Application of Geological, Geochemical, and Geophysical Techniques in Geothermal Explorations of Sri Lanka –A review

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REVIEW

Application of Geological, Geochemical, and Geophysical Techniques in Geothermal Explorations of Sri Lanka - A review

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Abstract

Sri Lanka has a number of geothermal springs, including those at Kapurella, Nelumwewa, Mahapelessa, Maha Oya, Wahawa, Rankihiriya, and Kinniyai. The highest surface temperatures have been recorded from Kapurella, with 73.5° C. This is a review of previous studies on geothermal resources in Sri Lanka, categorising under geological, geochemical and geophysical studies, with a focus and discussion on the suitability of the techniques used. A significant number of structural details has been reported using available geological and remote sensing data. Geochemical investigations have been undertaken to evaluate the reservoir temperatures, with the highest reservoir temperature assessed to be from the Marangala (Wahawa) hot spring (191°C). The depths and extent of the reservoirs have been determined by employing geophysical studies such as magnetotelluric, resistivity, gravity and magnetic surveys. The lowest resistivity areas, which could be the reservoir, have been identified around 500m and 1.5km-2.0km for Kapurella and Kinniyai respectively. The heat source could be deep seated magma chamber or a hot dry rock, or a steep geothermal gradient related to the HC/VC boundary, which acts as a thrust zone. Some researchers propose that dolerite dykes play an active role as a heat source, while others consider that they play a passive role as barriers cross cutting the deep fractures and forcing the heated ground water to surface as thermal springs. A plausible model, considering all available evidence is presented.

Keywords: Geothermal exploration, Sri Lanka, geochemical, geophysical techniques

1. Introduction

1.1 General background

The geothermal gradient may vary by location and depth with the influence of tectonic processes of thrusting and deformation, release of gravitational energy in subduction, igneous intrusion and as well with mineralogical and petrological transformations. The global average of geothermal gradient is about 25-30°C/km. As a result of the geothermal heat in the subsurface of the earth, springs with relatively higher temperatures (geothermal springs) are formed.

Geothermal heat is a result of several processes, primarily the heat remaining from the process of the earth's origin, decay of radioactive minerals of potassium, uranium, and thorium. In addition, exothermic reactions among some minerals, and from the minor contribution of solar energy absorbed at the earth surface ([1]) also contributed to the geothermal energy.

Hot springs are most prominent in volcanic zones, which may produce superheated water, and reach the surface as steam or hot water. However, some hot springs occur in non-volcanic regions, as a result of percolating water through the deep fracture zones and returning after being heated from a heat source or by the normal or above normal geothermal temperature gradient. Geothermal springs contain a considerable number of dissolved gasses such as H_2O, CO_2, H_2S, O_2, CH_4, Cl_2, and NH_3 which will be influenced by the chemical characteristics of the geothermal fluid and the reservoir properties. H_2S etc. are typical in springs associated with volcanic activity.

Although not situated close to an active plate boundary or volcanic region, Sri Lanka has several hot springs. Apart from assaying geothermal conditions for energy, it is interesting to study the origin of geothermal systems. For over a century, researchers have conducted studies on the geothermal systems. These studies are scattered and far from complete. This paper, discusses and review the geological, geophysical, and geochemical studies previously conducted on Sri Lankan geothermal systems. We also discuss the techniques commonly used for geothermal explorations and their suitability to study geothermal springs in Sri Lankan context. The techniques are discussed under three main categories: geological and remote sensing studies, geochemical studies and geophysical studies. The objectives of this paper is to review the previous studies, with emphasis on the techniques and methodologies used, and to evaluate and discuss the suitability of such methodologies to study our geothermal systems in local context.

1.2 Applications of geothermal energy

Geothermal energy is used as a renewable energy source. Since ancient times, geothermal energy has been used, mainly for space heating. Ancient Roman baths in Bath, England is a well-known example for the above. In certain countries like Iceland, direct use of geothermal energy is providing a significant part of their energy needs. Direct use of geothermal energy includes district and space heating, drying of agricultural products, warming greenhouses, and soil warming processes, in paper and sugar industries, in sanatoriums, and spa baths.

Power generation is the main indirect use of the geothermal energy, and probably the most important one. Use of geothermal energy is associated with a minimum impact on sensitive environmental factors. Where there is sufficient heat geothermal energy is used for power generation. At present, only around 5% ([2]) of the total geothermal energy potential is used in the world. Inadequate geological investigation and assessment of geothermal fields is known to prohibit secure investment. Further, investigation and installation capital costs are also considerably higher. However, long lifespan, low maintenance cost and the high capacity factor of around 70-90% [3], make geothermal power plants an economical investment worth risking.

1.3 Geology and geothermal springs of Sri Lanka

The exploration of geothermal springs in Sri Lanka has begun in early 20th century [4-5]. Subsequently, several studies have been performed on the geothermal springs and their linkage to the boundary of the Highland complex and Vijayan complex (HC-VC) along with the dolerite dike correlation. Initial studies have been conducted by shallow-level explorations and opinions have been expressed that hot water springs are generated from the water coming to the surface through weak geological boundaries [6].

Geothermal springs, Rankihiriya, Kinniyai, Nelumwewa, Kapurella, Maha Oya, Marangala (Wahawa) and Mahapelessa have so far been explored (Fig. 1). Apart from this, there are also a few other springs that have been studied with limited information (ex: Kivulegama). The springs are concentrated mainly along the southwest of Sri Lanka which are relatively near to the Highland – Vijayan boundary [7-8].

