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GEOTHERMAL ENERGY POTENTIAL IN SRI LANKA: A PRELIMINARY MAGNETOTELLURIC SURVEY OF THERMAL SPRINGS

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ABSTRACT

A magnetotelluric survey was conducted to map the lateral variation of resistivity with depth along ~9 km profiles across seven known hot springs of Sri Lanka for locating thermal waters within deep faults or hot dry rock that would help geothermal energy development. Data show three regions with resistivity less than 10 Ωm, two the vicinity of Kinniya hot spring, at depths ~1.5 and 2 km, and one at Kapurella at ~500 m. All three regions have 2D cross sections of a few hundred square metres. Three more regions with lower resistivity, 10 - 100 Ωm, were located at depths beyond 10 km at Padiyatalawa, Mahaoya and Kinniya. Their cross sectional extent is limited to a few square kilometres. It is known that optimum geothermal sources at the spring sites can be lateral to the MT traverses, and that 3D MT surveys should be undertaken to locate the most favourable geothermal reservoirs. Though the larger detected sources are outside the economic depth of exploitation, results show their association with hot springs, which means under favourable connectivity and/or with induced hydro-fracturing, extraction of thermal water could be achieved at shallower depths.

Keywords: *geothermal, magnetotellurics, thermal springs, resistivity, metamorphic terrains*

INTRODUCTION

Geothermal energy development in Sri Lanka has been considered as an alternative energy source for some time, inspired by the existence of several thermal springs whose outflow temperatures ranged between 44-65^{o}C. Presently, there is an increased trend to use enhanced geothermal energy system (EGS) that could be utilised worldwide (Blackwell *et al.*, 2006). The purpose of this magneto-telluric (MT) program was to locate any abundant thermal waters or hot dry rocks existing within an economic depth range of few kilometres (~5 km). Since thermal springs are located in a metamorphic terrain, thermal waters could exist in fractured fault zones. As thermal springs seem to border the Highland-Vijayan geologic boundary, a component of this MT work was extended to map the subsurface structure of this boundary at Mahapelessa in southern Sri Lanka.

BACKGROUND INFORMATION

There is limited information on geothermal energy development in Sri Lanka. Since the middle of the last century some researchers have studied the geochemistry of the thermal waters (Fonseka,, 1956, Dharmasiri and Basanayake, 1986, Dissanayake and Jayasena, 1988). Some other researchers (Millisenda *et al.*, 1988, Kagami *et al.*, 1990, Wijayananda and Brass, 1992) have discussed past geothermal events in Sri Lanka, of which dolerite intrusions are estimated to be the most recent at 150 Ma. Based on varied geological and geothermal hypotheses of the history of Sri Lankan terrain, there was a need for a comprehensive geophysical exploration studies to identify the source location and flow paths of geothermal fluids and to examine relative merits of different geophysical methods of electrical resistivity, magnetics, gravity and self-potential (Fonseka, 1994). Seismic methods were excluded due to their prohibitively high cost and weak resolution at imaging sub-vertical structures. Similarly geothermics were excluded on the grounds of costs. Presently, the most accepted physical parameter for the location of a geothermal reservoir is the electrical resistivity of the rock. Rock resistivity decreases due to hot saline waters and hydrothermal alteration occurring in fracture paths. Matrix induced additional (secondary) porosity further lowers rock resistivity. The resistivity of such rocks can be less than 10 Ωm and as high as few tens to a hundred Ωm in vapour dominated regions. Hot dry rock at elevated temperatures has lower resistivity due to electronic conduction governed by an Arrhenius equation (electrical resistivity is exponentially proportional to temperature). Lowering of resistivity is also known to occur in the presence of interconnected conducting materials, such as graphite, sulphides, iron oxides and clay minerals.

Previously, Kathriarachchi and Mudunkotuwa (1980) conducted Wenner four probe resistivity soundings at the Mahapelessa hot spring. An initial comprehensive geophysical investigation, comprising imager resistivity, self-potential, magnetic and gravity methods, was undertaken at the Mahapelessa and Mahaoya hot springs, and the results were presented (Fonseka, 2000). From this geophysical investigation the near subsurface resistivity structure was obtained to a maximum depth of a few hundred metres at the two springs, without any evidence for the existence of a sizable thermal water accumulation. There was evidence for the upward flow path. An important outcome of this survey was that the ground is low resistive near the surface but very resistive below, and the location and path of deeper thermal waters could only be realised by the superior depth penetration of the EM resistivity method of Magneto-tellurics (MT).

THE MAGNETOTELLURIC METHOD

In scalar magneto-tellurics, magnetic field time variations in one horizontal direction are correlated with time varying electric fields measured in the orthogonal horizontal direction. The ratio of the variations as a function of period can be used to determine the subsurface resistivity structure. Measurements are conventionally made with “x” to the north and “y” to the east. There are then two apparent resistivities and their phases to be obtained (or equivalently impedances) – one using the north electric field (Ex) with the east magnetic field (By) and the other in an orthogonal direction using the east electric field (Ey) and the north magnetic field (Bx). In tensor magneto-tellurics, four impedances are obtained, Ex with Hx (Zxx), Ex with Hy (Zxy), Ey with Hx (Zyx) and Ey with Hy (Zyy). The Zxx and Zyy impedances yield information about three-dimensional (3D) structures.

Electric field determinations are affected by the very local conditions around the electrodes used to make the measurements. This can lead to scaling problems known as “static shift”. The problem can be overcome by employing an additional technique, Transient Electromagnetics (TEM), in which only magnetic fields are used to give near-surface resistivities. TEM results are then used to scale the MT resistivities to their correct levels.

Survey Procedure

Prior to the field campaign, the Sri Lankan counterparts of the project visited all the hot spring sites designated for study and selected a number of potential sites where MT might be possible. Site selection was somewhat problematic with many areas of paddy fields unavailable, and there were indications of much potential interference from cultural sources. During the campaign, at the start of each traverse these potential sites were revisited and a final selection was made. Campaign participants were split into four groups – two manual groups for establishing an MT site and for its subsequent close down, one group for MT data acquisition and one group for TEM data acquisition. MT site preparation comprised laying out telluric lines along magnetic north and east directions, burying and connecting electrodes, digging trenches around 0.5 m deep in magnetic north and east directions, placing, levelling, burying and connecting magnetic coils, measuring telluric line lengths and recording serial numbers of the magnetic coils. No vertical magnetic field measurements were made. The MT acquisition group recorded GPS locations for each site, logged the MT measurements and made back-up disks of all field data for separate storage. The group had six coils and hence three sets of MT equipment. At any one time there were usually two sets in operation with one set in transit to a new site. Before MT recordings began, TEM measurements were made, where possible, with a transmitter loop size of 100 m by 100 m. An average of two MT stations per day was achieved throughout the survey, even with long moves between traverses.

Locations of the MT profiles are shown in Figure 1. Along profiles crossing each spring site, MT stations were established approximately every 1 km while traverse lines were about 7 – 9 km long. At Mahapelessa the profile was extended to 27 km to investigate the Highland-Vijayan boundary. Sites were generally occupied for several hours during one day and, for each profile, one or two sites were occupied continuously for several days to provide remote reference possibilities. A total of 86 MT stations were obtained over 7 hot springs, and almost all the stations were supported by TEM measurements for the control of static shift. A further 27 stations were occupied in the NW basin area of Puttalam – the relevant results are not presented here.

Figure 1: Figure 1. Locations of Magneto-telluric profiles

Data Quality

Some raw time variations for the two sets of orthogonal measurements for station 104 along the Mahapelessa profile are shown (Figure 2). The correlation is very good for the Ey-Bx (Zyx) combination but the Ex-By (Zxy) combination is poor and the data are obviously noisier. The data have, in fact, been found to be very noisy throughout the Mahapelessa profile, and we suspect this was due to a combination of power cables, electric '*elephant'* fences and irrigation pumps.

