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Comparison between geoelectric and electromagnetic sounding responses in volcanic areas

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Abstract
The structure of active and inactive volcanoes can be explored with electric and electromagnetic surveys. We test the actual applicability of prospecting methods that employ both stationary and time-varying fields, using mathematical models both for layered and complex structures. The geometry and the resistivities of the geological structures which are considered have been taken from real case studies reported in the literature. In particular we analyse the sensitivity of different methods to conductive and resistant bodies.

Key words *resistivity soundings – TDEM – magnetotellurics – volcanic structures – mathematical models*

1. Introduction

Several electric and electromagnetic prospecting methods are used in volcanic areas. Both stationary and transient controlled current sources are used, as well as natural electric and electromagnetic fields. In this paper we analyse the response of some of these methods when applied to volcanic structures.

We consider volcanic structures in a broad sense. In fact, we take into account not only volcanoes, but also calderas and areas where igneous rocks outcrop or could be present at some depth forming plutons, dikes, etc.

Among the targets of electric and electromagnetic prospecting in volcanic areas, we mention interfaces between sediments and igneous rocks, magma chambers, interfaces between volcanic rocks with different characteristics (composition, porosity, etc.).

We recall that electrical resistivity is influenced by several factors (see, *e.g.*, Parkhomenko, 1967), which are particularly important in volcanic areas. The presence of fluids can reduce the electrical resistivity of igneous rocks by some orders of magnitude. In volcanic areas we can have high temperatures and high temperature gradients: the effect of temperature on the electrical resistivity of rocks and of the fluid filling pores or fractures is therefore very important. Furthermore, the presence of a molten fraction can influence the value of electrical resistivity.

As a consequence, in volcanic areas we have to deal with both strong resistivity contrasts and complex three-dimensional structures. In this paper we want to evaluate the applicability of different electric and electromagnetic methods in these conditions. In particular we simulate the response of different prospecting methods for simple but realistic and significant one-dimensional models. Moreover, we

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show the effects of the simplest three-dimensional structures on direct current electrical soundings.

We now describe the prospecting methods that will be taken into account in this paper.

DC will denote half-Schlumberger soundings. The results for dipole-dipole polar arrays can be obtained from the results for half-Schlumberger arrays by means of the well-known transformation formulae (Al'pin, 1950, 1958; Patella, 1974; Alfano, 1974). Dipole-dipole arrays are more efficient than Schlumberger or half-Schlumberger arrays for executing deep soundings (Alfano, 1974); in areas where the geological structure is very complex the transformation formulae can be correctly applied only for continuous polar dipole-dipole arrays (Alfano, 1980).

MT will denote magnetotelluric soundings. In particular we shall consider frequencies from 10^{-4} to 10^{4} Hz. We shall represent the results plotting apparent resistivity *versus* square root of the period on log-log scales. With this kind of data representation, curves of apparent resistivities for equivalent geoelectrical models have the same shape and are shifted along the two axes.

EM will denote time domain electromagnetic soundings. In particular we consider a grounded electric dipole source (1000 m, 20 A) and a receiver with 10000 m^2 equivalent surface at a distance of 2000 m in the direction perpendicular to the orientation of the source dipole. The results will be shown by plotting the apparent resistivities using both the early time and the late time approximations.

The second section of this paper shows the theoretical results of DC, MT and EM for three one-dimensional cases. These results demonstrate the importance of executing both stationary and transient current prospecting in order to determine the underground structure in a more confident way. The third section shows the results of DC prospecting for the simplest three-dimensional structures, namely a resistive body with the form of a parallelepiped. We analyse both the effects of the limited extension and of a lateral interruption of this resistive body.

2. One-dimensional numerical examples

2.1. *Case A*

This example is based on the results obtained by electromagnetic prospecting on the Kilauea Volcano, Hawaii, as reported by Keller and Rapolla (1974). The field results show the

Table I. Geoelectrical models for case A.

