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Use of ground magnetic survey in exploration of geothermal springs in a metamorphic terrain: A case study from Sri Lanka

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A B S T R A C T

Magnetic surveys map anomalies by detecting interferences in the Earth's magnetic field caused by subsurface features. Metamorphic terrains, shaped by intense pressure and temperature, often host fractures and faults that channel fluid flow and are frequently enriched with ferromagnetic minerals. These structures can be effectively identified using ground magnetic surveys due to their distinct magnetic signatures. A magnetic survey was carried out in the Wahawa-Padiyathalawa hot spring area, Sri Lanka, to explore the subsurface geology and structures and their links to thermal discharges. An "Overhauser" magnetometer with GPS was used to collect magnetic data every two seconds across a 15 km^2 area, avoiding manmade interferences. Anomalies were corrected using International Geomagnetic Reference Field (IGRF) values, and Oasis Montaj® software was used for analysis. Filters such as Reduction to Equator (RTE), Pseudo-gravity, and Tilt Horizontal Derivative (THDR) were applied to enhance signals and highlight specific geological features.

The results reveal that RTE transformation poses challenges in interpreting geological structures due to paired dipoles and signal interference. In contrast, THDR and pseudo-gravity transformations provide clearer views of surface and subsurface features respectively. The hot spring cluster lies within high THDR and pseudo-gravity anomaly zones, indicating a strong relationship to surface and subsurface structural lineaments. The hot spring cluster connects with the surface structural lineaments in the THDR anomaly map. Pseudo-gravity map shows that the dolerite dyke disrupts subsurface fractures, suggesting it acts as a barrier to deep fluid flow and contributes to thermal spring formation. This study highlights the value of ground magnetic surveys, combined with THDR and pseudo-gravity transformations, in mapping structural controls on geothermal springs in metamorphic terrains.

1. Introduction

Historically, geothermal exploration has focused on volcanic regions because of visible indicators like hot springs and steam vents, which make geothermal activity easier to identify. However, there is a growing recognition of metamorphic terrains as promising sites for geothermal energy exploration in last two decades (Guo et al., 2018 and Reinecker et al., 2019). Metamorphic terrains inherit distinct geological and thermal properties, including well-interconnected secondary porosities and higher thermal conductivities that facilitate geothermal applications in metamorphic terrains, compared to the volcanic terrains (Hintze et al., 2018 and Cornetto, 2024).

Metamorphic terrains are often characterized by complex geological structures such as faults, folds, shear zones, and intrusions, which can significantly influence geothermal systems (Kayode and Adelusi, 2010; Olorunfemi et al., 1986). These terrains are subjected to intense pressure and temperature conditions and often contain fractures and faults that serve as pathways for fluid flow, making them potential targets for geothermal exploration (Chandrajith et al., 2013). Identifying these features is critical to understanding subsurface fluid pathways, which in turn can indicate geothermal potential.

Ground magnetic surveys have proven to be an effective tool for mapping structural features in metamorphic settings, as these features often show strong contrasts in magnetic susceptibility compared to the surrounding rocks. Ferromagnetic minerals; magnetite ilmenite and hematite that are commonly found in igneous intrusions such as dolerite dykes, or in mineralized shear zones, create distinct magnetic anomalies (Purucker and Whaler, 2007; Dutch et al., 2014). Magnetic surveys can also identify fractures, faults, and other structural discontinuities by detecting variations in magnetic susceptibility (Verduzco et al., 2004;

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Salem et al., 2008). For example, a ground magnetic survey in Wadi Fatima, within the Arabian Shield, successfully reveals subsurface structures in a metasedimentary terrain and provides estimates for the average depth of magnetic sources (Al-Garni, 2010). Similarly, in the Betul Belt of India, magnetic data are used to delineate a mafic–ultramafic intrusive body, estimate its depth, and map faults in a geologically complex setting containing volcanic and Precambrian metamorphic rocks (Baswani et al., 2017). Essa et al. (2022) demonstrate the effectiveness of advanced magnetic data processing techniques, including total magnetic intensity, reduced-to-pole (RTP) transformations, power spectrum analysis, analytic signal, tilt angle, and local wavenumber methods to identify magnetic source distributions, structural lineaments, and mineralized zones within Precambrian terrains in Egypt. Techniques like reduction to equator (RTE), horizontal derivatives, pseudo-gravity and Euler deconvolution are used in many literatures to understand subsurface intrusion, fluid conduits, magmatic source distribution and depth to magmatic source (Fairhead et al., 2011; Panepinto et al., 2014; Okpoli, 2019; Essa et al., 2020 & Rusman et al., 2023). In recent years, magnetic data processing techniques have been advanced with inversion algorithms, which demonstrate very good capabilities in resolving complex subsurface structures in complex terrain settings (Essa and Diab, 2025, 2022a, b & Essa & Toushmalani et. al.,

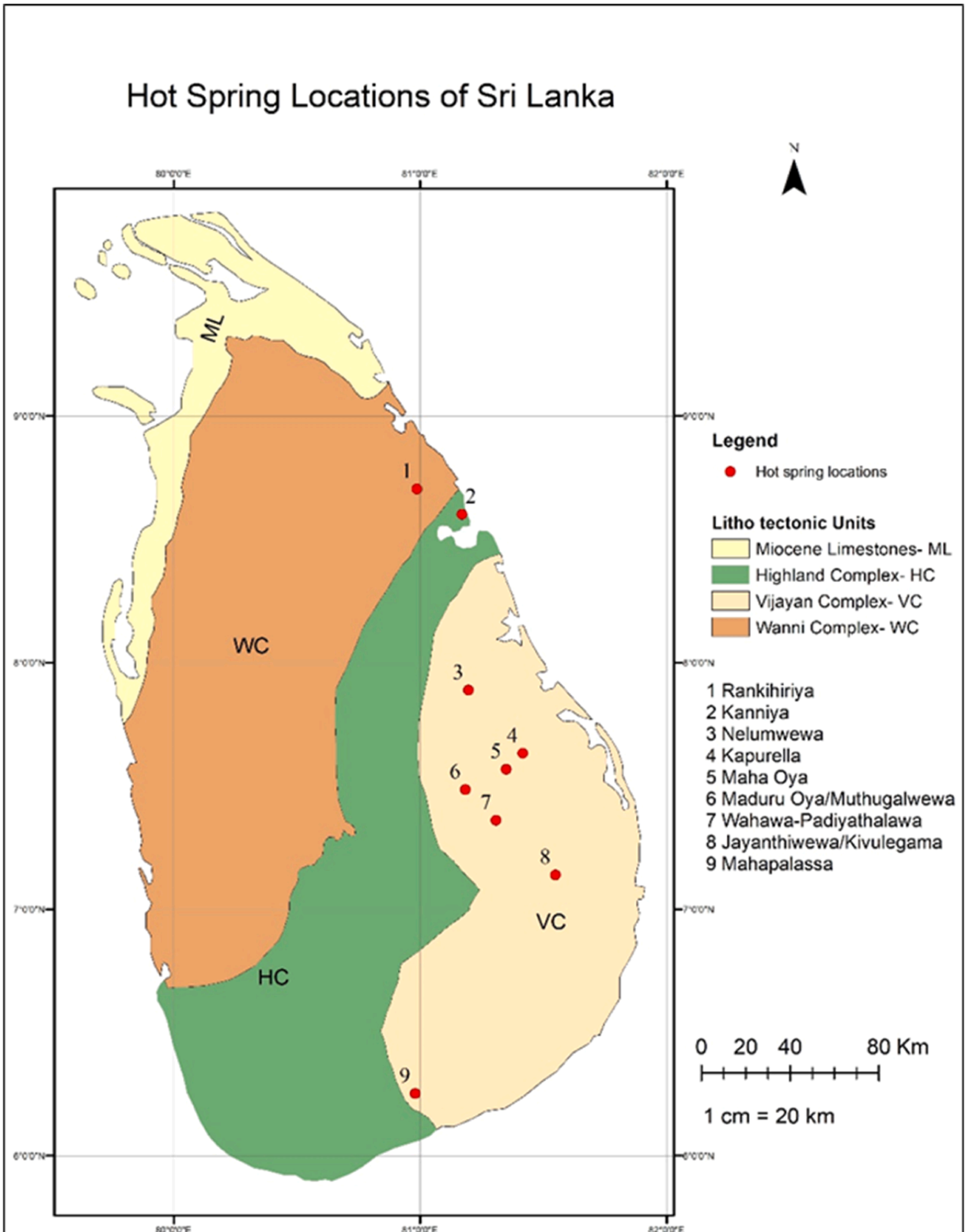

Fig. 1. Hot spring locations in Sri Lanka.

