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Representation and Interpretation of Resistivity Mapping Data in Groundwater Prospecting in Zambia

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Abstract. The interpretation of apparent resistivity maps in the field of groundwater exploration in Zambia is discussed. It is proposed to resolve iso-apparent resistivity maps into their regional and residual components to simplify their geological interpretation and therefore the selection of proper drilling sites for production wells. This technique is illustrated by a practical example of an area surveyed north-west of Kabwe, Republic of Zambia.

Key words: Iso-apparent resistivity maps – Regional-residual separation – Groundwater exploration.

1. Introduction

Geoelectrical resistivity measurements are common in the investigation of groundwater resources. Geoelectric sounding methods undoubtfully give the most valuable information on geoelectric underground structures and interpretation in terms of the hydrogeology of an area is often possible.

However geoelectric soundings are not only time consuming but also complicated in many parts of Zambia by recumbent folding which gives repetition of bands, and by iron sulphide mineralization. An economic alternative is to use geoelectric mapping techniques.

2. Difficulties Arising from the Interpretation of Iso-apparent Resistivity Maps

Geoelectric measuring techniques where the electrode array is kept constant and measurements are done most conveniently on a regular grid to cover an area of interest are called "geoelectric mapping techniques". Results are commonly represented in form of "iso-apparent resistivity maps".

Their interpretation is generally very difficult because apparent resistivity data not only depend on geoelectric subsurface structures but also on the specific electrode array used. It is the somewhat fictitious nature of the apparent resistivity itself that makes interpretation of apparent resistivity data sometimes ambiguous (Töpfer, 1969).

On the other hand, geoelectric measurements proved to be most efficient to locate groundwater reservoirs or just to site drilling sites within known aquifers (Flathe, 1955; Hallenbach, 1953; Krulc and Mladenovic, 1969; Serres, 1969; Töpfer and Legg, 1974; Flathe and Homilius, 1973; Van Dam and Meulenkamp, 1967).

Large geoelectrically and hydrogeologically unknown areas are most economically surveyed by mapping techniques. Since iso-apparent resistivity maps are difficult to interpret, several electrode spacings have to be applied to decrease at least some of the encountered uncertainties. A few supplementary geoelectric soundings further increase the reliability of geoelectrical interpretation (Kunetz, 1966).

Quantitive interpretation has been tried in the simple case where a sequence of sedimentary rocks of relatively low specific resistivities is underlain by highly resistive basements rocks. If the electrode spacing is selected long enough so that the total longitudinal conductance can be determined (Kunetz, 1966; Keller and Frischknecht, 1966) then the depth to basement rocks can be determined at each individual field station provided that either the depth to basement is known from few boreholes drilled in the area of investigation or the average resistivity becomes known from well-logging techniques. This interpretation procedure however implies that the average resistivity of sedimentary rocks remains constant over the area of investigation – a criterion which is probably never exactly met in nature.

Qualitative interpretation of iso-resistivity maps is more common and in many parts of Zambia this is the only alternative approach.

Main objectives in the field of groundwater exploration in Zambia are to locate zones of contacts between hydrogeologically different rock types, faults, intrusives into host rocks, dykes quartz veins, or to locate zones of fracturing and fissuring in otherwise solid rock (i.e. in limestones) or zones of less weathering (i.e. in schists and phyllites) (Töpfer and Legg, 1974).

3. Alternative Approaches to the Representation of Apparent Resistivity Data

Iso-apparent resistivity maps are often complex in their appearance thus complicating the process of qualitative interpretation. It appears that "smoothing techniques", – techniques which numerically allow to define restistivity "highs" and "lows" –, and "filtering techniques" which either enhance or reduce certain anomalies, may improve the resolving power of iso-apparent resistivity data and may therefore simplify the process of qualitative interpretation.

These techniques are in common use in the interpretation of gravity and magnetic field data for decades. In gravity and magnetic work these filtering techniques are aimed to separate the field into its regional (REG) and residual (RES) components (Nettleton, 1954). Since residuals are aimed to be interpreted quantitatively, optimal filters have to be applied to maintain magnitude and shape of the anomaly under consideration (Apell, 1974).

