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Characterization of a Low Enthalpy Thermal Spring System Using Magnetotellurics (MT) and Time Domain Electro Magnetic Method (TDEM) – an Example from Sri Lanka

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ABSTRACT

Padiyathalawa thermal spring system is located in the Eastern Province of Sri Lanka. Pioneering geophysical exploration using Magnetotelluric (MT) and Time domain electromagnetic (TDEM) exploration was carried out in Sri Lanka in 2010 covering seven thermal spring systems. One of these, Padiyathalawa, consists of more than 10 thermal springs spread around an artesian thermal water well. Eight MT soundings were placed along the N-NW S-SE direction. TDEM data were used for static shift correction of MT data. Joint 1D Occam inversion was performed using TEMTD software. Resistivity profiles up to 20 km depths and strike direction analyses were done using joint inversion results. Results show low resistive formation at the depths 100 to 400 m. Shallow resistivity profile suggests the main fracture dipped toward S-SE direction. Two moderately conductive (<100 Ωm) zones start from a depth of 10 km and extend up to 4km from the surface and are approximately 3 km and 2 km wide. The resistivity signature is comparable to thermal water-bearing fractures with slightly altered hydrothermal minerals from moderate temperature conditions. One highly resistive (>1000 Ωm) feature, approximately 1 -2 km wide, starts from 10 km depth and demarcates the low resistive zone, possibly the impermeable structure indicating the thermal water reservoir boundary. Strike direction analysis shows the same fracture orientation (N40E approx.) for shallow depths (period 0.001- 0.01s), medium depths (period 0.01-1s) and greater depths (period 1-10s) which is comparable to the regional fracture direction. Resistivity results suggest a possible geothermal reservoir at 4km depth and the main thermal water circulation path is a fracture dipped toward S-SE direction from the thermal water spring. Further laterally placed deep MT soundings and borehole data will be helpful to determine the dimensionality of the fracture system associated with Padiyathalawa thermal spring complex.

1. INTRODUCTION

The majority of geothermal fields in the world are closely associated with volcanic zones or hot spot regions. Lava eruptions, geysers, fumaroles and thermal springs can be identified as prominent surface manifestation features associated with potential geothermal fields. Though none of the thermal springs in Sri Lanka are associated with the above features, all hot springs daily spill their thermal water without being manifested as a geothermal resource.

Thermal springs of Sri Lanka are located in close-proximity to the geological boundary between the Highland Complex and the Vijayan Complex (figure 1). Along this boundary, an approximately 350 km long 'thermal spring line' was identified for investigation in a pioneer study (Hobbs et al., 2013, Nimalsiri et al., 2015) with the following key objectives.

1. To understand subsurface conditions in selected thermal spring areas of Sri Lanka
2. To model and propose thermal and spatial distribution of subsurface heat sources using state-of-the-art electromagnetic techniques.
3. To propose possible mechanisms of thermal water circulation.
4. To shed more light on geothermal resources in Sri Lanka with the view to develop them for national benefit.

Thermal springs at Padiyathalawa were selected from eight well known thermal spring locations for this study (figure 1).

1.1 TDEM method

TDEM method is a resistivity imaging technique used in shallow earth exploration. It is extensively employed in many exploration areas including mineral exploration and geothermal resource exploration. This method can be used in many areas where conventional electrical resistivity methods practically cannot provide good results such as marshy lands or glaciers.

The TDEM method uses a controlled source EM (electro-magnetic) transmitter and an EM receiver. The TEM method uses induced currents in the ground caused by primary electromagnetic waves generated from a transmitter loop. It measures the induced magnetic field with respect to the generated magnetic field from transmitter loop. During data processing steps, these magnetic field responses are converted to apparent resistivity values and modeled into true resistivity figures.

