A COMPUTER STUDY OF ELECTROMAGNETIC SOUNDING IN A POTASH MINE

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ABSTRACT

With the advent of powerful computer programs that calculate electromagnetic fields over a multilayered earth, it became possible to design coil parameters for specific geophysical applications. One such application is the measurement of rock-salt thickness above the workings of a potash mine. The system parameters in question are the coil spacing, coil orientation, and frequency of operation. These parameters are to be chosen to obtain maximum effect from the salt thickness and minimum effect from other geological features such as thin clay beds contained in the salt.

For the conditions in Saskatchewan potash mines, the optimum values are: 8 m coil separation, horizontal coplanar configuration, 30 kHz operating frequency.

INTRODUCTION

Recently, powerful computer programs have become available (Sinha, 1973; Sinha and Collett, 1973; Sinha, 1976) for the calculation of electromagnetic fields due to a dipole source over a layered earth. These programs make possible the analytic design of electromagnetic sounding systems for specific purposes. We present here an example of such a design showing how we optimize the frequency, coil separation and coil orientation for certain known and assumed physical conditions. Similar design programs could be applied to problems in other areas such as coal mine, permafrost, etc.

In the potash district of Saskatchewan the potash ore, sylvite, occurs in several thick beds near the top of the Prairie Evaporite Formation (Fig. 1). Evaporites, chiefly halite, occur above and below the ore zone. The total thickness of evaporites may be over 200 m but the potash ore is near the top, and there is usually only a few (5-35) metres of halite above the ore zone depending on which area of the province is considered. Halite above the ore zone is often referred to as the "salt back". Above the evaporite formation is a shale layer called the Second Red Bed which, usually, is 5 to 10 m thick. Above the shale is the Dawson Bay Limestone which is about 30.0 m thick.

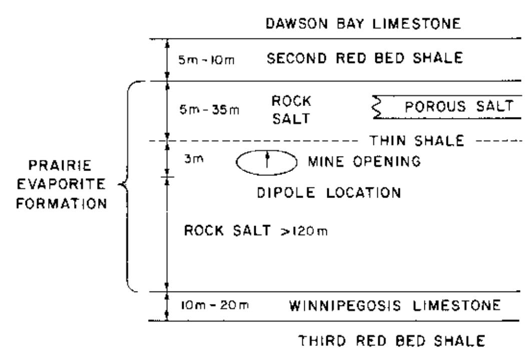

Fig. 1. Geologic section (in part) of the Potash district of Saskatchewan.

The salt back is regarded as a protective cover for the mine openings, and the design of the mine layout is governed by the mechanical properties of the salt back, its thickness, and the presence of thin clay seams that weaken it. The salt back is also regarded as a barrier that prevents the inflow of water from the porous limestone above. The salt-back thickness is fairly constant within the area of each mine,

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but local changes may indicate mining problems. For these reasons, the thickness of the salt back is of some interest to the miners. Seismic refraction measurements have been used to estimate the thickness, but they suffer from several disadvantages (Gendzwill, 1969).

Because of the contrast in electrical properties of shale and salt, an electromagnetic system could, in principle, detect the shale above the salt, thereby determining the thickness of the salt back. Such a system could have the advantage of rapid, convenient operation with immediate interpretation and no need for the drilling or explosives required in the seismic method. An electromagnetic system would also be sensitive to occurrences of brine such as have been found in several places in some of the mines (Gendzwill, 1967).

The usefulness of such a system would depend on several factors. The sensitivity should be good enough to estimate distances within a few percent. The system should be insensitive to the presence of thin clay seams in the salt, as well as to the shales and carbonates below the salt (usually 120 m or more below the mine level). The presence of brine within the salt should create a distinctive anomaly that cannot be confused with changes in the salt-back thickness. Lastly, the system must be designed to be used in the underground environment of the potash mines.

For a continuous wave (double coil) EM system as is being proposed here, three significant parameters have to be determined. They are i) coil separation, ii) frequency of operation and iii) the orientation of the coils with respect to one another. All other variables, such as the coil diameter, strength of the dipole moment, etc., are determined by factors not directly related to the geological characteristics of the target. The experiment then amounts to optimization of the above three parameters in terms of the geological and engineering objectives, namely:

1) Accurate determination of salt thickness.
2) Relative insensitivity to other features of the geology.
3) Ease of operation.

For purposes of computation, the formations to be mapped can be represented as horizontal layers. The expressions for the electromagnetic fields over a layered earth have been presented by Sinha (1973) and Sinha and Collett (1973). These expressions are valid when displacement currents are neglected, and are based on the earlier formulations due to Wait (1962, 1966), Dey and Ward (1970) and Ryu *et al.* (1970). The expressions when displacement currents are considered have been given by Sinha (1976). Figure 2 shows a vertical magnetic dipole situated at height 'h' above an n-layered earth; 'P' is point of observation and 'σ', 'μ' and 'ε' denote the conductivity, magnetic permeability and dielectric constant of a given layer. H^P is the intensity at 'P' of the primary field emitted from the transmitter: H^S is the intensity at 'P' of the secondary field induced from the earth.

