Geothermal Exploration in Gujarat: Case Study from Unai

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Abstract – **The present study emphasises the importance of geothermal exploration in Gujarat using integrated geological and geophysical techniques. A case example from Unai (20^o 51' N and 73^o 24' E) is presented here, which is a potential geothermal site identified by the authors of this paper. The proximal hinterlands juxtaposed to linear quaternary basins with fault bounded contacts, have anomalous crustal structure with high density mantle derived bodies. This is emplaced at shallow crustal levels reflecting high gravity anomalies. The hinterland domain is further characterized by high heat flow with thermal spring (54^{o}C temperature). The Magnetotelluric Survey carried out in this region suggests intense hydro-technical activity. This renders the area prone to geothermal activity warranting multi-disciplinary evaluation. Geochemical sampling of thermal spring water was carried out, which shows low level of carbonate and bi-carbonate component in water samples. It suggests that source of water is deep seated under the trapean flows. Attempts are made to connect shallow and deep reservoirs and a unified fluid flow model has been presented.**

Keywords **– Geothermal, Magnetotelluric, Gravity, Geochemical, Anomaly**

I. INTRODUCTION

Unai (20^o 51' N and 73^o 24' E) site, Navsari District is located in the southern part of Gujarat, 90 km away from coast of Cambay. This site is located 100 km from the Cambay basin, which hosts prominent oil and gas field. The elevation of surrounding area ranges from 10 m to 55 m. The area is mostly surrounded by dense forests and small hillocks. At places Deccan traps are exposed on the surface.

This research attempts to study the geothermal reservoir existing in shallow and deep crustal levels. The reason for believing that such reservoir exists is because of the fact that the region has registered high heat flow [3]. Hot springs are the surface manifestations of these reservoirs. High heat flow rates, presence of rift system and deep lithosphere piercing gravity fault systems have given rise to thermal springs. The present study is controlled by physical and chemical characterization of thermal springs, Audio Magnetotelluric (AMT) survey, Magnetotelluric survey (MT) and Gravity surveys. There have been no major geothermal studies carried out in the area. The study started with collection of water samples to determine major chemical parameters and trace elemental analysis. The physical parameters like colour, pH and conductivity of water samples were measured in situ and in the laboratory.

Based on the sample analysis, AMT and MT survey was performed at 56 sounding stations along with 3 MT profiles. The frequency range of the data collected was between 0.001 to 10000 Hz. Gravity measurement was conducted at several places, either on MT stations or at offsets.

The interpretation of geoscientific data helped us to identify the ascent of parental fluids through the trapeans. The ascending fluid and inter-mixing of fossil meteoritic water is postulated to be a reason for Unai hot spring.

II. TECTONIC FRAME WORK OF MAINLAND GUJARAT

Gujarat state carries the distinction of diverse and unique combination of geological, geo-morphological and physiographic attributes as shown in Fig. 1 & Fig. 2. The interplay of geologic, tectonic and climate have resulted into three physiographic domains in the region i.e., Mainland Gujarat, Saurashtra Peninsula and Kachchh Peninsula. Biswas [1], [2] has opined that the three depositional basins namely; Kachchh, Cambay and Narmada, represent that physiographic divisions of the state have formed due to the events of rifting during Triassic – Early Jurassic, Early Cretaceous and Late Cretaceous times respectively as shown in Fig.1.

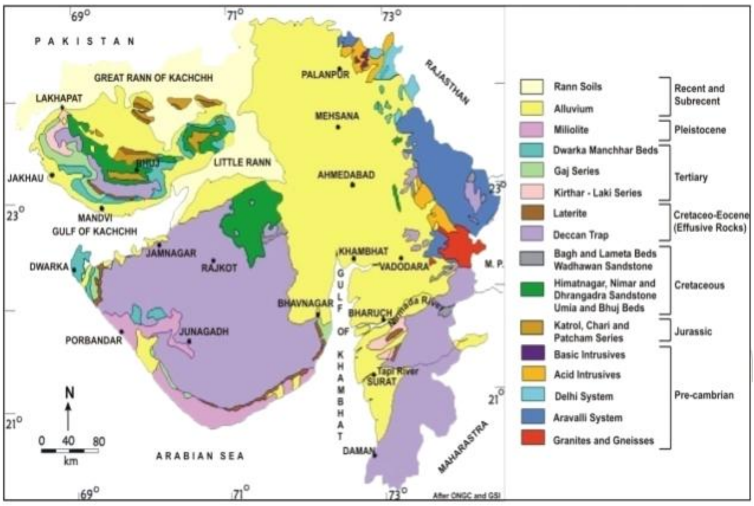

Fig 1: Geological map of Gujarat [7]

The Mainland Gujarat shares its northern margin with the southern part of the Aravali range; in the north east this basin is in contact with Satpura hills and further south Deccan traps make a sharp tectonic contact. The terrain is mostly covered with thick Deccan traps of Late Cretaceous to Early Eocene age. Prior to the commencement of Deccan volcanism, there was a period of non-deposition, as represented by the unconfirmative between the sedimentary rock and trapean flows laid during the upper Cretaceous and lower Eocene periods [7].

