A reader's commentary on

Landmark Papers in Well Logging and Formation Evaluation

Stephen Prensky, Editor

*(Petrophysics, 2017, (**58**)3, June, Society of Petrophysicists and Well Log Analysts, pp.302-313.)*

As noted in the Introduction of the paper, the effort to pick the "landmark" or the most significant papers in petrophysics was a multi-year multi-person effort, the result of which yielded nineteen papers that the committee felt made significant and lasting contributions to the science (and art) of petrophysics. In the Prensky publication, the papers are divided into two groups; *Well Logging*, which is about the hardware making the measurements and the principles that underlie the operation of the hardware, and *Petrophysics and Formation Evaluation*, which is about the interpretation of those measurements.

The papers are presented in two separate tables, and in alphabetical order by author in each table. In the body of the paper, the papers are presented in a single author-alphabetical list. From the orders of the papers, the question then arises; "In what order should the papers be read to gain the maximum understanding from each?"

This reader's answer to that question begins with a single list of papers, arranged in that "most beneficial" order, with font color based on the location of each paper in the *Well Logging* or the *Petrophysics and Formation Evaluation* list:

Author(s)	*Contribution*
Archie (1942)	Foundation of Petrophysics - ("Archie's (saturation) Equation")
Archie (1950)	Extends method of reservoir evaluation
Doll (1949)	Principle of induction resistivity logging
Duesterhoeft (1961)	Physical principles behind induction resistivity logging
Anderson (1986)	Discussed the use of modeling to solve unexplained log interpretation problems
Doll (1951)	Principle of laterolog resistivity logging
Allen et al (1967)	Basis of dual detector neutron porosity log
Wyllie et al (1956)	Acoustic porosity log interpretation ("Wyllie Time-Average equation")
Tittman and Wahl (1965)	Principles of the bulk density log
Pickett (1973)	Resistivity-porosity crossplot log interpretation method ("Pickett plot")
Waxman and Smits (1968)	Basis for modern shaly sandstone analysis ("Waxman-Smits equation")
Clavier et al (1984)	Dual-water method of shaly sandstone evaluation ("Dual Water Model")
Thomas and Steiber (1975)	Methodology for evaluation of thinly bedded shaly sandstones
Klein et al (1997)	Resistivity and permeability anisotropy
Zemanek et al (1969)	Acoustic borehole imaging
Ekstrom et al (1987)	Microresistivity borehole imaging
Timur (1968)	Permeability estimation on core samples
Luffel and Guidry (1992)	Basis for shale and tight sandstone laboratory analysis
Miller et al (1990)	Modern pulsed-NMR logging

As can be seen from the list above, the papers are generally in order from oldest to youngest (with some exceptions in grouping by the targets of some measurements).

While the presentation of measurements by historical occurrence is common in petrophysics books and training courses, it is, in this reader's experience and view, not the most effective way to learn about the measurements and the petrophysical interpretive process. As an example, beginning a course with resistivity before the class has covered types of porosity, and volumes and types of fluids present in the porosity may lead to confusion, because formation bulk resistivity, the measured quantity, depends on the presence and amounts of porosity and fluids.

While in a classroom or book it seems more efficient and leading toward better understanding to present the measurements in the context of a generic workflow, with measurements arranged by workflow steps and not by the underlying physics, addressing the underlying papers seems to call for another approach.

The general approach in addressing the progression of the measurements and their interpretation seems to work best in the historical flow (with some digression by measurement or measurement targets) to keep the reader in the context of the technology available at the time of publication, and helps answer the question, “Why did the author do it that way?”

Some examples:

- When Archie published his 1942 paper and presented his saturation equation, induction and laterologs had not been invented, so the determination of formation resistivity contained quite a bit of art as well as science. Also, no logging measurements of porosity existed, (although there were hints mentioned in Archie’s paper that the neutron log was somehow affected by porosity).
- The 1956 paper by Wyllie *et al* took a measurement originally designed for seismic survey calibration to a measurement from which porosity could be determined, with parameters dependent on lithology and fluid content, and which eliminated the requirement for porosity measurements on physical rock samples.
- Pickett’s 1973 paper was written in the era before the wide existence of computers and calculators, so a graphical (“pattern recognition”) method to determine water saturation without having to resort to slide rules or nomographs created substantial advancements in computation time and detail.

In conclusion, this reader is not presuming that the list shown here is the only way, or even the “best” way, to gain insight into the art and science of petrophysics, but only one of many possible approaches to understand the technology and the interpretations which arise from the indirect measurements of formation quantities of interest. The best sequence of readings probably varies by individual, with everyone’s order dependent on their expertise, experience, and interest in petrophysics.

Landmark Papers in Well Logging and Formation Evaluation

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*(Reformatted by Daniel Krygowski from Petrophysics, 2017, (**58**)3, June, Society of Petrophysicists and Well Log Analysts, pp.302-313.)*

Introduction

As part of AAPG's 100th anniversary, which was recently celebrated at the 2017 AAPG Annual Conference in Houston, SPWLA members participated in a project to identify the top ten 'landmark' papers in the various disciplines related to petroleum exploration. This was a multiyear volunteer effort to identify papers that represent paradigm shifts in how exploration has been conducted. One of the primary objectives of this project was to provide young professionals with ready-made lists of essential papers that they should familiarize themselves with as part of their professional training and growth. The results of this effort are reprinted here for the benefit of SPWLA members.

The Well Logging and Formation Evaluation subcommittee was formed in 2012 and chaired by Stephen Prensky. The committee comprised an international group of recognized experts in logging and FE and all long-time members of SPWLA: Richard Bateman, Robert Cluff, Dr. John Doveton, Mauro Gonfalini, Dr. Teruhiko "Terry" Hagiwara, David Kennedy, Pat Lasswell, Dr. Don Oliver, Philippe Theys, Dr. E.C. Thomas, and Dr. Paul Worthington. Sadly, two members of the subcommittee, Mauro Gonfalini and Robert Cluff, passed away before the project was completed.

