INVESTIGATION OF THE PHYSICAL PROPERTIES OF RESERVOIR ROCKS BY ELECTRIC WELL LOGGING, IN GRAHAM COUNTY, KANSAS

by

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TABLE OF CONTENTS

NOMENCLATURE

A	--	A function of layer depths resistivities r and λ
AM	--	Normal spacing
AO	--	Lateral curve spacing
a	--	Radius of drill hole
b	--	Radius of invaded zone
BHT	--	Bottom hole temperature in ^{o}F.
C	--	Salinity in ppm
E	--	Electromotive force in millivolts
F	--	Formation resistivity factor
G	--	Geothermal gradient
I	--	Electric current flow through a point electrode
Io	--	Bessel function of first order zero kind
K	--	Coefficient in SP formula
k	--	Permeability in millidarcies
Ko	--	Bessel function of second kind zero order
n	--	Saturation exponent
Pc	--	Capillary pressure
Q	--	Flow velocity
r	--	Radius from the electrode
Ri	--	Resistivity of the invaded zone
Rm	--	Resistivity of the mud
Rmc	--	Resistivity of the mud cake
Rmf	--	Resistivity of the mud filtrate
Ro	--	Resistivity of the formation when 100% water saturated

Rt	--	Resistivity of uncontaminated zone
Rw	--	Resistivity of the formation water
(Rw)e	--	Equivalent water resistivity
Sw	--	Water saturation
T	--	Absolute temperature
V	--	Electric potential
Vi	--	Potential in the invaded zone
Vm	--	Potential function within the mud
Vt	--	Potential in the uncontaminated zone
x,y,z	--	Cartesian coordinates
ϕ	--	Porosity in percent
λ	--	Parameter of integration
Δh	--	Difference in height
Δsp.gr.	--	Difference in water and oil specific gravity
ΔRt	--	Difference in true resistivities
∇^2	--	Laplacian operator

INTRODUCTION

Purpose of Investigation

This investigation was attempted for the quantitative interpretation of porosity, permeability, fluid saturation, salinity and temperature of petroleum reservoir rocks by use of electric logs from Graham County, Kansas. The investigation included the correlation of wells by using physical formation characteristics. This type of investigation is of considerable importance in searching for potential petroleum reservoirs.

Location of the Area

Graham County is located in northwestern Kansas and is the fourth county east of the Colorado-Kansas State line (Appendix, Fig. 9). The county is bordered on the north by Norton County, on the east by Rooks County, on the south by Trego County, and on the west by Sheridan County. It includes 25 townships--Ts. 6 S. to T. 10 S., and Rs. 21 W. to 25 W., and covers approximately 891 square miles. This county is a part of the high plains of the Great Plains Physiographic Province and topographically is an upland moderately dissected by streams, differing from the flat upland found farther west in the State.

Two-thirds area of this county is drained by the South Fork Solomon River and its tributaries in the central part of the county. North Fork Solomon river and its tributaries drain the northern part of the county while Saline river and its tributaries drain the southern part of the county.

Review of Literature

Previous investigation of Graham County consisted of stratigraphic and structural regional studies, and studies of individual oil and gas pools. Darton (1905) conducted studies on geology, structure and water resources of central great plains (1918). Structure was also described by Twenhofel (1925). The Dakota group was described by Bass (1926). Prescott published a report on geology and groundwater resources of Graham County (1955). Koester (1935), Merrian and Atkinson (1955) discussed the tectonic development of the Central Kansas Uplift and the Cambridge Arch.

The stratigraphy of Kansas was described by Moore (1951). Landis and Keroher (1942) reviewed the lithology of subsurface well cuttings. The Cambrian-Ordovician rocks in Kansas were described by Keroher and Kirby (1948); the Mississippian rocks by Lee (1939) and the Cretaceous and Tertiary formations by Swineford (1947) and Frye (1956). Low Southwest oil pool--a successful seismic discovery in Graham County was discussed by Richard L. Winchell (1959). Stratigraphy and structure as determined by Kansas Sample Log Service strip logs were also described by Sandlin in his master's thesis (1957). A Central Kansas correlation study was published by LANE-WELLS with a composite radioactive log. Halliburton Well Cementing Company calculated porosity and water saturation of Lansing-Kansas City formations by resistivity and radiation guard log.

Procedure

The information used in locating the formations was obtained by interpretation of electric logs of this county available in the Department of Geology. Some gamma ray logs, sonic logs, induction logs, neutron logs, laterologs, micrologs and microlaterologs were also used to supplement the data.

For calculating porosity, permeability, fluid saturation and salinity, Schlumberger's Log Interpretation Charts were used. Fluid saturation and porosity in limestone formations were calculated by Tixier's Rocky Mountain (Schlumberger's Charts D-8 and D-10) and Porosity Index methods (Chart B-2), while Archie's equation ($Sw = \sqrt{\frac{Ro}{Rt}}$) and Humble equation ($F = \frac{0.62}{\phi^{2.15}}$) were used in shale and sandstone formations. But the Rocky Mountain method was usually used due to the absence of 100 percent water saturated (Ro) sand zones in this area. This method was also used in evaluating other tight formations.

Schlumberger's empirical equation for permeability ($(K)^{1/2} = 250 \frac{\phi^3}{Sw}$) was not widely used due to a weakness inherent in the fact that the permeability is dependent on the sixth power of the porosity and second power of the water saturation. Thus the errors are raised to the square and sixth powers in calculating the permeability. Therefore permeability was calculated by Tixier's Resistivity Gradient method (Chart E-2). For salinity determination Schlumberger's Resistivity-Salinity Chart (A-6) was used. This chart did not indicate the true salinity in salt-formations. This might be due to the fact that temperature gets higher in salt formations and for a constant water resistivity, apparent salinity decreases as temperature abnormally increases in salt beds.

Temperatures of the formations were calculated by Geothermal Gradient Chart (A-2). A mean surface temperature has been taken, 80° F., which has been statistically determined by Schlumberger corporation and P.G.A.C. for this area.

A stratigraphic correlation chart (Fig. 10) was also constructed to show relative thickness and physical characteristics of the formations by using four electric well logs in different sections and a well in Gove County, Kansas (Appendix, Fig. 13).

ELECTRICAL MEASUREMENTS IN THE BORE HOLE

Electric logging records the resistivities of the subsurface formations and the spontaneous potentials generated in the bore holes.

Electrical resistance is the opposition offered by any substance to the flow of an electric current through it.

By Ohm's Law the rate of flow of electric current I in a conductor is proportional to the electric potential difference ΔV causing that flow. The proportionality constant is called resistance R:

$$\Delta V = IR$$

and

$$R = \frac{\Delta V}{I} \qquad (1)$$

The points M and N may be considered as representative of two spherical shells and A an electrode (Fig. 1). If the rock around A is considered to be homogeneous with a specific resistance , the resistance across a thin shell of thickness Δr will be:

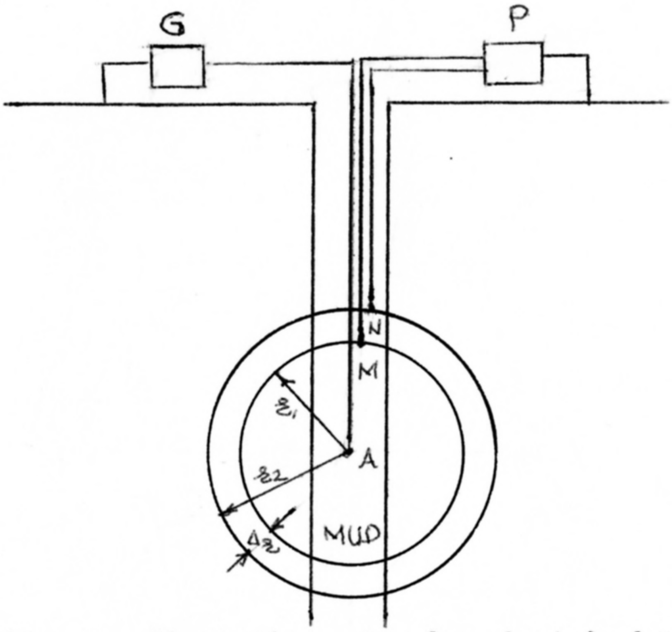


Fig. 1. Electrode system for electric logging.

$$\Delta R = \frac{\rho \Delta r}{A} = \frac{\rho \Delta r}{4\pi r^2}$$

and the total resistance between the shells of radius r_1 and r_2 will be:

$$R = \frac{\rho}{4\pi} \int_{r_1}^{r_2} \frac{\Delta r}{r^2}$$

Integrating:

$$= - \frac{\rho}{4\pi} \left(\frac{1}{r_2} - \frac{1}{r_1} \right)$$

$$= \frac{\rho}{4\pi} \cdot \frac{r_2 - r_1}{r_1 \quad r_2} \qquad (2)$$

By equating (1) and equation (2):

$$\frac{\Delta V}{I} = \frac{\rho}{4\pi} \cdot \frac{r_2 - r_1}{r_1 \quad r_2}$$

$$\therefore \quad \rho = 4\pi \cdot \frac{\Delta V}{I} \cdot \frac{r_1 \quad r_2}{r_2 - r_1}$$

Thus the resistance of the rock, opposite the two electrodes M and N can be computed.

The potential of a point on such a spherical surface of radius r_1 with respect to infinity is:

$$V = \int_{r_1}^{\infty} \frac{I\rho}{4\pi r^2} \, dr$$

$$= \frac{I\rho}{4\pi} \left(-\frac{1}{r}\right]_{r_1}^{\infty}$$

$$= \frac{I\rho}{4\pi r}$$

Spontaneous Potential

The electrochemical potential is defined by

$$E = \frac{RT}{F} \quad \text{Loge} \frac{a_1}{a_2}$$

a_1 and a_2 = activities of Nacl solutions

R = Gas constant

F = Faraday

T = Absolute temperature

Activities are usually known on a mole basis, so equation becomes:

$$E = \frac{RT}{nF} \quad \text{Loge} \frac{a_1}{a_2}$$

n = number of equivalents of mole.

And the potential developed by ionic movement for any liquid junction:

$$E = - \frac{RT}{F} \int_{1}^{2} \sum_{i} \frac{ti}{Zi} \, d \, loge \; a_i$$

ti = transference number of i th ions

ai = its activity

Zi = its valence

Activities a_1 and a_2 may be replaced by electrical conductivities of two solutions or its reciprocal Resistivity R:

$$E_{(volts)} = - \frac{RT}{F} \; loge \; \frac{R_2}{R_1}$$

R_1 = Resistivity of water, Rw

R_2 = Resistivity of mud filtrate Rmf

Therefore:

$$E = - \frac{RT}{F} \; loge \; \frac{Rmf}{Rw}$$

PHYSICAL PROPERTIES OF RESERVOIR ROCKS

Permeability

The permeability of a reservoir rock may be defined as its fluid conductivity or ability to let fluids to flow through its pore network at practical rates under reasonable pressure differentials. The empirical relationship was developed by Darcy who studied the flow of water through unconsolidated sands. The rate of filtration of fluid through a mudcake is given by:

$$Q = \frac{KA}{\mu} \cdot \frac{\Delta p}{x}$$

Q = flow velocity

μ = viscosity of flowing fluid

Δp = pressure differential

x = thickness of cake

K = permeability of the cake

Over a period of time the total amount of filtrate that passes through the cake is:

$$V = \int_0^t Q \, dt$$

$$= \int_0^t \frac{KA}{\mu} \cdot \frac{\Delta p}{x} \, dt$$

Porosity

Porosity is a measure of the void space within a rock expressed as a fraction or percentage of the bulk volume of the rock:

$$\phi = \frac{Vb - Vs}{Vb} = \frac{Vp}{Vb}$$

where

ϕ = porosity

Vb = bulk volume of the rock

Vs = net volume occupied by solids (grain volume)

Vp = pore volume.

Porosity determines the volume of oil and gas present, and all recovery computation must be based on a knowledge of its value.

Fluid Saturation

Pore space occupied by fluids is called fluid saturation. The fluid may be oil, gas or water.

The fluids can be calculated:

$$S_{(water)} = \frac{\text{water}}{\text{pore volume}}$$

$$S_{(oil)} = \frac{\text{oil}}{\text{pore volume}}$$

$$S_{(gas)} = 1 - Sw - So.$$

Salinity

Formation waters and drilling muds usually contain solutions of several different chemicals. The predominating chemical is sodium chloride. In case other chemicals are present, it is necessary to convert the amounts of such chemicals into their equivalent weights of sodium chloride.

The resistivity of formation waters and drilling mud at a certain temperature will differ due to the concentrations and the nature of the ions. When fluid resistivity is known from other sources, then we can calculate salinity in parts per million (ppm) or grains per gallon (by Schlumberger Chart A-5) as it is only the function of water resistivity and temperature. The following equation indicates that when water resistivity increases, salinity decreases:

$$Rw = \frac{5000}{C}$$

and

$$C = \frac{5000}{Rw}$$

C = salinity.

Temperature

We can solve Laplace's differential equation for calculating the temperature inside the well, as temperature increases towards the center of the earth:

$$\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0$$

$$\therefore \quad \frac{\partial T}{\partial t} = 0$$

and:

$$\nabla^2 T = \frac{1}{r} \cdot \frac{d^2(rT)}{dr^2} = 0$$

and integrating:

$$T = A + \frac{B}{r}$$

B = Geothermal gradient

A = Mean surface temperature

r = radius of the earth

T = temperature

t = time

T increases as r decreases.

LaPlace equation is applicable to an earth wherein the temperature is not a function of time. In this above equation temperature is a function of radial distance only.

This satisfies our equation for calculating temperatures of different formations in the bore hole:

$$T^{o} = A + (G \times \text{Depth}/100')$$

G = Geothermal gradient (0.8 to 1.2 degrees F./100')

ELECTRIC LOG ANALYSIS

WELL: IDA KEITH No. 3

FIELD: HOLLEY

LOCATION: SEC. 10-9S-24W

Total Depth: 4040'

Rm Mud Resistivity: 0.9 ohm-meters at BHT

(BHT) Bottom Hole Temperature: 108° F.

Bit Size (hole Size): 7 7/8"

Oil: 47°API Gravity

$$\therefore \underline{\text{Specific Gravity}} = \frac{141.5}{API + 131.5}$$

$$= \frac{141.5}{47 + 131.5} = 0.789$$

Physical Properties of the Formations

Smoky Hill Chalk: -564' - Bottom

Formation Temperature:

$$T^\circ = A + (G \times Depth/100')$$

$$A = \text{Average surface temperature } 80^\circ \text{ F.}$$

$$G = \text{Geothermal gradient } 0.70$$

$$T^\circ = 80 + (0.7 \times 564/100)$$

$$= 84^\circ \text{ F.}$$

and

$$T = 83.5^\circ \text{ (From Schlumberger/s Temperature Chart A-2)}$$

Log Datas: SP = - 30 millivolts

Ri16" = 22 ohm - meters

Rt(AO) = 30 ohm - meters

$$Rm \text{ of the formation} = \frac{BHT}{\text{Form. Temp.}} \times Rm\ BHT$$

$$\therefore Rm = \frac{108}{84} \times .90 = 1.17 \text{ ohm - m}$$

Rmf of the formation = 0.75 Rm

or Rmf by use of Schlumberger's Chart (A-4)

$$Rmf = \cdot 90 \text{ ohm - m}$$

To find Rw:

$$E = -\frac{Rt}{F} \int_{1\,Sol}^{Sol.\ 2} \sum_i \frac{Ti}{Zi}\ d\ \log e\ a_i$$

$$Em = -\frac{Rt}{F} \log e \frac{(a_{na}+)\ w}{(a_{na}+)\ mf}$$

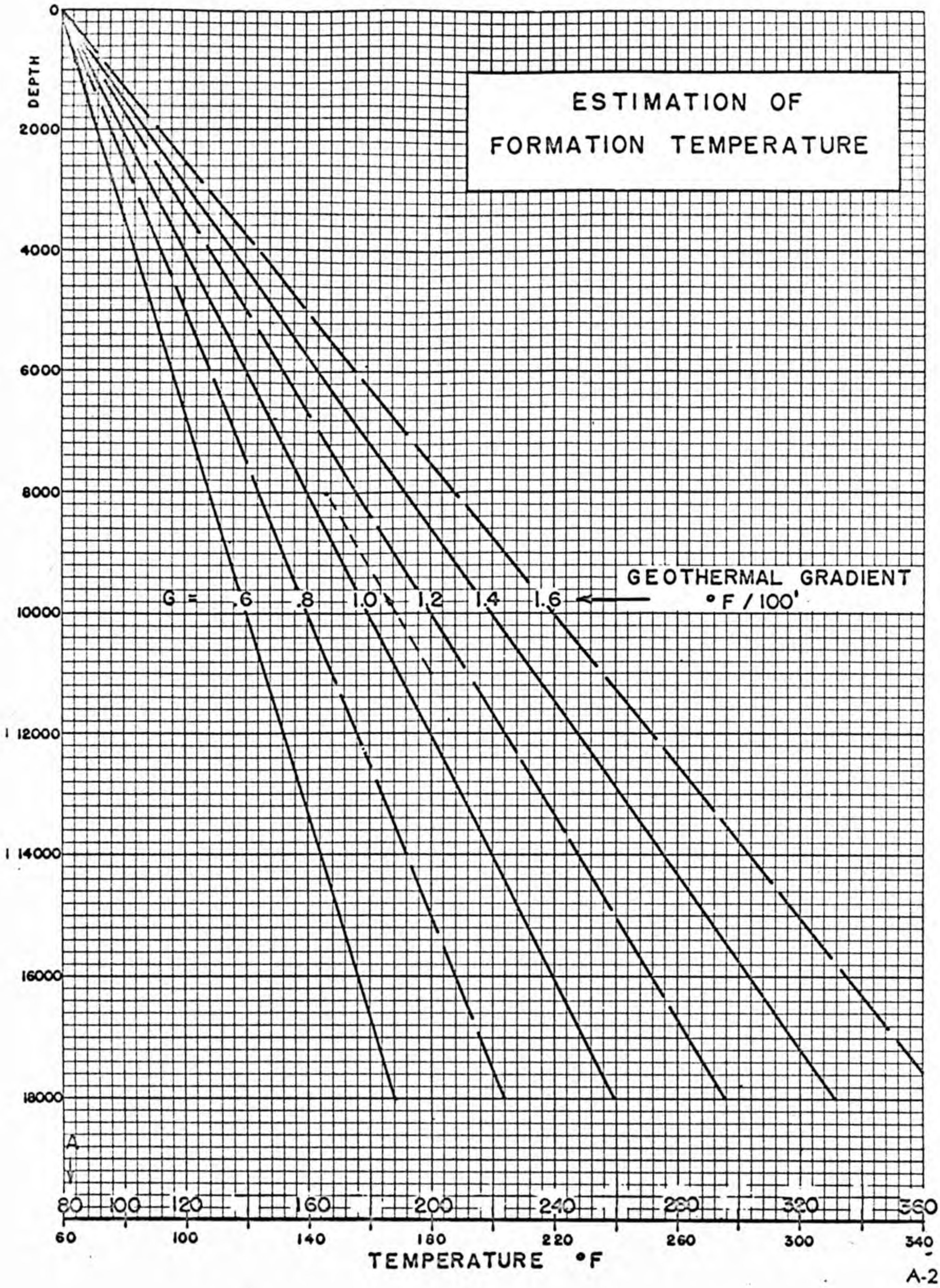
$$a_{na}^{+} = a_{cl}^{-} = a^{-+}\ NACL$$