Since no quantitative interpretation of apparent resistivity data is attempted, filters must not be necessarily optimal. Thus relatively simple smoothing and filtering techniques may already fulfil the main objectives of this exercise: smoothing of field data, defining analytically resistivity "highs" and "lows", and defining areas of high gradients. Anomalous zones are thus "enhanced" and either immediately suitable for qualitative interpretation or are selected for further detailed exploration programs, such as resistivity measurements on a reduced grid size, geoelectrical soundings and/or seismic refraction surveys.

The terms REG and RES are maintained in this paper although their meaning is certainly different from that common in gravity and magnetic work.

Four simple smoothing and filtering (averaging) techniques are presented and tested. The mathematics involved is relatively simple and can be done by hand or more conveniently by using small desk – or portable mini-computers with sufficient storage capacity.

The RES_i at the i-th field station is defined as

$$\mathrm{RES}_i = \rho_i - \mathrm{REG}_i \tag{1}$$

where ρ_i is the apparent resistivity measured at the i-th field station. Residuals are either positive, negative or zero.

3.1. Constant Average Method

The constant average method is certainly the most simple method to define analytically resistivity "highs" and "lows". The average apparent resistivity of an area is taken to be the mean of all individual measurements, thus

$$\mathrm{REG} = \frac{1}{n} \sum_{i}^{n} \rho_i \tag{2}$$

where n is the number of field station.

3.2. Moving Average Method

Bhattacharya, Jain and Mallick (1974) introduced a nine point averaging method to smooth apparent resistivity data. Eight points on the periphery and one at the center of a square grid are averaged. It is

$$\mathrm{REG} = \frac{1}{9} \left(\sum_{1}^{8} \rho_i + \rho_c \right) \tag{3}$$

where ρ_c is the apparent resistivity as measured at the center of the square grid. The author of this paper defines REG as

$$\mathrm{REG} = \frac{1}{8} \sum_{1}^{8} \rho_i \tag{4}$$

and

$$\mathrm{RES} = \rho_c - \mathrm{REG} \tag{5}$$

A similar method has been used in gravity work where four points on the periphery of a circle with radius s (s is the grid length) are averaged and be taken to be the REG at the center of the circle (Nettleton, 1954).

3.3. Least Squares Method

The best fitting REG to the observed data may be determined by least squares methods (Agocs, 1951). The most simple assumption is that a plane of first order is best fitting the observed data:

$$\mathrm{REG} = Ax + By + C \tag{6}$$

where A, B, C are constants and x, y are rectangular coordinates. The constants A, B, C can be determined from the following three independant, linear equations:

$$\begin{aligned} &A\Sigma x^2 + B\Sigma xy + C\Sigma x - \Sigma \rho x = 0\\ &A\Sigma xy + B\Sigma y^2 + C\Sigma y - \Sigma \rho y = 0\\ &A\Sigma x + B\Sigma y + nC - \Sigma \rho = 0 \end{aligned} \tag{7}$$

where n is the total number of field stations.

3.4. Moving Least Squares Method

The above outlined least squares method may be applied to eight resistivity values on the periphery and one at the center of a square grid. The mathematical procedure is the same than indicated in Section 3.3. However it must be noted that lines of singularity will necessarily occur where adjacent best fitting planes do intersect.

3.5. Comparison of Proposed Smoothing and Filtering Methods

REG – and therefore RES – values as derived from the proposed smoothing and filtering techniques depend either on the station density (or size of the area of

Table 1. Comparison of proposed smoothing and filtering methods

Method	Dependent on station density	Dependent on grid spacing	Measurements have to be done on an equal grid pattern
Constant average	yes	no	no
Moving average	no	yes	yes
Least square RES	yes	no	no
Moving least square RES	no	yes	yes

investigation) or on the selected grid spacing. Also some methods described require that field measurements are done on a square grid pattern. A summary of these characteristics is given in Table 1.

