Very Low-Frequency Electromagnetic modeling for deciphering shallow conductive features over geothermal prefecture in western Maharashtra, India

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Abstract - *A very low frequency electromagnetic (VLF-EM) survey was conducted at Tural and Rajawadi hot springs in Ratnagiri district, western Maharashtra, to map the lateral extent of subsurface geo-features. A total of four traverses have been taken at both these hot springs from West to East direction. Each traverse was 80-100 m long and separated by 10 m lateral distance. The inter-measurement spacing for each traverse was maintained at 2 m. Two transmitters with frequencies of 19.6 kHz (Anthorn, UK) and 22.3 kHz (NW Cape, Australia) were used. The data were processed to obtain tilt angle and ellipticity along with Fraser filtered data of real component, and current density value to identify conductive zones. The interpretation reveals three broad conductivity features at Rajawadi (Traverse-1, Traverse-2) and Tural (Traverse -3) at shallow depth levels of 12, 16, and 12.5 m respectively. The conductivity features are observed in the pseudo current density depth sections of Traverse-2 and Traverse-3. These high conductivity features can be inferred as fracture zones extending beyond 16 m depth, which feeds the hot spring.*

***Key Words*: Very Low Frequency (VLF), Geothermal spring, Tilt angle, Ellipticity, Maharashtra**

1. INTRODUCTION

The energy crisis has indisputably demonstrated that there is an urgent need to rapidly develop all possibly conceivable, renewable, alternative natural resources to meet the ever-increasing global and domestic demands of energy for multipurpose applications. One such renewable source of energy is geothermal energy. Hot springs have gained prominence as a viable alternative to hydrocarbons (Islami and Irianti, 2019). The heat source is usually a shallow magmatic body, which might arise from mantle plume activity, active tectonics, or the existence of radiogenic sources (Baranwal and Sharma, 2006). Exploration of geothermal systems is necessary in order to use geothermal resources for the benefit of civilization. The steam, water, or heat from such geothermal reservoirs can be used to generate electricity and for other commercial applications. Furthermore, toxic materials may combine with groundwater in the area of such reservoirs, thereby contaminating groundwater due to the hot water's higher solubility than regular groundwater, resulting in a variety of ailments in human beings as a result of contaminated groundwater (Kundu et al., 2002).

Geothermal springs have been explored using several geophysical methods by numerous researchers (Henkel and Guzman, 1977; Bernard and Valla, 1991; Benson et al., 1997; Cagler and Demirorer, 1999; El Qady, 2000; Routh et al., 2006) all over the globe. Such studies have been conducted in India by many researchers to quantify the thermal characteristics of different geological provinces in India and to evaluate their suitability for geothermal exploration (Panda, 1985; Arora, 1986; Ravi Shankar et al., 1991; Gupta, 1993; Majumdar et al., 2000, Baranwal and Sharma, 2006; Harinarayana et al., 2006; Sircar et al., 2015; Maitra et al., 2020; Subba Rao et al., 2022).

Geophysical exploration methods in general, and geoelectrical and electromagnetic methods in particular, play a vital role in the investigation of subsurface because it is non-destructive, has no environmental impact, is fast, and is relatively cheap (Telford et al., 1977). They are effective in determining the geothermal springs' characteristics by identifying high conductivity disparities between hot springs and surrounding host rocks. In India, a total of seven major geothermal provinces have been identified, viz. Himalayan geothermal province, Sohana geothermal province, Cambay geothermal province, West Coast geothermal province, Son-Narmada-Tapti (SONATA) geothermal province, Godavari geothermal province, and Mahanadi geothermal province (Chandrasekharam and Chandrasekhar, 2010). Over sixty geothermal springs are reported on the west coast of Maharashtra spread over a 350 km linear stretch in NNW-SSE orientation with temperatures varying between 47 to 72ºC (Reddy et al., 2013). These are located in the basaltic terrain belonging to the Deccan traps of Cretaceous to Paleocene age with low to intermediate enthalpy at shallow depths (Padhi and Pitale, 1995; Deshpande, 1998).

