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Delineation of Fresh Water Zones in Coastal Aquifers through quality check analysis of Electrical Survey Logs

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ABSTRACT
The separation of Short and Long Normal responses coupled with estimated R_w value delineated the fresh water bearing sands in the coastal region of Orissa, India. The log data interpretation yielded a geoelectric model of subsurface and key formation parameters. Even though Self-Potential (SP) curve is featureless, natural Gamma Ray (GR) curve has allowed estimations of shaliness (V_{sh}) and identification of clay beds. There seems to be a seven-layer sequence with a 37m thick fresh water zone of TDS value of 596 PPM at an approximate depth of 45m bounded by clay/ shaly sand zones. Based on derived geoelectric section, Short and Long Normal curves are synthesized by finite-difference based forward modeling. The computed logs closely match with the original data set, thereby validating the log interpretation.

INTRODUCTION

The importance of Electrical Survey (ES) logs is increasingly felt in delineation of fresh water zones in coastal regions, wherein fresh water bearing sands are usually sandwiched within clays overlain or underlain by saline sands and when surface geophysical surveys fail to resolve them.

The traditional interpretation of ES log data is dealt widely in geophysical literature (Schlumberger 1949, 1950, 1955; Lynch 1962; Serra 1984; Brock, 1986).

However, forward modeling can only check the quality of log interpretation and such a step is vital in geohydrological investigations of coastal zones. Mufti (1976, 1978, 1980) has presented a finite-difference based forward modeling algorithm in geoelectrics. Subsequently, several others have adopted it in different well log studies (Towle, Writman & Kin 1988; Drahos1984; Roy & Dutta,1994).

We have generated a versatile forward modeling software for electrical resistivity logs based on (Mufti, 1980) and (Towle, Writman & Kin 1988) and It can incorporate invasion effects (Fig.1) also. This log modeling software (LOGFORWAD) has been used here for quality check of log analysis results.

Electrical Log interpretation

The interpretation of Electrical Survey (ES) log (Fig. 2) data (Normal (16"), Lateral (64"), Gamma ray (GR) and SP logs) pertaining to a representative well (Fig.3) at Konark, Orissa is underdertaken. Usual sedimentary lithologies related to a typical coastal environment dominate the study region.

Interpretation

1. Bed boundaries: Visual analysis of resistivity logs (16" and 64" Normal) delineates different bed boundaries with SP and GR logs (Fig.2) serving as constraints. As a result, the entire log section is divided into several lithological units, viz., A, B, C, D, E, F and G (Fig.2) with the following observations:

a) Layer A is permeable with $R_{mf} < R_w$; $R_{16"N} < R_{64"N}$. SP curve should be inversed. But it is not so. Thus SP curve is rendered useless and one has to rely on GR log only for formation evaluation.

b) Layer B is a clay bed with $R_i = R_t$ and no invasion. In fact Archie's law cannot be applied here.

c) Layer C is permeable. In strict sense needs shoulder bed correctionfor ES logs. As SP log is featureless, one can't undertake this correction for it. For other resistivity logs it can't be applied due to lack of the respective departure curves.

d) Layer D is a clay bed with $R_i = R_t$ and no invasion. R_t = 5 ohm-m.

e) Layer E is again a permeable bed. It seems that increase of clay content increases from 83 – 100m.

f) No obvious F Layer. But for synthetic log generation one can consider it and the support for