It is believed that residual resistivity maps as derived from the constant average and least squares methods, as well as regional resistivity maps as derived from the moving average and the moving least squares methods, do represent the broad regional geology of an area at least to a certain degree of accuracy.

Residual resistivity maps as derived from the moving average and the moving least squares methods may help to site production wells within a geological formation.

4. Practical Example

The 4 techniques described above were examined and compared during a groundwater exploration program north-west of Kabwe, Republic of Zambia. All calculations were done by a Compucorp desk computer, model 425/44. The computing and print-out time for the four methods was 25 s per field station.

4.1. Geological and Geophysical Setting

The existing geological map, which was revised by Kerr (1969), suggests that the investigated area is underlain by metasediments of the Katanga System. The northern and eastern part is mapped to be underlain by schists, phyllites and shales, and the central and south-western parts by dolomites/limestones, both of the Broken Hill Series.

The resistivity contrast between schists and limestones was thought to be sufficiently large, so that these rock types may be located geoelectrically, see Table 2.

Table 2

Rock Type	Location	Spec. resistivity (Ωm)
Weath. schist	Lusaka West	8–100
	NW Dambo (Kabwe)	4–120
Solid schist	Lusaka West	100–900
Weath. chalky limestone	Lusaka West	40–100
Fractured limestone	Lusaka West	140–1,400
	NW Dambo (Kabwe)	250–1,000
Solid limestone	Lusaka West	500–5,000
	Kashitu (Kabwe)	1,500–5,000
	NW Dambo (Kabwe)	1,000–5,000
Cryst. limestone	Lusaka West	10,000–

Phyllites and schists generally represent poor aquifers because of their poor transmissivity whereas excellent production wells are known to occur in areas underlain by karst-type limestones and dolomites of the Katanga System, (Töpfer and Legg, 1974).

The aim of this exploration program was therefore to first locate the schist/limestone contact more precisely and thereafter to locate suitable drilling sites either close to the contact or within the central part of the limestone body itself.

The area was covered on a 100 × 100 m grid by 792 field stations. Two electrode arrays were used: the "long array" ($AB = 150$ meters; $MN = 20$ meters) and the "short array" ($AB = 20$ meters; $MN = 5$ meters).

This field procedure was thought to be necessary in order to ascertain whether low apparent resistivities as measured with the long array are either caused by decomposed, fractured limestone at depth or by conductive overburden, i.e. shales and dambo soils (10–60 ohmmeters) and whether high apparent resistivities as measured with the long array are caused by solid, unfractured limestone at depth or by highly resistive laterite cover (1,000–5,000 ohmmeters).

4.2. Representation and Processing of Field Data

It is not possible to deduce the "known" broad geology of this area from the iso-apparent resistivity map (long array), see Figure 1. Anomalies are scattered and complicated and no general trend is readily visible. It is believed that this is mainly caused by irregular sub-karstic surfaces and by lateral changes of resistivities of the overburden (laterites, shales).

Figures 2–5 present alternative maps as derived from the discussed averaging techniques, see Chapter 3.

Generally all derived regional and residual resistivity maps are smooth as compared to the iso-apparent resistivity map of Figure 1.

Residual maps as derived from the constant average method, see Figure 2, and by the least squares method, see Figure 4, and regional maps derived from the moving average methode, see Figure 3, and from the moving least squares method, see Figure 5, are of very similar appearance, respectively.

Only zero-residual lines are drawn for sake of clarity in Figures 2 and 4, respectively.

It appears that all derived maps clearly show five zones of similar electric properties. These zones are characterized by negative or positive residuals in Figures 2 and 4 and by smoothed ranges of apparent resistivities in Figures 3 and 5.

Zone *A* occurs in the north-west of the investigated area and is characterized by negative residuals, see Figures 2 and 4, and by relatively low smoothed apparent resistivities (50–100 ohmmeters) see Figures 3 and 5. Zone *A* is interpreted to be underlain by phyllites. This is in agreement with the existing geological map.

Zone *B* is located in the central part of the investigated area. Positive residuals, see Figures 2 and 4, and relatively high smoothed apparent resistivities (101–880 ohmmeters), see Figures 3 and 5, suggest that Zone *B* is underlain by dolomites/limestones of the Katanga System.

