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Review

A review of magnetic induced polarization with a special reference to its applicability to environmental restoration problems*

D.J. Jin
Chem-Nuclear Geotech, Inc., P.O. Box 14000, Grand Junction, CO 81502 (USA)

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Abstract

The Magnetic Induced Polarization (MIP) method can provide much greater resolving power than the conventional Electric Induced Polarization (EIP) method. The MIP method can be much more effective than the EIP method in areas where there is a highly conductive overburden. The ability of the MIP technique to provide useful information through a highly conductive overburden has been put to good use in Australia and South Africa. It is perceived that advantage can be taken of the ability of the MIP technique in other parts of the world (e.g., the western and southwestern United States) where similar highly conductive overburden exists. This paper reviews the MIP method and examines the applicability of the method to environmental restoration problems. Two identified areas of application of the method in environmental restoration problems are (1) monitoring leakage of heavy metals from recovery or treatment ponds of industrial waste water, and (2) detection of faults in a proposed site for hazardous waste repository or nuclear power plant. Further research is needed to study the effect of various nonmetallic contaminants on the membrane polarization effects of soil or rocks. Results of such a study could determine the applicability of the MIP technique to broad environmental restoration problems.

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1. Introduction

The magnetic induced polarization (MIP, MIP® is a registered trademark of Scintrex Ltd.) method derives information relating to the induced polarization characteristics of the subsurface through measurements of the magnetic field, in contrast to the electric field in the case of the conventional induced polarization (IP) method. To eliminate any possible confusion between the magnetic induced polarization and the conventional induced polarization method, the latter will be referred to as the electric induced polarization (EIP) method. The MIP technique is related to the magnetometric resistivity (MMR)

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method [1–5] in much the same way as the EIP method is related to the resistivity method. In other words, the MIP and MMR methods make observations of the magnetic field, whereas the EIP and resistivity methods make observations of the electric field. The MIP and EIP methods make use of observations of the secondary (induced polarization) fields, whereas the MMR and resistivity methods make use of observations of the primary fields.

It is claimed by some geophysicists [e.g., 6,7] that (1) the MIP method provides much greater resolving power than the conventional EIP method and (2) the MIP method is much more effective than the EIP method in areas where a highly conductive overburden exists or where the surface conditions render contact between electrodes and ground difficult [6–8]. These desirable attributes of the MIP technique are relevant to the solution of environmental remediation problems. A review of the literature and the fundamental concepts of MIP led to the identification of two areas of possible application of the method and to the recognition of an area requiring further research.

The main purpose of this paper is to provide a concise but easy-to-understand summary of the somewhat complex and peculiar concepts of the MIP technique to those who deal with buried hazardous materials but are not familiar with the method; and to draw their attention to the applicability of the method to environmental restoration problems. The concerned hazardous materials in the subsurface may be those leaked and migrated from their intended confined locations or those whose existence is known but exact location and/or extent are not known. This review may be viewed as a continuation of a series of papers that appeared in this journal previously [9–12] in that the present and the previous papers examine the applications of geophysical methods to buried hazardous materials.

Since the MIP method is very closely related to the EIP method, understanding the latter is desirable in discussion of the former. The following section summarizes the principles of the EIP method.

2. Electric induced polarization method

In a conventional four-electrode configuration at the earth's surface, induced polarization (IP) is manifested as an observable voltage between two potential electrodes after the electric current to the current electrodes is turned off. It is also similarly manifested as a voltage which increases for a certain period of time between two potential electrodes after the current is turned on. The causes of induced polarization are explained by the effects of electrode and membrane polarization, which are discussed below.

2.1 Causes of induced polarization

An excellent explanation of electrode and membrane polarization is provided in a classic textbook by Parasnis [13]. The following is mainly from his description.

2.1.1 Electrode polarization

The electric current in the earth is normally ionic. If the passage of ions is obstructed by certain mineral particles, in which the electric current is electronic, ionic charges accumulate at the particle–electrolyte interface. The positive ions accumulate on the side of a particle where the current enters the particle and the negative ones on the side of the particle where this current leaves. Then the particle is said to be polarized. The accumulated ionic charges create a voltage that opposes the flow of electric current across the interface. When the current is turned off, a residual voltage continues to exist across the particle due to the bound ionic charges until the ions slowly diffuse back into the pore electrolyte. This type of polarization is called *electrode polarization* because it is the same kind of polarization as that observed on the surface of electrodes during electrolysis. It is also called *overvoltage* because physical chemists had used the term before geophysicists recognized the IP effects. As described above, this type of polarization depends on the presence of metallic minerals in the earth.

2.1.2 Membrane polarization

The surface of a clay particle is negatively charged and thus attracts positive ions from the electrolyte. Thus, an electrically polarized double-layer is formed at the surface of the clay particle. The accumulated positive ions repel other positive ions and so act like an impervious membrane impeding cationic movement. When an electric current is forced through the clay, the positive ions are displaced and the current flows. When the current is turned off, the positive ions redistribute themselves into their former equilibrium. The process of the positive ions' redistribution constitutes the induced polarization. This type of polarization, which is called *membrane* or *electrolytic polarization*, does not depend on the presence of metallic minerals in the earth. For this reason, it is sometimes called the *background* or *normal IP effect.*

2.2 Quantities measured in induced polarization effect

Any of the electrode array configurations used in ordinary resistivity methods can be used for IP measurements. The IP effect can be measured in both the time and frequency domain. It should be noted that different authors define some IP-related terms slightly differently and that there is more than one way of describing a characteristic. The following discussion introduces definitions most commonly used in the geophysical literature. Different ways of defining various terms used in IP are given by, among others, Sumner [14] and Zonge et al. [15].

In the time-domain methods, a dc current (actually, of square or other wave forms) is sent into the ground for a definite period and then turned off, and the voltage between the potential electrodes is subsequently measured. The time duration for which the current is sent into the ground typically varies from a few seconds to about 20 s. The shorter durations are chiefly for reduced survey time. The elapsed time between the current cutoff and the residual voltage measurement may typically range between 0.1 and 10 s.

