

CONTROLLED SOURCE ELECTRICAL METHODS  
(CSEM)

by

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## ABSTRACT

Application of CSEM methods is impeded by natural field, electrification, geological, cultural, and topographic noise. Lateral resolution of parameters of adjacent steeply dipping bodies and vertical resolution of parameters of adjacent beds in a flatly dipping sequence are concerns with any CSEM method. Current channeling into a localized good conductor from a surrounding, overlying, or underlying conductor poses problems for the interpreter.

A summary of the results of several recent experiments with CSEM techniques illustrates that with care and difficulty they can be used to depths on the order of 20 km. If measurements are made on a relatively uniform resistive surface, as can be found in glaciated Precambrian terranes, then either a grounded bipole or a loop source is acceptable. Most of the recent CSEM experiments were made over resistive Precambrian rocks and all were directed toward detecting a conductive layer at about 20 km depth. However, for exploration beyond this depth, the MT/AMT method would seem to be preferred. The rationale behind this conclusion is largely contained in consideration of the ratio of signal to noise. Where thick irregular surficial overburden of low resistivity occurs, two- and three-dimensional modeling is necessary to strip off the effects of the shallow layers. This may not be possible for CSEM and then MT/AMT becomes the only alternative.

## INTRODUCTION

Controlled source electrical methods (CSEM) have been used in a limited way in exploration of the deep crust and upper mantle. Problems encountered with CSEM in this application include lateral and vertical resolution, current channeling, and natural field, electrification, geological, cultural, and topographic noise.

After briefly reviewing the above problems, a summary is given of some recent results using CSEM in exploration of the deep crust and upper mantle. A conductive horizon at a depth of about 20 km is commonplace in these studies, yet it is difficult to be certain of its geological meaning. Most of these studies have been conducted over resistive Precambrian terranes. When one attempts to apply CSEM to unravel geological problems in terranes where heterogeneous conductive geological materials exist near surface, deep crustal and upper mantle exploration by CSEM becomes problematical unless one fortuitously acquires the use of a transmission line hundreds of kilometers in length. Even then, two- and three-dimensional earths must be used in interpretation. We conclude by demonstrating, via some simple models, the pitfalls of this approach.

## PROBLEMS WITH CSEM

In Table 1 we have listed the problems encountered in application of controlled source electromagnetic methods. We shall briefly summarize each of these problems.

### *Natural field noise*

← Table 1  
about here

The slope of the natural field spectrum below 1 Hz is as steep as  $f^{-4}$  where  $f$  is the frequency of observation. Such a steep spectrum places serious constraints on measurements below about 0.1 Hz (Connerney et al., 1980; SanFilipo and Hohmann, 1982). Coherent stacking of data for days at a time is commonplace. SanFilipo and Hohmann (1982) demonstrate that high pass filtering prior to stacking reduces the time required for stacking. Ideally, one would use a remote reference (Gamble et al., 1979) to cancel coherent noise, but as SanFilipo and Hohmann (1982) demonstrate, the separation of the remote reference from the transmitter must be at least five times the separation of the receiver from the transmitter. Since separation of the receiver from the transmitters range up to 100 km, a serious problem is posed in transmitting the remote reference information to the receiver site. Hence, remote reference has not been used in deep crust/upper mantle CSEM studies.

### *Cultural noise*

Cultural developments create active and passive noise. Circuits completed through fences, pipelines, power lines, telephone lines, rails, and other conductive cultural structures produce anomalies largely unrelated to subsurface geology. These sources of noise can, in rare instances, be reduced by removing the offensive structure, but, by and large, they can only be avoided by placing transmitters and receivers well away from cultural structures. This is not always possible in areas of concentrated industrialization, and hence important geological problems simply cannot be

attacked in such areas.

Some of these cultural developments also serve as sources for narrow or broad-band electric and magnetic field noise, especially power lines, telephone lines, and electrified rails. Further compounding the problem is the fact that these active sources of cultural noise induce eddy current noise in the passive cultural noise sources such as fences and pipelines.

#### *Geological noise due to overburden*

Overburden can be described variously as unconsolidated sediments, weathered rock, or consolidated sediments above crystalline basement. The overburden may be resistive (e.g., glacial gravels) or conductive (e.g., unconsolidated valley fill in the Great Basin of the U.S.A.). In glaciated terrane both the overburden and the weathered layer may be totally removed as is typical of areas of extensive Precambrian exposure in North America and Scandinavia. The weathered rock is invariably conductive because the geological process of weathering leads to a) increased porosity, b) increased presence of clay minerals with their attendant surficial electrical conduction, and c) increased concentrations of ions in the pore waters of the weathered rocks. In dry climatic environments, evaporation strongly increases the concentration of ions in the pore waters, on average. Dilution of these ions takes place during the rainy season in dry or wet environments. A worldwide study of these factors points out that the shallow resistivity profile is closely related to local climatology, to glaciation, and to tectonic style. The depth of overburden related to weathering seldom exceeds 100 m but can easily reach 2 km for valley fill in the Great Basin of the U.S.A.

Whatever its origin, irregular conductive overburden will produce geologic noise which may render difficult the recognition of vertical

variations in the resistivity profile of the deep crust and upper mantle. Wannamaker et al. (1980) illustrate how two-dimensional modeling can be applied to strip off the effects of overburden from magnetotelluric data.

#### *Resolution and the effect of other geological noise*

To facilitate vertical resolution, i.e., resolution of the resistivities and thicknesses of horizontally layered media, an inductive electromagnetic system would need to sample at three or four frequencies per decade. At least four decades of spectrum are required if one wishes to explore both shallow and deep layers. If lateral inhomogeneities are superimposed on the layering, then an adequate spatial density of receiving stations must also be assured over a distance sufficiently large to permit delineation of all inhomogeneities of interest so that the geological noise they contribute can be removed and the layering more accurately delineated.

