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STRUCTURAL SIGNIFICANCE OF GEOTHERMAL SYSTEMS OF SRI LANKA; A STUDY ON A CLUSTER OF FOUR THERMAL SPRINGS

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ABSTRACT

Although the geothermal systems are common in volcanically or tectonically active areas, ten geothermal springs are present in the Precambrian basement of Sri Lanka, where such activities are unknown. Thermal springs of Sri Lanka are surface manifestations due to heating, and plume rises through the mixing zone of deep circulating meteoric water. The heating of this deep circulating water in an average geothermal gradient of 30 °C/km is increased by a relatively young dolerite dike, considered the heat source. To better elucidate the controls on fluid flow in the geothermal systems, understanding the underground geological structures is important to use this energy explored and extracted efficiently. To get a better scientific understanding of geology, structure, and hydrogeology, and to compile and propose possible geo-structural models associated with thermal springs in northeastern Sri Lanka, the present study has been carried out by geological mapping, and compile present data using computer-based GIS software and structural 3D modeling.

The study revealed that the underground geological structure of the Marangala thermal spring is a synform structure with rock contacts and East-West extending major joint set through which the percolating water flows through the dolerite dyke underground. The structure controlling the Nelum Wewa thermal spring is an antiform and a shear zone extending through the spring and nearly perpendicular to the antiform axis. The underground structure controlling the Mahaoya and Kapuralla thermal springs is a mega scale, which covers approximately 3,000 km^2 area of Vijayan complex of Sri Lanka. It has several ductile, and brittle structures contained in one mega-scale partially overturned synform. These results suggest that Marangala, Maha Oya, Kapuralla, and Nelum Wewa geothermal springs are associated with antiform and synform ductile structures. Brittle structures associated are shear zones and major joint sets. The probable heat source is a relatively young dolerite dyke. This detailed study of the thermal springs contributes to understanding the geological evolution of Sri Lanka and discovering potential energy sources.

Keywords: *Thermal springs, Structural model, Fault zone, Shear zone, Synform, Fault breccia*

INTRODUCTION

Hot springs are springs of amazing feature of the earth in which the water is warmer than the surrounding temperature. This is because the temperature of the earth's surface is much cooler than the earth's internal temperature. Water can gain heat in two ways while it is underground. First, and most commonly, groundwater may circulate near a magma chamber or a body of cooling igneous rock. They are associated with relatively recent volcanism (Carlson et al. 2011).

Groundwater can also gain heat as it circulates unusually deep in the earth along joints or faults. The average geothermal gradient is 25-30 °C/kilometer or 75 °F/mile (DiPietro, 2013). Thus, water circulating to a depth of few kilometers is warmed above normal surface water temperature. Regardless of its origin, warm water is lighter than cold water and readily rises to the surface.

Geothermal systems in the world are controlled by Geo-structural features such as faults, volcanic domes, crater lakes, associated volcanic features, shear zones, and fracture systems.

In Sri Lanka, ten thermal springs have surface temperatures range 39.1 ^{0}C to 62.2 ^{0}C (Chandrajith et al. 2012) have been identified. Using these thermal springs, Sri Lanka has many geothermal potentials for development as a sustainable and green energy resource. Even though Sri Lanka has ten thermal springs, no use is being taken from those at present. To develop, explore, and utilize geothermal energy of those thermal resources, a better understanding of the origin of these springs, characteristics, properties, and geostructural framework is essential.

The present study considers four hot spring occurrences in Mahaoya, Nelumwawa, Marangala, and Kapurella in the northern part of the Vijayan complex of Sri Lanka (Fig. 1).

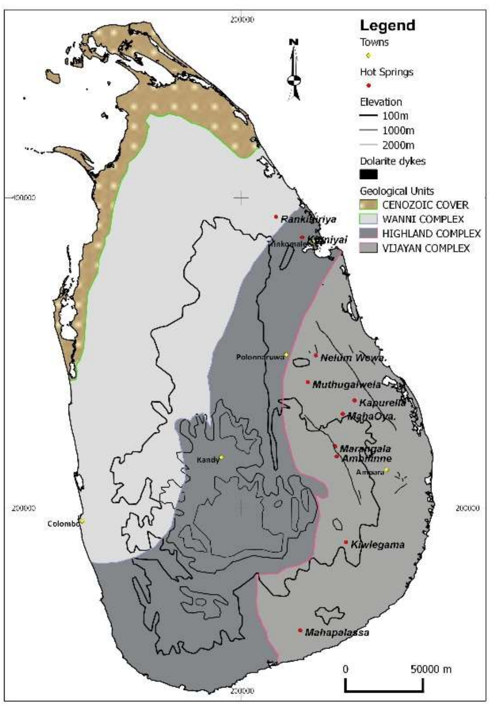

Fig. 1 The general geology, topography and distribution of hot water springs in Sri Lanka