This interpretation is supported by the existing geological map.

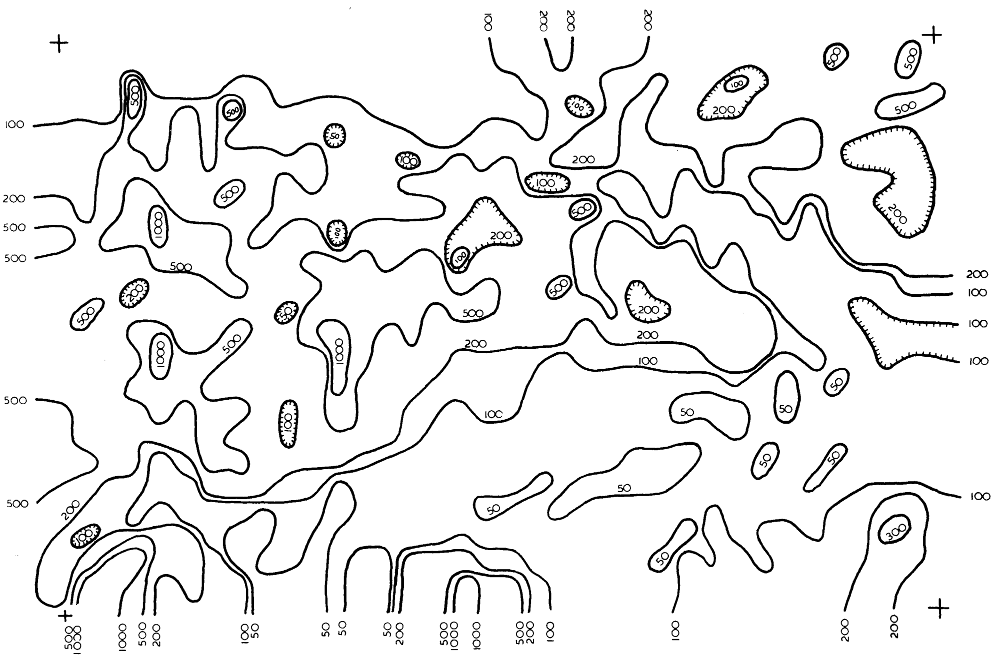

Fig. 1. Iso-apparent resistivity map ($AB = 150$ m, $MN = 20$ m)