2 Geological and remote sensing studies

Geological surveys are conducted to identify structural features, lithology and petrography in the regions of interest. Surface features are extended to the subsurface wherever possible assisted with borehole data. These, together with geochemistry of thermal waters can be related to the geothermal sources within the subsurface.

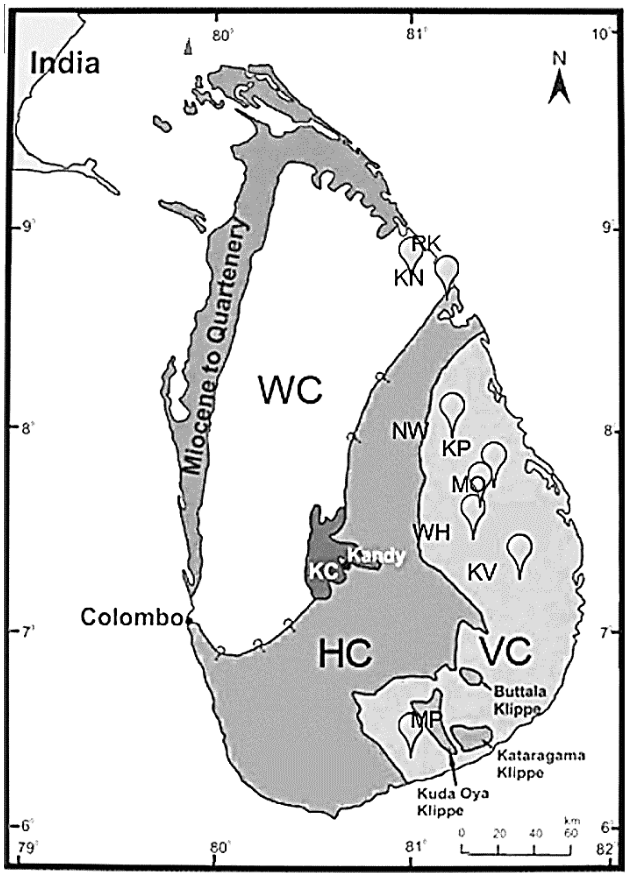

Fig. 1. Locations of the geothermal springs in Sri Lanka (HC-Highland Complex, VC- Vijayan Complex, WC- Wanni Complex, KN-Kinniyai, RK-Rankihiriya, NW-Nelumwewa, KP-Kapurella, MO-Maha Oya, WH-Wahawa, KV-Kivulegama, and MP-Mahapelessa). Map modified after [9].

[10] carried out geological and geochemical studies of the geothermal springs at Kinniyai, Kapurella, Maha Oya, Kivulegama and, Mahapelessa. Fissured quartzite, calc gneiss, charnockite, and granitic gneiss have been reported at Kinniyai, striking NE-SW direction. At Kapurella, Vijayan granites and tonalitic gneiss have been discovered. Granite and granitic gneisses have been discovered at Maha Oya, Pink feldspar granitic gneiss has been observed at Kivulegama and hornblende-biotite-gneiss at Mahapelessa.

[6] reviewed the past work done by several researchers [11-17] on structural geology and tectonics in Sri Lankan basement associated with thermal springs along with the previous studies on the gravity anomalies [18]. He suggested that the frictional sliding of fractures/thrust planes and the dolerite dikes could be a contributing factors to the heat production. A model was proposed that the geothermal springs are a result of the meteoric water driven to the deeper subsurface though fracture/fault zones in elevated regions, being heated by the normal or an above normal geothermal gradient and returned to the surface by artesian action.

From geological mapping, structural analysis, geophysical investigations along with satellite images and aerial photograph interpretations, [19] argued that the geothermal gradient at the depths of geothermal areas has increased as a result of heat generation from multiple thrust planes and a major tectonically active zone. As mentioned by Dissanayake and Jayasena [13], this zone is located between the Highland group and the eastern Vijayan complex. They have also stated that the thermal water is formed from the surface water percolation through the factures, gets heated at the depth, and returns to the surface.

[20] studied Wahawa Padiyathalawa (Marangala) geothermal area using Google earth satellite images and contour maps. They suggested a model that the meteoric water percolates from Maha Oya river upper catchment area through the factures and gets heated by the dolerite dyke(s) and comes to the surface. They also stated that the temperature of the geothermal water may have been reduced due to mixing with ambient groundwater.

Geothermal exploration at Nelumwewa was conducted by Kumara and Dharmagunawardhana [21] with geological field mapping and use of existing structural and tectonic data. Surface displacements that appear on aerial photograph of 1:50,000 scale, were used to study geological structures and fracture lineaments, thereby creating a geological and geotectonic map of the region.

Most of the investigators have so far based the origin of thermal waters to be a result of deep circulation of rainwater through the fractures.

3 Geochemical Studies

Geochemical studies can determine the geochemical properties of thermal fluids, vapours, gases, and as well as the properties of reservoir rocks. Initially, in-situ measurements such as spring temperature, pH, and Eh are measured. Samples from both thermal and non-thermal springs in the close proximity are taken for fluid analysis to compare and to study the correlation of their properties. Major geothermal analyses are cation (Li^+, Na^+, Ca^{2+}) analysis, anion (SO_2^{-4}, Cl^-, F^-, B^-) analysis, silica (SiO_2) analysis, gas analysis (H_2O, CO_2, H_2S, NH_3, He, Ar, O_2, N_2, H_2, CH_4, CO, HCL, HF), (oxidize species) isotope analysis, and alkalinity. In addition, Al, Rb, Cs, Br, As, and Hg are analysed. Cation analysis can be done with Atomic Absorption Spectroscopy (AAS) (flame for major, carbon furnace for minor cations), flame emission spectrometry (FES) (major cations), ion chromatography (major cations), and inductively coupled plasma with atomic emission spectrometry (ICP/AES) or mass spectrometry (ICP/MS) (major and minor cations). Ion chromatography is used for anion analysis. Automatic titration is performed to determine alkalinity. Boron and silica can easily be measured using spectrophotometry and ICP. Colourimetry and turbidometry are also frequently used to quantify sulphate. Gases are analysed with Titrimetry, gas chromatography, mass spectrometry, and radiometry.