The low resistivity, upper layer tectonic trends are active even today and are very much the underlying cause for neo-tectonism. These plains of weakness are in many cases thought to be cutting through the entire crustal thickness, ending almost with the upper mantle. This in turn creates a condition of tensional tectonics which facilitates mantle upliftment. The concept is useful in postulating the fluid model for explaining the presence of geothermal reservoirs where, such deep seated faults are thought to be the conduit between shallow and deep reservoirs.

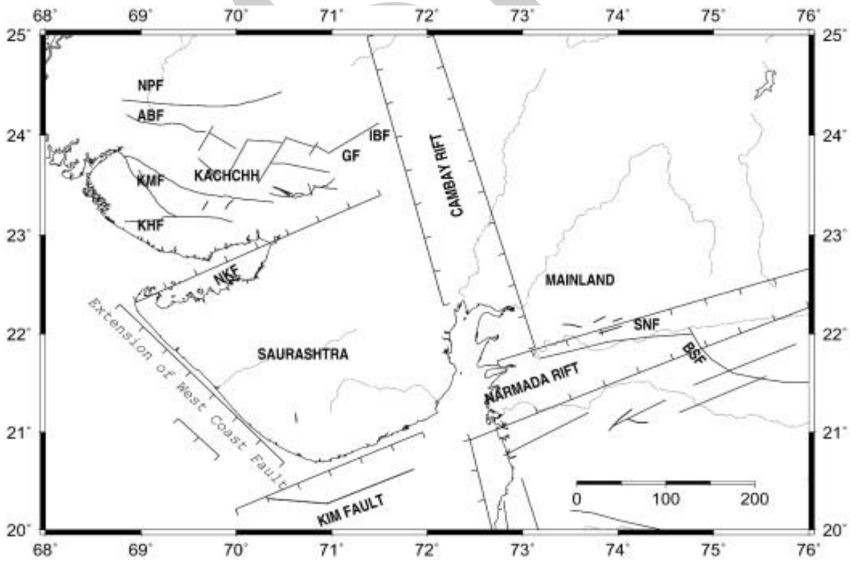

Fig 2: Tectonic framework of Gujarat [1]

III. GEOCHEMICAL ANALYSIS

For geochemical analysis, samples from thermal springs and ground water were taken from Unai. These samples were analysed for checking color, pH, hardness, salinity, conductivity and other physical properties (Table 1).

Detailed chemical analysis was carried out to check the presence of cations (Ca++, Mg++, Na+, K+) and anions (CO_3-, HCO_3-, Cl-, SO_4--) presented in Table 2. Table 3 depicts the elemental chemistry of thermal springs. Unai water samples have shown moderate to low salinity values. The conductivity values are moderate in nature. TDS values are in agreement with the salinity values. Lower carbonate hardness is understandable since the dominant anions species in these samples is chloride and sulphate. The water category is sodium potassium-chloride sulphate type. Low level of carbonate and bicarbonate components is an indication that the water has risen up from deeper levels. It is influenced by the formation water chemistry from the deeper sedimentary layer under the trapean flows. Fluoride is present in all the samples with variable concentration levels. High fluoride levels indicate that these waters are in interaction with sub-surface mica and apatite bearing rocks. Si shows variation between 32 mg/l to 5 mg/l [10]. Silicon contribution is expected to happen at deeper levels where thermal gradient is high. Silicon gets dissoluted from alkali feldspar, quartz and amorphous silica. The presence of zeolite (Fig 3) in the rock samples collected in the study area suggests that the water has interacted with the basement rocks and then migrated to the shallow level. Thus we can say that tectonic movement and mantle upliftment might have created higher flow gradients which in turn heat the water, which rises back to the surface as it reaches its boiling temperature [6].

Fig 3: Zeolite in Unai

Table 1: Geochemical report of Unai [10]

S.No	Location	Odour	pH	Conductivity Ms/cm	Salinity mg/l	TDS mg/l	CO_3 Hardness mg/l
1	Unai 1	"	8.38	1475	623	998	260
2	Unai 2	"	7.86	1840	948	1190	84
3	Unai 3	"	8.12	1662	957	1114	96

Table 2: Major chemical parameters of the thermal water samples [10]

S.No	Location	CO_3 mg/l	HCO_3 mg/l	Cl mg/l	SO_4 mg/l	Ca	Mg	Na	K
1	Unai 1	4.8	126	345	41.17	168.3	5	158	13
2	Unai 2	Nil	42	525	108.8	52	17	324	15
3	Unai 3	4	42	530	92.65	64	4.86	340	10

Table 3: Trace elemental chemistry of the thermal springs [10]

S.No	Location	B mg/l	F mg/l	SiO_2 mg/l	Pb mg/l	Ni mg/l
1	Unai 1	BDL	2.3	21.05	0.15	BDL
2	Unai 2	BDL	8	32.26	0.22	0.09
3	Unai 3	BDL	8.4	32.16	BDL	0.07

IV. GRAVITY SURVEY

Gravity survey was conducted in the study area. 44 station points were collected along the MT profiles or on its offsets. The data collected was corrected for surfacial elevations and tilt of the gravimeter. The gravity values collected were base referenced and were plotted on a 2D map. The Bouguer data were contoured and anomaly maps were prepared, which is shown in Fig 4. Deep seated faults trending north-east and south-west in the central part on the anomaly map can be attributed under heat flow category.

