Integrated geophysical study to decipher potential groundwater and zeolite-bearing zones in Deccan Traps

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Geo-scientific integrated study using surface 1-D Vertical Electrical Sounding (VES), 2-D Electrical Resistivity Imaging (ERI), geological drilling and litholog preparation and finally sub-surface resistivity logging was carried out in the Deccan Basalt, hard rock region both for zeolites and groundwater in and around Aurangabad region, Maharashtra, India. In Deccan Trap the presence of zeolites along with weathered/fractured basalt is the direct indication of availability of water.

The present study delineates different zones and the ERI results show the signature of high resistivity anomaly, indicating the cavity effect or cavity created due to zeolite. 2-D resistivity sections indicate zeolite-bearing zone with specific range of resistivity between 40–50 Ohm-m and 90–105 Ohm-m. Based on the resistivity anomaly and combined results, three borewells were drilled up to a maximum depth of 91.5 m. Resistivity logging was performed at three borewells and on quantitative interpretation the characteristic resistivity obtained for fresh basalt in association with zeolite has a resistivity range between 90 and 105 Ohm-m whereas the weathered zeolitic basaltic layer lies between 40 and 50 Ohm-m as compared to 500 and 600 Ohm-m which corresponds to fresh basalt without presence of the zeolite. It is interesting to note that the change in resistivity values and kinks in resistivity logs reflected different formations. The resistivity logging aids as a supplementary tool to understand better the geological set up of the Deccan Basalt.

Keywords: Groundwater, Deccan Traps, 1-D sounding, 2-D imaging, resistivity logging, zeolites.

DECCAN Traps have been defined as the 'greatest volcanic formation'. The Deccan Traps are largely made up of lava flows of basic composition. The age of these lava flows ranges from upper Cretaceous to lower Eocene. The Deccan Traps cover an area of over 500,000 sq. km in the central and western parts of India. Deccan Traps occupy major parts of Gujarat, Madhya Pradesh, Maharashtra and some parts of Andhra Pradesh. The maximum thickness of Deccan Traps is about 2000 m near Bombay in Western Ghats[1–3].

The Deccan Trap flows are generally horizontal in attitude, these lava flows are believed to have erupted subaerially through fissures in the earth crust and such fissures are now seen as dykes in Gujarat. Majority of the Deccan Trap flows are basaltic (specific gravity, 2.65) with a uniform chemical composition of acidic volcanic rocks like rhyolite, gronophyre, and more basic rocks like gabbro and limburgite. The essential minerals present in the Deccan Traps basalt are labrodiorie, augite and iron oxide, with secondary minerals like calcite, quartz, glauconite, etc. which generally fill the cavities in original rock. The traps are essentially a basic rock of basaltic composition and dark coloured or melanocratic. Basalts are mainly abundant in minerals and chemical composition is olivine and pyroxene.

To understand the Deccan Traps in Maharashtra region, an integrated geophysical study was carried out with an idea to delineate the potential aquifer zones and also to look for zeolites zones or an indication that they are trapped within the basaltic rocks. The integrated geophysical survey includes the 1-D vertical electrical sounding (VES), 2-D electrical resistivity imaging (ERI) and resistivity logging using newly fabricated logging tool. The individual trappean flows in the area can be easily identified geologically at shallow depths with the help of 0.6–1.5 m (even more) thick marker horizons of red boles. But to understand the deeper basaltic layers and its geological set-up, advanced geophysical resistivity imaging survey was carried out at eight sites using Wenner–Schlumberger and dipole–dipole arrays. In addition, 1-D Schlumberger sounding was also carried out at the 2-D imaging line at six sites. Due to large heterogeneity and variability in terms of resistivity of such hard rock, it was planned and carried out in nearby borewells, the resistivity logging at five sites using newly fabricated logging equipment to obtain the characteristic resistivity for different layers and to get more clear realistic picture of the sub-surface lithology. Bose and Ramakrishna[4] had shown that a combination of resistivity sounding and profiling is more effective in tackling problems for the location of wells in the Deccan Trap area.

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Zeolites are a group of silicates containing true water of crystallization. These minerals are porous crystalline solids and they are associated with vesicular/weathered basalt. Zeolites cavities are the contributing sources for groundwater and are formed due to the chemical reaction of volcanic ash and salt water. The zonal distribution of zeolites in the Western Deccan Traps was first recognized by Walker[5,6] and later Sukheswala *et al.*[7] studied zeolites and associated secondary minerals in the Deccan Traps of Western India. These authors had studied the chemical, optical and X-ray aspects in detail. On the other hand, Marathe *et al.*[8] studied the variation in the nature of Deccan Trap volcanicity of Western Maharashtra in time and space, while a systematic approach based on a lithological model observed widely over the Deccan basaltic province is well presented by Kulkarni and Deolankar[9]. But no extensive study on integrated geophysics was done for identification and quantification of the important mineral, zeolites based on the sub-surface electrical resistivity parameter.

Geological settings

Deccan Traps have been divided into three groups: the Lower Traps, the Middle Traps and the Upper Traps (Table 1).

Table 1. Three groups of Deccan traps

Upper Traps	450 m	Bombay region and Saurashtra lava flows with numerous ash-beds; sedimentary inter-trappean beds of Bombay with large number of fossil vertebrata and molluscan shells.
Middle Traps	1,200 m	Malwa and central India lavas and ash beds forming the thickest part of the series. (no fossiliferous intertrappean beds.)
Lower Traps	150 m	Madhya Pradesh, Narmada, Berar, etc. Lavas with few ash-beds. Fossiliferous intertrappeans numerous.

Electrical resistivity imaging technique

Electrical resistivity imaging (ERI) technique is an essential tool in groundwater prospecting and exploration, engineering problems and environmental site investigations. The 2-D resistivity images are created by inverting hundreds to thousands of individual resistivity measurements recorded within a short span of time to produce an approximate or true model of the subsurface resistivity variation. The application of geophysics in shallow investigations, such as in environmental, geotechnical and hydrogeological studies requires the development of fast, reliable, high-resolution field equipments and interpretation techniques. The improvement of resistivity methods over the conventional DC resistivity method by using multi-electrode arrays has led to an important development of electrical imaging for subsurface surveys mapping[10–13]. Such surveys are usually carried out using a large number of electrodes (24 or more) connected to a multi-core cable. A laptop microcomputer together with an electronic switching unit is used to automatically select the four relevant electrodes (i.e. pairs of current and potential electrodes) for each resistivity measurement. Apparent resistivity measurements are recorded sequentially sweeping any quadruple (combination of current and potential electrodes) within the multi-electrode array arrangements. As a result, high-definition pseudo-sections with dense sampling of apparent resistivity variation at shallow depth (0–100 m) are obtained in a short span of time with precision. It allows the detailed interpretation of 2-D resistivity distribution in the ground below the surface[14,15]. At present, field techniques and equipment to carry out 2-D resistivity surveys are fairly well-developed[16,17]. A resistivity meter called SYSCAL Junior Switch, with 48 electrodes connected to the resistivity meter through a multi-core reversible cable has been used in the present study for carrying out the work.