There are mainly three different ways of representing the IP effect in the time domain. Since the residual (secondary) voltage is proportional to the normal potential (the primary voltage, i.e., the voltage while the current is flowing), an appropriate form of representing the IP effect is the ratio of the residual voltage to the normal potential. Also since the residual voltage decays with time, it is appropriate to indicate the time elapsed between the current cutoff and the residual voltage measurement. Moreover, since the residual voltage is very small, the IP effect is customarily presented as a ratio of the residual voltage in mV to the normal potential in V (i.e. mV/V). Sometimes this quantity is expressed as a percentage in which case both the residual voltage and the normal potential are expressed in mV.

The second method is designed to preserve some information inherent in the shape of the voltage decay curve, which is generally logarithmic. It is a normalized time integral (NTI) given as

$$NTI=\frac{1}{V_0}\int_{t_1}^{t_2} V(t)\mathrm{d}t, \tag{1}$$

where V_0 is the normal potential, $V(t)$ is the residual voltage, and NTI is in ms time unit.

The third quantity, which is most commonly used in the time-domain IP measurements and is termed *chargeability* (m), is defined as the ratio of initial residual voltage to the normal potential. The initial residual voltage is the residual voltage at the instant of the current cutoff. Since it is not possible to measure the voltage right at the instant of the current cutoff, in practice the residual voltage a very short time after the current cutoff is measured. Thus the chargeability is expressed as $m=V_t/V_0$, were V_t is the measured residual voltage in volts and m is dimensionless. It should be noted that sometimes the quantity in eq. (1), NTI is referred to as the chargeability.

In the frequency-domain methods, ac currents of different frequencies are sent into the ground, and the variation of apparent resistivity of the earth with the frequency is observed, or the amplitude and phase of the voltage with respect to the current are observed. The second method is called the *complex impedance method*. Measurements of voltages at two or more frequencies are made either separately or simultaneously. In the latter case, either a dual frequency (as in an instrument by McPhar) or a fundamental and a higher harmonic of a single square wave (as in a Scintrex instrument) are used [16]. The frequencies usually used in the frequency-domain methods range between 0.1 and 10 Hz. Frequencies higher than these are avoided to reduce electromagnetic induction effects and frequencies lower than these are precluded by instrumentation constraints.

There are chiefly three ways of representing the measures of the IP effect in the frequency domain. One of them is termed *frequency effect* (*FE*) defined as

$$FE = (\rho_L - \rho_H)/\rho_H, \tag{2}$$

where ρ_L and ρ_H are, respectively, the apparent resistivities at a low and a high frequency, usually 0.1 and 10 Hz. When *FE*, a dimensionless quantity, is expressed in percent, it is referred to as *PFE* in the geophysical literature. A variation of frequency effect, called *metal factor* (*MF*), is defined as

$$MF = 2\pi(10^5)\frac{\rho_L - \rho_H}{\rho_L \rho_H}. \tag{3}$$

In other words, metal factor is frequency effect divided by ρ_L so that this measure reflects the conductivity (so called metal factor or *metallic conduction factor*, *MCF*) of the earth material and is in S/m. The multiplication factor 2π derives from the tradition that apparent resistivity was frequently given in the form of $\rho/2\pi$ and 10^5 is somewhat arbitrary and is used to make the quantity large enough to use conveniently [14].

The third way of representing the IP effect is the *phase difference* between voltage and current. The usual range of the phase difference is 0.01 to 0.1 radian. The upper limit is usually associated with electrode polarization, whereas the lower limit is usually associated with membrane polarization.

The IP effect, in general, is proportional to the concentration of polarizable minerals in the earth. However, as the "polarization contrast" reaches a certain level, its effect becomes "saturated" and reduces its influence in the IP effect [17]. Also, since interconnected mineral particles give IP effects only at their points of current entry and exit, minerals of high concentration (usually around 25% or greater) have a tendency to give less IP effects than minerals of lower concentration [17]. In other words, the IP effect depends on the mode of distribution of the mineral particles.

It is realized that all the quantities representing the IP effect require a knowledge of either the apparent resistivity or the normal potential which is used in computing the apparent resistivity. Since these quantities are those which resistivity methods measure, an EIP survey always implies a simultaneous resistivity survey.

3. Magnetic induced polarization method and its comparison with electric induced polarization method

The EIP method has been developed in order to take advantage of the polarizing property of certain earth materials and has been used successfully in many applications. A good example is its application to prospecting for disseminated minerals, for example, in porphyry copper deposits, for which other geophysical methods are largely ineffective. However, some weaknesses of the EIP method have been recognized. Probably the most critical weakness of the EIP method is its inability to provide useful information through a highly conductive overburden.

The basic difference between the MIP and EIP method is the mode of measurement. The MIP method measures magnetic field, in contrast to the EIP method which measures electric field, both due to the induced polarization current in the earth. Consequently, MIP measurements are expressed in terms of the same parameters as in EIP measurements, except that the electric field is replaced by the magnetic field.

In the EIP method, the action of the primary electric field is to create a volume distribution of current dipoles antiparallel to the field at each point in the polarization medium, with volume current moment strength

$$\boldsymbol{M} = -m\boldsymbol{J}_{\mathrm{P}}, \tag{4}$$

where $\boldsymbol{J}_{\mathrm{P}}$ is the primary (ohmic) current density in A/m^2 and m is the chargeability of the medium and is assumed to be constant within the polarizable medium. The total secondary potential in V at a field point at a distance r in meter from the volume dipole element $\mathrm{d}v$ of current strength $\boldsymbol{M}\mathrm{d}v$ in an external medium of conductivity σ in S/m is [17]

$$\Phi_{\mathrm{S}} = \frac{1}{4\pi}\int\int\int \frac{\boldsymbol{M}}{\sigma}\cdot\nabla\left(\frac{1}{r}\right)\mathrm{d}v. \tag{5}$$

The magnetic field in A/m due to the induced polarization current is [8]

$$\boldsymbol{H}_{\mathrm{S}} = \frac{1}{4\pi}\int\int\int \frac{\boldsymbol{J}_{\mathrm{S}}\times\boldsymbol{r}}{r^3}\mathrm{d}v, \tag{6}$$

where $\boldsymbol{J}_{\mathrm{S}}$ is the induced polarization current density in A/m^2. Equations (5) and (6) represent the fundamental equations of the two methods. Starting from these two equations, the investigators of the MIP method have shown the following aspects of the MIP method which distinguish it from the EIP method. Although the following two paragraphs are not word-for-word quotations, they are in content direct quotations from previous works. Thus they are presented with quotation marks with references shown at appropriate points.