The gravity high observed along the tectonic lineament has established Proteozoic basement (3-4 km). This supports the physical condition of the area. The observed Bouger gravity is a combined effect of low and high resistivity layers as attributed by MT survey discussed later. The unique crustal tectonics configuration supports the high heat flow condition of the region.

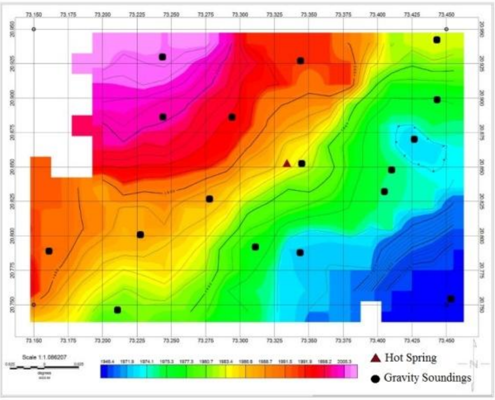

Fig 4: Bouguer Gravity at Unai

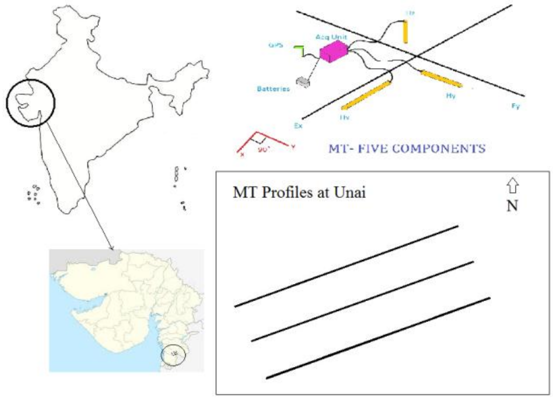

Fig 5: MT Profiles at Unai.

V. MAGNETOTELLURIC METHOD

The magnetotelluric method is passive surface measurement of the Earth's natural electric field and magnetic field in orthogonal direction. It can be shown that the relationship between the horizontal orthogonal magnetic and electric field depend on the sub surface resistivity structure. It is therefore used to determine the conductivity of the earth ranging from a few tens of meters to several hundreds of kilometres. MT generally refers to recording of 10 KHz to 0.001 KHz or as low as 0.0001Hz [12], [13].

Magnetotelluric measurements allow detection of resistivity anomalies associated with geothermal structures, faults and the presence of a cap rock, and allow for estimation of geothermal reservoir temperatures at various depths. Geological materials are generally poor electrical conductors and have a low conductivity. This change in conductivity is useful to map the subsurface geology and estimate the subsurface material composition [5].

AMT and MT were performed in Unai at 56 magnetotelluric / audio-magnetotelluric sounding stations along 3 profiles (Fig 5). The orientation of the profiles was WSW-ENE. The frequency range of the MT/AMT data are in the range of 0.001 – 10,000 Hz. Simultaneously synchronized measurements on reference station located in Kamalpura were carried out.

Measuring array was built of 2 perpendiculars Ex, Ey electric dipoles of length 100m and 3 magnetic senor recording magnetic horizontal components Hx, Hy, and vertical Hz [8].

The acquired electric and magnetic vectors were converted to apparent resistivity curves with respect to frequency.

1D Occam inversion was conducted considering earth is composed of uniform stratified layer. Many geoelectric models can match the data some may be complex in nature [4]. Resistivity of layer varies until a good fit is obtained between the calculated and observed data. 2D inversion is carried out using non-linear conjugate gradients [9]. The forward model simulations are computed using finite difference equations generated by using Maxwell's equation.

A. 1D Occam interpretation of Unai profile

The 1D Occam inversions is based on stratified layering at each station points. The first geoelectric layer has resistivity less than 250 Ωm and the second layer (basement) it is more than 2000 Ωm. The first layer thickness is 2-3 km deep. There are some low resistivity anomalies in this layer. The depth to the top of the basement decreases in ENE direction. Geophysical anomalies are seen at a depth less than 8 km. The upwelling anomalies can be interpreted as magma [8].

