https://doi.org/10.22581/muet1982.3063

2024, 43(4) 91-99

Evaluation of subsurface geothermal groundwater aquifers at Southern Kirthar Range Sindh province Pakistan through the application of vertical electrical sounding

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Received: 17 October 2023, Accepted: 23 September 2024, Published: 01 October 2024

K E Y W O R D S

Apparent Resistivity

Aquifers

Geothermal Energy

Kirthar range

Sindh

Pakistan

A B S T R A C T

Pakistan has significant geothermal potential but due to poor energy management and low utilization of rich geothermal energy, the country is ranked among the energy deficient nations in the world. In this study, integrated geophysical techniques were used to assess the geothermal energy potential of various hot springs in the Sindh province. The study revealed that Naing Shareef and Gaji Shah hot springs have remarkable potential for geothermal energy having pool water temperature of 43 °C and 45 °C, respectively. Geophysical resistivity survey was carried out at both Naing Shareef and Gaji Shah hot spring to determine depth, thickness and quality of thermal water. At Naing Shareef hot spring, only a single thermal aquifer zone has been pinpointed within the shale composition of the Oligocene Nari Formation, and it is on average 55.07 m depth and 29.8 m thick. At an average depth of 100.66 m and an aquifer thickness of 77.03 m, the Gaji Shah hot springs exclusively possess a thermal aquifer region established within the sandstone composition of the Oligocene Nari Formation.

1. Introduction

Exploitation of unconventional energy sources has increased recently due to the never-ending rise in energy demand. Both the use of renewable energy sources and the dependence on fossil fuels are crucial [1, 2]. Researchers are concentrating increasingly on developing effective, eco-friendly, and renewable energy sources in the current era of global warming [3]. Based on these criteria, geothermal energy holds one of the top spots because it offers weather-independent heat energy while also being sustainable, renewable, and almost completely free of greenhouse gas emissions [4, 5]. Geothermal energy is a type of renewable energy that can satisfy energy needs while posing least environmental threat [6]. Pakistan has experienced shortage of electricity for the last several years and spends $7 billion a year on the fossil fuels to meet its energy needs. This shortage frequently results in power interruptions especially severe during summer. The necessity to create alternative energy sources has been recognized in light of the diminishing fossil fuel supplies and increasing energy demands [7]. Pakistan shouldn't have shortage of commercially viable geothermal energy sources, with reference to the geotectonic framework. This opinion is further supported by the occurrence of a sizable number of hotsprings throughout Pakistan, the existence of alteration zones and fumaroles in several regions of the country, and the evidence of Quaternary volcanism [8]. These geothermal energy expressions can be found in Pakistan in three different geotectonic environments: the seismo-tectonic or suture-related systems, the geo-pressurized systems linked to basin subsidence, and the systems linked to Neogene-Quaternary volcanism. In addition to other potential resources, the country is home to numerous hot springs with temperatures ranging from 40°C to 170°C. High-temperature geothermal potential on earth can be found along seismically active belts and is associated with weak crustal regions like plate boundaries or volcanic zones. Pakistan's major fault lines have a lengthy geological history of geotectonic effects along its borders [9]. Cost-effectively, potential geothermal energy resource zones exist here, as shown by Pakistan's seismology monitoring [10]. Numerous mud volcanoes and hot springs can be found in Pakistan's seismic belt [11]. Some studies have highlighted the geothermal energy potential of Pakistan, but no practical work has been done particularly in the Sindh province [12]. Along the Indus basin zone, there is an abundance of thermal springs [13, 14, 15]. That denotes the extensive thermal system seen in northern regions. Thermal springs are probably the result of the deep meteoric water circulation that occurs alongside the faults. A series of parallel hills that are a component of the Kirthar range serve as the boundary between the Karachi and Dadu districts. There is a huge concentration of thermal springs which have an average surface temperature >45 °C such as Ranikot, Gaji Shah, Kai, Laki Shah Sadder, and Naing Shareef vicinities. The Dadu and Jamshoro districts' thermal springs present good geothermal investigation areas. [16]. Utilizing an integrated approach, electrical resistivity sounding assisted in the exploration of thermal aquifer geometry and subsurface aquifer properties. Instead of direct research, prospecting for geothermal resources often depends on geological and geophysical analyses, which provide a broad overview of the underlying conditions [17, 18]. The study is aimed to make use of the nation's energy system by investigating the geothermal energy potential in Sindh province, notably in the Kirthar range.