$$a^{-+}_{nacl} = \sqrt{(a_{na}^{+})\ (a_{cl}^{-})}$$

$$Em = -2.3\ \frac{RT}{F} \log e \frac{(a^{-+})\ w}{(a^{-+})\ mf}$$

where

$$2.3\ \frac{RT}{F} = 59 \text{ at } 75^{o}\ F.$$


ESTIMATION OF
FORMATION TEMPERATURE
DEPTH
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
G = .6 .8 1.0 1.2 1.4 1.6
GEOTHERMAL GRADIENT
°F / 100'
80 100 120 160 200 240 280 320 360
60 100 140 180 220 260 300 340
TEMPERATURE °F

and:

$$2.3\ (2^{T}\ cl - 1)\ \frac{RT}{F} = 12 \text{ at } 75^{\circ}\ F.$$

$$\therefore \quad K = (59 + 12) = 71 \text{ at } 75^{\circ}\ F.$$

Thus:

$$SP = -71 \text{ loglo } \frac{(a^{\pm})\ w}{(a^{\pm})\ amf}$$

It becomes:

$$SP = -71 \text{ loglo } \frac{Rmf}{(Rw)e}$$

or

$$-30 = -K \text{ log10 } \frac{Rmf}{(Rw)e}$$

and
$$\frac{Rmf}{(Rw)e} = \frac{30}{-71}\ (\text{log10})$$

$$= 2.65$$

$$\frac{Rmf}{(Rw)e} = 2.65 \text{ (By Schlumberger's Chart A-10)}$$

$$\therefore \quad (Rw)e = \frac{Rmf}{\frac{Rmf}{(Rw)e}}$$

$$= \frac{.90}{2.65} = .34 \text{ ohm - m}$$

$$Rw = .40 \text{ ohm - m (Chart A-12)}$$

$$\frac{Ri}{Rm} = \frac{22}{1.17}$$

$$= 19$$

Corrected for borehole $\frac{Ri}{Rm} = 17$ (Chart B-2)

$$\frac{Rt}{Rm} = \frac{30}{1.17}$$

$$= 25.6$$

corrected for bore hole $\frac{Rt}{Rm} = 21$ (Chart B-2)

$\therefore$ corrected Ri for bore hole $= (17 \times 1.17)$

$= 20$ ohm - m

correct

$$R_t = (21 \times 1.17)$$

$$= 25 \text{ ohm - m}$$

Tixier Rocky Mountain Method for Calculating Sw and Porosity

$$Ri = \frac{F \times R_z}{Si^2}$$

$$Rt = \frac{F \times Rw}{Sw^2}$$

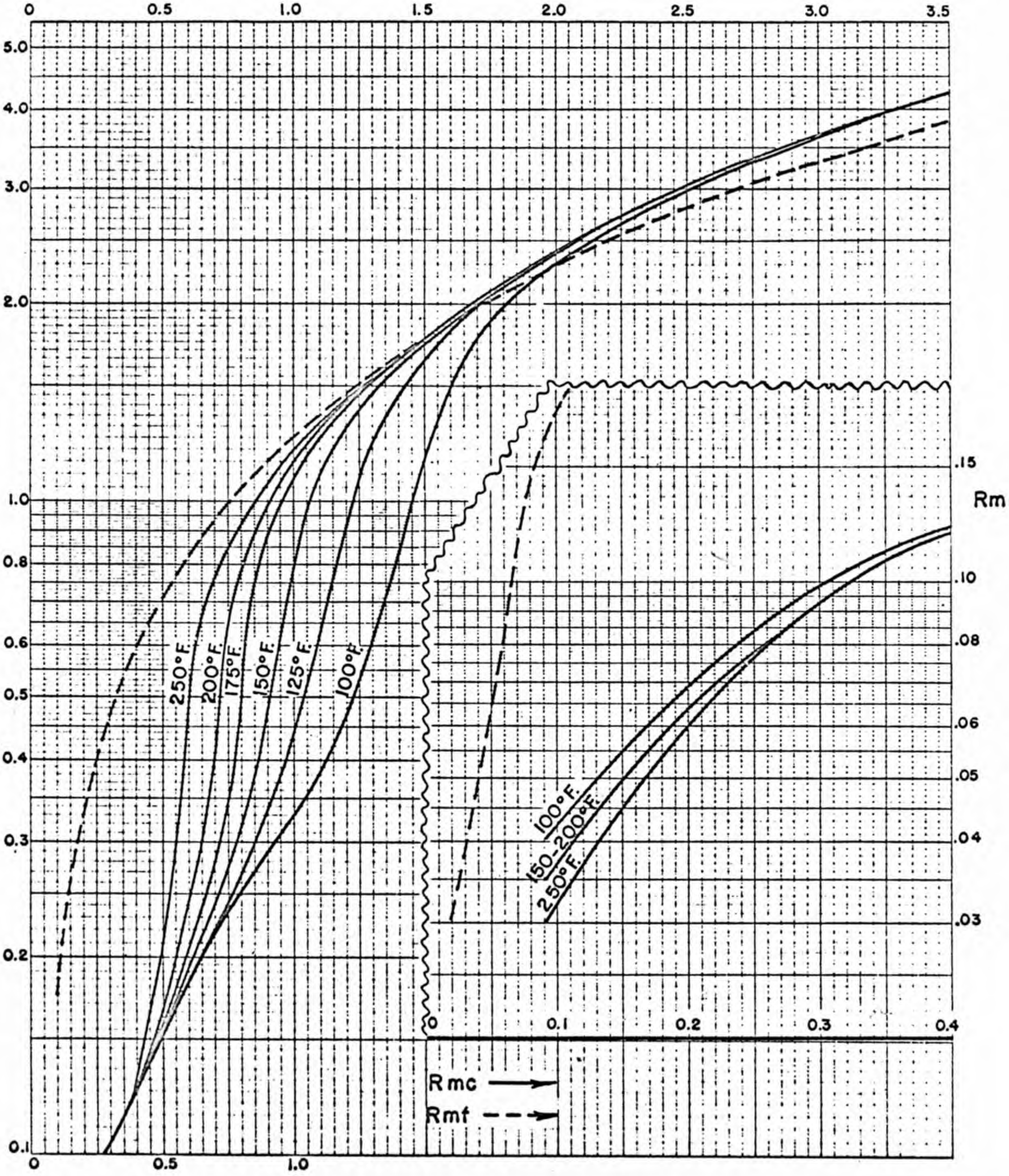
$$\therefore \quad \frac{Ri}{Rt} = \frac{Rz}{Rw} \cdot \frac{Sw^2}{Si^2}$$ Si = Sw in invaded zone

or

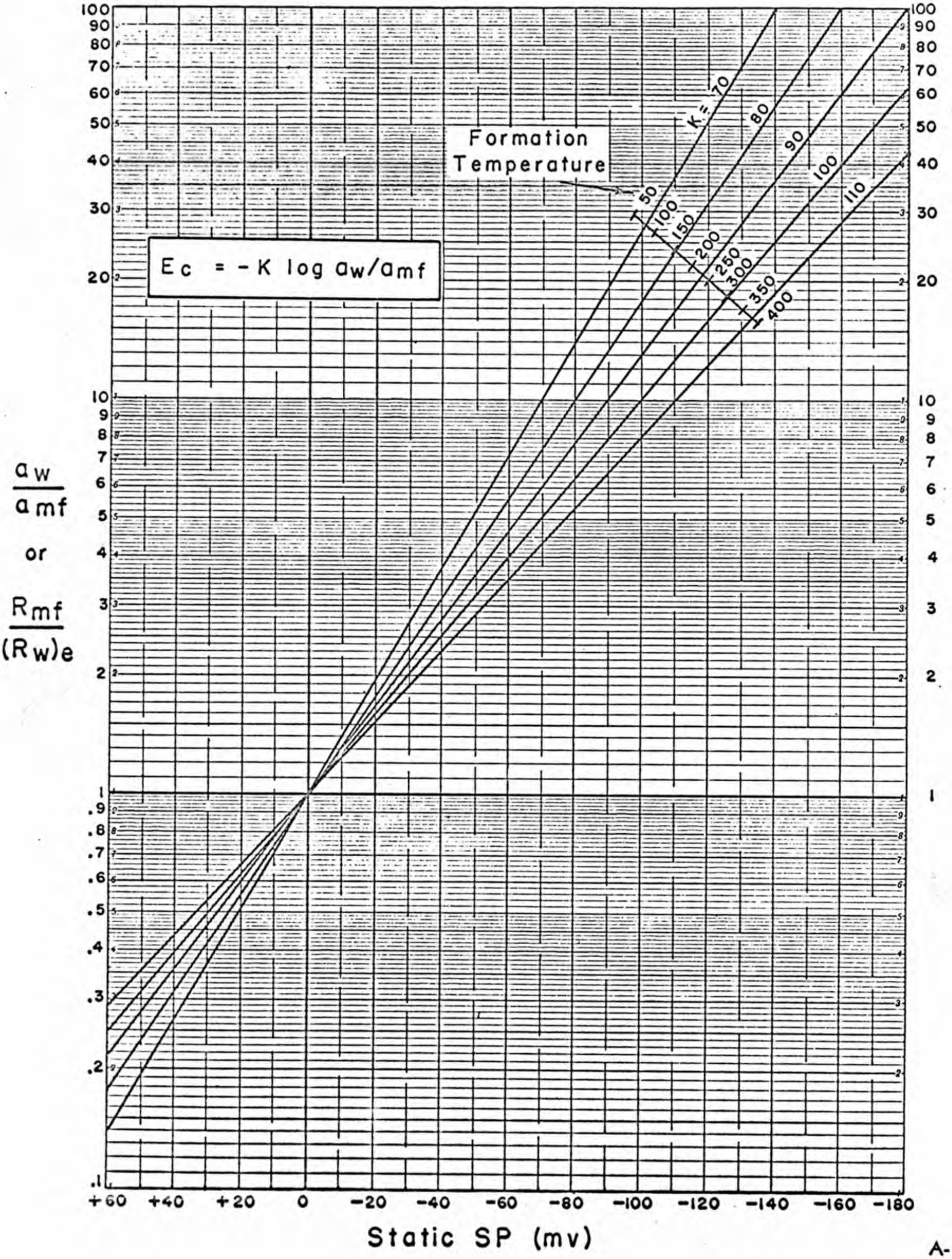
$$\frac{Sw^2}{Si^2} = \frac{Ri/Rt}{Rz/Rw}$$

$$\frac{Ri}{Rt} = \frac{20}{25} = 0.80$$

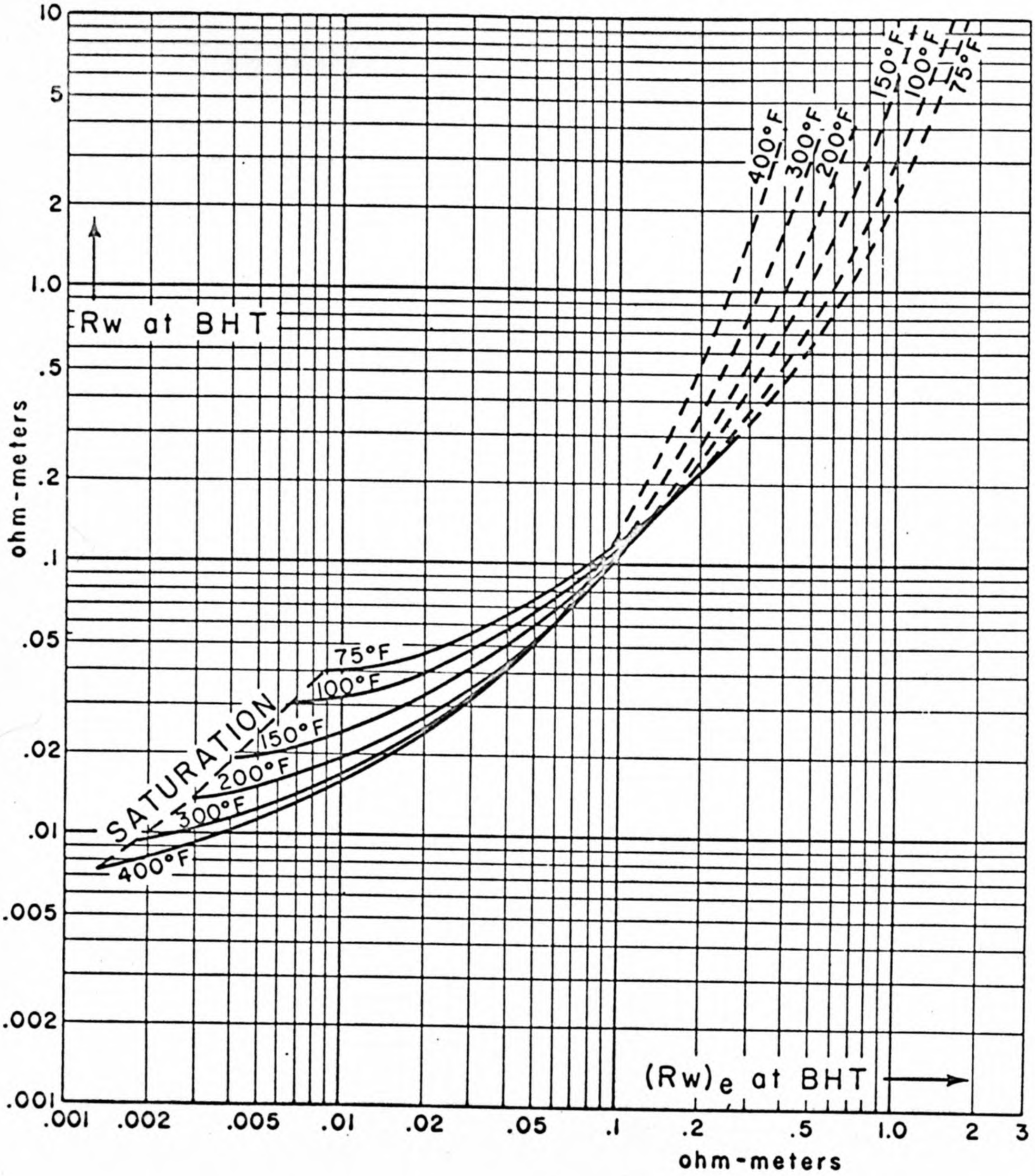
Rmc AND Rmf DETERMINATION
(Average Values)



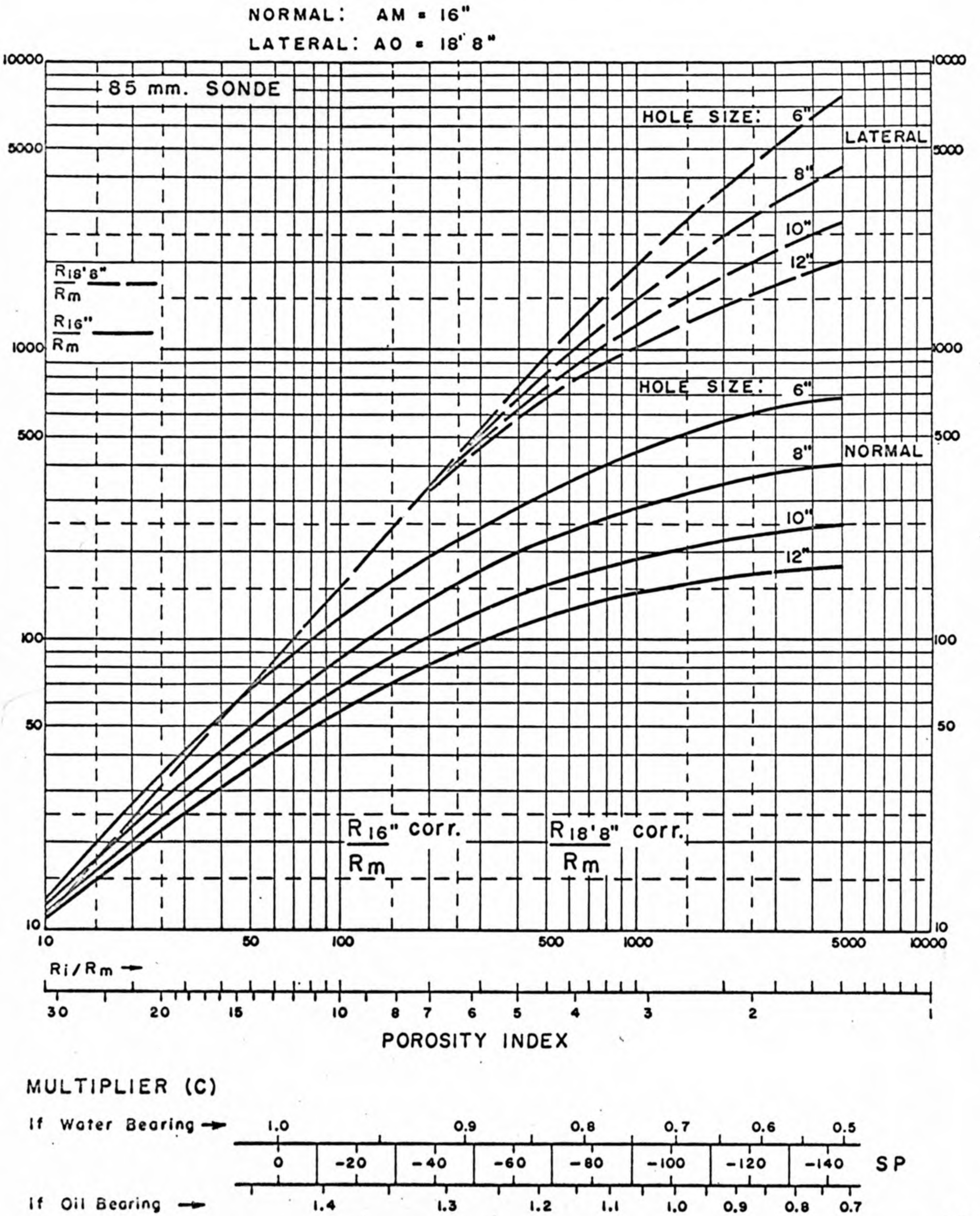
Rw DETERMINATION FROM THE SP
PART I: FINDING (Rw)e



TRUE Rw VS. EQUIVALENT (Rw)e



ELECTRICAL LOG
SIMPLIFIED RESISTIVITY DEPARTURE CURVES



and:

$$\frac{Rmf}{Rw} = \frac{.90}{.40} = 2.25$$

$\therefore$ $Sw = 42\%$ (By Schlumberger's Chart D-8).

