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Structure of a low-enthalpy geothermal system inferred from magnetotellurics — A case study from Sri Lanka

Thusitha Bandara Nimalsiri [a], Nuwan Buddhika Suriyaarachchi [a], Bruce Hobbs [b], Adele Manzella [c], Morrel Fonseka [d], H.A. Dharmagunawardena [e], Nalaka Deepal Subasinghe [a,*]

[a] *National Institute of Fundamental Studies, Hanthana Road, Kandy, Sri Lanka*
[b] *Department of Geosciences, University of Edinburgh, Edinburgh, United Kingdom*
[c] *CNR-International Institute for Geothermal Research, Via Moruzzi 1, 56124 Pisa, Italy*
[d] *Department of Physics, University of Ontario, Ontario, Canada*
[e] *Department of Geology, University of Peradeniya, Peradeniya, Sri Lanka*

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A B S T R A C T

First comprehensive geothermal exploration in Sri Lanka was conducted in 2010 encompassing seven thermal springs, of which Kapurella records the highest temperature. The study consisted of passive magnetotelluric (MT) soundings, in which static shifts were corrected using time domain electromagnetic method (TDEM). A frequency range of 12,500–0.001 Hz was used for MT acquisition and polar diagrams were employed for dimensionality determination. MT and TDEM data were jointly inverted and 2D models were created using both transverse electric and transverse magnetic modes. A conductive southeast dipping structure is revealed from both phase pseudosections and the preferred 2D inversion model. A conductive formation starting at a depth of 7.5 km shows a direct link with the dipping structure. We suggest that these conductive structures are accounted for deep circulation and accumulation of groundwater. Our results show the geothermal reservoir of Kapurella system with a lateral extension of around 2.5 km and a depth range of 3 km. It is further found that the associated dolerite dike is not the source of heat although it could be acting as an impermeable barrier to form the reservoir. The results have indicated the location of the deep reservoir and the possible fluid path of the Kapurella system, which could be utilized to direct future geothermal studies. This pioneering study makes suggestions to improve future MT data acquisition and to use boreholes and other geophysical methods to improve the investigation of structures at depth.

1. Introduction

Kapurella thermal spring is located in the Eastern Province in Sri Lanka, near the boundary between Baticaloa and Ampara districts (Fig. 1). It is in the form of a cluster of springs found in a marshy uninhabited area. Kapurella records the highest surface temperature (73.5 °C) amongst all Sri Lankan thermal springs, and the thermal water has a pH of 8.4 with an average conductivity around 1400 μS/cm (Subasinghe et al., 2011). Geochemical analyses carried out by Subasinghe et al. (2011) provided reservoir temperatures around 135 °C using Na–K–Ca geothermometers, whereas, Chandrajith et al. (2013) obtained a maximum temperature of 128 °C based on silica geothermometers.

Sri Lanka, though not located close to an active tectonic boundary, has a productive collection of thermal springs scattered around the country. The surface temperatures of these springs vary between 38 and 73.5 °C. Although most of these thermal springs have been known for several centuries, the literature on thermal springs is incomplete. The origin of these springs has been debated and is attributed to two different theories: 1) an upwelling of fluid through deep fractures facilitating circulation of groundwater heated by normal geothermal gradient and 2) a hot rock of young age (160–170 Ma) acting as the heat source.

Several investigations (Dissanayake and Jayasena, 1988; Fonseka, 1995) have been carried out on these springs, where geochemistry and origin of the systems have been put into consideration. A recent study by Senaratne and Chandima (2011) based on geological, structural and hydrogeological studies discusses the relationship of young (160–170 Ma) dolerite intrusions with the thermal springs at Wahawa area, which is 35 km from the Kapurella springs. They suggest that these dolerite dikes provide the heat for the thermal system where highly fractured metamorphic basement acts as the reservoir. The most recent study by Chandrajith et al. (2013) summarizes that the thermal waters

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* Corresponding author.
E-mail addresses: tnimalsiri@gmail.com (T.B. Nimalsiri), nuwan1985@gmail.com (N.B. Suriyaarachchi), bruce.hobbs@pentlandgeophysics.com (B. Hobbs), manzella@igg.cnr.it (A. Manzella), morrelf@gmail.com (M. Fonseka), dharmag@pdn.ac.lk (H.A. Dharmagunawardena), deepal@ifs.ac.lk, deepal@writeme.com (N.D. Subasinghe).