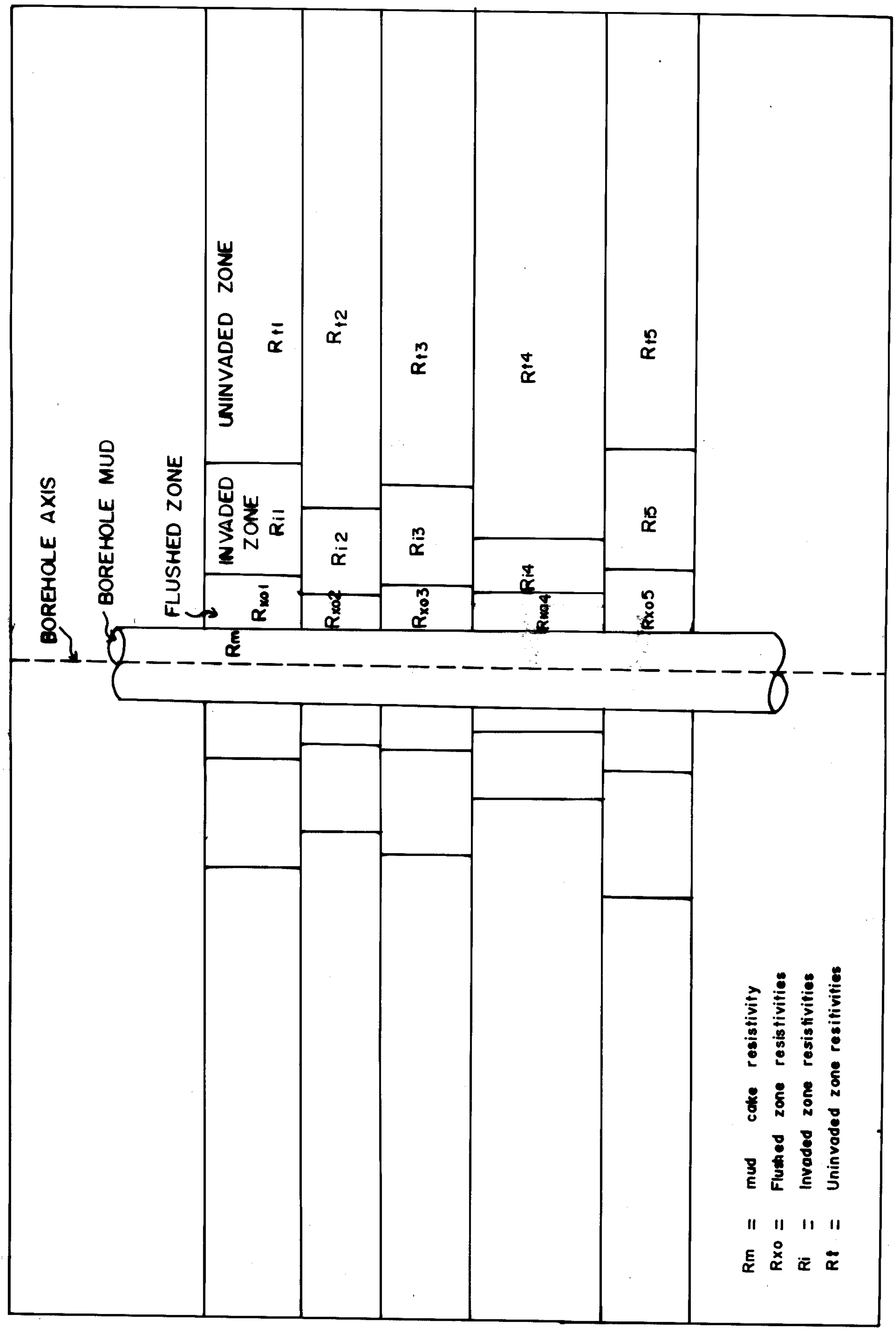

Figure 1. Electrical resistivity model around borehole axis for a multi-layered earth with varying diameter of invasion.

