Applied Geophysics

And

Mining Exploration Geophysics

Dr.A.BALUKKARASU

Electrical Properties of Rocks and Electrical Resistivity Methods

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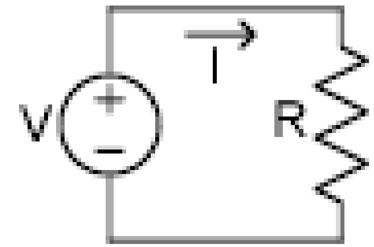
Resistance

Definition of an OHM

An ohm is a resistance in a conductor that produces a potential difference of one volt when a current of one ampere is flowing through it.

$$R = \frac{V}{A} = \frac{m^2 \cdot kg}{s^3 \cdot A^2}$$

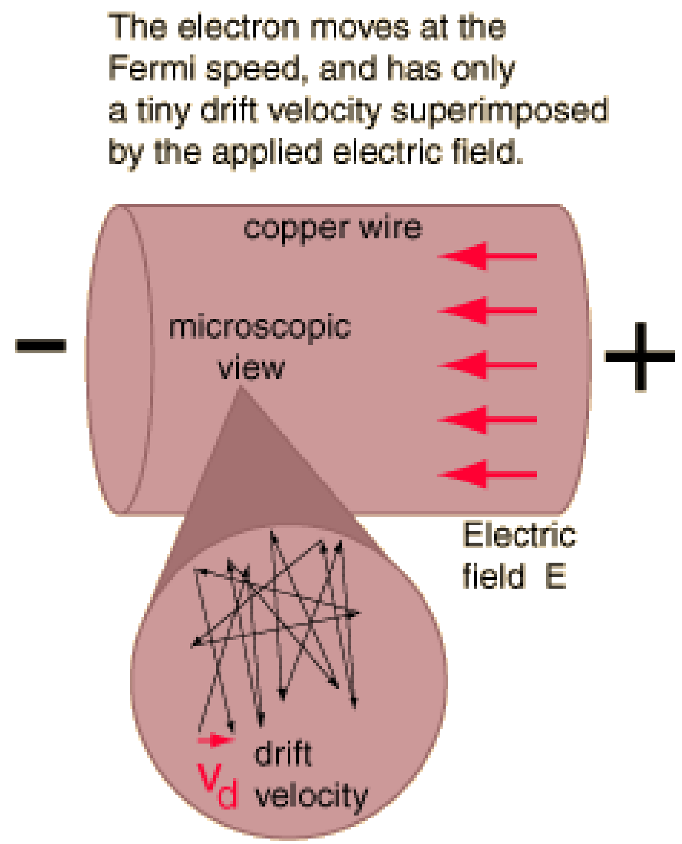


Ohm’s Law

Ohm's Law

$$I = \frac{V}{R}$$

Electric current = Voltage / Resistance



http://hyperphysics.phy-astr.gsu.edu/hbase/electric/ohmlaw.html#c1

Resistance vs Resistivity

Resistance is relevant only to a particular measurement circuit. Units: Ohms

Resistivity is an intrinsic property of all physical materials Units: Ohm-Meters

Apparent Resistivity is a resistivity estimate based on a assuming a half-space geometry. Units: Ohm-meters

Electrical Resistivity vs Electrical Conductivity

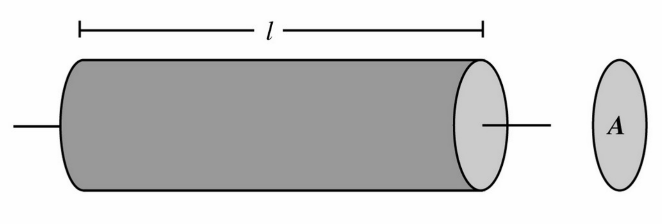
Resistance = ρ (ohm-meters)

Conductivity = σ = 1/ρ (mho/meters)

Calculating Resistance from Resistivity

The resistance (R) of a length of wire is given by

$$R = \rho \frac{L}{A},$$



where

ρ = resistivity of the medium composing the wire,
L = length,
A = area of the conducting cross section.

- http://www.cflhd.gov:80/agm/index.htm

Factors Influencing Electrical Conductivity in Rocks

Porosity (connected/effective - fractures or pores)

Pore saturation (% air or gas)

Hydrocarbon Fluid Saturation

Water salinity (TDS)

Clay Content

Metallic Sulfide Mineral Content

Fluid temperature

Rock Matrix intrinsic resistivity

Archie's Law

The minerals comprising a rock are almost always electrical insulators. Thus, electrical conduction occurs because of the moisture contained within the pores of the rock or soil. The resistivity of soil or rocks depends on several parameters. These include the clay content, moisture salinity, degree of saturation of the pores, and the number, size, and shape of the interconnecting pores. For soils, the degree of compaction (influencing porosity) is also an important factor. Archie (1942) developed an empirical formulae relating resistivity to porosity, degree of saturation and resistivity of the saturating moisture, shown below.

$$\rho_e = a\phi^{-m} s^{-n} \rho_w,$$

where ϕ is the fractional pore volume (porosity), s is the fraction of the pores containing water, ρ_w is the resistivity of the water, n is approximately 2, a and m are constants with a varying between 0.5 and 2.5 and m varying between 1.3 and 2.5.

Formation Factor

Since the conduction of current in soil and rock is through the electrolyte contained in the pores, resistivity is governed largely by the porosity, or void ratio, of the material and the geometry of the pores. Pore space may be in the form of intergranular voids, joint or fracture openings, and blind pores, such as bubbles or vugs. Only the interconnected pores effectively contribute to conductivity, and the geometry of the interconnections, or the tortuosity of current pathways, further affects it. The resistivity ρ of a saturated porous material can be expressed as

$$\rho = F\rho_w,$$

F = formation factor,

ρ_W = resistivity of pore water.

$$\frac{\sigma_w}{\sigma_f} = F = a\phi^{-m},$$

σ_w = conductivity of the water,

σ_f = conductivity of the formation as a whole,

a = empirical constant, typically 1 for unconsolidated sediments,

m = empirical constant, typically 2 for unconsolidated sediments,

ϕ = effective porosity, the fraction of interconnected pore space,

F = "formation factor," related to the volume and tortuaosity of the pore space.

The conductivity of most geological formations can be fit to Archie's Law

Influence of Permeability

A rock with a non-conducting matrix must be permeable (connected pores) as well as porous to conduct electricity.

Darcy's Law:

$$q = -k \frac{dV}{dh},$$

Ohm's Law:

$$j = -\sigma \frac{dV}{dh},$$

where

$q =$ fluid density,

$j =$ current density,

$\frac{dV}{dh} =$ head or voltage gradient, respectively.

Despite the similarity between Darcy's and Ohm's Laws, electric currents have zero viscosity so even a narrow crack can provide an effective electrical connection between pores that not contribute to hydraulic permeability.

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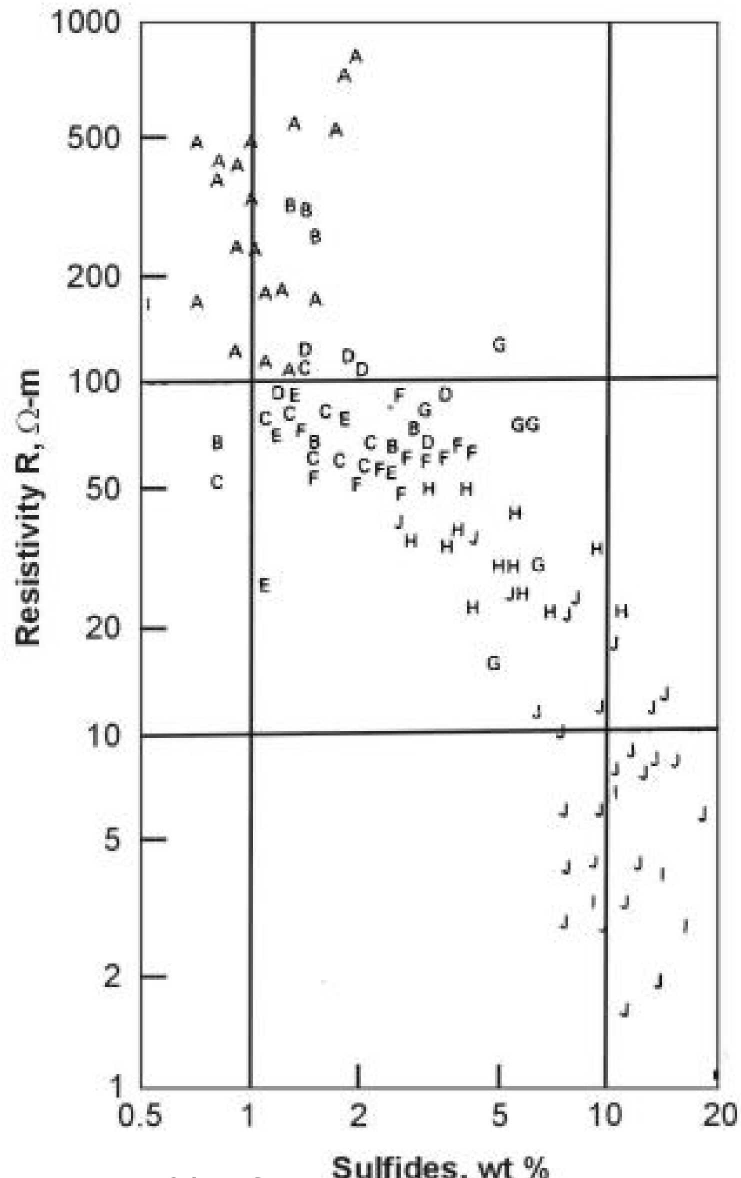
Comparison of electric and hydraulic properties.

Electrical	Hydraulic
Transverse resistance: $T = \Sigma h_i\rho_i = H\rho_l$	Transmissivity: $T_h = \Sigma h_i k_i = K_l H$
Longitudinal conductance: $S = \Sigma h_i/\rho_i = H/\rho_l$	Leakance: $L_h = \Sigma k_i/h_i = K_t/H$
Average aquifer resistivities: ρ_l, ρ_t	Average hydraulic conductivities: K_l, K_t

- http://www.cflhd.gov:80/agm/index.htm

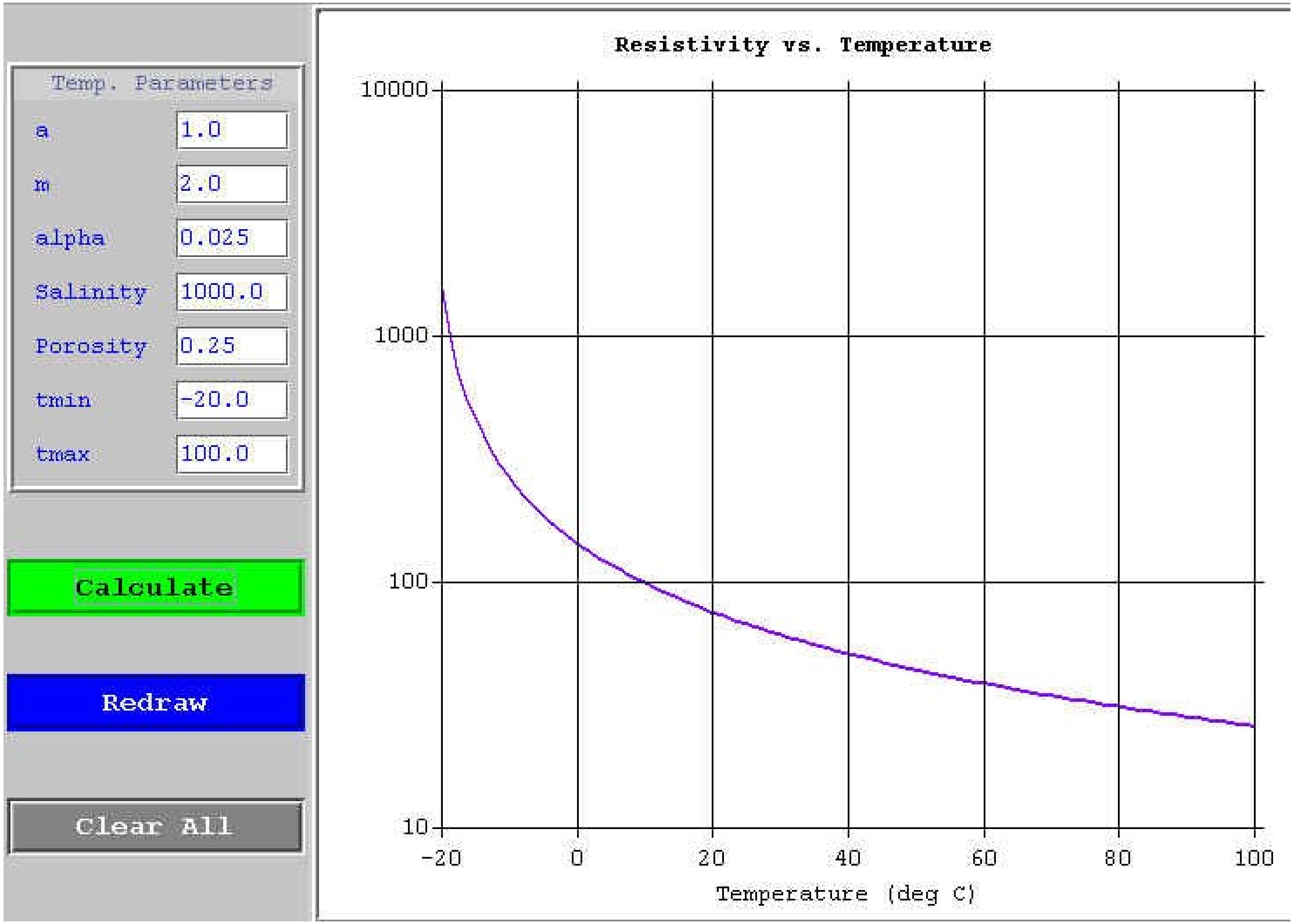
Metallic Sulfide Mineral Content



Electrical resistivity of rocks with various wt % of sulfide.

- http://www.cflhd.gov:80/agm/index.htm

Effect of Water Temperature



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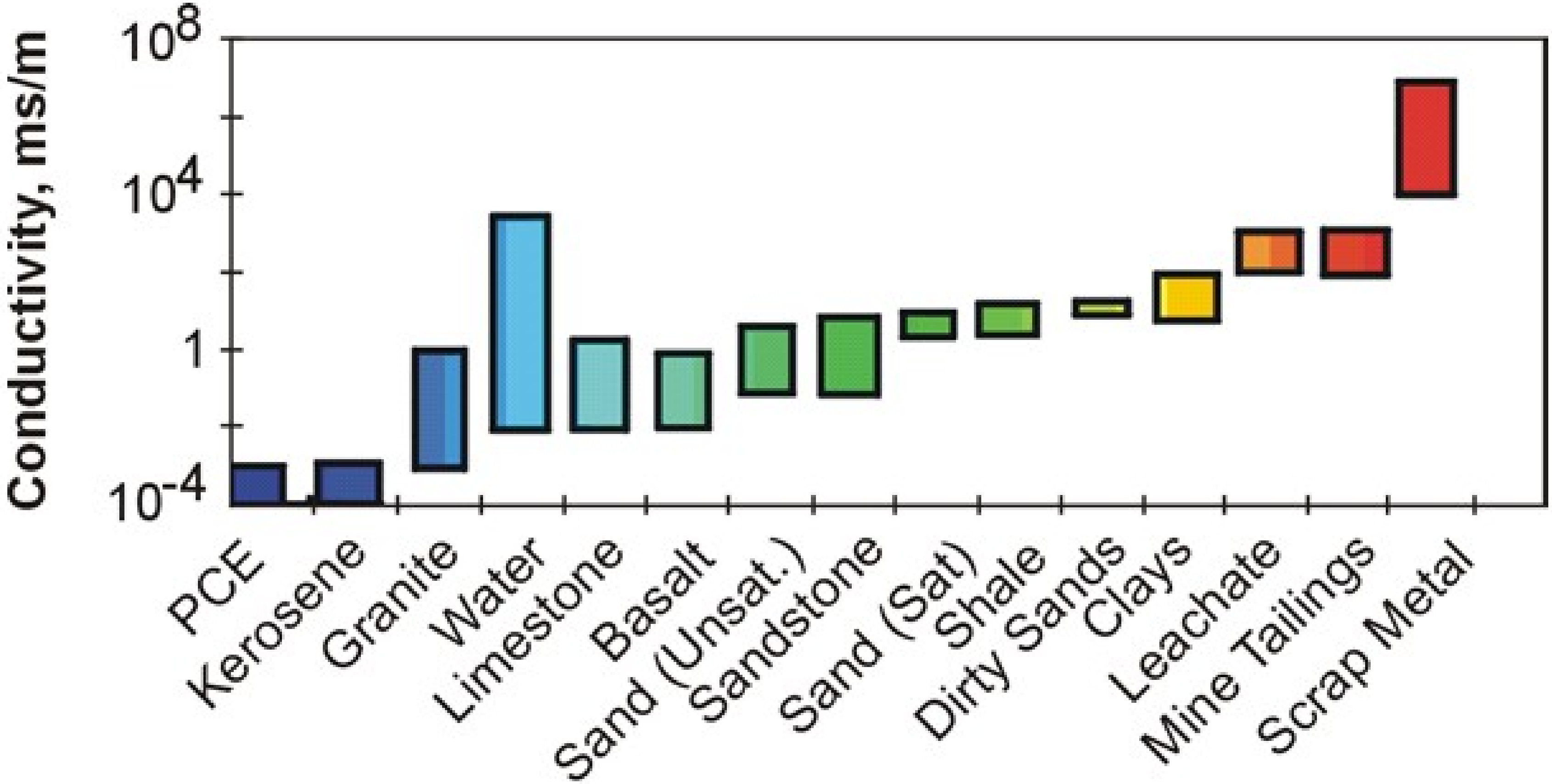
http://appliedgeophysics.berkeley.edu:7057/dc/figures/fig43_7.jpg

Conductivity Ranges of Various Materials



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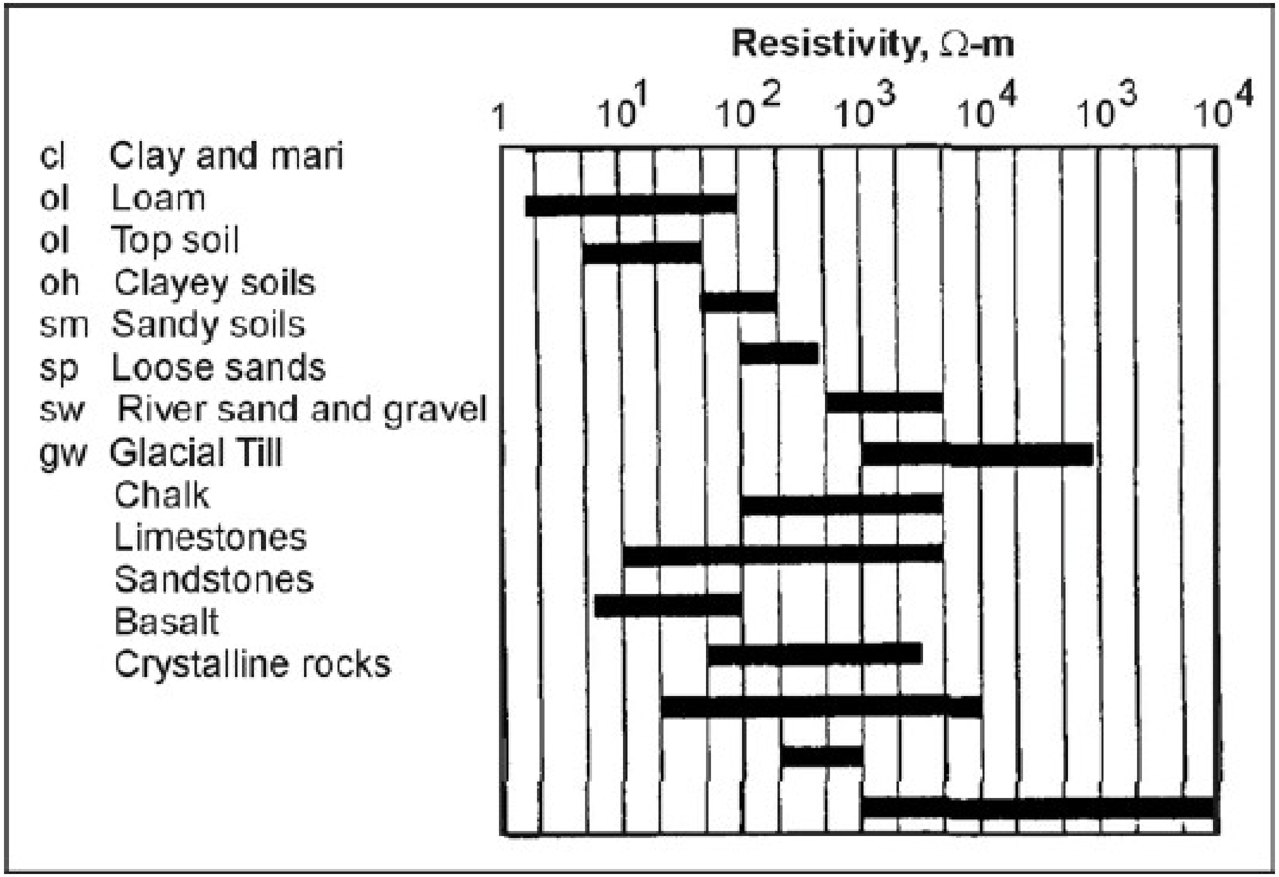

Figure 145. Resistivities of different rock types. (From TN5, Electrical Conductivity of Soils and Rocks, Geonics Ltd)

http://www.cflhd.gov:80/agm/index.htm

Table 17. Typical electrical resistivities of earth materials.

Material	Resistivity (Ωm)
Clay	1-20
Sand, wet to moist	20-200
Shale	1-500
Porous limestone	100-1,000
Dense limestone	1,000-1,000,000
Metamorphic rocks	50-1,000,000
Igneous rocks	100-1,000,000

http://www.cflhd.gov:80/agm/index.htm

Table 8. Cation Exchange Capacities (CEC) of common clay types.

Clay type	Cation Exchange Capacity
Kaolinite	3 - 15
Chlorite	10 - 40
Illite	10 - 40
Montmorillonite	80 - 150
Vermiculite	100 - 150

This table shows that kaolinite has the least influence on conductivity, and vermiculite has the greatest influence. However, other factors influence conductivity values, including the degree of saturation and the salinity of the saturating fluid.

Central Federal Lands Highway Division

http://www.cflhd.gov:80/agm/index.htm

Resistance vs Resistivity

Resistance is relevant only to a particular measurement circuit. Units: Ohms

Resistivity is an intrinsic property of all physical materials Units: Ohm-Meters

Apparent Resistivity is a resistivity estimate based on a assuming a half-space geometry. Units: Ohm-meters

Calculating Resistance from Resistivity

The resistance (R) of a length of wire is given by

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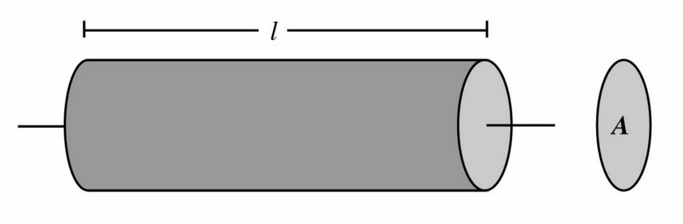

where

ρ = resistivity of the medium composing the wire,
L = length,
A = area of the conducting cross section.

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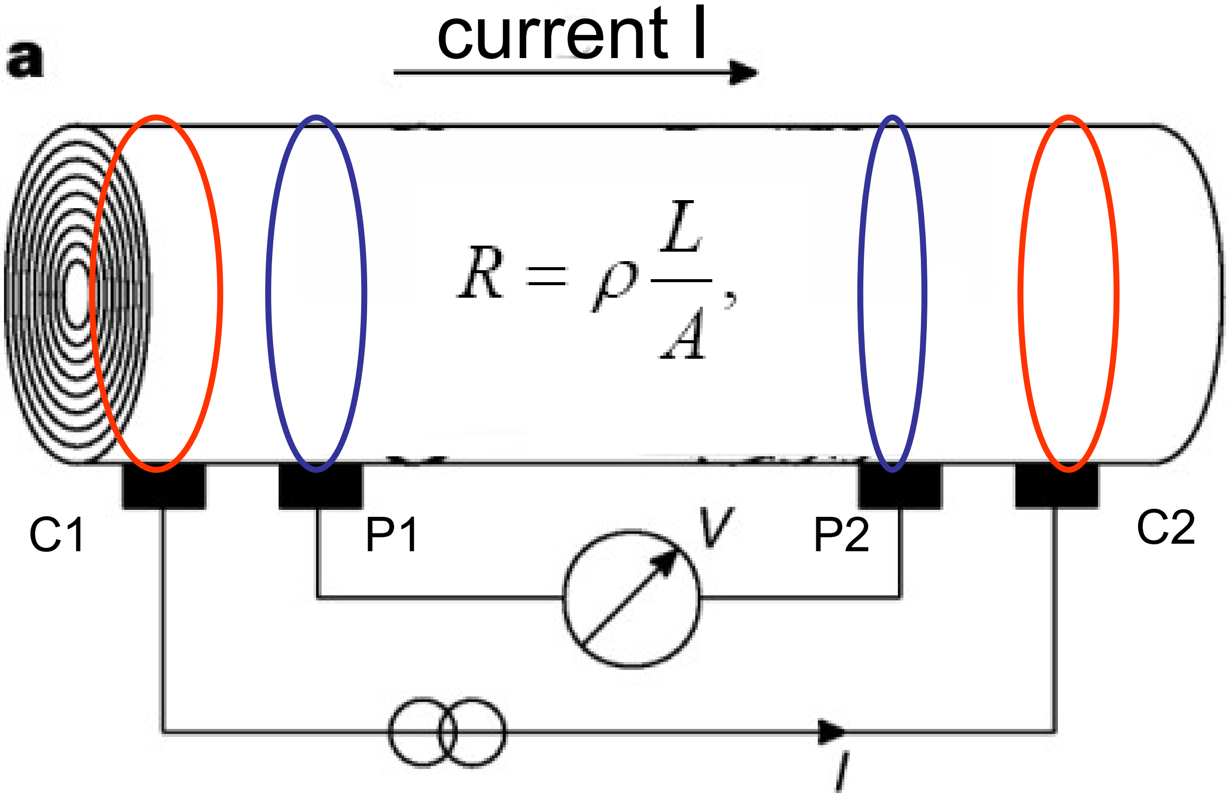
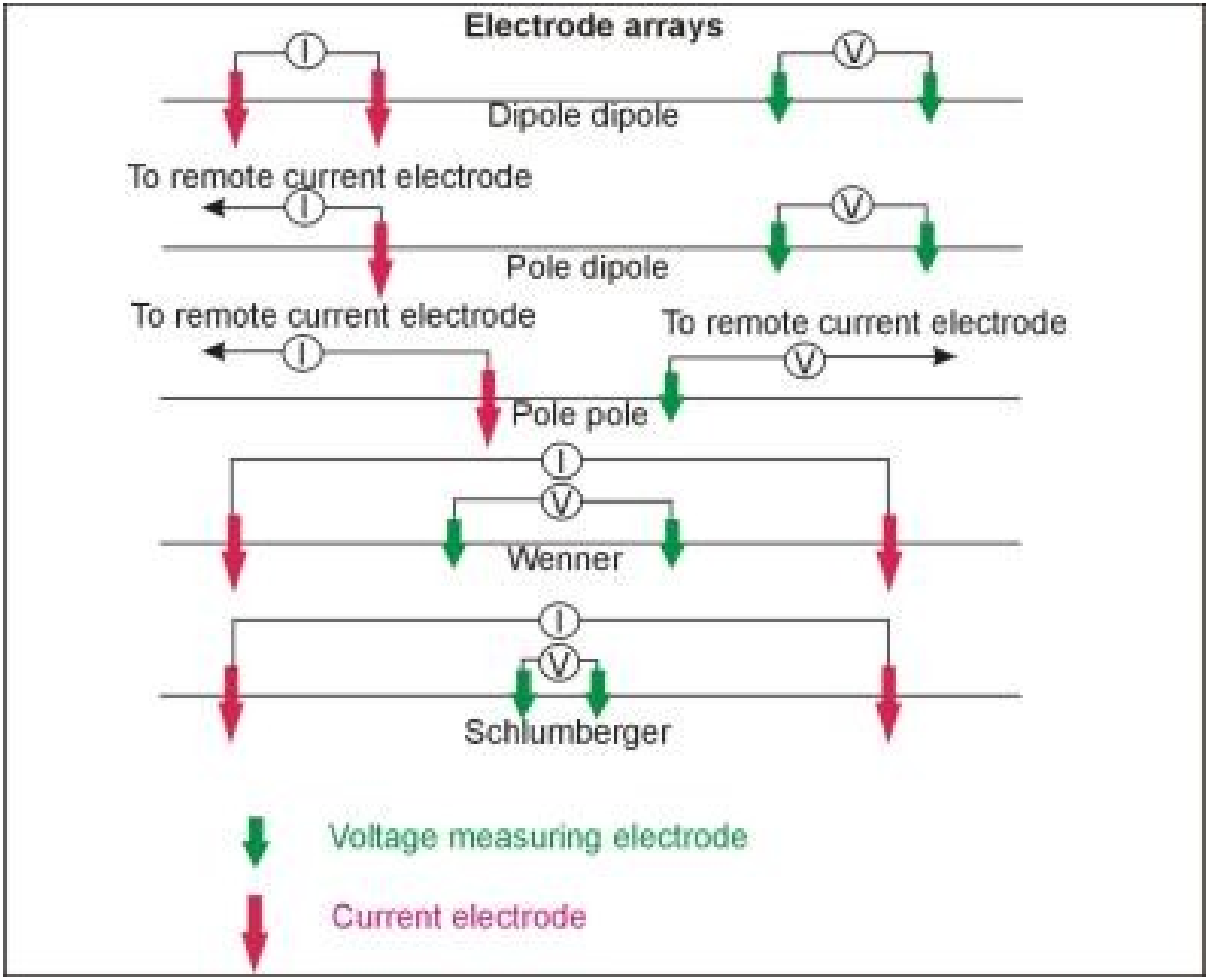
Four Electrode Resistivity Measurement on rock sample

… are used to avoid electrode contact resistance effects seen in two electrode measurements.