The ability of multi-electrode resistivity profilings/soundings to provide a detailed continuous 2-D map of the subsurface, identifying the different lithologies, delineating contact zones and faults, and measuring the thickness of the weathered regolith, makes this technique a useful tool for groundwater investigations/prospecting both for locating drilling sites and for obtaining an assessment of the general extent of the depth of weathering layer and the location of fractured/fissured zones, which are the principal groundwater targets/reservoirs and as geophysicists we are interested in these features in terms of resistivity anomaly with respect to the background resistivity. The method appears to be particularly well suited to the characterization of crystalline basement rocks and their weathered regolith profiles[18,19]. Though multi-electrode resistivity technique is more expensive than traditional DC resistivity survey, the additional cost may be justified where the demand for groundwater is relatively high, such as for municipal or irrigation development or any important scientific project.

Processing and interpretation of 2D resistivity sections

The field ERI raw data was first processed for eliminating any noisy or bad data points. In some of the profiles, the quality of the data obtained was not good due to tough terrain and poor contact resistance and this was well apparent from the inverted 2-D sections in terms of

RMS error between the observed and calculated apparent resistivity. The processed data was then used for inversion[16,17] using finite difference numerical algorithm to reproduce the subsurface true resistivity variation and thus these true resistivity subsurface models were finally interpreted in terms of geological formations/information and more important from the hydrogeological and mineralogical point of view, which is our main interest[19].

The 2-D resistivity inverted sections obtained from various profiles revealed that the subsurface consists of layered structure as well as prominent anomalies in some of the ERI profiles and also these 2-D sections depict highly heterogeneous medium. At the same time, these layered formations based on resistivity contrast indicated the potential zone(s) for groundwater which are trapped within the fractured host rock, basalt and there is also an indication of geological structural features as apparent from a few 2-D resistivity sections.

1-D resistivity sounding data and interpretation

The well-known Schlumberger sounding was carried out at the resistivity imaging lines at six sites with a maximum half of the current electrodes spacing (i.e. *AB*/2) of 200 m, using the SYSCAL Resistivity meter in standard mode switch[20]. The data for each sounding survey was measured and recorded and also stored within the memory of the resistivity meter. The data for all the six sites was plotted on a log–log scale and latter interpreted using the standard numerical algorithm software[21]. The inversion of the field data was carried out using ridge regression method[22]. In ridge regression method for each iteration calculation, a model correction is calculated using the best damping factor available for that iteration. Once it achieves the best fit in terms of RMS error, then it gives the model layer parameters of the subsurface lithology.

Procedure of newly designed resistivity logging tool

Basic principle and methodology

Geophysical logging method is well known to evaluate subsurface physical parameter of the earth by lowering a logging probe or sonde into the borewell. The variation of the different geophysical parameters with depth is called the geophysical log. These parameters can be used to evaluate and identify the subsurface geology, thicknesses of the lithological formations based on the different parameters namely resistivity, self-potential, magnetic susceptibility, gamma content, temperature, sonic, etc.[15,23–26]. The principle of basic Ohm's law stated here was used for resistivity measurement. An electrical current is sent into the geological formation through a pair of electrodes and potential difference developed due to current injected was measured across another pair of electrodes. Using the ratio of potential difference and current, and multiplying with the geometric factor of the electrode array configuration used gives the true resistivity of the formation, i.e.

$$\rho = K \times \frac{\Delta V}{I},$$

where ρ is true resistivity in Ohm-m, K the geometrical factor of the array in metre, ΔV the potential difference developed in milli volts and I the current injected in milli ampere.

The fabricated logging equipment as a whole consists of four electrodes system, though probe consists of two electrodes – one is used as current electrode through which current is sent to the formation and another electrode is used as potential electrode to receive the potential difference at the surface developed due to the injected current[27]. The special design for the distance between the current potential pair of 1 m is used to penetrate maximum current within the formation and secondly to get the deepest depth of information. The other two electrodes (acting as current and potential pair) were kept at infinity (at least more than 10 times from the measuring electrodes/probe) so that the measurement at the measuring electrodes was not affected by the far off electrodes[15,23]. The logging probe is lowered in the borewell initially up to the static water level (prior to the measurement of the formation resistivity, static water level in the borewell is measured using water level indicator with light and sound system) and then subsequently at an interval of 0.5 m, the measurement is recorded/stored from the bottom depth of the well while taking out the probe until the static water level. Stand off is used to maintain the logging probe straight and also in the centre of the wells. The instrument used for this technique is 'SYSCAL JUNIOR 48 Switch' which measures the current and potential values separately in a standard mode system[20]. The resistivity values so obtained when plotted against corresponding depth after making necessary correction in depth, finally gives the resistivity log. Based on the resistivity log values obtained directly from the subsurface formation, the various formation resistivities were interpreted which corresponds to true subsurface lithology. The location map of the study area, Aurangabad and surrounding is shown in Figure 1. The objective of the present work is to decipher both the groundwater and the zeolite-bearing zones or zeolite cavity in the problematic area of the hard rock in Deccan Traps in and around Aurangabad. The idea is to integrate the surface and subsurface geophysical results in understanding the Deccan Traps and effort to find out the potential groundwater and the zeolite-bearing zones which are associated with the vesicular/weathered basalt in the present geological set-up.