Previous Work

There are several studies and researches had been carried out on those thermal springs over the past years. Dharmasiri and Basnayake (1986) reported that the thermal spring waters of Sri Lanka are of meteoric origin where deep percolation of infiltrated rainwater returns to the surface after acquiring heat under the influence of the average geothermal gradient. A model for the origin of geothermal springs of Sri Lanka was proposed by Dissanayake and Jayasena (1988) and discussed the origin of geothermal systems of Sri Lanka. Senaratne and Chandima (2011) discussed the origin of the Marangala thermal spring, and Chandrajith (2013) discussed geochemical and isotope characterization of geothermal spring waters in Sri Lanka. It reveals that both water are hydrogeochemically and isotopically similar in composition. Jayawardena et al. (2016) discussed the mixing of thermal and non-thermal water at Mahaoya thermal springs to estimate the possible depth.

Even though some of the previous authors outlined the mechanisms of the artesian type of well in the area, the origin of the thermal springs, and also with related to the isotopic characterization of spring waters, the structural aspects of these hydrothermal systems are still not well understood and have not yet been well explained.

Therefore, the present study focuses on identifying the structural significance of thermal springs in areas of Mahaoya, Kapuralla, Nelumwewa, and Marangala. The main objectives of this work are,

- To reconstruct the surface geology and geological structure of four geothermal spring areas of Mahaoya, Kapuralla, Nelumwewa, and Marangala, with existing data and geological field mapping.
- To compile data into a Geo-structural model and propose the co-relation of the structure with the deformation events.
- To propose the possible geo-structural models associated with thermal springs.

Study Area

Sri Lanka is an island located south of the Indian peninsula and has 65,000 km^2, stretching over 433 km from North to South between latitude 5.55^0 North to 9.51^0 North, and 244 km East to West at its widest point longitude 79.41^0 East to 81.53^0 East.

Ninety percent of Sri Lanka mainly consists of high-grade crustal basement rocks subdivided into three major crustal blocks, namely Wanni complex (WC), Highland complex (HC), and Vijayan complex (VC). The rest of the island, the northwestern part, comprises Mesozoic, Tertiary, and Quaternary sedimentary formations. The present study area is located in the northern part of the Vijayan complex.

The study area covers approximately 3,000 km^2 out of the 65,000 km^2 of the Sri Lanka, (Fig. 2) including the locations of four geothermal sources of,

1. Nelumwawa thermal spring at geographic coordinates of 7^0 53.22̀N and 81^0 12.06̀E.
2. Mahaoya thermal spring at geographic coordinates of 7^0 33.08̀N and 81^0 21.11̀E.
3. Kapurella thermal spring at geographic coordinates of 7^0 38.02̀N and 81^0 25.08̀E.
4. Marangala thermal spring at geographic coordinates of 7^0 21.42̀N and 81^0 19.33̀E.

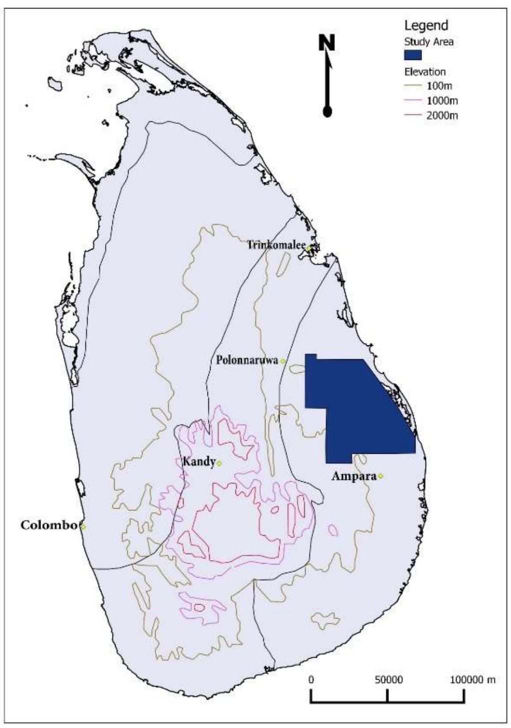

Fig. 2 *The study area*

The Vijayan complex rocks underlie the study area. The predominant rock type is a dark gray to black colored well foliated layered sequence of hornblende biotite gneisses (Cooray, 1994), and granitic gneisses, granites, augen gneisses, quartzofeldspathic gneisses are interbanded with the hornblende biotite gneisses (Dahanayake and Jayasena, 1983) are comprised in the study area.