"The primary magnetic field due to a current passing through an electrode embedded on the surface of a horizontally stratified medium, whose layers have conductivities which are uniform within a layer but different from layer to layer, is equivalent to the magnetic field of a cable extending vertically downward from the surface to infinity [6–8, also 8 refers to 18]. Hence, the primary magnetic field produced by current from a vertically emplaced current electrode on a horizontally stratified earth has only a horizontal component, which is perpendicular to the line joining the electrode with the observation point on the surface. Moreover, the current through the horizontal cable on a flat ground surface produces only a vertical magnetic field component when observations are made on the surface. Therefore, by measuring the horizontal magnetic field, one observes primarily the effects of subsurface condition [6,7].

"Also, because the primary magnetic field of a horizontally stratified medium, whose layers have conductivities which are uniform within a layer but different from layer to layer, is independent of the conductivities of the layers [1,4,6,8], such a medium can produce no IP effect. The MIP method is therefore sensitive only to lateral inhomogeneities in polarization and is a true lateral anomaly detection method [6–8]. Howland-Rose et al. [6] also show that a medium of constant IP characteristics but variable conductivity cannot give rise to an MIP response."

Seigel [8] shows that the magnetic field, immediately over its axis, due to a horizontal dipolar current source decreases as the inverse square of its depth, as compared with the inverse cube of the depth in the case of the electric field. A similar contrast of inverse square versus inverse cube relationship applies to the MIP and EIP responses, directly over the body, due to induced polarization current flow in a spherical body. He also observes that the MIP response from horizontal cylinders follows an inverse first power law, whereas the EIP response follows an inverse square law. Consequently, the attenuation of the signal strength with depth will be slower in the MIP than in the EIP method. Of course, the detection of an anomaly depends on its being above the noise level. The effect of the depth of a source on the signal strength is that as the depth increases the EIP signal approaches the noise level faster than the MIP signal.

Magnetic induced polarization responses show more complex and varied patterns than EIP responses [6]. Figures 1(a) and (b) depict the cause of this complex response pattern. Figure 1(a) (vertical section) shows the primary current density ($\boldsymbol{J}_{\mathrm{P}}$) which is in the same direction both within and outside the body. However, the induced polarization current is in the opposite sense to the primary current within the body ($\boldsymbol{J}_{\mathrm{I}}$), but in the same sense as the primary current outside the body ($\boldsymbol{J}_{\mathrm{R}}$) except off the ends of the body. Figure 1(b) shows, in a plan view, the horizontal secondary magnetic field ($\boldsymbol{H}_{\mathrm{s}}$) due to the induced polarization currents. Directly over the body, $\boldsymbol{H}_{\mathrm{s}}$ is in the opposite sense to the primary magnetic field ($\boldsymbol{H}_{\mathrm{p}}$), whereas on the flanks $\boldsymbol{H}_{\mathrm{s}}$ is in the same sense as the primary field. In the EIP method, the measured electric potential is associated with the return current $\boldsymbol{J}_{\mathrm{R}}$, which is in the same sense as the primary current $\boldsymbol{J}_{\mathrm{p}}$ in most regions of space.

The masking effect of a conductive overburden on the electric field responses of targets below is a serious problem in EIP measurements [6,7,13,16,19]. The