2025). Essa & Diab (2022) apply an automatic inversion approach called the global bat optimization algorithm (GBOA) to magnetic data to delineate ore deposits and basement rock intrusion in complex geological settings with schists in Canada. They also state GBOA can expand to explore geothermal resources in the future.

Data processing techniques that are used in this research include Reduction to Equator (RTE), Horizontal Tilt Derivatives (THDR) and Pseudo-gravity transformations. RTE and Pseudo-gravity anomaly concepts were first introduced in Baranov 1957 to interpret aeromagnetic data. The RTE approach involves transforming the data to eliminate the obliquity of the normal magnetic field, ensuring that the resulting anomalies are aligned vertically with the magnetized bodies. It was used to correct the effect of low magnetic latitudes over the collected raw data (Baranov 1957; Fairhead et al., 2011; Okpoli, 2019 & Rusman et al., 2023). The pseudo-gravity filter was used to analyse the signals coming from deeper levels, ignoring surface anomalies (Baranov 1957; Jekeli et al., 2010; Hinze et al., 2013; Panepinto et al., 2014 & Rusman et al., 2023). Non-linear filter was used to remove high amplitude and short-wavelength noise data (Stone, 1995). Tilt derivatives and its horizontal derivatives are useful for identification of shallow basement structures (Verduzco et al., 2004; Fairhead et al., 2011 & Salem et al., 2008) and mineral deposits (Verduzco et al., 2004). It also operates independently of magnetic inclination, is less affected by noise and exceptionally responsive to the shallow superimposed structures (Khalil, 2016).

In Sri Lankan high-grade metamorphic terrain, geothermal exploration needs to understand the distribution of fractures, faults, and intrusive bodies, because these features can act as conduits for thermal fluids (Chandrajith et al., 2013) or contribute to the residual heat of the system (Senaratne and Chandima, 2011). The high-grade metamorphic basement of Sri Lanka has no active volcanic regions or plate boundaries. Yet, there are 9 hot spring occurrences scattered in the eastern parts of Sri Lanka, which are called Nelumwewa, Maduru oya, Kapurella, Wahawa-Padiyathalawa, Maha Oya, Mahapelassa, Rankihiriya, Kanniyai and Jayanthiwewa (Fig. 1). There is a significant interest in studying these thermal springs since they can be utilized in many areas, such as in electricity generation, agriculture for crop drying, the health care industry, and tourism. Exploration of alternative renewable energy has attracted more attention due to the increase of energy consumption as well as the recent trend of turning towards renewable energy. Studies have to be carried out to understand the origin and the geothermal settings of these thermal springs to develop them as renewable energy. The literature has estimated the potential of these thermal springs using the Monte Carlo approach with a 90 % probability that the geothermal reservoir of Sri Lanka could produce 715–1335 MWe for 50–100 years. This estimation has been done with the assumption considering the ancient thrust zone of Sri Lanka. The discharge temperatures of these springs vary between 34 °C and 73.5 °C and all of them have been identified as low-enthalpy geothermal systems (Chandrajith et al., 2013; Wijetilake, 2011).

1.1. Comparison of structural controls on geothermal springs in Sri Lanka

Multiple studies have been conducted on the formation of these low-enthalpy geothermal systems, proposing various hypotheses (Dissanayake and Jayasena, 1988; Fonseka, 1994; Premasiri et al., 2006; Chandrajith et al., 2013; Kumara and Dharmagunawardhane, 2014; Nimalsiri et al., 2015; Suriyaarachchi, 2017; Bandara et al., 2018 & Bandara et al., 2024). However, no definitive conclusion has been deduced yet. Early investigations of the geothermal spring areas focused on surface-level explorations such as surface geology, geochemical analysis and information taken from scientific publications (Dissanayake and Jayasena, 1988 and Fonseka, 1994). Dissanayake & Jayasena (1988) mentioned that there is a thermal spring line at the tectonic contact between Sri Lanka's major lithological units, the Highland Complex and the Vijayan Complex. They proposed three potential sources for the formation of these hot springs: 1) heat-producing granites formed by the upward movement of magmatic fluid along the tectonic boundary, 2) heat generated from exothermic reactions caused by serpentinization, and 3) associated uranium within the granites. Fonseka (1994) suggested that Highland-Vijayan boundary is the source region of geothermal energy. He further explained that surface water that is driven by a high hydraulic pressure gradient in highlands infiltrates into deep faults and gets heated by an above-normal temperature gradient. Another study facilitates the hypothesis of a steeper geothermal gradient that is likely to be associated with Highland-Vijayan thrust zone and meteoric water infiltrates to shallower depths and heats up by a steeper geothermal gradient to rise through permeable zones (Chandrajith et al., 2013). A few researchers propose that the zone of Highland-Vijayan boundary and nearby deep-seated lineaments are the reasons for the formation of hot springs (Bandara et al., 2018 and Premasiri et al., 2006;). They suggest that meteoric water percolates through deep fractures and gets heated at greater depths to emerge back at the earth's surface. Bandara et al. (2024) suggests that hot water springs at Wahawa-Padiyathalawa and Mahapalessa are closely related to fault/fracture intersection zones.

Another hypothesis is that the percolated meteoric water absorbs heat from a "Hot Dry Rock" and returns to the surface along a vertical fault (Kumara and Dharmagunawardhane, 2013; 2014). A study on Nelumwewa thermal spring concludes that it is formed by percolated groundwater that rises towards the surface through the NE-SW running fault plane after getting heated up by hot dry rock/ doleritic plutons which, lie beneath Dimbulagala Mountain (Kumara and Dharmagunawardhane, 2014). Other hypotheses involve the active and passive roles of dolerite dykes present in some hot spring areas (Kumara and Dharmagunawardhane, 2014; Senaratne and Chandima, 2011 and Samaranayake et al. 2015). A few researchers suggest the hypothesis which, involves the active role of the dolerite dyke by proposing that the residual heat of the nearby dolerite dyke (160–170 Ma) contributes to the heat of the thermal springs at Nelumwewa (Kumara and Dharmagunawardhane, 2014 and Hettiarachchi and Dharmagunawardhane, 2022), Wahawa-Padiyathalawa (Senaratne and Chandima, 2011; Samaranayake et al., 2015 and Hettiarachchi and Dharmagunawardhane, 2022) and Kapurella (Samaranayake et al. 2015 and Hettiarachchi and Dharmagunawardhane, 2022). A study at Kapurella and Wahawa-Padiyathalawa developed a model, which concludes that meteoric water percolates through a deeply driven fracture, where it connects to the dolerite dyke and gets heated up by the remnant heat from the dolerite dyke. Heated water emerges back on the surface through fractures that are connected to the heat source (Samaranayake et al. 2015). Hettiarachchi and Dharamagunawardhane (2022) suggest that the associated structures, such as antiform, synform, shear zones and major joints sets and the remnant heat of the dolerite dyke contribute to the formation of the hot springs at Wahawa-Padiyathalawa, Nelumwewa, Maha Oya and Kapurella. However, another study suggests that dolerite dyke is not the heat source but it merely acting as an impermeable barrier (Nimalsiri et al., 2015).

Another study on two well-known hot springs; Kapurella and Maha Oya, suggests that the roots of the hot springs run into greater depths of >20 km and most possibly be connected to a magma source (Suriyaarachchi, 2017). The study showed that there are low resistive intrusive features based on their deep earth resistivity images in which, the resistivity values match with the semi-solid resistivity signature. Accordingly, it is suggested that the roots of both Kapurella and Maha Oya thermal systems are extended to a deep magma source. However, this hypothesis is ruled out due to the nonexistence of volcanic activities or plate tectonic boundaries in Sri Lanka.

