UIC-1001

OCD UIC PROGRAM

Exempted Aquifer Documents

The Analysis of Formation Water in the Noble Energy Rio Bravo 27-5

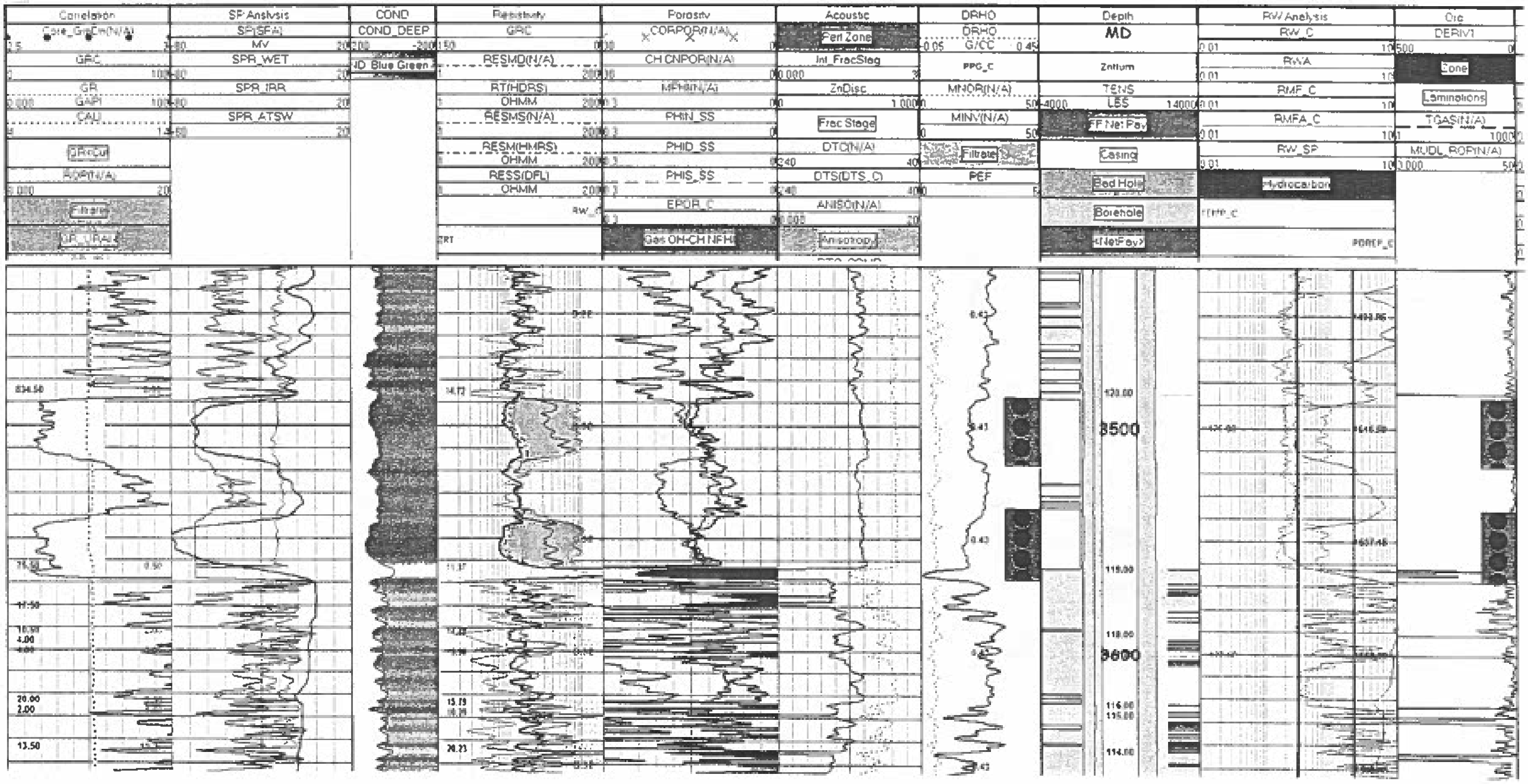
Mike Mullen; La Ventana sandstone/

Cliff House formation

The Analysis of Formation Water in the Noble Energy Rio Bravo 27-5

Mike Mullen
Denver, CO

Cliffhouse - Menefee

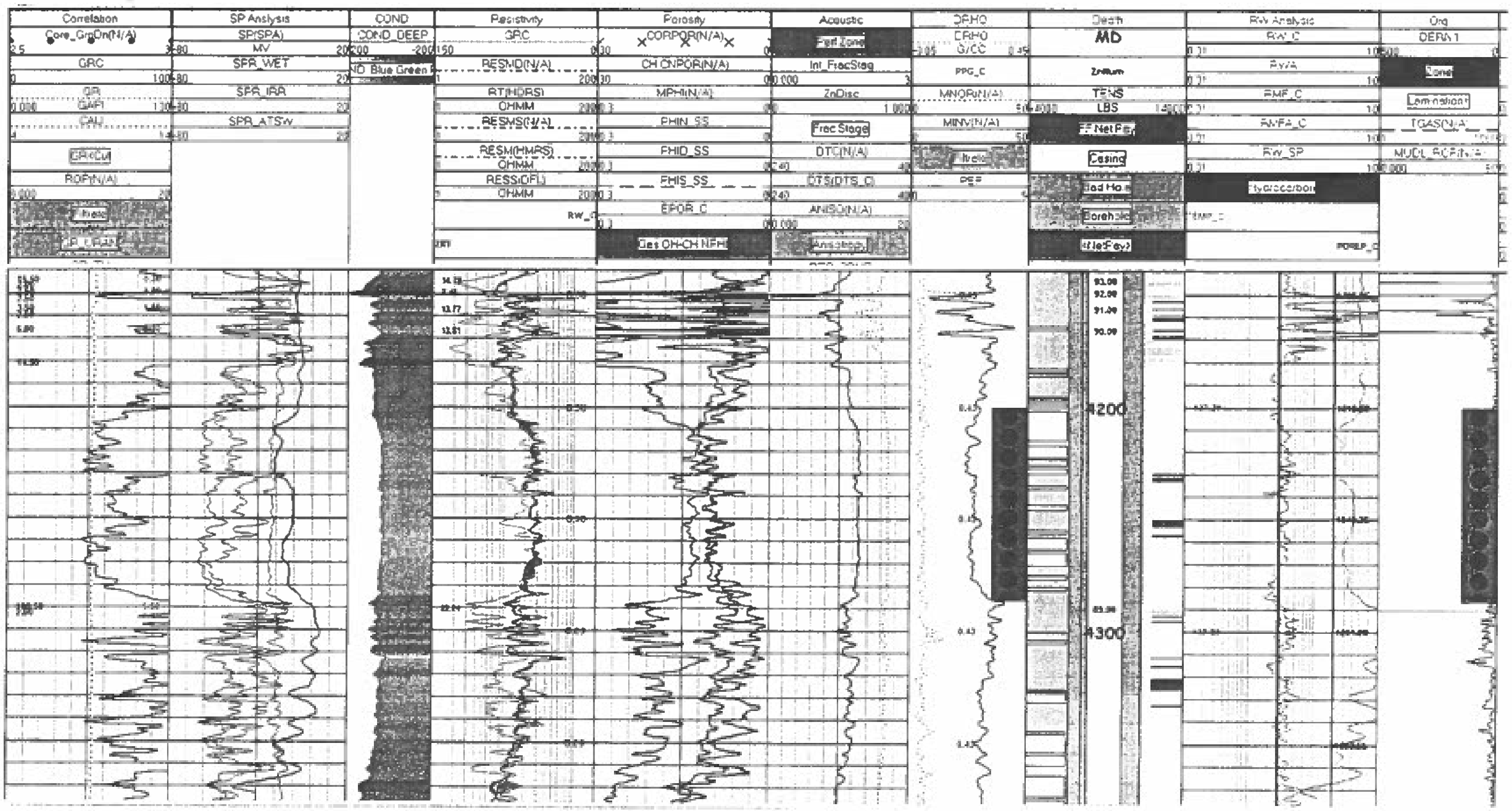


Cliffhouse RW Analysis: SP - .3 @ 126: Rwa - .2 @ 126

Menefee RW Analysis: SP - .18 @ 126: Rwa - .17 @ 126

RMFa is showing a normal invasion profile

Point Lookout



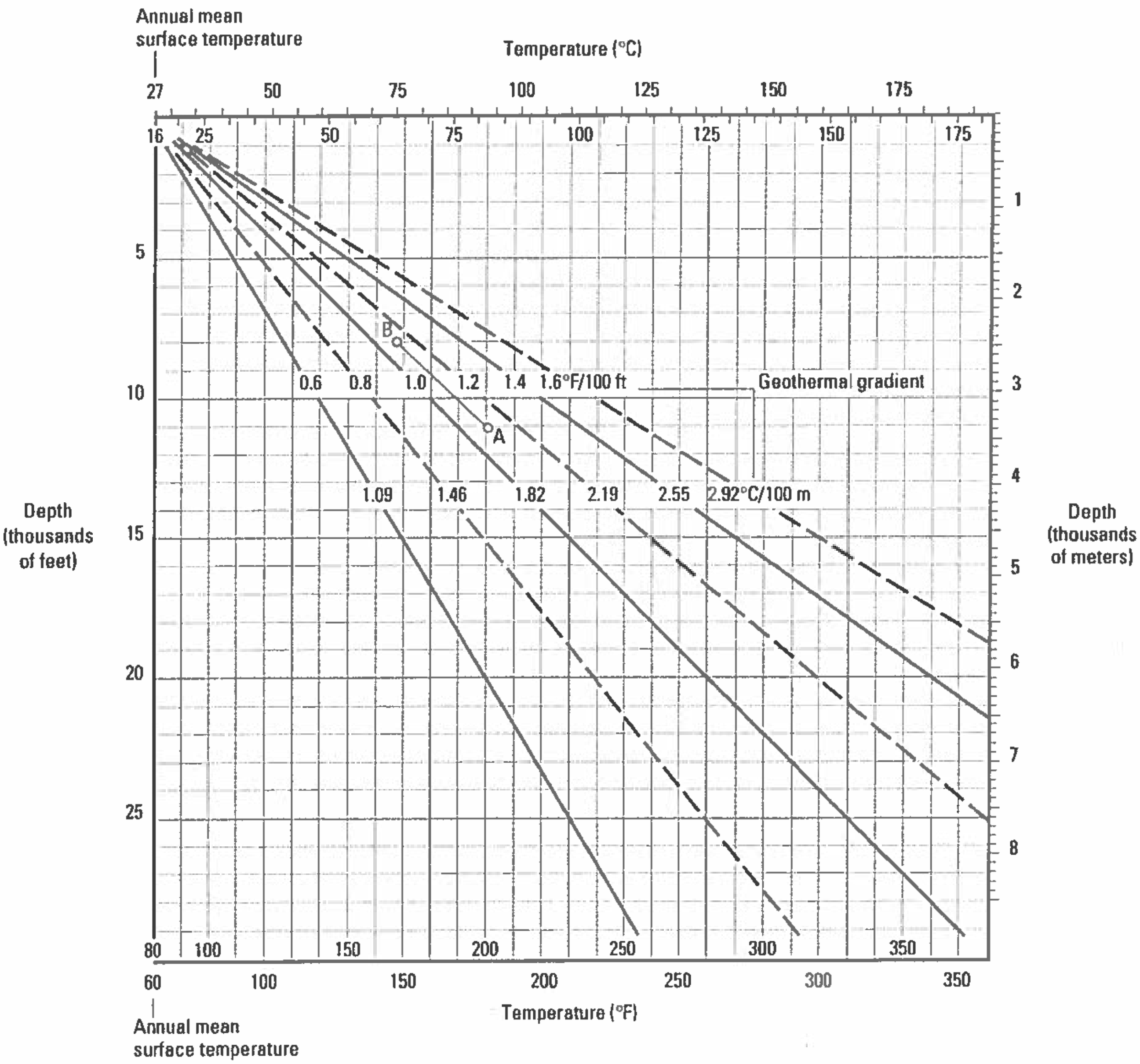
Rwa = RMFa suggests either very deep invasion or no invasion. If there would be deep invasion, one would expect Rwa = RMFa = RMF. This is not the case therefore our interpretation would be shallow invasion with Rwa = .35 @ 138. The suppression of the SP could be from low permeability or hydrocarbon effects. SW in this interval is 70%.