For geochemical interpretation of thermal springs, principal analysis supported by Schoeller plot, Cl-SO_4-HCO_3 ternary plot, and Longlier Ludwig square diagram are used. Geothermometers are used to calculate the reservoir temperatures. Silica (quartz and chalcedony), Na-K, and Na-K-Ca are the most common water geothermometers [22-24]. Chemical geothermometers such as silica geothermometers and ionic solute geothermometers have been used in previous studies to determine the reservoir temperature [25].

Isotope analysis of geothermal fluids provide information on the origin of water, rock water interaction, and mixing. Conduction, mixing, and boiling processes can be traced isotopically as the isotopic composition change with each process [26]. The most commonly used isotopes to determine the geochemical characteristics of geothermal springs are hydrogen ($^2H/^1H$ and ^3H), oxygen ($^{18}O/^{16}O$), sulphur ($^{34}S/^{32}S$), and helium (^3He, ^4He) [27].

The composition of the gases differs with different geothermal systems. Carbon dioxide with lesser hydrogen sulphide are the predominant gases in high-temperature systems, accounting for over 90% of the gas composition in many case. Ammonia, hydrogen, methane, and nitrogen, as well as trace amounts of oxygen, noble gases, hydrocarbons, and volatile species of boron, fluorine, arsenic, and mercury, may be present as minor and variable phases. For low-temperature systems, relative proportions of the gases can be different from those in high-temperature systems. Flow directions, reservoir rock type, and type of the geothermal system can be determined using gas analysis. Gas geothermometery can be used to determine the reservoir temperature [28].

[29] used naturally occurring deuterium, oxygen, and tritium present in the water, along with chemical analysis, to explore the origin and the mode of recharge of the Sri Lankan thermal springs.

[13] analysed data from the previous studies on the geothermal springs of Sri Lanka, and suggested a geothermal model. They have calculated sub-surface temperatures of 143°C for Kapurella, Maha Oya, and Marangala (Wahawa) and temperatures in the range 102°-131°C for all other thermal springs (Kanniya, Kivulegama and Mahapelessa) (Table 1) using silica geothermometers [30] and Na-K-Ca geothermometers [31]. They have asserted that the heat is originated during tectonic movements along deep-seated lineaments, where exothermic reactions had taken place as a result of serpentinization. They have also described the heat-producing granites formed by crust-mantle mixing and upward movement of magmatic fluids along the tectonic boundary and their association with anomalous concentrations of uranium which contribute to the heat balance of the geothermal system.

[7] conducted geochemical studies on seven geothermal springs at Rankihiriya, Kinniyai, Nelumwewa, Kapurella, Maha Oya, Marangala (Wahawa), and Mahapelessa. They used silica-based geothermometers to calculate the reservoir temperatures of the above systems. Reported surface temperatures are Mahapelessa-45.5°C, Rankihiriya-39.1°C, Kanniyai-41.7°C, Nelumwewa-62.2°C, Maha Oya-53.5°C, Marangala-43.4°C, and Kapurella-58°C (Table 2). Calculations have been performed to determine reservoir temperatures by applying different geothermometers. Highest temperatures have been obtained as 138° C and 137° C for Marangala and Nelumwewa respectively, by using modified silica geothermometer [34].

Table 2

Reservoir temperature of the thermal spring (NW-Nelumwewa, KP-Kapurella, MO-Maha Oya, MG-Marangala (Wahawa), MP-Mahapelessa, RK-Rankihiriya, KN-Kinniyai, KV- Kivulegama) after [7],[13],[32[and [33]

Reference	**Chemical geothermometer**	**Estimated Temperature of Thermal spring (°C)**							
		NW	**KP**	**MO**	**MG**	**MP**	**RK**	**KN**	**KV**
Chandrajith et al., 2013	Silica–quartz conductive cooling	132	126	131	97	116	131	97	
	Silica quartz max. steam loss	128	124	128	98	114	127	99	
	Silica–Chalcedony	92	87	92	57	76	92	57	
	Silica–Chalcedony	103	98	103	68	87	103	69	
	Modified silica geothermometere	137	128	121	138	118	133	105	
	Na–Li	129	124	127	122	96	99	103	
Dissanayake and Jayasena, (1987)	Na-K-ca (1)		143	143	143	102-131		102-131	102-131
	Silica geothermometer (2)		143	143	143	102- 131		102- 131	102-131
	Na-K Arnorsson (1983)			121	176				
	Na-K Arnorsson (1983)			148	191				
Jayawardhana et al., 2016	Na-K Truesdell (1976)			101	155				
	K-Mg Giggenbach (1986)			120	105				
	Na-Li Kharaka (1989)			96	189				
				81	103				
	Max	137	143	148	191	118	133	131	131
	Min	92	87	81	57	76	92	57	

Some of the elements (e.g. Fe, Mn, Cu, Cr, As) at low concentrations have been revealed. Stable isotopic compositions of the geothermal water range from -6.5 to -5.0‰ for $\delta^{18}OH_2O$ and $\delta^{2}HH_2O$ respectively, and these values are comparable with those of the non-geothermal water in the areas. Both the isotopic ratios have been scattered around the local meteoric water line in the dry and intermediate climatic zones of Sri Lanka. From the results, they have concluded that both geothermal and non-geothermal water originates from a common source, which is mostly fed by precipitation. A model proposed for the geothermal springs suggest that water from the rainfall percolates and penetrates downwards through the weak zones of the continental crust and is then heated from a steep or heterogeneous geothermal gradient which may have a close relationship with Highland-Complex and Vijayan complex thrust zone.