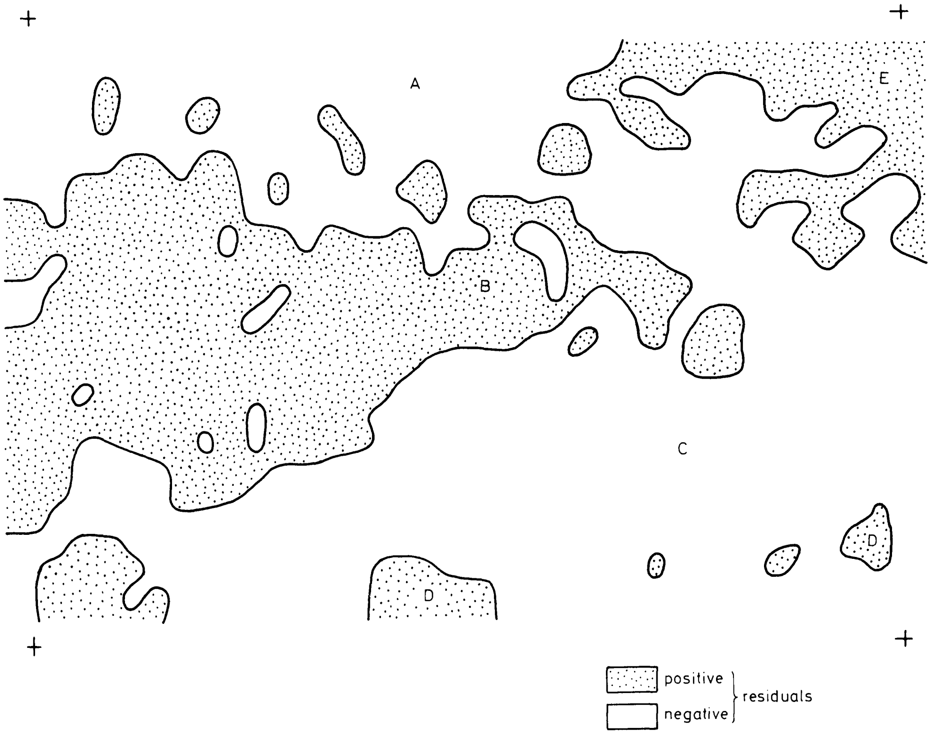

Fig. 2. Residual apparent resistivity map (constant average method)

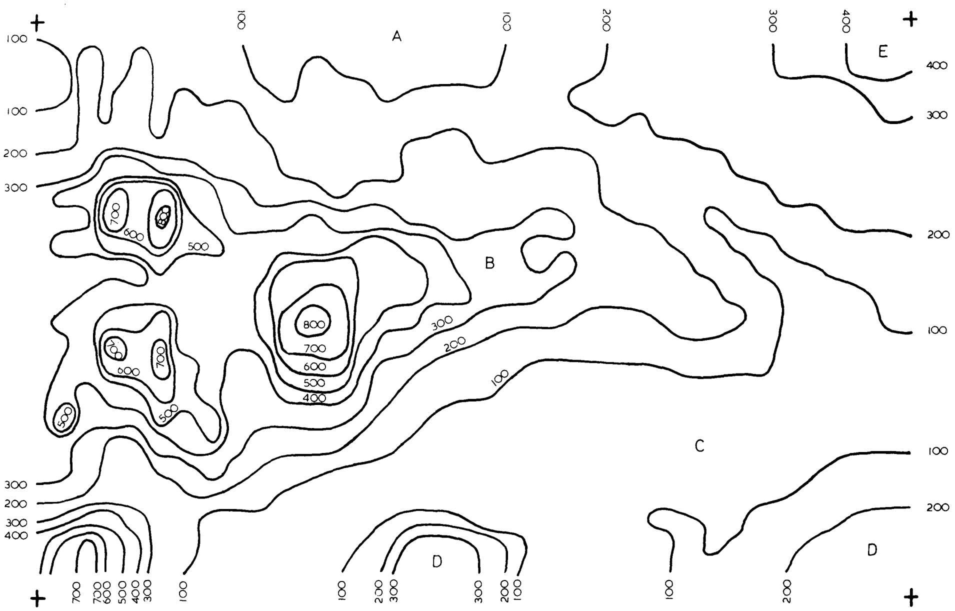

Fig. 3. Regional apparent resistivity map (moving average method)