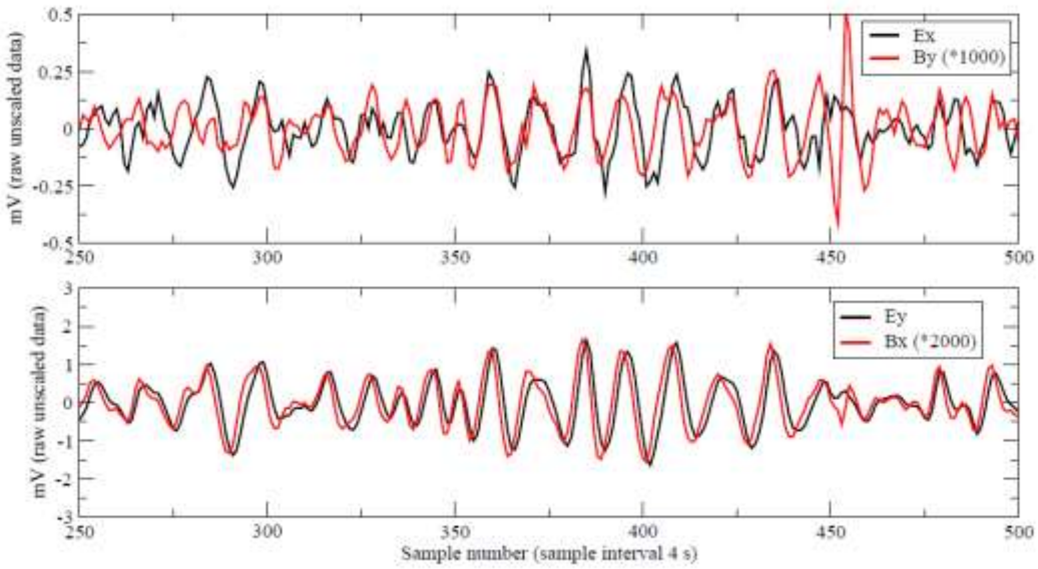


Figure 2. Magnetic and electric field variations at station 104, Mahapalessa

The data, further north are of better quality. Any MT site that showed excessively poor data was deleted from further analysis.

Data Analysis

Apparent resistivity

MT responses for all stations were obtained using the robust data processing algorithm of Chave and Thompson (1989) following manipulation of the measured data using the programs of Sophie Hautot. Estimates were generally obtained over the 6-decade period range of 10^{-3} to 10^{3} s, with TEM providing coverage over 2 x 10^{-4} to 5 x 10^{-3} s. TEM data were used to estimate static shift corrections for the MT data, and an example of the TEM response and corrected MT response is shown for Mahapalessa site 101 (Figure 3).

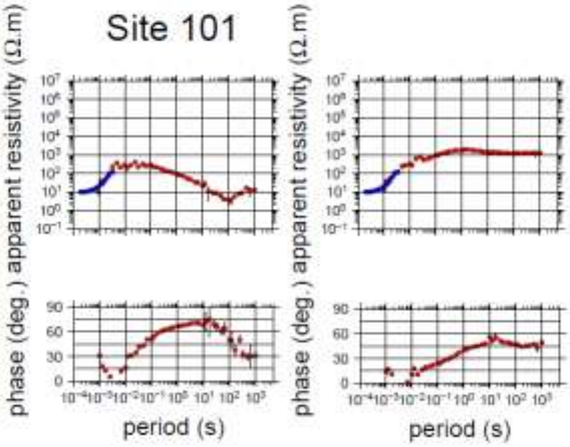


Figure 3. TEM apparent resistivities (blue) and MT apparent resistivities and impedance phases (red) for Mahapalessa site 101

If the subsurface structure was a relatively simple one-dimensional (1D) layered structure the apparent resistivities from the Zxy and Zyx impedances would be very similar at the same station. These results show that the sub-surface structure is more complicated than simple 1D. The horizontal period scale is a proxy for depth – the left hand side is near surface and depth increases to the right. The structure is seen to be fairly simple near surface, but complexities occur at depth. This is commonly the case with MT data; near surface 1D layered geometries respond at short periods but complex 3D bedrock geometries give complex responses at long periods. Using log period as a proxy for depth and collating all the stations along a profile, apparent resistivity and phase pseudo-sections can be created. These pseudo-sections give the first indication of resistivity variations along the profile and with depth.

Apparent resistivity pseudo-section for the Mahapalessa profile (Figure 4a) indicates a change from a resistive structure (blue colours) in the Vijayan Complex in the NE to a more conducting structure in the Highland region (green/yellow colours) in the SW. The apparent resistivity phase pseudo-section is also shown (Figure 4b) and again there is an indication of a boundary between the Vijayan and Highland Complexes with low phases (blues) in the NE indicative of resistive structures and high phases (reds) in the SW indicative of conductive structures. However, in these pseudo-sections the vertical scale is not true depth – this has to be determined by modelling. The depth represented in these plots is down to 200 km in some places but varies with the overlying resistivity values. Red colours in the apparent resistivity pseudo-section represent low resistivity and these may be indications of hot rock regions, although there can be other causes (rock type, graphite content, clay content, etc). Drawing conclusions from apparent resistivity vs. period maps can be very misleading, but they do give an excellent first view of the probable resistivity variation laterally.

2D Inversions

2D modelling was performed in association with the Dublin Institute for Advanced Science (DIAS) using the WinGLink Geophysical Processing and Interpretation Software package in conjunction with a range of pre-inversion programs to aid data preparation. The Rho+ algorithm of Parker and Booker (1996) was first applied to all the stations along a given profile and the results used to justify elimination of a number of estimate outliers. Groom-Bailey decomposition (Groom and Bailey, 1989) was then applied to the impedances to determine distortion parameters and in particular to investigate rotation angles providing the best decomposition into transverse magnetic (TM) and transverse electric (TE) modes for 2D inversion. In general, the average rotation angle for all periods and all stations along a given profile rotated impedances to be more-or-less parallel and perpendicular to the profile direction. This gave confidence that the chosen profile direction was approximately perpendicular to the geological structure. TM and TE modes were jointly inverted in WinGlink and the results for each profile are presented in the following sections.