Data Available

- Wireline Logs
  - Gamma Ray, SP, Resistivity, Density, Neutron
  - Digital LAS format
  - TIFF format
- Assumptions
  - Baseline shifted the SP for digital SP analysis
  - RMF from log header 4.53 @ 62
- Calculations
  - Rwa using shale corrected effective porosity and deep resistivity
  - RMFa using shale corrected effective porosity and shallow resistivity
  - RW_SP using baseline straightened SP and RMF at FT

Estimation of Formation Temperature with Depth

Temperature gradient conversions: 1°F/100 ft = 1.823°C/100 m
1°C/100 m = 0.5486°F/100 ft



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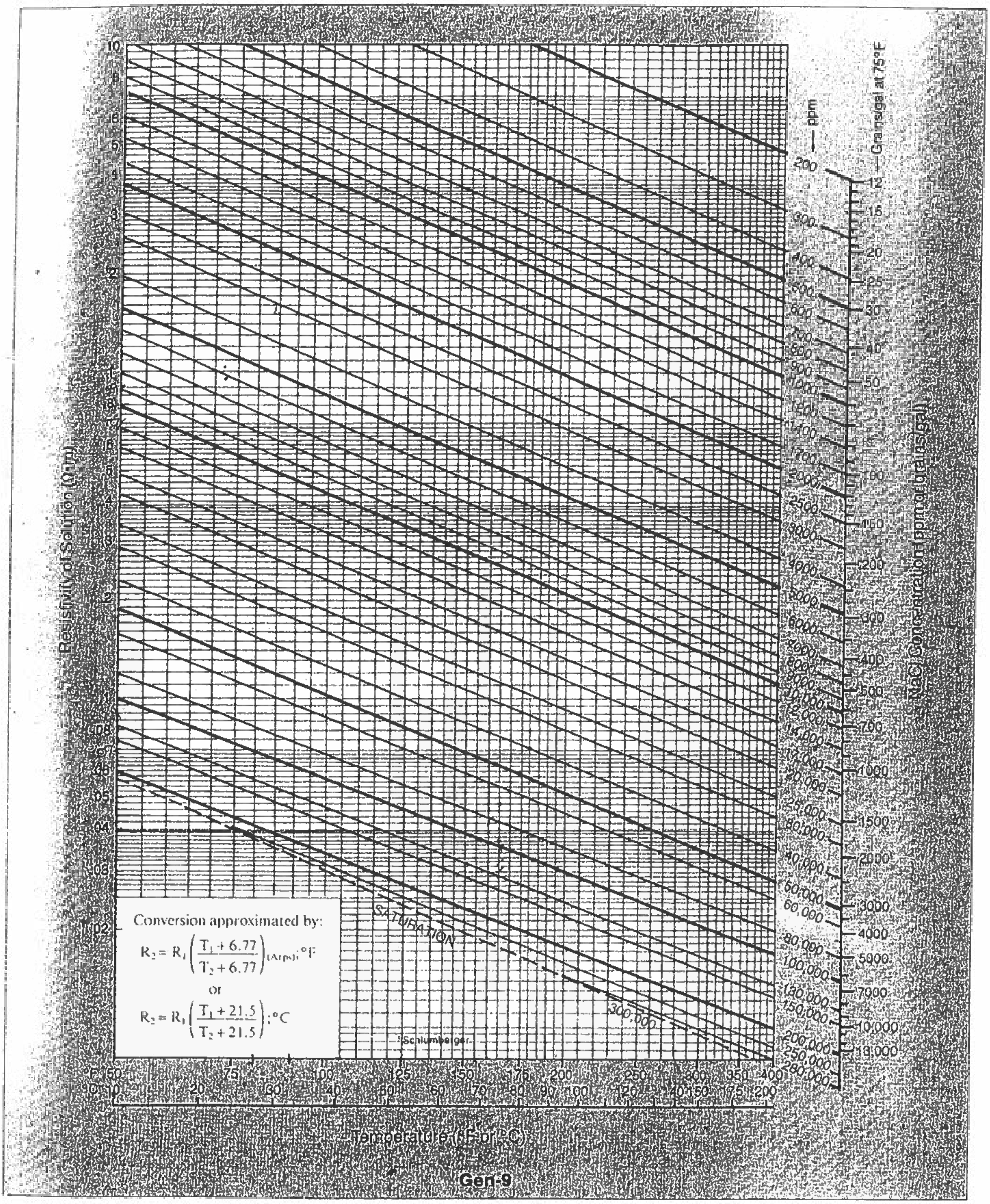
Resistivity of NaCl Solutions



Conversion approximated by:

$$R_2 = R_1\left(\frac{T_1+6.77}{T_2+6.77}\right)_{(Arps)};°F$$

or

$$R_2 = R_1\left(\frac{T_1+21.5}{T_2+21.5}\right);°C$$

Manipulation of equation 1 allows us to calculate the formation factor if R_w is known:

$$F = \frac{Ro}{Rw} \qquad \text{(EQN. 2)}$$

When dealing with the SFL we may substitute R_{sfl} for R_o and R_{mf} for R_w. This gives us the following relationship:

$$F = \frac{Rsfl}{Rmf^*} \qquad \text{(EQN. 3)}$$

R_{SFL} reads to close for an R_{xo} in most cases & chart corrections should be considered

Note: $^*R_{mf}$ is generally taken from the log header and then corrected to formation temperature.

Once F is determined we can manipulate equation 1 to solve for the apparent resistivity of the formation water (R_{wa}) by substituting the deep induction Resistivity (R_{DEEP}) for R_o as follows:

$$Rwa = \frac{Ro}{F} = \frac{R_{DEEP}}{F} \qquad \text{(EQN. 4)}$$

Once R_{wa} has been determined, type curves or mathematical relationships (Figs. 1 through 8) may be used to determine the apparent concentration of dissolved ionic solids in the formation (Aquifer).

Example

In a given water-bearing formation, the well log values are as follows:

$^*R_{sfl}$ = 50 ohm-meters
R_{mf} = 1.25 ohm-meters @ formation temperature (T_f=25° C)
$^*R_{DEEP}$ = 80 ohm-meters

* after standard corrections

Using EQN. 3: $F = \frac{Rsfl}{Rmf} = \frac{50}{1.25} = 40$

Using EQN. 4: $Rwa = \frac{R_{DEEP}}{F} = \frac{80}{40} = 2$ ohm-meters @ T_f

Utilizing Figure 1, the TDS concentration is estimated to be 2685 PPM. (using the "Best Fit" curve)

Based on 43 CFR 3162.5-2, this water is usable and should be protected.

Total Dissolved Solids (TDS)

Total dissolved solids in a water sample include all solid material in solution, whether ionized or not. It does not include suspended sediment, colloids, or dissolved gases. Theoretically, if all dissolved solids were determined accurately by chemical tests, total dissolved solids would be the numerical sum of these constituents.

Arps Eqn:

$$R_2 = R_1 \left(\frac{T_1 + 6.77}{T_2 + 6.77}\right);\ ^{\circ}F$$

$$R_2 = R_1 \left(\frac{T_1 + 21.5}{T_2 + 21.5}\right);\ ^{\circ}C$$

where:

R_1 = resistivity at T_1
R_2 = resistivity at T_2
T_1 = sample temperature
T_2 = desired temperature

I have found discrepancies of log calculated Rwa to measured Rwa in fresh waters.

Summary and Conclusions

It should be obvious that the foregoing methods assume certain conditions to exist at the time the well was logged. The most important assumptions are these:

1. The short normal (or SFL) tool reads mud filtrate in the flushed zone of the well bore and this filtrate has the same resistivity as the R_{mf} on the log header corrected to formation conditions. ($R_{sfl} = R_{xo}$)
2. The long normal (or Deep) tool reads formation water in the uninvaded zone.
3. The formation water is not contaminated with resistive fluids such as oil or gas.
4. The dissolved ionic solids concentration is representative of water quality, i.e., no organic contamination or toxic chemicals present.
5. The aquifer is 100% water saturated and is capable of production.
6. The aquifer is relatively free of clay minerals. Clay minerals increase conductivity indicating poorer than actual water quality.

Using the criteria and procedures outlined above, it is possible to relate resistivity recorded on conventional downhole well logs to formation water quality. Further refinements to the techniques presented above may increase the accuracy of the calculations but for the purposes of the Application for Permit to Drill (APD) process, the foregoing analysis is probably adequate.

References

Archie, G.E., 1942, The Electrical Resistivity Log as an Aid in Determining some Reservoir Characteristics: Petrol Technology, V.5, p. 54-62 in Asquith, G.B., 1982, Basic Well Log analysis for Geologists: AAPG Tulsa, Okla. 74101, p. 2.

Formation Water Type	Salinity Chloride mg/litre	ppm NaCl	Normal Pressure Gradient (psi/ft)	Equivalent Mudweight (lb/gal)
Fresh Water	0	0	0.433	8.34
Brackish Water	6,098	10,062	0.435	8.37
	12,287	20,273	0.438	8.43
	24,921	41,120	0.444	8.55
Seawater	33,000	54,450	0.448	8.63
Saltwater	37,912	62,554	0.451	8.67
	51,296	84,638	0.457	8.80
	64,987	107,228	0.464	8.92
Typical Offshore Gradient	65,287	107,709	0.465	8.96
	79,065	130,457	0.470	9.04
	93,507	154,286	0.477	9.17
	108,373	178,815	0.484	9.30
	123,604	203,946	0.490	9.43
	139,320	229,878	0.497	9.56
	155,440	256,476	0.504	9.71
	171,905	283,643	0.511	9.83
	188,895	311,676	0.518	9.97
Saturated Saltwater	191,600	316,140	0.519	9.99

Figure 3-2. Variation of hydrostatic pressure with formation water salinity

For example, if the normal pore pressure gradient is 8.34 lb/gal, then the pore pressure at 5000 feet is

5000 * 8.34 * 0.0519 = 2164 psi

WORKSHEET FOR ESTIMATING WATER QUALITY FROM ELECTRICAL WELL LOGS

From Log Header:

Well No. & Location ________________________________

Rmf __________ at __________°F

Max. Recorded Temp. __________°F

Bottom Logged Interval __________ feet

Temp. Gradient in degrees F/Foot = (max. Rec. Temp - 60°F ÷ Bottom Logged Interval = ______________

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

Sand between __________ and __________ Feet Depth

T_f = (Temp. Gradient x Depth of F_m) + 60°F = __________ °F

Rmf at T_f (From chart Gen-9 Schlumburger) = ________________

Rsfl (or equivalent) = __________ ohm-meters (From Log)

Rild (or equivalent) = __________ ohm-meters (From Log)

$F = \frac{Rsfl}{Rmf}$ = __________ = __________

$Rwa = \frac{Rild}{F}$ = __________ = __________ ohm - m at T_f

Convert Rwa @ T_f to Rwa @ 77°F (25°C) $R_{77°} = R_{T_f}\left(\frac{T_f + 6.77}{83.77}\right)$; in °F (Arps Eqn.)

Rwa @ 77°F (25°C) = ______________

Use chart or equation to relate Rwa to TDS ______________

(If TDS is less than 5000, continue to lower sand)

Attachment 6

Rio Bravo 27-5 TDS Determination

TDS calculations were performed for the Cliffhouse Formation of the Mesa Verde. The depth used for the calculations was 3512', because at this depth the formation was made up of clean shoreline sands and it had the greatest resistivity value for the Cliffhouse Formation.

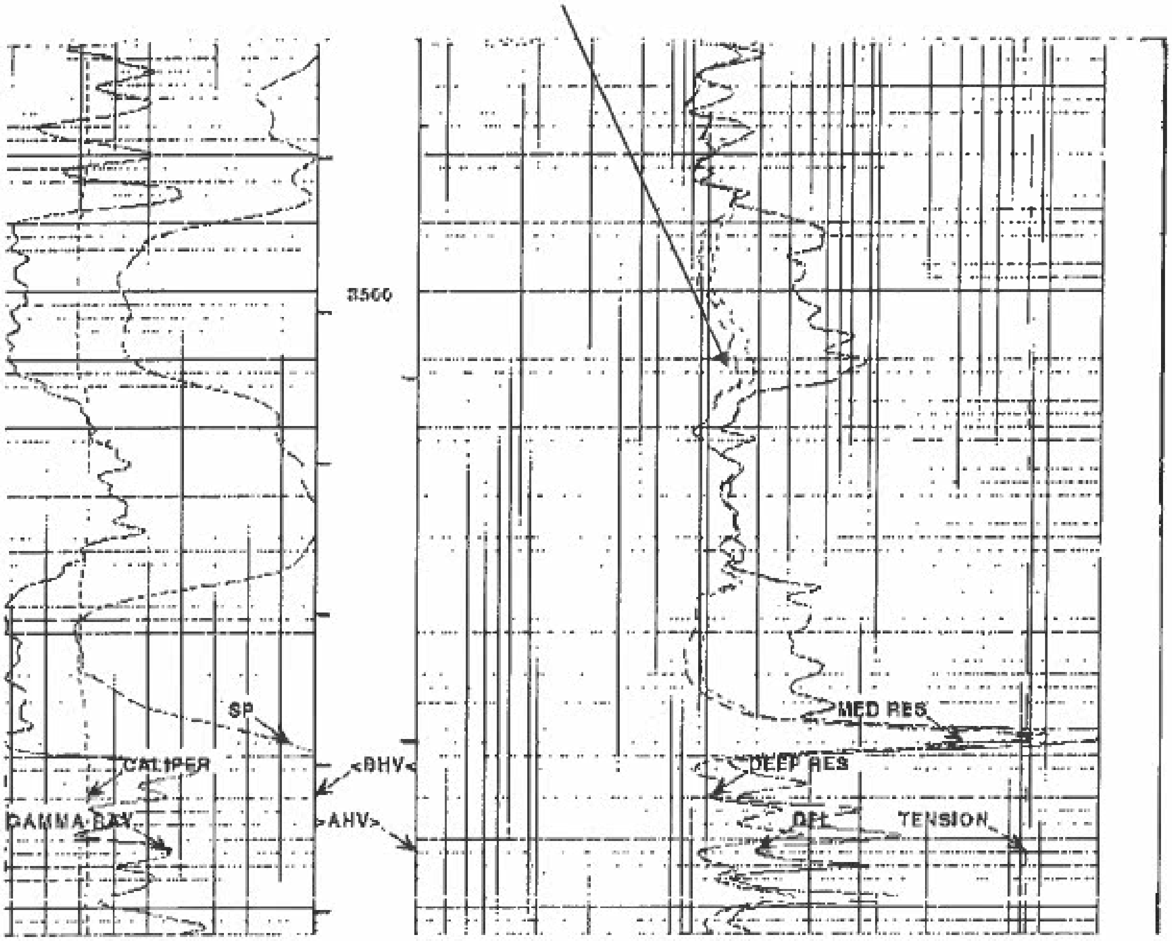
The deep resistivity log was used because it represents actual formation resistivity as opposed to the shallow resistivity which represented the mud water used for circulation.