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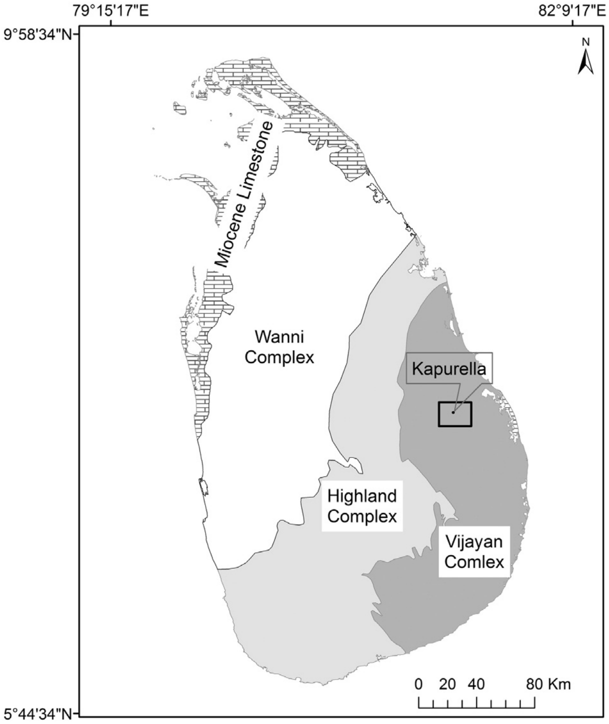

Fig. 1. Geological setting of Sri Lanka. Major crustal subdivisions, location of the Kapurella spring system and the study area (black rectangle) is marked here.

of these springs are fed by meteoric water of the dry/intermediate climatic zone of Sri Lanka.

Increasing price and the depleting resources of fossil fuel have raised interest in renewable energy. Its 24 h a day, 7 days a week operability independent of the weather conditions has made geothermal energy a better base load power source over solar, wind and wave power. In areas like Italy, Iceland and New Zealand, this energy has been utilized since early 20th century (Lund et al., 2005) where recent tectonism and related volcanism are prevalent. However, recently low enthalpy thermal systems have also been investigated for their geothermal potential in Australia and Italy (Brugger et al., 2005; Bruno et al., 2000).

The first comprehensive geophysical exploration of Sri Lanka, focusing seven thermal springs which are associated with a crustal complex boundary, possibly active in the past, was conducted in 2010 using magnetotellurics (MT) and time domain electromagnetics (TDEM). In that study, Hobbs et al. (2013) tried to locate any abundant thermal waters or hot dry rocks within the economically viable depths and provided the first insights of the thermal belt of Sri Lanka as a whole using the MT results. Their results show a low resistive formation of a few hundred square meters in extent at a depth of 500 m in Kapurella. The objective of our current work is to present a more detailed geophysical interpretation of the structures in Kapurella thermal system using the acquired MT data.

2. Geological setting

More than 90% of the crust in Sri Lanka is composed of amphibolite to granulite grade crystalline metamorphic rocks (Cooray, 1994). Geochronological and structural evidence (Braun and Kriegsman, 2003) confirms that three distinctive lithological units lie side by side to form the Precambrian basement of the island. The rest of the rocks belong to the Miocene sedimentary sequences found in the north and north western coast of Sri Lanka (Fig. 1). The Highland Complex (HC) is the oldest formation (<2 Ga) lying in the center bounded by the Wanni Complex (WC) (1.1–2 Ga) to the northwest and Vijayan Complex (VC) (1.1–2 Ga) to the East (Kehelpannala, 1997). The boundary between the HC and VC is identified as a mini plate boundary which is supported by several magmatic and hydrothermal fluid mineralizations (Dissanayake and Weerasooriya, 1986; Munasinghe and Dissanayake, 1979). Most of the ductile structures have been formed during the collision and the peak metamorphism periods (610–550 Ma) of the crustal units (Kröner et al., 1991, 2003; Osanai et al., 2006). However, the brittle structure of the island has no direct relationship with the ductile events but, has been formed during the break-up of East Gondwana about 130 Ma ago. These younger NE–SW trending fractures and lineaments were formed due to the continuous NNW–SSE compression which is still active in the Indian Ocean (Kehelpannala, 1997). The thermal spring belt of the island is loosely associated with the HC–VC boundary.

Kapurella thermal spring is located approximately 20 km away from the HC–VC boundary in the VC side. The area is generally a flat terrain with few outcrops. The lithology of units underlying the terrain is composed of pink granitoid gneisses, hornblende biotite–migmatite and biotite–hornblende gneisses and the study area is characterized by a number of fractures and faults (Fig. 2). The prominent fracture trends in the NE–SW direction and it makes up the lineament governing the structure of the area. Another identifiable fracture system is directed NNW–SSE and combines with the former to control the hydrology of the area.