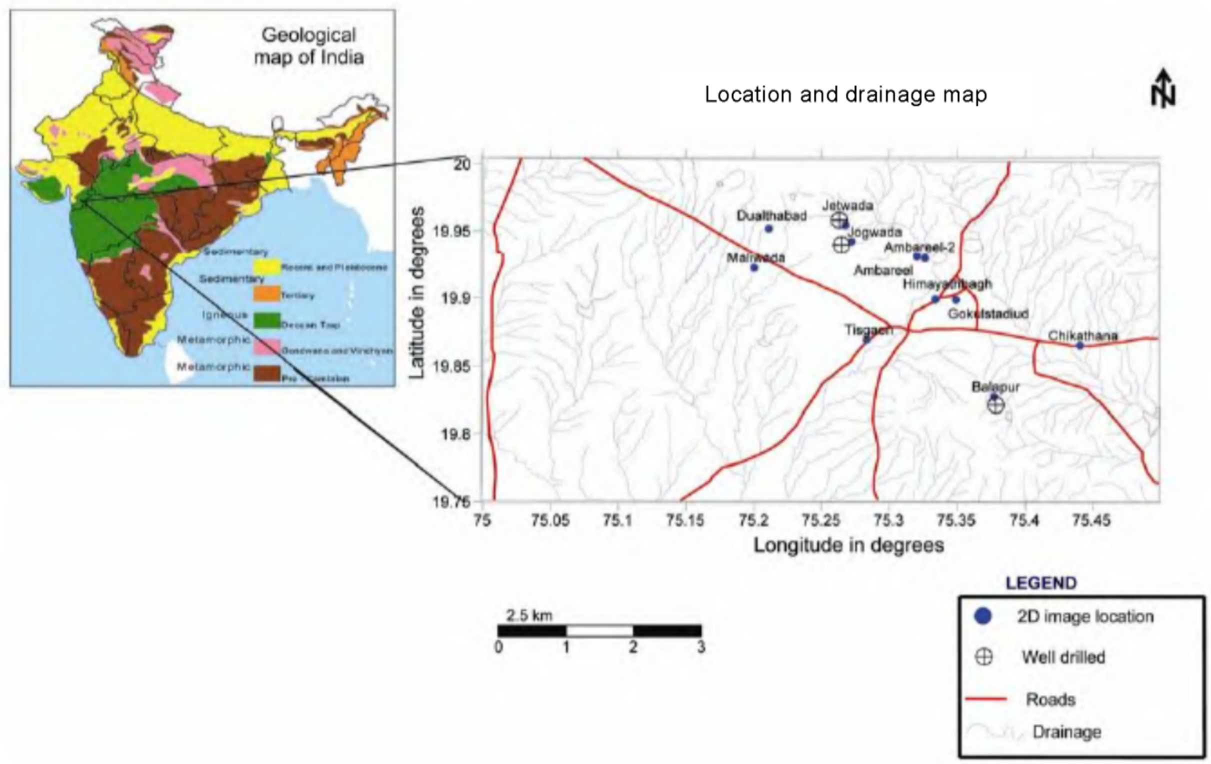

Figure 1. Location map of the study area.

Results and discussions

Combined analysis using 1-D sounding, 2-D resistivity imaging and resistivity logging

The 1-D VES curve with the measured field resistivity data, model curve and the corresponding depth model for the Jogwada site is shown in Figure 2. The interpreted model shows four-layered earth model with the layer parameters shown on the ρ–$AB/2$ (i.e. apparent resistivity versus current electrode spacing) logarithmic plot. The curve is of bowl type, i.e. H type. On interpretation, Figure 2 shows that the resistivity value first increases and then decreases and again starts increasing, showing first layer as top soil cover, the semi-weathered and weathered basalt with a resistivity value of 123 Ohm-m, 66 Ohm-m and 49 Ohm-m respectively. While on the other hand, 2D resistivity section using dipole–dipole (D–D) and Wenner–Schlumberger (W–S) profile was carried out along the same 1D line in N–S direction (Figure 3 *a* and *b*). Figure 3 *a* shows a highly heterogeneous zone throughout the section with few very low resistivity (ranging from 4 to 30 Ohm-m) pockets at irregular intervals. While the W–S profile (Figure 3 *b*) shows similar picture as compared to dipole–dipole section in the shallower part of the section and in deeper point, i.e. beyond 27 m, it shows gradual increase in resistivity with depth, the resistivity ranges between 100 and 200 Ohm-m which could be fresh/fractured basalt. Similar trend in resistivity is also observed in the modelled 1-D VES data.

The resistivity logging at this site (water level being at a depth of 13.25 m bgl) was carried out from down to a depth of 14.5–86 m at an interval of 0.5 m (Figure 4). The log shows resistivity value ranging from 130 to 175 Ohm-m between depths of 14 and 23 m. The average resistivity corresponding to depth between 14 and 18 m is of the order of 150 Ohm-m (Figure 4) shows the fresh basalt which corroborates with geological log (Figure 5). Between 18 and 20 m, there is a variation in resistivity with a magnitude of 136 Ohm-m which indicates weathered basalt and this lithology corroborates well with the geological log as shown in Figure 5. During drilling, it was confirmed by the weathered zeolitic basalt with presence of moisture around the same depth, i.e. 18–20 m (Figure 5). Subsequently, the drop in resistivity with a value of about 100 Ohm-m around 24 m suggests change in formation, and this is proved as fresh zeolitic basalt in geological log (Figure 5), still further down drop in resistivity with value of 40–50 Ohm-m indicates another formation and is confirmed as weathered zeolitic basalts (Figure 5). Beyond 24 m depth, there is no major change in resistivity value up to 62 m. At a depth between 65 and

70 m, there is a gradual increase in resistivity value and it correlates well with the geological log as fresh basalt followed by drop in resistivity which corresponds to fresh zeolitic basalt and still further drop in resistivity corresponds to weathered basalt and further decrease in resistivity corresponds to weathered zeolitic basalt. The main point here is that the presence of zeolite both in association with fresh and weathered basalt lowers the resistivity value and this was clearly delineated from the resistivity log and finally well confirmed by the drilling results to achieve the desired result. The efficacy of the combined method using 1D VES, 2D imaging and logging is brought here to identify the correct and detailed lithology.

The 1-D VES modelled data (Figure 6) shows the interpreted model as a four-layered case for the site Maliwada. The VES curve is increasing throughout, i.e. A type (Figure 6). The geological model as interpreted from the VES data: the first layer is the top soil cover with a resistivity of about 3 Ohm-m followed by highly weathered basalt ~9 Ohm-m, semi-weathered basalt ~40 Ohm-m, and then followed by massive basalt ~200 Ohm-m. On the other hand, closely looking at the D–D and W–S 2D sections at the same site shown in Figure 7, there is a constant increase in resistivity from surface to a depth of 91 m. The data quality is good at this site (Figure 7) and there is no problem of contact resistance. The D–D section shows a slightly layered structure with high resistivity (~100 Ohm-m) at the bottom end of the section. The W–S section shows a layered structure from surface to a depth of about 45 m (Figure 7 *b*) and then the layers dip towards the north and the bedrock is shallower towards the south of the profile with a resistivity of about 200 Ohm-m at a depth of about 91 m as seen in Figure 7 *b*.

Figure 8 shows the modelled VES curve and on interpretation it is a four-layer situation for the present VES data at the Ellora site. The qualitative nature says that it is a combination of H and A types of curves. Quantitatively it was found that the first layer as a top soil cover with a resistivity of 11 Ohm-m followed by a layer with low resistivity of about 14 Ohm-m indicates the highly

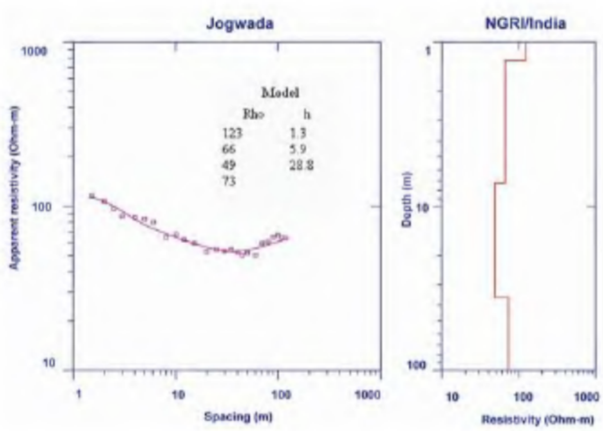

Figure 2. 1-D vertical electrical sounding field data (as square box), model curve (as smooth line) and the depth model for the site Jogwada.

