Finite difference modelling of overburden effects for delineating conducting ore deposits by electromagnetic induction methods

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Abstract. One of the most important problems encountered in induction prospecting is the presence of a conducting overburden covering an ore target. The present study aims to model various complex geological realities consisting of conducting targets covered by relatively less conducting overlying formations. The finite difference numerical approach has been employed, and several apparent resistivity vs. distance plots obtained to study the peculiarities in the apparent resistivity vs. distance variation patterns, due to changes in the physical and/or geometrical properties of the target ore body, overburden, and host medium. Analysis of the numerical results emphasises the importance of mapping such conducting targets of geophysical interest, coupled either conductively or inductively with the overlying structures. The study may be relevant to: (i) searching for mineral deposits underlying the conducting weathered rocks, particularly in low latitudes; (ii) understanding the response modifications due to the presence of undesirable overburden in the AFMAG frequency range; and (iii) identifying the frequency values giving rise to maximum resolution due to lateral conductivity contrasts in the subsurface conditions.

1. Introduction

Electromagnetic (EM) exploration has been applied most successfully in delineating shallow conducting targets (massive sulphides, graphites with predominant minerals like chalcopyrite, galena, sphalerite, pyrite, etc.) which are usually deposited within a series of different lithological units, giving rise to lateral variations in the host rock conductivity, and are covered by a less conducting oxidized layer. Both lateral variations in conductivity and the presence of overlying formations upset the conventional interpretation of the geoelectromagnetic data, and becomes the

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source of confusion by diminishing the ability of any EM exploration system to detect conducting ore bodies. There have been claims about removal of the noise due to overlying formations. However, field and model results have shown that any conductivity discontinuity (either in the lateral or vertical directions) between the target and receiver affects the observability of the conducting ore deposits.

In such complex geology, each component of the section, consisting of overburden, target, host, etc., responds according to its own response parameters (includes conductivity, permeability, frequency, size, depth, etc.) and thus the total induction response becomes complicated. Hence, modelling (either analytical or numerical) of such geological situations is a prerequisite for any exploration programme. It provides a priori information about the feasibility of the actual field surveys in a typical geoelectric section. Computer oriented approximation techniques permit the calculation of AFMAG and VLF anomalies for situations which cannot be conveniently modelled with analytical and/or analog techniques. Various efforts have been made to model such situations using the finite difference method, mainly due to the simplicity of the approximation forms. Saraf et al. (1996) extended the works of Jones and Pascoe (1971) and Pascoe and Jones (1972) on finite difference approximation to study the electromagnetic response of conductive inclusions of different sizes, shapes, and depths at various frequencies in the AFMAG range.

In the present study an attempt is made to study the EM response of laterally inhomogeneous mineralized conducting deposits (such that the size of the target in the lateral direction is greater than in depth) in the AFMAG range using the finite difference approximation technique. Changes in the size, depth, conductivity of the target both in galvanic and nongalvanic contact with the overburden are presented.

2. Description on the model

A semi-infinite conductivity medium occupies the region z>0, and it is assumed that the general changes in the conductivity are confined to the ZY plane and the configuration of the conductor is independent of the X coordinate. The incident plane EM wave in the AFMAG range (10^{-1} to 20×10^{3} Hz) is assumed to be oscillating with period $T=2\pi/\omega$, and the displacement currents are neglected. In the H-polarisation case, Maxwell's equations lead to

$$\begin{aligned} &\left(\partial E_z / \partial y\right)-\left(\partial E_y / \partial z\right) = -\, i\omega\mu H_x \\ &\frac{\partial H_x}{\partial z} - \sigma E_y = 0 \\ &\frac{\partial H_x}{\partial y} - \sigma E_z = 0. \end{aligned} \tag{1}$$

3. Finite difference formulation for H-polarisation

The governing wave equation for H - polarisation is expressed as (Jones and Pascoe, 1971)

$$\frac{\partial^2 H_x}{\partial y^2} + \frac{\partial^2 H_x}{\partial z^2} = + i\eta^2 H, \tag{2}$$

or in vector notation as

$$\nabla^2 H = + i\eta^2 H, \tag{2b}$$

where η^2=4$\pi\omega\sigma$, and the subscript of H is dropped, since H_x is the only component. The magnetic field H is a complex quantity and can be written in terms of real and imaginary components:

$$H = f + ig, \tag{3}$$

Therefore, eq. (2b) can be expressed as

$$\nabla^2 (f + ig) = + i\eta^2 (f + ig). \tag{4}$$

Separating the real and imaginary parts, one has

$$\nabla^2 f = - \eta^2 g \qquad (5)$$
$$\nabla^2 g = \eta^2 f.$$

The left-hand sides of eqs. (4) and (5) are space derivatives and can be replaced by the equivalent difference equations with the help of a Taylor series expansion.