There is a hypothesis involved with Uranium decay of heat-producing granites which were formed by crust-mantle mixing and upward movement of magmatic fluid along the thrust boundary during tectonic movement (Dissanayake and Jayasena, 1988).

Although several studies have been published on the formation of low-enthalpy geothermal systems in Sri Lankan, their origin remains inconclusive. Gaining a proper understanding of these non-volcanic geothermal systems is important for utilizing the geothermal resources. Understanding the role of structural controls in geothermal fluid circulation is essential for assessing geothermal potential in high grade metamorphic terrains. This study aims to investigate how ground magnetic surveys can be applied to identify subsurface structures and evaluate their relationship to fluid flow in metamorphic terrains. Wahawa-Padiyathalawa hot springs site is chosen in this context due to its special geological features, including the dolerite dyke and prominent fracture network, as many research concludes the involvement of fractures and dolerite dyke in thermal spring formation. Although, several geothermal studies have been carried out in this area, they lack the detailed ground magnetic analysis techniques applied in this research. These factors make Wahawa-Padiyathalawa an appropriate location to assess the use of ground magnetic surveys in identifying subsurface structures and their relationship to geothermal fluid circulation in a metamorphic terrain.

2. Objectives

The primary aim of this research is to assess how structural controls affect the geothermal fluid circulation in a metamorphic terrain, using ground magnetic surveys. The Wahawa–Padiyathalawa hot springs area has been selected as a case study to identify hidden subsurface geological structures, including intrusive bodies and structural discontinuities (faults and fractures) and to evaluate their relation to thermal discharges. Revealing hidden geo-structural controls and their correlation is crucial for guiding future exploration work and identifying suitable drilling targets.

A magnetic anomaly map for Wahawa-Padiyathalawa hot spring area is produced as part of the study to achieve the above primary goal, which is the supplementary objective in this study.

3. Study area

Sri Lanka is mainly a high-grade metamorphic terrain composed of three major litho-tectonic units: the Highland Complex (HC), Vijayan Complex (VC), and Wanni Complex (WC) (Kehelpannala, 1997). These units are separated by ancient tectonic boundaries, which are interpreted as paleo-thrust zones. The Highland Complex is separated by Vijayan Complex and Wanni Complex, by Highland-Vijayan Boundary (HC-VC) and Highland-Wanni boundary (HC-WC) respectively. The Wahawa–Padiyathalawa thermal spring cluster is situated within the VC, in close proximity to the HC-VC boundary. HC-VC boundary has been interpreted in various ways in the literature: as a paleo-subduction zone between the HC and VC (Dissanayake and Munasinghe, 1984); as a sub-horizontal ductile shear zone (Kriegsman, 1994; Kehelpannala, 1997, 2004); and as the site of double-sided subduction, which amalgamated the Vijayan and Wanni arcs, leading to the uplift of Mozambique oceanic crust and the formation of the HC in between (K. He et al., 2016). Similarly, the other eight hot spring occurrences in Sri Lanka (Nelumwewa, Maduru oya, Kapurella, Wahawa-Padiyathalawa, Maha Oya, Mahapelassa, Rankihiriya, Kanniyai and Jayanthiwewa) are also located in the eastern region, close to one of these paleo-thrust boundaries mentioned above (Fig. 1). Their occurrences near such paleo-tectonic zone may facilitate the thermal discharges with deep seated fractures and faults created by past tectonic events. The Precambrian high-grade metamorphic terrain of Sri Lanka has undergone multiple post-metamorphic ductile and brittle deformation events resulting in faulting, and fracturing (Kehelpannala et al., 2006), which are further crosscut by relatively young intrusions of Neoproterozoic granitoids and diorites (K. He et al., 2016) and Mesozoic dolerite (Takigami et al., 1999).

Wahawa-Padiyathalawa geothermal discharges occur as a cluster of about 18 individual thermal springs in the paddy fields and as one artesian well. They are located in Ampara district, nearly 274 km away from Colombo, the capital of Sri Lanka. The thermal spring lies in the dry zone lowland with an average elevation of 90 m above sea level. The area has an undulating topography that is controlled by underlying geology and structures (Dahanayaka and Jayasena, 1983). A geological and structural map of the study area is shown in Fig. 2.

The study area consists of various high-grade metamorphic rocks including alkali-feldspar gneiss/migmatite, granitic gneiss, hornblende-biotite migmatite, biotite-hornblende gneiss, marble, and quartzite (Figs. 2 and 4). Most of the rocks in the study area belong to amphibolite facies. Gneissic rock exposures in the study area have been subjected to migmatization and contain small leucosome veins and well-developed palaeosome–neosome separations. Originally, the area was a part of the Grenville-age magmatic arc characterized by dioritic and tonalitic intrusions. These rocks were subjected to a prograde tectono-metamorphic event, leading to the formation of granulite facies assemblages, followed by retrograde metamorphism resulting in amphibolite facies rocks and migmatites (Kröner et al., 2013). These lithologies are variably deformed and exhibit diverse structural orientations, creating meso-scale folds and shear zones that can be identified in the field.

General strike of the study area is oriented in the Northeast direction according to 1:100,000 geological map of Sri Lanka (Fig. 2). However, there are variations in the strike and dip directions of rock formations across the study area that can be identified during field mapping (Fig. 4). In the western and northwestern parts of the study area, the strike direction trends Northwest, with dips toward the Northeast and Southwest. In the northern parts, the strike is oriented in both Northeast and Northwest directions, while the dip ranges from Northwest to Southwest. In the southern parts, both strike and dip show significant variation.

The study area is characterized by a prominent regional-scale shear zone and a fault trending in a NE-SW direction, both of which are clearly identifiable on the geological map of Sri Lanka. In addition to these major structures, several local-scale fractures have been recognized through satellite imagery and Google Earth analysis, and their presence has been confirmed during field investigations (Fig. 4). A shear zone originates in the south of the study area and extends northeastward, while a second regional-scale shear zone lies to the south of the area, trending southwest. There is a second shear zones that extends on regional scale south to the study area, which runs in Southwest direction. A regional fault also traverses the central part of the study area in a southwest direction and aligns with the shear zone to form a continuous structural lineament when extended. The hot spring cluster is located just above this lineament. Several other small fractures orient towards the hot spring cluster, suggesting that if extended, they would intersect at the thermal spring site. Moreover, several local scale fractures are accumulated in the eastern, southern and southeastern parts of the study area. The Maha Oya river flows along the northeastern shear zone, further supporting the structural influence on surface hydrology. A dolerite dyke trending NNW–SSE, traverses the study area and is intersected by a Northeast trending fault and a fracture in the southern area, as well as by a meso-scale fracture trending in the NWW-SEE direction in the North (Fig. 4). It is discontinuous at the surface and only a few rock exposures are identified in the field. These dolerite dykes extend approximately 60 km regionally in a NW-SE direction. Together, these geological and structural features play a key role in shaping the undulating topography of the area.

4. Methodology

A preliminary desk study was carried out using geological maps, Google Earth images and satellite images to study surface geology including lithological variations, intrusions and structural features such as fractures, faults and shear zones. A geological mapping was carried out to identify localized structural features. A ground magnetic survey