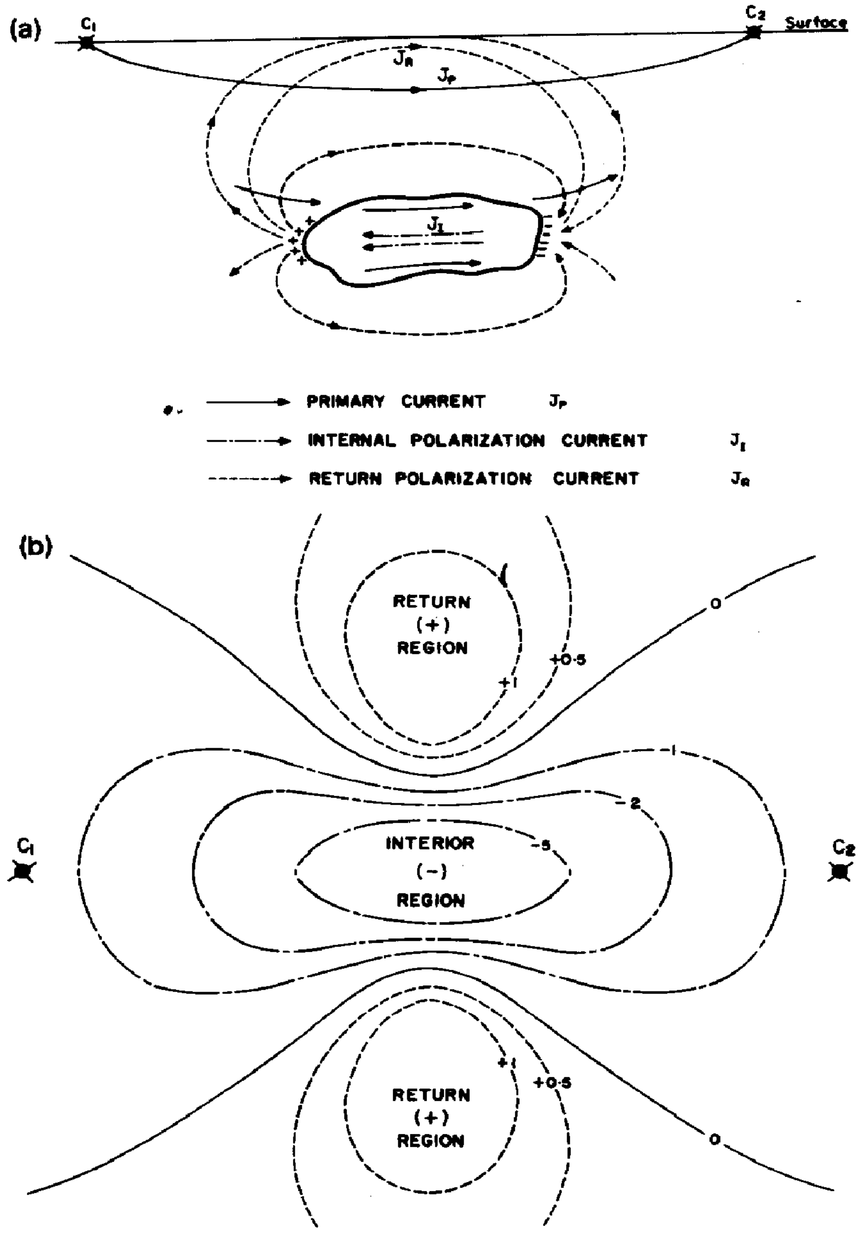

Fig. 1. (a) Primary and induced polarization current around a buried polarizable body with the current electrodes C_1 and C_2 at the surface (vertical section). (b) Horizontal magnetic induced polarization field at right angles to the line joining the current electrodes C_1 and C_2 (plan view); after Howland-Rose et al. [6].

conductive overburden may be at the surface of the earth or may be buried but lie above the target. To determine the relative effects of an overlying conductive layer on the EIP and MIP responses due to a buried source, Howland-Rose et al. [6] conducted model studies. The model consisted of a buried line current terminated by a source at one end and a sink at the other, both of equal current amplitude. The line current simulates the interior current flow, whereas the source and sink represented the return current flow described above. For MIP responses, the horizontal magnetic field at the surface perpendicular to the current line, traversing the middle of the current line, was measured. For EIP responses, the electric field at the surface parallel to the current line was measured. The model and results are shown in Figs. 2 and 3 for EIP and MIP, respectively. These figures depict the results obtained in three different geologic situations: homogeneous half-space, a conductive layer at the surface, and a buried conductive layer. The resistivity of the conductive layer in the models was 65 times greater than that of the rest of the medium.

Figure 2 shows that the conductive layer (whether at the surface or buried) reduces the electric field so drastically that the surface EIP response becomes negligible. On the other hand, Fig. 3 shows that the magnetic field is essentially unaffected by the conductive layer. This result demonstrates the ability of the MIP method to detect a target even through a highly conductive overlying layer. This result, however, shows only how the polarization signals from the body are affected by a conductive overlying layer. There is another problem of conductive overlying layers, i.e., attenuation of the primary current. However,

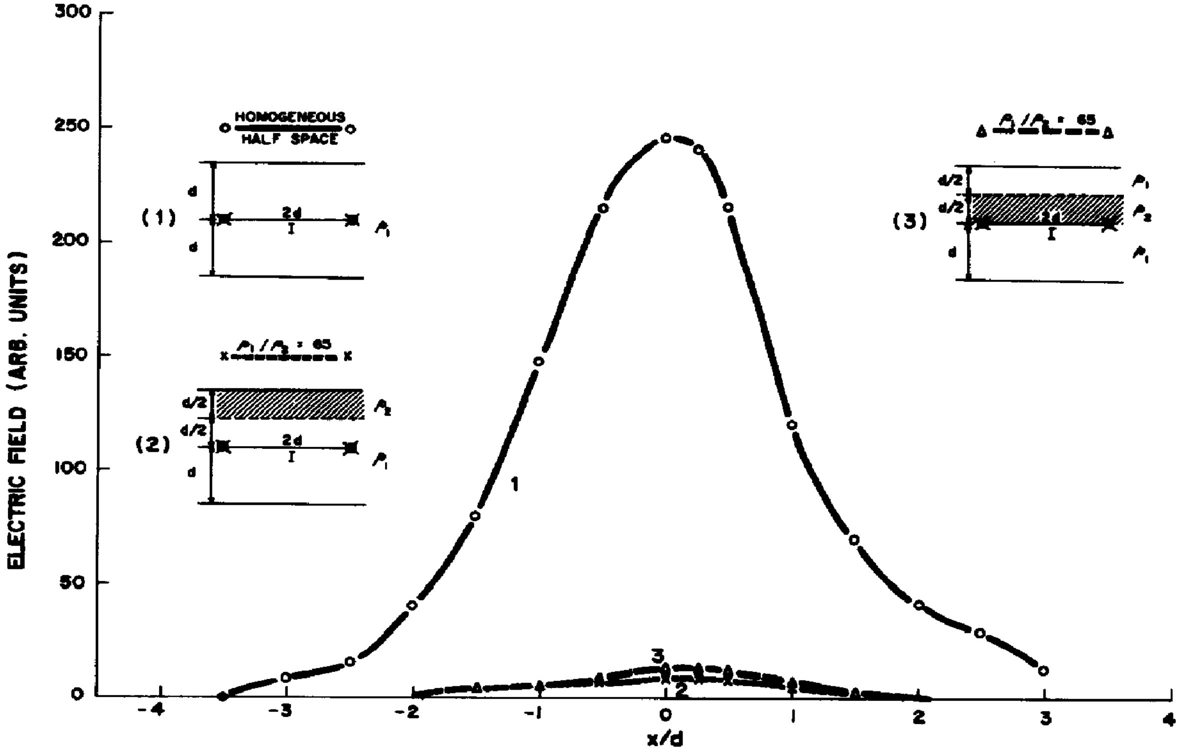

Fig. 2. Effect of a conductive layer on EIP: (1) Homogeneous half-space; (2) conductive layer at the surface; (3) conductive layer in the subsurface (after Seigel and Howland-Rose [7]).

