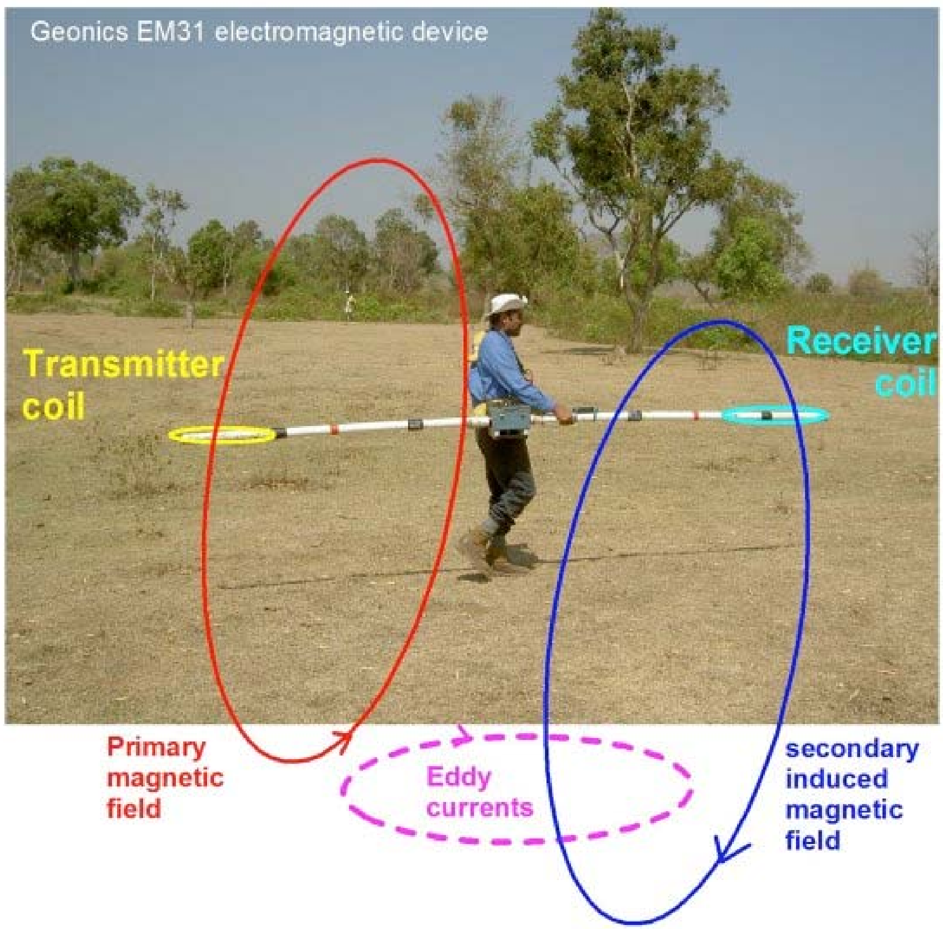
Documents
Geonics EM31 ISTerre



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EM31

MANUEL D'INSTRUCTION

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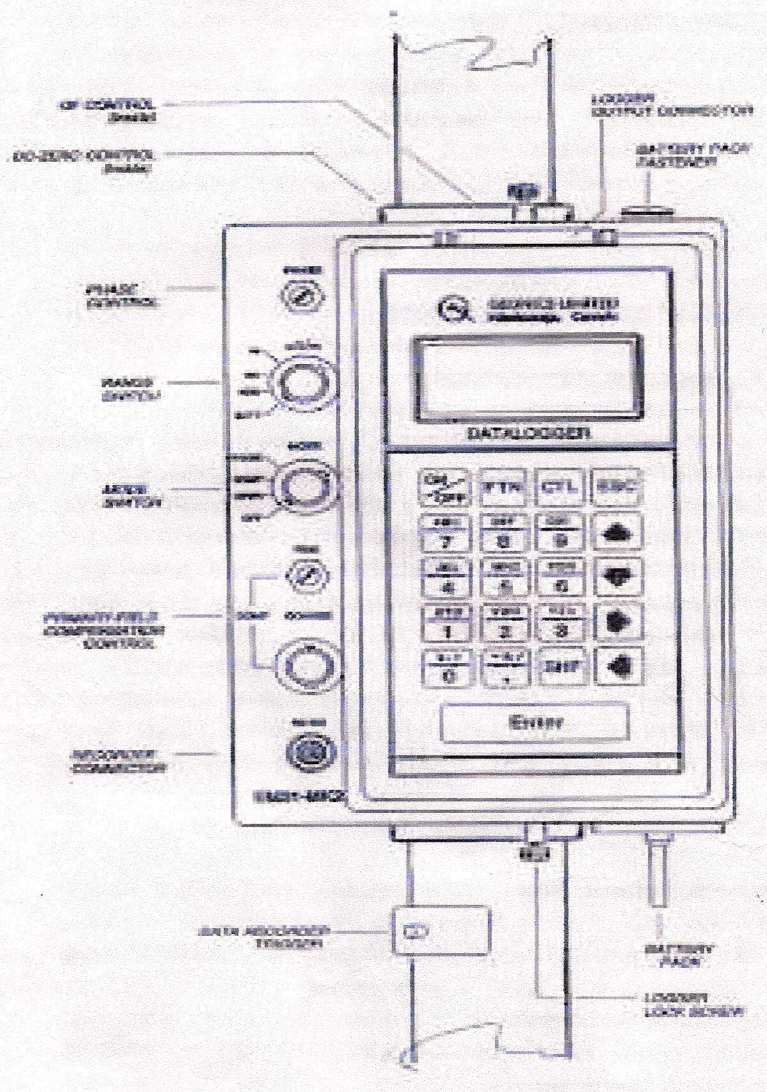
EM31-MK2 *MANUAL* *Page 9*



EM31-MK2 FRONT PANEL FEATURES

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EM31-MK2 SPECIFICATIONS

MEASURED QUANTITIES	(1) Apparent conductivity of the ground in millisiemens per meter (mS/m)*
	(2) Inphase component in parts per thousand (ppt) of the ratio of the secondary to primary magnetic field.
PRIMARY FIELD SOURCE	Self-contained dipole transmitter
SENSOR	Self-contained dipole receiver
INTERCOIL SPACING	3.66 meters
OPERATING FREQUENCY	9.8 kHz
POWER SUPPLY (For Main Console)	8 disposable alkaline "C" cells (approx. 20 hrs. life continuous use)
CONDUCTIVITY RANGES	10, 100, 1000 mS/m
INPHASE RANGE	±20 ppt
DATA LOGGER CAPACITY	a) 8,000 records (two components) b) 6,000 records (two components + GPS)
MEASUREMENT RESOLUTION	0.1% of full scale
MEASUREMENT ACCURACY	±5% at 20 mS/m
NOISE LEVELS	0.1 mS/m, 0.03 ppt
OUTPUT PORT FOR REAL TIME LOGGING	RS-232C, 9,600 baud rate
DIMENSIONS	Boom : 4.0 meters extended : 1.4 meters stored Shipping Case : 144x21.5x36 cm
WEIGHT	Instrument Weight : 12.4 kg Shipping Weight : 24 kg

**Millisiemens per meter (mS/m) are the same as millimhos per meter (mmhos/m)*

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INTRODUCTION

La mesure de résistivité terrestre est une des techniques géophysiques la plus vieille. La figure 1, venant directement de Heiland*, donne les valeurs typiques de résistivité pour une variété de matériels géologiques. Les valeurs données sont dans des centimètres Ohm-centimètre et doivent être divisées par cent pour donner des ohmmètres :

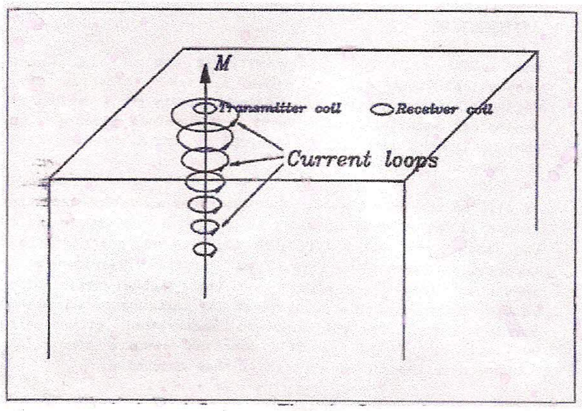

Figure 1

Nous observons dans la plupart des cas que la mesure de la résistivité seule n'est pas suffisante mais que la connaissance de la façon dont la résistivité varie latéralement et en profondeur est très importante. Cela nous permet "de voir", des anomalies grâce à leurs formes plutôt que les valeurs de résistivité réelles. Comme l'EM31 n'exige pas le contact électrique avec la terre, il permet la mesure rapide et précise de résistivité du sol.

Le principe de base de fonctionnement de l'EM31 est simple. En ce qui concerne la Figure 1, une bobine émettrice placée à un bout de l'instrument induit des boucles de courant de Foucault circulaires dans la terre. Dans certaines conditions requises par la conception de l'EM31 l'amplitude de ces boucles est directement proportionnelle à la conductivité de terrain aux alentours de cette boucle. Chacune des boucles produit un champ magnétique qui est proportionnel à la valeur du courant circulant dans cette boucle. Une partie du champ magnétique de chaque boucle est interceptée par la bobine réceptrice et produit une tension de sortie qui est donc aussi linéairement proportionnelle à la conductivité de terrain.

Cet instrument est calibré pour lire la conductivité correcte quand la terre est uniforme. Au cas où la terre est disposée en couches, avec chaque couche de conductivité différente, l'instrument lira une valeur intermédiaire comme discuté plus tard. L'unité de conductivité utilisée est le millimho par mètre (ou millisiemens par mètre). Pour obtenir la résistivité en ohmmètres, la lecture de l'instrument est divisée par 1000 (une lecture de quatre millimhos par mètre par 1000 donne deux cent cinquante ohmmètres).

Les calculs théoriques montrent, comme il sera rapidement évident pour l'opérateur, que la lecture obtenue est essentiellement indépendante de l'orientation de l'instrument en ce qui concerne la terre. Il y a, cependant, une petite dépendance concernant la hauteur de la mesure au-dessus du sol; le levage de l'instrument de la surface d'une terre uniforme à la hauteur normale de fonctionnement d'environ un mètre aboutit à une réduction de la lecture de 12 %. Le calibrage a été ajusté à l'usine pour que l'instrument lise correctement sur un demi-espace uniforme quand porté comme indiqué. Si la terre est disposée en couches, en levant l'instrument de la surface de la terre à la position normale de fonctionnement, on peut aboutir à une lecture qui reste la constante ou augmente même légèrement avec la hauteur. En général les lectures faites avec l'instrument à la hauteur de la hanche sont suffisamment précises, mais pour une exactitude maximale l'instrument peut être mis au sol.

Il y a deux composants du champ magnétique induit mesuré par l'EM31. Le premier est le composant en quadrature qui donne la mesure de conductivité terrestre comme, décrit. Le deuxième est le composant inphase utilisé principalement dans l'EM31 pour des buts de calibrage. Le composant inphase, cependant, est significativement plus sensible aux grands objets métalliques et de là, très utile en recherche de fûts métalliques enterrés (voir la Section 2.2).

2) MODES D'EMPLOI

L'EM31 peut être utilisé à la fois pour mesurer la conductivité électrique de la terre ou détecter des objets métalliques enterrés. La Section 2.1 décrit la procédure pour mesurer la conductivité terrestre et la Section 2.2 pour la détection de métal enterré.

2.1) MESURES DE conductivité TERRESTRES

2.1.1 PROCÉDURE DE PARAMÉTRAGE INITIALE

a) 1 En premier, vérifiez la tension des piles, (plus et moins), en mettant le commutateur "Mode" sur la position OPER et tournez la commutateur "RANGE" en sens inverse des aiguilles d'une montre sur la position de "BATT". Allumez le data logger et lancez le programme EM31-MK2, (voir manuel DL600). Si l'affichage est au-dessus de 4.4, les batteries sont en bon état, autrement remplacez les piles par un jeu frais piles alcalines modèle C. Pour accéder aux batteries, défaites l'attache de bloc de batterie et tirez le tiroir hors de la console.

a) 2 Batteries de l'enregistreur Numérique (Polycorder)

- Batteries principales

Le Polycorder est livré avec un bloc de batterie spécial qui contient six des batteries rechargeables Ni-Id.

- Batteries de sauvegarde

La batterie de secours est une batterie au lithium. La longue vie de cette batterie "non-remplaçable" maintiendra la mémoire de Polycorder pendant au moins cinq ans. Elle peut être remplacée si nécessaire, mais cela doit être fait à l'usine.

- autonomie de la batterie

L'autonomie de la batterie de Ni-Cd du Polycorder stocké est d'environ 18 mois. Selon le programme et l'opérateur, l'autonomie de fonctionnement avec des batteries entièrement chargées est comprise entre 30 et 50 heures.

Le système d'exploitation du Polycorder vous protège complètement de la perdre de données à cause de décharge des batteries. Voici comment il travaille : il contrôle les batteries pour qu'il puisse vous avertir quand ils doivent être chargées. Une fois que la tension de batterie baisse au-dessous d'un certain seuil, vous verrez un message étincelant (Figure 2) :

```
LOW BATTERIES
```

Figure 2

Chaque fois que vous appuyez sur ESC ou sur ENTER en exécutant un programme, vous verrez ce message. CHARGEZ VOS BATTERIES DES QUE VOUS POUVEZ".

Si vous oubliez de charger les batteries et si la tension descend au-dessous d'un deuxième seuil, le Polycorder affiche le message suivant (figure 3) :

```
CHARGE BATTERIES
CHARGE BATTERIES
CHARGE BATTERIES
CHARGE BATTERIES
```

Figure 3

Alors il s'éteint et commence à s'alimenter sur la pile de sauvegarde. Le polycorder ne peut pas fonctionner sur la batterie de secours seule. Si vous essayez de l'allumer à nouveau, le polycorder affiche immédiatement "CHARGE BATTERIES" et s'éteint de nouveau. La batterie de secours peut maintenir les données en mémoire pou plusieurs années.

- charger les batteries

Le Polycorder est livré avec un chargeur de batterie. Pour charger les batteries, branchez le chargeur dans le connecteur Série. Les batteries entièrement déchargées exigent une recharge pendant quatorze heures.
Notez que le datalogger peut être retiré de la console pour la charge des batteries et le transfert des données, en desserrant les deux vis de serrage de chaque côté de la console et soulevant le datalogger vers le haut.

- remplacement de Batteries

Les batteries Ni-cd peut être rechargées plusieurs centaines de fois, mais leur autonomie diminue continuellement. Finalement les batteries doivent être remplacées. C'est une bonne pratique de remplacer le bloc de batterie annuellement.

Vous pouvez changer des batteries sans perdre la mémoire.

Pour remplacer le bloc de batterie, éteignez le "Polycorder" et retournez-le. Desserrez les six vis, tirez la partie inférieure du boîtier vers le haut, mettez le de côté, et pour l'instant ne desserrez pas les six vis hexagonales. Enlever le support autour du bloc de batterie. Déconnectez le connecteur de batterie. Enlevez le bloc de batterie. Placez le nouveau bloc de batterie dans la même position que le vieux. Connectez le connecteur à deux broches. Placez le support autour du bloc de batterie et alignez les six trous sur les trous dans du boîtier. Remettez les six vis extérieures en place et serrez-les.

b) En utilisant les étiquettes d'identification sur les tubes, choisissez le tube de la bobine d'émettrice, alignez le avec le tube principal, insérez-le et serrez l'attache.

c) Allumez l'instrument en mettant le commutateur "Mode" sur la position "OPER" et vérifiez la lecture zéro. Le commutateur "RANGE" doit être mis à la position la moins sensible 1.000 mS/m (cela réduit au minimum les interférences externes pendant la vérification du zéro).
La tolérance pour ce contrôle est 1 mS/m. Si un ajustement zéro est nécessaire, Agir sur le potentiomètre "DC ZERO CONTROL" en utilisant un petit tournevis plat pour obtenir une lecture zéro. On accède au réglage par le petit trou sur le côté de la console. N'ajustez pas le potentiomètre Q/F à ce point.

d) Éteindre l'instrument en utilisant le commutateur "MODE", avant la connexion de la bobine réceptrice, alignez le et connectez le tube de bobine de réceptrice au tube de la console principale. L'instrument est maintenant prêt pour continuer les contrôles fonctionnels.

2.1.2 Contrôles Fonctionnels de l'équipement

Le commutateur "Gamme" doit être mis sur la position 100 Mme/m pour tous les tests suivants. (Si la lecture de conductivité est plus grande que 100 mS/m, voir la note à la fin de cette partie).

a) Mettre le commutateur "Mode" sur la position OPER et ajuster la lecture de la phase (I) à zéro utilisant le commutateur "COARSE" puis le potentiomètre fine. la Tolérance est de +0.1 ppt.

b) Vérifier la phase de l'instrument, mettez le commutateur "Mode" sur la position PHASE. Notez la lecture de la conductivité (Q) et faites tourner le contrôle "COARSE" d'un cran dans le sens des aiguilles d'une montre. Si la conductivité lue reste le même (la tolérance est de +0.2), la phase est déjà correcte. remettez le contrôle "COARSE" à sa position originale (un cran en sens inverse des aiguilles d'une montre) et aucun nouvel ajustement n'est nécessaire.

S'il y a une différence dans les lectures de conductivité prises avant et après la rotation du contrôle

"COARSE" d'un cran dans le sens des aiguilles d'une montre, alors l'ajustement de phase est nécessaire. Avec le contrôle "COARSE" dans sa position originale, ajustez le potentiomètre "PHASE" d'un 1/4 de tour dans le sens des aiguilles d'une montre et notez la nouvelle lecture de conductivité. Faites tourner le contrôle "COARSE" d'un cran dans le sens des aiguilles d'une montre, prenez la lecture de Q et remettez le contrôle "COARSE à sa position originale. Si la différence entre les lectures a diminué, répétez la procédure d'ajustement en tournant à nouveau le potentiomètre "PHASE" d'un 1/4 de tour, dans le sens des aiguilles d'une montre, jusqu'à ce que la rotation du contrôle "COARSE" d'un cran ne produise aucun changement de la lecture. Tolérance +0.2 mS/m.

Si, d'autre part, la différence entre les lectures a augmenté, le potentiomètre de PHASE doit être tourné dans le sens inverse des aiguilles d'une montre et la procédure décrite ci-dessus doit être répétée jusqu'à il n'y a aucun changement des lectures. Rappelez-vous toujours de remettre le contrôle "COARSE" dans sa position originale. Cela peut contrôler en vérifiant que la valeur inphase (I) est à zéro en mettant le commutateur "MODE" sur "OPER". Si elle n'est pas à zéro, utilisez les commandes de compensation "COARSE" et "FINE" pour obtenir le zéro sur la lecture du inphase.

c) Pour vérifier la sensibilité de l'instrument, mettez le commutateur "Mode" sur la position COMP et faites tourner le contrôle "COARSE" d'un cran dans le sens des aiguilles d'une montre. La lecture de conductivité doit augmenter d'une valeur comprise entre 22 et 26 mS/m. Il est peu probable que la sensibilité de l'instrument varie, cependant, il peut être utile d'enregistrer la lecture réelle pour une comparaison à une date ultérieure. Remettez le commutateur "COARSE" sur son réglage d'original et mettez le commutateur de mode sur OPER. L'EM31-MK2 est maintenant prêt pour faire des mesures de conductivité.

NOTEZ :

a) En conduisant les tests fonctionnels sur le terrain d'une conductivité plus grande que 100 mS/m, le commutateur "Range" doit être mis sur la gamme 1000 mS/m . Quelque soit la position du commutateur "Range", l'augmentation de la valeur lue en (c) doit toujours être entre 22 et 26 mS/m

b) La gamme de lecture maximale de l'instrument est 20 mS/m ou 200 mS/m, ou 2000 mS/m pour la composante de conductivité et 20 ppt pour dans la composant inphase.

c) À la fin de l'étude, Toujours éteindre le data logger et la console principale.

2.1.3 Procédure de fonctionnement

a) positionner l'instrument avec en réglant la bretelle pour que l'instrument repose confortablement sur la hanche comme indiqué. Tournez le commutateur de Mode sur OPER et faites tourner le commutateur "Gamme" pour que la conductivité lue soit dans le deux-tiers supérieur de la gamme complète. L'affichage de conductivité est directement en mS/m et la valeur de la pleine échelle est indiquée par le commutateur "Gamme".

b) L'instrument peut fonctionner en mode dipôle vertical ou horizontal (voir la Section 5 3). La réponse d'instrument en fonction de la profondeur varie significativement entre les deux modes. Il est important de reconnaître que le mode dipôle vertical fournit une exploration deux fois plus profonde que le mode de dipôle horizontal (respectivement 6 m et 3 m,). (On fournit une discussion complète des modes de dipôle verticaux et horizontaux dans la Note Technique Geonics TN-6).

c) En acquérant des données discrètes, l'opérateur peut prolonger l'autonomie de la batterie en éteignant tournant l'instrument d'entre les stations. Dans ce cas, l'opérateur remarquera un léger dépassement initial de l'affichage à la mise sous tension. C'est normal et on doit attendre moins deux secondes après l'allumage avant enregistrer la mesure.

Le bouton orange sur le tube émetteur est utilisé pour commander l'acquisition d'un point ou enregistrer des repères dans le fichier de données acquis les systèmes d'enregistrement.

Il est aussi possible d'acquérir des données en utilisant un ordinateur, type ALLEGRO en le connectant l'ordinateur directement au port de sortie RS-232 sur de l'EM31-MK2. Voir le manuel du programme DAT31-MK2, (partie 7, Enregistrement temps réel).

2. 2 DÉTECTION DE MÉTAL ENTERRÉ

2.2.1 Paramétrage et procédure de fonctionnement

La composante inphase du champ magnétique induit est significativement plus sensible aux grands objets métalliques que la composante en quadrature (Q) utilisée pour les mesures de conductivité terrestres. Typiquement la composante inphase de l'EM31 détectera un simple fût de 55 gallons à profondeurs d'environ 2 mètres au sommet du fût. Dans de certaines circonstances, cependant, des tambours simples ont été détectés aux profondeurs d'environ 3.5 mètres.

a) La composante inphase est directement lue sur l'afficheur e(I) avec le commutateur de mode dans la position OPER. Les mesures de inphase sont le rapport du champ magnétique secondaire induit au champ magnétique primaire en parties par mille (ppt). l'afficheur inphase montre directement la valeur en ppt et quelque soit la position du commutateur "gamme".

b) L'expérience a montré que la gamme de 100 mS/m est le réglage optimum de gamme et de sensibilité pour la plupart des situations géologiques. Pour effectuer une étude mesurant la valeur inphase, mettez le commutateur "Mode" sur la position OPER et ajustez les commandes "coarse" et "fine" pour que la lecture de la composante inphase soit à zéro (+/-0.1 ppt). Le manque d'une vraie référence zéro ne cause pas de difficulté sérieuse ou confusion avec l'interprétation puisque des cibles en métal sont généralement reconnus par des signatures d'anomalie dans les données.

Comme l'exemple de la Figure 3 montre la réponse typique du signal inphase quand l'instrument croise sur un pipeline métallique. La variabilité de la forme, de la profondeur et de l'orientation de la cible changera la forme de l'anomalie. Ces anomalies peuvent être caractérisées par une augmentation ou une diminution des valeurs, certaines pouvant probablement être négatives ou être une combinaison de tout cela.

NOTEZ :
Pendant l'acquisition pour la détection d'un objet enfoui, il est toujours recommandé d'enregistrer les deux composantes inphase et quadrature. Tandis que la composante inphase, en général, est la plus adaptée pour la détection du métal, la quadrature est plus sensible aux cibles longues et étendues (par exemple des pipelines) qui sont au moins partiellement, en contact galvanique avec le terrain.

3) CALIBRAGE D'INSTRUMENT

Avant l'expédition, l'instrument est calibré à l'usine pour lire correctement. Si nécessaire, les procédures de calibrage sont facilement effectuées comme décrit ci-dessous.

IMPORTANT - l'ajustement le plus critique est le potentiomètre QF (la quadrature) qui a été précisément ajusté à l'usine.

Avant de faire n'importe quels ajustements, il est important de mettre l'instrument en station sur un point connu et de noter la conductivité du terrain lue. Si cet ajustement est décalé, l'instrument devra être re-calibré sur le terrain de conductivité connue.

3.1 Calibrage du zéro

La mise à zéro de l'EM31 peut être aisément faite en suivant la procédure décrite dans la Section 2.1.1 (c)

3.2 Calibrage absolu

Le calibrage absolu d'instrument est facilement réalisé sur n'importe quel terrain dont la conductivité du terrain est constante et connue sur la profondeur d'investigation de l'EM31. La procédure est simple. L'instrument est placé sur un secteur connu au niveau du sol et le contrôle de compensation QF est ajusté jusqu'à ce l'affichage est de 1.12 fois la conductivité de terrain. Si la conductivité du terrain est forte, la Figure 2 doit être utilisée pour correctement mettre la lecture d'instrument. Il est sage de garder une zone comme référence de contrôle de la calibration même si on ne connaît pas exactement la variation de la conductivité avec la profondeur de ce secteur. C'est utile pour le recoupement avec des mesures futures (figure 4) :

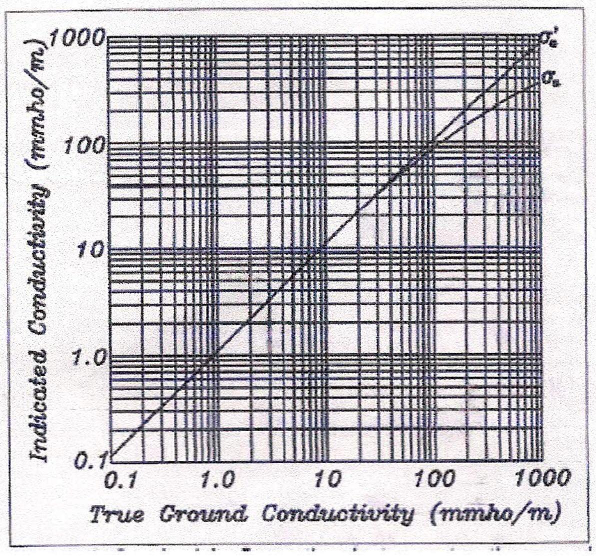

Figure 4

4) TECHNIQUE D'ÉTUDE

La prise de mesures avec l'EM31 est directe. Comme désigné dans 2.1.3. (c) des mesures peut être fait continuellement ou sur une base de station-par-station. Dans l'un ou l'autre cas on recommande toujours un repérage soigneux des lignes et des stations de mesure. L'erreur la plus commune est de faire des lignes d'étude trop courtes, qui ne se prolongent pas suffisamment au delà de la région de l'anomalie attendue pour permettre à l'opérateur d'établir la valeur de référence de la conductivité de terrain.

La décision quant à l'espacement correct sera basée sur une connaissance de la dimension latérale de l'anomalie de résistivité prévue.

La résolution dans la conductivité de l'EM31 est très bonne, car les changements de 5 % sont rapidement perçus. Cet instrument est capable de donner une étude extrêmement précise avec une information sur de petites variations dans le terrain.

On l'a vu dans la Section 1 que le courant induit dans la terre est constitué de séries en cercles concentriques, en supposant que la conductivité est latéralement uniforme. Donc, dans le cas d'un demi-espace uniforme, la rotation de l'instrument dans le plan horizontal de la bobine d'émetteur comme un pivot ne produira aucun changement de la lecture. Au contraire, n'importe quel changement de lecture avec cette procédure est une indication des homogénéités latérales dans la conductivité. Il est plus simple et suffisamment précis pour l'opérateur pour faire tourner l'instrument de 90 ° en s'utilisant comme pivot

À chaque station de mesure, ainsi si les lignes sont Nord/Sud, l'opérateur marche normalement le long de la ligne avec l'instrument pointant dans la direction Nord/Sud. A chaque station de mesure il peut aussi prendre une lecture avec l'instrument portant Est-Ouest pour vérifier si la valeur lue est la même que la lecture Nord-Sud. Au cas où cette lecture est significativement différente, il peut être valable pour l'opérateur de faire tourner l'instrument pour faire deux lectures de conductivité, une avec la valeur maximale et une avec la valeur minimale. La valeur moyenne peut alors être utilisée pour la réduction de données.