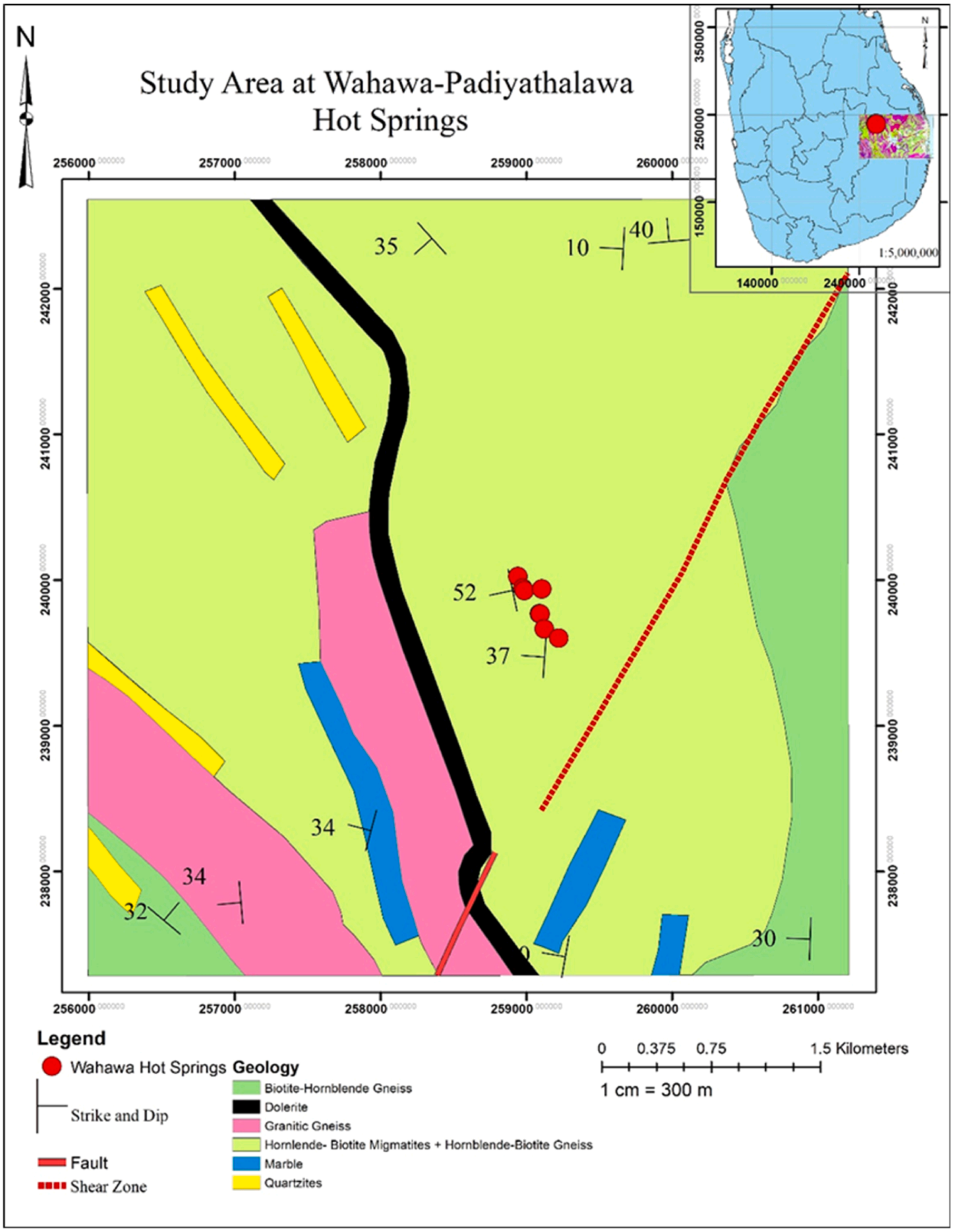

Fig. 2. Study area for the ground magnetic survey at Wahawa-Padiyathalawa hot springs extracted from the 1: 100,000 geology map sheet Padiyatalawa-Tampaddi (sheet number 15) produced by the Geological Survey and Mines Bureau of Sri Lanka in 2008.

was performed at Wahawa-Padiyathalawa hot spring area and different magnetic maps were prepared. All the geological and structural features, along with the magnetic maps were compiled into digital maps using Arc GIS software to understand structural controls and fluid flow. A flow-chart that illustrates the steps of the methodology is shown below (Fig. 3).

4.1. Ground magnetic survey

Magnetic surveys can map the magnetism of underlying rocks. The basic principle of the technique is detecting an interference created by a buried feature in the Earth's magnetic field. Dolerite dykes contain ferromagnetic minerals such as magnetite and ilmenite in small amounts and hence can be mapped using magnetic surveys (Dutch et al., 2014; Purucker and Whaler, 2007 & Samaranayake et al., 2015). Furthermore, some structural features such as rock boundaries, fractures, faults and shear zones can be mapped using their magnetic susceptibility due to mineral depositions (Kayode and Adelusi, 2010; Olorunfemi and Oni, 2019; Olorunfemi et al., 1986 & Oni et al., 2020).

A ground magnetic survey was conducted using an "Overhauser"

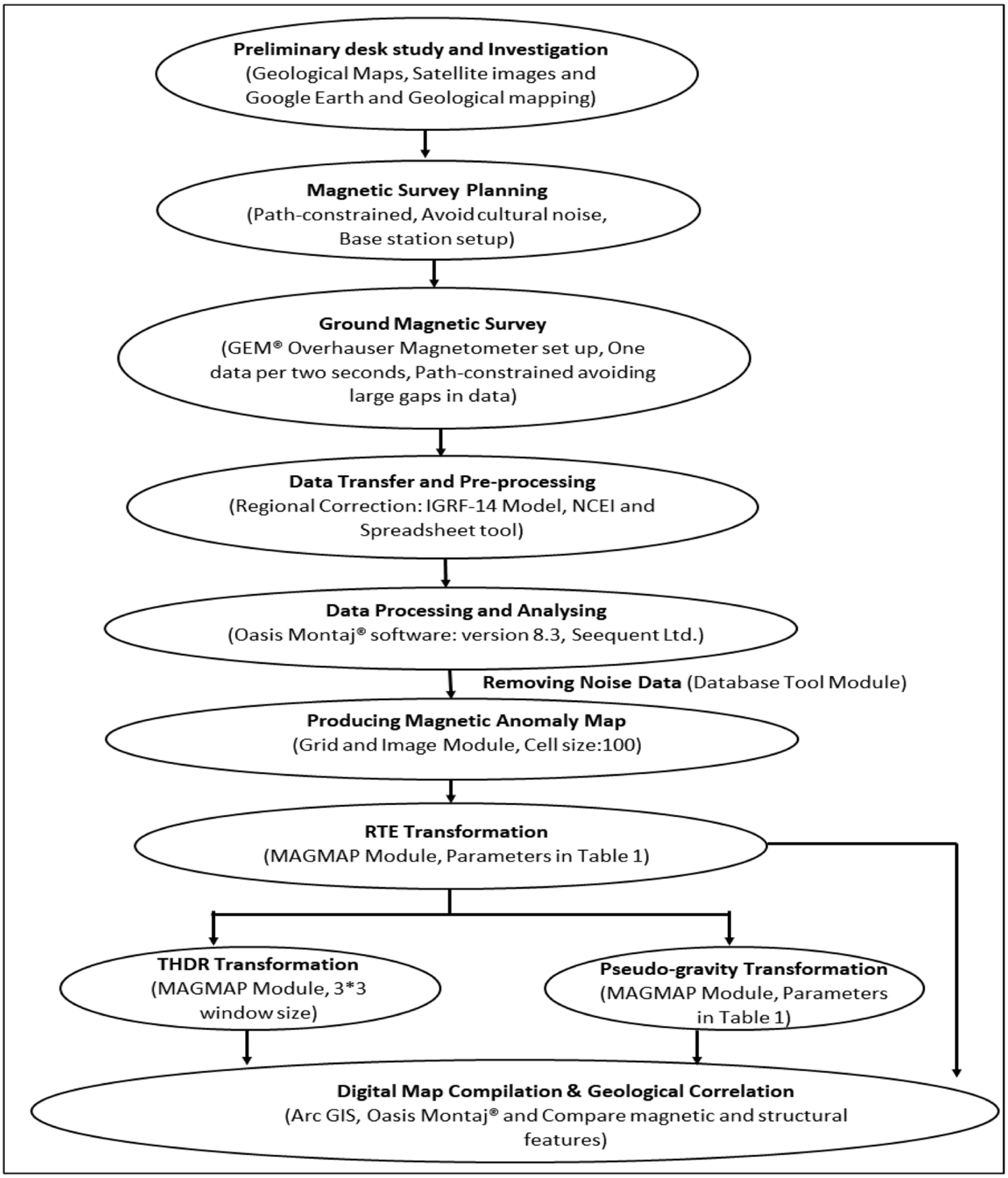

Fig. 3. The flowchart that illustrates the steps of the methodology used in this study.

magnetometer from GEM® (Geophysical Electromagnetic Systems Ltd.), with two magnetic sensors and a GPS (Global Positioning System) receiver mounted in a backpack. The total magnetic field and corresponding GPS coordinates were automatically recorded in the console every 2 s. The average special interval of data points along survey pathways is approximately 0–1 m depending on the walking speed of the operator and terrain condition. The data were taken covering a 15 km^2 area around the hot spring cluster. To maintain data quality and minimize acquisition-related errors, several precautions were implemented during the survey. Manmade metallic structures such as buildings, iron fences, culverts, gates, and bridges were carefully avoided during both survey planning and field execution to reduce the influence of cultural noise. The operator refrained from carrying mobile phones or metallic objects while collecting data to prevent local signal distortion. Additionally, data acquisition was temporarily paused whenever vehicles or individuals came within approximately 50 m of the sensor.

