APPLICATIONS OF ESTIMATED FORMATION WATER RESISTIVITIES TO BRINE STRATIGRAPHY IN THE KANSAS SUBSURFACE

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Introduction

Formation water chemistry has wide applications in both hydrogeology and petroleum geology so that subsurface brine databases are widely available across the U.S. and elsewhere. In Kansas, the brine data have been made available on the Kansas Geological Survey website. Typically, these measurements include ion contents of sodium, calcium, magnesium, chloride, sulfate, and bicarbonate, as well as pH, specific gravity, and water resistivity.

The inclusion of water resistivity provides a characteristic that can also be estimated from wireline log combinations of porosity and resistivity. Formation water resistivity (Rw) is controlled by temperature and ionic composition. However, if standardized to a constant temperature, Rw, is primarily a measure of total dissolved solids, with dominance by sodium chloride below the shallow subsurface. In cases where the formation water resistivity is not available, it can be estimated very closely by a simple algorithm from the brine composition.

Although numerous, the geographic distribution of these data is markedly uneven, with a tendency to concentrate in areas of historically high production but with sparse control in peripheral regions (see Figure 1). Consequently, systematic patterns from regional mapping of formation brine geochemistry are often localized with speculative extrapolations elsewhere.. The increasing availability of digital well log files on the Kansas Geological Survey website gives the immediate opportunity to augment brine analyses with estimations of formation water resistivities (and implied salinities) in wells from areas that lack adequate sampling of brines. Because well control with resistivity and porosity logs vastly exceeds wells with brine samples, the mapping of brine anomalies could be refined and extended through strategic digitizing of additional logs.

The creation of a "brine stratigraphy" is an important product of log estimations of apparent water resistivity (Rwa) from resistivity and porosity logs. By contrast, a brine analysis at any location is representative of a restricted interval and has no information

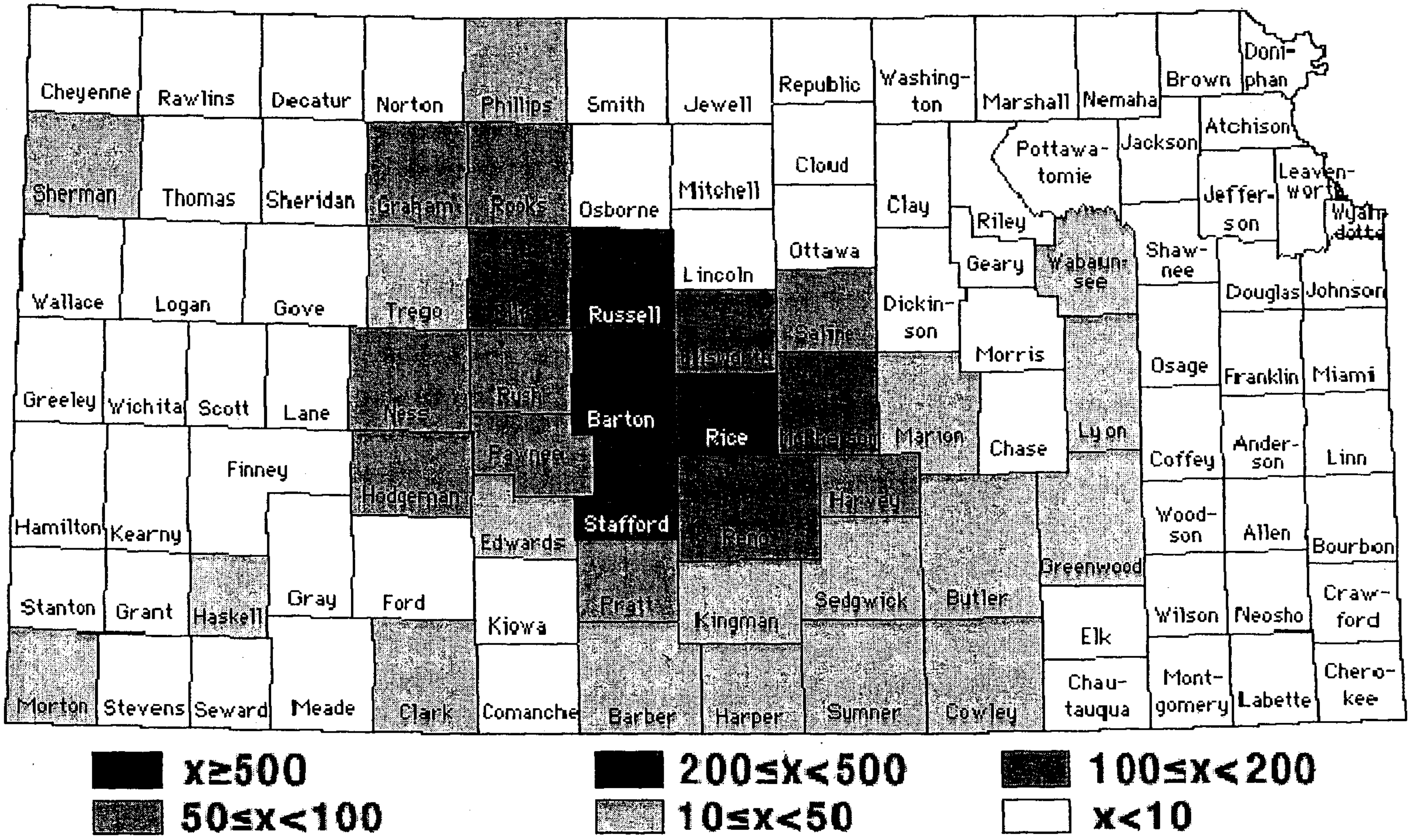


Figure 1. Distribution of brine data analyses in Kansas on the KGS website database c. 2002 (Courtesy Dana Adkins-Heljeson)

on potential variability with depth. The combination of brine stratigraphic patterns with brine lateral variability can be used to address questions of regional flow paths, compartmentalization, recharge and other aspects of interest in energy exploration and production.