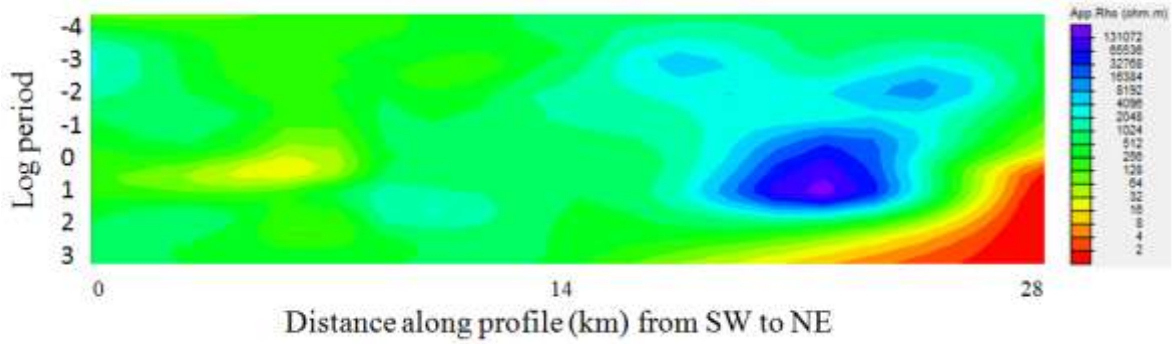


Figure 4a. Mahapelessa apparent resistivity pseudo-section

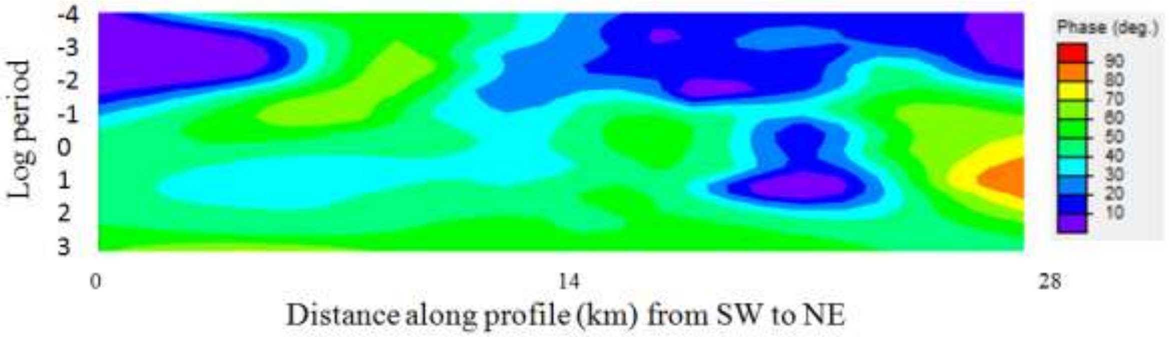


Figure 4b. Mahapelessa apparent phase pseudo-section

RESULTS AND DISCUSSIONS ON 2D RESISTIVITY MAPS ACROSS HOT SPRINGS

Mahapelessa Hot Spring

Location of the Mahapelessa hot spring, the MT traverse line running approximately from SW to NE from Angunakolapelessa to Suriyawewa through Mahapelessa, and the geologic cross-section approximately coincident with the MT traverse are presented (Figure 5). The resistivity-depth model beneath the MT traverse is shown (Figure 6) and this indicates a high resistivity region towards the NE of the traverse and a relatively lower resistivity region to the west, as expected from inspection of the pseudo-sections. There is no evidence of any very low resistivity regions that could be associated with a significant amount of hot water saturated rock or hot dry rock to economic depths, which at present is about a few kilometres. This resistivity cross section does not show convincing evidence for expected geothermal reservoirs. The Udawalawe river fault is seen as a low resistivity region (red/yellow on map) close to the earth's surface in the west between stations 109 and 108. It runs deep enough to be heated by an above average geothermal gradient in Sri Lanka, estimated to be ~30 °C/km by CEYPETCO Sri Lanka (Fonseka, 1994).

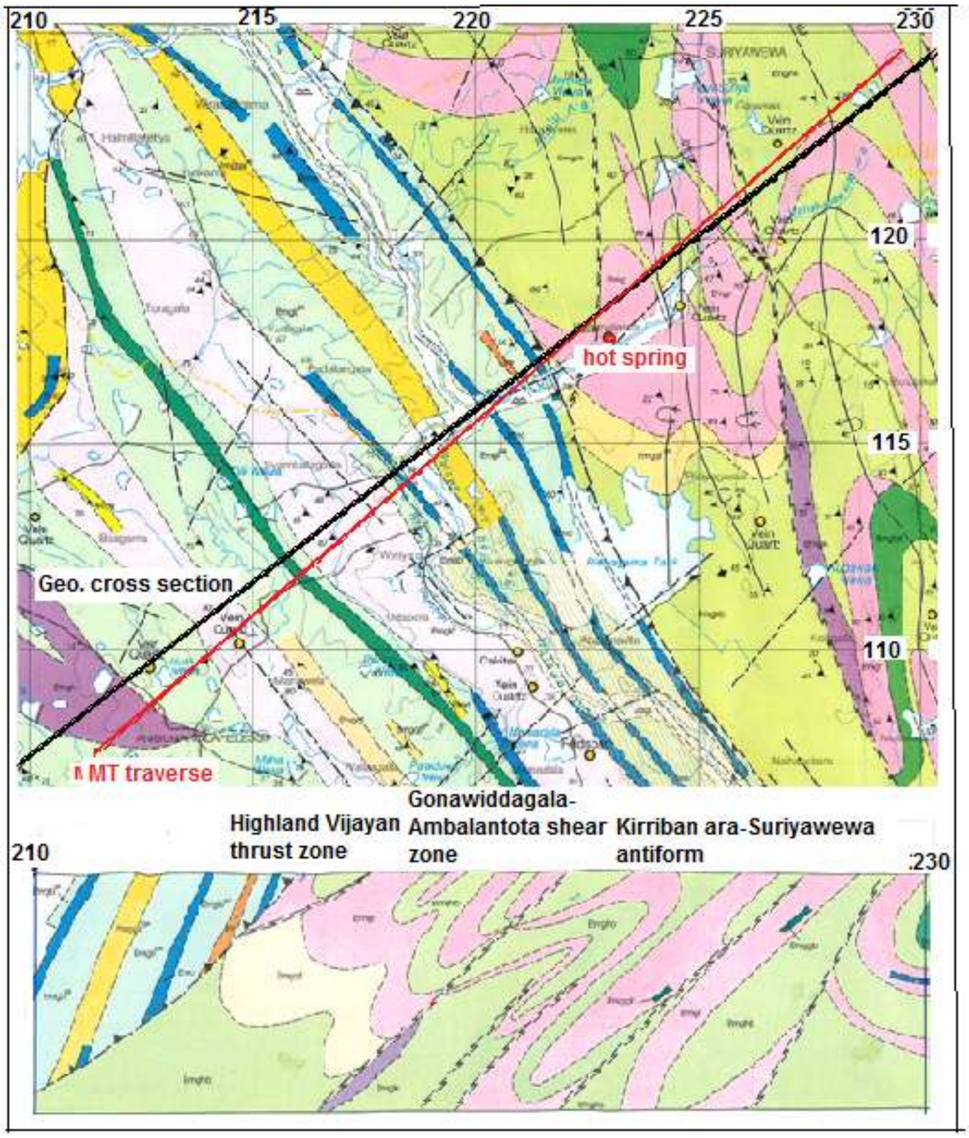


Figure 5. Geology of the Mahapelessa hot spring region (coordinates in kilometres) and the geologic cross section as indicated. (Geology map-courtesy, GSMB, Sri Lanka)

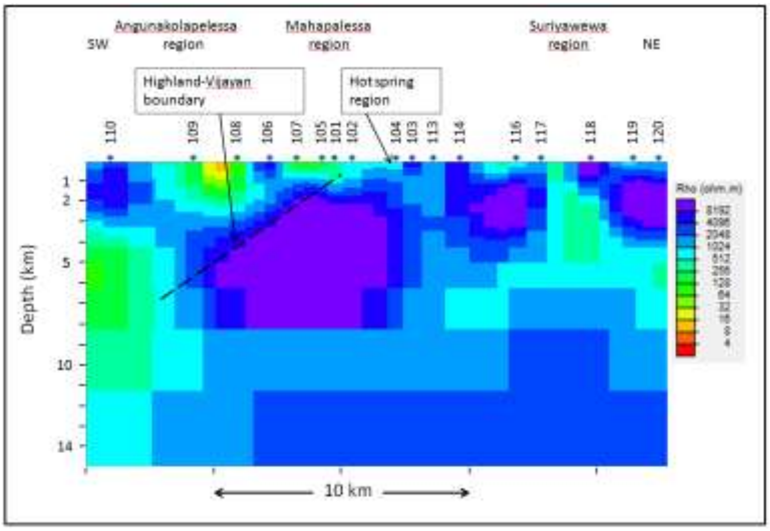


Figure 6. Mahapelessa resistivity-depth section from 2D inversion of MT response estimates

Based on the surface geology of the region, the boundary between high and relatively low resistivity may be identified with the Highland-Vijayan bounday. It seems here that the HV boundary is a thrust/shear zone. The HV boundary at the Earth's surface, according to this model, is to the west of the hot spring, which correlates with that of the geology map of the Geological Survey and Mines Bureau (GSMB). A self potential (SP) anomaly was observed at the Mahapelessa hot spring that was modelled (Fonseka 1996) as a double dipole at a depth range of 300 - 500 m, and can be attributed to rising thermal waters along the shear zones at Gonawiddagala-Ambalantota shear zone (Figure 5). It is identified here as the high-low resistive boundary of the MT resistivity section.

The origin of the Mahapelessa hot spring cannot be discerned here, it could well be waters of the Walawe river fault in higher elevations running a few kilometres deep to be heated by the normal geothermal gradient and then rising upward by artesian action along fine fractures or fissures of the Gonawiddagala-Ambalantota shear zone. Even though there is no noticeable very low resistive region at reasonable depth in this model to be identified as a geothermal reservoir, there could be such a region elsewhere that could feed the Mahapelessa hot spring. Identification of such hot water bodies/ HDR demands a 3D MT resistivity survey.