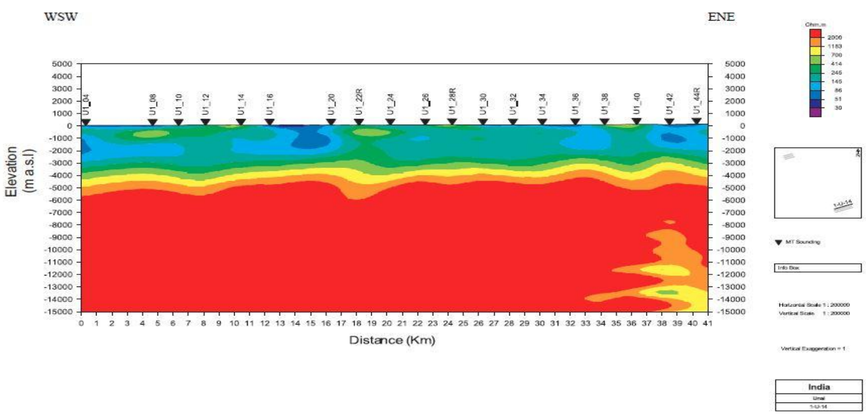

Fig 6: 1D resistivity cross-section along profile 1

Fig 6 is the 1D deep resistivity cross-section along first profile for deep imaging. It is observed that in this cross section low resistivity layer is sandwiched between high resistivity layers. However the low resistivity layer is patchy and pinches out at places. Some low resistivity anomalies are seen in the basement between 9000-14000 m in the North Eastern Side of the profile.

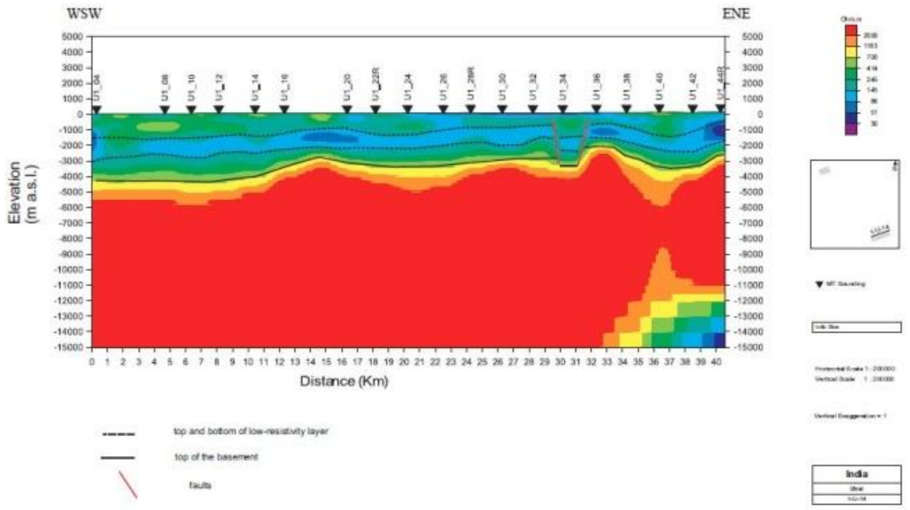

Fig 7: Resistivity cross-section based on 2D NLCG inversion along profile 1.

B. 2D *Deep Geoelectric Model Interpretation in Unai*

The resistivity cross-section based on 2D NLCG inversion along profile 1 is shown in the Fig. 7. In the shallow sections, up to 4 km depth a small graben is clearly seen between stations U1_32 and U1_36, which might be acting as a migration path for the geothermal fluid. Deep geophysical anomalies within basement are seen between 11 km to 15 km once again in the ENE direction, which was also visible in the 1D deep geoelectric models.

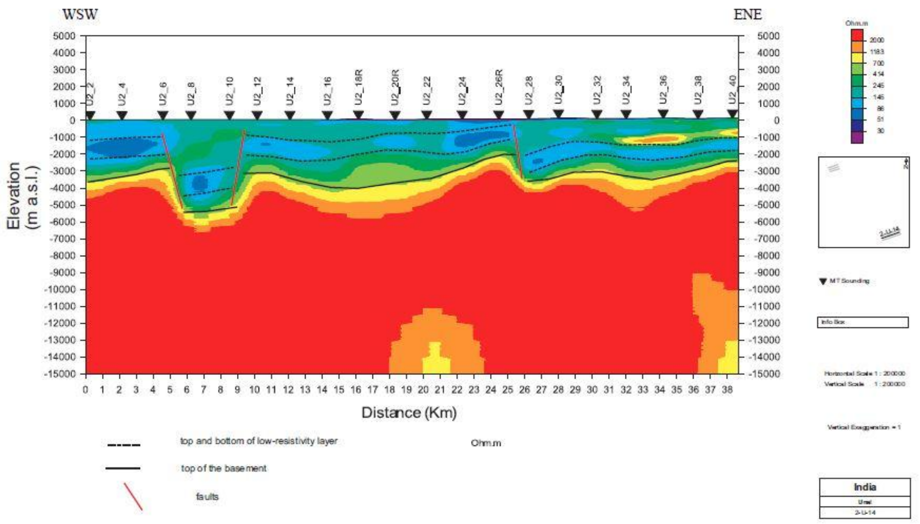

Fig 8: Resistivity cross-section based on 2D NLCG inversion along profile 2

The resistivity cross-section based on 2D NLCG inversion along profile 2 is shown in the Fig 8. A graben can be seen between stations U2_6 and U2_12. The throw of the fault is significantly high. There is a normal fault seen between stations U2_26R and U2_28, which is near to the hot spring. This fault may be acting as a conduit for the geothermal fluids which are migrated to the surface.