The Kansas Brine Database: measured and estimated formation water resistivities

For many years, the Kansas Brine Database was maintained as a hardcopy list of 3785 samples, before being made available as searchable digits on the Kansas Geological Survey website. While chemical composition was available on most of these records, measurements of water resistivity were restricted to 1473 samples. However, the formation water resistivity, Rw, at 75°F (24°C) can be estimated from salinity in ppm equivalent NaCl, c, using the approximate formula:

$$R_{w75} \approx 0.0123 + \frac{3647.5}{C^{0.955}}$$

When compositions are reported in terms of ppm "chlorides" (from titration test) the figure should first be converted to equivalent ppm NaCl:

$$c = 1.65 * \text{chloride ppm}$$

Most natural waters contain other ions in addition to sodium and chloride. The most common (and significant) ions are:

the cations:

sodium	Na^+
calcium	Ca^{++}
magnesium	Mg^{++}

and the anions:

chloride	Cl^-
bicarbonate	HCO_3^{--}
sulfate	SO_4^{--}

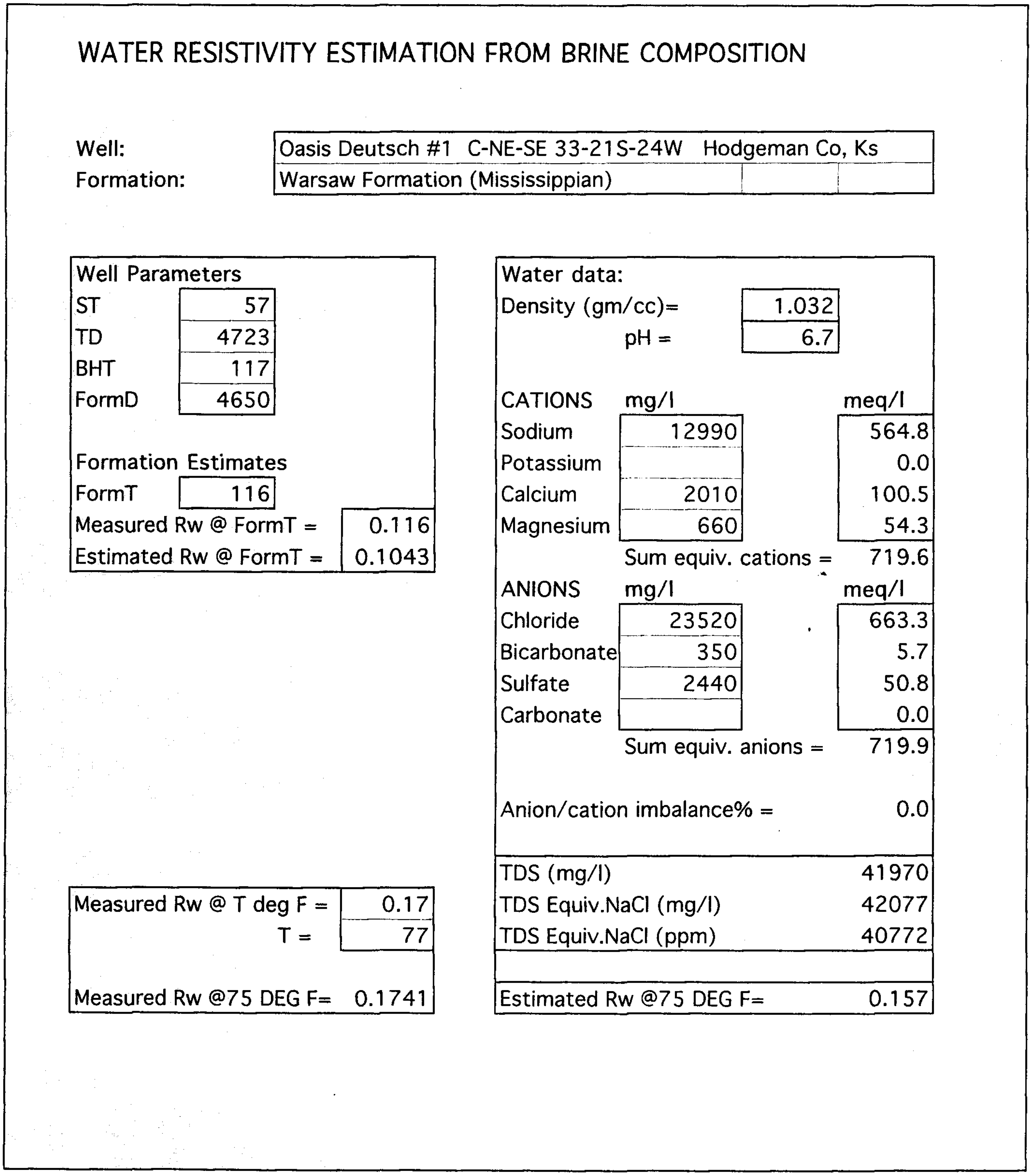
Brine data reported on measurements of ionic composition in mg/l can be used to estimate formation water resistivity by the following procedure.

(i) Convert the concentration of each ion from mg/l to meq/l by dividing each ion's concentration in mg/l by its equivalent weight in g/mol, where the equivalent weight of each ion is given by the molecular weight of the ion divided by its valency.

(ii) Sum the cations and anions separately to see if the milliequivalent subtotals are approximately equal. If there is a significant imbalance, then there is a problem with the data.
(iii) The concentrations of the ions in mg/l sums to TDS (the total dissolved solids). The equivalent TDS for the brine if it had only sodium and chloride ions is computed from adding the sum of the cations multiplied by the molecular weight of sodium and the sum of the anions multiplied by the molecular weight of chlorine. The result is divided by the density of the brine in g/cc to give the TDS sodium chloride equivalent in units of ppm.
(iv) The equation listed at the top of the page can then be used to estimate the formation water resistivity at 75 deg F (24 deg C).

The procedure is best coded as a spreadsheet template for use with brine compositional data. An example is shown on Figure 2, using a brine composition analysis from the Warsaw Formation in southern Kansas, where the estimated value of 0.157 ohm-m shows a reasonable match with the measured value of 0.174 ohm-m (both at 75 degrees Fahrenheit).

A comparison between estimations of water resistivity and actual measurements for 1104 Kansas brine samples (both corrected to an equivalent 75 degree Fahrenheit temperature) showed a remarkably good degree of correlation (Figure 3). Consequently, the estimation can be extended to the entire database with a high degree of confidence and used in conjunction with formation water resistivities estimated from logs.