Fig. 1 illustrates a region ABCD with a finite mesh superposed. The mesh points or grid are the discrete points in a continuous space. The finite difference solution requires relating the field values to these discrete points. This amounts to picking up the field values from a continuous function at these selected discrete points. The point "0" and the surrounding points 1, 2, 3 and 4 are chosen to compute difference equations. Let the real and imaginary field components at these points be defined as f_0, f_1, f_2, f_3, f_4 and g_0, g_1, g_2, g_3, g_4 respectively. These field values can be approximated in terms of the field at point 0 as

$$f_1 = f_0 + (\partial f / \partial y)_0 d_1 + \frac{1}{2}(\partial^2 f / \partial y^2)_0 d_1^2 + \text{higher order terms},$$

$$f_2 = f_0 + (\partial f / \partial z)_0 d_2 + \frac{1}{2}(\partial^2 f / \partial z^2)_0 d_2^2 + \text{higher order terms},$$

$$f_3 = f_0 - (\partial f / \partial y)_0 d_3 + \frac{1}{2}(\partial^2 f / \partial y^2)_0 d_3^2 + \text{higher order terms},$$

$$f_4 = f_0 - (\partial f / \partial z)_0 d_4 + \frac{1}{2}(\partial^2 f / \partial z^2)_0 d_4^2 + \text{higher order terms}.$$

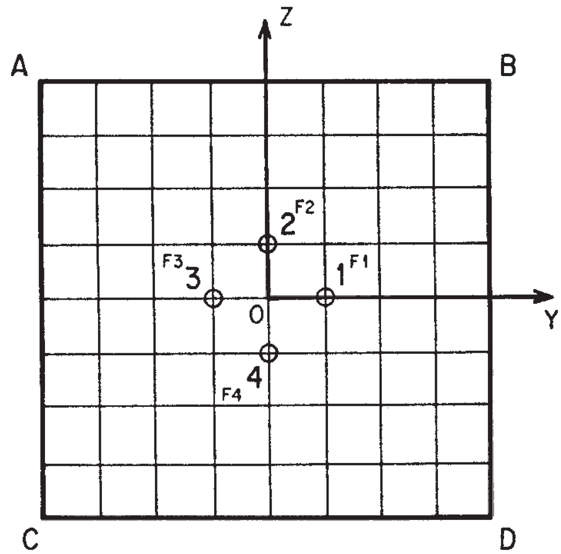

Fig. 1 - Finite difference scheme.

Here, d_1, d_2, d_3 and d_4 are distances of the four points from 0. To simplify the calculation, one can assume d_1=d_2=d_3=d_4=d. In such situations, one has

$$f_1 + f_2 + f_3 + f_4 = 4 f_0 - \eta^2 g_0 d^2,$$
$$g_1 + g_2 + g_3 + g_4 = 4 g_0 - \eta^2 f_0 d^2.$$

By shifting the origin, similar calculations are carried out over the entire model space and the resulting equations assembled. This gives rise to a system of simultaneous equations. The values of η are appropriately incorporated with different regions in the model.

3.1. Boundary conditions

Since conductivity values are assigned to each mesh, the boundary conditions between different interfaces are automatically satisfied. Special care is taken at the air-earth boundary. At the end of the mesh, the mesh points or grids are assigned field values obtained analytically at those specific points for a homogeneous earth model.

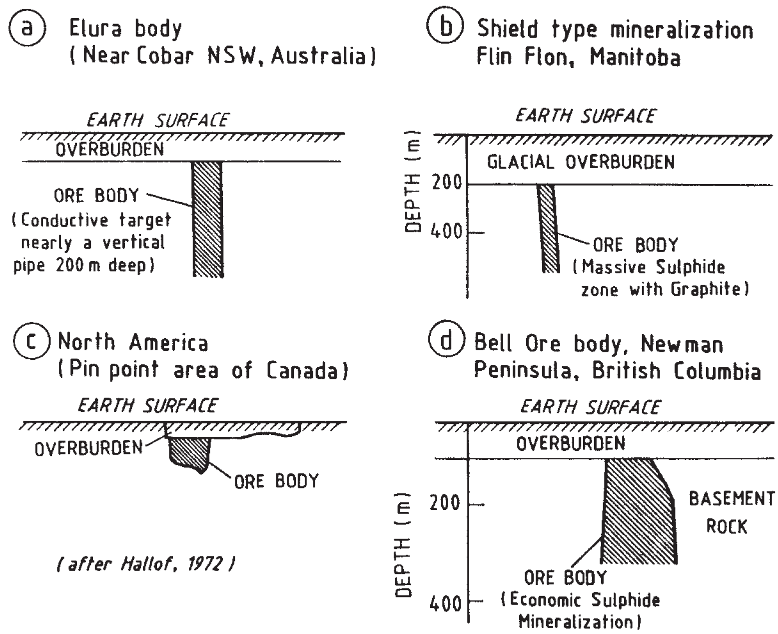

Fig. 2 - Geological sections representig an ore body in galvanic contact with the overburden: a) Elura ore body Australia (from Agostini, 1980); b) Pinpoint area Canada; c) Flin flon, Manitoba (from Hallof, 1972); d) Bell ore body, British Columbia (from Hallof, 1972).

3.2. Solution of the system of equations

The finite difference analysis finally reduces to relating the magnetic fields to the mesh points of the geological model. This is achieved by solving the system of simultaneous equations. In the present study, the Gauss-Seidel iterative method is employed to get the magnetic field. The electric field is computed from the magnetic field with the help of Maxwell's equations. The apparent resistivity values on the ground surface have been obtained, and are presented in the following section.