In addition, dolerite dikes occur across the Vijayan complex's granitic gneisses (Dahanayake and Jayasena, 1983). The regional strike of these rocks is mainly NNE-SSW, and brittle and strong ductile structures are common in this area, such as folds, antiforms, synforms, and domes (Cooray, 1994).

The study area is situated in the lowest peneplain of Sri Lanka. All four thermal springs have less than 110 m elevations above the mean sea level (Fig. 1), and in the dry zone of the island. The rain falls from NE monsoon during October to January. The dry season is from May to September.

METHODOLOGY

Using topographic maps, geological maps, available aerial photographs, google satellite images and field studies, general foliation strike and dip, geological structures such as folds, fractures, shear zones, drainage patterns, and variously important information were extracted using computer-based software of Geographic Information System (GIS). 'Quantum GIS (1.7.4)' was used for data acquisition, data management, spatial measurement, data analysis, graphic output, and visualization.

Geological mapping was carried out in 1:20,000 scale for the Marangala area for better understanding of small-scale geological features of the area such as lithological and structural variations. Lithological units were identified by the presence of minerals, textures and structures of rocks and rocks were classified according to their rock types. Strikes and dips of foliation planes and joint planes were obtained and recorded. Variant rock occurrences identified during the field were sampled for thin section preparation and further studies. Thin sections were prepared for micro scale textural and mineral identifications and interpret about the origin of some variant rock units. With the all joint plane orientation readings, stereo-net projected diagrams and rose diagrams were produced, which used to identify the major pathway up of the hot water to the external image of thermal spring of Marangala.

Computer-based drawing software Photoshop and advanced three-dimensional drawing tool blender were used to prepare the three-dimensional representative model for the underground settings of the study area.

RESULTS & DISCUSSION

The landscape of the study area is almost a peniplained area has little disturbed by occasional inselbergs. The area is comprised of VC and lies close to the eastern boundary of the HC. Amphibolites facies rocks are present in the area.

Geology and the Structure of the Marangala Thermal Spring

Marangala area is characterized by a northward-plunging synform. The core of this structure is occupied mainly by microcline granites and granitic gneisses. Such rocks are surrounded by hornblende-biotite gneisses, augen gneisses and migmatites. Within these gneisses, isolated discordant and cross-cutting doleritic intrusion is present. The dominant rock types of the area are hornblende biotite gneiss and granitic gneiss, which characteristically forms a layered sequence. Their contacts with adjacent rocks are poorly exposed. The thickness of bands varies from several meters to kilometers.

The rock of fault breccia could be found in several locations. This rock has angular-shaped medium to coarse quartz and feldspar grains and rock fragments embedded in a fine-grained reddish to yellowish color matrix. The matrix material contains an iron-bearing formation, and it has a considerable amount of cavities and highly weathered.

In thin sections of the breccia rock sample, it could identify the mineral grains un-weathered. Angular fragments of quartz, microcline feldspar and plagioclase feldspar in a matrix of fine-grained iron oxide cement present. Mineral grains are randomly arranged, and some are not touching each other. Mineral grains are fine to coarse in size and well graded (Fig. 3).

Brittle and ductile structures were observed locally in the study area. Foliation, lineation, and folding are identified as ductile structures, whereas joints and veins are identified as brittle structures (Fig. 4 (a)).

The main structural element in rocks of the area is the well-developed gneissic foliation (S_1) formed during the deformation (D_1*). These are made up of compositional layering of differentiated felsic and mafic minerals in the rock. The foliation formed during the D_1* is almost parallel to the lithological contact of the rock in the area (Kehelpannala, 2004).

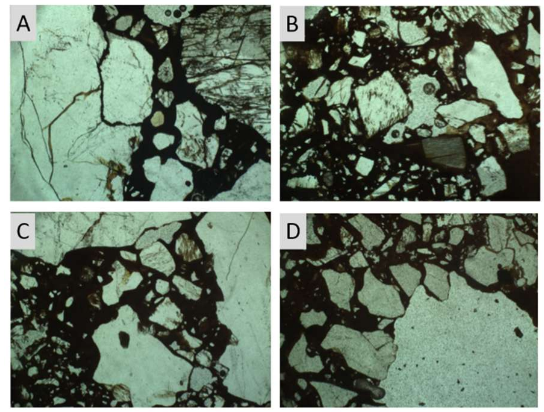

***Fig. 3** Thin section images of the fault breccia rock samples*

According to the joint plane analysis, the directions of the major joint sets are 060^0-100^0, 240^0-280^0. The maximum intensity of the major joint set is 11.9%. Joint intensity varies from 1 m^{-1} to 8 m^{-1}. The spacing of the joint varies from about tight to few centimeters (Fig. 4 (b)).