WATER RESISTIVITY ESTIMATION FROM BRINE COMPOSITION

Well:	Oasis Deutsch #1 C-NE-SE 33-21S-24W Hodgeman Co, Ks
Formation:	Warsaw Formation (Mississippian)

Well Parameters	
ST	57
TD	4723
BHT	117
FormD	4650

Formation Estimates	
FormT	116
Measured Rw @ FormT =	0.116
Estimated Rw @ FormT =	0.1043

Measured Rw @ T deg F =	0.17
T =	77
Measured Rw @75 DEG F=	0.1741

Water data:

Density (gm/cc)=	1.032
pH =	6.7

CATIONS	mg/l	meq/l
Sodium	12990	564.8
Potassium		0.0
Calcium	2010	100.5
Magnesium	660	54.3
	Sum equiv. cations =	719.6
ANIONS	**mg/l**	**meq/l**
Chloride	23520	663.3
Bicarbonate	350	5.7
Sulfate	2440	50.8
Carbonate		0.0
	Sum equiv. anions =	719.9
Anion/cation imbalance% =		0.0

TDS (mg/l)	41970
TDS Equiv.NaCl (mg/l)	42077
TDS Equiv.NaCl (ppm)	40772
Estimated Rw @75 DEG F=	0.157

Figure 2: Excel spreadsheet template for use with brine compositional data. In the example a brine composition analysis from the Warsaw Formation in southern Kansas is used, resulting in an estimated value of 0.157 ohm-m as contrasted with the measured value of 0.174 ohm-m (both at 75 degrees Fahrenheit).

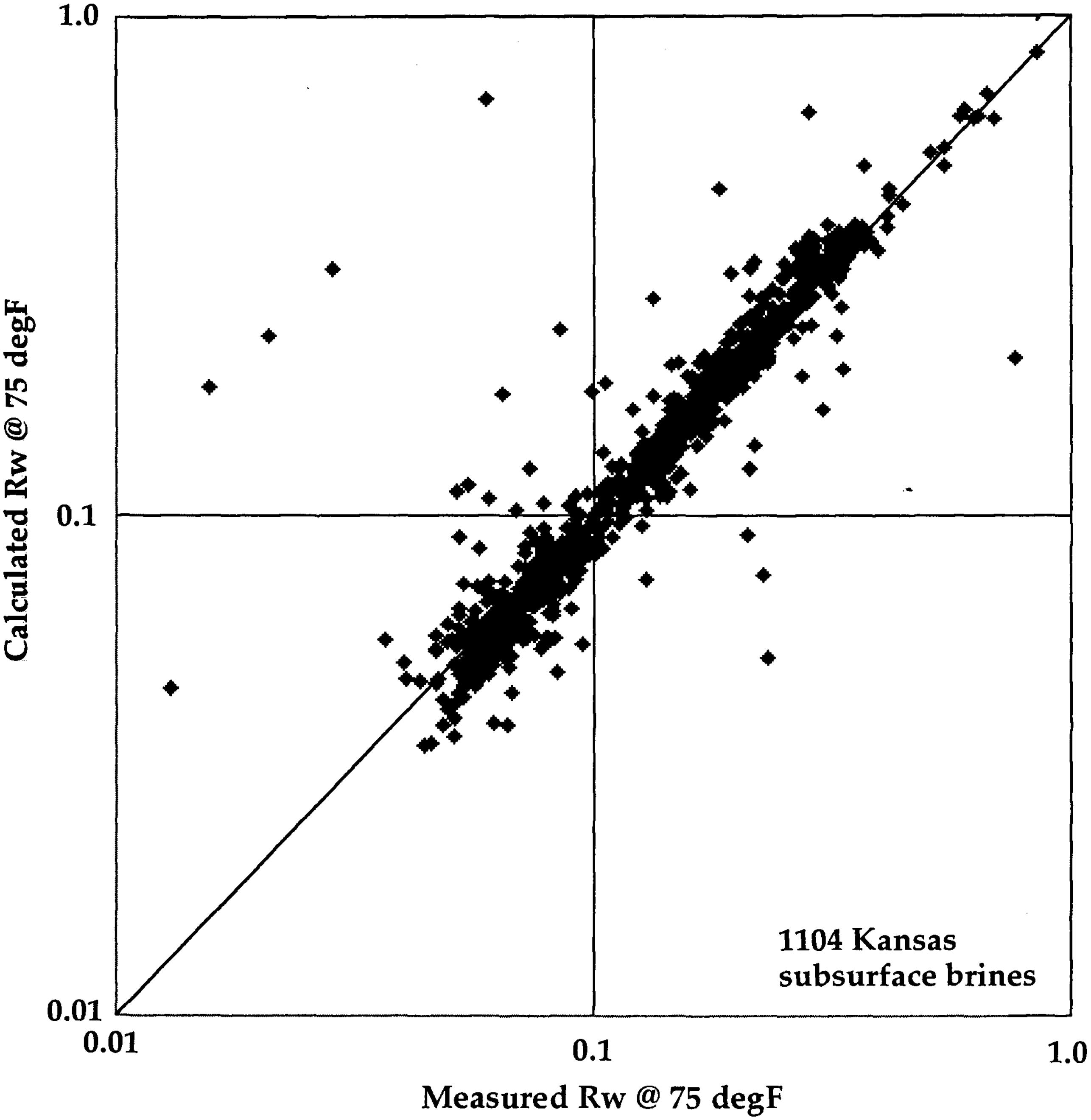


Figure 3: A comparison between estimations of water resistivity and actual measurements for 1104 Kansas brine samples (both corrected to an equivalent 75 degree Fahrenheit temperature)

Logging estimates of formation water resistivity

There are three common methods to estimate formation water resistivity from wireline logs:

1. the SP log
2. the reconnaissance water resistivity (Rwa) method, that applies the Archie equation and
3. the ratio water resistivity (Rwr) method that uses the contrast of the resistivity of the formation with the flushed zone.

The methodologies are described briefly below and compared in the context of a real example, using logs from MLP Koenig #1-28 (28-29S-34W) over a short section of Pennsylvanian limestones overlying an incised-valley Chester Sandstone that has cut into Mississippian limestones.