The dolerite dikes are the youngest intrusions found in the Sri Lankan basement within the age between 160 and 170 Ma (Takigami et al., 1999). These are mostly found in the Vijayan complex and many are found in a north-western strike relative to the current location of the island.

3. Methodology

Normally, geothermal explorations are carried out using various geophysical methods including reflection seismic (Bibby et al., 1995; Brogi et al., 2005), gravity (Hochstein and Hunt, 1970; Stagpoole, 1994) and DC resistivity (Risk et al., 1994; Zohdy et al., 1973). The combination of various methods usually provides a better image of the subsurface. The necessity of a strong active source for deep probing reflection seismic and the limited funds excluded active seismic methods in Sri Lankan exploration program. Since the geothermal area at Kapurella is in crystalline units with fractures and interconnected fluid pathways, they should be characterized by strong electrical resistivity contrasts where EM methods can effectively be employed (Spichak and Manzella, 2009). But, since DC resistivity method does not have favorable investigation depths, geothermal explorations are often employed by magnetotellurics (Thanassoulas et al., 1987; Volpi et al., 2003).

Tikhonov (1950) and Cagniard (1953) first discussed the theory of MT and pointed out that the relationship between horizontal electric and magnetic fields measured in orthogonal directions at the surface is sensitive to the electrical properties of the subsurface. MT uses natural electromagnetic fields of wide frequency range, depending on the purpose, to provide information about the resistivity distribution of the subsurface (Vozoff, 1972). Further, with the advent of tensor MT (Cantwell, 1960), the directionality and dimensionality of the structures could also be characterized. With increasing period the EM waves can provide information on greater depths where the depth of penetration is controlled by the resistivity of the structures. If magnetic permeability (μ) is assumed to be unvarying in geological medium, EM wave with an angular frequency ω travels according to $p = (2/\mu\sigma\omega)^{1/2}$, where p is the depth of penetration (skin depth) and σ is the conductivity (Schmucker, 1973; Simpson and Bahr, 2005).

The ratio between the electric (E_x, E_y) and magnetic (B_x, B_y) fields measured at the surface of the Earth gives complex impedance Z (Eq. (1)), with an associated phase (ϕ), which describes the shift between electric and magnetic field components and is given by the ratio between the real and the imaginary components of the impedance. These can further be related with the subsurface resistivity (ρ) (Eq. (3)). Since the