4. Discussions of the numerical results

Some representative numerical results have been obtained to demonstrate changes in the variation of apparent resistivity with distance for the following specific cases of geophysical interest:

(A) target bodies in galvanic contact with the overburden

(B) target bodies in nongalvanic contact with the overburden.

Scales in the Y and Z directions are not assumed to be the same. Hence, specifications of the

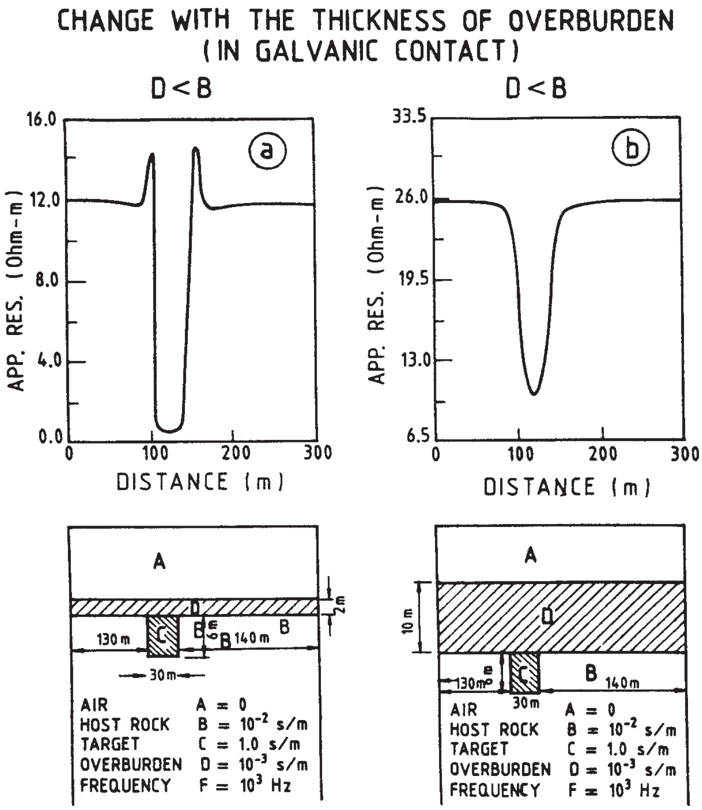

Fig. 3 - Variation of apparent resistivity with distance with change in the thickness of the overburden, which is in galvanic contact with the ore body, for the case when overburden (D) is less conducting than the host medium (B).

model parameters are given for each model, separately.

4.1. Ore body in galvanic contact with the overburden

In several geological situations, the ore body is in galvanic contact with the overlying formations. In Fig. 2, four such situations have been chosen to show that in nature one gets a variety of geological conditions with overburden-ore formations in galvanic contact.

(i) The Elura ore body (Fig. 2a) in Australia is covered by a weathered layer (100 m depth). This ore body is an important producer of gold and base metals (Agostini, 1980).

(ii) Shield type mineralization in Manitoba (Fig. 2b). This is a massive sulphide ore body with graphite, and it is found on the Precambrian green shield. The ore body is in galvanic contact with glacial/limestone overlying formations.

(iii) The Pinpoint area in Canada (Fig. 2c).

(iv) The Bell ore body of British Columbia (Fig. 2d). Both the last bodies are in galvanic contact with the overburden.

In all these four representative cases, it is evident that the ore deposits, the overburden and the host medium may have different physical and geometrical properties.

Hence, in the following section, distortions in the apparent resistivity vs distance plots have been presented for various parameter changes. Specifications of the model parameters are given in each case since the vertical and horizontal scales are chosen differently.

CHANGE WITH THICKNESS OF THE OVERBURDEN. - The depth of the overburden varies according to the composition, mineralogy and porosity of the various surface layers, and also on topography and regional settings (presence of fractures, shear zones, etc.). Usually, such a conducting overburden situation is the source of geological noise which conceals the signal from the ore body being looked for. In Figs. 3, 4 and 5 three different cases of changing overburden properties have been plotted and are discussed in details in the following subsections.

• Overburden is less conducting than the host medium i.e., D<B.

In Fig. 3, two models have been considered and their specifications are as follows:

	Fig. 3a	Fig. 3b
(1) Overburden:		
thickness	2 m	10 m
conductivity D	10^{-3} S/m	10^{-3} S/m
(2) Target body:		
(a) length in lateral direction Y	30 m	30 m
(b) depth in direction Z	6 m	6 m
(c) conductivity C	1 S/m	1 S/m
(d) depth of the target	0 m	0 m
(3) Host medium conductivity B	10^{-2} S/m	10^{-2} S/m
(4) Frequency F	10^3 Hz	10^3 Hz

In Fig. 3, the effect of changing the thickness of the overburden is illustrated and the following pieces of evidence are found.

(i) In Fig. 3a, there are two significant peaks, indicating the presence of a laterally inhomogeneous nature in the subsurface conditions. Rao and Saraf (1993) obtained such peak values in the case of an outcropping target only. A thin overburden in galvanic contact with the ore body also gives a response pattern similar to an outcropping ore body. In the case of thick overburden such peaks are not observed, indicating that the target body is well immersed in the conducting earth (Rao and Saraf, 1993).

