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Geoelectrical investigation for potential groundwater zones in parts of Ratnagiri and Kolhapur districts, Maharashtra

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ABSTRACT
Study of significant variations in nature and extent of weathering due to the presence of fractures and lineaments at depth and the geomorphological features at the surface is vital for groundwater exploration in a hard rock terrain. An attempt is made here to understand the vertical distribution of water bearing zones in the shallow formations over Devrukh-Ganapati Pule and Malkapur-Ratnagiri sections through geoelectrical studies. Two-dimensional geoelectrical cross-sections along five profiles reveal potential aquifer zones at a few sounding locations viz. 1, 2, 4, 5, 6, 7, 17, 18, 20, 21 and 22 with resistivities varying from 22-36 Ω-m over Devrukh- Ganapati Pule profile. Potential aquifer zones are also revealed at sounding points 24, 25, 34, 37, 39, 40, 41 and 42 in the eastern part of the Malkapur-Ratnagiri profile in the resistivity range of 22-37 Ω-m. Several lineaments cris-crossing this region play a significant role in the occurrence and movement of groundwater as revealed by low resistivities near VES 6, 5, 4, 16 and 17 over Devrukh-Ganapati Pule profile and VES 24, 25, 34 and 37 over Malkapur-Ratnagiri profile.

INTRODUCTION

The availability of surface and groundwater governs the process of planning and development. The demand for groundwater has increased over the years as the available surface water resources are inadequate to meet the entire water requirement for various purposes. Of all the surface geophysical methods, the electrical resistivity profiling and vertical electrical sounding (VES) methods are most widely deployed to delineate different layers such as top soil, weathered, fractured and bedrock zone for construction of suitable groundwater structures.

The Deccan Volcanic Province (DVP) is one of the most important regions of continental flood basalt (CFB) in the world (Sheth, 2005). The crust in DVP is covered by the fissure erupted basaltic magma, which has spread over an area of about 500,000 km^2 in the western part of the Indian peninsula. The continental flood basalts with a thickness ranging from a few meters to about 2000 m are emplaced over the northern part of the Dharwar craton. Due to the severe scarcity of water, the need for locating auxiliary sources of groundwater for exploitation is felt almost all over the Deccan Plateau.

The VES method has been successfully used by a number of researchers for various applications which include groundwater investigations (Devi et al., 2001; Gowd, 2004; Lenkey et al., 2005; Hamzah et al., 2007; Gupta et al., 2012), groundwater contamination studies (Frohlich et al., 2008; Karlik and Kaya, 2001; Kundu and Mandal, 2009; Park et al. 2007; Mondal et al., 2013), saltwater intrusion problems (Edet and Okereke, 2001; Hodlur et al., 2006, 2010; Song et al., 2007; Adeoti et al., 2010; Hermans et al., 2012; Maiti et al., 2013), and geothermal explorations (El-Qady et al., 2000; Majumdar et al., 2000; Kumar et al., 2011).

Systematic hydrogeological and geophysical investigations were carried out in the Deccan trap region (Bose and Ramakrishna, 1978; Singhal, 1997; Pawar et al. 2009; Rai et al., 2011, 2012, 2013; Ratnakumari et al., 2012) to delineate aquifers and study the occurrence and movement of groundwater in the inter-trappeans/ vesicular and fractured zones within the trap sequence and sedimentary formations below the traps, which are considered to be a potential source of groundwater.

With the available database in the northern part of DVP, CGWB (http://cgwb.gov.in/CR/achi_geo_stu.html) suggested the following probable resistivity ranges for different litho units vis-à-vis water bearing zones in the Deccan basalts:

- 20-40 Ω-m - weathered/fractured vesicular basalt saturated with water
- 40-70 Ω-m - moderately weathered/fractured basalt/ vesicular basalt saturated with water
- > 70 Ω-m - hard and massive basalts

These ranges may slightly vary either side from place to place depending on the proportion of clay, joints/ fractures.

The present study attempts to delineate potential aquifers obscured within and below the traps in the DVP of Ratnagiri and parts of Kolhapur districts for groundwater exploration using geoelectrical method, particularly Vertical Electrical Sounding (VES).

THE STUDY AREA

Two regions surveyed in this area, Devrukh-Ganapati Pule profile situated between 17.00^0 to 17.15^0 N and 73.30^0 to 73.70^0 E and Malkapur-Ratnagiri profile between 16.90^0 to17.04^0 N and 73.30^0 to74.00^0 E form a part of Ratnagiri and adjoining Kolhapur districts. Ratnagiri is one of the coastal districts of Maharashtra situated between the Western Ghats and the Arabian Sea between latitudes 16°30'N and 18°04'N and longitude 73°20'E and 73°52' E and covers an area of 8326 km^2. It is bounded in the north by Raigad district, west by Arabian Sea, in the east by Satara, Sangli, Kolhapur districts and in the south by Sindhudurg district. Kolhapur district lies between 15°43' and 17°16' N latitudes and 73°40' and 74°42' E longitudes. It is surrounded by Sangli district to the North, Belgaum district of Karnataka State to the East and South and Ratnagiri and Sindhudurg district to the West. The geological map along with the VES locations of both the study regions is shown in Fig. 1. A few lineaments cris-crossing this region are also marked in Fig. 1.

GEOLOGY AND HYDROGEOLOGY OF THE STUDY AREA

Kolhapur region

In Kolhapur district, two distinct trends of the hill ranges are seen, one runs north-south and the other trend is stretching eastward and merging gradually into plains. The district has minimum and maximum temperatures of 15° and 40°, respectively with an average temperature of 27°. The average rainfall in the area is 543.90 mm and humidity of 55%.