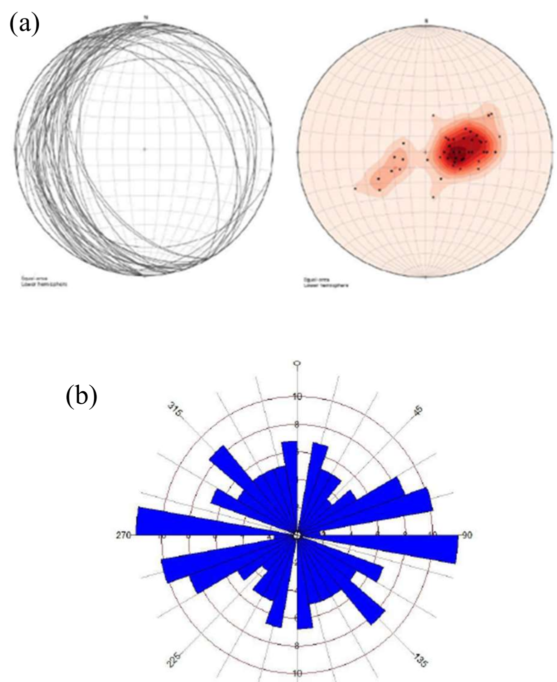

***Fig. 4 (a)** Maximum density foliation planes and the orientation of the axial plane of the synform structure of the area, **(b)** Rose diagram for the joint planes in the study area*

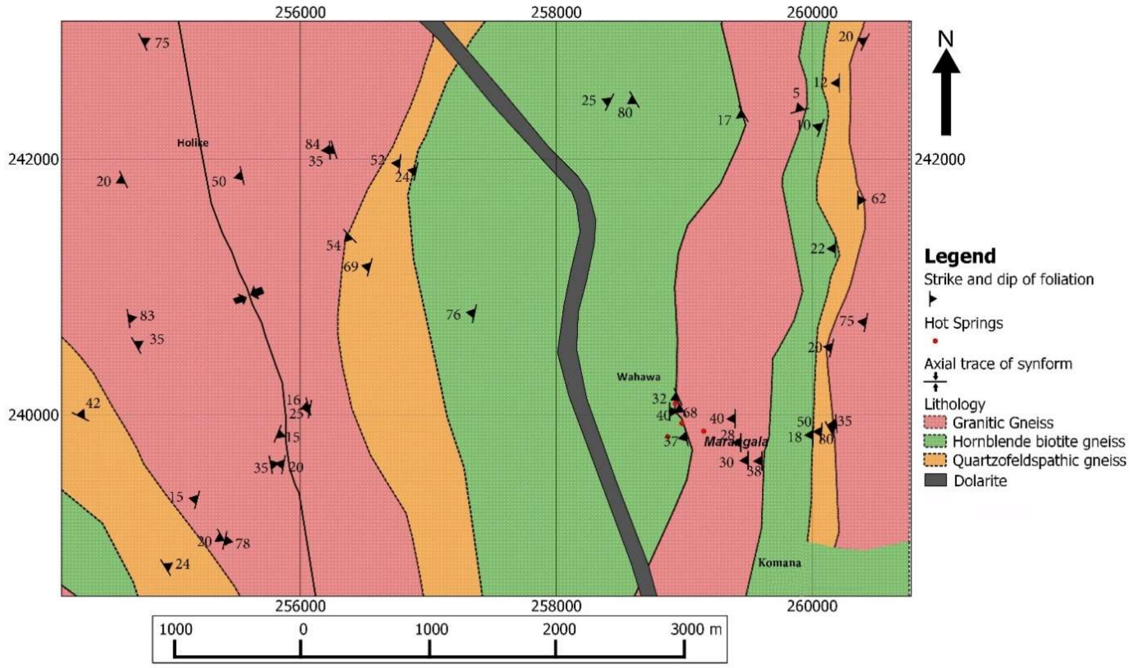

***Fig. 5** Reconstructed geology map of the Marangala area*

A perennial artesian tube well that discharges water to approximately two meters height results from good permeability for water circulation along East-West directed major joint set. The main regional geological structure that influences the Marangala thermal spring is a synform. The thermal spring is located on the granitic gneiss and hornblende biotite gneiss contact zone and the Eastern limb of the synform structure (Fig. 5).

The heat source of Marangala thermal spring is the dolerite dyke. The dolerite dyke intersects the synform through the N-S direction. The synform structure and the major joint set of E-W can drive water from West to East through the dyke underground. The meteoric water that got heated rises to the surface through the contact zone, which crosscuts the major joint system in the area.

