, **b** discharge water temperature and **c** estimated energy flux obtained for 6-month period

Fig. 10 **a** Variations in the concentrations of Cl^- and Ca^{2+} over a 24 h period and **b** chloride and calcium content in distilled water (DW), tap water (TW) and hot spring water (HSW)



Integrated interpretation of results

Self-potential, ground temperature and soil carbon dioxide anomalies

The general trends in the profiles were seen by examining the SP, GT and soil CO_2 concentration patterns along the profile as a function of distance. Interpreting a SP profile was quiet tedious. The simple interpretation of SP profile similar to Richards et al. (2010) was used to determine the direction of groundwater flow. Different groundwater flow patterns affect the general shape of the SP profile. The work of Lénat (2007) indicated that an upward flow of hot fluids in the active areas produced positive SP anomalies. In the present study, a significant increase in the SP signal on the SP profile can be attributed to upward flow of hot groundwater which coincides with the hot spring discharge. With the results from SP survey, the positive anomaly at the hot spring discharge zone is attributed to rising hot fluids. Further analysis of SP variations is presented in the next section.

Thermal anomaly seen in the GT profile indicated an increase in GT at the hot spring site. In volcanic setting, the elevated GT is likely due to the presence of magmatic heat source at depths under surface at the spring site. This is supported by numerous examples, which can be found in the literature (Mauri et al. 2012). The atmospheric temperature ranged from 25 to 30 °C. However, GT of

~ 39 °C was observed at the hot spring site. This is relatively high when compared to GT measured at sites away from the geothermal zones. A GT of ~ 39 °C at a depth of 0.3 m explains the existence of high thermal gradient at the hot spring site, which is likely to be caused by hot rising thermal fluids or gases.

For soil CO_2 concentration anomaly, a single interpretation of soil CO_2 concentration is quite difficult. Numerous studies have shown that various factors such as soil moisture, temperature, soil porosity, plant activity, soil organic carbon content and vegetation's influence soil CO_2 content and greatly influence the CO_2 degassing pattern (Davidson and Trumbore 1995; Fang and Moncrieff 1999; Flechard et al. 2007; Hamada and Tanaka 2001; Jassal et al. 2005). These factors need to be taken into consideration while reporting soil CO_2 concentration. The average soil CO_2 concentration was above the normal soil degassing rates (~ 450 ppm), and therefore, it could be assumed due to the presence of hydrothermal system as indicated by surface manifestation of hot spring. The degassing of CO_2 through soil is considered to be supplied by two sources. Firstly, it can have volcanic origin emanating from deep environment and secondly a shallow one that results from vegetation activity (Kanda 2010).

The profile patterns and the spatial distribution map indicated that SP signals highly correlated with GT and soil CO_2 concentration results. The overall shape of the profiles showed that the correlation between SP, GT and soil CO_2 concentration is direct (i.e., the anomalies are coincident in their location and extent). The maximum peak in SP, GT and soil CO_2 concentration at the hot spring discharge zone highlighted a direct correlation between these measured parameters. The location of soil CO_2 concentration anomalies matched well with other parameters measured, especially at the thermal water discharge zone. Therefore, our results support the hypothesis of intense rising thermal waters from deep down a magmatic source. This clearly points to the existence of buried fault zones (zones of fluid circulation allowing fluid release to the surface) across the investigated area. The spatial distribution map indicates additional SP anomalies in the area. Therefore, the hot spring site could be considered for further extensive geophysical investigations. The missing regions should be surveyed to investigate the fault zones and determine its contribution to the overall geothermal system at Rabulu, Fiji.

Despite investigating a small area, it is clear that the strong CO_2 degassing occurs at the fault zone and is evident by good spatial correlations with SP and soil temperature anomalies. Continuous thermal water discharge indicated the presence of a magmatic body below the hot spring area. When all three anomalies (i.e. SP, GT and soil CO_2 concentrations) are present at a distinct location, it can be interpreted that a hydrothermal system is present (Zlotnicki et al. 1998). This is indicative of heat conduction from uprising thermal fluids due to subsurface features. In general, the SP and GT distribution map indicate elevated SP and GT anomaly at the hot spring discharge zone.