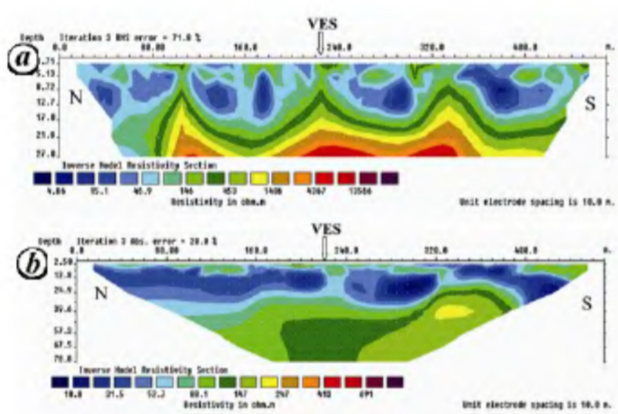

Figure 3. Resistivity imaging at Jogwada. ***a***, Dipole–dipole section; ***b***, Wenner–Schlumberger section.

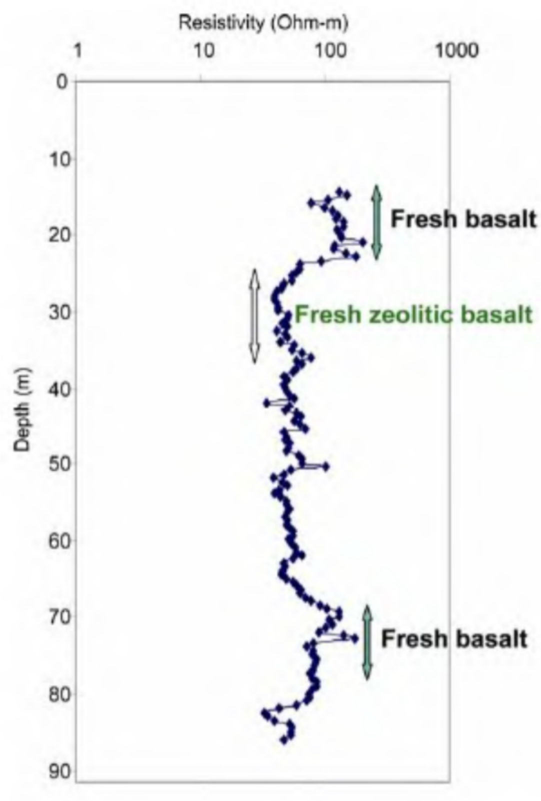

Figure 4. Resistivity logging at Jogwada.

weathered basalt, which is followed by a layer of resistivity of 121 Ohm-m, indicating the weathered/fractured zone of enormous thickness of about 29 m. This is followed by hard massive basalt of resistivity value of 450 Ohm-m. In the same VES line, D–D and W–S profile was carried out in NE–SW direction (Figure 9) to know better both the shallow and deeper subsurface features in 2-D. The 2-D sections show heterogeneity at a shallow depth of about 9 m. At 9 m depth, the layers are slightly undulating as seen in Figure 9 *a*. In D–D section, at a depth of 27 m, a high resistivity body is seen corresponding to a position of 320 m on the surface (Figure 9 *a*), while in W–S section, there is slight depression in the layers at the same position (around 320 m on the surface) as seen in D–D section. From 40 m downward, the layers dip towards the SW direction as seen in Figure 9 *b* and these layers vary in resistivity values with a contrast of

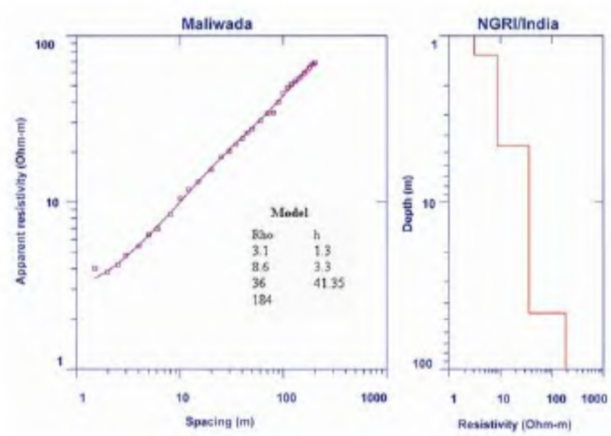

Figure 6. 1-D VES field data (as square box), model curve (as smooth line) and the depth model for the site Maliwada.

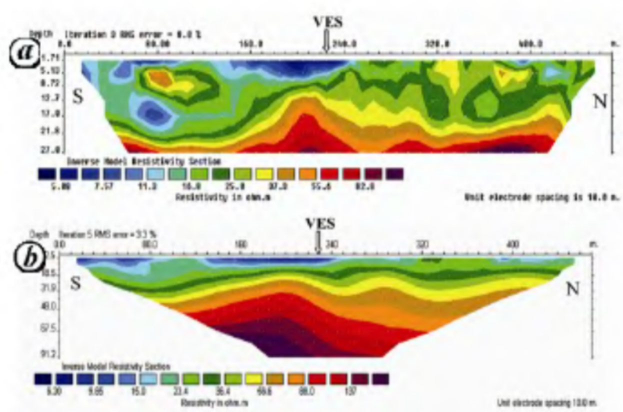

Figure 7. Resistivity imaging at Maliwada. ***a***, Dipole–dipole section; ***b***, Wenner–Schlumberger section.

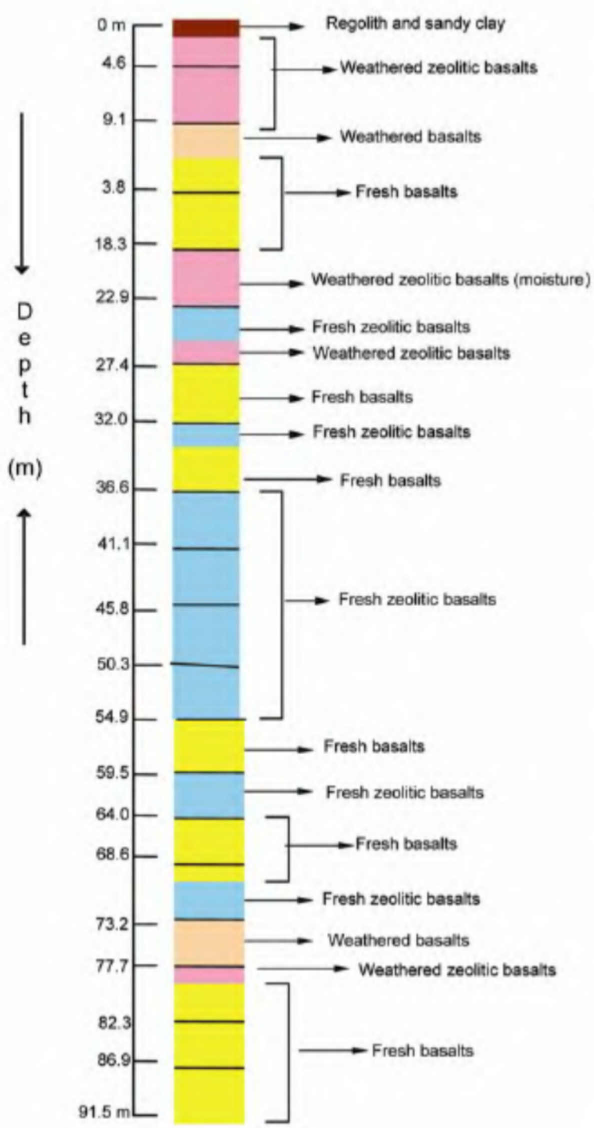

Figure 5. Lithological variation at Jogwada well.