L'EM31 est sensible aux conducteurs enfouis comme de grands tuyaux, des fûts, etc. Ceux-ci sont d'habitude facilement reconnus par les grandes fluctuations de lecture qui arrivent sur une distance courte, comme indiqué dans la figure suivante :

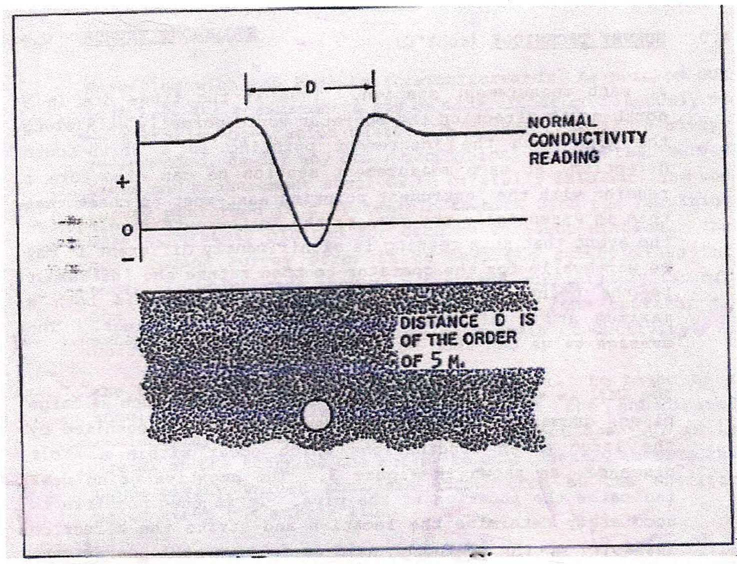

Figure 5

Le pic négatif indique l'emplacement du tuyau. Il est alors possible de déterminer exactement l'emplacement et la direction (l'azimut) de l'axe du conducteur comme suit : l'emplacement approximatif est indiqué ci-dessus et un profil transverse est alors fait sur le conducteur avec l'EM31 pointant dans la direction approximative de l'axe de conducteur.

La lecture sera maintenant un maximum positive quand l'instrument sera sur le conducteur et aligné suivant l'axe de conducteur.

L'instrument est relativement insensible aux barrières, aux lignes haute tension aériennes et d'autres objets métalliques voisins. Pour déterminer si la lecture est influencée par de telles structures l'opérateur doit faire tourner l'instrument pour vérifier les changements de la lecture. L'opérateur doit être méfiant si un maximum ou un minimum arrive quand l'instrument est perpendiculaire ou parallèle à la structure. Avant la prise de mesure, l'opérateur doit s'éloigner de la structure jusqu'à ce que il ne voie aucune homogénéité latérale quand l'instrument est tourné.

Nous rappelons que l'EM31 est un outil électromagnétique et un soin particulier doit être pris près des conducteurs évidents jusqu'à ce que l'opérateur se soit assuré quant à leur effet possible. Dans chaque cas c'est déterminé en faisant tourner l'instrument et si le maximum et le minimum lus semblent en rapport avec la structure, il n'est pas recommandé de prendre la valeur moyenne des deux lectures comme dans une indication de la conductivité du terrain.

En général les lectures de conductivité obtenues avec l'EM31 varient sans à-coup d'une région à un autre. Dans quelques cas, cependant quand, par exemple, un contact vertical bien défini sépare un pauvre conducteur d'un très bon conducteur, il peut apparaître des effets de bord dans lesquels les lectures varient rapidement avec la position et dans ce cas les lectures n'indiquent peut être pas la conductivité du terrain.

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Les effets de bord peuvent aussi arriver sur un très bon conducteur (quelques ohmmètres ou moins) dont les dimensions sont de l'ordre de l'espacement d'inter-bobine et de nouveau les lectures indiquées ne peuvent pas exactement refléter la vraie conductivité du terrain. Dans n'importe quelle circonstance où la conductivité apparente varie significativement sur une courte distance de l'ordre de l'espacement d'inter-bobine, on doit considérer la présence possible d'effets de bord ou des conducteurs superficiels locaux.

Finalement, particulièrement au milieu de l'été, l'électrique statique (la radiation électromagnétique d'orages locaux ou éloignés) peut provoquer des lectures bruyantes. Le bruit apparaît comme des sauts brutaux de valeurs. Des lectures bruyantes peuvent aussi être notées en faisant des mesures près de grandes lignes à haute tension.

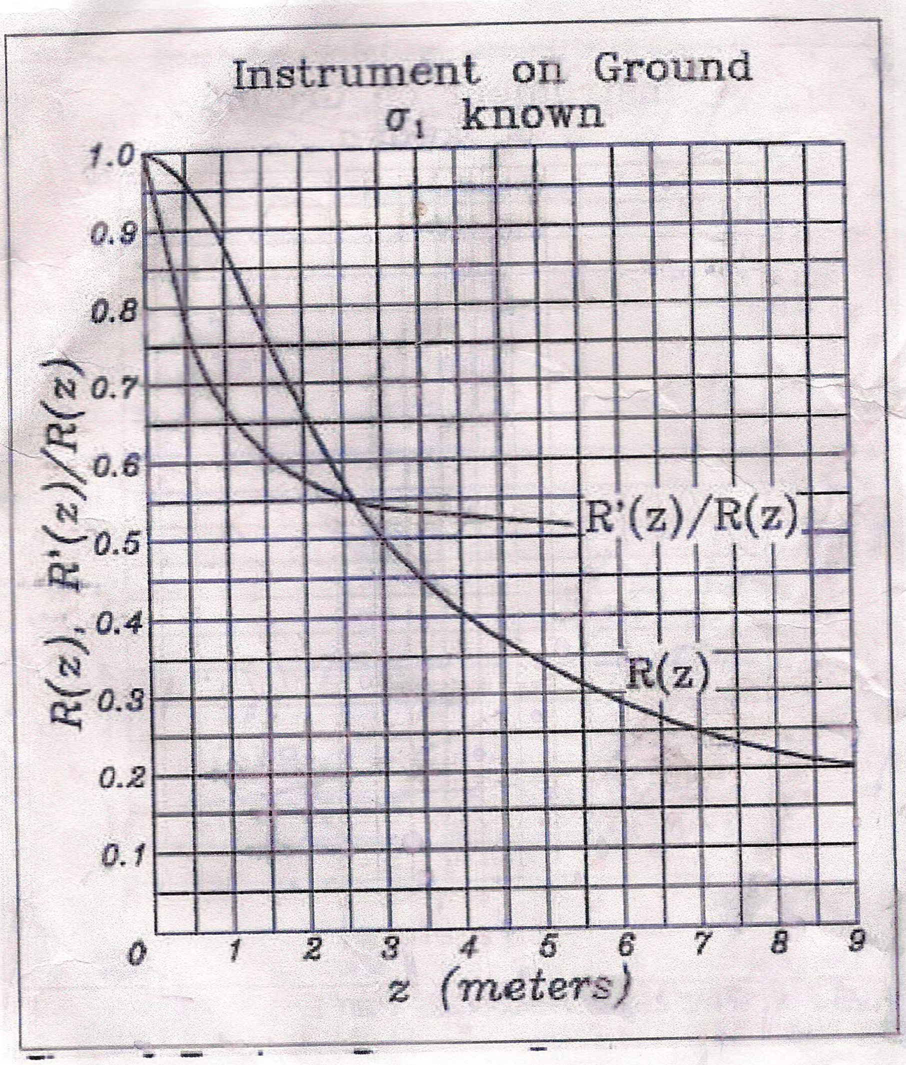

Figure 6

Figure 7

EM31

Guide d'opération

Mise en place

0) Test batterie : Mode OPER, Range BATT . Si >4.4, OK, sinon changer batteries.

1) Installation des bras :
    a. Mettre le bras « émetteur »., en alignant les marques rouges.
       Ne pas tordre les goupilles. Ne pas laisser tomber les tubes.
    b. Mode OPER, Range 1000mS/m. Si entre -1.0 et +1.0, OK, sinon *cf.* manuel
    c. Mettre le bras « récepteur », en alignant les marques.
       Ne pas tordre les goupilles. Ne pas laisser tomber les tubes.
    d. Mode OPER, Range 100mS/m. Si entre -1.0 et +1.0, OK, sinon *cf.* manuel

2) Test de la phase :
    a. Mode OPER, Jouer sur COARSE pour mettre la phase à 0 (+/- 0.1).
    b. Mode PHASE. Tourner COARSE d'un cran vers la droite. Revenir d'un cran vers la gauche. Si la valeur n'a pas bougé (différence<0.2) -> OK

3) Test de sensitivité
    a. Mode COMP. Tourner COARSE d'un cran vers la droite. Revenir d'un cran vers la gauche. La valeur doit changer de 22-26 mS/m

Mesure

1) Mode OPER. Tourner RANGE de sorte que l'aiguille soit au 2/3 du max. C'est ainsi qu'on a la meilleure résolution.

2) Se positionner sur le point à mesurer. Noter l'orientation de l'outil. Noter l'orientation du dipôle.
    a. Le panneau de contrôle en haut -> dipôle vertical (Prof d'exp ~6m)
    b. Le panneau de contrôle sur le côté -> dipôle horizontal (Prof d'exp ~3m)

Operateur : Date :

Plan du site

Site :

Ligne :

Pas d'acquisition :

# Station	Bras // ligne		Bras ⊥ ligne		Hauteur	Commentaires
	Dip. Vert.	Dip. hor.	Dip. vert.	Dip. hor.		

Using the Geonics EM31

Battery Check

1. Set MODE switch to OPER position and rotate RANGE switch to BA TT position.

2. If meter reads above ±4.4 then batteries are in good condition (C size)

Initial Set-up

1. Using Identifying labels, attach transmitter coil tube.

2. Set MODE switch OPER and cheek the zero reading. Set the RANGE switch to least sensitive position (1,000 mS/m)

3. The tolerance for this test is ±1 mS/s. To adjust reading use the DC ZERO CONTROL, located under front panel. Remove battery pack to gain access to the controls.

4. Turn instrument off and attach receiver coil tube

Equipment Functional checks

1. Set RANGE switch to 100 mS/m. (if reading on the meter is off-scale, i.e. >100 mS/m, set to 1000 mS/m.

2. Set MODE switch to OPER position and adjust the inphase meter reading to zero using the COARSE and FINE COMPENSATION controls. Tolerance +0.1 ppt.

3. To check the phase of the instrument, set the MODE switch to PHASE position. Note meter reading and rotate the COARSE control one step clockwise. If the conductivity meter reading remained the same (tolerance ±0.2), the phase is already correct. Return COARSE control to its original position.

4. If there is a difference in the readings, with the COARSE control in its original position, adjust the PHASE potentiometer about ¼ turn

clockwise. Repeat the phase test. If the difference in readings has decreased, repeat procedure or if the difference has increased, the PHASE potentiometer should be rotated counter-clockwise.

5. N.B. Always remember to set the COARSE control back to its original position. This can be confirmed by checking that the inphase meter reads zero with the MODE switch set to OPER.

6. To check the sensitivity of the instrument, set MODE switch to COMP position and rotate COARSE control clockwise one step. The conductivity reading should change between 22 to 26 mS/m.

Operating Procedure

1. Position instrument so that it rests on the hip. Set MODE switch to OPER position and rotate RANGE switch so that the conductivity meter reads in the upper two-thirds of the full range.

Vertical Dipole
Reading panel on top
Effective depth of exploration =6m

Horizontal Dipole
Reading panel is facing horizontally
Effective depth of exploration =3m

Using the Polycorder DL720/31 data logging system

Battery check

Switch on logger and at MODE prompt press 0. Use arrow keys to select BA TTERY, then press Enter

Initial Setup

Switch on logger and at MODE prompt press 0. Use arrow keys to select EM31, press ENTER

SET CLOCK (y/n): N (if yes, the program will abort and you will have to re-run EM31)
FILE: Enter filename (Use Shift keys to select letters)
PHASE Q/I/B: B Select what parameter to record (Quadphase/Inphase/Both)
MODE V/H/B: B Select which dipole orientation to record (Vertical/Horizontal/Both)
ORIENTA TIONS 1/2: 1 Select 1 or 2 orientations to record (different heights or orthogonal)
OPERATOR: Enter operator's name (not mandatory, press ENTER to skip)
COMMENT: Enter comment (not mandatory, press ENTER to skip)
AUTO (Y/N): N Select N for normal operation
LINE: Enter line number, then ENTER
DIR W/E/S/N: Select direction of the line (Conventionally N or S)
START STATION: Enter start station, then ENTER
INCREMENT: Enter station increment, then ENTER (the units here are irrelevant)

CONNECT THE LOGGER TO THE EM31 WHEN EM31 IS IN THE OPER POSITION and Press ENTER to start logging

REVIEW DATA MODE Press 6 (To review previous station information)
COMMENT Press 7 (enter comment then ENTER)
NEXT STN Press 5 (automatically skips a station)
NEW SEGMENT Press 1 (if you have to skip a large section)
NEW LINE Press 4 (Enter line no & Start stn. Enter '-'increment for reverse direction)
MEMORY Press 2 (See how much room is left on logger)
ESC Press ESC (Only use when finished logging)

Downloading the data from the Polycorder to your PC
1. Run DAT31 program on the PC and select COPY FILES FROM POLYCORDER (MOD-720)
2. Set Polycorder to MODE 5-2 and check that:
baud rate = 9600
data bits = 8
parity = N
mating call carriage return (CTRL 0 1 3)

3. Press ESC

4. On PC, Enter filename to store data: - Enter Hxxx file created in logger (CAPITALS), press RETURN

5. Set Polycorder to MODE 2-2 - Select corresponding file on polycorder press ENTER. And then press RETURN on PC.

6. Repeat procedure for Data files (D prefix)

7. Return to main menu (PC) and select CONVERT DL55 TO DAT31 FORMAT. Enter Hxxx filename and both the Hxxx and Dxxx files will be converted to xxx.G31 file format.

8. Use appropriate option to convert to Surfer format

Warning

Do not fill up logger completely with data as this will lead to problems downloading. If there is insufficient memory, delete all unwanted data files. If there is still a problem, delete the EM31 program from logger. When downloading is complete, refer to manual for re-installation of EM31 program.

Last updated by Tim Young (Tim.Young@GeoArch.demon.co.uk) 1st October 1998.

EM31 field how-to

Equipment needed in the field:

- field notebook
- map
- Geonics EM31 unit
- compass
- GPS or equivalent
- small flathead screwdriver for calibration

General instructions:

1. Remove the EM31 from its box and before attaching the transmitter and receiver, check that the batteries are good by turning scale knob to BATT and then mode knob to OPER. Values displayed will be +/- 6.0 more or less for new batteries and the manual suggests replacing if below +/- 4.3. Turn mode to Off. The instrument uses 8 C cel lalkaline batteries.
2. Many times, you can now attach the transmitter and receiver and hold the instrument about 1m off the ground, meter facing up. Turn the mode knob to OPER. The range knob will be at either 100 mS/m or 10 mS/m for most of our uses. The display has two numbers. The top, labelled conductivity, is the quadrature phase measurement and is usually the number we are interested in, as this should reflect the ground conductivity. The in-phase number is generally used for calibration but also can be used when looking for buried metal.

Calibrations

1. The general calibration is first done with only the transmitter attached. With the instrument on resistive ground, set the range knob to 1000 mS/m. The instrument should read 0 in the resistivity window. If not, the zero control knob can be adjusted: it is accessed from the battery compartment and is the adjustment screw closest to the "bottom" end of the box (part farthest from the meter displays). Note to be sure that the nut on this screw is tight when done so that the instrument doesn't drift while being used.

2. With the instrument off, attach the receiver coil. Set the range to 100 mS/m and the mode switch to COMP. The display should read 0; if not, use the coarse and fine compensation knobs to get it to 0.
3. The phase check is more awkward. Turn the mode switch to PHASE. Note the value in the conductivity window. Turn the coarse compensation knob one click clockwise. If the value displayed is the same (within +/-0.2 mS/m), all is well and you can click the coarse knob back to its original position.
4. If there was a difference, then after returning the coarse knob to its original position, turn the phase screw 1/4 turn clockwise and compare the reading you now have and that with the coarse knob turned one step clockwise. If the difference in values has decreased, continue rotating the phase screw clockwise until the two readings match within 0.2 mS/m. If the value has increased, turn the phase screw counterclockwise and repeat until the two readings with two settings of the coarse knob match. When done, make sure the nut is tightened to prevent the phase screw from turning during operation and return the coarse knob to its original orientation.

Absolute calibration

1. We have measured the resistivity ~10m west of the Bummers Rock trail about 50-75m from the edge of the parking lot. Our 1-D model suggests the EM31 should get measurements of about 1.25 mS/m; wandering about the area shows variations from about 0.7 to 1.5 mS/m. If the EM31 yields these values, all is good and no further calibration is needed. Note that the values in the parking lot will be much higher and there is a pipe under part of the lot.
2. If necessary to calibrate, place the instrument on the ground in the location chosen as the reference location. Adjust the QF knob (under the battery panel, farther one from the box side) until a value 1.12 times the correct conductivity is obtained. Resistivity of bedrock near Bummers Rock trail is about 1300 ohm-m, so a value of 0.86 mS/m would be desired but note that given the variability in the area a somewhat higher value might be appropriate (one approach is to first find the lowest conductivity values and then do this calibration in that spot).

Wednesday, August 31, 2011 3:48 PM

Please send mail if you encounter any problems or have suggestions.

Last modified at Wednesday, August 31, 2011 3:48 PM

GROUND CONDUCTIVITY METERS

EM31-MK2

The EM31-MK2 maps geologic variations, groundwater contaminants or any subsurface feature associated with changes in ground conductivity, using a patented electromagnetic inductive technique that allows measurement without electrodes or ground contact. With this inductive method, surveys can be carried out under most geologic conditions including those of high surface resistivity such as sand, gravel and asphalt.

Ground conductivity (quad-phase) and magnetic susceptibility (in-phase) measurements are read directly from an integrated data logger (which can easily be removed from the console for data transfer). Real-time (RT) graphical presentation of data is possible by connecting a computer directly to the RS232 output port on the front panel with an optional RS232 interconnect cable.

The effective depth of exploration is about six metres, making it ideal for geotechnical and environmental site characterization. Important advantages of the EM31-MK2 over conventional resistivity methods are the speed with which surveys can be performed, the precision with which small changes in conductivity can be measured and the continuous readout and data collection while traversing the survey area. Additionally, the in-phase component is particularly useful for the detection of buried metallic structure and waste material.

EM31-SH

The EM31-SH is a "short" version of the EM31-MK2 providing an effective depth of exploration of about four metres. With a smaller coil separation (2 m) and lighter weight, the EM31-SH offers improvements in sensitivity to smaller near-surface targets, lateral resolution and portability, while maintaining the high levels of accuracy and stability provided by the standard EM31-MK2. A "trailer-mount" (inset) is available for either instrument, offering greater convenience in field operation.

Specifications

MEASURED QUANTITIES	1: Apparent conductivity in millisiemens per metre (mS/m) 2: In-phase ratio of the secondary to primary magnetic field in parts per thousand (ppt)
INTERCOIL SPACING	3.66 metres
OPERATING FREQUENCY	9.8 kHz
POWER SUPPLY	8 disposable alkaline "C" cells (approx. 20 h continuous)
MEASURING RANGES	Conductivity: 10, 100, 1000 mS/m; In-phase: ± 20 ppt
MEASUREMENT RESOLUTION	± 0.1 % of full scale
MEASUREMENT ACCURACY	± 5 % at 20 mS/m
NOISE LEVELS	Conductivity: 0.1 mS/m; In-phase: 0.03 ppt
DATA STORAGE	10,000 records (2 components); 16,500 records (1 component); ext. memory available
DIMENSIONS	Boom: 4.0 m extended, 1.4 m stored Shipping Case: 145 x 38 x 23 cm
WEIGHTS	Instrument: 12.4 kg; Shipping: 28 kg

EM34-3

The EM34-3 is a simple-to-operate, cost-effective instrument for the geologist and hydrogeologist alike; applications have been particularly successful for the mapping of deeper groundwater contaminant plumes and for the exploration of potable groundwater resources.

Using the same inductive method as the EM31-MK2, the EM34-3 uses three intercoil spacings - 10, 20 and 40 m - to provide variable depths of exploration down to 60 metres. With three spacings and two dipole modes (horizontal as shown, and vertical) at each spacing, vertical electrical soundings can be obtained. In the vertical dipole (horizontal coplanar) mode, the EM34-3 is very sensitive to vertical geologic anomalies, and is widely used for groundwater exploration in fractured and faulted bedrock.

The EM34-3 includes connectors for an analog signal output, as well as an input which can be used with a rechargeable battery option. Digital signal output, required for data collection with the DAS70 system, is available as an option for all models of the EM34-3.

In regions of particularly high cultural and/or atmospheric noise, the EM34-3XL - including increased transmitter power and a larger transmitter coil - improves the signal-to-noise ratio by a factor of 10 at the 40 m spacing, and by a factor of 4 at the 10 m and 20 m spacings.

Specifications

MEASURED QUANTITIES	Apparent conductivity in millisiemens per metre (mS/m)
PRIMARY FIELD SOURCE	Self-contained dipole transmitter
SENSOR	Self-contained dipole receiver
REFERENCE CABLE	Lightweight, 2 wire shielded cable
INTERCOIL SPACINGS & OPERATING FREQUENCY	10 m at 6.4 kHz 20 m at 1.6 kHz 40 m at 0.4 kHz
POWER SUPPLY	Transmitter: 8 disposable or rechargeable "D" cells Receiver: 8 disposable or rechargeable "C" cells
CONDUCTIVITY RANGES	10, 100, 1000 mS/m
MEASUREMENT RESOLUTION	± 0.1 % of full scale
MEASUREMENT ACCURACY	± 5 % at 20 mS/m
NOISE LEVELS	0.2 mS/m (can be greater in regions of high power line interference)
DIMENSIONS	Receiver Console: 19 x 13.5 x 26 cm Transmitter Console: 155 x 8 x 26 cm Receiver & Transmitter Coil: 63 cm diameter EM34-3XL Transmitter Coil: 100 cm Shipping Case: 27.5 x 75 x 75 cm
WEIGHTS	Instrument: 20.5 kg; XL: 26.5 kg Shipping: 43 kg; XL: 51 kg

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Technical Note TN-5

ELECTRICAL CONDUCTIVITY OF SOILS AND ROCKS

J.D. McNEILL

October, 1980

Table of Contents

I. INTRODUCTION

It was near the beginning of this century that Conrad Schlumberger first employed the technique of mapping sub-surface geology by injecting electrical currents into the ground and mapping the resulting potential field distribution. Since that time measurement of terrain resistivity has been applied to a variety of geological problems. A partial list of applications includes the determination of rock lithology and bedrock depth; the location and mapping of aggregate and clay deposits; mapping groundwater extent and salinity; detecting pollution plumes in groundwater; mapping areas of high ice content in permafrost regions; locating geothermal areas; mapping archaeological sites, etc.

In many instances resistivity mapping provides definite geological information; however there are also cases where the results are uninterpretable since the "geological noise" is too high. A limitation of resistivity surveying is that the actual value of terrain resistivity itself is seldom diagnostic. As a result of this ambiguity we generally examine the variations of resistivity, either laterally or with depth, to outline the geological features of interest. But a problem arises in that conventional surveys are time-consuming to carry out and the area actually surveyed is often smaller than one might wish in order to fully ascertain the background against which the anomalous feature is to be defined. Furthermore, although conventional resistivity techniques sense to a characteristic depth (determined by the interelectrode spacing) resistivity inhomogeneities much smaller than that depth can, if they are located near the potential electrodes, yield large errors in the measurement and thus a noisy survey profile.

For these reasons application of resistivity surveys to engineering problems is not as common as it might be, particularly in North America. Such surveys have achieved success in Europe and are used more routinely.

It was an awareness both of the potential of resistivity measurements for solving geological problems and equally of some of the drawbacks of conventional resistivity mapping which lead Geonics Limited to develop two new lines of instrumentation employing electromagnetic techniques to measure terrain conductivity. In the first of these a sinusoidally varying magnetic field electromagnetically induces currents in the ground in such a manner that their amplitude is linearly proportional to the terrain conductivity (reciprocal of resistivity). The magnitude of these currents is determined by measuring the magnetic field which they in turn generate. Through the use of electromagnetic techniques, ground contact is avoided and with these patented instruments it is possible to map terrain conductivity virtually as fast as the operator(s) can walk; furthermore the sample volume is averaged in such a manner as to yield excellent resolution in conductivity. Two instruments have been developed by Geonics to cover the range of depths generally useful for engineering geophysics: (i) the EM31, one-man portable, has an effective penetration depth of 6 meters and (ii) the EM34-3, two-man portable, has stepwise selectable depths from 7.5 meters to 60 meters.

In the second approach the current flowing in a loop situated on the ground is abruptly terminated, inducing eddy currents in the ground which diffuse away from the transmitter loop in a manner controlled by the ground conductivity. In this case the dispersal of the currents is determined by measuring the transient decay of their magnetic field. Based on this principle, the Geonics EM37 can be used to determine the electrical properties of the earth to depths of several hundred meters.

These devices are assisting in the solution of many geological problems. With the renewed interest in resistivity it has become apparent that there is a requirement for a short note which discusses, from the point of view of survey interpretation, the various factors that influence terrain resistivity. For example, typical questions raised include (1) When are gravels more resistive than finer material? (2) What is the influence of the depth to water table? (3) It rained heavily last week; will this affect the measurements? (4) What are typical resistivities for the following soil types?, etc., etc.

By describing the various factors that control the electrical conductivity/resistivity of soils and rocks under typical in-situ conditions this note will attempt to provide the technical background against which these questions can be answered and to thus give the operator greater confidence in his survey interpretation. The emphasis throughout this technical note is on those factors that influence the near-surface ground resistivity, particularly of soils.

The various topics are dealt with in the following sequence.

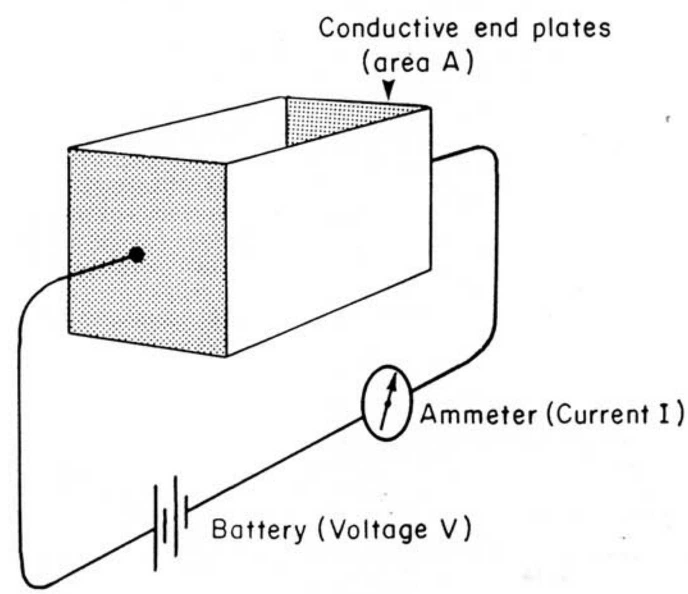
Section II: definition of conductivity & resistivity
Section III: description of relevant physical properties of soils and rocks
Section IV: relation of physical properties to the electrical conductivity
Section V: discussion of conventional resistivity measurements of soils in different climatic zones.

As mentioned above, this technical note is directed towards the user. Many readers will be familiar with the physical properties of soils and we ask their indulgence. None of the material on the electrical properties of soils is original; some has been taken verbatim from the references. However the compilation has been derived from many sources and we hope that it will prove useful.

II. RESISTIVITY/CONDUCTIVITY

Basically the electrical resistivity/conductivity of a substance is a measure of the difficulty/ease with which an electrical current can be made to flow through it. Suppose that we construct a tank with insulating sides and two conductive end plates as shown in Figure 1. The end plates are connected to a battery through an ammeter with which we measure the current flow through the sample. If the tank is empty there is of course no path by which the current can flow from one end plate to the other and the ammeter reads zero.

Suppose we fill the tank with a mixture of clean gravel and tap water. The ammeter will read a finite current and, depending on



RESISTIVITY (ρ)	CONDUCTIVITY (σ)
$\rho = \frac{RA}{L}$ ohm·metres	$\sigma = \frac{GL}{A}$ mhos/meter
where $R = \frac{V}{I}$ ohms	where $G = \frac{I}{V}$ mhos

FIGURE 1. Resistivity/conductivity tank.

various parameters to be discussed in Section IV, might indicate a current flow of a few thousandths of an ampere i.e. a few milliamperes, for a voltage of one volt. If the ammeter reads two milliamperes the electrical resistance of the material in the tank, given by the ratio of the voltage divided by the current, is 500 ohms.