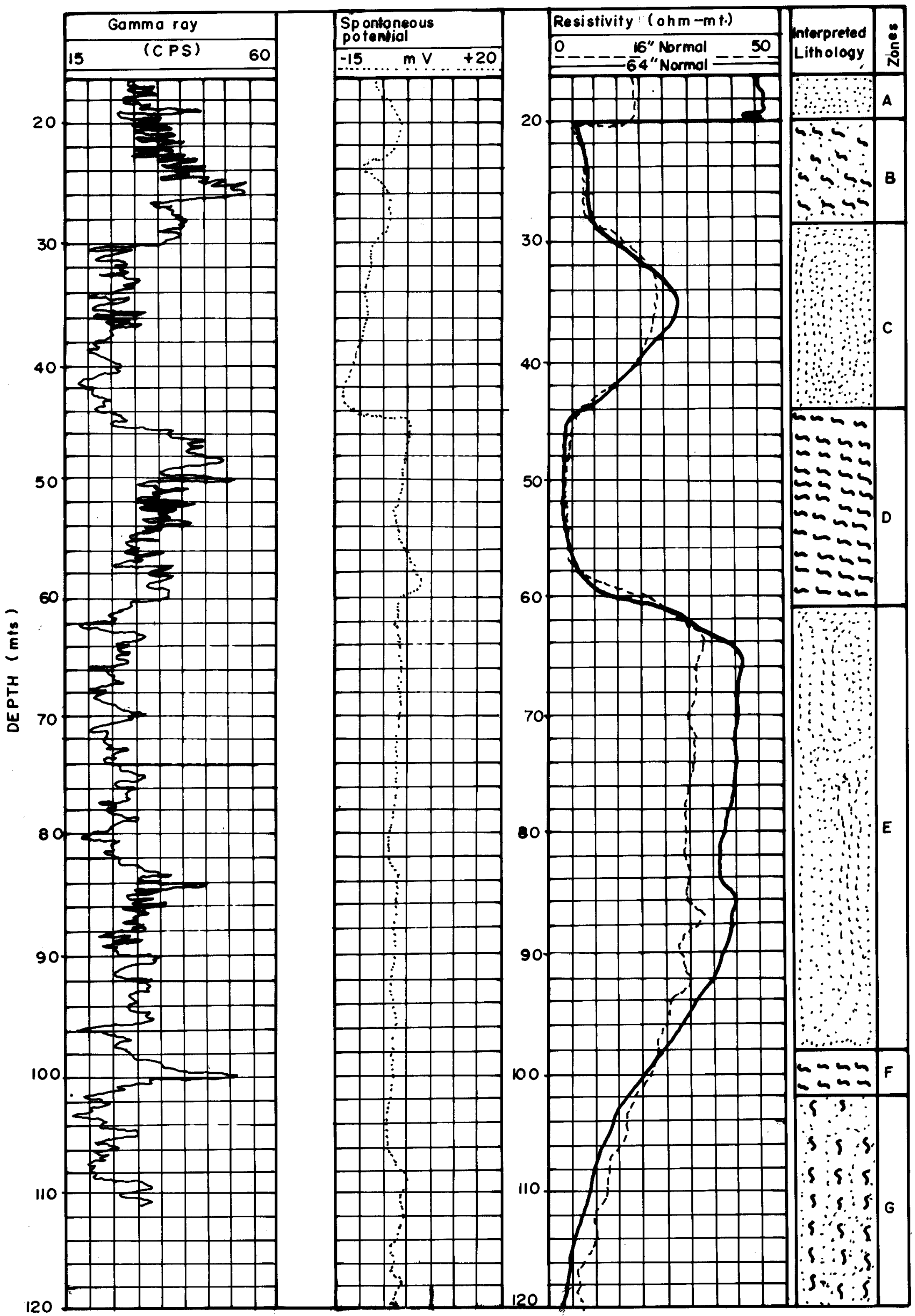

Figure 2. Electrical Survey (ES) logs along with interpreted lithology. The identified lithological zones are A, B, C, D, E, F and G. They are respectively sands, shaly sands, sands, clays, sands, clays and marine shaly sands containing saline water.

such a decision comes from GR log.

g) Layer G is permeable with some clay. $R_{mf} > R_w$ and since $R_w < 6$ ohm-m, the bed contains salty water.

h) As no specific conversion chart is available, as per practice, one can consider $R_{mf} = 0.75\ R_m$.

2) Log digitization and Geoelectric Model generation: The electrical resistivity Short Normal and Long Normal logs (SN, LN) are initially digitized at one-meter interval. Then, a representative resistivity value is computed for each lithological unit by considering the average of digital samples in that zone, leading to a resistivity model. Similar procedure is adopted for other components of ES log. The relevant details are included in Table 1.

3)Environmental corrections and R_t & R_i determination:

a) Borehole temperature is determined for each lithological zone by standard methods and the mud resistivity (R_m) values are corrected for the temperature effect.

b) The ratio of observed resistivity, R_{obs} to mud resistivity, R_m is determined for each zone.

c) Departure curves are used to find corrected true resistivity, R_t and invaded zone resistivity, R_i values for each zone. These values are included in Table 1.