Porosity:

$$F = Sw^2 \frac{Rt}{Rw}$$

$$= (.42)^2 \frac{25}{.40} = 10$$

By Humble equation:

$$F = \frac{0.62}{\phi^{2.15}}$$

$$\therefore \quad \phi = \frac{0.62}{2.15 \sqrt{F}} = \frac{0.62}{2.15 \sqrt{10}} = 27\%$$

Porosity By Tixier Chart D-10:

$$\frac{Rt}{Rm} \cdot \frac{Rm}{Rw} = \frac{Rt}{Rw} = \frac{25}{.40} = 62.5$$

$$\therefore \quad \phi = 27\%$$

Permeability: (By Tixier Resistivity Gradient Method)

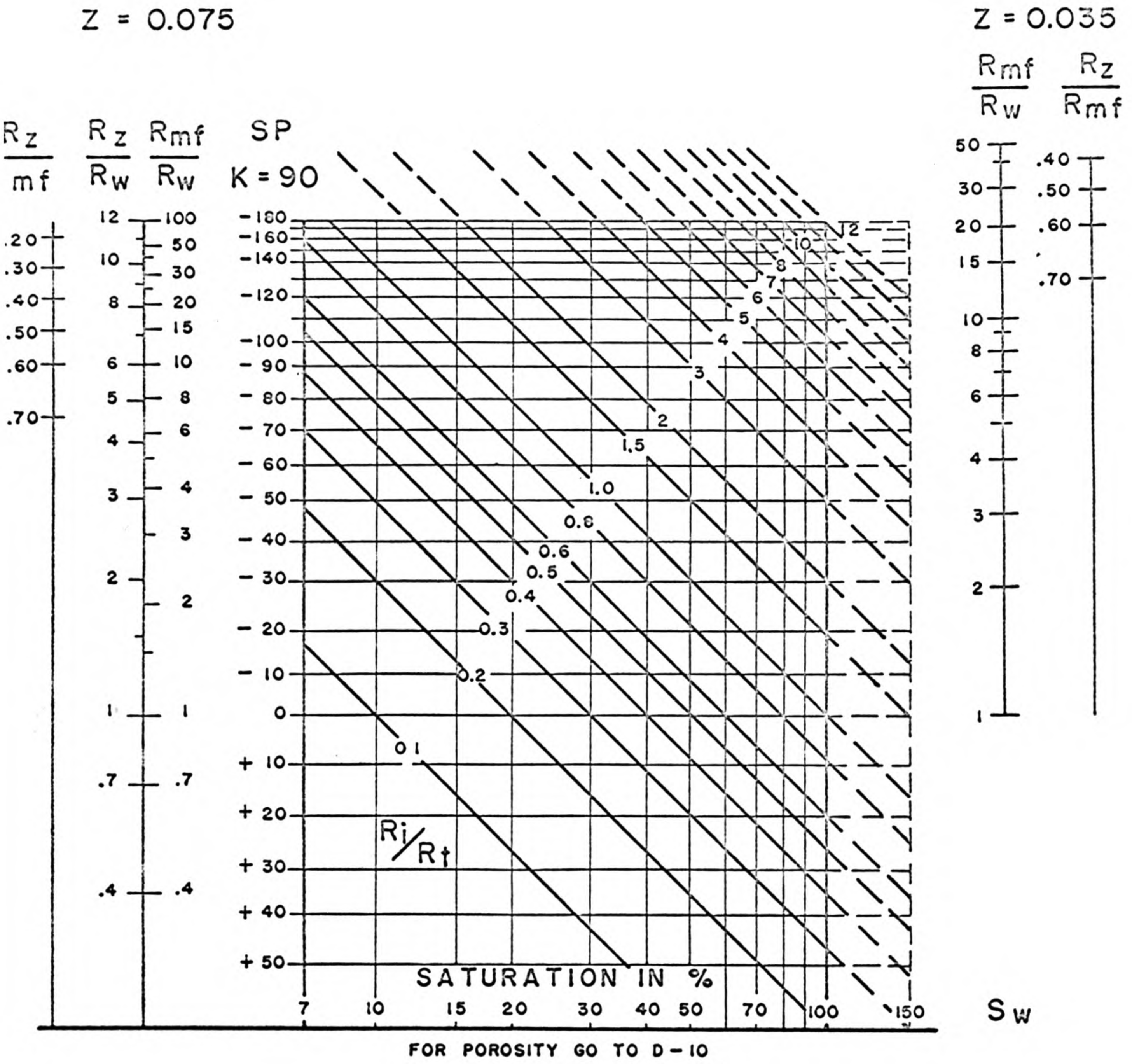
$$Rt = Ro + \frac{\Delta Rt}{\Delta h} h$$

Rt = Difference in true resistivities

Δh = Difference in depth

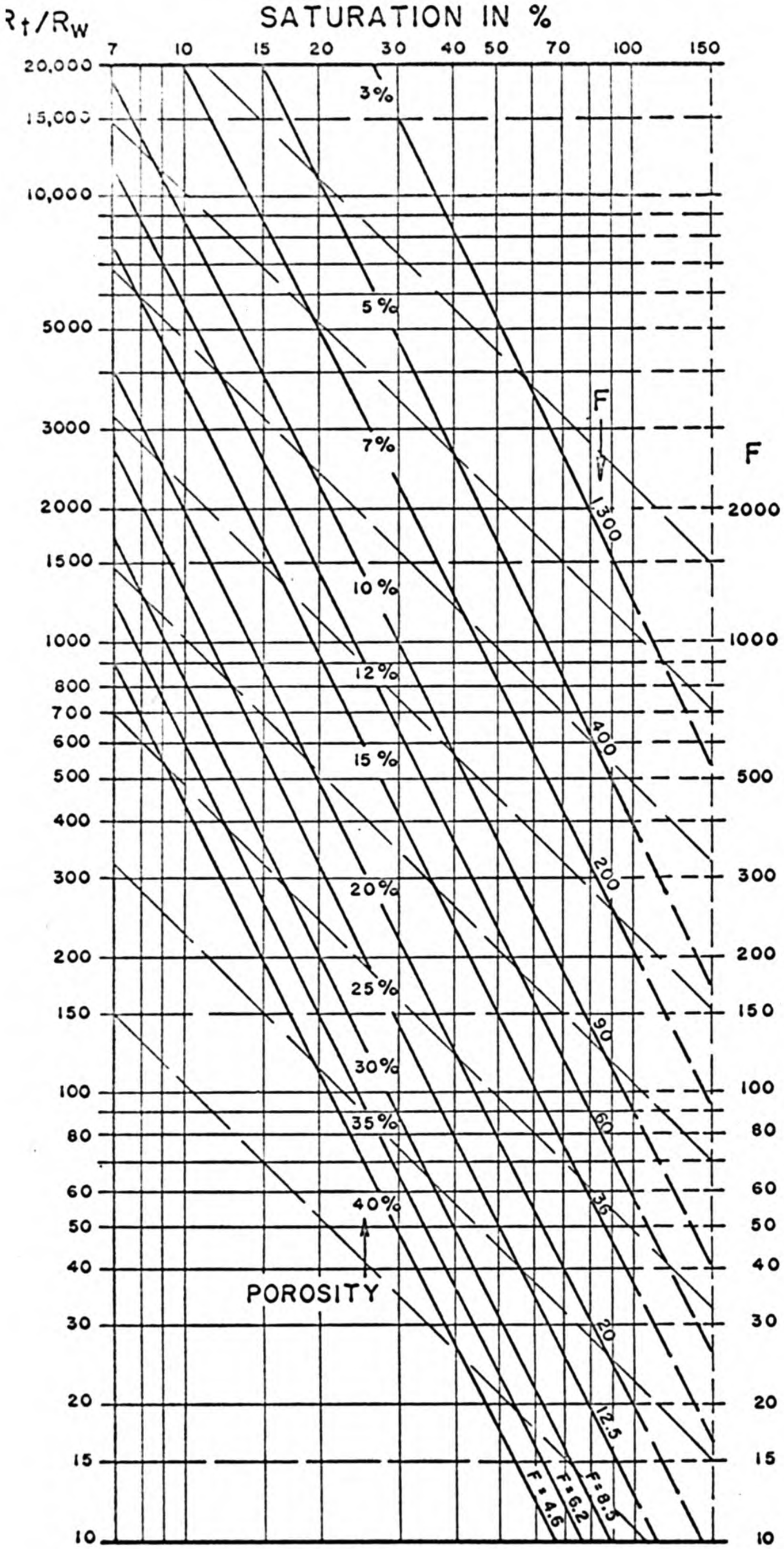
h = Height above the water table where Rt is measured.

ROCKY MOUNTAIN METHOD FOR S_w



REFERENCE: Tixier, M. P. "Electric Log Analysis in the Rocky Mountains." *Oil & Gas Journal,* June 23, 1949.

POROSITY DETERMINATION



POROSITY BALANCE FOR ROCKY MOUNTAIN METHOD

If balance does not exist, move from the calculated porosity.

a) along a 45° line until the correct porosity is met (case of R_t wrong). (R_i Method)
Exception: $R_{IL} \simeq R_t$ when $R_{16c}/R_{IL} < 1.2$ for 5FF40, or when $R_{16c}/R_{IL} < 1.4$ for 6FF40.

b) along a horizontal line until the correct porosity is met (case of R_i wrong). (Archie Method)
i.e. $FR_z > R_{16"}$

This final point indicates a more correct S_w.

Beware of high SP

when the final $S_w \geq \frac{R_z}{R_{mf}}$.

The zone may be wet.

By Archie's Law:

$$Sw = \sqrt{\frac{Ro}{Rt}}$$

substituting Rt by its value in the above,

$$Sw = \sqrt{\frac{Ro}{Ro + h \dfrac{\Delta Rt}{\Delta h}}}$$

$$= \sqrt{\frac{1}{1 + h \dfrac{1}{Ro} \cdot \dfrac{\Delta Rt}{\Delta h}}} = \sqrt{\frac{1}{1 + ha}}$$

where

$$a = \frac{1}{Ro} \cdot \frac{\Delta Rt}{\Delta h} \quad \text{Resistivity gradient}$$

At the level h there is a capillary-pressure relationship:

$$h = 2.3 \frac{Pc}{\Delta sp \cdot gr.}$$

$\Delta sp \cdot gr.$ = Difference in specific gravity of water and oil.

From empirical data:

$$Sw = \sqrt{\frac{1}{1 + F_k \ Pc}}$$

F_k = lithologic factor

equating the above equations:

$$\sqrt{\frac{1}{1 + F_k \ Pc}} = \sqrt{\frac{1}{1 + a(2.3 \ Pc/\Delta sp \cdot gr.)}}$$

$$\therefore \quad F_k = 2.3 \frac{a}{\Delta sp \cdot gr.} = \frac{2.3}{\Delta sp \cdot gr.} \cdot \frac{1}{Ro} \cdot \frac{\Delta Rt}{\Delta h}$$

The capillary data shown by Tixier:

$$F_k = \sqrt{\frac{K}{C}}$$

Average value of C = 20

$$\therefore \quad \sqrt{\frac{K}{C}} = 2.3 \frac{a}{\Delta sp \cdot gr.}$$

$$= \frac{2.3}{\Delta sp \cdot gr.} \cdot \frac{\Delta Rt}{\Delta h} \cdot \frac{1}{Ro}$$

$\Delta sp \cdot gr.$: water gravity = 1.025 (for normal salinity)

oil gr. = 0.787

$\Delta sp \cdot gr. = (1.025 - .789)$

$= 0.23$

$$\sqrt{\frac{K}{C}} = \frac{2.3}{.23} \cdot \frac{\Delta Rt}{\Delta h} \cdot \frac{1}{Ro} = \frac{2.3}{.23} \times \frac{37.5}{270} \times \frac{1}{4}$$

$$= .35$$

$$\frac{K}{C} = (.35)^2$$

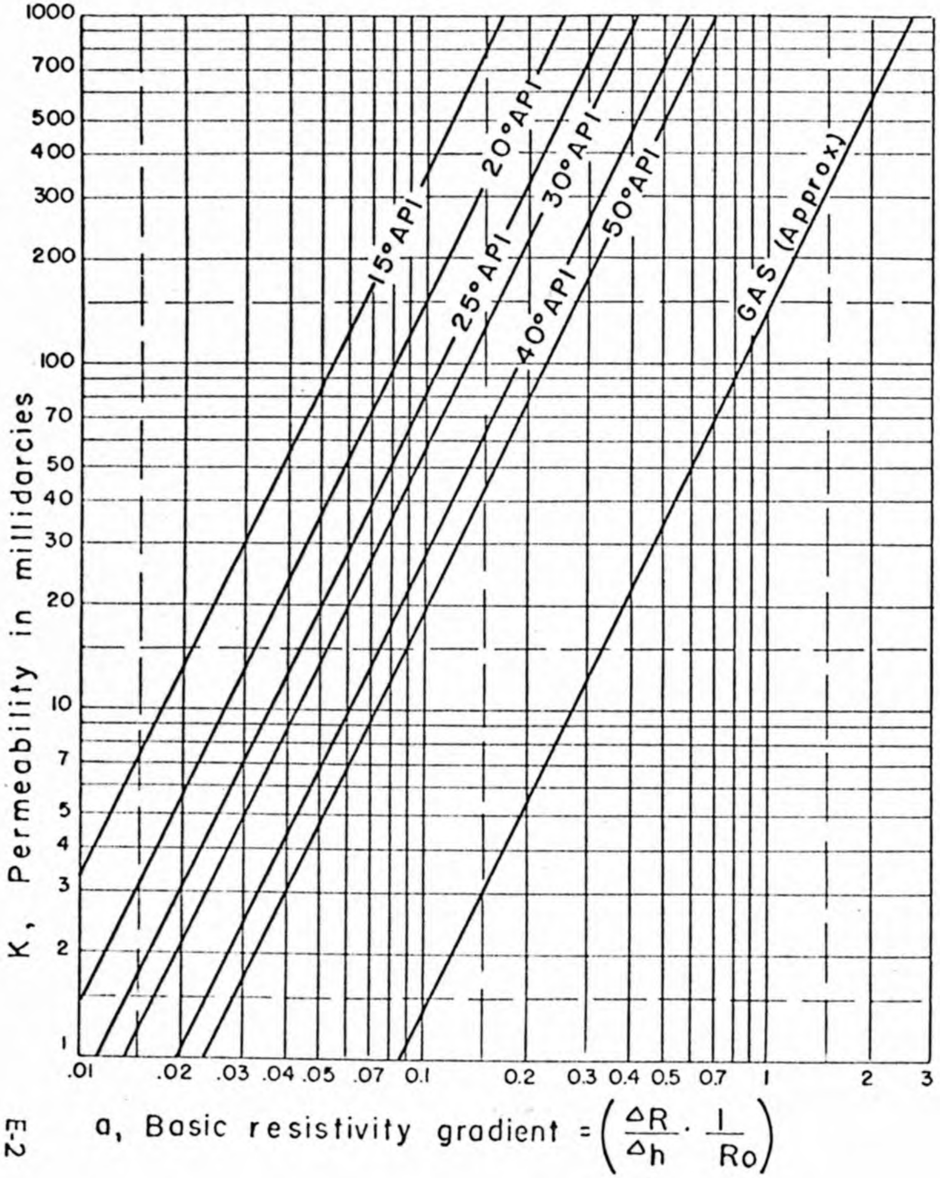
$$K = (.35)^2 \times C = (.35)^2 \times 20$$

$= 3.5$ millidarcies

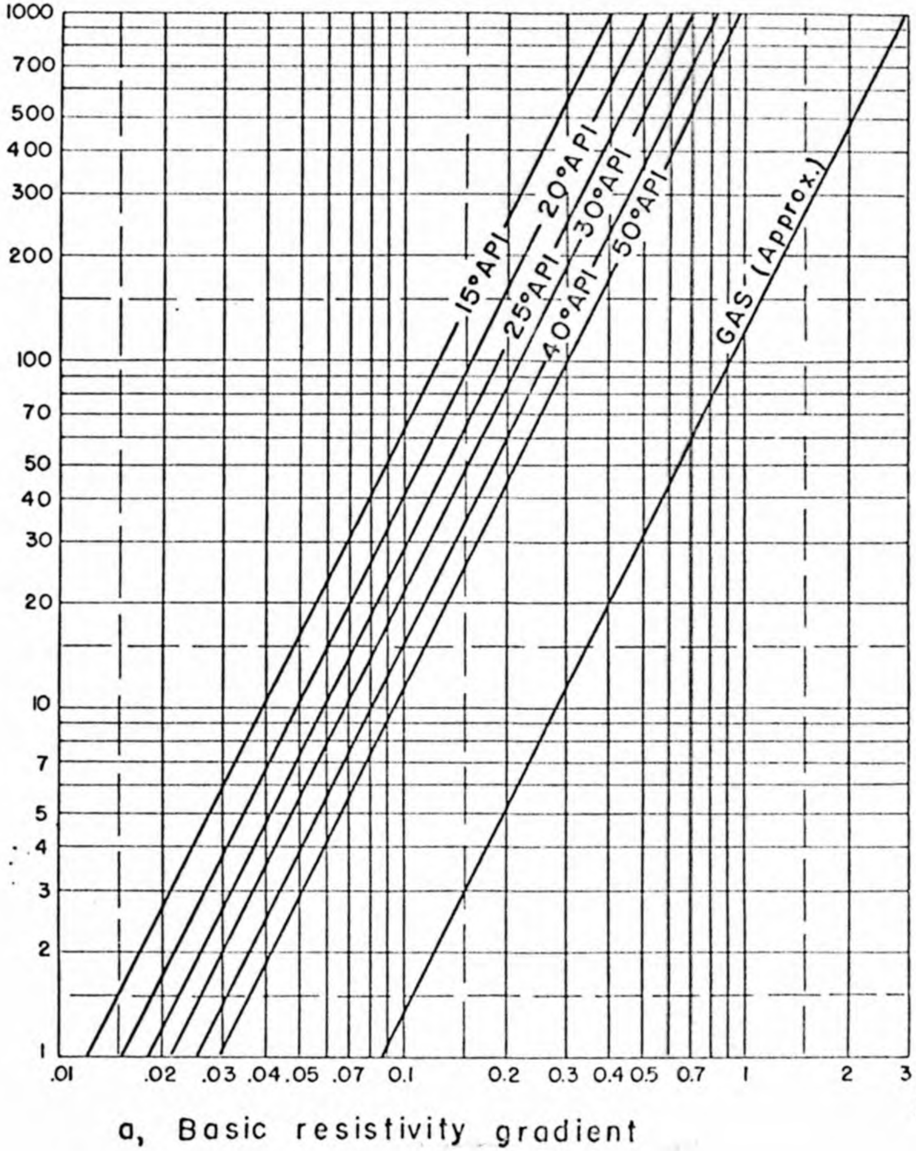
Permeability = 3.4 millidarcies (By Chart E-2)