1. The spontaneous potential (SP) log method (Rwsp)

The magnitude of the electrochemical potential is a function of the chemical activities of the formation water (aw) and the mud filtrate (amf) :

$$E = -K.\log(aw/amf)$$

where K is a factor which is a function of temperature. The chemical activity of a single-salt solution is inversely proportional to the salt concentration. The salt concentration is inversely related with the solution resistivity. If mud filtrate and formation waters may be approximated by pure sodium chloride solutions, the equation becomes:

$$E = -K.\log(Rmf/Rw)$$

where E is the displacement between the "shale line" and "sandstone line" on the SP log measured in millivolts (see Figure 4), Rmf is the mud filtrate resistivity and Rw the formation water resistivity. The magnitude of the shift is a function of the resistivity contrast between the mud filtrate and the formation water and gives a method to estimate the formation water resistivity. Unfortunately, the simple equation is true for single-salt solutions and either empirical charts or equations must be applied as correctives for multiple ionic formation waters. The algorithm can be coded in an Excel spreadsheet as shown in Figure 5, where the analysis of the SP log in Koenig #1-24 gives an estimated formation water resistivity of 0.0522 ohm-m at formation temperature.

The SP method works well for sandstone-shale sequences, but results can be highly variable in carbonates, probably because of a combination of greater invasion depths and higher resistivities of low-porosity carbonates. So, while the method has been used successfully in evaluating water quality in the Dakota Sandstone aquifer of Kansas, water resistivity estimations can often be problematic in the long Paleozoic carbonate sections that typify the Kansas subsurface.

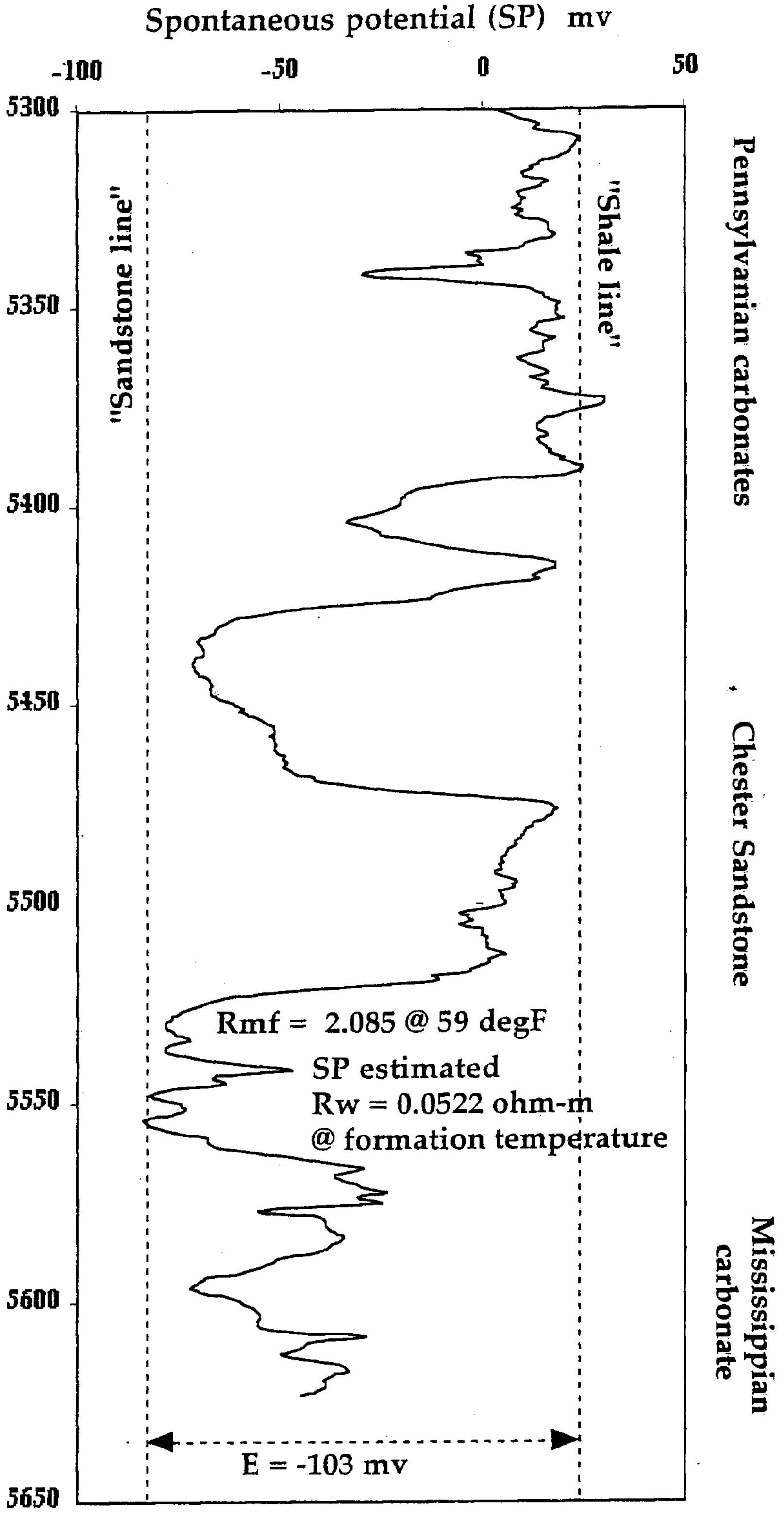
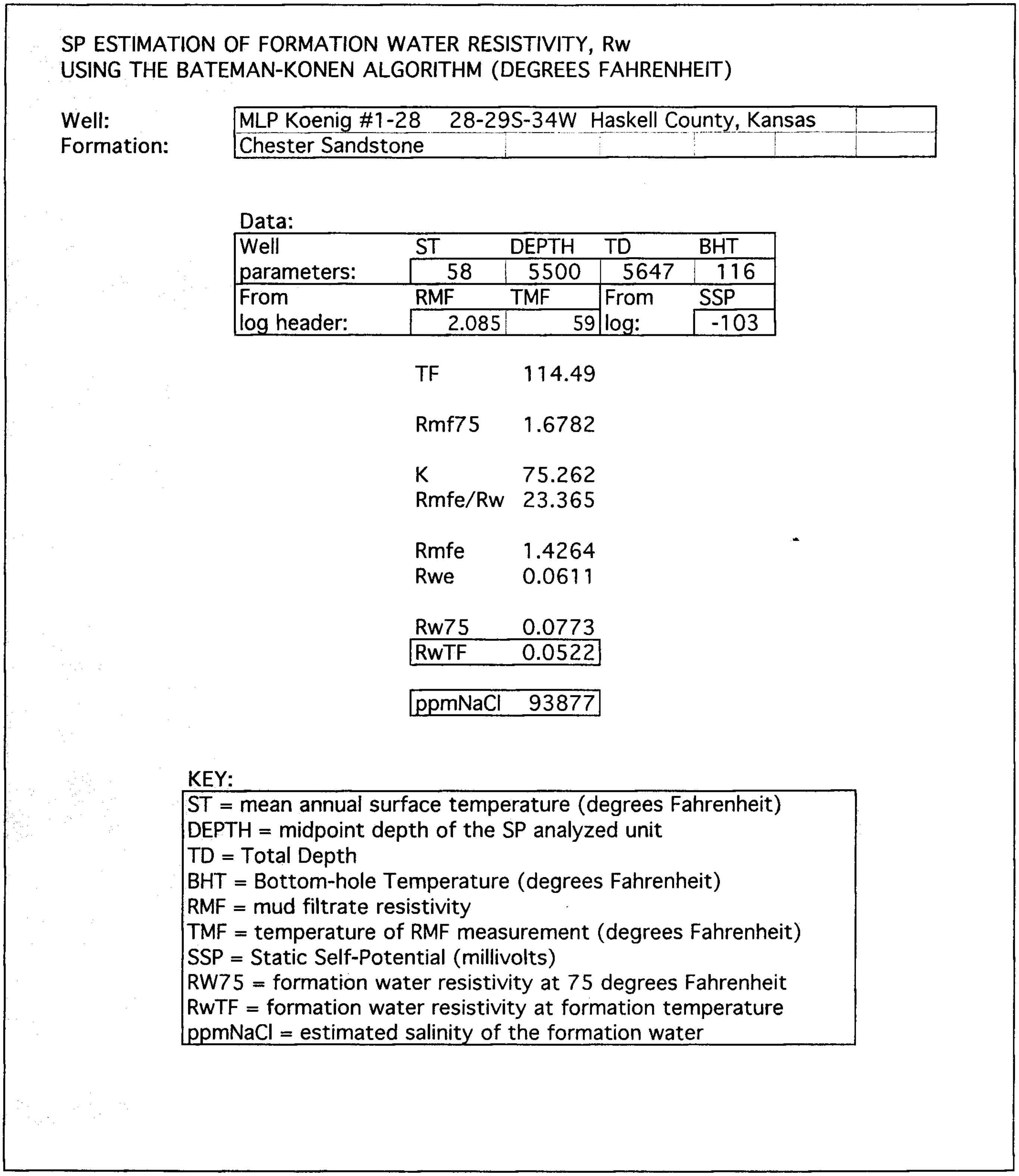