(ii) In Fig. 3b, a remarkable observation is that on increasing the thickness of the overburden, the apparent resistivity value increases, i.e., in case of thicker overburden (Fig. 3b) the apparent resistivity value is higher than in the case of thin overburden (Fig. 3a). Usually, the targets are screened because of the thick overburden. However, if a highly conducting target is in galvanic contact with less conducting overburden, the currents may be channeled into the target and thus the target anomaly also increases. This effect will be more sensible in the case of a thicker overburden than a thinner one. In other words, increased overburden thickness may be mistaken for a better conducting target if the overburden and the conducting target are in galvanic contact with each other. This also agrees with the experimental results of Joshi et al. (1984) and Lamontagne (1975).

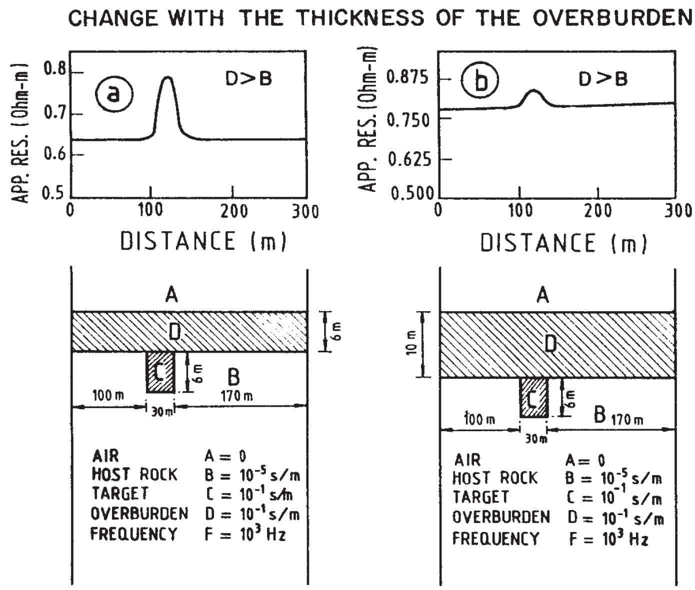

Fig. 4 - Variation of apparent resistyvity with distance with change in the thickness of the overburden, which is in galvanic contact with the ore body, for the case when the overburden (D) is more conducting than the host medium (B).

- Change with thickness of the overburden when the overburden is more conducting than the substratum i.e., D>B and C=D.

Specifications of the model parameters for Fig. 4 are as follows:

	Fig. 4a	Fig. 4b
(1) Overburden:		
thickness	6 m	10 m
conductivity D	10^{-1} S/m	10^{-1} S/m
(2) Target:		
(a) size in lateral direction Y	30 m	30 m
(b) size in vertical direction Z	6 m	6 m
(c) conductivity C	10^{-1} S/m	10^{-1} S/m
(3) Host medium conductivity B	10^{-5} S/m	10^{-5} S/m
(4) Frequency F	10^{3} Hz	10^{3} Hz

In Figs. 4a and 4b it is assumed that the overburden (D) and the target (C) have the same conductivity values. This type of geological section is found in places where the physical properties of different rock types are swamped by weathering, such that their contrasts (for example in this case electrical contrast between overburden and the target bodies) are reduced considerably (i.e., C/D=1). The following two specific points are clearly brought out:

(i) distortion effects, in the apparent resistivity vs. distance variation patterns, due to the presence of overburden in Fig. 3 (D<B) and in Fig. 4 (D>B), show reverse trends and may serve as a means of identifying contrasts in the overburden and the substratum conductivities;

(ii) the channeling effect is more sensible in the case of a thick conductor (Fig. 4b), and this