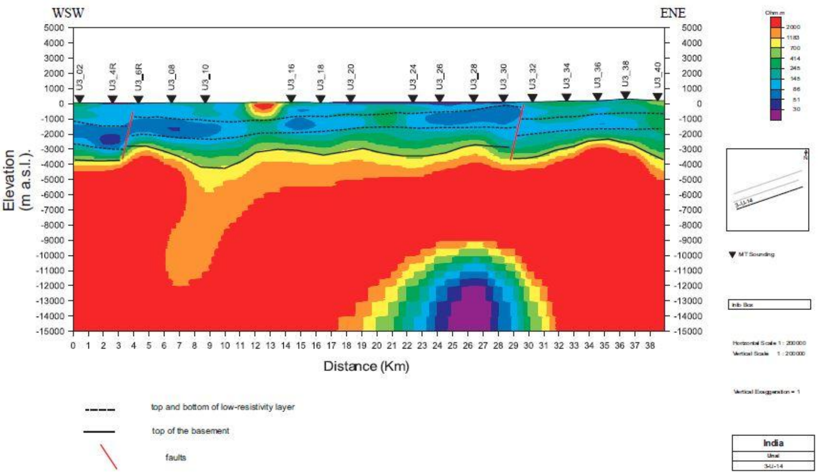

Fig 9: Resistivity cross-section based on 2D NLCG inversion along profile 3

The resistivity cross-section based on 2D NLCG inversion along profile 3 is shown in the Fig. 9. The high resistivity anomaly - a relatively low resistivity block is visible from 9000 m to 15000 m depth between stations U3_20 and U3_32. This anomaly may be indicating the mantle upliftment. A normal fault is seen between stations U3_30 and U3_32 of shallow depths.

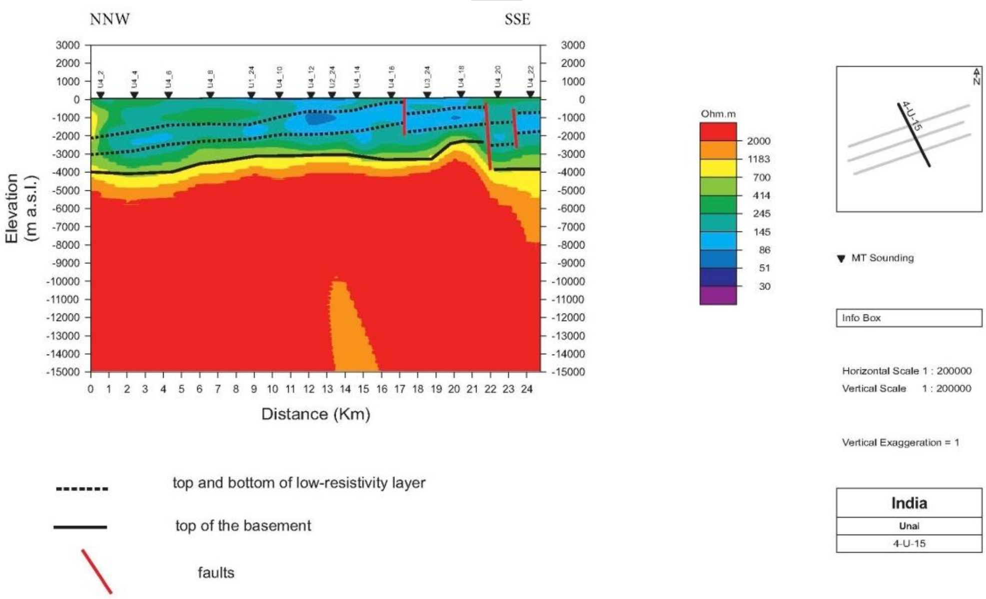

Fig 10: Resistivity cross-section based on 2D NLCG inversion along profile 4

The resistivity cross-section based on 2D NLCG inversion along profile 4 is shown in the Fig. 10. This profile is perpendicular to the previous ones. There is system of faults in the ENE part of the cross-section, which may be caused by complicated morphology of high resistivity basement. Hot fluids can migrate through this system of faults.