[35] have reported 21 parameters including major cations, anions, heavy metals, and trace elements at Maha Oya geothermal system. They stated that the thermal water may enrich the intermediate groundwater and indicate common recharge sources and circulation patterns.

According to the geochemical studies of [36], the Maha Oya thermal spring cluster has a good hydraulic connection to shallow groundwater, and the high-yielding outlets have more effective preferential paths that extend to depths.

A geochemical study has been carried out by [33] at Maha Oya and Marangala (Wahawa) Sri Lanka. They have proposed the existence of a non-volcanic thermal reservoir extending from intermediate to higher depth resulting higher reservoir temperature for geothermometers. They have concluded that thermal water and cold water are mixed at increasing distance from the geothermal reservoir.

[37] collected water samples from four thermal springs situated at Nelumwewa, Maha Oya, Kapurella, and Wahawa and analysed for the chemistry. The average geothermal reservoir temperatures for all four thermal springs has been calculated using Na–K, K–Mg, Na–K–Mg and SiO^{2-} temperature geothermometry. Their results indicate temperatures about 150°C for all four thermal springs.

According to the geochemical compositions along with geological and geographical parameters, [19] categorised geothermal springs under different provinces as follows: Group 1: Mahapelassa, Group 2: Kapurella, Maha Oya, Padiyatalawa, Palanoya and springs around Mahiyangana and Ampara and, Group 3: Kanniya, Rathkhiriya (Rankiriulpotha) and Adampane areas.

[38] also divided geothermal springs into four geochemical provinces, namely Kinniyai (Kinniyai and Rankiriulpotha), Kapurella (Kapurella and Nelumwewa), Maha Oya (Maha Oya and Wahawa) and Mahapelessa as per their geochemical properties.

From the geochemical and isotopic analysis done on Wahawa geothermal area, geothermal waters in Wahawa have been assumed to be mixed [39].

Among other gases, geothermal hydrogen in Sri Lanka was reported by [32, 47] and as well chemical analyses.

4 Geophysical Studies

Geophysical methods play a major role in geothermal explorations and can be categorised as direct and indirect methods. Thermal methods, four probe and multi electrode resistivity methods, and self-potential (SP) are examples of direct methods, whereas structural (indirect) methods include magnetic measurements, gravity measures, active seismic methods, and passive seismic monitoring. Globally, seismic surveys, resistivity surveys, gravity surveys, magnetic surveys, magnetotelluric (MT) surveys, and time-domain electromagnetic (TDEM) surveys are the most commonly used geophysical techniques in geothermal explorations.

DC electrical resistivity survey is an active geophysical method, which introduces an electrical current into the ground using two electrodes. Apparent resistivity is determined by the potential difference measured using another pair of electrodes. Multi electrode systems are an extension of DC resistivity for rapid profiling from the variations in the apparent resistivity, information on the surveyed subsurface can be obtained. Electrical surveys are usually conducted as One-Dimensional (1-D) and Two-Dimensional (2-D) surveys. One-Dimensional surveys provide a linear 1-D log, while Two-Dimensional surveys provide a 2-D resistivity profile.

[41] used a One-Dimensional and Two-Dimensional resistivity survey and magnetic survey for subsurface mapping of the Kinniyai geothermal spring area. They concluded that the near-surface water flow path in Kinniyai hot water spring is towards the North-East direction.

[42] conducted 2D resistivity surveys at Nelumwewa Geothermal area and obtained subsurface profiles. He interpreted low resistivity zones as water accumulation areas where geothermal water gets mixed with normal ground water. He suggested that some of the low resistivity zones represent small scale water saturated fractures.

[21] carried out Vertical Electrical Resistivity Sounding (VES) to explore the fractures and faults that have been observed in aerial photographs and satellite images. They hypothesized that the Nelumwewa thermal spring evolved as a result of deep groundwater percolation through a regional fault zone, heated by hot dry rock beneath the Dimbulagala Mountain, and then returning to the surface along a NE-SW trending regional vertical fault plane in the area.

Four probe and multi electrode electrical resistivity surveys, SP, magnetic and gravity surveys at Mahapelessa and Mahaoya were conducted and methodologies and results were presented by [32]. Geophysical information from these surveys gave the structure of contrasting rock boundaries in density, magnetisation while resistivity, SP anomalies resulting from rising thermal waters were noted at these boundaries. Lower resistivity was noted at depth (100-400m) likely to be rock saturated with thermal water. Deeper subsurface is highly resistive and avoided deeper penetration with DC resistivity methods. With a need for deeper investigation of subsurface, this work was extended to a MT survey in 2010.

The magnetotelluric (MT) method is a passive electromagnetic (EM) technique that determines the resistivity distribution in the relatively deeper subsurface compared to nearer subsurface by acquiring orthogonal directional measurements of the electric (E) and magnetic (B) fields on the earth's surface. The ratio of the electric and magnetic variations provides information pseudo resistivity-depth information that is inverted to true resistivity-depth information of the subsurface. Collecting time domain electromagnetic (TDEM) data simultaneously done in MT surveys to give near surface resistivity [43].