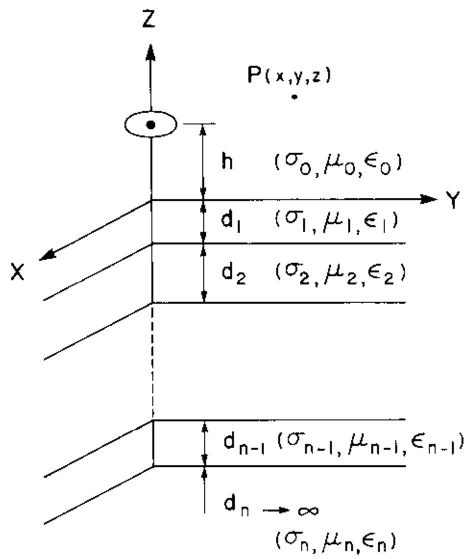

Fig. 2. Magnetic dipole over an n-layered earth.

The four standard coil arrangements used in EM prospecting are shown in Figure 3.

The computer program used to calculate the magnetic fields and thus the ratio H^S/H^P for the four coil configurations was provided by A. J. Sinha of the Geological Survey of Canada. (See also Sinha and Collett, 1973.) However, one point should be noted here. In the computations of the integrals, Sinha used 9- to 11-figure accuracy, while the present study has been limited to a 7-figure accuracy only. Table 1 shows the results of computation for one model using the above two levels of accuracy. The 7-figure accuracy, therefore, seems adequate for this study.

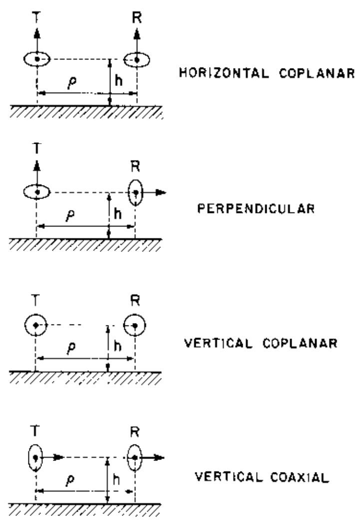

Fig. 3. Four coil configurations used in EM dipole prospecting.

Parameters		11-Figure Accuracy (ppm)	7-Figure Accuracy (ppm)
Horizontal Coplanar	In phase	759.699	759.646
	Quadrature	984.030	984.025
Perpendicular	In phase	74.5657	74.2830
	Quadrature	443.444	443.441
Vertical Coplanar	In phase	377.733	377.555
	Quadrature	599.922	599.915

Table 1. Comparison between the 7-figure and the 11-figure accuracy in computation of H^S/H^P.

Physical Parameters

(a) *Conductivity of the beds:* For modelling purposes, the electrical conductivity of the beds has to estimated. An induction log from a drill hole was used to estimate the conductivity of the shale and the porous limestone beds. Values of 0.1 and 0.3 mho/m were used for the former and 0.05 mho/m for the latter. The conductivity of rock salt is much too low to be measured on the induction log. Consequently, values of 10^{-3}, 10^{-4} and 10^{-5} mho/m were tried.

Minor clay seams in the salt usually generate a response from the induction log, but it cannot be reliably interpreted. It is thought that the thin clay seams are less conductive than the Second Red Bed Shales because the thin seams contain more salt. A value of 0.01 mho/m was assigned to the clay seams.

The effect of the conductivity of salt needs further discussion. Figures 4a and 4b show the variation of the ratio H^S/H^P with salt conductiv-

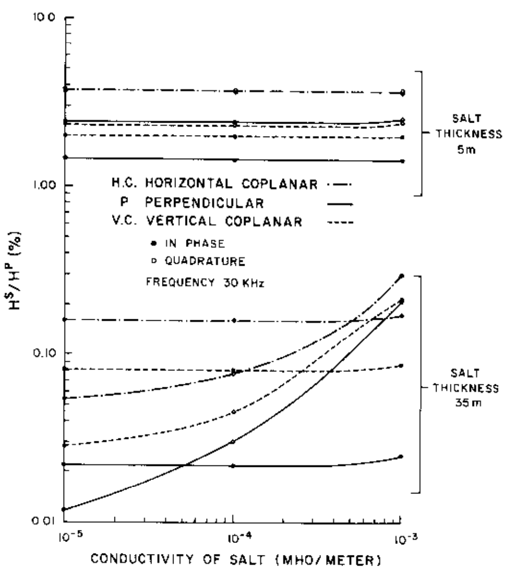

Fig. 4a. Variation of H^S/H^P (%) with conductivity of salt for different coil configurations. H.C. — Horizontal Coplanar; P - Perpendicular; V.C. - Vertical Coplanar. Coil separation 8 m, conductivity of shale = 0.1 mho/m.