The stratigraphy of the area is given below (Deshpande, 1998),

Recent	- Soil and Laterite
Lower Eocene	- Deccan Trap
Cuddapah	- Lower Kaladgi series
Archaean	- Granite gneiss Dharwars

The Dharwar Phyllites and amphibolites intruded by granite – gneiss are the oldest rocks found as small inliers in this district near Ajra (Radhakrishna, 1982). Granite gneiss crops out as small inliers along the junction of the Kaladgis and the Deccan trap near Hadige, Tarewadi and Chandewadi. It shows diversity of texture from fine grain to rather course porphyrite type.

The lower Kaladgi series rest unconformably over the Dharwars and granite gneiss. It consists of conglomerates, compact to gritty quartzites with minor ferruginous bands and statins, variegated and sandy – shales and re-crystallised sandstone.

The Deccan traps overlie the Kaladgi beds and are seen spread over almost in the entire district (Subbarao, 1988). It occurs in the form of layered flows. It exhibits characteristic spheroidal weathering and forms rounded boulders. These boulders are generally seen scattered along the foot hills and the hilly terrain throughout the district. Prismatic or columnar jointing is also a common feature. Generally two types, viz. vesicular and non-vesicular traps are noticed. Vesicular traps are soft and non-vesicular are hard and compact. Generally in the trappean country, fluviatile and

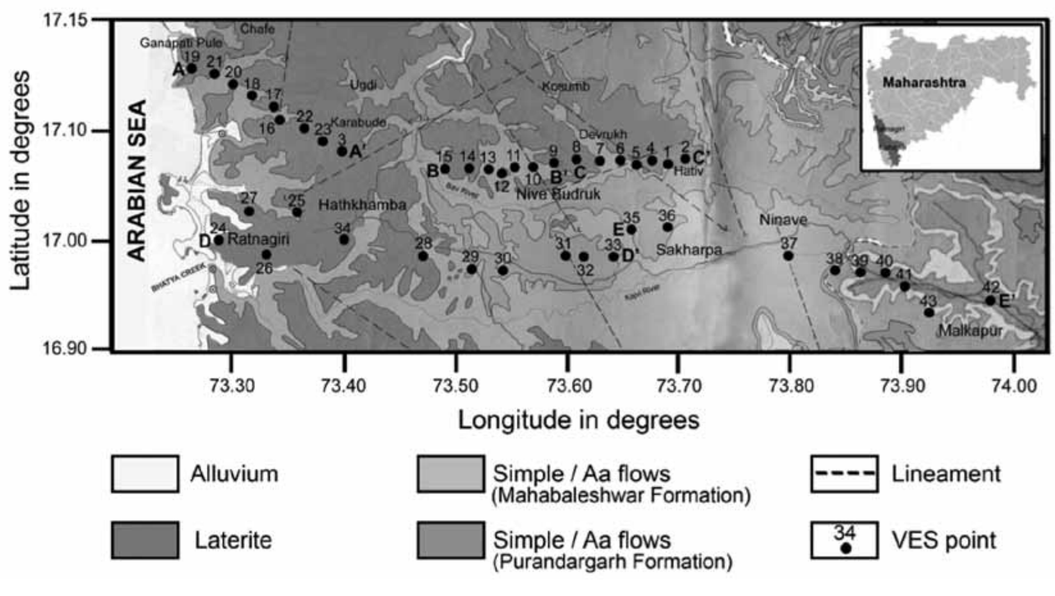

Figure 1. Geological map depicting the study area in Devrukh-Ganapati Pule and Malkapur-Ratnagiri region. Shown here are the VES locations and the lineaments present in the study area. (Lineament locations redrawn after Ratnagiri District Resource Map, GSI).

lacustrine deposits are formed during the interval between the successive lava flows. These sedimentary deposits are known as intertrappean beds. It has been reported by Ghosh et al (2006) that if these beds are clay rich, then it is not a prospective zone of groundwater and such beds are known as bole beds. Intertrappean beds together with the underlying vesicular basaltic layers form groundwater potential zones between two massive basalt layers (Rai et al., 2013).

Ratnagiri region

Ratnagiri, being a coastal district, maximum temperature rarely goes beyond 38°C and in the interior, sometimes crossing 40°C. Climate of the district is very humid and relative humidity seldom goes below 50%. The normal annual rainfall over the district varies from 2657.8 mm (Guhagar) to about 3973.4 mm (Mandangad). It is minimum in the western part of the district along the coast and gradually increases towards east and northern parts of the district. The stratigraphy of the area is as given below (Deshpande 1998),

Recent	- Alluvium
Pleistocene	- Laterite & Lateritic spread
Miocene	- Shale with peat & Pyrite nodules
Cretaceous to Eocene	- Basaltic lava flow
Upper pre Cambrian	- Kaladgi series – quartzite Sandstone, shale & associated lime stone

In Ratnagiri district, Deccan Traps (upper Cretaceous to lower Eocene age), Kaladgi sandstone (Precambrian), Laterite (Pleistocene) and Alluvial deposit (Recent) are the water bearing formations (Mandal, 2009). However, Kaladgi formation occurs in very limited patches and does not form potential aquifer in the district. Alluvium is found over a limited areal extent mainly along the coast.