1.1 Study Area

The study area lies in the Kirthar mountain ranges in the Lower Indus Basin in the Sindh province. Two hotsprings (Gaji Shah hotspring and Naing Shareef hotspring) are selected for this study. Gaji Shah Hotspring is about 4 km from the town of Gaji Shah and about 35 km southwest of Johi town in the Dadu district (Toposheet Sheet No. 35N/2), situated at latitude 26°35' 42" N and longitude 67°14' 21" E, and about 600 feet above sea level. In the Kirthar mountain range, the hot spring is located. Naing Shareef Hotspring is located at a distance of about 48 km in the southwest of Sehwan Sharif at latitude 26° 17' 33" N and longitude 67° 30' 45" E in the hill torrent of Nai Naing that runs through the valley. The mountains of Bhit and Bado encircle the valley.

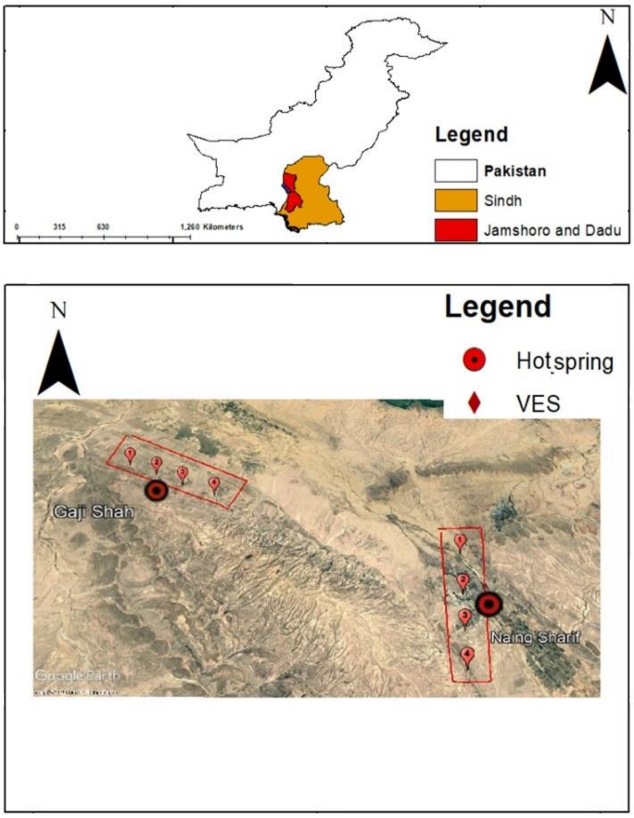

Fig. 1. Location Map of Study Area

1.2 Geology Of The Study Area

The study area is present in the Lower Indus Basin, which is one of the major sedimentary and structural basins of Pakistan. The rocks exposed are exclusively sedimentary and range in age from Early Eocene to Pleistocene. Mostly sedimentary rocks are present in study area and their lithology consists of sandstone, compacted limestone, shale and clay etc (Fig.2). The majority of the region is made up of compacted limestone, shale and sandstone lithology of Nari Formation Oligocene age which may exhibit significant resistivity (Fig. 2). Gaji Shah hotsprings are found in sandstone lithology of Nari Formation [19] (Fig. 2). The hotsprings of Naing Shareef are found in the Oligocene-aged Nari Formation, which is composed of sandstone, shale, and limestone [20]. As a result of the region's structural folds, faults, and joins, hot water can erupt on the earth's surface. The formation of this structural complexity is caused by the collision of the Indian and Eurasian plates. There is fault control for the nearby hotsprings. Significant anticline structures, multiple reversal and thrust faults, as well as other geological elements, control the locations hotsprings.