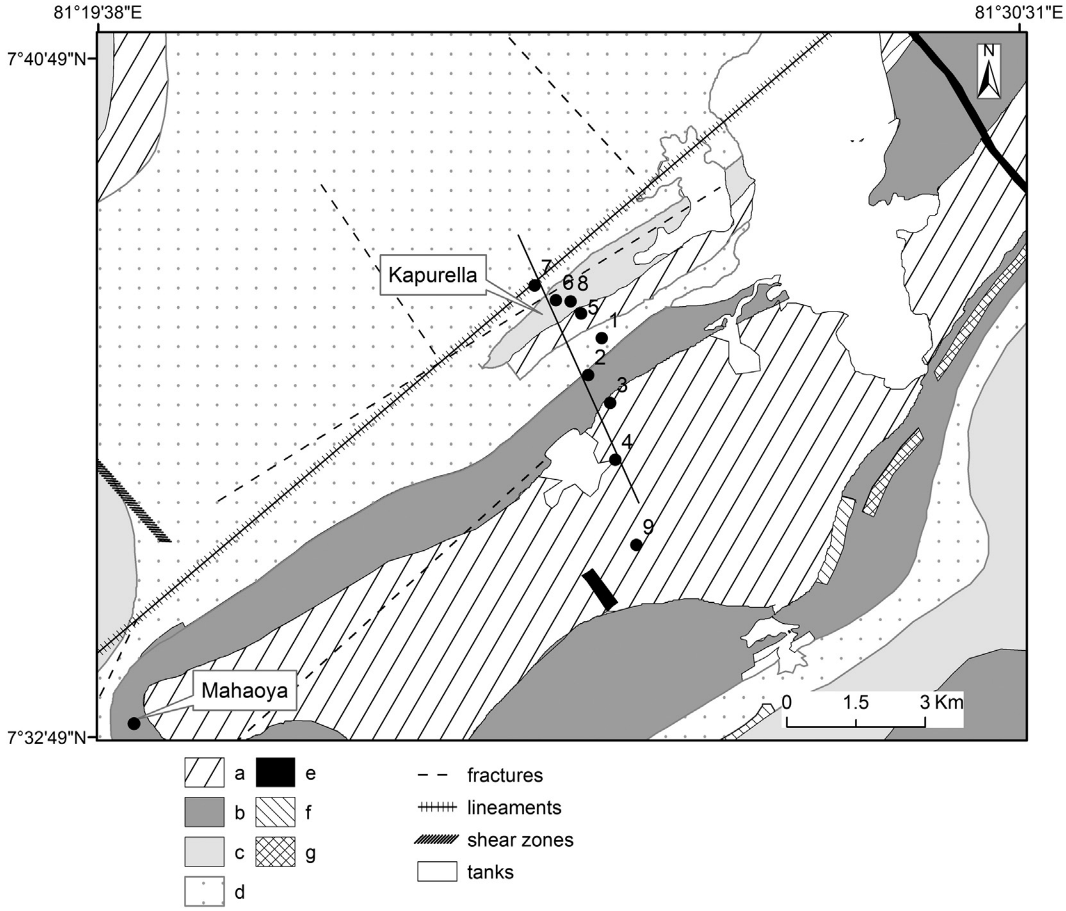

Fig. 2. Geological features around Kapurella thermal spring system. Geophysical sounding points are marked from 1 to 9. Thermal springs are located near sites 6 and 8. The dark line running NW–SE is the profile used for inversion. a — augen gneiss, b — biotite hornblende gneiss, c — granite gneiss, d — hornblende biotite migmatite, e — dolerite, f — calc gneiss, g — hornblende gneiss.

Earth is not always a uniform half-space, the calculated resistivity is the volumetric average of the underlying layers and more appropriately identified as the apparent resistivity (Chave and Jones, 2012; Hermance, 1973).

$$Z = E/\mu B \quad (1)$$

$$\phi = \tan^{-1}(Z_{\mathrm{Im}}/Z_{\mathrm{Re}}) \quad (2)$$

$$\rho = |Z|^2/\mu\omega \quad (3)$$

The MT survey around Kapurella area was carried out in July 2010 using 9 soundings with about 1 km spacing. The S.P.A.M. MkIV (Ritter et al., 1998) system, which was developed at the University of Edinburgh, along with Metronix GMS05 induction coil magnetometers and silver chloride electrodes were used to collect the MT data. The data frequency range was 10,000–.001 Hz and different sampling rates, defining eleven bands belonging to two sets (high frequency and medium frequency), were used.

The effect of local surficial inhomogeneities on MT measurements is inevitable. The electric fields, generated by boundary charges on local bodies, shift the apparent resistivity curves vertically in a log–log scale. This effect is known as the static shift (Berdichevsky and Dmitriev, 1976; Jones, 1988; Pellerin and Hohmann, 1990). As the name implies, static shift is time independent and thus does not affect the impedance phase. To correct for this effect, it is common practice to obtain the resistivity of the shallow units by means of another EM method that is not or less affected by static shift. Time domain electromagnetics (TDEM) method acts as a better alternative to DC resistivity methods (Vozoff and Jupp, 1975) since it lacks direct contact with the ground and it measures only the variations of magnetic field at the surface, which is less affected by the near surface inhomogeneities. This active geophysical tool creates a primary magnetic field that induces a secondary magnetic field in the subsurface. Using the resistivity information of the first few hundred meters gathered by the TDEM technique static shift can be eliminated (Sternberg et al., 1988). The relationship between MT frequency (f) and the turn off time (t) in TDEM has been experimentally shown to be approximated by $t = 1/3.9f$ (Meju, 1996; Sternberg et al., 1988).

TDEM data were collected using Geonics Protem system (Transmitter-Protem 47 and receiver-Protem 58) at all the MT sites with repetition rates ranging from 267.5 to 0.25 Hz. Central loop configuration was implemented while maintaining a transmitter area of 2500 m^2 in all the cases and the receiver antenna area was 31.4 m^2.

4. Data processing and modeling

Of the acquired nine MT soundings, site 9 had to be removed due to extreme noise and unusual behavior of phase. Time series data were processed using B.I.R.R.P. code described in Chave and Thomson (2004). Here, the response functions are estimated based on bounded influence estimator in which outliers and leverage points are effectively removed.