Major part of the Ratnagiri district is covered by basaltic lava flows of upper cretaceous to lower Eocene age. The lava flows are predominantly of 'aa' type with 'pahoehoe' type flows occurring at few places. Deccan traps form a very extensive formation covering the entire northern portion and parts of the southern portion of the district. The rocks have a porphyritic texture with a fine grained matrix. The different units of flows are represented by: (1) coarse grained massive basalts characterized by spheroidal weathering or development of columnar joints, (2) amygdaloidal basalt with zeolites, (3) agglomerates and (4) breccias.

Deccan Traps form an important water bearing formation in the district. The secondary porosity due to cooling joints, partition planes, cracks and fissures play an important role in groundwater circulation, especially in the highly porous 'pahoehoe' flows. Degree of weathering and topographic setting also play a major role in respect of groundwater storativity. In Deccan Traps, groundwater occurs in vesicular basalt, intertrappeans as well as in weathered mantle and fractured zones (Rai et al., 2013). In general, groundwater occurs under water table conditions in shallow aquifer and semi- confined to confined conditions in deeper aquifer. The unconfined aquifer in the study region is developed due to the weathering and fracturing of upper lava flows down to depths of 15-20 m below ground level (bgl). Yield of the wells tapping such aquifer varies from 15 to 145 m^3/ day. Bore wells are not common in the district due to poor groundwater potential of deeper aquifer. In lateritic formation, groundwater is found only in dug wells down to about 15 m and their yield varies from about 4 to 22 m^3/day (Mandal, 2009).

DATA ACQUISITION AND ANALYSIS

Electrical resistivity technique is based on measuring the potentials between one electrode pair while transmitting direct current (DC) between another electrode pair. The depth of penetration is proportional to the separation between the current electrodes and provides information on the stratification of the ground (Dahlin, 2000).

The VES carried out in the study area with a SSR-MP-ATS resistivity meter over Devrukh-Ganapati Pule and Malkapur-Ratnagiri profiles are shown in Fig. 1. The Schlumberger soundings were carried out at 43 locations with a maximum current electrode spacing (AB) of 200 m (AB/2=100 m) for delineating vertical distribution of water bearing zones. The resulting geoelectrical layer sequence was used for delineating various conductive zones. Employing Schlumberger configuration, the apparent resistivity was calculated by using the expression (Kearey and Brooks, 1988),

$$\rho_a = \pi\ [(L/2)^2 - (b/2)^2] / b] * V/I$$

where, L and b are the current and potential electrodes spacing, respectively.

The data obtained from the field was processed and modeled using IPI2WIN software, version 3.0.1.a7.01.03 (Bobachev, 2003) for interactive semi-automated interpretation. The plot of apparent resistivity (ρ_a) vs half of the current electrode separation (AB/2) suggests three to six layered structure in the study area (Figs. 2a, b). The layer resistivity, layer thickness, total thickness (H) and the RMS error for all the 43 VES stations are shown in Tables 1 and 2.

Table 1: Summary of VES data interpretations and qualitative analysis of curve types over Devrukh-Ganapati Pule profile

VES No.	Layer resistivity (Ωm)						Layer thickness (m)					Total thickness H(m)	RMS error
	ρ1	ρ2	ρ3	ρ4	ρ5	ρ6	h1	h2	h3	h4	h5		
VES 1	1588	353	123	74.9	24.9	----	0.5	11.4	22.6	2.87	----	37.4	1.12
VES 2	1271	115	239	93.1	34.7	----	0.40	3.68	8.95	44.1	----	57.1	1.17
VES 3	687	47.6	1077	116	133	----	0.5	2.85	4.14	29.1	----	36.6	2.40
VES 4	1274	507	326	509	22.1	----	0.5	0.58	5.52	14.1	----	20.7	0.9
VES 5	407	193	252	62.4	35.8	----	0.5	2.79	5.71	32.0	----	41.0	0.68
VES 6	82.1	114	169	49	31.8	----	0.51	1.9	6.0	33.0	----	41.4	0.91
VES 7	877	581	1983	113	33.9	----	0.5	2.4	3.69	36.4	----	43.0	1.05
VES 8	1624	203	605	21.8	107	----	0.51	0.32	7.19	4.27	----	12.3	1.03
VES 9	1596	438	301	28.1	71.3	----	0.39	2.34	8.65	11.4	----	22.8	1.43
VES 10	491	2472	564	82.3	----	----	0.5	0.675	9.66	----	----	10.8	1.35
VES 11	1242	314	199	79.1	----	----	0.37	9.03	19.7	----	----	29.1	1.03
VES 12	910	638	257	19.5	1402	----	0.91	7.59	17.2	28.0	----	53.7	1.48
VES 13	628	455	1299	541	72.7	----	0.58	0.85	0.44	5.54	----	7.42	1.13
VES 14	190	73.1	601	114	74.3	----	0.55	0.63	0.57	13.9	----	15.7	1.72
VES 15	413	74.9	472	17.1	1417	----	1.31	7.54	11.2	16.5	----	36.6	1.28
VES 16	1737	7568	2221	174	25	----	0.5	0.98	5.26	85.0	----	91.7	1.22
VES 17	2687	2738	3410	39.3	4844	----	0.5	7.85	0.4	42.4	----	50.6	3.50
VES 18	3164	1761	3473	32.1	712	----	2.42	2.32	4.74	71.7	----	81.2	3.30
VES 19	946	2902	724	19.7	4545	----	0.53	2.19	9.98	11.5	----	24.2	1.64
VES 20	3433	2008	258	23.1	----	----	0.5	8.52	15.5	----	----	24.5	1.63
VES 21	4363	1865	302	54.6	24.0	----	0.50	5.91	22.8	2.74	----	31.4	1.83
VES 22	870	1303	8.72	24.1	912	----	5.22	3.5	4.09	35.7	----	48.6	1.03
VES 23	1140	250	73.7	3026	----	----	0.5	0.62	52.2	----	----	53.3	1.50