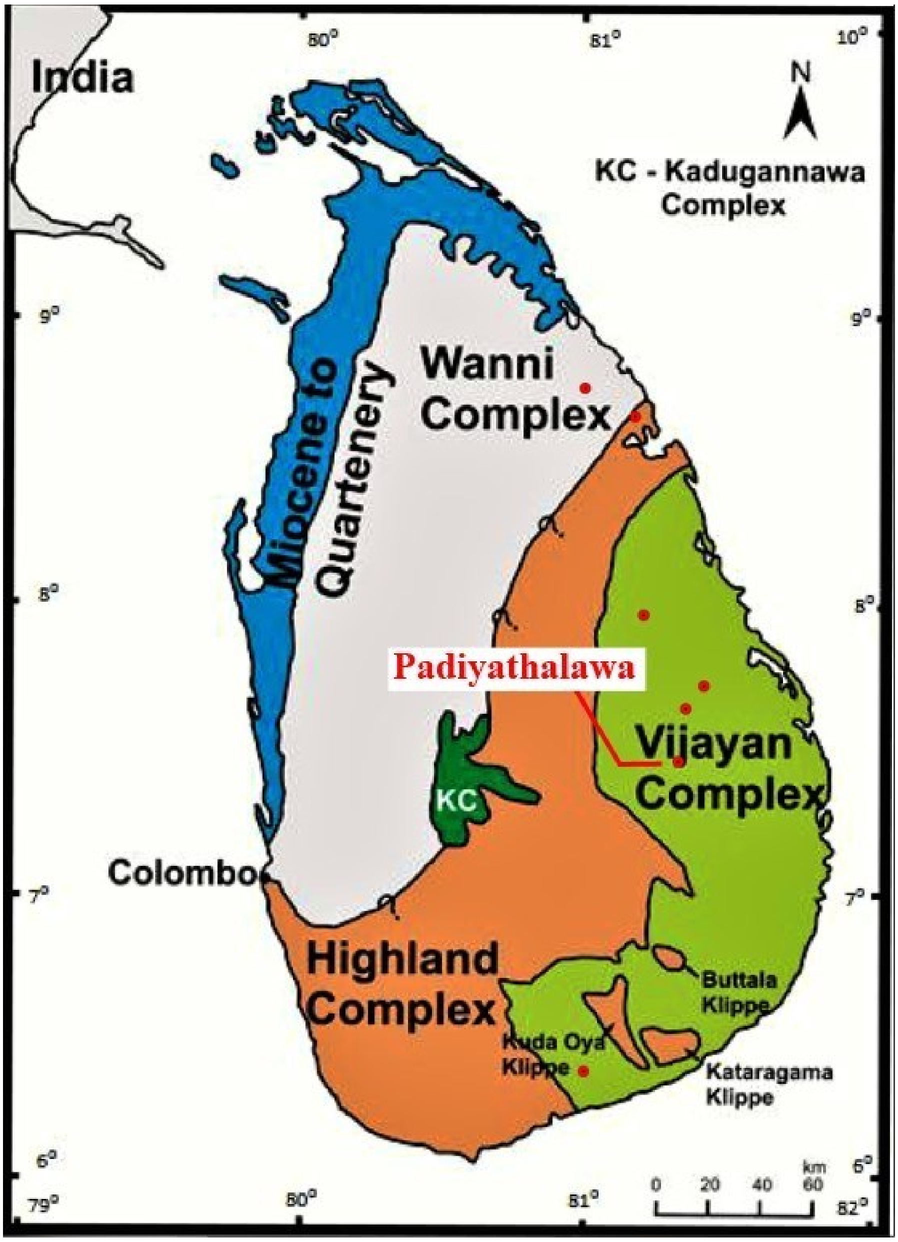


Figure 1: Relative locations of thermal springs of Sri Lanka (red dot) to Highland Vijayan complex boundary (Modified from Cooray, 1994). Study location (Padiyathalawa) is marked here.

1.2 MT method

Magnetotellurics (MT) is a passive geophysical exploration technique. It uses naturally occurring EM waves (from lightning, solar wind) as its source and it measures both the electric field (E) and magnetic field (B) in orthogonal directions generated from secondary induced fields. According to the frequencies and amplitudes of the measured electric and magnetic field components, apparent resistivity of earth is calculated. These apparent resistivity vales are then modeled to a multi layered model (say 50 layers) to construct true resistivity as a function of depth.

Resistivity data processing includes several pre-processing, inversion and graphing stages. Open source data processing software namely temx, tem, temtd authored by Árnason, (2006) were used during the above mentioned steps to achieve desired results. The 2D resistivity profiles were prepared using TEMCROSS software (Eysteinsson, 1998) and resistivity maps were plotted using TEMRESD (Eysteinsson, 1998) for different depths.

1.3 Data acquisition

The map (figure 2) shows the relative locations of MT sounding sites located close proximity to three thermal springs, namely, Padiyathalawa, Mahaoya and Kapurella. All thermal springs discharge only thermal water around 35 – 45 °C at the surface with occasional gas bubbling. Approximately 8 deep soundings (MT) ware located close to each thermal spring system. For this case study, EM data from Padiyathalawa thermal spring system was used. 8 MT soundings and 8 TDEM sounding were carried out. TDEM sounding were co-located with MT soundings to minimize static shift problem. Approximately 1 km spacing was maintained between soundings. Each MT sounding carried out for 8 to 10 hours duration.