Model A1		Model A2		Model A3	
Resistivity ($\Omega \cdot$ m)	Thickness (km)	Resistivity ($\Omega \cdot$ m)	Thickness (km)	Resistivity ($\Omega \cdot$ m)	Thickness (km)
1000	0.015	10000	0.015	1000	0.015
10	1	10	1	8	0.125
2		2		24	0.125
				8	0.125
				24	0.125
				1000	0.125
				8	0.125
				24	0.125
				8	0.125
				2	

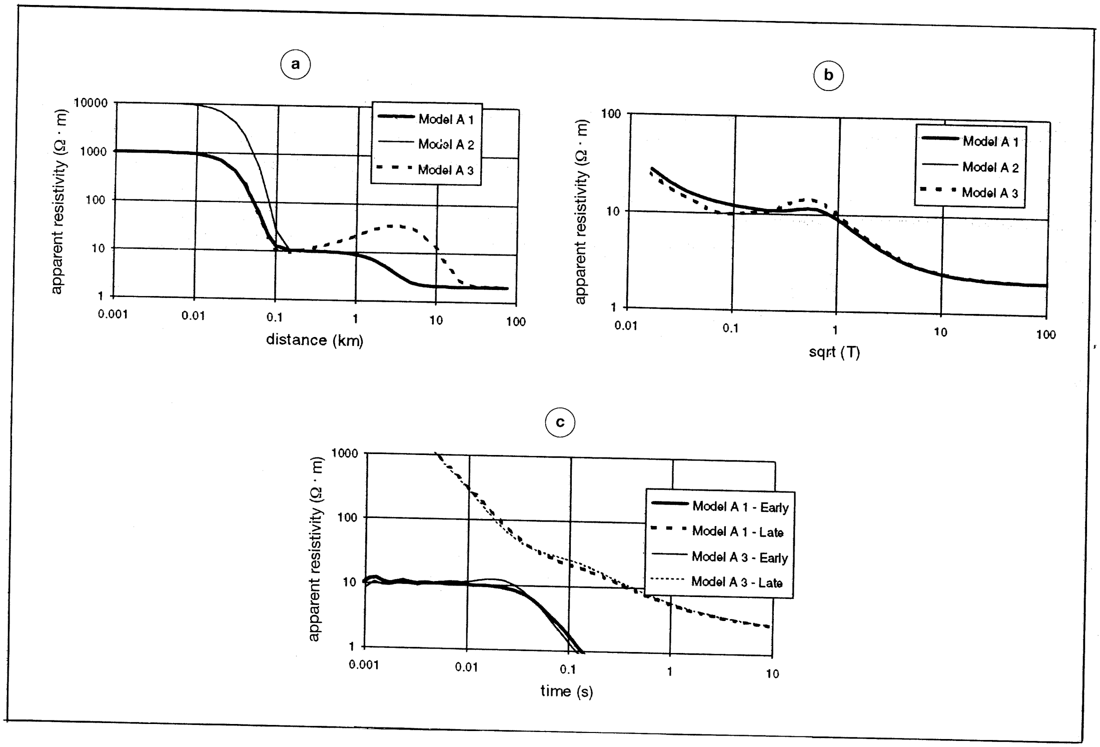

Fig. 1a-c. Results for the models of table I: a) DC; b) MT; c) EM.

presence of a conductive body (2 Ω · m) at a depth of about 1 km, underlying a body with a resistivity of 10 Ω · m. At the surface, vertical electrical soundings reveal the presence of shallow layers (thicknesses of about 10-20 m) with resistivities varying between 1000 and 10000 Ω · m. The geoelectrical models A1 and A2 listed in table I are based on these results. Moreover, we consider a model similar to model A1, but where the conductive layer with resistivity 10 Ω · m is substituted by a sequence of layers whose resistivities vary between 8 and 24 Ω · m in an alternate way, but for a layer with resistivity 1000 Ω · m in the middle of them. The thickness of each of these layers is 125 m. This model is referred to as model A3 and is described in table I.

The response of DC, MT and EM to these one-dimensional models is represented in fig. 1a-c.

We note that DC prospecting can reveal the existence of the resistive shallow layers. MT shows the presence of a shallow resistive layer for periods lower than 0.01 s; EM shows the presence of this layer if time is lower than 0.001 s. However we cannot determine the value of resistivity from MT and EM, at least for the considered ranges of period (MT) and time (EM) values.