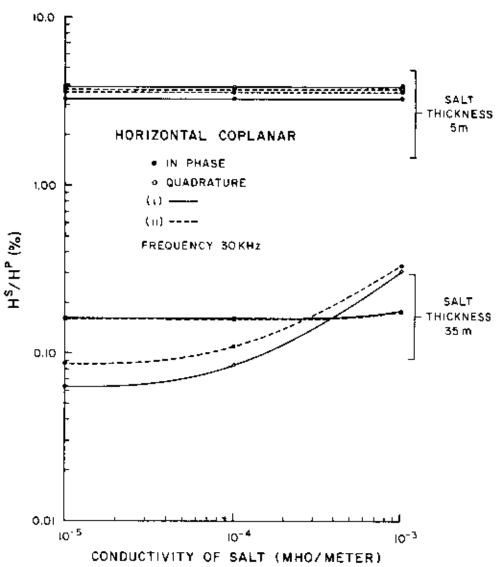

Fig. 4b. Variation of H^S/H^P (%) with conductivity of salt taking into account i) finite thickness of shale bed (taken as 5 m), (ii) Shaly salt (0.01 mho/m.) layer 0.10 m thick on top of the salt layer. Coil separation 8.0 m. Conductivity of limestone = 0.05 mho/m.

ity for different physical models and coil configurations. One conclusion is obvious from these plots; namely, that the In-phase response in a variety of cases is not significantly affected by the conductivity of the salt within the range considered here. The behaviour of the Quadrature response varies with the thickness of the salt layer. When the thickness is small, the variation in salt conductivity produces a negligible effect on the Quadrature response. For thicknesses around 35 m (roughly the maximum value encountered), the response depends on the conductivity of salt, especially if it is close to 10^{-3} mho/m.

For the example of porous salt containing brine, the conductivity was determined by using Archie's law assuming the intergranular porosity to be 2 percent and 4 percent respectively. Since the conductivity of saturated brine at a formation tempature of 26.7°C is 25 mho/m, the respective salt conductivities in the above cases become 0.01 and 0.04 mho/m.

(b) *Thickness of the beds:* The salt back is known to vary in thickness from 5 to 35 m. For a 2-layer model consisting of the salt back and the 2nd Red Bed Shale, these thicknesses were taken as the minimum and maximum values. Finite thickness — 5 and 10 m respectively — of the shale bed was considered, too, in a 3-layer model. The thin clay seams are generally 1 to 10 cm thick, and were taken as such in the models involving them. For thin beds, neither conductivity nor thickness can be uniquely determined, as their effect depends mainly on the product of conductivity times thickness. For computational purposes, the thickness of the salt containing moisture was somewhat arbitrarily chosen to be 5 m.

(c) *Distance between the coils and the mine roof:* Two metres of air was assumed between the coils and the roof for all computations.

(d) A unique aspect of the underground measurement is the presence of conductive rock both above and below the coil system. In fact, the rocks above the coils are of more interest than those below. However, it can be shown that the effect of all the conductive rock is added linearly in the electromagnetic response if propagation effects are ignored. In the potash-mine environment we feel that this is a safe assumption, because the nearest significant conductivity below the mine is much farther away than that above it.

Design Parameters

(a) *Coil Separation*: To determine the appropriate coil separation, the In-phase and Quadrature components of H^S/H^P were computed for varying coil separation using a two-layer model. The computations were done at a frequency of 2.4 and 25 kHz respectively; the results obtained in the latter case are plotted in Figures 5a and 5b.

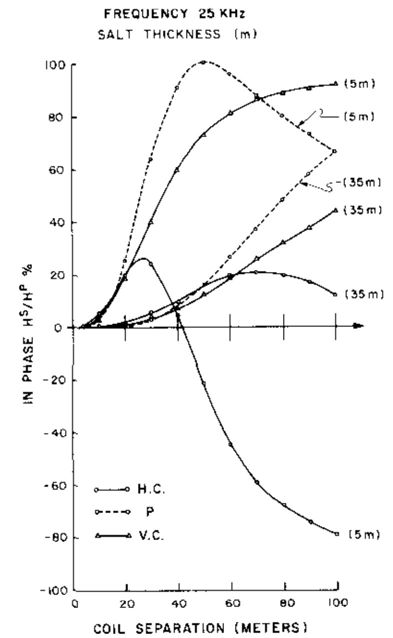

Fig. 5a. Variation of H^S/H^P (In-phase) (%) with coil separation. Conductivity of salt = 0.0001 mho/m.; conductivity of shale = 0.1 mho/m.