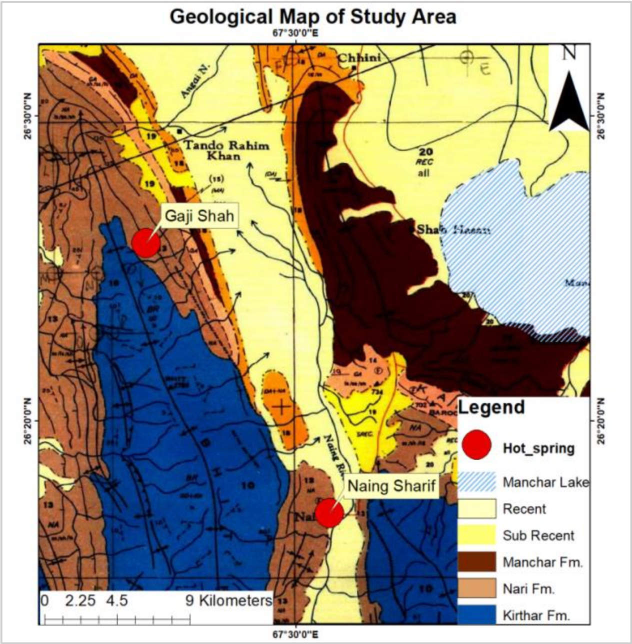

Fig. 2. Geological Map Of The Study Area (Modified And Reproduced After Hunting Survey Corporation, 1960) [22]

2. Methodology

2.1 Electrical Resistivity Survey (ERS)

The most efficient geophysical survey technique for geothermal exploration and the main approach for evaluation of geothermal deposits are measuring subterranean electrical resistance [21]. To evaluate the resistivity contrast of subsurface materials, the electrical resistivity method is a dynamic geophysical method. It involves introducing an artificial current into the ground and then analysing the electrical response that occurs at the surface of the earth. The geophysical resistivity survey is typically the most advantageous method for evaluating a geothermal reservoir before drilling. It is a geoelectrical technique used in the quest for geothermal energy. The electrical resistivity of rocks is affected by crucial geothermal factors such as temperature, fluid type and salinity, porosity, rock composition, and the presence of altered minerals [23]. Electrolytes' electrical conductivity quickly rises with temperature [24]. Fluids are more conductive because they are also saltier than cold meteoric fluids. Additionally, hydrothermally altered rocks that are in contact with geothermal fluids have lower resistivity. When these variables are combined, values in geothermal energy reservoirs with a preponderance of water are often less than 5 Ωm [25]. The resistivity values are consistent with the observed values of several rocks showing a clear connection to the underlying strata of the geothermal spring [26, 27]. Geothermal exploration uses geophysical electrical resistivity surveys to ascertain the earth's electrical resistivity distribution in a variety of ways. It is possible to learn about lithological changes and geological structural changes from the apparent resistivity distribution in the subsurface [28]. The fundamental concept is that a current of electricity is introduced into the subsurface, resulting in an electromagnetic signal that can be seen at the surface. A resistivity survey's key insight is that different subsurface materials can be distinguished by variations in their unique potential differences. Calculations of changes in the electrical potentials of subsurface materials are based on applying a specific amount of electric current to the material and measuring the potential difference. According to Ohm's law, the voltage (V) of an electric circuit is equal to the electric current (I) times the medium's resistivity (R) (V=IR) [29]. The resistivity survey finds fewer geologically significant geoelectrical regions. A segment that exhibits a comparable electric resistivity value is said to be geoelectrical. Although it is not always the case, a geoelectrical section can correlate to a geologic one. Data was gathered in the Kirthar range using the Schlumberger electrode array technique. The Schlumberger array method is a quick and straightforward approach for gathering accurate subsurface resistivity data. In order to conduct a resistivity survey, two current electrodes (C1 and C2) are typically utilized to drive current into the ground. Two potential electrodes (PI and P2) are used to measure the resulting voltage difference. The current (I) and voltage (V) measurements are used to calculate an apparent resistivity (a) value [30].