Figure 1a-c shows that MT and EM responses for models A1 and A3 are almost the same, although the characteristics of the two models are very different. On the other hand the DC results highlight the existence of the 500 m deep resistive layer; however from a diagram of apparent resistivity as that of model A3 for DC, it is not possible to determine in a unique way the thickness and the resistivity of this resistive layer.

2.2. *Case B*

This case is based on the hypothesis of the existence of igneous rocks at depth. Our experience shows that igneous rocks often have resistivities higher than 20000 Ω · m. We obtained these values, for instance, on the rocks forming the plutonic body of Val Masino, in Northern Italy.

Table II describes the four models for this case; the results for these models are represented in fig. 2a-d. In particular we consider two basic models (B1 and B3) and two models (B2 and B4) whose MT and EM results are in

Table II. Geoelectrical models for case B.

Model B1		Model B2		Model B3		Model B4	
Resistivity (Ω · m)	Thickness (km)	Resistivity (Ω · m)	Thickness (km)	Resistivity (Ω · m)	Thickness (km)	Resistivity (Ω · m)	Thickness (km)
100	0.5	100	0.5	100	0.5	100	0.5
1000	3	1000000	3	4000	1	1000	
100		100		20000	2		
				1000			

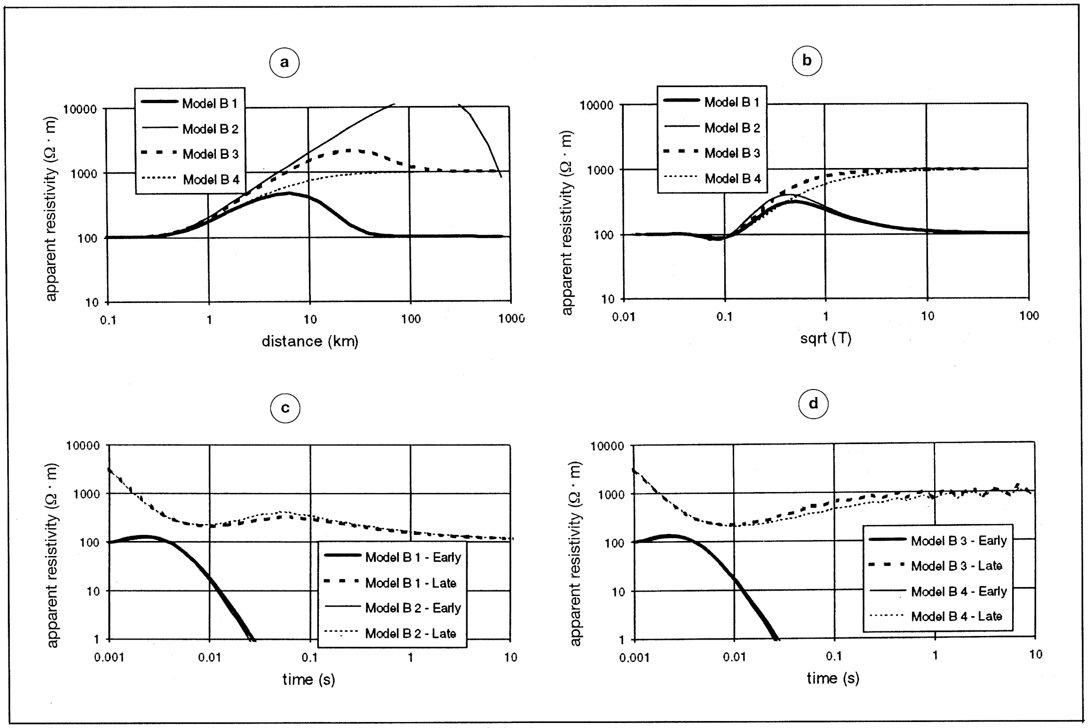

Fig. 2a-d. Results for the models of table II: a) DC; b) MT; c) and d) EM.

some sense equivalent to the results for the basic models.

The diagrams of apparent resistivity for DC are very different from each other, so that in principle it could be possible to reveal the existence of the resistive bodies. However, we must stress that in order to reveal the deep layers for models B1, B2 and B3, the distance between the current electrode and the potentiometric dipole must be very great: at least 10 km for model B1 and even more for the other models.