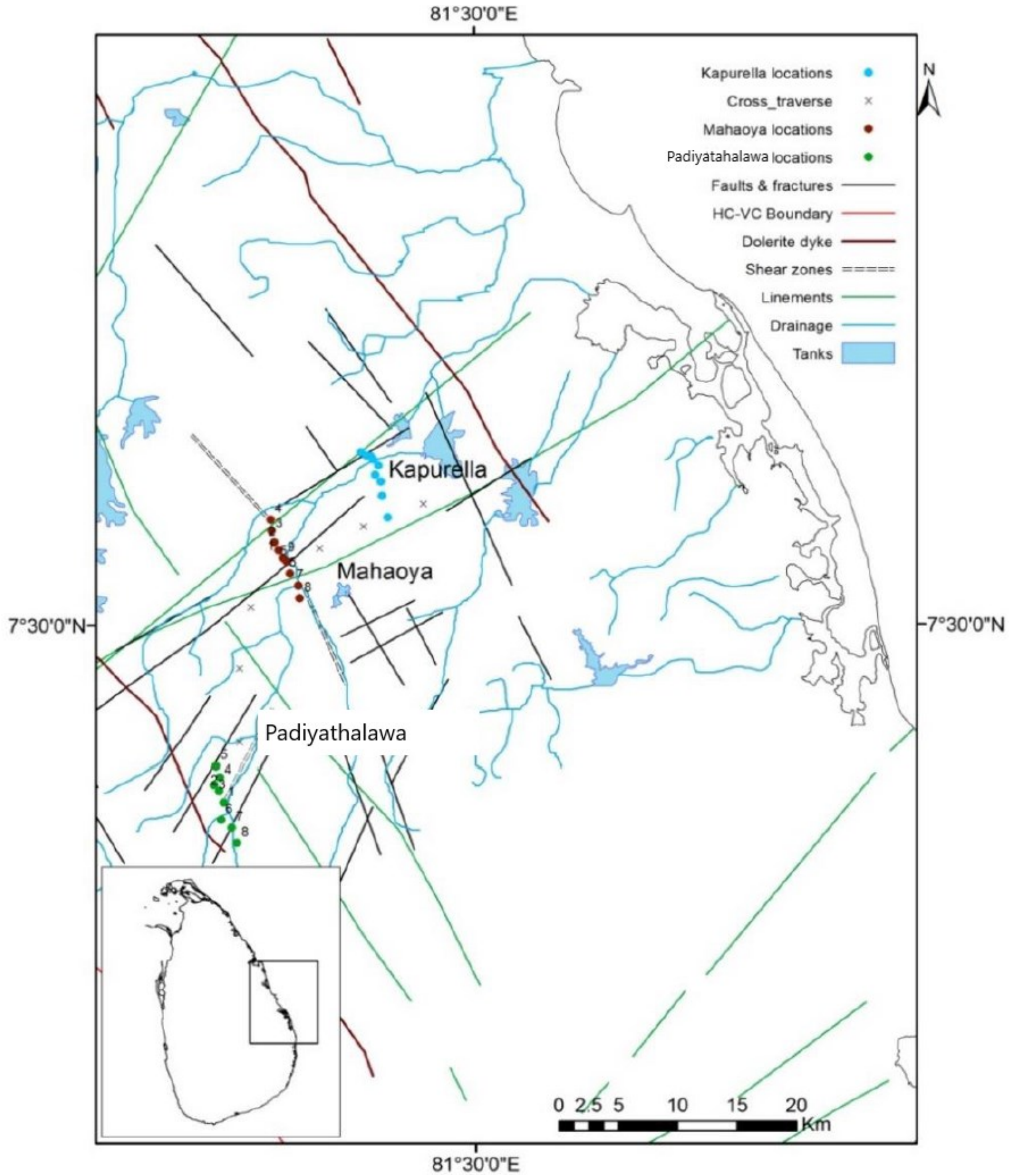


Figure 2: Relative locations of MT sounding locations around Padiyathalawa, Mahaoya and Kapurella thermal springs of Sri Lanka

2. RESULTS AND DISCUSSION

2.1 Shallow resistivity profiles

Resistivity profile at Padiyathalawa (figure 3) shows relatively high surface resistivity across the studied area. Highly resistive zone (>1000 Ω m) around 30 m thick appears in the cross section suggesting existence of dry soil or non-permeable layer up to 30 m depth. Within the high resistive layer, a few slightly lower resistive (500 -1000 Ω m) zones (below site No 6 and 8) around 30 m thick are visible.

Around sounding point 2 (site 02), a low resistive zone is located. Swampy conditions are observed around the sounding point, possibly caused by hot discharge from the thermal spring. In support of that, the whole area next to the hot spring is covered with marshy paddy fields which extend towards sounding point 01. Very low resistive area (1 – 10 Ω m) is located below sounding site 6, and it is extended toward sites Nos 01 & 02.

Below Site No 3 and 6, a very high resistive (>1000 Ω m) zone dominates up to depths of 50 m b.s.l.(-50 m.a.s.l). There are two possibilities to make highly resistive zone with high resistivity signature. Very dry soil condition (very low moisture) or non-permeable layer (rock) can appear as a high resistive zone. Here is possibly the location of a low permeable rock layer over the thermal water reservoir and thermal water flows through another fracture plane, which is not visible as a resistivity contrast in this resistivity profile.

Apart from the main low resistive zone (below site No 6), another low resistive region (20 – 100 Ω m) is located directly below the No 2 sounding point. Considering the depth and the resistivity signature, it is possible to have a thermal water bearing fracture in this location which is possibly connected to the main thermal water circulation fracture below sounding site No 6. According to this shallow profile, the main thermal water circulation path could be located between site Nos 6 and 1 which is demarcated by the white dotted oval.