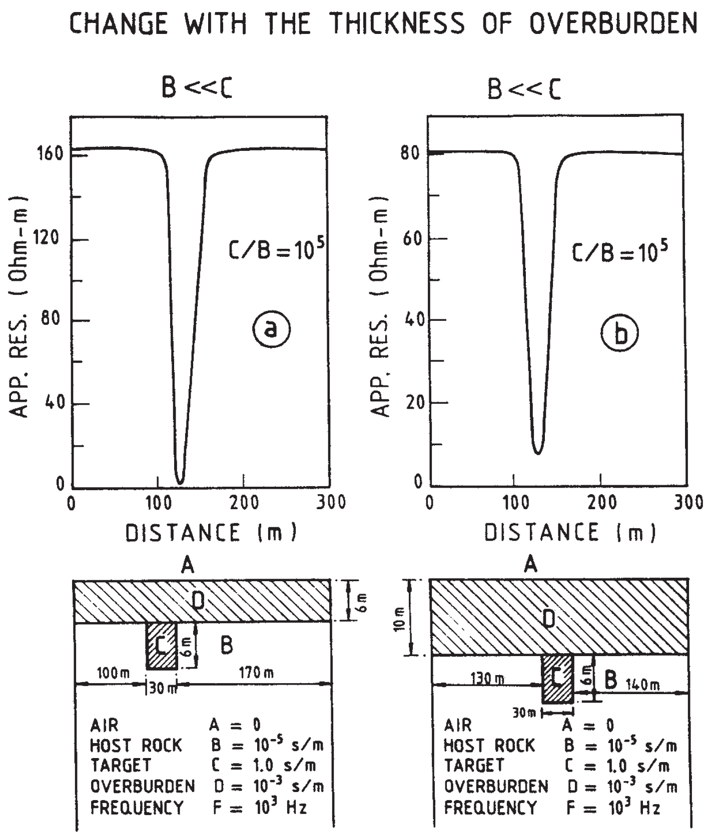

Fig. 5 - Variation of apparent resistivity with distance with change in the thickness of the overburden, which is in galvanic contact with the ore body, for the case when overburden (D) is more conducting than the host medium (B), when the targe (C) is placed in a highly resistive medium C/B=10^5.

gives rise to an enhanced value for the apparent resistivity.

• Change with thickness of the overburden when B<D<C (i.e., B<<C) (Resistive host medium). In Fig. 5 it is assumed that the conducting target C is placed in a highly resistive host medium i.e., C/B=10^5. Here the upper layer (oberburden) is also a better conductor than the substratum (i.e., D/B=10^2). The other specifications of the model parameters are as follows:

	Fig.5a	Fig. 5b
(1) Overburden:		
Thickness	6 m	10 m
Conductivity D	10^{-3} S/m	10^{-3} S/m
(2) Target:		
(a) size in Y direction (lateral direction)	30m	30 m
(b) size in Z direction (depth-wise)	6m	6m
(c) conductivity C	1 S/m	1 S/m
(3) Host medium conductivity B	10^{-5} S/m	10^{-5} S/m
(4) Frequency F	10^3 Hz	10^3 Hz

Unlike Fig. 3, the channeling effect due to a highly conducting target is more sensible in the case of Fig. 5a (with thin overburden). Here almost negligible currents will be induced in the substratum, and most of the currents will be concentrated in the upper layer and the target. In the case of thick overburden, it is also possible that, due to dissipation of energy in the overburden, a major portion the energy may not reach the target. On comparing the variation of apparent resistivity vs distance patterns in Figs. 3b (C/B=10^3) and 4b (C/B=10^5), one finds that in the latter case the magnitude of the apparent resistivity is three times greater than in the earlier case. In other words, the effect of changing the conductivity of the environment/host is quite significant on the EM response parameter. Hence, if one has to find ore, one must study the nature of the surrounding/overlying rocks.

• Change with the frequency of the EM waves.

In Fig. 6, the variation of apparent resistivity with distance has been plotted for change in the frequency of the EM waves (Fig. 6a 10^3 Hz, and Fig. 6b 10^4 Hz). All other parameters are assumed to be the same. Specifications of the model are:

	Figs. 6a and 6b
(1) Overbuden:	
(i) thickness of the overburden	6 m
(ii) conductivity D	10^{-3} S/m
(2) Target:	
(i) size in lateral direction Y	30 m
size in vertical direction Z	6m
(ii) conductivity C	1 S/m
(3) Host medium conductivity B	10^{-2} S/m

Comparison of the variation patterns in Figs. 6a and 6b clearly shows that in Fig. 6b (with frequency 10^4 Hz) the response of the model is quite different than that obtained in Fig. 6a (with frequency 10^3 Hz). Hence, for analysing signals obtained from covered conducting targets, the EM measurements should by taken over more than one frequency.

4.2. Ore bodies in nongalvanic contact with the overburden

Several geological situations are also found where the overburden formations are not in galvanic contact with the ore bodies. Two representative situations, illustrated in Figs. 7a and 7b are chosen to show ore bodies inductively coupled with the overburden, i.e., Wisconsin (lead and zinc deposits) and Noranda, Quebec (gold and base metals). Similar geological realities with overburden ore formations in nongalvanic contact are approximated, theoretically, in this section.

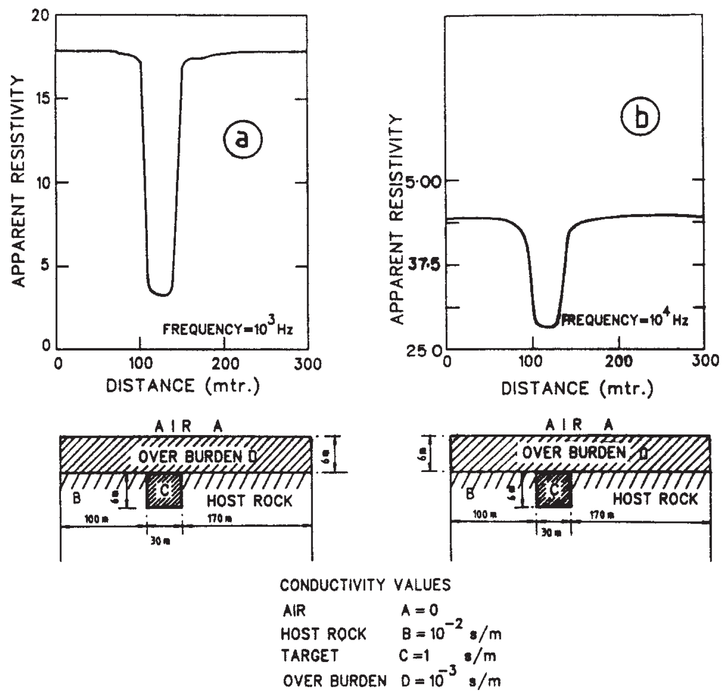

Fig. 6 - Variation of apparent resistivity for the case when overburden (D) is less conducting than the host medium (B), when the frequency of the EM waves is changed i.e., a: F=10^3 Hz; b=10^4 Hz.