Figure 4: Spontaneous potential (SP) log of Pennsylvanian/Mississipian section in the Koenig #1-24 well, marked with sandstone and shale baselines and annotated with numbers used in the estimation of the formation water resistivity.



SP ESTIMATION OF FORMATION WATER RESISTIVITY, Rw
USING THE BATEMAN-KONEN ALGORITHM (DEGREES FAHRENHEIT)

Well:	MLP Koenig #1-28 28-29S-34W Haskell County, Kansas
Formation:	Chester Sandstone

Data:

Well	ST	DEPTH	TD	BHT
parameters:	58	5500	5647	116
From	RMF	TMF	From	SSP
log header:	2.085	59	log:	-103

TF	114.49
Rmf75	1.6782
K	75.262
Rmfe/Rw	23.365
Rmfe	1.4264
Rwe	0.0611
Rw75	0.0773
RwTF	0.0522
ppmNaCl	93877

KEY:

ST = mean annual surface temperature (degrees Fahrenheit)
DEPTH = midpoint depth of the SP analyzed unit
TD = Total Depth
BHT = Bottom-hole Temperature (degrees Fahrenheit)
RMF = mud filtrate resistivity
TMF = temperature of RMF measurement (degrees Fahrenheit)
SSP = Static Self-Potential (millivolts)
RW75 = formation water resistivity at 75 degrees Fahrenheit
RwTF = formation water resistivity at formation temperature
ppmNaCl = estimated salinity of the formation water

Figure 5: Algorithm for computation of water resistivity from the SP log coded in an Excel spreadsheet, where the analysis of the SP log in Koenig #1-24 gives an estimated formation water resistivity of 0.0522 ohm-m at formation temperature.

2. The "reconnaissance water resistivity" method (Rwa)

The Rwa method is widely used by log analysts to establish formation water resistivity from a porosity and deep resistivity measurement. Its formulation is a rewrite of the Archie equation. Now, $F = a/\Phi^m$ (Archie equation) and $F = R_o/R_w$ (by definition), where F is the formation factor, f is porosity, a is an empirical constant (but with a value of unity in a homogeneous petrofacies), m is the cementation exponent, and Ro is the resistivity of a rock completely saturated with formation water.

Therefore, $R_w = R_o\ \Phi^m/a$

By analogy, $R_{wa} = R_t\ \Phi^m/a$ where Rt is the actual value of formation resistivity.
For any zone: When $S_w = 1$, $R_{wa} = R_w$ otherwise, when $S_w < 1$, $R_{wa} > R_w$
If the Archie equation constants are known, R_{wa} values may be calculated from the resistivity and porosity log readings. Within any oil or gas reservoir section, these values will be high and will fluctuate in sympathy with variations in water saturation. In fully water-saturated zones, the values will tend to stabilize at a lower limiting value which corresponds to an estimate of the true formation water resistivity.

Examination of Figure 6 shows computed values of Rwa for the Koenig #1-24 using a generic value of cementation exponent (m) as 2, the constant a a value of unity. Zones with gamma ray values in excess of 50 API units were eliminated from the calculation as reflecting shales or shaly units. A minimum cut-off of 5% porosity was also applied, not only because low porosity values cause instability in Rwa estimation, but because the cementation values drop markedly below the value 2, probably as a result of the increased influence of fracture porosity at these low volumes. The array induction logs run in this well are particularly desirable because their two-foot resolution gives them vertical compatibility with the neutron and density porosity devices. The best estimate of Rw is in the lower Chester Sandstone where values are typically about 0.035 ohm-m. The discrepancy with the SP estimate of 0.05 ohm-m is caused by the Chester Sandstone cementation exponent of 1.8, rather than the generic value of 2 used in the estimation. With a corrected value for m, the Rwa values match the SP estimate in the water leg. Note how the Rwa values increase, moving upwards through the Chester Sandstone, in response to lower water saturations in the oil leg of this reservoir section. Values in the Pennsylvanian and Mississippian limestones conform approximately to an Rw of 0.05, although median filtering would probably be useful in stabilizing the greater variability.