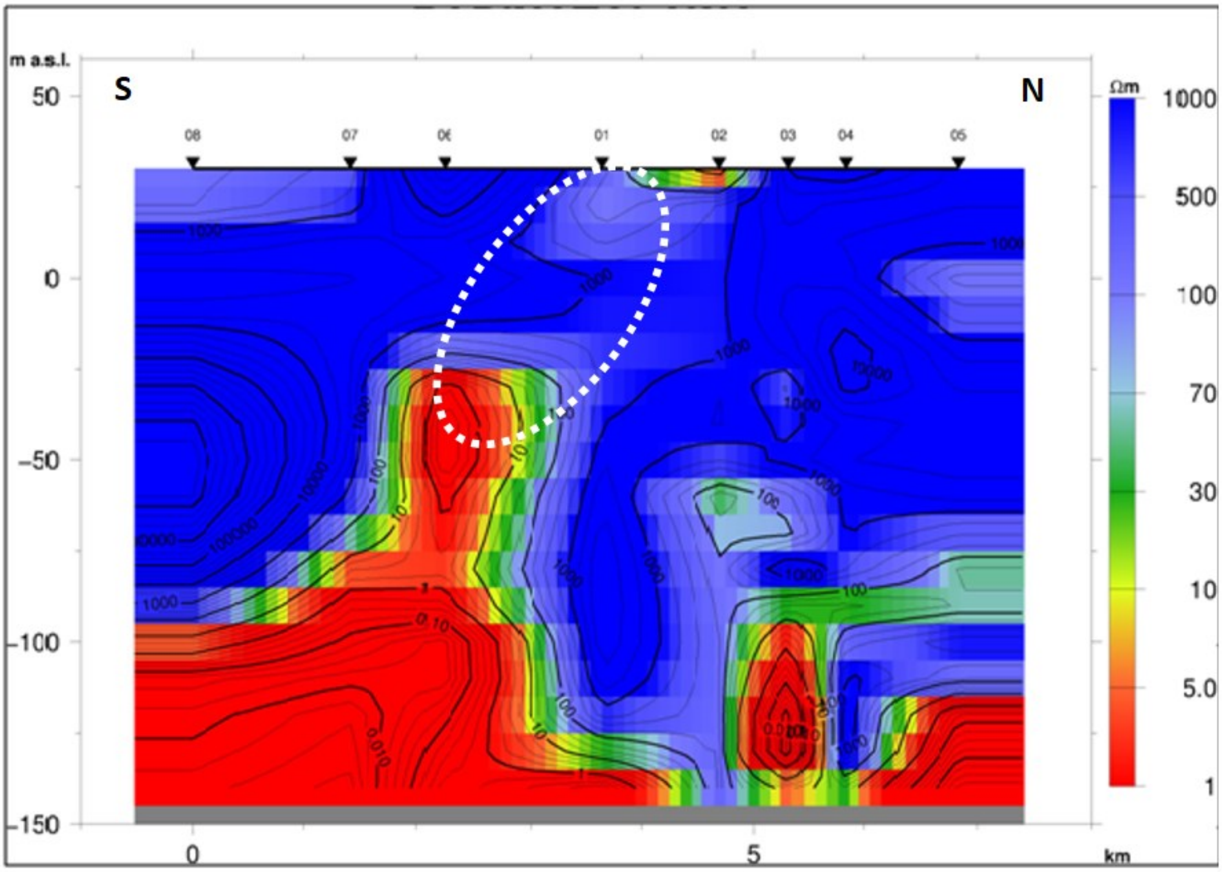


Figure 3: Resistivity profile for shallow depths, Padiyathalawa hot spring area, depth meters above sea-level (m.s.a.l)

2.2 Deep resistivity profiles

Deep earth resistivity images show low resistive intrusive features below Nos 07, 01 and 02 sounding points. Compared to the shallow profile data, the low resistive feature is shifted further toward No 07 (figure 4, figure 5).

In the resistivity cross-section (figure 4) at Padiyathalawa thermal spring area, moderately low resistive values are located close to the surface. Below the No 7 sounding point, a low resistive pocket can be seen. This is the same location where TDEM resistivity profile shows low resistive pocket at shallow depths.

For the depths from 500 m to 2000 m below sea level (figure 4), high resistive conditions (> 1000 Ω m) are dominant for the whole profile. At 2000 m depth, below the No 7 sounding site, a moderately low (100- 800 Ω m) resistive zone starts to appear. In the middle of the low resistive zone (below the No 7 sounding site) resistivity values drop further to 50 Ω m. In addition, another moderately low resistive zone emerges below No 2 sounding site at the depths of 4500 m.

Beyond 5000 m depth (figure 5), one deep driven narrow low resistive (< 70 Ω m) feature below the site No 7 and another low resistive zone (< 70 Ω m) below the Sounding sites 1, 2 and 3 can be observed. A moderately low resistive cap (< 1000 Ω m) can be observed above the low resistive feature. According to Harinarayana et al.(2006), resistivity values lower than 10 Ω m could be a resistivity signature of a cooling magmatic body. Considering the resistivity values of Padiyathalawa thermal spring system, resistivity and temperatures could be comparable to a cooling magmatic body.