Two methods used for TDS calculation:

1. $S_w = [\ (a / \Phi^m)*(R_w / R_t)\ ]^{(1/n)}$

Knowns:

$Sw=$ 100%, a=1, m=1.82, n=2, R_t=11 ohms, Φ=12%



Attachment 6

Rewrite the equation to determine R_w

$$R_w = R_t * \Phi^m$$

$= 11 \text{ ohms} * (.12^{1.82})$

$= .232 \text{ ohms}$

Correction for temperature at depth: 3512 ft

Knowns:

BHT = 127°F @ 4650 ft., depth: 3512 ft, surface temp= 60°F

Temperature Gradient = (BHT-Surface Temperature)/Bottom Hole Depth

=(127°F-60°F)/4650 ft

= 0.014409°F/ft

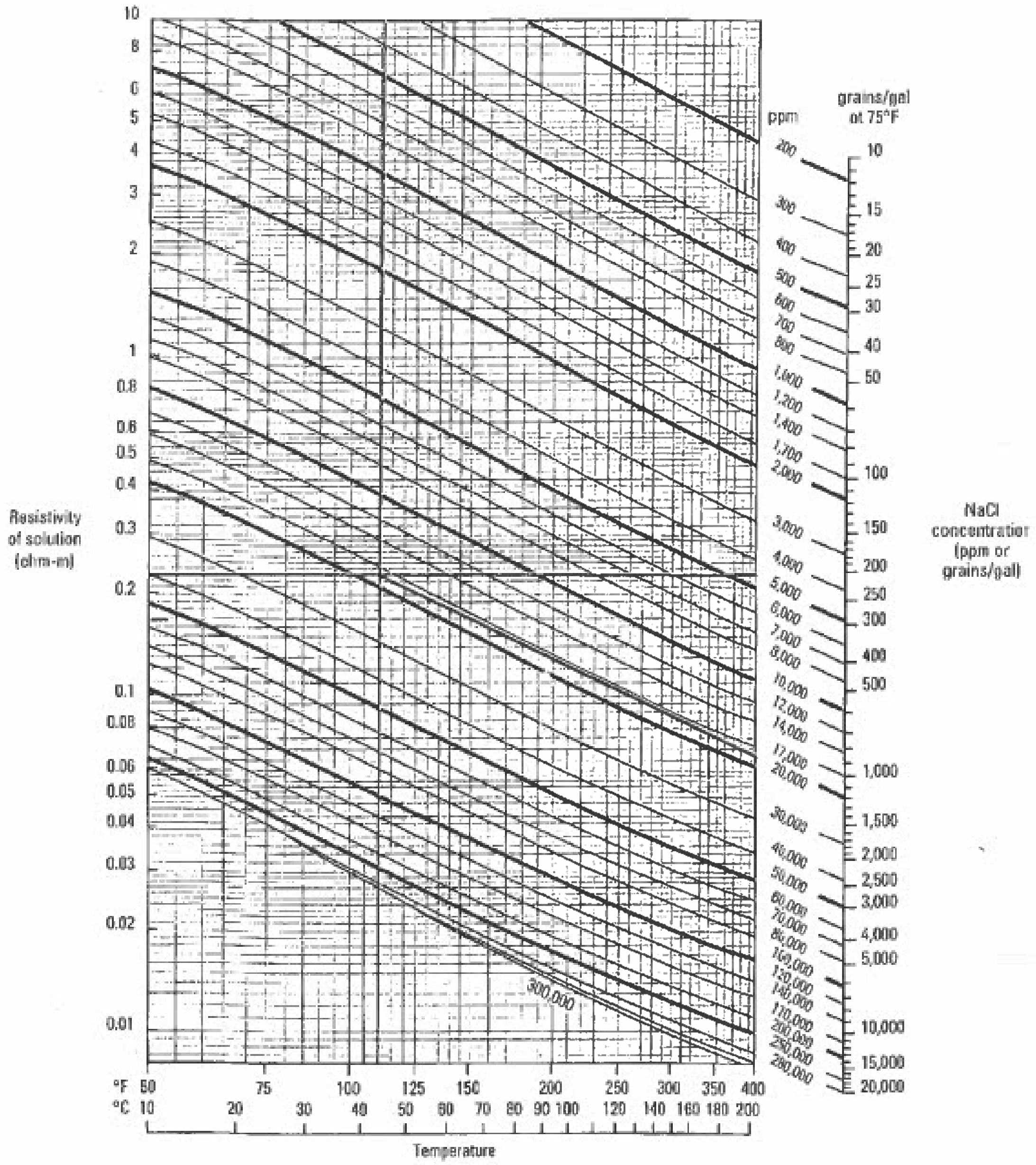
Temp at 3512ft = (Temp Gradient * Depth) + surface temperature

= (0.014409°F/ft *3512 ft) + 60°F

= 110.6°F

Attachment 6

Conversion approximated by $R_2 = R_1 [(T_1 + 6.77)/(T_2 + 6.77)]$°F or $R_2 = R_1 [(T_1 + 21.5)/(T_2 + 21.5)]$°C



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TDS Evaluation: Use of Water Resistivity derived from Archie's Equation

TDS content is approx 18,000 ppm according to Chart.

2. R_{weq} Determination from E_{ssp}

Knowns:

SP = 67 mv deflection, Rmf: 4.63 ohms @ 61 °F

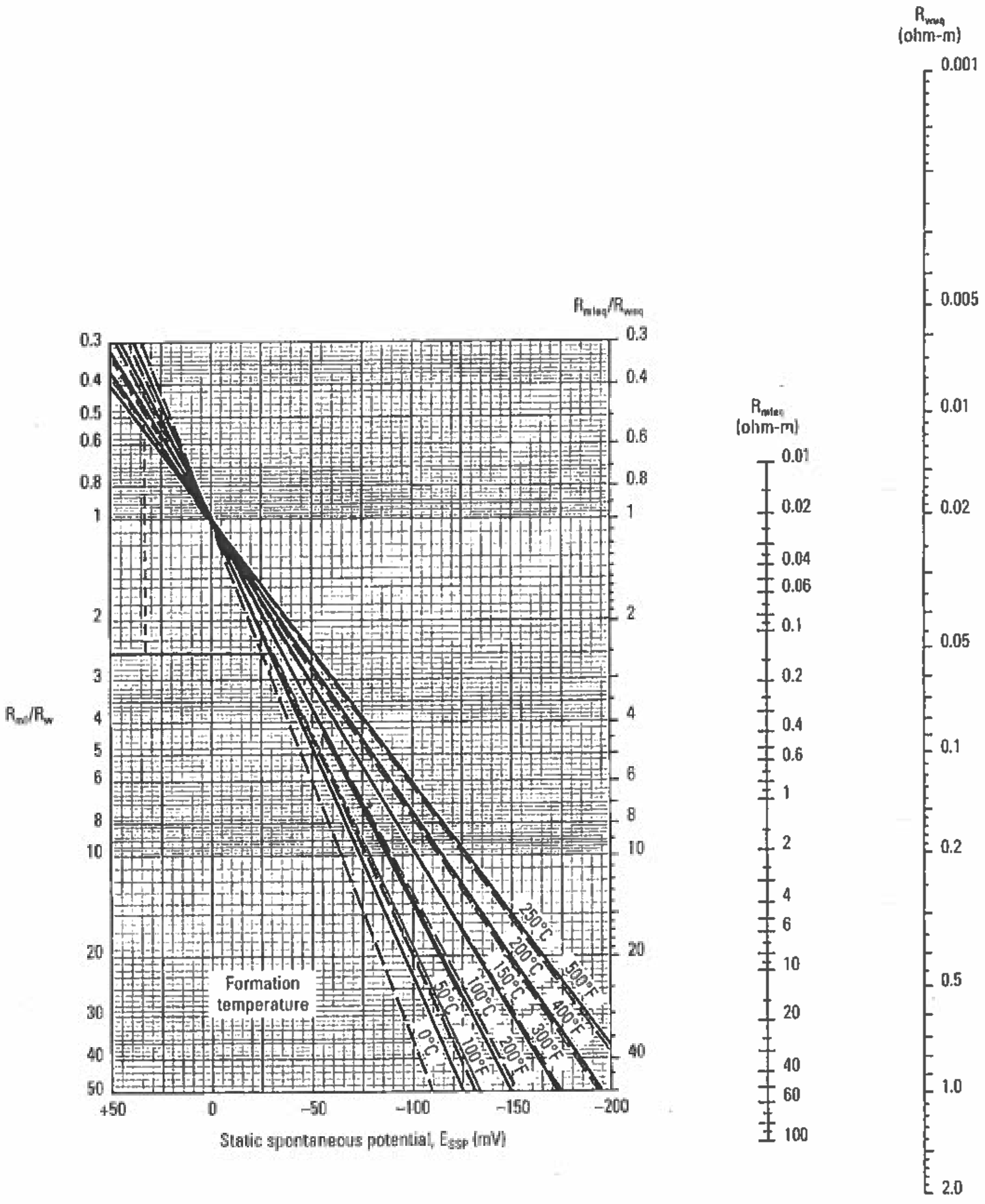
Rmf correction for temperature at depth:

$[(61^{\circ}F + 6.7^{\circ}F)/(110.6^{\circ}F + 6.7^{\circ}F)]*4.53 \text{ ohms} = 2.519 \text{ ohms}$

Attachment 6

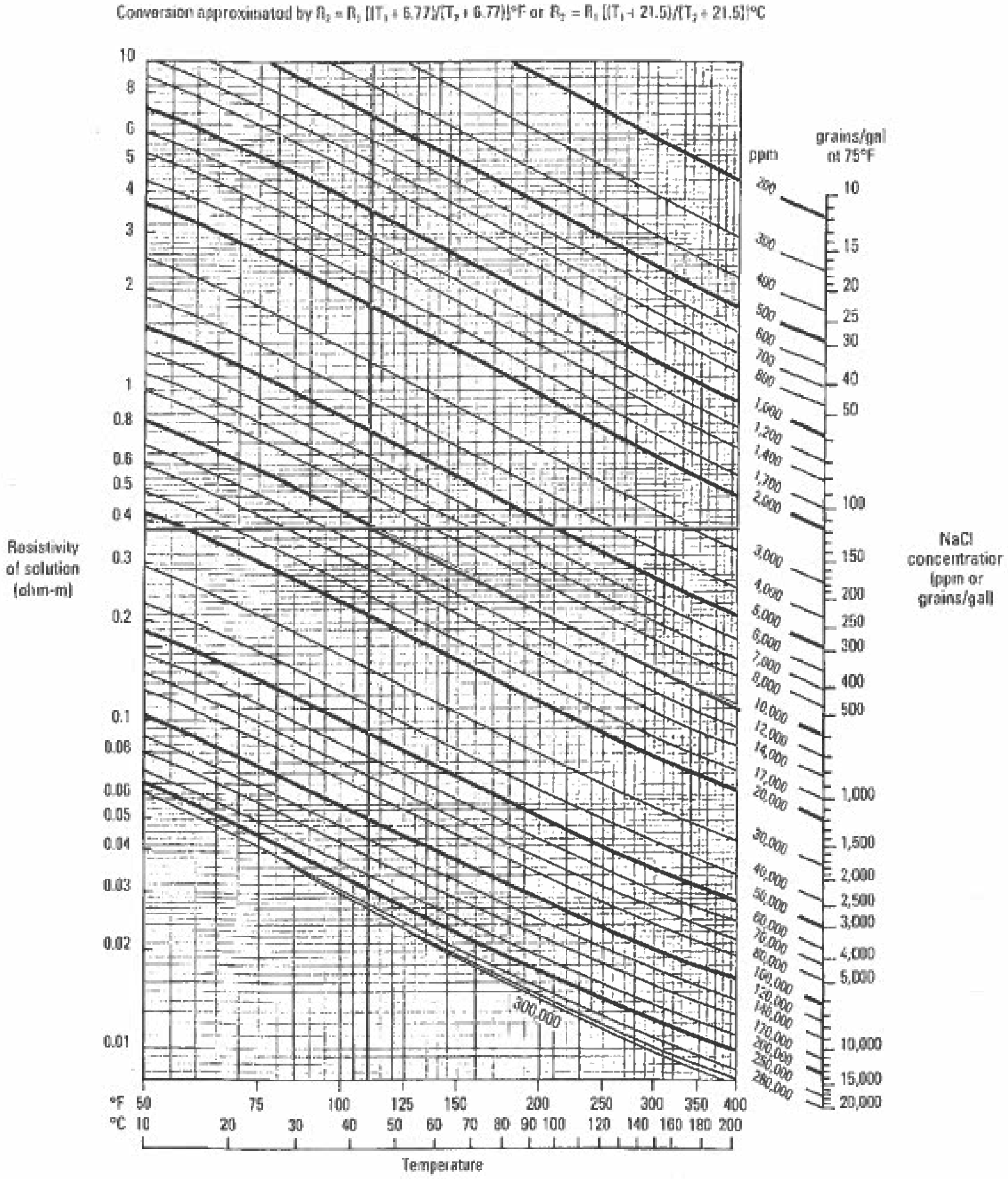
R_{weq} Determination from E_{SSP}

SP-1
(former SP-1)



Rw=.39

Attachment 6



Conversion approximated by $R_2 = R_1 [(T_1 + 6.77)/(T_2 + 6.77)]$°F or $R_2 = R_1 [(T_1 + 21.5)/(T_2 + 21.5)]$°C

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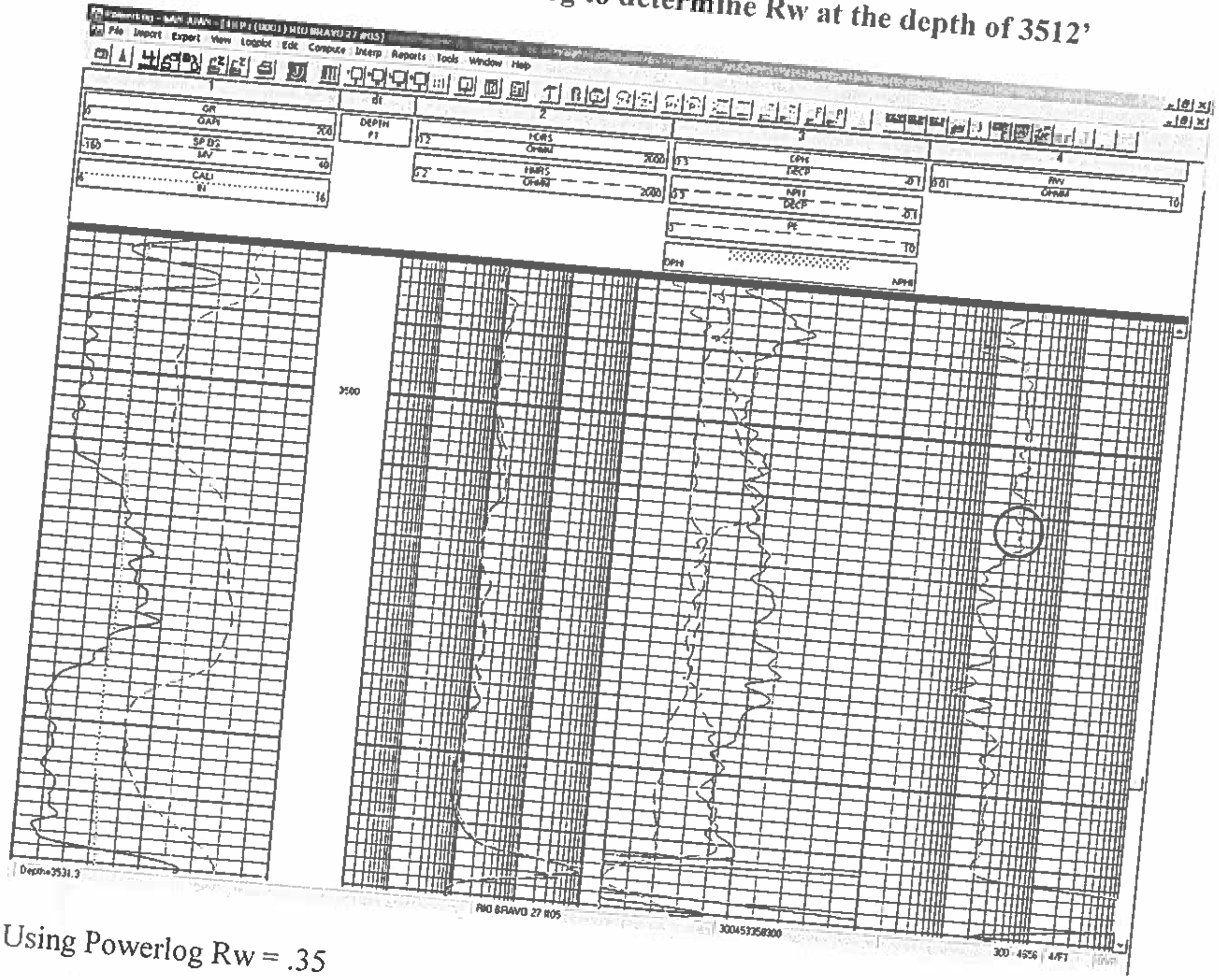
TDS Evaluation: Use of Water Resistivity derived using Sp

TDS content is approx 10,000 ppm according to Chart.