Table 2: Summary of VES data interpretations and qualitative analysis of curve types over Malkapur-Ratnagiri profile

VES No.	Layer resistivity (Ωm)						Layer thickness (m)				Total thickness H (m)	RMS error
	ρ1	ρ2	ρ3	ρ4	ρ5	ρ6	h1	h2	h3	h4		
VES 24	150	1168	246	21.5	----	----	0.9	7.18	16.0	----	24.1	1.60
VES 25	329	17.3	596	25.3	----	----	2.34	2.1	9.98	----	14.4	0.8
VES 26	701	5019	1641	99.2	58	----	0.51	0.82	8.18	19.8	29.3	1.7
VES 27	937	3290	241	56.3	----	----	0.5	7.7	25.4	----	33.6	1.31
VES 28	12.2	2.6	107	6714	----	----	2.13	1.62	9.96	----	13.7	1.95
VES 29	146	3169	69.4	630	54.2	----	0.5	0.339	0.323	17.3	18.5	0.91
VES 30	162	1556	61.4	----	----	----	8.62	3.93	----	----	12.6	0.54
VES 31	165	1027	120	56.2	----	----	2.15	0.45	39.6	----	42.2	1.78
VES 32	35.9	102	64.7	----	----	----	2.24	32.4	----	----	34.6	0.76
VES 33	65.7	13.7	597	69.5	----	----	0.316	2.64	3.81	----	6.76	0.87
VES 34	113	665	9.55	37.4	25	----	1.28	8.61	12.7	30.4	53.0	1.34
VES 35	60.5	72	129	220	66.6	----	0.5	0.65	8.9	13.1	23.1	0.67
VES 36	42.7	202	70.3	40	59.3	----	1.33	11.1	10.2	17.4	40.0	0.62
VES 37	45.1	114	36.6	66.6	----	----	0.62	5.6	42.3	----	48.6	0.59
VES 38	95.9	71.6	31	54.4	62	54.4	0.5	0.41	4.0	9.0	13.91	0.45
VES 39	76.9	134	34.1	69	----	----	1.52	4.68	59.4	----	65.6	1.0
VES 40	419	333	161	36.1	65.7	----	0.5	3.67	5.88	42.2	52.3	0.45
VES 41	277	103	13.4	28	----	----	0.60	8.8	3.69	----	13.1	0.94
VES 42	109	701	147	34.4	107	----	0.50	0.83	24.1	42.5	68.0	0.9
VES 43	44.5	279	116	8.59	69	----	0.75	1.64	12.9	14.5	29.7	1.11