Geology and the Structure of the Nelumwewa Thermal Spring

Nelumwewa thermal spring is situated in the middle of the Nelumwewa irrigation tank. Only the ridge present in this area is Dimbulagala rock. The main rock types of the area are granitic gneiss and hornblende biotite migmatized gneiss. Nelumwewa hot spring field is also characterized by NNW-SSE trending two dolerite dykes extending several kilometers in length. The Eastern dyke is closer to the Nelumwawa thermal spring.

Shear zone and antiform structures are present as brittle and ductile structures in the Nelumwewa thermal spring area. Several kilometers long shear zone extending in the NE-SW direction. Galwewa antiform axis is oriented towards the NW-SE direction and approximately perpendicular to the shear zone. The thermal spring is situated on the shear zone that intersects the Galwewa antiform axis (Fig. 6). This point can make a very deep running week zone of the area and provide a pathway for the thermal water while a dolerite dyke is the heat source.

Geology and the Structure of the Mahaoya and Kapurella Thermal Springs

Mahaoya and Kapurella thermal springs are situated in granitic gneiss and quartzofeldspathic gneiss rocks (Fig. 7). The rock types of the area are granitic gneiss, alkali feldspar granitic gneiss, quartzofeldspathic gneiss, hornblende biotite gneiss, hornblende biotite migmatite, biotite hornblende gneiss, granodioritic gneiss and highly deformed augan gneiss. All these rocks occur on 0.5 km to 5 km thick layers. In addition, quartz veins, pegmatite bodies, and dolerite dykes (more than 60 km long) are also present. The dolerite dyke is considered the heat source that belongs to a relatively younger age group of Triassic-Cretaceous 152.6±7.6 Ma (Yoshida et al. 1988).