Magnetic data acquisition was carried out using a semi-systematic, path-constrained survey pattern, primarily along existing village footpaths, track roads, forest trails, open grasslands, and paddy fields. A regular survey grid could not be implemented due to a combination of natural and manmade constraints, including dense spiked shrub forests, restricted zones imposed by local authorities due to potential wildlife hazards (such as elephants and snakes), and the presence of cultural noise sources like metallic fences, gates, bridges, and culverts. Completely random sampling was also impractical in such terrain. However, attempts have been made to collect data covering areas as close as possible to keep the separation distance minimum.

A base magnetometer was positioned near the central part of the study area in a location identified as magnetically quiet and stable based on initial test readings and visual inspection of the surroundings. The site was chosen away from roads, buildings, fences, utility lines, and buried infrastructure. Readings were recorded twice per hour throughout the survey to monitor the variations in the Earth's magnetic field. The base data were used to verify the absence of significant magnetic fluctuations during data acquisition and to support the overall integrity of the walking magnetometer data.

4.2. Magnetic data processing

The data were transferred to a computer. Magnetic data were processed and interpreted using Oasis Montaj® software (version 8.3, Seequent Ltd.), in combination with spreadsheet-based tools for preliminary corrections. The regional geomagnetic corrections were done using the International Geomagnetic Reference Field (IGRF-14 model). IGRF values, including total field strength, inclination, and declination, were obtained from the British Geological Survey (BGS) online calculator as provided by the National Centers for Environmental Information (NCEI, 2024), using the geographic coordinates and dates of the survey. The anomaly was calculated by subtracting IGRF values from the magnetic measurements of the walking magnetometer.

$$Magnetic\ Anomaly\ (nT) = Measured\ Total\ Magnetic\ Field\ (nT) - Total\ IGRF\ Magnetic\ Field\ (nT) \quad (1)$$

Different filters, such as non-linear filter, reduction to equator (RTE), tilt horizontal derivative (THDR) and pseudo-gravity were used to enhance the signal for different reasons. A non-linear filter was used to remove high-amplitude noise without distorting key geological signals using the "Database Tool" module. A magnetic anomaly map was generated using the "Minimum Curvature" gridding method with a cell size of 100, within the "Grid and Image" module. To enhance the interpretability of the data, three transformations (RTE, THDR and pseudo-gravity) were applied using the "MAGMA module. RTE transformation was applied to correct the distortion caused by the low magnetic inclination in the region. Since the inclination and declination values exhibited minimal spatial variation within each individual survey day, average daily values for inclination and declination were used in the RTE transformation (Table 1). Following this, daily map grids were merged to produce a composite map of RTE representing the entire study area. THDR was computed using the composite RTE map and default 3 × 3 window size, which is effective in enhancing the edges of shallow magnetic sources and highlighting linear structural trends. Pseudo-gravity transformation was performed on the RTE-corrected data to visualize deeper underground structures. This transformation was also performed separately for each day, using default software values for density contrast (1 g/cm^3) and magnetization (0.5 Gauss) and inclination and declination values derived from the survey data (Table 1). Finally, the individual grids were merged to produce a composite pseudo-gravity map for the entire study area.

Different magnetic anomaly maps were prepared using the above filters. These maps were studied along with geological and structural features using GIS software for possible correlations.

Table 1
Average IGRF, inclination and declination values used for both RTE and pseudo-gravity transformations.

Date	Average IGRF	Average Inclination	Average Declination
02/09/2023	41,226	−1.949	0.825
19/10/2022	41,175	−1.962	0.836
20/10/2022	41,172	−1.967	0.755
30/09/2022	41,170	−1.964	0.831
29/09/2022	41,169	−1.913	0.816
01/07/2022	41,156	−1.969	0.784
22/06/2021	41,095	−1.992	0.652
21/06/2021	41,094	−1.992	0.652

5. Results and discussion

Geology and structural features that were identified on the geology map of Sri Lanka, Google Earth images, satellite images and in the field are shown in Fig. 4. The study area comprises a regional scale shear zone, a fault and several local-scale fractures.

5.1. Field data analysis and magnetic data interpretation

The magnetic survey traverses done during the study cover an area of 15 km^2. Fig. 4 shows the extent of data collected during the study in the years 2021, 2022 and 2023. Data are unavailable in certain parts of the area due to the presence of inaccessible thorny shrubs and urban developments such as electricity lines, bridges and other man-made things that affect the magnetic signal. The map depicting magnetic anomaly variation around Wahawa hot spring is presented in Fig. 5.

This magnetic anomaly variation encompasses the corrected data according to the International Geomagnetic Reference Field (IGRF) and the changes made using the non-linear filter and the reduced-to-equator filter. The non-linear filter removes high amplitude and short wavelength noise from raw data (Seequent, n.d.). The reduced-to-equator filter function is to transform magnetic anomalies as they were measured at the magnetic equator (Rusman et al., 2023). It corrects the effect of low magnetic latitudes over the collected raw data.

In the southern part of the study area, there is a prominent low magnetic anomalous area. This area contains several small fractures at a local scale, as well as a regional fault. The maximum anomalies occur in the middle part of the study area with an elongated shape aligned in the Northwest and Southeast direction. Additionally, a cluster of hot springs is located near to the margins of this low anomalous area and the high anomalous area. Two fractures run in the Northwest and Southeast directions to the hot spring cluster, and the hot spring cluster is aligned with the line connecting these two fractures. However, the RET magnetic anomalies depicted in Fig. 5 do not appear to have a direct relationship with the existing lineaments (Fault, shear zone and fractures) in the study area, nor do they seem to be related to the dolerite dyke crossing the area. RTE transformation helps to position magnetic anomalies accurately over their geological features by minimizing the positional distortion caused by the Earth's varying magnetic inclination. Despite this advantage, interpretation of RTE magnetic anomalies can still be challenging due to the presence of paired dipoles occuring in the magnetic field (Rusman et al., 2023). This can cause complications in accurate locating of the geological and structural features.

Apart from the above issue, there are other reasons for these uncorrelated RTE magnetic anomalies, where data gaps and interference of magnetic signals play a significant role. The RTE magnetic anomaly map is produced by interpolating the RTE data points processed from raw magnetic data collected during the field survey. There are areas in the northern parts where magnetic data are lacking due to inaccessible thorny shrubs and the presence of manmade structures. These data gaps influence the magnetic anomalies shown in the anomaly maps. Consequently, the RTE magnetic anomaly variations in these data-sparse areas may deviate from the actual conditions. Interference of surface signals with deep signals could also be a contributing factor. Hence, the maps are drawn separately to show surface and sub-surface features using THDR (Fig. 6) and pseudo-gravity filters (Fig. 7) respectively. Better outcomes were achieved for surface and subsurface features separately with THDR and pseudo-gravity anomaly maps.

There are data gaps in the area that can lead to inaccurate map representations, as the maps are generated by interpolating the available data points. For a more accurate representation of natural structures with high resolution, it is recommended to position survey lines at a distance of <100 m. Due to practical constraints such as inaccessible thorny shrubs and manmade structures that interfere with the magnetic signal, the survey was conducted along random paths, resulting in sections where the 100-meter separation distance was not maintained.