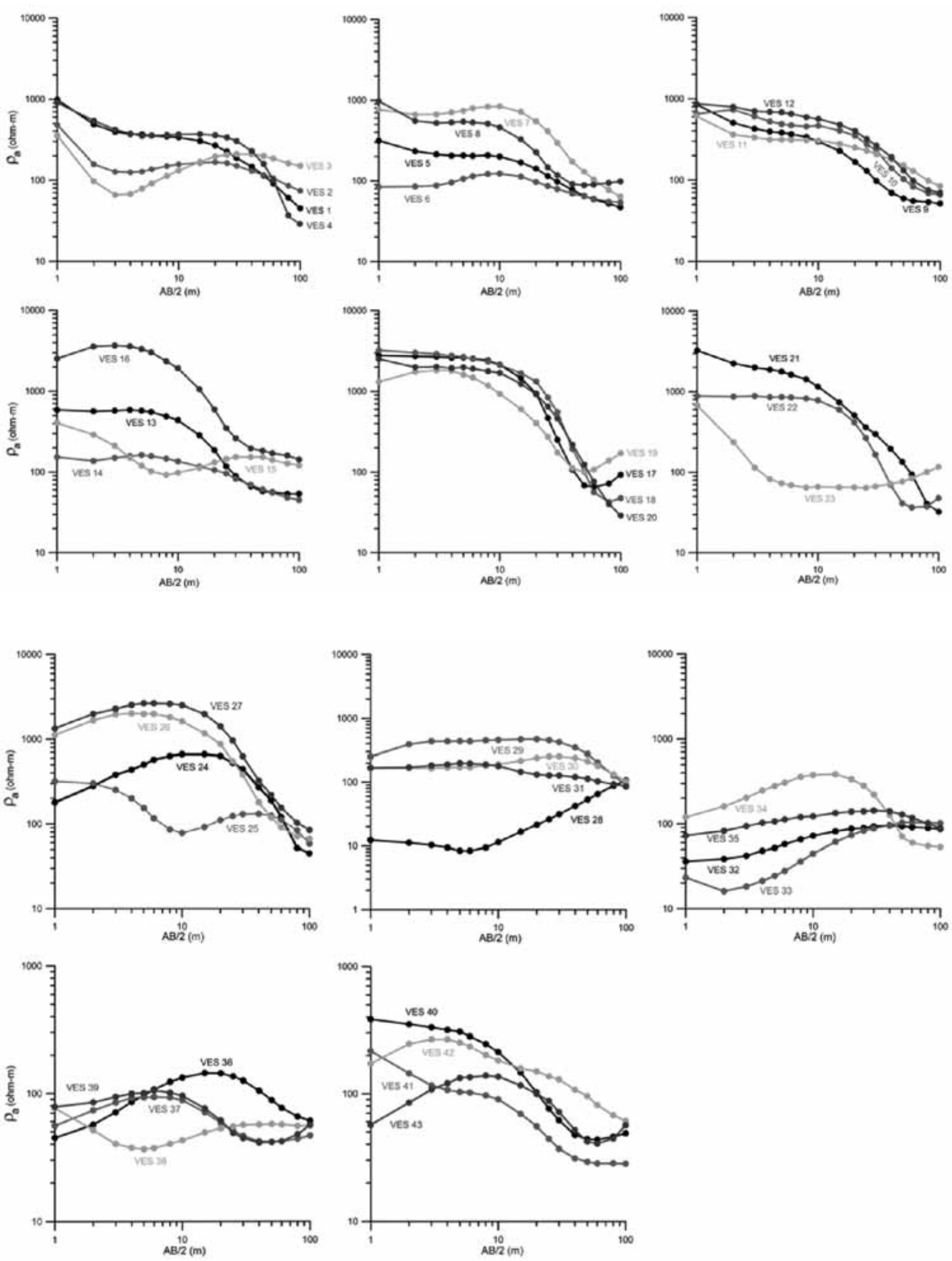

Figure 2a, b. Interpreted VES curves

RESULTS AND DISCUSSIONS

The two dimensional (2-D) geoelectrical sections has been generated over five selected profiles (3 over Devrukh-Ganapati Pule marked as A-A', B-B' and C-C', and 2 over Malkapur-Ratnagiri marked as D-D' and E-E') in the study region in order to understand the geometry of the aquifers (Fig. 1). The 2-D geoelectrical cross-sections based on the true resistivities are shown in Figs. 3a, b, c and Figs. 4a, b and thus the interpretation and discussion is based on the true resistivity cross-sections of the profiles.

Devrukh-Ganapati Pule region

In Ganapati Pule to Devrukh region, 2-D geoelectrical section of three profiles namely A-A', B-B' and C-C' have been interpreted consisting of 23 VES points.

A-A' Profile:

Profile A-A' covers the stations VES 19, 21, 20, 18, 17, 16, 22, 23 and 3 from west to east. It can be seen from the resistivity section (Fig. 3a) that all the stations are covered

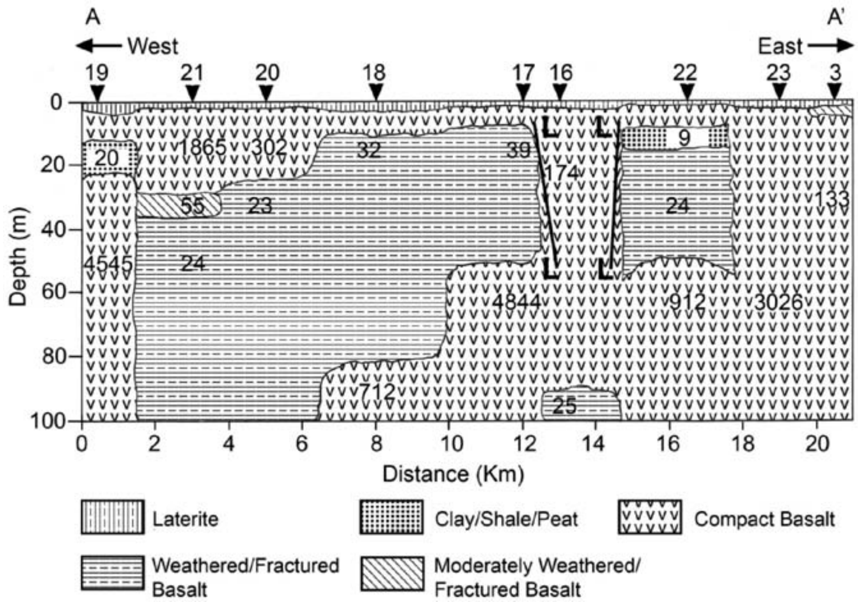

Figure 3a. Geoelectric section along profile A-A'. Lineaments are marked as L-L.

by laterite at the top followed by hard and compact rocks of different resistivities from shallow to depths of about 13-30 m below the stations 17,18, 19, 20, 21 and 22. At VES 16, 23 and 3, compact basalts underlie the laterites as evidenced from the high resistive layer (258-302 Ω-m) up to depths penetrated by the sounding. Below VES 19, a low resistivity zone (about 20 Ω-m) is revealed at depths of 12 m extending up to about 24 m. Beneath this low resistive layer, compact basalts with resistivity of 4545 Ω-m are encountered. Lithological section of a dug well (Suryawanshi and Golekar, 2014) in the vicinity of VES 19, reported that the top 12.5 m revealed lateritic formation followed by a 4 m thick layer of shale and peat underlain by compact basalt thus making a good correlation with the dug well lithology. The low resistivity (about 20 Ω-m) may be attributed to shale/peat layer, albeit some difference in its thickness. It is pertinent to mention here that VES 19 is near to the coastal tract with tertiary sediments at the top. Lignites and peat layers were reported in the dug well/bore well by several workers in Ratnagiri district of Maharashtra (Kumaran et al., 2004). A wide low resistivity zone (20-39 Ω-m) is revealed beneath VES stations 21-17 at depths of 10-40 m and extending down to different depths which forms a potential aquifer zone beneath the laterites and traps. Below VES 18 and 17, compact rocks having resistivities of 712-4844 Ω-m are encountered beneath the aquifer at depths of 80 and 50 m respectively. Further east beneath VES 16, a resistive (174 Ω-m) layer of compact basalt overlies a conductive (25 Ω-m) layer which may be weathered /fractured basalt. Below VES 22, a very thin low resistive (9 Ω-m) layer is delineated beneath the laterites at depths of 10 m above an aquifer body with resistivity of 24 Ω-m underlain by compact rocks up to the depth probed by the sounding. The low resistive zones beneath VES 17 and 22, juxtaposed on either side against a high resistive zone beneath VES 16, are controlled possibly by a dyke passing in the vicinity of 16. Dessai and Bertrand (1995) reported that the lineaments in the western Indian continental margin represent dykes, fracture zones and faults. VES 23 revealed a thick resistive (250-3026 Ω-m) layer beneath the thin lateritic formations up to the depth probed by the sounding. The eastern most station on this profile, VES 3, is characterized by a very thin conductive (about 48 Ω-m) layer sandwiched between two high resistive (687 and 1077 Ω-m) layers in the top 3 m. Beneath this hard rock with resistivities of 116-133 Ω-m is revealed.