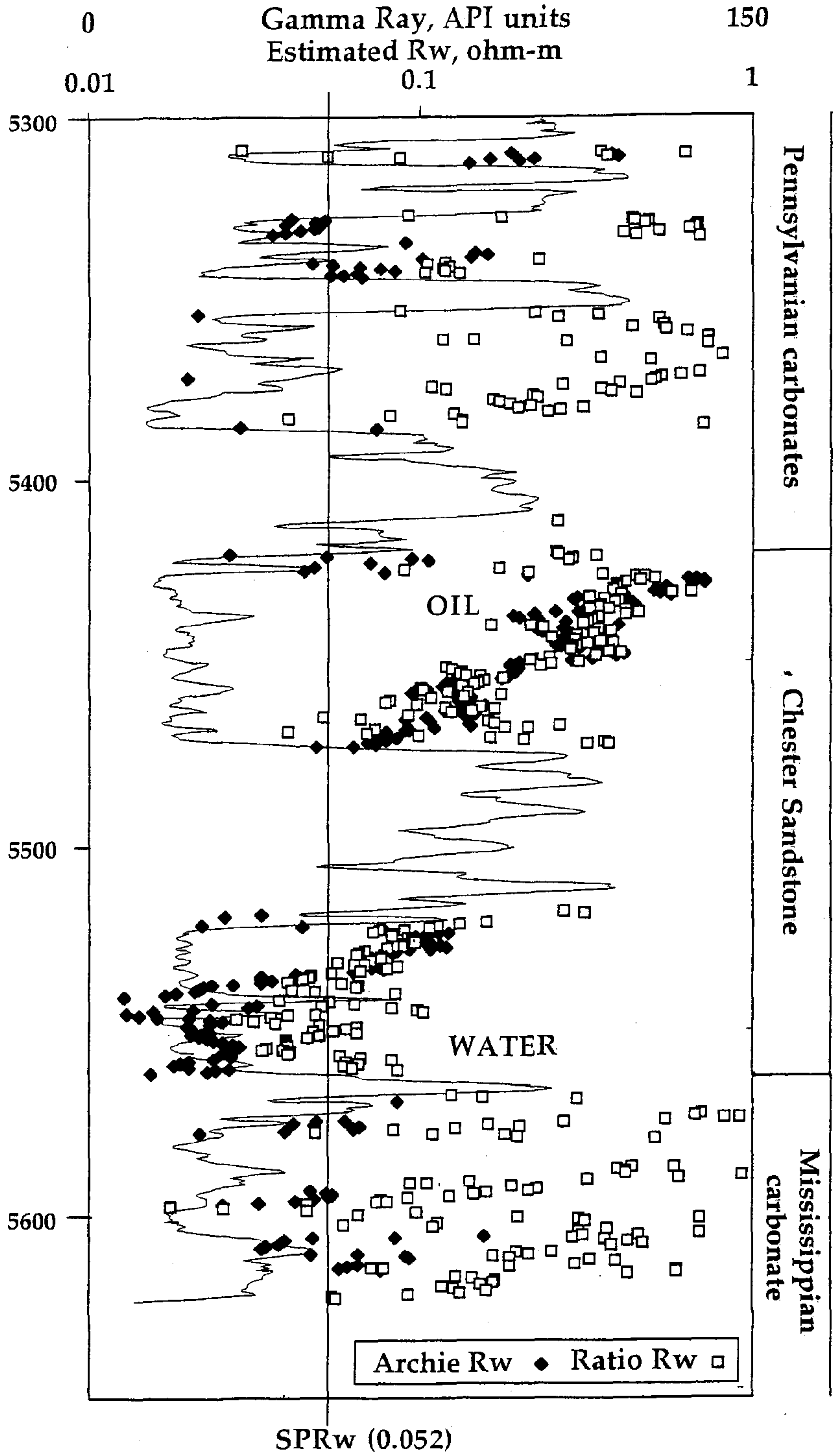


Figure 6: Comparison of formation water resistivity estimated by three different methods: SPRw (0.052) from the SP log, Archie equation reconnaissance water resitivity (Rwa) (black diamonds), and resistivity ratio Rwr (white squares) in the Koenig #1-24 well.

2. The "resistivity ratio" method (Rwr)

The formation factor F is defined as the ratio of the resistivity of a formation completely saturated with water (Ro) and the formation water resistivity (Rw). As an equation, this is simply written as: $F = R_o / R_w$. Now, the same relationship will apply in the "flushed zone" immediately behind the borehole wall where all the formation water has been replaced by mud filtrate. In this case, $F = R_{xo} / R_{mf}$ where Rxo is the resistivity of the flushed zone and Rmf is the resistivity of the mud filtrate. Because the mud filtrate resistivity is measured by the logging crew and recorded on the log header, together with its temperature of measurement, the two equations can be combined to estimate formation water resistivity as $Rwr = (Ro / Rxo).Rmf$. The value is a valid estimate of Rw in water saturated zones. In zones with partial saturations of oil or gas, the estimates will be higher and take values predicted from the Archie equation as: $Rwr = (Sxo / Sw)^2 (Ro / Rxo).Rmf$ where Sxo is the water saturation of the flushed zone and Sw is the water saturation of the uninvaded formation.

Notice on Figure 6 that the values of Rwr in the water leg of the Chester Sandstone of Koenig #1-24 conform quite closely with the water resistivity of 0.05 ohm-m. Also the values show a systematic increase above the water leg reflecting the decline in water saturation. However, in the Pennsylvanian and Mississippian carbonates, the Rwr estimates show a strong systematic bias to much higher values of water resistivity. This same characteristic is also shown when using the ratio method in carbonate sections of other Kansas wells. The excellent performance of the array induction tool within the Chester Sandstone suggests that this is not a logging measurement problem but a failure in the assumptions of the ratio method. The ratio method presumes that in fully water-saturated zones, the formation water is completely replaced by mud filtrate in the flushed zone. However, the flushed zone resistivities are markedly lower than would be expected if the pore space was completely filled with mud filtrate. A hypothesis that would explain the discrepancy is that the invasion process selectively floods more accessible fractions of the (often complex) carbonate pore system as it accommodates the mud filtrate. If true, then the flushed zone would contain both mud filtrate and formation water and consequent lower resistivity than the ratio method expectation. This invasion behavior would contrast with that expected for the simple granular framework of a sandstone, where almost all the pore space would be accessed by invading mud filtrate.