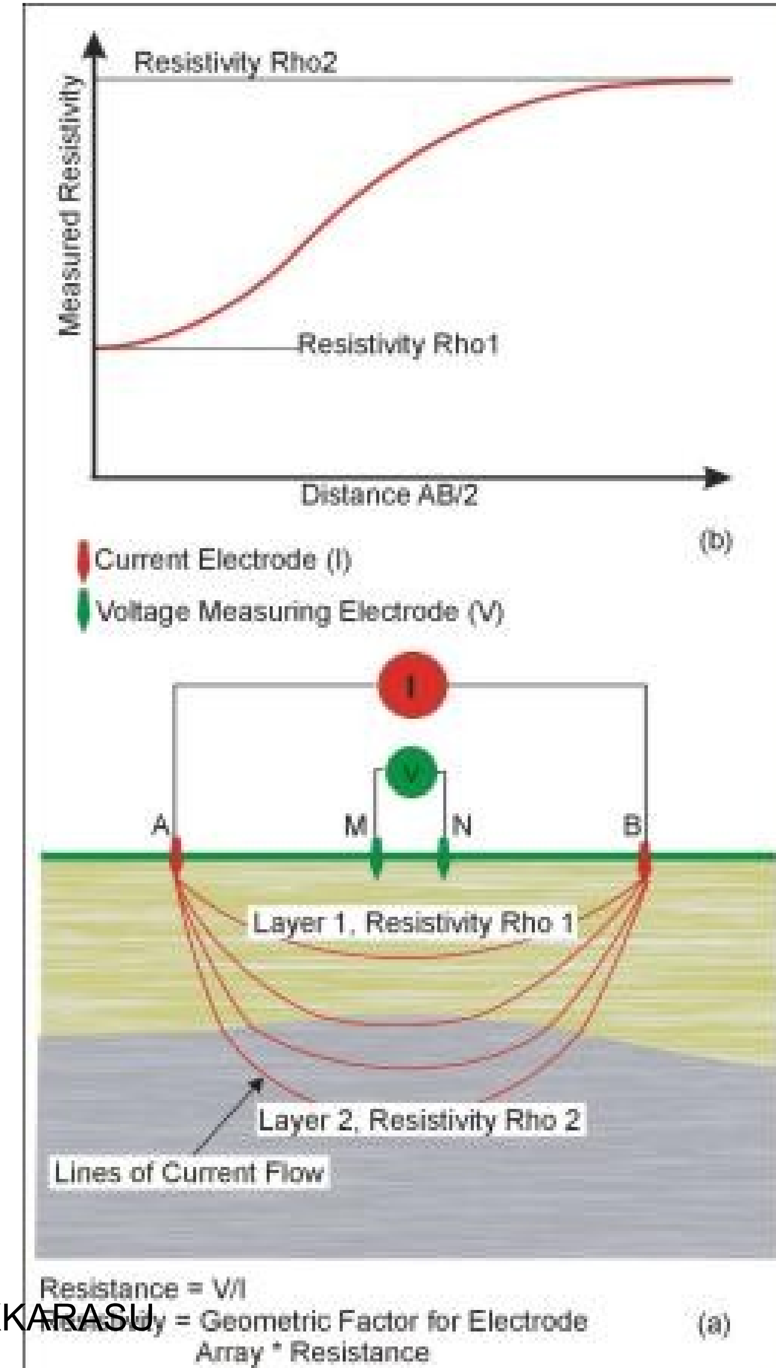


Four electrode resistivity arrays



http://www.cflhd.gov/agm/images/fig90.jpg

The Basic Concept of an Earth Resistivity Measurement



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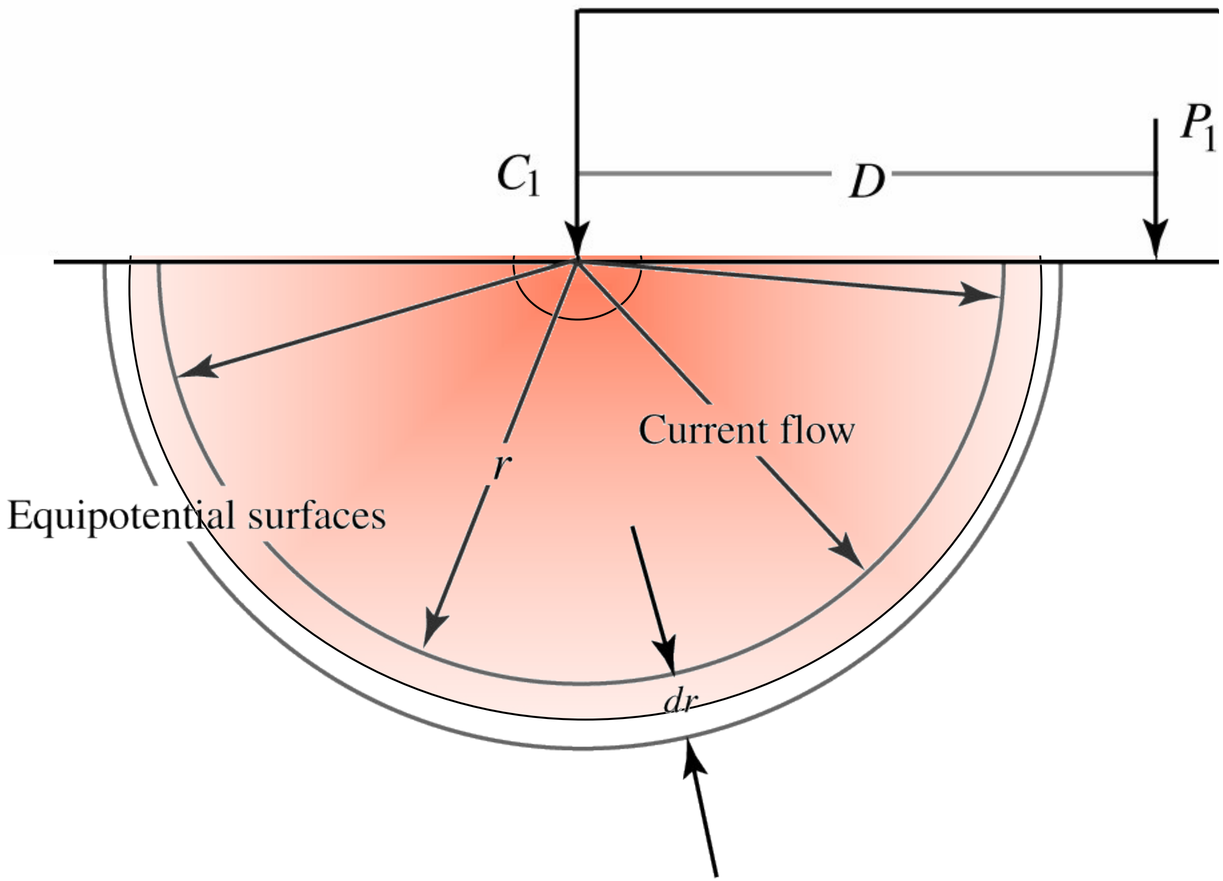
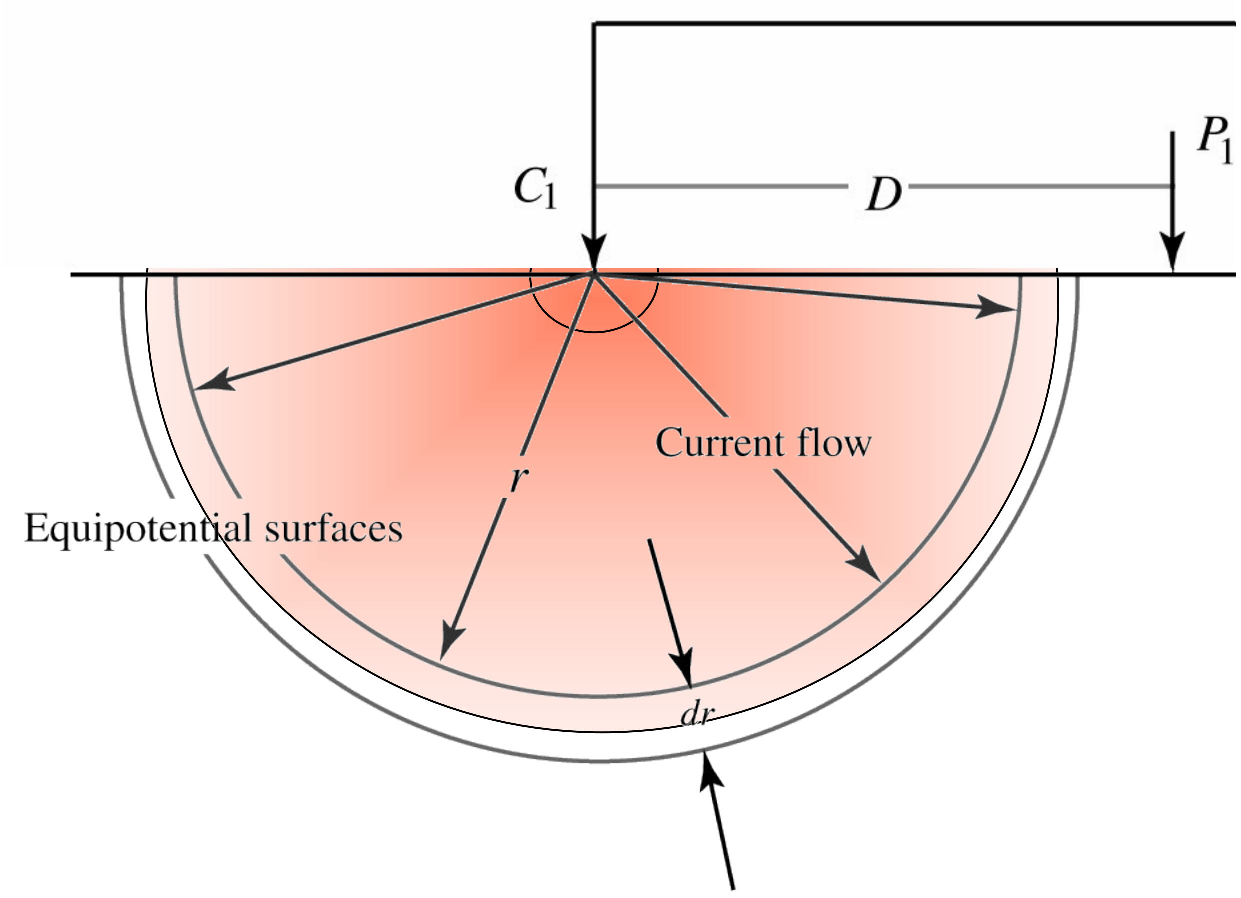
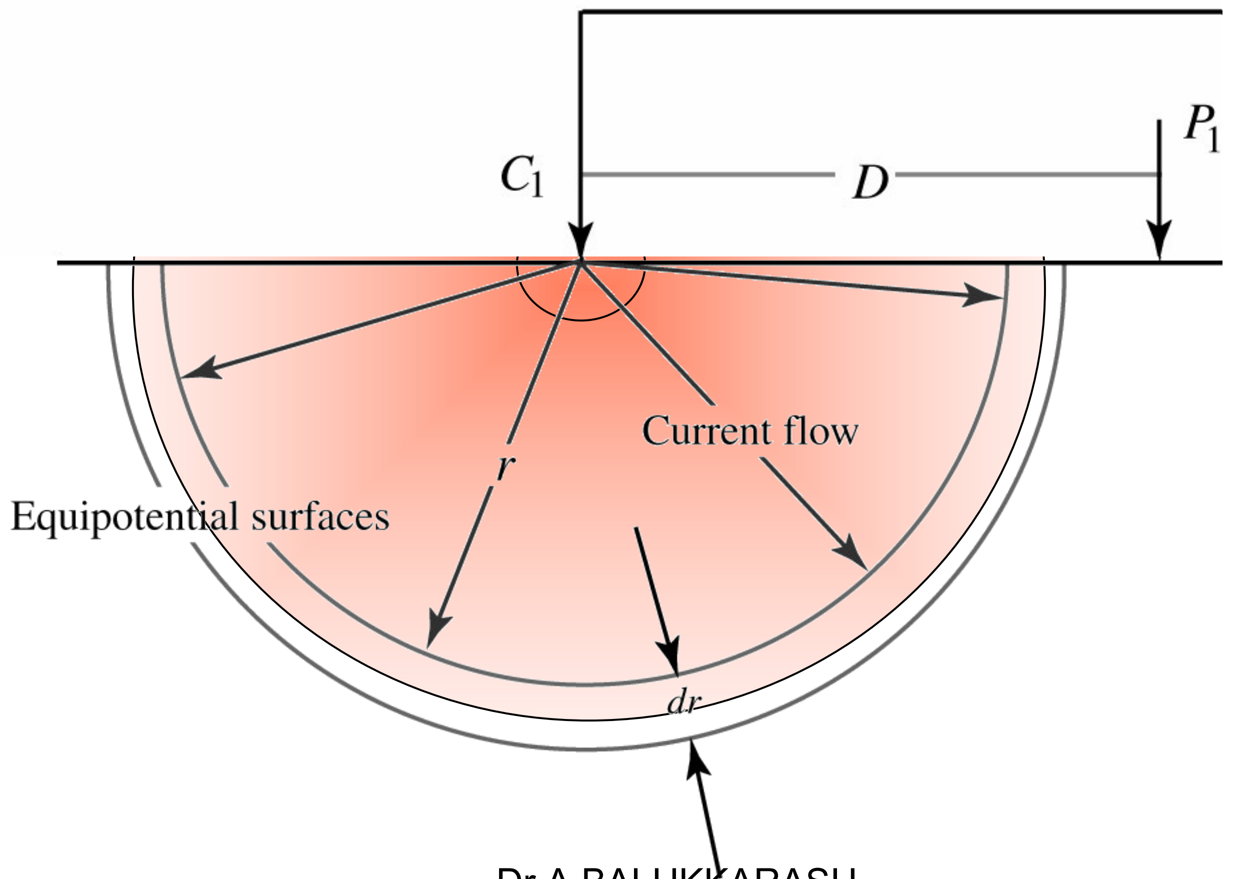
Electrode Contact Resistance is typically much higher than the intrinsic earth *resistivity*



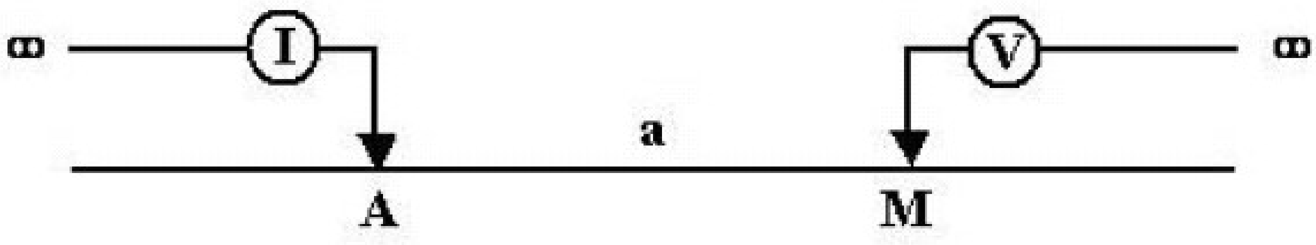
Electrode Contact Resistance is concentrated around each electrode



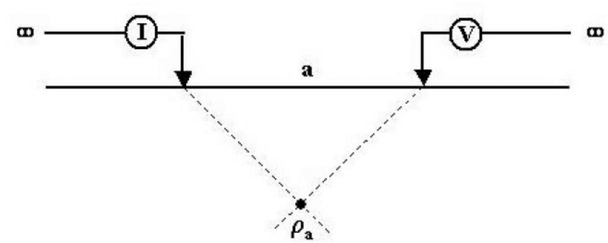
If a standard two electrode resistivity meter were used to measure the earth's "resistance" we only obtain information on the quality of the electrode contacts – not the earth's resistivity



Pole-Pole Array



$$\rho_A = \frac{V}{I} 2\pi a$$



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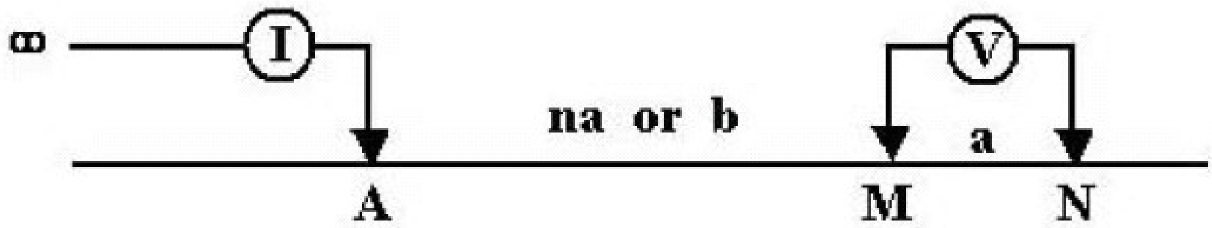
Pole-Dipole Array

If only one of the current electrodes is placed at "infinity" the configuration and the apparent resistivity are as shown:



$$\rho_A = 2\pi \frac{b\,(a+b)}{a} \frac{V}{I}$$

http://appliedgeophysics.berkeley.edu:7057/dc/em44.pdf

Pole-Dipole Array

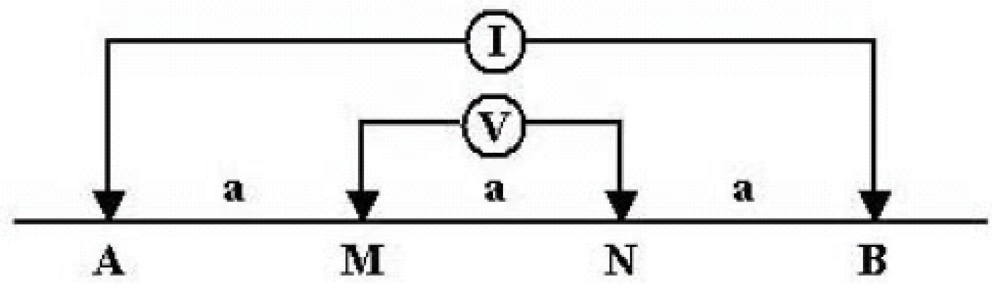
This array is used frequently in resistivity surveying and the spacings are usually described, and taken, in integer multiples of the voltage electrode spacing b. The standard nomenclature is to call the potential electrode spacing a so the configuration and apparent resistivity become:

$$\rho_A = 2\pi\, a\, n\left(n+1\right)\frac{V}{I}$$

http://appliedgeophysics.berkeley.edu:7057/dc/em44.pdf

Wenner Array

The Wenner array is now seen to be a simple variant of the pole-dipole in which the distant pole at infinity is brought in and all the electrodes are given the same spacing, a, as seen in the following configuration



$$\rho_A = 2\pi a \frac{V}{I}$$

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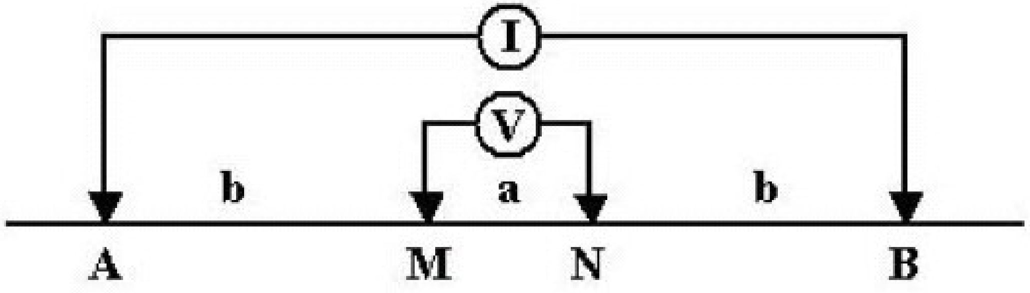
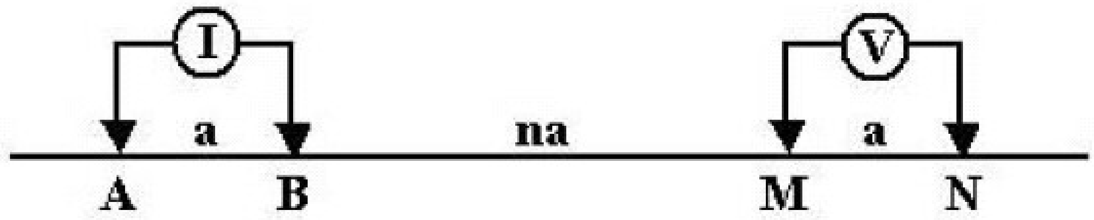
Schlumberger



$$\rho_A = \frac{V}{I}\pi\frac{b\,(b+a)}{a} \approx \frac{V}{I}\pi\frac{b^2}{a} \quad \text{if } a << b$$

Dipole-Dipole Array



The apparent resistivity is given by:

$$\rho_A = \frac{V}{I}\pi\, a\, n(n+1)(n+2).$$

The electric potential varies as 1/r around a single current electrode on a *homogeneous half-space*

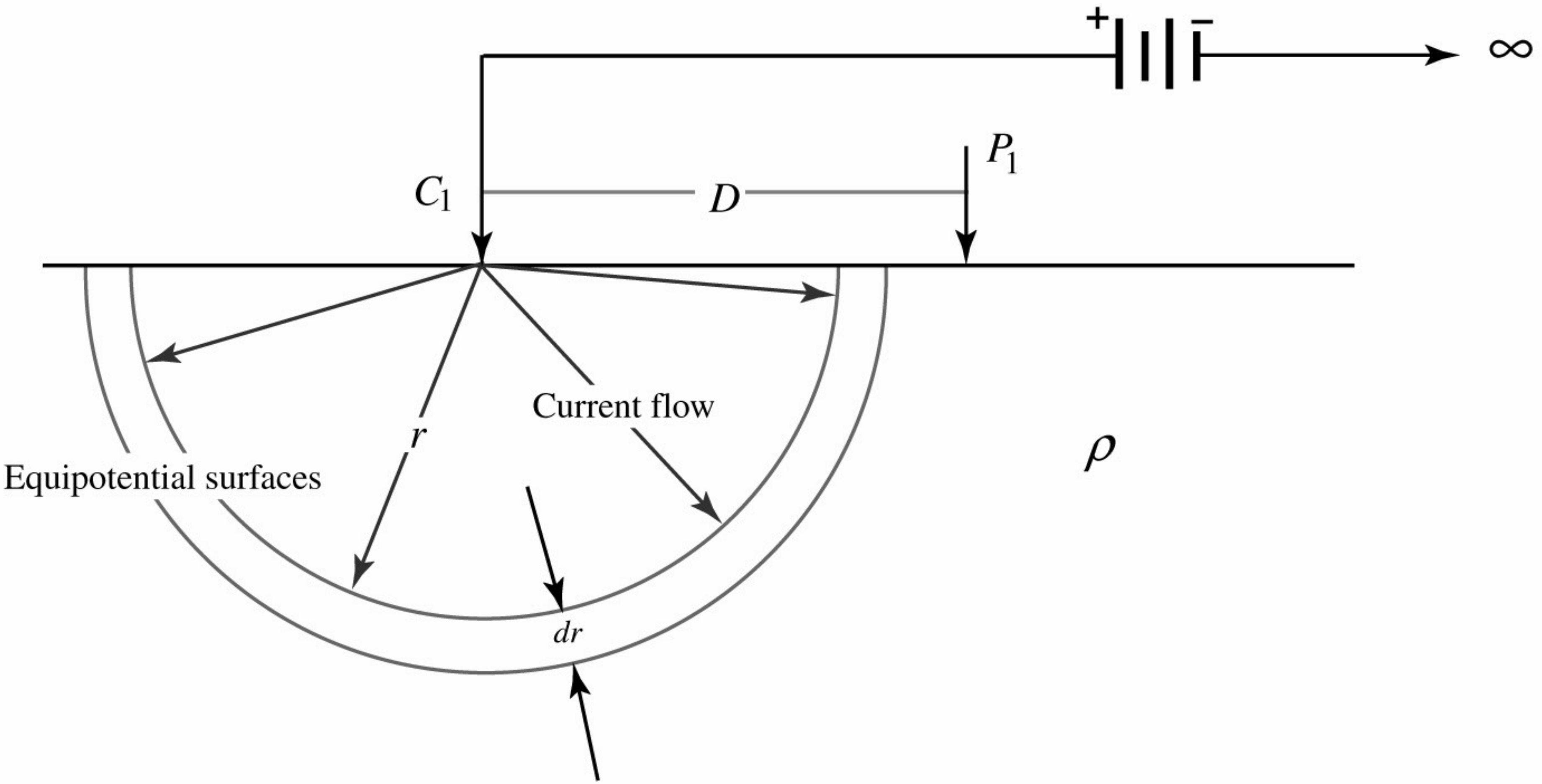


FIGURE 5.4g

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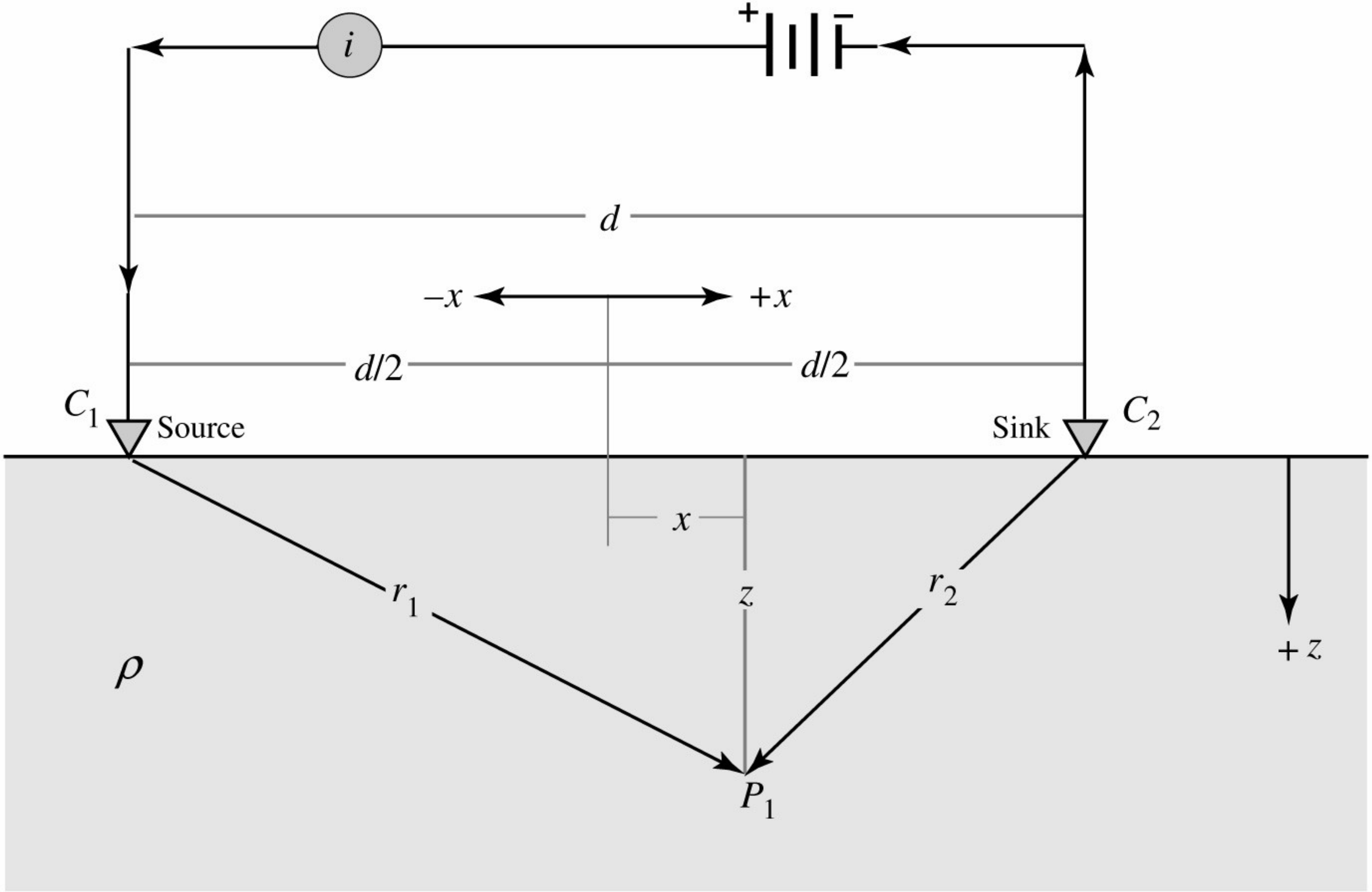