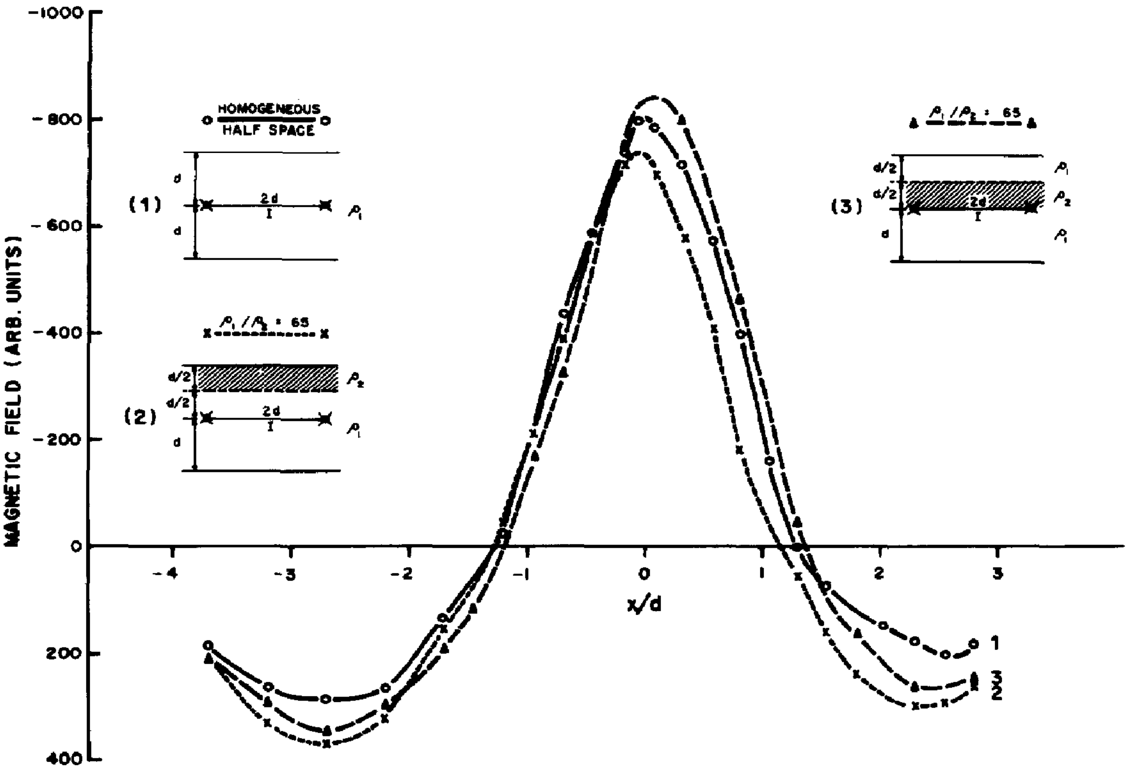

Fig. 3. Effect of a conductive layer in MIP: Curve labels represent the same geologic situations as in Fig. 2 (after Seigel and Howland-Rose [7]).

since the attenuation of the primary current will be the same for both the EIP and MIP methods, the result described here is sufficient in demonstrating the *relative* responses of EIP and MIP, at the surface, of a buried target. Numerous field examples supporting this result have been shown by various authors [6,7].

Magnetic induced polarization measurements are essentially point measurements, because the physical dimensions of the magnetic sensors are less than 0.6 m [6]. Electric induced polarization measurements, on the other hand, are usually made by two poles with an extended distance between them (typically 3 to 100 m). Thus the spatial resolving power of MIP measurements is expected to be much greater than that of EIP measurements. Comparable EIP resolution may be obtainable by reducing the potential electrode spacing, but this will be at the expense of a proportionate reduction in signal strength. Figures 4 and 5 show available examples of greater resolving power of MIP relative to that of EIP.

Figure 4, which is reproduced from Seigel and Howland-Rose [20], shows results of field surveys conducted in Widgimooltha, Western Australia. At the bottom is shown the geological section constructed based on the results of drilling. The target consists of two easterly dipping lenses of nickeliferous sulfides

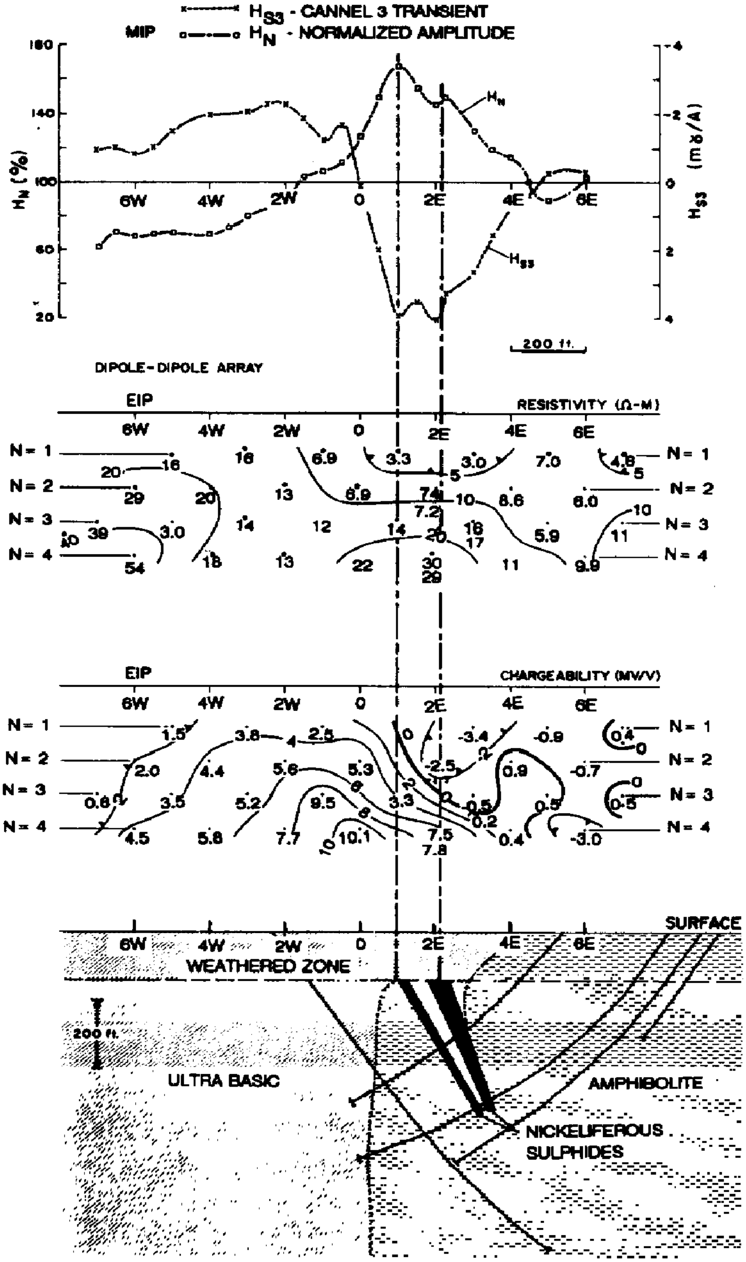

Fig. 4. Comparison in resolving power between MIP and EIP (after Seigel and Howland-Rose [20]).

with 1 to 3% nickel. The two lenses are approximately 30 m apart from each other and their average thicknesses are 4 and 8 m, respectively. These targets are overlain by a highly conductive (3 to 10 Ω-m) overburden of 45-m thick weathered zone.