This result depends upon two characteristics of the considered models. First of all, shallow conductive layers cause the electrical current to flow mainly in these shallow layers, so that only a small fraction of electrical current flows below the resistive layers; in order to obtain information on the deepest structures, it is necessary to put the electrode current far away from the potentiometric dipole, at distances much greater than the thickness of the resistive layer, so that electric current can flow even through the deepest bodies. The results are different if the surface conductive layer is absent, as shown for case A. In the second place, we assume that the resistive body consists of igneous rocks; they can appear as intrusions, dikes, or plutons. These geological structures often have a limited extension, so that the 1D approximation may not be valid. We discuss in the next section the effect of the limited extension of resistive bodies on DC soundings.

The MT and EM response for models B1 and B2 is almost the same, notwithstanding the fact that the resistivity of the intermediate layer varies by three orders of magnitude. This means that MT and EM are insensitive to the value of resistivity of the intermediate layer for a geoelectrical model like B1. The response of EM and MT is practically the same for models B3 and B4, too. Therefore we can conclude that when a resistive layer is located above a more conductive background it is difficult to put it in evidence and to determine its resistivity by methods using transient fields. However these methods are more effective than DC to gain information on the deep conductive background.

2.3. *Case C*

The third case is based on the results reported by Kaufman and Keller (1983), obtained on Krafla Caldera, Iceland. Kaufmann and Keller (1983) described a complex structure, with significant lateral variations. In particular the area can be divided into two parts: the first one outside the caldera and the second one located at the top of the caldera. Therefore we considered two 1D models (models C1 and C2) which represent the structure in the two distinct areas. Model C3 is the same as model C2, but for the resistivity of the resistant layer whose value is higher by 250 times. For the description of these models see table III.

The response of the prospecting methods is represented in fig. 3a-d.

These results confirm the remarks of the previous cases. In particular DC is more efficient to reveal resistive layers, whereas EM and MT are not sensitive to the value of resistivity of resistive layers confined by more con-

Table III. Geoelectrical models for case C.

Model C1		Model C2		Model C3	
Resistivity ($\Omega \cdot$ m)	Thickness (km)	Resistivity ($\Omega \cdot$ m)	Thickness (km)	Resistivity ($\Omega \cdot$ m)	Thickness (km)
1	0.02	1	0.02	1	0.02
50	1	5	0.3	5	0.3
290	0.3	400	1.5	100000	1.5
500		15		15	