3. Results and Discussion

Four vertical electrical soundings (VES) were performed at each of the sites along the profile line in the Kirthar range using the ABEM Terrameter SAS-4000. This examination was carried out to ascertain the size of the aquifer in the study region and the depth of hotsprings aquifers (Fig. 1).

Table 1

Interpretation of the depths, resistivity, and underlying strata at Gaji Shah and Naing Shareef hotsprings

Site	VES Number	Identified Lithology	Apparent Resistivity (Ωm)	Thickness (m)	Depth (m)
Gaji Shah	VES-01	Alluvium	76.6	2.33	2.33
		Shale	37.2	23.19	25.53
		Aquifer in Sandstone	84.39	64.66	90.19
		Compacted Limestone	579.2	109.81	200
	VES-02	Alluvium	101.5	2.40	2.40

		Shale	44.73	20.66	23.06
		Aquifer in Sandstone	94.97	76.2	99.27
		Compacted Limestone	263	100.73	200
	VES-03	Alluvium	140.4	4.15	4.15
		Shale	49.24	22.11	26.27
		Aquifer in Sandstone	86.28	86.27	112.5
		Compacted Limestone	434.3	87.5	200
	VES-04	Alluvium	141.5	3.69	3.69
		Shale	42.17	16.03	19.72
		Aquifer in Sandstone	80.73	81.02	100.7
		Compacted Limestone	377.5	99.3	200
Naing Shareef	VES-01	Alluvium	48.2	4.12	4.12
		Limestone	121	15.7	19.8
		Aquifer in Shale	33.3	26.2	46
		Compacted Limestone	929	154	200
	VES-02	Alluvium	48.9	2.98	2.98
		Limestone	94.6	20.7	23.7
		Aquifer in Shale	45.7	34.6	58.3
		Compacted Limestone	605	141.7	200
	VES-03	Alluvium	42.8	3.72	3.72
		Limestone	108.5	22.7	26.49
		Aquifer in Shale	36.12	26.72	53.21
		Compacted Limestone	628	146.79	200
	VES-04	Alluvium	112	4.26	4.26
		Limestone	83.2	27.4	31.6
		Aquifer in Shale	47.6	31.2	62.8
		Compacted Limestone	392	137.2	200

3.1 Gaji Shah Hotspring VES Data Interpretation

To examine the depth of the aquifer and its expansion along the profile line in the research area, four VES were conducted in the Gaji Shah region near the hotspring and with the aid of the IPI2win programme the data was analysed.

Up to a depth of 200 m, the VES-01 identified four subsurface geological layers. Data interpretations illustrate subsurface top layer shows the apparent resistivity (AR) of 76.6 Ωm and thickness of strata is 2.33 m represents the top alluvium, whereas the second layer shows an AR of 37.2 Ωm and strata thickness is 23.19 m with depth of 25 m showing shale lithology. 64.66 m strata thickness and 90.19 m depth, the layer three shows an AR of 84.39 Ωm delineated geothermal aquifer in sandstone lithology. It is believed that the fourth layer is compacted limestone of the Nari Formation since it shows an AR of 579.2 Ωm and thickness of strata is 109.81 m with total depth of 200 m (Table 1, Fig. 3).