The subcommittee was presented with several large spreadsheets containing potential candidate papers that were compiled from various published sources, such as topical review papers, society review reprint volumes and specialized bibliographies, as well as personal favorites of subcommittee members. Candidate papers included advancements in technology, interpretation methods, and application in both exploration and production. Over five years (2012-2016) several rounds of reviews were conducted to refine the list to a manageable number of papers. Once this was achieved, comments about each paper were added by the subcommittee members. A list of finalists was arrived at by committee vote and citations for each paper were prepared. These citations, which are printed below, address the following criteria:

- What is the most significant contribution made by this paper?
- What is the evidence this contribution has made a lasting impact?
- How did this contribution change the way we think or do geoscience?
- How broad is the application of this contribution, i.e., does it have global application?
- Did this paper make a paradigm change? If so what was it?

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The Papers

Landmark Papers in Well Logging (primarily hardware development)	
Author(s)	*Contribution*
Tittman and Wahl (1965)	Principles of the bulk density log
Allen et al (1967)	Basis of dual detector neutron porosity log
Doll (1949)	Principle of induction resistivity logging
Duesterhoeft (1961)	Physical principles behind induction resistivity logging
Doll (1951)	Principle of laterolog resistivity logging
Anderson (1986)	Discussed the use of modeling to solve unexplained log interpretation problems
Zemanek et al (1969)	Acoustic borehole imaging
Ekstrom et al (1987)	Microresistivity borehole imaging
Miller et al (1990)	Modern pulsed-NMR logging

Landmark Papers in Petrophysics and Formation Evaluation (primarily interpretation methods)	
Author(s)	*Contribution*
Archie (1942)	Foundation of Petrophysics - ("Archie's (saturation) Equation")
Archie (1950)	Extends method of reservoir evaluation
Wyllie et al (1956)	Acoustic porosity log interpretation ("Wyllie Time-Average equation")
Pickett (1973)	Resistivity-porosity crossplot log interpretation method ("Pickett plot")
Waxman and Smits (1968)	Basis for modern shaly sandstone analysis ("Waxman-Smits equation")
Clavier et al (1984)	Dual-water method of shaly sandstone evaluation ("Dual Water Model")
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Klein et al (1997)	Resistivity and permeability anisotropy
Timur (1968)	Permeability estimation on core samples
Luffel and Guidry (1992)	Basis for shale and tight sandstone laboratory analysis

Paper Citations

Allen, L.S., Tittle, C.W., Mills, W.R., and Caldwell, R.L., 1967, Dual-Spaced Neutron Logging for Porosity, Geophysics, 22(1), 60-68.

Prepared by Dr. Don Oliver

The primary contribution of this paper was to show that a two-detector neutron-logging tool could be developed that was sensitive to formation porosity and less sensitive to borehole and salinity effects than previous neutron logging tools. The authors found that placing the neutron detectors at sufficiently long spacing, using high-intensity neutron sources, and using the ratio of the counting rates obtained at the two detector locations would allow the logging instrument to have good precision for formation porosity measurement, and minimum effects from other, adverse influences, such as borehole salinity, mudcake, washouts, etc. This led to the widespread application of two-detector neutron logging tools for measuring formation porosity. The authors used one- and two-group neutron diffusion theory to calculate the response of a two-detector neutron tool. This is Jlso a significant contribution as diffusion theory has been used for many years to calculate compensated neutron log responses in the borehole/formation environment.

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This work is considered to be a seminal work for dual-detector neutron logging. Today, all logging companies provide two-detector neutron logging services (commonly called compensated neutron logs) and the tool is one of the most important tools for the measurement of formation porosity. There are literally thousands of compensated neutron instruments in the industry and most are designed as described in this paper. This paper has been cited many times through the years, and books and training courses commonly include a review of the concepts and illustrations presented in the original paper.

This paper showed that a dual-detector neutron logging tool could be used for a quantitative measurement of formation porosity. Combined with other logging tools, such as formation density, the tool could be used to calculate formation lithology and identify gas bearing zones.

These tools are used in most logging provinces in the world. They are almost always included in any logging run. The tools are not only used in wireline logging but tools with very similar configurations are also used in logging-while-drilling.

Prior to the development of two-detector neutron logging tools the neutron log was considered to be principally qualitative. With the development and understanding of two-detector tools provided by this paper the compensated neutron tool became an important instrument for measuring formation porosity.

Anderson, B., 1986, The Analysis of Some Unsolved Induction Interpretation Problems Using Computer Modeling, The Log Analyst, 27(5), 60-73.

Prepared by David Kennedy/Dr. Teruhiko Hagiwara

Early "electrical survey" logs exemplified by short normal, long normal, and long lateral arrays were plagued by various eccentricities in their responses, including borehole and thin-bed effects. The apparent-resistivity response of the deep-sensing long lateral array is asymmetric and continually varying across an ideal thick bed of constant resistivity. Thus, the wiggles visible on the recorded responses could be more reflective of the instrument impulse responses than of the resistivity variation in the formation. Corrections to the logs recorded in the field were effected by laborious application of "departure curves", but the departure curves were designed by the analytic solution of boundary value problems in geometries of unrealistically high symmetry; other departure curves were created using analog computer resistor networks. There was no practical method for correcting conventional electrical survey logs for complicated formation resistivity distributions. Early in the 1950s H.G. Doll introduced two types of "focused" resistivity logs: the laterolog and the induction log. The apparent-resistivity responses of these instruments were designed to be symmetric in symmetric beds, with the apparent resistivity being approximately equal to the formation resistivity in thick-enough formations. In the evolution of the induction log, a 1957 publication proclaimed, "The induction log accordingly gives the value of R without correction" (Dumanoir et al., 1957, Transactions' AIME). Although this statement was properly qualified in the paper, it entered the logging lexicon as "for induction logs, Ra = Rt." Of course, this was never true, but for thick-enough beds in conductive-enough rocks and in vertical boreholes, it was approximately true, and came to be universally believed. However, in cases where resistivities are high, where beds are thin and laminated with conductive shales, and where boreholes are deviated, apparent resistivities depart significantly from formation resistivities. In the decades following the 1950s, electronic computers were becoming increasingly capable, common, and affordable to large companies. In the late 1970s mathematical analysis of resistivity instrument responses began to appear in the technical literature, and with increasing frequency into the 1980s.