At the top of the figure are shown time-domain MIP results. The current electrodes were 360 m apart. The plotted quantity, H_{s3}, is $\mu_0 H_s/I$ in pT/A (mγ/A) where μ_0 is the magnetic permeability of free space in Wb/A-m and I is the primary current in A. The second subscript 3 represents the third time gate (1170–1690 ms) integrated employing a 2-s on/off timing. Also shown is the primary magnetic field normalized by division by the theoretical field due to a uniform earth, expressed in percent (H_N).

In the middle of the figure are shown time-domain EIP results. A dipole–dipole array with electrode spacing (a) of 60 m and $n=1$ to 4, where n is the distance, in number of a's, between nearest current and potential electrodes, was used. Resistivity and chargeability are shown in a pseudo-section form. The same integration time gate as in MIP was used.

As can be seen from the figure, the two separate targets are easily resolved as two separate peaks on MIP curves even though their separation is less then their depth, whereas they are hardly resolved from EIP measurements.

Figure 5 shows another similar result. The exact location of the survey, which was conducted in Australia by Howland-Rose et al. [6], is withheld for a proprietary reason. The geologic section, confirmed by drilling, shows two sulfide zones, which are targets of the survey. The sulfide zones, each 2 m thick, contain 60% pyrrhotite and galena, are approximately 50 m apart from each other, and are covered by a 40-m thick highly conductive (7 Ω-m) overburden.

The results of the time-domain surveys are shown for MIP at the top and for EIP at the middle of Fig. 5. M_3 represents the MIP chargeability measured through channel 3; H_N is the same quantity as in Fig. 4. The plotted EIP chargeability is actually normalized time integral defined in eq. (1). As can clearly be seen from the figure, the two separate targets are easily resolved as two peaks of the MIP curves even though they are only 2 m thick and at the depth of 40 m, whereas they are not resolved from the EIP data.

Two possible sources of noise in EIP measurements are [16] capacitive coupling, which is due to leakage currents between current electrodes and potential wires or between current and potential wires, and electromagnetic coupling, which results from mutual inductance between current and potential wires. The absence of potential electrodes and wires eliminates these sources of noise in MIP measurements.

The MIP method provides a detection of areas of anomalous polarizability rather than a measurement of a physical property. Since, as pointed out earlier, EIP measurements require apparent resistivity information and also it is a common practice to conduct a resistivity survey in parallel with an EIP survey, the true resistivity of the earth can be deduced when EIP surveys are done. Similarly, a magnetometric resistivity (MMR) survey may be conducted in parallel with an MIP survey. However, absolute values of resistivity cannot be determined by the MMR method. Rather, only resistivity contrasts or reflection coefficients can be deduced by comparing observed MMR anomaly with theoretical values. Thus, although the interpretation of both MIP and EIP

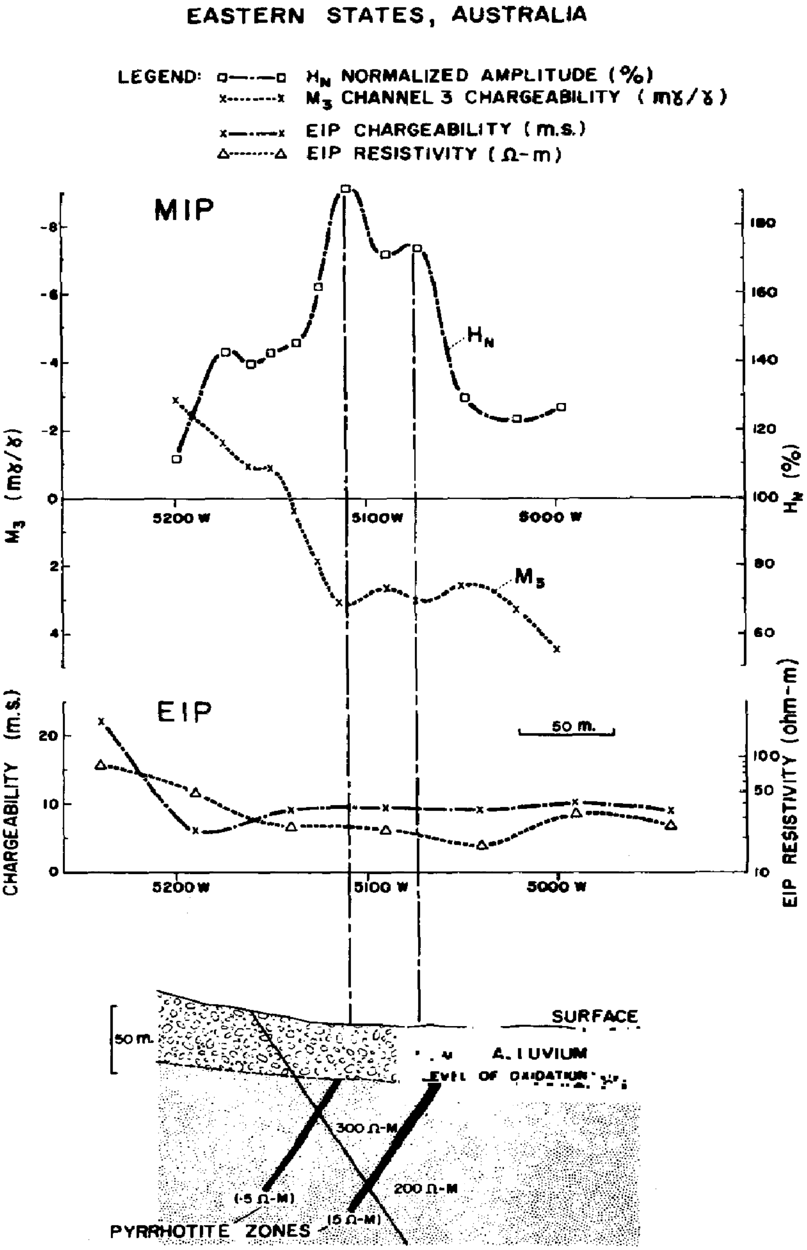

Fig. 5. Comparison in resolving power between MIP and EIP (after Howland-Rose et al. [6]).

data is largely qualitative, a physical property of the earth can be deduced from the EIP method, but not from the MIP method. This is a disadvantage of the MIP compared with EIP method.