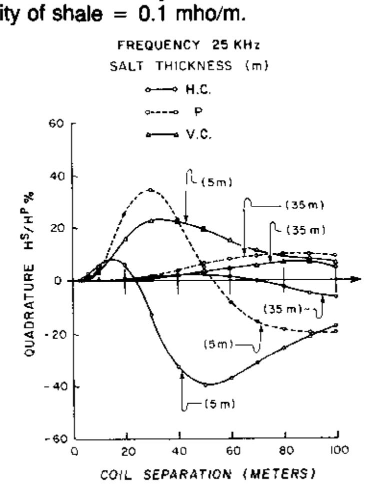

Fig. 5b. Variation of H^S/H^P (Quadrature) (%) with coil separation. Conductivity of salt = 0.0001 mho/m.; conductivity of shale = 0.1 mho/m.

As the coil separation increases initially, both components of H^S/H^P increase in magnitude and remain positive. Although not shown in the figure(s), the response increases with frequency and, as expected, decreases with increase in salt thickness. This monotonic behaviour continues as long as the separation is below 15 m or so. Beyond this value, all plots either have a turning point or tend toward one. The coil separation corresponding to a given turning point, of course, depends on the different parameters involved, including frequency. A decrease in frequency alone shifts the turning point to the right (that is, to a larger coil separation). For convenience in interpreting field data, it is preferable to choose values of parameters such that the ratio H^S/H^P varies monotonically with thickness of the salt back. If measurements are to be carried out at frequencies around 25 kHz, it is clear from Figure 5 that the coil separation for the proposed system must be less than 14 m. It should be repeated here that within this range the greater the separation, the higher the magnitude of H^S/H^P.

Although the response to the shale target increases with coil separation, so does the response to other, more distant shales. The next thick shale is the third Red Bed, which occurs under the Winnipegosis carbonate under the salt (see Fig. 1). In order to minimize the electromagnetic response to these rocks, the coil separation should not be too large. Table 2 shows a comparison of response between the

	Frequency (kHz)	Horizontal Coplanar	(A/B) Perpendicular	Vertical Coplanar
In-phase	30	0.059	0.022	0.058
	40	0.057	0.021	0.057
	50	0.057	0.020	0.056
Quadrature	30	0.023	0.009	0.023
	40	0.020	0.009	0.023
	50	0.022	0.009	0.021

Conductivity of salt: 0.0001 mho/m.
Conductivity of shale: 0.2 mho/m.
A = (H^S/H^P) when the 2nd Red Bed is 35 m from the mine roof (that is, the salt thickness is 35 m).
B = (H^S/H^P) when the 3rd Red Bed is 100 m from the mine floor (that is, the salt thickness is 100 m).

Table 2. Ratio of the electromagnetic response H^S/H^P when the Red Bed Shale is 35 m from the mine roof and the 3rd Red Bed is 100 m from the mine floor.

second and third Red Bed shales for an unfavourable case; *i.e.*, the second Red Bed at a maximum distance 35 m and the third Red Bed at a minimum distance of 100 m. For an 8 m coil separation, the third Red Bed contributed less than 6 percent of the anomaly. There is still another factor that influences the value of coil separation. It has to do with the fact that the system must operate in mine openings, which are usually horizontal and 5 to 15 m wide, 3 to 4 m high and hundreds of metres long. The system has to be lowered and hoisted in the mine shaft and carried on vehicles or on foot. Consequently, it should be as small and light as possible, probably built on a light-weight framework that can be folded. With the various factors in mind, a value of 8.0 m was chosen for the coil separation.

(b) *Frequencies of Operation:* The response of the electromagnetic system is proportional to the frequency and the target concuctivity. In general, a large response is preferred, except that we wish to avoid interference from non-target beds, and complications arising from displacement currents.

The frequency controls the skin depth of currents induced in the rock. For the stated problem, to determine depth to the shale rock with minimum interference from rocks above or below the shale, we should desire little absorption from the rock salt, and large absorption of the electromagnetic wave in the shale. Table 3 lists the skin depth 'δ' in metres for the selected conductivities and frequencies.

	ROCK SALT		SHALE	
σ (mho/m) =	10^{-4}	10^{-3}	0.1	0.3
Frequency (kHz)	δ (m)	δ (m)	δ (m)	δ (m)
2.5	1007	318	31.8	18.4
5.0	712	225	22.5	13.0
10.0	503	159	15.9	9.2
20.0	356	113	11.3	6.5
30.0	291	92	9.2	5.3
40.0	251	80	8.0	4.6
50.0	225	71	7.1	4.1

Table 3. Skin depth 'δ' for selected conductivities and frequencies.

If the skin depth is greater than the thickness of the rock unit, there should be little absorption, but if it is less, there should be great absorption of the electromagnetic energy.

Maximum rock salt thickness is about 35 m, so there should be little absorption at any frequency. When the conductivity is 10^{-3} mho/m, the skin depth is only two or three times the maximum rock salt thickness at the higher frequencies, so there may be some minor interference as shown in Figure 4.