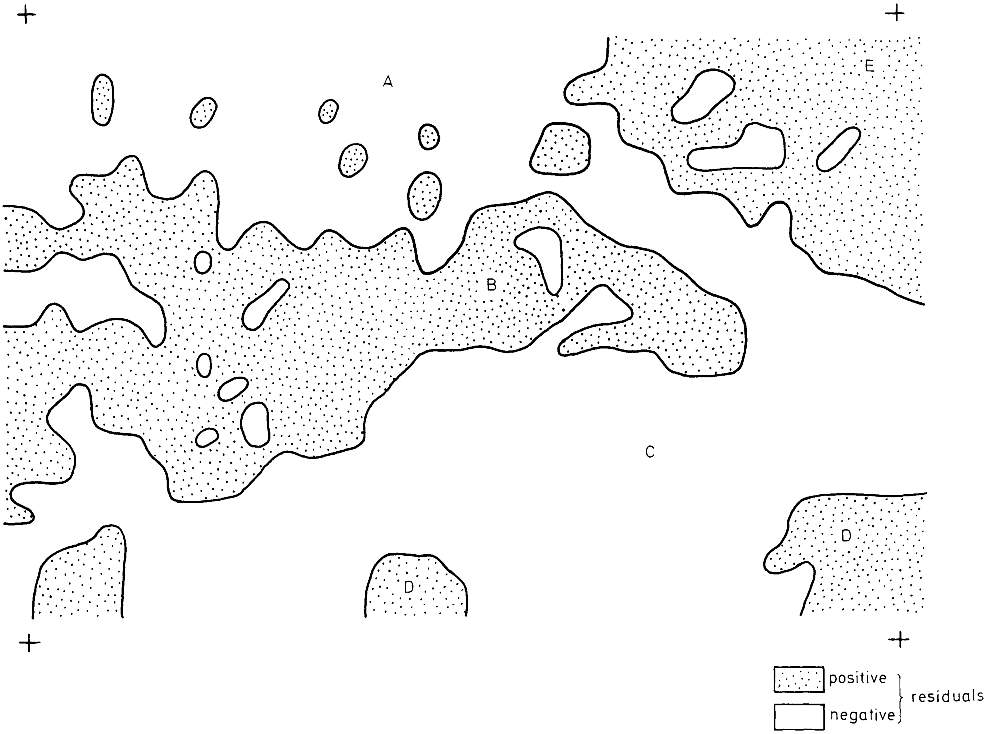

Fig. 4. Residual apparent resistivity map (least squares method)

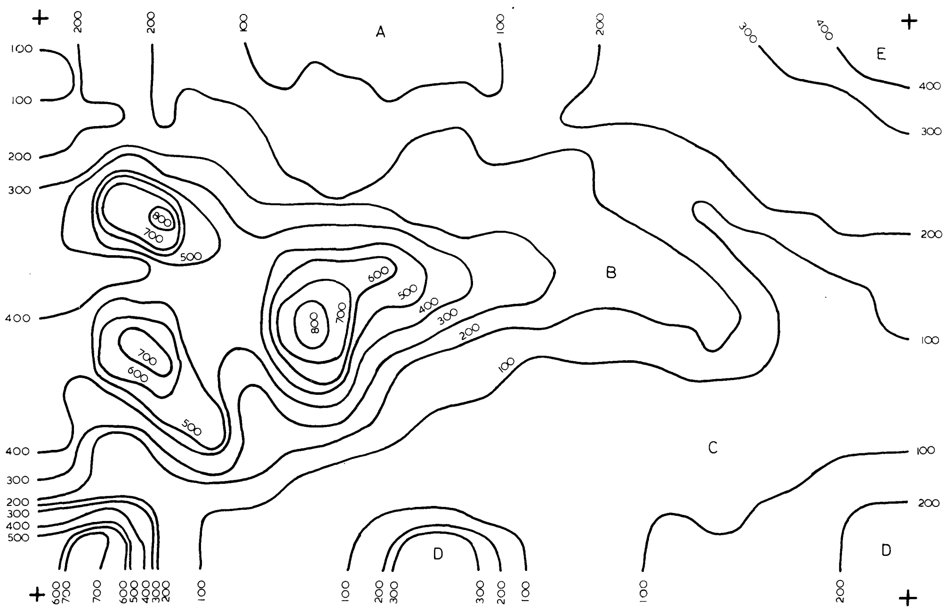

Fig. 5. Regional apparent resistivity map (moving least squares method)

Zone *C* in the south and south-east reveals negative residuals, see Figures 2 and 4, and low smoothed apparent resistivities (40–100 ohmmeters), see Figures 3 and 5. The existing geological map suggests that this zone is underlain by dolomites/limestones. The uniform low apparent resistivities, which characterize Zone *C*, however do suggest that this zone is underlain by phyllites. This interpretation is supported by drilling logs of one borehole which has been drilled recently in this zone.