If we now fill a number of different rectangular tanks, of different dimensions, with the same mixture we would find that the electrical resistance is proportional to the length of the tank and inversely proportional to the area of the conductive plate electrodes. The constant of proportionality, a property of the mixture only, independent of the tank dimensions, is defined as the electrical resistivity. In the MKS system it has the units of ohm-meters and is the electrical resistance measured on a cubic sample whose dimensions are all one meter. In the CGS system of units the resistivity is defined as the resistance across two opposite faces of a cubic sample one centimeter on each side and the units are ohm-centimeters. From the defining relation we see that, given the resistivity in ohm-centimeters, we must divide by 100 in order to get the resistivity in ohm-meters.

Suppose that we empty our tank (now assumed to be one meter on a side) and fill it with a mixture of clay saturated with water. We might find that the ammeter read a few tenths of an ampere, perhaps as much as half an ampere. The resistance would then be two ohms, the resistivity two ohm-meters. The range of resistivities displayed by unconsolidated materials at temperate ambient temperatures usually lies between one ohm-meter and one thousand ohm-meters; the resistivity of rocks can vary from a few tens of ohm-meters to as high as 100,000 ohm-meters, discussed in further detail in Section IV.

The reciprocal of the electrical resistivity of our sample is defined as the electrical conductivity. In the MKS system the unit of conductivity is the mho per meter and a resistivity of one ohm-meter exhibits a conductivity of one mho per meter, 100 ohm-meters is equivalent to a conductivity of 0.01 mhos per meter, etc. The electromagnetic instruments actually measure terrain *conductivity* rather than *resistivity* and for this reason much of the remainder of this technical note will be concerned with the conductivity of various terrain materials rather than the resistivity.

It was stated above that a resistivity of 100 ohm-meters corresponds to a conductivity of 0.01 mhos per meter. To avoid the inconvenience of having zeros immediately following the decimal point all conductivities will be expressed in millimhos per meter: a conductivity of .01 mhos per meter corresponds to 10 millimhos per meter, etc. This has the advantage that the range of resistivities from 1 to 1,000 ohm-meters is covered by the range of conductivities from 1,000 to 1 millimhos per meter and such numbers are easily handled. Table 1 lists the conversion from resistivity and conductivity in various units to conductivity in millimhos per meter.

In the experiments described above a direct current was employed. Had we used an alternating current and varied the frequency we might have discovered that the electrical properties of the sample varied with frequency. In reality soils and rocks are complex substances in which there are many (some poorly understood) mechanisms which govern the mode of current flow through the sample [1–5].

TABLE 1. Resistivity/conductivity unit conversion factors

mhos/meter × 1000	⟶	millimhos/meter
$\frac{1000}{\text{ohm-meters}}$	⟶	millimhos/meter
$\frac{100{,}000}{\text{ohm-centimeters}}$	⟶	millimhos/meter
$\frac{\text{cgs electrostatic units}}{9 \times 10^6}$	⟶	millimhos/meter

Note: 1 Siemen (S) = 1 mho

Fortunately, for materials with conductivity of the order of one to 1,000 millimhos per meter the electrical properties which control the current flow are relatively independent of frequency and the DC or low frequency conductivity measured with conventional resistivity equipment will be essentially the same as that measured using low frequency electromagnetic techniques.

Finally it should be noted that measurement of the electrical conductivity or resistivity of geological samples is, in reality, a very difficult procedure requiring much more complex equipment than the simple tank referred to above.

III. FACTORS AFFECTING TERRAIN CONDUCTIVITY

Most soil and rock minerals are electrical insulators of very high resistivity. However on rare occasions conductive minerals such as magnetite, specular hematite, carbon, graphite, pyrite and pyrrhotite occur in sufficient quantities in rocks to greatly increase their overall conductivity. This note assumes that such minerals are absent.

In general the conductivity is electrolytic and takes place through the moisture-filled pores and passages which are contained within the insulating matrix. The conductivity is therefore determined for both rocks and soils by

(1) porosity; shape and size of pores, number, size and shape of interconnecting passages
(2) the extent to which pores are filled by water i.e. the moisture content
(3) concentration of dissolved electrolytes in the contained moisture
(4) temperature and phase state of the porewater
(5) amount and composition of colloids

Since the constituents, structure, and included moisture of soil or rock are of great importance in determining the conductivity, this section will discuss the various physical and chemical properties in sufficient detail to illustrate how they affect the material conductivity.

III. 1. Soil Constituents

Soils consist basically of four components namely (i) mineral material (ii) organic material (iii) water and (iv) gases.

Figure 2 shows schematically the relative proportion of these components in an unsaturated loam soil (to be defined later). The illustration refers to a temperate zone soil; for humid region soils about 45% of the solid space may be occupied by clay minerals and 5% by organic matter.

The mineral fraction of a soil can be extremely variable, however some generalizations can be made based on grain size [6]:

sand size range – mostly quartz, small amounts of feldspar and mica present, all grains coated to some extent with iron and aluminum oxide (the rusty reddish-brown colour observed is due to the iron).

silt size range – quartz still dominant, less feldspar and mica than in the sand fraction, more iron and aluminum

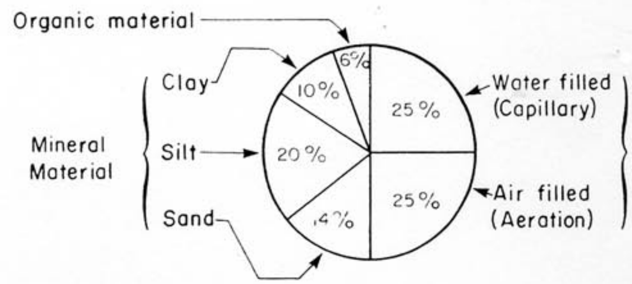


FIGURE 2. The volumetric composition of a loam soil when excess water has been removed. On a weight basis the percentage composition of the dry soil would be: organic matter 4%, clay 22%, silt 44% and sand 30% (after L.R. Webber [6]).

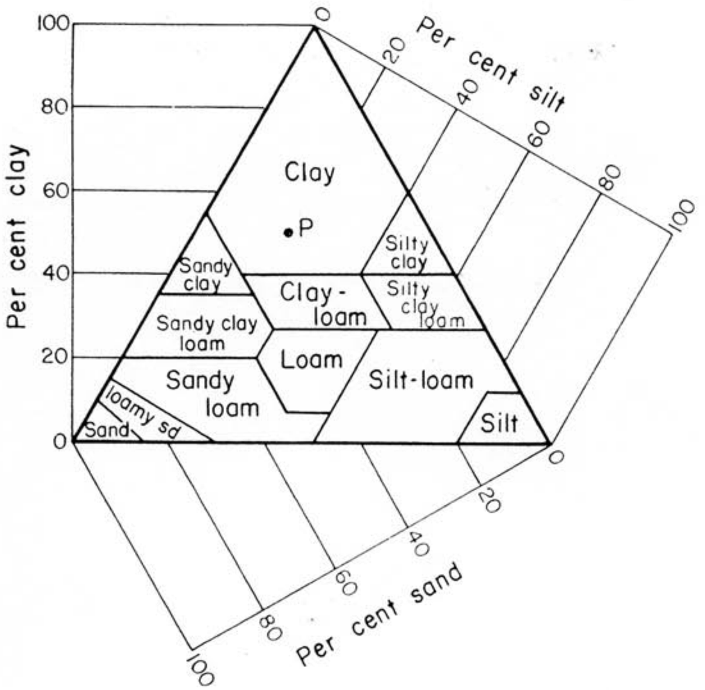


FIGURE 3. U.S. Department of Agriculture textural classification triangle with axes added. The point P represents a clay (soil) containing 50 per cent clay, 20 per cent silt, and 30 per cent sand (after D. Kirkham [7]).

oxides in the form of coatings due to the greater particle surface area on which the coatings may reside.

clay size range – finely divided quartz, feldspar, mica, iron and aluminum oxides, all of which appear in the coarser part of the clay fraction (0.002 millimeters – 0.001 millimeters in diameter); the finer part (less than 0.001 millimeters) is colloidal and consists mainly of layer silicates with smaller amounts of iron and aluminum oxides.

As indicated above soils are classified on the basis of texture or grain size independently of the mineralogical content of each particle size component. Sand is defined as particles with diameters between 0.05 millimeters and 2 millimeters, silt has diameters between 0.002 millimeters and 0.05 millimeters and clay has diameters less than 0.002 millimeters. Figure 3 shows the classification triangle for various types of soil and is useful as it allows an estimate of the clay content which often consists essentially of clay minerals which affect the soil conductivity.

The minerals in the sand and silt fractions of the soil are electrically neutral and are generally excellent insulators. Completely dry clay is also an insulator but the introduction of moisture changes the situation radically. Clay consists of microscopically fine particles

TABLE 2. Exchange capacity of common clays (after Keller and Frischknecht [5])

Clay	Exchange Capacity
Kaolinite	3 to 15 m-equiv/100 g
Halloysite . $2H_2O$	5 to 10
Halloysite . $4H_2O$	40 to 50
Montmorillonite	80 to 150
Illite	10 to 40
Vermiculite	100 to 150
Chlorite	10 to 40
Attapulgite	20 to 30

TABLE 3. The cation exchange capacity (CEC) and colloid content of five soils of different textures (after L. R. Webber [6]).

Soil Texture	Organic Matter %	Clay %	CEC* me/100 g
Sand	1.7	7	6.3
Sandy loam	3.2	13.2	13.7
Loam	4.9	16.8	20.2
Silt loam	5.4	18.4	24.0
Clay loam	5.5	31.2	27.2

*The cation exchange capacity of a soil is expressed in terms of milliequivalents per 100 grams of soil (meq/100 g). A milliequivalent is defined as 1.0 milligram of hydrogen or the amount of any other element that will combine with or displace it. The milliequivalent weight of any element may be found as follows:

$$\frac{\text{atomic weight of element}}{\text{valence of element} \times 1000} = \text{milliequivalent weight}$$

exhibiting a sheet-like structure, for which reason clays are often called "layer silicates". Composed of stable secondary minerals that have formed as a result of weathering of primary minerals such as feldspar, mica, etc, the particles are so fine-grained that they are described as micro-crystals.

Their crystalline structure is such that, as a result of crystal imperfections, the surface appears to be negatively charged [5]. During the formation of the clay through weathering, positive charges (cations) are adsorbed to the surface. These cations (typically Ca, Mg, H, K, Na, NH_3) are loosely held to the surface and can subsequently be exchanged for other cations or essentially go into solution should the clay be mixed with water. For this reason they are called exchangeable ions and the cation exchange capacity (CEC) of the soil is a measure of the number of cations that are required to neutralize the clay particle as a whole i.e. the weight of ions in milliequivalents adsorbed per 100 grams of clay.

The exchange capacities of some common clays are given in Table 2 and of some different soil textures in Table 3. It is seen from Table 3 that the cation exchange capacity increases with clay content and from Table 2 that this will depend on the type of clay.

Clay minerals are not the only materials which have cation exchange capacity; indeed any fine-grained mineral including quartz displays this property. The special significance of clay in this respect is that, because of the extremely small particle size, the surface area per unit volume of clay is very large and a great many ions are adsorbed. It will be seen in the next section that these adsorbed ions can contribute appreciably to the soil conductivity which thus becomes a function of the clay content.

The organic matter includes the remains of plant and animal life in the soil. The end products of decay accumulate as a blackish, finely-divided colloidal substance known as humus [6] which has large surface area per unit volume, takes up large amounts of water and can develop a negative electrical charge of varying intensity. Little is known of the effects of such colloidal characteristics on the electrical conductivity of humus but they may be significant.

The important influence of soil moisture on the electrical conductivity of soils is discussed at length in a later section.

The direct effect of soil gases on conductivity is negligible, however the indirect effect of CO_2 is important and is also described in a later section.

III. 2. Formation of Soils [8] and Soil Profiles [9]

Soils are the result of mechanical, chemical, and biological weathering processes acting on surficial materials in such a way as to grossly alter their physical and chemical properties. In the process of decomposition of parent materials new and stable substances such as clay minerals and humic materials are formed.

As an example of the weathering process consider the chemical weathering of orthoclase feldspar (an important constituent of granites and other intrusive rocks) to kaolinite, a clay. Atmospheric carbon dioxide is slightly soluble in water so as to form carbonic acid.

$$\underset{\text{Carbon dioxide}}{CO_2} + \underset{\text{Water}}{H_2O} \rightleftharpoons \underset{\text{Carbonic acid}}{H_2CO_3} \tag{1}$$

A small amount of the carbonic acid dissociates so as to produce a hydrogen ion and a bicarbonate ion

$$H_2CO_3 \rightleftharpoons \underset{\text{Hydrogen ion}}{H^+} + \underset{\text{Bicarbonate ion}}{HCO_3^-} \tag{2}$$

The bicarbonate ion and water combine with the feldspar to form kaolinite, dissolved silica, free potassium ions and free bicarbonate ions

$$\underset{\text{Orthoclase feldspar}}{2K\,Al\,Si_3O_8} + 2H^+ + 2HCO_3^- + H_2O \longrightarrow \tag{3}$$

$$\underset{\text{Kaolinite}}{Al_2Si_2O_5(OH)_4} + \underset{\text{Silica}}{4\,SiO_2} + \underset{\text{Potassium ion}}{2K^+} + \underset{\text{Bicarbonate ion}}{2HCO_3^-}$$

The formula for kaolinite can also be written in the following manner

$$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$$

to show that it consists of alumina, silica, and water.

These equations illustrate three important points: (i) The potassium and silica produced by dissolving the feldspar appear as dissolved material. Note that the potassium, converted to a potassium ion, goes into solution and may or may not be present depending on the drainage. (ii) Water is used up in the reaction; it is absorbed into the kaolinite structure. (iii) Hydrogen ions are used up in the reaction and the solution becomes more basic (i.e. less acidic) as the reaction proceeds. All of the reactions described herein affect the electrical properties of the soil by varying either the clay content or the ionic type and concentration in the soil water.

Now let us examine how various factors control this weathering process. The production of soil is a positive feedback process in that once a thin veneer of soil forms, the parent material weathers more rapidly, and more soil is formed. Suppose for example that we have a thin layer of soil on granite. This layer retains moisture which supplies both water that converts carbon dioxide to carbonic acid and water that is hydrated to form kaolinite. Other acids present in the soil contribute additional supplies of hydrogen ion to convert more feldspar to kaolinite as the equations indicate. Plant roots and the process of bacterial decay produce quantities of carbon dioxide to yield more carbonic acid (the amount of carbon dioxide in soil can be as much as ten times greater than that of rainwater, which makes soil water a particularly efficient dissolver of feldspars).

The speed of weathering is a function of climatic type since the rate at which chemical reactions proceed increases with temperature and, more importantly, biological process also proceed faster with higher temperature. Furthermore, since water is needed for the weathering reactions and vegetation grows more lushly in humid climates weathering is most intense in tropical climates which are wet and warm. The surface water resulting from rainfall percolates downwards through the soil, which is more or less permeable, and as it passes reacts chemically with minerals within the soil. The higher the rainfall the more water is available and the more the

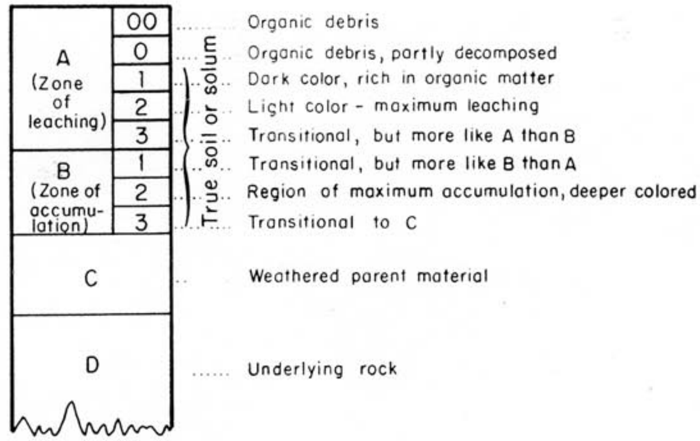


FIGURE 4. Normal or zonal soil profile (after G.B. Maxey [9]).

minerals will react with the undersaturated water. The longer the time the water percolates through, the more time it has to react chemically and again the higher the temperature, the faster the reaction rates.

As a result of these factors tropical soils tend to be thick. Well drained soils tend to be devoid of most unstable minerals. Arid soils contain a variety of minerals. The clay minerals which form are a function of temperature and humidity and there is a tendency for different clays to form in the various climatic belts [10].

As long as there is rainfall and the temperatures are not too low there is a tendency for soils to form a layered structure. In general three different regions or horizons are recognized as we move down through the soil profile, usually designated by the letters A, B, and C. These horizons can vary in thickness from a centimeter to several meters or tens of meters and differ in colour, texture, structure, and other properties.

The chief characteristics of a profile are illustrated in Figure 4. The A horizon, closest to the surface, is the most intensely weathered and has the soluble minerals leached out and most other minerals altered. This layer usually contains much humus, which contributes to its dark colour. Structurally it is friable, granular, or platey. When either friable or granular this horizon is permeable, much more so than the underlying B horizon which is generally a zone of clay accumulation, some of which was formed in-situ and some of which was transported downwards from the A zone by the soil water. The B horizon generally displays a vertical structure in widely or closely spaced joints and it is this horizon that exerts the greatest influence on water movement vertically downwards. When the clay is dry these joints allow rapid downwards movement but when the clay is wet it expands and can close the joints to make the layer impermeable, which may in turn cause the A horizon to become saturated for appreciable periods of time. The C horizon consists of less-weathered parent material and is usually relatively permeable [9].

This layering, with its relatively clay-free A horizon and clay-rich B horizon, greatly influences the vertical profile of electrical conductivity which will be seen to be a function of both clay and water content.

III. 3. Soil Moisture

It was noted at the beginning of this section that the electrical conductivity of soils and rocks was primarily electrolytic and took place through the moisture filled pores and passages which lie within the matrix of insulating minerals. For this reason a knowledge of the way in which soil moisture is distributed in typical terrain is important in understanding terrain conductivity.

When rainwater or irrigation falls on the surface of the soil a fraction runs off directly as surface runoff and the remainder percolates directly into the soil. A fraction of this moisture is retained by the soil, the remainder moves vertically downwards under the force of gravity until it reaches the water table. In a soil moisture profile it is generally possible to distinguish four stages of moisture occurrence depending on the relative continuity of the moisture films across the soil grains [11] as shown in Figure 5. In the uppermost region we have the pendular state in which the pore space is largely filled with water vapour. The actual liquid water exists only in very small isolated rings around the grain contacts and a continuous path does not exist between the various moisture occurrences. At greater depth we have the funicular stage in which the pendular rings have coalesced to the point where the liquid films have just become continuous throughout the pore space and entirely enclose or encapsulate the vapour phase. Across the sample the moisture path is now continuous. Again further down, in the capillary stage, all pore spaces are occupied by liquid but the liquid pressure within the pores is less than the total pressure caused by gravity since capillary action within the fine pore spaces has caused the moisture to ascend into these pore spaces. Capillary rise, determined effectively by pore size and type, seldom exceeds several meters. Finally we arrive at the phreatic surface (water table) at which the atmospheric pressure is in equilibrium with the hydrostatic pressure. All pores within the phreatic surface are completely filled with liquid under hydrostatic pressure and this is the region of groundwater, also known as the zone of saturation. The three regions above the phreatic surface are collectively referred to as soil moisture, suspended water, vadose water, or zone of aeration.

Figure 5 also illustrates typically the fraction of pore space filled by liquid in the different zones.

A term that is often used in discussing the moisture content of soils is field capacity. Suppose that the water table is very deep below a surface soil of homogenous nature. After a heavy rainfall or irrigation the moisture content reaches a quasi-equilibrium condition in one to three days. As the water percolates down through the soil on its way to the water table capillary forces will retain a certain fraction of the moisture in the small pore spaces. This is the field

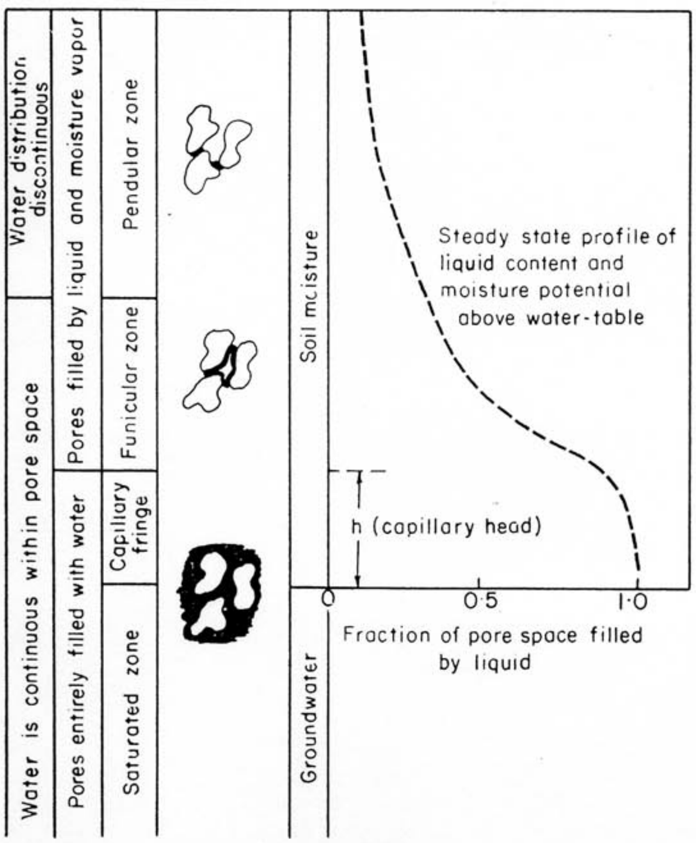


FIGURE 5. Liquid occurrence in soils (after P. Meyboom [11]).

TABLE 4. Permeability of soils (after D. K. Todd [12])

SOIL CLASS	Clean gravel	Clean sands; mixture of clean sands & gravels	Very fine sands, silts, mixtures of sand, silt and clay, glacial till, stratified clays etc	Unweathered clays
FLOW CHARACTERISTICS	Good aquifers		Poor aquifers	Impervious

PERMEABILITY (gal/day/ft²): 10^6 — 10^4 — 10^2 — 10^0 — 10^{-2} — 10^{-4}

capacity and it is the moisture content of the soil after the gravitational water has been removed by deep seepage.

Note that in the event that we have a layered situation in which a soil with very fine pores overlies more granular material, both being far removed from the water table, moisture content of the upper layer will be many times that of the lower which, as will be seen later, affects the electrical conductivity.

Groundwater is free to move laterally with velocities ranging from a meter or more per day to less than a meter per year, depending on the hydraulic pressure differential and the permeability of the material. Table 4 illustrates the permeability of various materials in gallons per day per square foot of cross-section per foot of hydraulic head per lateral foot of distance. It is seen from the Table that for soil materials a factor of 10^{10} separates permeable from impermeable materials. The saturated hydraulic conductivity decreases with clay content, increasing compaction, and decreasing radius of the soil pores.

The laws of hydraulic movement of water produce a water table which in general is not horizontal and in fact is often a subdued version of the local topography, all other factors being equal. Two examples are shown in Figure 6; for the humid zone the moisture moves from topographic high regions down to the draining streams whereas in an arid zone the moisture moves downwards away from the streams.

The wide ranges of permeability greatly influence the final profile of the water table or phreatic zone sometimes leading, for example, to the occurrence of a perched water table as shown in Figure 7. Again such layering will be seen subsequently to influence the electrical properties.

It will be shown in Section IV that the electrical conductivity of soils and rocks depends on the porosity and on the degree to which the pores are filled with moisture. Figure 2 showed the volumetric composition of a loam soil from which the excess water has been removed i.e. the soil is undersaturated. We see that in this temperate zone example approximately 50% of the soil is occupied by either gas or capillary water. This division into about 50% solids is fairly typical of most soils.

If all of the moisture in a soil sample is removed by drying, the ratio of the empty volume to the total volume of the soil matrix is known as the soil porosity, a parameter that is relevant to the soil conductivity. Table 5 illustrates the porosity for a variety of typical terrain materials.

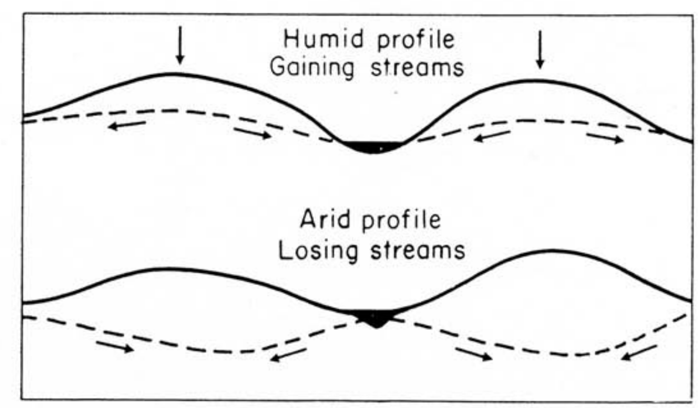
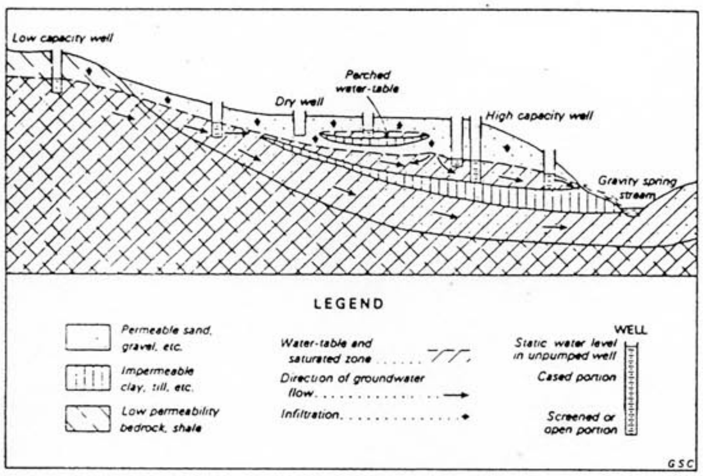


FIGURE 6. Profiles of water tables in arid and humid zones (after G. B. Maxey [9]).



Water-table conditions (unconfined aquifers).

FIGURE 7. Water-table conditions – unconfined aquifers (after I.C. Brown [13]).

TABLE 5. Representative porosity ranges for sedimentary materials (after D. K. Todd [12])

Material	Porosity, %
Soils	50–60
Clay	45–55
Silt	40–50
Medium to coarse mixed sand	35–40
Uniform sand	30–40
Fine to medium mixed sand	30–35
Gravel	30–40
Gravel and sand	20–35
Sandstone	10–20
Shale	1–10
Limestone	1–10

Table 6 gives further data on porosity and also indicates the value of the ratio ρ_x (mixture resistivity) divided by ρ_1 (electrolyte resistivity) about which more will be said later in Sections IV and V.

It is obvious that the degree of compaction of a soil will affect the magnitude of the soil porosity.

IV. ELECTRICAL CONDUCTIVITY OF SOILS AND ROCKS

In Section III it was noted that the conductivity of soils and rocks was principally electrolytic. This section will discuss the parameters that determine the conductivity of electrolytes and the effects that arise when electrolytes are present in both clay-free and clay-rich soils and rocks.

IV. 1. Properties of Electrolytes

As an introduction suppose we empty our hypothetical tank of Section II and refill it with distilled water. The measured conductivity is very low. If however a small amount of table salt (NaCl) is dissolved in the distilled water the conductivity increases substantially.

TABLE 6. Porosity of soils and rocks (after C. A. Helland [14])

Rock or Formation	Porosity	Ratio $\frac{\rho_x}{\rho_1}$
Igneous and metamorphic rocks	½– 2	100
Dense limestones and sandstones	3– 4	50 –100
Clays and sands in general	8–15	20 – 40
Porous clays, sands, sandstone, cellular limestones, and dolomites	15–40	3 – 20
Marl, loess, clay, and sandy soil	40–75	1.5– 4
Peat, diatomaceous earth	80–90	1.0– 1.5

TABLE 7. Mobility of common ions at 25°C (after Keller and Frischknecht [5])

ion	Mobility (m^2/sec V)
H^+	36.2×10^{-8}
OH^-	20.5×10^{-8}
SO_4^-	8.3×10^{-8}
Na^+	5.2×10^{-8}
Cl^-	7.9×10^{-8}
K^+	7.6×10^{-8}
NO_3^-	7.4×10^{-8}
Li^+	4.0×10^{-8}
HCO_3^-	4.6×10^{-8}

The conductivity of an electrolyte is proportional both to the total number of charge carriers (ions) in the solution and their velocity. In distilled water there are few ions and the conductivity is low. The dissolved sodium chloride molecules dissociate to form both positively charged sodium ions and negatively charged chloride ions which greatly increase the conductivity.