Geological, geophysical, and geochemical studies have been carried out over a few hot springs in the West Coast province of Maharashtra to understand the structural characteristics and source geometry and to assess water quality, geothermal characters, and utility for direct uses

(Pitale et al., 1987; Sarolkar, 2005; Gupta et al., 2010; Kumar et al., 2011; Reddy et al., 2013; Gurav et al., 2016; Chatterjee et al., 2016; Monterio et al., 2019; Low et al., 2020). Geoelectrical studies in and around the Aravali, Tural, Rajawadi, and Unhavare geothermal springs of the West Coast province of Maharashtra were directed towards delineation of the geothermal reservoirs and associated geological features like faults and fractures responsible for vertical movement of geothermal water (Kumar, et al., 2011). These authors have delineated potential geothermal reservoirs at some locations and advocated their association with a fault extending to deeper depths. Vertical electrical sounding studies (Gupta et al., 2010) delineated a few groundwater potential zones with normal temperature for exploration purposes to meet the local water supply-demand and also observed very low resistivity values of about 10 Ω-m linked to geothermal reservoirs at Aravali and Tural. Geochemical studies (Sarolkar, 2005; Reddy et al, 2013) revealed that the thermal water from most of the West Coast hot springs is alkali chloride type with high sulphate content. Further, the stable isotope analysis implies that the geothermal water is predominantly of meteoric origin (Sarolkar, 2005). Major and trace element analyses of thermal springs from 15 locations along with groundwater and surface water samples (Gurav et al., 2016) revealed the variations in the trace element concentration in the thermal waters indicating involvement of different rock types although all the thermal emergences are within the Deccan volcanic flows.

With the foregoing understanding, an attempt is made here to map the shallow sub-surface features at Tural and Rajawadi hot springs using the very low frequency (VLF-EM) method, as it is capable of delineating fractures in a lateral direction effectively.

2. GEOLOGY OF THE STUDY AREA

As mentioned earlier, the temperature of hot springs on the West Coast varies from 42°C at Rajapur in Sindhudurg district, to 71°C at Unhavre (Khed) in Ratnagiri district. Other major hot springs in this region are Sativli, Ganeshpuri, Aravali, Tural, Rajawadi, and Unhavre. It is also reported that some of these springs emanate gaseous activity. Tural and Rajawadi hot springs are considered for the present study (Fig. 1a,b). These hot springs are bounded by 17.25° to 17.26° N latitude and 73.55° to 73.56° E longitude, located about 10-18 km north of Sangameshwar. The hot springs are aligned along an N 20° W - S 20° E fracture zone/mega lineament (Fig. 1a). This region is also seismically active with small to medium earthquakes with magnitude ranging from 3.5 to 6.0 occurring frequently (Chadha, 1992).

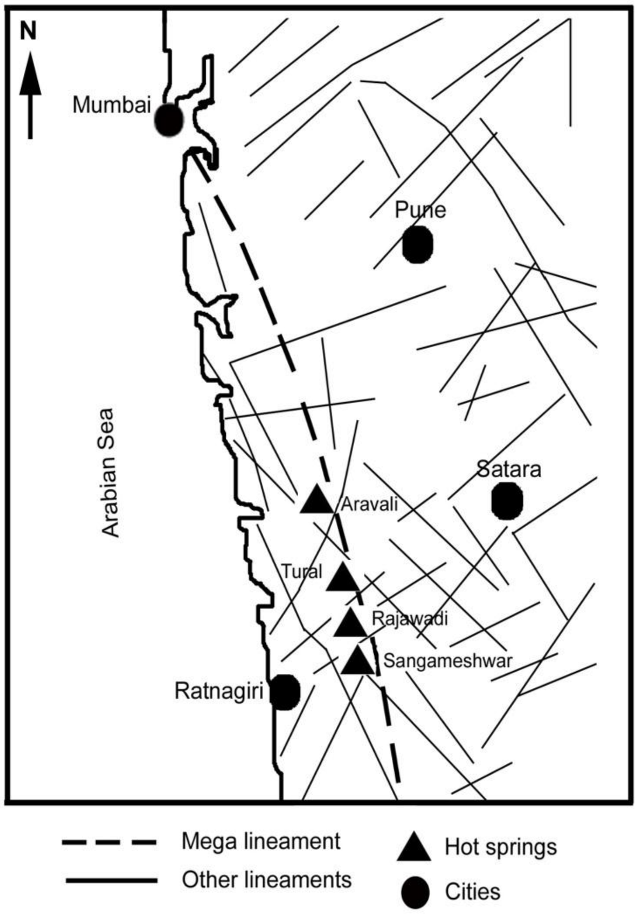

Fig -1a: Generalized map showing the lineaments and hot springs.