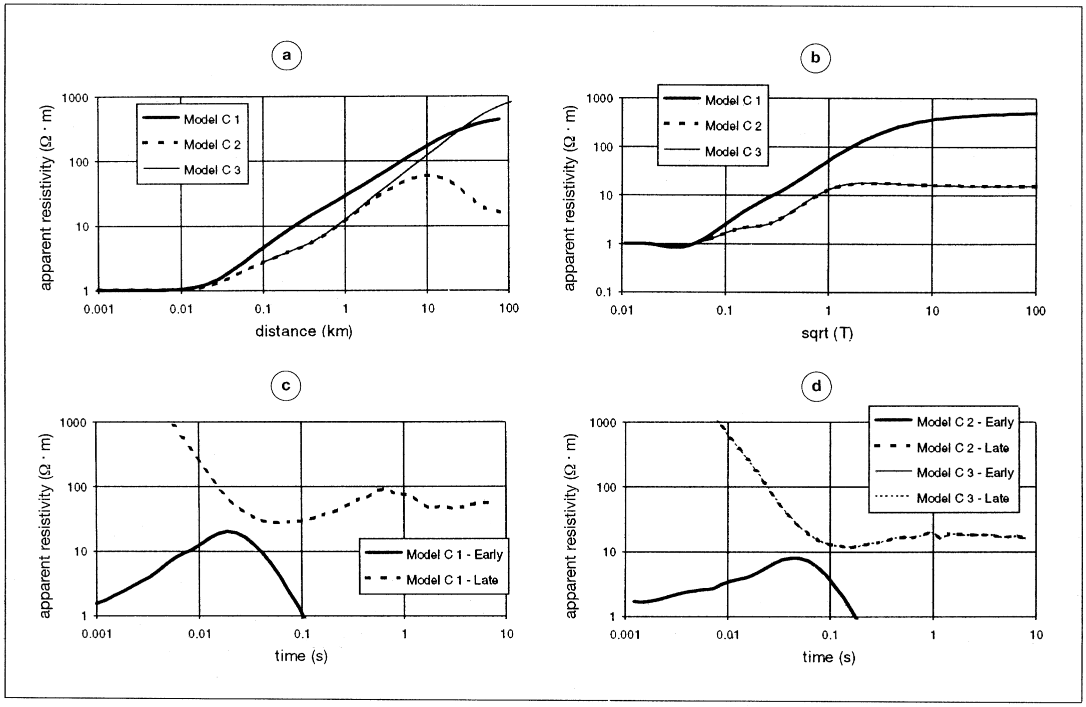

Fig. 3a-d. Results for the models of table III: a) DC; b) MT; c) and d) EM.

ductive bodies; in fact the response of MT and EM for models C2 and C3 is practically the same. On the other hand MT and EM are more effective in giving information about the deepest conductive layers.

3. DC response to a 3D model

As a basis for a three-dimensional model we consider the three-layers model of table IV. Actually, the resistive body will not be infinitely extended; we represent it as a parallelepiped within an homogeneous background with resistivity of 100 Ω · m, as sketched in fig. 4. The thickness of the resistive body is the same as the thickness of the resistive layer of the three-layers model of table IV. The top is at the same depth as the top of the resistive layer of the three-layers model. The extension in the direction perpendicular to the sounding direction is $\Delta y = 15$ km, whereas the extension along the sounding direction varies for each test and is denoted with Δx.

Table IV. One-dimensional three-layers model; reference model for the 3D case.

Three-layers model	
Resistivity (Ω · m)	Thickness (km)
100	0.5
10000	3
100	

We evaluate the effect of the limited extension of the resistive body and the effect of an interruption of this body on the results of DC soundings.

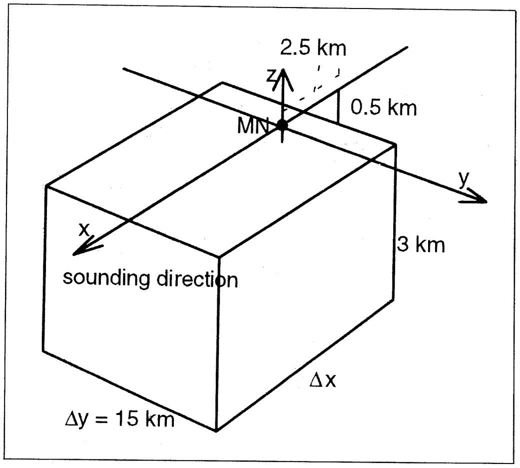

Fig. 4. The geometry of the 3D model.

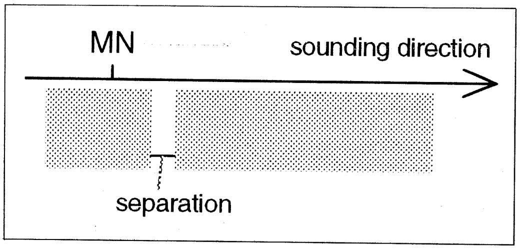

Fig. 5. Vertical section of the three-dimensional model with an interruption.

We apply the surface charge (boundary element) method to compute DC half-Schlumberger apparent resistivity curves. The method is described, for instance, in Alfano (1959, 1984) and Okabe (1981). It is very useful when the three-dimensional anomalous body has a limited volume.

The effect of the limited extension of the resistive body has been evaluated by computing the DC response for different values of Δx. In particular we consider three models for $\Delta x = 5$ km, 10 km and 15 km (models M1, M2 and M3). This means that the projection of the edge of the resistive body onto the surface is located at a distance from the centre of the potentiometric dipole MN equal to 2.5 km, 7.5 km and 12.5 km, for models M1, M2 and M3 respectively. For similar results we refer the reader to another paper of ours (Giudici and Alfano, 1996).

The effect of an interruption of the resistive body is evaluated by means of three-dimensional models whose vertical section is represented in fig. 5. Essentially the parallelepiped is divided in two blocks, separated by a variable distance. Three models are considered (models P1, P2 and P3), which correspond to separation distances of 0.5 km, 1 km and 2.5 km, respectively.