FIGURE 5.5g

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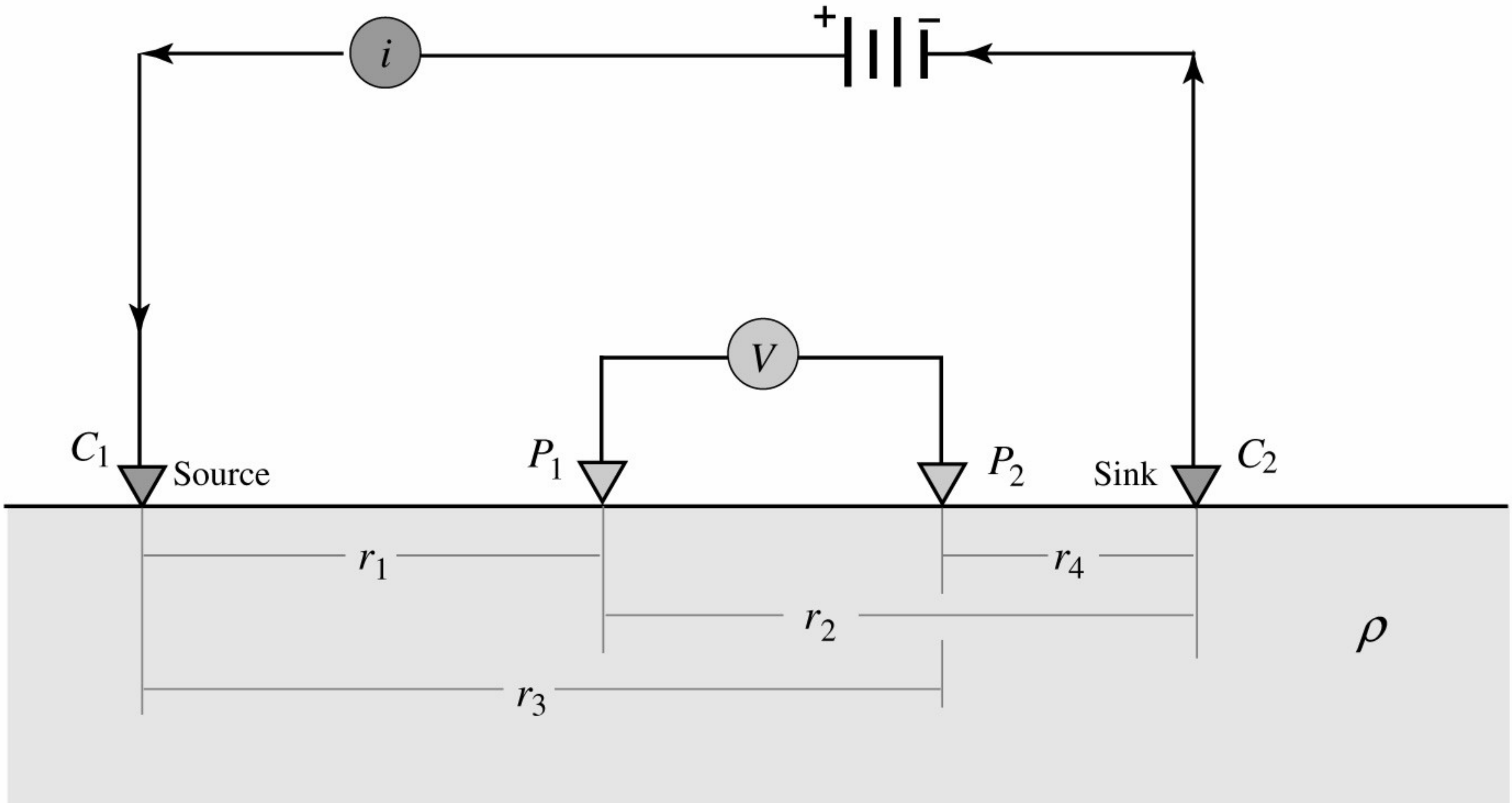

FIGURE 5.9g

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Equal potential voltage surfaces between the electrodes

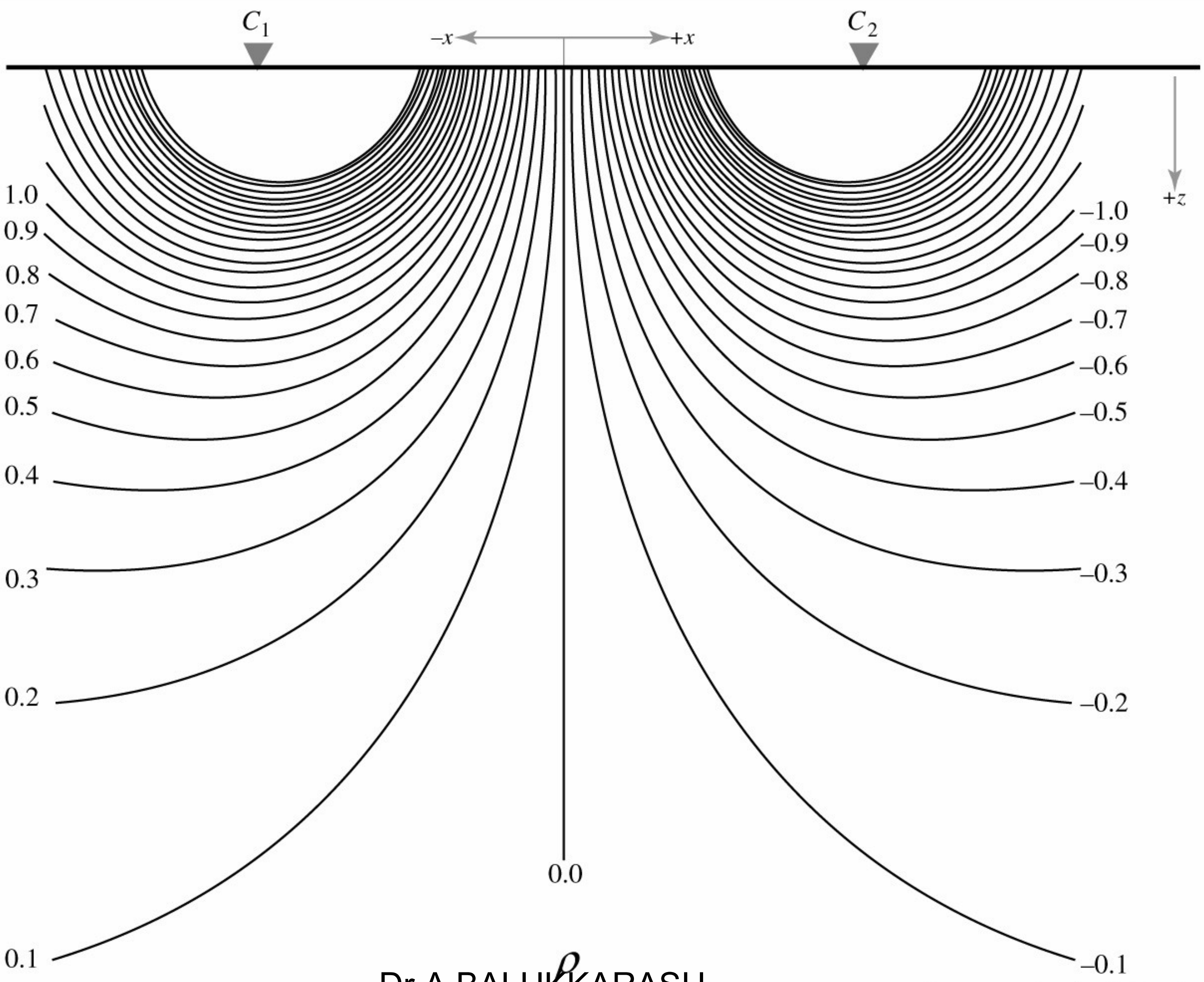

FIGURE 5.6g

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Depth of current flow between two current electrodes

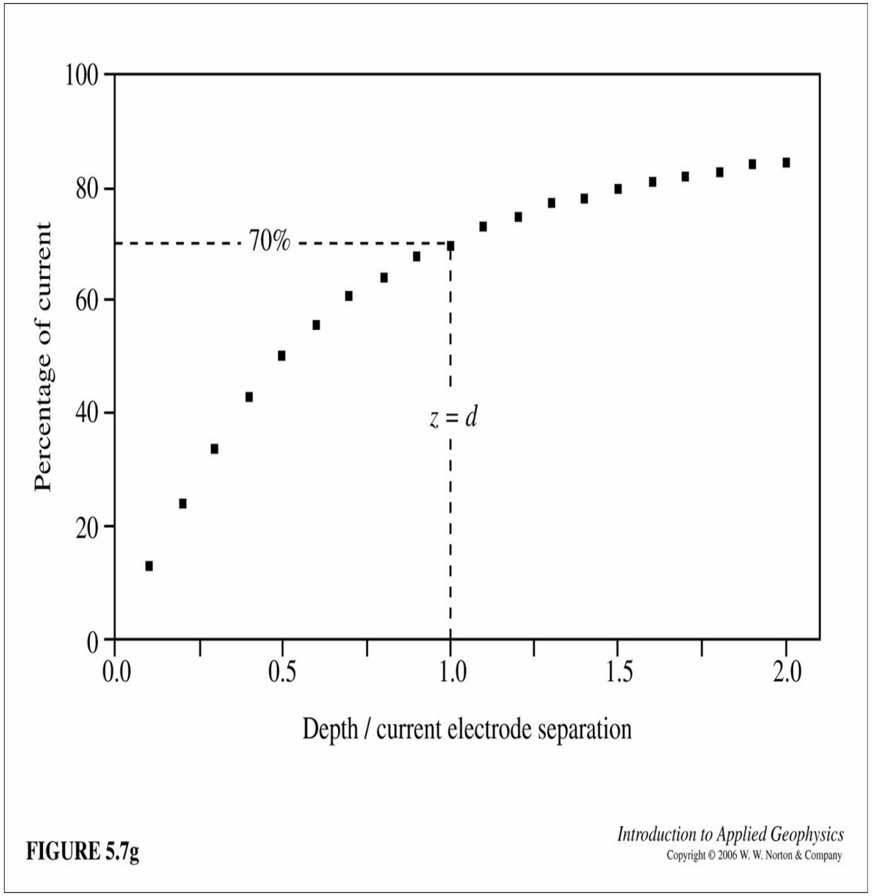
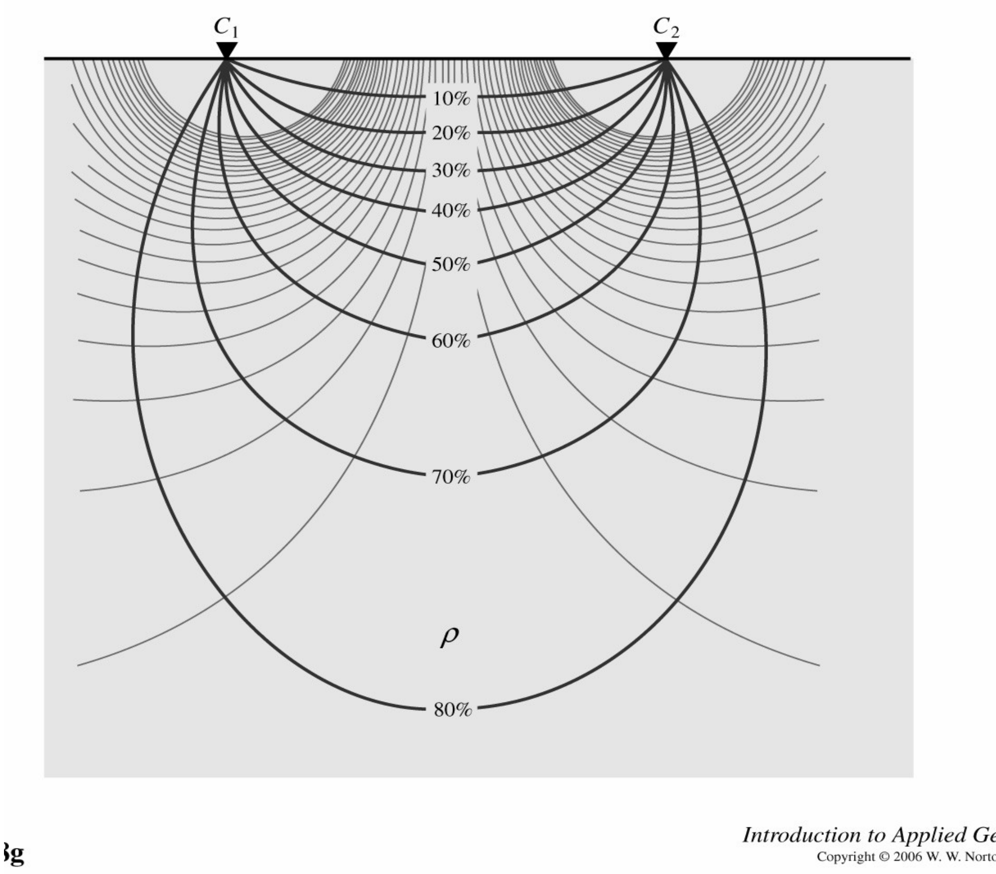


FIGURE 5.7g



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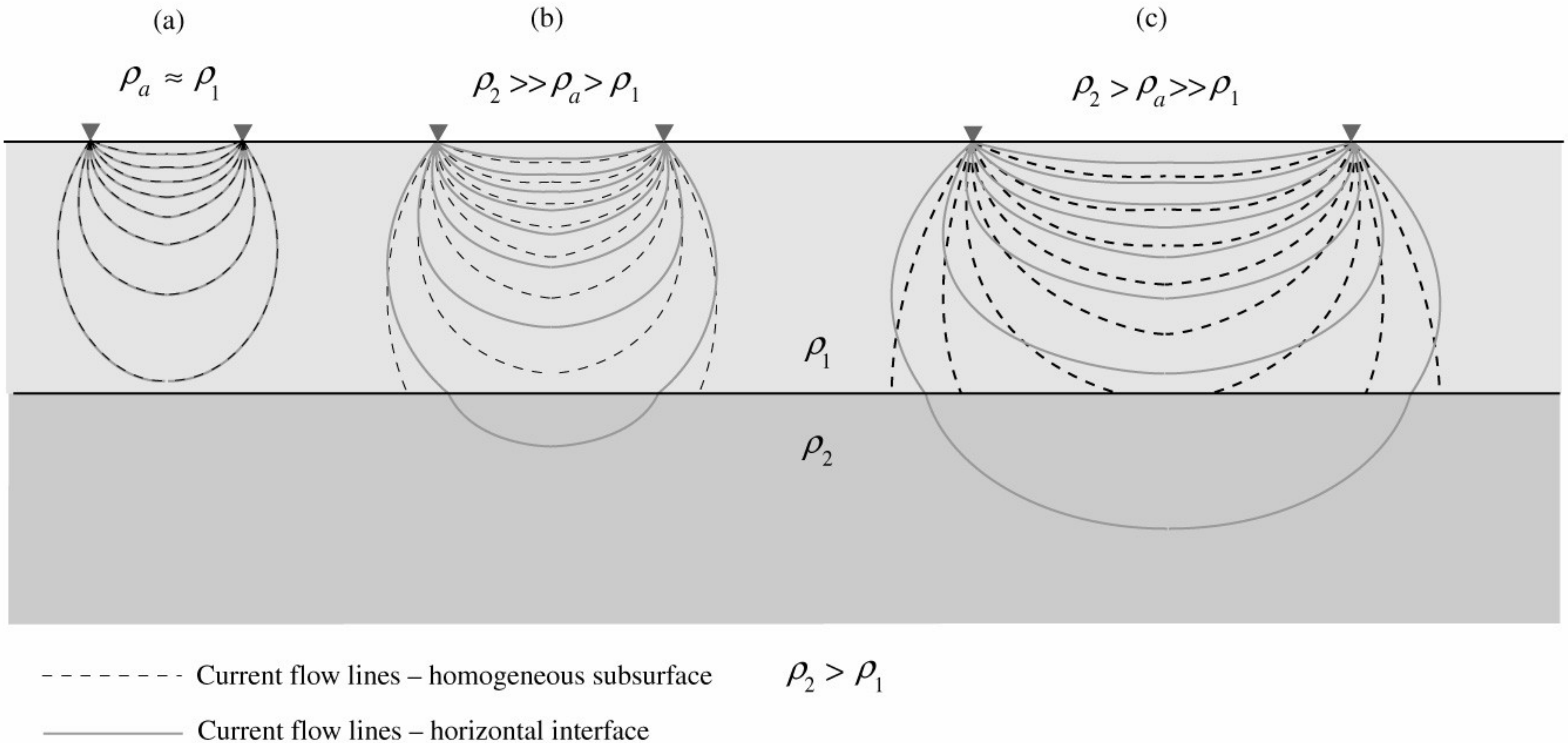

FIGURE 5.14g

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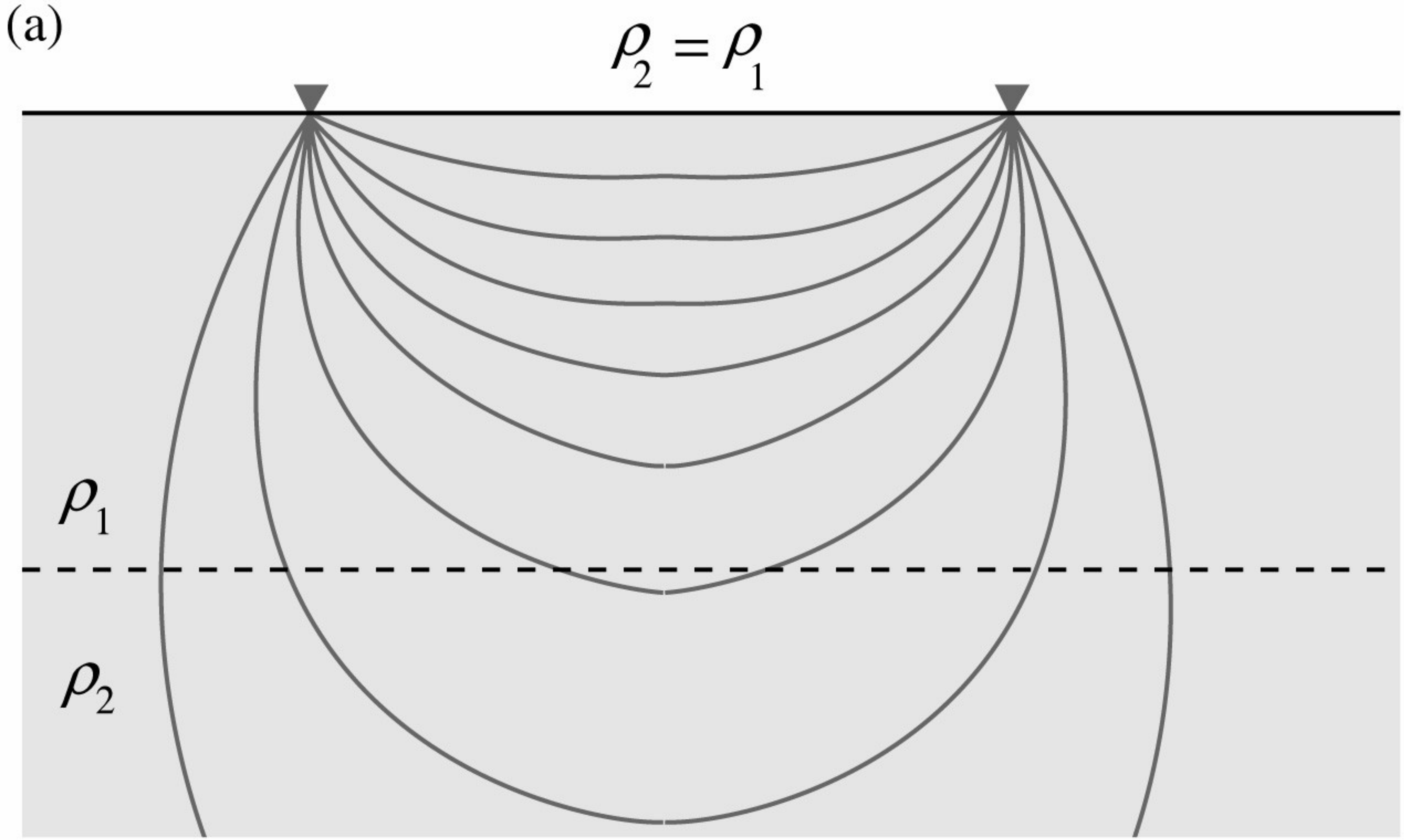

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FIGURE 5.13g (a)

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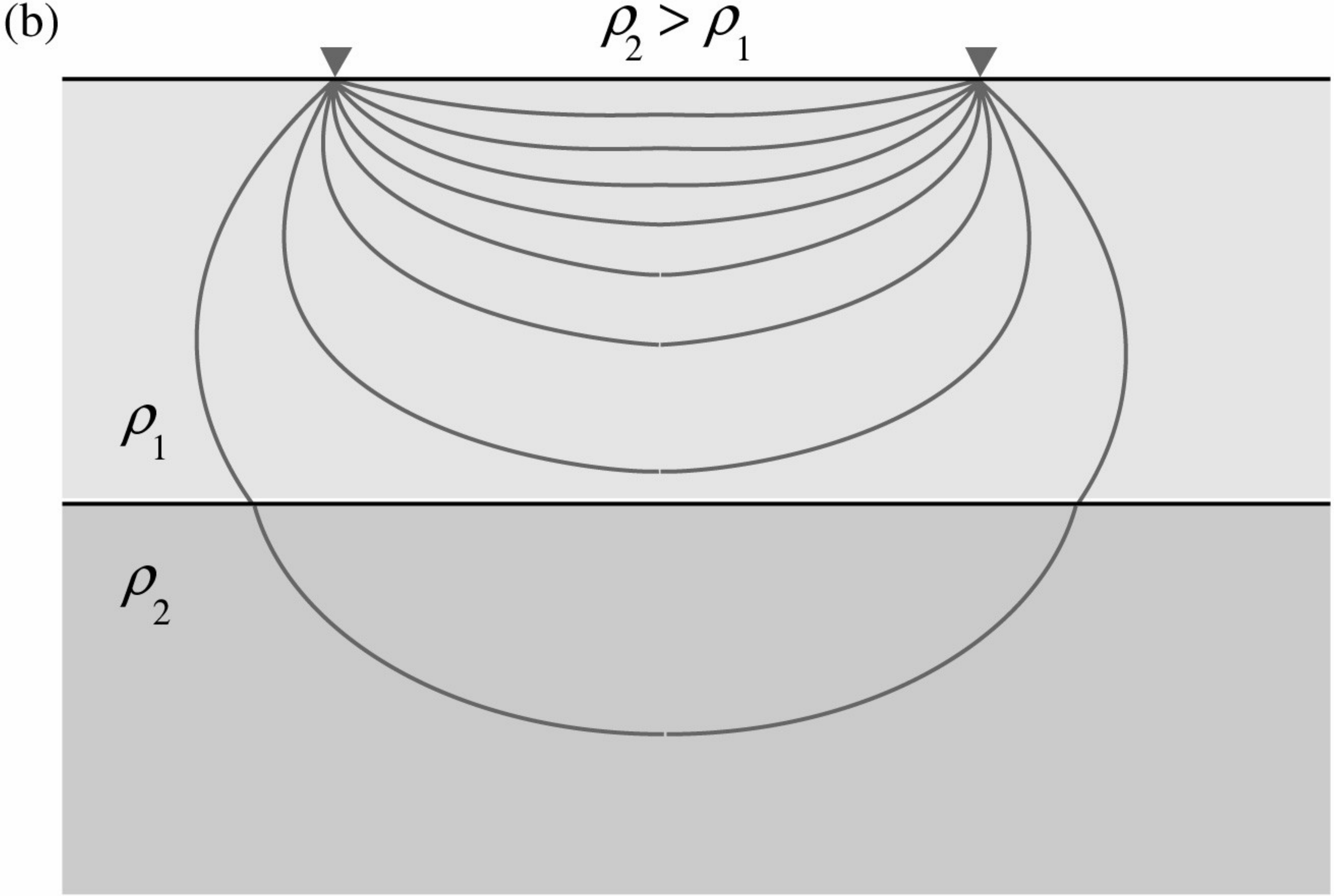

FIGURE 5.13g (b)

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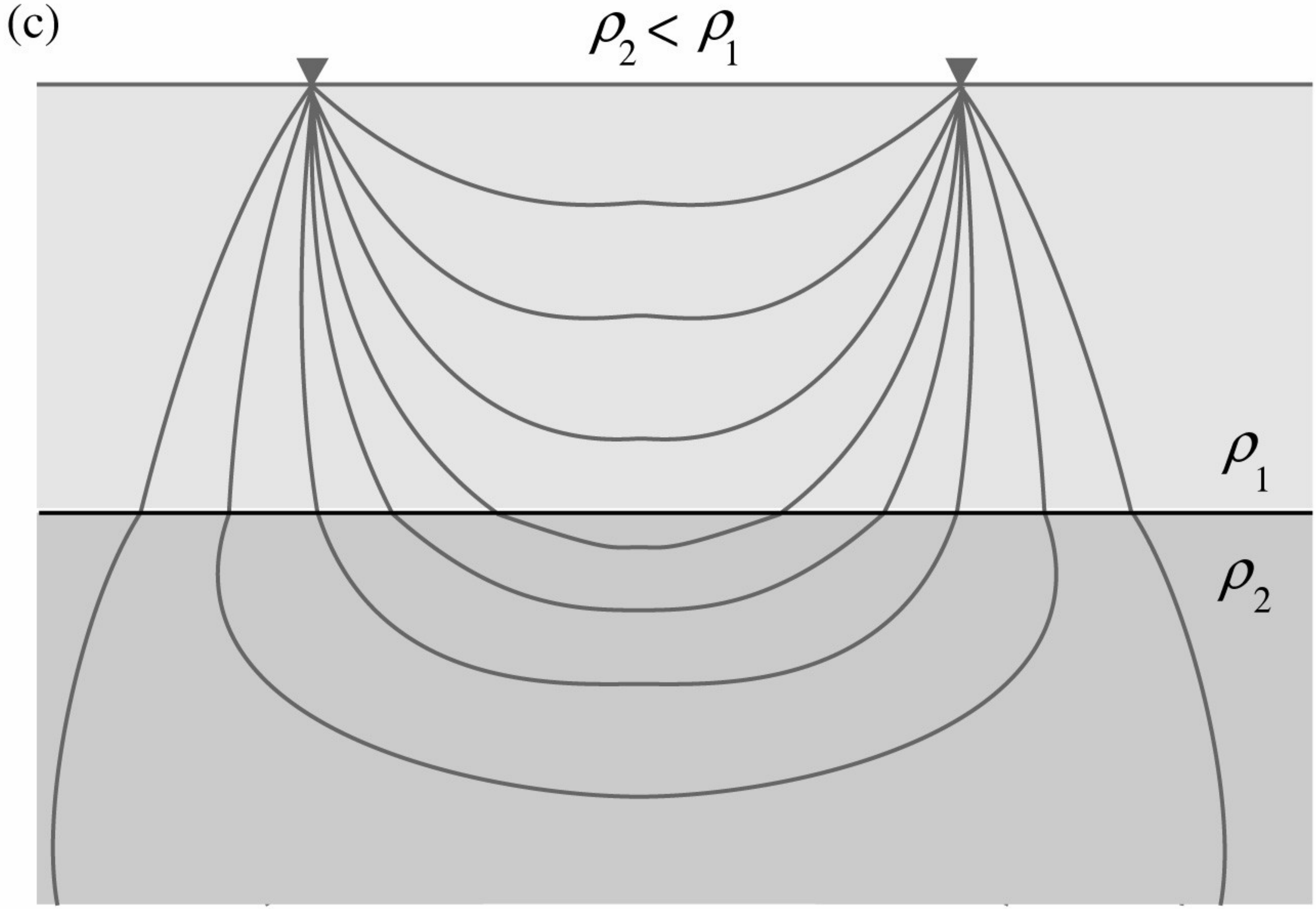

FIGURE 5.13g (c)

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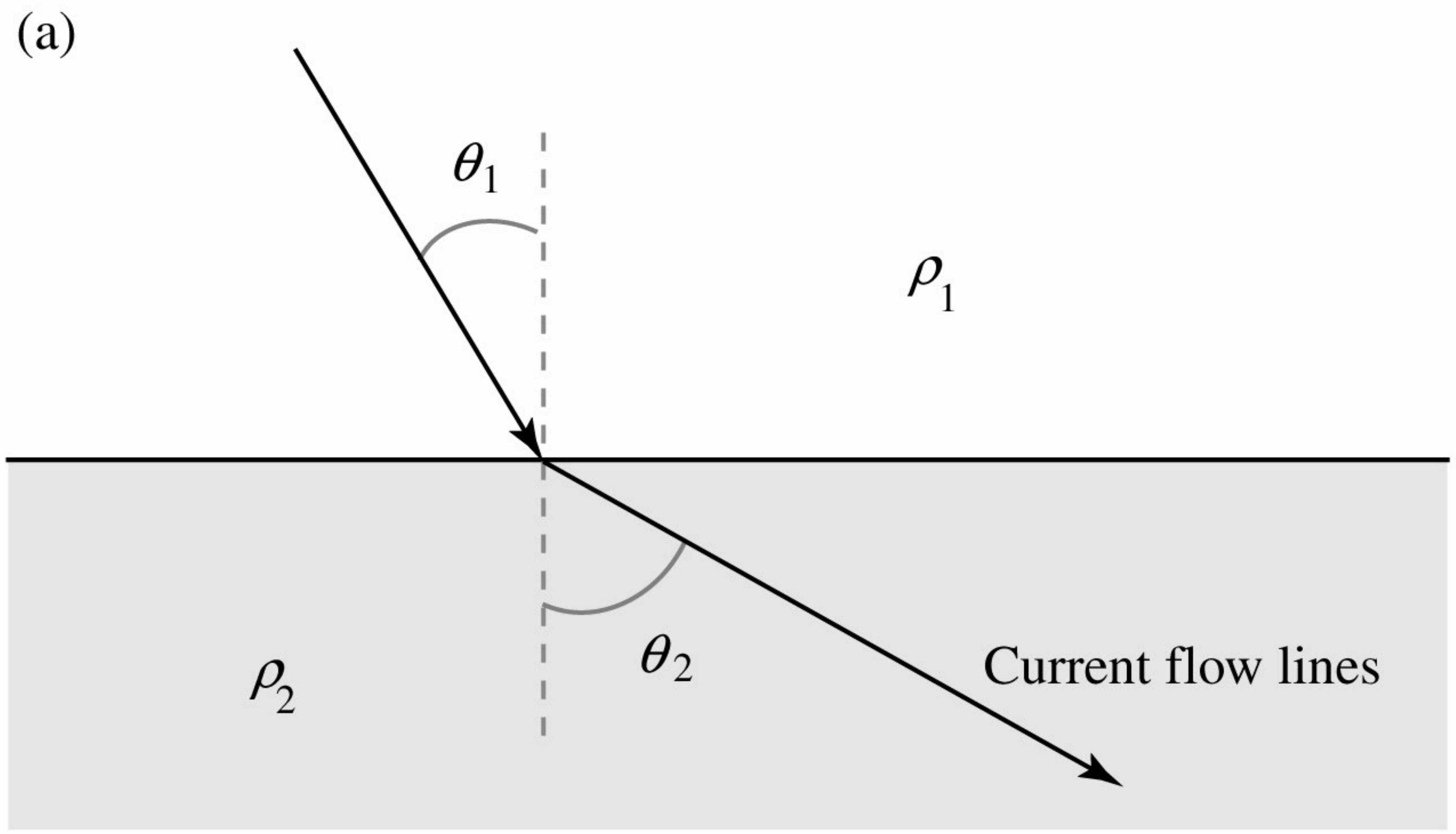