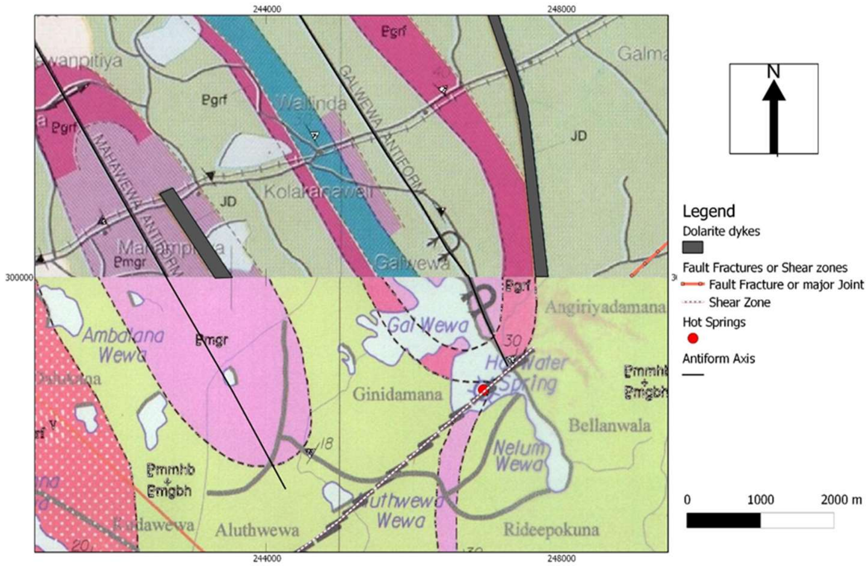

Fig. 6 *Geology and structural map of the Nelumwewa area (Source: GSMB 2011)*

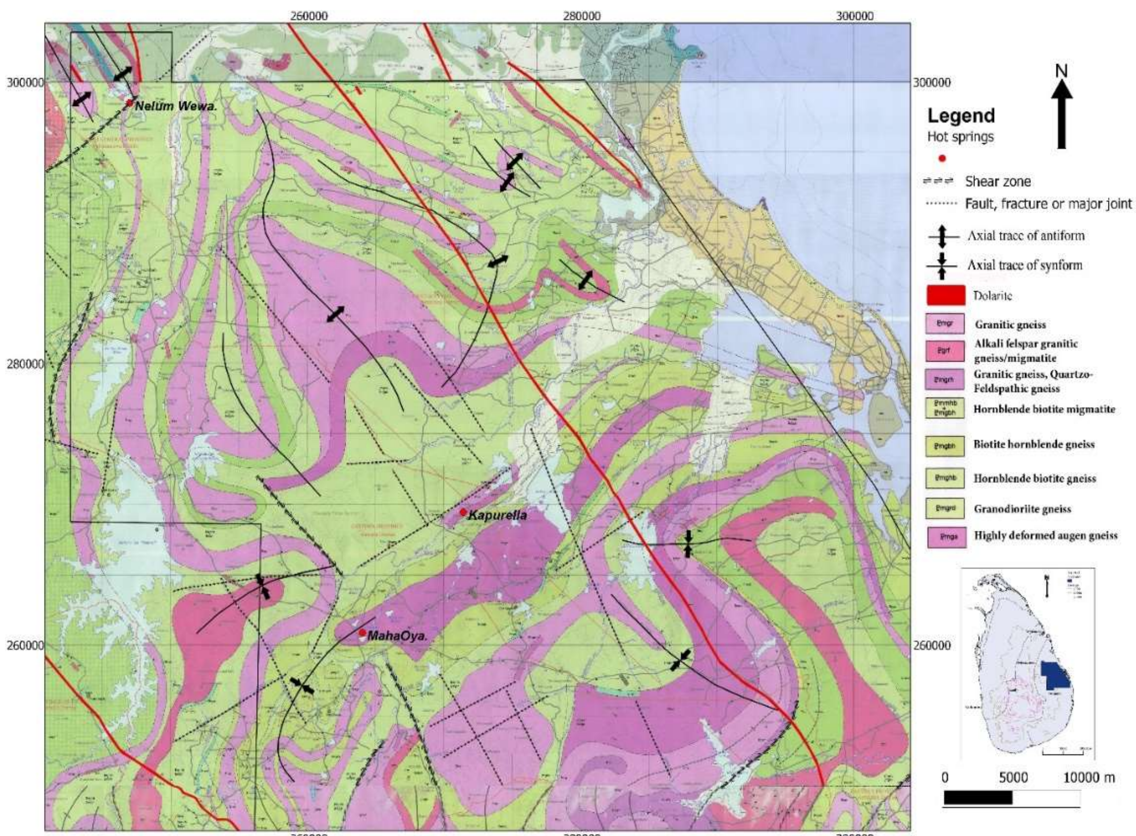

Fig. *7 Geology and structural map of the Mahaoya and Kapurella area. (Source: GSMB 2011)*

The thermal springs of Kapurella and Mahaoya do not show a distinctive local structure which may lead to the occurrence of the thermal spring. Instead, the surrounding area shows various important ductile and brittle structures on a regional scale. Several antiforms, synforms, and folds as ductile structures with 5 km to 20 km long axes are present in the area. Dykes, faults, fractures, major joints, and shear zones of even 10 km in length are present as brittle features in this region. Rivers and streams of the area mainly follow the mega lineaments of the area.

The megastructure of the Mahaoya and Kapurella covers an area of approximately 3,000 km^2 on the surface.

The lithological units of the geology map also show an equal sequence from either side of an axis drowns in NE-SW direction through the Mahaoya thermal spring location. Also, special folding pattern wrapping the antiforms and synform axis showing a lithological surface unit of "ω" pattern towards the NW direction and another overturned "ω" pattern towards the SE part can be seen in the area (Fig. 8).

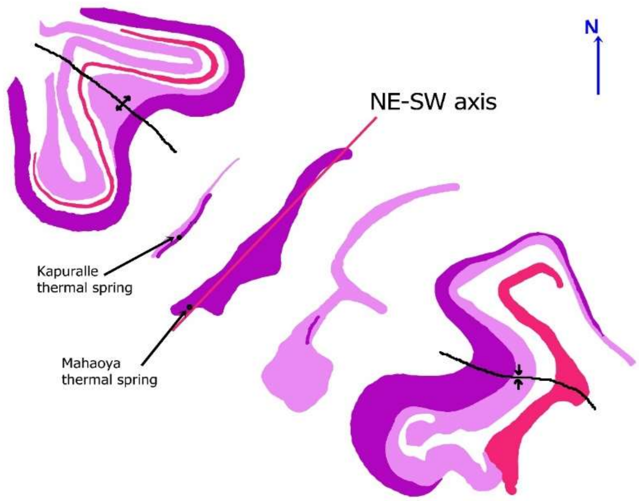

Fig.8 *Representative surface lithology and brittle structure (Prior to shearing)*