Application of log-estimated water resistivity profiling to brine stratigraphy

A comparison of the results of the three different approaches to estimate formation water resistivity from logs suggests that the reconnaissance water resistivity (Rwa) is the best procedure for the long carbonate-shale sequences that typify the Kansas subsurface. Water resistivities computed from the SP log are fairly reliable for sandstones, but can be anomalous for many carbonates. In addition, the establishment of the static self-potential (difference between sandstone and shale baselines) requires an interval, rather than the continuous estimation allowed by the resistivity methods (Rwa and Rwr). The resistivity ratio method of Rw estimation works well in sandstones but appears to be adversely affected by differential invasion within carbonates and so generates spuriously high apparent formation water resistivities.

The application of the reconnaissance water resistivity (Rwa) to carbonates draws on several criteria for optimum performance:

1. Vertical compatibility between resistivity and porosity measurements are preferable, so as to minimize artifacts caused by scaling differences. The two-foot array induction resistivity tool is probably the best choice available, because it conforms approximately with the vertical resolution of porosity tools.
2. Estimation of volumetric porosity is best made from the average of the neutron and density porosity measurements scaled to limestone porosity units to compensate for lithological variations caused by changes in limestone, dolomite, and chert composition. In addition, correction for small shale effects can be added by a simple procedure: first, the volume of shale (Vsh) can be estimated from the gamma-ray log by: Vsh = ((G-C)/(S-C) where G is the reading for the zone, C is the estimated value for a "clean" or shale-free zone, and S is the value considered to typify a gray shale. In this reconnaissance procedure, values of C = 10 and S = 110 have been found to be serviceable.
3. A gamma-ray shale cutoff should be applied to eliminate spurious Rw estimates generated in shales and shaly units. A gamma-ray value of 50 API units was selected as this shale cut-off value.
4. A porosity cut-off that eliminates low-porosity carbonates should be applied, both because of the instability of powering small fractional numbers in the estimation, but also because cementation exponents show a distinctive decline below the value of 2 that is probably attributable to increasing influence of fracture porosity. Experience

with both core measurements and log analyses of Pickett plots suggest that 5% porosity is an effective cut-off value.

5. Because the resistivity of a saline solution varies with temperature, the estimated values should be related to a constant (even if arbitrary) temperature. For whatever reason, 75 degrees Fahrenheit is the most commonly used temperature to report brine resistivity measurements and this standard is adopted here.
6. Oil and gas zones should be disregarded in salinity profile interpretations and will be associated with high values of Rwa.
7. A cementation exponent with a value of 2 has proven to be a robust value in carbonates dominated by interparticle (intercrystalline and/or intergranular) pore space. Zones with vuggy or oomoldic porosity will cause high apparent Rwa estimates; zones with a high degree of fracturing will suppress Rwa to lower values.
8. Even with the application of all these criteria, the variability in Rwa estimate values should be filtered in order to discriminate the potential architecture of a brine stratigraphy. Outlier values are likely to adversely affect averaging procedures, so that a median filter is better suited to isolating representative values that pick up trends and breaks in salinity profiles.

The Rwa estimation procedure was applied to gamma-ray, induction resistivity, density, and neutron porosity logs from Hallwood Petroleum Pyle #1 C-8-33S-R25W, downloaded as an LAS file from the KGS website. The section analyzed ranges from the Lecompton Limestone down to the Arbuckle, shown as a gamma-ray log with Rwa75 estimates filtered by a 40-foot median window (Figure 7). The salinity profile implied by the Rwa75 points has two major elements: a generalized baseline drift to lower values at greater depths reflecting higher dissolved solids, punctuated by intervals with excursions to higher Rwa75 values that may mark compartments with relatively fresher water. Potential brine stratigraphic units are particularly noticeable in the Mississippian section and is considered in more detail in the final example, where Rwa75 profiles are compared from three wells.

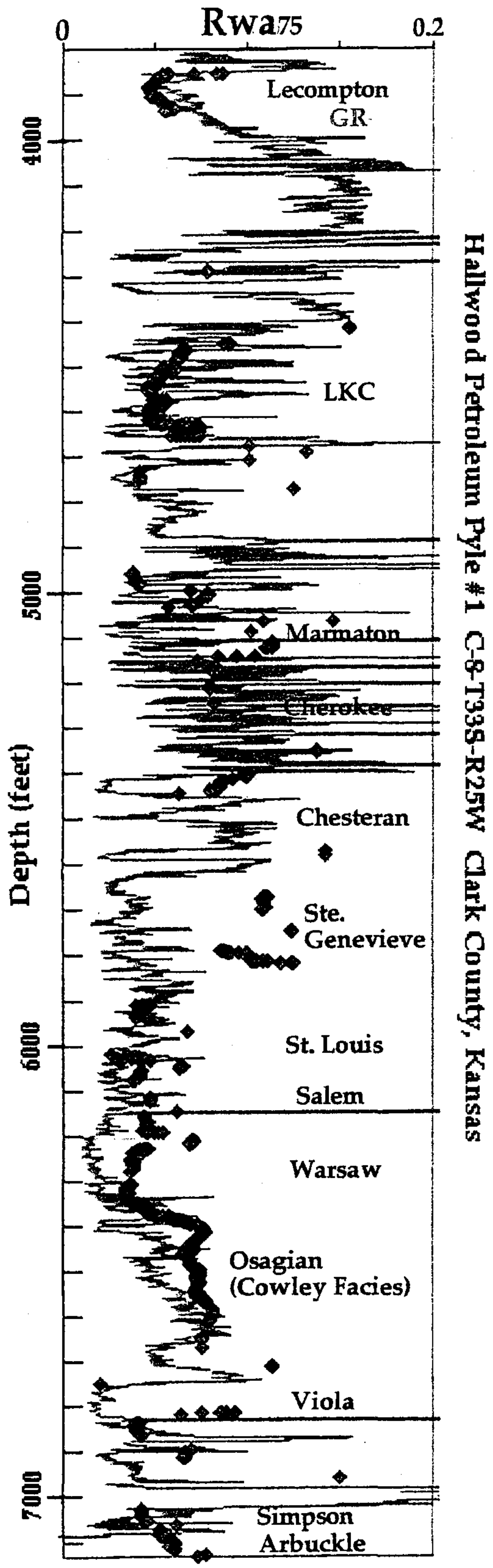


Figure 7: Gamma-ray log and Rwa75 profile in the Hallwood Petroleum Pyle #1 C-8-33S-R25W well, filtered by a 40-foot median window.