After data processing, the data analysis was focused on defining the strike of the underlying geoelectric structures, which plays a major role in 2D modeling of MT data. Swift (1967) described a method maximizing and minimizing certain combinations of impedance elements in MT tensor data to evaluate the strike direction. The *Swift strike* however has an ambiguity of 90° that cannot be removed by a mathematical method alone. A reliable and complete strike is represented using the impedance polar plots (Berdichevsky and Dmitriev, 2008; Reddy et al., 1977; Savvaidis et al., 2000) where the individual impedances (Zxy and Zxx) are plotted against a rotation direction. As Reddy et al. (1977) describes, diversions from a perfect 2D Earth or noisy data can result in distorted impedance polar ellipses where a homogeneous Earth would always yield circular plots. In a perfect 1D condition, the Zxy component acquires a circular plot where the Zxx component is a point. The Zxy plot elongates either parallel or perpendicular to the geoelectric strike direction depending on its position with respect to the discontinuity in a 2D Earth. The Zxx component, on the other hand, acquires a symmetric flower structure in a 2D Earth and in a 3D Earth it elongates in one direction where its amplitude become comparable with those of the Zxy component.

Fig. 3 shows the complete representation of polar diagrams and hence strike for the Kapurella thermal springs. Polar plots of highest frequencies symbolize more local, shallow structures, whereas those related to the lowest depict regional structures. Except for the low frequencies of sites 7, 8 and 3, showing uncertain inferences of data noise and higher dimensionality, the rest of the polar plots agree into a regional 2D structure. There are two distinctive elongation directions observed in the polar diagrams, one towards the NW and the other towards NE. The sites 7 to 8 on NW show a north-westward elongation direction that gradually transforms into a north-eastward direction starting from site 5. This flipping of the polar plots means that there is a change in the preferred current flowing direction accounted by a contrast in the resistivity structure underneath and identified as the geoelectric strike. The strike for the 2D modeling was fixed at N65E, based on both polar diagram directions and the maximum separation of the Zxy and Zyx components taken into consideration.

In Occam's 1D inversion algorithm (Constable et al., 1987), instead of merely fitting the experimental data, a smooth model is produced within a certain limit of tolerance which reduces the model roughness. The