High SP values are most likely due to rising thermal waters and presence of faults at the hot spring location. Studies of different geothermal sites show that often positive SP values indicated upward flow of water (water vapour in some cases) in the ground, while negative SP values indicated downward motion of water (Byrdina et al. 2009; Maucourant et al. 2014). In our study, negative SP values are also observed in the North–East direction, which can be interpreted as downward flow of groundwater. The thermal anomalies provide evidence on groundwater flow patterns at the hot spring area. Based on the outcome of this study, it can be inferred that SP and GT distribution maps can be used as an important tool for dissecting broad regional pattern of groundwater flow in this region. In the area of high temperature, an increase in SP characterises the existence of an indicative of upward movement of geothermal fluid (Ariki et al. 2000; Kikuchi et al. 1987). This holds true for the present case study as elevated SP signals with correlating thermal anomalies are observed at the hot spring discharge zone. The observed SP, GT and soil CO_2 concentration correlations are attributed to the rising hot fluid and the high thermal conductivity of the investigated area.

SP against elevation

Through the evaluation of SP/elevation gradient (in short, we term this as *SEG*), SP method allows to differentiate gravitational groundwater flow from uprising hydrothermal fluids (Mauri et al. 2012). The *SEG* values were estimated using the SP profile along the main slope, which is assumed to match that of water flow as specified by Mauri et al. (2012). This study undertook an analysis of SP against elevation with an aim to find the major contributor of SP anomaly. For clarity, the *SEG* plots (Fig. 11) were separated into six portions (P1–P6) to ensure heterogeneities in the profile to be analysed in greater detail.

Anomalies can easily be identified at the hot spring discharge zone but difficult to discern at other locations along the profile. The SP/elevation analysis identified many negative and a positive *SEG* value. The strongest SP increase is located on the location of the hot spring discharge zone (Fig. 11). The hot spring discharge area (P1) is mainly characterised by a large negative SP/elevation gradient of about − 8 mV/m. This abnormal gradient is considered to represent water upwelling zones (Lénat 2007). The relatively large negative *SEG* in P6 indicates

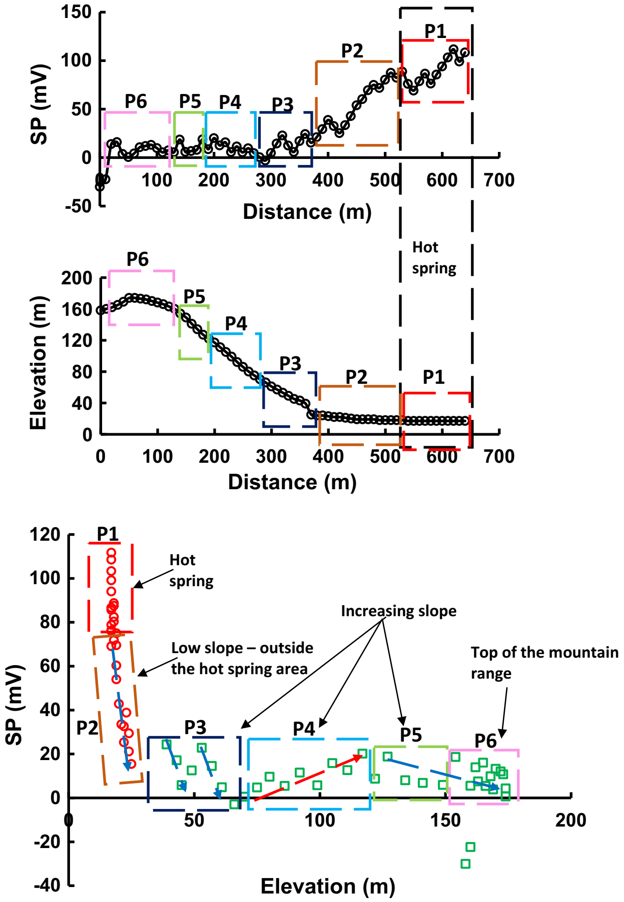


Fig. 11 SP and elevation relationship

groundwater upwelling zone, which could be the main source of SP anomaly as suggested by Mauri et al. (2012).