However, the shale thickness is less than 10 m, so that the frequencies below 20 kHz are not strongly absorbed. Thus the response due to the shale may interact significantly with that due to the rocks on the other side of the shale.

It appears, therefore, that 30 to 40 kHz would offer the best compromise from the above consideration.

At higher frequencies, the displacement currents become significant. For most of the calculations done here, the displacement currents were neglected, but they do put a limit on the upper frequency that can be used.

To test the seriousness of the error involved if the displacement currents are neglected, some sample computations involving the effect due to their presence were made. In the models considered, the conductivity of salt was taken as 0.0001 and 0.00001 mho/m, while that of shale was taken as 0.1 to 0.3 mho/m; and the dielectric constants chosen for the salt and shale beds were 6.0 and 20.0 respectively. The respective frequencies used were 40 and 50 kHz. The percentage error in neglecting the displacement current was determined for the In-phase and Quadrature components for all coil configurations.

The following conclusions were obtained:

i) When the thickness of the salt bed is 5 m, the error in ignoring the displacement currents is less than 0.2 percent, no matter which coil configuration is used.

ii) When the thickness is increased to 40 m, the results are more involved. The In-phase response of the horizontal coplanar configuration shows an error of 2-4 percent, depending on the frequency used. A similar response for the perpendicular and vertical coplanar configurations, however, shows error up to 25-40 percent. In contrast, the error in the Quadrature response is generally less than 1 percent.

The above conclusions are not affected in any significant way if the dielectric constants of salt and shale are changed to 5 and 40 respectively. It should be kept in mind that the above errors decrease as the frequency is lowered. The choice of frequency (or frequencies) of operation thus depends on the acceptable limit of error in the determination of the salt-back thickness.

(c) *Choice of coil configuration(s):* Figures 6a and 6b show the In-phase and Quadrature response respectively as a function of frequency for different coil configurations and thicknesses of the salt back. It is obvious from these figures that the horizontal coplanar configuration yields the maximum response irrespective of the thickness of the salt, and does so over the entire frequency range studied here. The response of the vertical coplanar configuration is the second best from the point of view of its magnitude. From these considerations alone, the horizontal coplanar coil orientation is the best choice.

A further reinforcement of this choice is provided when one takes the effect of displacement currents into account. The error introduced by neglecting the displacement currents is least in the case of the horizontal coplanar configuration when the In-phase response is considered. The actual error is 4 percent or less for salt-back thicknesses up to 40 m at 50 kHz. As

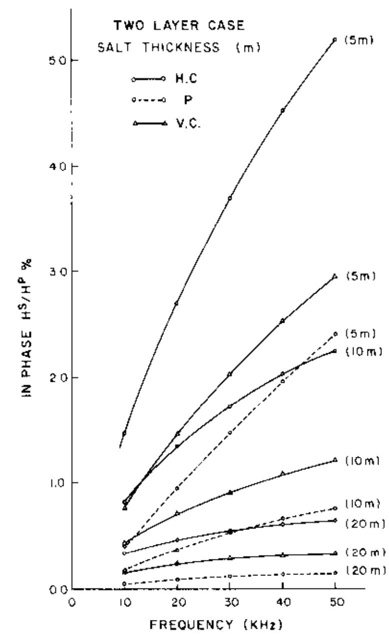

Fig. 6a. Comparison of the In-phase response of the Horizontal Coplanar (H.C.), Perpendicular (P) and Vertical Coplanar (V.C.) coil configurations.

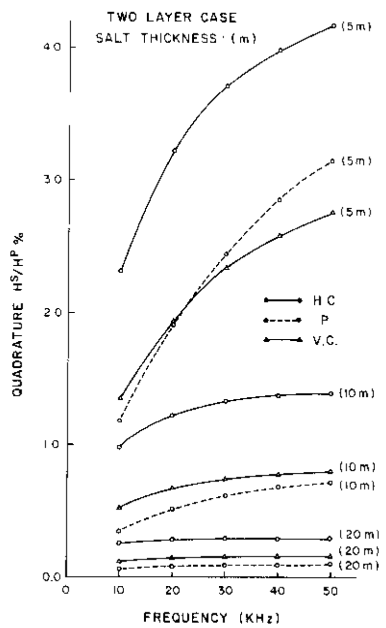

Fig. 6b. Comparison of the Quadrature response of the Horizontal Coplanar (H.C.), Perpendicular (P) and Vertical Coplanar (V.C.) coil configurations.

mentioned earlier, the errors in Quadrature response are less than 1 per cent for all coil orientations and operating frequencies.