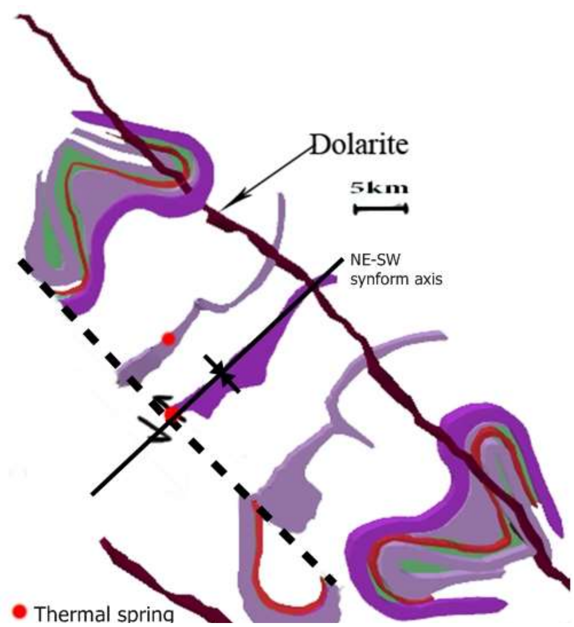

Fig. 9 *Representative surface lithology and brittle structure (Present condition)*

The structure forms the two "ω" pattern on the surface is a mega synform with NE-SW synform axis. The NW part of the regional structure is an antiform, while the SE part is a synform (Fig. 7, 8). This is due to the overturning of the mega synform structure.

The Mahaoya thermal spring has appeared on the axis of the mega synform structure (Fig. 7, 8). Also, NW-SE trending two shear planes are present in the NW side and SE of the Mahaoya thermal spring. Thus, Mahaoya thermal spring is situated at the intersection of the axial trace of the mega synform and this shear zone.

Alkali feldspar granitic gneiss/migmatite rock is well exposed in the southern "ω" structure in both eastern and western limbs (Fig. 7). In the eastern limb, this rock is contact with granodioritic gneiss and hornblende biotite migmatite. In the limb of the west, it buckles and gets contact with granitic gneiss and biotite hornblende gneiss. When it comes to the other limb of the mega synform the Alkali feldspar granitic gneiss/migmatite rock is poorly exposed due to thinning layers at the surface. Alkali feldspar granitic gneiss/migmatite rock should contact the granitic gneiss at the western limb of the northern "ω" shape layering. It is not present as the west of limb of the "ω" shape layering. At the southern part of the shear plane through Mahaoya in the western side, the missing limb of the "ω" layering is present as alkali feldspar granitic gneiss/migmatite rock in contact with granitic gneiss outer side of the missing limb (Fig. 9).

It implies that the rocks beneath the surface got exposed with the shearing. The force that resulted from the shearing may have caused the formation of the fractured hillock present at the eastern side of the shear plane.

The Kapurella Thermal spring is located near the contact of massive granitic, leucocratic quartzofeldspathic gneiss and augan gneiss and close to the axis of the mega synform structure of the area.

Compared to the scale and the structure, the Kapurella and Mahaoya have the same heat source, which might be dykes that are not exposed to the surface and still cooling underground at depth. Meteoric water can percolate deep along the week zones of the mega and the regional scale structures. Heated water rice to the surface probably vertically while mixing with cool water through the week zone where the mega synform axis crosscuts the shear zone at Mahaoya.

Geostructural Model of the Mahaoya and Kapuralla Geothermal System of Sri Lanka

Polyphase deformational event sequence having different directional kinematic frameworks should have been involved in forming this megastructure. D1* to D4* deformation events of VC of Sri Lanka (Kehelpannala, 2004) can describe the evolution of the structure of the model as shown by Fig. 10, 11.

Primitive deformation D_1* event is the formation of the primary foliation plane, more intense deformation of strong flattening parallel to lithologic contacts (Berger and Jayasinghe, 1976., Kehelpannala, 1977, 2003).

Then intrusion of leucocratic material and some granitoids along S_1 formed by D_1* and isoclinal folding of this rock unit with first upright folding resulting present "ω" shape folds with upside-down facing have occurred due to a force applied in NE-SW direction.

The third step of the deformation event D_3* resulted in the re-folding of the previously formed structure, making the mega-scale second upright fold which causes the present mega synform structure with the direction of the stress applied is NW-SE compression (Berger and Jayasinghe, 1976., Kehelpannala, 1977, 2003).

Later the Shearing, fracturing, and Joint formation have been taken place in the NE of the VC of Sri Lanka in the D_4* deformation and dolerite intrusions (Kehelpannala, 1977, 2003).