Up to a depth of 200 m, the VES-02 identified a total of four subsurface geological strata. Data interpretations illustrate the subsurface strata one shows an AR of 101.5 Ωm and thickness of strata is 2.40 m represents the top alluvium, whereas the strata second, which shows an AR of 44.73 Ωm and strata thickness is 20.66 m with depth of 23.06 m represents the shale lithology. 76.2 m strata thickness 99.27 m depth, the strata three shows an AR of 94.97 Ωm delineated geothermal aquifer in sandstone lithology. The strata four, which has a 100.73 m layer thickness and an AR of 263 Ωm is assumed to be made up of compacted limestone (Table 1, Fig. 3).

Up to a depth of 200 m, the VES-03 identified a total of four geological strata. The strata one, shows an AR of 140.4 Ωm and thickness of strata is 4.15 m represent the top alluvium is located, according to the data. The second strata, which shows an AR of 49.24 Ωm and strata thickness is 22.11 m with depth of 27 m represents the interpreted the shale lithology. The strata third confirm an AR of 86.28 Ωm and 86.27 strata thickness with depth of 112.5 m is believed to be a geothermal aquifer in the sandstone lithology. The strata four, which has a strata thickness is 87.5 m strata and an AR of 434.3 Ωm is assumed to be made up of compacted limestone.

Up to a depth of 200 m, the VES-04 identified four geological strata. The strata one shows an AR of 141.5 Ωm and thickness of strata is 3.69 m contains the most alluvium, according to the data. The second strata, which shows an AR of 42.17 Ωm and strata thickness is 16.03 m with depth of 19.72 m is analysed shale lithology from the Nari Formation. The strata third, confirm an AR of 80.73 Ωm and 81.02 m strata thickness with depth of 100.7 m delineated geothermal aquifer in sandstone lithology. The strata four, which has a strata thickness of 99.3 m with depth of 200 m and an AR of 377.5 Ωm is believed to be a lithology of compact limestone from the Nari Formation.

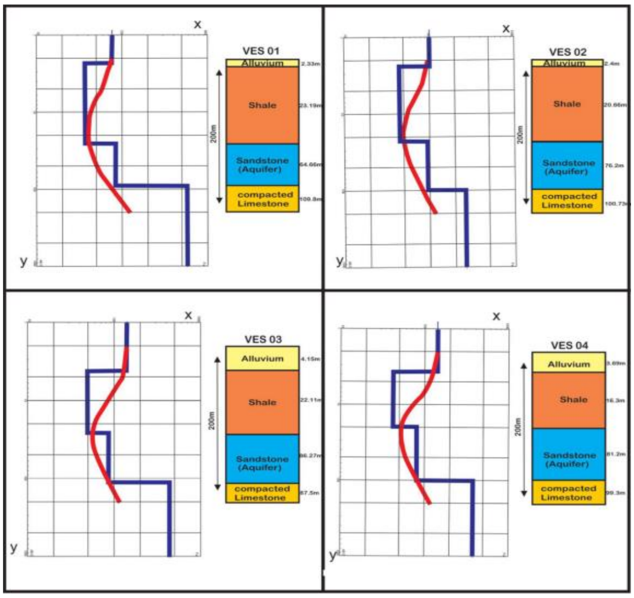

Fig. 3. Geoelectrical Section of Gaji Shah VES 01, 02, 03, and 04 Stacked Along Profile

3.2 Profile Of Gaji Shah's Pseudo Section And Resistivity

VES 1 to 4 data were analyzed in Gaji Shah to create the pseudo-section. There is 50 m distance between each VES making a total length of 150 m for the profile. The overall identification of low, moderate, and high resistivity zones was based on three major lithological variations: shale, aquifer containing sandstone, and compacted limestone lithology representing low, mid, and high resistivity zones. The Oligocene-aged Nari Formation sandstone lithology's geothermal aquifer zone was located there at an average depth of 100.66 m and a thickness of 77.03 m. Excellent potential exists for using the sandstone-containing aquifer in Gaji Shah as a geothermal energy reservoir (Fig. 4).