It is well known that inductive techniques, passive or active, usually provide information on conductivity-thickness products of conductive layers, whereas they usually provide only thickness information on resistive layers. On the contrary, resistivity techniques usually provide information on resistivity-thickness products for resistive layers and conductivity-thickness products for conductive layers. Vertical resolution of resistive and conductive layers is well illustrated via inversion (e.g., Fullagar and Oldenburg, 1982). Joint inversion of inductive and resistive data sets can markedly improve the resolution (Petrick et al., 1977).

#### *Effects of topography*

Variations in elevation of the receiver relative to the transmitter will produce *elevation errors* in electric or magnetic fields along a traverse, relative to the fields that would be observed over a flat surface. These can be severe for short separations between transmitter and receiver but they are

not expected to be large for the large separations associated with deep crust/upper mantle studies.

If topographic relief is large, one seeks to assure that a square coil or bipole source is horizontal and that measurements are made of horizontal and vertical magnetic and horizontal electric fields. Alternatively, the plane of the transmitting coil must contain the axis or the plane of the receiving coil and orthogonal magnetic field components are measured relative to this axis or plane. If either one of these alternatives is ignored, *alignment* errors will result.

A third effect of topography must also be considered. If, for example, a transmitter is located below and adjacent to a ridge, *induced currents* will occur in the ridge at the higher frequencies and will contribute a source of noise which may obscure subsurface features.

#### *Current channeling*

Current channeling occurs due to discontinuity in electric field and a consequent charge accumulation at a boundary between media of different resistivities. The normal component of current density  $J_n$  is continuous across an interface while, by definition, the resistivity  $\rho$  is discontinuous. Hence at an interface between media 1 and 2 we find

$$J_{n1} = \frac{E_{n1}}{\rho_1} = \frac{E_{n2}}{\rho_2} = J_{n2} ,$$

forcing  $E_n$  to be discontinuous at the interface. If  $\rho_1 > \rho_2$  then  $E_{n1} > E_{n2}$  in order to satisfy this relation; normal electric fields are larger in the medium of highest resistivity adjacent to the boundary. Therefore, at an interface, dielectric displacement  $D = \epsilon E$  must be discontinuous and the fourth Maxwell equation must be written as  $\nabla \cdot D = \rho_s$  where  $\rho_s$  is a surface charge accumulation. Thus, since two interfaces bound the sides of a two- or three-

dimensional body in a homogeneous exterior, a dipolar charge distribution occurs across the body. When the electric field of this body is added to the inducing electric field, the net result is an electric field distribution that causes the current flow in the external medium to be channeled, or "short-circuited" into the body. For two- or three-dimensional sources, current channeling may occur along one or all axes of the body, depending upon the direction of propagation of the plane wavelets associated with the source.

Interpretation of CSEM data obtained over an inhomogeneous earth must be made with mathematical techniques which include current gathering in the formulation.

*Lack of interpretational aids*

Undoubtedly the greatest hindrance to application of CSEM is the lack of interpretational aids. One cannot stress too much the need for cost-effective analytic or numerical solutions to problems involving three-dimensional sources over two-dimensional structures (2D-3D), and three-dimensional sources over three-dimensional structures (3D-3D). Since Hohmann (this volume) treats this problem in detail, I shall not dwell on it here.



## APPLICATIONS TO THE DEEP CRUST AND UPPER MANTLE

### *Some recent deep crustal CSEM studies*

Table 2 summarizes the results of five recent CSEM field experiments. ← Table 2 about her  
Two experiments used grounded dipole sources of about 20 km length, one used a grounded power line of 1400 km length, one used power and telephone lines in numerous Schlumberger arrays, while one used a loop source of 4.5 km diameter. The other pertinent details of the experiments are included in Table 2. Even the most casual inspection of Table 2 will reveal that these deep crustal studies are logistically difficult. Lienert and Bennett (1977) performed their sounding in the western Basin and Range Province, U.S.A.; Sternberg (1979) performed his in Precambrian terrane of Wisconsin, U.S.A.; Connerney et al. (1980) worked in the Precambrian of the Adirondack Mountains, U.S.A.; Duncan et al. (1980) made measurements in the Precambrian of eastern Canada; while Van Zijl (1977) made his measurements in the Precambrian of southern Africa. Each of the five experiments detected a conductive (10 to 1000  $\Omega$ -m) layer in the deep crust at depths varying from about 20 to 40 km.

The most widely accepted explanation for such low resistivity at such great depths is hydrated mantle rock in the form of serpentinite but this explanation is suspect. G. R. Olhoeft (pers. comm., 1982) confirms that serpentine at 500°C and riebeckite (an amphibole) at 400°C can exhibit resistivities as low as 10  $\Omega$ -m. Stesky and Brace (1973) note that serpentine with abundant magnetite, as is common, exhibits resistivities less than 10  $\Omega$ -m at 6 kbar (15 to 20 km) due to electrical contact between the magnetic mineral grains. The presence of hydrated minerals in the lower crust in sufficient quantities to form a widespread interconnected phase, while appealing in that it would satisfy both electrical and seismic anomalies at 15 to 25 km depths, is debatable (Connerney et al., 1980).

The notion of conducting mineral grains in contact to form a low resistivity network, as found by Stesky and Brace (1973) provides stimulus for finding conducting minerals, other than magnetite, to serve this purpose. Graphite is abundant in Archean rocks, especially schists (e.g. Nash, Granger, and Adams, 1981). If the film of graphite was sufficiently thin and was connected around all silicate mineral grains, much less than 1% graphite would be sufficient (Olhoeft, pers. comm., 1982). Partial melting in the lower crust is the explanation preferred by Lienert and Bennett (1977) for low resistivities in the northwestern Basin and Range Province in the U.S.A.

One might question the assumption of an infinite line source and the ignoring of near-surface geologic noise in the experiment performed by Lienert and Bennett (1977). Duncan et al. (1980) admitted that lateral variations in resistivity were probably affecting their interpretations. Van Zijl (1977) performed numerous detailed Schlumberger arrays in order to assess the effects of lateral inhomogeneities. Connerney et al. (1980) and Sternberg (1979) seemed to have found locations largely devoid of lateral inhomogeneities.