CHANGE WITH PRESENCE OF THE OVERBURDEN. - In Figs. 8a and 8b, the effect of the presence of resistive overburden is shown. The specifications of the model parameters are:

	Fig. 8a	Fig. 8b
(1) Overburden:		
thickness	nil	2m
conductivity D	nil	10^{-3} S/m
(2) Target:		
(a) depth from the earth's surface	12 m	12 m
(b) lateral direction Y	20 m	20 m
(c) thickness Z	2 m	2 m
(d) conductivity C	1 S/m	1 S/m
(3) Host medium conductivity	10^{-2} S/m	10^{-2} S/m
(4) Frequency	10^3 Hz	10^3 Hz

Comparison of the variation patterns in Figs. 8a and 8b reveals that the presence of a resistive overburden may increase the apparent resistivity value. This may be explained by the fact that less amount of current concentrate in the resistive overburden and thus increase the amplitude of the target anomaly.

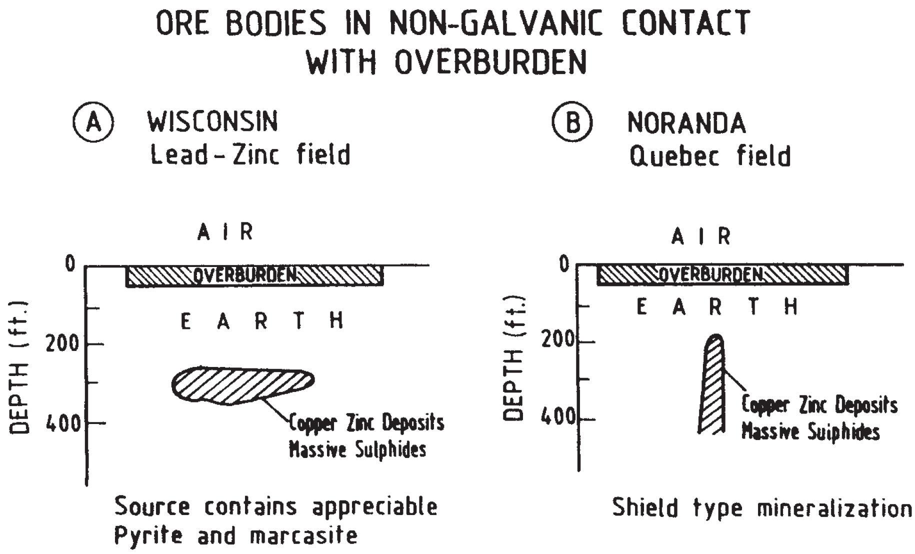

Fig. 7 - Geological sections representing overburden ore situations in nongalvanic contact: a) Wisconsin ore body, b) Noranda ore body (from Hallof, 1972).

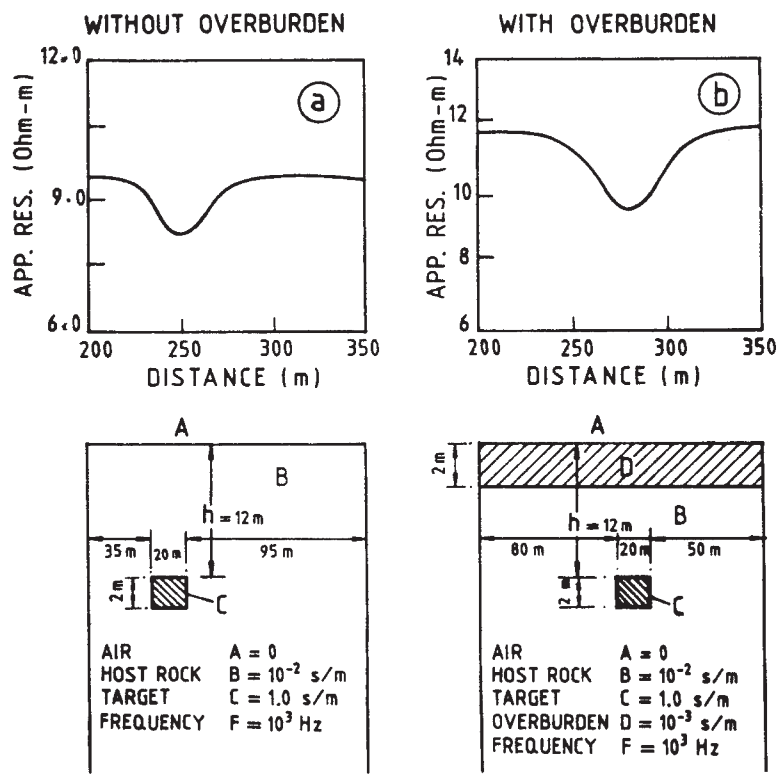

Fig. 8 - Variation of apparent resistivity with distance for: a) the case of a target without overburden; b) the case of overburden covering a target.