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In the early l980s, some oil companies and service companies started modeling resistivity log responses using computer models to characterize logging tool responses as well as to help log interpretation by analyzing the modeled tool responses. Barbara Anderson is one of the early investigators of resistivity log modeling. In this paper, she discussed induction log response to thinly laminated sand/shale formation, the shoulder-bed effect in dipping formations, and a case study of anomalous induction log response that may be attributed to a nearby conductive anomaly. The paper illustrates how mathematical modeling of tool responses could be useful to understand subsurface formation and improve formation evaluation, particularly in explaining anomalous responses that could not be explained by the standard models.

This landmark paper was quickly followed by many others, e.g., Anderson and Barber (1988) "Strange Induction Logs," that led to the understanding of induction log responses that had been misunderstood or unexplained for the previous three decades. Moreover, while the 6FF40 array remained the industry standard, commercially available induction log modeling programs became de rigueur. Although the introduction of proprietary array induction tools put an end to routine resistivity modeling for formation evaluation, such modeling is still available through university consortiums, and is still used to better understand log responses of the array induction (and other) logs.

Prior to the introduction of the numerical modeling of log responses in general, and resistivity log responses in particular, logs displayed many features that went unexplained. Paradoxically, other features of logs that at the time were considered to be well understood turned out to be due to different causes than had been believed. The modem response to unexplained log responses is "let us numerically model this strange response to see if we can understand the cause."

Resistivity log modeling has been used to understand anomalous (or "strange") resistivity logs of all vintages, recorded on all continents beneath all oceans. Resistivity modeling is "global" not only in the geographic sense of the word, but also in the sense of its being extended to the modeling of all logging instrument responses.

The paper was a harbinger of modem interpretation methods that rely heavily on computers for viewing field logs, computing derived logs, and tool response modeling as an adjunct to standard interpretation methods. The paper was not the cause of the shift in paradigm, but rather heralded that a shift was about to begin.

The use of computer modeling to analyze logging tool responses was the paradigm change already underway during early 1980s. Barbara Anderson was one of leading figures in that effort. This paper documented some results of this paradigm change. The "parallel conductance model" of thinly bedded formation that was the result of modeling induction log response in thinly bedded formations discussed in the first part of this paper, had been already in practice in Shell Oil Company and US patent 4,739,255 had been filed earlier. The "macroscopic anisotropy model" had been also developed to analyze dipping thinly bedded formations in the mid-1980s using computer modeling of tool response in deviated boreholes. The more prominent dip effect had been identified for higher frequency induction-type (propagation) LWD resistivity tools as the polarization-horn effect at bed boundaries and was explained by computer modeling, though this paper did not address in the second section. However, this paper provided a good example of using computer modeling to understand some anomalous log data in the third section. This paper showed that computer modeling was not only useful for tool developers in an oilfield service company to characterize tool responses but also for petrophysicists and log analysts to use to understand log data and to help improve formation evaluation.

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Doll, H.G., 1949, Introduction to Induction Logging and Application to Logging of Wells Drilled with Oil Base Mud, Paper SPE-949148-G, Journal of Petroleum Technology, 1(6), 148-162.

Prepared by David Kennedy

Resistivity logging was invented in 1927. The first instruments were passive galvanic arrays that measured varying potential drops in the borehole due to various geometrical arrangements of current electrodes injecting and returning current as the electrode array was pulled up the wellbore. The resulting log responses were asymmetric even in symmetric formations, and in randomly varying formations could be interpreted only qualitatively. In 1941, G.E. Archie's invention of a method of quantitatively interpreting resistivity logs provided an impetus to produce resistivity instruments capable of producing more interpretable responses. However, the development of new logging technology remained in limbo for five years while World War II was fought and won, but within the four years following victory in 1945, H.G. Doll invented the two principal resistivity logging technologies that remain the cornerstone of resistivity logging to ·this day. The first introduced was the induction logging instrument. The response of this instrument was symmetric in symmetric formations, did not depend upon conductive mud in the borehole to couple its transmitter signals to the conductive formation, and seemed to promise a means to improve both vertical and radial resolution of the instrument response by judicious design of its antenna array. This inaugural model for the induction instrument established that the response can be modeled as the convolution of the formation conductivity with a geometrical factor, a model that remains in use, with refinement, to this day. From the late 1950s, induction logging, continually-if episodically-refined, became the principal technology used for resistivity logging.

Since the early 1960s, induction logging instrument technology been the principal means of estimating formation resistivity in formations with resistivities less than 100 to 500 ohmm, comprising (as a guess) at least two thirds of all resistivity logs that have ever been, and are being, run.

The introduction of this technology was the first step on the journey that has led inexorably, if slowly, to the state-of-the-art that is enjoyed today. Although induction logging antennas are mere coils of wire, the elaboration of the technology had to wait upon the invention of transistors and integrated circuits, computer hardware and software, telemetry and materials science, and accurate modeling of formation resistivity as a biaxial, second order tensor. In the 1950s, it was widely believed in the logging community that all formations of interest were isotropic, if not necessarily homogenous and infinite; the modem view, engendered by having to explain induction log responses, is that most formations are anisotropic and heterogeneous. This change in thinking was thrust upon us by induction log responses.