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FIGURE 5.12g (a)

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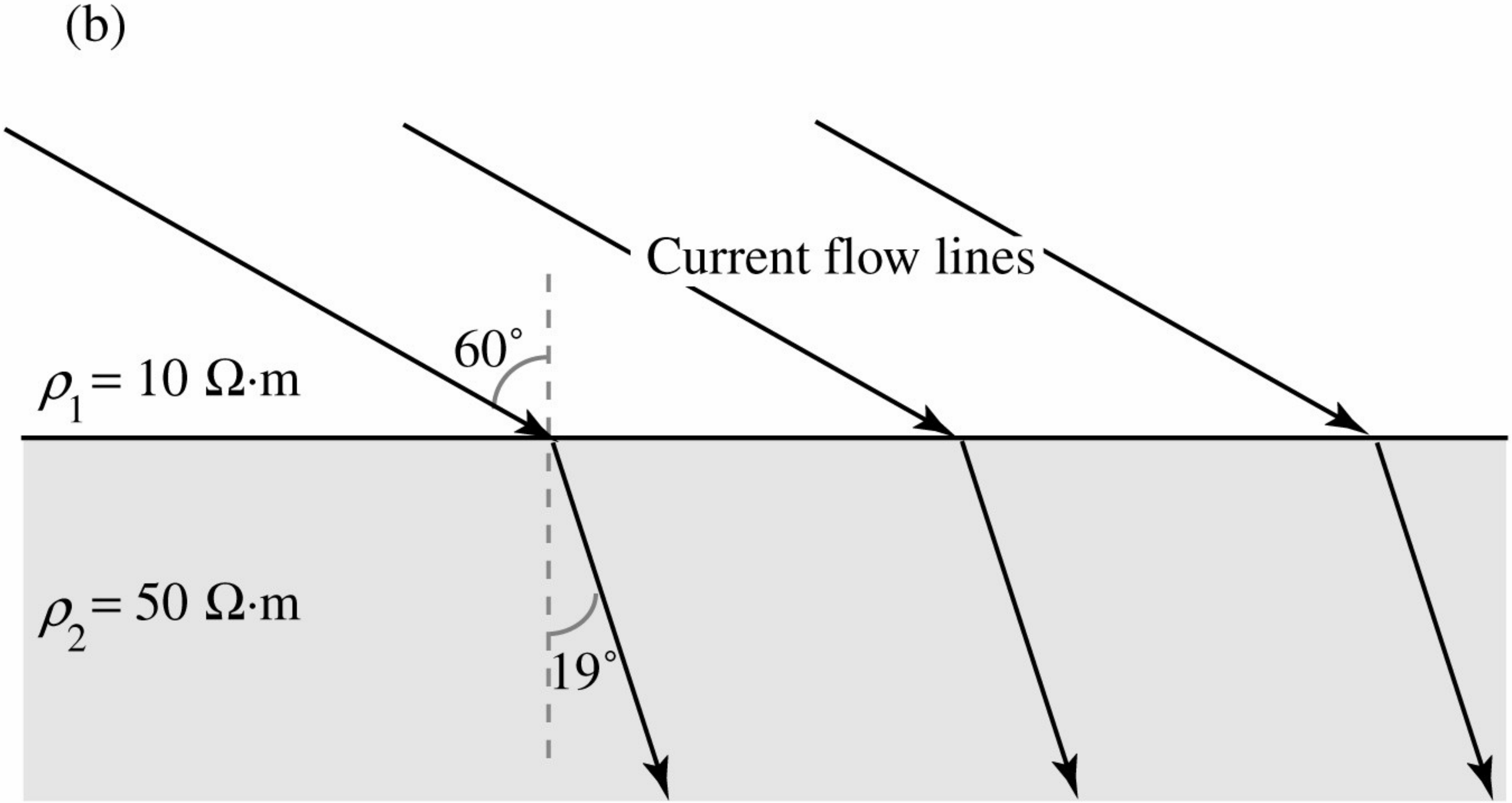

FIGURE 5.12g (b)

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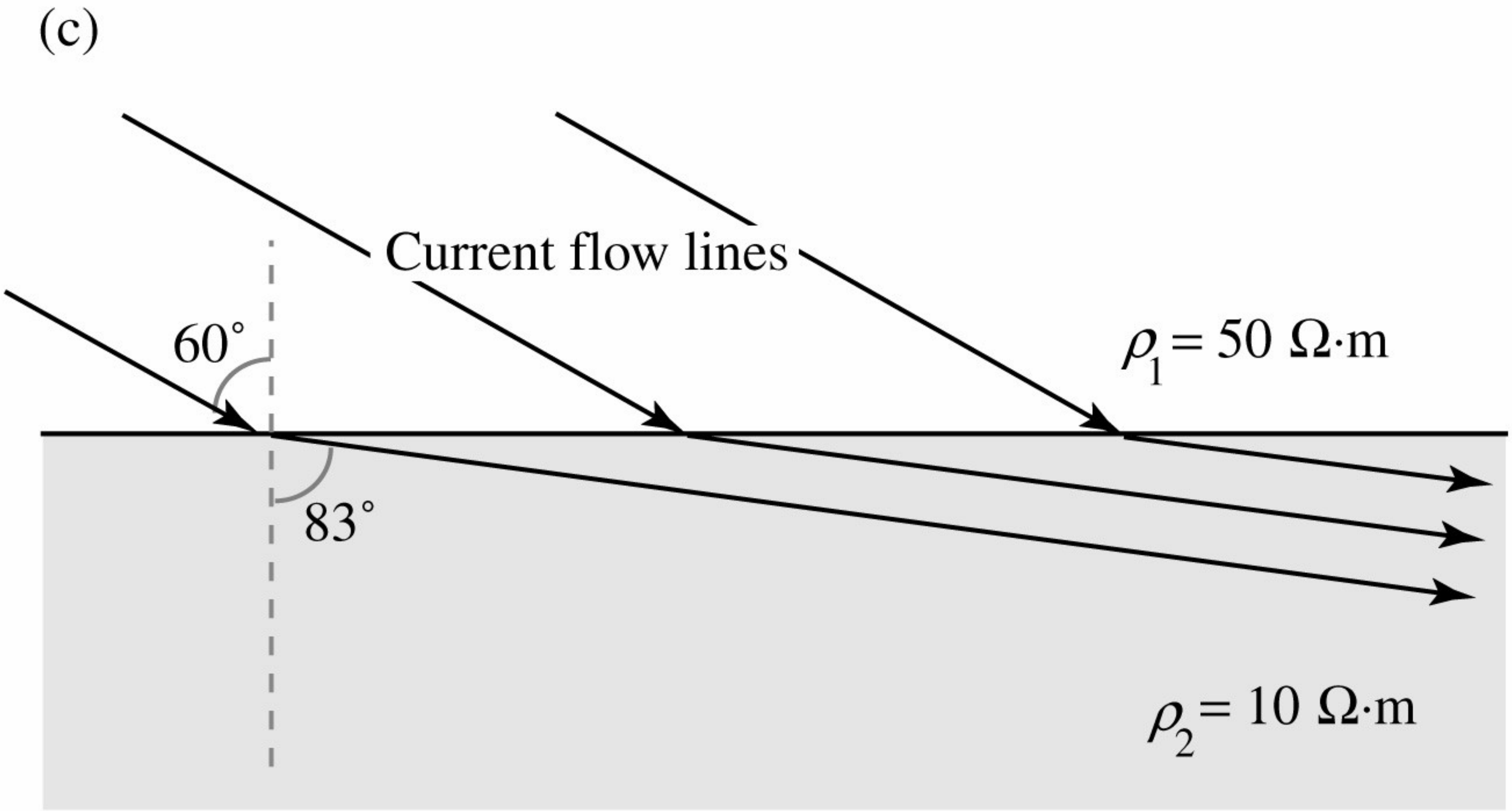

FIGURE 5.12g (c)

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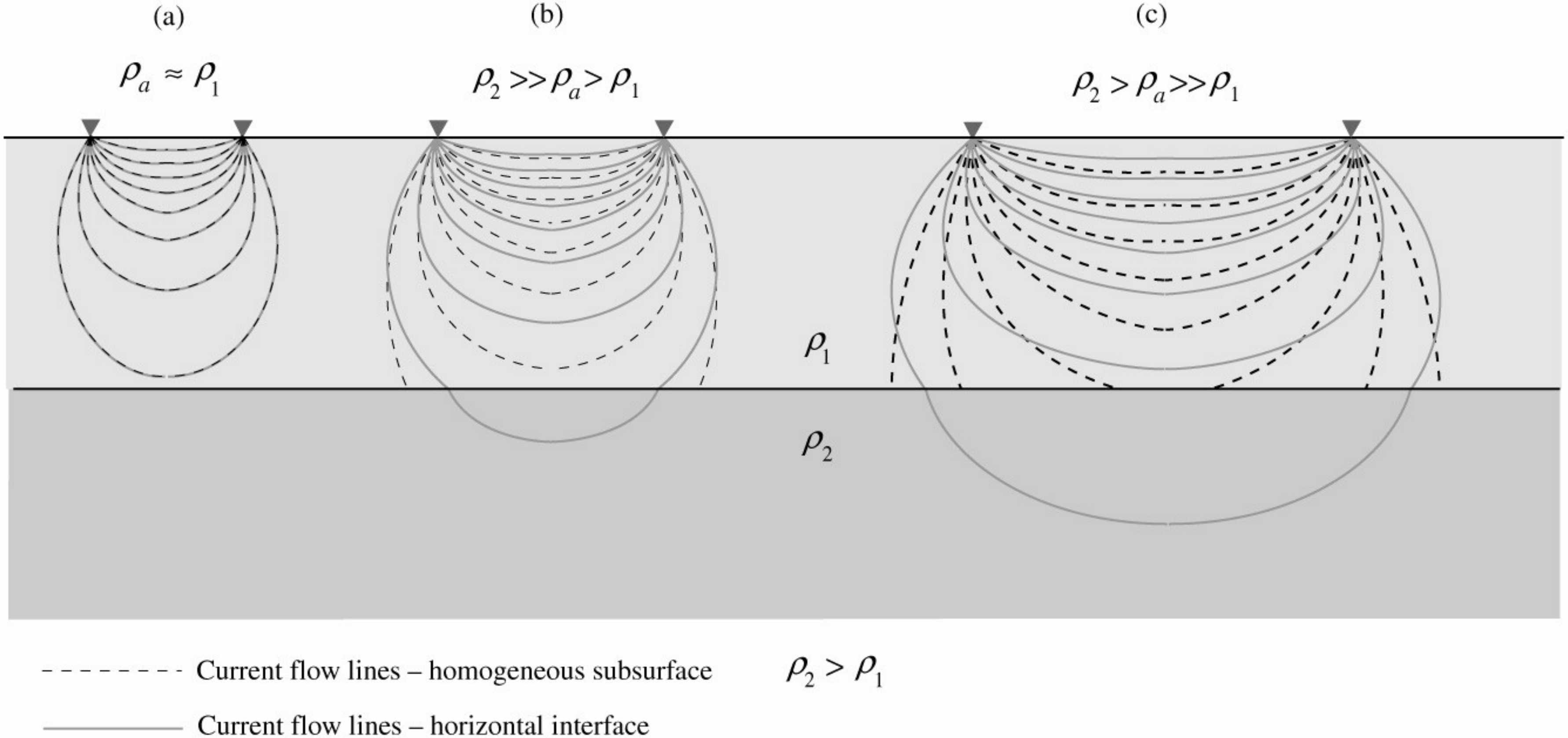

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FIGURE 5.14g

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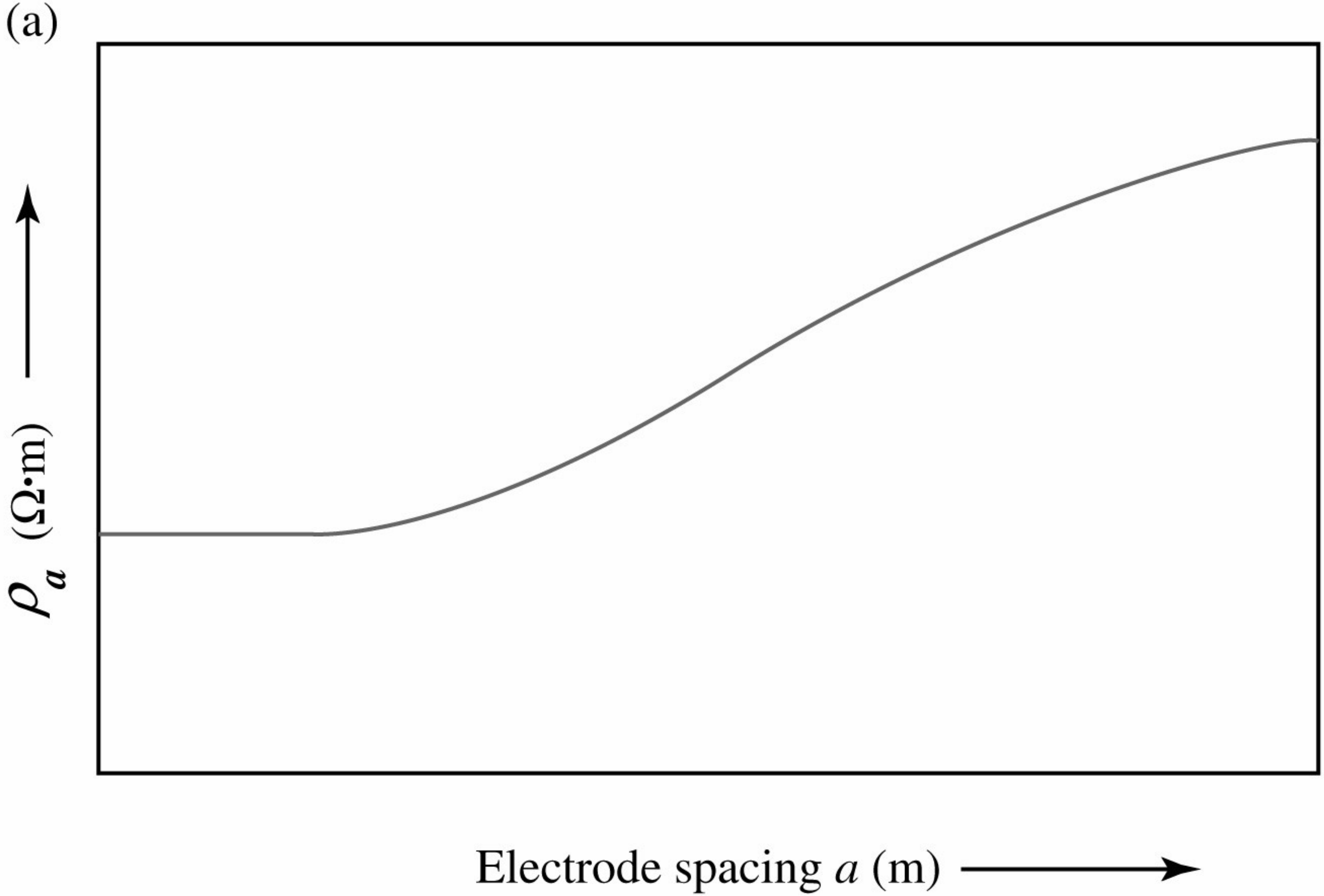

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FIGURE 5.15g (a)

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(b)

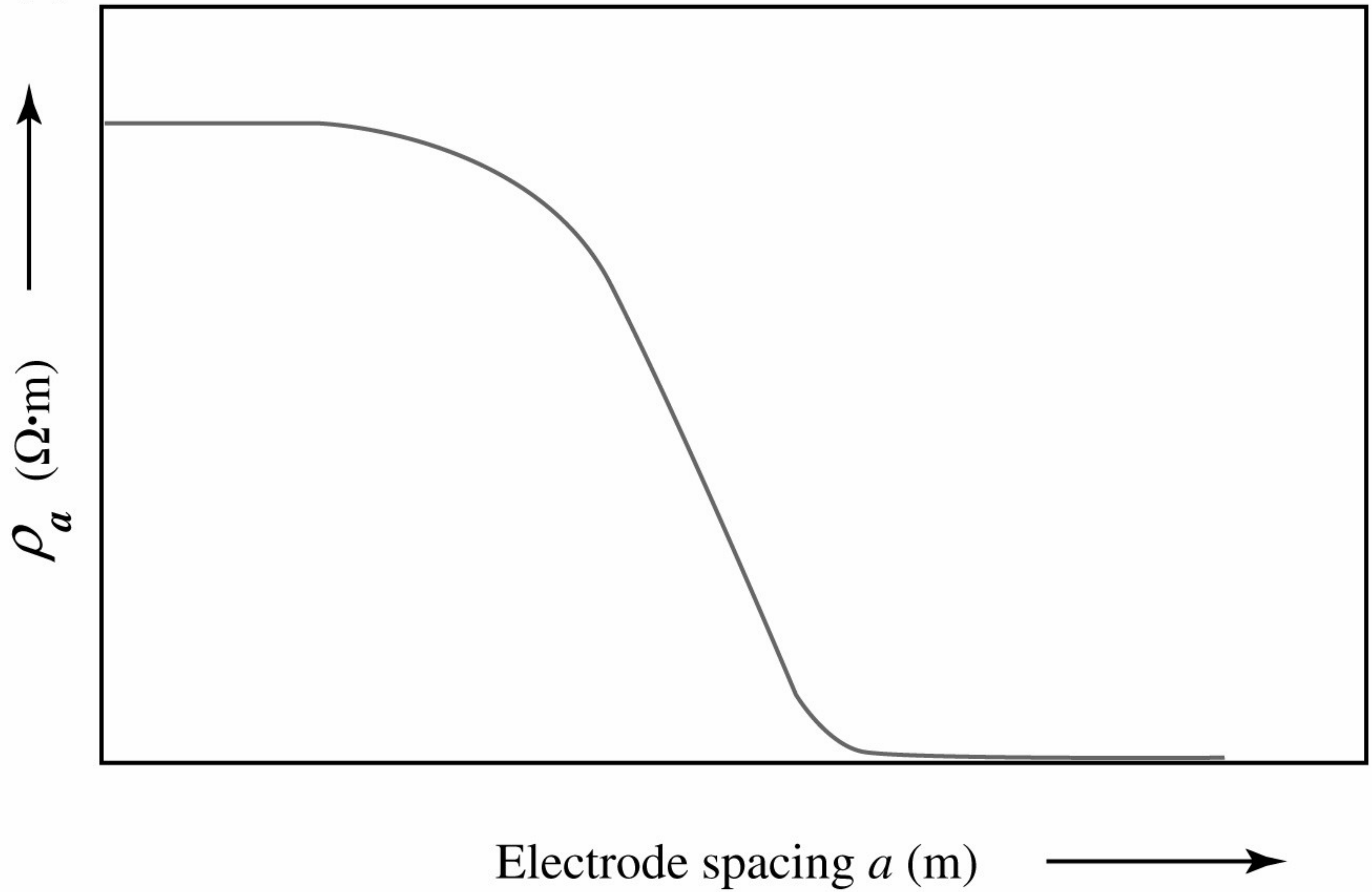

FIGURE 5.15g (b)

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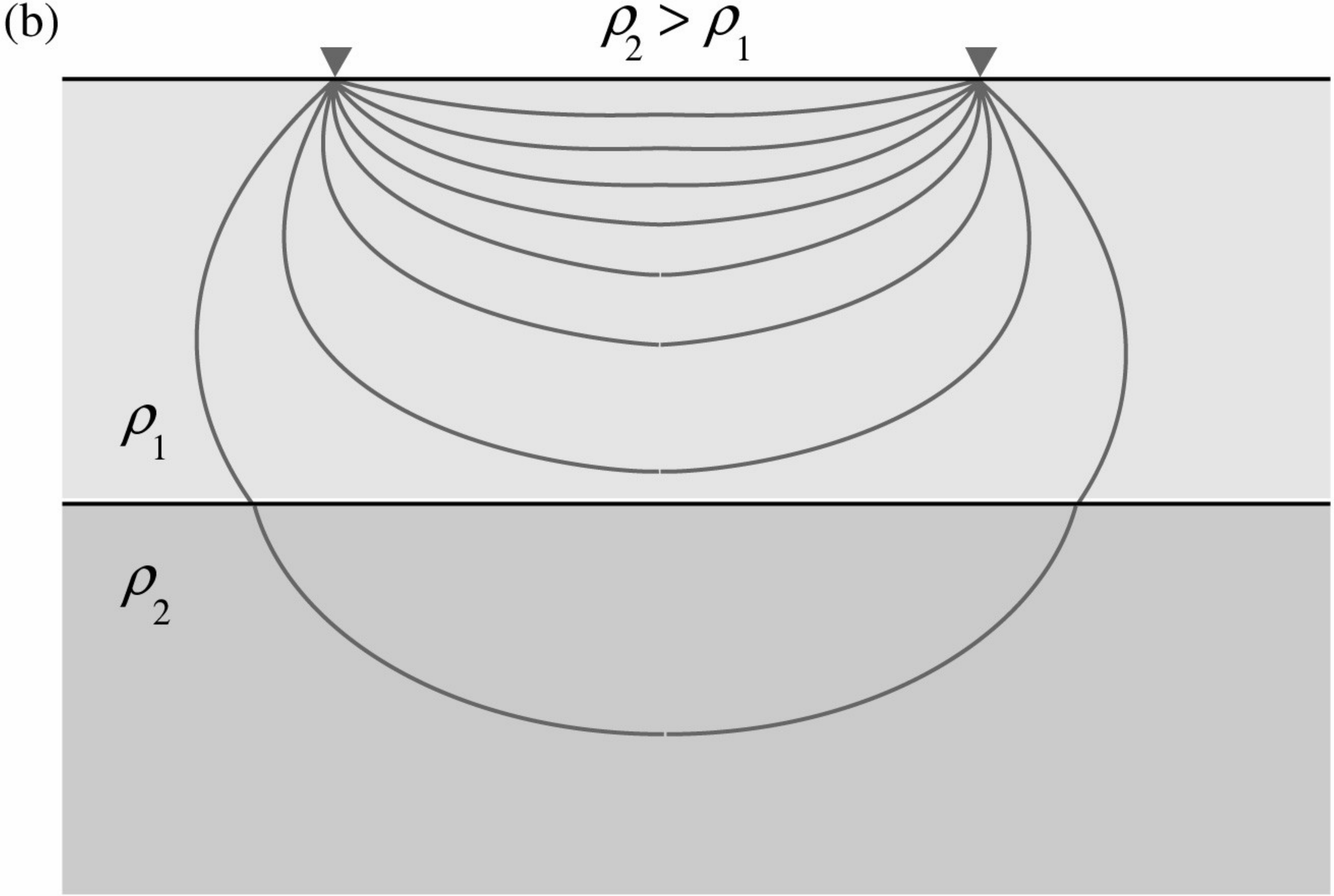

FIGURE 5.13g (b)

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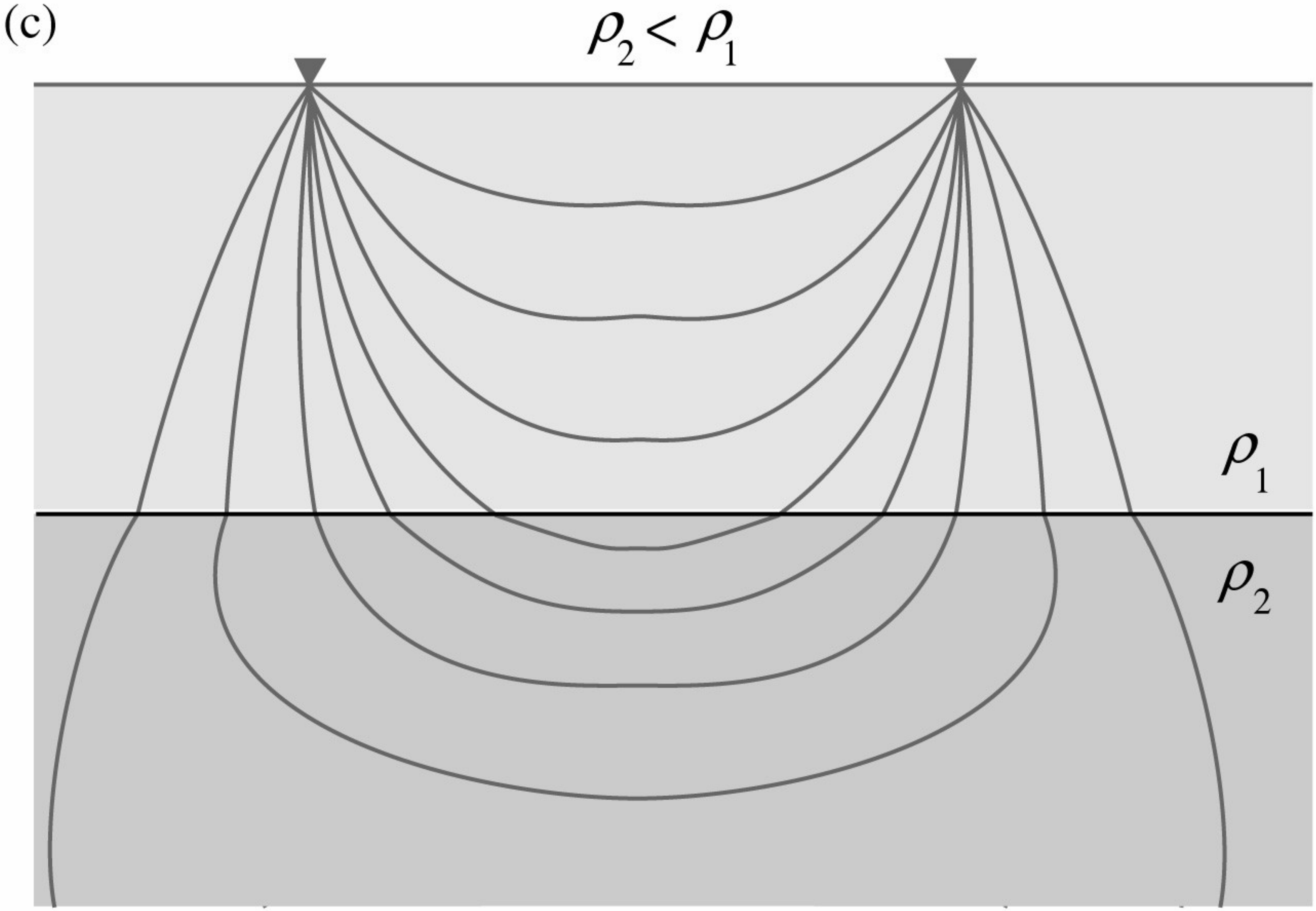

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FIGURE 5.13g (c)