*Deep crustal exploration in the eastern Basin and Range Province, Utah, USA*

The Basin and Range Province is characterized by NNE-trending mountain ranges and deep sediment-filled valleys. Regional lithospheric extension commencing about 20 m.y. ago yielded the elongate uplifted mountain blocks bounded by normal faults. Subsequent erosion filled the intervening valleys with conductive sediments commonly as deep as 2 km. The mountains, in contrast, are electrically resistive. Performing electrical exploration of the deep crust and upper mantle beneath this superficially complex geoelectric section requires the use of two- and three-dimensional numerical modeling algorithms.

In 1977 we experimented with crustal exploration in the Basin and Range

Province using the dipole-dipole array. The site we chose was near a high-temperature geothermal resource located at Roosevelt Hot Springs near Milford, Utah. Figure 1 shows the pseudosection resulting from this survey. Both 3 km and 6 km dipoles were used and resulted in, according to criteria employed by Roy and Apparao (1971), depths of exploration of 3 km and 6 km respectively. However, when the 3 km data were inverted to three or five alpha centers, the locations of the alpha centers (Figure 2) were only reliably estimated at depths of much less than 1 km (Petrick et al., 1981). The near-surface resistivity inhomogeneities precluded exploration to depths predicted on the basis of a plane-layered earth model. The effects of near-surface inhomogeneities on electrical exploration of the crust are dramatically illustrated by this example.

In 1976, 1977, and 1978 we carried out extensive magnetotelluric soundings in an area of the eastern Basin and Range near Milford, Utah (Wannamaker et al., 1980). Although the geoelectric section in the top 2 km was clearly three-dimensional, we approximated it by two-dimensional models since the mountain and valley involved in our studies were quite elongate. However, we restricted our interpretations to the TM mode of excitation (or E perpendicular to the axes of mountain and valley) since it is the only 2D mode that includes current channeling. The algorithms we use for modeling MT or CSEM with 3D bodies are modifications of an integral equation formulation attributable to Hohmann (1975). They are expensive to utilize for all but the simplest of bodies. Further, the 3D body cannot be at surface if convergence of the numerical approximation is to be at all within time and cost bounds. Still further, they are limited to a resistivity contrast between the 3D body and its surroundings of about 2500:1.

Finally, because of excessive costs, one cannot consider modeling more

than one valley and one mountain at a time. This latter constraint forces us to limit the source dimensions to the valley dimensions. From a practical viewpoint one could not lay out a grounded bipole in the mountains due to lack of access. Even if access was not a problem, the source would assume a very irregular shape if it was draped along or across a mountain range. Thus the source must sensibly be kept in the valley or in the low foothills of the mountains. All of the above explains our reasons for selecting the source dimensions and the simple model of conductive valley fill which we shall discuss next.

+ Fig. 3 about here

Figure 3 shows the simple model of a conductive valley fill simulating the Milford valley; it is 36 km NS, 14 km EW, and 1 km deep and is buried 1 km beneath resistive overburden. It is excited at 0.03 Hz in turn by a 20 km NS grounded bipole, i.e., parallel to the long axis of the valley fill, by a 20 km EW grounded bipole, and by a square loop 5 km to the side. We chose 0.03 Hz as the lowest practical frequency one would attempt to use with these sources since low ratio of signal to noise would virtually prohibit use of lower frequencies. A somewhat larger NS grounded bipole and a somewhat larger square loop would be used for deep crust/upper mantle exploration, but a larger EW grounded bipole could not sensibly be used because of the mountains. A Schlumberger array is out of the question at this locality, for if AB was set equal to 36 km, the maximum length that could be deployed in the valley, then the depth of exploration would only be 4.5 km.

Figure 4 shows the amplitude and phase of the total horizontal magnetic (EW) field normalized by the primary field values for the north-south grounded bipole. The amplitude of the horizontal magnetic field over the body rises to more than 3 times the primary field. Off the body it falls to 60% of the primary field.

Channeling of the bipole return current through the valley fill would explain the above observations. As far as deep crust and upper mantle exploration is concerned, the source looks like a loop and not a bipole. One could calculate whether or not the various crust and mantle layers found with MT here could be detected with such a complex source. We have not yet done this. It seems problematical to us that we could model the geoelectric section in full three dimensions to a sufficient degree of precision to permit detecting layering at depths greater than the 2 km depth of the near-surface inhomogeneities. In this example we set the NS bipole 1 km to the east of the valley fill because in Milford Valley a north-south access road occurs in this locality. The bipole could not be moved further east because of the mountains.

← Fig. 5 about here

Figure 5 portrays the behavior of the amplitude and phase of the normalized east-west horizontal magnetic field for a 5 km by 5 km square loop. The distortions in the horizontal magnetic field are every bit as severe as for the NS grounded bipole.

← Fig. 6 about here

Figure 6 exhibits the behavior of the amplitude and phase of the normalized horizontal magnetic field for a 20 km grounded bipole placed across the valley fill model of Figure 3. The distortions are not as bad for this source type as they are for the other two. This probably occurs because the grounds of the bipole were 3 km on either side of the valley. Such a placement is possible in the Milford Valley but the source would have the appearance of a catenary because of the topographic relief of the sloping valley floor and the mountains. However, the ends would be only 1.5 km above the center of the catenary. This seems to be the most promising source type to use, and since it excites the TM mode primarily, it seems possible that 2D-3D modeling rather than 3D-3D modeling could be used if an algorithm existed

for this case. Cost and accuracy improvements are expected with 2D-3D compared to 3D-3D modeling.

*Selection of a source for exploration of the deep crust and upper mantle*

For deep exploration one would certainly elect to use transmission lines and/or telephone lines as Lienert and Bennett (1977) and Van Zijl (1977) have done, if such lines were available. They both afford adequate ratio of signal to noise without excessive stacking. Further, they both explore to upper mantle depths. Without such long line sources, which only occasionally become available, one is then left with MT/AMT, grounded bipole, or loop sources. In terranes where thick irregular conductive materials exist at surface it would appear prudent, from our computations, to use MT/AMT. However, if no overburden exists then either a loop source or a grounded bipole source may be used provided their moments are equal and provided ground contacts are not a problem for the bipole source. ← Table 3 about here

In Table 3 we list the minimum characteristics a CSEM system would need for complete crustal sounding and profiling. This system would be used to detect both lateral and vertical variations in resistivity from surface to depths of order 30 to 40 km. The system used by Connerney et al. (1980) meets most of the characteristics listed in Table 3. These authors prewhitened their data but did not describe otherwise the filter characteristics used to reject low-frequency noise. Their highest frequency was 400 Hz since they did not attempt to map the near surface.