4. How broad is the application of this contribution (Does it have global application?)

It is safe to say that on any given day, and possibly at any given hour, an induction log is being run somewhere on planet earth. They have sampled formation resistivity on every continent, and beneath every ocean, for 65 years.

The induction instrument technology introduced in this paper is the poster child for paradigm shifting in technology. In 1949, when the paper appeared, the only logging technologies available were the so-called "conventional electrical survey" comprising electrode arrays called "normals" and "laterals"; by the 1970s it was hard to find any conventional electrical survey hardware left in field locations. In 20 years the preferred technology changed entirely.

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Doll, H.G., 1951, The Laterolog: A New Resistivity Logging Method with Electrodes Using an Automatic Focusing System, Paper SPE-95130-G, Journal of Petroleum Technology, 3(11), 305-316.

Prepared by Dr. Teruhiko Hagiwara

The induction log, which was introduced earlier by Doll, is a conductivity log that measures formation conductivity and works well for highly resistive, i.e., oil-based mud systems and low formation resistivity (high conductivity). However, the induction log is not suited for conductive mud and high-resistivity formations. Galvanic resistivity tools, e.g., normal and lateral logs, had been used for such formations, but mudcake and mud-filtrate invasion caused significant problems for reading formation resistivity. Because of their asymmetric electrode configuration, the interpretation of log response was very difficult. Doll introduced the laterolog galvanic resistivity tool that works better in high-resistivity formations with conductive mud. The tool achieves its deep depth of investigation by focusing currents into highly resistive formation using auto-controlled guard electrodes.

The laterolog is the tool of choice in most carbonate reservoirs with high formation resistivity and water-based mud. The dual laterolog is commonly used to better profile mud-filtrate invasion into the formation. Recently, array laterologs have been developed for improved invasion profiling.

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The laterolog made resistivity well logging possible in highly resistive formation and very conductive mud without being impeded by mudcake and near-borehole effects.

Duesterhoeft, William C., 1961, Propagation Effects in Induction Logging, Geophysics, 26(2), 192-204.

Prepared by David Kennedy

Prior to the Duesterhoeft paper the only treatment of induction log response characteristics had been H.G. Doll's inaugural introduction to the technology in 1949. The theory included in the Doll paper turned out to be valid only for very low frequencies or very low conductivities; consequently, there was no recognition in the Doll theory of the existence of skin effect, borehole effects, or shoulder-bed effects. In the Doll approximation, every formation element contributed to the total response only according to its location with respect to the receiver coil and its conductivity. Duesterhoeft's paper was first to formulate the problem of induction logging in terms of Maxwell's equations for electromagnetic wave propagation in penetrable, conducting media. Duesterhoeft's solution is in terms of the Hertz potentials. He gives the solution to three important special cases; the induction instrument's response in (1) an infinite, homogeneous, conducting medium without borehole or layering; (2) in a horizontally layered one-dimensional formation without borehole; (3) in a radially layered medium without layering. Although this Duesterhoeft article was for two-coil sondes only, it was followed 1961 by a companion article by Duesterhoeft et al., "The effect of coil design on the performance of the induction log (SPE-1558-G)" which elucidated the application of the two-coil theory to multicoil, "focused field" induction logging instruments. More than a year following the 1961 publication of the Duesterhoeft papers, Moran and Kunz of Schlumberger-Doll Research, published essentially identical results in Geophysics (Moran, J.H., and Kunz, K.S., 1962, Basic theory of induction logging and application to study of two-coil sondes, Geophysics, 27(6), 829-858.) The formulation of the electromagnetic boundary value problem in the Moran and Kunz paper is in terms of the electromagnetic vector potential (as opposed to the Hertz potential used by Duesterhoeft) but the resulting electromagnetic fields (derivatives of the potentials) are the same, confirming the Duesterhoeft analysis. The three boundary-value problems were used for three decades to compute (1) the apparent resistivity response and skin effect for the multicoil 6FF40 antenna array in infinite, homogeneous, isotropic media (this is the apparent resistivity presented on a log), (2) thin-bed corrections, and (3) tornado-chart invasion corrections.

The ability to use the Duesterhoeft formulation to model the apparent resistivity response of the 6FF40 antenna array (ubiquitous in every service company in the 1960s, 1970s, 1980s, and early 1990s) taught us that our understanding of the response of induction logs was seriously flawed. For example, the apparent resistivity response in the center of a 100-ft thick, infinitely resistive reservoir sandwiched between 1 ohmm shoulder beds is about 90 ohmm, with the entire signal coming from the shoulder beds 50 ft from the center of the antenna array. It also revealed many pitfalls in the interpretation of thin beds and low-resistivity pay, instrument responses in deviated wellbores, and the egregious effects of rugose boreholes combined with saline mud and high-resistivity reservoirs, to name just a few.

The three boundary-value problems that Duesterhoeft first presented analytical solutions for are approximations when applied to any real logging job. For example, every horizontally layered medium that is logged is penetrated by a borehole, which gives each layer its own radially layered conductivity distribution due to invasion. Every radially layered medium is bounded on the top and bottom by a layer of different conductivity. To achieve a thorough understanding of all of the effects when combined requires that all of the effects must be simultaneously included in the model of the electromagnetic field. The two radially layered boundary value problems are used to provide the basis for solutions of so-called hybrid methods, which use the analytic solutions for part of the solution, and numerical transforms for the remainder of the solution. -It must be said that this is still an area of active research to this day.