There is one consideration, though, that favours the perpendicular configuration over the other two. Because of the rapid decrease in response due to increase in salt thickness in this configuration, it is the most suitable choice when the contribution of the 3rd Red Bed Shale (120 m or more below the mine level) is to be ignored. Table 2 illustrates this point for the unfavourable case where the third Red Bed is close and the second Red Bed is far. As shown in this table, the error in ignoring the contribution due to the 3rd Red Bed is about 6 percent for the horizontal and vertical coplanar orientations but only 2 percent for the perpendicular case.

However, when all three factors discussed above are taken together, it seems that the advantages in choosing the horizontal coplanar configuration outweigh the disadvantages. Operating convenience, too, is another point in its favour. Vertical coplanar configuration could be used also, especially when it comes to distinguishing between the different physical models in certain cases.

In summary, then, the design parameters of the proposed EM device can be stated as follows:

Coil Configuration: Horizontal Coplanar (Vertical Coplanar)?
Coil Separation: 8 m
Frequency of Operation: 30, 40 kHz.
Height of coils below the mine roof: 2 m

Some Additional Considerations

In this section the following topics will be discussed; a) effect of the finite thickness of the 2nd Red Bed shale, b) effect of a presence of shaly salt layers in the salt back, and c) effect of the presence of moisture in the salt back.

(a) *Finite thickness of the 2nd Red Bed Shale*

The two-layer model assumes an infinite thickness of the 2nd Red Bed Shale. To determine the validity of this assumption, three-layer models were considered in which the

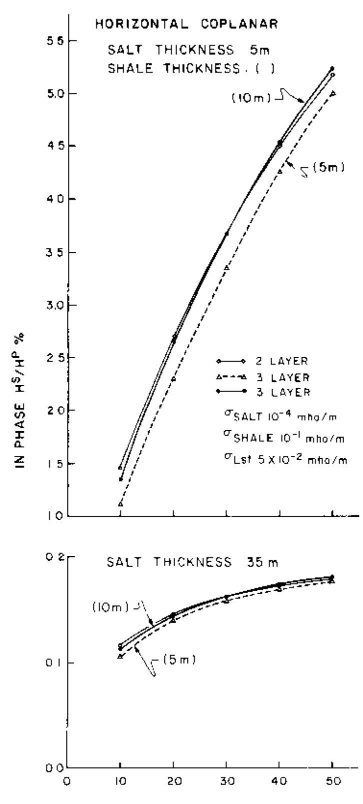

Fig. 7. Effect of the finite thickness of the 2nd Red Bed Shale. In-phase response.

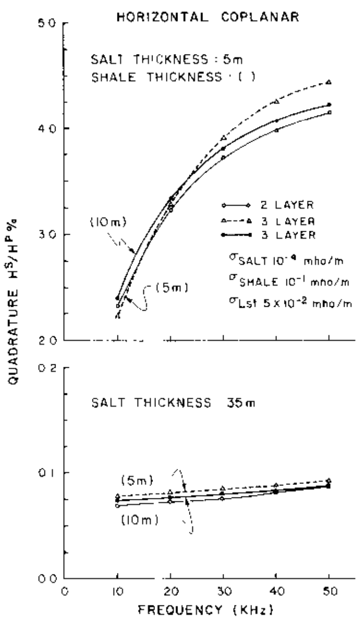

Fig. 8. Effect of the finite thickness of the 2nd Red Bed Shale. Quadrature response.

Frequency	Component	Two layers	Three layers	Six layers
615 Hz	In Phase	0.0183	0.0108	0.0103
	Quadrature	0.0357	0.0293	0.0290
2400 Hz	In Phase	0.0656	0.0497	0.0489
	Quadrature	0.0690	0.0682	0.0688

Layer	σ	t	σ	t	σ	t
1	0.0001	15	0.0001	15	0.0001	15
2	0.1	∞	0.1	9	0.1	9
3			0.05	∞	0.05	36
4					0.0001	15
5					0.1	12
6					0.05	∞

Conductivity: σ mho/m
Thickness: t m

Table 4. Response H^S/H^P of low-frequency EM systems to changes in layer structure.

thickness of the 2nd Red Bed was taken as 5 and 10 m respectively. Results of such a study for horizontal coplanar coils are plotted in Figures 7-8. For frequencies 30 kHz and beyond, and shale thicknesses greater than 10 m, the two-layer model seems a satisfactory approximation for the two extreme thicknesses of the salt back. If the shale thickness falls to 5 m, an error of 5-6 percent is introduced as a result of this approximation.

A number of commercial electromagnetic systems are available, but we felt that the operating frequency of all of them was too low for the objectives of this study. The major problem is that the depth penetration of the low-frequency systems is so great that conductivity changes in distant strata have more effect than changes in depth to the nearest shale.

To demonstrate this, we calculated the response of a typical system with 30 m coil separation, and frequencies of 615 and 2400 Hz. The initial model was a six-layer one based on well log information, subsequently simplified to three layers and then to two layers.