C. 2D Geoelectrical Shallow Model

2D geoelectric shallow models (up to 1500 m depth) show the resistivity distribution (Fig. 11, 12 and 13). Between stations U4 to U16 in profile 1, high resistivity zone is clearly visible and it shows high resistivity rocks are exposed on the surface.

The shallow model suggests that geothermal reservoirs attributing low resistivity are encased within high resistivity backgrounds. Possible water zones are demarcated by black rectangular box. The cross section along profile 2 looks interesting as the shallow aquifer body is identified below the hot spring, where a temple exists. It is believed, that if a well is drilled up to 1 km, the same may encounter this shallow reservoir. No well has been drilled so far, to test the hypothesis. The same reservoir body is also seen in profile 3. These reservoirs have been confirmed on the cross section 4 (Fig. 14). The top clay layer identified based on resistivity value can act as a cap rock to the geothermal reservoir. The tomographic slice at a depth of 750 m delineates the catchment area (shaded area shown in Fig 15).

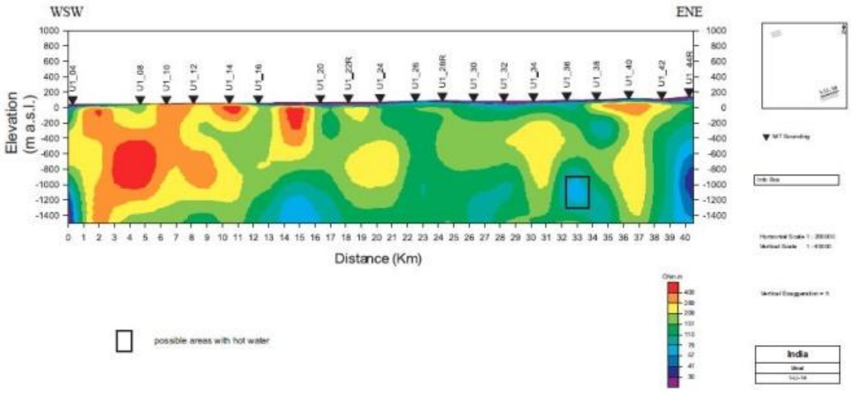

Fig 11: Resistivity cross-section based on 2D NLCG inversion along profile 1.

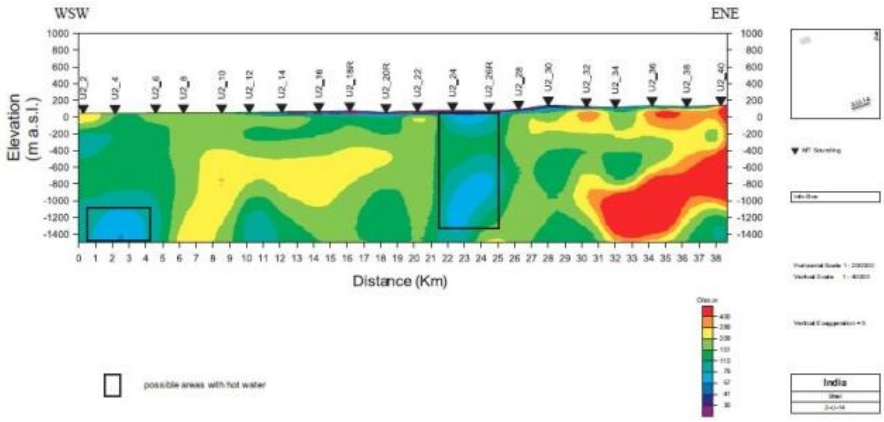

Fig 12: Resistivity cross-section based on 2D NLCG inversion along profile 2

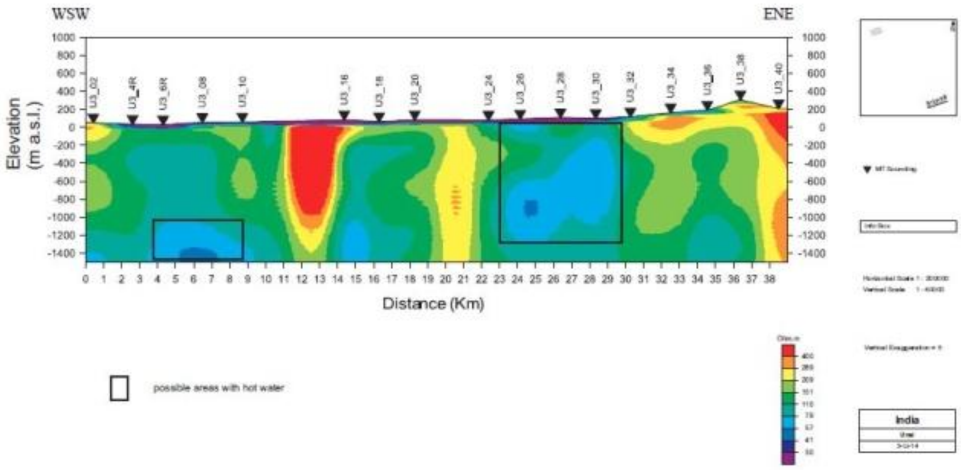

Fig 13: Resistivity cross-section based on 2D NLCG inversion along profile 3 shallow model