SanFilipo and Hohmann (1982) have established that a remote reference must be placed at a distance of at least 5 times the separation between the receiving and the transmitting sites. Achievement of this remote reference would seem to be impractical when Tx-Rx separations as large as 100 km are required for deep crust/upper mantle exploration.

One might want to use both a grounded bipole and a loop source and employ joint inversion to improve the resolution of the layered media in the geoelectric section.

## CONCLUSIONS

If a CSEM experiment is to deduce the lateral and vertical variation in resistivity to depths on the order of 30 to 40 km, it should be placed to avoid regions of electrification, geological, cultural and topographic noise. The main problem then met is dealing with natural field noise; a lower frequency limit near  $3 \times 10^{-2}$  Hz probably would be dictated by this noise. While most deep crust/upper mantle experiments performed so far have concentrated on layered resistivity distributions, experiments of the future should be designed to ensure resolution of both lateral and vertical variations in resistivity from surface to the maximum depth of the experiment.

Controlled source electrical methods offer an advantage over MT/AMT in that they do not suffer nearly as much from current channeling in distant overburden or oceans. On the other hand, frequencies as low as  $10^{-4}$  Hz are readily available for MT and hence deeper exploration is possible with this latter method. Either a grounded bipole or a loop source is satisfactory for deep crustal exploration if a controlled source is warranted. Use of both source types in the same experiment offers the improved resolution of layered models available via joint inversion of the two resulting data sets. CSEM experiments do not seem well suited to delineating deep crust and upper mantle resistivity distributions in regions where irregular overburden exists; the MT/AMT method is preferred there, because of the availability of 2-D modeling algorithms and because of the availability of ultra-low frequencies.

Five recent experiments each detected a low-resistivity zone in the crust at depths ranging from about 15 to 30 km. The geological explanation most commonly offered for this zone is surficial conduction in serpentized rocks but other explanations should be sought. Graphite is a logical alternative. Of the five experiments, four were performed in Precambrian terranes with two



using grounded bipoles, one using a loop source, and one using a Schlumberger array via transmission and telephone lines. The fifth experiment was conducted in the western Basin and Range Physiographic Province in the U.S.A. The logistics involved in all five experiments were formidable.

## ACKNOWLEDGEMENTS

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## **PROBLEMS WITH E.M.**

- **NATURAL FIELD NOISE**
- **CULTURAL ~~EFFECTS~~ NOISE.**
- **EFFECT OF OVERBURDEN**
- **EFFECT OF OTHER GEOLOGIC NOISE**
- **EFFECT OF TOPOGRAPHY**
- **RESOLUTION**
- **CURRENT CHANNELING**
- **NEED FOR MORE 2D, 2D-3D,  
AND 3D ALGORITHMS**

**RECENT EXPERIMENTS USING CSEM FOR DEEP CRUSTAL STUDIES**

INVESTIGATORS	SOURCE TYPE	SOURCE CURRENT	BANDWIDTH	Tx-Rx SEPARATION	WAVEFORM	STACKING TIME	CRUSTAL MODEL
LIENERT & BENNETT, 1977	1400 km GROUNDED POWER LINE	300A	0.001-0.01 Hz	5-55 km	SQUARE	20 STACKS	0 20 35-45 km $\frac{10^2 - 10^3 \Omega m}{100 \Omega m}$
BTERNBERG, 1979	22-24 km GROUNDED BIPOLE	70A	0.5-10 Hz	5-40 km	SQUARE	100 STACKS	0 10 14-22 km $\frac{10^3 \Omega m}{50-1200 \Omega m}$
CONNERNEY, ET. AL, 1980	4.5 km DIA. LOOP	85A	0.05-400 Hz	20-65 km	SQUARE	TO DAYS	0 10 20 30 km $\frac{10^4 \Omega m}{10^3 \Omega m}$ $\frac{10^2 - 25 \Omega m}{10^4 \Omega m}$
DUNCAN ET AL, 1980	20.5 km GROUNDED BIPOLE	5A	1.0-50 Hz	35-85 km	PRBS	TO 10 HRS	0 17-29 km $\frac{1.5 \times 10^4 \Omega m}{270 \Omega m}$
VAN ZIJL, 1977	SCHLUMBERGER	72A	D.C.	AB TO 1000 km	SQUARE	174 STACKS	0 28-30 30-40 km $\frac{2 \cdot 10 \times 10^3 \Omega m}{10^2 - 60 \Omega m}$ HIGHLY RESISTIVE

TABLE 2

# CSEM FOR DEEP CRUSTAL PROBING

- $T_x$  - BIPOLE 20 km LENGTH  
- LOOP 20 km CIRCUMFERENCE
- $R_x$  -  $E_x, E_y, H_x, H_y, H_z$ , (H sensor RMS noise  $< 10^{-4} \gamma$ )
- $3 \times 10^{-2}$  Hz TO  $10^4$  Hz, 3 TO 4 PER DECADE
- 50 TO 100 AMPS
- 1 TO 100 km, HIGH DENSITY
- 12 BIT A TO D.
- COHERENT DETECTION
- HIGH PASS FILTER PLUS STACKING
- CRYSTAL CLOCK REFERENCE

## FIGURE CAPTIONS

- Figure 1 Resistivity pseudosection from combined 3 km and 6 km dipole-dipole survey near Roosevelt Hot Springs, Utah, U.S.A.
- Figure 2 Dipole-dipole resistivity data and two sets of inversion results illustrating the trade-off between data fit and parameter resolution when more  $\alpha$  centers are used in the inverse solution. The plots to the left show the results when only three  $\alpha$  centers are used to define the conductivity distribution, while those on the right show the results for five centers. If any deep conductors exist in this region, the  $\alpha$  center inversion scheme failed to discriminate between their response and the near-surface conductive areas. The dipole length is 3 km. Data acquired near Roosevelt Hot Springs, Utah, U.S.A. (After Petrick et al., 1981).
- Figure 3 Model used to calculate approximate response of a valley fill to excitation of a NS 20 km grounded bipole (x directed), an EW 20 km grounded bipole (y directed), and a 5 km square loop.
- Figure 4 Amplitude and phase of the normalized horizontal magnetic field for the NS grounded bipole adjacent to the valley fill model shown in Figure 3.
- Figure 5 Amplitude and phase of the normalized east-west horizontal magnetic field for the 5 km square loop overlapping the valley fill model shown in Figure 3.
- Figure 6 Amplitude and phase of the normalized NS magnetic field for the EW grounded bipole straddling the valley fill model shown in Figure 3.