The development of the modern generation of induction logging instruments featuring their multicoil asymmetric arrays and software focusing for different depths of investigation and vertical resolutions, and triaxial coils for interpretations of anisotropic media follow directly from the first analytic solution of the induction log boundary value problems. It was modeling based upon these solutions that brought the realization that no real understanding of the conductivity structure of the earth is possible without use of more elaborate antenna arrays that fully sample all possible components of the fields induced by sources capable of exciting all possible modes of response. All modern wireline and L WD induction and propagation instrumentation owe their designs and interpretations to the solutions of the boundary values problems first introduced by Duesterhoeft.

Ekstrom, M.P., Dahan, C.A., Chen, M.Y., Lloyd, P.M., and Rossi, D.J., 1987, Formation Imaging with Microelectrical Scanning Arrays, The Log Analyst, 28(3), 294-306.

Prepared by Dr. John Doveton

This paper introduced borehole electrical imaging with a clear explanation of the technology and a variety of examples of immediate geological interest. The authors pointed out that the dramatic resolution of the images at a scale of millimeters made them comparable with core photographs in the evaluation of both elastics and carbonates. The graphic output of image logs encouraged geologists to look at other logs as sources of lithological information rather than simply as curves for correlation.

Electrical imaging is routinely run in many wells around the world for a variety of purposes. As an extension of dipmeter technology, it provides the orientation of sedimentological, stratigraphic, and fracture systems. Continuous advances in technology improve image resolutions at a much finer scale than conventional logs, and so have been a major factor in thin-bed sand analysis of turbidite plays.

Although the physics of conductivity imaging differs from visual core observation, the similarity between image logs and cores in elastic successions meant that no special training was needed for experienced geologists to interpret them. In contrast, image logs of carbonates require a different perspective because of their sensitivity to pore volume and size rather than matrix textural features used in core description. Consequently, developments in carbonate image interpretation promote new ideas in interpretation and analysis that supplement conventional core description.

Image logging is now available from all major service companies and finds application in both conventional and non-conventional reservoirs all over the world.

The technology was introduced at a time of significant industry downturn, so that its relative expense discouraged initial commercial application. However, its widespread use in the Ocean Drilling Program opened the eyes of a generation of academic geologists to the capability of image logs, and by extension, to other logs as tools for geology rather than simply as correlation frameworks.

Miller, M.N., Paltiel, Z., Gillen, M.E., Granot, J., and Bouton, J.C., 1990, Spin Echo Magnetic Resonance Logging: Porosity and Free Fluid Index Determination, Paper SPE-20561, presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, 23-26 September.

Prepared by Richard Bateman

This paper reported on the introduction of a working nuclear magnetic resonance (NMR) logging tool (given the trade name MRIL) that did not require any special borehole treatment, provided a continuous record of lithology-independent porosity and irreducible water saturation. The description of the methodology was sufficiently detailed to explain why the tool was blind to any contribution for the borehole fluid itself, a grave failing of prior attempts to create a working tool.

The paper provided well-documented and favorable comparisons between the MRIL log derived porosity and both core and conventional neutron-density porosity from a Conoco test well in Oklahoma. Further discussion in the paper extended the interpretation of the basic T 1 , T2 and diffusion measurement to the estimation of permeability, fluid viscosity and formation resistivity factor.

Prior to publication of this paper the use of the NMR technique had been limited to benchtop laboratory equipment or a seldom-used logging tool that only made stationary measurements and required doping of the borehole mud system.

The lasting impact of these disclosures has been the adoption of the MRIL technology by two of the three major wireline service companies to provide a frequently used service filling an important technological niche. Subsequent to the publication this paper, the technology has been refined to provide wellsite porosity, permeability, pore-size distribution, pore-fluid type, viscosity and moveability.

Tittman, J., and Wahl, J.S., 1965, The Physical Foundations of Formation Density Logging (Gamma-Gamma), Geophysics, 30(2), 284-294.

Prepared by Philippe Theys

There are several significant contributions brought by this paper. Electrical measurements were introduced as early as 1927, and formation gamma ray in the 1940s. But, what the industry also needed was a quantitative evaluation of formation porosity. Many "porosity" measurements have been developed (acoustic, neutron, and even magnetic resonance) but as early as the 1960s, the density measurement brought a quantitative assessment of density from which, and through a simple, non-empirical equation, formation porosity could be derived. Tittman and Wahl describe how a robust density measurement can be performed using Compton electron interactions. From this electronic density, a formation density that is very accurate. in the common sedimentary rocks could be obtained. The apparatus can handle the photoelectric parasitic effect and also the impact of borehole mudcake. The paper also clearly leads the way to further developments that involve spectral measurements and the use of multiple detectors. It has the merit to confirm sound physics with a good amount of experimental data. From this paper emerges the "spine-and-rib" approach that is still being much used by a number of logging companies.

These critical innovations have wan-anted an incomparable success. Many petrophysicists rely only on this density measurement for porosity derivation as other measurements have weak measurement-to-porosity transforms (e.g., acoustic or "sonic") or doubtful and poorly documented environmental connections (e.g., neutron porosity). All logging companies have copied the design described in this paper.

Before the density measurement, porosity was qualitatively estimated from the spontaneous potential curve. In addition, the uncertainties of the density measurement are the best understood and the best managed.

Second only to the resistivity log, the density log is run in almost every openhole section. Logging companies have collected considerable revenues from running this measurement.

The proposed measurement enables the derivation of a quantitative porosity.

Zemanek, J., Caldwell, R.L., Glenn, Jr., E.E., Holcomb, S.V., Norton, L.J., and Strauss, A.J.D., 1969, The Borehole Televiewer-A New Logging Concept for Fracture Location and Other Types of Borehole Inspection, Journal of Petroleum Technology, 21(6), 762-774.