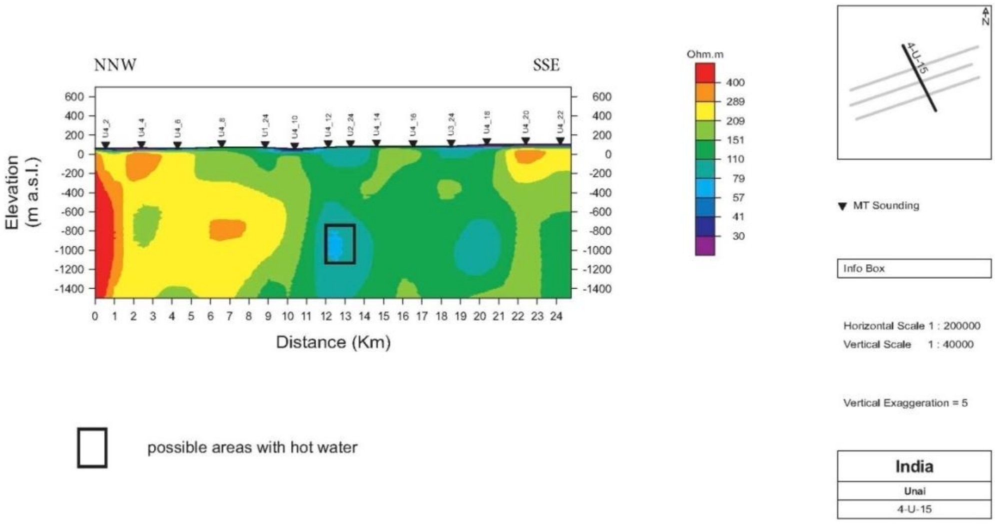

Fig 14: Resistivity cross-section based on 2D NLCG inversion along profile 4 shallow model