Attachment 6

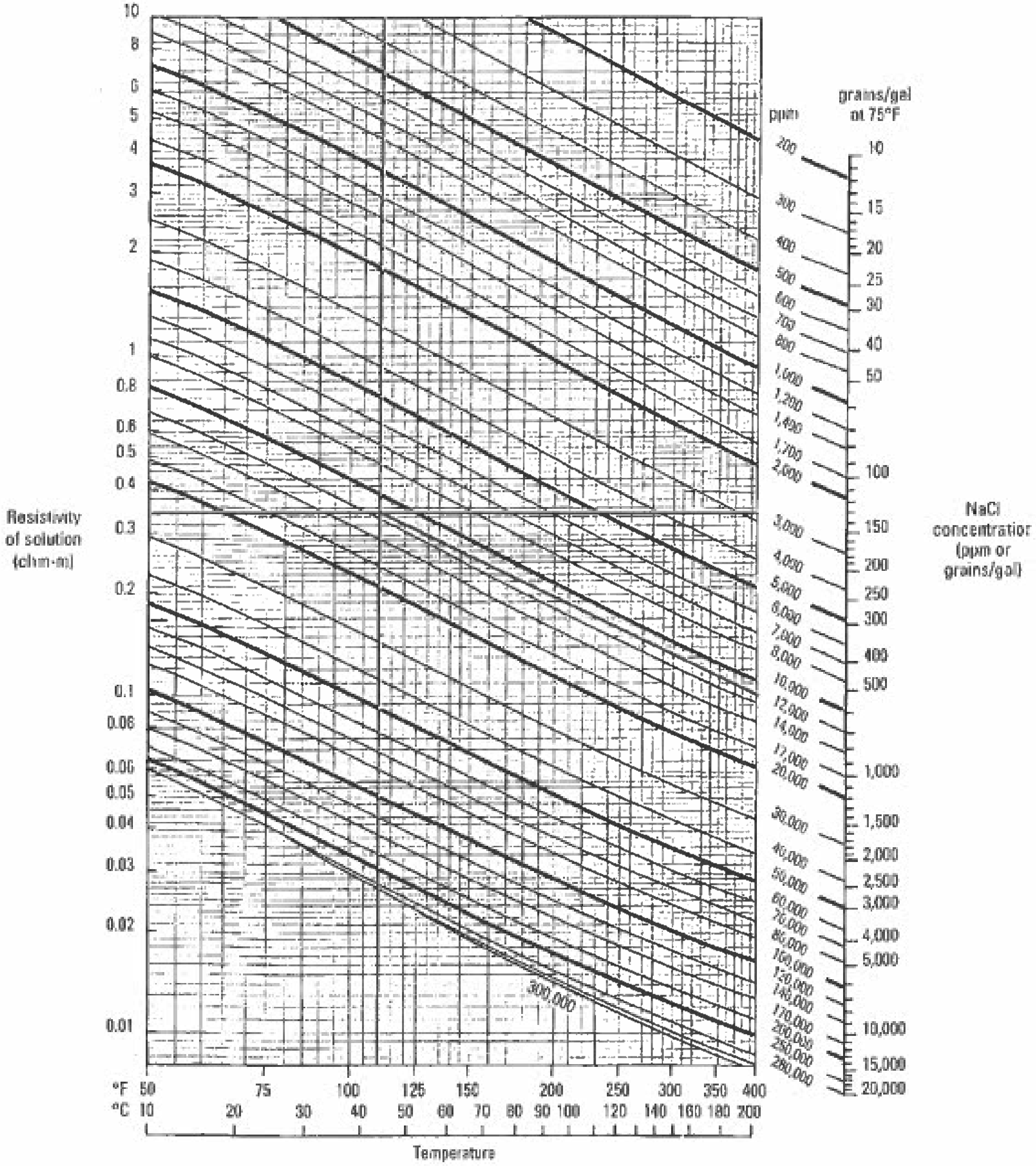
Utilization of the program Powerlog to determine Rw at the depth of 3512'



Using Powerlog Rw = .35

Attachment 6

Conversion approximated by $R_2 = R_1 [(T_1 + 6.77)/(T_2 + 6.77)]$°F or $R_2 = R_1 [(T_1 + 21.5)/(T_2 + 21.5)]$°C



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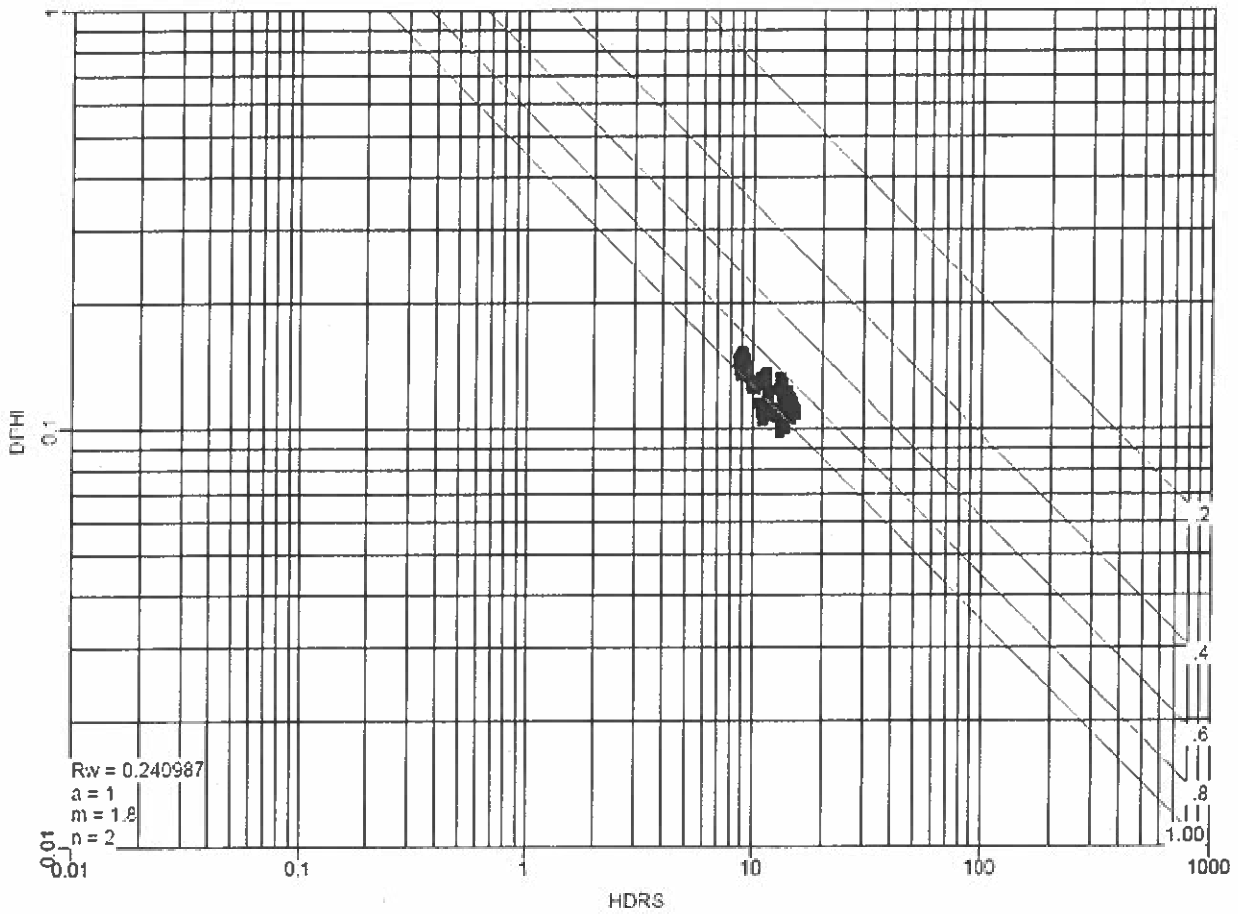
TDS Evaluation: Use of Water Resistivity determined using Powerlog program

TDS content is approx 11,000 ppm according to Chart.

Attachment 6

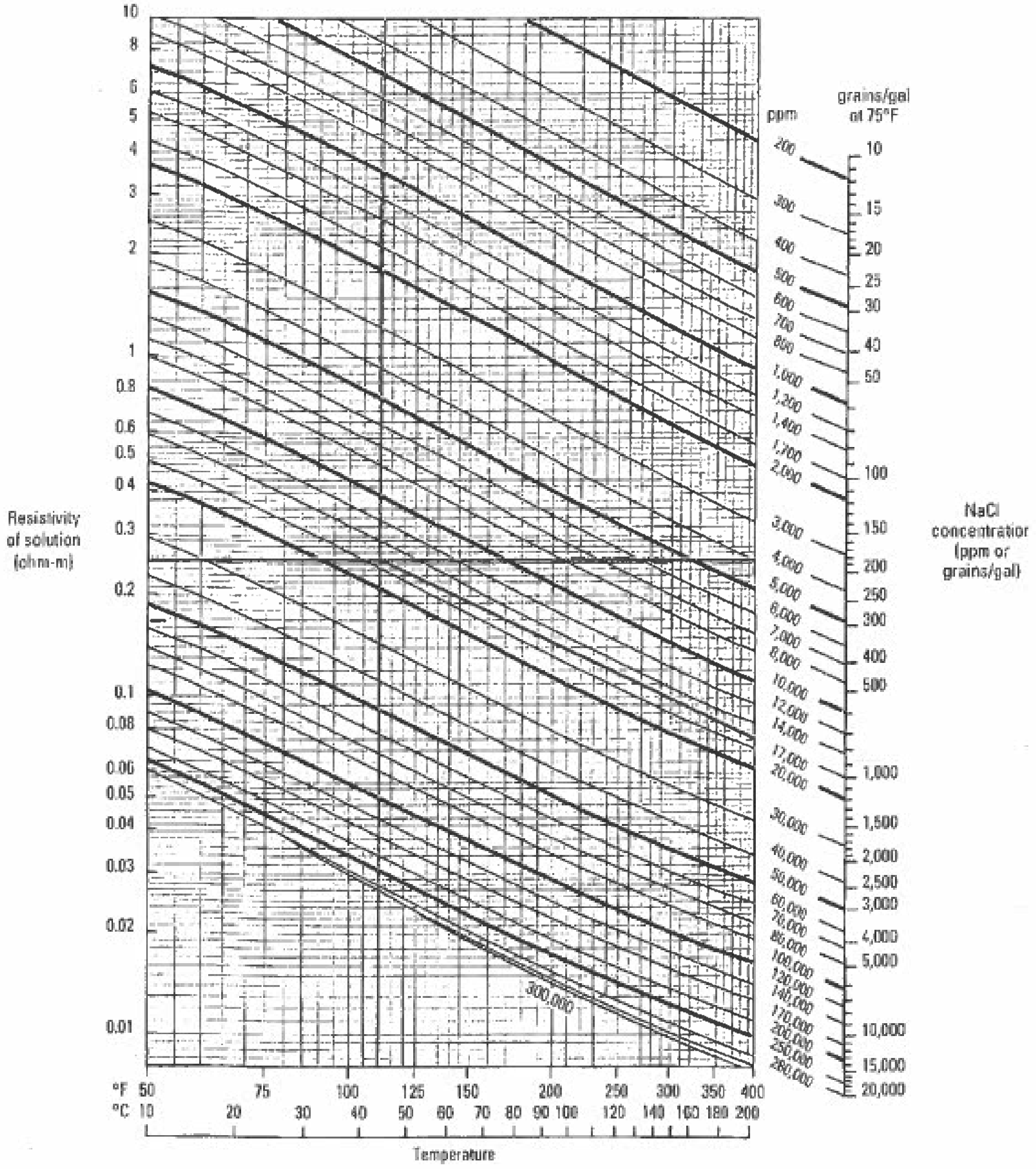
Utilization of the Pickett Plot to determine Rw at the depth of 3512'
Water saturation is delineated by the lowermost line on the plot. Tight Grouping indicated that the unit within question is well saturated with water. Using the Pickett Plot the Rio Bravo 27-5 has a water resistivity of .24 ohms.



WELL: RIO BRAVO 27 #05
ZONE: 3488.000 - 3516.000 FT
DATE: 20 Aug 2009 @ 14:24

Attachment 6

Conversion approximated by $R_2 = R_1 [(T_1 + 6.77)/(T_2 + 6.77)]$°F or $R_2 = R_1 [(T_1 + 21.5)/(T_2 + 21.5)]$°C



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TDS Evaluation: Use of Water Resistivity derived from Archie's Equation within use of the Picket Plot

TDS content is approx 16,000 ppm according to Chart.

Attachment 6

Based upon the various calculations above the Cliffhouse Formation of the Mesa Verde Member is estimated to have a TDS value between 10,000 and 18,000 ppm.