DIPOLE — DIPOLE

•  $a = 3\text{ Km}$  □  $a = 6\text{ Km}$

$\rho_a (\Omega\text{-m})$

3 Km

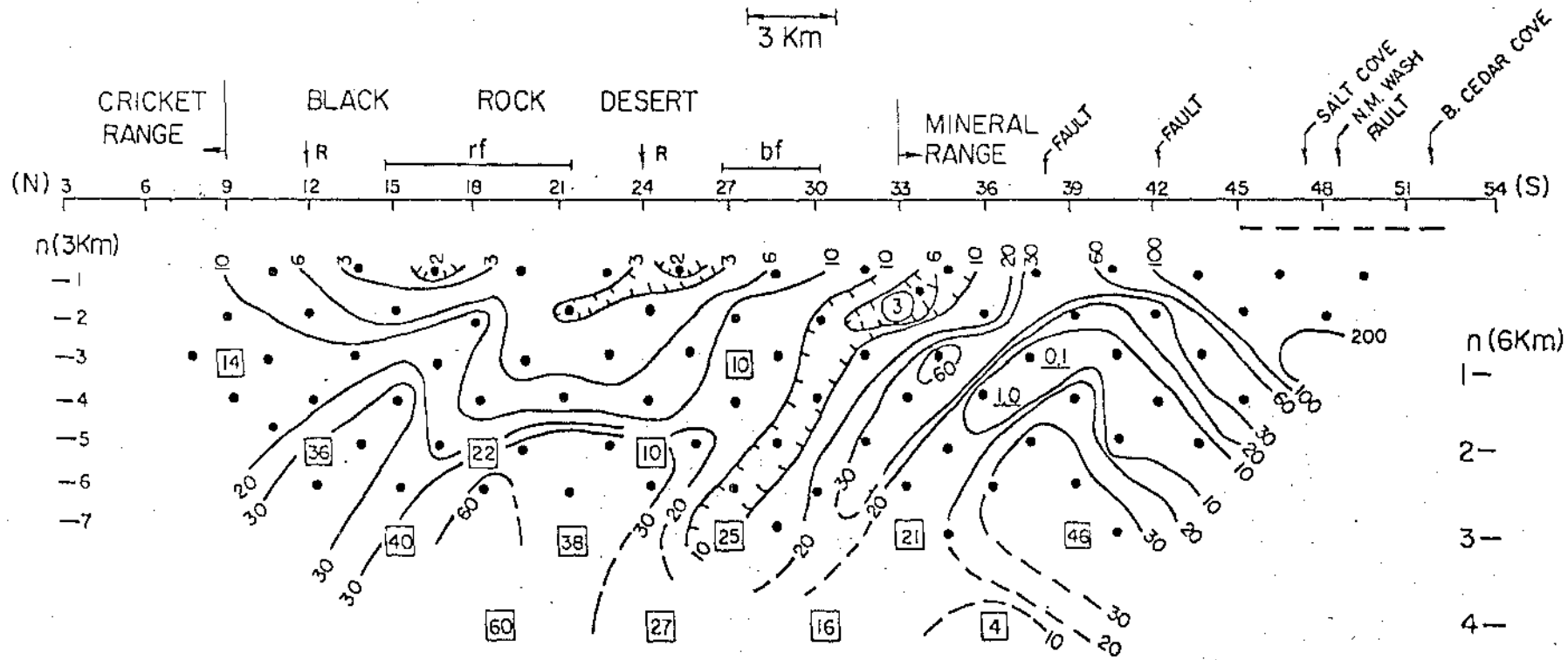
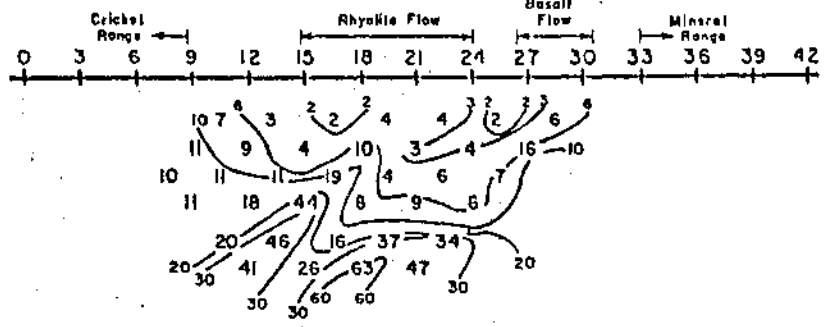


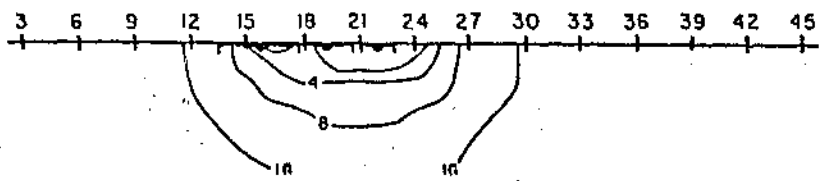
FIG. 1.