Moving towards the northern flank of the study area, the SP variations are inversely associated with decreasing elevation. Portions P2, P3, P5 and P6 on the profile are characterised by smaller negative *SEG* than P1. The negative linear relationship between elevation and SP in these portions is typical of gravitational downward flow of water in a hydrological system (Bedrosian et al. 2007; Lénat 2007). These computed results coincide with field observations as no discharge zones were observed on other portions of the profile. A small positive *SEG* is obtained for P4. For P4, as there is no correlating thermal and soil CO_2 anomaly, the SP variations of ~ 20 mV are most likely due to internal variation in the subsurface geometry.

Ground temperature-depth profile analysis

This increasing temperature can be attributed to the presence of deep heat source. The work of Monteith and Unsworth (2007) stated that GT at non-geothermal environment decreases from surface to a depth of 50 cm. This does not hold true for this system as GT increased constantly with depth. This indicated the presence of high geothermal gradient at the hot spring location. The thermal water discharge region is having a high ground temperature, necessitates further detailed temperature monitoring and interpretation.

Monitoring of GT variations indicated that the temperature at shallow depth above (< 0.3 m) is affected by short-term ambient temperature changes. These variations begin to diminish upon reaching a depth greater than 0.3 m. After 0.3 m depth, the temperatures are relatively constant and are unaffected by seasonal temperature changes. Florides and Kalogirou (2005) suggested that the earth's temperature beyond 0.3 m is insensitive to the diurnal cycle of air temperature and weather pattern. In addition, the obtained ground temperature-depth analysis results coincide with a similar study conducted for the Wairakei geothermal site (Dawson and Fisher 1964). The work of Dawson and Fisher (1964) established that diurnal variation was less than 1 °C for depths greater than 0.3 m. The observed elevated GT anomalies with constant ground temperature at depths below 0.3 m quantify the existence of high thermal gradient in the area. Ground temperature-depth profiles also provided important information regarding the geothermal resource available in the Rabulu area. However, to establish the real energy capacity of the Rabulu hot spring system a more detailed and condensed investigation is required.

Additional parameter result analysis

The analogous results in discharge rate, hot water temperature measurements and estimated energy flux monitored over 6-month period explain the existence of a steady geothermal activity at Rabulu with very little diurnal variations. The chloride content in the sampled thermal water ranged from 142.1 to 146.5 mg/L suggests that water is chloride-rich and comes from the up-flow zone. Similar interpretation is found in other geothermal sites Niyigena (2014). The Cl^- and Ca^{2+} content were found to be much higher in the hot spring water sample, than the DW and TW samples. Lower chlorine content in geothermal fluids indicates invasions of freshwater into thermal fluids while greater chloride content specifies hot water upwelling from greater depths and indicates permeable zones such as faults and fractures. In the present hydrological system, chloride is most likely to be derived directly from deep reservoir as suggested by Kolker (2008). This interpretation still needs further investigations with other isotopic analysis. Overall, the discussion presented in this study is based on preliminary results and obtaining a more precise near-surface characteristics of the hot spring system at Rabulu would warrant further detailed investigations.

Key recommendations for future work

Preliminary results from this study indicate the existence of a steady geothermal system at Rabulu, Fiji. However, additional and/or repeated geophysical investigations on the site are required to quantify the claim presented in this study. After analysing the results obtained in this investigation and studying similar investigation available in the literature, the following recommendations are made:

1. Repeated SP profile measurements are required to investigate the possible effects of environmental conditions and monitor variations due to changes in climatic conditions. SP repeatability measurements form an important monitoring tool for geothermal exploration and should be carried out extensively in Rabulu. The preliminary SP survey conducted in the present study showed zones of SP anomalies necessitating further investigations and interpretation.
2. The shallow thermal measurements results provided an estimation of the high thermal gradient at the Rabulu hot spring site. However, detailed and more in-depth thermal and heat flow measurements are required. This can be conducted using either a shallow well and (or) through deep well (drilling). Thermal measurements are necessary to forecast information about the exact capacity of the geothermal reserve. Knowledge of thermal gradient and conductivity should provide a measure of heat flow in the area (Kana et al. 2015). According to Wang et al. (2013), the thermal conductivity of the ground is directly related to the temperature-depth relationship and is sensitive to the local onsite geology and affected by factors, such as mineral composition, density, pore fluids and saturation. This study recommends that deeper levels of ground temperature are needed to estimate the available geothermal resource. It is important to note that drilling will be a fairly expensive task for a small developing country like Fiji and shallow wells are not always adequate to get accurate result. However, investing in geothermal exploration investigations could prove beneficial to Fiji as it can lead to an unearthing a new renewable energy reserve offering benefits to the people of Fiji.
3. Other geophysical measurements to map the subsurface structures of the Rabulu hot spring site are needed. Application of geophysical methods such as Electrical Resistivity Tomography (ERT) surveys can be instrumental in providing 2D and 3D images of the distribution of the electrical resistivity of the underlying geological structures of the hot spring system. Also, magnetic and gravity method over the entire Rabulu area could bring reliable information on the location of the magmatic chamber and the main geothermal reservoir. Ground penetrating radar can also be used to characterise subsurface processes and structures at the Rabulu hot spring site. In addition, frequency domain electromagnetic (FDEM) and remote sensing surveys can provide vital information on the faults and the geological framework of the area.

Conclusion

This present study investigated the SP, GT and soil CO_2 concentrations distribution at the Rabulu hot spring zone. Profiles for SP, GT, soil CO_2 concentration and elevation were constructed at the hot spring site. The SP profile peaked at the hot water discharge zone with a maximum potential of $\sim$ 120 mV. Ground temperatures followed similar pattern and correlated with the SP profile. Soil CO_2 concentration results showed similar trends as SP and GT profiles. Highest soil CO_2 concentration of 674 ppm was measured at precisely the same location where maximum SP and GT values were observed. Variations in SP with elevation revealed that the groundwater upwelling zones correlated with the hot spring discharge location observed at the surface. Elevated ground temperatures were observed at the thermal water discharge area at the hot spring site. The thermal probe measurements also delineated high-temperature anomalies at the hot spring location. The highest GT of $\sim$ 32.7 °C was recorded at 1 m depth by the probe installed directly at the hot water discharge zone. This result indicated an area of possible high thermal gradient and high reservoir temperature beneath the hot spring system. Ground temperature profiles and its spatial distributions described some major thermal anomaly in the area necessitating further investigation. The elevated high CO_2 concentrations observed at the surveyed area were attributed to the geothermal system and possibly due to a magmatic source underneath the hot spring system. Hot spring water temperature remained constant with no significant variation over the measurement period. In addition, a discharge rate of $\sim$ 0.2 L/s was recorded throughout with no major variations with an estimated $\sim$ 60.4 kJ/kg energy flux recoverable from the Rabulu geothermal field. On average, Cl^- and Ca^{2+} content were found to be 144.0 mg/L and 41.1 mg/L, respectively. When compared with the tap water and distilled water samples, hot spring water was found to have greater amount of Cl^- and Ca^{2+} content. Diurnal temperature variations were found to have no effect on the temperature of discharged thermal water. The integrated multi-disciplinary geophysical methods used in this study were apposite in characterising near-surface features of the Rabulu hot spring system. Initial findings from this study suggest that the presence of the geothermal energy source at the studies location can be of economical benefit to the people of Rabulu settlement and nearby Fijian communities. In this regard, a comprehensive investigation on the energy capacity of the reserve needs to be conducted as future work.

Acknowledgements The authors would like to acknowledge University of the South Pacific (USP), Faculty of Science Technology and Environment Research Committee for funding this study. The authors also acknowledge the local community of Rabulu for allowing access to the site. Lastly, the authors acknowledge the associate editor and the two reviewers for their comments and suggestions, which helped in improving the manuscript.

Compliance with ethical standards

Conflict of interest The authors of this paper declare that there is no conflict of interest.

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