API	WELL NAME	OPERATOR	FTG NS	NS CD	FTG EW	EW CD	UL2	Sec	Tsp	Rge	OGRID_CDE	TVD DEPTH
-045-29732	JUNIPER SWD #001	COLEMAN OIL & GAS INC	880	N	730	W	D	16	24N	10W	4838	4125
-045-21463	Monument #002	PRE-ONGARD WELL OPERATOR	800	N	800	W	D	16	24N	10W	214263	6190
-045-21912	Monument #001	PRE-ONGARD WELL OPERATOR	1650	N	990	E	H	17	24N	10W	214263	6100
-045-32783	JUNIPER SWD #004	COLEMAN OIL & GAS INC	660	S	2015	W	N	17	24N	10W	4838	3940
-045-05114	PRE-ONGARD WELL #001	PRE-ONGARD WELL OPERATOR	660	N	660	E	A	18	24N	10W	214263	5053
-045-28537	TARGET #00i	DUGAN PRODUCTION CORP	1980	N	1980	W	F	20	24N	10W	6515	4930
-045-05098	Case #001 → P&A	PRE-ONGARD WELL OPERATOR	1980	S	660	W	L	20	24N	10W	214263	4900

Gallup well, Ran PIPE, P&AED

200 SX
7 7/8" HOLE
4 1/2" PIPE

4897 KB

Jones, William V., EMNRD

From:	Jones, William V., EMNRD
Sent:	Monday, August 25, 2008 7:00 PM
To:	'Pham.Lisa@epamail.epa.gov'; Chavez, Carl J, EMNRD; Sanchez, Daniel J., EMNRD
Cc:	Leissner.Ray@epamail.epa.gov; Price, Wayne, EMNRD; Ezeanyim, Richard, EMNRD; Warnell, Terry G, EMNRD; Hayden, Steven, EMNRD
Subject:	RE: Cowsaround No. 1 Class II saltwater disposal well

Hello Lisa:
Thanks to Jim Walker for this analysis on the Cliff House member of the Mesaverde Formation in San Juan County New Mexico. As you said, there are no resis logs on this Cowsaround SWD #1 well operated by Coleman Oil & Gas so we have to look at offset wells for information - and none of us had not done that yet.

I agree with the particular analysis on the well he looked at. It does show about 20 ohm-meters on the deep resis, over a decent sand interval. The logs are old and the mud used was relatively fresh -> Rmud = 4. The logs show that the shallower resis was higher in resistivity than the deep reading - which means to me that the formation waters are MORE saline than the mud used to drill the well. This well is almost 2 miles from the Cowsaround SWD and the sands appear lower in depth from surface. I did not check structure and don't know how that would fit in.

To check this out further, I looked at electric logs on every deep well within the 9 square miles surrounding the Cowsaround SWD well (all closer than the well Jim looked at) and none of them have the sand development or high resistivity of this well that Jim looked at. The highest deep resis I saw was 17 or so (see the 30-045-05919 Frontier A # 1). This well's sand development was NOT good - none are as good as the Juniper Area.

Coleman took over this well after all the action happened to it. Pendragon was the operator when it was permitted and perforated. It was permitted for the Point Lookout, then "corrected" to include the upper Mesaverde. No application paperwork justification exists in our files for the "correction", so if there is a problem, this will be explored. The operator would have to produce the paperwork. There were no other wells around at this depth in the 1/2 mile Area of Review.

However, Coleman has since done Step Rate Tests on both upper and lower Mvrd intervals in this well and it is relatively tight. The logs show the well to be relatively tight also - in my opinion.

The Cowsaround well seems not to have the low salinity or large clean sands that the Juniper wells did in the Cliff House. It is definitely tight compared to the Juniper area. Another thing to consider is that an offset to the Juniper wells was perfed and sampled in the upper Cliff House and the sample was NOT below 10,000 TDS - even though the logs calculated close to 10,000. Could have been several reasons for this - but that IS a data point.

The bottom line is, I don't think we have enough to convince a hearing officer to revoke this permit in the upper Mvrd.

However, welcome any other feedback - AND anyone who wants to testify at a hearing asking to revoke this permit.

I do NOT want to discourage Jim Walker from using his expertise and sharing it with us. We must all work together whenever we can.

I don't believe, we have granted any Cliff House injection permits in several years. The operators know we are all watching this closely.

Regards,

William V. Jones PE
New Mexico Oil Conservation Division

1220 South St. Francis
Santa Fe, NM 87505
505-476-3448

-----Original Message-----
From: Pham.Lisa@epamail.epa.gov [mailto:Pham.Lisa@epamail.epa.gov]
Sent: Wednesday, August 20, 2008 9:19 AM
To: Chavez, Carl J, EMNRD; Sanchez, Daniel J., EMNRD; Jones, William V., EMNRD
Cc: Leissner.Ray@epamail.epa.gov; Price, Wayne, EMNRD
Subject: Fw: Cowsaround No. 1 Class II saltwater disposal well

Hi Carl, Daniel, and Will,

Do you have any comment regarding Jim's analysis on this well?

A few years ago, we searched NMOCD records for this well but could not find any SP - Conductivity logs. Region 9 even contacted Wendy Rogers of Coleman O&G 505-327-0356 but she could not find any either; as a result, TDS was calculated using data from nearby wells, as stated by Jim Walker.

Lisa
----- Forwarded by Lisa Pham/R6/USEPA/US on 08/20/2008 10:04 AM -----

Jim Walker/R9/USEPA/US
08/14/2008 03:23 PM

To
Lisa Pham/R6/USEPA/US@EPA
cc
David Albright/R9/USEPA/US, David Basinger/R9/USEPA/US
Subject
Cowsaround No. 1 Class II saltwater disposal well

Hi Lisa,

How are you doing? Well, I hope.

The subject well is on non-Navajo land in the SW/4 of Section 16-T26N-R12W and was permitted by NMOCD a few years ago for disposal in the Mesa Verde Formation, including the Cliff House member. Initially, I thought that the well was located on Navajo surface trust land. After checking with the operator, Coleman Oil & Gas Co. and BIA,, it turns out that it is located in a quarter section that is either state and/or private fee land, but is surrounded by Navajo surface trust land. If on Navajo land, the well would require a Class IID permit from EPA and NNEPA. In researching the well data, it appears that the upper Cliff House contains less than 10,000 mg/l TDS in that area, based on log calculations of formation water resistivity by means of the modified Archie equation. There were no open hole logs run in the well apparently, so my calculations were based on resistivity and density-neutron logs from a nearby well, the Westfork No. 1 in the NW/4 of Section 14-26N-R12W. Other logs in the general area are consistent with that analysis. TDS ranges from 4,000 to 10,000 mg/l, increasing with depth in the Cliff House sandstone, but averaging well under 10,000 mg/l.

I thought I should apprise you of my analysis and concerns about this well. You may want to discuss this with NMOCD and get their assessment of the well. I believe it was originally permitted for just the Menefee and Point Lookout members of the Mesa Verde

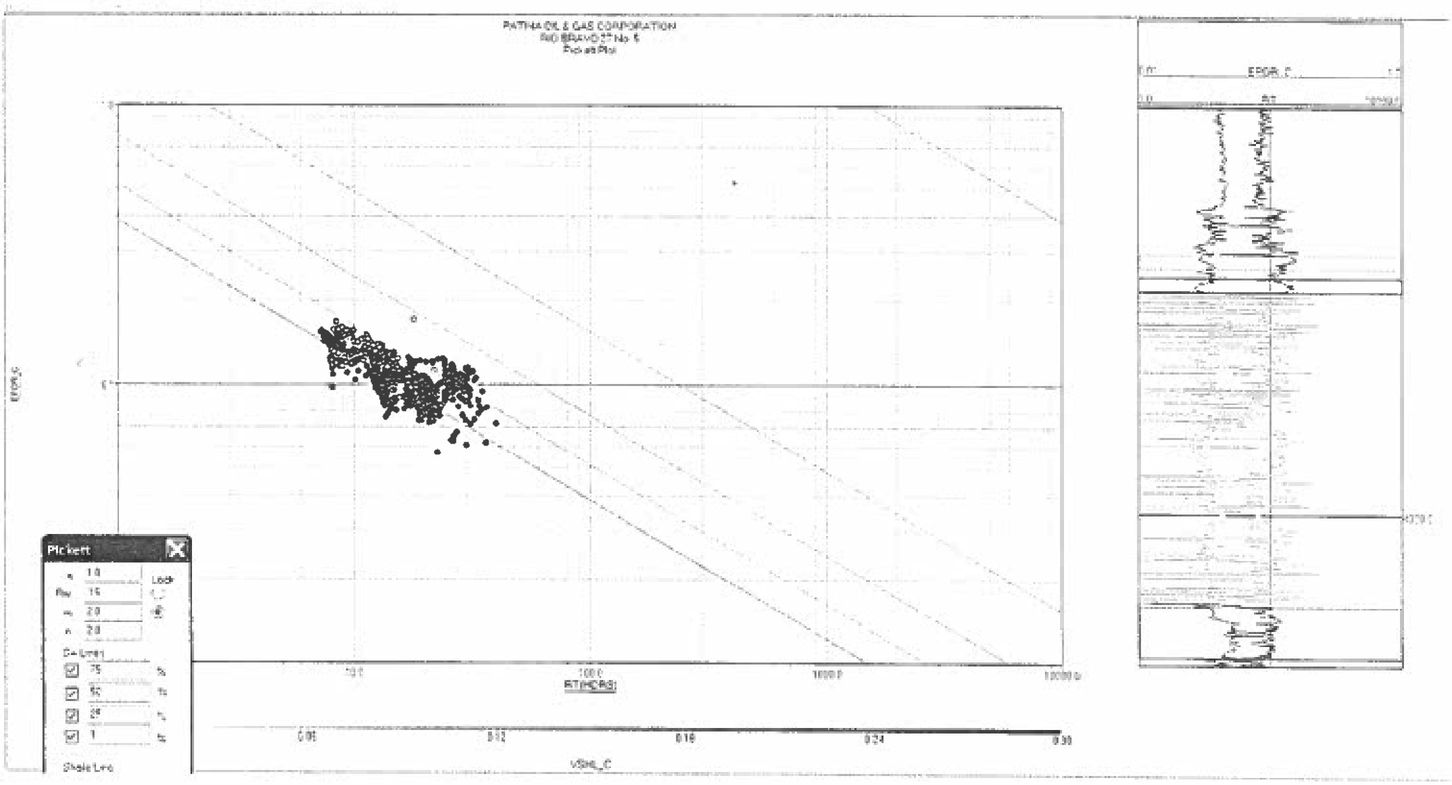
Group, which are clearly non-USDWs, but was later modified to add the Cliff House member.

Please let me know if you have any questions about my assessment.

Jim Walker
Environmental Engineer
US EPA Region 9
Ground Water Office
Navajo UIC Program
Farmington Field Office
(505) 599-6317

Pickett Plot

Red – Point Lookout; Magenta – Menefee; Lt Blue - Cliffhouse



PATHA OIL & GAS CORPORATION
RIO BRAVO 27 No. 5
Pickett Plot

Pickett
a 1.0
Rw 15
m 2.0
n 2.0
Lock
Sw Lines
☑ 75 %
☑ 50 %
☑ 25 %
☑ 1 %
Shale Line

The Pickett plot suggests an “m” = 2 is sufficient for this analysis

WORKSHEET FOR ESTIMATING WATER QUALITY FROM ELECTRICAL WELL LOGS

From Log Header:

Well No. & Location Tsah Tah SWD #11 30-045-34082 at 2485'

Rmf 1.01 at 72.6 °F

Max. Recorded Temp. 110 °F

Bottom Logged Interval 4508 feet

Temp. Gradient in degrees F/Foot = (max. Rec. Temp - 60°F ÷ Bottom Logged Interval = .011

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

Sand between 2481 and 2488 Feet Depth

T_f = (Temp. Gradient x Depth of F_m) + 60°F = 87.335 °F

Rmf at T_f (From chart Gen-9 Schlumburger) = .63

Rsfl (or equivalent) = 25 ohm-meters (From Log)

Rild (or equivalent) = 100 ohm-meters (From Log)

$$F = \frac{Rsfl}{Rmf} = \frac{25}{.63} = 39.68$$

$$Rwa = \frac{Rild}{F} = \frac{100}{39.68} = 2.52$$ ohm - m at T_f

Convert Rwa @ T_f to Rwa @ 77°F (25°C) $R_{77°} = \overset{2.52}{R_{T_f}}\left(\frac{\overset{87.335}{T_f} + 6.77}{83.77}\right)$; in °F (Arps Eqn.)

Rwa @ 77°F (25°C) = 2.83

Use chart or equation to relate Rwa to TDS 2800 mg/L

(If TDS is less than 5000, continue to lower sand)

WORKSHEET FOR ESTIMATING WATER QUALITY FROM ELECTRICAL WELL LOGS

For Sample@2469' High Res Ind 26 Jan'07

From Log Header:

Well No. & Location Tsah Tah SWD#11 30-045-34082

Rmf 1.01 at 72.6 °F

Max. Recorded Temp. 110°F °F

Bottom Logged Interval 4508 feet

Temp. Gradient in degrees F/Foot = (max. Rec. Temp - 60°F ÷ Bottom Logged Interval = .011

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

Sand between 2460 and 2480 Feet Depth

T_f = (Temp. Gradient x Depth of F_m) + 60°F = 87,16 °F

Rmf at T_f (From chart Gen-9 Schlumburger) = .63

Rsfl (or equivalent) = 10 ohm-meters (From Log)

Rild (or equivalent) = 15 ohm-meters (From Log)

$F = \frac{Rsfl}{Rmf} = 10/.63 = 15.87$

$Rwa = \frac{Rild}{F} = 15/15.87 = .945$ ohm - m at T_f

Convert Rwa @ T_f to Rwa @ 77°F (25°C) $R_{77^\circ} = \overset{.945}{R_{T_f}}\left(\frac{\overset{87.16}{T_f} + 6.77}{83.77}\right)$; in °F (Arps Eqn.)