Alluvium lithology is indicated by the Gaji Shah profile's high resistivity zone value, which ranges from 76.6 to 141.5 Ωm down to a depth of 4 m. Resistivity readings below the alluvium layer are decreasing between 37 and 49 Ωm up to a depth of 24 m, revealing the shale lithology of the Nari Formation with a resistivity reading between 37 and 49 Ωm. Interbedded lithology response rises in resistivity in the 80 to 94 Ωm range point to the existence of a geothermal water aquifer in the lithology of sandstone, which has an average thickness of 77.03 m. Up to 200 m below the surface, this lithology of hard compacted limestone has an average resistivity of 413.3 Ωm (Fig. 5).

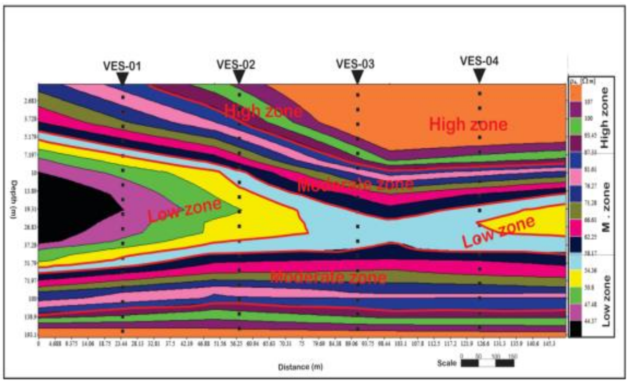

Fig. 4. Pseudo Section Along Gaji Shah Profile

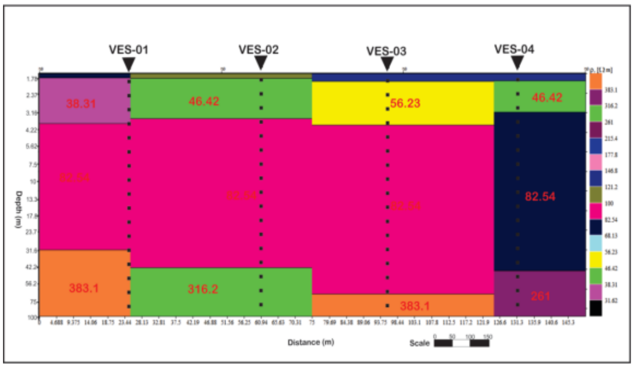

Fig. 5. Resistivity Section Along Gaji Shah Profile

3.3 Naing Shareef hotspring VES Data Interpretation

With the aid of the IPI2win programme, data from a total of 04 VES were analysed.

Up to a depth of 200 m, the VES-01 identified four subsurface geological strata. The strata one, shows an AR 48.2 Ωm and thickness of strata is 4.12 m represent the top alluvium is located, according to data. The limestone lithology is represented as the second strata, which have an AR of 121 Ωm, a thickness of 15.7 m and a depth of 19.8 m. Strata three exhibits an AR of 33.3 Ωm, and thickness of strata is 26.2 m with depth of 46 m and is thought to be a geothermal aquifer present in shale lithology. While strata four displays an AR of 929 Ωm, and layer thickness of 154 m with depth of 200 m interpreted as limestone lithology (Table 1, Fig. 6)

The VES-02 discovered four subsurface geological strata down to 200 m in depth. The top layer of alluvium, which has an AR of 48.9 Ωm and a thickness of 2.98 m is strata one. The second strata, which has an AR of 94.6 Ωm and is believed to be a limestone layer of the Nari Formation, has a layer thickness of 20.7 m and a depth of 23.7 m. At 58.3 m below the surface and 34.6 m thick, the AR of layer three is 45.7 Ωm. The Nari Formation's shale lithology, which is expected to be an open thermal aquifer with low resistivity, is predicted to contain this layer. The AR in layer four is 605 Ωm. This formation has layers ranging in thickness from 141.7 m to 200 m, and its lithology is believed to be compact limestone from the Nari Formation (Table 1, Fig. 6).

