

## TECHNICAL NOTE

### The Bateman-Konen Resistivity-Salinity Transform

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#### INTRODUCTION

With the introduction of time-lapse resistivity modeling it became necessary to describe the salinity of the aqueous fluids surrounding a borehole as a function of time to model the displacement of interstitial brine with its concomitant salinity by mud filtrate with a generally different salinity. Salinity modeling is not an end in itself but is the first step in describing a time-dependent radial resistivity function for use in modeling the responses of resistivity logging instruments as the resistivity profile continually changes radially with time. The pioneering work in this technique was by Yao and Holditch (1996), and Zhang et al. (1999). This technique has since been raised to a high state of development by Professor Carlos Torres-Verdin and his students at the University of Texas (e.g., Salazar et al., 2006; Moinfar et al., 2010). Although the change in salinity, modeled as a change in sodium chloride concentration in parts per million (by mass) of the aqueous solution, is analytically described by a fractional fluid flow model, implemented by finite-difference modeling, the conversion from salinity to resistivity is by means of a formula, to date attributed to Bigelow, 1992 (Fig. 3-36, page 111) or the earlier version published under the auspices of Dresser Atlas (1982)<sup>2</sup> (Fig. 3.1, page 16), or in the case of Yao and Holditch (1996), without a citation. One purpose of this article is to rectify this lapse in proper scholarship and recognize the original source of the salinity-resistivity-temperature transform as Bateman and Konen (1977).

This note has two purposes, the first is to attribute the formula to its proper inventors, Professor Richard Bateman and Charles Konen; the second objective is to explain the provenance of such a weird-looking formula.

According to Bateman and Konen (1977), if  $C$  is NaCl (i.e., sodium chloride) concentration in parts per million and  $R_{75^\circ F}$  is the brine resistivity at 75°F, then

$$R_{75^\circ F} = 0.0123 + \frac{3647.5}{C^{0.955}} \quad (1)$$

Resistivities are extended to other temperatures by means of Arps (1953) approximating formula. The Bateman-Konen formula is also used in its alter-ego forms for estimating NaCl concentrations given resistivity, namely

$$C = \left( \frac{3647.5}{R_{75^\circ F} - 0.0123} \right)^{\frac{1}{0.955}} \quad (2)$$

and

$$C = 10^{\frac{1}{0.955} \log \frac{3647.5}{R_{75^\circ F} - 0.0123}} \quad (3)$$

The Bateman and Konen paper does not discuss the method that led them to their resistivity-concentration formula; they mention the formula almost as an afterthought (Bateman and Konen, 1977). Their method was to fit a function to the resistivity-concentration pairs at 75°F read from the 1972 Schlumberger Chartbook Chart Gen 9 (personal communication, Richard Bateman, 2013).

#### BATEMAN-KONEN FORMULA PROVENANCE

Petrophysicists are familiar with the power law given by Archie's formula  $F = \phi^{-m}$  relating formation resistivity factor to porosity. It is a power law with  $-m$  giving the slope of the line representing the function when it is plotted on log-log paper, and  $a$  giving the intercept of the line with the porosity = 1.0 axis. When plotted on log-log paper the function is always a straight line regardless of the values chosen for  $m$  and  $a$ . The linear characteristic is a limitation if the trend represented in the data appears to require a curved line for a best fit. When the curvature is required on the left (low porosity) side of the function "variable  $m$ " techniques are employed to accommodate the curvature.

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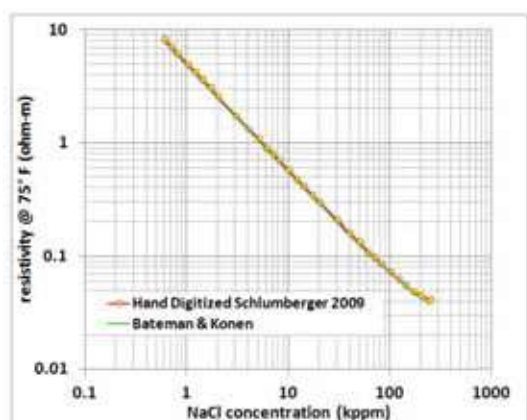
<sup>2</sup> Charles Konen had moved his employment to Dresser Atlas and contributed to the publication of the 1982 *Introduction to Wireline Log Analysis* volume.

<sup>3</sup> The numerology of this formula is too interesting to pass over without comment: beginning with the count 0123 and then continuing with 3 blank 4 blank 5 with the blanks being filled with 6 and 7; how fortuitous is that! So, although arcane, the function is easily memorized.

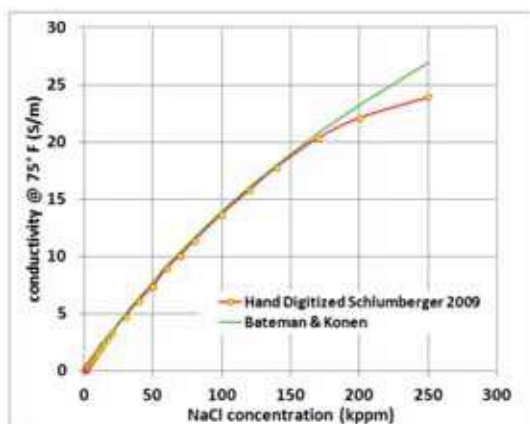
Although it is unnecessary for formation resistivity factor–porosity functions to curve on the right side of the function (the high porosity side), if such curvature were needed, the appropriate modification of the power law would be  $F = b + a/\phi^m$ . The inclusion of the additive  $b$  term permits a power law to curve up or down on the right side of the independent variable axis.

Figure 1 plots resistivity vs. NaCl concentration at 75°F as read from the Schlumberger resistivity-temperature-salinity chart (yellow-filled dots). Note the slight upturn of the function in the lower right quadrant. The green curve is the Bateman and Konen approximating function. Note that the approximation tends to follow the upward trend; this is the effect of the 0.0123 factor.

Although it is customary to present resistivity data in logarithmic format (because of the four-decade range of resistivity in sedimentary rocks), this format tends to conceal variations at higher resistivities. These variations are better viewed as conductivity plotted against concentration (Fig. 2).



**Fig. 1**—Comparison of the data digitized from the Schlumberger Chart Book and the Bateman-Konen function that approximates the data plotted as is conventional on log-log scales.



**Fig. 2**—Comparison of the data digitized from the Schlumberger Chart Book and the Bateman-Konen function that approximates the data plotted on a linear grid. On linear scales a departure of the approximation from the data at high salinity is easily seen.

In linear format it is clear that the Bateman-Konen approximation departs to some degree at both the low and high concentration ends of the concentration domain, but it is a time-tested and adequate approximation for most purposes.

Hopefully, in the future, authors using this resistivity-concentration relationship will properly cite the original source publication, Bateman and Konen (1977).

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