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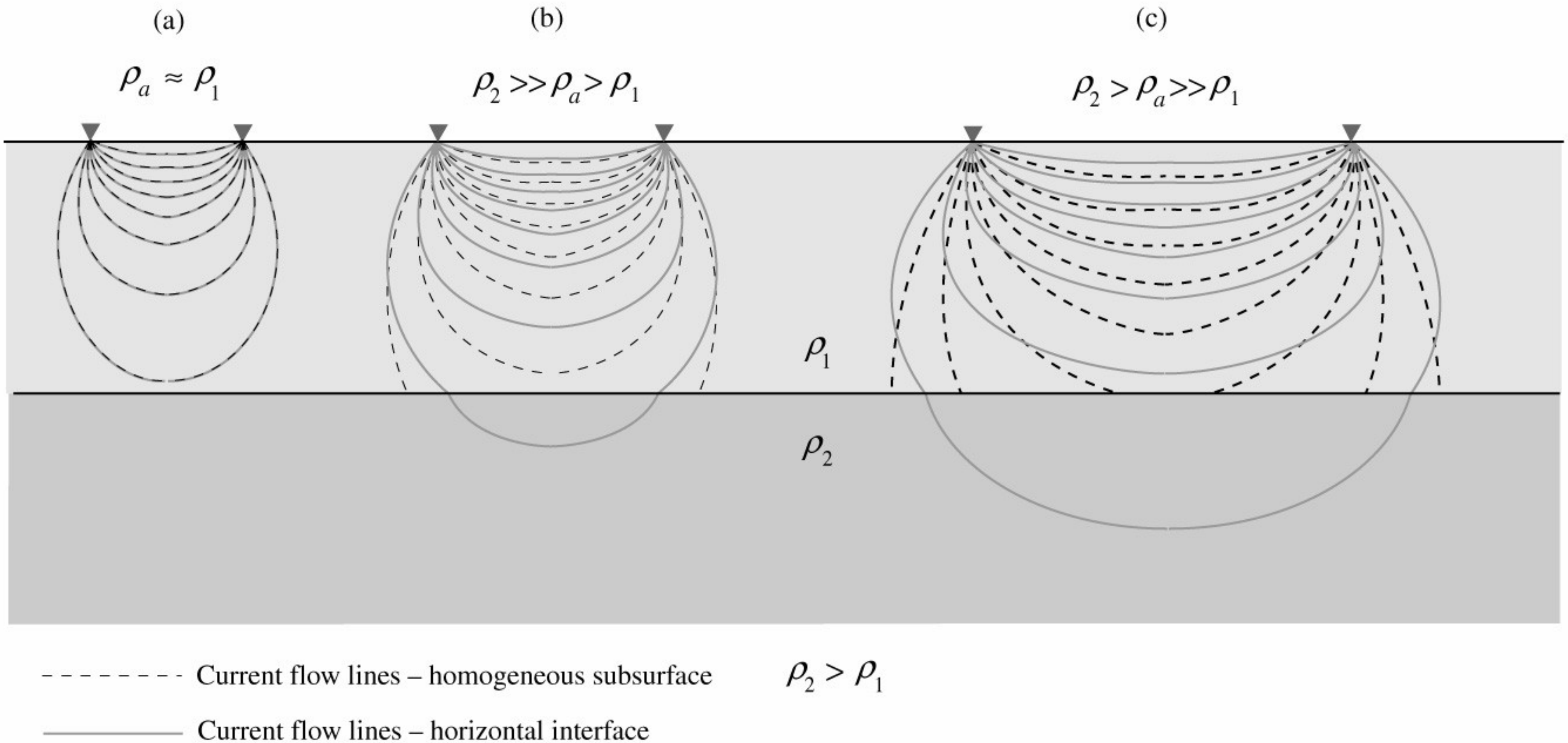

FIGURE 5.14g

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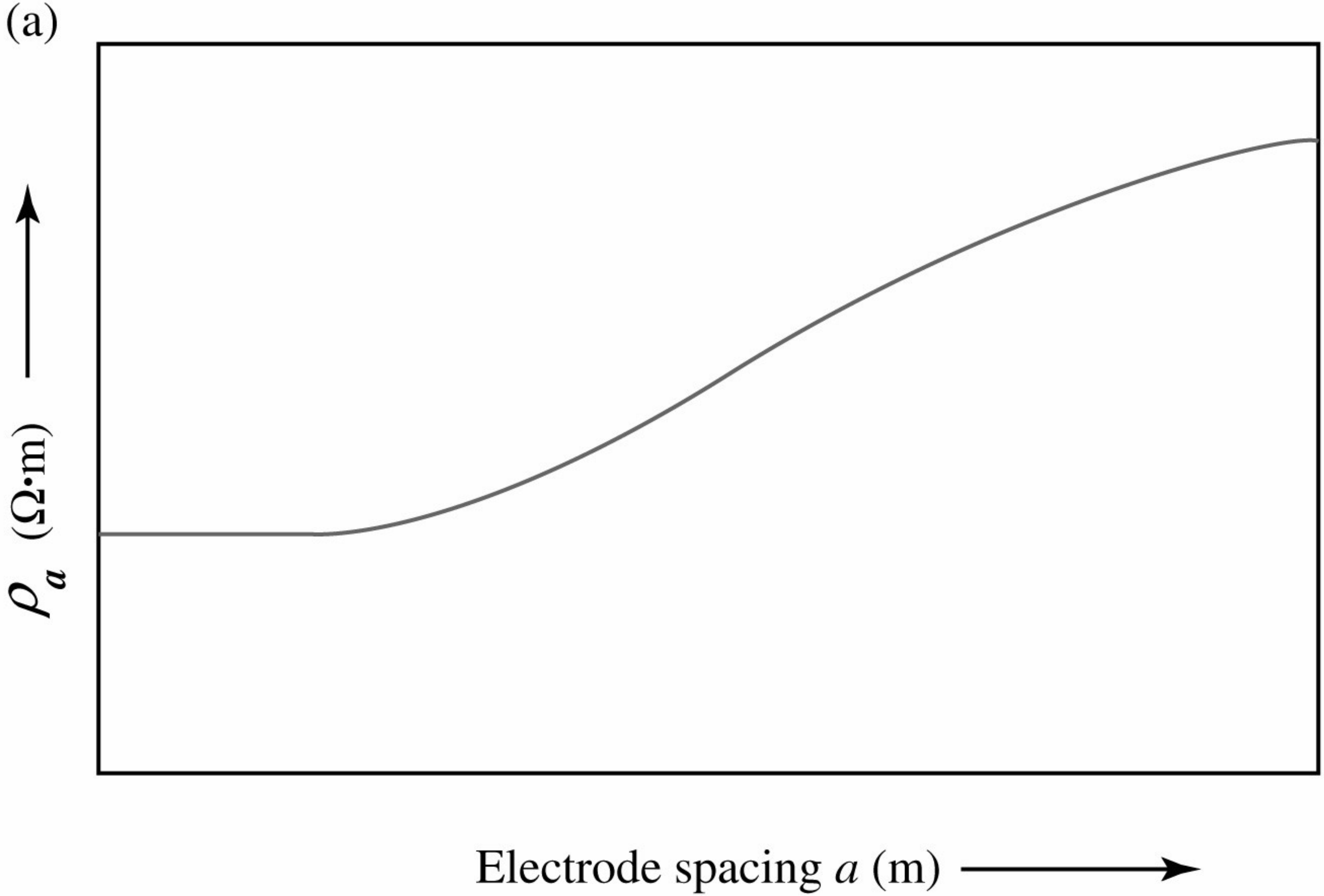

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FIGURE 5.15g (a)

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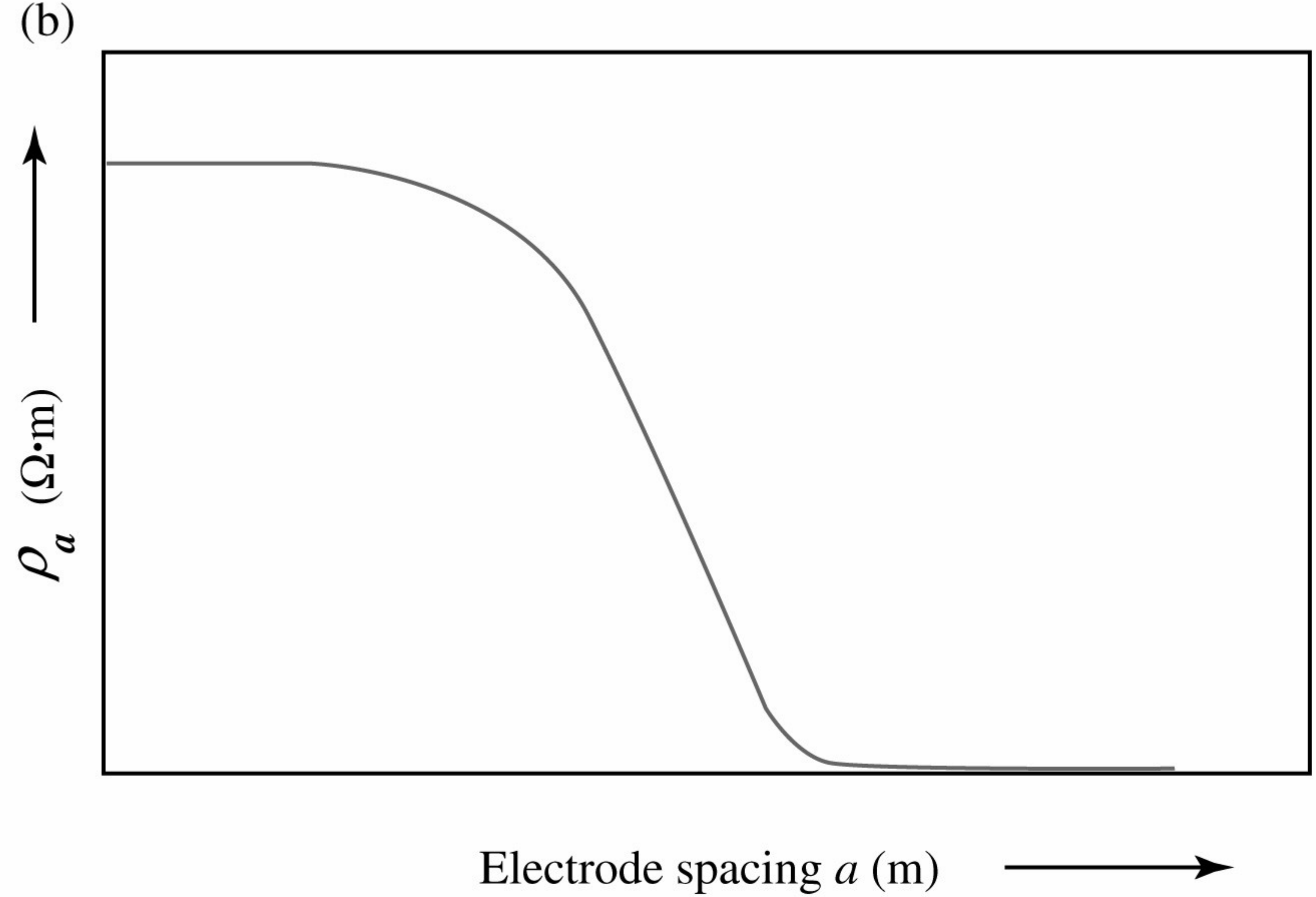

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FIGURE 5.15g (b)

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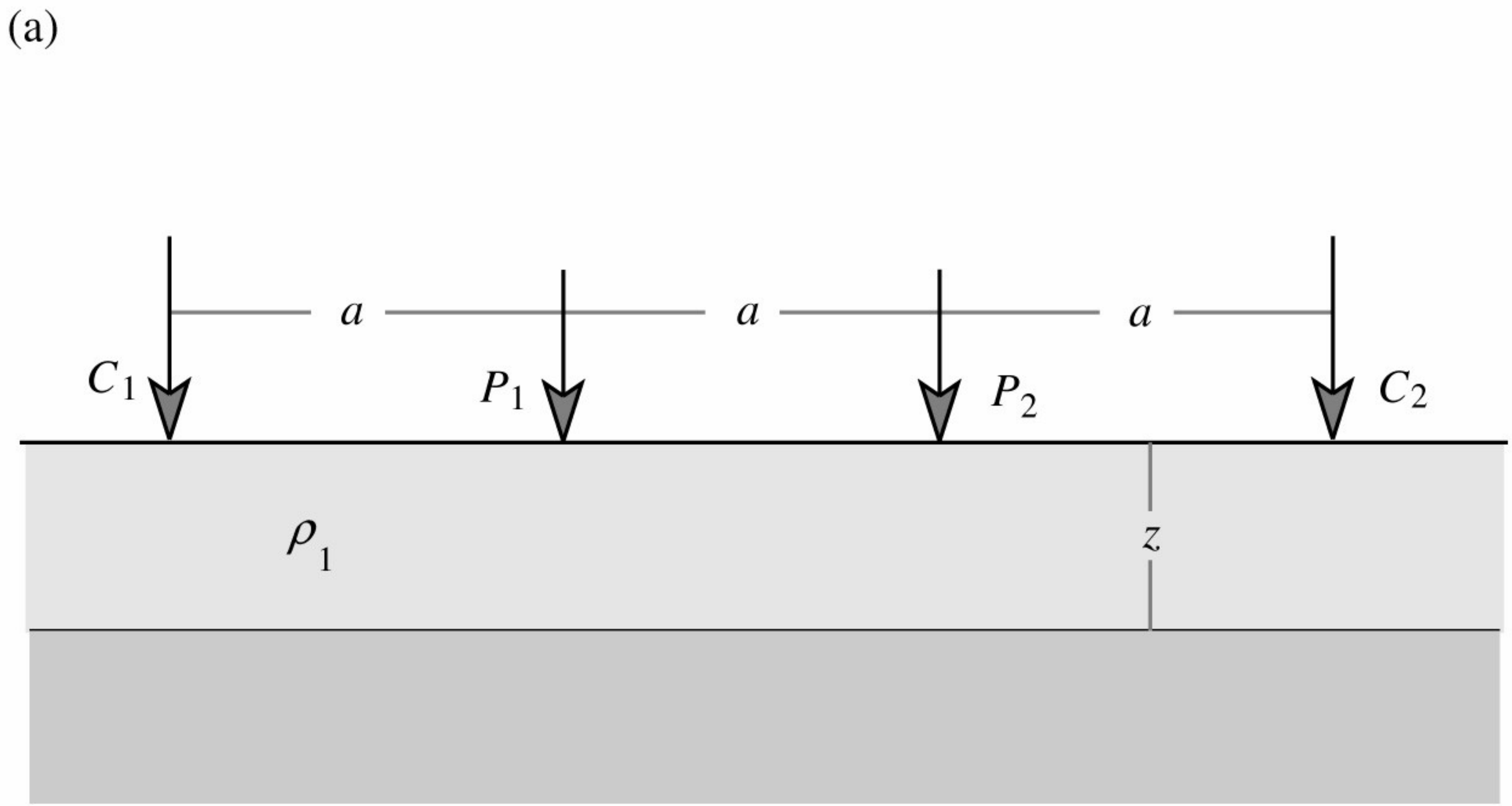

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FIGURE 5.18g (a)

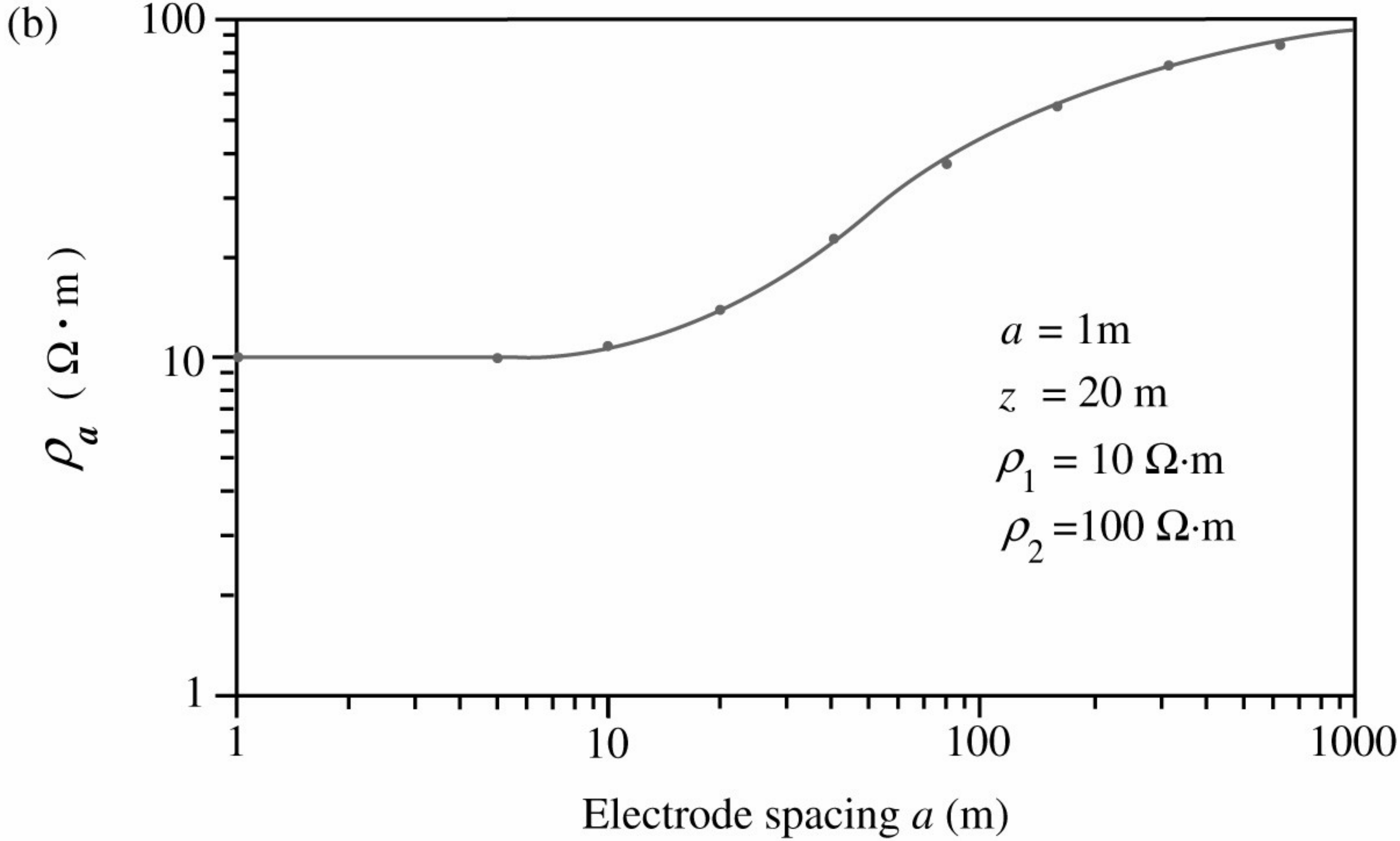

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FIGURE 5.18g (b)

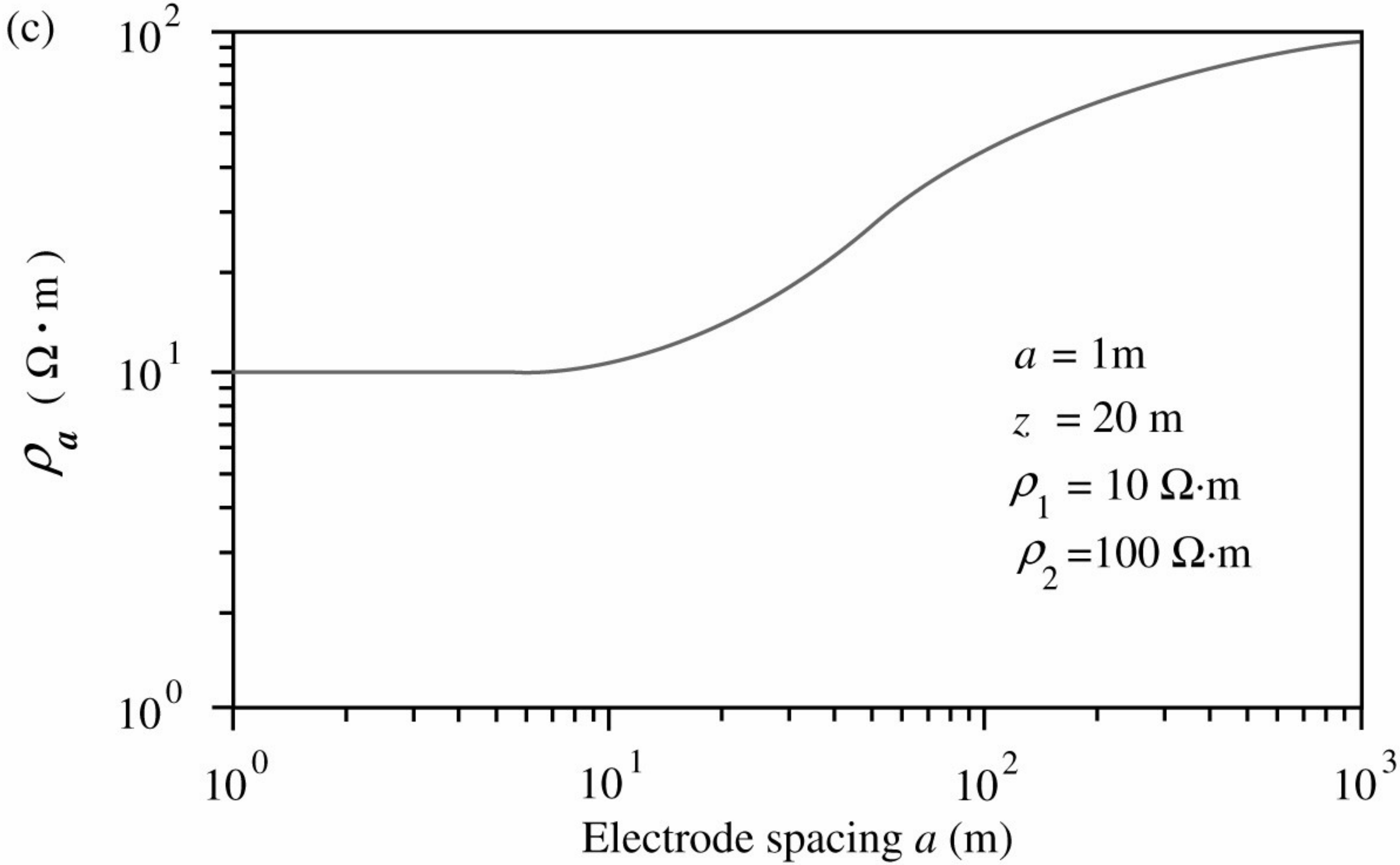

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FIGURE 5.18g (c)

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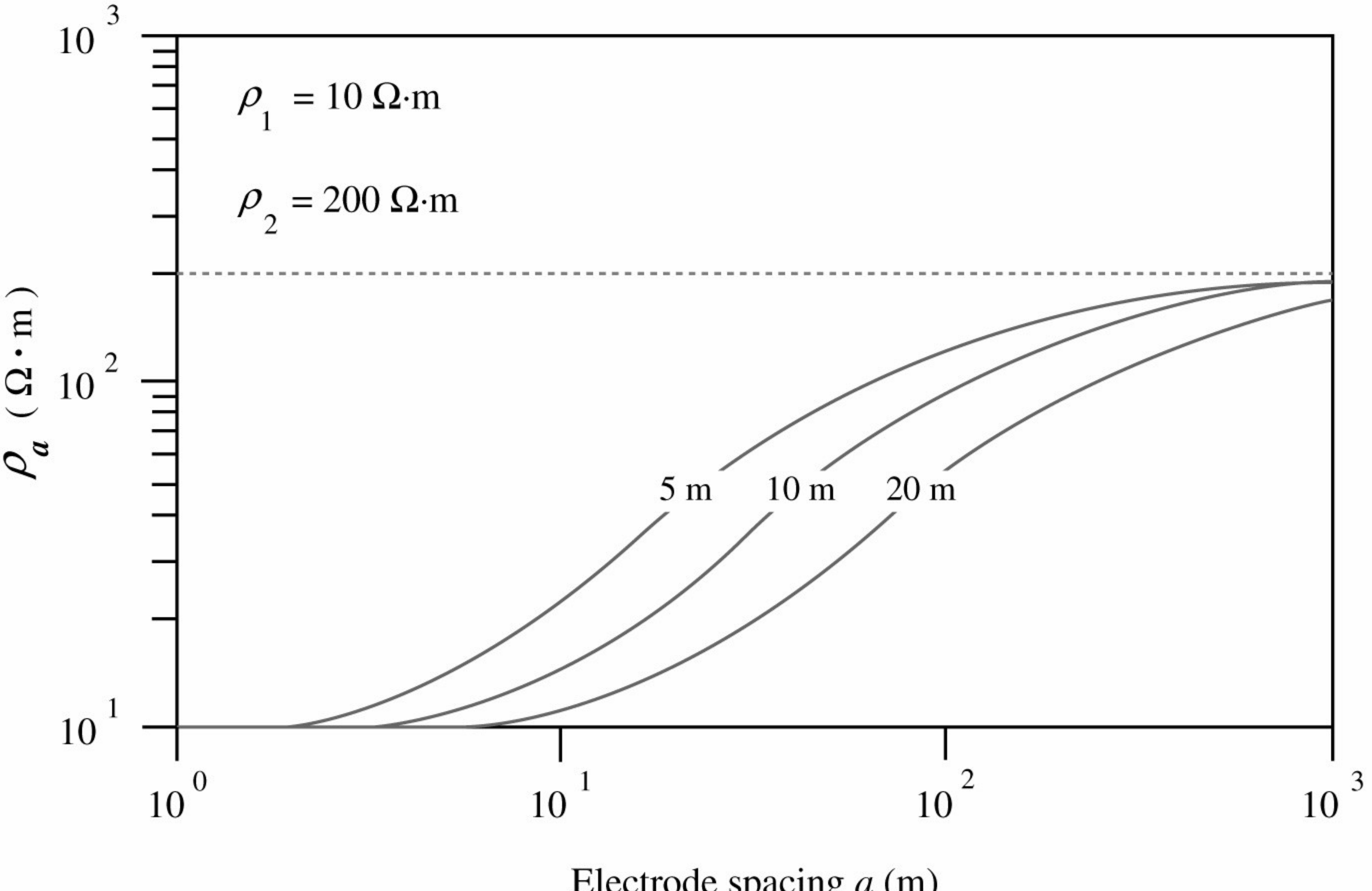

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FIGURE 5.19g

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(a)

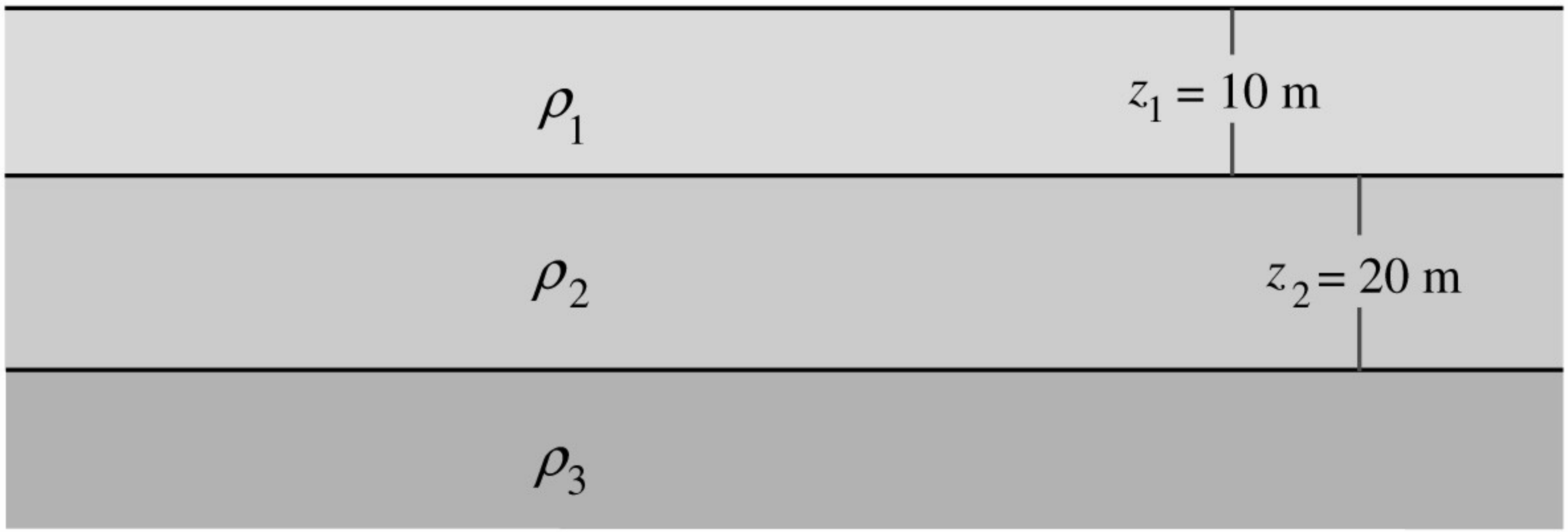

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FIGURE 5.21g (a)