In TDEM, a transmitting loop is laid on the ground and a constant current is transmitted through the loop inducing a magnetic field with known strength. When the transmitting current is stopped abruptly, decaying magnetic field will generate a secondary electrical current in the ground. The secondary electric field produces a secondary magnetic field decaying with time. The production of the secondary magnetic field in the absence of primary sources is called a transient electromagnetic wave (TEM-Wave). The decay rate of the secondary magnetic field is monitored in different time intervals.

A Magnetotelluric survey complemented with a TDEM was conducted in 2010. This is the first-ever deep-earth geothermal exploration carried out in Sri Lanka through seven hot water springs (Kapurella, Maha Oya, Nelumwewa, Padiyathalawa (Wahawa/Marangala), Mahapelessa, Rankihiriya, and Kinniyai). True resistivity-depth profile from raw data were inverted to true resistivity depth profiles are presented in “Fig. 2.” by [44]. MT results are presented as resistivity-depth cross sections up to 20km depths. From the interpretation of data, areas where the resistivity is less than 10 Ωm have been encountered at Kapurella at the depth of ~500m and at Kinniyai, at the depth of ~1.5km and 2km. In Padiyatalawa, Maha Oya, and Kinniyai, resistivity ranges have found to be around 10-100Ωm at depths beyond 10 km. 2-D resistivity models have illustrated relatively low resistivity regions that have been suggested as the possible path of the thermal water from the subsurface to the surface. The low resistivity zones at Kapurella and Nelumwewa indicate that the heat source is not directly beneath the MT traverse, because the cross section might have cut the water flow paths. I.e. fracture zones, at an angle, or perpendicularly. Padiyatalawa-Maha Oya-Kapurella cross traverse has displayed evidences of the geothermal source of Maha Oya. At Padiyathalawa, bands of lower resistivity in high resistivity subspace, extends to the deep interior, while a larger low resistivity region can be observed at depths of 15km. Even though doleritic intrusions have been observed near the area, the relationship between the dike and thermal water has not established beyond doubt. Based on an average temperature gradient, temperatures here could be over 300°C. The low resistivity region 3km below the Kinniyai hot spring is seen to have a connection to a lower resistivity region below 10km, where the normal geothermal temperature can be 300˚C, but has no known association with a dolerite intrusion and is likely to be related only to thermal water (Fig. 3). The Highland-Vijayan boundary has been suggested as a thrust zone by [44] using the 2D resistivity model Mahapelessa (Fig. 4).

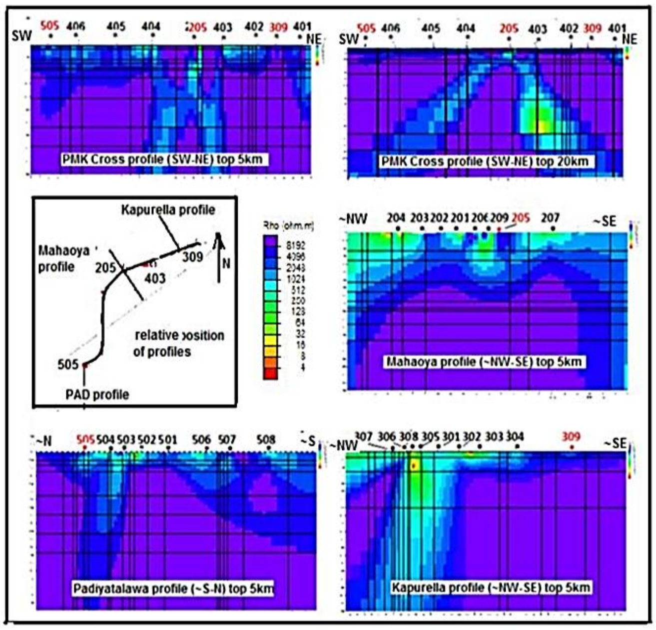

Fig. 2. Resistivity profiles of Kapurella, Maha Oya and Padiyathalawa [44]. Purple colour represents the high resistivity regions while red colour represents the low resistivity regions.

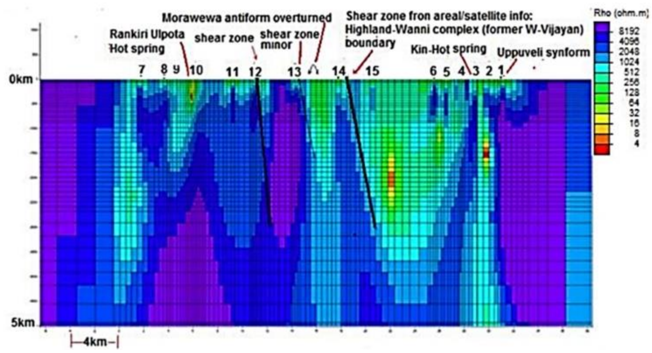

Fig. 3. Resistivity-depth section for Kinniya-Rankiri Ulpotha [44].

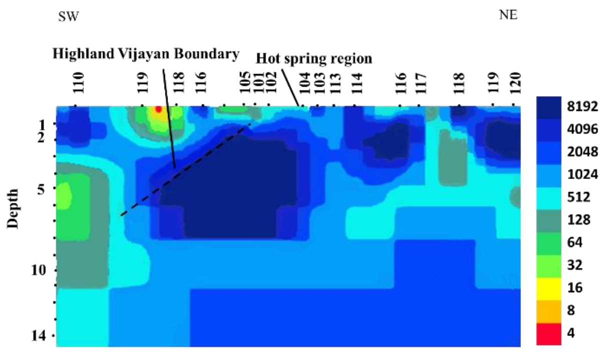

Fig. 4. Resistivity profile of Mahapelessa using MT data (after [44])

Later, [38] interpreted the data of the Kapurella geothermal spring from the above survey and concluded that the Kapurella geothermal reservoir has a depth of 3km with lateral extension around 2.5 km. Also, the dolerite dike could be playing a passive role by acting as an impermeable barrier to the formation of the reservoir. The temperature of the reservoir has been calculated as 135°C.