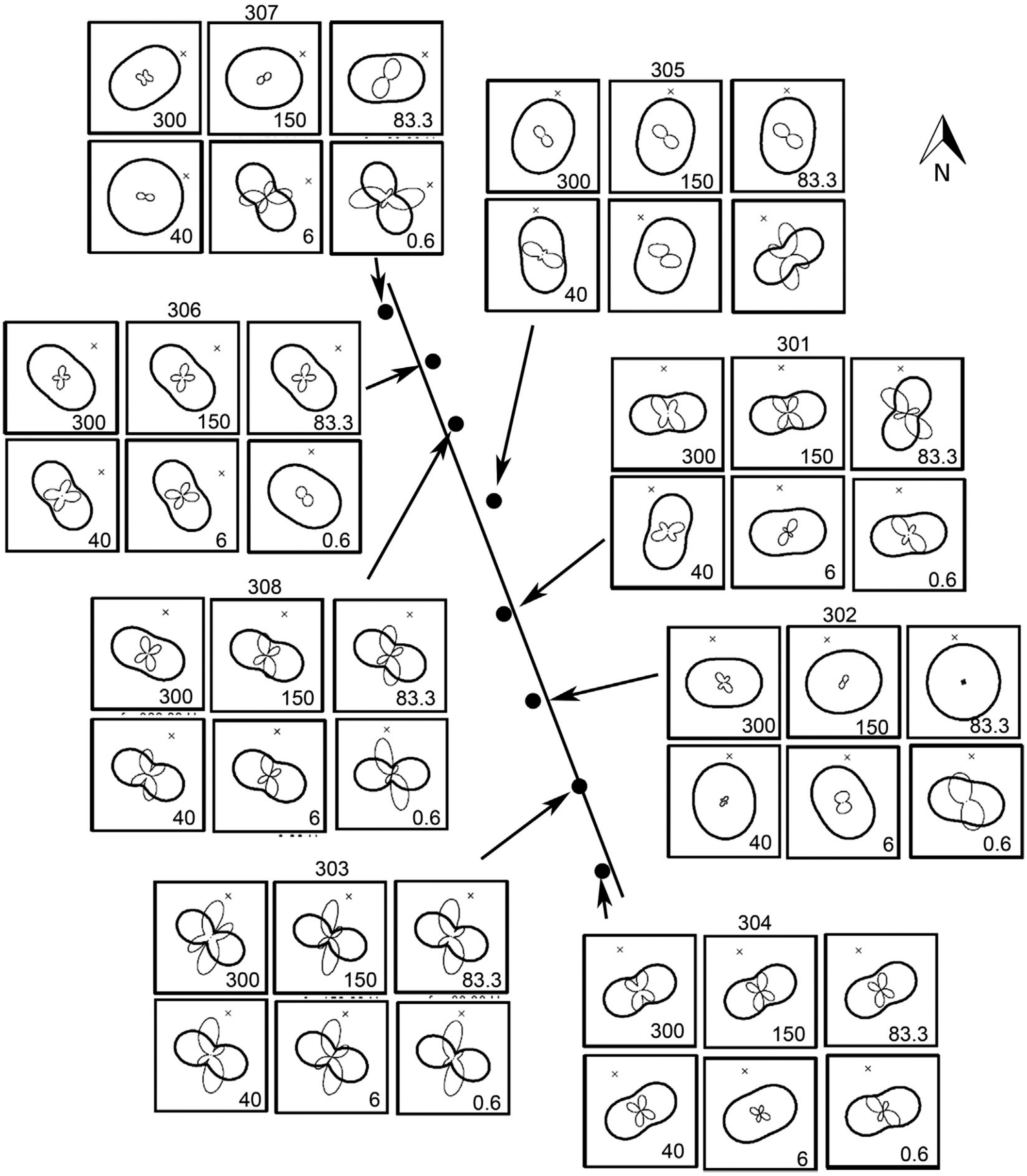

Fig. 3. Impedance polar diagrams of the Kapurella spring system. The dark NW–SE trending line represents the profile on which the 2D inversion model is constructed. Sites are marked on the profile with black circles. The thick outer ellipses denote Zxy component and the lighter inner ellipses the Zxx component. The 'x' marked here is the impedance strike. Frequency of each polar diagram is given at the bottom of each ellipse.

TDEM data were modeled based on the Occam's inversion where 3 layers were selected to fit the data. Then, using the smooth model a layered model was guessed to optimize the inversion. The modeled TDEM curves were used to eliminate the static shift before the 2D inversion (Manzella et al., 2004). MT data were also modeled using the Occam inversion method to produce 1D cross sections but in this paper the discussion is concentrated towards the results from the 2D inversion, which was carried out using an algorithm based on a nonlinear conjugate gradient scheme (Rodi and Mackie, 2001).

The use of different components for the interpretation of MT 2D data has been argued though several authors have suggested different combinations. Theoretically, the transverse electric (TE) component has better ability to resolve vertical structures, whereas the transverse magnetic (TM) mode deciphers the lateral variations better. Wannamaker et al. (1984) discusses the effect of boundary charges that is not accounted for in TE mode and which could give false resistivity values at shallow depths, similarly, the TM mode is less affected by three-dimensional structures and is preferred in 2D modeling (Volpi et al., 2003). However, Berdichevsky et al. (1998) points out that these two modes have different responses to structures at different depths and their robustness towards local 3D inhomogeneities is also different depending on their resistivity, making them both important in identifying the true structures. In our study we have used the strike rotated data, where both TE and TM modes are jointly inverted. Many inversion runs were carried out to estimate the robustness of inversion by checking what features were required by data and what were, instead, produced by numerical fitting. The results we show in the next section has an RMS of 8.78 with an error floor of 3% for apparent resistivity and 4% for phase. The less weight given for phase here is to develop the best fit model while accommodating the relatively higher error bars observed in the phase data.

5. Results and discussion

The selected profile runs along NW–SE direction and was selected perpendicular to the structural patterns observed in the geological and structural map of Sri Lanka. Data with minimal noise were expected in the area that lacks power lines or electric water pumps. Though the lowest selected frequency was 0.001 Hz, the data only up to 0.01 Hz could be used due to insufficient amount of data and the low signal over noise ratio. The amount of data collected for each frequency in the TDEM method was lower. This resulted in distorted curves in TDEM data modeling.

The first insight of the resistivity structure is given by the apparent resistivity and phase pseudosections (Fig. 4). In both TE and TM modes the shallow occurrence of a low resistive funnel shaped structure can be identified near the sites 8 and 6, and this could be the near surface accumulation of thermal water where the springs are fed. The remarkable feature from TM mode is the extension of the above low resistive formation towards SE of the profile as depth increases where it is not present in the TE diagram. This feature complies with what is observed under the same sites in the phase pseudosection diagram. In both modes a high resistive structure is found with a lateral extension of a few km starting from the SE end of the profile.