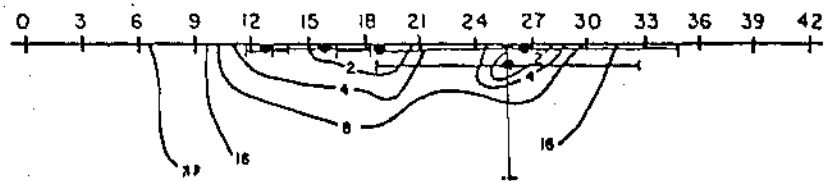
Field data-North and Roosevelt  
3km dipole-dipole profile



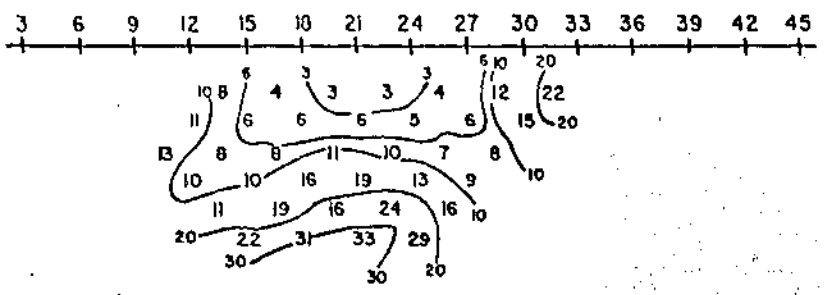
Alpha media resistivity distribution - 3  $\alpha$  centers



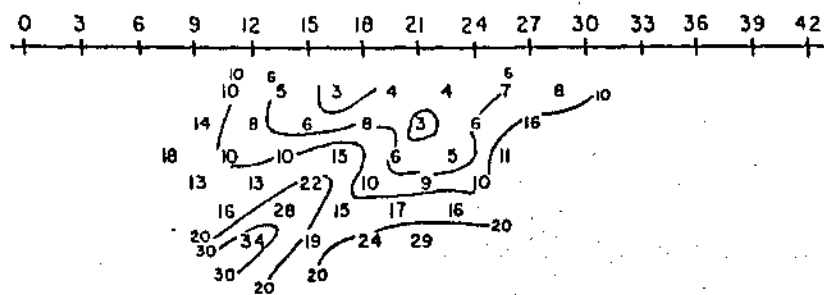
Alpha media resistivity distribution - 5  $\alpha$  centers