B-B' Profile:

The B-B' profile covering the central part of the study region encompasses the VES stations 15, 14, 13, 12, 11, 10 and 9 from west to east. The geoelectric cross-section (Fig. 3b) reveals that the top layer is about 1 m thick with resistivity varying from 190-1596 Ω-m at all the VES points corresponding to the lateritic top layer. Beneath this layer, a conductive layer (17-19 Ω-m) is delineated below VES 15 and 12 at depths of 20 m. These localized features are probably due to compact clay/peat formations. A thin weathered zone is revealed beneath VES 9 with a resistivity value of 28 Ω-m at a depth of about 10 m, which could be an aquifer. Further east, VES 8 (not shown in this section) also shows a similar layer but with less thickness. Rest of the profile shows hard and compact rocks as reflected from the resistivity values in excess of

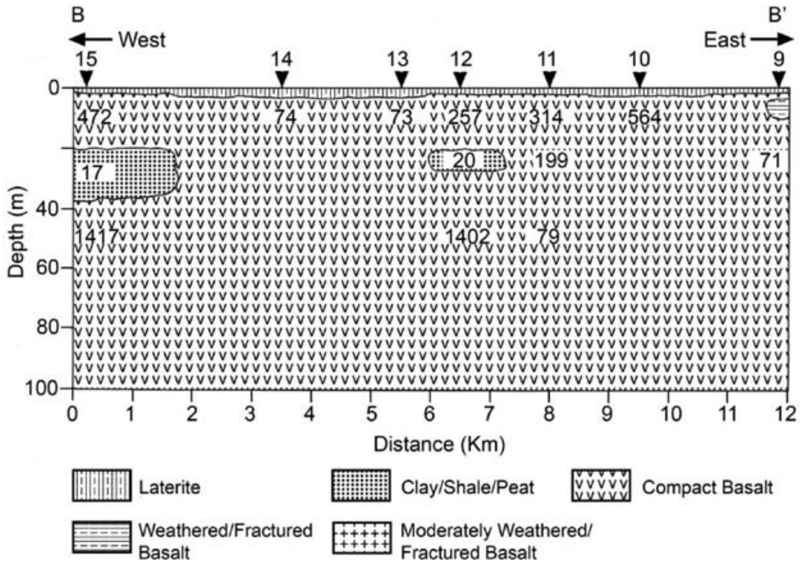

Figure 3b. Geoelectric section along profile B-B'.

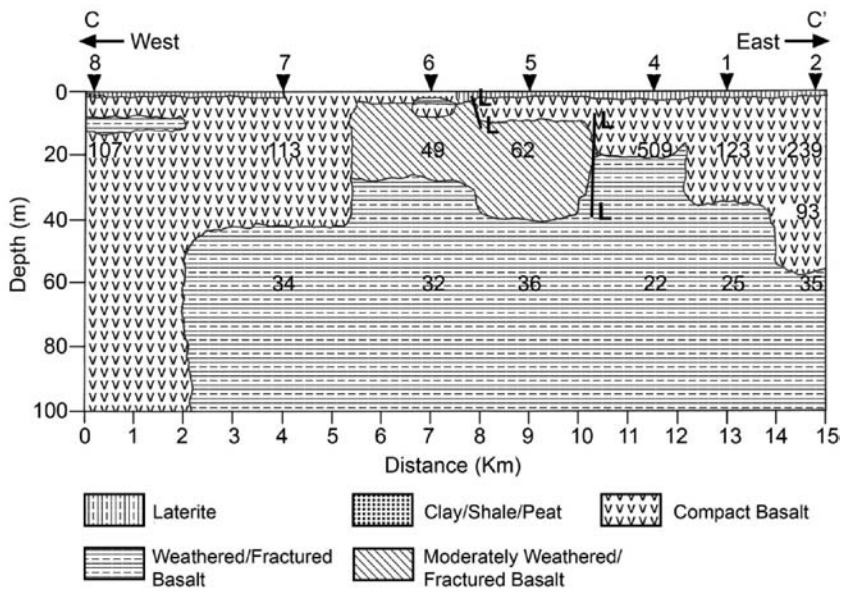

Figure 3c. Geoelectric section along profile C-C'. Lineaments are marked as L-L.

70 Ω-m. A lineament is passing through VES 10 (Fig. 1) does not show any influence in the resistivity section. In lateritic terrain, groundwater usually occurs under phreatic conditions. Majority of the VES stations over this profile are not conducive for groundwater exploration.