Since Sri Lanka is not on a highly active tectonic zone, we cannot conclude these roots are part of convection magma currents. The study by Gokarn et al (2002) in Puga valley India, suggested anomalous resistivity less than 10 Ω m could indicate presence of partial melts. The resistivity value of the low resistive zone (figure 5) at a depth of 9-10 km is comparable with the above suggestions. However, resistivity of the magmatic source is usually lower than 5 Ω m and our resistivity values do not reach that limit. Therefore, there is no evidence for liquid magma chamber. The alteration zones are clearly visible in TEM profiles (shallow resistivity profiles) as low resistivity zones. Low temperature alteration minerals such as smectite, zeolites and mixed layer clay minerals could be formed in hydrothermal water convection zones. Shallow depth resistivity structure should be studied further to understand the dimensionality of shallow fluid flow paths. Laterally spaced TDEM soundings study around the manifestation area is highly useful to determine complete fracture system and possible shallow thermal water bearing zones.

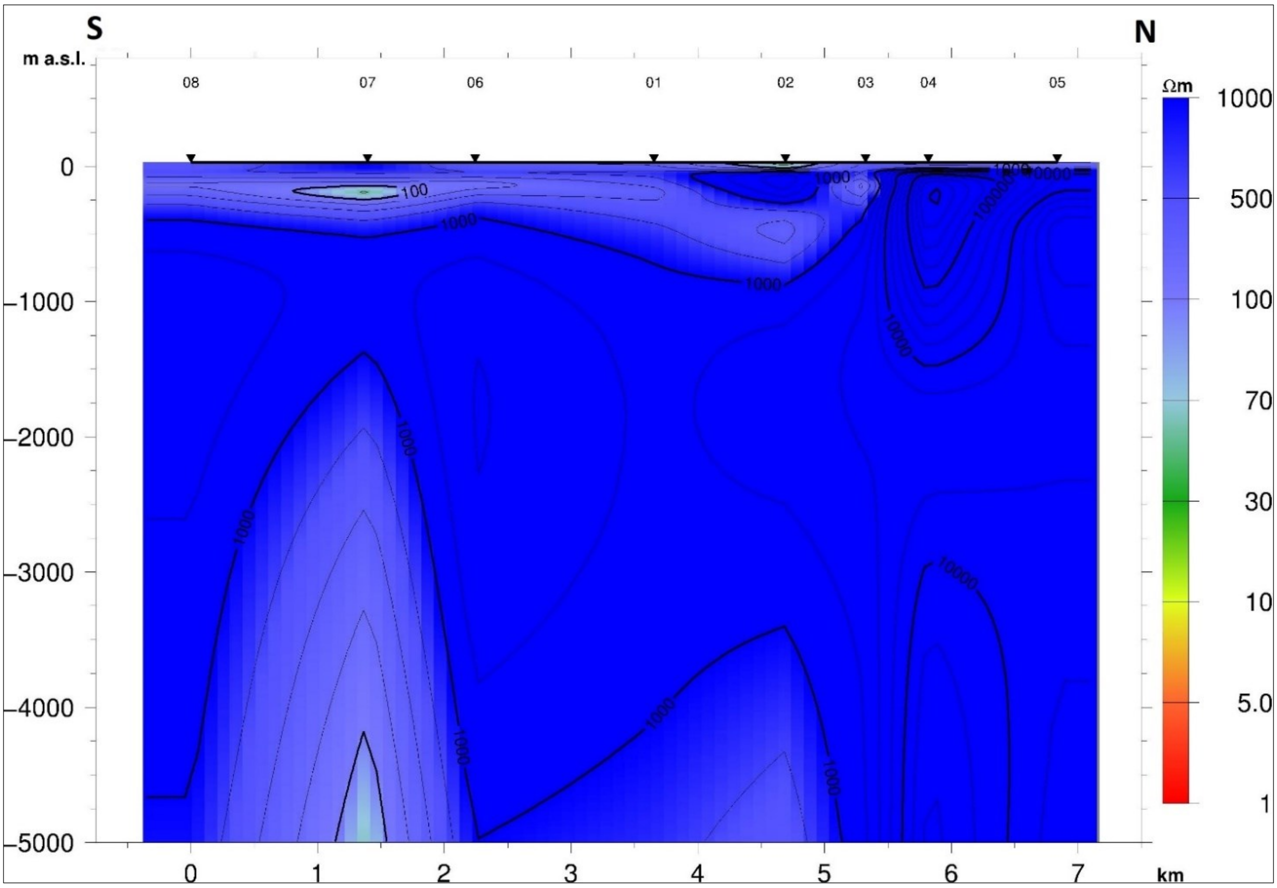


Figure 4: Resistivity profile Up to 5000 m depth, Padiyathalawa hot spring area, depth in meters above sea-level (m.s.a.l)