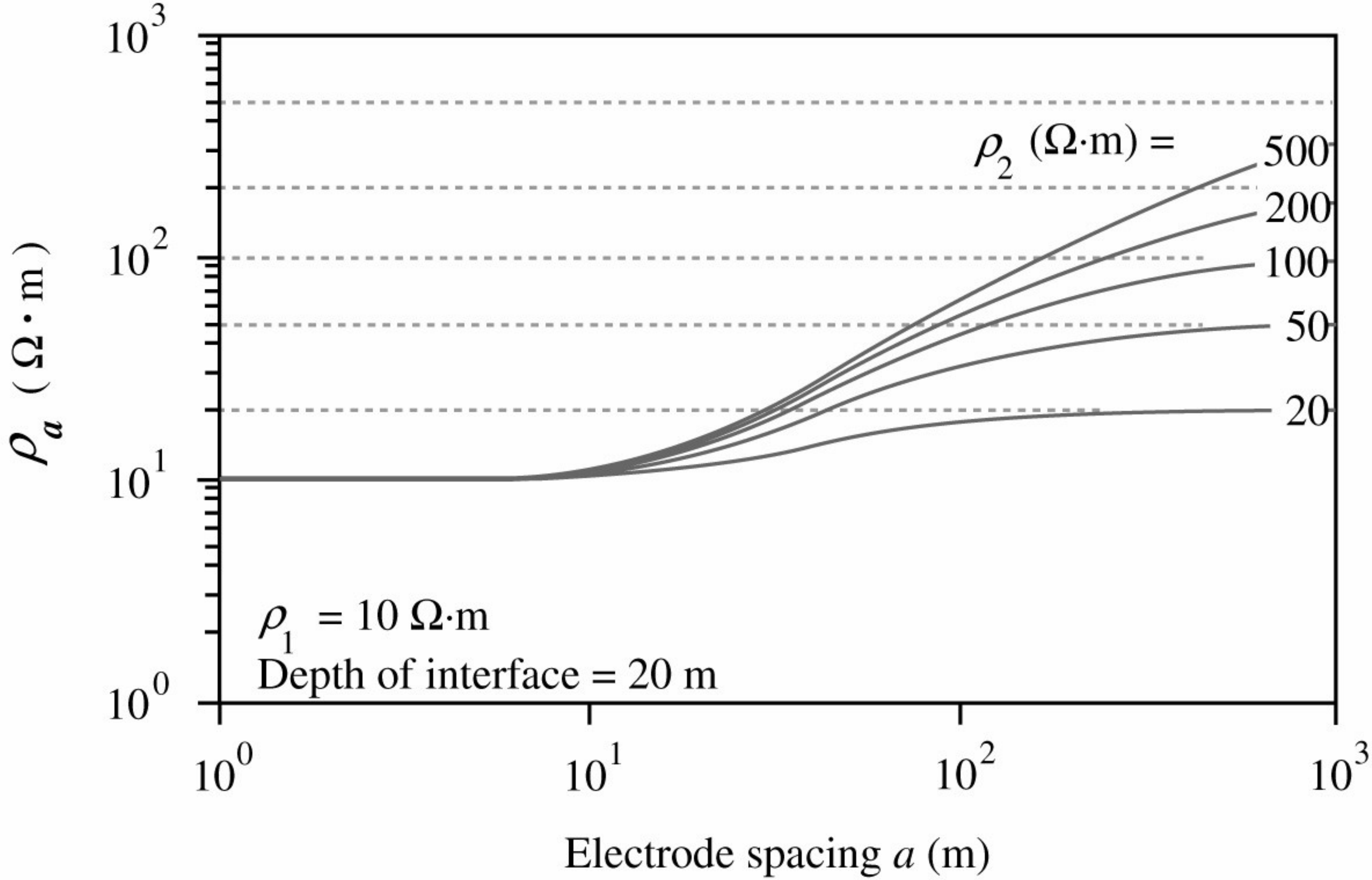

FIGURE 5.20g

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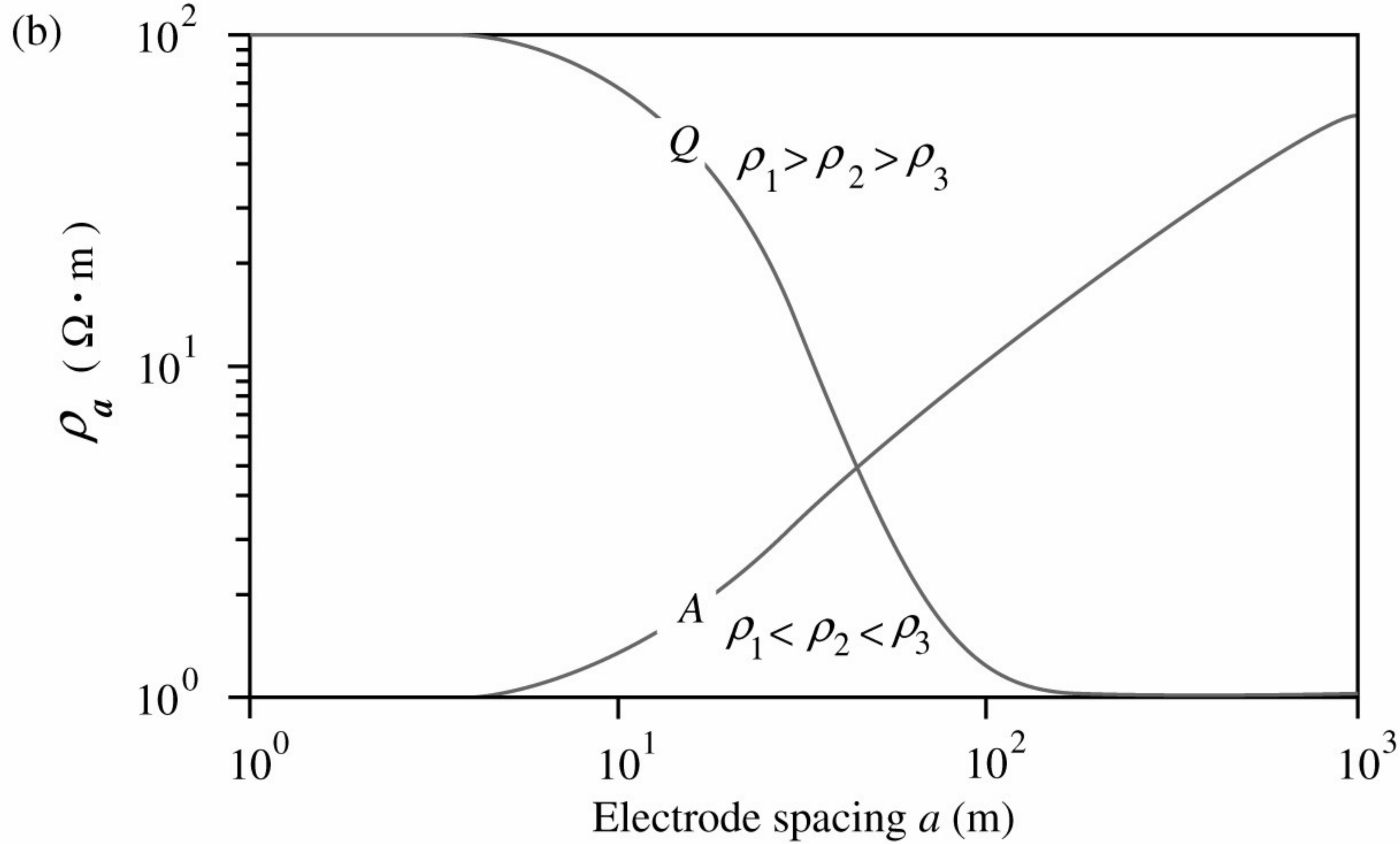

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FIGURE 5.21g (b)

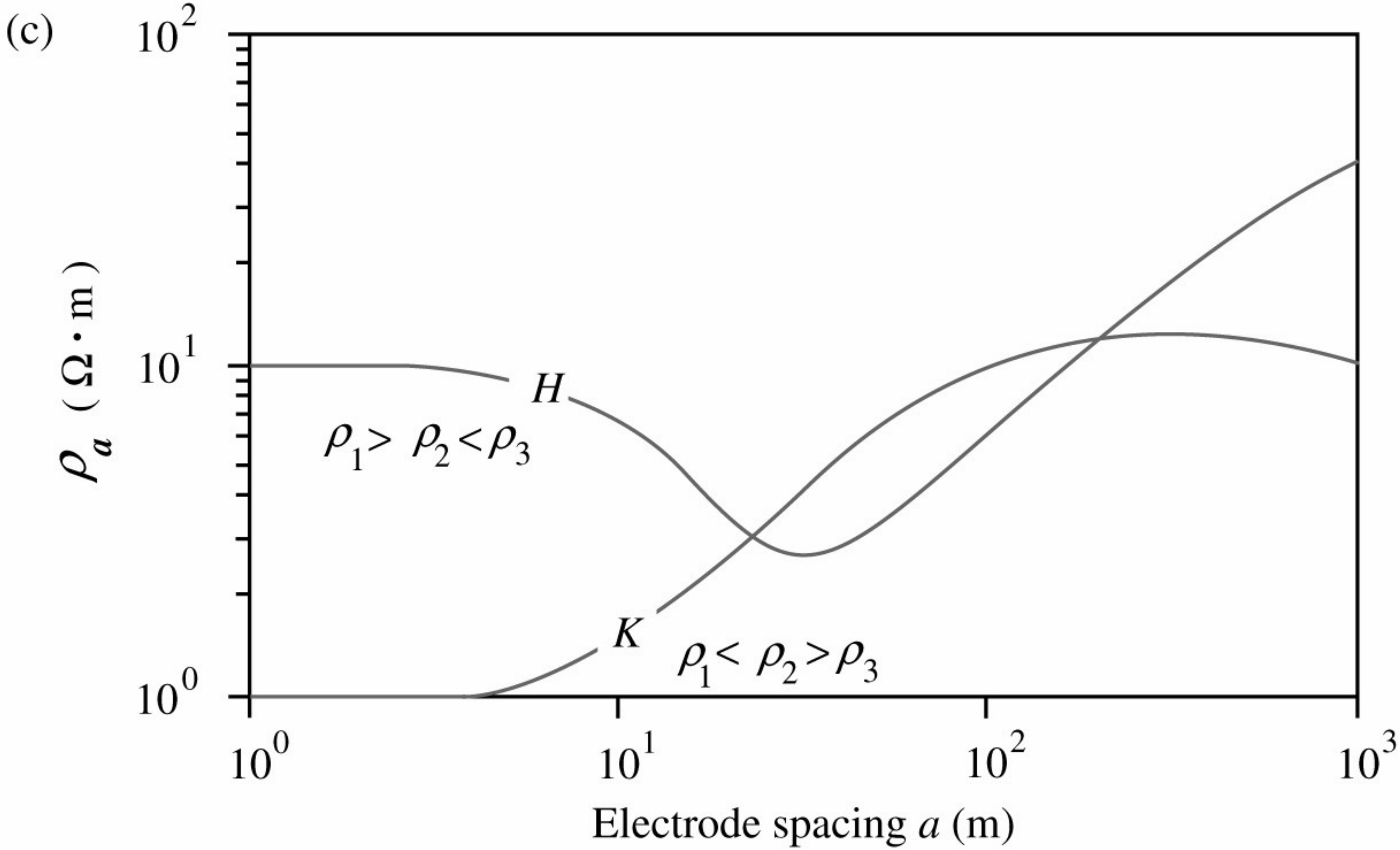

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FIGURE 5.21g (c)

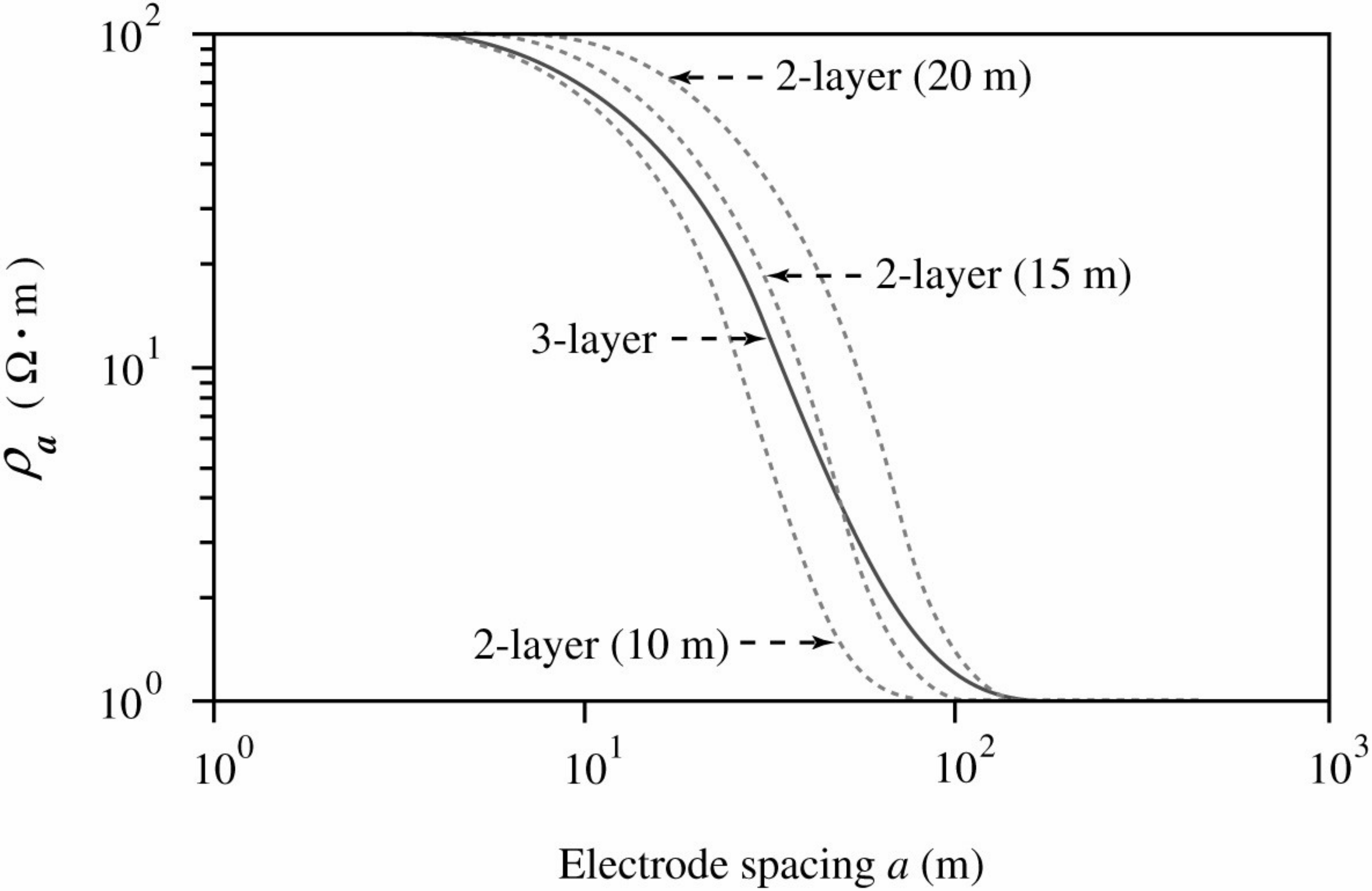

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FIGURE 5.22g

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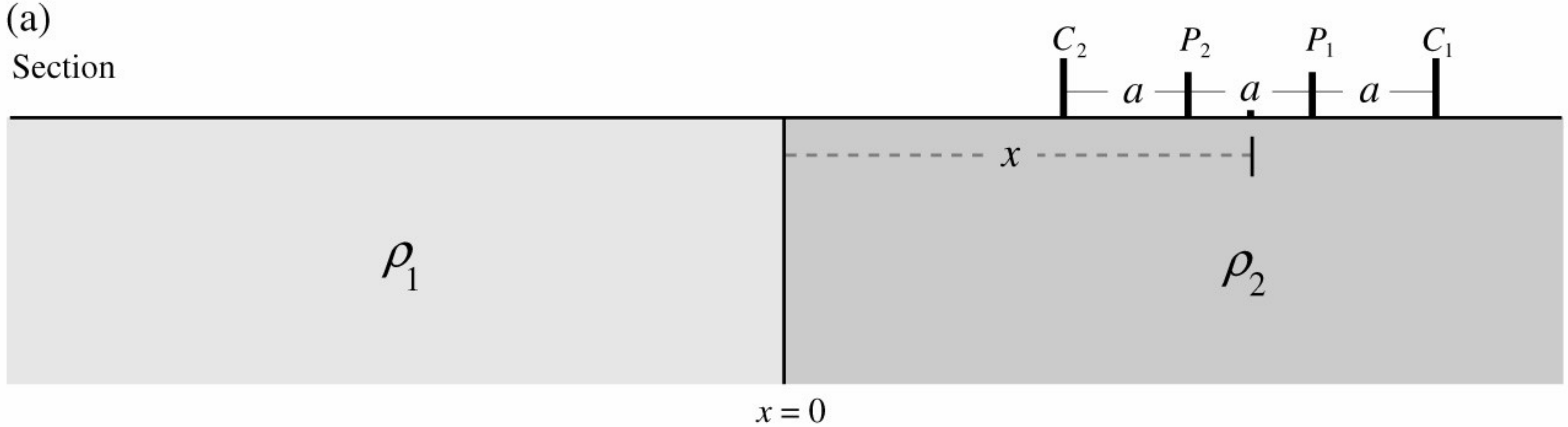

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FIGURE 5.23g (a)

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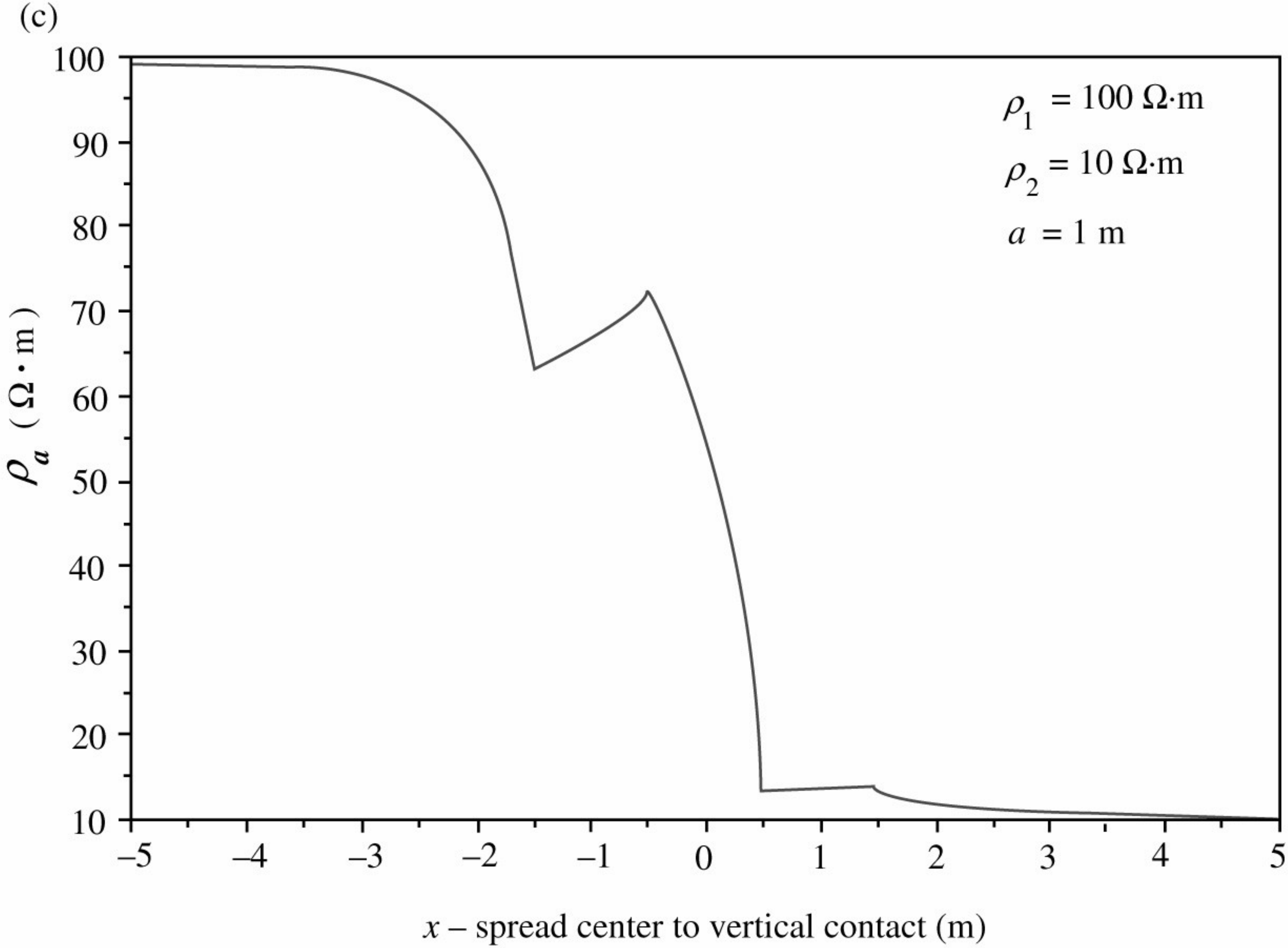

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FIGURE 5.23g (c)

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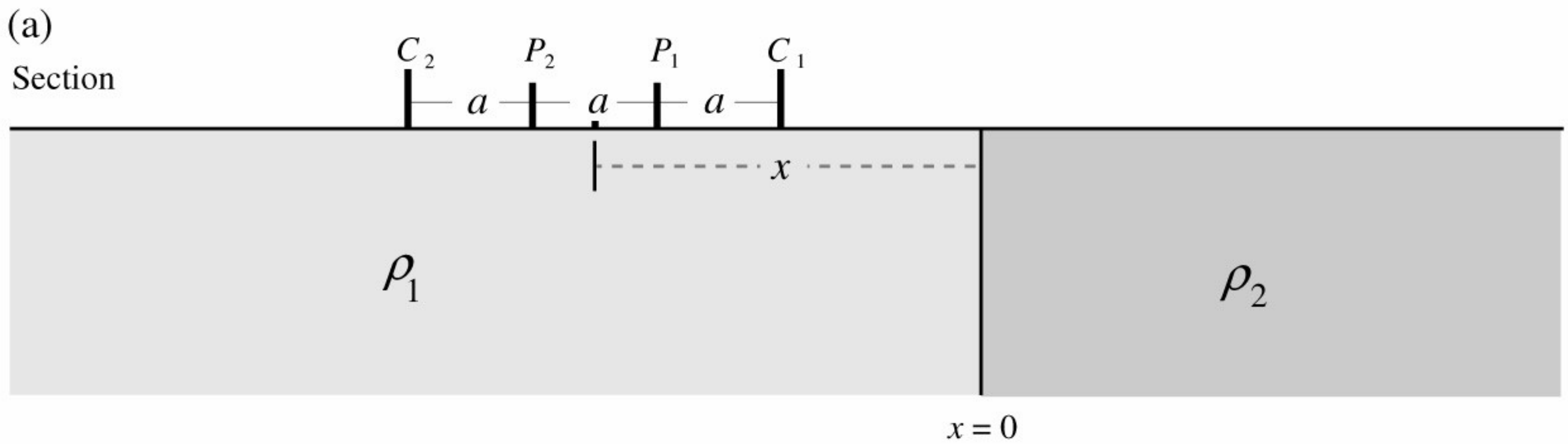

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FIGURE 5.24g (a)

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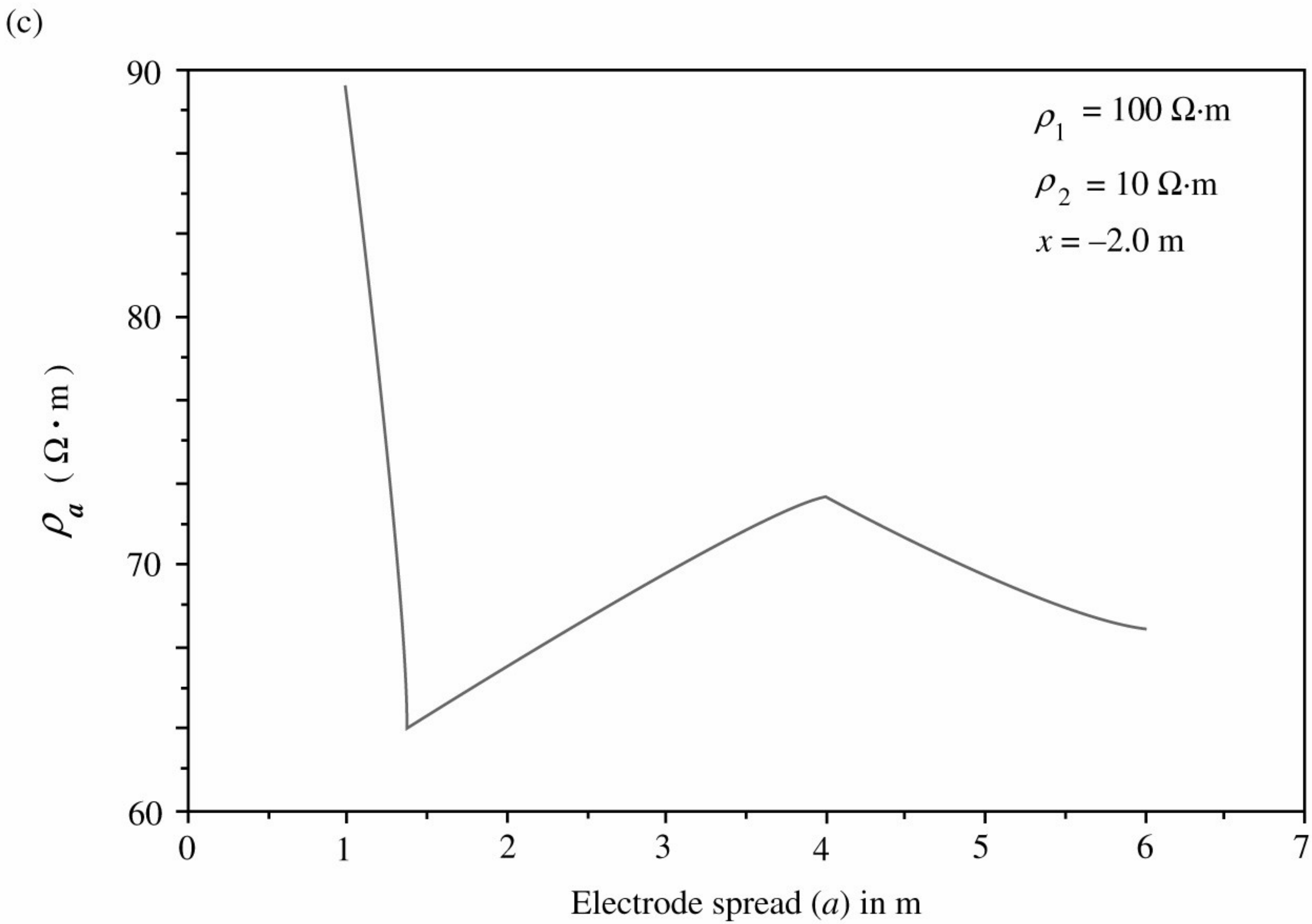

FIGURE 5.24g (c)

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(a)

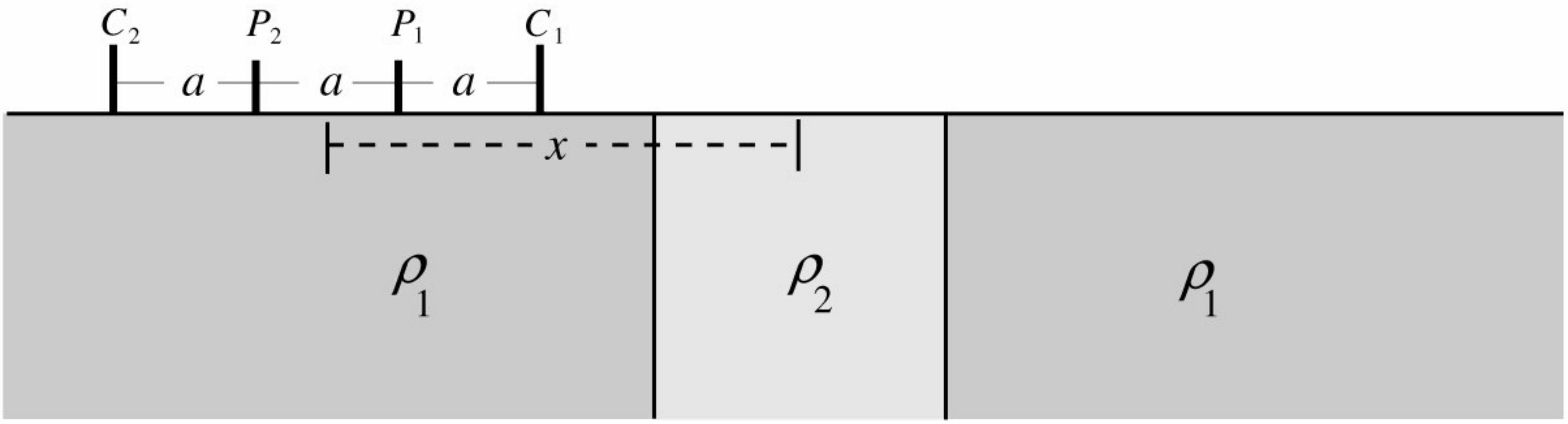

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FIGURE 5.25g (a)

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(b)

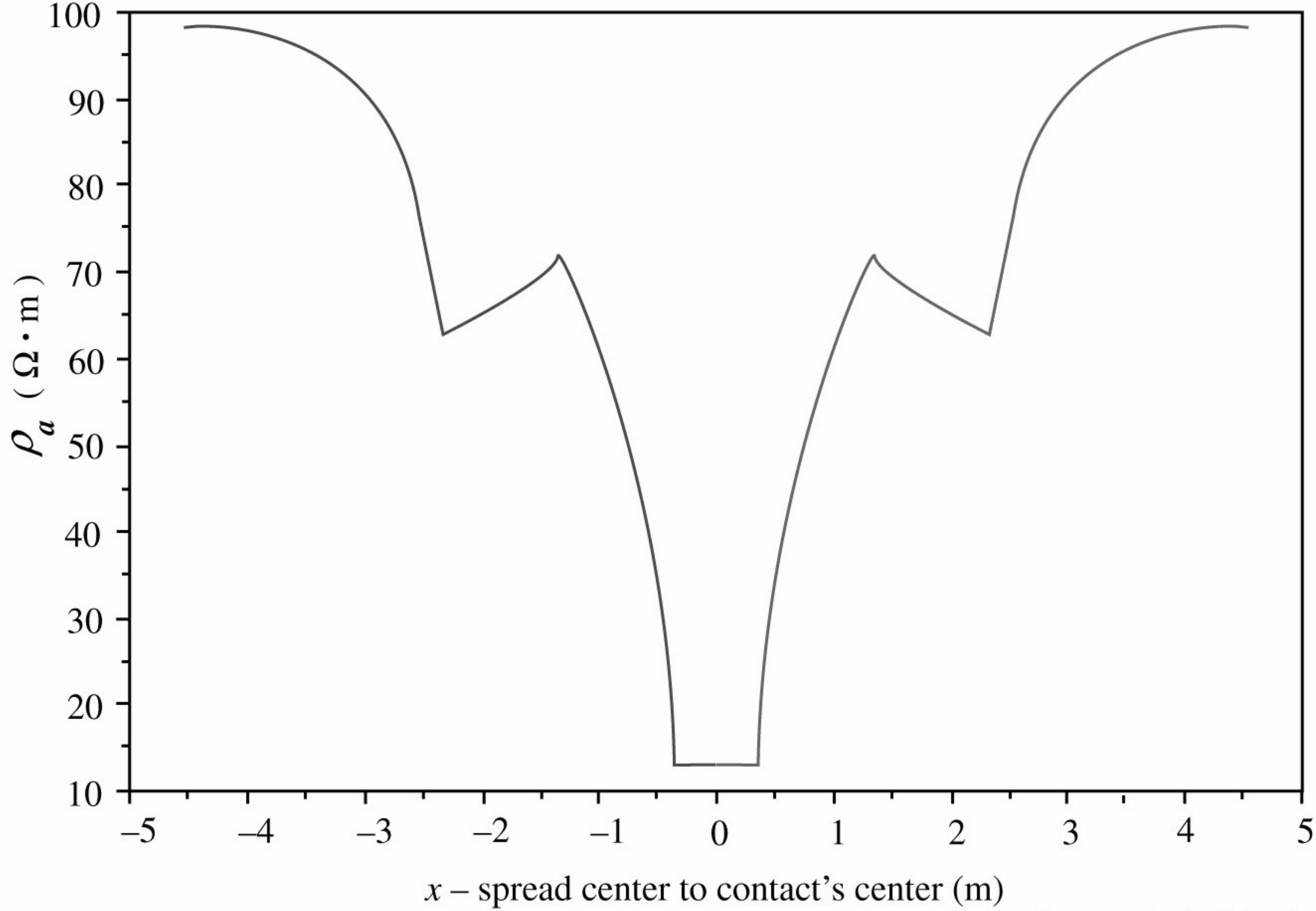

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FIGURE 5.25g (b)