Mahaoya Hot Spring

MT traverse and the geology of the Mahaoya region are shown (Figures 7 and 8). Excellent low noise data were obtained at the Mahaoya MT sites. Mahaoya 2D resistivity model to a depth of 6 km is presented (Figure 9). There is no evidence of very low resistivity that could be holding (hot) water or HDR. To the contrary, the model infers that the basement is highly compact and free of any fluid-filled fractures. The moderately low conducting region near the surface at the spring is a combined effect of the lake and the spring.

Kapurella Hot Spring

The location and MT traverse of the Kapurella hot spring (Figure 7), the MT traverse line and the geology (Figure 10) and the resistivity model to a depth of 5 km (Figure 11) are shown. A very low resistive region is found at a depth of ~500 m below the hot spring region (MT sites 306, 308 and 305); rock elsewhere in this region is extremely resistive. The low resistivity can be identified with hot water accumulation with in fissured rock. Kapurella thermal spring is the hottest known spring, with a surface temperature of 65 ^{o}C. Considering an ambient temperature of 35 ^{o}C for Kapurella, the excess temperature is 30 ^{o}C. With an average geothermal gradient of 30 ^{o}C/km one would expect thermal water to be originating at least at a depth of ~1 km if no heat losses and near surface mixing with surface waters are considered. Geothermal water accumulated at this shallow depth is to be considered as an intermediate accumulation that should be fed from a deeper source region. Due to lack of long period (=deep probing) MT data on the Kapurella traverse, a deeper resistivity model is not available. Hence a deeper low resistive region that could hold a larger quantity of higher temperature water or an HDR is not known. Alternatively, the shallow source could have continuity laterally to a source at a greater depth. Only a 3D MT survey could resolve such a situation.

Padiyatalawa (Marangalawahawa) Hot Spring

The location of MT sites and the geology of the Padiyatalawa hot spring region are shown in Figure 12. The resistivity-depth 2D models inverted from apparent resistivity data are shown to a depth of 2 km (Figure 13a). On the north end of the traverse, there is a large conducting region through a highly resistive layer. The resistivity here is most likely influenced by the dolerite intrusion that is observed on the surface (Figure 13a). Such broad sized low resistivity regions were not observed at the other MT traverses. A more detailed 3D MT survey should show any connection better. Figure 13(b) shows the steep nature of the intrusion closer to the surface. Based on the normal geothermal gradient in Sri Lanka, the temperature at 10 km depth is ~ 330 °C. It is likely that the Padiyatalawa hot spring has a contribution from the deep low resistive region. Again within an economic depth range, there does not exist a very low resistive region that would represent a geothermal reservoir or a hot dry rock.

Padiyatalawa-Mahaoya-Kapurella (PMK) Cross Profile

PMK cross profile deviates very much from linearity, as a result of road accessibility and limited time availability (Figure 7). This traverse was not intended in the original plan. However, it is now noted to be an important traverse in the geothermal source location (Figure 14).

The Padiyatalawa-Mahaoya-Kapurella (PMK) cross traverse shows a low resistive region at a depth of ~12 km in the neighbourhood of MT site 403, where the geothermal temperature can be estimated to be ~350 °C (Figure 14). On the PMK resistivity model, there are two low resistivity bands on either side of MT site 205. The one to the NE is towards the 12 km deep low resistivity below site 403, the other on the SW trends deeper. The latter is directed towards the deeper north end of Padiyatalawa traverse (MT site 505) where there is a dolerite dyke. MT site 205 is closest to the Mahaoya hot spring. Hence when comparing the cross profile with individual profiles (Figure 14), it is most likely that Mahaoya hot spring is fed mostly from the low resistivity region below site 403 and, to an extent, from Padiyatalawa. In comparison, the shallow low resistivity at Kapurella must have a connection to a deeper source. It is necessary to consider a 3D MT survey to get a clearer picture (Figures 11 and 14).

Nelumwewa (Welikanda) Hot Spring

Nelumwewa hot spring is one of the hottest springs similar to Kapurella hot spring. The MT profile location and the geology of the neighbourhood are shown (Figure 15). The survey had to be conducted in a built up area where there was considerable “cultural noise”. The data were found to be too noisy at the higher frequency range, and some MT sites had to be discarded for the 2D inversion.

The 2D inversion of the accepted sites is presented (Figure 16). The inverted depth is 10 km and greater depth could not be achieved due to lack of long period data. An inclined low resistivity region within the high resistivity can be identified with the fault/shear zone crossing the MT profile at the hot spring (Figure 15). As there is no very low resistivity path observed within the relatively low resistance region, thermal water must rise through narrow fissures within this fault zone. It is likely there is a deeper low resistivity region off the present MT traverse feeding this hot spring, as was the case for the Mahaoya hot spring.

Kinniya-Rankiriulpotha Hot Springs

The locations of MT sites and the geology of the Kinniya and Rankiri Ulpotha hot spring region are presented (Figure 17). The 2D resistivity maps after inversion are shown (Figure 18). Several faults identified on the geology maps can be correlated with the resistivity maps. The low resistivity region at a depth of 3 km below the Kinniya hot spring is seen to have a connection to a lower resistivity region below a depth of 10 km, where the normal geothermal temperature can be ~300°C. To the east of MT site 715, a low resistivity region occurs at a depth of 4 km. However, this does not seem to have a connection to the deeper interior on this section, but could do so lateral to the traverse. The fault running along the Wanni Complex and Highland Complex of rock can act as a channel for this low resistivity region. The state of affairs at Rankiriulpota only shows a minor low resistivity closer to the surface. Though not seen on the resistivity model, narrow fissures must bring thermal waters upward from greater depths but the maximum thickness of these fissures can be calculated to be unresolved by MT.