The hot springs are geologically settled in Deccan Volcanic Province (DVP) and expose about 1 km thick basaltic sequence of lava flows overlying Precambrian sedimentary and meta-sedimentary (Kaladgi and Dharwar) rocks and Archaean igneous complex. The Dharwar and Kaladgi formations lying below the basaltic formations are of both ‘Aa’ and Pahoehoe type flows (Deshpande, 1998). The southern part of Ratnagiri and Sindhudurg districts are characterized by the ‘Aa’ type flows whereas the Pahoehoe type flow is confined to the northern part of the Thane district. While some flows are non-porphyritic, the primary flows are porphyritic and contain feldspar phenocrysts (Deshpande, 1998). Several NNE-SSW, NNW-SSE, and EW-oriented lineaments traverse this region. It is reported by CGWB (2014) that the discharge rate is Tural 250 lpm, whereas at Rajawadi the discharge rate is about 50 lpm.

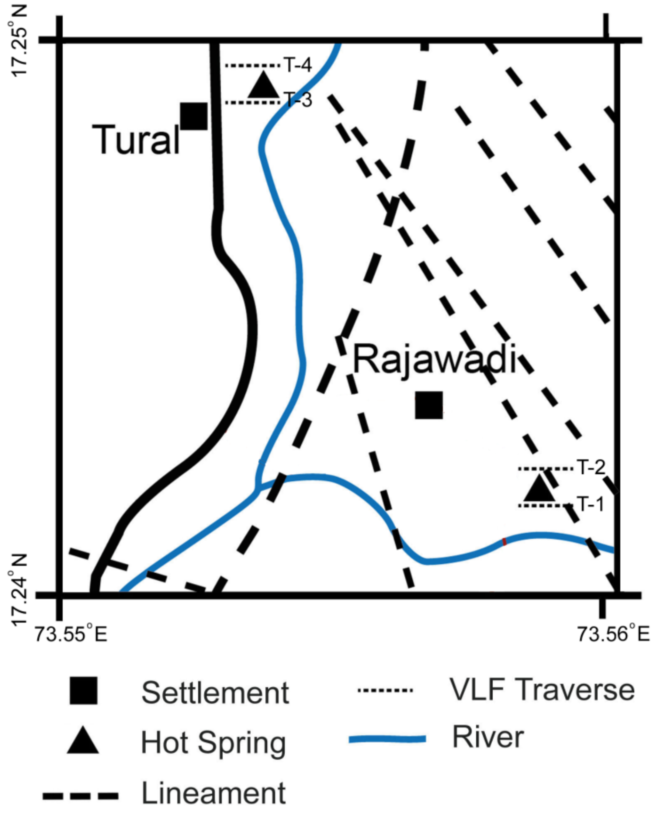

Fig -1a: Study area around hot springs showing the VLF traverses

3. METHODOLOGY

The very-low-frequency electromagnetic method (VLF-EM) is one of the widely used geophysical methods for mapping shallow subsurface conductivity variations. It utilizes radio signals as a source that is transmitted from powerful radio transmitters located in different parts of the world. The horizontal primary magnetic field induces secondary magnetic fields which are generated by the eddy currents in the presence of a conductive body (Parasnis, 1973). The resultant magnetic field which is produced with the interaction of this primary and secondary magnetic field makes an ellipse of polarization around a conductive body. The resultant measured parameters from the VLF survey are the tilt angle and ellipticity computed using the expression given by Smith and Ward (1974),

$$\text{Tilt angle: } \tan(2\theta) = \frac{2\,(^{H_z}/_{H_x})\cos\Delta\emptyset}{1-(^{H_z}/_{H_x})^2} \quad (1)$$

$$\text{Ellipticity: } \varepsilon = \frac{H_z\,H_x\,\sin\Delta\emptyset}{[\,H_2 e^{i\Delta\emptyset}\sin\theta + H_x\cos\theta]} \quad (2)$$

where H_z and H_x are the amplitudes of the vertical and horizontal components of the magnetic fields: $\Delta\emptyset = \emptyset_x - \emptyset_z$ in which $\emptyset_z$ is the phase of H_z and $\emptyset_x$ is the phase of H_x.