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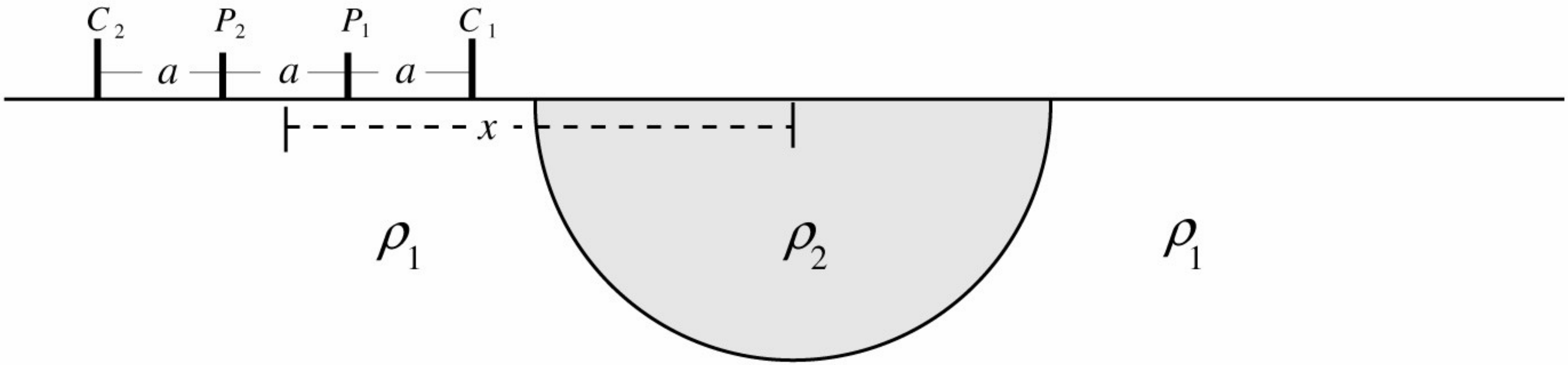

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FIGURE 5.26g

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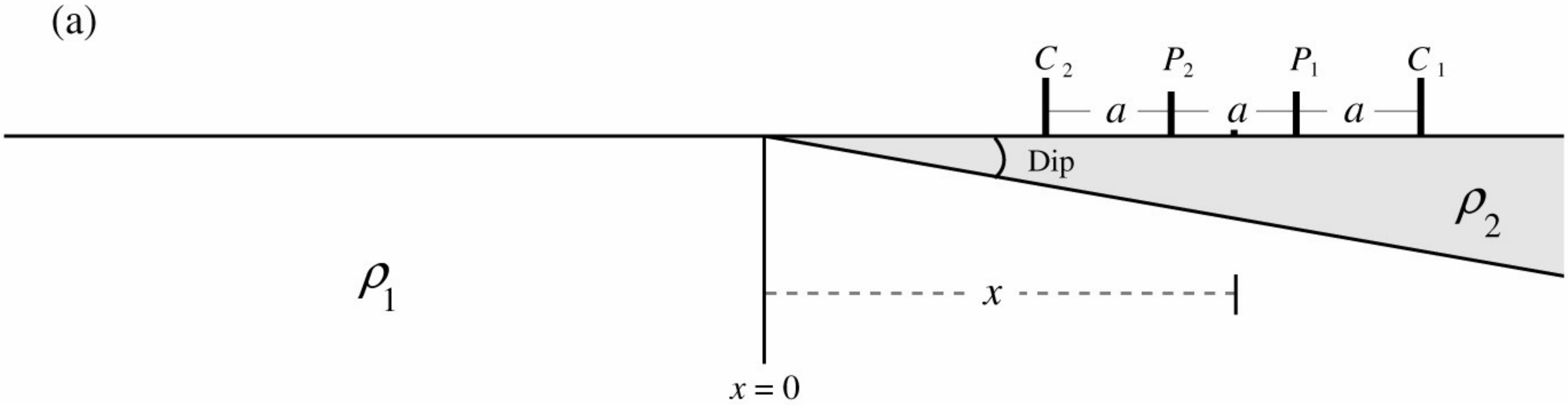

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FIGURE 5.27g (a)

Introduction to Applied Geophysics

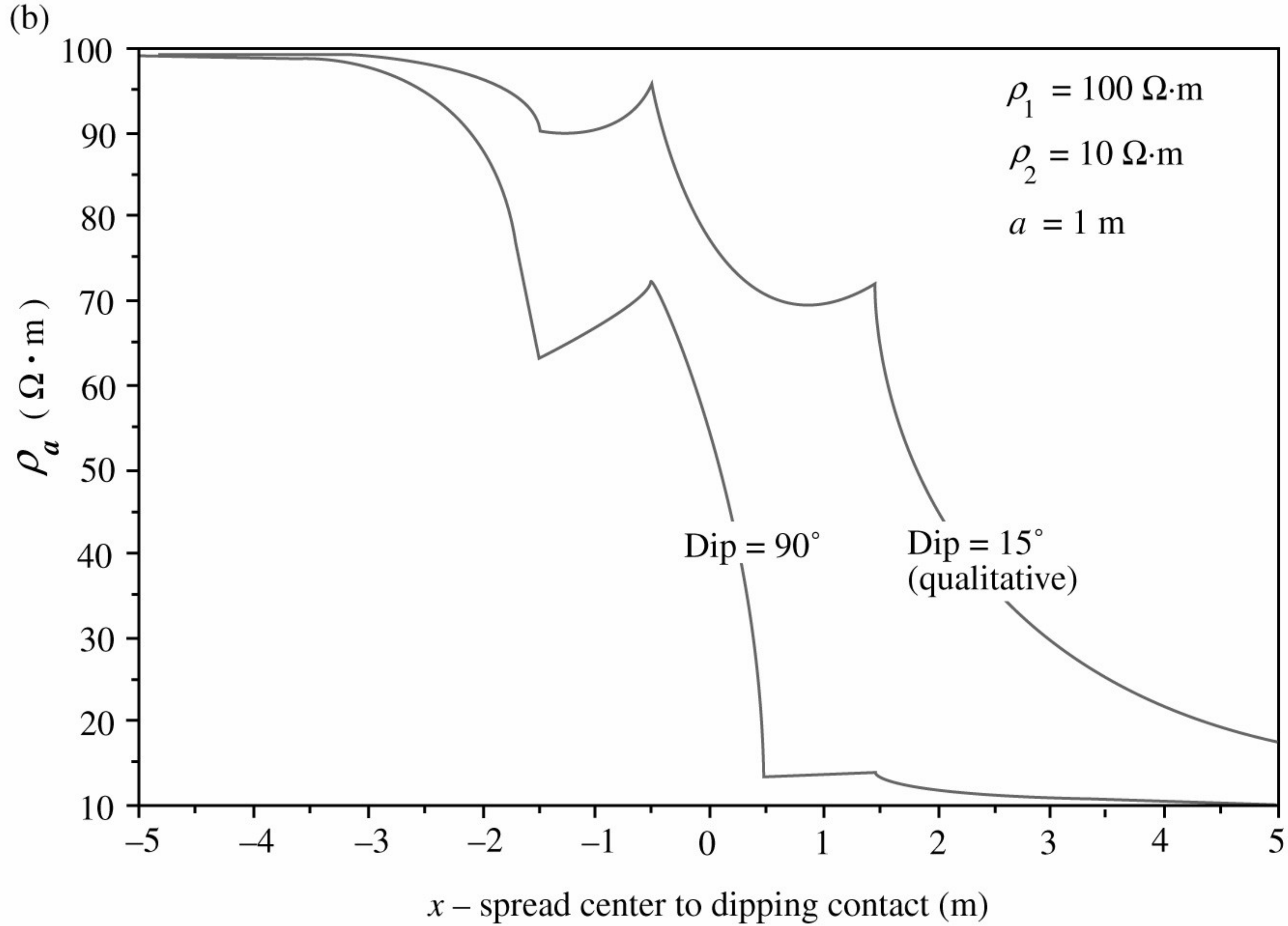

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FIGURE 5.27g (b)

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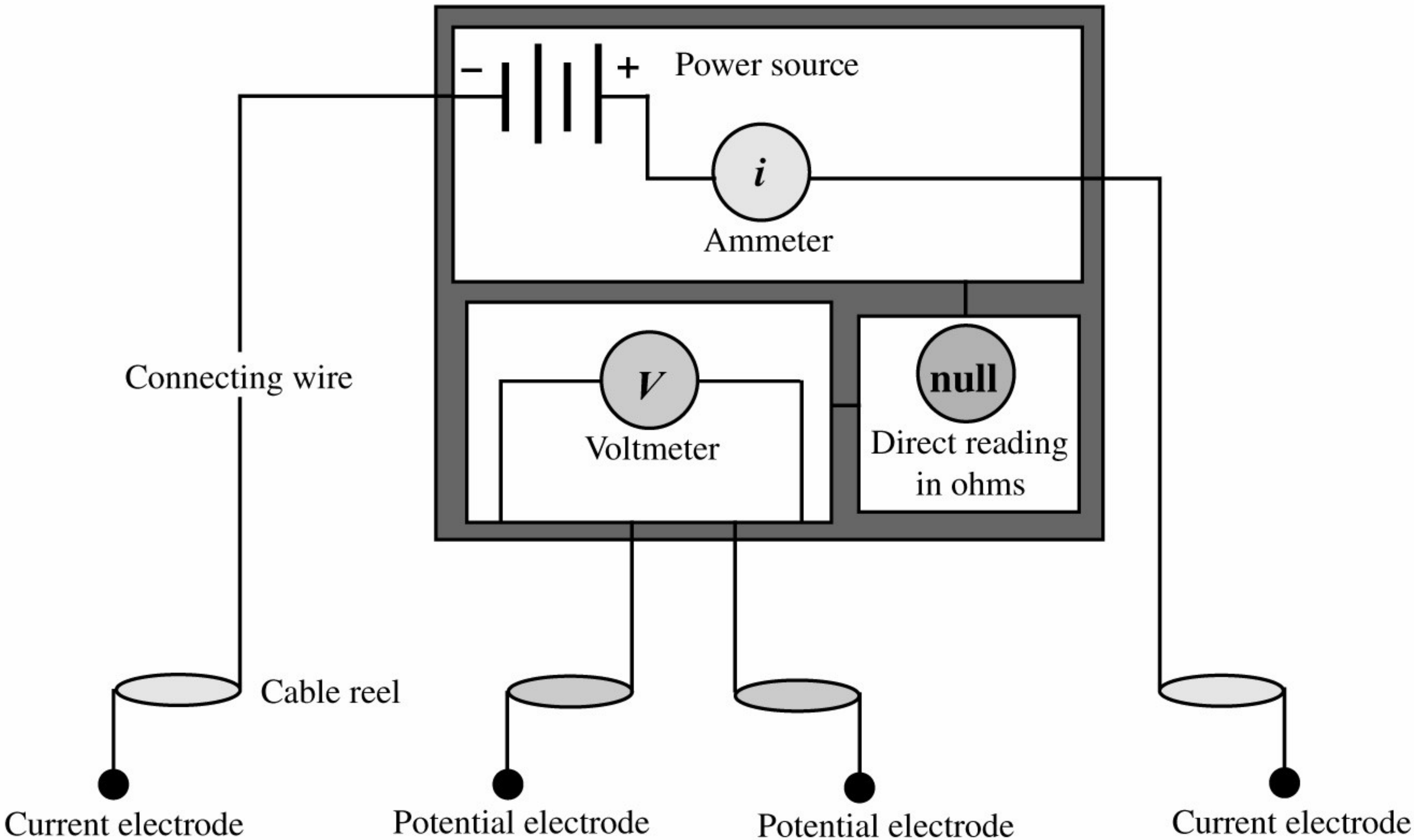

FIGURE 5.28g

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FIGURE 5.29

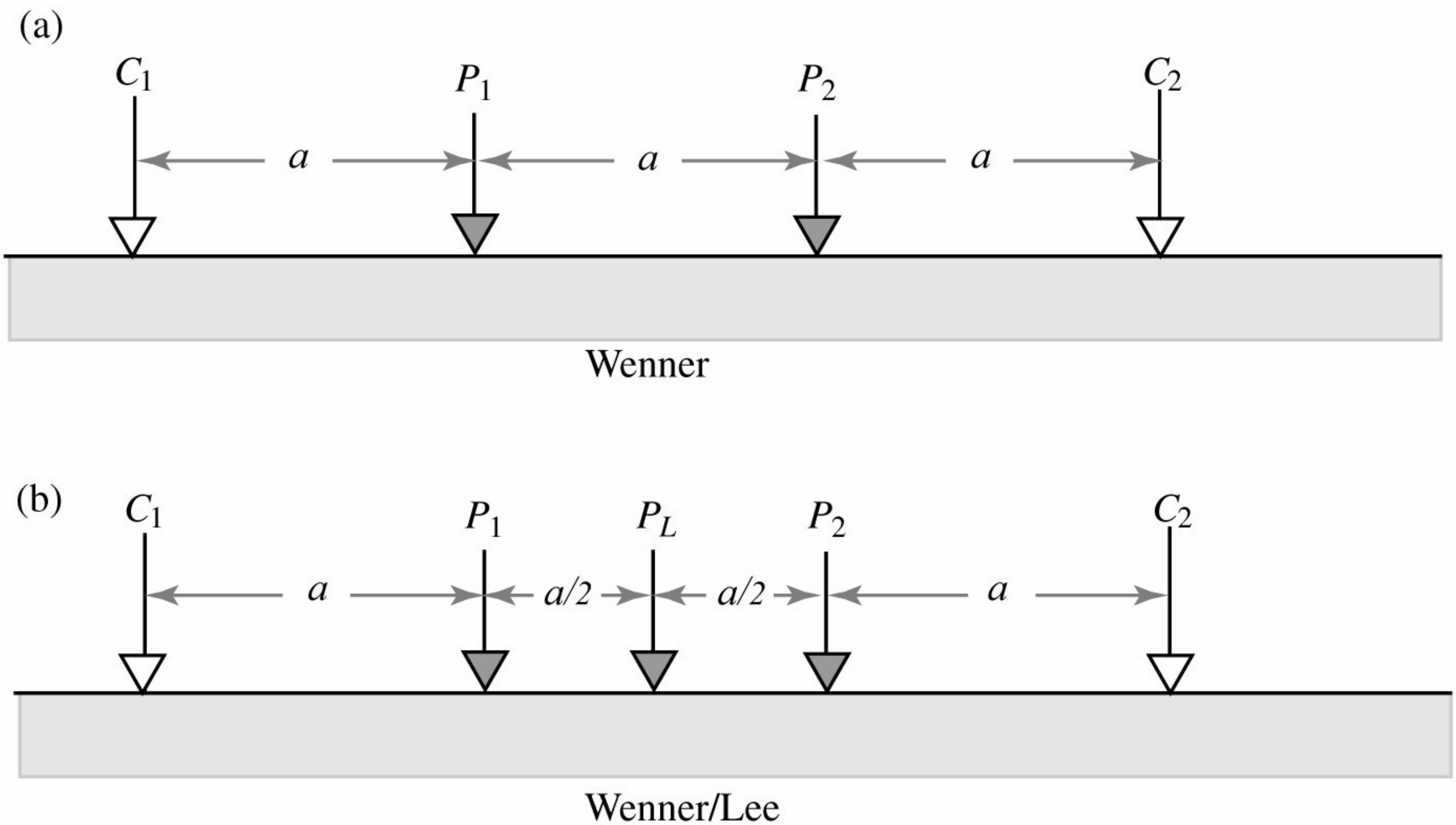

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FIGURE 5.30g (a,b)

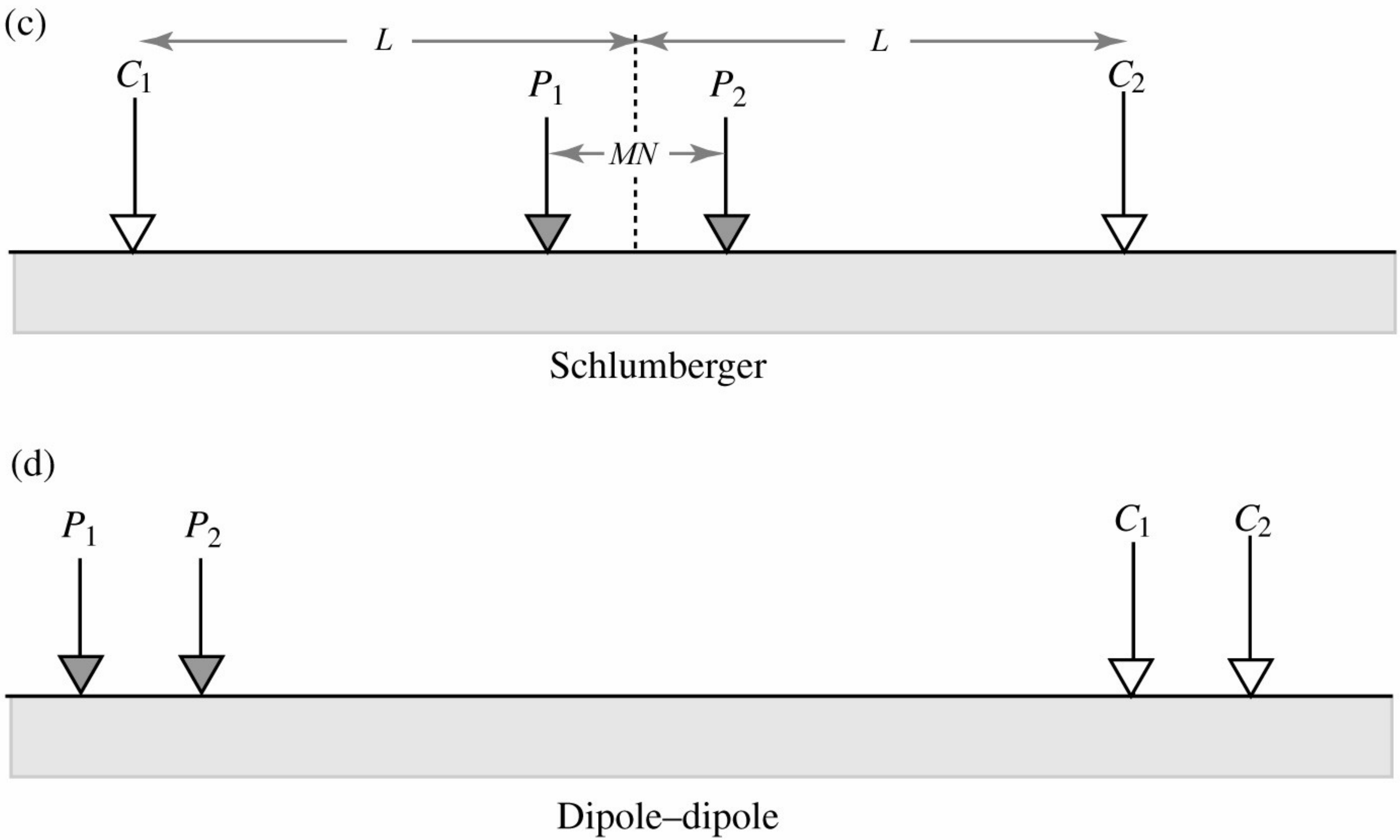

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FIGURE 5.30g (c,d)

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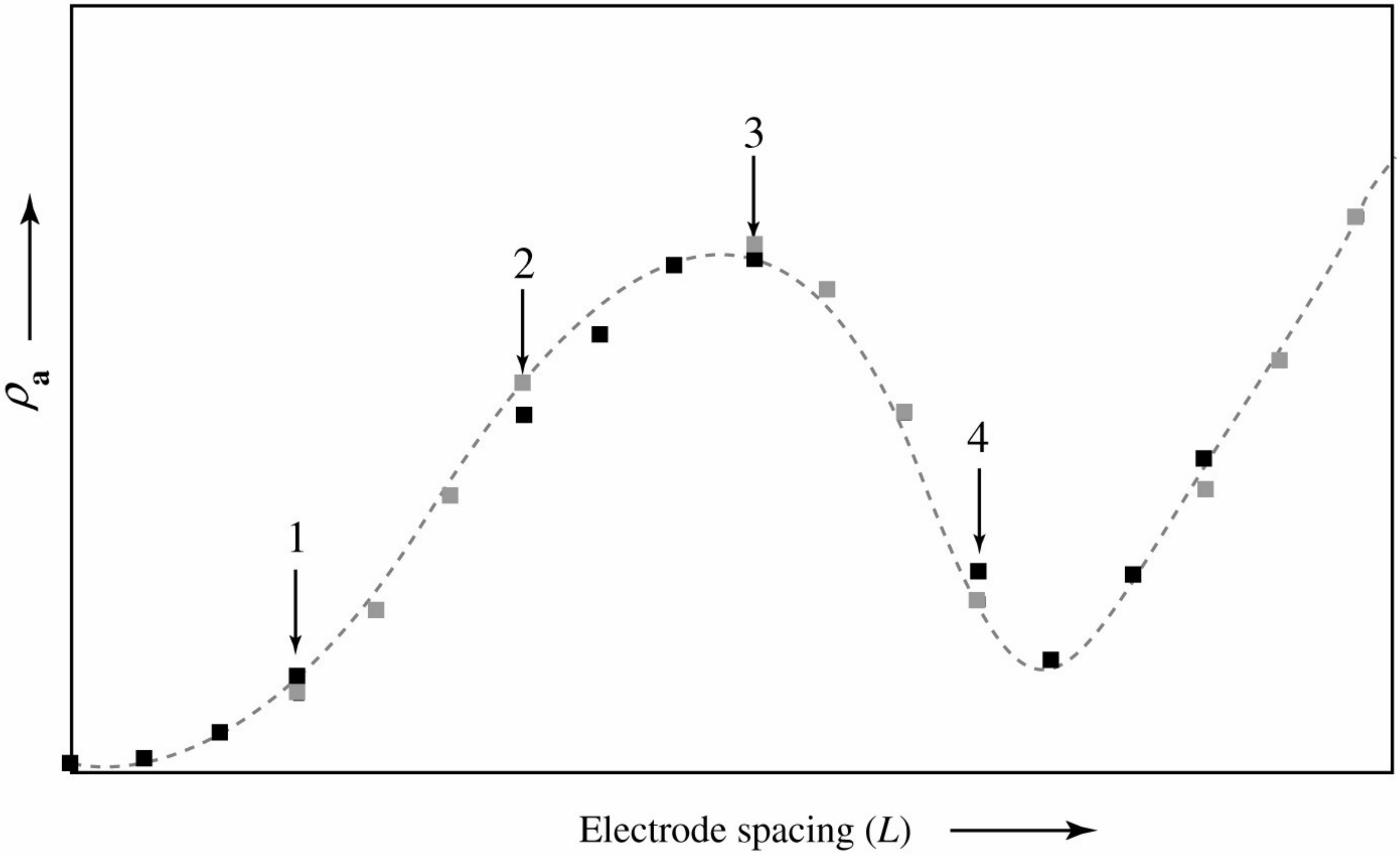

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FIGURE 5.31g

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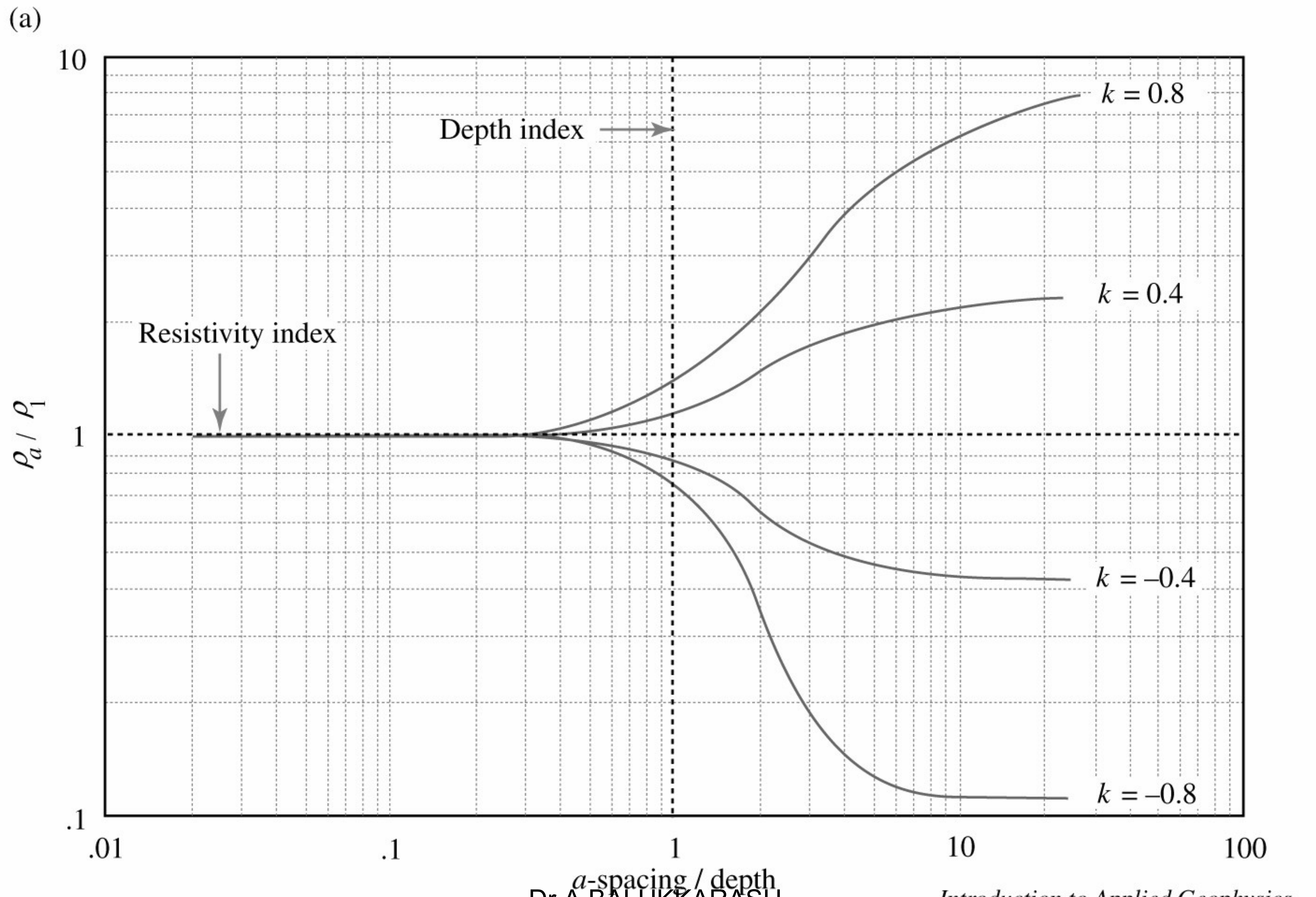

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FIGURE 5.33g (a)

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(b)