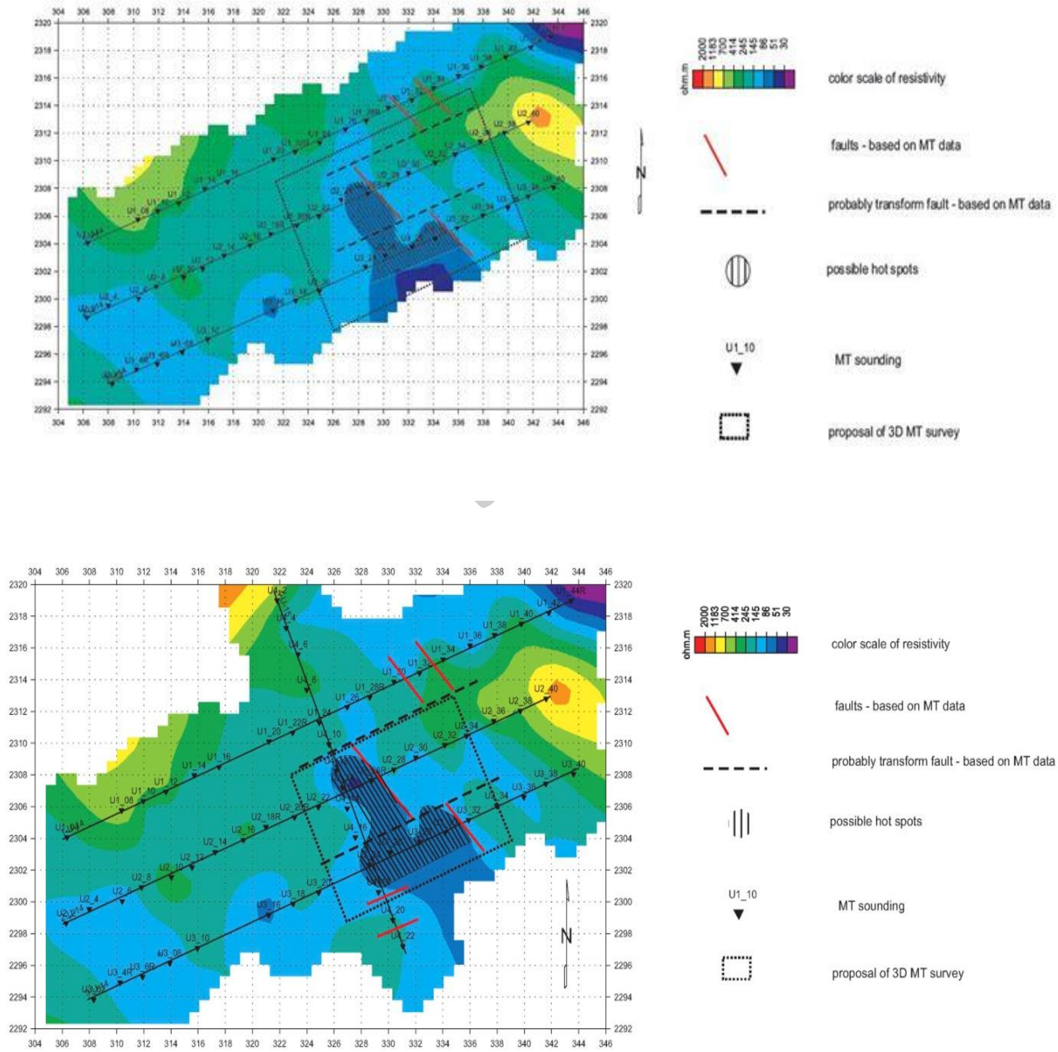

Fig 15: Resistivity distribution at the depth of 750 m bsl at Unai.

VI. FLUID FLOW MODEL

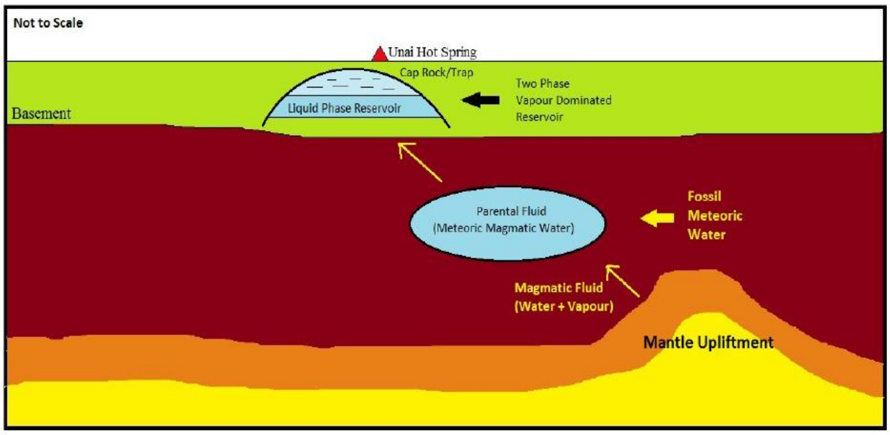

Fig 16: Fluid flow model of Unai

The geochemical, gravity and 2D MT data analysis helped the researchers to understand that geothermal anomalies exist in both shallow and deeper levels; however the extent of the same need to be understood. The reservoir extent can be brought out qualitatively based on passive 3D Magnetotelluric data gathering. As it is an indirect method for reservoir studies care should be taken for proper processing of the data set and use of non unique methods for interpretation. The following paragraph illustrates the fluid flow model postulated for the present study.

One of the important elements of the geothermal reservoir is the cap rock which prevents cold ground water from invading into the high temperature reservoir. In the depth shallower than 200 m clay altered minerals may be present and are formed under the circumstances below the temperature ranging approximately 70 to 100^{o}C. Therefore, it is considered that the formation at the depths shallower than 500 m acts as a cap rock of the geothermal system due to clay alterations that are generally impermeable.

Fig 16 depicts that the parental fluid ascends through the high permeable zones developed along the faults. The high resistivity rock exists at the deep sub-surface and geothermal source exists at deep and shallow regions. We postulate that both are connected with fault system. The main direction of movement at the central section of the acquired profiles appears to be vertical with very limited lateral movement. The faults identified are normal in nature. The ascending hot fluid yields convective circulation systems beneath the cap rock. The fluid reaching shallower part may be of two phase or vapour dominated reservoir. Important outflow can be located on the MT at sites U-24 to U-30 of profile 2.

VII. CONCLUSION

Unai geothermal site is the southernmost tip of the Mainland Gujarat. Oil and Gas exploration in this area has not been done because of volcanic exposures on the surface. Thick basalts prohibit drilling of wells because of perceived uneconomical exploitation of hydrocarbon in this area. High heat flow and hot water springs motivated the researchers to look into this area for geothermal subsurface reservoir bodies. With this objective, the present study group explored this area using integrated geoscientific studies such as geochemical, gravity, surface exposure studies and magnetotelluric studies. The investigation brought out important dimensions towards geothermal exploration in Gujarat. Areas have been identified which are devoid of basalts or where inter-trapeans play an important role in holding geothermal water bodies.

The subsurface picture has been depicted as two different layers, one which has a resistivity of 400 ohm-m, and other with a very high resistivity which is identified as basalt. Within the shallow layer which is up to 3 km, lower resistivity geo-bodies are attributed to be aquifers and the researchers have proposed to drill a well to validate the hypothesis derived out of the model. The deep basalts also have conductive bodies within it which are attributed to be hot plumes. Both the shallow and the hot reservoirs are connected through faults and a fluid flow model has been developed to explain how the parental juvenile water has ascended upwards to the faults to give surface manifestation to the hot spring, where a temple is erected. This paper is a step towards the findings till date and requires further work for testing of the hypothesis given here.

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