When a voltage is applied between the two end plates an electric field is established in the tank; the positively charged ions are attracted towards the negative plate, the negatively charged ions to the positive plate. The velocity of the ions is effectively controlled by the viscosity of the fluid. This velocity is slightly different for different ions since it depends upon their effective diameter, as illustrated in Table 7, where it can be seen that chloride ions move slightly more rapidly than the sodium ions.

In a sodium chloride solution the amount of current that flows, and therefore the electrical conductivity, is proportional to the sum of the number of sodium ions multiplied by their mobility (velocity per unit electric field) and the number of chloride ions multiplied by their mobility.

The further addition of different salts to our tank would increase the electrical conductivity independently of the presence of the sodium and chlorine ions as long as the concentrations remain reasonably dilute. The following equation is often used to calculate the approximate electrical conductivity in mhos per meter of a dilute solution of various salts at normal ambient temperatures:

$$\sigma = 96500[C_1M_1 + C_2M_2 + ...] = 96500 \sum C_iM_i \quad (4)$$

where C_i = no. of gram equivalent weights of i^{th} ion per 10^6 cm^3 of water

M_i = mobility of i^{th} ion in meters per second per volt per meter.

For example, suppose that one gram of salt is dissolved in our tank which holds 10^6 cm^3 of water. The atomic weight of sodium is 23, of chlorine is 35, so the atomic weight of sodium chloride is 23 + 35 = 58. Since we have introduced one gram of sodium chloride we have introduced

$$\frac{23}{58} \text{ grams of sodium and } \frac{35}{58} \text{ grams of chlorine.}$$

The gram equivalent weight of an ion is the atomic or molecular weight of the ion divided by its valence. In the case of both sodium and chlorine the valence is one so the gram equivalent weight of sodium is 23 grams, of chlorine 35 grams.

Then the number of gram equivalent weights of sodium per 10^6 cm^3 of water is given by

$$C_{Na} = \frac{\text{weight of Na per } 10^6 \text{ cm}^3 \text{ H}_2\text{O}}{\text{gram equivalent weight}} = \frac{23/58}{23} = \frac{1}{58}$$

and that for chlorine is given by

$$C_{Cl} = \frac{\text{weight of Cl per } 10^6 \text{ cm}^3 \text{ H}_2\text{O}}{\text{gram equivalent weight}} = \frac{35/58}{35} = \frac{1}{58}$$

Using the data from Table 7 for the mobilities at 25° C we find that the conductivity for one gram of sodium chloride in 10^6 cm^3 of water is given by

$$\sigma = 96500\left[\frac{1}{58} \times 5.2 \times 10^8 + \frac{1}{58} \times 7.9 \times 10^8\right]$$
$$= 0.00022 \text{ mho/m.} \quad (5)$$

The addition of only one part per million of sodium chloride by weight has produced the appreciable conductivity of 0.22 millimhos per meter.

The concentration of dissolved salts in natural groundwaters is substantially higher than one part per million, as a result of which their conductivity is much greater than 0.22 millimhos per meter. For example Table 8 illustrates the contribution of various ions to the measured conductivity of three of the Great Lakes. Lakes Erie and Huron which both occur in regions of Paleozoic carbonate rocks contain more dissolved salts than Lake Superior which is situated largely in Precambrian crystalline rocks, and this is reflected in the higher conductivities of the first two lakes. The bottom line of the table gives the measured conductivity: agreement with the calculated values using the above equations is good.

The following data from Heiland [14] illustrates typical values for the conductivity of various natural waters.

1. Meteoric waters, derived from precipitation; 1 to 30 millimhos per meter.
2. Surface waters (lakes, rivers) vary from 0.3 millimhos per meter for very pure water to as large as 10,000 millimhos per meter for salt lakes. Surface waters in districts of igneous rocks are estimated to range from 2 to 30 millimhos per meter; surface waters in areas of sedimentary rocks vary from 10 to 100 millimhos per meter (compare the Great Lakes above).
3. Soil waters (discharged into the atmosphere by evaporation) may be as large as 10,000 millimhos per meter but their average is around 10 millimhos per meter.
4. Normal groundwater in areas of igneous rock ranges from 6 to 30 millimhos per meter and in areas of sedimentary rocks to as large as 1,000 millimhos per meter.
5. Mine waters (copper, zinc, etc., sulfates) are of high conductivity, generally not less than 3,000 millimhos per meter.

TABLE 8. Conductivity of Great Lakes with contribution of the various ions (after L. H. Doherty [15])

Ion	Lake Erie	Lake Huron	Lake Superior
HCO_3	5.8	4.1	2.6
Ca	10.1	7.3	3.8
Mg	3.6	3.2	2.4
Na	1.8	0.6	0.2
Cl	3.9	1.2	0.2
SO_4	3.4	1.8	0.3
Calculated Conductivity (mmhos/m)	28.6	18.2	9.5
Measured Conductivity (mmhos/m)	26.7	18.2	8.4

The temperature dependence of the electrical conductivity of the electrolyte is almost entirely due to the temperature dependence of the viscosity of the liquid, which in turn directly affects the ionic mobility. The variation of either quantity with temperature is approximately linear over normal ambient temperatures. The temperature coefficient for a sodium chloride solution is 0.022 which value applies approximately to most other ions so that the electrolyte conductivity for a temperature other than 25°C is given by

$$\sigma(T) = \sigma(25°C)[1 + \beta(T - 25°)]$$

where $\beta = 2.2 \times 10^{-2}$ per °C

T = temperature (°C) at which conductivity is to be calculated.

A change of conductivity of 2.2% per degree centigrade implies that a change in temperature of 40°C will cause the conductivity to nearly double. The effect of temperature is illustrated in Figure 8 which shows calculated conductivity of four of the Great Lakes as a function of season.

The change of conductivity with temperature and therefore with season is not negligible and this applies equally well to ground conductivity over the normal range of ambient temperatures.

IV. 2. Conductivity of Saturated Clean (Clay-Free) Mixtures

We have examined how the electrical conductivity of the electrolyte in our tank varies with the concentration of dissolved salts and with temperature. Let us now start to fill the tank with perfectly insulating spheres of uniform radius (for example uniform pebbles). Assume for the time being that we can maintain these spheres uniformly dispersed throughout the solution. Since the spheres are insulating, the electrical current will find it more difficult to cross the tank and the conductivity will be reduced. A relationship was derived by Maxwell for the conductivity σ_x of a mixture consisting of a medium with conductivity σ_1 in which spherical grains of conduc-

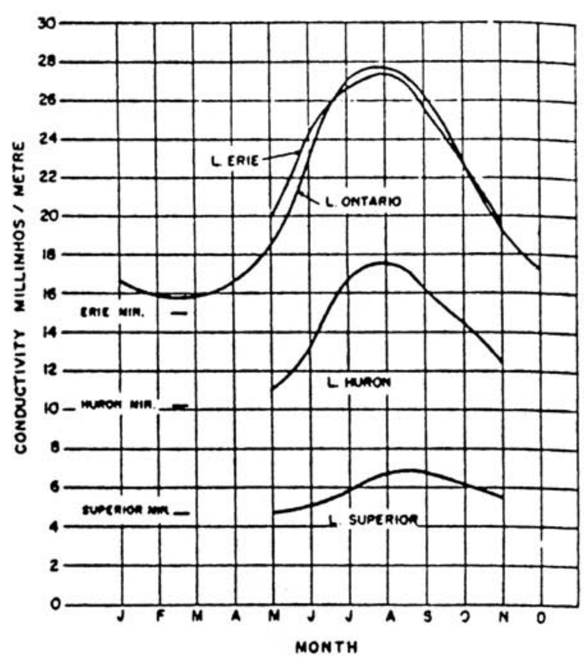


FIGURE 8. Seasonal variation of conductivity of Lakes Ontario, Erie, Huron and Superior (after L.H. Doherty [15]).

tivity σ_2 (here assumed to be zero) are imbedded in regular arrangement and in such a manner that their spacing is large compared with their radius [14]. Letting n be the porosity of the mixture (defined as the ratio of the volume of solution only, divided by the total volume of the solution including the spheres) Maxwell showed that the conductivity of the mixture was given by

$$\frac{\sigma_x}{\sigma_1} = \frac{2n}{3 - n} \tag{7}$$

In Section II it was shown that the conductance of a current path is directly proportional to the cross-sectional area and inversely proportional to the length. The addition of insulating spheres to the tank tends to reduce the cross-sectional area available for current flow and to increase the effective length of the current paths, reducing the overall conductivity.

This dilute mixture does not resemble a soil so we continue to add insulating spheres until the tank is full. The condition for Maxwell's derivation, that the inter-particle distance be large compared with the particle radius, is invalid and the above equation can no longer be expected to apply. It turns out however that an almost equally simple empirical relationship called Archie's Law [5] is applicable to clean (i.e. clay-free) saturated mixtures. This equation is

$$\frac{\sigma_x}{\sigma_1} = n^m \tag{8}$$

where n is the fractional porosity defined above and m is a constant. The reciprocal quantity ρ_x/ρ_1 is often called the formation factor (FF) of the rock or soil sample.

Originally derived from resistivity measurements on samples of consolidated porous rock, this equation also applies to a variety of unconsolidated materials. That such a simple law should give excellent results for a variety of both consolidated and unconsolidated materials with widely differing porosities is a surprise and indeed the underlying reasons for its success are not well understood [4]. It has been established [16] that in the case of marine sands the exponent m is dependent on the *shape* of the particles, increasing as they become less spherical (i.e. more platey) and that variations in the *size* of the particles and in the *dispersion* of sizes appear to have a very small effect.

Values of m are listed in Table 9 where it is seen that m varies from 1.2 for insulating spheres to 1.85 for very platey fragments of shell. Samples of natural sands have values in the range 1.4 to 1.6. The value of 1.85 for shell fragments is in good agreement with earlier measurements made on kaolinite particles and marine illite clays. This fact may or may not be significant for clays in normal soils depending on the extent to which ion exchange effects also contribute to the conductivity as discussed further on in this section.

Archie's Law for various exponents is plotted in Figure 9 along with Maxwell's Law. Over the range of porosities of most unconsolidated terrain materials (20% to 70% – see Tables 5 and 6) the different exponents do not greatly affect the mixture conductivity. Interestingly enough, Maxwell's Law gives excellent agreement with Archie's Law with exponent m = 1.3 over all ranges of porosity.

It would appear that for relatively clay-free substances located beneath the water table (so that the mixture is completely saturated) the primary matrix property measured through the electrical conductivity is the porosity of the matrix, essentially independent of the particle size or the particle size distribution. This explains why it is a relatively difficult matter using resistivity techniques to distinguish between sand and gravel. As long as the porosity is the same for both sand and gravel the resistivity or conductivity contrast may be quite small.

Another point is that if the porosity is assumed to vary from 20% to 70% the conductivity of the mixture varies by a factor of approximately 8, depending somewhat on which value of exponent is adopted. Even in clean mixtures we do not expect a large range of conductivities and experimentally this has been confirmed.

TABLE 9. The effect of particle shape on the FF/n relation using artificial samples of decreasing sphericity. (after P. D. Jackson et al. [16])

Sample no.	Mean size ϕ*	Spread of sizes	Sphericity	Best fit Archie line FF = n^{-m} m ± 0.01
Spheres	0.38	0.17	1.0	1.20
Rounded sand	0.38	0.17	0.83	1.40
Shaley sand	0.50	0.34	0.78	1.52
Shell fragments	0.38	0.17	0.5	1.85

*$\phi = -\log_2$ (diameter in mm).

Figure 9 is useful for the following type of calculation: in many glacial deposits gravel appears as pebbles (of the order of a few centimeters in diameter) dispersed throughout a mixture of finer relatively clean sand. How does the presence of this gravel modify the mixture conductivity? To obtain an approximate answer let us assume that the sand itself has a porosity of 30%. Using Archie's Law with m = 1.6 the electrical conductivity of the sand/water mixture will be 15% of the conductivity of the water. Assuming a water conductivity of 20 millimhos per meter gives a conductivity for the mixture of 3 millimhos per meter, a not uncommon value. We use this value in conjunction with Figure 9 to determine the effect of introducing pebbles into the mixture. If for example the pebbles occupy 50% of the volume the conductivity of the mixture will fall to one-third or approximately 1 millimho per meter, also a value that commonly occurs in actual practice. As will be seen later the addition of a relatively small amount of clay can increase these numbers by virtue of increasing the conductivity of the pore water but the relative values may well be similar.

IV. 3. Conductivity of Unsaturated Clean Mixtures

For Archie's Law to apply the material must be fully saturated with fluid. If the mixture is partially saturated the conductivites will be decreased since gas or air bubbles act as insulating particles to further impede the current flow. In the funicular stage of soil moisture the pendular rings have coalesced so that the liquid films are continuous throughout the pore space but only a fraction of the available pore space is filled with water. This moisture varies with time and temperature as a result of drainage, evaporation, and loss of water to plant roots.

In the event that the soil is partially desaturated the following approximate expression applies [5]

$$\frac{\sigma_x}{\sigma_1} = s^n \tag{9}$$

where s is the fraction of total pore volume filled with electrolyte and n is a parameter experimentally determined to be approximately 2. This expression is equivalent to Archie's Law with m = 2 and indicates as seen from Figure 9 that if a small fraction of the total pore volume is filled with water the conductivity can be very low.

More recent work on soils has shown that the electrical conductivity varies as follows with moisture content when the soil is partially desaturated [17]

$$\sigma_x = \sigma_1 \theta(a\theta + b) + \sigma_s \tag{10}$$

where θ is the volumetric water content (cm^3 of water per cm^3 of soil), a and b are constants which depend on the soil texture, and σ_s is a contribution from "surface conductivity" which will be discussed under Colloidal Conductivity. The values of the empirically determined constants a and b for a variety of soils are shown in

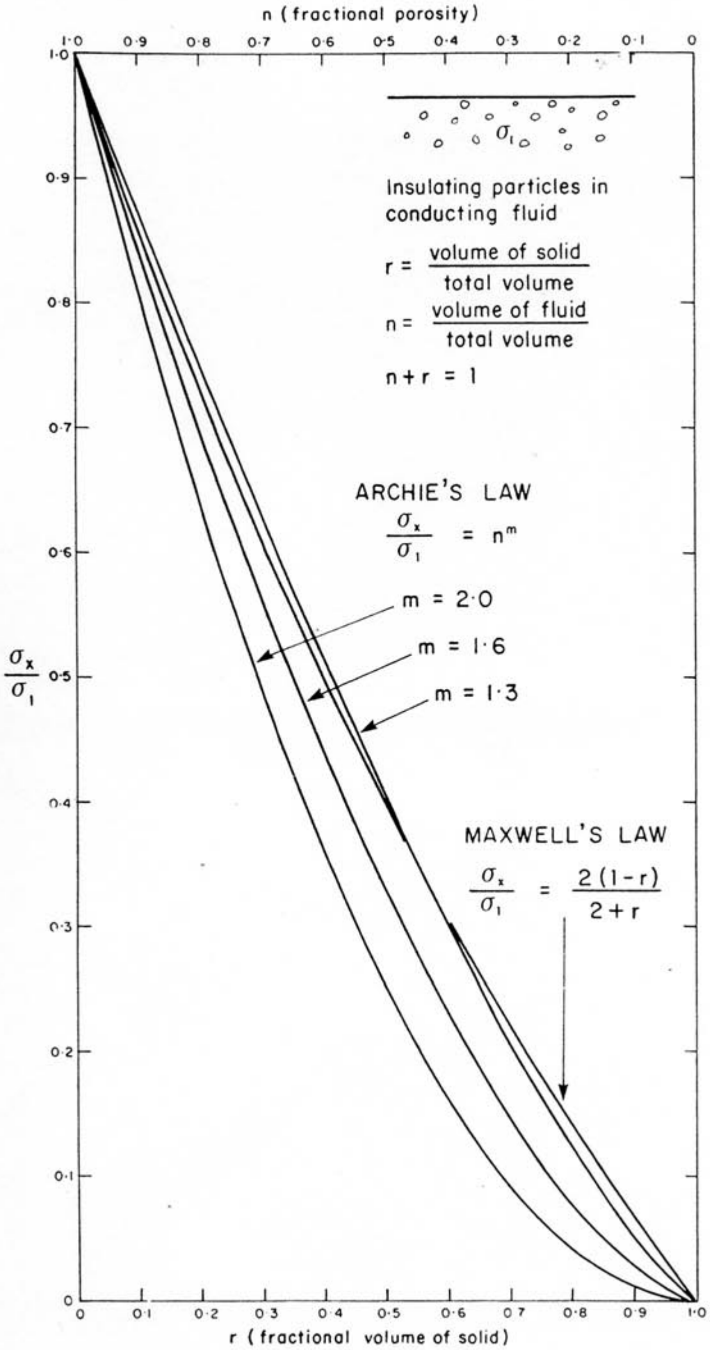


FIGURE 9. Graph of Archie's Law and Maxwell's Law.

Table 10 from which it is seen that except for very low moisture the relationship is essentially a square law with mosture content.

It has been suggested by Rhoades et al [17] that it might be possible to estimate the values of σ_s, a, and b on the basis of soil texture and mineralogy and, given a measurement of the bulk soil conductivity and the moisture content, to determine the conductivity of the fluid and thus salinity.

IV. 4. Electrical Layering Arising from Soil Moisture

From the preceding paragraphs we observe that, even if the soil material is physically homogeneous, for example consists of clean well-sorted silt, as soon as we introduce soil moisture of finite electrical conductivity we have established a medium in which the electrical conducvitity can vary strongly with depth. Near surface where the moisture content is low the conductivity is also low. With increasing depth the conductivity rises rapidly as the moisture films become continuous, then more slowly as the available pore volume starts to fill, eventually saturating with complete filling of the pores. This situation will be rendered even more complex if the porosity itself is, as is often the case, a function of depth as suggested by the profile of Figure 4.

TABLE 10. Measured moisture content constants and surface conductivities (after J. D. Rhoades et al. [17])

Soil type	a	b	σ_s
			mmho/cm
Pachappa fsl	1.382	−0.093	0.18
Indio vfsl	1.287	−0.116	0.25
Waukena l	1.403	−0.064	0.40
Domino cl	2.134	−0.245	0.40

IV. 5. Colloidal Conductivity

It will be recalled that for clays the cation exchange capacity (CEC) was a measure of the number of ions adsorbed to the surface of clay particles. When the clay particles are immersed in a liquid there is evidence to show that these adsorbed ions can partially dissociate themselves from the clay particles and become available for ionic conductivity. Since the ion exchange capacity of clays can be great due to their large surface area many ions may be supplied for electrical conductivity; the addition of a small amount of clay to an otherwise clean mixture can substantially increase the electrical conductivity.

The addition of clay appears to affect the electrical conductivity of the mixture in two ways. Repeating equation (10)

$$\sigma_x = \sigma_1 \theta(a\theta + b) + \sigma_s \qquad (10)$$

the added ions increase the value of σ_1 above the value that the porewater would have in the absence of the clay. Furthermore although dry clay is highly resistive, as soon as a thin layer of moisture (perhaps only a few molecules thick) surrounds the clay particles ion movement across the surface of the clay particle within the cloud of adsorbed ions may occur. This surface contribution to the conductivity, essentially independent of the moisture content, is the second term in the equation. It will be most significant at low moisture contents.

The contribution to σ_1 from clay content will be most evident for soils in which the porewater is relatively pure (and therefore has low conductivity) and will be least effective in soils having highly saline porewater. For either contribution we should expect that clays with higher CEC will produce more conductive soils and a comparison of Table 11 with Table 2 shows that this is the case

In summary, in areas where the soil porewater is not particularly saline the electrical properties of the soil may be strongly influenced by and indeed in some cases completely dominated by the amount and type of clay minerals present. The possible influence of clay materials should always be kept in mind. It is also possible that a similar effect arises as a result of the colloidal properties of humus which might be important in tropical climates where the humus layer is well leached and contains few clay minerals.

IV. 6. Effects of Freezing on Soil Conductivity

Suppose that we take our tank, filled with a clean sand/water mixture, and start to lower the temperature. The electrical conductivity of the mixture will decrease in exactly the same way that the conductivity of the electrolyte does. When the temperature reaches 0°C the water freezes and since the conductivity of ice is extremely low the conductivity of the mixture falls essentially to zero.

Now suppose that in addition to the sand some clay is introduced to the mixture and the temperature is again reduced. As the temperature passes through 0°C some of the water freezes; however the

TABLE 11. Physical properties of typical Upland and Lowland soils in western Puerto Rico (after J. W. Walker et al. [18])

Topographic location	Sample no.	Moisture (%)	Conductivity (mmho/m)	Clastic material (%)	Clay fraction (%)	Clay type(s) (%)
Uplands	1	42	16.0	21	79	100% kaolinite
Uplands	2	46	1.2	42	58	100% kaolinite
Uplands	3	25	1.0	5	95	100% kaolinite
Lowlands	4	21	65.0	66	34	100% montmorillonite
Lowlands	5	32	169.0	39	61	60% montmorillonite 40% kaolinite
Lowlands	6	25	269.0	15	85	90% montmorillonite 10% kaolinite

electrical field of the adsorbed ions on the clay particles locally orients the neaby water molecules to prevent their freezing [17]. Furthermore as the solvent freezes there is a tendency for the impurity ions to stay within the liquid fraction and the actual electrical conductivity of the remaining liquid water increases with decreasing temperature. The net result is that mixtures containing clay or silts tend to have an electrical conductivity which decreases relatively slowly with temperature as the temperature passes through 0°C and indeed to retain a moderate conductivity even at temperatures well below freezing as illustrated in Figure 10.

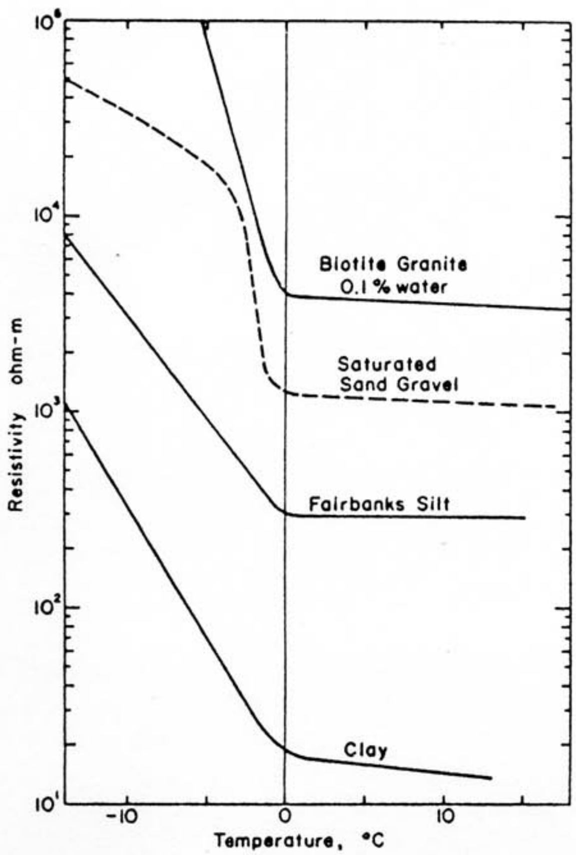


FIGURE 10. Resistivities for several soils and one rock type as a function of temperature (after Hoekstra and McNeill [20]).

IV. 7. Electrical Properties of Rocks

As with unconsolidated materials the matrix of most water-bearing rocks is insulating and the electrical conductivity is also electrolytic. A major difference between unconsolidated sediments and rocks lies in the types of pore geometries. For example in sedimentary rocks the porosity is generally inter-granular and consists of voids still remaining from the compaction process. In igneous rocks the porosity of the rock itself may be extremely small, however moisture circulates through fractures in the rock which are the result of mechanical breakage. These cracks are called joints and may be sufficiently large and/or numerous that their presence completely dominates the electrical conductivity. Such jointing may also play a major role in the conductivity of the more impermeable sedimentary rocks. When large joints are present the local conductivity may be expected to vary strongly with position. A third form of porosity which may not make a major contribution to electrical conductivity as normally measured is vugular porosity. It consists of cavities (as might be caused by solutions circulating in limestone) interconnected by small pores which dominate the D.C. electrical behavior. It should be noted that in the case of electromagnetic excitation of currents direct electrical (ohmic) inter-cavity connection is not necessary and appreciable response to this excitation may come from the fluid in each cavity separately.

Table 12 illustrates normal porosity for various rock types. It is seen that the total porosity can be very small, of the order of a few percent, and we would therefore expect, particularly for unfractured Precambrian igneous rocks and high-ranking metamorphosed rocks, the electrical conductivity to be very low, as is generally the case. On the other hand shales may be relatively porous and in addition the conductivity of the pore water may be high as a result of ion exchange effects. For this reason shales can be as conductive as 30 to 40 millimhos per meter and in some cases even higher.

Since in general the porosities are smaller for consolidated materials and furthermore at this end of the scale the various exponents in Archie's Law have a large effect, it is difficult to predict the electrical properties of any given rock type.

There is another feature which occurs in sedimentary rocks and which is of importance in determining their electrical characteristics. Being depositional in nature these rocks are layered and the electrical conductivity perpendicular to the bedding planes may be less than the conductivity parallel to the planes.

This feature is illustrated in Table 13 which lists the coefficient of anisotropy for various layered rocks. The coefficient is defined in Figure 11.

Another type of rock conductor called a structural conductor [21] occurs as a result of fracturing and is often linear in shape. Such conductors arise in the interior of faults, shear zones, contact frac-

TABLE 12. Normal ranges in porosity for rocks (after Keller and Frischknecht [5])

Rock type	Intergranular porosity (%)	Joint porosity (%)	Vugular porosity* (%)
Paleozoic sandstones and shale	5–30	0–1	0
Paleozoic limestones	2–10	0–2	0
Paleozoic clastic volcanics	5–30	0–2	0
Post Paleozoic sandstones and shale	10–40	0	0
Post-Paleozoic limestones	4–20	0–2	0
Post-Paleozoic clastic volcanics	10–60	0	0
Precambrian sediments and low-rank metamorphosed sediments	1–8	0–2	0
Precambrian igneous rocks and high-rank metamorphic rocks	0–2	0–2	0
More recent igneous rocks	0–10	0–2	0

*Vugular porosity accounts for an appreciable total porosity only in rare cases.

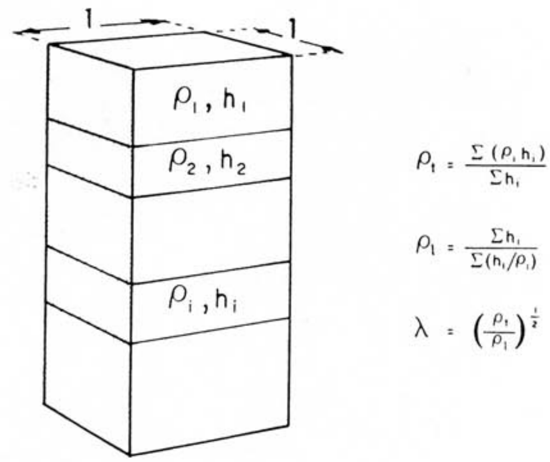


FIGURE 11. Definition of coefficient of anisotropy (λ) for layered sediments (after Keller and Frischknecht [5]).

TABLE 13. Coefficients of anisotropy for layered rock (after Keller and Frischknecht [5])

Rock type	Coefficient of anisotropy
Volcanic tuff, Eocene and younger, from Nevada	1.10–1.20
Alluvium, thick sections from the southwestern United States	1.02–1.10
Interbedded limestones and limey shales from northeastern Colorado	2.0 –3.0
Interbedded anhydrite and shale, northeastern Colorado	4.0 –7.5
Massive shale beds	1.01–1.05
Interbedded shale and sandstone	1.05–1.15
Baked shale or low-rank slate	1.10–1.60
Slates	1.40–2.25
Bitumenous coal and mudstone	1.7 –2.6
Anthracite coal and associated rocks	2.0 –2.6
Graphitic slate	2.0 –2.8

ture zones, etc., where the rock material has been ground into small particles which allows increased circulation of groundwater resulting in enhanced weathering to produce clay minerals. Structural conductors occur in a wide range of sizes.

V. EXAMPLES OF CONVENTIONAL MEASUREMENTS OF SOIL AND ROCK RESISTIVITIES

The material in this section gives a broad indication as to the range of resistivity or conductivity which might be encountered in various terrain materials in various climatic zones. Extreme caution must be exercised in employing these values for anything other than a rough guide as to anticipated survey results.

As an introduction Table 14 illustrates the resistivities of igneous and metamorphic rocks as given by Telford et al [22]. Table 15 lists resistivities of sediments from the same source. Table 6, from Heiland [14], lists the ratio ρ_x/ρ_0 as defined in Section IV for various consolidated and unconsolidated materials.