A better understanding of the underlying structures is gained from the 2D modeled data. Fig. 5a shows the 2D model of Kapurella thermal spring survey along the selected profile. This model is in broad agreement with what derived from the TE and TM modes separately reported in Hobbs et al. (2013), but increased detail can now be seen resulting from a more thorough and intricate analysis. The thermal springs and the shallow accumulation of thermal water are imaged well in Fig. 5a as a conductive pocket covering the same soundings as was in pseudosection diagram (Fig. 4). Most part of the section is composed

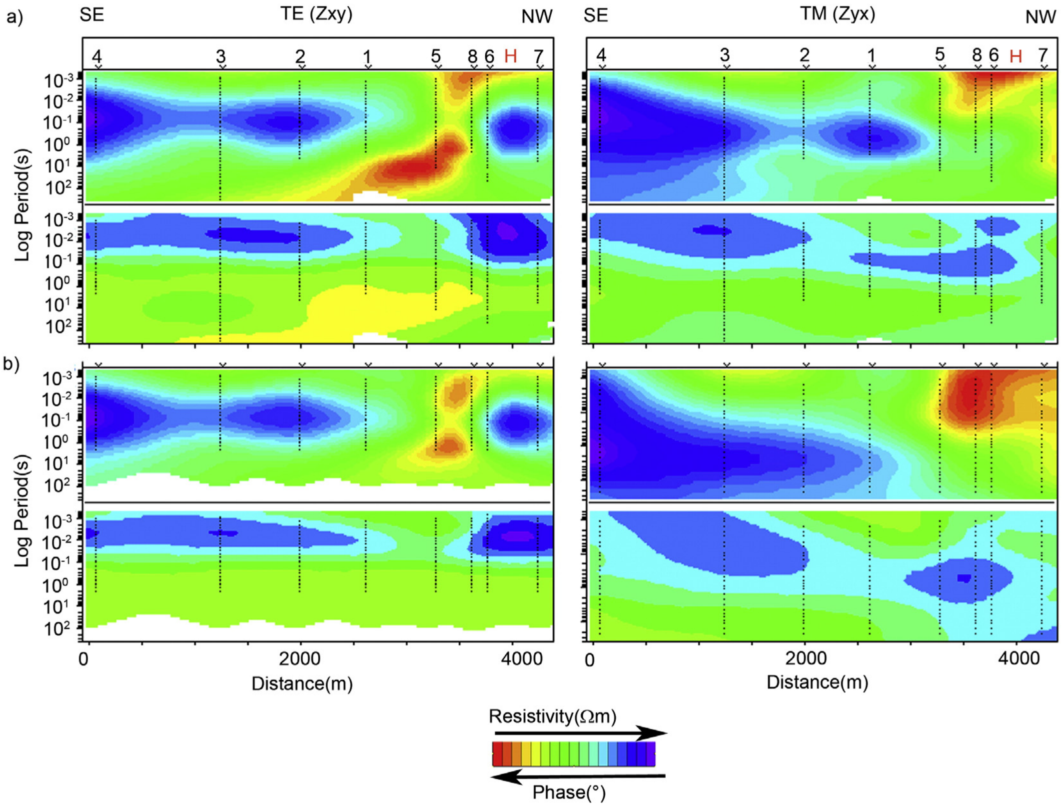

Fig. 4. Resistivity and phase pseudosections of Kapurella for TE and TM components. a) Observed data. b) Responses of the inversion model. In both 'a' and 'b' the top pseudosection shows the apparent resistivity and the bottom one the phase. 'H' shows the hot spring location. Black dots in the body show the periods used for inversion.