Prepared by Dr. Don Oliver

This paper was the first detailed description of the instrumentation, application, and results received from a new downhole logging system that provided acoustic images of the borehole environment. Called the Borehole Televiewer, the new system presented a "picture" of the borehole wall and gave a highly definitive view of the borehole environment. This paper provided a description of the logging tool and presented a large number of acoustic images that clearly showed fractures in open holes. In cased holes, the paper showed that the tools could be used to find perforations and to inspect and measure possible damage to the casing.

The technology introduced in this paper was primarily developed by research workers of what at the time was Mobil Research and Development Corporation. A fair measure of lasting impact of this technology is that all major logging service companies subsequently developed similar instrumentation for commercial applications. In most cases, these companies have now developed 2nd and 3rd generation borehole acoustic imaging tools. This paper has been cited many times since it was published, and books and training courses commonly include a review of the concepts and illustrations presented in the original paper. The Mobil workers who developed this technology were familiar to and admired by most research workers in the logging industry whether or not they have read the original paper.

This paper showed that a pictorial description of the borehole environment could offer a clear method for locating and evaluating fractures in the formation. Prior to the development of the televiewer, other logs, such as resistivity, acoustic, or nuclear logs, were used to try to identify fractures but were difficult to interpret and seldom definitive. Other techniques, such as core analysis, impression packers, and downhole cameras were also used to search for fractures but were often unsuccessful. With this new technology, fractures could be clearly seen and their orientation quantified. This technology was particularly successful in medium- to low-porosity carbonates due to the strong reflection of the acoustic signals in these environments. For higher porosity formations, the technology was less successful, but the tool had shown industry analysts the value of a pictorial representation of the borehole wall. This provided an impetus to look for technologies that could be used in other downhole environments and led to the development of electromagnetic imaging logging tools.

At first this technology was most commonly used in the low porosity, highly fractured limestones of West Texas, but subsequently has been used for applications all over the world. As mentioned previously, all the major logging service companies have developed acoustic imaging tools and these tools are used in many reservoirs worldwide.

The change this paper made was to show geologists and other industry analysts that natural and/or induced fractures could be clearly identified in situ and their orientations calculated. Applications of this technology in cased holes provided a direct image of the location of perforations and casing damage.

Archie, G.E., 1942, The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics, Paper SPE- 942054-G, Transactions AIME, 146, 54-62.

Prepared by Dr. E.C. Thomas

Gustave Archie had university training irr Geology and Mining Engineering. He also had practical· experience working in his father's quarry. Thus, he had the unique knowledge to both appreciate the complexity of rocks and the mathematical acumen to devise laborat01y measurements on the electrical properties of rocks and to interpret the experimental results into simple equations useful to both geologists and petroleum engineers. He gave examples of actual borehole electric logs and how to use his new equations to obtain water saturation and connate water resistivity. He also published graphs showing all the experimental data points.

One measure is the citation history of this publication. The number of citations is too large to state with accuracy. It is usually the first citation listed in the references of any paper concerning field resistivity log interpretation and laboratory-derived measurements. Even today, the equations provide quicklook techniques that are good enough for preliminary evaluation of many rock types. Subsequent equations that have found widespread use when Archie's equation is insufficient, are in fact Archie's equation with a correction factor.

This paper began a revolution in resistivity well-log interpretation that led us out of the dark forest of guesswork or hunches about the value of a given bed's worth in a wellbore into the open sunshine of the possibility of a quantitative evaluation of the fractional hydrocarbon saturation surrounding the wellbore. When this datum is combined with geologically derived formation parameters, we can estimate a value for hydrocarbons in place.

This paper has experienced acceptance and use worldwide.

Until this paper was published the general belief was that reservoir rocks were too complex to ever be understood well enough to use a mathematical equation to predict hydrocarbon volume in place. Today it is the norm.

Archie, G.E., 1950, Introduction to the Petrophysics of Reservoir Rocks, AAPG Bulletin, 34(5), 943-961.

Prepared by Richard Bateman

In this seminal paper, Archie sets out not only to give a name ("petrophysics") to the then nascent discipline of the study of the physics of rocks and fluids but also meticulously sets down on paper the intimate relationships between the key factors of pore-size distribution and fluid distribution of each phase (oil, gas and water) within the pores of a rock system. This opened the door to changing an art into a science.

The fact that today we routinely refer to the study of rocks and fluids as "petrophysics" and to those that conduct the studies as "petrophysicists" is witness to the lasting impact that this publication had on subsequent generations of earth scientists.

Prior to this publication by Archie, the interrelationships between the key factors had been "Balkanized" through unconnected studies and publications from the likes of Purcell, Leonardon, Wyllie, Fearon and Doll. For the first time, Archie set out clearly the waft and weave of the complex fabric that is petrophysics. He logically traced the interconnections between rock type, porosity, permeability, fluid saturations, water salinity, hydrogen content, capillary pressure, natural radioactivity, response to neutron bombardment, spontaneous potential, and electrical resistivity. The paper includes two timeless figures (12 and 13) that stunningly encapsulate an entire study guide for a modem petrophysics course.

Archie included in the paper detailed experimental data obtained from a wide variety of hydrocarbon producing fields. His rock samples came from both sandstones and carbonates. The trends that he richly illustrated with copious plots underline the universality of his petrophysical relationships that endure up to the present.

The analysis of cores and well logs prior to Archie's publication was a somewhat ineffective process due to the fragmented approach, which he so aptly described by "In actual practice, further complications arise due to practical difficulties, economic considerations and the personal equation." The publication of his "petrophysical road map" clarified the workflow needed for a logical and semi-quantitative approach to formation evaluation. In the day when the tools available were somewhat primitive compared to those available today his paper laid out a practical method for a log analyst to integrate many different threads to form a working formation evaluation fabric. That was new and innovative.