V. 1. Temperate Zones

Table 16 records the ranges of resistivity compiled for different terrain materials from a variety of survey and laboratory measurements, from Culley et al [23].

Table 17 from Sellman et al [24] shows survey data over different soil types made with three different measurement techniques (i) radio-frequency magneto-telluric at approximately 300 kHz, (ii) low-frequency magnetically induced currents using dipole transmitter and receiver at 10 kHz, and (iii) standard Wenner array at DC. The measured resistivities are relatively independent of the method of measurement; the general trend of increasing resistivity with particle size should be noted.

A complete set of measurements by Smith-Rose [25] on a variety of soils from different depths, with different moisture contents, and measured at various frequencies, shows that at the lower frequencies (i.e. between 1 and 100 kHz) the conductivity of soils is essentially independent of frequency. At higher frequencies the conductivity rises and the increase in conductivity is generally greatest for the most poorly conducting samples. The results of his laboratory measurements on soil samples taken from various parts of England are illustrated in Table 18 and profiles of conductivity with depth

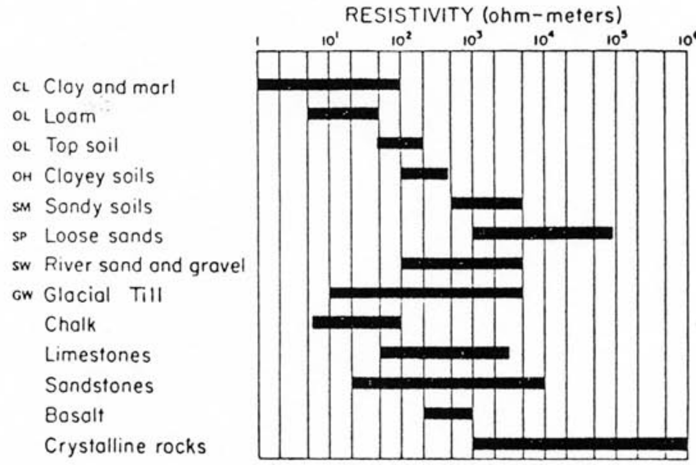
TABLE 14. Resistivities of igneous and metamorphic rocks (after W. M. Telford et al. [22])

Rock type	Resistivity range (Ωm)
Granite	3×10^2–10^6
Granite porphyry	4.5×10^3 (wet)–1.3×10^6 (dry)
Feldspar porphyry	4×10^3 (wet)
Albite	3×10^2 (wet)–3.3×10^3 (dry)
Syenite	10^2–10^6
Diorite	10^4–10^5
Diorite porphyry	1.9×10^3 (wet)–2.8×10^4 (dry)
Porphyrite	10–5×10^4 (wet)–3.3×10^3 (dry)
Carbonatized porphyry	2.5×10^3 (wet)–6×10^4 (dry)
Quartz porphyry	3×10^2–9×10^5
Quartz diorite	2×10^4–2×10^6 (wet)–1.8×10^6 (dry)
Porphyry (various)	60–10^4
Dacite	2×10^4 (wet)
Andesite	4.5×10^4 (wet)–1.7×10^2 (dry)
Diabase porphyry	10^3 (wet)–1.7×10^5 (dry)
Diabase (various)	20–5×10^7
Lavas	10^2–5×10^4
Gabbro	10^3–10^6
Basalt	10–1.3×10^7 (dry)
Olivine norite	10^3–6×10^4 (wet)
Peridotite	3×10^3 (wet)–6.5×10^3 (dry)
Hornfels	8×10^3 (wet)–6×10^7 (dry)
Schists (calcareous and mica)	20–10^4
Tuffs	2×10^3 (wet)–10^5 (dry)
Graphite schist	10–10^2
Slates (various)	6×10^2–4×10^7
Gneiss (various)	6.8×10^4 (wet)–3×10^6 (dry)
Marble	10^2–2.5×10^8 (dry)
Skarn	2.5×10^2 (wet)–2.5×10^8 (dry)
Quartzites (various)	10–2×10^8

TABLE 15. Resistivities of sediments (after W. M. Telford et al. [22])

Rock type	Resistivity range (Ωm)
Consolidated shales	$20\text{–}2 \times 10^3$
Argillites	$10\text{–}8 \times 10^2$
Conglomerates	$2 \times 10^3\text{–}10^4$
Sandstones	$1\text{–}6.4 \times 10^8$
Limestones	$50\text{–}10^7$
Dolomite	$3.5 \times 10^2\text{–}5 \times 10^3$
Unconsolidated wet clay	20
Marls	3–70
Clays	1–100
Alluvium and sands	10–800
Oil sands	4–800

TABLE 16. Resistivity ranges for various terrain materials (after Culley et al. [23])

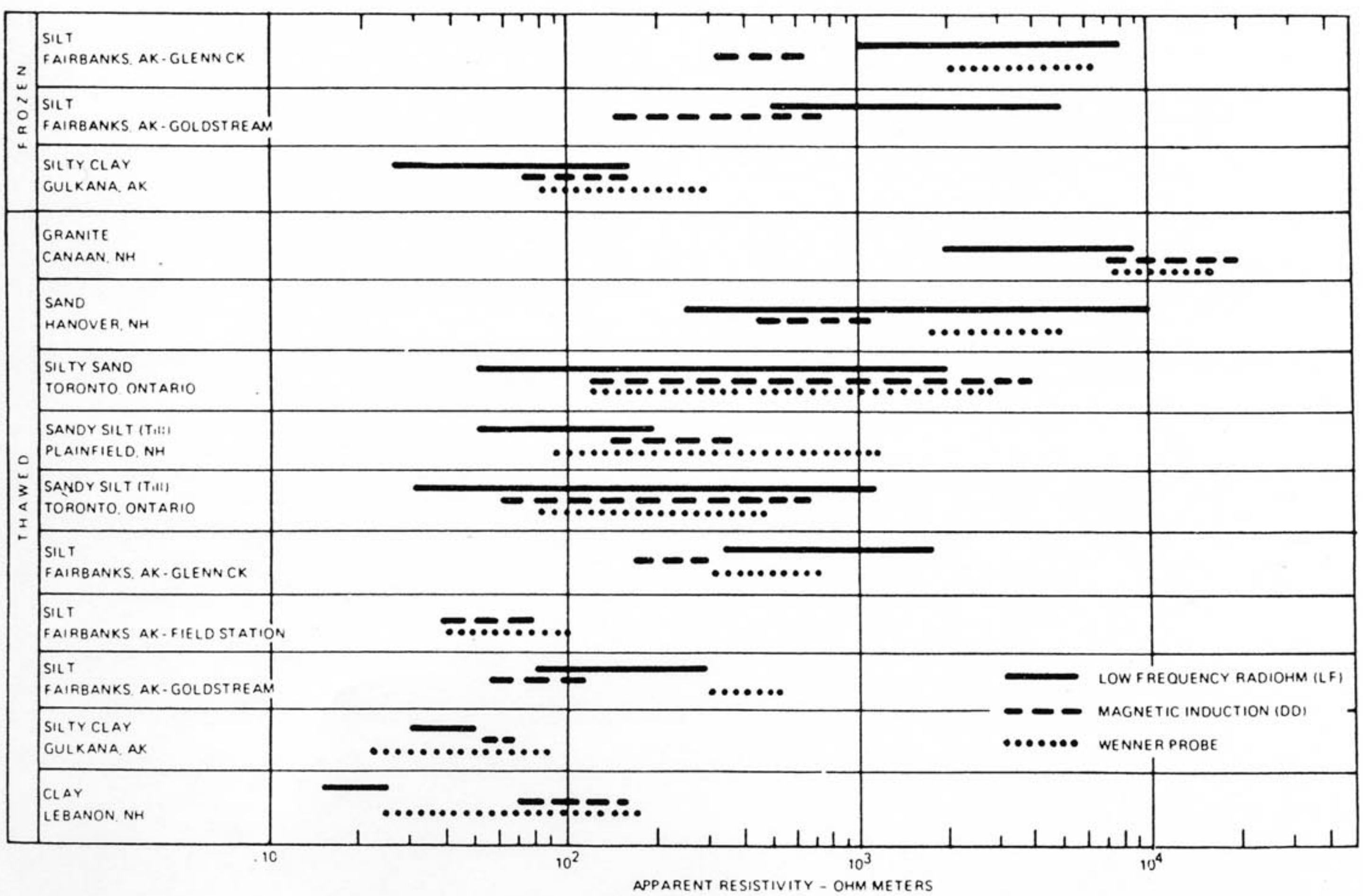


from these measurements are shown in Figure 12. It is seen from Table 18 that the soil type varies rapidly with depth, as does the soil moisture content; both of these influence the conductivity profiles. Smith-Rose concludes that clays have the highest conductivities, greater than 10 millimhos per meter, loams and chalks are of the order or 10 millimhos per meter and sandy or gritty soils are appreciably less. He also points out that a diurnal temperature range of 20°C at the surface of the soil represents a temperature change of approximately 1.4°C at a depth of one foot. Measurements made on a soil sample at 1.2 MHz as a function of moisture content by weight show a conductivity that increases approximately as the square of the moisture content.

V. 2. Tropical Humid Zones [26]

The examples given above have been taken from temperate zone soils and seem to be fairly representative. In the case of soils occurring in tropical humid climates (annual temperatures of the order of 25°C; annual precipitation of greater than a meter, generally falling during a part of the year) the weathering can be very deep. Indeed, unweathered parent rock may not occur until 30 meters in flat country, 60 meters in hilly country and in rare occasions depths

TABLE 17. Apparent resistivity data obtained for various material types using three measuring techniques (after Sellman et al. [24])



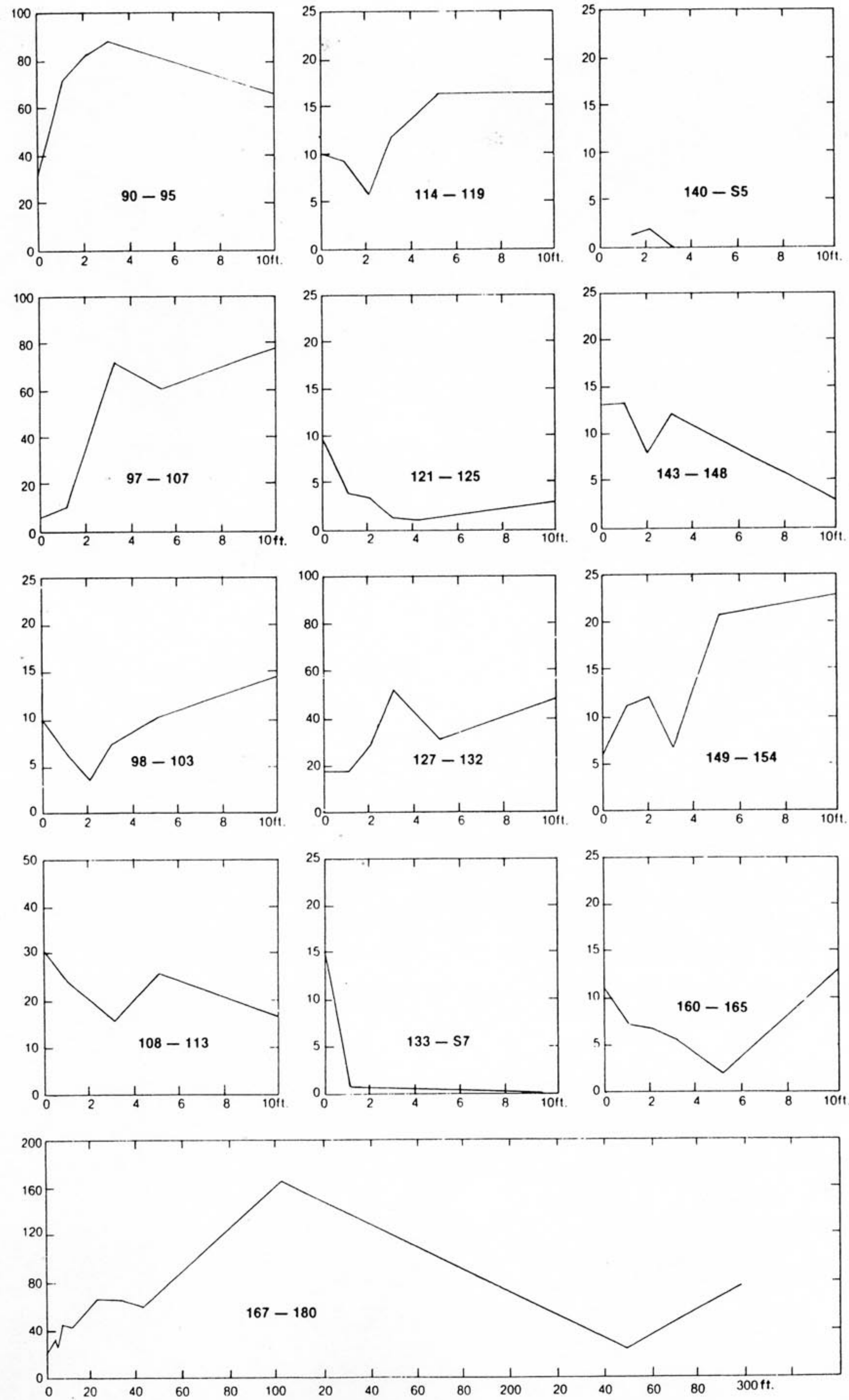


FIGURE 12. Plots of conductivity (mmhos/m) versus depth (feet) for data in Table 18.

TABLE 18. Measurements of samples of soil taken from different depths at various sites (after R. L. Smith-Rose [25])

Sample No.	Site	Geological classification	Depth	Description of sample	Moisture content	Conductivity at 20°C Millimho/m	
						1 kHz	100 kHz
			ft.		per cent		
90	Rugby Radio	Lower lias	Surface	Dark fibrous loam	60	33	38
92	Station (1)		1	Loam and clay	33	72	78
93			2	Clay and sand	26	83	89
94			3	Blue clay	25	89	100
95			10	Blue clay	23	67	72
97	Rugby Radio	Lower lias	Surface	Loam	22	6.1	7.2
104	Station (2)		1	Loam and clay	13	9.4	9.4
105			3	Blue clay	27	72	83
106			5	Clay and sand	21	61	61
107			10	Blue clay	25	78	89
98	Baldock, Herts	Chalk	Surface	Fibrous loam	21	9.4	10.0
99	(P.O. Receiving Station)		1	Chalky loam	21	6.1	6.1
100			2	Chalk	24	8.1	2.9
101			3	Chalk	27	7.2	7.8
102			5	Chalk	26	10.1	15.6
103			10	Chalk	27	14.4	15.6
108	Tatsfield, Kent	Upper	Surface	Fibrous loam	37	30	38
109	(B.B.C. Receiving Station)	greensand	1	Brown, sandy clay	11	24	27
110			2	Brown sand	15	20	22
111			3	Light brown sand	13	15.6	10.7
112			5	Light brown sand	20	26	26
113			10	Yellow sand	15	16.7	19
114	Brookmans Park, Herts	London	Surface	Fibrous loam	19	10.0	10.6
115	(London Regional Station)	clay	1	Stony loam	18	9.4	10.0
116			2	Light sandy clay	22	5.6	7.2
117			3	Sandy clay	22	12.2	13.3
118			5	Sandy clay	21	16.7	18.8
119			8 to 10	Clay and shingle	10	16.7	17.8
121	Daventry	Upper lias	Surface	Fibrous loam	28	9.4	10.6
122	Northants		1	Sandy loam	16	3.8	3.8
123			2	Brown sand	14	3.2	3.2
124			3	Brown sand	5.0	1.1	1.2
126			5	Sand and sandstone	8.5	0.8	1.0
125			10	Sand and sandstone	24	2.9	3.7
127	Washford Cross, Somerset	Red Marls	Surface	Reddish-brown loam	23	16.7	18.9
128	(West Regional Station)		1	Reddish-brown clay	20	16.7	18.9
130			2	Reddish-brown clay	18	28.9	31
129			3	Reddish-brown clay	21	52	54
131			5	Reddish-brown clay	19	31	34
132			10	Reddish-brown clay	15	48	50
133	Brendon Hills, Somerset	Devonian	Surface	Black fibrous loam	210	14.4	16.7
134			1	Loam and slate	9.0	0.3	0.3
135			2	Loam and slate	9.0	0.2	0.2
136			3	Loam and slate	8.0	0.1	0.1
137			5	Loam and slate	5.5	0.0	0.0
S.7			10	Slate	—	0.0	0.0
140	Merrivale, Dartmoor, Devon	Granite	1	Gritty loam	18	1.3	1.3
141			2	Gritty loam	13	1.6	1.6
S.1			3 to 10	Granite	—	0.0	0.1
S.2			3 to 10	Granite	—	0.0	0.1
S.5			3 to 10	Granite	—	0.0	0.0
139	Dousland, Dartmoor, Devon	Devonian	Surface	Loam	47	6.1	6.7
142			1	Dark brown loam	41	2.7	2.7
S.4			Below 1	Slate	—	0.0	0.0
S.6			Below 1	Granite	—	0.0	0.0
143	Moorside, Edge, Yorks	Millstone grit	Surface	Fibrous loam	130	13.3	17.8
144	(North Regional Station)		1	Dark grey clay	60	13.3	15.6
145			2	Dark grey clay	35	7.8	10.6
146			3	Dark grey clay	39	12.2	16.7
147			5	Dark grey clay	19	9.4	11.1
148			10	Yellow and grey clay	15	3.4	3.7
149	Westerglen, Falkirk	Boulder	Surface	Fibrous loam	38	6.1	7.2
150	(Scottish Regional Station)	clay	1	Fibrous loam	30	11.1	11.1
151			2	Clay and loam	19	12.2	12.2
152			3	Dark grit and clay	18	6.7	7.8
153			5	Dark grit and clay	18	21	24
154			10	Dark grit and clay	15	23	26

(continued over)

TABLE 18. (*concluded*)

Sample No.	Site	Geological classification	Depth	Description of sample	Moisture content	Conductivity at 20°C Millimho/m 1 kHz	100 kHz
			ft.		per cent		
160	Teddington, Middlesex	London	Surface	Fibrous loam	26	11.1	12.2
161	(N.P.L.)	clay	1	Sandy loam	20	7.2	7.8
162			2	Sandy loam	13	6.7	7.2
163			3	Fine gravel	6.5	5.6	6.7
164			5	Coarse gravel	2.9	1.9	2.0
166			7	Fine sand	2.6	1.6	1.6
165			10	Sand and shingle	20	13.3	15.6
167	Wychbold, Droitwich	Red Marls	1	Red clay and loam	15	16.7	20
168	(Midland Regional Station)		2	Red clay	13	34	32
169			3	Red clay	14	23	24
170			5	Red clay and stones	15	43	51
171			10	Red clay and stones	21	41	44
172			20	Red clay suspension	31	67	78
173			30	Red clay suspension	41	67	78
174			40	Red clay suspension	25	61	72
175			50	Red clay	27	78	83
176			100	Grey clay and salt	28	177	233
177			150	Red clay and salt	27	—	—
178			200	Red clay and salt	24	—	—
179			250	Red clay and salt	22	24	26
180			300	Red clay and salt	31	73	89

of 250 meters have been observed. The resulting soils are red to yellow, soft with a high clay content, and with a specific gravity approximately one-half of that of the parent rock. Compared with the soils of temperate climates they are thick, humus poor, permeable, and have a high clay-silt ratio. Although the clay content is high this is somewhat compensated for by the fact that in well drained soils the clays are kaolinitic and the cation exchange capacity is less than in temperate zones (see Table 11). Iron-rich concretionary horizons called laterites form as a result of reprecipitation. These are hard, permeable, and if dry are usually very resistive.

The nature and the extent of the soil formation is a function of the rock type, texture, jointing, surface relief, vegetation, water-table, and micro-climate. For example, the relative absence of silt is due to the fact that fine-grained rocks weather faster than coarse-grained rocks; the abundance of clay results from the fact that it is a stable mineral.

An excellent series of measurements of the electrical properties of the weathered zones in tropical climates has been carried out by Palacky and Kadekaru in Brazil [27]. The measurements were done with conventional resistivity techniques and many soundings were taken. The results gave good agreement with a three-layered earth model and are summarized in Table 19. In general a resistive soil, relatively thin, is situated on top of a thick quite conductive weathered zone, in turn situated on the relatively resistive parent rock.

V. 3. Tropical Arid Zones

It is in tropical arid zones that the most conductive soils are encountered. As for humid zones the weathered layer can be many tens of meters in thickness, however in arid climates this material often contains a high salt concentration due to evaporation. Whereas the surface materials are usually dry, possibly lateritic, and resistive, deeper material may approach resistivities of the order of 1 ohm-meter. Furthermore substantial lateral variations of resistivity are not uncommon.

In the humid tropical zones referred to above the conductivity of the intermediate zone was due to the presence of an abundance of colloidal particles with moderate ion exchange capacities: abundant rainfall means that drainage patterns are well established and soil salts have long since been leached into major river channels and

TABLE 19. Tropical resistivity profiles (after Palacky and Kadekaru [27])

	Site	Soil Thickness (meters)	Soil Resistivity (ohm-meters)	Weathered Zone Thickness (meters)	Weathered Zone Resistivity (ohm-meters)	Bedrock Type	Bedrock Resistivity (ohm-meters)
Humid Tropical	Nova Lima	5–10	2000–15000	20–80	50–100	schists	∞
					200–400	granodiorite	∞
	Canabrava	5	90	3–18	15–27	basic	∞
		5	360	12–30	3–12	ultrabasic	∞
	Santa Fé	3	11000–18000	35	80–100	dunite	∞
	Quatipuro	0–1	200	15–35	10–30	phyllites	∞
			300–700	3–8	35–20	serpentinites	> 300
Arid Tropical	Santa Luz	–		3.5	65	granite	910
		1	120	10–20	13	basic volcanic	∞
	Curaça	–		6–10	20–35	amphibolites	1200
				15–20	80–130	gneiss	2000

TABLE 20. Diagnostic criteria for distinguishing between unaffected soil sites and encroaching and developed saline seeps (after Rhoades and Halvorson [28])

Site type	Salt content	Water content	Soil electrical conductivity
Unaffected	Low, increasing with depth	Low, increasing with depth	Low, increasing with depth
Encroaching saline seep	Low, increasing to a peak at a relatively shallow depth, then decreasing with further depth	Moist surface, becoming wet with depth	Intermediate, increasing to a peak at a relatively shallow depth, then decreasing with further depth
Developed saline seep	High, decreasing with depth	Relatively uniformly wet to the water table	High, decreasing with depth

thence into the oceans. In hot arid climates drainage patterns are poorly established and drainage basins may have no outlet to permanent streams. Salt-bearing waters drain from topographically high regions into lower areas where the water evaporates, leaving a high residual salt content, largely a reflection of the imperfect drainage channels.

The occasional addition of water might be due either to precipitation or irrigation. In the cultivated dry land soils of the northern Great Plains the near surface (plant root-zone) is leached with essentially pure water derived from rain and snow melt during the wet months. Rhoades and Halvorson [28] discuss how this results in a soil salinity concentration which increases with depth. However during the summer months when a saline water table in this climate is situated within approximately one meter from the surface an upwards flow of moisture is caused by evaporation at the soil surface and transpiration within the root zone. This upwards flow reverses the original leaching which transported salts downwards and causes them to ascend so that a concentration peak can form in the soil salinity profile. The soils can remain excessively wet as a result of the hygroscopic nature of the salts and because the salts reduce the effective use of water by plants via evapo-transpiration. Rhoades defines such a condition as a "saline seep" and notes that it can form without the water table actually emerging at the surface. As this seep develops the peak in the soil salinity profile moves upwards until it finally appears at or near the surface as indicated in Table 20 which illustrates the various conditions that can exist in a region which sees seasonal precipitation followed by seasonal drought. Figure 13 illustrates vertical profiles of resistivity versus depth as determined by an expanding Wenner array for the three conditions described in Table 20.

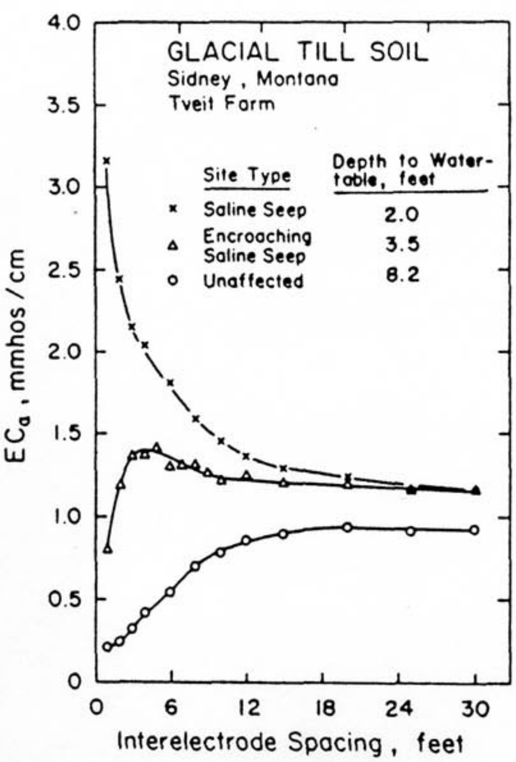


FIGURE 13. Relation between soil electrical conductivity, EC_a, and interelectrode spacing for a saline seep, an encroaching saline-seep site, and an unaffected site for glacial till-clay loam soil near Sidney, Montana (after Rhoades and Halvorson [28]).

For saline soils, the contribution to conductivity from salt concentration generally outweighs that from cation exchange capacity and the conductivity is relatively independent of clay content.

The effect of weathered-zone salinity is probably at its worst in western Australia where the zone is often 100 meters in thickness and has been known to exceed 300 meters. Hygroscopic salts maintain soil moisture at levels substantially above the water table and resistivities of the order of 1 ohm-meter have been observed. Large lateral variations result from the imperfect drainage patterns; slight changes in surface topography often show up as large changes in subsurface conductivity. A lateritic hard pan is not unusual on the surface. This layer is extremely resistive and completes the complexity and difficulty of making conventional electrical measurements in this environment.

V. 4. Arctic Zones

Finally we turn our attention to arctic regions in which permafrost is a major consideration. It should be noted that the definition of permafrost requires only that the mean annual temperature of the ground be less than 0°C for several years; the definition is completely independent of the nature of the material, the amount of moisture, and indeed whether or not the moisture is frozen. In

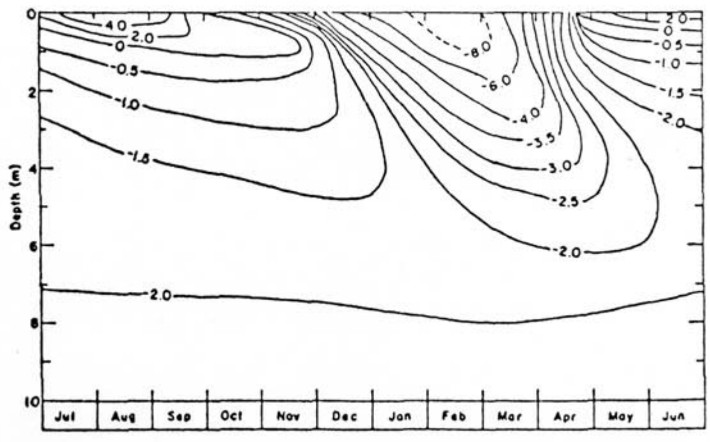


FIGURE 14. Vertical and temporal temperature variations – contoured in °C (after Arcone et al [29]).

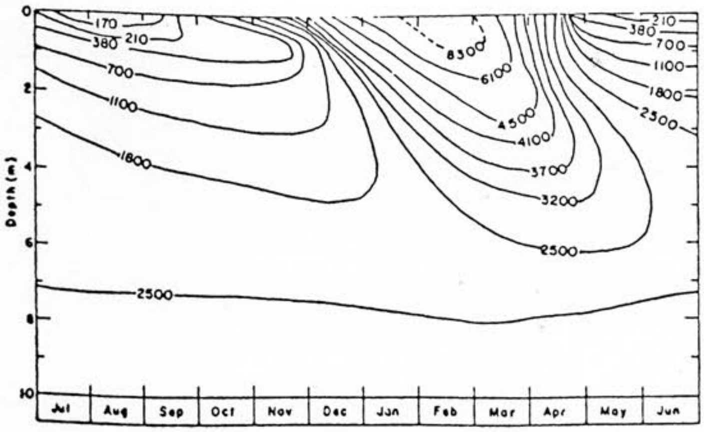


FIGURE 15. Computed vertical and temporal resistivity variations from data of Figure 14 – contoured in ohm-meters (after Arcone et al [29]).

northern climates we find that mineralogy, porosity, free water content, and ionic concentration within the free water are important resistivity factors as they are for temperate zones. In permafrost regions we have the additional complexity that small changes in temperature of the ground near 0°C may exert a large influence on terrain conductivity. The effect depends on the nature of the material and also the moisture content since as we have seen earlier even at temperatures substantially below 0°C considerable moisture may remain unfrozen in the case of clays whereas in the case of coarser material virtually all will be frozen. In short, ice content is a complicated function of many variables.