Rwa @ 77°F (25°C) = 1.0596

Use chart or equation to relate Rwa to TDS ~4300 mg/L

(If TDS is less than 5000, continue to lower sand)

R_{weq} Determination from E_{SSP}

Energen calculations for Bluff formation water PPM from SP:

Rmf = 1.072 @ 80 deg (from log header)

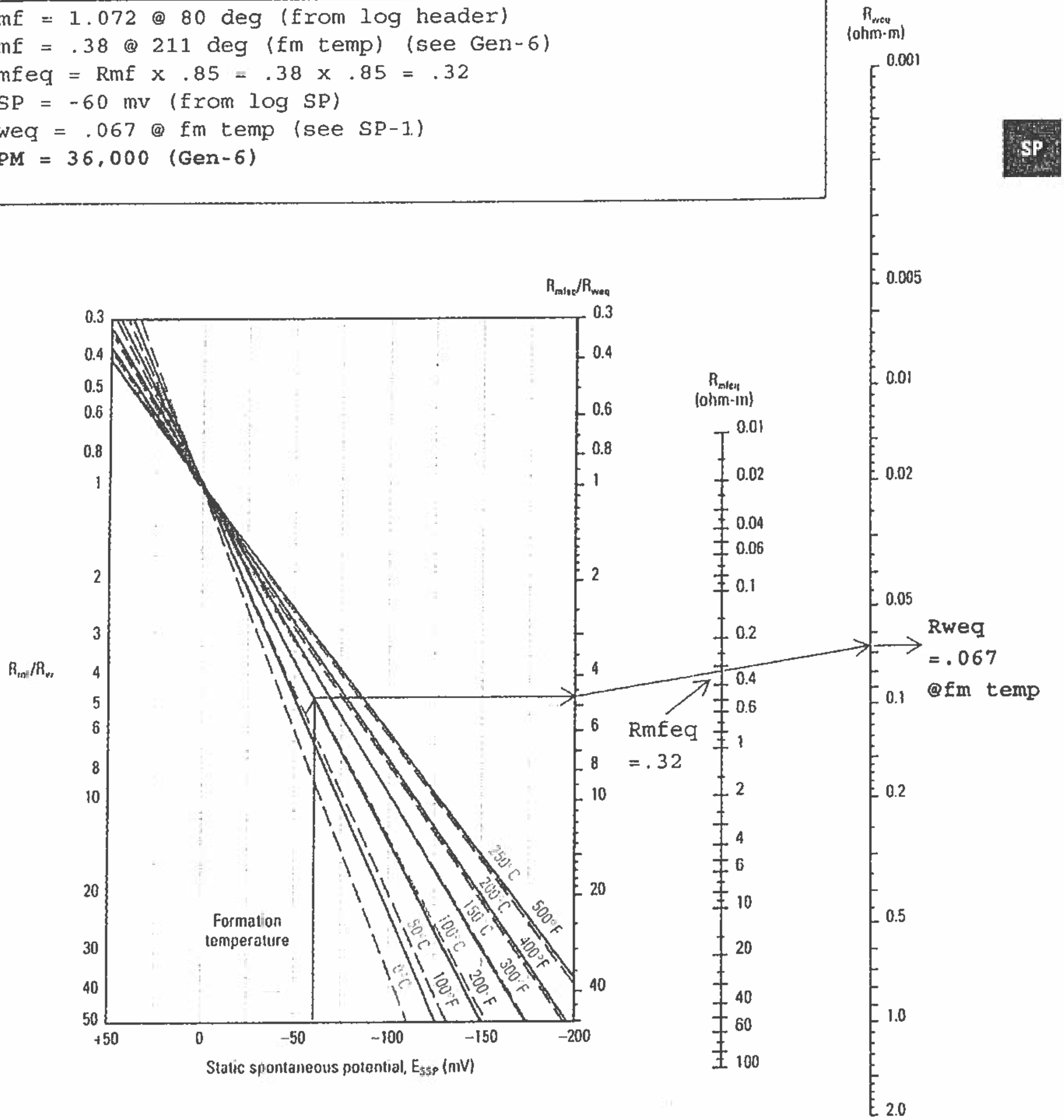
Rmf = .38 @ 211 deg (fm temp) (see Gen-6)

Rmfeq = Rmf x .85 = .38 x .85 = .32

SSP = -60 mv (from log SP)

Rweq = .067 @ fm temp (see SP-1)

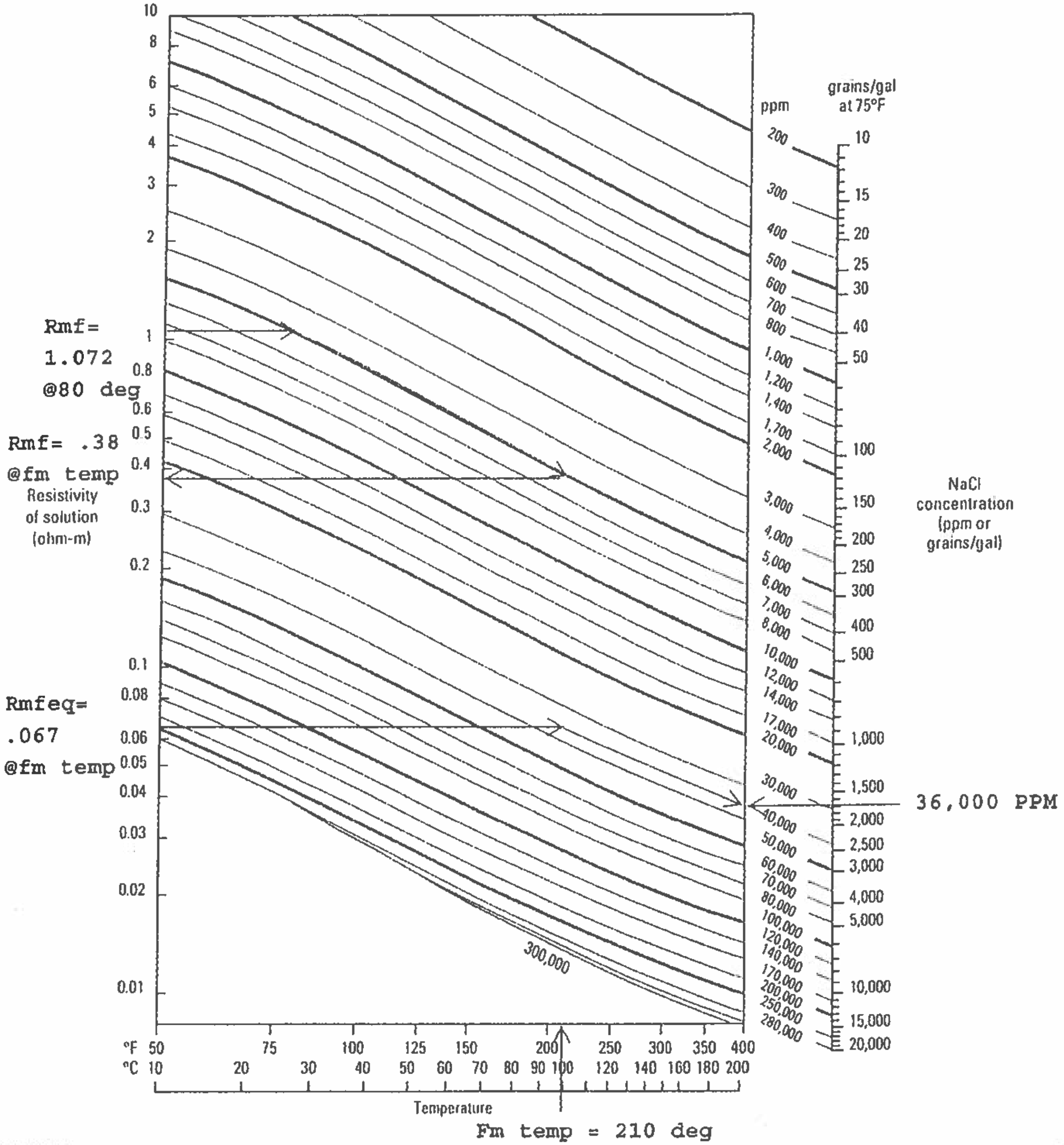
PPM = 36,000 (Gen-6)



Resistivity of NaCl Water Solutions

Gen-6
(former Gen-9)

Conversion approximated by $R_2 = R_1 [(T_1 + 6.77)/(T_2 + 6.77)]$°F or $R_2 = R_1 [(T_1 + 21.5)/(T_2 + 21.5)]$°C



Rmf= 1.072 @80 deg

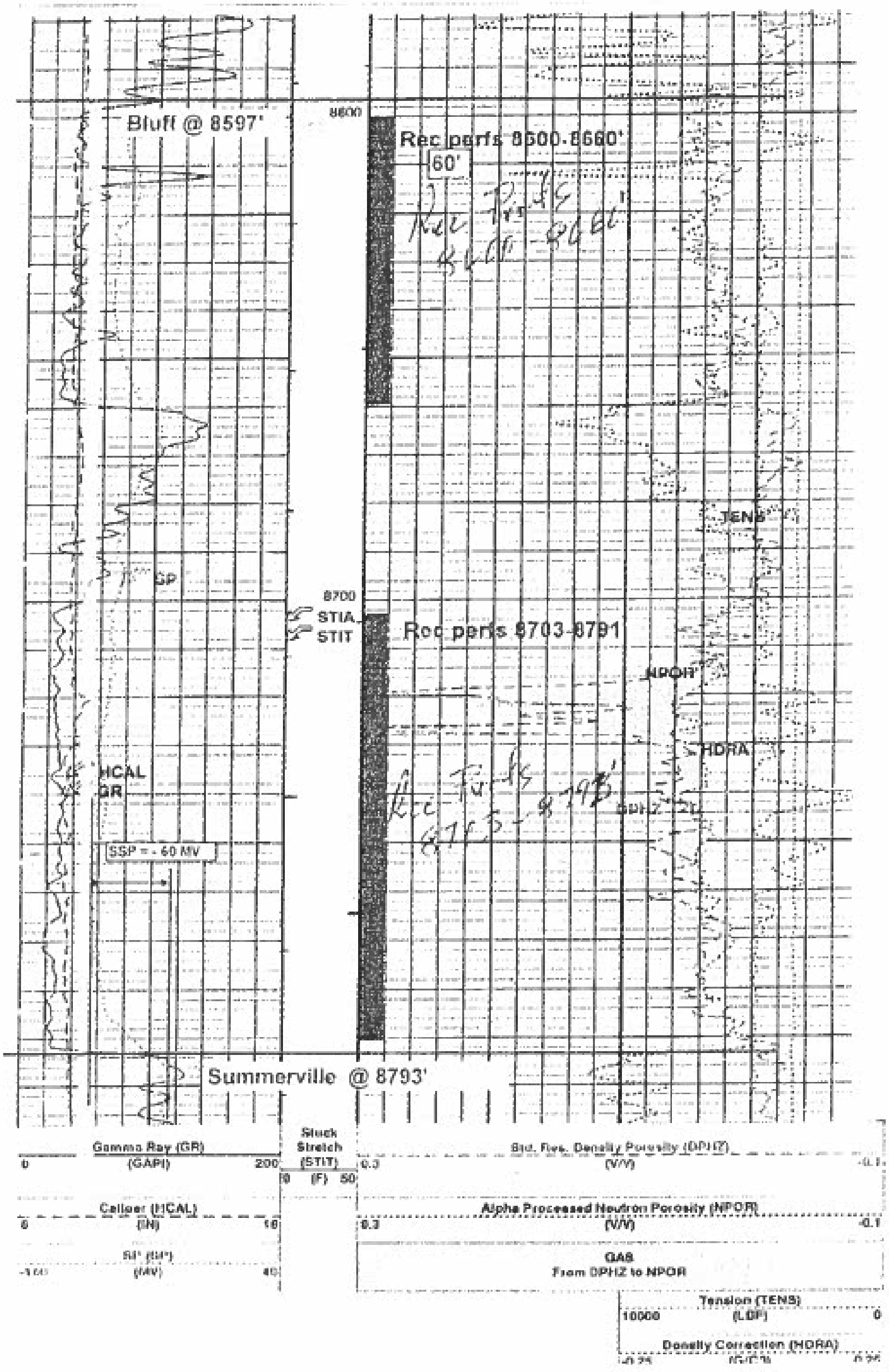
Rmf= .38 @fm temp

Rmfeq= .067 @fm temp

36,000 PPM

Fm temp = 210 deg

Energen Resources Carraca SWD #2 - Compensated Neutron Density log



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FORMATION WATER RESISTIVITY (R_W) DETERMINATION: THE SP METHOD

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ABSTRACT: Formation water resistivity represents the resistivity value of the water (uncontaminated by drilling mud) that saturates the porous formation. It is also referred to as connate water or interstitial water. Its resistivity can be determined by a number of methods, one of which is by the SP curve discussed in this work. Analysis of wire-line log data depends on the assumption that the only conductive medium in a formation is the pure water which supplies the energy and drive in reservoirs. So, physical properties of this formation water can be determined, one of which is its electrical resistivity and this eventually leads to water saturation determination – an important aspect of reservoir evaluation. This paper presents a review and comparative assessment of the graphical, vis-à-vis the calculative means of R_w determination by the SP method. @*JASEM*

Many of today's oil reservoirs are composed of sediments, which were once deposited in Marine, deltaic and other aquatic environments. Consequently, these sedimentary beds were originally saturated by salt water. Part of this water was displaced in the process of diagenesis and oil accumulations, the other remains, suspending the hydrocarbons because of their density contrast. That which remains generally is known as "Connate" or "Interstitial" water because the water was "born with" and is stored in the interstices of the sediments.

Schlumberger (1989) defined formation water as the water uncontaminated by drilling mud that saturates the formation rock. Analysis of wire line log data depends on the assumption that the only conductive medium present in the formation is the pore water; the matrix and hydrocarbons are non-conductive. Physical properties of this formation water can be determined, one of which is electrical resistivity. Formation water is the free water which supplies the energy for the water drive in reservoirs; and its resistivity is variable depending on the salinity, temperature and whether or not the formation contains hydrocarbons. At a given salinity, the higher the temperature the lower the resistivity, and the water resistivity at any formation temperature, can be calculated from the water resistivity at another formation temperature, knowing both the temperature and temperature offsets using this formula:

R_w at FT_2 = R_wFT_1, $(FT_1 + C)(FT_2 + C)$.
Where FT_1 = Initial formation temperature
FT_2 = Formation Temperature for which R_w is being determined.
C = 21.5 for Temperature in °C
(Smolen, 1977).

It has also been established (Schlumberger, 1989) that the water resistivity determined from a hydrocarbon-bearing zone is usually greater than that from the zone bearing only formation water. Determination of formation water resistivity is very important in calculating water and/or hydrocarbon saturation, in the determination of salinity if temperature is known and in understanding the variations of resistivity from the well wall into the formation by comparing it with the resistivity of the mud filtrate. In both SP and R_{wa} comparison methods, wire-line logs provide all the needed parameters to determine the formation water resistivity.