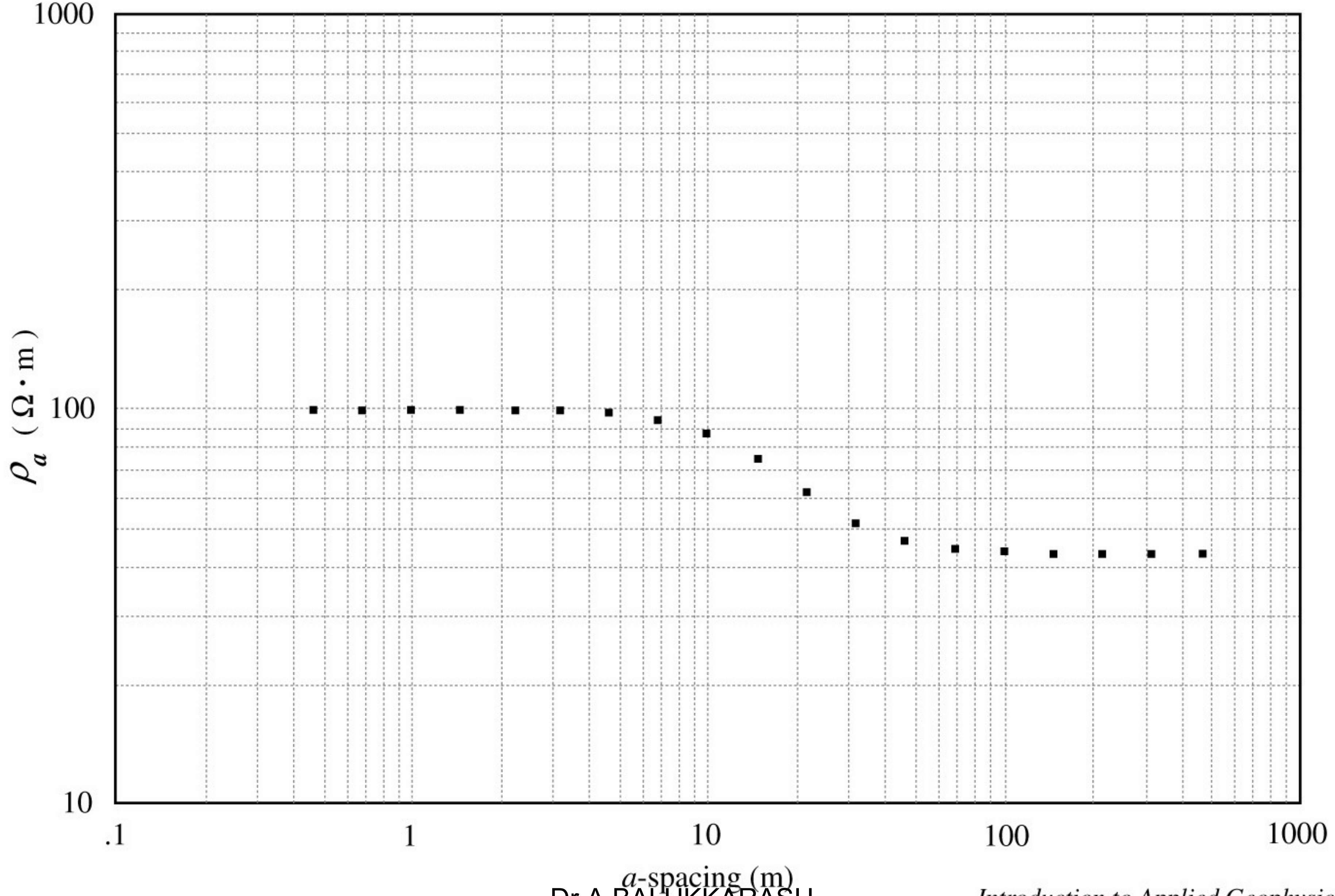

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FIGURE 5.33g (b)

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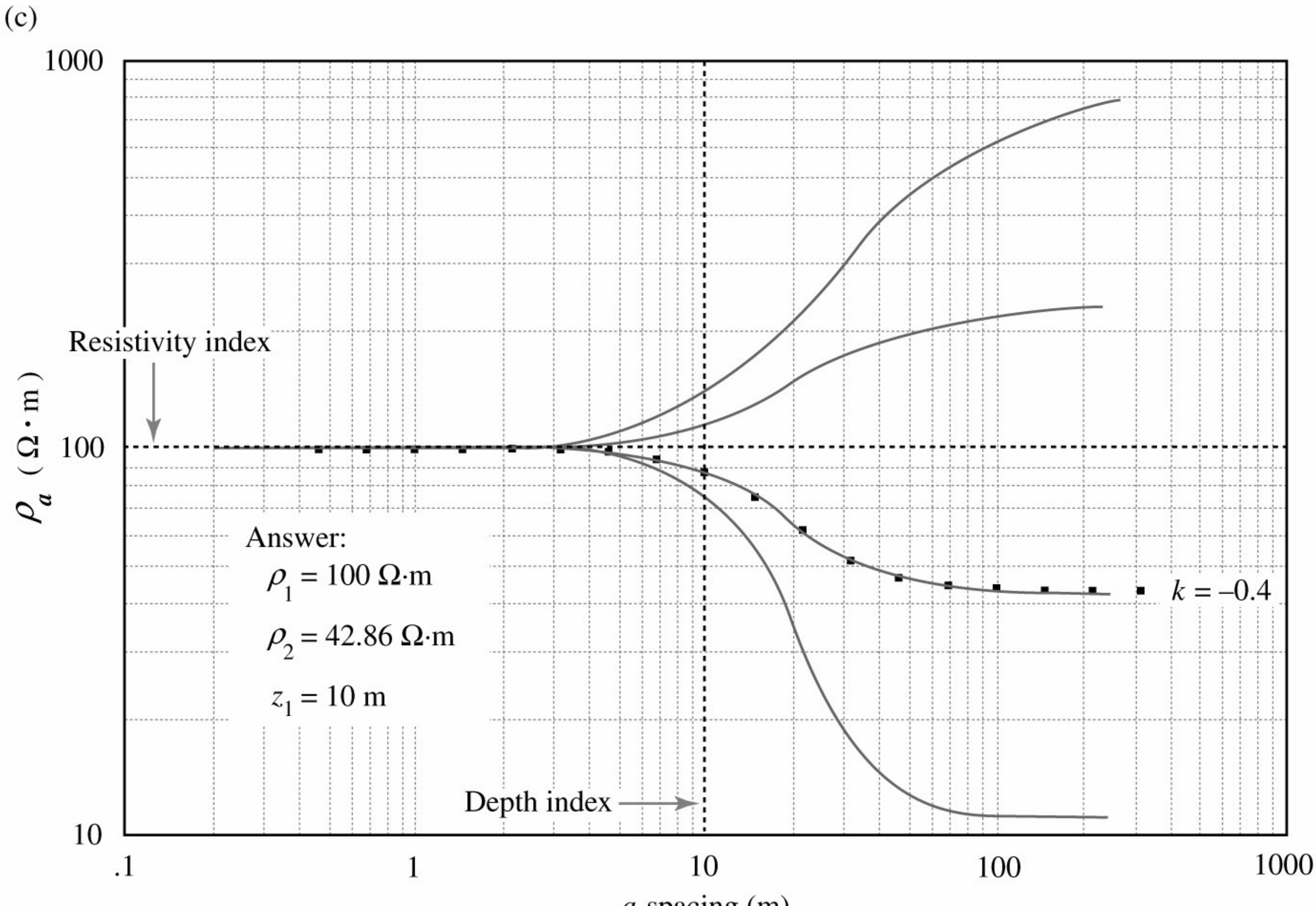

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FIGURE 5.33g (c)

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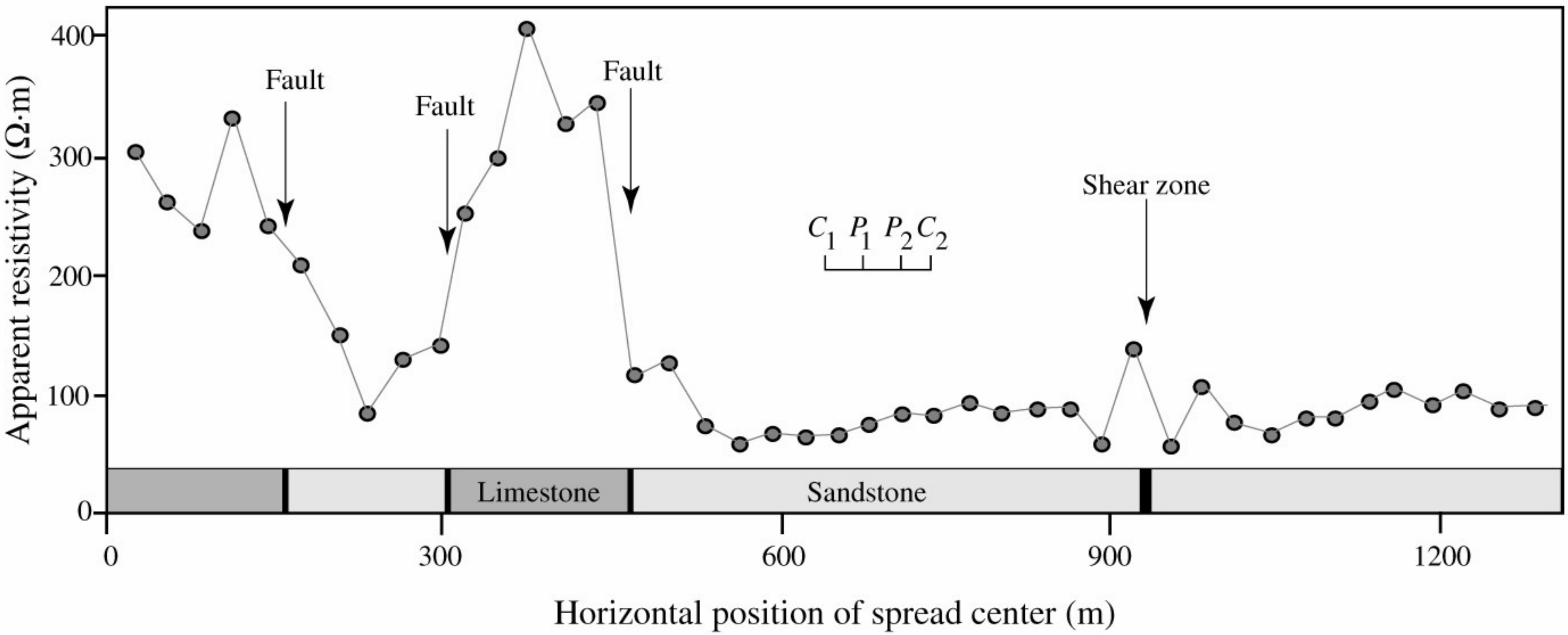

FIGURE 5.39g

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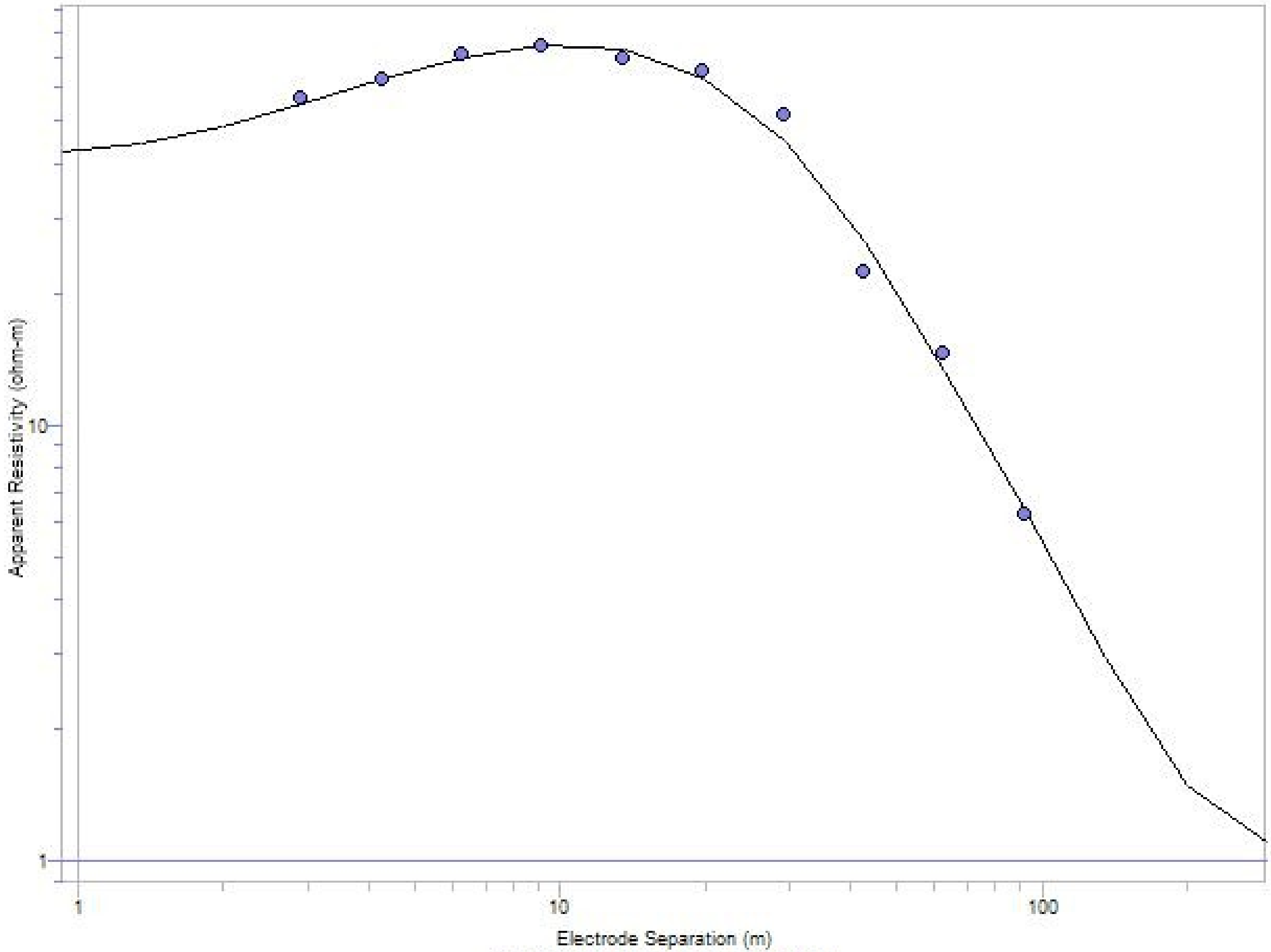
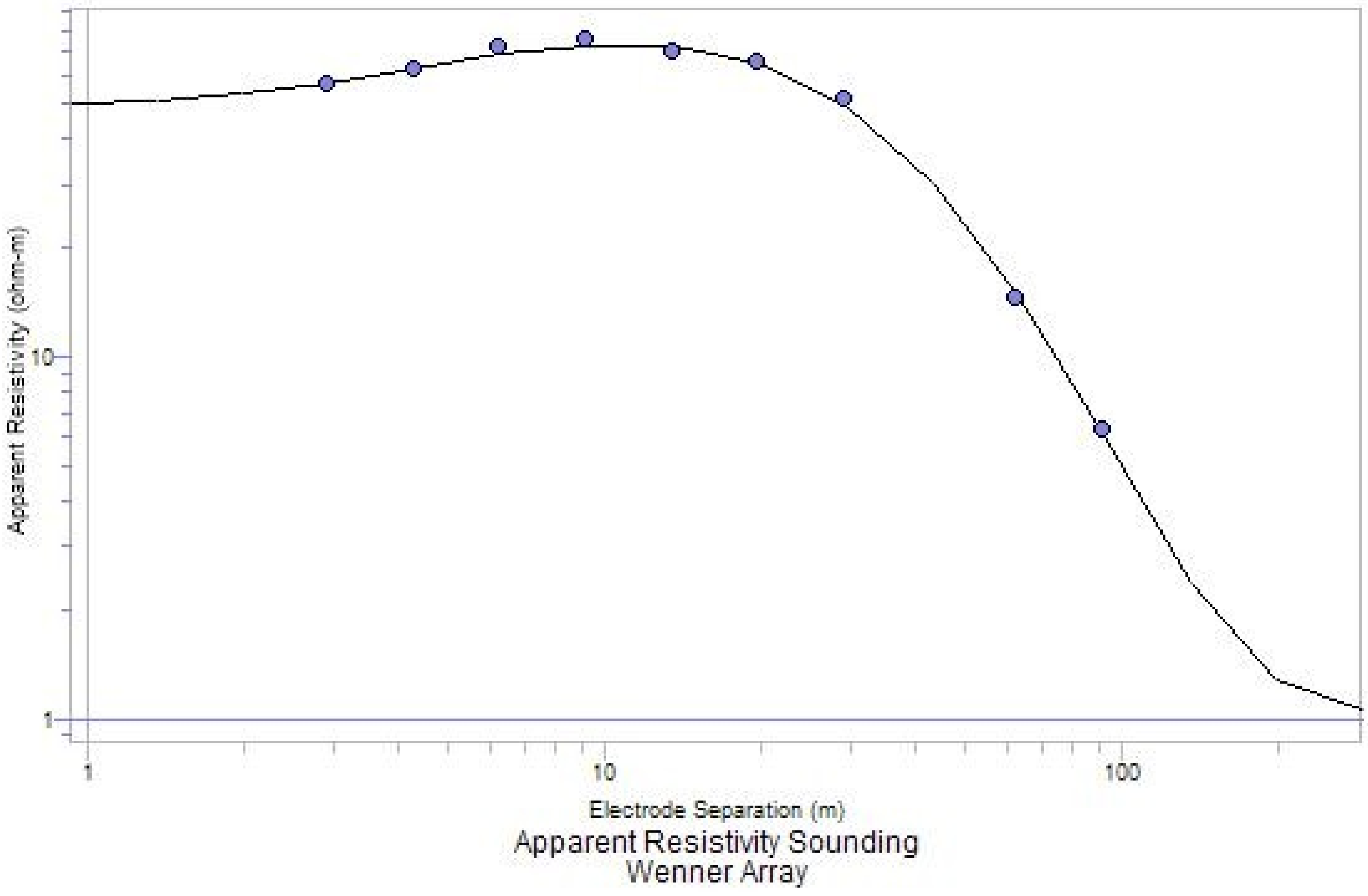


Apparent Resistivity Sounding
Wenner Array

One point removed



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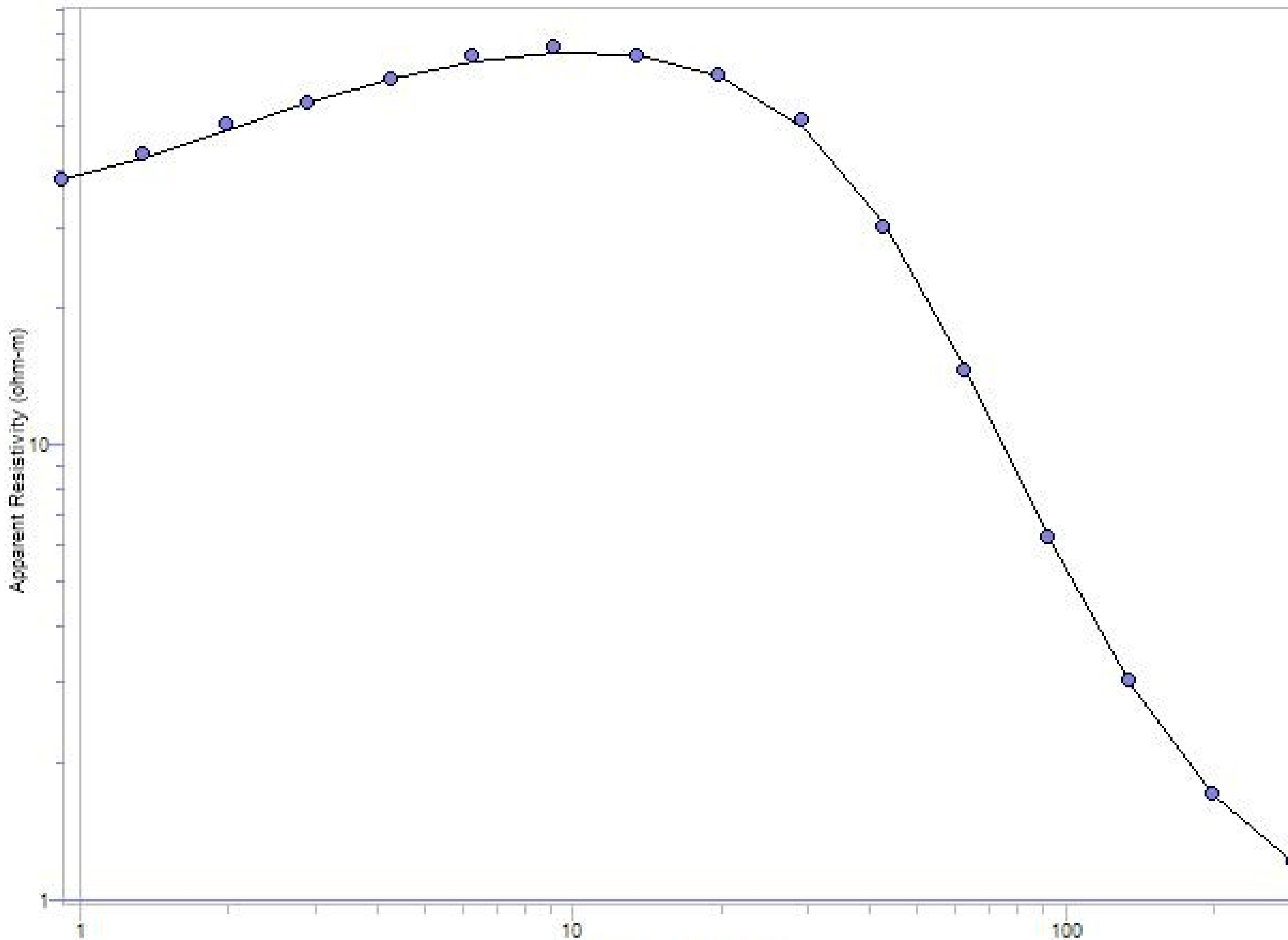

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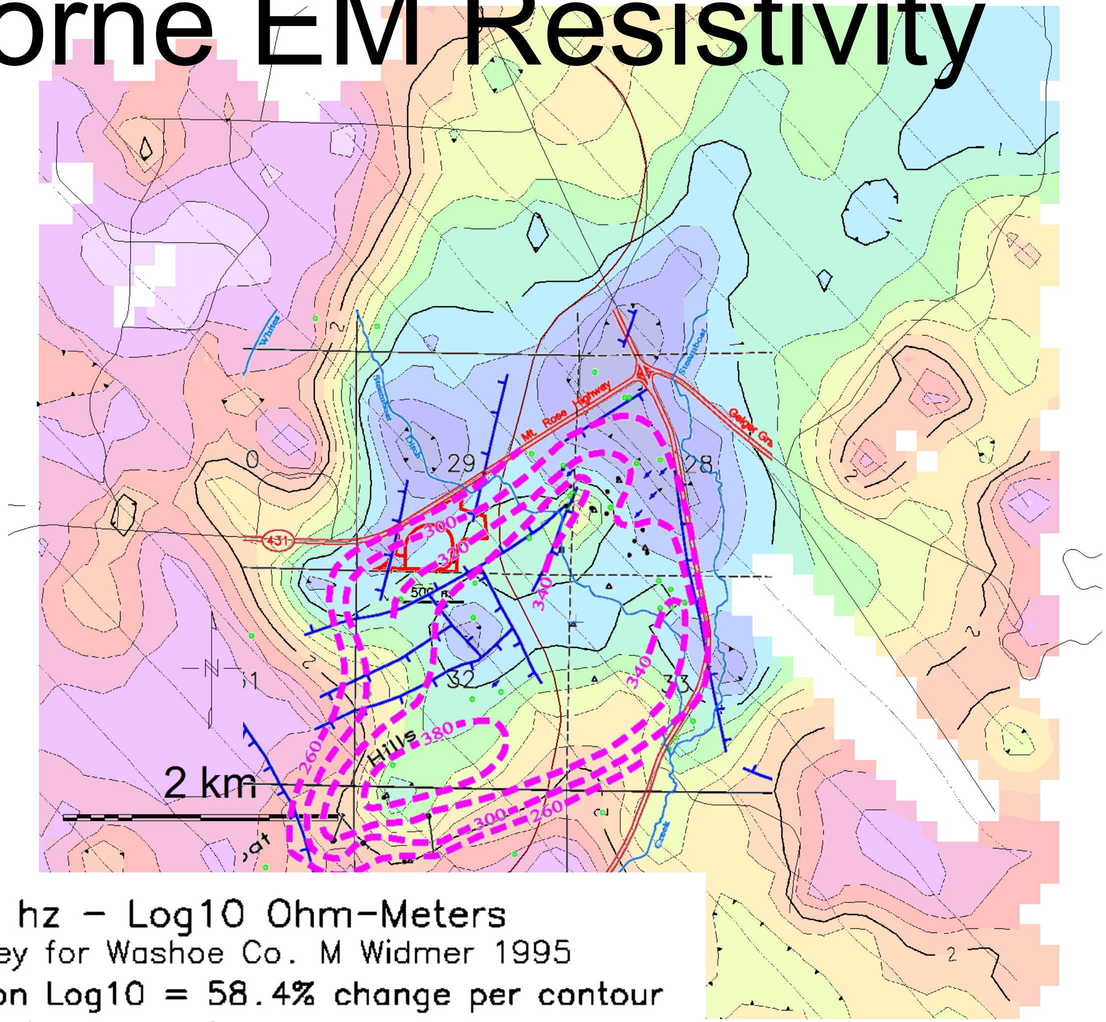
Apparent Resistivity Sounding
Wenner Array

C:\Shortcut to Geo-CD-ROM.exe

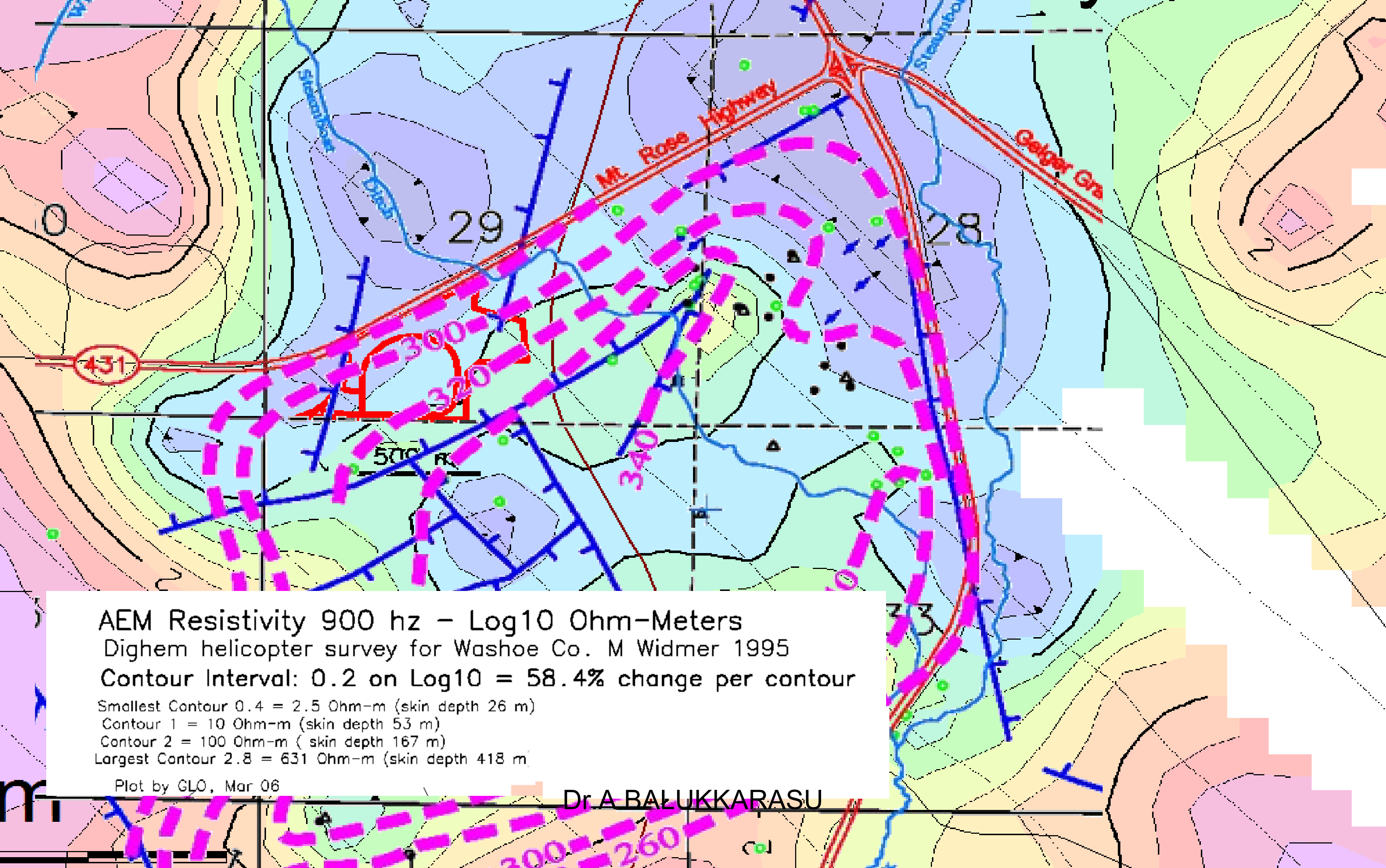
Airborne EM Resistivity



AEM Resistivity 900 hz – Log10 Ohm-Meters
Dighem helicopter survey for Washoe Co. M Widmer 1995
Contour Interval: 0.2 on Log10 = 58.4% change per contour
Smallest Contour 0.4 = 2.5 Ohm-m (skin depth 26 m)
Contour 1 = 10 Ohm-m (skin depth 53 m)
Contour 2 = 100 Ohm-m (skin depth 167 m)
Largest Contour 2.8 = 631 Ohm-m (skin depth 418 m)

Plot by GLO, Mar 06

Airborne EM Resistivity



Skin depth, δ

- Is defined as the depth at which the electric amplitude is decreased to 37%

$$e^{-1} = 0.37 = (37\%)$$

$$e^{-\alpha z} = e^{-1} \text{ at } z = 1/\alpha = \delta$$

skin depth.

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = \sqrt{\frac{2\rho}{2\pi f\, 4\pi \cdot 10^{-7}}} \approx 500\sqrt{\frac{\rho}{f}}$$

where δ is in meters, ρ in Ohm-m and f in Hz.

http://appliedgeophysics.berkeley.edu:7057/dc/archie/index.html