Table 4 indicates the models and the corresponding EM responses. A large difference is shown between the two- and three-layer models and a smaller difference between the three- and six-layer models. On comparing this result with those in Figures 7 and 8; it is apparent that high frequencies are needed to avoid interference from distant strata.

(b) *Effect of the presence of thin clay partings in the salt back*

Thin clay beds have a much higher conductivity than salt and, for the present study, a value of 0.01 mho/m has been assigned to them. Physically, they can be located at any depth within the salt back; their thicknesses usually are a few centimetres.

There are two questions of interest here. First, does the presence of these beds produce unacceptable errors in the determination of the salt-back thickness? Second, is it possible to detect their presence even if the answer to the first question is in the negative?

To answer these questions, a three-layer model was chosen. The thin clay bed was placed on the surface of the salt, to produce the maximum deviation from the response of a two-layer model. Implicit here is the assumption that, given the present system parameters, the response increases as a conductor is brought closer to the system coils.

Percentage deviations from the two-layer case were computed for three thicknesses — 1 cm, 5 cm and 10 cm — of the clay parting over the entire (10-50 kHz) frequency range and for the three coil configurations. Salt-back thicknesses considered here were 5 and 35 m respectively. *At one frequency (30 kHz), intermediate (10,* 20 and 30 m) thicknesses were used also to study any systematic effects such variations might produce. The results of this study are summarized below in three parts.

i) When the thickness of the salt layers is 5 m: Over the entire frequency range, and considering all the coil configurations, the maximum deviation from a two-layer model due to the presence of a thin clay parting is about 2 percent. This is true for both the In-phase and Quadrature components.

ii) When the thickness of the salt layer is 35 m: As the effect due to the shale bed is considerably reduced in this case, the presence of a conducting layer such as a thin clay band may be expected to produce relatively large percent deviations in the response from a two-layer case. The point to note is that the In-phase component remains within 1 percent of the two-layer values whereas the Quadrature components show larger deviations, especially in the perpendicular configuration. The deviations increase with the thickness of the clay parting (refer to Table 5), and also with frequency.

iii) When the thickness of the salt layer is 10, 20 and 30 m: As expected from the above discussion, the In-phase components show deviation around 1 percent. The Quadrature component deviates in successively higher amounts because of increases in thicknesses of the salt and the thin clay layer.

Therefore, from this test we conclude that a shale parting 10 cm thick near the mine roof could cause a significant distortion in the Quadrature component. The In-phase component is relatively unaffected.

The horizontal coplanar configuration is the least sensitive to thin clay seams, and the distortion is reduced with a decrease in frequency. For the assumed conditions, 30 kHz appears to be the best compromise frequency.

(c) *Effect of moisture in salt*

As mentioned earlier, the conductivity of porous salt containing brine ranges, for example, from 0.0001 to 0.01 or 0.04 mho/m, depending on the intergranular porosity. The three models using such a salt bed were as follows; i) near the surface of the mine, ii) adjacent to the shale bed and iii) sandwiched within the salt layer. Conductivity of the salt was taken as 0.0001 mho/m; conductivities of the shale were taken as 0.1 and 0.3 mho/m respectively.

A general conclusion can be stated here. Both the In-phase and Quadrature components increase in magnitude, thus masking the response due to the 2nd Red Bed Shale. The components shift to values that correspond to smaller salt thicknesses and lower shale conductivities (Fig. 9).

If, however, brine solution is present within wide fractures in the salt layer, the In-phase component increases dramatically (>> 10%). It should be possible, therefore, to detect brine pockets quite readily.

Salt Thickness Determination

Figure 9 is an interpretation diagram showing the In-phase and Quadrature responses for vertical and horizontal coplanar coils and a range of salt thicknesses and shale conductivities, and showing also the effects of a few perturbations.

Frequency (kHz)	Clay Seam Thickness (cm)	Horizontal Coplanar		Perpendicular		Vertical Coplanar	
		In-Phase	Quadrature	In-Phase	Quadrature	In-Phase	Quadrature
	1	0.07	- 2.8	0.3	- 18.6	0.07	- 8.1
20	5	0.20	-14.2	-0.7	- 92.5	0.2	- 40.0
	10	0.48	-28.6	0.8	-183.7	0.4	- 79.4
	1	0.06	- 4.0	0.2	- 22.1	0.07	- 11.0
30	5	0.18	-20.4	0.3	-110.0	0.2	- 54.8
	10	0.37	-40.9	0.4	-218.2	0.4	-108.7
	1	0.06	- 5.1	0.2	- 24.4	0.06	- 13.4
40	5	0.17	-25.7	0.2	-121.0	0.2	- 66.7
	10	0.35	-51.7	0.2	-241.1	0.3	-132.3

Table 5. Percentage deviation of (H^S/H^P) from a 35-m. two-layer case for different clay seam thicknesses.