As per standard logging practice, both short normal (16") and long normal (64") logs are used for estimation of Formation Factor (F), Formation water resistivity (R_w), Total Dissolved Solids (TDS) and Water Saturation (S_w). However, shaliness (V_{sh}) is determined from GR log. For these estimations, the following expressions are used.

1) Formation Factor (F)

It is the ratio (Brock 1986) of resistivity of formation completely saturated with water, R_o to formation water resistivity, R_w.

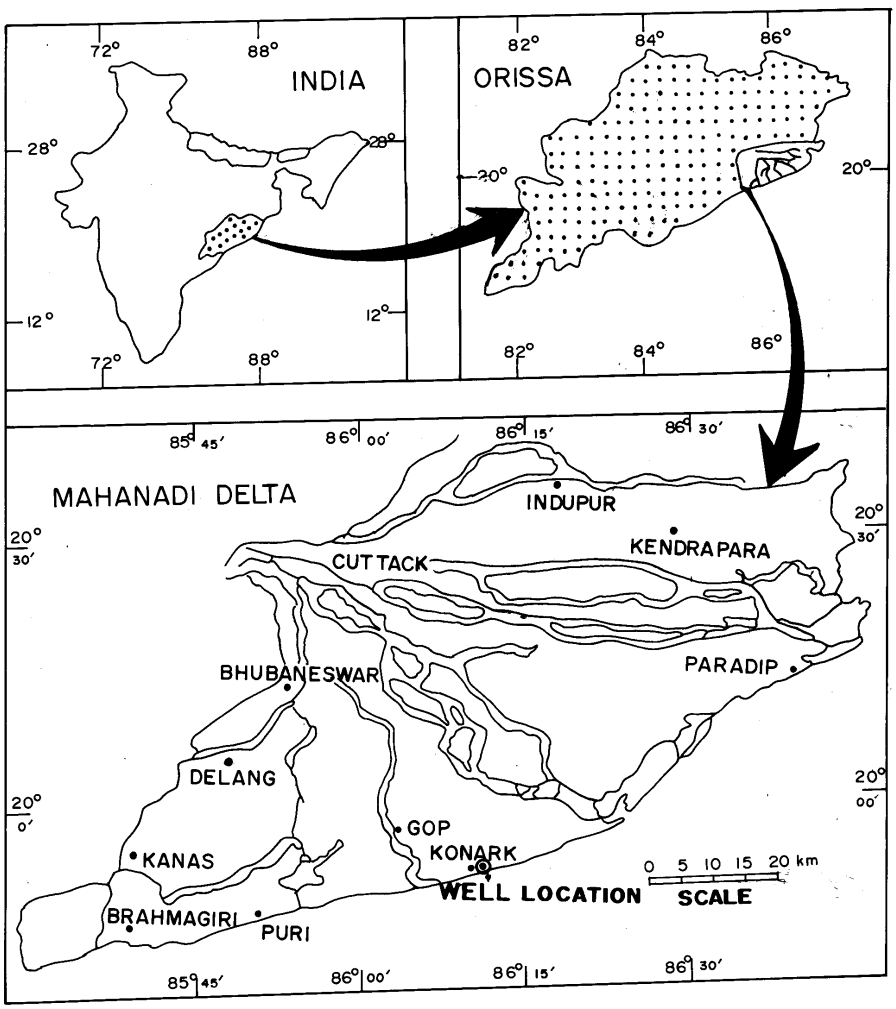

Figure 3. Location map of study region

Table 1. Observed and corrected Electrical Survey log data

S.No	Zone	Thick-ness (m)	Depth (m)	GR (CPS)	SP (mV)	R_a (16"N) Ohm-m	R_a (64"N) Ohm-m	T°C	R_m Ohm-m	$R_{16"N}/R_m$	$R_{64"}/R_m$	$(R_{16"N}/R_m)$ Corr	$(R_{64"}/R_m)$ corr	$(R_{16"N})$ Corr Ohm-m	$(R_{64"N})$ Corr Ohm-m
1	A	4	16-20	28	-3.75	17.5	45	27.3	6.75	2.59	6.67	2.3	6	15.52	40.5
2	B	9	20-29	40	-10	6.2	8	27.5	6.73	0.93	1.18	0.9	1.1	6.05	7.4
3	C	15	29-44	25	-8	19	25	27.7	6.7	2.83	3.73	2.5	3.6	16.75	24.1
4	D	17	44-61	36	-2	4.37	3	28.1	6.64	0.65	0.45	0.6	0.4	3.98	2.65
5	E	37	61-98	26	-3	30	38	28.4	6.6	4.54	5.75	3.75	5.5	24.75	36.3
6	F	4	98-102	52	-4	22	20	28.8	6.55	3.35	3.05	3.05	3	20	19.6
7	G	At least 20	>102	23	-3	12.5	5	29	6.53	1.91	0.76	1.75	0.7	11.08	4.56

Table 2. Formation parameter estimation

Zones	Lithology	R_i (Ω-m)	R_t (Ω-m)	V_m	$R_{mf} = 0.75\ R_m$ (Ω-m)	$F = R_i/R_{mf}$	$R_W = R_t/f$ (Ω-m)	TDS = 6400/R_w ppm	φ
A	Alluvium	15.52	43.88	0.33	5.06	3.06	14.31	447.14	45
B	Shaly sand	6.99	7.94	0.66	5.05	1.39	5.72	1117.50	>45
C	Saline sands	15.075	16.94	0.25	5.02	3.0	5.32	1201.14	45
D	Clay	3.49	2.98	0.55	4.98	N.A	N.A	N.A	N.A
E	Fresh water bearing sand	24.75	53.71	0.27	4.95	5.0	10.74	595.79	35
F	Clay	22.27	32.44	0.32	4.91	N.A	N.A	N.A	N.A
G	Saline sands	11.75	8.40	0.19	4.90	2.40	3.50	1020.57	>45