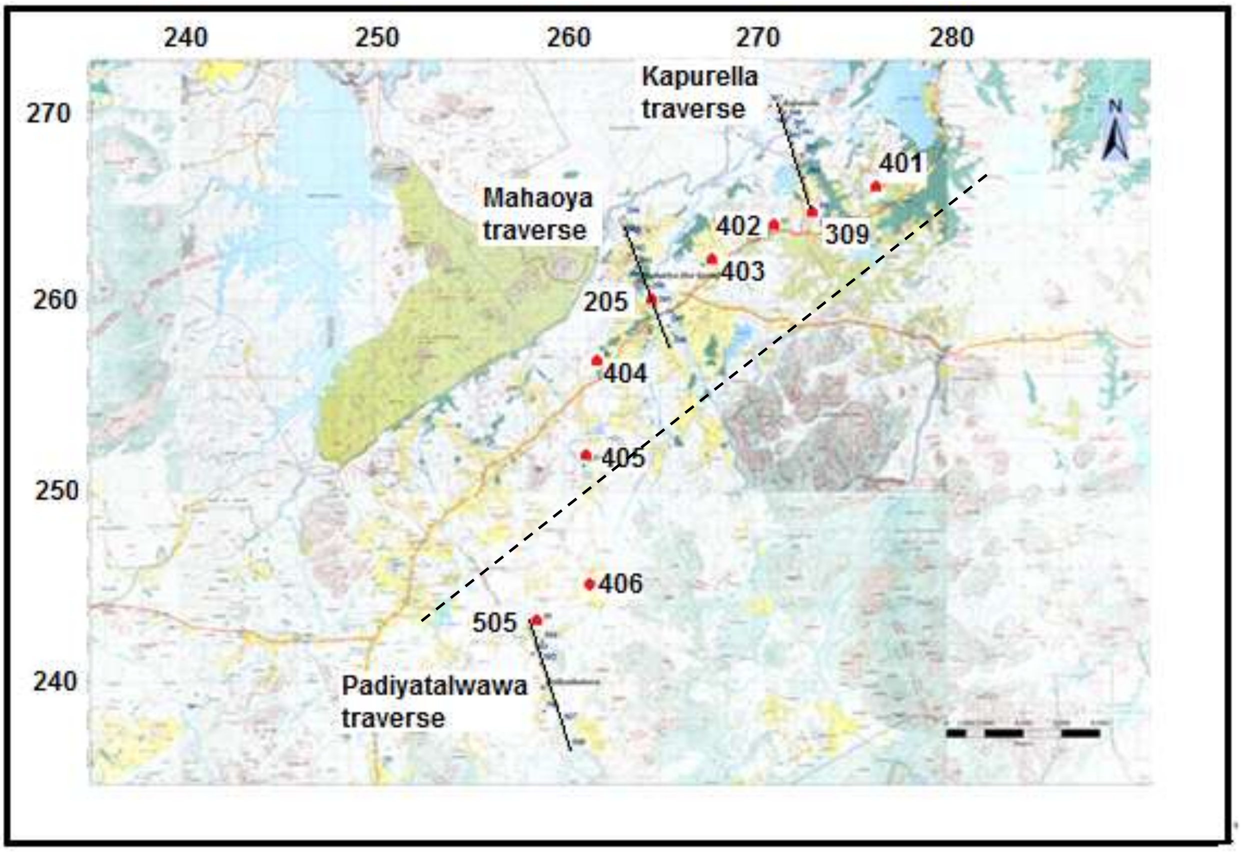
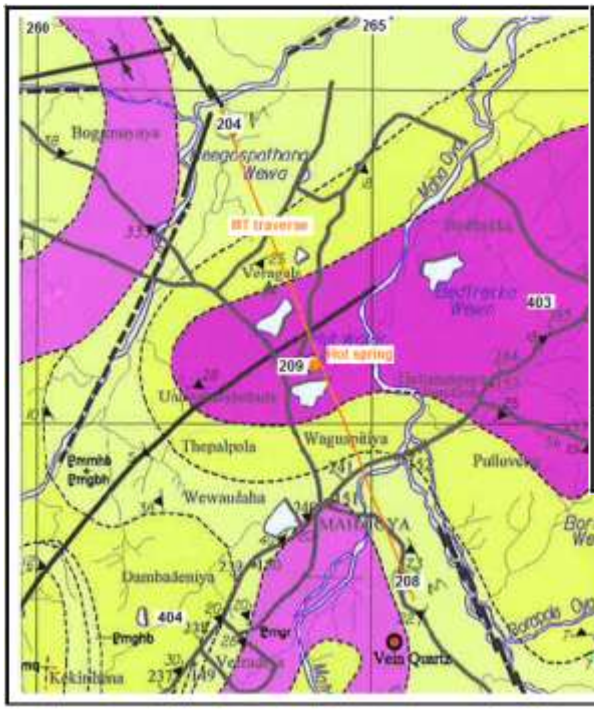


Figure 7. Location of MT stations of Padiyatalawa -Mahaoya-Kapurella (PMK) cross traverse (national grid coordinates in km). A low resistive region was noted below a depth of ~12 km at the MT site 403 of cross traverse. (Survey map courtesy Survey Department of Sri Lanka). The line of cross section in 2D inversion is also shown



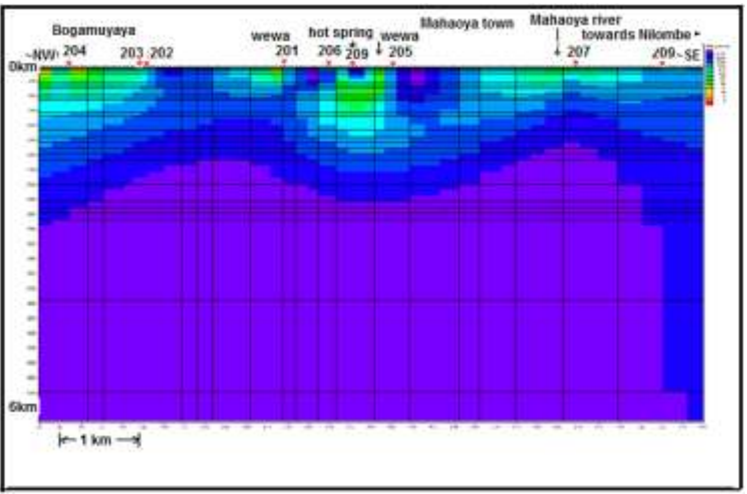


Figure 9. showing 2D resistivity-depth sections for Mahaoya to a depth of 6km

Figure 8. Geology map of the Mahaoya hot spring region (national grid coordinates in kilometres) and the position of the MT traverse. (Geology map courtesy - GSMB Sri Lanka)

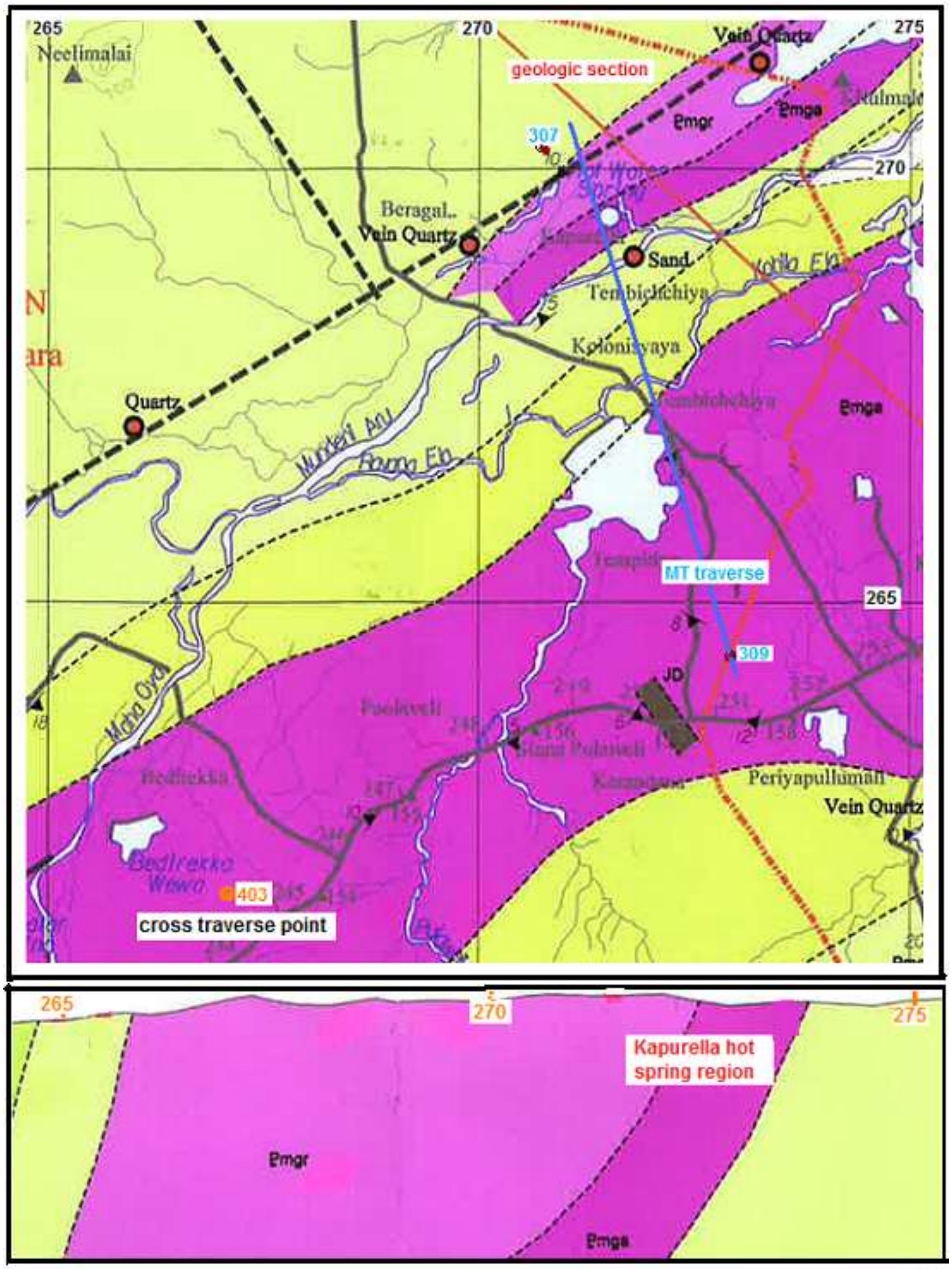


Figure10. Showing the geology of the Kapurella hot spring region and the MT traverse and an adjacent geologic cross section (below) (national grid coordinates in kilometres, geology map courtesy - GSMB Sri Lanka).MT traverse is also shown in Figure 7.