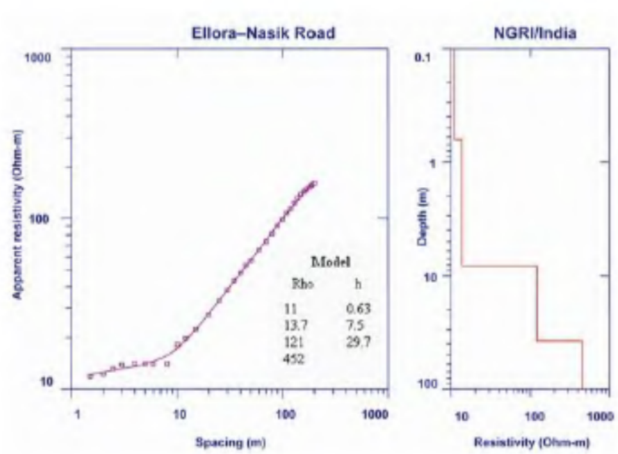

Figure 8. 1-D VES field data (as square box), model curve (as smooth line) and the depth model for the site Ellora.

about 80–100 Ohm-m and also the NE part is more massive with a resistivity of about 500 Ohm-m compared to SW part of the section (Figure 9 *b*), which is also reflected in 1-D VES data as discussed here.

The resistivity logging for the Ellora site shows that from 6.5 m onward to a depth of about 11 m, the high resistivity >1000 Ohm-m is a clear indication of the casing effect (Figure 10). From 11.5 m onward, the measurement reflects the actual geological formation effect. The resistivity log obtained shows only slight variation in resistivity throughout the log. The log shows an increase in value from 12 to 21.5 m and then it decreases with a zigzag pattern. On quantitative analysis, it was seen that the minimum resistivity is 73 Ohm-m and the maximum resistivity is 650 Ohm-m. The 73 Ohm-m corresponds to weathered zone basalt at a depth of 12.5 m, while the value with 650 Ohm-m found at a depth of about 64 m indicates the massive basalt.

The 1-D VES curve is modelled and is shown in Figure 11 along with the depth model for the Thisgaon site. Here the interpreted model curve shows a four-layer case as usual, but is slightly different from previous sounding curves. On quantitative interpretation, it was found that apparent resistivity values do not vary much for a given sounding except for the top layer and the last layer. The interpreted model shows that the resistivity of the first layer is about 55 Ohm-m followed by weathered layer of about 9 m thickness and then followed by another slightly higher resistivity of about 98 Ohm-m with a quite sufficient thickness could be fractured zone, which is

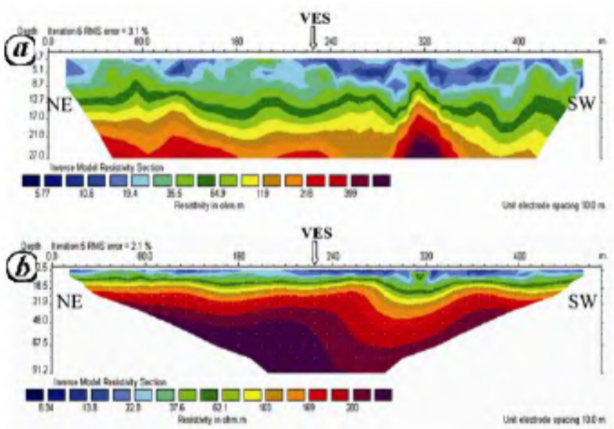

Figure 9. Resistivity imaging at Ellora. ***a***, Dipole–dipole section; ***b***, Wenner–Schlumberger section.

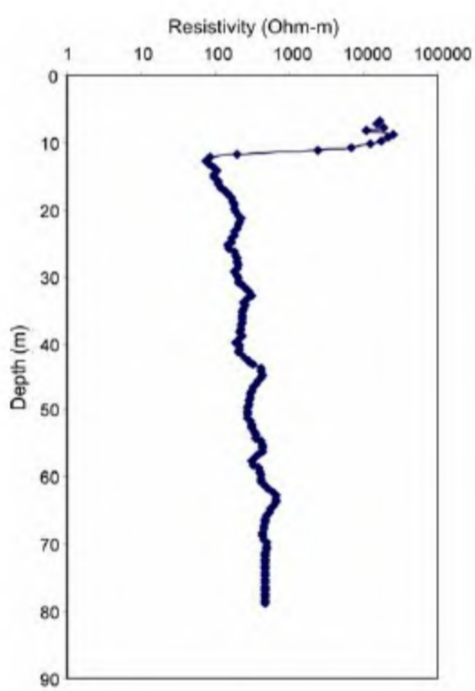

Figure 10. Resistivity logging at Ellora.

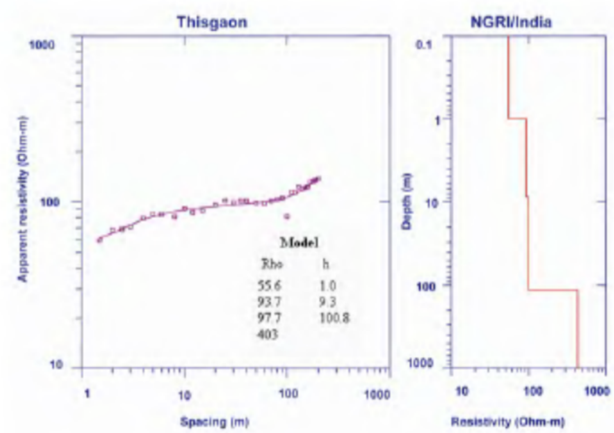

Figure 11. 1-D VES field data (as square box), model curve (as smooth line) and the depth model for the site Thisgaon.