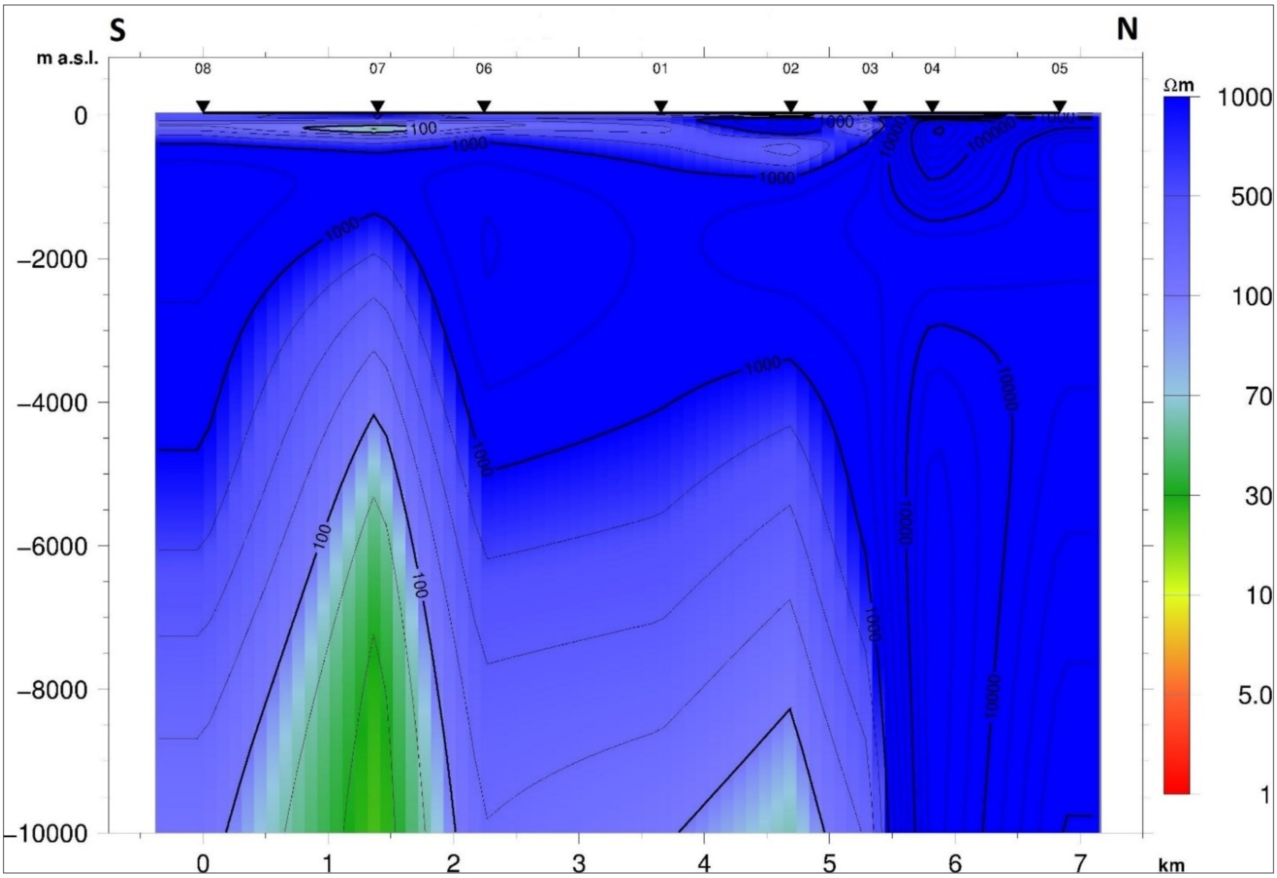


Figure 5: Resistivity profile up to 10,000 m depth, Padiyathalawa hot spring area, depth in meters above sea-level (m.s.a.l)

2.3 Strike data analysis for Padiyathalawa hot spring area

A study done by Kehelpannala (1987) suggests regional lineament direction is oriented approximately 40 º to 60º from north to east ward (figure 6).

Comparable strike direction was given by MT method for Padiyathalawa thermal spring system (N40E) for shallow depths (period 0.001-0.01s). Fracture pattern direction (from strike analysis) remains unchanged for all depths (figure 7). But in Site No 07 for medium period (period 0.01-1s) (figure 7 a) and long period (period 1-10s) (figure 7 d) fracture direction is oriented to north-south direction. Change of strike direction at longer periods (greater depths) reflects the 3D nature of fracture system at greater depths.