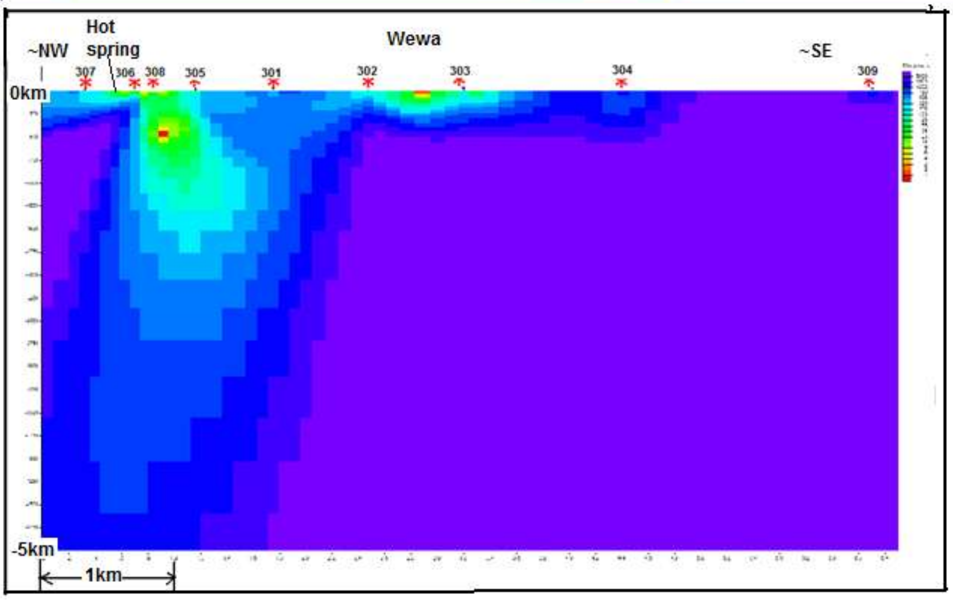


Figure11. showing resistivity depth section for Kapurella to 5km depth

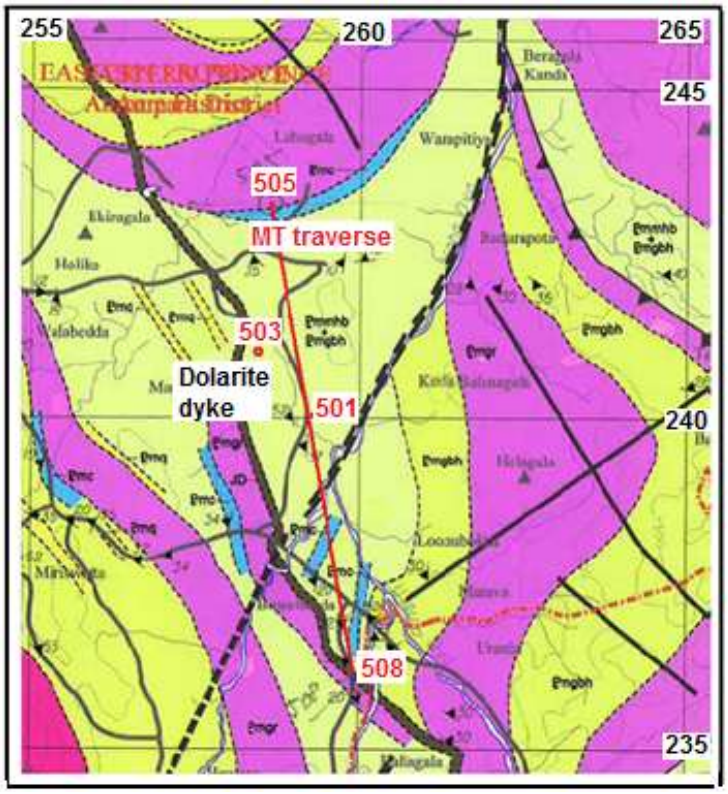


Figure 12 showing the location of MT sites, geology of the Padiyathalawa hot spring region (national grid coordinates in kilometres)

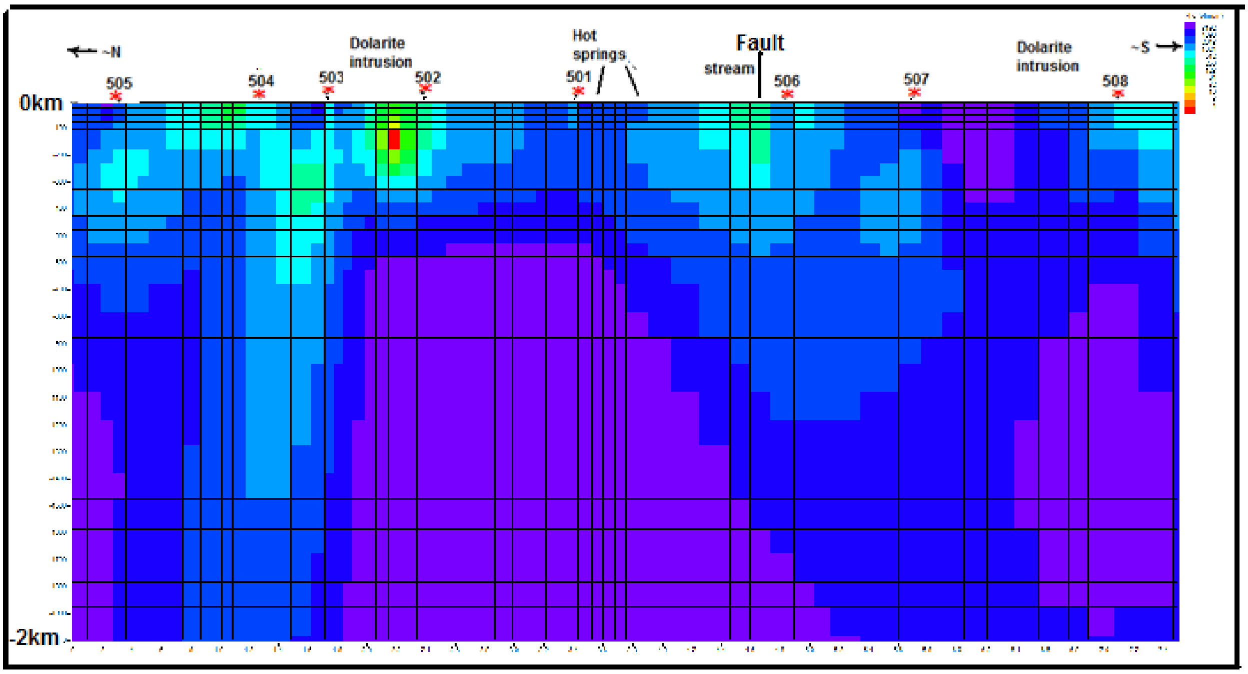


Figure 13(a) showing the resistivity- depth section for Padiyathalawa hot spring to a depth of 2km