As an example of electrical layering arising due to temperature only consider Figure 14 which illustrates annual variations in ground temperature recorded near Fairbanks, Alaska. The region is in a discontinuous permafrost zone and subsurface material consists primarily of perennially frozen organic silt containing a varying amount of ground ice. From laboratory measurements on saturated organic silt to determine the variation of electrical resistivity with temperature, a plot of electrical resistivity with depth and time was derived [23] and is shown in Figure 15. We see from this figure that a resistivity range of 50 to 1 can occur as a result of temperature changes alone.

In the discontinuous zone of permafrost subsurface temperatures are subtly influenced by many variables and even in ground which is

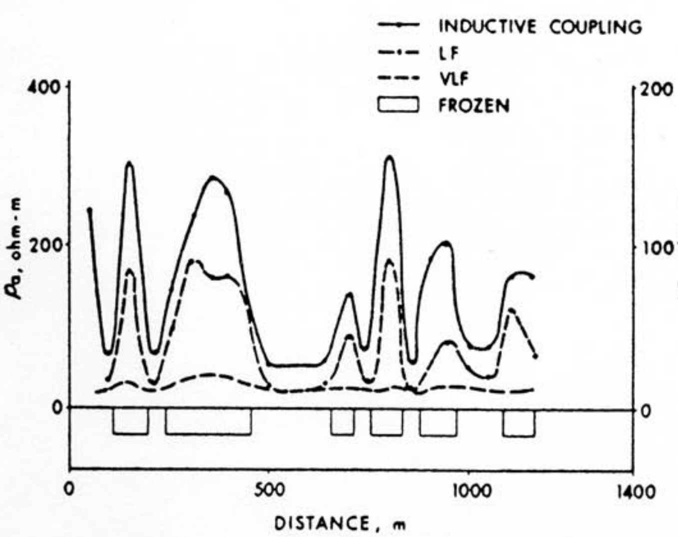


FIGURE 16. Results of the apparent resistivity measured with VLF (18.6 kHz), LF (375 kHz) radiohm and a magnetic induction instrument (EM31) over a section of shallow discontinuous permafrost (after P. Hoekstra [30]).

laterally uniform insofar as material type is concerned lateral temperature variations can bring about large changes in electrical resistivity as shown in Figure 16 where the survey traverse was taken over glacial lake basin sediments. The frozen areas outlined on the figure were derived from resistivity measurements and confirmed by drilling [24].

VI. SUMMARY

In this technical note we have discussed the concept of terrain conductivity, examined some of the properties of soils and rocks that affect their conductivity, and reviewed some measurements on typical terrain materials under a variety of climatic conditions.

To summarize, terrain conductivity is usually determined by one or more of the following parameters:

(1) clay content, clay type
(2) moisture profile with depth
(3) moisture salinity
(4) moisture temperature

Of these the most complex is usually the moisture profile, by which is meant the way in which (i) the porosity, (ii) the extent to which the pores are filled with water, and, (iii) the number, size and shape of interconnecting passages all vary with depth. The moisture profile is affected by material type (directly influencing porosity etc., or indirectly influencing permeability and water table location), topography (influencing the water table location), compaction (influencing porosity), and season (rates of precipitation, evaporation).

It is evident that many parameters may affect the ground conductivity. Fortunately at any given location relatively few are usually dominant however the survey interpreter should be aware of the possible alternatives. It is hoped that this brief treatment will be useful in assessing those parameters that are influential in the survey area and will thereby lead to a more accurate interpretation of survey data.

The bibliography gives a good indication of current interest in the electrical properties of rocks and soils and the curious reader will find much valuable material in the cited references.

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Technical Note TN-6

ELECTROMAGNETIC TERRAIN CONDUCTIVITY MEASUREMENT at LOW INDUCTION NUMBERS

JD McNEILL

October, 1980

Table of Contents

I. INTRODUCTION

The measurement of terrain resistivity to map geology has been utilized for over half a century. Several shortcomings, however, have prevented this technique from being widely accepted for engineering purposes. The first of these is that conventional galvanic resistivity surveys require a relatively large amount of manpower to execute and are thus expensive. Secondly, the actual value of resistivity itself is seldom diagnostic; it is the lateral or vertical variations of resistivity which form the basis of any interpretation. However the high cost of resistivity surveying generally means that fewer measurements are made than would be desirable, with the result that either (i) the survey area is not made large enough to establish a reasonable background against which the anomalous areas are to be delineated or (ii) the anomalous area itself is obscure and lacks definition.

An additional problem inherent to conventional resistivity techniques is that although the effective depth of exploration is determined by the selected inter-electrode spacing, resistive inhomogeneities which are small compared to this depth but which are located near the potential electrodes can cause a significant error in the measurement. Such fluctuations in the measured results are truly geological "noise" because it is not possible to determine the physical size, resistivity contrast, or location of the source. As a result of such inhomogeneities resistivity profiles carried out at constant interelectrode spacing tend to be noisy, limiting the resolution in resistivity that can be achieved, even though the instrumentation itself is capable of producing much higher accuracy.

It was an awareness of both the advantages of resistivity for engineering geophysical surveys and the disadvantages of conventional resistivity techniques that led Geonics Limited to examine the possibility of employing electromagnetic (inductive) techniques as an alternative for resistivity surveys. With the development of the EM31 and the EM34-3 it is now possible to map terrain conductivity virtually as fast as the operator(s) can walk; furthermore the sample volume is averaged in such a manner as to yield unexcelled resolution in conductivity.

These patented instruments have been designed to cover the range of depths generally useful for engineering geophysics; the EM31, one-man portable, has an effective depth of approximately 6 meters and the EM34-3, two-man portable, has stepwise selectable depths from 7.5 meters to a maximum of 60 meters.

Typical applications for the EM31 and EM34-3 instrumentation are:

(i) Delineating regions of permafrost (frozen pore water)
(ii) Locating gravel
(iii) Extending known gravel deposits
(iv) Mapping saline intrusions
(v) Detecting cavities in carbonate rocks
(vi) Mapping pollution plumes in groundwater
(vii) Mapped bedrock topography
(viii) Mapping terrain conductivity for electrical grounding
(ix) General geological mapping (soil types, fault and fracture zones, etc.)
(x) Archaeological exploration
(xi) Locating pipes (EM31) and metallic-type conductors

This technical note describes both the principles and the instrumentation employed to measure terrain conductivity using electromagnetic techniques at low induction numbers. For a detailed discussion of the concept of terrain resistivity/conductivity and of the various factors that control this parameter the reader is referred to Geonics Limited Technical Note "Electrical Conductivity of Soils and Rocks".

II. PRINCIPLE OF OPERATION

The application of electromagnetic techniques to the measurement of terrain resistivity, or more properly, conductivity* is not new and excellent descriptions of this technique are given in the literature [1], [2].

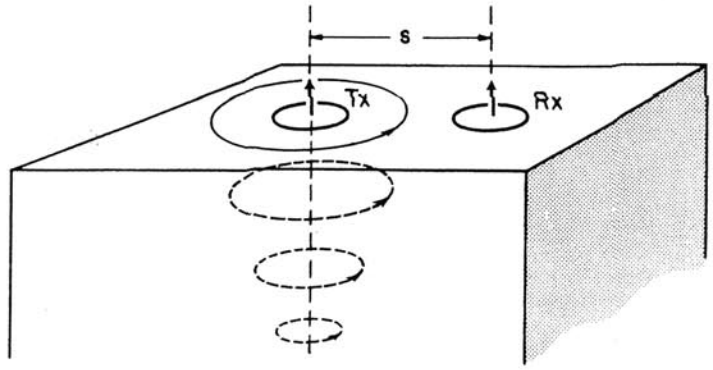


FIGURE 1. Induced current flow (homogeneous halfspace).

Consider Figure 1 in which a transmitter coil Tx energized with an alternating current at an audio frequency, is placed on the earth (assumed uniform) and a receiver coil Rx is located a short distance s away. The time-varying magnetic field arising from the alternating current in the transmitter coil induces very small currents in the earth. These currents generate a secondary magnetic field H_s which is sensed, together with the primary field, H_p, by the receiver coil.

In general this secondary magnetic field is a complicated function of the intercoil spacing s, the operating frequency, f, and the ground conductivity σ. Under certain constraints, technically defined as "operation at low values of induction number" (and discussed in detail in the appendix) the secondary magnetic field is a very simple function of these variables. These constraints are incorporated in the design of the EM31 and EM34-3 whence the secondary magnetic field is shown to be:

$$\frac{H_s}{H_p} \simeq \frac{i\omega\mu_o\sigma s^2}{4} \quad (1)$$

where H_s = secondary magnetic field at the receiver coil
H_p = primary magnetic field at the receiver coil
$\omega = 2\pi f$
f = frequency (Hz)
μ_o = permeability of free space
σ = ground conductivity (mho/m)
s = intercoil spacing (m)
$i = \sqrt{-1}$

The ratio of the secondary to the primary magnetic field is now linearly proportional to the terrain conductivity, a fact which makes it possible to construct a direct-reading, linear terrain conductivity meter by simply measuring this ratio. Given H_s/H_p the apparent conductivity indicated by the instrument is defined from equation (1) as

$$\sigma_a = \frac{4}{\omega\mu_o s^2}\left(\frac{H_s}{H_p}\right) \quad (2)$$

The MKS units of conductivity are the mho (Siemen) per meter or, more conveniently, the millimho per meter.

III. INSTRUMENTATION

The EM31 (shown in Figure 2) has an intercoil spacing of 3.7 meters, which yields an effective depth of exploration of about 6 meters. The instrument can also be operated on its side, in which

*Conductivity is preferred with inductive techniques since the response is generally proportional to conductivity and inversely proportional to resistivity.

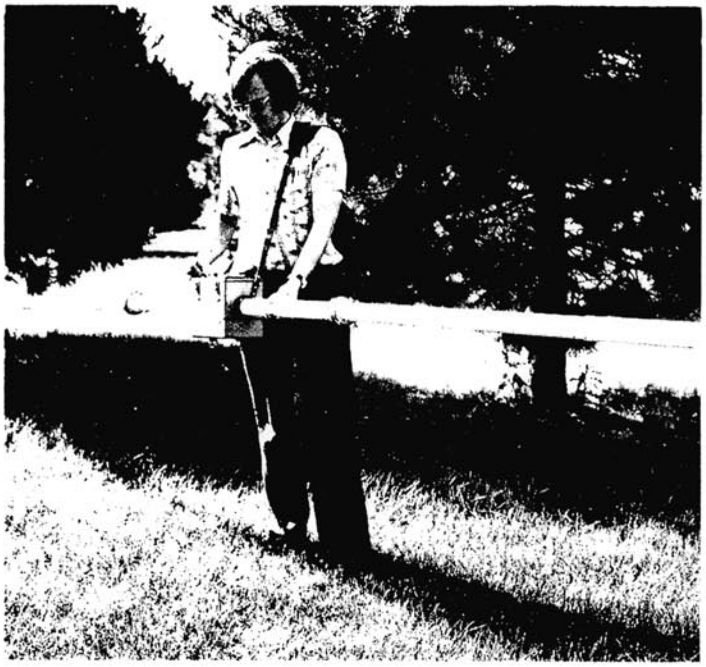


FIGURE 2. EM31 in field operation.

case as will be seen in Section IV., the effective depth of exploration is reduced to approximately 3 meters. The instrument is one-man portable and can be used either in "station-by-station" mode or read continuously. The presence of layering in the earth can be detected by raising the instrument and noting the readings as a function of instrument height. If the earth is two-layered the conductivity of both layers and the upper layer thickness can be resolved.

The EM34-3 which is two-man portable has the two coils flexibly connected (Figure 3). The intercoil spacing is measured electronically so that the receiver operator simply reads a meter to accurately set the coils to the correct spacing, which can be 10, 20, or 40 meters so as to directly vary the effective depth of exploration as shown in Table 1.

FIGURE 3. EM34-3 in field operation.

TABLE 1. Exploration depths for EM34-3 at various intercoil spacings

Intercoil Spacing (meters)	Exploration Depth (meters)	
	Horizontal Dipoles	Vertical Dipoles
10	7.5	15
20	15	30
40	30	60

To measure terrain conductivity the transmitter operator stops at the measurement station; the receiver operator moves the receiver coil backwards or forwards until his meter indicates correct intercoil spacing and he reads the terrain conductivity from a second meter. The procedure takes 10 to 20 seconds. The coils are normally carried with their planes vertical (horizontal dipole mode) since in this configuration the measurement is relatively insensitive to misalignment of the coils. In the event that the greater depth of penetration resulting when the two coils are in the vertical dipole mode is desired, more care must be taken with intercoil alignment. Because of the relatively short intercoil spacing correct alignment is usually not difficult to achieve.

Both instruments are calibrated to read terrain conductivity in millimhos per meter. To convert these readings to resistivity (in ohmmeters) one simply divides them into 1,000, i.e. 50 millimhos per meter is the equivalent of 20 ohmmeters.

IV. SURVEY TECHNIQUES AND INTERPRETATION

For either the EM31 or EM34-3 it can be shown that in a homogeneous or horizontally stratified earth the current flow is entirely horizontal. Furthermore under the constraints by which the instruments are designed the current flow at any point in the ground is independent of the current flow at any other point since the magnetic coupling between all current loops is negligible. Finally, under these constraints the depth of penetration is limited only by the intercoil spacing. We say that the depth of penetration is "source" or "geometry" limited rather than "skin depth" limited since it is now controlled by the fall-off with distance of the dipolar transmitter field. For this reason all dimensions are normalized with respect to the intercoil spacing in subsequent sections of this technical note.

IV. 1. Instrumental Response as a Function of Depth (Homogeneous Halfspace)

Consider a homogeneous halfspace on the surface of which is located an EM31 or an EM34-3 transmitter as shown in Figure 4. Fixing our attention on a thin layer of thickness dz at depth z (where z is the depth divided by the intercoil spacing s) it is possible to calculate the secondary magnetic field in the receiver coil arising from all of the current flow within this or any other horizontal thin layer. One can thus construct the function $\phi_V(z)$ shown in Figure 4 which describes the relative contribution to the secondary magnetic field arising from a thin layer at any depth z. We see from this figure that material located at a depth of approximately 0.4 s gives maximum contribution to the secondary magnetic field but that material at a depth of 1.5 s still contributes significantly. It is interesting to note that the ground at zero depth, i.e. the near surface material,

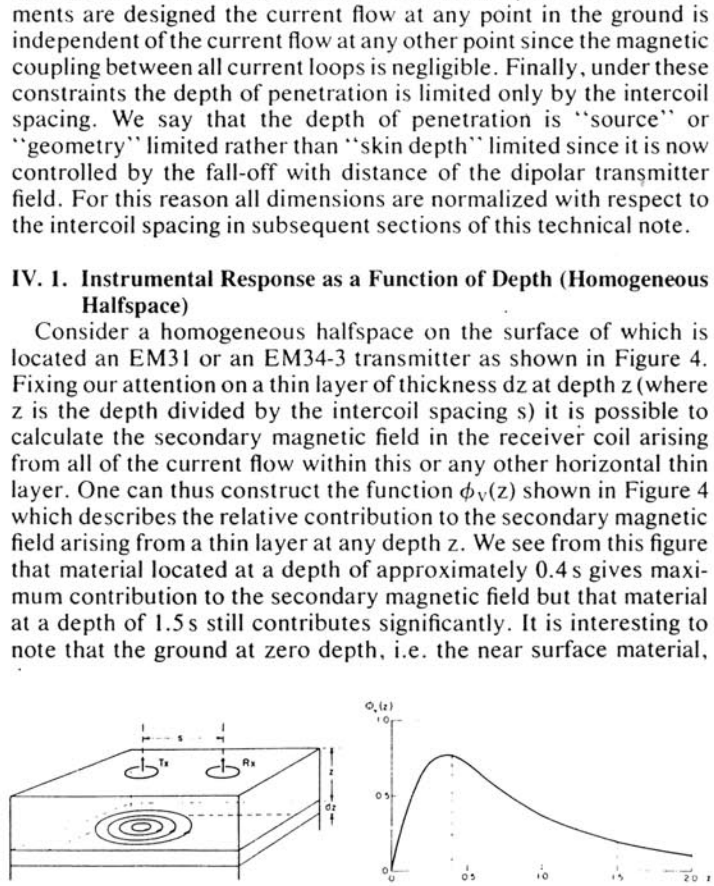


FIGURE 4. Relative response versus depth for vertical dipoles. $\phi_V(z)$ is the relative contribution to H_s from material in a thin layer dz located at (normalized) depth z.

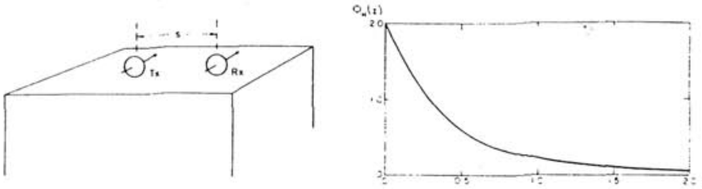


FIGURE 5. Relative response versus depth for horizontal dipoles

makes a very small contribution to the secondary magnetic field and therefore this coil configuration is insensitive to changes in near surface conductivity.

Figure 5 illustrates the function of Figure 4 for the case of both transmitter and receiver dipoles horizontal coplanar rather than vertical coplanar. For the coil configuration of Figure 5 (commonly used for the EM34-3 since it is less critical to intercoil alignment) the relative contribution from material near-surface is large and the response falls off monotonically with depth.

A comparison of the function ϕ for both coil configurations in Figure 6 emphasizes the different manner in which they respond to material at different depths. The difference is important since either instrument can be rolled over so that the vertical dipole transmitter/receiver geometry becomes a horizontal dipole transmitter/receiver geometry and vice versa. As will be seen later, this feature is useful in diagnosing and defining a layered earth. The figure also shows that for regions greater than one intercoil spacing in depth the vertical transmitter/receiver dipole gives approximately twice the relative contribution of the horizontal transmitter/receiver dipole.

To summarize, with either horizontal or vertical transmitter/receiver dipole orientation it is possible to construct a function which gives the relative response to the secondary magnetic field at the receiver from a thin layer of ground at any depth. That this is possible arises from the fact that (i) all current flow is horizontal and (ii) all current loops are independent of all other current loops. It should be noted that it is not possible to construct such functions for conventional resistivity techniques.

Finally, since as shown in Section II the definition of apparent conductivity is given in terms of the secondary magnetic field at the receiver, the functions in Figure 6 also give the relative contribution from material at different depths to the *apparent conductivity* indicated by the instrument meter. The integral of either function from zero to infinity gives the total secondary magnetic field at the receiver coil from a homogeneous halfspace which is directly related to the electrical conductivity of the halfspace by equation (1). It is therefore possible to state with great precision the relative influence of material at different depths to the indicated apparent conductivity.

IV. 2. Multi-Layered Earth Response

The functions shown in Figure 6 are useful for describing the relative sensitivity of either of the two coil configurations to material at various depths. However a function derived from them is more useful for performing calculations. It is defined as the relative contribution to the secondary magnetic field or apparent conductivity from all material below a depth z and is given by

$$R_{\substack{V\\H}}(z) = \int_z^{\infty} \phi_{\substack{V\\H}}(z)dz \qquad (3)$$

Called the cumulative response, this function is illustrated in Figure 7 for vertical coplanar transmitter/receiver dipoles. The figure shows, for example, that for this configuration all material below a depth of two intercoil spacings yields a relative contribution of approximately 0.25 (i.e. 25%) to the secondary magnetic field at the receiver coil.

Suppose now that our homogeneous halfspace has a conductivity of 20 millimhos per meter (50 ohmmeters). The equipment having been calibrated according to equation (2), the output meter indicates 20 millimhos per meter. From Figure 7 we observed that the material below two intercoil spacings contributed 25% to the secondary magnetic field and therefore 25% to the indicated meter reading. Suppose that we replace this deep material with an infinitely resistive (zero conductivity) substance. Since we have reduced to zero the 25% that this material contributed to the meter reading the new reading will be 75% of 20, or 15 millimhos per meter. Conversely, if we leave all of the material below two intercoil spacings at 20

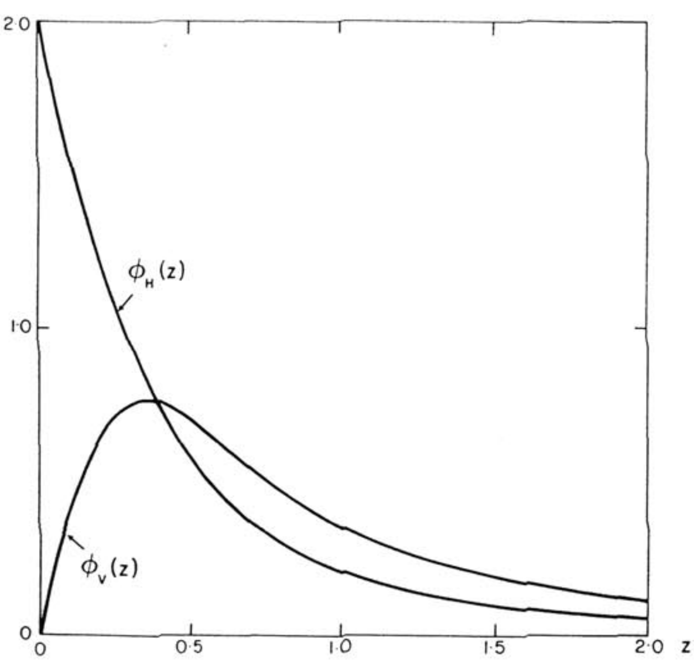


FIGURE 6. Comparison of relative responses for vertical and horizontal dipoles.

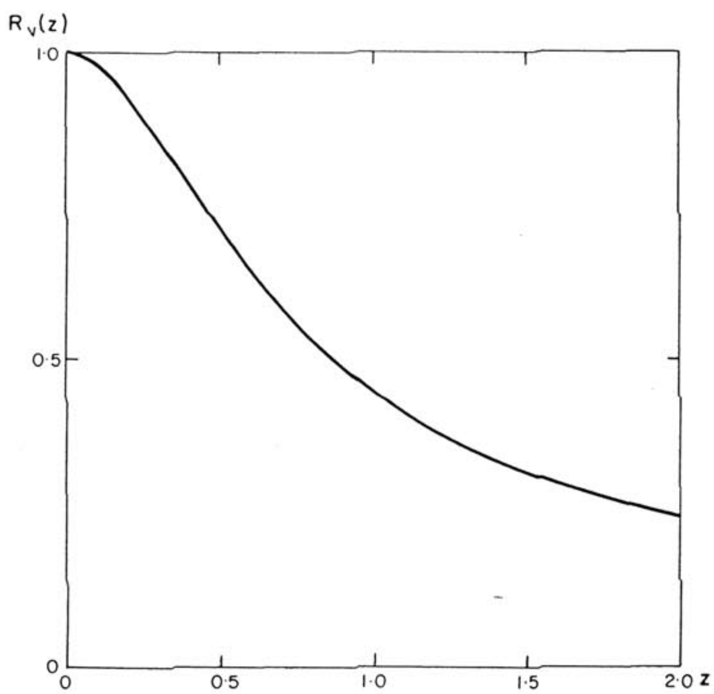


FIGURE 7. Cumulative response versus depth for vertical dipoles. $R_V(z)$ is the relative contribution to H_s from all material below a (normalized) depth z.

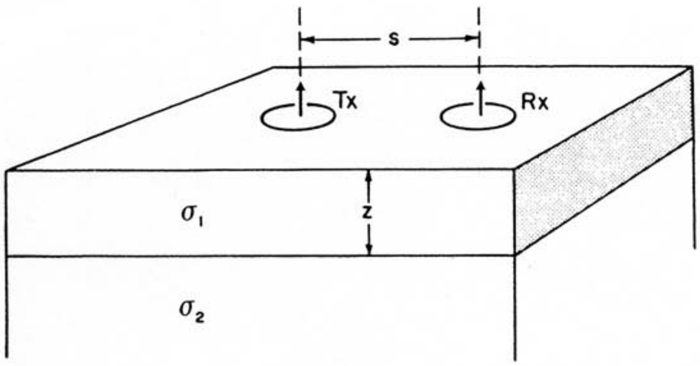


FIGURE 8. Two layer earth model.

millimhos per meter but make all material above two intercoil spacings infinitely resistive the meter reading will fall from the original 20 millimhos per meter for the homogeneous half space to 5 millimhos per meter, since, if all of the material below two intercoil spacings contributed 25% of the meter reading, all of the material above two intercoil spacings must contribute 75%; when removed the meter reading becomes 0.25×20 or 5 millimhos per meter.

From this example we see that there is a simple way to calculate the instrument reading on an arbitrarily layered earth as long as the intercoil spacing is much less than the skin depth in all of the layers. We simply add the contribution from each layer independently, weighted according to its conductivity and depth according to Figure 7. For example assume that we have a two-layer case as shown in Figure 8. The contribution from the upper layer is given by

$$\sigma_a = \sigma_1[1 - R_V(z)] \qquad (4a)$$

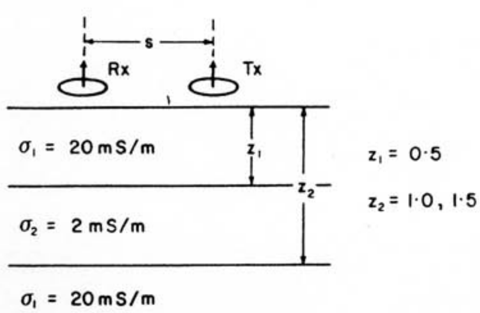
since all of the material below zero depth yields a relative contribution of unity or 100% to the meter reading. Conversely all of the material in the lower layer adds a contribution given by

$$\sigma_a = \sigma_2 R_V(z) \qquad (4b)$$

and the actual instrument reading will therefore be the sum of these two quantities

$$\sigma_a = \sigma_1[1 - R_V(z)] + \sigma_2 R_V(z) \qquad (5)$$

If the earth is three-layered as shown in Figure 9 the same procedure is employed to determine the instrumental response. In this example the calculations are performed for different middle layer thicknesses.



$$\sigma_a = \sigma_1[1 - R(z_1)] + \sigma_2[R(z_1) - R(z_2)] + \sigma_3 R(z_2)$$

$$z_2 = 1{\cdot}0, \quad \sigma_a = 20[1 - 0{\cdot}70] + 2[0{\cdot}70 - 0{\cdot}44] + 20 \times 0{\cdot}44 = 15{\cdot}3 \text{ mmho/m}$$

$$z_2 = 1{\cdot}5, \quad \sigma_a = 20[1 - 0{\cdot}70] + 2[0{\cdot}70 - 0{\cdot}32] + 20 \times 0{\cdot}32 = 13{\cdot}2 \text{ mmho/m}$$

FIGURE 9. Calculation of response to three layer earth – center layer thickness varying.

The ease with which such calculations are performed facilitates survey preparation and interpretation. It is sometimes possible to make advance estimates of the electrical properties of the materials to be encountered during a survey or, alternatively, once on-site the operator can obtain the same information from sample measurements of the different materials. The procedures outlined above are then employed to estimate the apparent conductivity measured under various terrain conditions. Examples of such calculations for the EM31 are shown in Figure 10. As is seen in the appendix the algebraic expressions for $\phi(z)$ and $R(z)$ are very simple and are easily programmed on hand held calculators.

In Figure 10 the vertical dimensions are greatly exaggerated with respect to the horizontal dimensions. The question arises as to what degree of lateral uniformity is required before the earth can be considered as horizontally stratified or homogeneous. Survey experience indicates that if the ground conductivity does not significantly vary with horizontal distance within a radius of one intercoil spacing from the instrument the ground can be considered to be laterally uniform.

The above discussion referred to the use of vertical transmitter/receiver dipoles; it is equally possible to construct a cumulative response function for the horizontal coplanar dipole configuration and Figure 11 illustrates this function for both coil configurations. A comparison of the two curves illustrates that the vertical dipole mode of operation has approximately twice the effective exploration depth of the horizontal dipole mode.