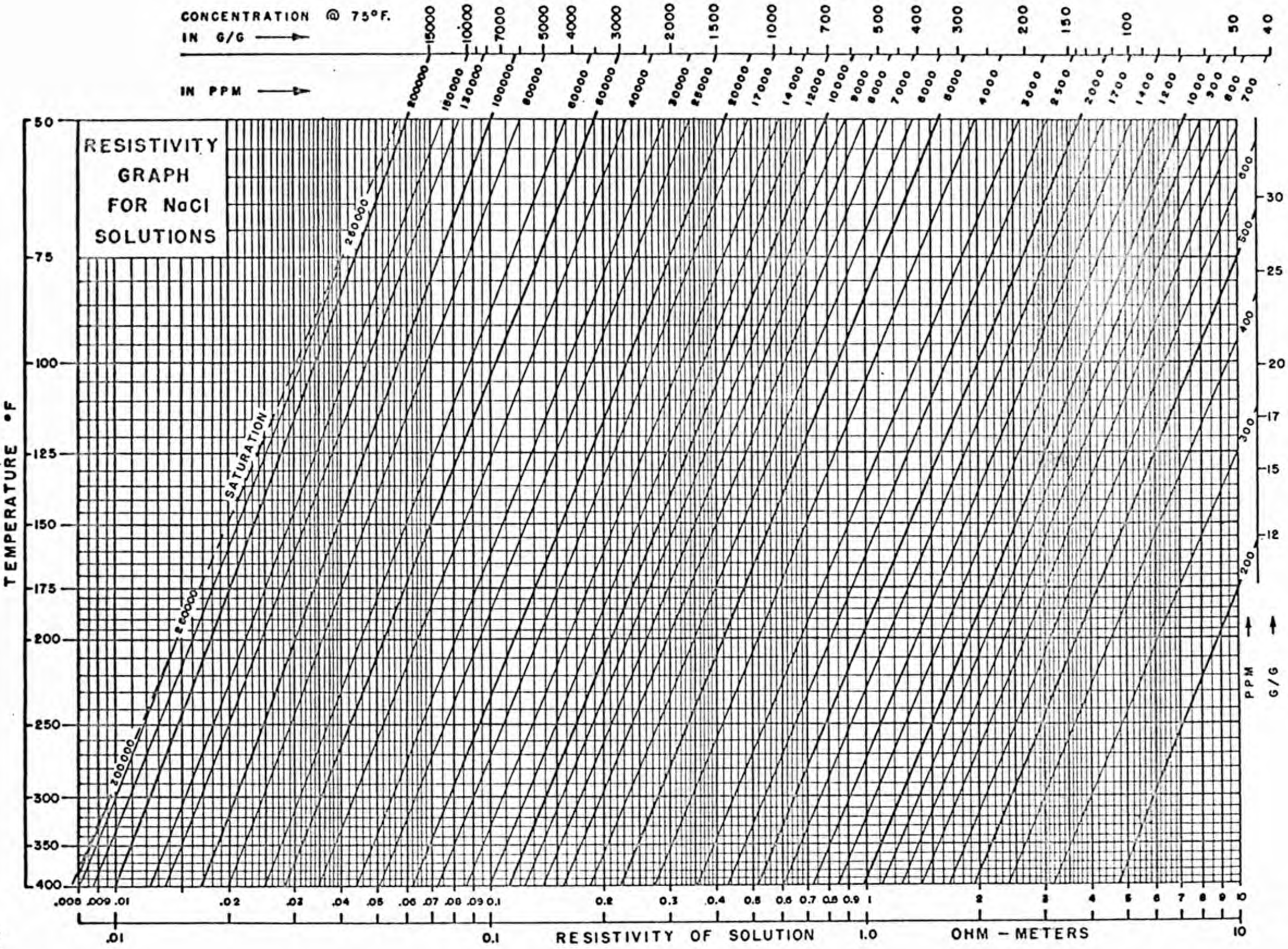
PERMEABILITY FROM RESISTIVITY GRADIENT

For dw = 1.025 (sea water)



For dw = 1.1 (150,000 p.p.m. in formation water)




RESISTIVITY GRAPH FOR NaCl SOLUTIONS
CONCENTRATION @ 75°F.
IN G/G
IN PPM
TEMPERATURE °F
RESISTIVITY OF SOLUTION OHM - METERS
SATURATION
PPM
G/G

Salinity:

$$Rw = 0.40 \text{ ohm - m}$$

$$\text{Temp.} = 84^{o} \text{ F.}$$

$$\therefore \text{Salinity} = 13{,}000 \text{ PPM}$$

$$= 1.3\%$$

Chart A-6

Fort Hays Limestone

TOP - 564', Bottom 624'

Temp. = 85^{o} F. (By Chart A-2)

$$Rm = \frac{108}{85} \times .90 = 1.15 \text{ ohm - m.}$$

$$Rmf = 0.75\ Rm$$

$$= 0.85 \text{ ohm - m (Chart A-4)}$$

$$Sp. = -27 \text{ Mv.}$$

$$Ri = 15 \text{ ohm - m}$$

$$Rt = 22 \text{ ohm - m}$$

$$SP = -K \log 10 \frac{Rmf}{(Rw)e}$$

$$\frac{Rmf}{(Rw)e} = 2.64 \quad \text{(Chart A-10)}$$

and

$$(Rw)e = \frac{Rmf}{Rmf/(Rw)e} = \frac{.85}{2.64} = 0.323 \text{ ohm - m}$$

$$\therefore Rw = 0.38 \text{ ohm - m} \quad \text{(Chart A-12)}$$

$$\frac{Ri}{Rm} = \frac{15}{1.15} = 13 \quad \text{corr. for bore Hole } \frac{Ri}{Rm} = 13 \quad \Bigg) \ \text{B-2}$$

$$\frac{Rt}{Rm} = \frac{22}{1.15} = 19 \quad \text{corr. for bore hole } \frac{Rt}{Rm} = 16$$

$\therefore$

corrected Ri = (13 x 1.15) = 15 ohm - m

corrected Rt = (16 x 1.15) = 18.5 ohm - m.

Sw and ϕ By Tixier Rocky Mountain Method:

$$\frac{Ri}{Rt} = \frac{15}{18.5} = 0.80$$

$$\frac{Rmf}{Rw} = \frac{0.85}{0.38} = 2.22$$

$\therefore$ Sw = 42% (Chart D-8)

<u>Porosity</u>:

$$\frac{Rt}{Rm} \cdot \frac{Rm}{Rw} = \frac{Rt}{Rw} = \frac{18.5}{0.38} = 49$$

$\therefore$ ϕ = 27% (D-12)

<u>Porosity By Tixier "Porosity Index" Method</u>:

$$\frac{Ri}{Rm} = 13$$

$\therefore$ Porosity Index = 27.5) Chart B-2
Multiplier = 0.945)

$\therefore$ Porosity = (27.5 x 0.945)
= 26%

Permeability: By Resistivity Gradient Method

$$\sqrt{\frac{K}{20}} = \frac{2.3}{\Delta sp \cdot gr.} \cdot \frac{\Delta Rt}{\Delta h} \cdot \frac{1}{Ro}$$

$$= \frac{2.3}{.23} \times \frac{8}{56} \times \frac{1}{6.4}$$

$$= .22$$

$$\frac{K}{20} = (.22)^2$$

$$K = (.22)^2 \times 20 - 0.968 \text{ nd.}$$

$$= .97 \text{ md.}$$

Salinity:

Temp. = 85° F.

Rw = .38 ohm - m

.˙. Salinity = 13800 ppm

= 1.38% Chart A-6

Codell Sandstone:

624' - Top

672 - Bottom

Temperature = 85° F. (A-2)

$$Rm = \frac{108}{85} \times .90 = 1.15 \text{ ohm - m}$$

Rmf = .75 Rm

= 0.85 ohm - m (Chart A-4)

$$SP = -30 \text{ Mv.}$$

$$Ri = 7 \text{ ohm - m}$$

$$Rt = 15 \text{ ohm - m}$$

$$Sp = -K \log10 \frac{Rmf}{(Rw)e}$$

$$\frac{Rmf}{(Rw)e} = 2.7 \quad \text{(Chart A-10)}$$

$$\therefore \quad (Rw)e = \frac{Rmf}{Rmf/(Rw)e} = \frac{.85}{2.7} = .315$$

$$Rw = 0.36 \text{ ohm - m} \quad \text{(Chart A-12)}$$

<u>Wittie's Method for Porosity:</u>

$$F = \frac{Ri}{Rmf}$$

$$= \frac{7}{.85} = 8.25$$

By Humble equation:

$$F = \frac{0.62}{\phi^{2.15}}$$

and

$$= \frac{0.62}{2.15 \sqrt{F}}$$

$$= \frac{0.62}{2.15 \sqrt{8.25}} = 29\%$$

<u>Water Saturation:</u>

$$Sw^2 = \frac{Rw \dfrac{0.62}{\phi^{2.15}}}{Rt}$$

$$Sw = \sqrt{\frac{Rw \dfrac{0.62}{\phi^{2.15}}}{Rt}}$$

$$= \sqrt{\frac{.36 \times 8.25}{15}} = .44$$

$$Sw = 44\%$$

Permeability:

$$\sqrt{\frac{K}{20}} = \frac{2.3}{.23} \times \frac{Rt}{h} \cdot \frac{1}{Ro}$$

$$= \frac{2.3}{.23} \times \frac{16}{54} \times \frac{1}{3} = .95$$

$$\frac{K}{20} = (.95)^2$$

$$K = (.95)^2 \times 20 = 18 \text{ md.}$$

Salinity:

Rw = .36 ohm - m

Temp. = 85° F.

∴ Salinity = 14200 PPm

= 1.42% (Chart A-6)

Blue Hill Shale

672' - Top

790' - Bottom

Temp. = 86° F. (A-2)

$$Rm = \frac{108}{86} \times .90 = 1.13 \text{ ohm - m}$$

$$Rmf = 0.75 \, Rm$$

$$= 0.85 \text{ ohm - m} \quad (A\text{-}4)$$

$$SP = -26 \text{ Mv.}$$

$$Ri = 4 \text{ ohm - m}$$

$$Rt = 3.5 \text{ ohm - m}$$

$$SP = -K \log 10 \frac{Rmf}{(Rw)e}$$

$$\frac{Rmf}{(Rw)e} = 2.3 \quad \text{(Chart A-10)}$$

$$\therefore \quad (Rw)e = \frac{Rmf}{Rmf/(Rw)e} = \frac{.85}{2.3} = 0.37 \text{ ohm - m}$$

$$Rw = .40 \text{ ohm - m} \quad \text{(Chart A-12)}$$

Sw and Ø By Rocky Mountain Method:

$$\frac{Ri}{Rt} = \frac{4}{3.5} = 1.14$$

$$\frac{Rmf}{Rw} = \frac{.85}{.40} = 2.125$$

$$\therefore \quad Sw = 60\% \quad \text{(Chart D-8)}$$

$$\frac{Rt}{Rm} \cdot \frac{Rm}{Rw} = \frac{Rt}{Rw} = \frac{3.5}{.4} = 8.8$$

$$\therefore \quad \phi = 40\% \quad \text{(Chart D-10)}$$

Wittie's Method:

$$F = \frac{Ri}{Rmf} = \frac{4}{.85} = 4.7$$

By Humble equation:

$$F = \frac{0.62}{\phi^{2.15}}$$

$$\phi = \frac{0.62}{2.15 \sqrt{F}} = \frac{0.62}{2.15 \sqrt{4.7}} = .39$$

<u>Permeability:</u>

$$a = \frac{\Delta Rt}{\Delta h} \cdot \frac{1}{Ro} = \frac{1}{120} \cdot \frac{1}{1.88} = .0044$$

$$\sqrt{\frac{K}{20}} = \frac{a \times 2.3}{.23}$$

$$= \frac{.0044 \times 2.3}{.23} = .044$$

$$\frac{K}{20} = (.044)^2$$

$$K = (.044)^2 \times 20$$

$$= .04 \text{ Md.}$$

<u>Salinity:</u>

Rw = .40 ohm - m

Temp. = 86° F.

∴ Salinity = 13,000 PPm

= 1.3% (A-6)

Fairport Chalky Shale

Top - 790'

Bottom - 880'

Temp. = 86° F. (A-2)

$$Rm = \frac{108}{86} \times .9 = 1.13 \text{ ohm - m}$$

$$Rmf = .75\ Rm$$

$$= .85 \text{ ohm - m} \quad (A-4)$$

$$SP = -28\ Mv.$$

$$Ri = 12 \text{ ohm - m}$$

$$Rt = 8 \text{ ohm - m}$$

$$SP = -k \log 10 \frac{Rmf}{(Rw)e}$$

$$\frac{Rmf}{(Rw)e} = 2.5 \quad (A-10)$$

$$\therefore \quad (Rw)e = \frac{Rmf}{Rmf/(Rw)e} = \frac{.85}{2.5} = .33 \text{ ohm - m}$$

$$Rw = 0.35 \text{ ohm - m} \quad (\text{Chart A-12})$$

Sw and Ø by Rocky Mountain Method:

$$\frac{Ri}{Rt} = \frac{12}{8} = 1.5$$

$$\frac{Rmf}{Rw} = \frac{.85}{.35} = 2.4$$

$$\therefore \quad Sw = 70\% \quad (\text{Chart D-8})$$

$$\frac{Rt}{Rm} \cdot \frac{Rm}{Rw} = \frac{Rt}{Rw} = \frac{8}{.35} = 22$$

Witte's Method

$$\therefore \quad \phi = 26\% \quad (D-10)$$

$$F = \frac{Ri}{Rmf} = \frac{12}{.85} = 14$$

$$\phi = \frac{.62}{2.15 \sqrt{14}} = 23\%$$

Permeability:

$$a = \frac{1}{5.11} \times \frac{7}{90} = .015$$

$$\sqrt{\frac{K}{20}} = \frac{a \times 2.3}{.23}$$

$$= \frac{.015 \times 2.3}{.23} = .15$$

$$\frac{K}{20} = (.15)^2$$

$$K = (.15)^2 \times 20$$

$$= .45 \text{ nd.}$$

Salinity:

$$Rw = .35 \text{ ohm - m}$$

$$\text{Temp.} = 86^{\circ} \text{ F.}$$

$$\therefore \text{Salinity} = 15{,}000 \text{ PPm}$$

$$= 1.5\% \quad \text{(A-6)}$$

$$Rw = \frac{5000}{C}$$

$$C = \text{Salinity}$$

$$C = \frac{5000}{Rw} = \frac{5000}{.35}$$

$$= 14500 \text{ PPM}$$

continued (Appendix, Table 1)

STATIGRAPHY AND ELECTRIC INTERPRETATION

Precambrian

The Precambrian is reported as granite, schist, gneiss and quartzite. These are mostly composed of quartz, feldspar and biotite. Electric logs of the Precambrian rocks were not studied in this county.

Cambrian System

<u>Croixian Series</u>:

The Reagan sandstone uncomfortably overlies the Precambrian rocks. This sandstone is composed of white to gray medium- to coarse-grained, frosted quartz-grains.

Ordovician System

<u>Lower Ordovician</u>: Arbuckle Group:

The Arbuckle is composed of finely crystalline limestone and gray to brown dolomitic limestone with some streaks of dense and impervious dolomitic limestone.

Electric Interpretation:

The negative potential in the center indicates electrolyte containing saline water.

In nonproducing regions resistivity values are comparatively low. This may be due to large number of sodium chloride ions present in the solution. In producing wells this formation has greater resistivities. Oil and gas are almost perfect nonconductors of electricity.

Middle Ordovician: Simpson Group:

This group consists of green shales and white to gray, angular to subrounded sandstone. In most of the wells this group is absent.

Viola Group:

The Viola group is composed of a very coarsely crystalline, white, pink, light gray limestone and finely crystalline, gray cherty to non-cherty limestone.

This group is absent in almost all wells.

Mississippian System

Osage Series:

The Kinderhook shale consists of green to brown shale and ranges in thickness from 0 to 150 feet. It is often absent on the logs.

Pennsylvanian System

Desmoinesian Series: Cherokee Group:

The lowermost unit of this group is basal Pennsylvanian conglomerate, composed of detrital chert and quartz grains imbedded in micaceous shale. Above this formation, the Cherokee group consists of shales and crystalline limestones.

Electric Interpretation:

Resistivity is low possibly due to connate water and the SP curve is also not so negative due to lack of porous permeable beds.

Marmaton Group:

This group consists of shales and thin gray limestones containing gray to tan chert.

Missourian Series: Pleasanton Group:

This group consists of sandstone and shale.

Lansing-Kansas City Group:

The Lansing-Kansas City group consists of white, tan to buff, fine to microcrystalline limestone with interbedded gray to dark shale. Beds of oolitic limestone varying in thickness, are found in this zone. Total thickness of this group is about 200 to 230 feet in this county.

Electric Interpretation:

Minimum SP curve values are for thin interbedded shales. Resistivity curves are extremely high due to the presence of hydrocarbons and high permeability. Due to this higher permeability SP is having much negative deflection. In their less porous parts, these formations are also extremely resistive.

Virgilian Series: Pedee Group:

This group consists of Weston shale and Iatan limestone. Total thickness of this group is about 20 feet.

Douglas Group:

The Douglas group consists of undifferentiated coarser clastics and shale in this county.

Shawnee Group:

The Shawnee group is composed of cherty dolomitic limestones and shales. Topeka limestone is at the top and Heebner shale is near the base of this group.

Electric Interpretation:

SP deflection is mainly negative which indicates higher permeability of the bed. Resistivity curves also have higher deflections. Possibly, this may be due to higher percentage of fluid saturation and comparatively higher permeability.

Wabaunsee Group:

Tarkio limestone is the predominating formation in this group. This group mostly consists of crystalline limestone with shales and sandstones.

Electric Interpretation:

SP has maximum negative values at the top due to porous crystalline limestone. In the middle part lower values of SP indicate the presence of interbedded shales.

Permian System

Wolfcampian Series: Admire Group:

This lower group consists of limestone, dolomite with shale and sandstones.

Council Grove Group:

Neva limestone in the middle of the group is a marker bed on an electric log. Spieser shale is at the top of the group. Foraker at the bottom consists of cherty limestone.

Electric Interpretation:

Both the SP and resistivity curves at the top of this group are least deflective on tight shale. At the lowermost region of this group, low values of resistivities and SP indicate the presence of interbedded shales.