4. Field procedures and equipment requirements for MIP measurements

Since the horizontal component of the magnetic field is measured in the MIP technique, whereas the horizontal electric potential gradient is measured in the EIP method, any of the electrode array configurations used in EIP measurements can be used in MIP measurements with potential electrodes replaced by a vector magnetometer.

In MIP surveys, the current electrodes are set up parallel to the probable strike direction of the target. The target then looks like a set of resistors in parallel, which conduct different currents, and a perturbation in the magnetic field will be produced. This is in contrast to the standard practice in EIP measurements, in which the current electrodes are set up perpendicular to the probable strike direction of the target so that the target looks like a set of resistors in series, which have different potential differences across them (see Fig. 6).

Seigel and Howland-Rose [7] describe a typical and most commonly used field layout of equipment and measurement points for production surveys as follows (see Fig. 7). The current electrodes C_1 and C_2, a distance $2L$ apart, are connected by a U-shaped loop of cable which is approximately $2L$ long on a side. A rectangular area, about L wide and $2L$ long, may usually be surveyed from one specific current electrode setup. The horizontal magnetic field is measured along the survey line direction, which is orthogonal to the line joining the current electrodes. The station interval, in general, should not exceed one-half of the mean depth of burial of anticipated targets; the line spacing should not greatly exceed the average expected strike length of anticipated targets.

The maximum value of L is normally determined by the mean strike length of targets expected to occur in the area. As a rule of thumb, in order to maintain

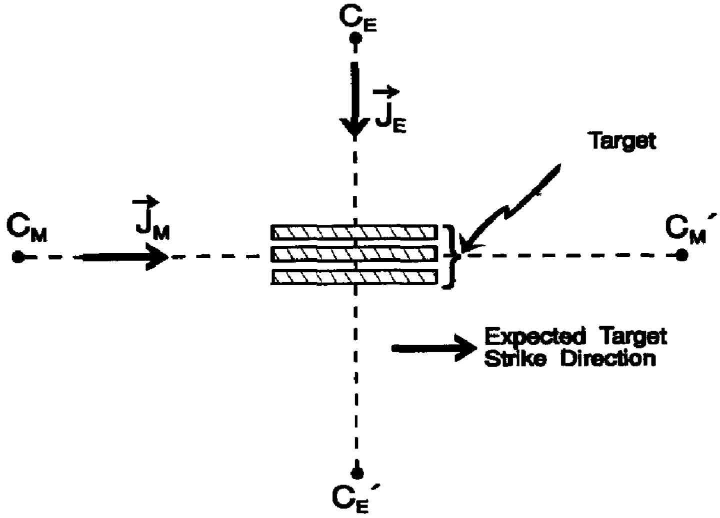

Fig. 6. Plan view of current-electrode deployment in relation to the expected strike direction of the target. C_M, C_M': current electrodes for MIP; C_E, C_E': current electrodes for EIP; J_M: current direction in MIP; J_E current direction in EIP.

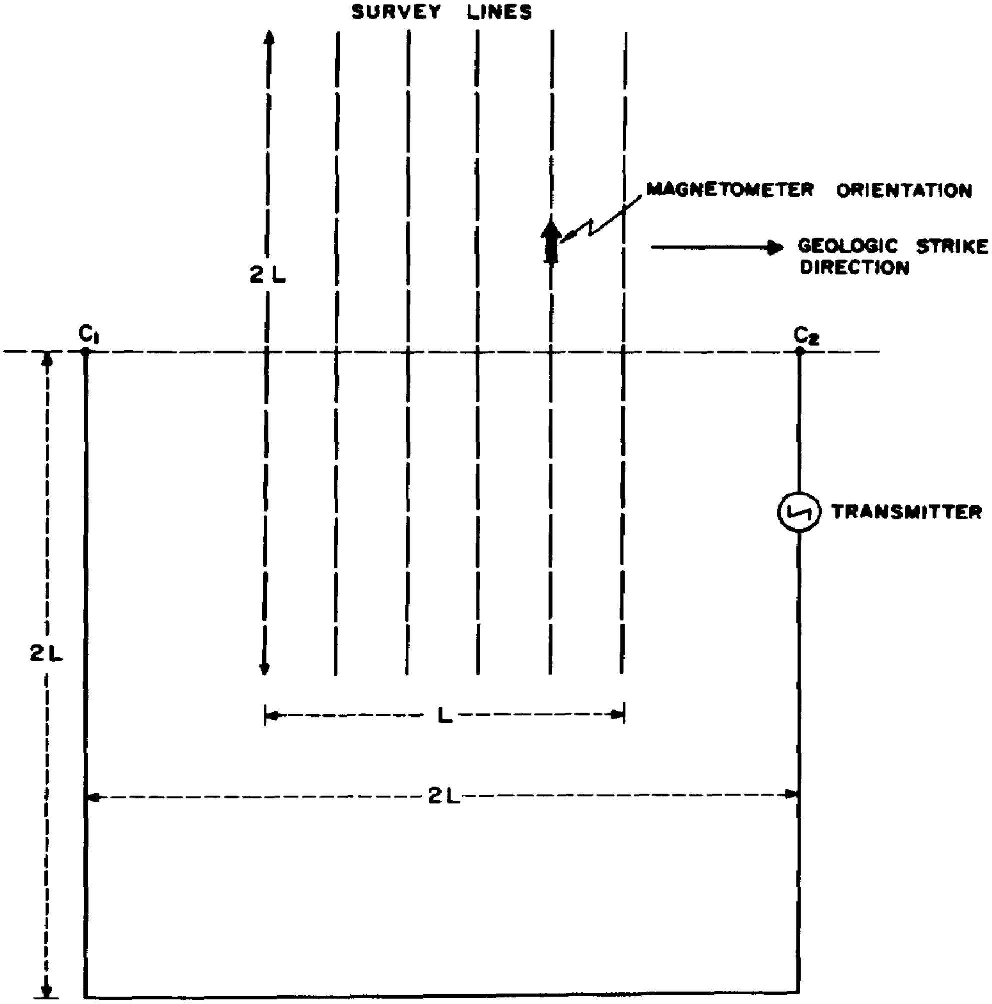

Fig. 7. Typical field layout for MIP production surveys (after Seigel and Howland-Rose [20]).