C-C' Profile

Profile C-C' encompasses VES stations 8, 7, 6, 5, 4, 1 and 2 from west to east. Except VES 6, which is over the exposed traps, the other VES points are in lateritic formations. The top layer in the geoelectric section (Fig. 3c) reveals resistivities ranging from 407-1624 Ω-m while VES 6 reveals a resistivity of 82 Ω-m with thickness of 0.5 m, which is compact basalt. The second layer in the geoelectric section is more resistive (114-581 Ω-m) with thickness ranging from 0.3-11 m. High resistivity (123-1983 Ω-m) third layer indicative of compact basalt is revealed beneath all the VES stations having a thickness ranging from 4-22 m. The fourth layer is of moderate resistivity (22-64 Ω-m) at VES 8, 6 and 5 which could be probably due to moderately weathered/fractured basalt saturated with water. High resistivity layer (in the range of 75-509 Ω-m) is revealed at VES 1, 2, 4 and 7, which is due to compact

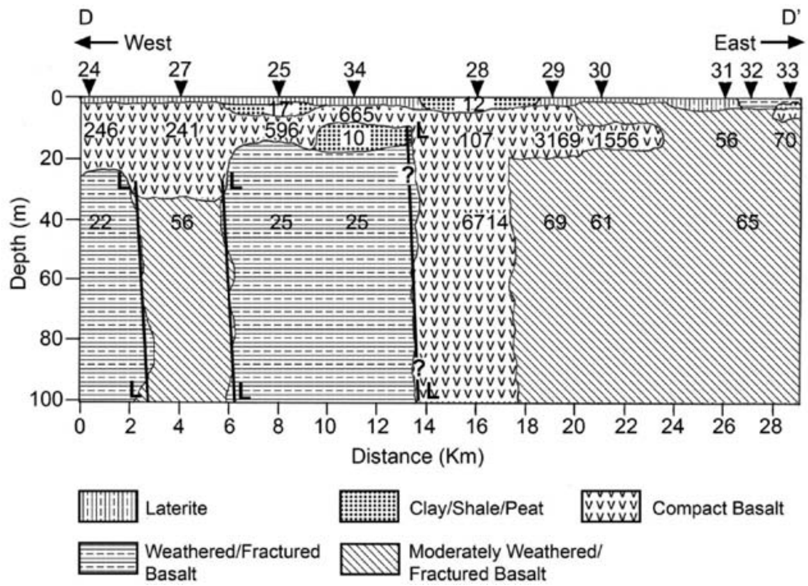

Figure 4a. Geoelectric section along profile D-D'. Lineaments are marked as L-L

basalt. The bottom most layer probed by the soundings along this profile is conductive with resistivities of 22-36 Ω-m at all stations except VES 8 (revealing a resistivity of 107 Ω-m). Two lineaments trending NW-SE and NE-SW are in the vicinity of VES 5 and 6 (Fig. 1). The low resistive feature revealed at VES 5 and 6 bounded by high resistive bodies on either side, is an influence of the lineaments present here. It can be seen from the geoelectric section that the eastern part of the study region reveals promising aquifer zone at depths varying from 21-57 m below VES points 1, 2, 4, 5, 6 and 7.

Malkapur-Ratnagiri region

A total of 20 VES points have been carried out in Malkapur (Kolhapur) and Ratnagiri region and only 19 VES are considered for interpretation purpose. The entire study region (VES points 24 to 43) is divided into two profiles (D-D' and E-E') for the sake of discussion (Fig. 1).

D-D' Profile:

The geoelectrical section along profile D-D' covering the VES stations 24, 27, 25, 34, 28, 29, 30, 31, 32 and 33 (Fig. 4a) indicates that the top 0.5-8 m covered by lateritic formation reveals a large variation of resistivity (12-937 Ω-m) perhaps due to variations in proportions of clay and sand/water content in the top layer. Beneath this layer, at VES stations 25, 28 and 33, conductive (resistivity values varying from 3-17 Ω-m) layer is revealed having thicknesses ranging from 1.6-2.6 m while the other stations reveal higher resistivity (102-3290 Ω-m) reflecting hard rock. The third layer is moderately resistive with resistivities ranging from 61-597 Ω-m at all VES stations except at VES 34, where the resistivity value is about 10 Ω-m. The fourth layer at all stations is less resistive (21-69 Ω-m) except at stations 28 and 29, which is reflecting high resistivity (6714 and 630 Ω-m respectively). From the geological map (Fig. 1), a lineament is noticed in the vicinity of VES 25. The geoelectric section suggests a very low resistivity (17and 5 Ω-m) at depths of 2 and 10 m at VES 25. Also this lineament appears to extend beneath VES 24 as reflected by a low resistive (21 Ω-m) at depths of 24 m and beyond. Zhu et al. (2009) reported that a low resistivity zone observed from near surface extending down can be attributed to a fault zone or lineament. Thus, it may be mentioned that the low resistivity zones (which extend down to depths of 100 m) signify the presence of fault/lineament (Fig. 4a). Another lineament shown in the geoelectric section at VES 34 as a low resistivity feature juxtaposed against a high resistive block beneath VES 28 is not noticed on the geological map (Fig. 1). On the other hand, the lineaments present in the vicinity of VES 31 and 32 (Fig. 1) are not reflected in the geoelectric section. It can be surmised from the geoelectrical section that prospective groundwater aquifer zones exist beneath the locations of VES 24, 25 and 34.