Chase Group:

This group consists of gray to tan flinty limestones separated by varicolored shales. The Wreford limestone is the lowermost unit and contrasts rather sharply to the underlying Speiser shale on electric logs.

Electric Interpretation:

These impervious and compact limestone and dolomitic beds are highly resistive in the lowermost unit, because of their very small interstitial water content. Farther south these beds are reservoirs for gas. Low permeability indicates absence of hydrocarbons in this area.

Leonardian Series: Summer Group:

Wellington shale with some limestone is at the base of this group. Hutchinson salt is at the middle of this formation, only in the southern and eastern part in this county. Ninnescah shale consists of red and gray shales. Stone Corral is at the top of this group.

Electric Interpretation:

Resistivity curves show maximum value on anhydrite at the top of this group. Hutchinson salt is also marked on some of the logs due to its higher resistivity values. These compact and impervious rocks have very small interstitial water content.

Nippewalla Group:

This group consists of shales with thin anhydrite beds at the top.

Electric Interpretation:

Minimum values of resistivity indicate the presence of connate water.

Jurassic System

Morrison formation of Jurassic system is present everywhere except in the eastern and extreme southeastern part of the county. This formation consists of green to gray sandy shale, limestone, anhydrite and chert. Anhydrite is present only in the western part of the county.

Cretaceous System

<u>Commanchean</u> <u>Series</u>:

This series is represented by the Cheyenne sandstone and the Kiowa shale in Graham County. These formations were not differentiated from the Dakota formation.

<u>Gulfian</u> <u>Series</u>: Colorado Group:

The Colorado group consists of Dakota formation, Graneros shale, Greenhorn limestone, Carlile shale, Niobrara formation and Pierre shale in ascending order.

The Dakota formation consists of clays with small amount of silt and sandstone, containing pyrite, siderite, limonite and other iron minerals.

The Graneros formation is a uniformly thick, gray, fissile, silty and pyritic shale.

The Greenhorn formation is a chalky limestone and shale with the fencepost limestone bed at the top of the formation.

The Carlile formation includes the Fairport chalky shale and Blue Hill gray and micaceous shale.

The top of this formation is called Codell sandstone.

The Niobrara formation is divided into the Fort Hays limestone and the Smoky Hill chalk members.

The Pierre shale is light to medium-gray, soft, micaceous and calcareous.

Electric Interpretation:

The Dakota formation is highly conductive due to the presence of pyrite, siderite, limonite and other iron minerals, and so its reciprocal resistivity is minimum.

Resistivity is minimum in the Graneros soft shaly and water bearing formation.

The Greenhorn limestone shows comparatively higher resistivities.

In some of the electric logs Carlile shales are most negative on spontaneous potential curve; this is because the mud may be very saline, or has a very high activity due to silicate muds, or because the interstitial waters are fresh. Resistivity is low due to high porosity of shale.

In the Niobrara formation maximum resistivity on the lateral log indicates the presence of fresh water. Here charged ionic movement is not sufficient to conduct a larger current so resistivity is higher.

Tertiary System

Pliocene Series:

The Ogallala formation is the only representative of the Tertiary system in this county. This is composed of unconsolidated sand, gravel and silt. It is divided into the Valentine, Ash Hollow, and Kimball members in ascending order.

In most of the wells this formation is not recorded on the electric logs.

Quaternary System

<u>Pleistocene Series</u>:

The Quaternary system consists of unconsolidated sand, gravel and silt. Electric logs are not recorded in this formation.

STRUCTURE

Cambridge Arch and Central Kansas Uplift are the two major structural features of the broad arcuate anticlinal axis across the mid-continent in western Kansas.

The southern end of the Cambridge Arch is separated from the Central Kansas Uplift by a structural saddle in northwestern Graham County. The structures form an arc of uparched features convex to southwest. The arch is flanked by several smaller paralleling anticlinal and synclinal features. Jennings Anticline which plunges southward, is on the west side of the arch.

The Cambridge Arch and the Central Kansas Uplift separate the Hugoton Embayment on the west from the Salina and Sedgwick Basins on the east.

Central Kansas Arch is a name sometimes used for the combined Ellis and Chautauqua Arches. The Ellis Arch was the ancestral Central Kansas Uplift (Merriam and Jewell, 1959). The Precambrian complex on the Central Kansas Uplift consists of a variety of igneous and metamorphic rocks.

The Salina Basin lies between the Nemaha Anticline and the Central Kansas Uplift. Small structures of importance in the basin include the

Abilene Anticline, northern part of the VoShell Anticline and others--parallel to the Nemaha Anticline.

The Kansas part of the Anadarko Basin is known as the Hugoton Embayment (Maher and Collins, 1958). The Hugoton Embayment covers about one-third of the area of Kansas.

CONCLUSIONS

In Graham County, Kansas, quantitative interpretation of electric logs entails determining fluid saturation, porosity, permeability, salinity and the lithology of the formation, particularly of porous zones. Porous formations may be of two types: permeable and nonpermeable. Permeable porous formations exhibit higher resistivity when they are fully or nearly saturated with a nonconducting fluid: oil, gas, or fresh water.

A producing well in the Holly Pool area in this county shows a permeability of 274 millidarcies for the Lansing-Kansas City group, which in dry hole areas has a calculated permeability of only 58 millidarcies in Griffin, 3.2 millidarcies in Alexander and 6.8 millidarcies in "Krug" B for the same Lansing-Kansas City zone. From this result, it can be concluded that the beds have relatively higher permeability in the oil producing zone than in the nonproducing localities. For beds which have a rather large oil saturation, the relative permeability to oil will be appreciably greater than that to water. Porosity may be considered a secondary factor in this case. Calculated porosity for the Lansing-Kansas City group is approximately the same in producing wells as in the dry well areas. Carbonate rocks which contain fractures and vugs, on the other hand, seldom have a high porosity, but the permeabilities might be tremendous.

Fine grained rock may have a lower permeability than a coarse grained rock of the same porosity.

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APPENDIX

BASIC THEORY OF ELECTRIC LOGGING

To compute the potential distribution, a cartesian coordinate system will be used (Fig. 2).

x, y and z are the three coordinates and:

$$F(x, y, z) = C$$

and

$$V = F(x, y, z)$$

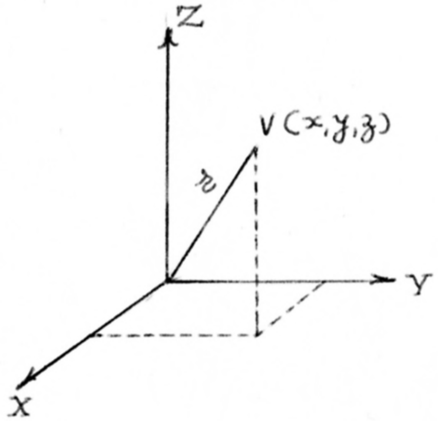


Fig. 2. Coordinate Systems

By Laplace's equation:

$$\nabla^2 V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0$$

and

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

V will be a function of r distance from the current source.

$$\therefore \quad \frac{\partial V}{\partial x} = \frac{\partial r}{\partial x} \cdot \frac{\partial V}{\partial r}$$

where:

$$r = \sqrt{x^2+y^2+z^2}$$

so

$$\frac{\partial r}{\partial x} = \frac{x}{\sqrt{x^2+y^2+z^2}} = \frac{x}{r}$$

also

$$2r \frac{\partial r}{\partial x} = 2x \quad \text{or} \quad \frac{\partial r}{\partial x} = \frac{x}{r}$$

thus

$$\frac{\partial V}{\partial x} = \frac{x}{r} \cdot \frac{\partial V}{\partial r}$$

or

$$\frac{\partial V}{\partial x} = \frac{\partial r}{\partial x} \cdot \frac{\partial V}{\partial r}$$

and

$$\frac{\partial^2 r}{\partial x^2} = \frac{r - x\left(\frac{x}{r}\right)}{r^2} = \frac{1}{r} - \frac{x^2}{r^3}$$

$$\frac{\partial^2 V}{\partial x^2} = \left(\frac{1}{r} - \frac{x}{r^2} \cdot \frac{\partial r}{\partial x}\right) \cdot \frac{\partial V}{\partial r} + \frac{x}{r} \cdot \frac{\partial r}{\partial x} \cdot \frac{\partial^2 V}{\partial r^2}$$

$$= \left(\frac{1}{r} - \frac{x^2}{r^3}\right) \cdot \frac{\partial V}{\partial r} + \frac{x^2}{r^2} \cdot \frac{\partial^2 V}{\partial r^2}$$

similarly

$$\frac{\partial^2 V}{\partial y^2} = \left(\frac{1}{r} - \frac{y}{r^2} \cdot \frac{\partial r}{\partial y}\right) \cdot \frac{\partial V}{\partial r} + \frac{y}{r} \cdot \frac{\partial r}{\partial y} \cdot \frac{\partial^2 V}{\partial r^2}$$

$$= \left(\frac{1}{r} - \frac{y^2}{r^3}\right) \cdot \frac{\partial V}{\partial r} + \frac{y^2}{r^2} \cdot \frac{\partial^2 V}{\partial r^2}$$

and

$$\frac{\partial^2 V}{\partial z^2} = \left(\frac{1}{r} - \frac{z}{r^2} \cdot \frac{\partial r}{\partial z}\right) \cdot \frac{\partial V}{\partial r} + \frac{z}{r} \cdot \frac{\partial r}{\partial z} \cdot \frac{\partial^2 V}{\partial r^2}$$

$$= \left(\frac{1}{r} - \frac{z^2}{r^3}\right) \cdot \frac{\partial V}{\partial r} + \frac{z^2}{r^2} \cdot \frac{\partial^2 V}{\partial r^2}$$

Substitution of these values of $\frac{\partial^2 V}{\partial x^2}$, $\frac{\partial^2 V}{\partial y^2}$ and $\frac{\partial^2 V}{\partial z^2}$ into

Laplace's equation $\nabla^2 V = 0$,

yields

$$\frac{\partial^2 V}{\partial r^2}\left[\frac{x^2+y^2+z^2}{r^2}\right] + \frac{\partial V}{\partial r}\left[\frac{3}{r} - \frac{x^2+y^2+z^2}{r^3}\right] = 0$$

or

$$\frac{\partial^2 V}{\partial r^2} + \frac{\partial V}{\partial r} \cdot \frac{2}{r} = 0$$

Since r is the only independent variable, the partial derivatives may be replaced by total derivatives, and the equation becomes:

$$\frac{d^2 V}{dr^2} + \frac{2}{r} \cdot \frac{dV}{dr} = 0$$

This equation can be integrated by multiplying by r^2, thereby forming an exact differential. That is

$$\frac{d^2 V}{dr^2} + \frac{2}{r} \cdot \frac{dV}{dr} = 0 = r^2 \frac{d^2 V}{dr^2} + 2r \frac{dV}{dr}$$

and

$$\int \left(r^2 \frac{d^2 V}{dr^2} + 2r \frac{dV}{dr} \right) dr$$

$$= \int d\left(r^2 \frac{dV}{dr} \right) = r^2 \frac{dV}{dr} = \text{constant} = S$$

Hence

$$\frac{dV}{dr} = \frac{S}{r^2}$$

and

$$V = - \frac{S}{r} + C$$

S and C are determined by boundary conditions of the problem.

If the value of V at infinity is zero, C vanishes.

The constant S may be expressed in terms of the total current I which flows out of the source.

So

$$- \frac{1}{\rho} \cdot \frac{dV}{dr} = - \frac{1}{\rho} \cdot \frac{S}{r^2}$$

The total current is

$$I = - 4 \pi r^2 \left(\frac{1}{\rho} \cdot \frac{S}{r^2} \right) = - \frac{4 \pi S}{\rho}$$

$$S = - \frac{I \rho}{4 \pi r}$$

Hence

$$V = \frac{I \rho}{4 \pi r}$$

We shall derive the potential distribution for the case where the insulating sonde on which the electrode is mounted is located in an infinite cylindrical borehole of radius b, surrounded by a homogeneous medium of the Resistivity R_t (Fig. 3).

The borehole is filled with a drilling fluid of resistivity Rm; let Vi denote the potential in the invaded zone and V_t is the potential outside the invaded zone, that is, the uncontaminated part of the formation.

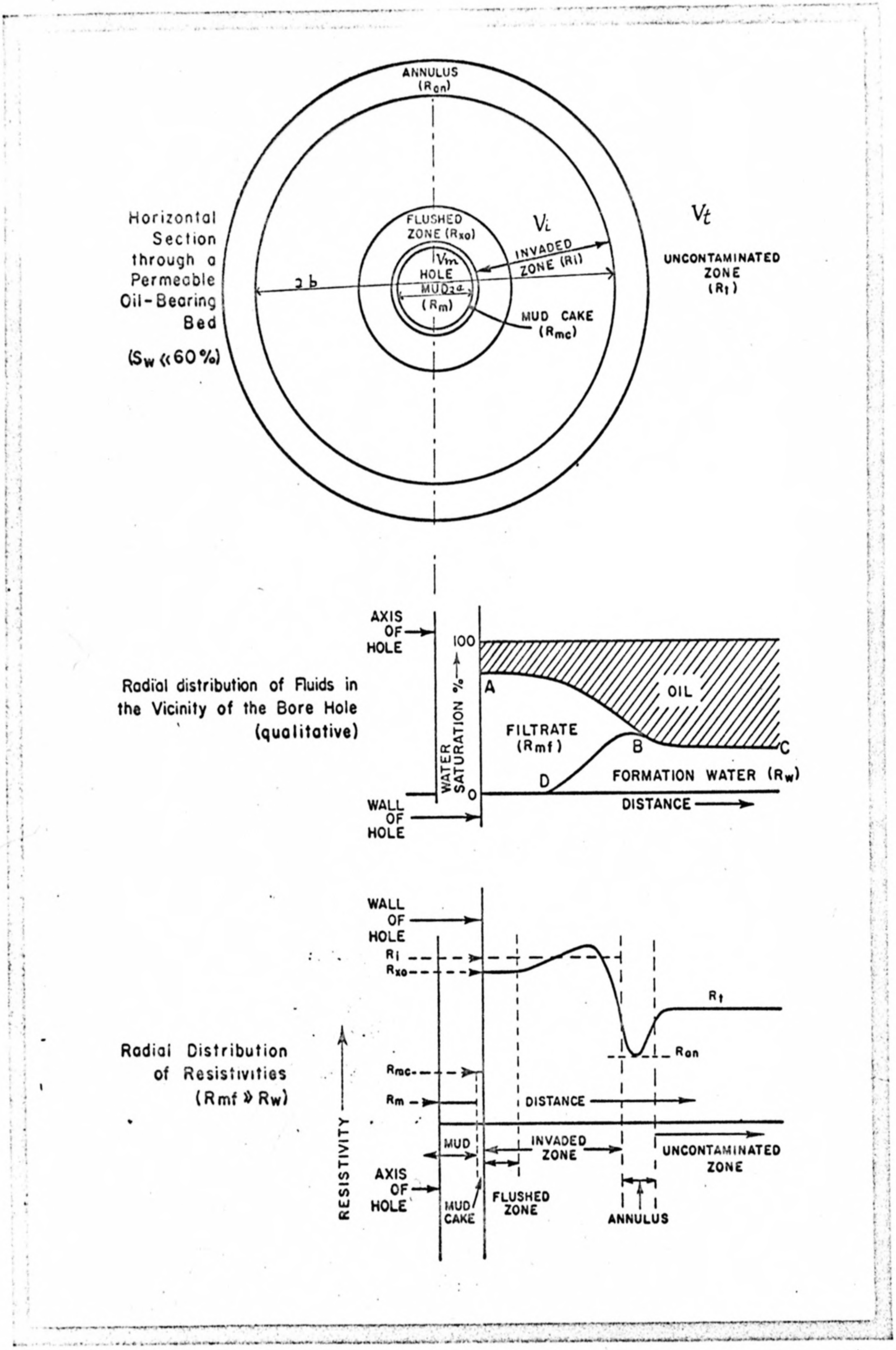


Fig. 3. Distribution of resistivities around the borehole in an oil bearing formation.

$$Vm = Vi \qquad \frac{1}{Rm} \cdot \frac{\partial Vm}{\partial r} = \frac{1}{Ri} \cdot \frac{\partial Vi}{\partial r} \quad \text{(at invaded boundary)}$$

$$V_i = V_t \qquad \frac{1}{Ri} \cdot \frac{\partial Vi}{\partial r} = \frac{1}{Rt} \cdot \frac{\partial Vt}{\partial r} \quad \text{(at uncontaminated boundary)}$$

At infinite distance from electrode, the potential tends toward zero, as:

$$\frac{1}{\sqrt{r^2 + Z^2}}$$

V_i and V_t will be of the general form of the equation by Stefanesco:

$$V = \int_0^{\infty} A(\lambda)\, Io(\lambda r) + B(\lambda)\, Ko(\lambda r) \cos \lambda Z d\lambda$$

r = radius from the electrode

Ko = Bessel function of the second kind and zero order

λ = Parameter of integration from $\lambda = 0$ to $\lambda = \infty$

Io = modified Bessel function of first kind

A = a function of layer depths resistivities r and

Since V_t must go to zero for infinite r the coefficient of the Io must be zero and so:

$$V_t = \int_0^{\infty} B_t(\lambda)\, Ko(\lambda r) \cos \lambda Z \; d\lambda$$

since V_i is present only in the region where $a \leq r \leq b$, therefore:

$$V_i = \int_0^{\infty} A_i(\lambda)\; Io(\lambda r) + Bi(\lambda)\, Ko(\lambda r) \cos \lambda Z d\lambda$$

we now apply the following boundary conditions at r = a

Since area under the curve of δ function is unity:

$$\int_{-\infty}^{\infty} \delta(Z)\, dZ = 1$$

and function $\delta(Z)$ as defined by Dirac:

$$\delta(Z) = \lim_{\alpha \to 0} \left(\frac{1}{\pi} \cdot \frac{\alpha}{Z^2 + \alpha^2} \right)$$

so

$$I\,\delta(Z) = -\frac{1}{Rm} \left(\frac{\partial Vi}{\partial r} \right)_{r=a} 2\ a$$

At the first boundary condition of borehole, potential is continuous at the boreface:

$$(V_i)_{r=b} = (V_t)_{r=b}$$

The second boundary condition at the boreface is that the normal component of current density must be continuous. This expressed by:

$$\frac{1}{Rm} \left(\frac{\partial V_i}{\partial r} \right)_{r=b} = \frac{1}{R_t} \left(\frac{\partial V_i}{\partial r} \right)_{r=b}$$

Table 1. Electric Log Analysis: Well--Ida Keith No. 3.