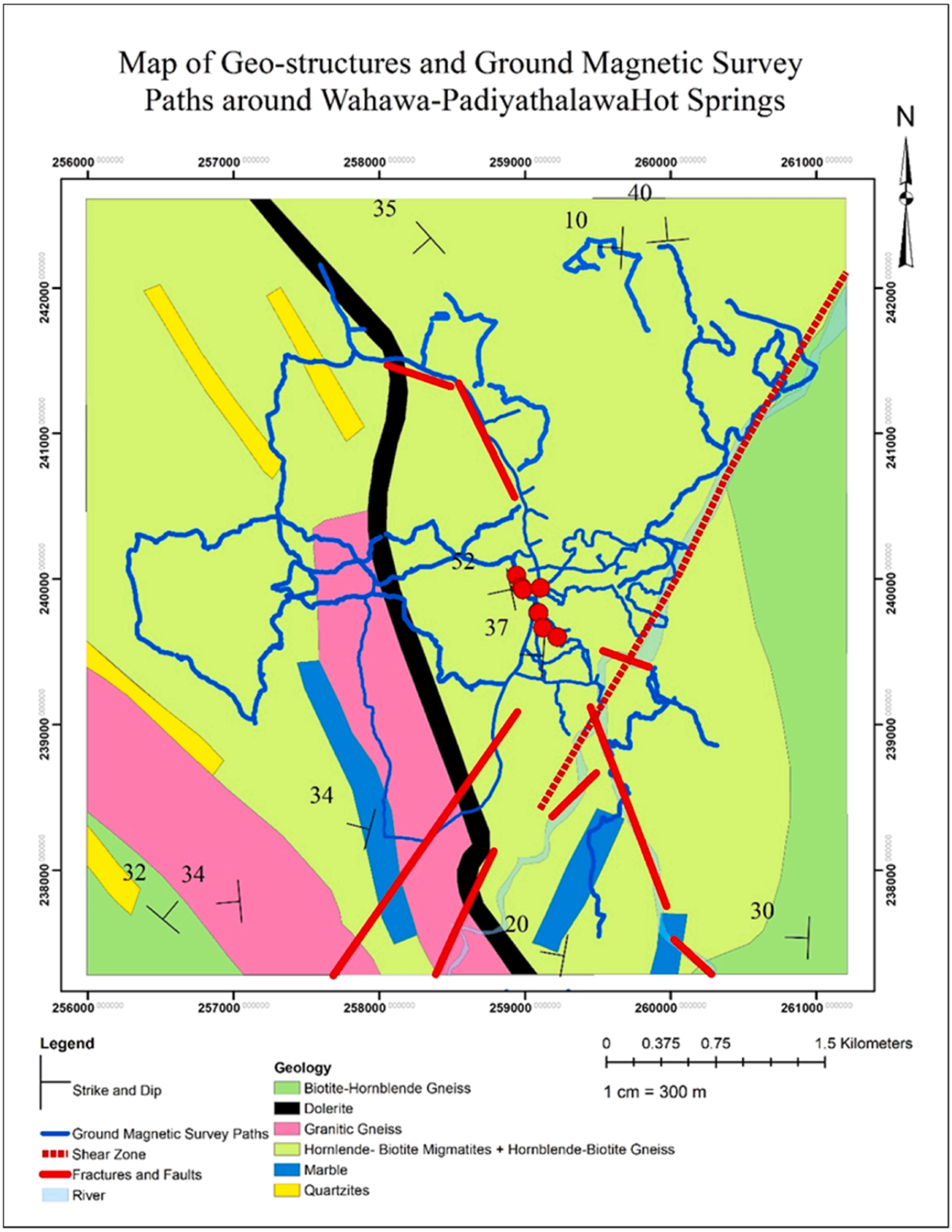

Fig. 4. Geological and structural features around Wahawa hot spring area modified after 1: 100,000 geology map sheet Padiyatalawa-Tampaddi (sheet number 15) produced by the Geological Survey and Mines Bureau of Sri Lanka in 2008 (Map also shows the pathways of collected magnetic data).

In the THDR map, prominent linear features are evident. The maximum THDR anomaly is generated over the structural lineaments. The structural lineaments identified in satellite maps, Google Earth images, and the geology map of Sri Lanka can be distinctly observed in the THDR map. Additionally, there are new lineaments that can be identified in the western part of the study area in a northwestern direction and the northeastern part of the study area in a northeastern direction. The THDR anomaly maps provide better representation of the width and margins of structural features compared to geological maps. However, these features shown on the map could be the result of a combination of all the structures present at different depths. Therefore, the actual structural features may not necessarily have the same shapes and margins as illustrated in the THDR map.

In addition to the structural lineaments, the dolerite dyke is also visible along the maximum THDR anomaly. The dolerite dyke appears as a discontinuous band in the field with outcrops only visible in a few places within the study area. The THDR map shows a continuous band across the study area, which overlaps with the dolerite dyke as indicated in the geological map of Sri Lanka. Therefore, we can interpret that while there are only a few surface outcrops of dolerite dykes, they exist

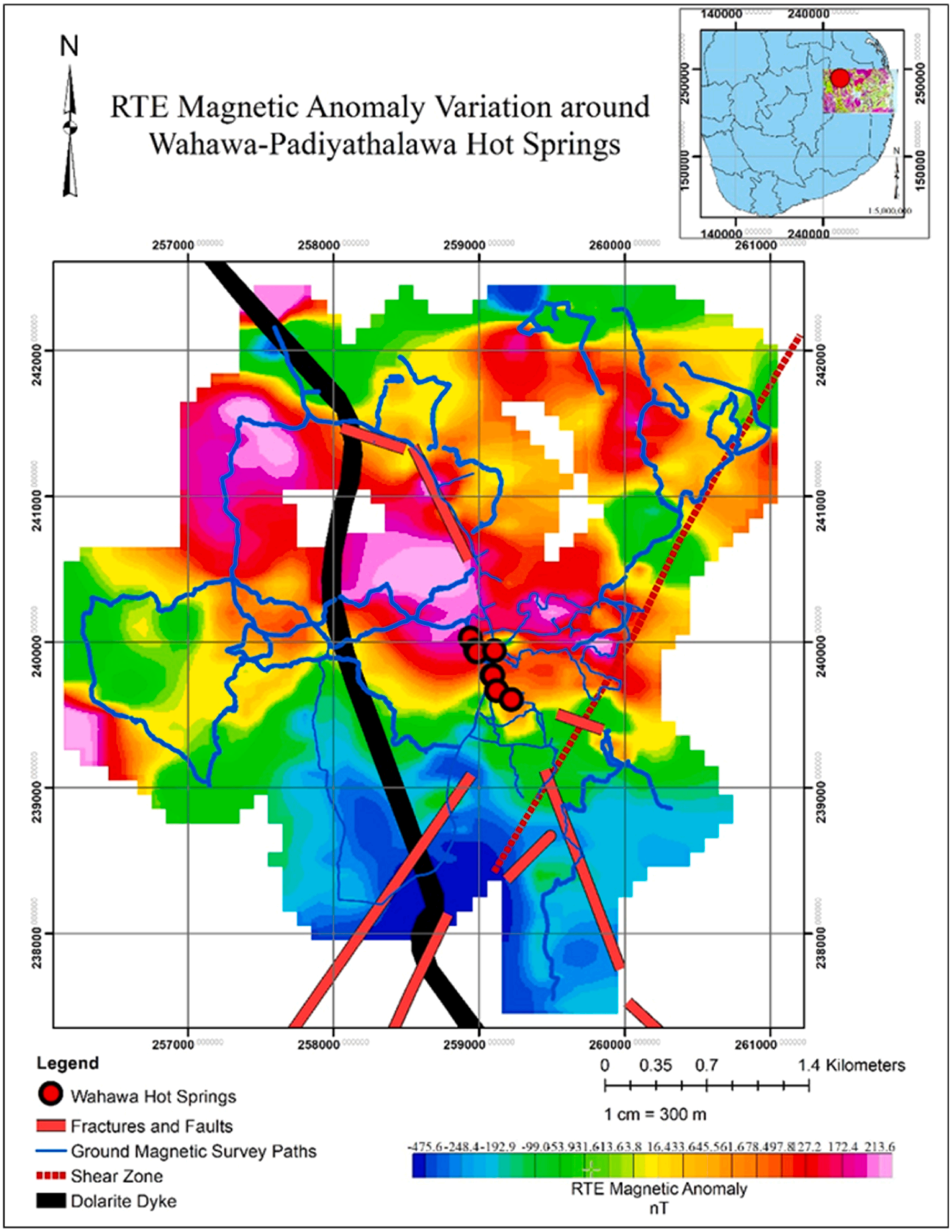

Fig. 5. RTE magnetic anomaly map around Wahawa hot springs (RTE transformation was done).

continuously at shallow depths. Moreover, the hot spring cluster is also located over the high THDR anomaly regions and is connected with the surface structural lineaments.