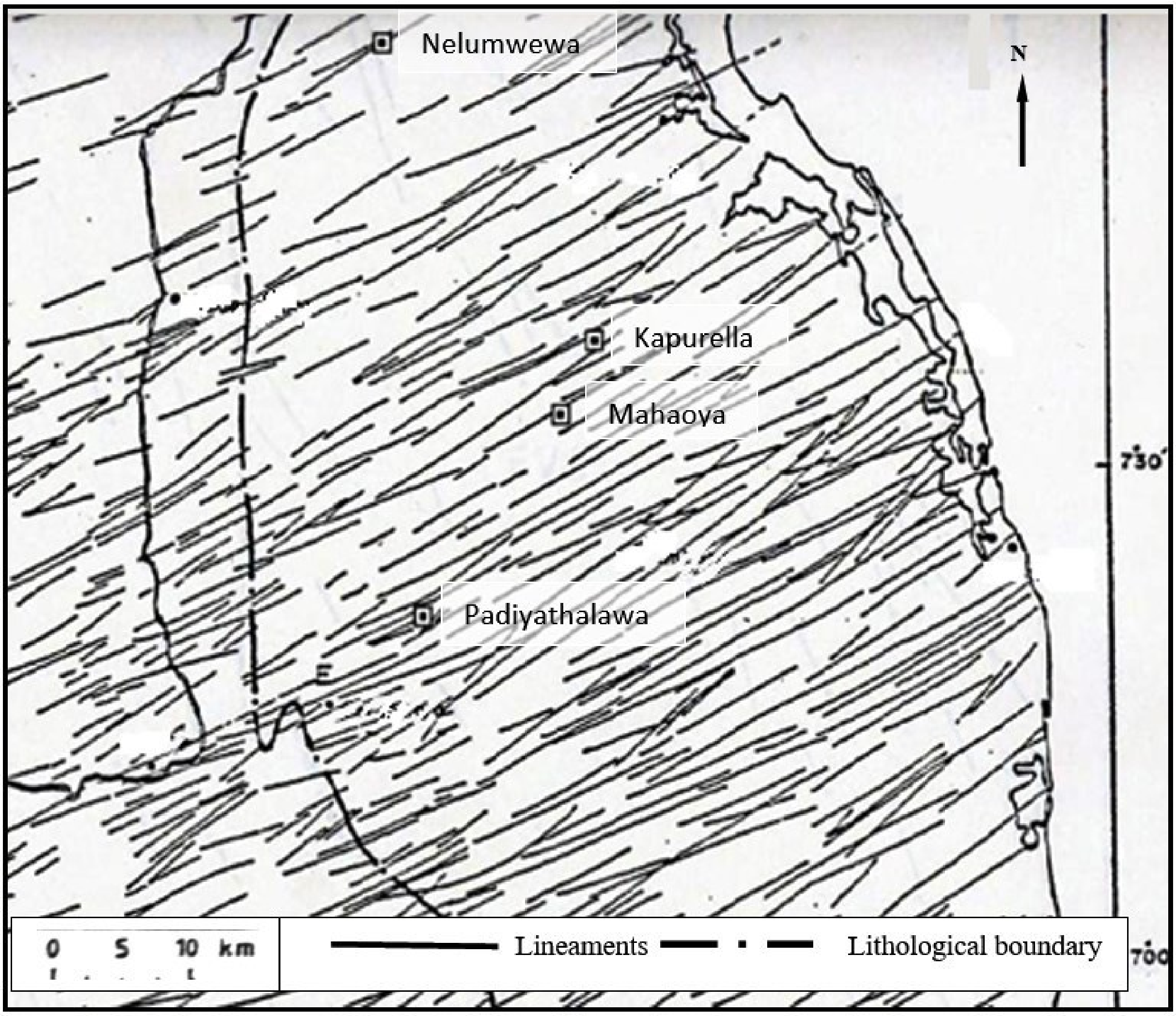
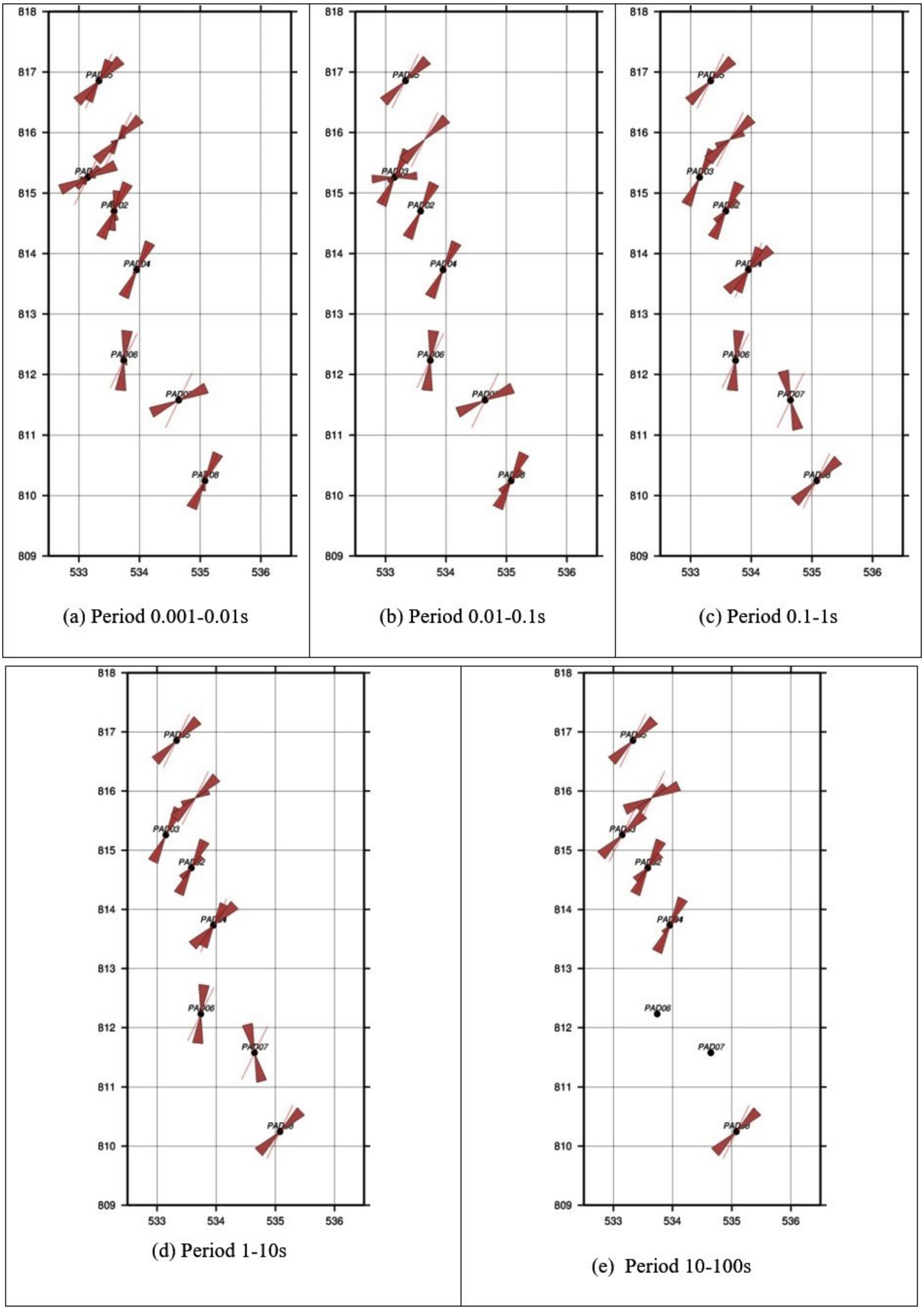