Clavier, C., Coates, G., and Dumanoir, J., 1984, Theoretical and Experimental Bases for the Dual-Water Model for the Interpretation of Shaly Sands, Paper SPE-6859, SPE Journal, 24(2) 153-168.

Prepared by Philippe Theys

Landmark Papers in Well Logging and Formation Evaluation

Stephen Prensky, Editor

*(Reformatted by Daniel Krygowski from Petrophysics, 2017, (**58**)3, June, Society of Petrophysicists and Well Log Analysts, pp.302-313.)*

The interpretation of shaly sand formations has been recognized early as a challenge for petrophysicists. Many saturation equations introduce a shale component and a shale resistivity. In 1968, after extensive laboratory work, Waxman and Smits proposed a saturation-resistivity relationship involving the cation exchange capacity of the shale portion. Unfortunately, a direct measurement of CEC is rarely available. The dual-water model was developed by Clavier et al. as a practical solution that is based on three premises:

- The conductivity of clay is due to its CEC.
- The CEC of pure clays is proportional to the specific surface area of the clay.
- In saline solutions, the anions are excluded from a layer of water around the surface of the grain.

The thickness of this layer expands as the salinity of the solution (below a certain limit) decreases, and the thickness is a function of salinity and temperature. In the dual-water model, clay is modeled as two components: bound water and clay minerals. The clay minerals do not contribute to conductivity and the clay electrical conductivity only originates from the clay-bound water. The amount of bound water varies according to the clay type, being higher in montmorillonite, and lower in kaolinite. All parameters (clean formations and shaly zones) can be directly identified on the logs and a quicklook interpretation can be completed in a short time at the wellsite.

Thirty years after its conception, the dual-water model is still one of the favorite options in computer-processed interpretation.

Before the dual-water model, the interpretation of shaly sands was considered an art, not a science.

The dual-water model is extensively used in the interpretation of ail shaly sands reservoirs. The dual-water model has been implemented in Schlumberger's Cyberlook computer processing and is still an option in modem interpretation software.

The paper definitely introduced some real physics to solve the challenge of interpreting shaly formations. Other methods were mostly empirical, and the Waxman-Smits method was missing a key item, namely "how to derive the CEC of the formation."

Klein, J.D., Martin, P.R., and Allen, D.F., 1997, Petrophysics of Electrically Anisotropic Reservoirs, The Log Analyst, 38(3), 25-36.

Prepared by David Kennedy

Resistivity anisotropy in earth formations had been recognized from the days of surface electrical prospecting, and had been mentioned as an effect on electrical logs from the earliest logging literature. However, early models in formation evaluation treated reservoir rocks as massive and isotropic; according to this model anisotropy was a property recognized in, and confined to, reservoir seals. Analysis of anisotropy was confined to explanations of anomalous log responses in these, and other, shale beds. No petrophysical analysis of the effects of anisotropy in a reservoir was attempted. By the last quarter of the 20th century, laminated shale-sand, low-resistivity reservoirs had become recognized as significant sources of hydrocarbon storage and production. Drilling technology from offshore platforms and Arctic drilling pads necessitated an increase in the number of deviated wells penetrating these formations. Resistivity log responses in deviated wells are different from the responses of the same instruments in the same formations in vertical wells. This paper was the first analysis that tackled the problem of analyzing log responses in laminated shale-sand formations in terms of the resistivities and thicknesses of the individual laminations comprising the shale-sand packages. Making the assumption that Archie's model for isotropic sands would apply in the sand layers individually, and with the volume fraction and conductivity of the conductive shale laminations known from log analysis, then the water saturation in the sand fraction can be estimated. The Klein et al. model is formulated in terms of macroporous sandstones interbedded with microporous mudstones, the water saturations in the components determined by the capillary pressure-water-saturation functions of the respective layers. Completing the petrophysical model, Klein et al. offer estimates of the anisotropic permeability components in terms of the anisotropic resistivity components. The authors anticipated the introduction of triaxial induction resistivity instruments by four years. With the introduction of these new instruments, the tensor components of resistivity could be estimated directly from the instrument responses. The interpretation methods developed to use the data provided by the new instruments, are all built upon the foundational principles set out in this paper.

A search of OnePetro on the phrase "resistivity anisotropy" yielded a total of 382 hits; the same search restricted to the years 1996-2015 yields 353 papers. Thus, before the initial publication of Klein, Martin, and Allen in 1996, which appeared as a conference paper in the SPWLA Transactions, only 29 papers on the topic had appeared. Since that date, 353 papers, or an average of 17 papers per year. Without having looked at each of the 353 papers to check for citations of Klein et al. the prima facie (and I believe correct) conclusion is that their paper opened the floodgate to a deluge of research concerning resistivity anisotropy and related topics.

With the publication of this paper, the formation evaluation community realized that the incorporation of transversely isotropic resistivity and permeability anisotropy in routine interpretation models was ·mathematically quite tractable. Prior literature had treated resistivity anisotropy in terms of electromagnetic instrument responses, rather than petrophysics, and appeared to be quite complicated. With the appearance of this paper, journeymen petrophysicists and log analysts could embrace anisotropy into their interpretation workflows.

Klein et al. anticipated the introduction of triaxial induction resistivity instruments and the generalization of their interpretation method (to which Klein continued to contribute) to explicitly include the deviation of well bore axes with respect to bed boundaries. Their interpretation method (and its extensions) is part of every commercial log analysis program, and is used each time a triaxial induction instrument is logged.

In 1997, times were ripe for a new understanding of formation resistivity incorporating anisotropy. If the paper did not initiate a paradigm shift in resistivity interpretation, it can certainly be said to have been the first rolling stone of what turned out to be an avalanche of understanding that followed in the next decade.

Luffel, D.L., and Guidry, F.K., 1992, New Core Analysis Methods for Measuring Reservoir Rod< Properties of Devonian Shale, Paper SPE-20571, Journal of Petroleum Technology, 44(11), 1184-1190.