The THDR map displays surface structural features, but it does not display subsurface structures. The pseudo-gravity transformation is identified as a good tool to interpret subsurface anomaly sources (Pratt and Shi, 2004; Panepinto et al., 2014 & Mashhadi and Safari, 2020). The pseudo-gravity transformation simplifies the interpretation process by converting magnetic anomaly data into gravity anomaly data. The interpretation of pseudo-gravity data is less problematic than magnetic data because the tilt of the normal magnetic field and its bipolar nature do not affect the pseudo-gravity anomaly (Panepinto et al., 2014). Fig. 7 shows the pseudo-gravity transformation of the magnetic data, indicating signals from deeper levels while ignoring surface anomalies.

The pseudo-gravity map indicates a very high density anomaly in the central part of the study area, oriented in the North-South direction. A low anomaly is visible in the southwest part of the study area. The hot spring cluster is located inside the high density anomalous region. The dolerite dyke on the pseudo-gravity anomaly map mostly lies at the boundary between areas of low and high anomalies. However, in some areas, it deviates from these boundaries. In the field, the dolerite dyke does not extend as a continuous structure throughout the study area and

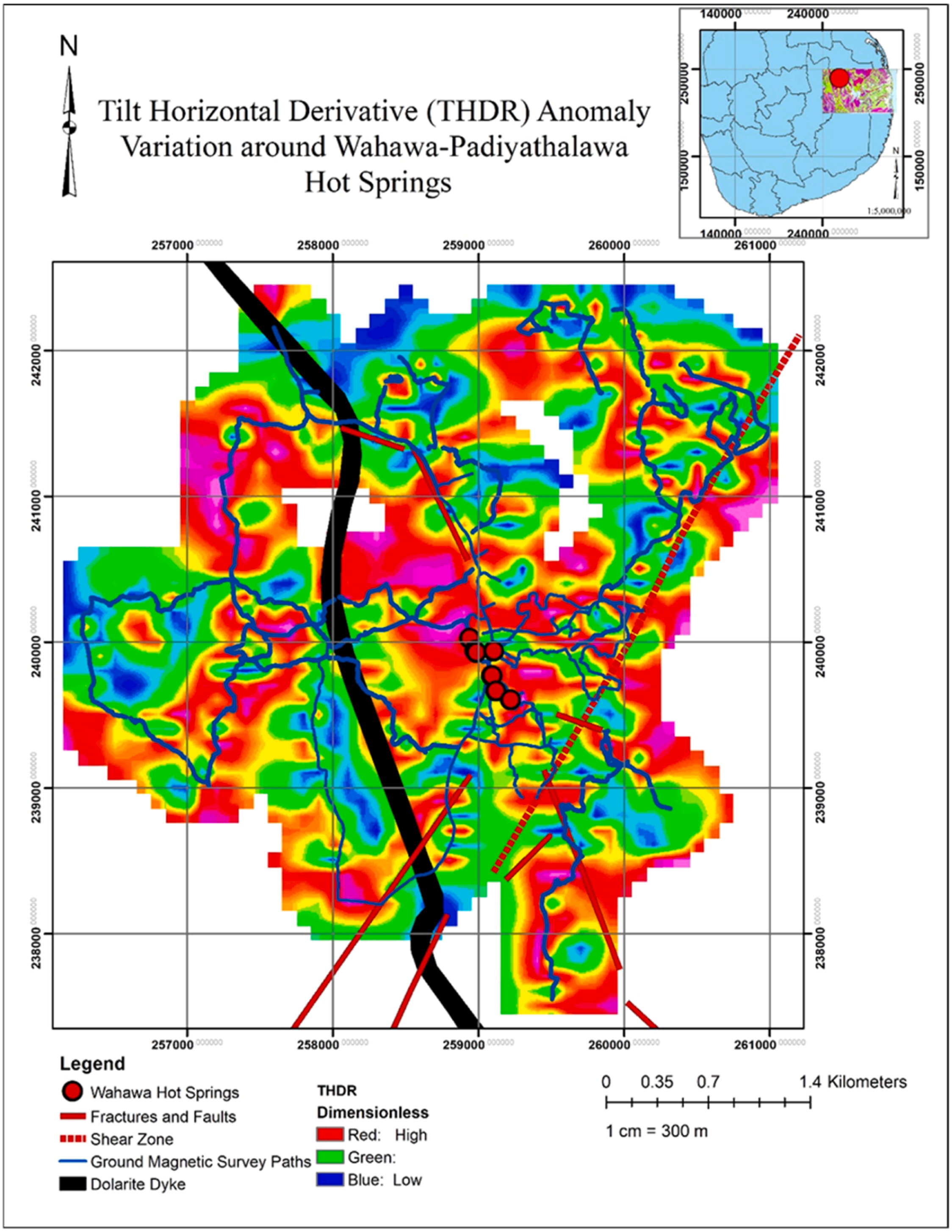

Fig. 6. Tilt Horizontal Derivative (THDR) anomaly variation around the Wahawa hot spring cluster.

it is only exposed to the surface at a few locations. It's possible that the position of the dolerite dyke in the subsurface may differ from its surface continuation due to dipping and folding. The cartographic line in Fig. 7 demonstrates the possible continuation of the dolerite dyke (west margins of the dyke) in the subsurface. It is also possible that the thickness of the dolerite dyke increases at greater depths, which could explain the broader width of the high pseudo-gravity anomaly. This broader width may also indicate the cumulative anomaly of several lineaments at different depths that have the same horizontal position.

A comparative analysis of the total magnetic intensities and pseudo-gravity anomalies shows both spatial and structural coherence, as well as areas of differences. Near Wahawa Hot Springs, both maps display a clear high anomaly, suggesting that structural features such as faults or lithological boundaries may be controlling the movement of geothermal fluids. The original magnetic intensities show high magnetic responses confined to the dolerite exposures at the northern and southern parts of the study area but do not exhibit similar elevated magnetic signatures at the central parts where the dyke continues below the surface. This inconsistency may reflect localized variations in magnetic mineral content, hydrothermal alteration and high burial depth of dolerite dyke in the central parts. It is also important to acknowledge that the interpretation derived from the pseudo-gravity anomaly can be influenced by