Zone *D* is apparent as two separated patches in the extreme south of the investigated area. Positive residuals, see Figures 2 and 4, and relatively high smoothed apparent resistivities (101–370 ohmmeters), see Figures 3 and 5, are predominant in this zone. The existing geological map suggests that Zone *D* is underlain by phyllites. This is in contrast to the relatively high apparent resistivites encountered. It is rather thought that Zone *D* is underlain by quartzites or by phyllites interbanded with quartzites. This interpretation is supported by a few quartzite outcrops found in the extreme south-east of the investigated area (Mdala, 1975). Zone *E*, in the north-east, shows positive residuals, see Figures 2 and 4, and moderate smoothed apparent resistivities (200–460 ohmmeters), see Figures 3 and 5. Apparent resistivity values are believed to be too high to represent phyllites, as suggested by the geological map. Resistivity surveys done north and north-east of Zone *E* would rather suggest that the north-eastern part of Zone *E* represents a bed of quartzites which apparently separates gneisses and granites of the Basement Complex from meta-sediments of the Katanga System.

Geoelectrical classification of Zones *A* to *E* and their geological interpretation is summarized in Table 3.

Table 3. Geoelectric Properties

Zone	Geological interpretation	Constant average method (Fig. 2)	Moving average Method (Fig. 3)	Least squares method (Fig. 4)	Moving least squares method (Fig. 5)
A	Phyllite	negative residuals	50–100 Ωm	negative	50–100 Ωm
B	Dolomite	positive residuals	101–815	positive	101–880
C	Phyllite	negative residuals	40–100	negative	45–100
D	Quartzite	positive residuals	101–770	positive	101–815
E	Quartzite	positive residuals	200–460	positive	200–460

4.3. Proposed Hypothetical Geological Model as Derived from this Resistivity Survey and Recommendation of Drilling Sites for Pilot and Possible Production Wells

The qualitative interpretation of apparent resistivity data is based on residual and regional resistivity maps. Their geological interpretation reveals that the investigated area may be underlain by phyllites, dolomites/limestones and by quartzites. This derived geological model, see Figure 7, does not correspond entirely with the existing geological map. Since there are only few outcrops ovserved in the extreme south of the investigated area, pilot wells become necessary in order to verify the proposed geological model.

It is thought that production wells may be possible only in the central part of the investigated area (Zone *B*). Drilling sites are recommended either close to the

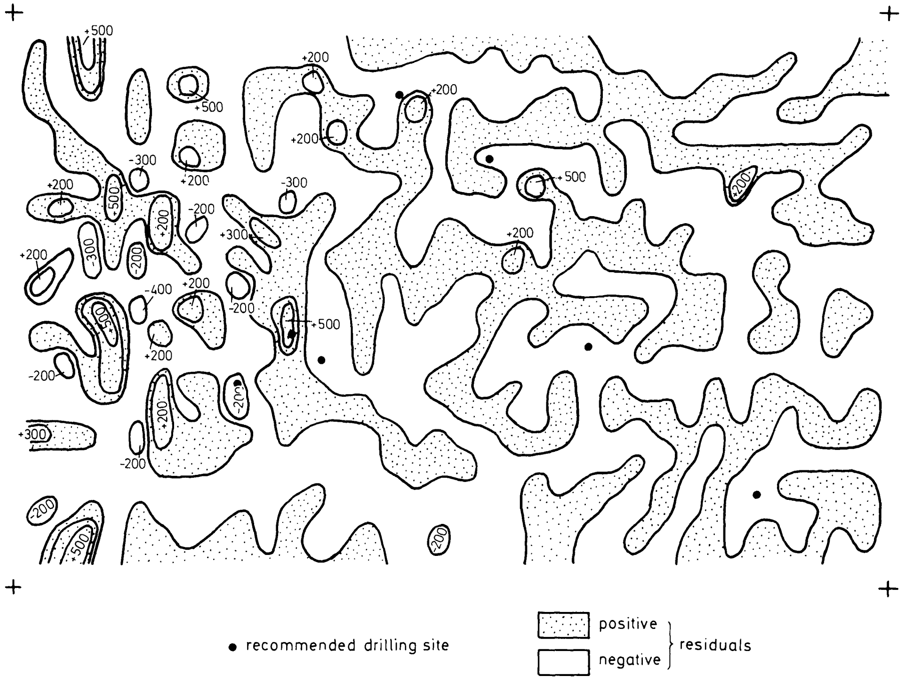

Fig. 6. Residual apparent resistivity map (moving average method)