Resistivity profiles of [44] and [38] display relatively similar low resistivity zones, which are described as flow paths and water accumulation zones (Fig. 5 and Fig. 6) at Kapurella. Vertical low resistivity regions were assumed to be fractures feeding the geothermal spring.

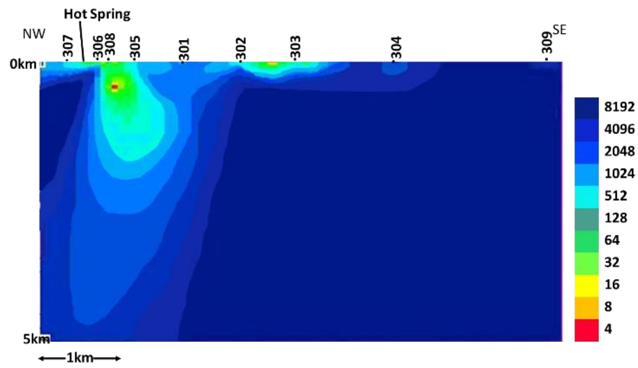

Fig. 5. Resistivity profile of Mahapelessa using MT data (after [44])

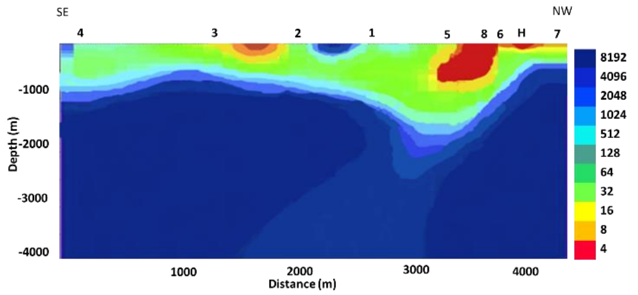

Fig. 6. Joint TE- TM, 2D inversion model for Kapurella springs (after [38])

From the TDEM surveys that have been conducted around Maha Oya and Wahawa (Padiyathalawa/Marangala) springs, a low resistivity region has been observed below the location of the artesian well at Wahawa, which has been considered as the place where the accumulation of water takes place before it comes to the surface [8]. In studies on Maha Oya geothermal system, low resistivity regions could not be distinguished as in Wahawa location. Nearly vertical low resistivity regions have been assumed as structural discontinuities such as faults or fractures.

[42] studied and interpreted Time Domain Electromagnetic (TDEM) survey data of Mahapelessa hot spring. They identified low resistivity (less than 10Ωm) zones directly below the geothermal spring and assumed them to be thermal water-bearing fractures. On the evidence that most of the low resistivity zones are spread towards HC/VC boundary, they suggested that the heat source is possibly in the HC/VC boundary or at a close proximity to the boundary zone at Mahapelessa hot spring (Fig. 7).

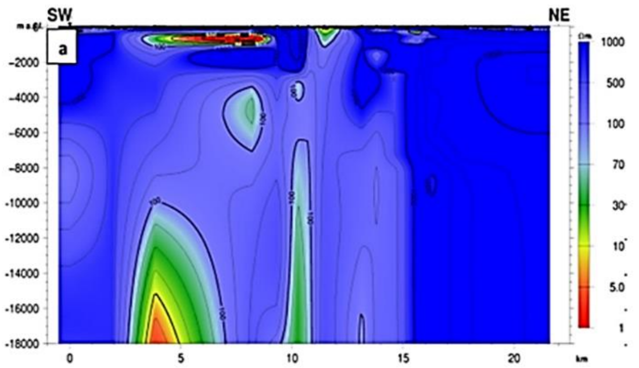

Fig. 7. Resistivity profile for the area near Mahapelessa hot spring created using MT and TDEM data [42].

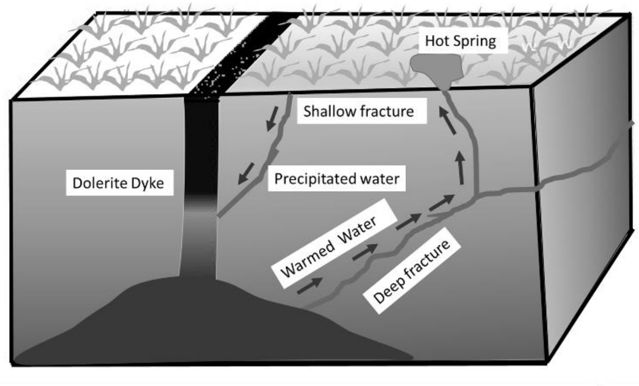

Fig. 8. Proposed model for geothermal systems in relation to the dolerite dykes (after [46]).

Resistivity profiles of Mahapelessa area by [44] (Fig. 4) and [42] (Fig. 7) using MT data, indicate a very low resistivity zone at 500m, while [42] has shown another low resistivity area below 15 km depth. Also, [42] has encountered a low resistivity zone directly below the geothermal spring, extending to the deeper subsurface, which has not been displayed in the [44], in which a profile does not show below 15km.