THE SP METHOD

In many cases, a good value of formation water resistivity R_w can easily be found by the SP curve read in clean (non-shale) formations because the SP can be used to distinguish lithology such as shaly from sandy formations. The static SP (SSP) value in a clean formation is related to the chemical activities (a_w and a_{mf}) of the formation water through the formula:

$$SSP = K\log {}^{a_w}\!/_{a_{mf}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where K = Constant and varies in direct proportion with temperature especially in NaCl solutions

K = 61 + 0.133T in °F
K = 65 + 0.24T in °C
a_w = Chemical activity of water
a_{mf} = Chemical activities of mud filtrate.

For pure Nacl solutions that are not too concentrated, resistivities are inversely proportional to activities. Therefore,

$$SSP = -K\log {}^{R_{mfe}}\!/_{R_{we}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where R_{we} = 0.075/S_w at 77°F (25°C) and is the equivalent formation water resistivity; and R_{mfe} = equivalent mud filtrate resistivity.

After we have been able to relate these resistivities to the SP value for a particular zone, we would then follow the procedure below in determining the formation water resistivity (R_w) using the SP method.

1. Establish the shale baseline on the SP curve.
2. Pick out clean permeable zones.
3. Do all the thick zones have about the same SP value? If yes, then pick any thick zone, but otherwise, pick thick zone near and/or the zone you are interested in.
4. Determine the formation temperature i.e. the temperature of this zone chosen, using surface temperature, the bottom hole temperature and the total depth with the formula:

$$T_f = (T_{TD} - T_0)\frac{D_f}{T_D} + T_0$$

Where T_f = Temperature of the formation in °F or °C.
T_{TD} = Temperature at total depth (Bottom hole Temp.) in °F or °C.
T_0 = Mean surface temperature (in °F or °C).
D_f = Depth to formation (in *ft* or *m*).
T_D = Total depth (in *ft* or *m*).

5. Now, from the R_{mf} and R_m values recorded on the log heading, determine the R_{mf} and R_m values at that particular formation temperature using the formula:

$$R_{mf}\ at\ T_f = R_{mf}\ at\ T_0(T_0 + C / T_f + C)$$

Where C is the temperature offset.
C = 6.8 if imperial units are used and 21.5 if metric units are used.
T_0 = Initial temperature at which R_{mf} was first measured.
R_m = Resistivity of mud, usually recorded on the log heading

6. Now read off SP amplitude from shale baseline to maximum constant deflection.
7. Determine bed thickness from SP deflection points.
8. Check whether the SP needs correction. If need be, correct for bed thickness, hole diameter, invasion and resistivity contrasts using the appropriate charts.
9. Now, knowing the formation temperature (T_f), the static SP or SP (Corrected), recorded opposite a porous and permeable, non-shaly formation can be transformed into the resistivity ratio R_{mf}/R_{we} in two ways: graphically as in figure 1 and by calculation.

Graphically by use of chart:

With the ratio R_{mfe}/R_{we} now determined and the resistivity R_{mf} of a sample of mud filtrate measured, the equivalent formation resistivity, R_{we}, is easily calculated. However, the mud filtrate resistivity reported on the log heading or calculated at the formation temperature is its actual resistivity not its equivalent resistivity (Edwards *et al* 1963). To convert the measured mud filtrate resistivity (R_{mfe}, the following rules are employed:

(a) For predominantly NaCl Muds.

i. If R_{mf} at 75°F is greater than 0.1ohm-m, use R_{mf} 0.85ohm-m at Formation Temperature. This relationship is based on measurements made on many typical muds.

ii. If R_{mf} at 75°F is less than 0.1ohm-m, use the NaCl (solid curves) in figure 2 to derive a value of R_{mfe} from the measured R_{mfe} value corrected to formation temperature.

(b) For fresh water or gypsum muds: the dashed curves of the chart in fig. 2 are used to convert R_{mf} to R_{mfe}.

(c) Lime-based muds, despite their name, usually have negligible amounts of calcium and are treated as regular mud (see rule a).

(d) For predominantly NaCl Muds.

iii. If R_{mf} at 75°F is greater than 0.1ohm-m, use R_{mf} 0.85ohm-m at Formation Temperature. This relationship is based on measurements made on many typical muds.

iv. If R_{mf} at 75°F is less than 0.1ohm-m, use the NaCl (solid curves) in figure 2 to derive a value of R_{mfe} from the measured R_{mfe} value corrected to formation temperature.

(e) For fresh water or gypsum muds: the dashed curves of the chart in fig. 2 are used to convert R_{mf} to R_{mfe}.

(f) Lime-based muds, despite their name, usually have negligible amounts of calcium and are treated as regular mud (see rule a).

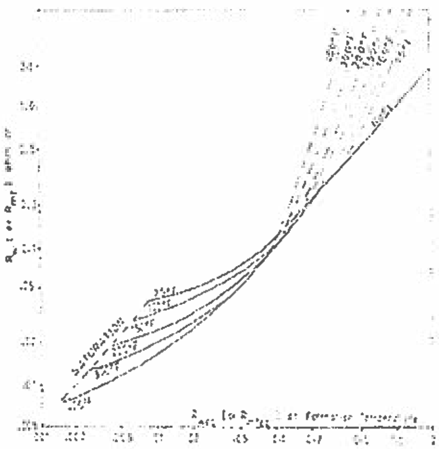

Fig 2 R_w and R_{we} (Also R_{mf} and R_{mfe}) Relationships.

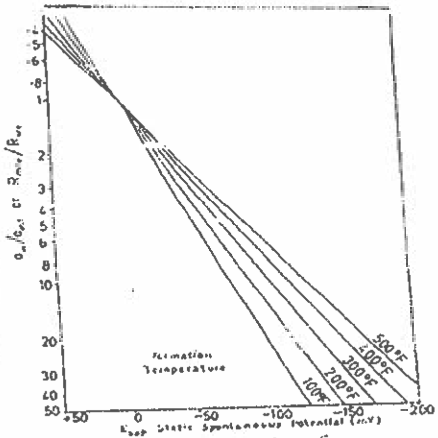

Fig. 1: R_{we} determination from E_{ssp} (clear formation)

By Calculation:

The log units should be metric for the calculation to be done.

(i) First determine the R_{mfe}

(ii) If R_{mf} at $T_f \leq 0.1$, then $R_{mfe} = (1.46\ R_{mf}$ at $T_f + 77)$.

(iii) If R_{mf} at $T_f > 0.1$, then $R_{mfe} = 0.85$fl at T_f.

(iv) But

$$SSP = K \log R_{mfe} / R_{we} ,$$

$$\frac{SSP}{K} = Log\ R_{mfe} / R_{we}$$

$$\therefore R_{mfe} = \frac{R_{mfe}}{R_{we}} = 10^{(-SSP/K)}$$

Lets denote $10^{(-SSP/K)}$ as R_{sp}.

$$\therefore \frac{R_{mfe}}{R_{we}} = R_{sp}$$

and $\therefore R_{we} = \dfrac{R_{mfe}}{R_{sp}}$

10. (a) Determine R_w from R_{we} value. The chart in Fig. 2 is also used to convert R_{we} to R_w. The solid curves, for very saline brine are derived from laboratory data on pure Nacl solutions. Thee solid curves are used for R_{we} and R_w values less than 0.1 ohm-m, they assume that in formation waters of this salinity Nacl is the dominant salt.

(b) By simple calculation as follows:

i. If $R_{we} > 0.12$, then R_w at T_f $(0.58-[(6.9R_{we}+2.4)]$

ii. If $R_{we} \leq 0.12$, then R_w at Tf $(77R_{we}+5)/146-337R_{we}$

11 Check R_w from Sp against another source.

PRECAUTION AND CONCLUSION

The static SP value can only be obtained directly from the SP curve, if the bed is clean thick, porous and only moderately invaded; and if the formation is saline and the drilling mud is not too reactive. These conditions are not always met. When they are not, the recorded SP deflection (in milivolts) must be corrected to a static SP value for bed thickness, hole diameter, invasion and resistivity contrasts (Pirson, 1963, Frick 1962).

It is assumed that the recorded SP curve seldom contains an electrokinetic potential component. Although this is generally the case very low permeability formation, depleted pressure formation, or the use of very heavy drilling mud give rise to a significant electrokinetic potential. In these cases, an R_w derived from the SP curve will probably be too low, so other sources of R_w data should be explored (Tixer et al, 1965). Knowledge of R_w values is invaluable. It opens the lock to some other important parameters in formation evaluation. Rw is useful in calculating water saturation in the formula

$$S_w = FR.{}^{R_w}/_{R_t} .$$

When water saturation is known, then hydrocarbon in place, HC = $(1-S_w)$, is derivable. And since qualification on hydrocarbons and calculation of reserves is indispensable in production, formation water resistivity, R_w, remains one of the most important interpretational parameters in well log analysis.

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Wireline logs are used for:

- Correlation
- Bed thickness
- Porosity
- Water saturation

These measurements enable conclusions to be drawn on:

- Lithology
- Permeability
- Presence and type of hydrocarbons
- Mobility of hydrocarbons

5.58 Classification

Wireline logs can be separated into four functional groups which measure the following:

- Resistivity
- Porosity/lithology
- Production characteristics
- Miscellaneous parameters

5.59 Resistivity: Depending on the type of resistivity measurements required, various tools are used. These are discussed below.

- Direct Resistivity Measurements. Tools of this type measure the electrical resistivity of the formation by passing an electric current out into the formation. Since the current must pass through the mud, mud cake and invaded zone (see Figure 5-29), the resultant measurement is a combination of their resistivities (Rm, Rmc and Rxo) with the true resistivity of the undisturbed formation (Rt). The standard unit of measurement of resistivity used in well logging is ohm.metre^2/metre. Commonly this unit is expressed in the simpler form of ohmmetres.

  It is possible to make correction for these effects or to minimize their importance by forcing the electric current deeper into the formation. Older logging tools (e.g., 16-inch or "short" normal) achieved greater depth of investigation by increasing the spacing between electrodes. This led to longer tool length and loss of vertical bed definition. Modern resistivity tools (e.g., Laterologs, Spherically-Focused Log) achieve deeper investigation by means of a "focused beam" without excessive electrode spacing.

  Even focused tools are affected by the mud and filtrate. If the resistivity of the mud is much greater than that of the formation water, e.g., the mud is less saline, these effects will be too great and the tools will be unreliable. If the mud is nonconductive (for example, an oil-based mud; see Appendix C), no conductive path will exist into the formation and the tools cannot be used.

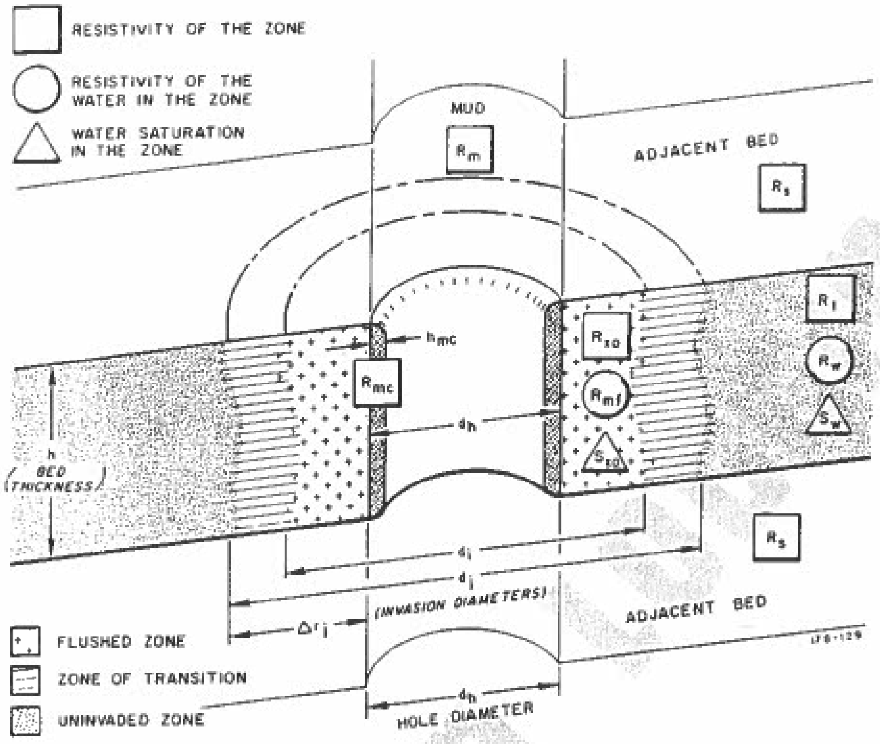

Figure 5-29. Symbols Used in Wireline Log Interpretation

- Micro-Resistivity Measurements. These tools (Micro Laterolog, Proximity Log, Micro-SFL) are direct resistivity devices which are run with the tool forced against the borehole wall and are referred to as "pad" tools. Being adjacent to the borehole wall and having only a very shallow depth of investigation, these tools measure the resistivity of the invaded zone (Ri) with some slight effect from mud cake resistivity (Rmc), and approximate the resistivity of the flushed zone (Rxo).

  It is sometimes the practice to leave these tools turned on when going into the hole, with the pad retracted. This gives a reading of mud resistivity (Rm) in the hole and may confusingly be referred to as a "mud log."

- Induction Measurements. In this type of tool an alternating electric current is passed through transmitter coils. This induces secondary eddy currents to flow in the formation which in turn induces signals in the receiver coils. The receiver coil current is proportional to the conductivity of the formation. Since the tool is investigating the formation's ability to conduct an electric current rather than to resist one, it is the convention to scale the log in conductivity, the standard unit in well logging being millimho/metre (i.e, 1000/ohmmetre), thus avoiding the almost continuous use of fractional numbers.

Induction logs are focused and have deep investigation and so give a good estimate of true formation resistivity (Rt). There is, however, some interference caused by eddy currents in the mud and invaded zone. These tools therefore work best in nonconductive (e.g., oil-based) muds, and work worst where the mud is more conductive (e.g., saline) than the formation water. This is the opposite of the Laterolog response. Thus, the two logs will work best at opposite extremes of logging conditions. Under many common logging conditions (of mud and formation water salinity), both logs may be applicable but the results may require some correction.

Combinations of direct resistivity and induction (conductivity) devices with varying depths of investigation are commonly run together. Comparison of the various signals can yield informaion about invasion profiles, diameter of invasion, better values of Rt (true formation resistivity), and ratios of Rxo/Rt for water saturation determination.