E-E' Profile:

The resistivity section E-E' is drawn based onVES stations 37, 38, 39, 40, 41, 43 and 42 (Fig. 4b) located mostly on the traps. The geoelectric section reveals that the subsurface is heterogeneous in nature. The top layer of the geoelectrical

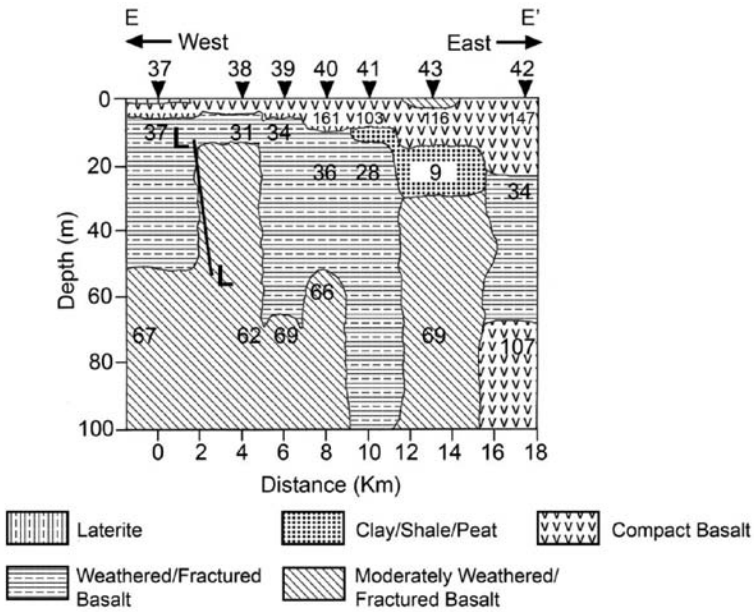

Figure 4b. Geoelectric section along profile E-E'. Lineament is marked as L-L.

section reveals a resistivity 45 Ω-m having thicknesses less than 1m at VES stations 37 and 43, which reflects moderately weathered/fractured rocks saturated with water. Beneath VES 38, 39, 40, 41 and 42, the top layer resistivities range from 77-419 Ω-m indicating compact basalt. The second layer with resistivities (71-701 Ω-m) at all stations corresponds to hard and massive basalt. The third and fourth layers are relatively conductive at VES 37, 38 and 41 with resistivities varying from about 13-66 Ω-m and thicknesses ranging from about 4 m up to depth probed by the sounding. At VES stations 39, 40, 42 and 43, the third layer reveals high resistivity values ranging from 116-161 Ω-m, while the resistivity values of fourth layer at these stations vary from 9-36 Ω-m. The very low resistivity (9 Ω-m) layer beneath VES 43 at depths of about 14 m is indicative of clayey/peat layer. The fifth layer is moderately resistive (62-69 Ω-m) at all station except at VES 42 where it is 107 Ω-m. The geoelectric section reveals a potential aquifer zone at VES 37 up to depths of about 48 m. Also a lineament present in the vicinity of VES 37 appears to aid in recharging this aquifer. Further east over the profile, likely aquifer zones are observed at VES 39, 40 and 42 up to depths of 65 m, 52 m and 68 m, respectively while VES 41 reveals aquifer up to the depth probed by the sounding.

CONCLUSIONS

In the present study, groundwater potential zones were identified using vertical electrical resistivity soundings over parts of Ratnagiri and Kolhapur districts located in the hard rock terrain of DVP. The geoelectric sections obtained after inversion of measured apparent resistivity data at 43 VES stations over five profiles suggest that the sub-surface structure is divided into multiple units due to weathering, fracturing and faulting that influence the occurrence of groundwater in basaltic rocks.

Two-dimensional geoelectric modeling of the Devrukh-Ganapati Pule profile revealed that the top layer is dominated by very high resistivity indicating lateritic formation. A conductive zone (8-20 Ω-m) was revealed beneath VES 12, 15, 19 and 22 having thickness varying from 1.5-20 m, presumably due to shale/peat formation. Low resistivities varying between 22 and 40 Ω-m at sounding locations viz. 21, 20, 18, 17, 22, 7, 6, 5, 4, 1 and 2 are potential for groundwater exploration. These zones are weathered/fractured basalts saturated with water and underlying the laterites/traps. The geoelectric cross-section over Malkapur-Ratnagiri area reveals prospective aquifer zones at VES points 24, 25, 34, 37, 39, 40, 41 and 42 with resistivity values ranging from 22-37 Ω-m. This region is a typical basaltic area, where massive traps exist between top soil and bottom weathered to moderately weathered/ fractured basalt. A few lineaments were identified in the study area some of which revealed influence on the groundwater potential.

The geoelectric sections reported here suggests that most of the potential aquifer zones are between 10-40 m below ground level. It has been reported by Deolankar (1980) that the weathered basalt shows highest aggregate porosity (34%) in DVP, whereas the specific yield is less (around 7%). Though the porosity is high, the specific yield is very small signifying higher specific retention of the weathered basalt. This may be caused due to the presence of clay minerals in the weathered basalt which has higher water retention capacity. Over Devrukh-Ganapati Pule profile at VES 18, 17 and 22 (Fig. 3a), shallow dug wells are viable as the weathered fractured basalt saturated with water is revealed at depths of about 10 m below ground level. At VES 21, 20, 7, 6, 5, 4, 1 and 2, bore wells are preferable as the weathered and fractured basaltic zone is at depths of about 20-50 m below ground level. Malkapur-Ratnagiri area reveals that the saturated zone lies at depths of about 8-20 m below ground level. Dug wells at VES stations 24, 25, 34, 37, 39, 40, 41 and 42 may yield copious water.

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