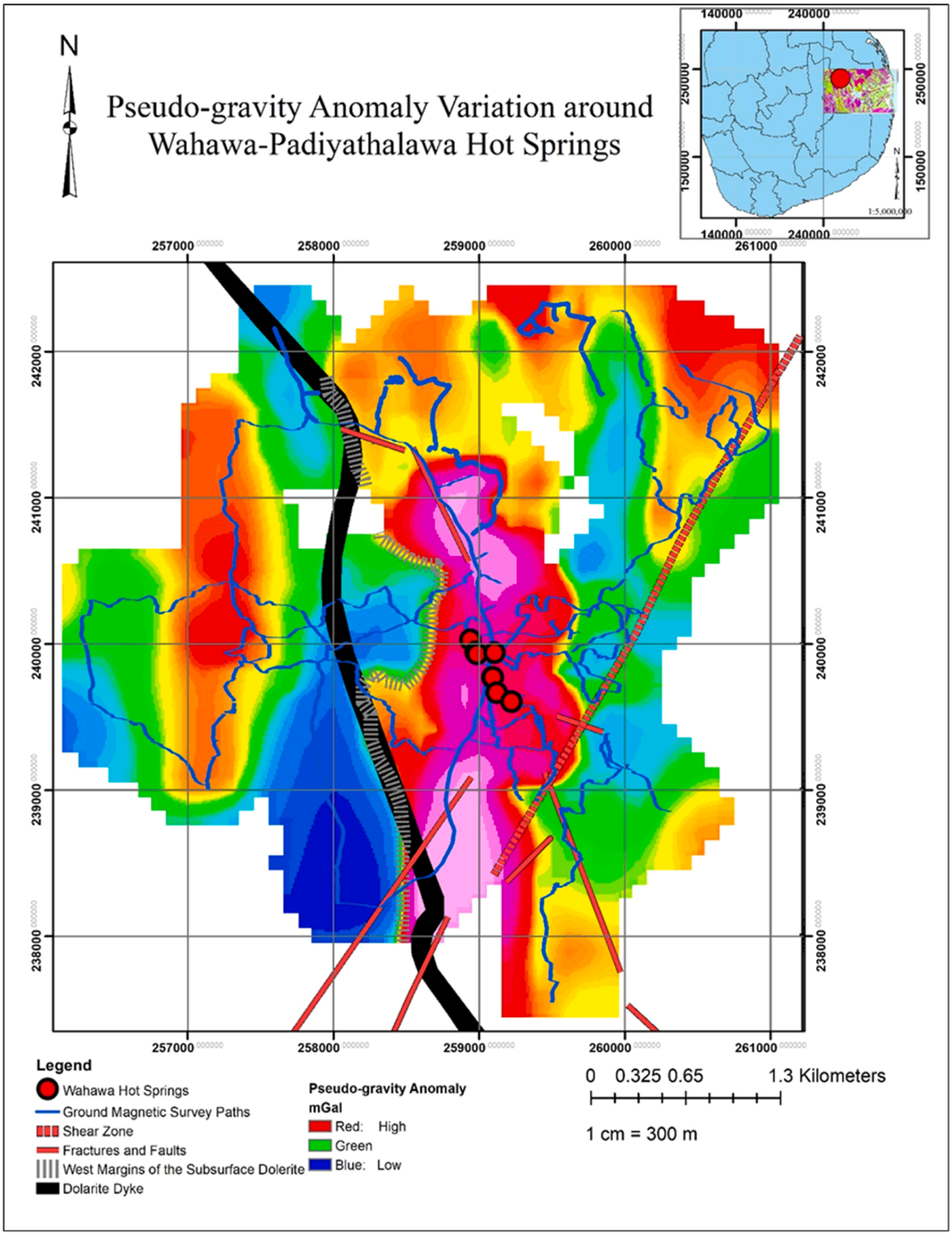

Fig. 7. Pseudo-gravity anomaly variation around the Wahawa-Padiyathalawa hot spring cluster.

spatial data gaps and can impact the accuracy of inferred subsurface features.

Unlike in the THDR map, the faults and fractures identified in the geological map of Sri Lanka, Google Earth imagery, and satellite images are not clearly visible in the pseudo-gravity anomaly map. This suggests that these features may represent surface-level lineaments rather than deeper structures. However, the pseudo-gravity map does display other structural lineaments in the western and northern parts of the study area, potentially representing subsurface fractures extending to greater depths. The elongated high-density anomalous body in the central region appears isolated, with no connection to similar anomalies on its western side and is bordered by a low anomalous area. In contrast, in the northern and southeastern parts, it is connected to other high anomalous linear structures. This reveals that the deep fractures in the North, Northeast and south are interrupted by the dolerite dykes and do not carry water to the west side of the dolerite dyke. Therefore, we can assume that these deep fractures carrying water are interrupted by the dolerite dyke and rise upward to emerge as springs at the surface. This water retains a considerable amount of heat at the surface. The temperature of the thermal discharges varies between 32.5 °C and 41.1 °C.

Senaratne and Chandima (2011) and Samaranayake et al. (2015) conclude that the residual heat of the nearby dolerite dyke (160–170 Ma) contributes to the heat of the thermal springs at Wahawa. Chandrajith et al. (2013) conclude that Wahawa hot springs are formed by the heating of meteoric water that infiltrates to shallow depths through a steeper geothermal gradient. However, the source of heat is not evident in the magnetic results mentioned above.

The details of all transformations (RTE, THDR and pseudo-gravity) including their function, interpretation of geological structures in the study area, and strengths and limitations discussed above, are summarized in Table 2.

Magnetic survey methods, when combined with advanced processing techniques, offer a non-invasive, cost-effective, and efficient approach to overcome limitations of traditional exploration methods such as geological mapping and geochemical analysis. Surface geological mapping provides valuable insights into lithology and structural patterns, but it is often limited by vegetation cover, weathering and inability to detect deeper or concealed features. Similarly, geochemical analyses can provide surface fluid composition and approximate estimates of reservoir temperature, but they do not directly delineate subsurface structures or the extent of heat sources. Magnetic surveys can provide a comprehensive understanding of the subsurface structures, including their depths and spatial distribution to aid identification of geothermal mechanisms and promising geothermal sites. Geological mapping can be incorporated to aid and enhance the magnetic survey interpretation for a more promising outcome.

Although magnetic survey is very important tool in geothermal exploration it contains inherent limitations. Magnetic surveys are sensitive only to contrasts in magnetic susceptibility. As a result, subsurface features such as fluid conduits can only be detected if they exhibit a sufficient contrast in magnetic properties relative to the surrounding host rock. Moreover, narrow or deeply buried conduits may fall below the resolution of the survey, making them difficult to detect. Furthermore, magnetic surveys cannot detect heat sources, such as radiogenic heat production or deep magmatic intrusions. Therefore, magnetic methods alone are insufficient for reliably locating thermal conduits or heat sources. To overcome these limitations and identify these underground structures, magnetic surveys should be integrated with other exploration methods, such as resistivity-based geophysical surveys (e.g., magnetotellurics), drilling and geochemical measurements.

6. Conclusion

This study demonstrates the effectiveness of utilizing ground magnetic surveys in exploration of geothermal systems within metamorphic terrains. The magnetic study around the Wahawa-Padiyathalawa hot spring cluster identifies the distribution of structural lineaments, fractures, and igneous intrusions through magnetic anomaly maps and provides an insight into its potential formation mechanism. Maps utilizing THDR and pseudo-gravity transformations reveal the distribution of potential fractures and dolerite dyke at different depths. These maps also show that hot spring cluster is located in high THDR and pseudo-gravity anomaly regions depicting relationships to existing structures. The hot spring cluster connects with the surface structural lineaments in the THDR anomaly map. The pseudo-gravity map shows that subsurface fractures are interrupted by the dolerite dyke. This supports the interpretation that deep groundwater may be redirected upward along these fractures, potentially contributing to the emergence of thermal springs. Existing magnetic survey data support that the dolerite dyke may play a passive role in producing thermal springs.

Therefore, ground magnetic survey, when combined with advanced processing techniques offer a rapid, non-invasive and cost-effective exploration method to delineate subsurface structures like fluid conduits and dolerite dykes in metamorphic terrains. However, magnetic surveys cannot directly detect heat sources such as radioactive decay zones or magmatic bodies. Therefore, conclusions regarding whether the dolerite dyke acts as a residual heat source cannot be confirmed by magnetic data alone. To verify this possibility, additional exploration methods such as drilling and fluid inclusion analysis are necessary.

Table 2
Comparison of RTE, THDR, and pseudo-gravity filtering methods in magnetic data interpretation.

Transformation	Function	Interpretations	Strengths	Limitations
RTE	Corrects the effect of low magnetic latitudes	Known structural lineaments were not identified	Useful to Position anomalies caused by broad features closer to its' geological source	Poor correlation with narrow geo-structural lineaments
THDR	Enhances horizontal gradients and highlights near-surface structures	Existing and new near-surface lineaments are identified, hot spring cluster is connected with near surface fractures	Near surface structural lineaments are well-defined with their boundaries.	Does not represent deep structures; resolution may blend features at different depths
Pseudo-gravity	Converts magnetic data into gravity-like anomaly to infer depth structures	Reveals deep fractures and continuity of dolerite dyke; Interruption of deep fluid flow by the dolerite dyke	Highlights deeper anomaly sources	The anomaly represents the cumulative of all the deep signals come from different depths

CRediT authorship contribution statement

M.P. Thilakarathna: Writing – original draft, Investigation, Formal analysis, Data curation. **A.M.A.M. Abeysinghe:** Methodology, Investigation, Data curation. **N.D. Subasinghe:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

N.D. Subasinghe reports equipment, drugs, or supplies was provided by University of Peradeniya Faculty of Science. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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