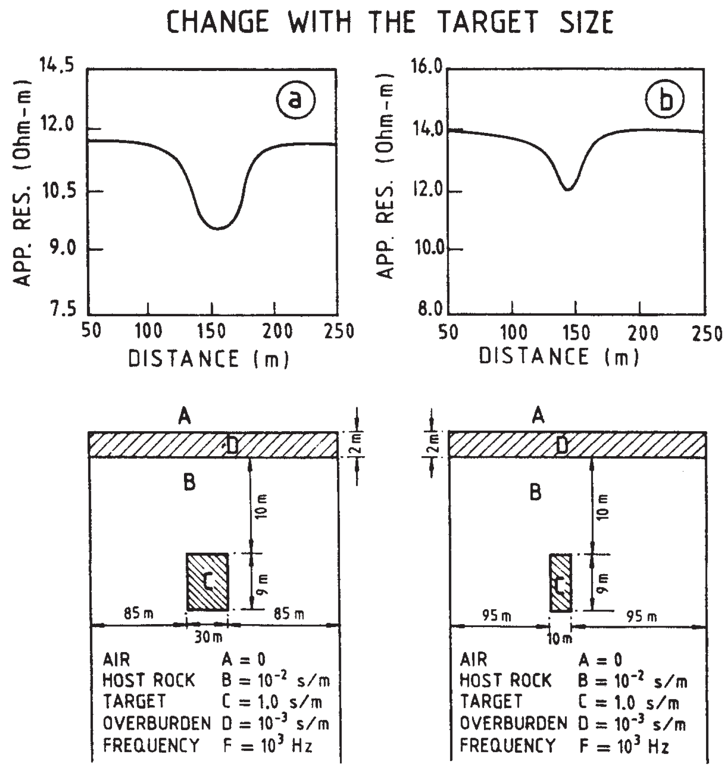

Fig. 9 - Variation of apparent resistivity with distance for an ore body in nongalvanic contact with an overburden, for change in sizes of the target body.

CHANGE WITH THE SIZE OF THE TARGET. - In Figs. 9a and 9b, the size of the target is changed. The other specifications of the model are as follows:

	Fig. 9a	Fig. 9b
(1) Overburden:		
thickness	2 m	2 m
conductivity D	10^{-3} S/m	10^{-3} S/m
(2) Target:		
(a) size in lateral direction Y	30 m	10 m
(b) size in vertical direction Z	9 m	9 m
(c) depth of the target	12 m	12 m
(d) conductivity C	1 S/m	1 S/m
(3) Host medium conductivity B	10^{-2} S/m	10^{-2} S/m
(4) Frequency of the EM waves F	10^{3} Hz	10^{3} Hz

Two observations are worth making:
(i) the shape of the body is reflected in the slag part of the variation curve; and
(ii) a change in the lateral direction of the body also changes the magnitude of the apparent

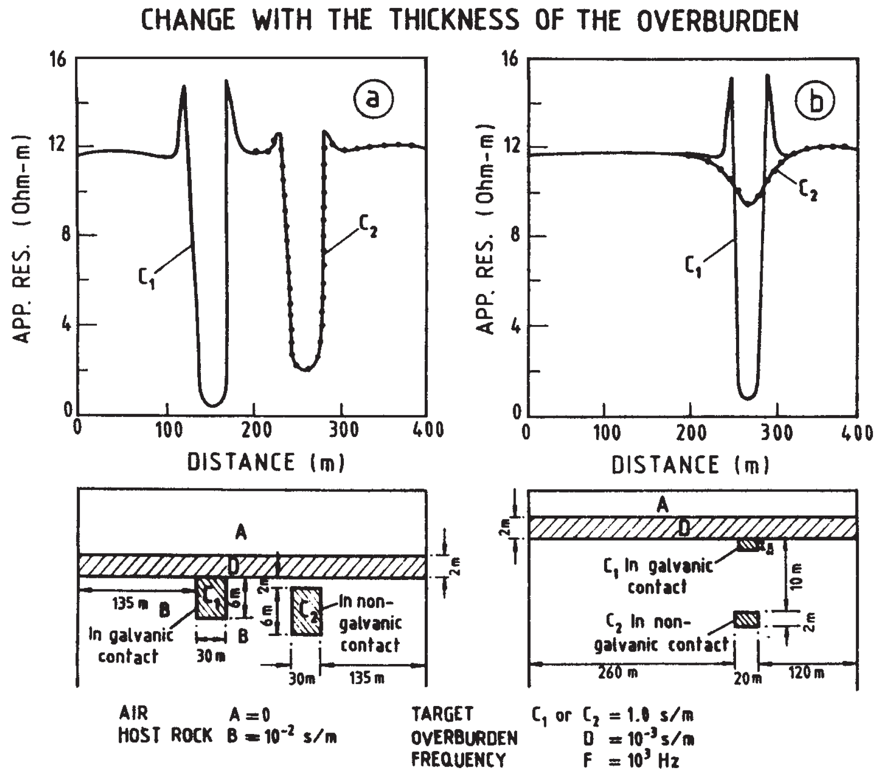

Fig. 10 - Variation of apparent resistivity with distance for an ore body with an overburden, for changes in the depth of the target from (a) galvanic to nongalvanic and (b) galvanic to deep inside the earth.

resistivity value.