The DC response to the above described three-dimensional structures is represented in fig. 6a-b. We stress that the curves of apparent resistivity show sharp variations in correspon-

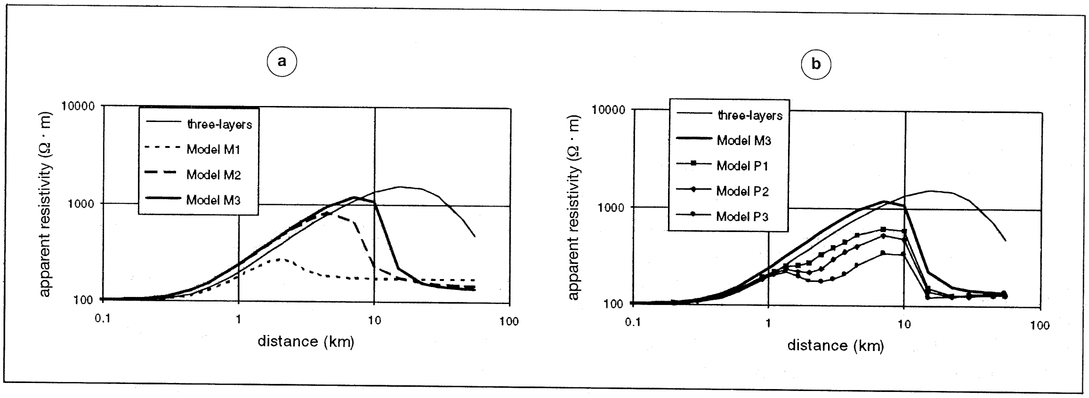

Fig. 6a,b. DC response for three-dimensional structures.

dence of the edge of the resistive parallelepiped (see fig. 6a). Furthermore we can observe that the curves of apparent resistivity are affected by the limited extension of the resistive body for distances lower than those corresponding to the sharp decreases of apparent resistivity. From these remarks it follows that such a mathematical model is a useful tool to determine the minimal lateral extension of resistive bodies which are possibly shown by DC measurements.

Sharp variations of apparent resistivities are obtained also for models P1, P2 and P3 (see fig. 6b), at a distance of 1.5 km, where the current electrode enters in the region of separation between the two resistive blocks. When the current electrode reaches the resistive block further from the potentiometric dipole, apparent resistivity increases again. The decrease of apparent resistivity in the region of interruption of the resistive body is the more pronounced the greater the separation distance. At a distance of 10 km the current electrode reaches the projection of the edge of the resistive body onto the surface and apparent resistivity decreases as for the models whose results are shown in fig. 6a.

4. Conclusions

Although it is well known that results from geophysical surveys cannot be definite if only one exploration technique is used, many researchers forget this important fact. Our examples show that this is of fundamental importance when electric and electromagnetic methods are used for surveys of volcanic structures. In particular, the simple one-dimensional models presented in this paper show that prospecting with stationary or transient fields provides complementary information. No definite answer to the problem of characterising the electrical structure of the underground can be given if only one prospecting method is used. In particular we have shown that the methods using transient fields are almost insensitive to resistive layers located between several conductive bodies. For this kind of geoelectrical structures it is generally quite difficult to reveal the presence of deep conductive bodies using stationary currents. The methods based on transient currents are more effective to obtain information about the deepest conductive layers.

Furthermore we have shown the importance of considering the three-dimensional complexity of the geological structures. In particular we have investigated the effects of the limited extension of resistant bodies on the results of electrical soundings with half-Schlumberger arrays, showing that from the curves of apparent resistivities the minimal lateral extension of the body can be inferred. We have also shown that an eventual interruption of the resistant body gives a decrease of apparent resistivity that is not limited to the area where the interruption occurs, but is evident also for greater distances.

These results are valid for all the geoelectrical models similar to those discussed in this paper, *i.e.*, when the ratios between the electrical resistivities and the ratios between the lengths are the same as for these models. Therefore our results apply to a wide class of geoelectrical models.

Finally we stress that these results are of great importance in the interpretation of field curves. We believe that simple mathematical models are necessary to study the effects of three-dimensional heterogeneity also for magnetotellurics and electromagnetic prospecting, in order to help the correct interpretation of the field results, both from a qualitative and quantitative point of view.

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