IV. 3. Comparison with Conventional Resistivity Techniques

Many readers will be familiar with the two-layer curves employed to interpret data from conventional resistivity surveys using a Wenner array of four equally spaced electrodes. Using the techniques described in the previous section it is a simple matter to calculate two-layer curves for the electromagnetic technique; Figure 12 shows such curves for both the vertical and horizontal dipole configurations superimposed on standard Wenner curves. The general shape is similar but there are marked differences in detail. For vertical coplanar transmitter/receiver dipoles we see that when the substrate is the more resistive the response of the two systems is similar; however when the substrate is the more conductive the electromagnetic technique sees deeper in that the influence of the substrate, for a given conductivity contrast, is felt at smaller intercoil spacing than inter-electrode spacing. This is a general characteristic of electromagnetic systems which prefer to look through an insulator to a conductor rather than through a conductor to an insulator.

For the horizontal dipole configuration if the lower layer is the more resistive the effective exploration depth of the inductive technique is slightly less than the Wenner array; however, once again, in the case where the lower layer is the more conductive the exploration depth of the inductive technique is substantially greater.

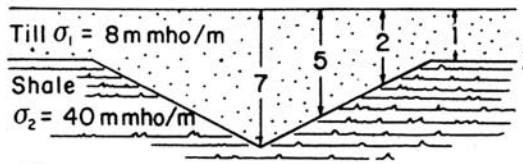
IV. 4. Resolution of Two-Layered Earth by Varying Intercoil Spacing

The principal advantage of the inductive electromagnetic technique over conventional resistivity lies in the speed and accuracy with which lateral changes of terrain conductivity can be measured. However this technique can also be used to measure the vertical variation of conductivity by expanding the intercoil spacing in a manner analogous to that in which the electrode spacing is expanded in conventional resistivity sounding techniques. The current state-of-the-art, however, is such that relatively few intercoil spacings can be employed; for example the EM34-3 can be operated with an intercoil spacing of 10, 20 or 40 meters. This feature is somewhat mitigated by the fact that the instruments can be used in either the vertical or horizontal dipole modes which, as shown in a previous section, exhibit different sensitivity to various depths thus yielding more information than would be available by simply using three spacings with one coil orientation.

To interpret a two-layer geometry the two-layer curves for both dipole configurations are superimposed on a common plot as shown

CROSS-SECTIONS

BURIED RIVER VALLEY

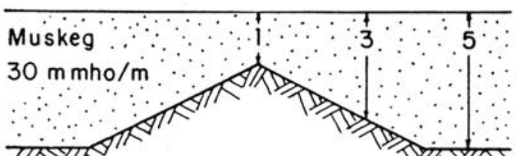


$$\frac{\sigma_a}{\sigma_1} = 1 - R(Z_1) + k_2 R(Z_1)$$

$$k_2 = \frac{\sigma_2}{\sigma_1} = \frac{40}{8} = 5$$

Z_1 (m)	σ_a (mmho/m)
1	32·6
2	26·9
5	18·6
7	16·0

BEDROCK HIGH

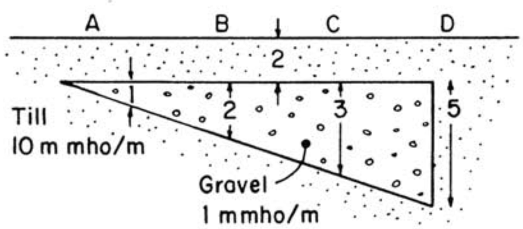


$$\frac{\sigma_a}{\sigma_1} = 1 - R(Z_1) + k_2 R(Z_1)$$

$$k_2 = \frac{\sigma_2}{\sigma_1} = \frac{0 \cdot 1}{30} = 0{\cdot}0033$$

Z_1 (m)	σ_a (m mho/m)
1	6·9
3	15·9
5	20·1

GRAVEL DEPOSIT



$$\frac{\sigma_a}{\sigma_1} = 1 - R(Z_1) + k_2[R(Z_1) - R(Z_2)] + k_3 R(Z_2)$$

$$k_2 = \frac{\sigma_2}{\sigma_1} = \frac{1}{10} = 0{\cdot}10$$

$$k_3 = \frac{\sigma_3}{\sigma_1} = 1{\cdot}00$$

station	σ_a (m mho/m)
A	8·9
B	8·2
C	7·7
D	6·9

FIGURE 10. EM31 calculated response across various geological features, using R (Z) corrected for instrument operation at waist (1 meter) height. Coil separation s = 3.67 meters.

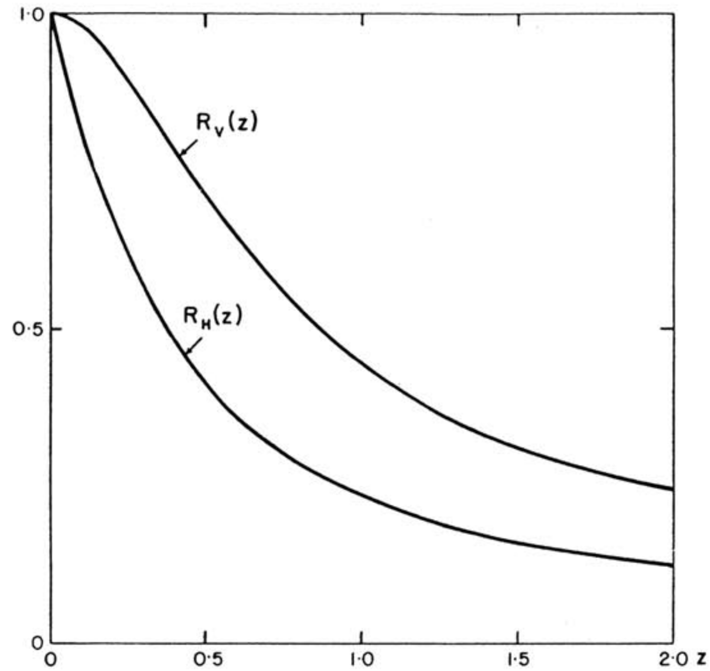


FIGURE 11. Cumulative response versus depth for vertical and horizontal dipoles.

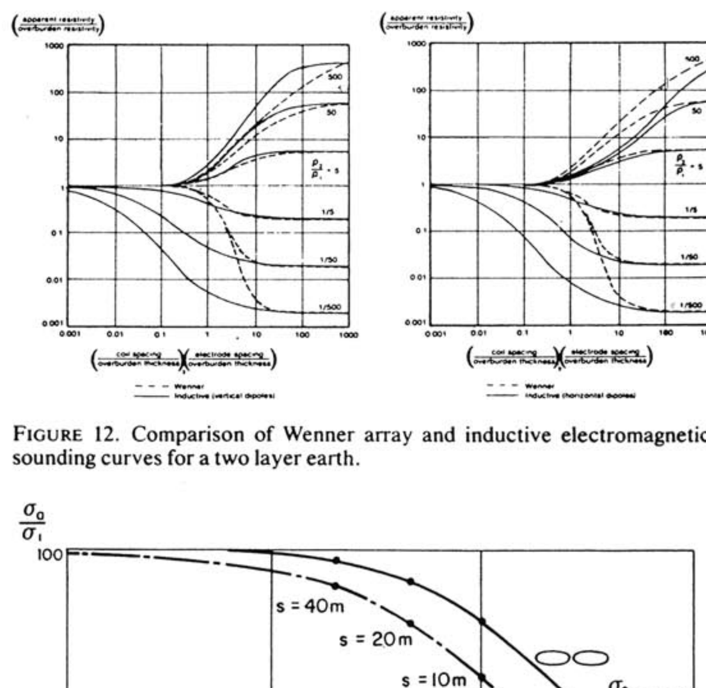


FIGURE 12. Comparison of Wenner array and inductive electromagnetic sounding curves for a two layer earth.

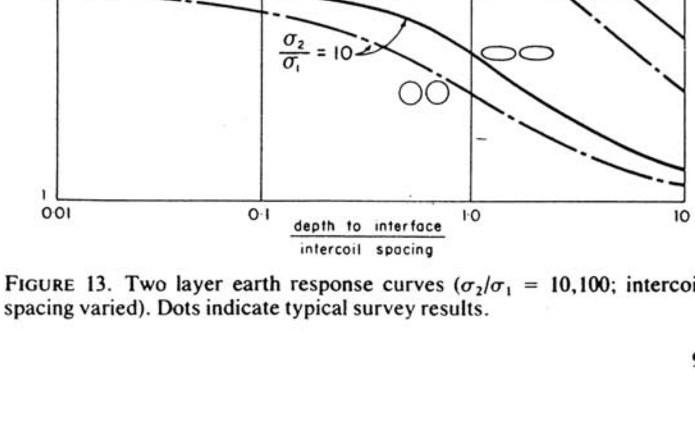


FIGURE 13. Two layer earth response curves (σ_2/σ_1 = 10,100; intercoil spacing varied). Dots indicate typical survey results.

in Figure 13. The six data points obtained by making measurements with two coil orientations and three intercoil spacings are plotted to the same scale on a piece of transparent paper and are translated vertically and horizontally on the two-layer curves to ascertain whether a satisfactory fit can be achieved. In the event that such a fit can be made, the earth does exhibit two-layer characteristics and the values of conductivity for both layers and the thickness of the upper layer are directly read off.

IV. 5. Resolution of Two-Layered Earth by Varying Instrument Height

In the case of the EM31 the intercoil spacing is rigidly fixed so that the technique described above is not available to analyse a layered earth. It is, however, possible to raise the instrument above the ground, measuring the apparent conductivity as a function of instrument height for both the vertical and horizontal dipole configurations. This has the effect of shifting the response curves of Figure 6 upwards through the various regions of the earth and the variation of apparent conductivity with height is therefore of diagnostic value in determining the nature of any layering. It is a straightforward matter to calculate the response of the instrument as a function of height for various two-layered earth geometries and typical curves are shown in Figure 14b. To use the curves one simply plots the measured apparent conductivity versus height for both coil configurations on a piece of transparent paper to the same scale as Figure 14b and shifts the plotted data vertically until good agreement is achieved with one of the curves, whereupon the two conductivities and the upper layer thickness are immediately determined as in the illustrated case history of Figure 14c.

In the event that the conductivity of either one of the two layers is known to be much less than the other, so that its contribution to the meter reading is negligible, it is simply necessary to lay the instrument on the ground, take a reading, lay it on its side, take a second reading, and from these two values one can immediately calculate the conductivity of the more conductive layer and the thickness of the upper layer.

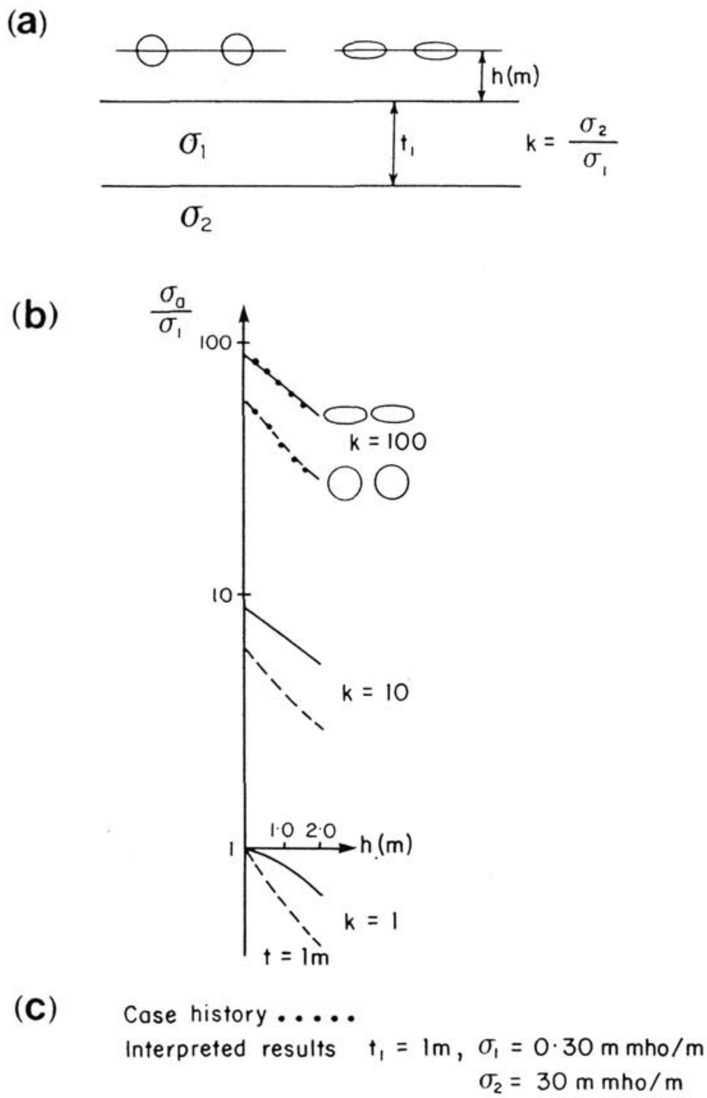


FIGURE 14. Two layer earth response curves (σ_2/σ_1 = 1, 10, 100; instrument height varied). Dots are actual survey results.

V. ADVANTAGES AND DISADVANTAGES OF INDUCTIVE TERRAIN CONDUCTIVITY MEASUREMENTS

V. 1. Advantages

The advantages of the use of inductive electromagnetic techniques to measure terrain conductivity are as follows:

(i) *Excellent resolution in conductivity*. It was stated in Section I that a problem with conventional resistivity was that the presence of localized resistivity inhomogeneities near the potential electrodes caused large errors. If we examine the current flow in a homogeneous halfspace for the inductive technique described herein we realize that in the vicinity of the transmitter the current density is very high and we might expect the presence of a conductive inhomogeneity located here to have a large effect. However where the current density is high, the radius of the current loops is small and their distance from the receiver coil large, so that these loops do not couple well magnetically with the receiver. The effect of changing this current by varying the local conductivity is consequently negligible. The lateral extent of the volume of earth whose conductivity is sensed by the inductive technique is approximately the same as the vertical depth. The result is that small changes in conductivity, for example of the order of 5% or 10%, are easily and accurately measured.

(ii) *No current injection problems*. Since currents are magnetically induced in the earth, current injection problems encountered with conventional resistivity in materials such as gravel, bedrock, permafrost, snow and ice, etc., are not encountered with this type of instrumentation.

(iii) *Simple multi-layered earth calculations*. This matter is dealt with at length in Section IV.

(iv) *Easy, rapid measurements*. A problem with the conventional Wenner array is that in order to survey to an effective depth a the array must be 3a in length and the total length of wire required 4a, used in four sections. This presents many opportunities for snagging and breaking the wire. Furthermore each measurement requires insertion of four electrodes and relatively careful measurement of the inter-electrode spacing. These features are avoided with the inductive electromagnetic techniques and it is no exaggeration to say that a survey can often be carried out five to ten times faster using this technique. Indeed with either the EM31 or the EM34-3 it is usually possible under average terrain conditions to survey 5 to 7 line-kilometers a day with a station spacing of 25 or 50 meters.

V. 2. Disadvantages

As with all geophysical instruments, there are some limitations and disadvantages to the use of inductive electromagnetic techniques and these are as follows:

(i) *Limited dynamic range (1 – 1000 mmhos per meter)*. At low values of terrain conductivity it becomes difficult to magnetically induce sufficient current in the ground to produce a detectable magnetic field at the receiver coil. Conversely at high values of conductivity the quadrature component of the received magnetic field is no longer linearly proportional to terrain conductivity as is shown in the appendix.

(ii) *Setting and maintaining the instrument zero*. Ideally in order to set the zero the instrument would be suspended in free space and the zero set there. The more acceptable alternative is to search out a region of very resistive ground, to accurately measure its conductivity using conventional techniques, and to set the instrumental zero at that location. This is the procedure which is actually followed.

It is necessary that this zero be accurately maintained over long periods of time and over the wide variations of temperature encountered during geophysical survey in various parts of the world. This produces tight constraints on the circuitry, with the result that the zero may be in error by up to ± 0.2 mmhos per meter. Such an error would be negligible over the usual range of terrain conductivities; however in the event that measurements are being made on highly resistive ground the zero error can become significant.

(iii) *Limited Vertical Sounding Capability*. In theory it is possible to use a system such as the EM34-3 at a continuum of intercoil spacings to yield more information about electrical layering in the ground. To achieve a wide variety of inter-electrode spacings with conventional resistivity equipment is simple; in the case of the inductive electromagnetic technique the rapid fall-off of the magnetic field from the dipole transmitter introduces a serious dynamic range problem. In due course there will undoubtedly be instrumentation with a wider variety of spacings at the expense of additional complexity.

VI. CASE HISTORIES

This section describes several case histories obtained with the EM31 and the EM34. The surveys (i) illustrate the resolution in conductivity that can be achieved, (ii) compare the results obtained with conventional resistivity and (iii) illustrate the use of the latter for locating sand, gravel and conductive minerals, determining bedrock topography (including locating a buried river channel) and mapping the pollution plume from a land-fill site. In some cases the indicated conductivity has been converted to resistivity to facilitate comparison with conventional resistivity survey results.

Case History #1

Location: Mississauga, Ontario
Instrument: EM31
Application: Illustrates resolution and repeatability of EM31

For this case history a Rustrak chart recorder was used to monitor the output of an EM31. A line of length 200 meters was traversed in a field in both easterly and westerly directions. Figure 15 demonstrates that the instrument is resolving conductivity changes of less than 1 mmho/m (1% of full scale deflection) and that the repeatability is of the same order. In fact the repeatability is limited in this case by the resolving power of the chart recorder itself. It should furthermore be noted that the instrument is detecting spatial changes in conductivity of a few meters in length – compatible with the intercoil spacing of 3.7 meters.

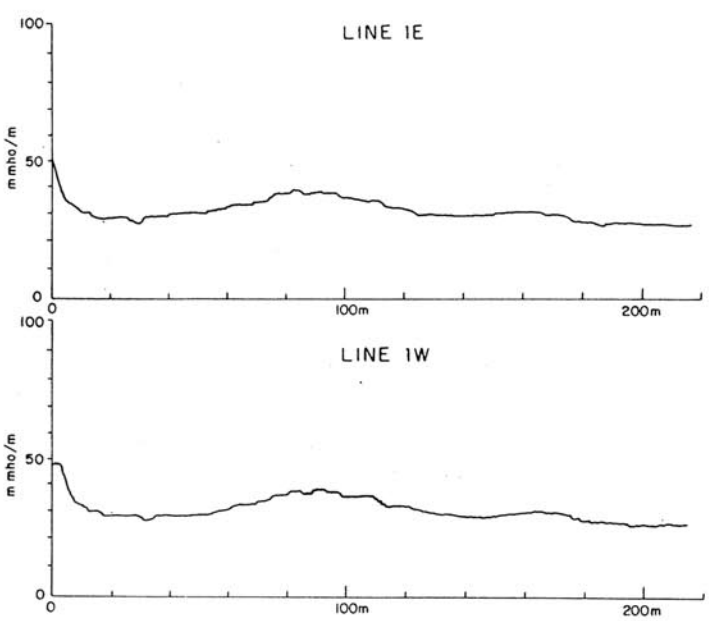


FIGURE 15.

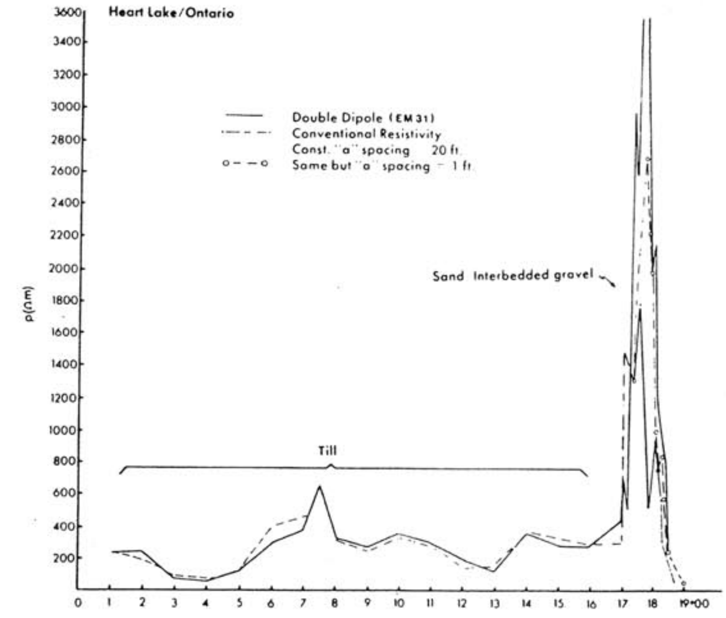


FIGURE 16. Test survey line – Heart Lake, Ont.

Case History #2

Location: Hearth Lake, Ontario
Instruments: EM31
Conventional resistivity apparatus
Application: Location of sand/gravel
Comparison of EM31 and conventional resistivity

In this survey a line 1900 ft. (580 meters) in length was surveyed with a measurement interval of 100 ft. (30 meters). The survey area was generally located on a buried esker, however the last few survey stations, 17 + 00 to 19 + 00, traversed a region of exposed sand and gravel (often occurring in the form of concretions) and over this portion of the line measurements were made every 10 ft. (3.0 meters).

The conventional resistivity profile was carried out using a Wenner array with an a spacing of 20 ft. (6.1 meters) except between stations 17 + 00 and 19 + 00 where the a spacing was reduced to 1 ft. (0.30 meters).

In general the correlation between the two sets of data is excellent, and demonstrates the ability of the EM31 to generate good quantitative data even in regions of low conductivity. Over the esker the EM31 was actually read continuously down the line – the data was recorded only at the 100 ft. intervals, with the exception of the reading at station 7 + 50 which was also recorded since it was noted that a conductivity low occurred there. Such an anomaly was, of course, missed by the conventional resistivity where measurements were only made every 100 ft.

Both sets of data become rather erratic between stations 17 + 00 and 19 + 00 as a result of the very rapid lateral changes in resistivity arising from the concreted material referred to above.

Case History #3

Location: Cavendish, Ontario.
Instrument: EM31
Application: Location of metallic type conductors

This survey line, of length 2000 ft. (610 meters), is located at a site

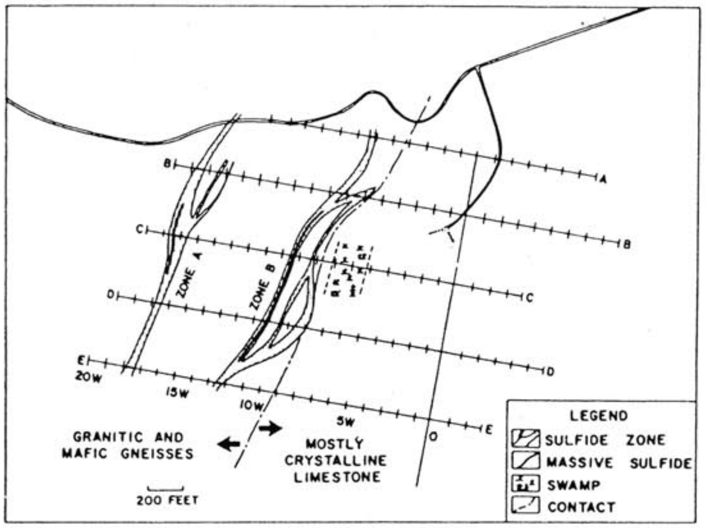


FIGURE 17. Geologic map of the Cavendish test site and the grid of traverse lines used in geophysical studies (after Ward et al [3]).

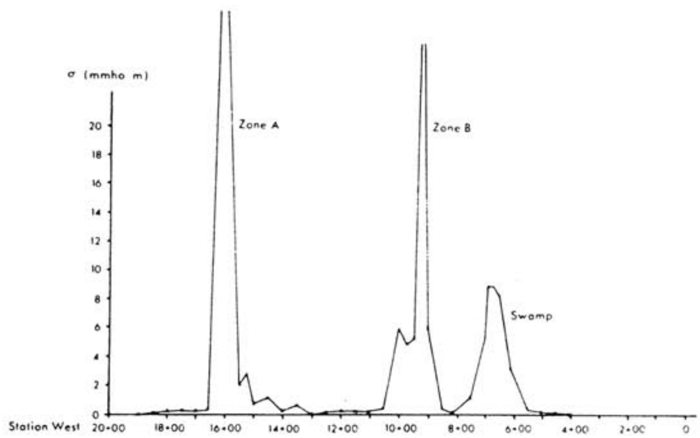


FIGURE 18. EM31 survey of Cavendish test range Line 'C'.

in Ontario which is often used by Canadian instrumentation manufacturers to test new electromagnetic geophysical equipment. The survey, along line C, illustrates response from both the swamp and the two zones of metallic mineralization. Although measurements were only taken every 50 ft. (15 meters) both zones are well delineated and when such high responses are encountered localization to within a few meters is quickly and easily carried out.

Inasmuch as the EM31 and EM34-3 were designed to map terrain conductivity at the conductivity levels encountered in typical soils both instruments are extremely sensitive electromagnetic detectors. For example on the most sensitive scale, full scale deflection for the EM31 is 800 ppm of the primary magnetic field and for the EM34-3 it is 3800 ppm. Such sensitivity makes either instrument useful for detecting metallic type conductors at what are very low conductivity levels by normal standards.

Case History #4

Location:	Mississauga, Ontario
Instruments:	EM31, EM34
Application:	Determination of bedrock topography

Total line length for this survey was 8400 ft. (2600 meters) and measurements were made every 100 ft. (30 meters) with both the EM31 and the EM34 – an earlier version of the EM34-3 which had two intercoil spacings vis. 100 ft. (30 meters) and 50 ft. (15 meters). The survey was performed to outline the cross-sectional profile of a

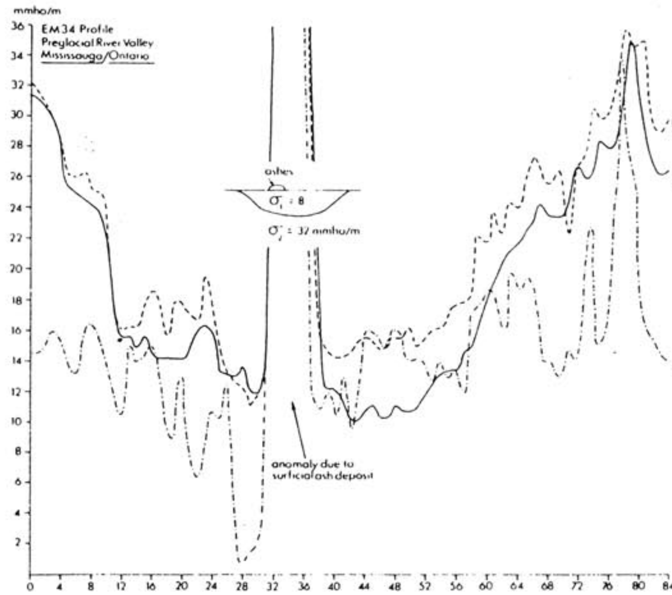


FIGURE 19. EM31 and EM34 survey line over preglacial river valley, Mississauga, Ontario.

buried preglacial river valley whose existence had been suggested from water-well data. At either intercoil spacing the time required for the EM34 profile was 1-1/2 hours, resulting in approximately one survey measurement per minute – including the time to walk the 100 feet between measurement stations. The time taken for the subsequent EM31 survey was similar.

Typical bedrock conductivity in the area is approximately 30 mmho/m, whereas an average value for the conductivity of the infilling glacial till is of the order of 8 to 12 mmho/m. Thus the EM34 at either intercoil spacing yields approximately 30 mmho/m at the valley edges where the overburden is thin and 12 to 14 mmho/m at the valley centre. The EM31 yields values of 14 to 18 mmho/m at the valley edges (slightly affected by the presence of bedrock) and approximately 10 mmho/m at the valley centre. The interpreted depth of the valley, based on the model shown in the figure, is approximately 120 feet (36 meters) which is in reasonable agreement with the water-well data value of 150 feet (45 meters), bearing in mind that the three sets of data show that a two-layer model is an over simplification.

The conductivity high which occurs between stations 32 and 38 results from a very large pile of waste furnace ash lying on the surface.

Case History #5

Location:	Camp Borden, Ontario
Instruments:	EM31, EM34
	Conventional resistivity apparatus
Application:	Mapping groundwater salinity
	Comparison of EM34 and conventional resistivity

Geophysical surveys were carried out over a sanitary landfill site using, in addition to other instruments, an EM31, EM34 and conventional resistivity [4]. The survey results in the accompanying figures illustrate the good agreement between these techniques and also indicate the reduction in survey time achieved using inductive electromagnetic techniques. Particularly interesting are the vertical variations in resistivity as shown by the EM31 at 3.7 m intercoil spacing and the EM34 at 15 and 30 m spacing.