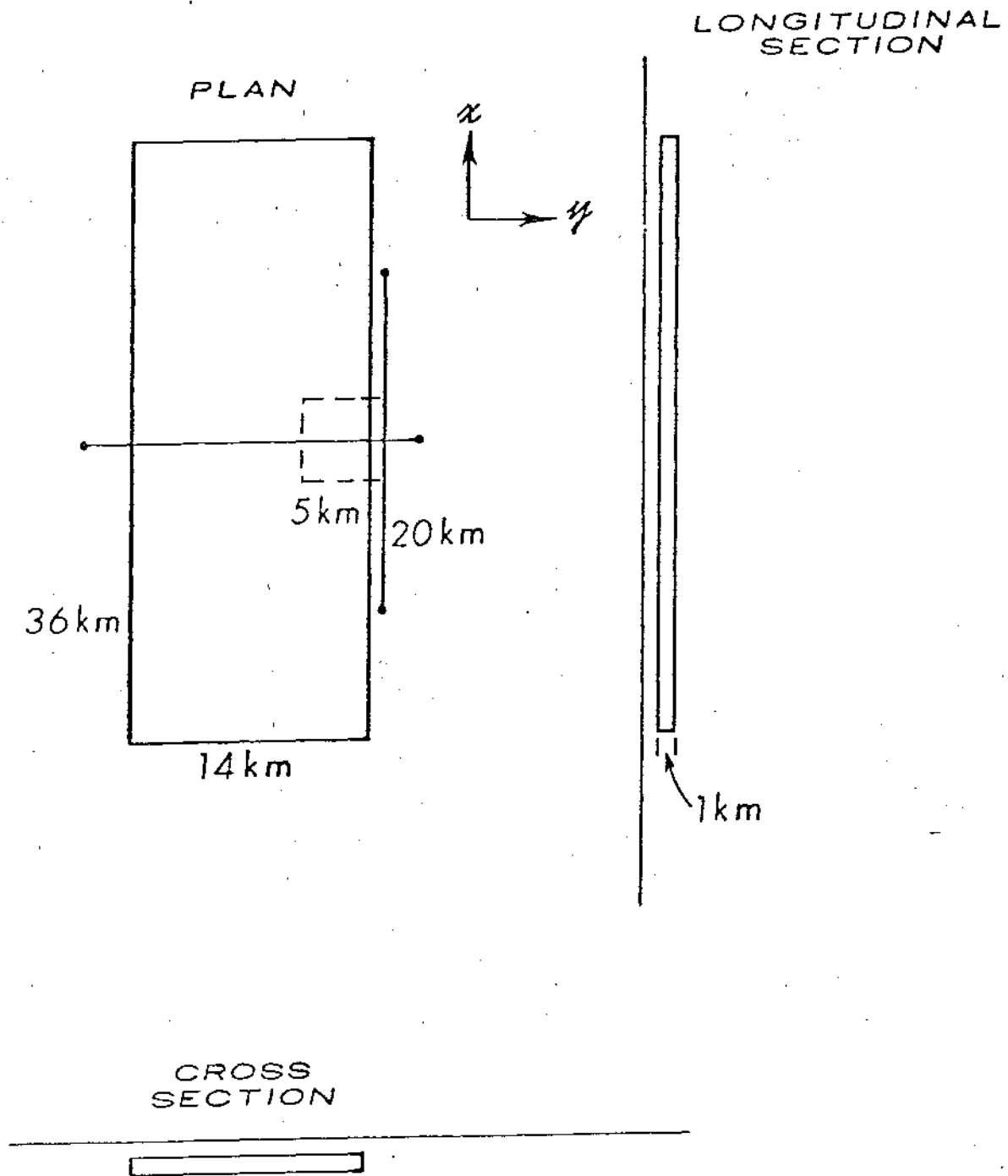


Best fit alpha center pseudosection - 3  $\alpha$  centers



Best fit alpha center pseudosection - 5  $\alpha$  centers

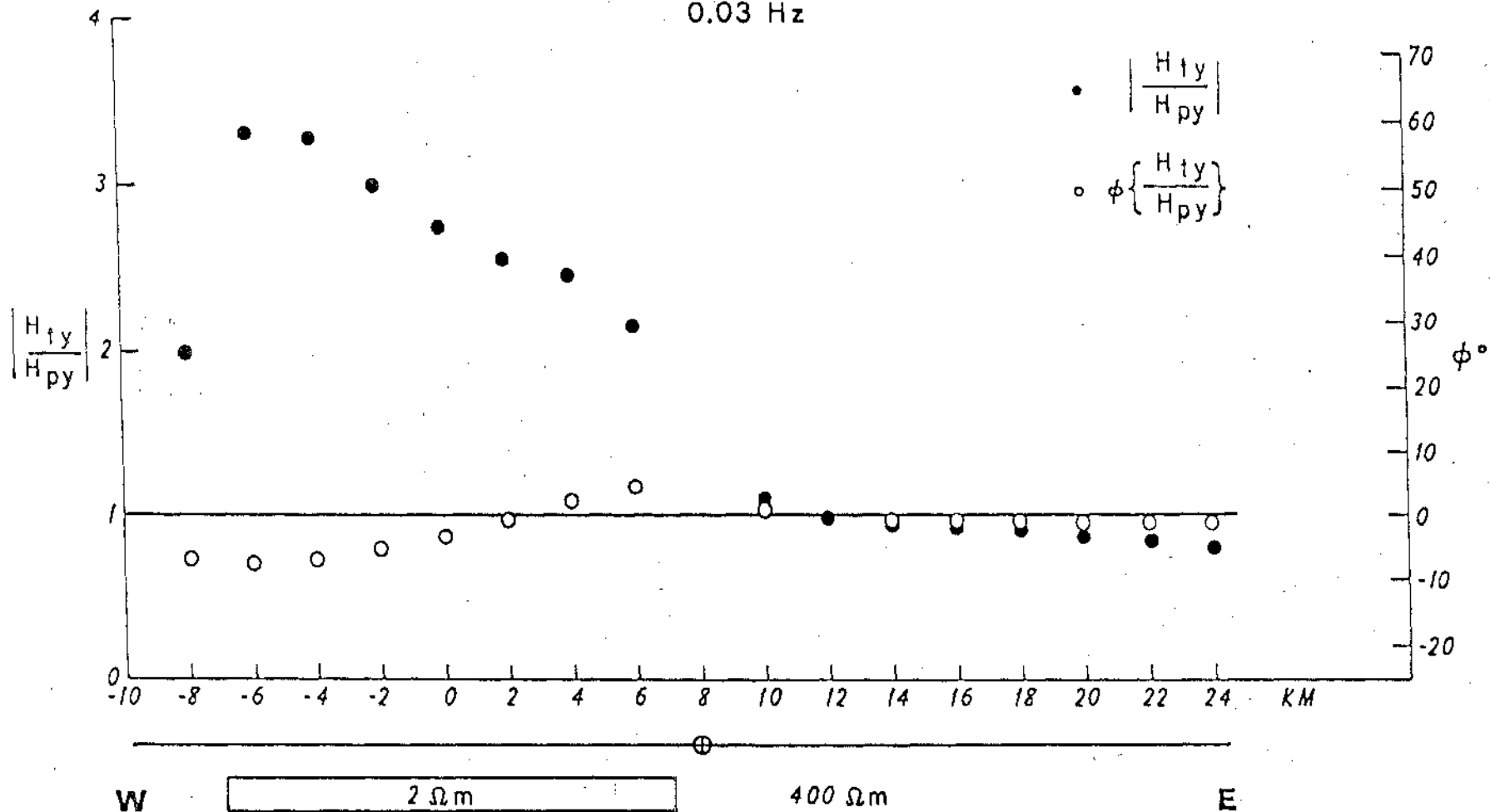




VALLEY FILL MODEL

EFFECT OF VALLEY FILL  
 NS GROUNDED BIPOLE SOURCE

20 km  
 0.03 Hz