Figure 6: NE-SW set of (long) lineaments (modified from Kehelpannala, 1987)



(a) Period 0.001-0.01s

(b) Period 0.01-0.1s

(c) Period 0.1-1s

(d) Period 1-10s

(e) Period 10-100s

Figure 7: Strike directions derived using higher period-MT data from Padiyathalawa hot spring area, plotted on Sri Lanka Grid System. Depth increases from (a) to (e), since longer periods (longer wavelengths) represent higher penetration depths.

3. CONCLUSIONS

From this shallow and deep earth resistivity study, a possible geothermal reservoir, heat sources and possible fracture system patterns were identified in the Padiyathalawa thermal spring area. Observed near surface resistivity contrasts show possible water flow patterns, which are not clearly noticeable from conventional resistivity survey results. From the TDEM method, most of the water bearing fractures can be clearly identified. Further, ascending thermal water flow patterns were identified from shallow depth resistivity profiles.

Padiyathalawa thermal spring systems show very low resistivity zones in shallow depths (50 – 125 m). According to the resistivity signature, it is highly possible that this system has low temperature alteration minerals in thermal water circulation paths or in confined thermal water pockets. Assuming alteration temperature and formation temperature are in equilibrium, the temperature could be estimated between 50 ºC to 150 ºC at shallow depths. All low resistive zones are confined to shallow depths (30-40 m below surface) and are not continued to the surface, suggesting most of thermal energy (and temperature) are possibly lost during the circulation. That is a possible indication for high ground water mixing with thermal water at the shallow depths.

According to the resistivity profile, roots of this system run very deep (>20 km) and may be connected to an active heat source such as a magma chamber. Also this resistivity signature (<100 Ωm) is comparable with slightly altered minerals indicating medium temperature values, 250 ºC ~ 400 ºC. Since highly resistive layers (possibly very low permeability) are located in the low resistive zones, low hydrothermal alteration could be expected. In such situations, estimated temperature can reach up to 750 °C. For this thermal spring system, the primary heat transfer could be expected through conduction and secondary hydrothermal convection currents transport heat from the depths of 750-1000 m.

Padiyathalawa thermal spring area and associated area show the same fracture orientation for the whole profile depth, approximately 40º - 60º from North (N40E-N60E) which also agrees with the surface lineament orientation. Only site No 7 shows slightly different strike directions indicating the possibility for 3D fracture system at 20,000m depths. It is also possible that the fracture zone may have encountered higher activity at its formation.

4. RECOMMENDATIONS

For future exploration works, these results can be used to locate possible geothermal resources and possible thermal water circulation zones. A few closely spaced MT soundings are highly recommended around these hot spring areas to reduce possible systematic errors.

In order to remove any ambiguities, another geophysical exploration method such as the seismic method is suggested.

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Geological Survey and Mines Bureau(GSMB), Sri Lanka

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