VII. SUMMARY

This technical note describes in detail the principles of mapping the electrical conductivity of the ground using magnetically induced

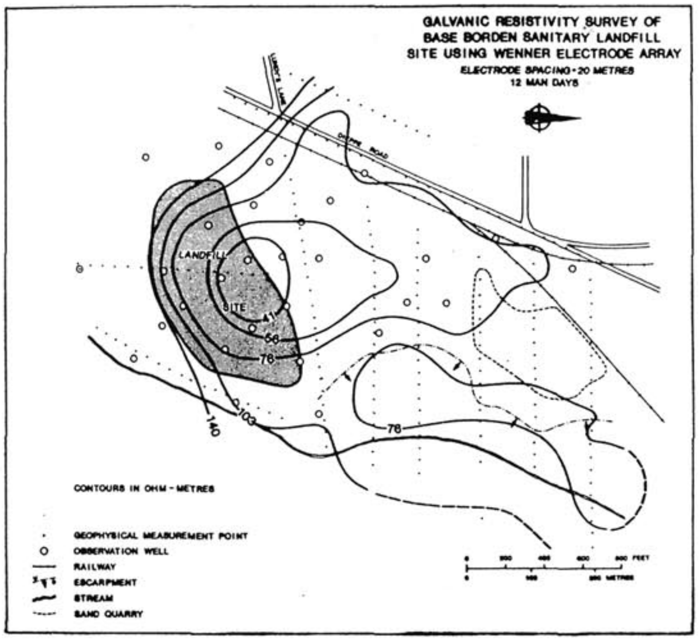


FIGURE 20(a).

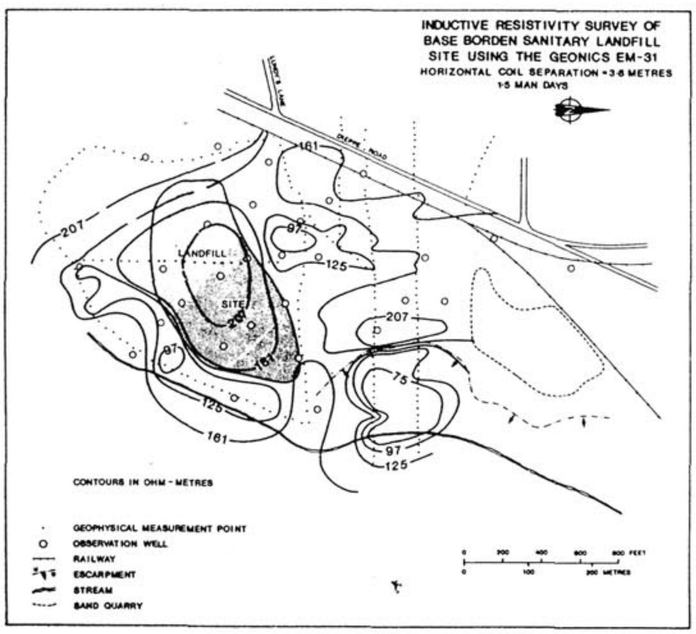


FIGURE 20(b).

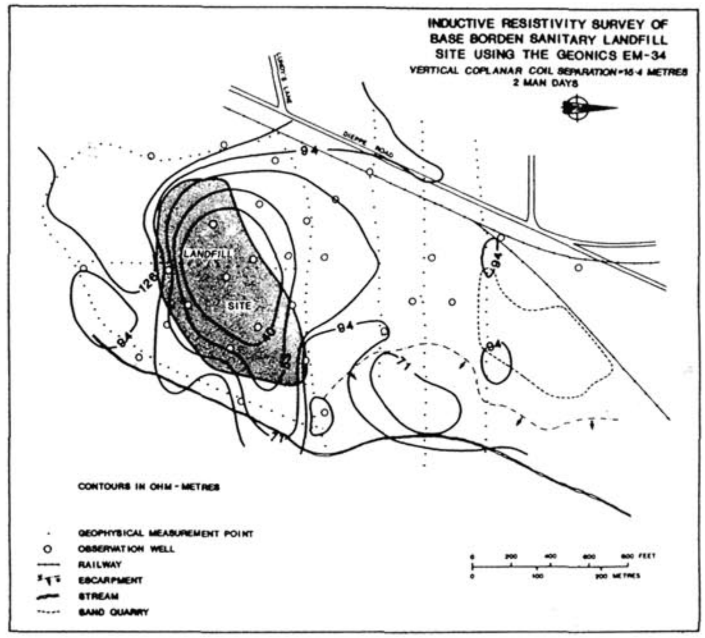


FIGURE 20(c).

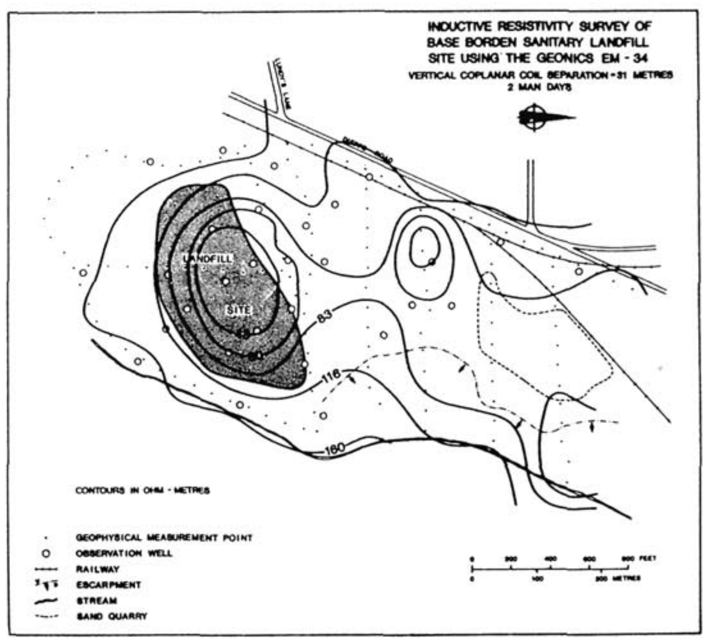


FIGURE 20(d).

currents at low frequencies. It has been shown that certain advantages can be derived from working at low values of induction number. Amongst these are excellent resolution in conductivity, a substantial reduction in man-hours necessary to carry out a conductivity survey and a simplification in the calculation of layered earth response.

Two points should be kept constantly in mind when performing surveys of this type to map geology. The first is that these instruments map only the electrical conductivity. If the conductivity does not vary significantly with the geological environment, or if parameters other than the geology also influence the conductivity, the survey results may be difficult to interpret.

The second point is that measurement of terrain conductivity, like any other geophysical measurement, must begin and end with geology. Such measurements are only an aid to help visualize geological conditions which cannot be seen. It is always necessary to interpret geophysical data against known geology from out-crops, boreholes, or any other such "bench marks". Geophysical measurements can be very effective by allowing interpolation between such sources, or extrapolation away from them. However in every case knowledge derived from geophysical measurements must be eventually reconfirmed against known geological conditions.

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(2) Wait, J.R. 1962. A Note on the Electromagnetic Response of a Stratified Earth. Geophysics V.27, pp 382-85.

(3) Ward, S.H.; Pridmore, D.F.; Rijol, Glenn W.E. Multispectral Electromagnetic Exploration for Sulphides. Geophysics Vol. 39 No. 5 p. 666. 1974.

(4) Survey carried out by Dr. J. Greenhouse, University of Waterloo, Waterloo, Ontario.

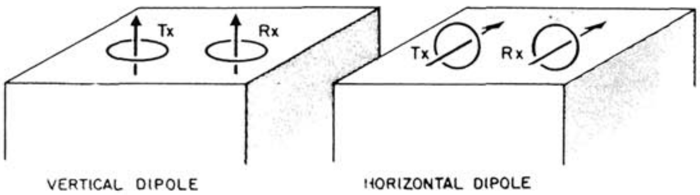

FIGURE AI. Vertical and horizontal dipole coil configurations.

APPENDIX: Theory of Operation at Low Induction Numbers

Consider the two coil configurations shown in Figure AI. In each case the transmitter coil is energized with alternating current at a frequency f Hertz. The measured quantity is the ratio of the secondary magnetic field H_s at the receiver when both coils are lying on the surface of the homogeneous half-space of conductivity σ to the primary magnetic field H_p in the absence of the half-space (i.e. as if the coils were in free space). The spacing between the coils is s meters.

The field ratios for vertical and horizontal dipole configurations are given by equations (1) and (2) respectively.

$$\left(\frac{H_s}{H_p}\right)_V = \frac{2}{(\gamma s)^2}\{9 - [9 + 9\gamma s + 4(\gamma s)^2 + (\gamma s)^3]\,e^{-\gamma s}\} \quad (1)$$

$$\left(\frac{H_s}{H_p}\right)_H = 2\left[1 - \frac{3}{(\gamma s)^2} + [3 + 3\gamma s + (\gamma s)^2]\frac{e^{-\gamma s}}{(\gamma s)^2}\right] \quad (2)$$

where $\gamma = \sqrt{i\omega\mu_o\sigma}$
$\omega = 2\pi f$
f = frequency (Hz)
μ_o = permeability of free space
$i = \sqrt{-1}$.

These expressions are complicated functions of the variable γs which is in turn a reasonably complicated (complex) function of frequency and conductivity. However, as will be shown below, under certain conditions they can be greatly simplified.

A well known characteristic of a homogeneous half-space is the electrical skin depth δ, which is defined as the distance in the half-space that a propagating plane wave has travelled when its amplitude has been attenuated to 1/e of the amplitude at the surface. The skin depth is given by

$$\delta = \sqrt{\frac{2}{\omega\mu_o\sigma}} = \frac{\sqrt{2i}}{\gamma} \quad (3)$$

and therefore

$$\gamma s = \sqrt{2i}\,\frac{s}{\delta} \quad (4)$$

The ratio s/δ, the intercoil spacing divided by the skin depth, is defined as the induction number B, whereupon

$$\gamma s = \sqrt{2i}\,B \quad (5)$$

Now if B is much less than unity (ie $\gamma s \ll 1$) it is a simple matter to show that the field ratios of equations (1) and (2) reduce to the simple expression

$$\left(\frac{H_s}{H_p}\right)_V \simeq \left(\frac{H_s}{H_p}\right)_H \simeq \frac{iB^2}{2} = \frac{i\omega\mu_o\sigma s^2}{4} \quad (6)$$

which is the equation given in Section II.

The magnitude of the secondary magnetic field is now directly proportional to the ground conductivity and the phase of the secondary magnetic field leads the primary magnetic field by 90°.

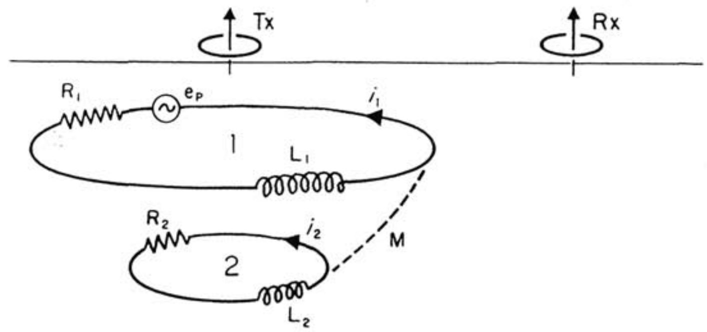

FIGURE AII. Electrical model for vertical dipoles.

To make B much less than unity we see that we must make s very much less than δ and thus

$$\omega \ll \frac{2}{\mu_o\sigma s^2} \quad (7)$$

That is, having decided on a value for s (which fixes the effective depth of penetration under the condition $B \ll 1$), the maximum probable ground conductivity is estimated and the operating frequency is chosen so that equation (7) is always satisfied.

The apparent conductivity which the instrument reads is then defined by

$$\sigma_a = \frac{4}{\omega\mu_o s^2}\left(\frac{H_s}{H_p}\right)_{\text{quadrature component}} \quad (8)$$

To examine the reasons for this simplification let us focus our attention on the vertical dipole coil configuration shown in Figure AII since symmetry makes this configuration the simplest to understand.

Consider current loop 1. The primary emf e_p causing this current to flow is given (through Faraday's law) by the time rate of change of the primary magnetic flux from the transmitter through this loop. Three impedances cause the current to be limited. These arise from (i) the electrical resistance R_1 of the loop, (ii) the fact that the current i_1 generates its own magnetic field which causes a time-varying secondary magnetic flux through the loop (self-inductance, L_1), and (iii) the fact that all other current loops such as i_2 generate their own magnetic fields which in turn cause a time-varying magnetic flux to link with loop 1 (mutual-inductance, M).

The equivalent circuit for this configuration is easily derived from elementary circuit theory with the result shown in Figure AIII.

The complex impedance Z incorporates all of the affects of magnetic coupling between current loop 1 and any other current loop 2. We see from this expression that Z can be made arbitrarily small by reducing $\omega = 2\pi f$, the operating frequency. When Z is thus

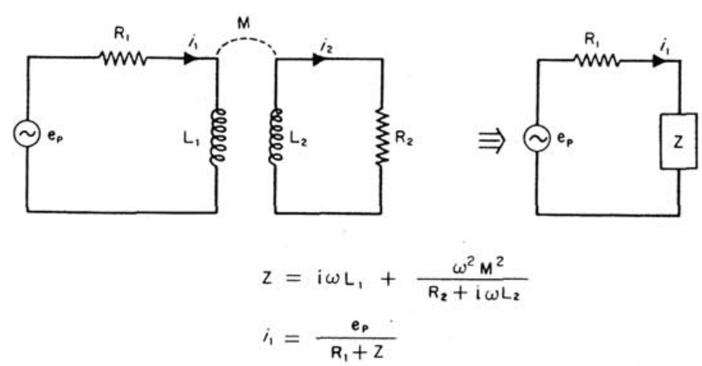

FIGURE AIII. Equivalent circuit for model of Figure AII.

made much smaller than R_1 the current flow in loop 1 is simply given by

$$i_1 = \frac{e_p}{R_1} = \frac{i\omega\phi_p}{R_1} = i\omega\phi_p G_1 \quad (9)$$

where ϕ_p = primary flux linking loop 1
G_1 = conductance of loop 1($G_1 = 1/R_1$)
$i = \sqrt{-1}$

We see that the magnitude of the current is linearly proportional to the loop conductance and furthermore that the phase of the current leads the primary flux by 90°. Since the secondary magnetic field at the receiver from current i_1 is in phase with and directly proportional to i_1 it too will be directly proportional to G and will lead the primary flux by 90°. Thus

$$\left(\frac{H_s}{H_p}\right) \propto i\omega G_1 \quad (10)$$

which has the same dependence on frequency and conductance as equation (6). We infer therefore, that the condition $B \ll 1$ is equivalent to stating that for all current loops that affect the receiver output the operating frequency is so low that we can ignore any magnetic coupling between the loops. Thus the current that flows in any loop is (i) completely independent of the current that flows in any other loop since they are not magnetically coupled and (ii) is only a function of the primary magnetic flux linking that loop and of the local ground conductivity.

The lack of interaction between current loops is of great importance in simplifying the data reduction procedures. Of equally great significance is the fact that for any value of B and for any orientation of a magnetic dipole (or indeed of any magnetic source) over either a uniform halfspace or a horizontally stratified earth it can be shown that all current flow is horizontal. That this is the case for a vertical dipole is easy to see from symmetry; for a horizontal dipole it is less evident but equally true. Thus, in a horizontally layered earth no current crosses an interface which is fortunate since, if it did, changing either of the conductivities would, by virtue of refraction of the current, change the direction of the current as it flowed from one medium to the other.

If no current flow crosses an interface and if there is no magnetic coupling between current loops, changing the conductivity of any one of the layers of a horizontally stratified earth will not alter the geometry of the current flow. Varying the conductivity of any layer will proportionately vary only the magnitude of the current in that layer. To calculate the resultant magnetic field at the surface of a horizontally layered earth it is simply necessary to calculate the independent contribution from each layer, which is a function of its depth and conductivity, and to sum all the contributions.

The functions $\phi(z)$ and R(z) discussed in Section II define the relative influence of current flow as a function of depth. Their derivation is involved and will not be given here. The resultant expressions are, however, simple and easily programmed into hand calculators:

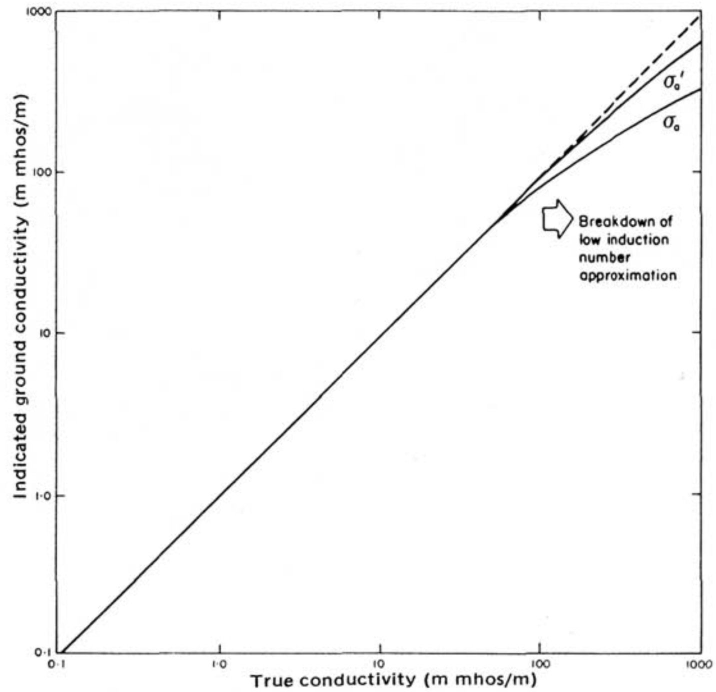

FIGURE AIV. Plot of indicated conductivity for EM31 versus true (homogeneous half-space) conductivity for both vertical (σ_a) and horizontal (σ_a') dipoles.

$$\phi_V(z) = \frac{4z}{(4z^2 + 1)^{3/2}} \quad (11)$$

$$\phi_H(z) = 2 - \frac{4z}{(4z^2 + 1)^{1/2}} \quad (12)$$

$$R_V(z) = \frac{1}{(4z^2 + 1)^{1/2}} \quad (13)$$

$$R_H(z) = (4z^2 + 1)^{1/2} - 2z \quad (14)$$

where z is the depth divided by the intercoil spacing.

Finally it should be noted that for a given frequency and intercoil spacing as the terrain conductivity increases the approximation of equation (6) eventually breaks down and the instrumental output is no longer proportional to terrain conductivity. This effect is illustrated in Figure AIV. which plots apparent (indicated) conductivity against true (homogeneous halfspace) conductivity for both vertical and horizontal transmitter/receiver dipoles for the operating parameters of the EM31. As would be expected the horizontal dipoles exhibit linearity to greater values of conductivity as a result of the reduced depth of penetration in this configuration.

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Technical Note TN-11

USE OF EM31 INPHASE INFORMATION

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GEONICS LIMITED

TECHNICAL NOTE TN-11

USE OF EM31 INPHASE INFORMATION

The Geonics EM31 measures the quadrature-phase component of the induced magnetic field, since this component of the magnetic field is linearly related to the ground conductivity and hence most readily interpretable in terms of the geological structure.

Another major use of the EM31 is for carrying out surveys of ground-water contamination by mapping the electrically conductive (or in some cases the highly resistive) contaminant plumes. These waste disposal sites however often contain buried metal containers of hazardous waste which can generally be detected by the EM31 (or metal detectors or magnetometers) if they are not buried too deeply.[1,2]

Other users, such as archaeologists and treasure seekers, are also interested in the detection of buried metallic targets.

The detectability of these large metal objects and more specifically the detection of buried metal drums can be greatly enhanced by measuring the inphase component of the induced magnetic field. This component can be readily measured by the EM31 by simply taking the reading with the mode switch in the COMP position. The procedure for doing this is to set the mode switch to the COMP position and then adjusting the COARSE and FINE COMPENSATION controls so that a deflection of about 20% of full scale deflection is obtained. This is usually carried out with the RANGE switch set to the 30 mmho/m position, although less sensitive ranges can also be used. The survey is then carried out exactly as if the conductivity were being measured.

Experiments at Geonics have indicated that the EM31 will detect a single 45 gallon oil drum out to distances of about 3.7m (12 ft) using the inphase component, whereas Koerner, et al will only be able to detect drums to a depth of 2m (6 ft) using the quadrature-phase component.

Two points will have to be considered however when surveying in the COMP position mode. The first is that the true zero level of the inphase component is not known since the reference level is arbitrarily set as described earlier. Generally this is not a problem since when operating in this mode, one is looking for relatively localized meter deflections indicative of the presence of metallic objects. The second point is that if the instrument is suddenly jarred the inphase zero level may change and settle down at a new value. This fluctuation in the zero level should not cause any serious difficulty or confusion in the interpretation, since the detection of buried metal objects will generally be recognized by a single pulse or series of pulses corresponding to the number of buried objects and their spacing.

Overall, these two disadvantages are relatively insignificant when compared with the increase in sensitivity of the EM31 for detecting buried metal objects which puts the EM31 in a class by itself relative to the magnetometer and metal detectors.

For some surveys it is useful to record both the inphase and quadrature-phase components simultaneously. In this case the EM31 can be modified to provide both outputs for an analog chart recorder.

References

(1) Evans, Roy B. Currently Available Geophysical Methods for Use in Hazardous Waste Site Investigations, Risk Assessment at Hazardous Waste Sites, 8. Geophysical Methods for Investigations p.93-115. ACS Symposium Series, No. 204.

(2) Koerner, Robert M. et al Drexel University, Use of NDT Methods to Detect Buried Containers in Saturated Silty Clay Soil, 1982 National Conference on Management of Uncontrolled Hazardous Waste Sites, Site Investigation, p.12-16.

Instruments Geonics

EM38

Faible espacement (fixe) entre dipôles magnétiques

EM31

Espacement plus important (fixe) entre dipôles

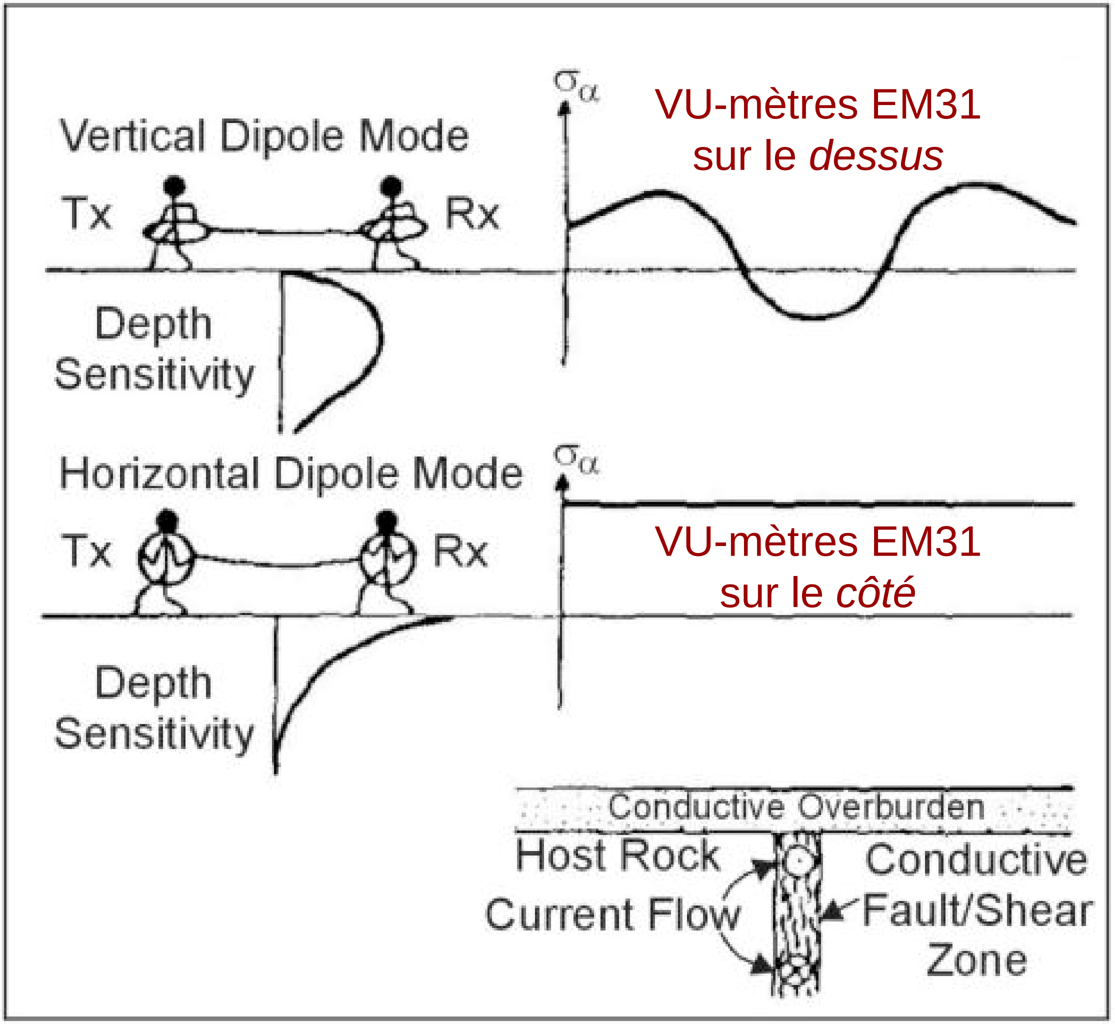
EM34

Espacement variable (nécessite 2 opérateurs)

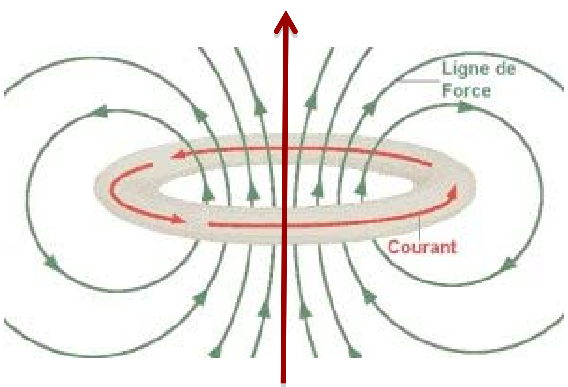
Orientation des dipôles magnétiques

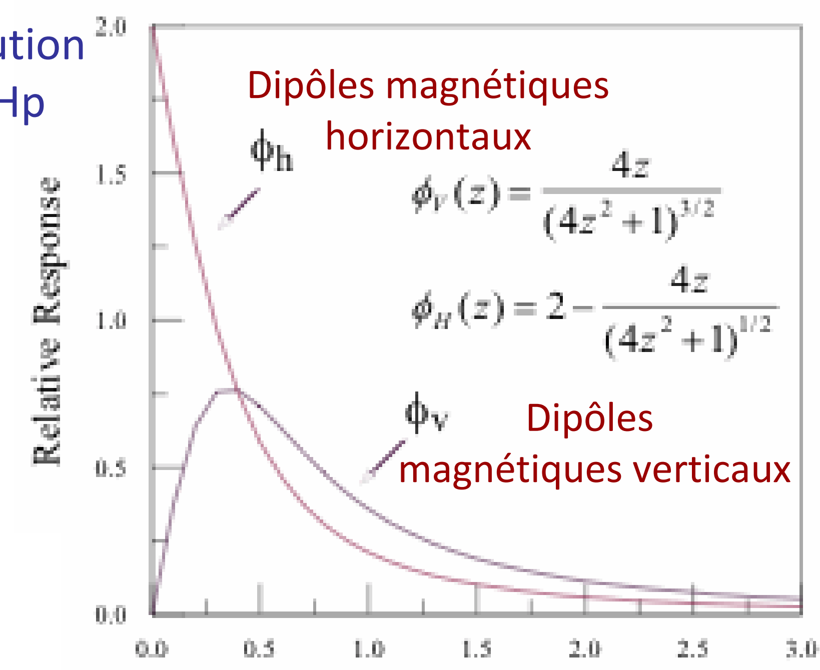
Dipôles verticaux

Dipôles horizontaux (en ligne)



Sensibilité des mesures EM





Le maximum de sensibilité est à une profondeur égale à 40% de la distance entre les deux bobines lorsque les dipôles magnétiques sont verticaux (spires dans le plan horizontal).

Les dipôles magnétiques verticaux permettent une meilleure pénétration que les dipôles magnétiques horizontaux.

Spécifications des instruments Geonics

Instrument	Distance entre bobines	Fréquence	Profondeur de pénétration typique		Résolution (~1/5 d_{bob})
			Dipôles verticaux	Dipôles horizontaux	
EM38	1 m	14.6 kHz	1.5 m	0.75 m	0.2 m
EM31	3.66 m	9.8 kHz	6 m	3 m	0.7 m
EM34	10 m	6.4 kHz	15 m	7.5 m	2 m
EM34	20 m	1.6 kHz	30 m	15 m	4 m
EM34	40 m	0.4 kHz	60 m	30 m	8 m