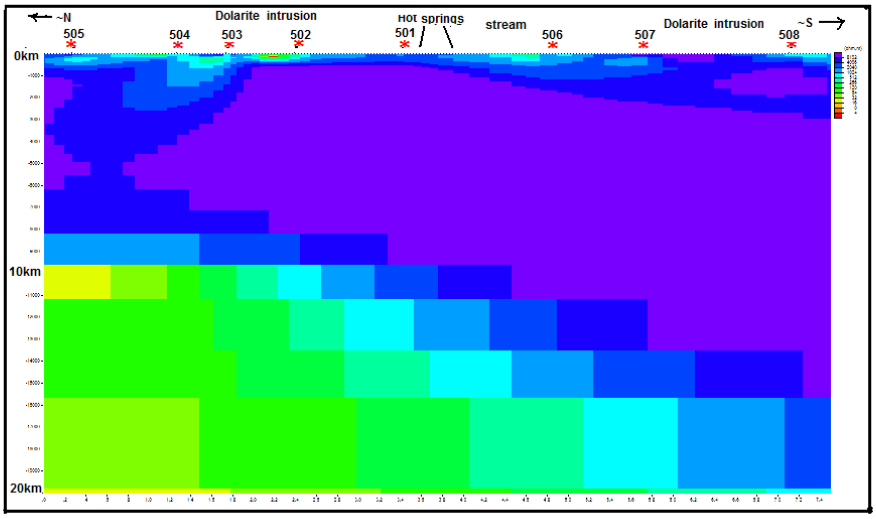


Fig 13(b) showing the resistivity- depth section for Padiyathalawa hot spring to a depth of 20km

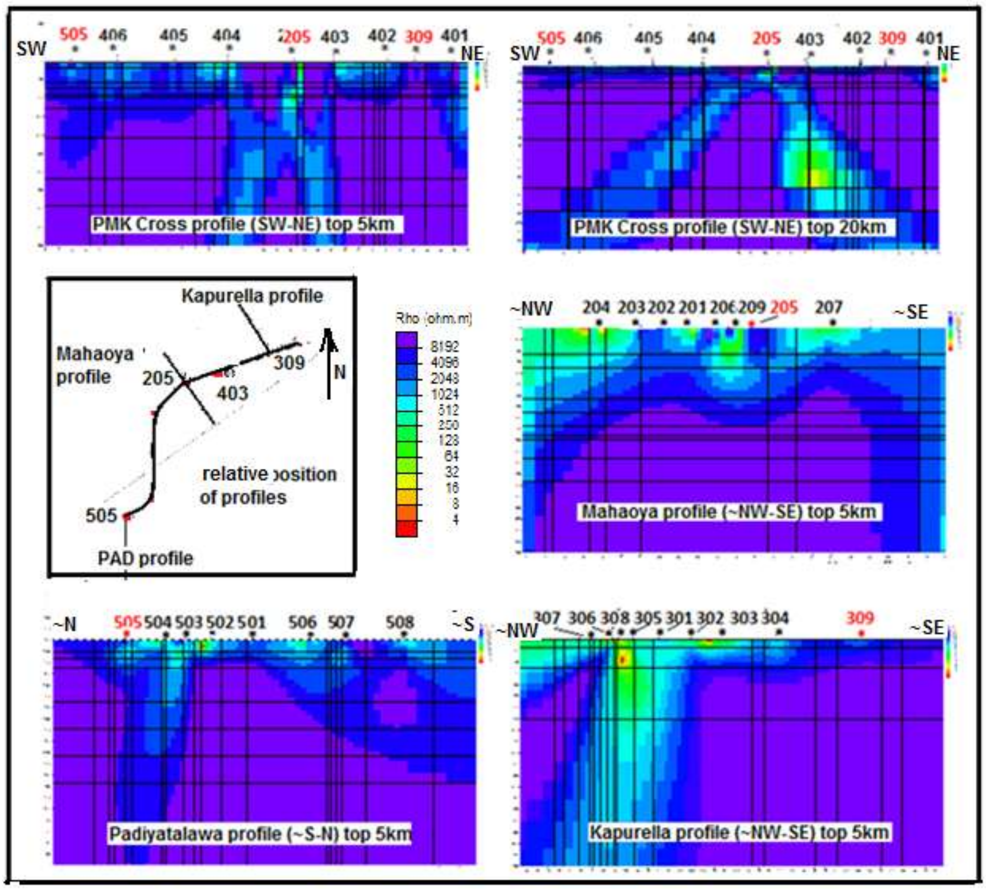


Figure 14 comparing resistivity-depth sections - among Padiyatalawa, Mahaoya, Kapurella and PMK cross traverses

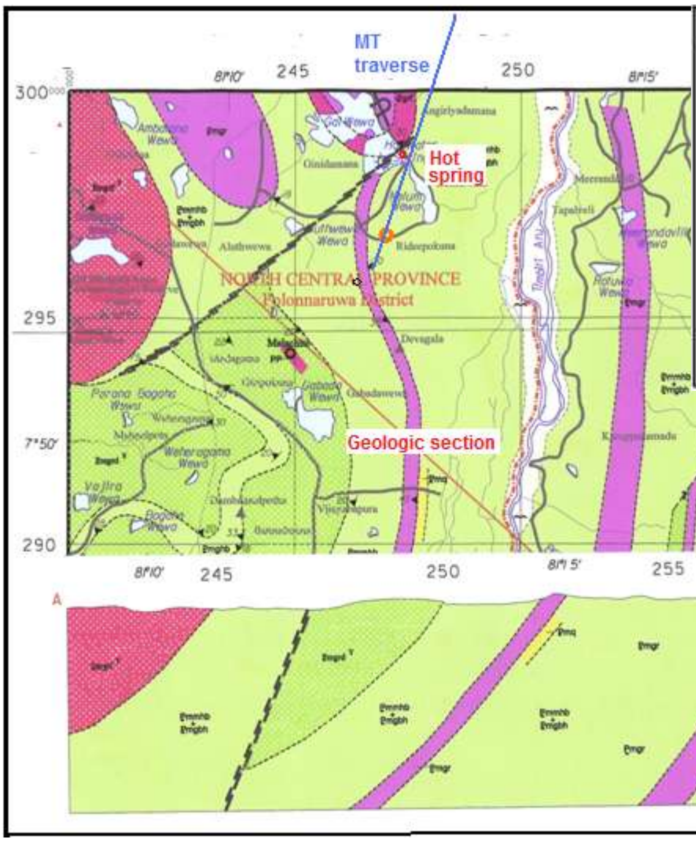


Figure 15. Geology of the Nelumwewa hot spring region and a cross section in the neighbourhood

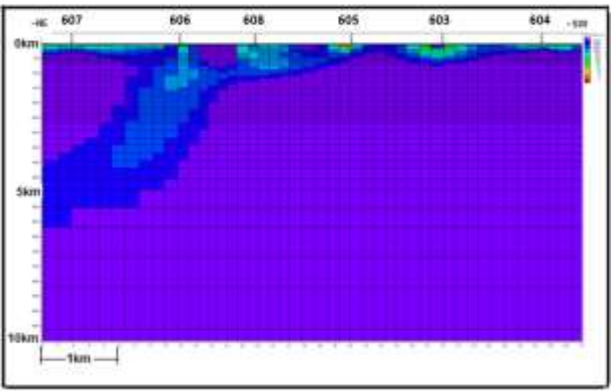


Figure 16. Resistivity depth section for Nelumwewa after 2D inversion to 10km depth