An exploratory study of apparent brine salinity variations in the Mississippian of Kansas

Exploratory studies that integrate log analysis with geological interpretation can now be achieved in a few hours using digital data from the KGS website, rather than several months when the information was available only from paper records. This case-study of the Mississippian brines provides a good illustration of this enhanced capability. The KGS database of brines was searched for all Missippian brine analyses. The data for 233 wells were downloaded and latitude, longitude, and Rwa75 values were copied into a Surface III file and mapped on a framework whose margins approximately match the boundaries of the state of Kansas (Figure 8). The overall decline to lower values in formation water resistivity to the south are matched by corresponding increases in depth and higher dissolved solids. The higher resistivity values to the east are close to the outcrop and, to the west, there is a lobe of higher values that may be associated with the movement of relatively fresher water.

Two additional LAS files of logging data were downloaded from wells with an extensive length of section for comparison with the Mississippian section of Pyle #1, analyzed previously (Figure 7). The Rwa75 profiles are shown on a logarithmic scale (Figure 9) and without median filtering so that the raw variability can be assessed by eye. The three wells are located on an approximate east-west line so that correlations and trends have implications in both depth and geography. While there appear to be some brine stratigraphic features of bounding surfaces that subdivide compartments of different salinity brines, there also appear to be lateral patterns such as a distinctive westerly drift to lower Rwa75 values in the Warsaw that may be linked with hydrodynamic movements.

Figure 8: Rwa75 values recorded in 233 wells from the KGS website database of all Missippian brine analyses mapped on latitude-longitude grid whose margins approximately match the boundaries of the state of Kansas.

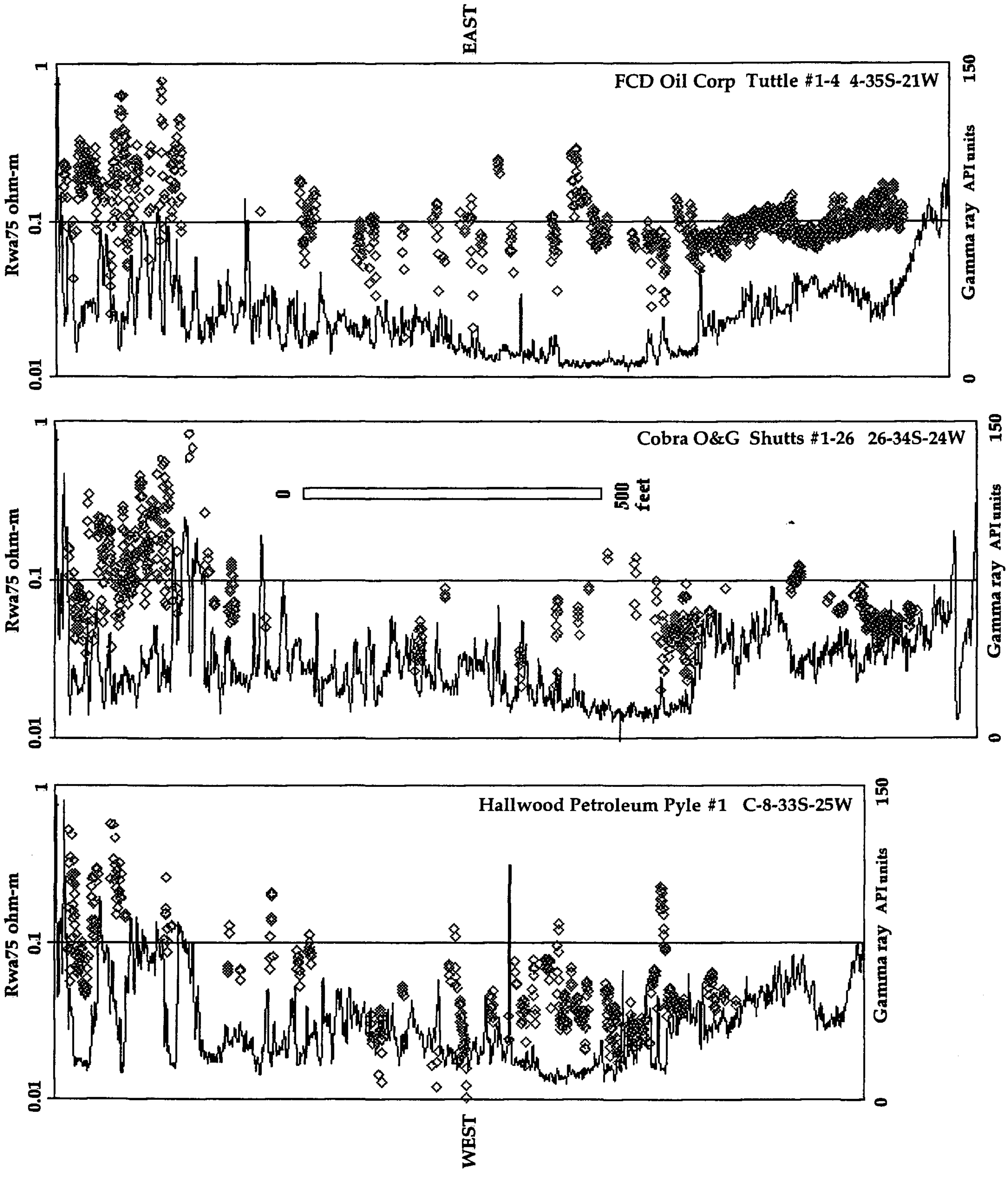


Figure 9: Gamma-ray logs and Rwa75 profiles for Mississippian sections from three wells in southern Kansas.

Conclusions

The purpose of this openfile report is to outline and demonstrate methods of water resistivity estimations from wireline logs which have immediate implications of brine salinity that can be coupled with a conventional brine database. There are two major advantages of such an integration. First, the ability to augment brine sample well control for improved mapping in sparsely sampled areas. Secondly, an ability to examine potential changes in water salinity with depth, both in the recognition of a "brine stratigraphy" of confined water units with contrasting salinities and to trace lateral changes within communicating units as indications of hydrodynamic flow.