Formation or Member	Depth (Feet) Top	Depth (Feet) Bottom	Temp. (°F.) $T^o = A + (G x \frac{D}{100})$ (A-2)	SP (Milli-volts)	Rm (ohm-m)	Rmf (ohm-m) (A-4)	Rw (ohm-m) (A-12)	Ri (Corr.) (ohm-m)	Rt (Corr.) (ohm-m)	Sw (%) Sw = $\frac{Ri/Rt}{Rz/Rw}$	Sw (%) Sw = $\sqrt{\frac{Rw \frac{0.62}{\phi^{2.15}}}{Rt}}$	∅ (%) Rocky Mt. Method	∅ (%) Porosity Index Method	∅ (%) Wittie's Method	K (milli-darcys) $\sqrt{\frac{K}{C}\frac{\Delta Rt}{\Delta h}} \cdot \frac{1}{Ro}\frac{Pc}{\Delta sp \cdot gr}$	Salinity (%) (A-6)
Smoky Hill Chalk	--	564	84	-30	1.17	0.90	0.40	20	25	42		27			3.40	1.30
Fort Hays Ls.	564	624	85	-27	1.15	0.85	0.38	15	18.50	42		27	26		0.97	1.38
Codell Sandstone	624	672	85	-30	1.15	0.85	0.36	7	15	--	44			29	18	1.42
Blue Hill Shale	672	790	86	-26	1.13	0.85	0.40	4	3.5	60		40		39	0.04	1.30
Fairport Chalky Shale	790	880	86	-28	1.13	0.85	0.35	12	8	70		26		23	0.45	1.50
Greenhorn LS	880	970	86.5	-22	1.12	0.82	0.50	19.50	18.50	72		19			0.40	0.98
Graneros Shale	970	1007	87	-23	1.10	0.80	0.37	4	6	--	55			37	1.80	1.32
Dakota Group	1007	1306	90	-23	1.08	0.80	0.40	10	15	--	57	34		24.50	2	1.22
Commanchean Series	1306	1434	92	-48	1.05	0.80	0.17	5	4	--	50			34	0.70	3.20
Morrison	1434	1500	93	-60	1.03	0.78	0.12	4.50	4	--	78	19		19	0.40	4.50
Nippewalla Group	1500	2150	94.50	-65	1.025	0.77	0.11	4	2.20	--	82.50	23		23	0.13	5.0
Stone Corral	2150	2190	96	-42	1	0.75	0.20	330	430	25	--		2.30		0.03	2.70
Ninnescah Shale	2190	2490	98	-32	0.99	0.74	0.28	5	7	30	--			32.50	2	1.60
Wellington	2490	2650	101	-45	0.96	0.71	0.17	8	6	40	--	35			0.50	2.60
Herrington LS	2820	2912	102	-60	0.95	0.70	0.11	17	3.50	--	88	--	20.50		1.20	4.80
Wreford LS	3044	3064	103	-75	0.94	0.70	0.076	17	3.30	--	80	--	19.40		1.50	6.40
Spieser Shale	3064	3090	103	-15	0.94	0.70	0.61	5	2.30	90	--	32		32	0.58	0.68
Foraker LS	3300	3354	104	-35	0.93	0.70	0.23	15	10	90	--	15			0.80	2
Indian Cave SS	3354	3404	104	-50	0.93	0.70	0.14	8	4	55	--	28			8	3.50
Brownville LS	3404	3424	104	-28	0.93	0.69	0.275	18	7	--	76.50	--	21		1	1.60
Tarkio LS	3540	3575	105	-73	0.925	0.69	0.075	18.50	8	45		18	18		2.60	7
Topeka LS	3575	3660	106	-72	0.915	0.67	0.08	50	11.50	--	72	--	10.70		0.73	6.30
Deer Creek LS	3660	3695	106.50	-63	0.914	0.66	0.10	32	14	60	60	--	14.50		20	4.80
Plattsmouth LS	3695	3760	106.80	-75	0.914	0.66	0.071	55	11	76	76	--	10.50		1.35	7.20
Heebner Shale	3760	3780	107	+ 5	0.91	0.655	1.60	12	13	100	100	--		19	0.50	0.55
Toronto LS	3795	3820	107.25	-32	0.91	0.65	0.26	25	12	--	72	--	17.50	--	21	1.66
Pedee	3820	3840	107.30	-71	0.905	0.65	0.81	34.50	12	--	53	--	13.50	--	37	7.50
Lansing-Kansas City LS	3840		108	-70	0.90	0.65	0.80	51.40	112.50	10	23	--	11		274	6.30

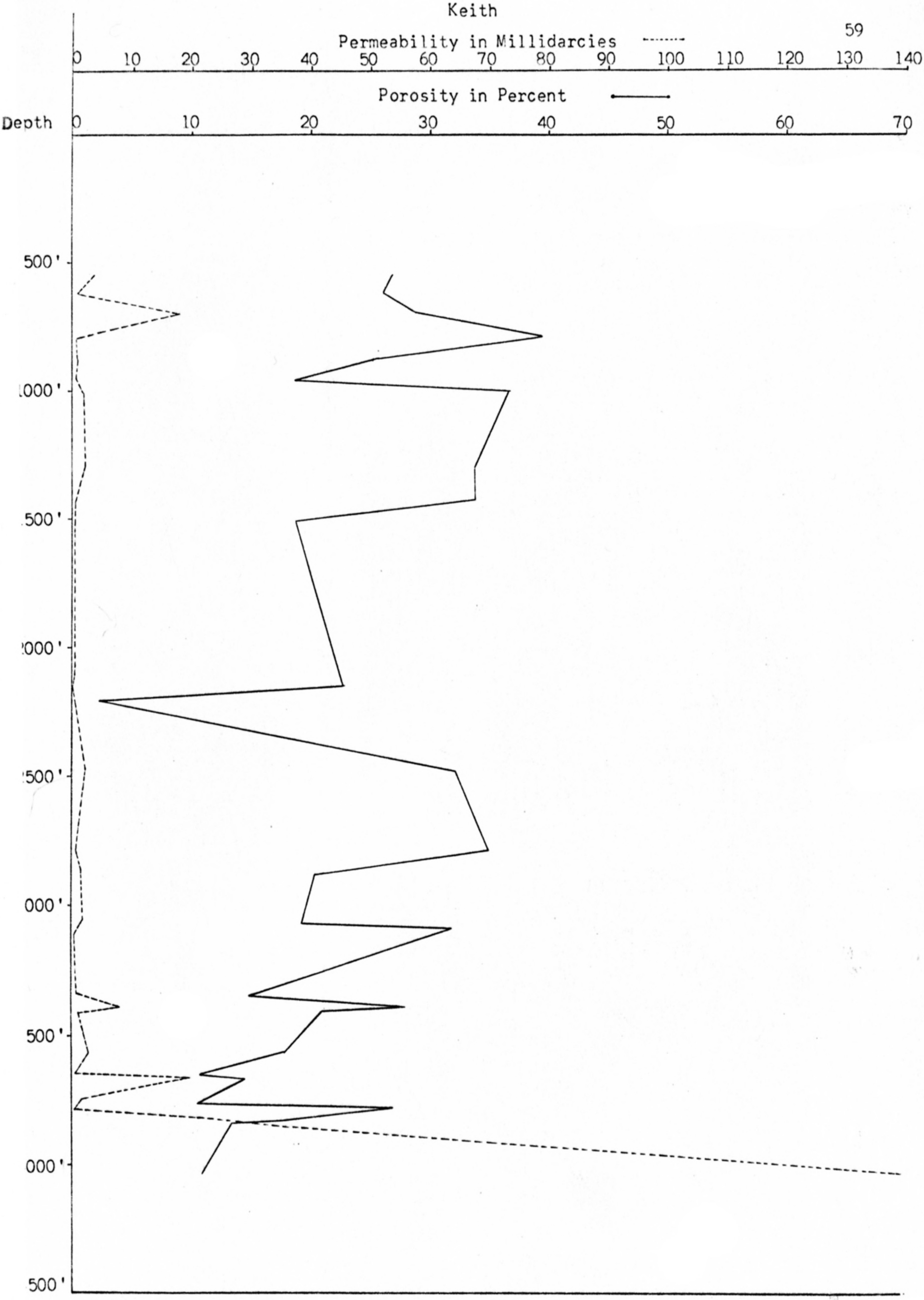

Keith
Permeability in Millidarcies
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
Porosity in Percent
Depth
0 10 20 30 40 50 60 70
500'
1000'
1500'
2000'
2500'
3000'
3500'
4000'
4500'

Fig. 4

Electric Log Analysis

Table 2.

Well: Alexander #1
Location: 24-75-21W

Rm = 1 ohm-meters at BHT
BHT = 104° F.
Bit Size = 7 7/8"

Formations or Members	Depth (feet)	Temp. (°F.)	SP (milli-volts)	Resistivity (ohm - m) R_i	Resistivity (ohm - m) R_t	Rm (ohm-m)	Rmf (ohm-m)	Rw (ohm-m)	Sw %	Porosity %	Permeability (milli-darcy)	Salinity (PPM)
Ft. Hays Limestone	270	82	+ 5	27	40	.92	.69	2.5	100	18	.10	4,500
Codell Sandstone	270-300	82	-10	20	26	.92	.69	.53	76	17	5	10,000
Blue Hill Shale	300-440	83	-20	5	5.5	.90	.67	.40	60	38	.45	13,000
Fairport Chalky Shale	440-548	84	-20	25	26	.89	.67	.40	60	18	1.70	13,000
Greenhorn Limestone	548-640	85	-19	40	28	.88	.66	.40	80	14	1.25	13,000
Graneros Shale	640-690	85	-20	7	6	.88	.66	.38	70	30	1.80	14,000
Dakota and Commanchean	690-1200	87	-40	17	18	.87	.65	.20	36	25	.23	27,500
Nippewalla	1200-1690	90	-45	13	6	.83	.62	.15	65	22	.10	38,000
Stone Corral	1690-1740	90	-28	125	265	.83	.62	.24	20	7.50	.008	22,000
Ninnescah Shale	1740-1954	93	-30	12	28	.80	.60	.22	20	22	3.3	23,000
Wellington Shale	1954-2310	95	-52	27	36	.79	.59	.12	20	26	2.3	40,000
Herrington LS	2310-2350	95.5	-65	63	10	.785	.59	.095	81.50	9.50	1.3	55,000
Wreford LS	2535-2590	97	-76	34	11	.77	.58	.075	63	12	4.2	70,000

Table 2 (concl.).

Formations or Members	Depth (feet)	Temp. (^{o}F.)	SP (milli-volts)	Resistivity (ohm - m)		Rm (ohm-m)	Rmf (ohm-m)	Rw (ohm-m)	Sw %	Poros-ity %	Perme-ability (milli-darcy)	Salin-ity (PPM)
				R_i	R_t							
Spieser Shale	2590-2610	98	-28	3	3	.76	.57	.22	95	24	.90	23,000
Neva LS	2700-2713	99	-54	33	5	.755	.565	.11	87	13	1.4	48,000
Foraker LS	-2780	99	-73	60	16	.755	.565	.072	67	9.20	3.20	75,000
Admire	2880-2935	100	-56	12	4.50	.75	.56	.105	70	19	1.6	50,000
Tarkio LS	2935-2980	100	-32	21	8	.75	.56	.23	83	18	.50	20,000
Topeka LS	3110-3190	101.5	-76	41	13	.74	.55	.065	55	11	5	85,000
Heebner Shale	3190-3210	101.5	-28	12	13	.74	.55	.22	40	28	1.2	23,000
Toronto LS	3210-3300	102	-81	73	26	.73	.54	.059	50	9	6	10,000
Pedee Group	3300-3330	102	-38	38	15	.73	.54	.15	69	13	6	32,500
Lansing-Kansas City	3330-3540	103.5	-42	360	290	.725	.535	.15	42	5.20	3.2	33,000
Cherokee	3540-3590	103.75	-24	33	18	.725	.53	.25	74	14	4.8	18,000
Pennsylvanian Basal Conglo.	3590-2623	104	-35	5	6	.72	.53	.20	38	28	1.6	23,000
Arbuckle	2623-	104	-73	25	14	.72	.53	.067	44	14	49	78,000

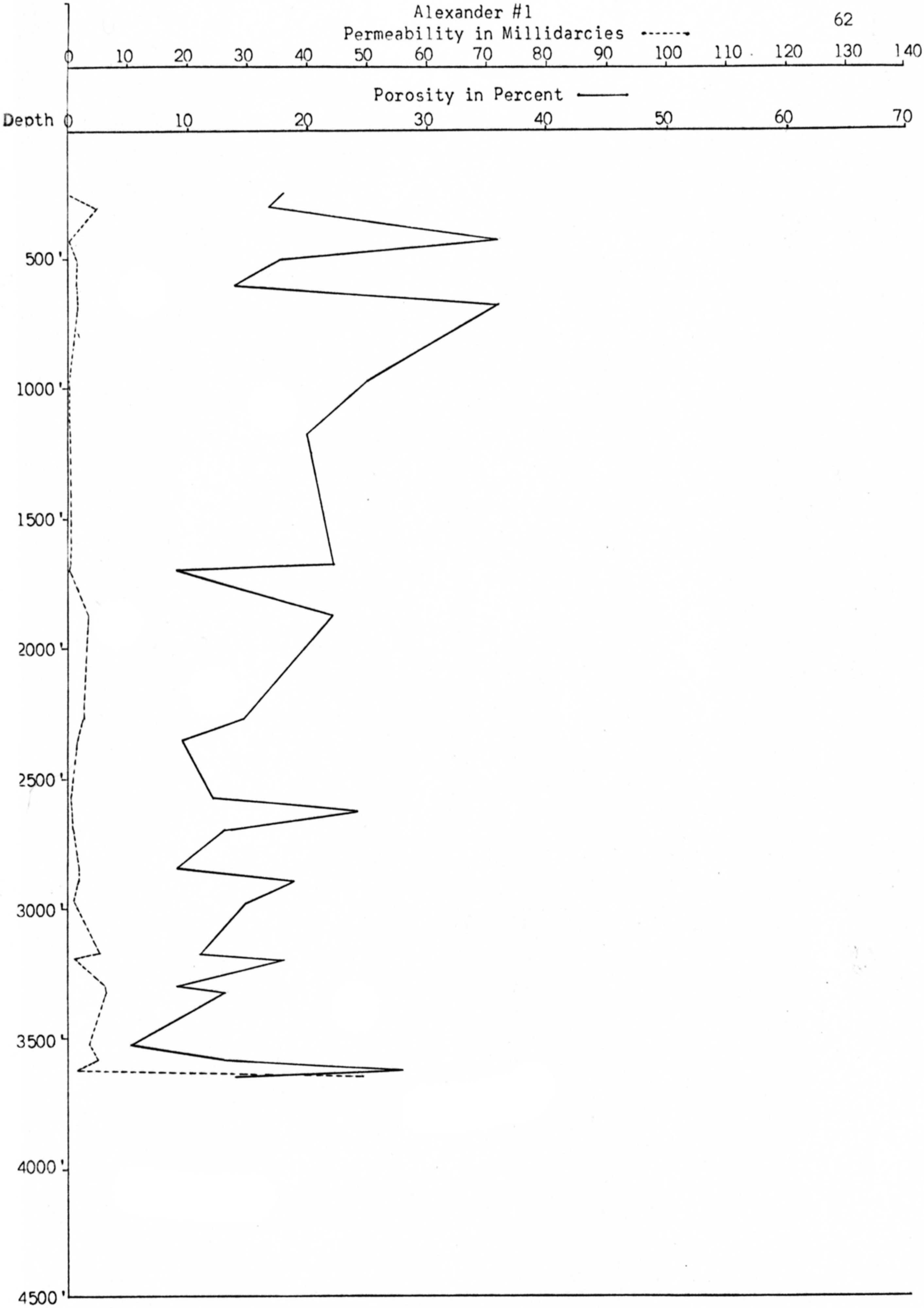

Alexander #1
Permeability in Millidarcies
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
Porosity in Percent
Depth 0 10 20 30 40 50 60 70
500'
1000'
1500'
2000'
2500'
3000'
3500'
4000'
4500'

Fig. 5

Table 3.

Well: Griffith #2
Location: 2-8S-23W

Rm = .93 ohm-m BHT
BHT = 104° F.
Bit Size = 7 7/8"

Formation or Member	Depth (feet)	Temp. (°F.)	SP (mv)	Resistivity (ohm - m)		Rm (ohm-m)	Rmf (ohm-m)	Rw (ohm-m)	Sw %	Ø %	K (md)	Salinity (PPM)
				R_i	R_t							
Fort Hays LS	295-360	81	-15	19.5	40	1.15	.90	.80	48	9	.125	6,500
Codell SS	360-390	81.5	-20	23	50	1.15	.90	.70	38	26	5.4	7,500
Blue Hill Shale	390-530	83	-25	4.5	4	1.155	.895	.40	45	39.5	.40	13,000
Fairport Chalky Shale	530-625	84	-23	20	13	1.15	.89	.62	95	19	.16	8,000
Greenhorn LS	625-720	84.5	-28	23	25.3	1.15	.89	.375	45	20.50	4.4	13,000
Graneros Shale	720-760	85	-32	5	4.5	1.14	.883	.30	60	32	.45	17,200
Dakota	760-1050	86	-35	17	23	1.125	.875	.30	30	30	1.25	17,000
Morrison	1183-1250	90	-50	5	2	1.08	.80	.17	72.50	33.5	.50	30,000
Nippewalla	1250-1885	92	-70	7	5	1.05	.80	.095	28	37	.03	60,000
Stone Corral	1885-1930	93	-45	624	208	1.04	.80	.22	78	4	.008	21,000
Ninnescah Shale	1930-2146	96	-50	7	9.50	1.00	.75	.15	22	40	1.7	35,000
Wellington Shale	2146-2440	97	-45	12	5	1.00	.75	.20	75	22	1.2	24,000
Herrington LS	2440-2520	98	-90	28	4	.98	.74	.06	76	14	5	95,000
Wreford LS	2685-2760	98.5	-90	22	5	.98	.74	.062	70	14	1	90,000

Table 3 (concl.).