Using TDEM data, [45] created six iso-resistivity maps from 0 to 150 m depth levels at Kapurella Geothermal spring. Their results indicate a low-resistive structures below 75 m, which extend to very low resistive zones that continue to higher depths. They suggested that these low resistivity zones indicate the flow paths and geothermal water accumulation zones.

[46] proposed a model for the geothermal springs in relation to dolerite dykes using geophysical data. According to their model, dolerite dykes play a major and active role in the formation of geothermal spring, by supplying heat, as well as acting as a barrier to groundwater (Fig. 8).

5 Discussion

5.1 Geological and remote sensing studies

Detailed geological and remote sensing studies have been conducted on major geothermal springs in Sri Lanka ([10], [19], [20-21], [37]). However, an up-to-date geothermal map with all the details of geothermal areas has yet to be created. Therefore, it is preferable to conduct a large-scale geological study that includes all the geological information on geothermal springs that can be used to emphasize the structural and geological relationship among hot springs.

5.2 Geochemical studies

In geochemical studies, both cation and anion analyses along with isotope analysis have been done on the geothermal springs ([7], [13], [19], [21], [32], [38], [48]). Isotope studies indicate that both geothermal and non-geothermal waters are formed from precipitation. The discharge temperature of the springs lies between 34°C (Kivulegama) ([13]) and 73.5°C (Kapurella) ([8]) (Table 2) and the calculated reservoir temperatures range from 57°C to 191°C (Table 1).

Table 2
Reservoir temperature of the thermal spring (NW-Nelumwewa, KP-Kapurella, MO-Maha Oya, MG-Marangala (Wahawa), MP-Mahapelessa, RK-Rankihiriya, KN-Kinniyai, KV- Kivulegama) after ([7], [13], [19], [21], [38], [48])

Reference	Estimated Temperature of Thermal spring (°C)							
	NW	KP	MO	MP	RK	KN	KV	WH
Dissanayake and Jayasena, (1987)		55	54	44		42	34	48
Premasiri et al., (2006)	45	55	54.2	44.9	42.0	42.0	34.1	46.8
Chandrajith et al., (2013)	62.2	58.0	53.5	45.5	39.1	41.7		43.4
Kumara and Dharmagunawardhana, (2014)	61	56	54					48
Nimalsiri et al., (2015) (Thesis)	55-62	58-73.5	47-54	46	39	42-44		44-48
Bandara et al., (2019)	62	70	55	45	39	41		50-60

According to the geothermometers used, the temperature of the reservoirs varies greatly. Higher temperatures are resulted from Na/K geothermometer ([49]) whereas the lowest is from Silica–Chalcedony geothermometer ([50]). The difference between discharge temperatures and the reservoir temperatures are interpreted as the thermal water and cold water being mixed before reaching the surface. From geothermal studies, researchers generally agree that the geothermal springs are formed from the deep percolation of rainwater through the fractures and returning after been heated from a heat source at depth. However, researchers so far have mainly focussed on the geothermal water. No reasonable attention has been paid to gas analysis, only a few details have been obtained from limited studies. [32], [47] reports existence of H2 among other gases.

5.3 Geophysical studies

As of today, the MT survey, which was conducted in the year 2010 ([44]) can be considered as the only comprehensive deep geophysical survey carried out on thermal springs in Sri Lanka. From that MT survey, subsurface profiles for seven geothermal springs have been obtained. At Kapurella and Kinniyai MT traverses, low resistive regions, possibly water-bearing fractures, have been observed at relatively low depths. When deep profiles are considered, low-resistive zones are encountered again at deeper levels, indicating a possible continuation of the fractures or another set of weak, water-bearing zones.

Due to time and resource limitations, as well as other factors beyond the control, only one MT traverse each could be conducted at each thermal spring. The MT traverse at Kinniyai-Rankiriulpotha (40Km) and Mahapelessa (20km) were the longest, while the other traverses were confined to approximately 9km length. Despite the fact that the researchers gathered a large amount of information, one profile is still insufficient for proper understanding of the subsurface, a 3D MT survey will give more detailed lateral information than with a single cross section. Geothermal sources need not be necessarily deep under the spring location. Suggestion was made for a 3D MT survey, [44].Other geophysical surveys have been confined to near subsurface investigations.

In addition to the MT survey, magnetic surveys have also been conducted at, Kapurella ([46]) and Nelumwewa ([42]). A VES has been conducted near Nelumwewa by [21], a 2D resistivity survey has been conducted at Nelumwewa by [42] and 1D survey at Kinniyai geothermal springs by [50]. [32] conducted Magnetic, gravity, SP, multielectode resistivity soundings and geochemical analyses. Subsurface profiles have been created with these geophysical information and models for geothermal systems have been proposed.

5.4 Drawbacks of the geothermal exploration techniques in Sri Lankan context

As the first phase in geothermal investigations, geological mapping and remote sensing research are fundamental. However, sufficient amount of information at a high resolution, is not available for some of Sri Lanka's geothermal locations. Due to lack of outcrops and rock exposures, it is difficult to construct a detailed geological map at every location. On the other hand, up to today no borehole data are available in Sri Lanka to the adequate depth (500m-1km). In those instances, extrapolation can be done by considering indirect data.

Geochemical studies should be carried out with much consideration because obtained results can be drastically affected due to numerous factors and experimental conditions. Contamination may take place at any moment from the sample collection. Care should be taken to minimise sampling errors, human errors and random errors, as much as possible. Even the environmental factors like rain, humidity, temperature can affect the chemical composition of water. Also some of the hot springs are located at close proximity to the sea. Therefore, salt water intrusions may occur, affecting the composition of the thermal water from the heat source.