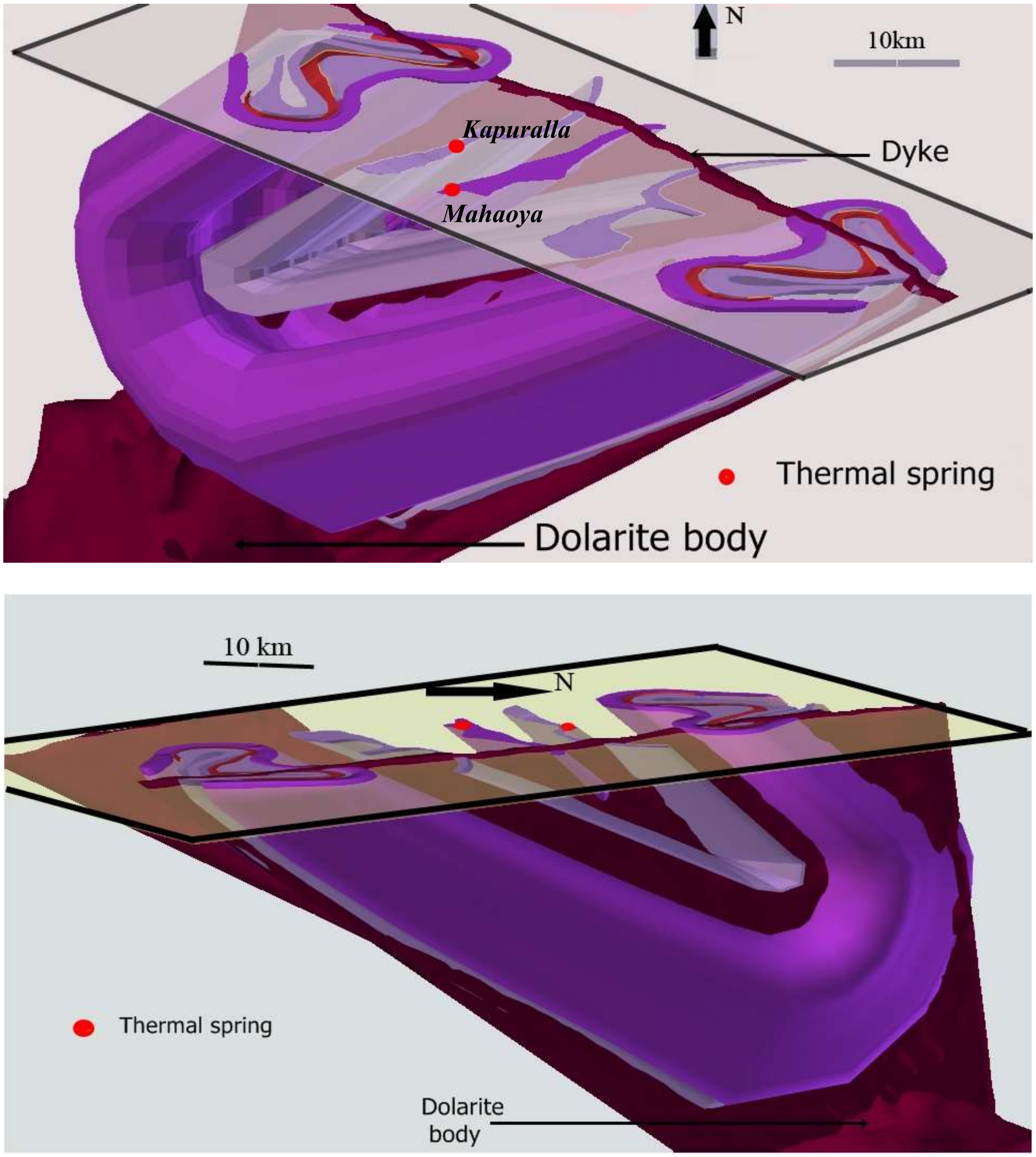

Fig. 10 & 11 *Possible underground geological model for the Mahaoya and Kapurella*

CONCLUSION

The present study reveals that the genesis of thermal springs of Sri Lanka is highly structurally controlled by structures resulting from D_1* to D_4* deformation events. Thermal spring-associated brittle structures are shear zones, fracture zones, and major and minor faults and joint sets. All four thermal springs studied are associated with the axis of the synform or antiform structure intersection with the shear zone or fault axis.

The ductile geological structure controlling Nelumwewa geothermal system is an antiform, whereas the Marangala thermal system is situated on a local synform.

The underground structure controlling the Mahaoya and Kapuralla thermal springs is a mega scale structure that covers approximately 3,000 km^2 surface area of Vijayan complex of Sri Lanka. It has several large-scale ductile structures such as antiforms, synforms and several brittle structures of shear zones and dykes containing in one mega-scale overturned synform of which the axial plain is oriented along NE-SW.

Intrusions of dolerite dykes in these areas could still be sufficiently hot at a depth of several kilometers. Moreover, it can propose that the assumed depth of folding plane week zone of the NE-SW overturned fold is about 15-25 km deep compared to the surface projection scale of the structure. Deep percolating ground water through fractures acquire heat and return to the surface easily along the deep running axis plain of the synform, forming the thermal springs associated with these structures.

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