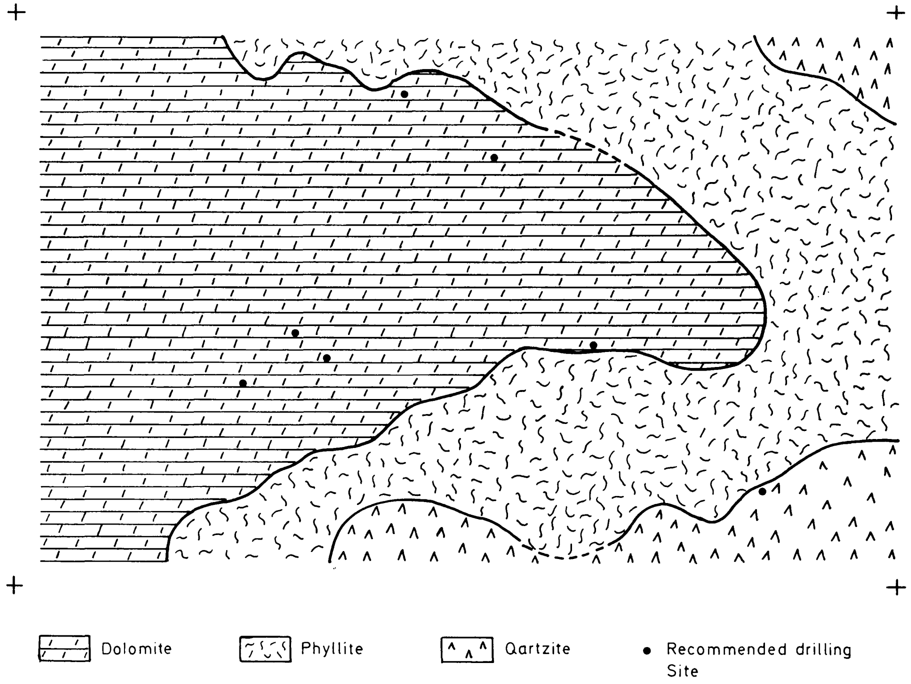

Fig. 7. Interpretation of apparent resistivity data and recommendation of boreholes

interpreted phyllite/limestone contact, or where large negative residuals may indicate cavitation.

A residual resistivity map, as derived from the moving average method, is shown in Figure 6. Large negative residuals and gradients are apparent in the western part of Zone *B*, whereas small negative and positive residuals are predominant in the remaining parts of the investigated area. Recommended drilling sites for pilot and possible production wells are shown in Figure 7.

5. Discussion of Results and Conclusions

The proposed regional–residual separation apparently does largely improve the resolving power of apparent resistivity data, and does therefore facilitate qualitative interpretation at least in those cases where the isoapparent resistivity map itself appears to be very complicated.

The residual map, as derived either from the constant average method, see Figure 2, or from the least squares method, see Figure 4, are very similar in their appearance. Areas characterized by positive or negative residuals are thought to represent different geological formations. Although the zero iso-residual lines may not necessarily coincide with geological boundaries, they certainly do approximately outline areas of similar geoelectrical properties. The constant average method is very simple to apply in the field whereas the least squares method makes the use of mini-computers necessary.

The regional resistivity maps of Figures 3 and 5, which were derived from the moving average and the moving least squares methods, respectively, look very similar and represent a smoother image of the iso-apparent resistivity map, shown in Figure 1. This representation of smoothed apparent resistivity data has the advantage that apparent resistivity data can be related to those which were measured elsewhere in similar geological environments. The regional resistivity map as derived from the moving least squares method is extremely smooth, see Figure 5. Its compilation however is only possible by using mini-computers with sufficient storage capacity.

Residual resistivity maps, as derived from the moving average method, see Figure 6, or by the moving least squares method, are thought to represent local anomalies within a geological formation. Large negative residuals, as observed in the western part of Zone *B*, see Figure 6, may indicate localized fissuring or cavitation in limestones.

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