$F = R_o/R_w$ (1)

For the invaded zone, F is given by

$F = R_{16"N}/R_{mf} = R_i/R_{mf}$ (2)

As short normal responds to invaded zone, the resistivity of pore fluids is considered to be mud filtrate.

2) Formation water resistivity, R_w

R_w is estimated (Serra 1984) by

$R_w = R_t/F = R_{64"N}$ (3)

3) Total Dissolved Solids (TDS)

The TDS is estimated using the relationship

$TDS = 6400/R_w$ (4)

Shaliness (Serra 1984) can be estimated with the help of GR log data by

$Vsh = (GR-GR_{min})/(GR_{max}-GR_{min})$ (5)

Where

V_{sh}, shale volume content

GR, observed log reading from field GR log

GR_{min}, minimum GR log reading in the field log and

GR_{max}, maximum GR log reading in field log

By utilizing the relationships (1 through 5) R_w, TDS and V_{sh} are estimated for the identified zones and are included in Table 2.

Based on log data (Fig.2), the qualitative interpretation has resulted in seven major lithological units. These are alternately clay and sand horizons and are depicted as Zones A, B, C, D, E, F and G (Fig. 2).

The differences between the apparent resistivity values of short normal and long normal curves reach maximum opposite zone E, thereby indicating that it to be a highly permeable bed. Further, a simultaneous occurrence of higher $R_{64''N}$ values and low TDS values (Table 1) in this zone proves that it is a fresh water zone.

The fresh water bearing sands (zone E) in turn overly thin impermeable clay bed (zone F), which is corroborated by a sudden decrease in $R_{64''N}$ values and higher gamma ray, GR, counts. This clay horizon (Fig. 2) separates the overlying fresh water sands (zone E) from underlying saline sands (zone G). Further, the saline sands show higher TDS and low $R_{64''N}$ values. A numerical forward modeling checks the validity of interpretation.