The tilt angle is a ratio of the real component of the vertical secondary magnetic field to the horizontal primary magnetic field. The ellipticity is the ratio of the quadrature component of the vertical secondary magnetic field to the horizontal primary field (Paterson and Ronka, 1971). The secondary field has tilt (in-phase) as a real component and ellipticity (quadrature) as an imaginary component. The percentages of the real and imaginary components can be deduced using the following equations (Karous and Hjelt, 1983; Ogilvy and Lee, 1991);

Real or (in-phase) component= $\tan\theta$ *100% (3)

Imaginary or (Quadrature) component= ε * 100% (4)

4. DATA FILTERING

The VLF data can be efficiently interpreted by applying a filtering technique that will remove biased noise and enhance the signal-to-noise ratio. The two numerical filters proposed by Fraser (1969), and Karous and Hjelt (1983) are applied to the present VLF field data.

4.1 Fraser filter

The temporal variations in the magnetic field (e.g., due to changes in the wave guided by the surface and bottom of the ionosphere), affect the VLF data, which can be removed by the Fraser filtering. It is performed by converting the cross-over points of real and imaginary anomalies into peak values. The Fraser filter transforms the anomaly such that those parts with the maximum slope appear with the maximum amplitude (Nabighian, 1982). The expression for the filter operation is made by differencing the successive values of in-phase data along the traverse and is given by;

$$F_{2,3} = [(M_3 + M_4) - (M_1 + M_2)] \quad (5)$$

Where M_1, M_2, M_3, and M_4 are four consecutive readings of the measured raw data and $F_{2,3}$ is the resultant filter value plotted midway between the M_2 and M_3 (Fraser, 1969).

4.2 Karous and Hjelt (K-H) filter

Karous and Hjelt (1983) is an extension of the Fraser filter and it is applied to VLF in-phase data. The K-H filter converts the in-phase values into pseudo depth sections which could delineate the subsurface conductive features. The following equation is given for calculating the K-H filter,

$$\frac{\Delta Z}{2\pi} I_a(\Delta x/2) = (-0.102\,H_{-3} + 0.059\,H_{-2} - 0.561\,H_{-1} + 0.561\,H_1 - 0.059\,H_2 + 0.102\,H_3) \quad (6)$$

Where ΔZ is the assumed thickness of the current sheet, I_a is the anomalous current density, Δx is the distance between the data points and also the depth to the current sheet, the coefficients H_{-3} to H_{+3} are the values of real and imaginary components of the measured VLF-EM anomaly.

5. VLF-MEASUREMENT

The IRIS (France) make T-VLF instrument is specially designed for high productivity surveys in groundwater and mining exploration. It is light-weight, its ease of use, its automatic measuring process, its high sensitivity, its data presentation, and its solid-state memory make T-VLF a field survey instrument ideal for the search of conductive or resistive structures located at a few tens of meters depth. No orientation of the operator with respect to the direction of the transmitter is required since three magnetic sensors measure the components of the VLF field.

The VLF survey has been performed along four traverses at two geothermal springs (Tural and Rajawadi) with frequencies of 19.6 kHz and 23 kHz. The VLF surveying was accomplished in VLF-EM mode or tilt mode and the measured parameters are the tilt angle and ellipticity. The VLF transmitter should always be in the strike direction and the measuring profile should be perpendicular to strike direction (Sharma and Baranwal, 2005). If the measuring profile is parallel to the strike direction, then there will be no VLF anomaly. The traverse T1 is located south of the Rajawadi hot spring with W-E orientation, while, the traverse T2 lies in the northern part of Rajawadi hot spring with W-E alignment (Fig. 1b). The two traverses are separated by 10 m with 2 m station spacing. Similarly, in the vicinity of the Tural hot spring, traverse T3 is performed to the south and T4 to the north of the hot spring with 10 m traverse separation and 2 m interstation spacing in W-E direction respectively (Fig. 1b).