Formation or Member	Depth (feet)	Temp. (°F.)	SP (mv)	Resistivity (ohm - m) R_i	R_t	Rm (ohm-m)	Rmf (ohm-m)	Rw (ohm-m)	Sw %	Ø %	K (md)	Salinity (PPM)
Spieser Shale	2760-2790	99	-35	5	4.5	.97	.73	.24	45	40	1.6	19,000
Neva LS	2865-2885	100	-82	18	5	.965	.72	.07	57.50	18	7.2	75,000
Foraker LS	2885-3020	100	-59	19	13	.965	.72	.11	41	19.50	2.9	48,000
Admire	3020-3105	100	-45	4	5	.96	.72	.20	86	22	5	24,000
Tarkio	3105-3300	100.5	-81	27	14	.96	.72	.07	42	15	1.5	78,000
Topeka LS	3300-3470	101	-95	56	22	.958	.720	.052	46	9.50	1.36	115,000
Heebner Shale	3470-3490	101	-10	13	15	.958	.720	.80	90	23	.30	54,000
Pedee Group	3490-3510	102	-44	30	19	.450	.715	.19	54.50	16.5	50	25,000
Lansing-Kansas City	3510-3715	103	-75	164	188	.94	.70	.07	15	12	58	77,000
Cherokee	3715-3920	104	-42	34	37	.93	.70	.183	60	11	.40	24,500

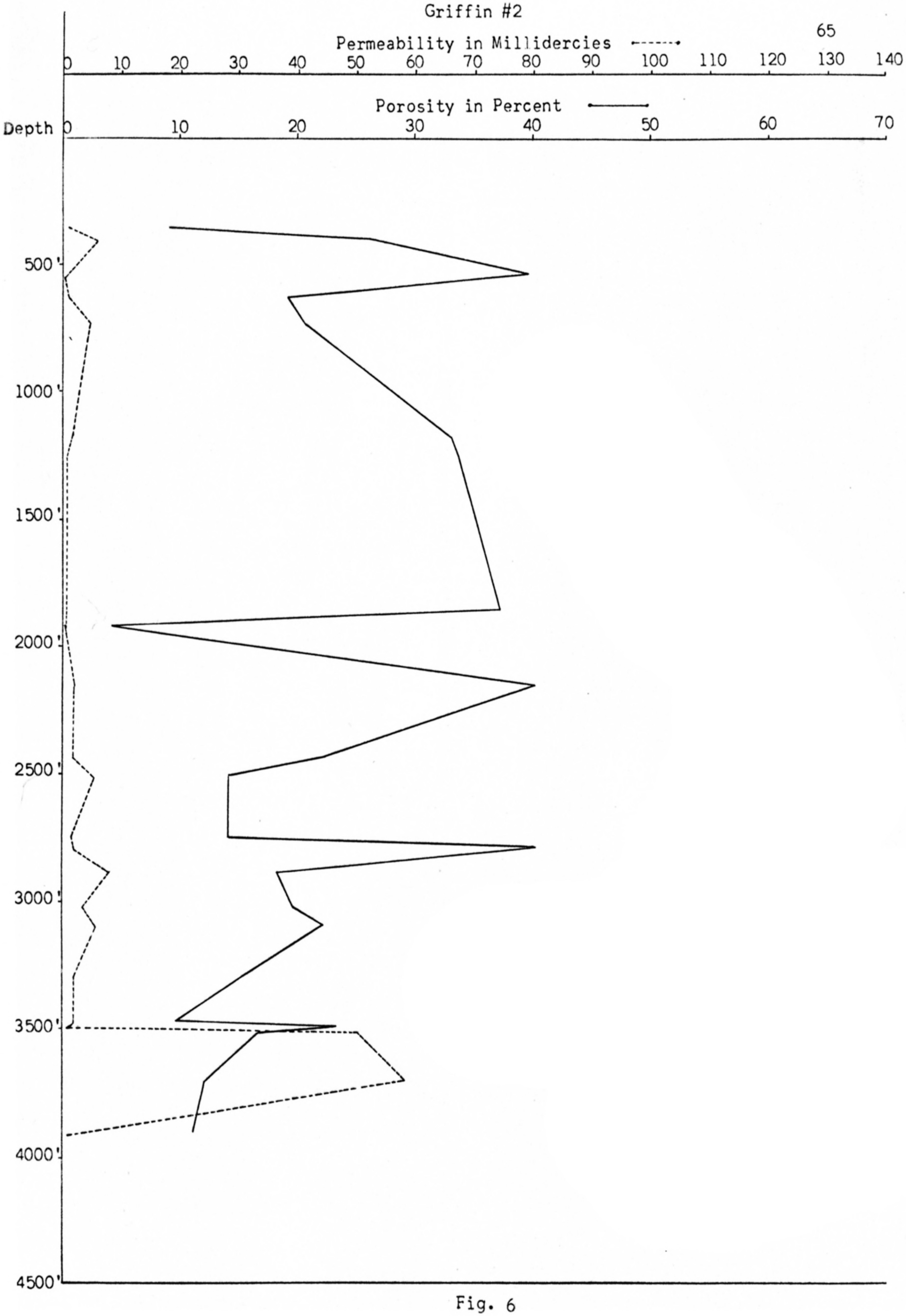

Griffin #2
65
Permeability in Millidercies
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
Porosity in Percent
Depth
0 10 20 30 40 50 60 70
500'
1000'
1500'
2000'
2500'
3000'
3500'
4000'
4500'

Fig. 6

Table 4.

Well: Krug "B" #1
Location: 20-10S-25W

Rm BHT = .35 ohm - m
BHT = 106° F.
Bit Size = 7 7/8"

Formation or Member	Depth (feet)	Temp. (°F.)	SP (mv)	Resistivity (ohm - m) R_i	Resistivity (ohm - m) R_t	Rm (ohm-m)	Rmf (ohm-m)	Rw (ohm-m)	Sw %	Ø %	K (md)	Salinity (PPM)
Smoky Hill Chalk	-530	82	-35	26	63	.452	.34	.12	33	12	.26	51,000
Fort Hays Limestone	530-590	82	+ 5	16	36	.452	.34	.425	75	14.50	.80	12,200
Codell Sandstone	590-620	82.50	-13	14.50	18.50	.45	.338	.20	50	19	5.5	27,000
Blue Hill Shale	620-780	83	-50	7.5	5	.44	.332	.08	38	32	.27	78,000
Fairport Chalky Shale	780-875	84.50	-40	17.20	10.30	.43	.32	.095	65	15	.40	65,000
Greenhorn Limestone	875-980	86	-46	17	12	.427	.32	.09	55	14	1.80	70,000
Graneros Shale	980-1010	86	-58	6	8	.427	.32	.065	23	33	2.20	100,000
Dakota Group	1010-1500	87	-20	12	33	.42	.315	.16	27	25	5	35,000
Morrision	1500-1590	88	-10	9	13	.418	.314	.20	50	22.50	3	25,000
Nippewalla	1590-2195	92	-31	5	4	.40	.30	.12	53	30	6	47,000
Stone Corral	2195-2240	92	-23	320	440	.40	.30	.15	42	4	.03	37,000
Ninnescah Shale	2240-2445	93	-33	8	24	.40	.30	.11	17	35	1.2	50,000
Wellington	2445-2720	94	-25	8	30	.38	.29	.13	22	33	1	43,000
Hutchinson Salt	2515-2557	94	-25	18	56	.38	.29	.13	15	10.50	.05	---

Table 4 (concl.).

Formation or Member	Depth (feet)	Temp. (^{o}F.)	SP (mv)	Resistivity (ohm - m) R_i	Resistivity (ohm - m) R_t	Rm (ohm-m)	Rmf (ohm-m)	Rw (ohm-m)	Sw %	Ø %	K (md)	Salinity (PPM)
Wreford LS	-3140	97	-34	9	8	.389	.285	.088	70	16	6	65,000
Spieser Shale	3136-3166	99	-15	4	3.50	.38	.28	.18	70	28	2	27,000
Foraker LS	3250-3310	100	-26	10	8	.37	.27	.11	57	18	5	48,000
Admire	3310-3360	100	-18	8	10	.37	.27	.14	50	24	12.80	32,000
Tarkio LS	3360-3600	101	-33	12	8	.365	.27	.098	70	13.50	11	53,000
Topeka LS	3600-3660	101	-30	10	7	.365	.27	.10	60	20	8	51,000
Heebner Shale	3825-3845	103	- 8	4	7	.36	.267	.22	50	30	2.90	22,000
Toronto LS	3845-3885	104	-30	19	10	.355	.26	.11	70	12.70	6.80	45,000
Pedee Group	3885-3900	104.5	-14	21	11	.353	.26	.16	86	12.50	12.50	29,000
Lansing-Kansas City LS	3900-4100	106	-28	75	195	.35	.26	.12	20	11	8.50	40,000

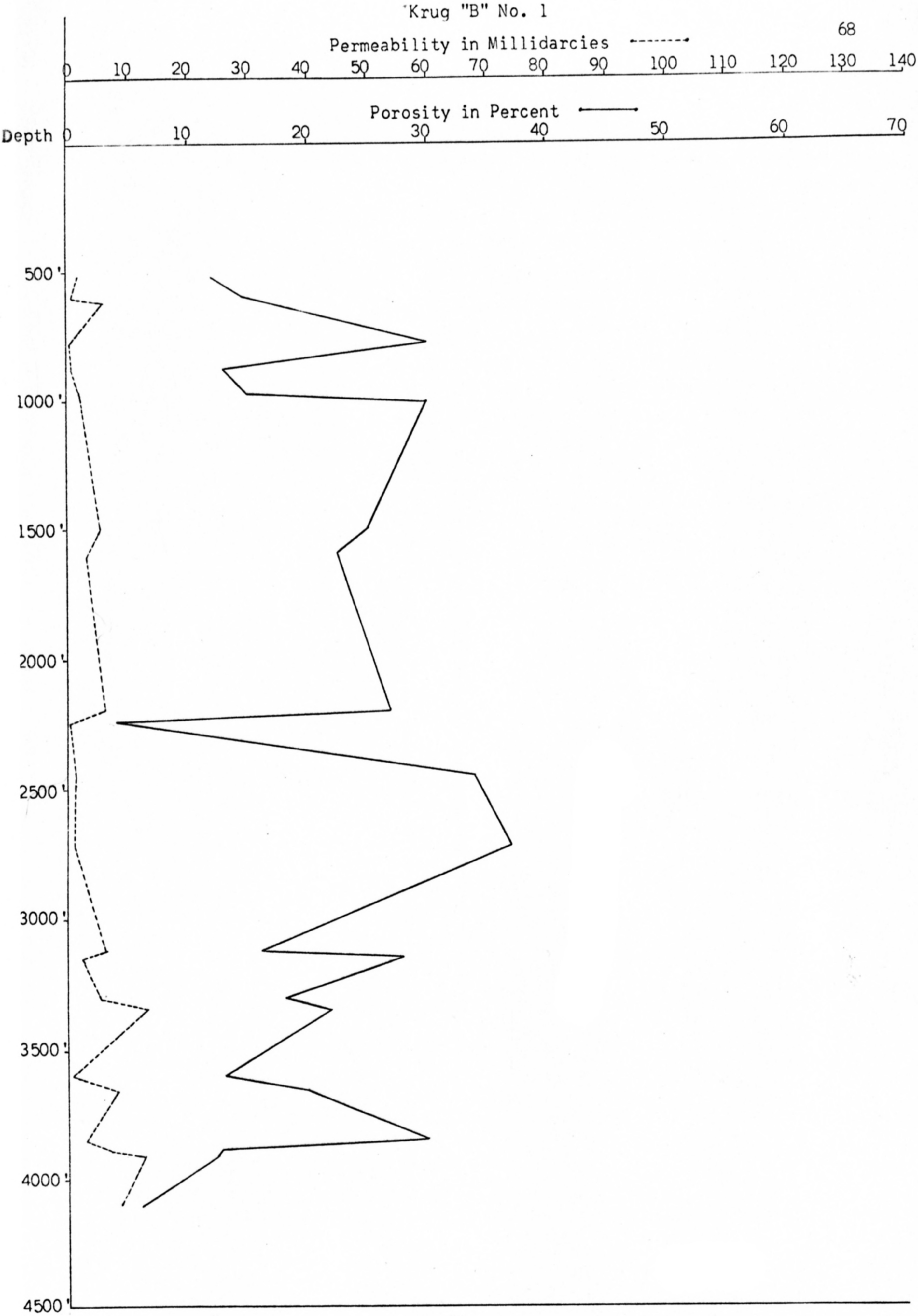

Krug "B" No. 1
Permeability in Millidarcies
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
Porosity in Percent
Depth 0 10 20 30 40 50 60 70
500'
1000'
1500'
2000'
2500'
3000'
3500'
4000'
4500'

Fig. 7

Table 5. Exact Locations of points used in Fig. 8.

Points	Location	Section	Township	Range
1	SE - SE - NW	20	10S	25W
2	NW - SW - NW	10	9S	24W
3	SE - SE - SW	2	8S	23W
4	NW - NW - SE	24	7S	21W

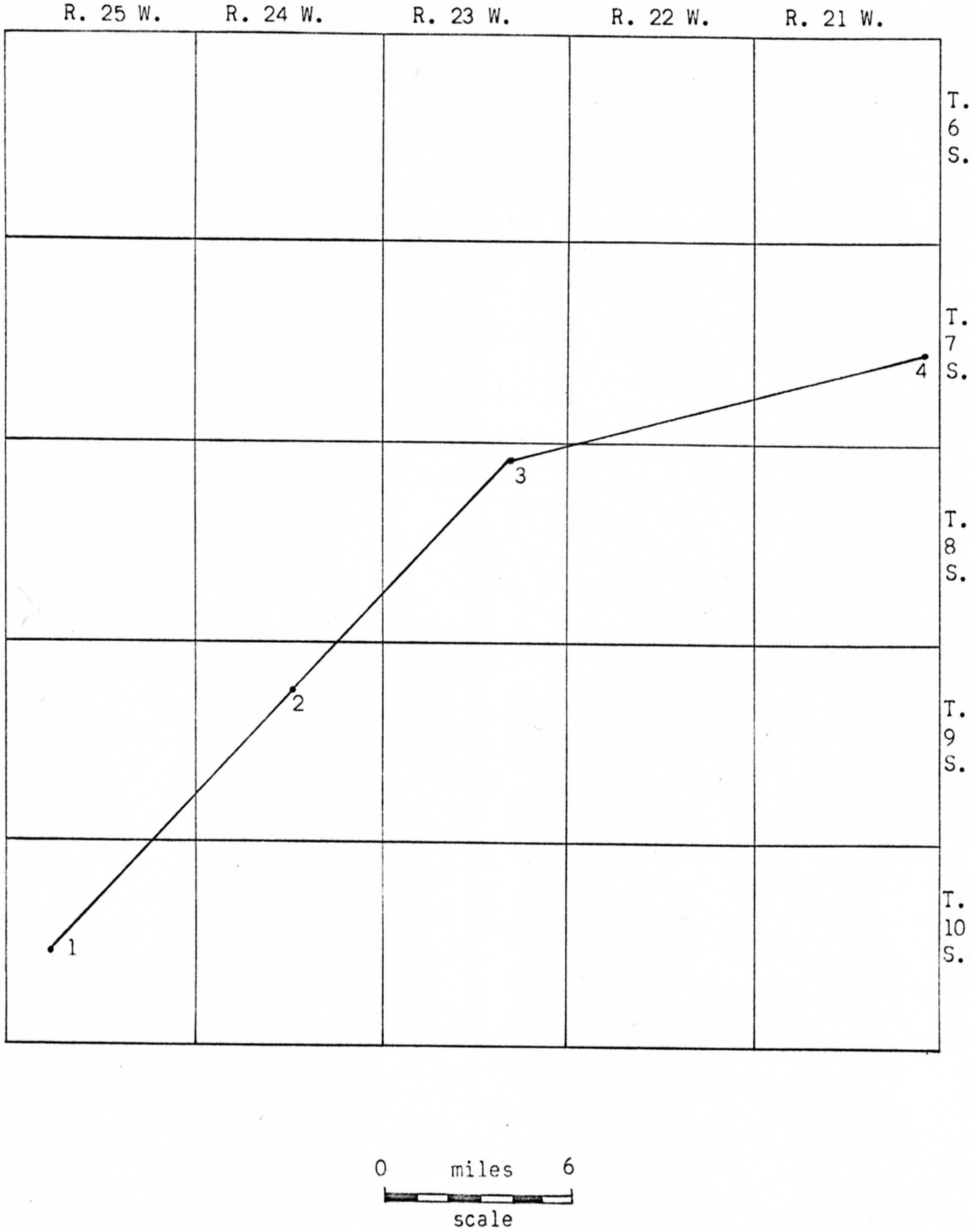
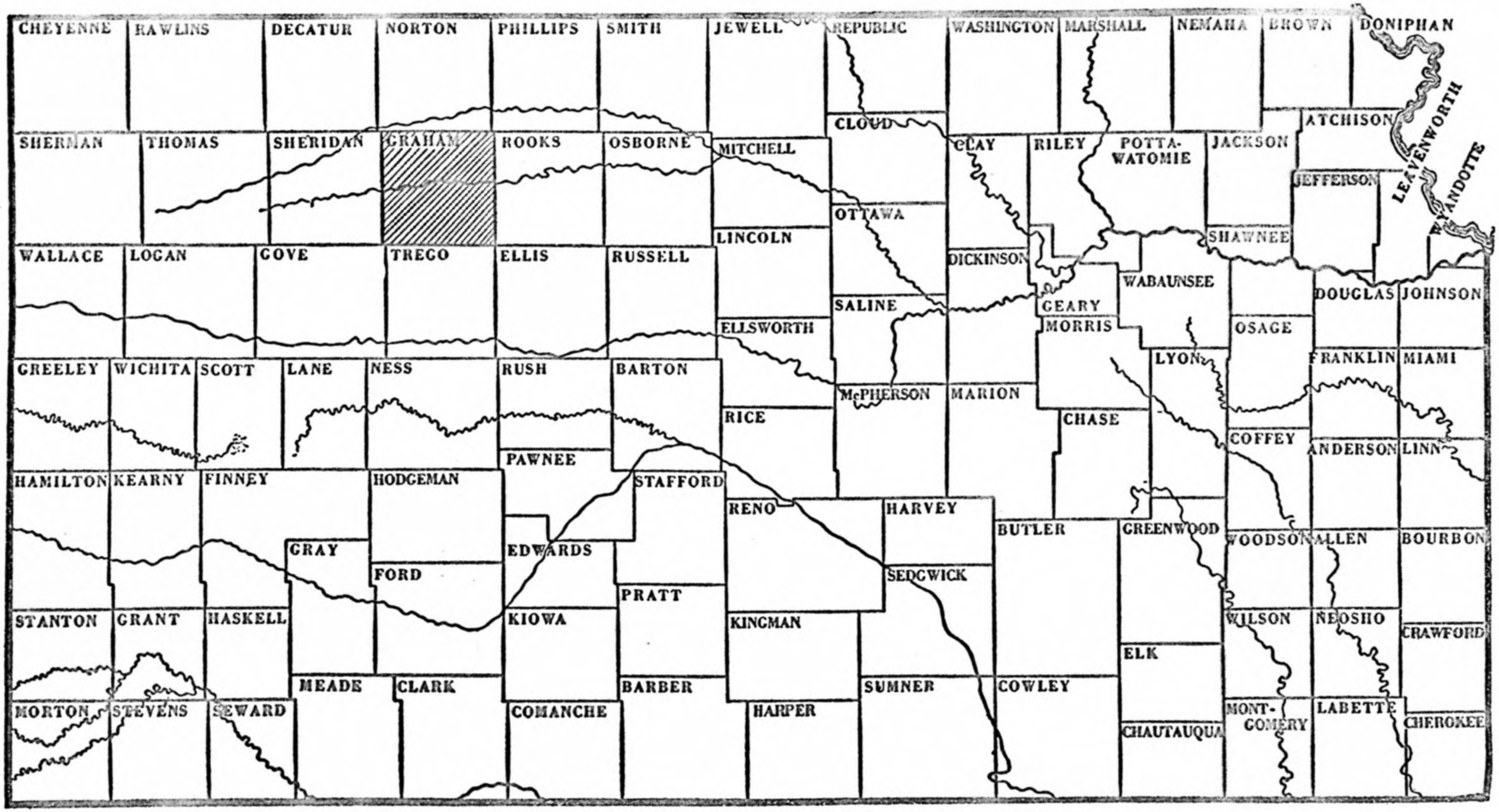


Fig. 8. Map of Graham County showing the location of wells used in Fig. 13.