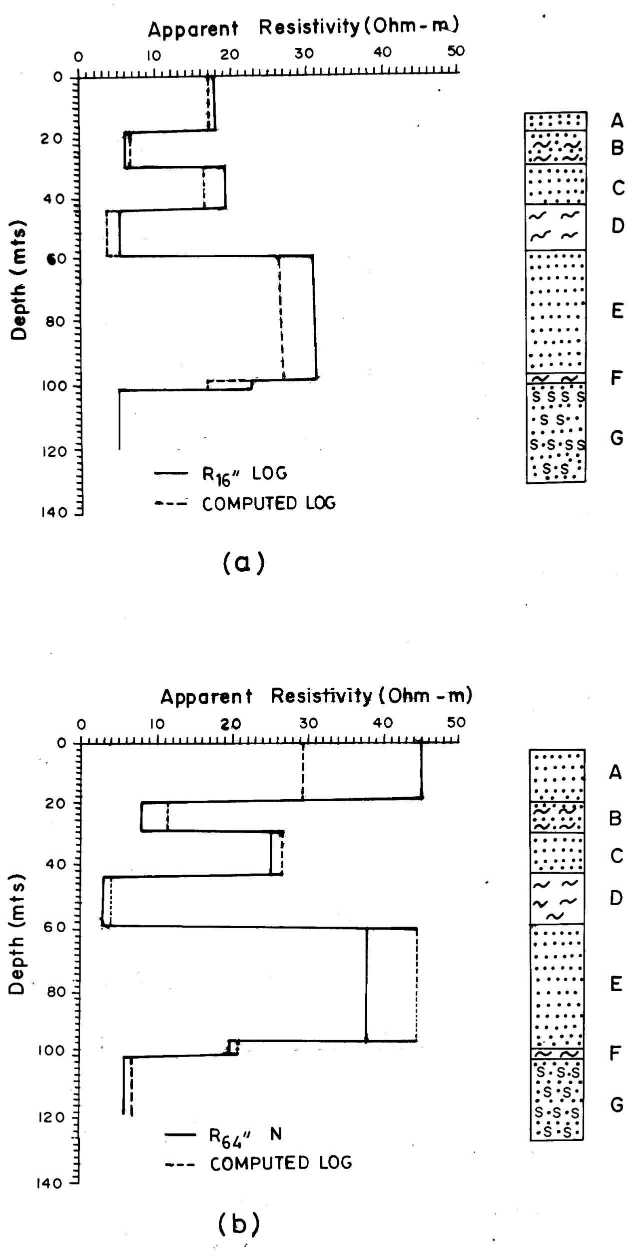

Figure 4. Comparison of observed and computed Normal logs a) Short Normal (AM = 16"), b) Long Normal (AM = 64")

RESULTS AND DISCUSSION

The interpreted model outlined previously (Table 1) served as an input for our forward modeling software (LOGFORWD) and it has computed the short and long normal log responses (Fig. 4).

The synthetic Normal and Lateral logs (Fig.4a and 4b) generated using Finite-Difference based Method (FDM), matches fairly with the observed logs, thereby validating our analysis and emphasizes the need of such a check in conventional log interpretation.

Table 3 provides the comparison between the computed and observed log data. The discrepancies between the computed and observed logs (Fig. 4a and 4b) indicate that the quality of traditional log interpretation as practiced in geohydrological investigations. In the present case, this discrepancy is within reasonable limits. The parameters can be altered slightly to improve upon the analysis results, but such an exercise may be needed in case of complex geohydrological investigations.

Table 3. Comparison between observed and computed logs

Zones	Depth (m)	Observed Log Residstivity (Ω-m)		Computed Log Resistivity (Ω-m)	
		$R_{16''N}$	$R_{64''N}$	R_i	R_t
A	0-20	17.50	45.00	16.89	29.51
B	20-29	7.01	8.00	6.38	11.36
C	29-44	16.00	19.50	16.10	26.60
D	44-61	3.50	3.00	2.87	3.93
E	61-83	30.00	36.46	25.25	44.63
F	83-100	26.88	32.44	16.40	20.93
G	100-120	12.50	8.40	6.21	5.80

CONCLUSIONS

1.For the delineation of a fresh water bearing sands sandwiched within clays of a coastal region, electrical survey logs are highly useful. The short and long Normal logs referred to a representative well of such a region, identify the permeable and impermeable horizons at the qualitative analysis stage.

2.A combination of GR and Electrical logs has allowed detection of a fresh water aquifer, which could not otherwise be detected, as SP is featureless.

3.The integrated log analysis identifies the fresh water bearing sands and provides a geoelectric model, which can be verified by 2D Finite-Difference based Electrical log modeling.

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