adequate signal level, L should not greatly exceed this mean strike length for best detectability. On the other hand, in order that the current density at the depths at which the targets may occur, may be comparable in magnitude to those near the surface, L should be no less than the expected depth of the targets.

The secondary magnetic field strength commonly measured is several picoteslas. Hence a high-sensitivity vector magnetometric is required for MIP measurements. General requirements for such a magnetometer are as follows [7]: (1) noise level less than 1 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$, (2) resolution better than 1 pT, and (3) frequency response essentially flat for 0–1000 Hz.

Two of currently available sensors which satisfy these requirements are, to the best of the author's knowledge, Scintrex MFM-3 High Sensitivity Vector

Fluxgate Magnetometer (noncryogenic) and the Superconducting Quantum Interference Device (SQUID) magnetometer (cryogenic) [21].

To improve signal-to-noise ratios (S/N), the following measures may be taken [7]: (1) use of greater current densities, (2) use of narrow-band filters in the frequency domain, (3) statistical S/N enhancement by digital stacking and averaging, and (4) use of a reference magnetometer.

The criteria for selection between the time-domain and frequency-domain methods are the same as in the EIP method. The time-domain method has advantages of the relative simplicity in the instrumentation and measurement of broadband characteristics. The frequency-domain method has an advantage of yielding better S/N by narrow-band filtering in noisy situations, but the information is limited to only those passed frequencies.

5. Applicability of the MIP method to environmental restoration problems

As discussed so far in the present paper and in other works which were referred to in this paper, the MIP method has been successfully applied to resource exploration. The method, however, has not been applied to environmental restoration problems. We examined the method with its applicability to environmental problems in mind and arrived at the conclusion that there is no reason why the method should not be applicable to the following two areas of environmental restoration problems.

One area is monitoring leakage of heavy metals from collection ponds constructed for recovery or treatment of heavy metals from sludge. Scientists at some laboratories (e.g., at the Idaho National Engineering Laboratory) are looking at ways to recycle valuable metals from industrial waste water and, at the same time, to reduce the discharge of heavy metals into the environment. At some stage during the process of recovery, the waste water has to be stored somewhere (currently in landfills in most cases [22]). Waste water leaked from the storage areas will migrate through the earth. As the waste water travels along the earth, heavy metals may precipitate and remain in the earth while the rest of water travels further or transpires. The heavy metals precipitated in this manner will likely be in a form very similar to naturally occurring mineral grains disseminated in the earth for which the induced polarization methods are most effective in their detection. In situations where waste water migrates through the earth which is overlain by conductive earth material, the MIP method should be the most effective tool in detecting the disseminated heavy metals precipitated from the waste water. Metal-bearing waste streams are one of the largest sources of pollution in the United States [22] and very likely in many other industrialized countries [23]. Considering the magnitude of this problem, the MIP method may be a useful and practical tool in waste management efforts.

The second application is detection of faults in a proposed site for a hazardous waste respiratory or nuclear power plant where a conductive overburden exists. Crushed rock or fine fissures in a fault zone can produce high polarization effects [13]. Howland-Rose et al. [6] have demonstrated by model studies that the MIP method is capable of delineating a fault which defines a contact between two different blocks of earth.

The above-discussed applicabilities are conceptually acceptable but, to some extent, conjectural in that the method has never been applied to environmental field problems. As an effort to verify the applicabilities, tests of the method in the field are planned and funding for the tests is being sought. The results of field tests, when done, will be reported in a future paper.

6. Conclusions and recommendations

The following conclusions and recommendations are made based on the examination of the status of the art of the MIP method.

The most important asset of the MIP method which has been theoretically demonstrated and practically useful is its ability to provide information on buried targets in areas where there is a highly conductive overburden, which may be at the surface or buried in the earth. Therefore if the target of a geophysical survey is expected to possess polarizing properties and is located below a highly conductive section of the earth, this method should be the first one to be applied.

Supposedly, the method is expected to possess higher spatial resolving power than the EIP method, although its superior resolution is difficult to determine quantitatively. Better resolution of the method relative to that of the EIP method is observed in some field examples [6,7]. However, there are other examples where the resolution of the MIP method is not superior to that of the EIP method [24]. Therefore it seems fair to say that a greater resolving power of the MIP over EIP method is case-specific.

Other advantages of the method are less attenuation of signal strength with depth to the target than in the EIP method; ease of field operation due to use of a magnetometer in place of two potential electrodes and accompanying cables and a receiver; absence of capacitive and electromagnetic coupling problems; and the absence of the problem of ground contact of potential electrodes in dry, sandy of gravelly soil.

The application of the method to environmental restoration problems is recommended for (1) monitoring leakage of heavy metals from recovery or treatment ponds of industrial waste wate and (2) detection of faults in proposed sites for hazardous waste repositories or nuclear power plants.

Further research is recommended to study the effect of various nonmetallic contaminants in the membrane polarization effect of soil or rocks. The results of this proposed study could determine applicability of the MIP method to broad environmental restoration problems. Olhoeft [25] shows field examples of application of the EIP method to organic contamination detection, but recognizes that there exists an incomplete understanding of interactions between clays and organics. Walther et al. [26] suggest applicability of the EIP method to some of their ten hypothetical cases of subsurface organic contamination and recommend further research on the subject. Research on the effect of various nonmetallic contaminants on the membrane polarization effect in various types of soils and rocks is needed, and its results will benefit both the EIP and MIP techniques used in environmental restoration efforts.

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