Area covered by this thesis

Fig. 9

Graham County, Kansas

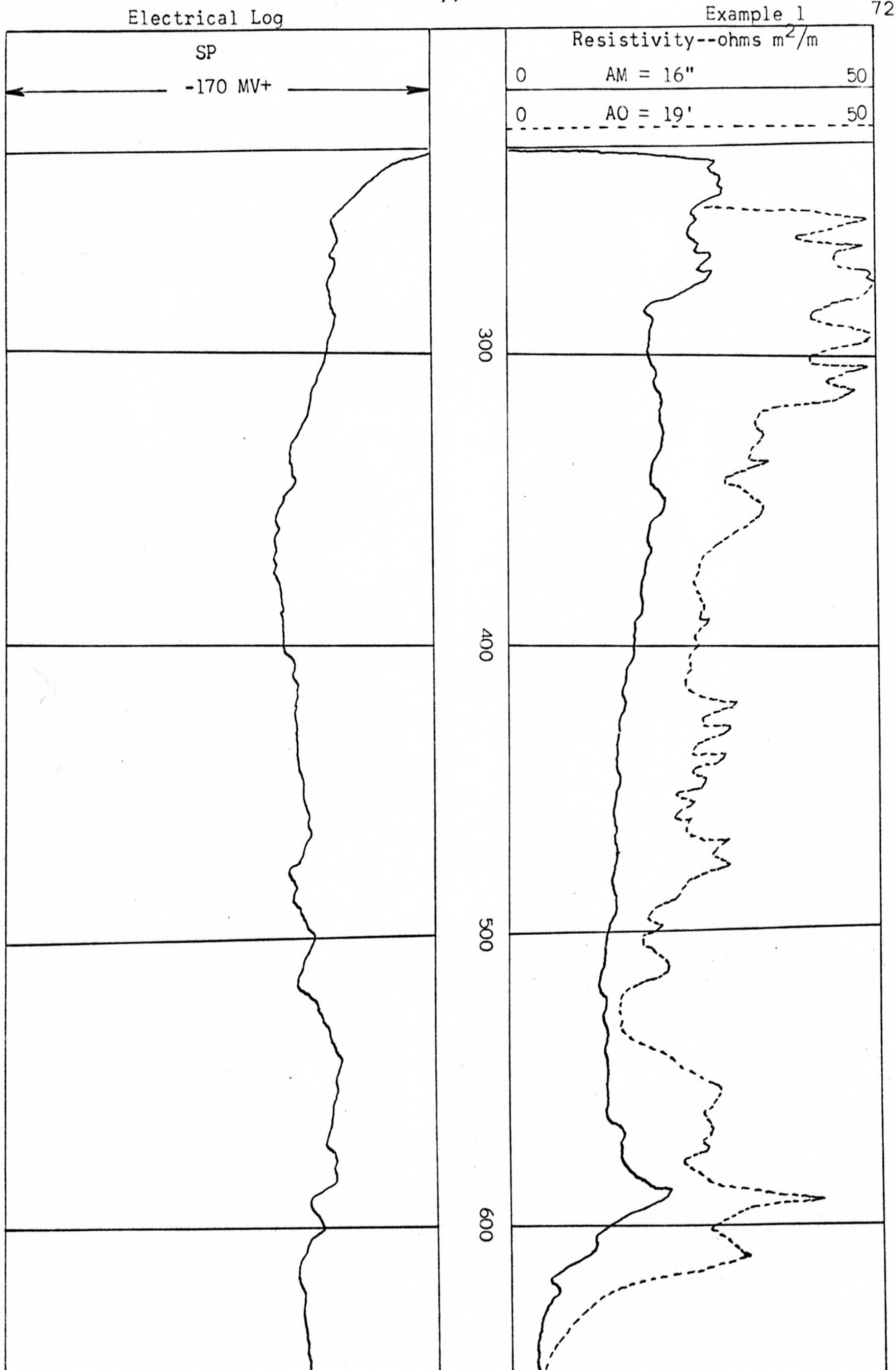


Fig. 10

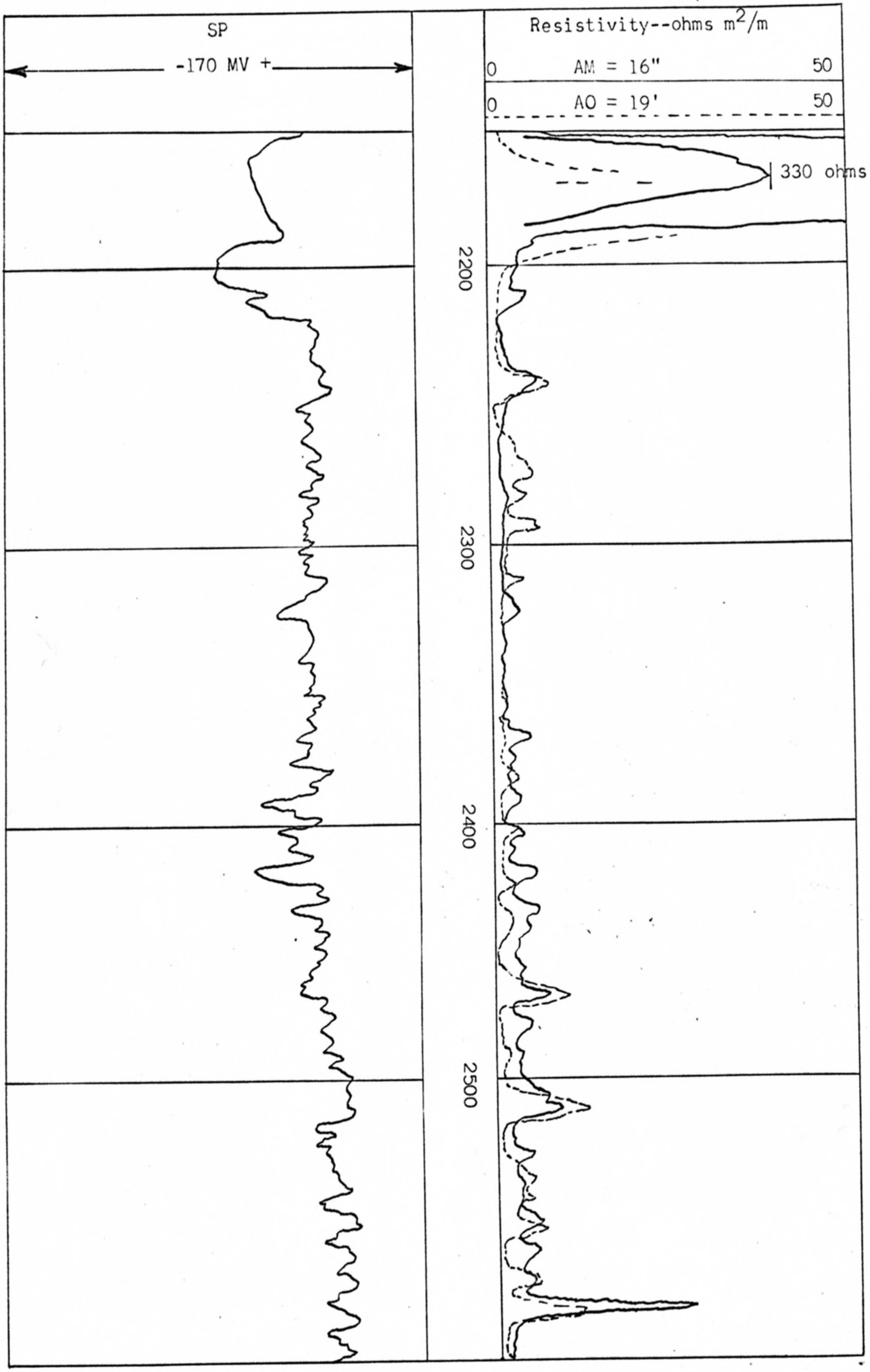

SP
-170 MV +
Resistivity--ohms m²/m
0
AM = 16"
50
0
AO = 19'
50
330 ohms
2200
2300
2400
2500

Fig. 11

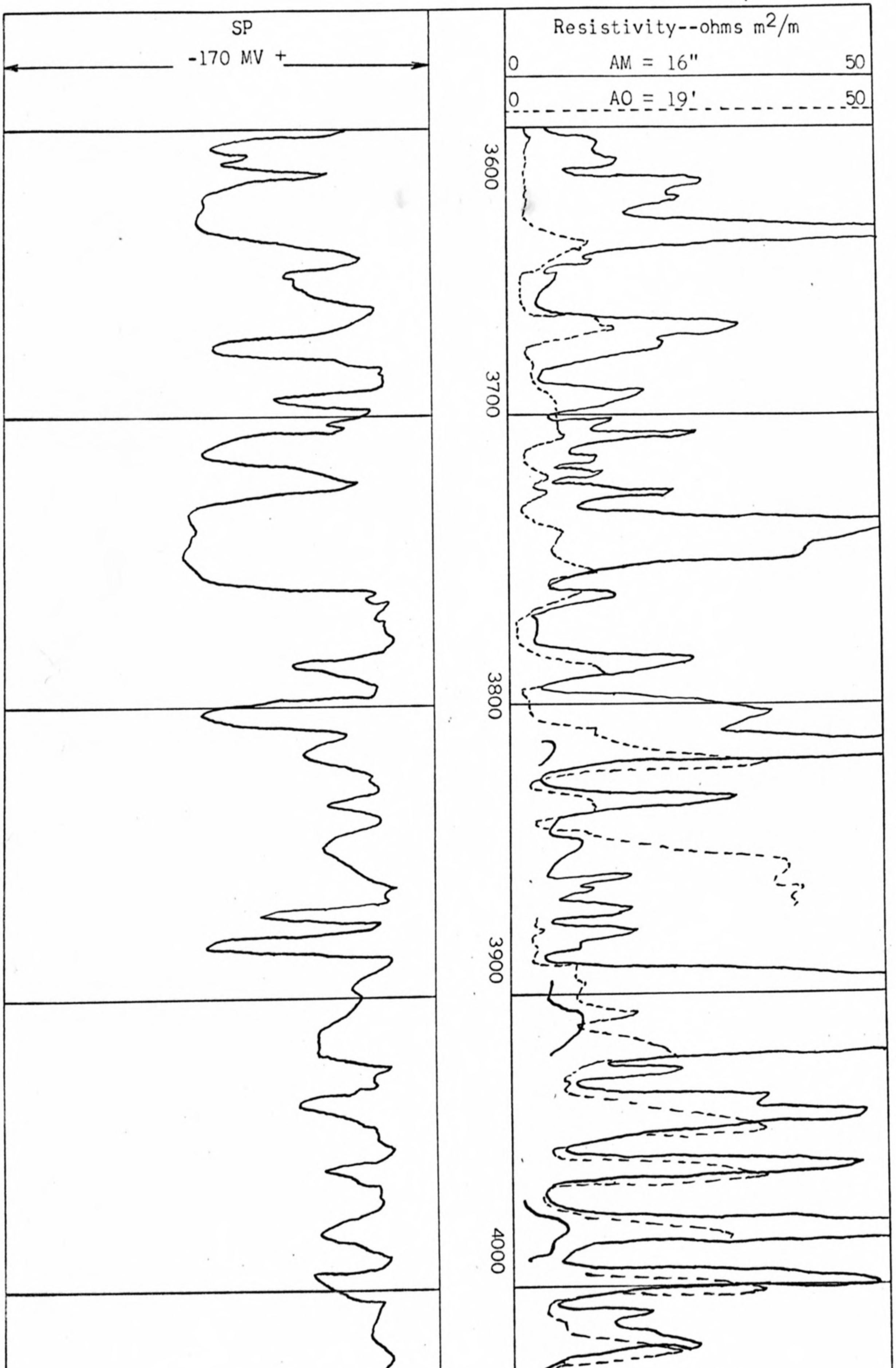
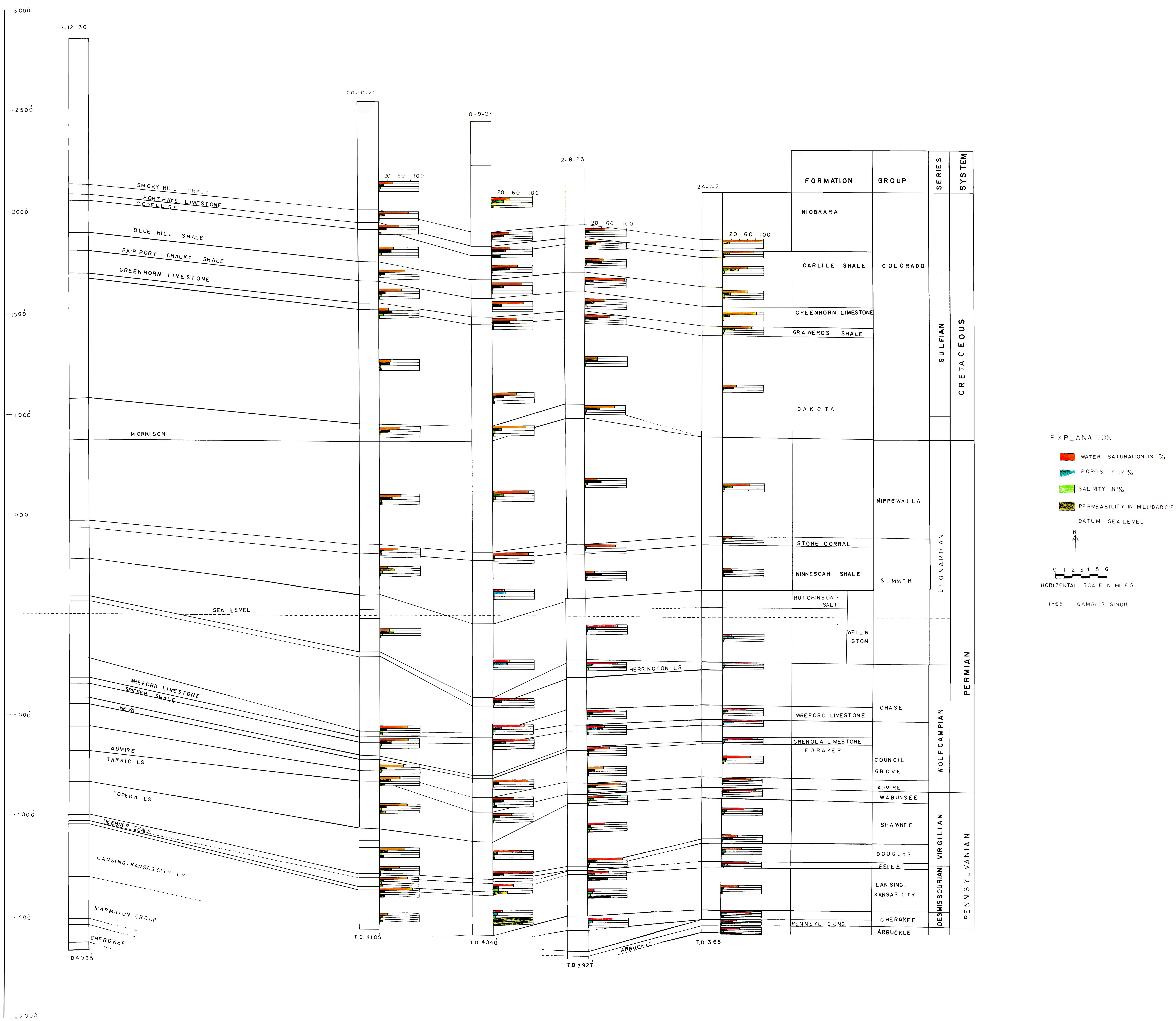

SP
-170 MV +
Resistivity--ohms m2/m
0
AM = 16"
50
0
AO = 19'
50
3600
3700
3800
3900
4000

Fig. 12

Fig. 13. Correlation and physical characteristics of wells in Graham County, Kansas.

CORRELATION AND PHYSICAL CHARACTERISTICS OF WELLS IN GRAHAM COUNTY, KANSAS



INVESTIGATION OF THE PHYSICAL PROPERTIES OF RESERVOIR ROCKS
BY ELECTRIC WELL LOGGING, IN GRAHAM COUNTY, KANSAS

by

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Graham county covers 25 townships in northwestern Kansas. The purpose of this investigation was the quantitative interpretation of the physical properties of reservoir rocks in searching for potential petroleum reservoirs by use of electric logs. A stratigraphic correlation chart was constructed to show relative thickness and physical properties of the formations in different sections of the county.

Schlumberger's Log Interpretation Charts were used to calculate porosity, permeability, fluid saturation, salinity and temperature. Tixier's Resistivity Gradient method was widely used to calculate the permeability. Porosity and fluid saturation in limestone and other tight formations were calculated by Tixier's Rocky Mountain and Porosity Index methods. Archie's and Humble equations were used in sandstone and shaly formations.

Here porous beds are considered of two types: permeable and non-permeable. Permeable porous formations exhibit comparatively higher resistivity when they are saturated with a nonconducting fluid or gas. It is also concluded qualitatively that the greater the fraction of the available pore space which is occupied by oil, the higher the rock resistivity will be. For beds which have a rather large oil saturation, the relative permeability to oil will be appreciably greater than that to water.

Petroleum reservoirs are concentrated more highly in permeable beds. This is predicted by evaluating the calculated permeability of the Lansing-Kansas City productive group in different producing fields as well as in the nonproducing fields in Graham county. It seems that structure plays a secondary role for the accumulation of oil in the producing zones of this county. Electric logging is still imperfect and so quite a few potentially productive formations are probably still unnoticed on the electric log. Therefore with the development and improvement of other new logging tools provided by more sophisticated electronics and instrumentation, and the use of parameters which are a function of intrinsic rock properties, more accurate porosity and permeability determinations may be obtained with the combination of electric logs.