- Spontaneous Potential (SP). This is the measurement of the electrical potential between a point in the borehole and a grounded electrode at the surface. This potential is caused by electromotive forces in porous and permeable formations which are of electrochemical and electrokinetic origins. Where formations are impermeable no potential will exist, and a baseline will be developed which is commonly referred to as a "shale baseline." Any deviation from this baseline will be an indication of the presence of permeability. In fact, there is a slight potential adjacent to shales due to the migration of sodium ions, but this is constant and is ignored.

  Where a porous and permeable zone is invaded by mud filtrate, ions migrate between the mud filtrate and formation water when there are differences in salinity. There is also a flow of positive ions from the formation water to the adjacent shale due to the inherent negative charge of the shale particles. These two electrochemical actions form in essence a battery, causing a potential to be developed which is measured as a small voltage in the borehole.

  Since mud and formation water have similar electrolytes (predominately sodium chloride), it can be said that SP deflection is dependent on permeability and relative salinities of mud filtrate and formation water. This is shown in Figure 5-30 in which each of the sand stringers have equal permeability. Stringers A and B deflect the SP to the left in proportion to the salinity. Stringer C gives no deflection since no ionic migration is taking place. Stringers D and E deflect to the left in proportion to their salinity although, since the ratio is now inverted, their deflection is not so great as that seen in A and B (e.g., 5/2 is greater than 2/5).

  The SP can be used to detect permeable beds, define bed boundaries, determine formation water resistivity (and hence salinity), and give qualitative indications of shaliness in sandstones. Although rarely used quantitatively, the SP gives an excellent, easily read correlation log with good bed definition. The deflections, when caused by thin sands of

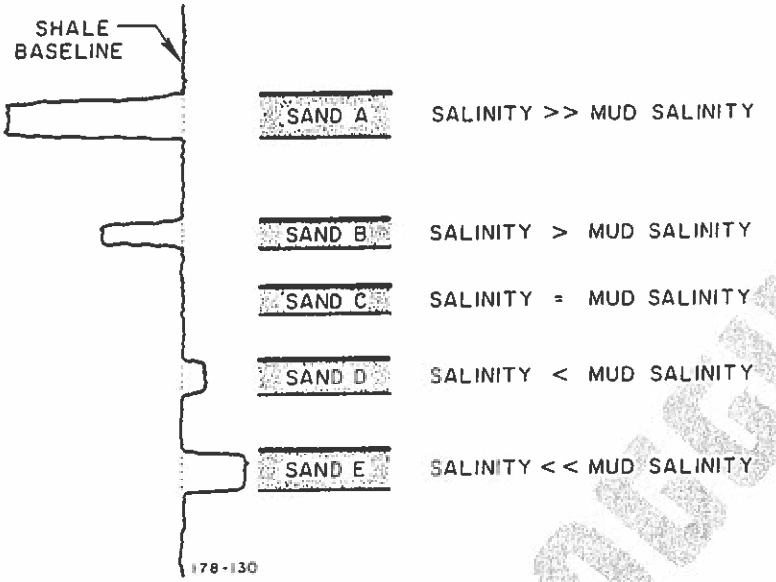

Figure 5-30. The Effect of Salinity on SP Response

varying shaliness in a massive shale section, give good correlation with drilling breaks and can be a useful aid to the geologist. Note that Figure 5-30 is for demonstration only; salinities do not normally change this rapidly within a section.

5.60 Porosity/Lithology: The tools used for these measurements are discussed below.

- Sonic. This tool measures the time required for a sound pulse to travel a fixed distance between a transmitter and receiver. The tool is centered in the borehole and uses multiple transmitters and receivers to remove the effects of travel through mud and mud cake. In this way, only the time taken to pass through a fixed length of formation is recorded (Interval Transit Time, microseconds/ft).

  Transit time (the reciprocal of velocity) is directly related to porosity in a known rock matrix. Charts or computer programs can be used to carry out this conversion. Because interstitial clay has an interval transit time similar to that of formation water, the sonic response to clay-filled porosity is the same as if the pore space contained all water. Therefore, porosities derived from the sonic in a porous sandstone with some clay filling will be optimistic compared to the effective liquid-filled porosity of that same sandstone.

  Gas in the mud, unconsolidated formations, formation fractures, gas saturation in a porous reservoir rock, aerated muds and highly rugose holes will tend to attenuate the sonic signal and cause "cycle skipping." Because of the multiple transmitters and receivers and centralization of the tool in the borehole, hole irregularities and sonde tilt have little effect on the sonic signal.

- Formation Density. This is a pad tool containing a high-energy gamma-ray source. The gamma rays "collide" with electrons, lose energy and are detected at the tool. The degree of scattering of gamma rays is proportional to the electron density and hence to the bulk density of the formation (gm/cc):

$$\rho_b = \phi\rho_f + (1 - \phi)\rho_m$$

where

ρ_b = bulk density
ρ_f = fluid density
ρ_m = matrix density
ϕ = porosity

hence

$$\phi = \frac{\rho_m - \rho_b}{\rho_m - \rho_f}$$

The porosity may be calculated if the rock matrix is known. Since the tool has a very shallow depth of investigation, the fluid is assumed to be mud filtrate with a density of 1.0 (fresh) or 1.1 (salt).

The presence of a mixed matrix leads to possible errors in the assumption of matrix density. Low-density interstitial clays will especially result in overestimates of porosity. By filling the pore space, the clay reduces the volume of liquid-filled porosity — but its low density decreases the bulk density of the rock, indicating that a portion of that porosity remains. In this instance, i.e. the clay has a lower density than the matrix but higher than the fulid, the porosity shown by the tool will be higher than the actual liquid-filled volume in the rock but lower than the total pore volume (the total void space between the matrix grains). If the void space is filled with interstitial material having a density similar to that of the matrix, the tool will indicate a correct value of liquid-filled porosity, although this will be less than the total void space in the rock. Similarly, the presence of gas in the pore space, with a density much lower than that assumed, will produce a slightly optimistic apparent porosity.

- Neutron. This tool, which may be a pad-type or centralized, bombards the formation with high-energy neutrons. These neutrons rebound from heavy nucleii with high energy but lose energy when colliding with light hydrogen nucleii. Low-energy neutrons are detected at the tool. Capture rate is proportional to the hydrogen content of the formation, i.e., the water and hydrocarbons contained in porosity. The log is normally calibrated in limestone porosity units (i.e. porosity (%) in an assumed limestone matrix). Conversion charts are used to determine actual porosity in other rock types. On more recent logs, the log may be rescaled for the matrix types of major interest in the section being logged.

Clay contains bound or interlayer water which, when interstitial clay is present in a reservoir, contributes to the hydrogen index of the formation, while the clay reduces the porosity. Interstitial clay in a formation will therefore result in an optimistic apparent porosity. Gas which has a lower hydrogen index than water or oil gives a lower neutron response and hence pessimistic apparent porosity.

Although the direct response of the porosity tools may be misleading, each of the tools responds differently in different lithologies and to the presence of interstitial clay and gas. For this reason it is possible to crossplot the various results to assist in the determination of the composition of mixed lithologies, clay content, gas, and true porosity.

- Gamma Ray. A scintillation detector measures the natural radiation of the formation. Since shale contains potassium which has radioactive isotopes, it establishes a relatively consistent maximum. Normal sandstones and carbonates have little or no radioactivity and therefore will be offset. Micaceous or argillaceous sandstones or carbonates show an intermediate response. Gamma ray is therefore a useful tool for correlation and a quick assessment of potential payzones. Certain evaporites (e.g., sylvite) have high radioactivity but can usually be discriminated from shales by their much higher density.

5.61 Production Characteristics: There are various logs which can determine the fluid type production rate, productivity and current status of a reservoir. They will not be studied here.

5.62 Miscellaneous Parameters: These parameters are related to the physical characteristics of the hole. Hole size, shape and deviation can be measured using the following tools:

- Caliper. This measures hole diameter and is useful for sidewall sample selection and calculating cement volume. It will indicate permeable formations by reduced diameter due to filter cake development. The caliper can read borehole diameters ranging from 5 to 20 inches.

- Borehole Geometry Tool (BGT). This records hole deviation, azimuth and relative bearing. Two calipers measure hole volumes in cubic feet. It can measure an opening that ranges from 5 to 40 inches, and is useful to detect eccentricity and calculate cement volumes.

- High-Resolution Dipmeter Tool (HDT). There are four pads, each of which has micro-resistivity electrodes. Depth differences between signals give angle and direction of formation dip. Also, there are two calipers measuring two diameters in two vertical planes 90° apart. It records deviation, azimuth, relative bearing, and (consequently) hole deviation (inclination and direction). All data is sent uphole on FM mode and appears on film and tape. Interpretation is carried out with the help of computers.

5.63 Interpretation

The analysis of wireline log data depends upon one fundamental assumption which is that the only conductive medium present in the formation is water in the pore space, and that matrix material and hydrocarbons are essentially nonconductive. Hence the electrical conductivity (or resistivity) of the formation will be a function of:

- Porosity – the percentage of bulk volume available for fluid.
- Water saturation – the percentage of pore volume filled with water. The remainder will be filled with oil and/or gas. Empty porosity does not exist!
- Salinity – assuming the only electrolyte present is NaC1, the resistivity can be directly converted to salinity.
- Temperature
- Shape, size and communication of the pore spaces

It can therefore be said that the resistivity (Ro) of a porous and permeable rock material which is 100 percent saturated with an aqueous solution is directly proportional to the resistivity of that solution (Rw). Thus

$$\frac{Ro}{Rw} = \frac{Ro'}{Rw'} = \frac{Ro''}{Rw''}, \text{ etc.}, = F$$

where Ro, Ro', Ro" are the resistivities of a formation (at constant temperature) when flushed with various aqueous solutions of resistivities Rw, Rw', Rw". The constant of proportionality, F, is called the Formation Factor and is a function of porosity, permeability, and the shape, size and distribution of the pore spaces. Archie (1942) proposed the relationship

$$F = \frac{a}{\phi^m}$$

where m is the "cementation factor," a function of the type and degree of consolidation of the rock. The constant "a" is empirically derived and varies from section to section.

The Humble Formula proposed by Winsauer et al (1952) provides general values which are suitable in most rocks:

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

For ease of calculation it is common to use a value of 2 for cementation factor. Satisfactory results can then be obtained with

$F = \frac{.81}{\phi^2}$ in clastic formations (e.g., sandstones)

$F = \frac{1}{\phi^2}$ in consolidated formations (e.g., carbonates and indurated sandstones)

Although departing at extremes, all three formulae give very similar results in the commonly encountered porosity range.

Since oil and gas are nonconductive, the Ro/Rw relationship can be modified as follows:

$$\frac{Ro}{Rw} = \frac{Rt}{Rw}(Sw)^n = \frac{Rxo}{Rmf}(Sxo)^n = F$$

where n is the "saturation exponent" and is generally taken to equal 2 (see Figure 5-29 for other nomenclature).

In a clean formation (i.e., none shaley) with regularly distributed porosity and where porosity, (Rt Laterolog or Induction), Rxo (Micro-Laterolog), Rmf (from a surface filtrate measurement) and temperature (from a maximum reading thermometer on the tool) are known, these formulae can be used to determine:

- Hydrocarbons in place (1 - Sw)
- Mobility of hydrocarbons (Sxo - Sw)
- Salinity of the pore water (from Rw and temperature)

In more complex reservoirs, some corrections are required and more complicated mathematics, sometimes using a computer. The same basic principles are nevertheless used.

5.64 Abnormal Pressure Evaluation

Formations exhibiting high pressures at a particular depth are zones of abnormally high porosity. It is possible, therefore, to plot parameters which are a function of porosity and observe the deviation from the normal trend. Thus, plots of shale acoustic transit time, bulk density, neutron response and resistivity-versus-depth should deviate from the normal trend when abnormally high-pressure zones are encountered.

These methods are practiced by Exploration Logging and are explained in detail in the Pressure Log manual (MS-156).

5.65 FORMATION TESTS

Formation testing is a direct means of obtaining information concerning the liquids and pressures in a formation open to a borehole. The traditional method of achieving this is by way of a temporary completion with a drillstem test (DST). For an outline of Exploration Logging's role in drillstem testing, refer to Appendix E.

5.66 DRILLSTEM TESTING

A drillstem test is made by lowering a valve, a packer, and a length of perforated tailpipe on the end of the drillpipe to the level of the formation. The packer is set against the wall of the borehole so that it seals off the test interval from the mud column above. The valve is then opened. This procedure effectively reduces the

"Schmitt, Dennis A" <DSchmitt@CHEVRONTEXACO.COM> 4/29/03
The Humble formula is a variation of the basic F =a/(phit**m)
a and m are set to certain values. If you are a practitioner of the
Pickett plot, you might set 'a' to 1 and vary m for your sands.
A good practice is to gather SCAL (special core analysis) data from Core
to get measured values of a, m, & n. The Humble was developed for Gulf of
Mexico wells, but did not work for all areas.

Soft Formations
F =a /phit ^ m
Humble F =0.62 /phit ^ 2.15
Trixier F =0.81 /phit ^ 2
Hard Formations
F =1 /phit ^ m
Shell m =1.87 + 0.019 /phit
where phit < 9%

Here are some estimates of 'm' used by various people.

Estimated	**m' values**
Uncemented sands	<1.4
Very slightly cemented	1.4-1.6
Slightly cemented	1.6-1.8
Moderately cemented	1.8-2.0
Highly cemented sands	>2.0
Carbonates	>2.0
Completely unconsolidated	1.3-1.4
Slightly consolidated	1.4-1.6
Moderately consolidated	1.6-1.8
Consolidated	1.8-2.2
Highly cemented (consolidated)	2.2-2.6
Average Gulf Coast	1.8 or Humble
Gulf Coast Wilcox Sand	2.1
Gulf Coast Miocene Sand	1.5
Consolidated Carbonates	2.2
Reef Carbonates	2.4
Fractures	approaches 1

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https://www.emnrd.nm.gov/ocd/contact-us

State of New Mexico
Energy, Minerals and Natural Resources
Oil Conservation Division
1220 S. St Francis Dr.
Santa Fe, NM 87505

CONDITIONS

Action 534547

CONDITIONS

Operator: NEW MEXICO ENERGY MINERALS & NATURAL RESOURCE 1220 S St Francis Dr Santa Fe , NM 87504	OGRID: 264235
	Action Number: 534547
	Action Type: [IM-SD] Admin Order Support Doc (ENG) (IM-AAO)

CONDITIONS

Created By	Condition	Condition Date
pgoetze	None	12/12/2025