6. RESULTS AND DISCUSSIONS

6.1 Rajawadi hot spring (Traverse-1)

The VLF traverse (T-1) at Rajawadi hot spring has a spread length of 80 m and is oriented in the W-E direction (Fig. 1b). The tilt angle values range between -87 to 64 while the ellipticity values range between -64 to 19 siemens. The Frazer filtered values range between -74 to 158 siemens. The original data of tilt angle (red color), and ellipticity (blue color) were plotted along with the Fraser filtered tilt values (grey color) and it is depicted in Figure (2a). The Karous- Hjelt pseudo depth section for this traverse is shown in Figure (2b). From Figure (2a) it can be seen that positive values of tilt, ellipticity, and Fraser are observed at the horizontal distance of 15 m. It is suggested by Jeng et al. (2004) that there exists a direct relation between ellipticity and tilt. In Fig. (2a), the ellipticity shows a positive polarity with tilt angle, which indicates poor conductive subsurface. This feature can be seen in the corresponding depth section (Fig. 2b) up to about 4 m. A strong peak for Fraser value (both positive and negative) is observed at a horizontal distance of 30-44 m, representative of the conductive feature. This feature is extending from shallow up to a depth of 12 m (Fig. 2b). Similarly, a prominent high peak value of Fraser is observed at a horizontal distance of 60 to 70 m indicating a conductive zone. These two conductive features are seemingly joined as one unit at depth of about 8 m extending up to the depth of study. This broad conductive zone is likely to extend deeper and is the signature of the Rajawadi thermal spring. However, a small patch of high resistivity is observed in between this broad conductive zone at a horizontal distance of 44 to 56 m (Fig. 2b), which may be the signature of overburdened sediments.

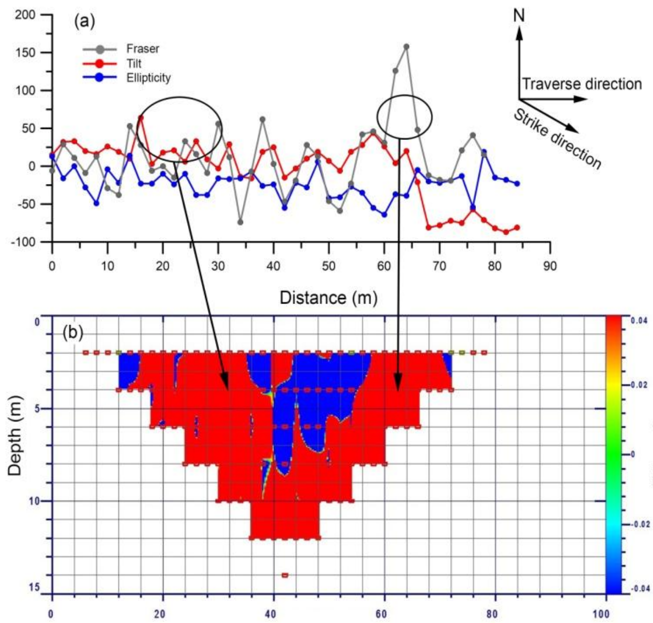

Fig -2: (a) Plot of tilt, ellipticity, and Fraser filter; (b) Karous- Hjelt pseudo depth section over Traverse 1.

Electrical resistivity tomography (ERT) studies (Kumar et al., 2011) were carried out over two parallel profiles at the Rajawadi thermal spring site. The conductive feature observed here broadly coincides with a low resistivity zone (<15 Ωm) up to a lateral distance of about 75 m over one ERT profile. These authors are of the view that this zone is associated with the lateral movement of hot water from nearby thermal springs.

6.2 Rajawadi hot spring (Traverse-2)

The second traverse at Rajawadi hot spring (T-2) is 100 m in length and is at a distance of 10 m from T-1. The tilt angle values range between -80 to 73 siemens and ellipticity values range between -59 to 43 siemens. The Frazer filtered values vary between -124 to 112 siemens. The plot of tilt, ellipticity, and Fraser filter is shown in Figure 3a. The corresponding depth section is given in figure 3b. A broad conductive zone is revealed between lateral distances 30 to 52 m, which is marked by both positive and negative tilt and Frazer values (Fig. 3a). This conductive zone is observed up to depths of about 16 m from the surface (Fig. 3b) in the current density pseudo section. The traverse shows three prominent positive filtered tilt values at 28 m, 40 m, and 52 m distance (Fig. 3a), which signifies the presence of fracture marked as F-F in Fig. 3b. Beyond the lateral distance of 52 m and up to 80 m, the tilt angle anomalies follow the same manner as ellipticity anomalies, reflecting poor conductor, which is presumably due to overburden sediments. Kumar et al. (2011) delineated another low resistivity zone (<15 Ωm) up to a distance of about 30 m on the second ERT profile, indicating a swampy region formed due to seepage of hot water from the nearby hot spring.