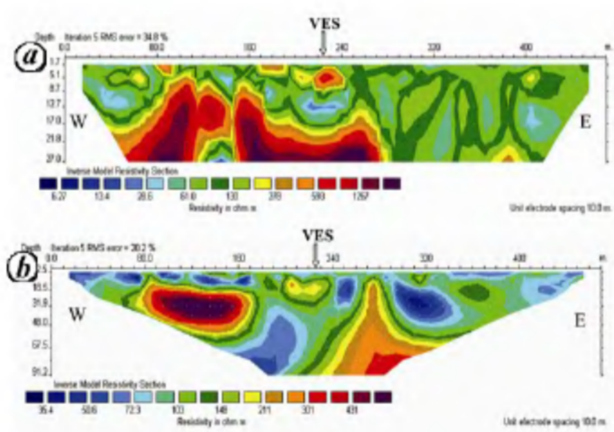

Figure 12. Resistivity imaging at Thisgaon. ***a***, Dipole–dipole section; ***b***, Wenner–Schlumberger section.

well seen in VES curve before attaining high resistivity. Beyond 100 m, the rising trend in VES curve indicates massive or compact basalt formation with a resistivity of 400 Ohm-m. On the other hand, D–D and W–S profiles were carried out in E–W direction along the same 1-D line and is shown in Figure 12. The D–D section shows a highly heterogeneous character throughout the section with resistivity ranging from <10 to about 1500 Ohm-m. The high resistivity body are more concentrated around the western side of the profile as compared to eastern part (Figure 12 *a*). While in the W–S section towards west and at a depth of about 32 m a high resistivity value of about 600 Ohm-m (Figure 12 *b*) clearly reflect a void created due to geological process or any other structural body sitting at this position. This could be the possible zeolite cavity zone. The W–S section too shows the heterogeneous character of the region. Also in the middle of the profile in W–S section, a high resistivity peaky anomaly is identified from near surface to a depth of 90 m, could be geologically another resistive body. Between these two high resistive bodies, a low resistivity (about 40–60 Ohm-m) appears from the west part of the section and has continued up to a depth of 32 m, and this could be the possible potential groundwater-bearing zone at deeper depth (Figure 12 *b*).

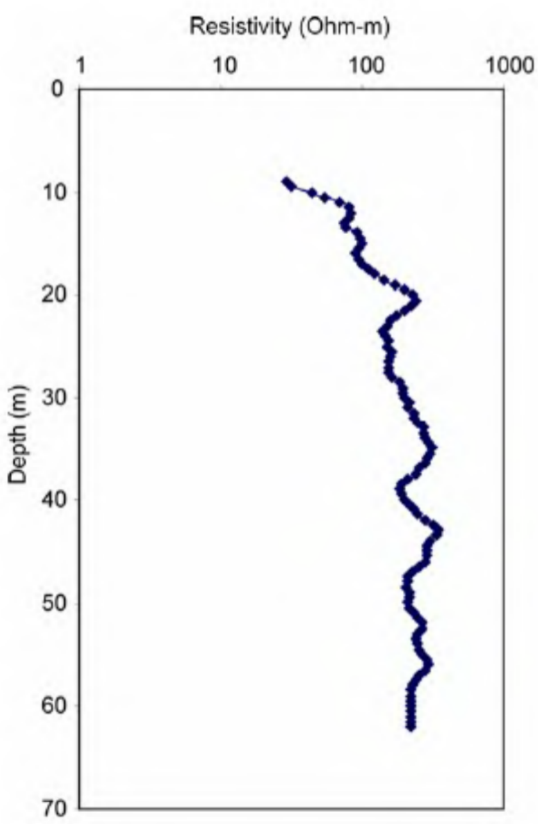

Figure 13. Resistivity logging at Thisgaon.

At Thisgaon, the static water level is at 8.04 m bgl and is comparatively deeper than the Ellora site. The resistivity logging was carried out from down to a depth of 8.5–61.5 m at an interval of 0.5 m as shown in Figure 13. The resistivity log indicates a resistivity value of 29 Ohm-m at a depth of 8.5 m which shows the weathered basalt. The log shows a gradual increase in resistivity value (about 200 Ohm-m) up to a depth of 20 m and then it decreases and is followed again by an increase in resistivity. At a depth of about 40 m, there is a fall in the resistivity value, which indicates the weathered/fractured basalt (Figure 13). The log showing a increasing trend in the resistivity value is followed by a gradual decrease in the resistivity and then at a depth of about 58 m (Figure 13), there is saturation in the resistivity value till the bottom end of the log, i.e. at 61.5 m suggesting the bottom depth of the well.

The 1-D VES modelled curve depicts a H type of curve (Figure 14) for the Sundarvadi site. The final model parameters are shown on the ρ_a–$AB/2$ plot and the depth model is shown by its side (Figure 14). The model shows that the first layer is a top soil cover with a resistivity of 10 Ohm-m. This is followed by low resistivity zone with a resistivity of about 8 Ohm-m, followed by comparatively high resistivity zone of 43 Ohm-m with a sufficient thickness of 83 m indicating weathered basalt and then follows massive basalt with a resistivity of about 4000 Ohm-m which is a direct indication of fresh basalt. On the same VES line, D–D and W–S profiles in SE–NW direction were performed. The D–D section shows a heterogeneous character of the formation at a shallow depth in lateral direction with resistivity varying from about 2 Ohm-m to about 100 Ohm-m (Figure 15 *a*). While in W–S section, no major anomaly is seen, only two high resistive bodies are seen at the two corners of the profile at the bottom end of the section (Figure 15 *b*), otherwise it appears as a layered structure with slight dipping at the

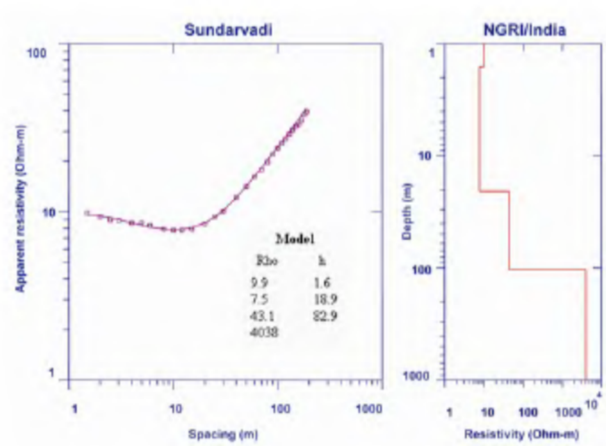

Figure 14. 1-D VES field data (as square box), model curve (as smooth line) and the depth model for the site Sundarvadi.

centre of the profile. The bedrock resistivity is about 120 Ohm-m which is seen at a depth of 91 m in the present section.

Resistivity logging was performed at Sundarvadi site from down to a depth of 22.5–82 m (Figure 16). The resistivity log shows at first glance few interesting features at different depth levels. On analysing the log, it shows four major anomalies at depths of 28, 43, 61 and 69.5 m (Figure 16) having resistivity values as follows: 137, 380, 620 and 146 Ohm-m respectively. These resistivity values indicate the weathered, fractured and massive basalt but after the high value of 620 Ohm-m, a low resistivity of 146 Ohm-m at a depth of 69.5 m could be the indication of weathered/fractured basalt saturated with water and it suggests a potential water-bearing zone around this depth.