Up to a depth of 200 m, the VES-03 identified four subsurface lithological strata. The uppermost alluvium layer, with a layer thickness of 3.72 m display an AR of 42.8 Ωm according to the data interpretation Layer two's AR is 108.5 Ωm, and its layer thickness is 22.7 m up to depth of 26.49 m., with layer three having a layer thickness of 26.72 m and an AR of 36.12 Ωm layer three is a thermal aquifer with low resistivity that is unconfined. Its lithology is assumed to be limestone from the Oligocene-age of the Nari Formation. With a layer thickness of 146.79 m and AR of 628 Ωm, layer four is thought to represent a thick layer of compacted limestone that extends down to a depth of 200 m (Table 1, Fig. 6).

Four subsurface lithological layers were identified by the VES-04 up to a depth of 200 m. According to the interpretation of the data, the topmost alluvium layer, which has a layer thickness of 4.26 m, has an AR of 112 Ωm. Layer two displays an AR of 83.2 Ωm its lithology is thought to be limestone from the Oligocene-age Nari Formation and its layer thickness is 27.4 m up to a depth of 31.6 m. The Nari Formation's shale lithology contains layer three, a low resistivity, unconfined thermal aquifer, which has a layer thickness of 31.2 m and an AR of 47.6 Ωm with a thickness of 137.2 m and a depth of 200 m. Layer four is assumed to be a thick layer of limestone since it has an AR of 392 Ωm (Table 1, Fig. 6).

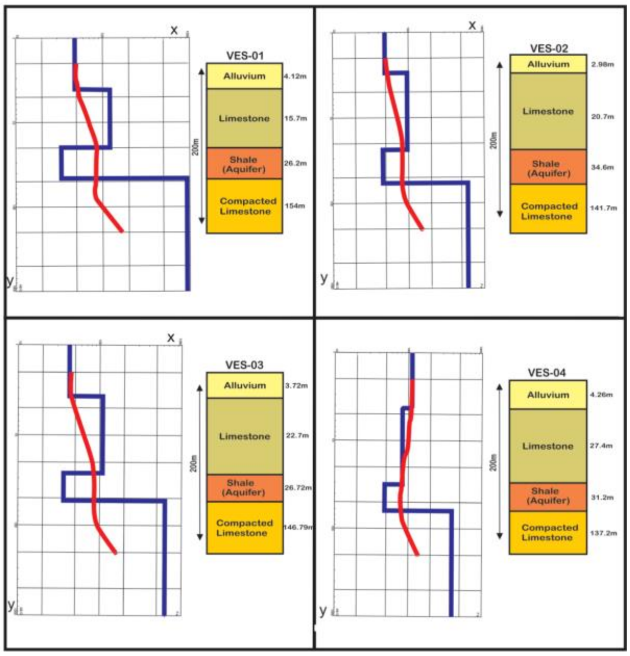

Fig.6. Geoelectrical Section of Naing Shareef VES 01, 02, 03, and 04 Stacked Along Profile

3.4 Pseudo Section And Resistivity Inversion Of Naing Shareef Profile

Analysing the resistivity data from Naing Shareef profile VES 1 to 4 resulted in the pseudo-section inversion. There is 50 m distance between each VES making a total length of 150 m for the profile. Low, moderate, and high resistivity zones were generally identified using three fundamental lithological variations: compacted limestone, aquifer-bearing shale, and limestone. The thermal aquifer zone was found in the Oligocene-aged Nari Formation's shale lithology at a depth of 55.07 m on average. Below this zone, the aquifer's typical thickness is 29.68 m.