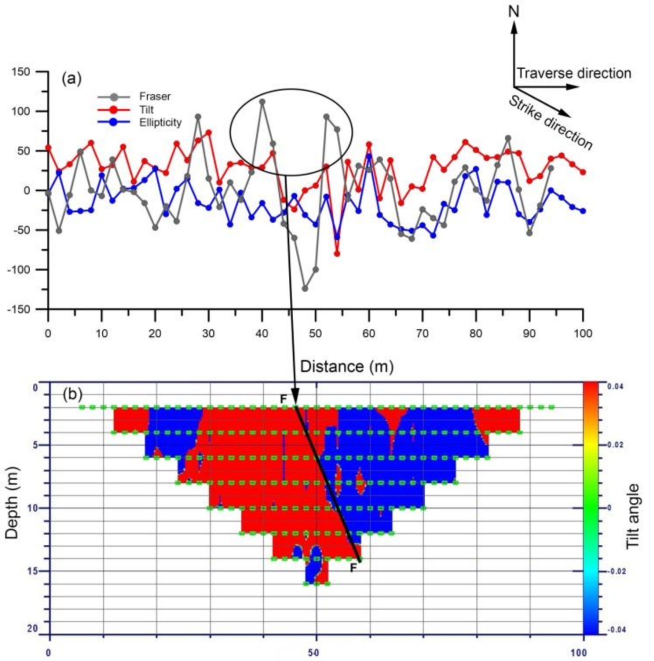

Fig -3: (a) Plot of tilt, ellipticity, and Fraser filter; (b) Karous- Hjelt pseudo depth section over Traverse 2.

6.3 Tural hot spring (Traverse-3)

Traverse 3 is oriented from west to east and is passing very close to the Tural hot spring on its south. The tilt angle values range between -87 to 86 siemens, ellipticity values range between -43 to 54 siemens and Frazer filtered values range between -277 to 364 siemens. The plot of tilt, ellipticity, and Fraser filter is shown in Figure 4a and the corresponding depth section is given in figure 4b. A significant positive peak is observed in the Fraser filtered tilt values at a horizontal distance of 10 m, however, no conductive zone is observed at the corresponding depth section in Fig. 5b. Cyclic Fraser filtered positive and negative tilt anomalies are observed from horizontal distances 32 m onwards up to 65 m, coinciding with the Tural hot spring at about 55 m (Fig. 5a).

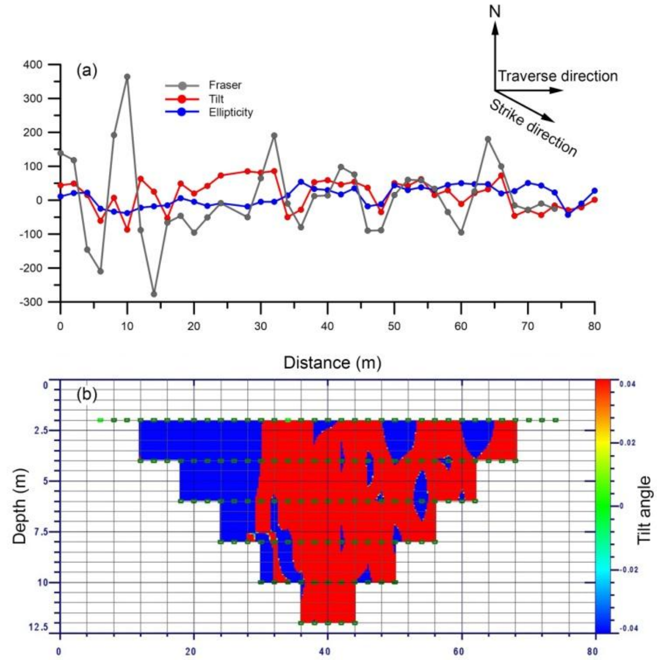

Fig -4: (a) Plot of tilt, ellipticity, and Fraser filter; (b) Karous- Hjelt pseudo depth section over Traverse 3.