EFFECT OF VALLEY FILL  
 SQUARE LOOP SOURCE  
 5 km × 5 km  
 0.03 Hz

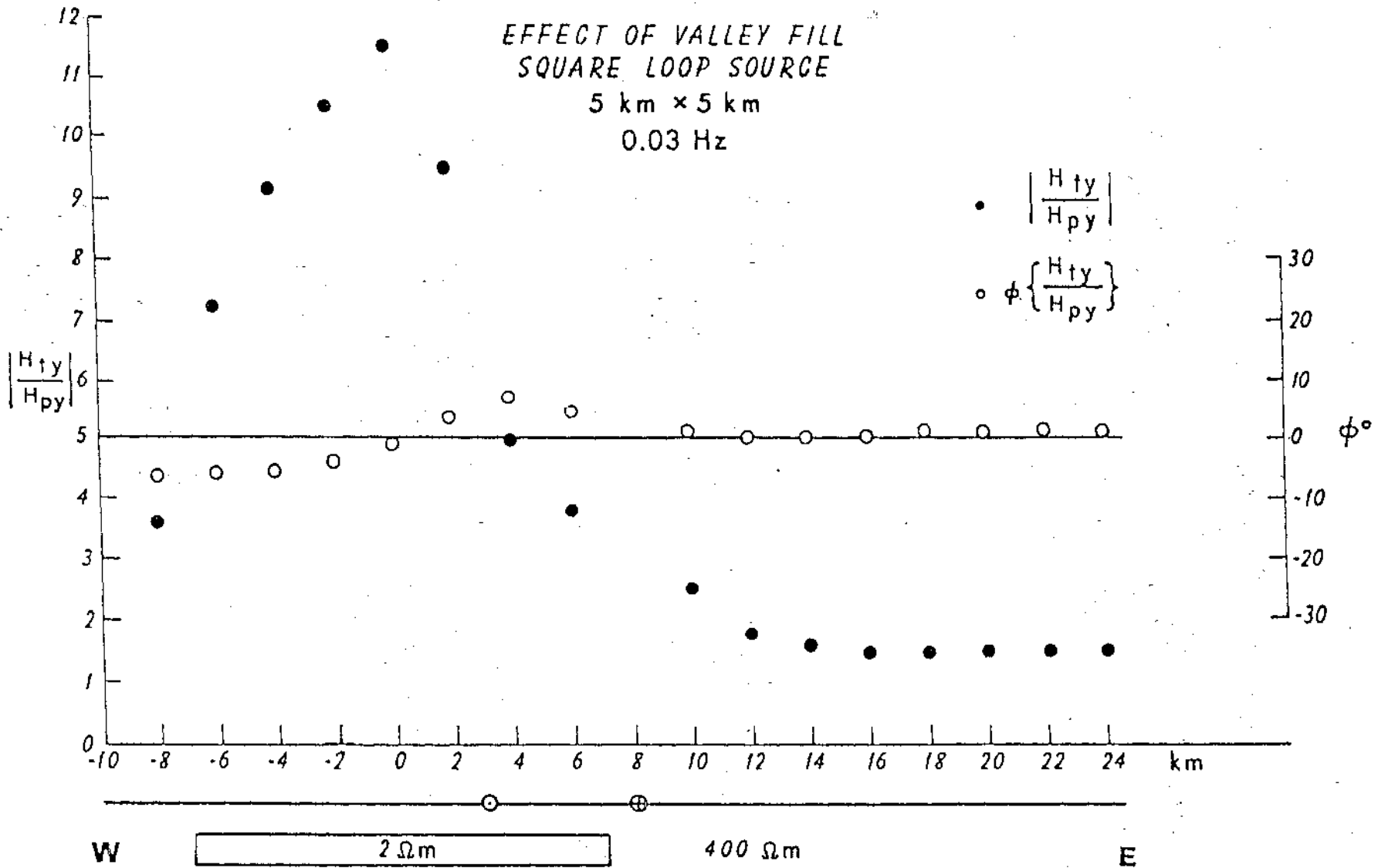


FIG. 5

EFFECT OF VALLEY FILL  
 EW GROUNDED BIPOLE SOURCE  
 20 km  
 0.03 Hz

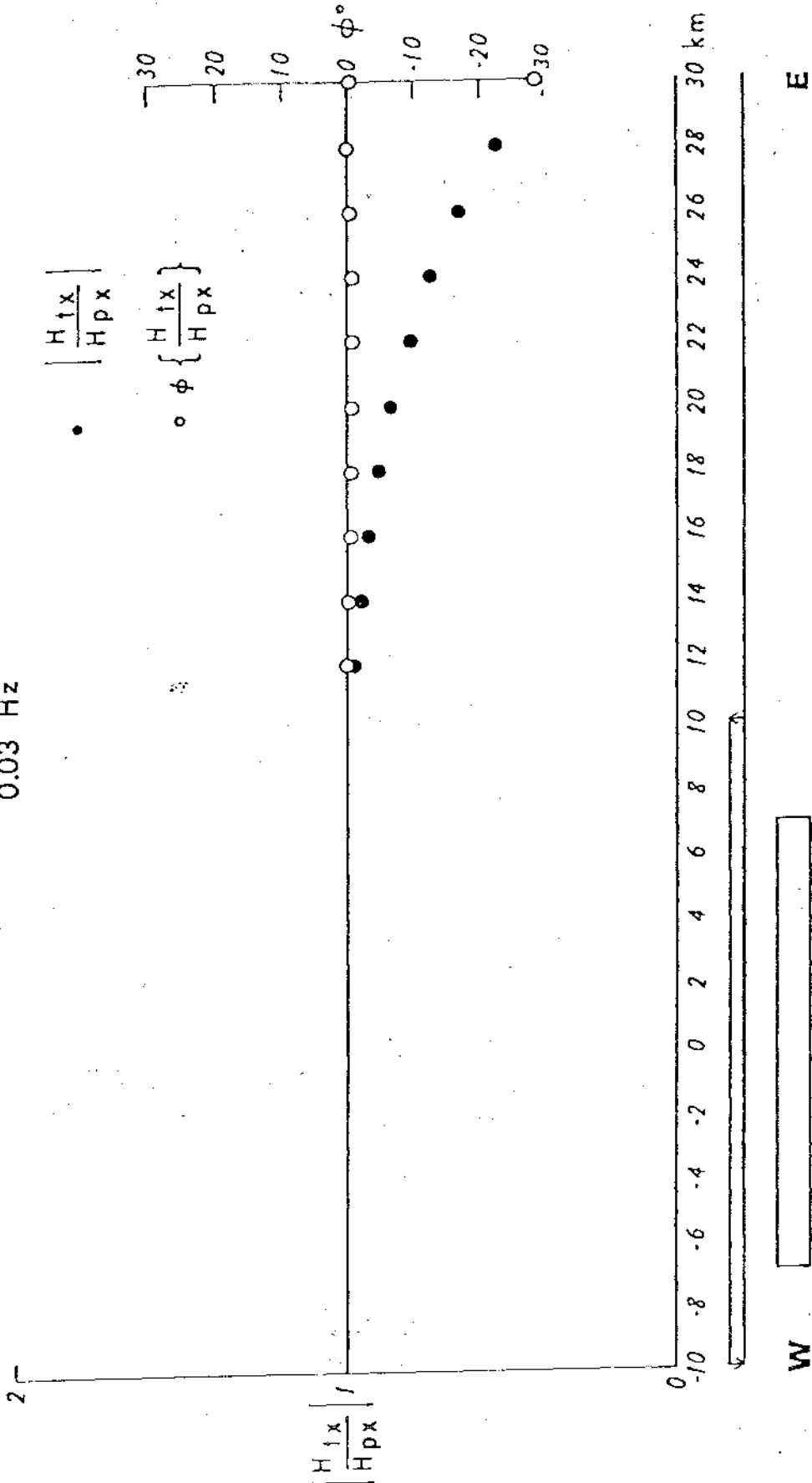


FIG. 6.

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