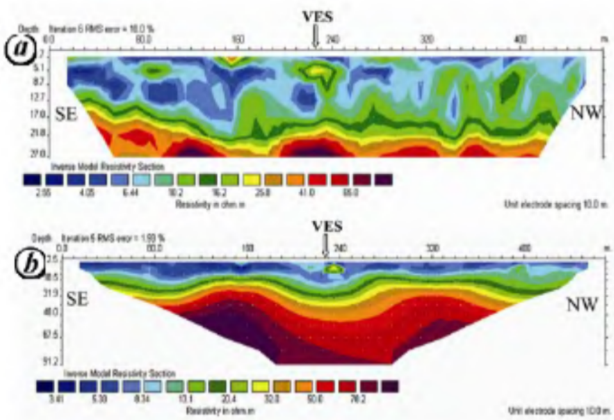

Figure 15. Resistivity imaging at Sundarvadi. ***a***, Dipole–dipole section; ***b***, Wenner–Schlumberger section.

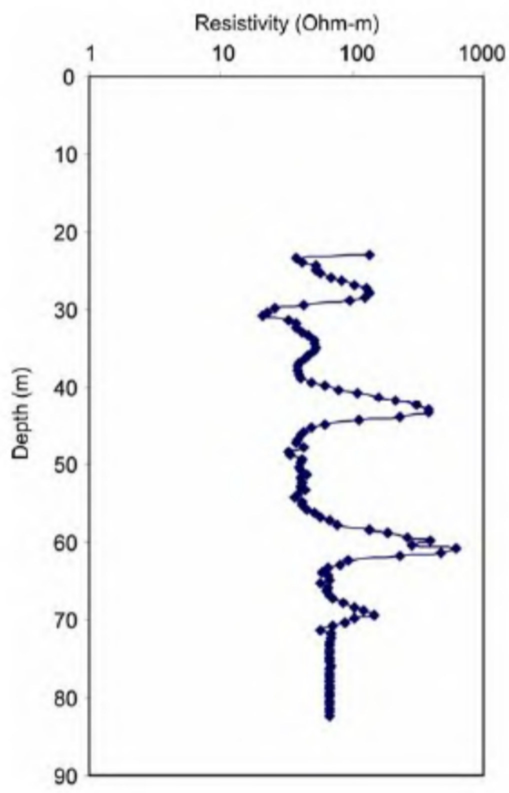

Figure 16. Resistivity logging at Sundarvadi.

Figure 17 presents the 1-D VES data with the interpreted model curve, which is quite different from the other curves for the Balapur site. Qualitatively it is a K-type curve. On quantitative interpretation, the data shows a five-layer earth model. The first layer is the top soil cover with resistivity of about 29 Ohm-m and thickness of 0.6 m and it matches with the drilling result, followed by resistivity of 50 Ohm-m indicating highly weathered basalt of thickness of 7.8 m which again well corroborates the geological log (Figure 18). Subsequent to this layer follows another layer of resistivity 94 Ohm-m showing fresh basalt, which was later confirmed by drilling results. The fourth layer showing a low resistivity value of 32 Ohm-m (Figure 17) could be a potential water-bearing zone and this could be the weathered basalt which is of sufficient thickness. As seen in 1-D depth model (Figure 17), sudden drop in resistivity indicates the favourable groundwater zone. This was confirmed on drilling as fresh samples of basalt with presence of moisture at the field site, while the fifth layer with a resistivity of about 300 Ohm-m indicates that fresh basalt is evident from the 1-D depth model with a sharp increase in resistivity value. Along the same 1-D line, D–D and W–S profiles were carried out in N–S direction (Figure 19). The D–D profile shown in Figure 19 *a* shows heterogeneous character at shallow depths right from south to north end of the profile. This figure also shows two high resistivity bodies of the order of 280 Ohm-m both at the

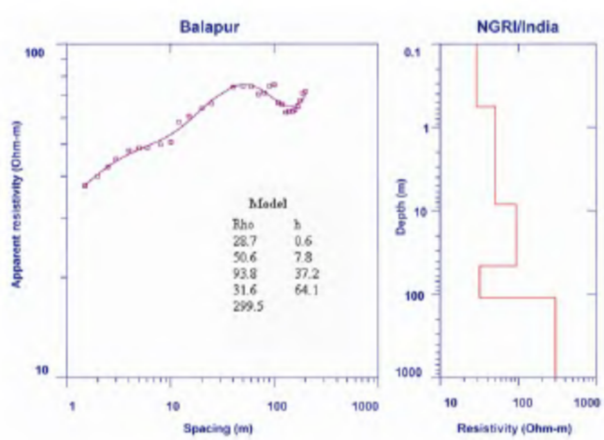

Figure 17. 1-D VES field data (as square box), model curve (as smooth line) and the depth model for the site Balapur.

south and north end of the profile (Figure 19 *a*), which could probably be the zeolite cavity. Between two major anomalies, a number of anomalies are seen with a high and low resistivity values (Figure 19 *a*) in the range of 150–250 Ohm-m and 20–50 Ohm-m respectively. While on the other hand, in W–S profile, the section too matches with the D–D profile at shallower depth. The W–S profile also shows heterogeneous character of the geological formation. At a depth of about 48 m, a big round low resistivity anomaly of the order of about 30–50 Ohm-m is seen in 2D section (Figure 19 *b*) almost in the centre of the profile. Interestingly, this big anomaly was also noticed in the 1-D model depth as described here. This is a possible indication of potential groundwater zone due to the presence of weathered zeolitic basalt and which acts as a source of water, since zeolites contain water of crystallization and the amount of water varies depending on the SiO_4 bonding with H_2O molecule. It is seen from the section (Figure 19 *b*) that this anomaly zone is connected to the south end of the profile at a depth of nearly about 68 m, which is confirmed from the litholog as highly weathered zeolitic basalt (Figure 18). Just at the opposite side on a 2-D section and at a depth of about 48–51 m, there is another anomalous zone of resistivity value of about 100 Ohm-m (Figure 19 *b*), which seems to be a zeolite-bearing zone and is confirmed during drilling as a zeolitic basalt at a depth of 48 m (Figure 18). Again at a depth of 70–71 m, moisture is found along with weathered basalt layer and beyond 71 m depth, it was found during drilling massive/fresh basalt along with zeolite. This fresh zeolitic basalt continues up to depth of 83 m and from 83 to about 87 m weathered basalt and then follows the fresh basalt which is seen in the geological log (Figure 18) and reflected in 2-D resistivity section in terms of sufficient resistivity contrast between depths of 70 and 90 m (Figure 19 *b*).