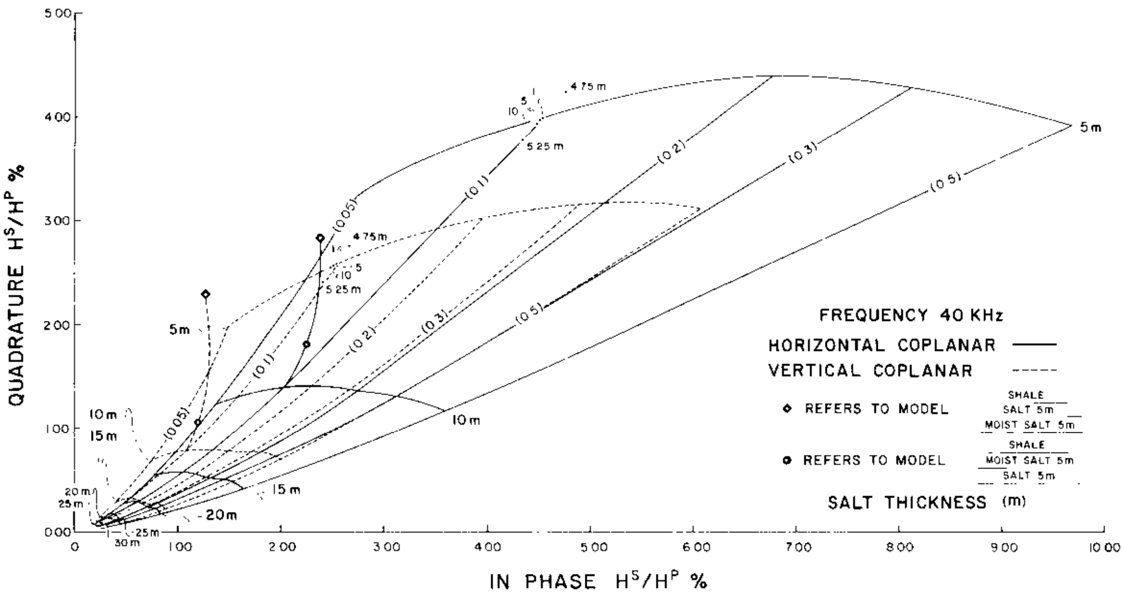

Fig. 9. Interpretation diagram for a two-layer model. Conductivity of shale = 0.05, 0.1 . . . 0.5 mho/m.; conductivity of salt = 0.0001 mho/m. Thickness of salt = 4.75 m, 5.0 m, 5.25 m, 10 m . . . 30 m. Thickness of shaly salt = 0.01 m, 0.05 m and 0.1 m.

The lines emanating from the origin of the graph are lines of equal conductivity of the 2nd Red Bed Shale, and the transverse lines are for constant salt thickness. Thus a given value of In-phase and Quadrature reading can be interpolated to yield a value of salt thickness and shale conductivity. Perturbations due to thin clay seams are plotted near the 0.1 mho/m, 5 m intersection, where it is obvious that such perturbations are not important. However, thin clay seams would produce a similar effect where the salt is 20 m or greater, and the effect would be more significant as a percentage error of the depth estimate due to the smaller anomaly. Because of this and other possible systematic errors, it may be necessary to calibrate the electromagnetic system at a place where the salt thickness is known.

The other perturbation is the effect to be expected from a 5-m thick porous salt containing 1 percent brine. In some of the potash mines such porous, brine-filled salt appears to overlie or underlie some limited areas, from which it leaks into the mine. In this case, there is a substantial change in response. The interpretation of electromagnetic readings in such circumstances would have to depend on comparisons with other nearby electromagnetic data or with some geological interpretation. The presence of brine might be detectible because the apparent shale conductivity as well as the salt thickness would change substantially.

Summary

The purpose of the program was to design an electromagnetic system capable of accurate sounding through rock salt up to 35 m thick in contact with shale. Interference from other formations and thin beds was to be kept to a minimum.

With these conditions, the lower limit of frequency was set by the minimum desirable response and by interference from conductive rocks more distant than the shale. The upper frequency limit was set by interference from nearby thin conductive layers, and our desire to avoid the effects of displacement currents. The system should operate around 30 to 40 kHz.

The coil separation was chosen to obtain a response monotonic with depth to shale, yet maintain a reasonably large amplitude for the operating frequency. Coil separation should be small for underground operation. The separation was chosen to be 8 m.

Coil orientation was chosen to obtain the maximum and most nearly linear response. We found also that the effect of displacement currents depended on coil orientation. The best coil orientation was horizontal coplanar.

The proposed system appears to have good operating characteristics with very small error in determining both the thickness of salt and the conductivity of shale. The best accuracy was achieved with small (about 5 m) thickness of salt, which is most important for the mining operation. Small disturbances cause larger percentage errors when the salt thickness is large (about 35 m). Areas containing significant amounts of brine in the rock should produce large and erratic response.

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