As mentioned earlier, MT is one of the best techniques to study the deep underground resistivity structures. Due to the cost and the lack of instruments, it is hard to carry out more MT surveys. Further, MT traverses require, unobstructed long stretches with little or no cultural noise. Since Sri Lanka is a highly populated country, Magnetotelluric surveys are often affected by cultural noise, especially the 50Hz signal generated by the AC power lines and farmers using electrical generators. It is also hard to find flat and unobstructed terrain extending up to several kilometres, which is ideal for MT surveys, However topographic corrections can be performed where necessary with topography information and additional computer software.

Seismic surveys mostly provide structural information to density contrasts. However, as with others lack of facilities to conduct a deep seismic survey has prevented obtaining such information.

Resistivity surveys can be conducted in Sri Lanka with little or no difficulty, as they are not affected by cultural noises and require only a few hundred meters of a straight line. However, the depth of penetration will be limited to about 60m, especially in marshy terrains like at Kapurella, because the water content reduces the resistance at upper layers. On the other hand, resistivity surveys cannot be done in the geothermal springs located within lakes such as Nelumwewa because of the unavailability of the ground.

TDEM is the best solution in marshy areas or lakes, because TDEM measurements are not affected by water. However, due to a lack of operational equipment, TDEM surveys in Sri Lanka are hard to undertake.

Magnetic surveys are easy to carry out compared to the other geophysical techniques aforementioned. Unlike data from resistivity surveys, magnetic data are not affected by the water-logged or low-resistive upper layers. However, magnetometer readings are affected by cultural noises. Ground magnetic surveys carried out using walking magnetometers, or carried on non-motorised non-magnetic vehicles or rowing boats. Two magnetometers, one stationary at the base station to detect the diurnal changes and other noises, and other being the “walking” magnetometer providing time-series data, are used for best results. Resolution of the images created using inverted data is generally reduced with the depth.

5.5 Model for Sri Lankan geothermal systems

From the previous studies several assumptions have been made on the origin and the structure of the geothermal springs. Almost all the researchers have agreed that geothermal springs are formed by rain water percolating through deep fractures, mainly along the HC/VC boundary as it is a highly-fractured thrust zone, and returning to the surface ([7], [21], [35], [36]). However, there are debates on the heat source of these springs. Some of the researchers suggest that an igneous intrusion such as a dolerite dyke act as the heat source, stating that the fractures connected to the hot springs are associated with dolerite dykes ([20], [46]) whereas some others believe that the heat source could be a magmatic source ([43]); or hot dry rock ([21]).
By reviewing the previous studies, we can suggest an improved model for the formation of geothermal springs. Precipitated water may percolate through fractured rocks, and get heated by a steep geothermal gradient or a heat source and then return back to the surface. Since HC/VC boundary is a thrust zone, there could be a high probability that deep-water percolations are most prominent in this zone. Further, the relatively younger dolerite dykes may facilitate the formation of springs, since they cross-cut the deep ancient fractures and act as a barrier to direct the water flow to the surface (Fig. 9). In some places we can observe both cold water and hot water springs with close proximity to each other (Mahapelessa). This happens when there are both deep and shallow level fractures in the same area. When deep level fractures are intercepted, geothermal springs are formed and when the shallow level fractures are intersected cold water springs area formed.

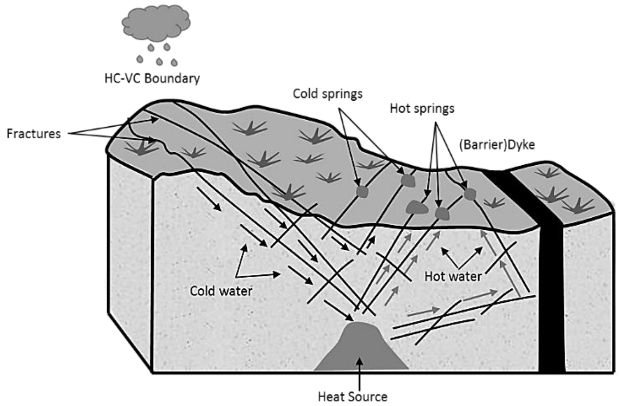

Fig. 9. Schematic diagram of the formation of hot springs. This heat source could be hot dry rock or a steeper-than-average geothermal gradient.

Geophysical studies are composed of more advanced techniques, such as seismic, gravity surveys advanced GIS, as well as remote sensing techniques. Since only a few techniques have been used in the investigations, comparisons have not been made to assure the validity of the results. Most of the techniques used for geothermal explorations are indirect methods. Therefore, direct methods such as borehole data is needed for the confirmation of the results.

When considering all the previous studies, several investigations have been conducted on geological and remote sensing, geochemical, and geophysical aspects. Detailed integrated investigations are not available. In most of the studies, only one or two types of technique have been used. No sufficient data for complementary models, except for a few cases ([13, [43], [46]). Even though all these investigations give some interpretations of the thermal springs, their main focus was on the origin, their flow paths and the possible reservoir temperatures.

6 Summary and suggestions

Large-scale detailed geological maps should be created in order to identify the geological and structural details using different geological, geochemical, and geophysical techniques such as IR mapping, gravity, and seismic surveys.

Detailed gas analysis, in addition to water analysis, is required to properly understand geothermal systems.

A deep borehole program need to be established in locations of interest. Borehole information should be compared with the aforesaid surveys

[32] Successfully established foreign assistance for the MT work in 2010. Such collaborations need to be further pursued.

Geothermal energy exploration techniques should be focused for their potential and application, to national development.

Conflicts of Interest

There are no conflicts to declare

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