CHANGE WITH THE POSITION OF THE TARGET. - In Figs. 10a and 10b, the change in the position of the target for changes from galvanic to nongalvanic contact with the overburden is shown. The model parameters are as follows:

	Fig. 10a C1	Fig. 10a C2	Fig. 10b C1	Fig. 10b C2
(1) Overburden:				
thickness	2 m	2 m	2 m	2 m
conductivity D	10^{-3} S/m		10^{-3} S/m	
(2) Target size:				
(a) in lateral direction Y	30 m	30 m	20 m	20 m
(b) in vertical direction Z	6 m	6 m	2 m	2 m
(c) depth from the earth's surface	2 m	4 m	2 m	4 m
(d) conductivity C	1 S/m	1 S/m	1 S/m	1 S/m
(3) Host medium conductivity B	10^{-2} S/m		10^{-2} S/m	
(4) Frequency F	10^3 Hz		10^3 Hz	

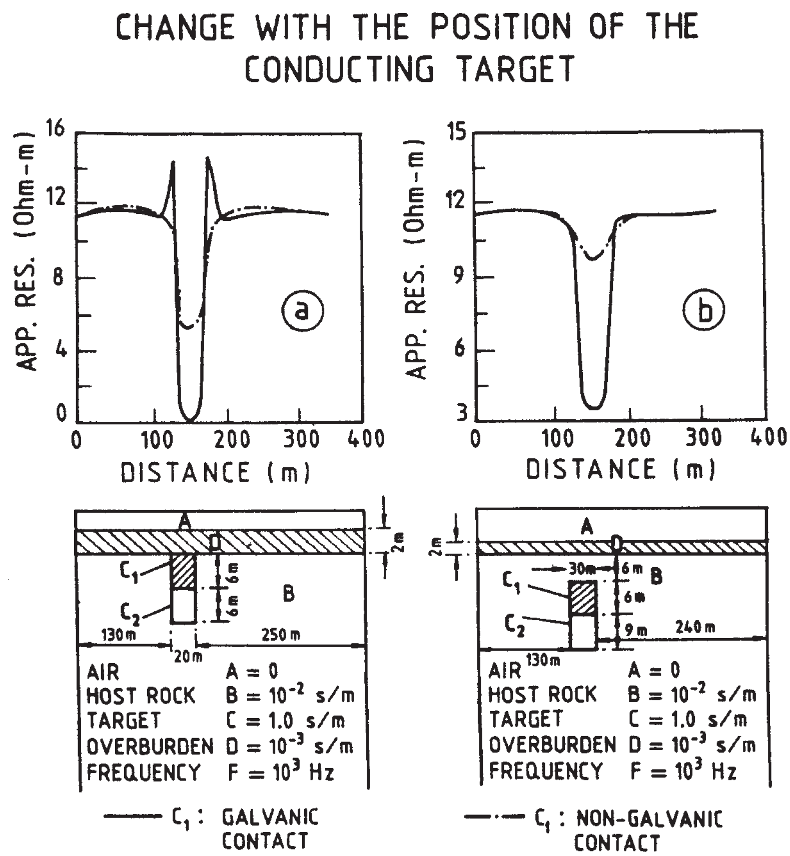

Fig. 11 - Variation of apparent resistivity with distance for an ore body in nongalvanic contact with an overburden, for change in the position of the ore body: a) galvanic to nongalvanic; b) nongalvanic to deep inside.

Two targets of different size have been assumed in Figs. 10a and 10b (all other physical and geometrical parameters are unchanged).

In both the figures the C1 curves represent the case of overburden in galvanic contact with the target bodies, and one finds a distinct change in the apparent resistivity vs. distance variation pattern due to change in the size of the target body.

Curves with dotted lines, indicated by C2, represent the situations when the target conditions are in nongalvanic contact with the overburden. Here one finds:

(1) the nearer the target from the earth's surface, the better the response;

(2) the peak values are obtained when the target conductor is in galvanic contact with the overburden and overburden is also very thin;

(3) when the target conductor is assumed to be at a depth sufficient to dissipate the EM energy (Fig. 10b, C2 curve), the response of the target reduces, significantly.

CHANGE WITH THE POSITION OF THE TARGET. -

(i)	Galvanic	→	nongalvanic	(Fig. 11a)
(ii)	Nongalvanic	→	deeper position	(Fig. 11b)

In Figs. 11a and 11b, two representative situations have been assumed, in which the position of the same target body is changed from:

(i) galvanic contact to nongalvanic contact;

(ii) nongalvanic contact near to the surface changed to deeper locations.

In both cases the effects of changing the position of the target is significantly reflected.

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