Resistivity logging at the Balapur site was also carried out from down to a depth of 10–85.5 m at Balapur site (Figure 20). The resistivity log at a glance shows clear anomaly at depths of 11–13, 42, 67 and 76 m. The moment the logging starts, it shows an increase in resistivity value (Figure 20) which corroborates with the geological log depicting as fresh basalt (Figure 18) and is comparatively very hard with resistivity of the order of 590 Ohm-m. Subsequently, there is a decrease in resistivity value from 590 Ohm-m to an average value of 60 Ohm-m which corresponds to depth between 15 and 22 m and the formation is weathered zeolitic basalt as seen in drilling cuttings. The change in formation at a depth of about 25 m (Figure 18) is seen in the resistivity log (Figure 20) with a drop in resistivity value from 67 to 43 Ohm-m. This formation is the weathered zeolitic basalt as seen in the geological log (Figure 18). Later from 28 to 31 m, the increase in resistivity is correlated with the change in formation from weathered to fresh basalt. At a depth of about 42 m, an increase in resistivity clearly shows another formation and it was confirmed by drilling. Again the resistivity log shows two more prominent anomalies at depths of 67 and 76 m (Figure 20), which were well corroborated

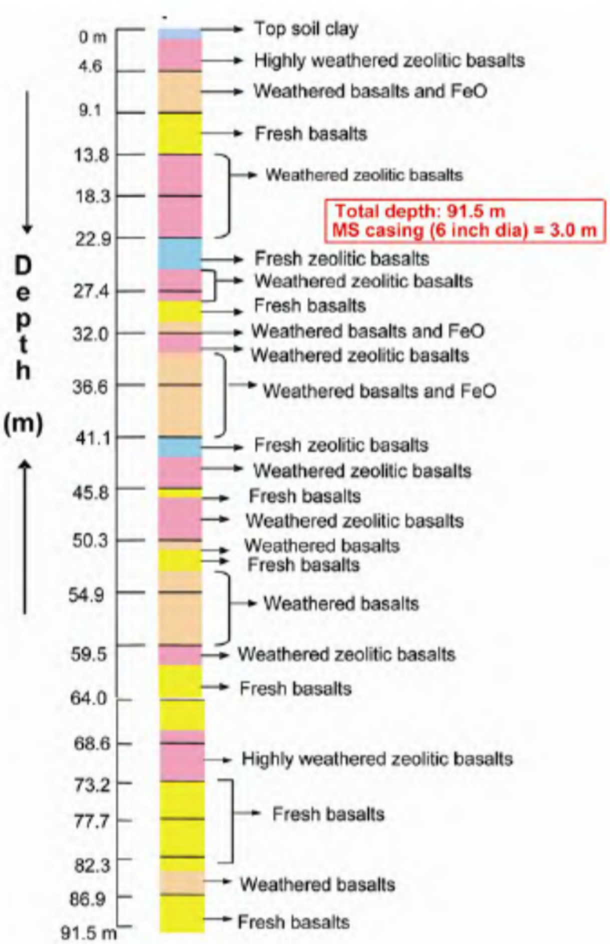

Figure 18. Lithological variation at Balapur well.

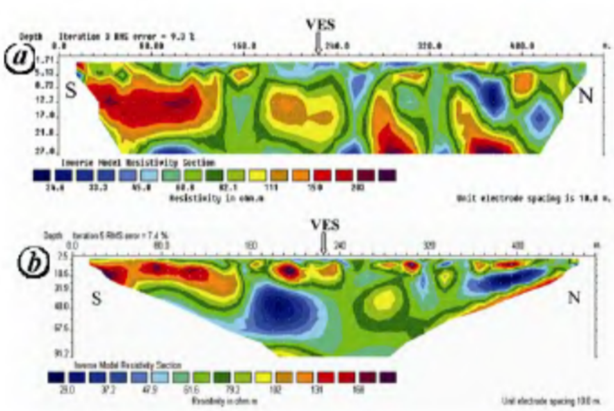

Figure 19. Resistivity imaging at Balapur. ***a***, Dipole–dipole section; ***b***, Wenner–Schlumberger section.

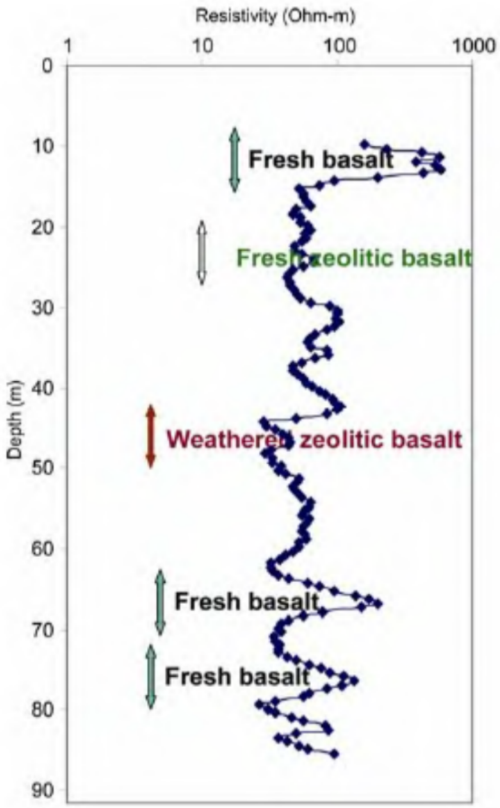

Figure 20. Resistivity logging at Balapur.

with the geological log (Figure 18) as fresh basalt zone. This is the beauty and the efficacy of the resistivity log to detect minor and major changes in the lithological formation and these aid in confirming our major findings about the geological set-up of the Deccan basalt.

Conclusions

The present integrated study using 2-D ERI, 1-D Schlumberger sounding and resistivity logging has delineated the different zones both at shallow and deeper depths. The ERI results have shown the signatures of high resistivity anomaly, indicating the cavity effect or cavity created due to zeolite. At the same time, the low resistivity zone/anomaly in few 2-D sections has clearly indicated the potential water bearing zone(s). The various layers of basalt formation are seen in the 1-D and 2-D resistivity results with variation in the resistivity values with appreciable resistivity contrast. In addition, 1-D VES at the imaging lines had delineated mostly the four-layer case of the subsurface. The percentage of RMS error for the 1-D sounding interpretation ranges from 2.79 to 5.86 which shows that the interpreted models represent the subsurface lithology closely. The qualitative nature of the model curves indicates different types, viz. A, H and K and its combination which shows variation in the geological set-up of the basaltic rock. The resistivity logging performed at the three drilled borewells and the other two existing new wells drilled by local farmers near the 2-D and 1-D survey sites had provided the characteristics resistivity of the various layers; in addition aided in the interpretation of the 2-D and 1-D data. Combining 1-D, 2-D and resistivity logging results, the efficacy of the integrated geophysical method is seen at different sites in deciphering the correct and detailed lithology. The resistivity characteristics obtained for fresh basalt in association with zeolite have a resistivity range between 90 and 105 Ohm-m while the weathered zeolitic basaltic layer has a resistivity between 40 and 50 Ohm-m as compared to 500 and 600 Ohm-m which corresponds to fresh basalt without zeolite. It is interesting to note that the change in resistivity values at depths reflects different formations and the kinks observed in these logs show even minor variations in resistivity. The present integrated study successfully delineates the zeolite and groundwater zones and demonstrates the efficacy of the different tools used.

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