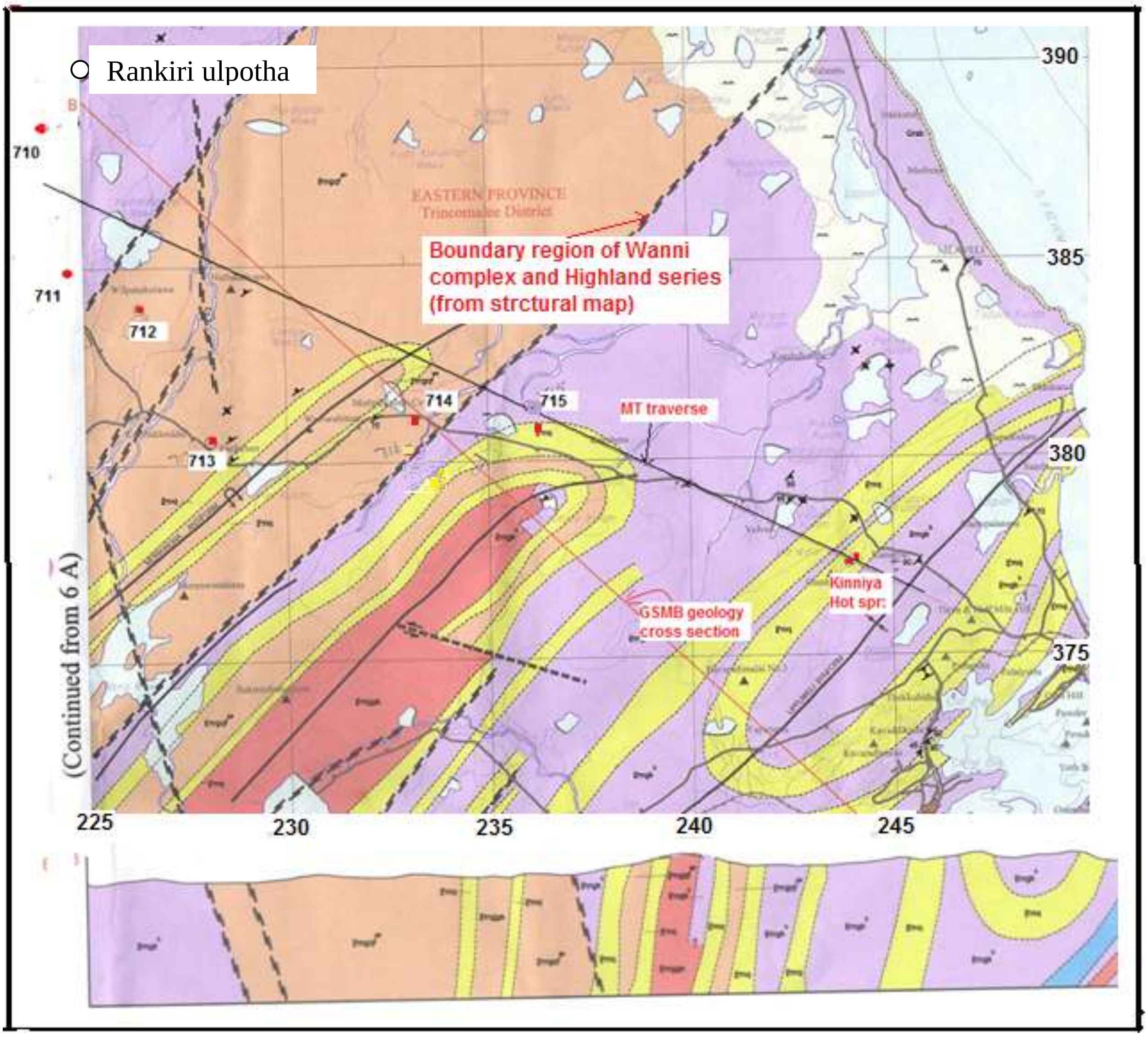


Figure 17. Geology, MT traverse and the site locations in the region of Kanniya and Rankiri Ulpota hot springs (national grid coordinates in kilometres)

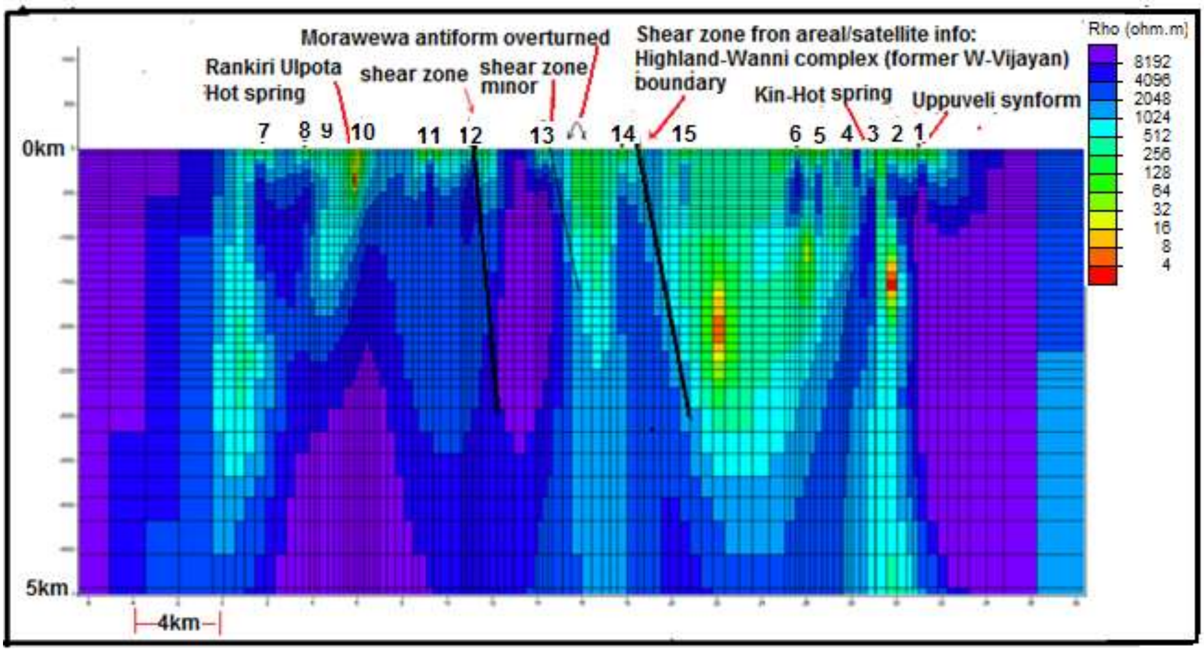


Figure 18. Resistivity-depth section for Kinniya-Rankiri Ulpotha after 2D inversion to 5km depth. Station numbers are 700 plus the number shown above the model

CONCLUSIONS

The 2D MT survey conducted along six profiles in the regions of thermal springs of Sri Lanka was used to reveal the resistivity variations in rocks at depths of 10 to 20 km. For the purpose of geothermal source location, low resistivity regions with resistivity values less than 30 Ωm, are revealed within very resistive rock with resistivity greater than 10,000 Ωm. Low resistivity regions at depths greater than ~10-12 km, and of a few square kilometres in cross-section, occur at Padiyatalawa, Mahaoya and Kinniya. At Padiyatalawa the deep low resistivity is seen to be extensive, covering several square kilometres in 2D. Shallower low resistivity regions a few hundred square metres in extent occur at depths of ~500 m at Kapurella and ~3 to 4 km at Kinniya.

The computed 2D resistivity models indicate a connection from the low resistivity regions at depth towards the hot springs through less resistive bands, though these are not of very low resistivity. This suggests that thermal water rises along narrow passages that are not resolved with MT sites which were too far apart for such detection in the present survey. Though Kapurella and Nelumwewa are the hottest springs, 2D resistivity models to depths of 5 km only show low resistivity bands within high resistivity that connect the hot springs to the interior, suggesting sources are either deeper or lateral to the MT traverse. A source region for the Mahaoya hot spring, though not evident on the Mahaoya traverse, was detected on the Padiyatalawa-Mahaoya-Kapurella cross traverse.

A dolerite intrusion noted adjoining the Padiyatalawa MT profile, and the intrusive nature of resistivity bands with relative low resistivity through high resistive rock, suggest that they are the same or have a physical relationship to the dolerite intrusion. The low resistivity at ~12 km depth at Kinniya has no known association to a dolerite intrusion, and is likely to be related only to thermal water.

The results for the ~27 km long MT traverse at Mahapelessa do not show any low resistivity regions in 2D that are of a geothermal nature. Low resistivity below the Walawe river extending to a few kilometres is evident. The Mahapelessa 2D resistivity model suggests that the Highland-Vijayan boundary is most likely a thrust zone and is in the same region as indicated by surface geology.

Knowledge acquired from the 2D MT survey suggests that source regions for thermal waters could exist at locations laterally off the present MT profiles and may even be shallower, worthy of geothermal exploitation at present times. Though the upward passages of thermal waters were not resolved with the present MT site separations, it is possible that thermal waters from within the relatively low resistive bands extending to the surface from the deeper low resistive regions may have fluid connectivity that aids extraction at relatively shallower depths. For future exploration, 3D MT surveys are strongly recommendeded.

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