The resistivity inversion of the Naing Shareef profile reveals a sequence of different lithologies at various depths. At the topmost layer, there are low to intermediate resistivity values ranging from 48 to 112 Ωm, extending down to 3.75 m, indicating alluvium lithology. At a depth of 25.39 Ωm below this layer, resistivity values rise to a range of 80 to 121 Ωm, indicating limestone lithology from the Nari Formation. The resistivity values drop to a range of 33 to 48 Ωm below the limestone lithology, indicating the presence of an unconfined aquifer made up of shale lithology. This aquifer has an average thickness of around 29.68 m, and it probably includes thermal water. A firm, compacted limestone lithology with an average resistivity of 638.5 m is present up to a depth of 200 m, according to the abrupt shift in resistivity response that occurs with depth (Figs. 7 and 8).

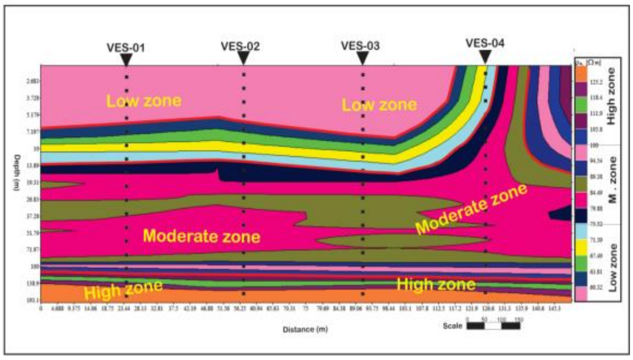

Fig. 7. Pseudo Section Along Naing Shareef Profile

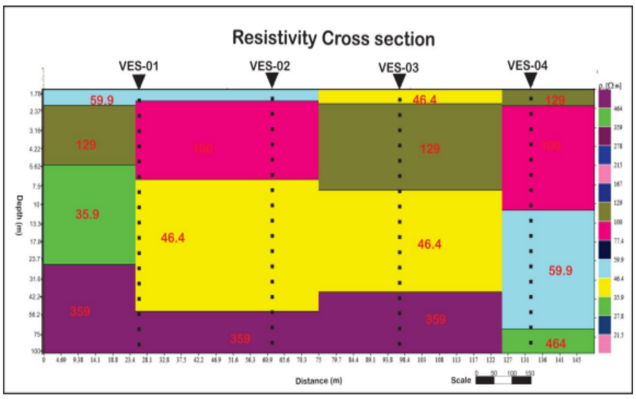

Fig. 8. Resistivity Section Along Naing Shareef Profile

4. Conclusion

Most of the geothermal locations are associated with structural dimensions such as faults, folds, and fractures, suggesting a strong correlation with these geological structures especially in the Laki and Kirthar ranges, are primarily responsible for controlling the up flow in the region. According to the resistivity data from the Naing Shareef hotspring, just one thermal aquifer zone was identified in the Oligocene Nari Formation's shale lithology at an average depth of 55.07 m and an average thickness of 29.68 m. The Oligocene Nari Formation sandstone lithology was only the thermal aquifer zone defined, according to the hotsprings at Gaji Shah, and its average thickness is 77.03 m. The sandstone-containing aquifer known as Gaji Shah has enormous prospective for use as a geothermal energy source. This study is the first in-depth investigation of its sort and contributes to the understanding of Pakistan's geothermal energy resources and exploration methods. The authorities are expected to be encouraged to display keen interest in the nation's geothermal energy reservoirs and conduct a comprehensive feasibility examination, particularly in Sindh province and any other regions where geothermal potential is evident.

5. Declaration Of Competing Interest

The authors hereby declare to have no competing interests to disclose regarding the research. Authors have not received any funds, financial support, or other benefits from any organization or individual that could be perceived as having influenced the research or its outcomes.

6. Acknowledgement

The Centre for Pure and Applied Geology, University of Sindh, Jamshoro, Pakistan, is acknowledged for providing Terrameter equipment and supporting the technical assistance during the survey.

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