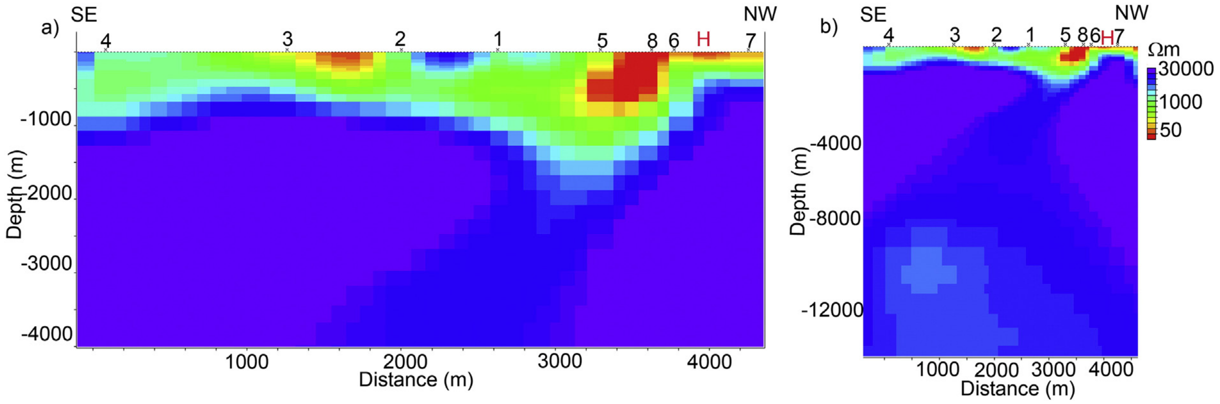

Fig. 5. Joint TE-TM 2D inversion model for Kapurella springs. a) First 4 km. b) To a depth of 14 km. The resistivity range is selected to improve structure imaging. The soundings are marked from 1 to 8 and the thermal spring location is identified as H.

of high resistive structure, which probably represents the underlying metamorphic rock. The striking feature in the 2D profile is the SE dipping low resistive formation that divides the resistive basement. This can be found all the way to the depth of 4 km and appears to be extending further. Fig. 5b shows the same profile down to a depth of 13.5 km where the extension of the conductive plume seems to open into a chamber like formation. The same feature is observed in the TM pseudosection (Fig. 4) depicted both as a decrease in apparent resistivity and an increase in phase.

The unit inferred below 7.5 km depth has a resistivity significantly lower than that of the surrounding, suggesting that it represents the reservoir from which the Kapurella spring is fed. Such reservoir, being hosted in metamorphic rocks, would not produce the typical volcanic conceptual model described in Pellerin and Hohmann (1990) where the reservoir has a higher resistivity than the overlying clay cap. In our case, considering that alteration minerals in metamorphic rocks do not produce a low resistivity and widespread distribution, the low resistivity would indicate volumes of enhanced fluid connectivity, i.e., the reservoir itself. The low resistive southwest dipping feature suggests a fracture which controls the morphology of the area and representing a fluid pathway for thermal water up to the surface. The river "Maha Oya" lies between the sites 1 and 5 and the inferred fracture delineates its flow path over the terrain.

To create thermal anomaly and produce geothermal regions, intrusive bodies need to be younger than 10^4–10^6 years (Berktold, 1983). The dolerite dikes of the study area (Takigami et al., 1999) are older than this range. Moreover, the resulted resistivity structure does not clearly suggest the presence of an intrusive body in the vicinity. Nevertheless, it does not necessarily exclude dikes as the source for the geothermal manifestations. More likely the fluid circulation takes place in volumes of rocks of enhanced permeability produced by fractures and faults. The geothermometric calculations indicate a reservoir temperature around 135 °C, that for an average temperature gradient of 25 °C/km would correspond to a depth of 4–5 km since the medium air temperature at Kapurella is around 30 °C. Thus, for the case at Kapurella, meteoric water may percolate deep through the fractures where it gets heated up in the fractured basement creating a reservoir, and routed back to the surface through another set of deep fractures (Chandrajith et al., 2013; Dissanayake and Jayasena, 1988).

6. Conclusions

In this study we attempted to understand the structure of the Kapurella thermal springs in Sri Lanka with magnetotellurics and time domain electromagnetics. The resulting interpretations indicate the conductivity variation of the area characterizing the structures below. The near subsurface of the locality of thermal springs is marked by a high conductive pocket. The SW dipping extension from this high conductive pocket shows the feeding fracture zone. The impermeable metamorphic basement, in either side of the fracture zone, is characterized here by higher resistivity. The current analysis shows the deep reservoir of the Kapurella system to begin at 7.5 km depth.

Future geothermal explorations can be improved based on the results of this study. MT data acquisition at long periods should be done with extended time spans to improve the data quality. Once the borehole data in the area is available, 2D inversion modeling could be improved by using them to produce initial, priori inversion models. Employing the vertical component of the magnetic field could help to eliminate the ambiguity in deciding the strike direction. It would be vital to use another geophysical technique (e.g. seismic) to confirm the structures controlling the fluid migration. Nevertheless, the MT technique is superior to any other method in identifying deep fluids in high resistive crystalline rocks, and future explorations with the suggestions made here are recommended to continue with MT.

In order to economically tap the geothermal heat the shallow reservoir should be identified. Thus, the data acquisition in an extended profile with closer profile spacing could be employed. Further, acquiring of vertical magnetic component, long recording and synchronized sites to take advantage of remote-reference technique should be guaranteed. Moreover, TDEM data should be acquired with higher quality to improve shallow resolution.

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