These anomalies reflect the conductive nature of the subsurface due to the signature of the thermal spring. This is evident in the pseudo depth section also and extends up to depths of 12.5 m in the present case. From the pseudo depth section (Fig. 4b), a sharp resistivity contrast is observed at 25 m which may be the indication of the fracture zone. ERT studies in and around the Tural hot spring (Kumar et al., 2010) observed a sharp resistivity contrast over one ERT profile and attributed it to a fault. These authors also suggested that the observed low resistivity of about 13 Ωm in the region is due to the hot spring reservoir.

6.4 Tural hot spring (Traverse-4)

Traverse 4 is located 10 m away from traverse 3 in Tural hot spring zone. Traverse 4 is also oriented from west to east direction. The tilt angle values range between -70 to 19 siemens, while ellipticity values range between -73 to 62 siemens and Frazer filtered tilt values range between -130 to 221 siemens. The plot of tilt, ellipticity, and Fraser filter is shown in Figure 5a and the corresponding depth section is given in figure 5b. From figure (5a), a high positive Fraser filtered peak is observed at a horizontal distance of about 22 m which is the signature of a conductive zone and is reflected in the pseudo density depth section up to shallow depths of about 6.25 m. Yet another positive peak in Fraser filtered value is revealed at 62 m lateral distance. This conductive anomaly is reflected in the depth section up to about 6 m.

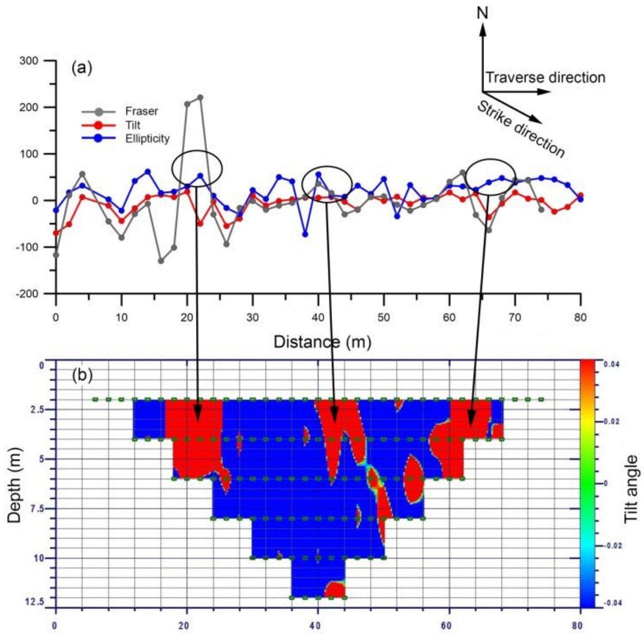

Fig -5: (a) Plot of tilt, ellipticity, and Fraser filter; (b) Karous- Hjelt pseudo depth section over Traverse 4.

From resistivity sounding studies over the Tural region (Gupta et al., 2010), a low resistivity feature is observed at shallow depths coinciding with the Tural hot spring. The conductive zone inferred from VLF broadly matches the resistivity findings.

3. CONCLUSIONS

The very low frequency (VLF) electromagnetic method was employed to delineate the lateral conductivity distribution of fracture zones in and around the geothermal springs. Four VLF traverses have been conducted at two geothermal springs (Tural and Rajawadi). The traverse (T-1) at Rajawadi hot spring revealed broad conductive features and extended from the surface to the depth of 12m. The broad conductive feature is identified as fracture zone which is marked as F-F in the second traverse (T-2) at Rajawadi hot spring. The boundaries of these fracture zones are having high resistivity contrasts. The traverse 3 at Tural hot spring revealed one broader conductive feature beyond the lateral distance of 32 m to 65 m and also two fractures are marked F4 and F5. This conductive feature is the signature of thermal spring and it extended up to the depths of 12.5 m. Traverse 4 at Tural suggests conductive zones at shallow levels at a lateral distance of 22 m, 60 m, and beyond.

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