Prepared by Pat Lasswell

Don Luffel and his team published three papers in 1992 and 1993, concentrating on physical property dete1minations in gas shales. This work became the Gas Research Institute method for shale property determinations, abbreviated as the GRI method. The first paper in this effort, SPE-20571, established the groundwork outlining the main challenges and concepts facing shale property investigations. Primarily, it asked the question, can legitimate laboratory-based porosities be determined in shales? The question was answered by offering an analytical alternative; crushing the material to yield greater surface area, facilitating access to the pore structure.

Over the last 20 years, almost without exception, crushed property determination (the basis of the GRI process) is put forward as the method best suited for porosity and fluid saturation determinations in shales and other tight unconventional reservoirs. In a search of publications using OnePetro, the method was referenced a total of 2,179 times.

In shales, the crushed-properties (GRI) method provided a means whereby defensible porosity and fluid saturations were obtainable. Without this new process, the basic volumetrics would not have been properly assessed or realistically understood. However, the crushed method did not show that the plug-based method was entirely suspect or ill-suited for use in shales. Rather, the experimental work showed that property dete1minations in shales were variable from a play or interval perspective.

While the Luffel investigations dealt with North American Devonian shales, the process has been successfully applied to worldwide use. In addition, the method, with relatively minor adjustments, has been adapted for use in more complicated shale/tight unconventional oil plays.

The analytical method put forward by Luff el 's team, became the new industry standard for shales and other tight unconventional plays. This was not by accident. True, the solution proved to be insightful and novel, but more importantly, it was robustly tested and verified. The team started with the plug-based method and built a direct bridge to their new crushed-properties method. Experimentation was done sequentially on a large set of intact shale plugs obtained from different shale plays. They provided the understanding that method-based property response was related directly to the specific shale play. The two methods might provide comparable results in one play, yet in another play, the porosities might be significantly different. In all cases, if a porosity difference was observed, the crushed porosities were the better numbers.

Pickett, G.R., 1973, Pattern Recognition as a Means of Formation Evaluation, The Log Analyst, 14(4), 3-11.

Prepared by Dr. Daniel Krygowski

This paper provided a detailed explanation, with examples, of a method introduced in an earlier paper (Pickett, 1966). This graphical ("pattern recognition") technique minimizes the need to calculate water saturation (SJ via Archie's equation (in a time before calculators). It also provides the means to quickly determine Sw without the knowledge of porosity matrix values, or values for Archie equation parameters porosity (cementation) exponent (m), and formation water resistivity (Rw). The method, under appropriate conditions, can predict those parameters from the data directly.

The method has survived the introduction of computer software, the output of which was initially text only, became one of the plots available with early alphanumeric printer-based graphics, and is implemented at this time in many technical software packages as an interactive application. In addition, extensions to the method (e.g., Greengold, 1986; Aguilera, 2004; and Krygowski and Cluff, 2012, 2015) have enhanced its use.

It helped moved petrophysical ·technology from algorithm-based interpretive techniques, which required knowledge of calculation parameters, to graphical techniques that provide both qualitative answers and quantitative results from parameters predicted from the method.

Landmark Papers in Well Logging and Formation Evaluation

Stephen Prensky, Editor

*(Reformatted by Daniel Krygowski from Petrophysics, 2017, (**58**)3, June, Society of Petrophysicists and Well Log Analysts, pp.302-313.)*

As a graphical solution to Archie's saturation equation, it has global application to all "Archie reservoirs," and may be of help in the identification and interpretation of "non-Archie reservoirs" as well.

Prior to this method, determination of water saturation was largely numerical or algorithmic, with required knowledge of calculation parameters. Graphical methods (e.g., Tixier et al., 1959; Hingle, 1959) while in some use, required specialized graphical displays which were not a versatile as the full logarithmic plot used here, nor could those plots commonly predict all the parameters that could be predicted from this method. With this graphical technique, determination of water saturation became much quicker, required knowledge of fewer parameters, and could overcome several types of calibration errors in porosity and resistivity measurements.

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Thomas, E.C., and Stieber, S.J., 1975, The Distribution of Shale in Sandstones and its Effect Upon Porosity, Paper T, Transactions, SPWLA 16th Annual Logging Symposium, New Orleans, Louisiana, USA, 4-7 June.

Prepared by Dr. E.C. Thomas

Thomas and Stieber demonstrate the necessity to handle the effects of anisotropy on the determination of porosity. Since porosity enters into the computation of water saturation, permeability and hydrocarbons-in-place as well, it follows these computations are effected as well. The earth is manifestly not isotropic; anisotropic formations are the norm.

One measure is the enormous citation history of this publication. The equation is now programmed into every commercial digital well-log evaluation package and is a standard evaluation step for all shaly sands to first make a Thomas-Stieber correction to make a first-order correction for anisotropy, then apply the Waxman-Smits equation to take care of the shaliness effects of a now isotropic formation.

This paper demonstrates that one should always consider an anisotropic model first when interpreting shaly sands. Only after one can determine that the bed or formation is homogeneous can we take the step to use homogeneous saturation models.

This paper has experienced worldwide acceptance and application.

Landmark Papers in Well Logging and Formation Evaluation
Stephen Prensky, Editor
*(Reformatted by Daniel Krygowski from Petrophysics, 2017, (**58**)3, June, Society of Petrophysicists and Well Log Analysts, pp.302-313.)*

Until this paper was published, the usual evaluation methodology only used isotropic, infinite-medium approximations in formulating the transform needed to convert logging tool responses into the values presented on the log as well as the transform from log readings into reservoir properties.

Timur, A., 1968, An Investigation of Permeability, Porosity, and Residual Water Saturation Relationships for Sandstone Reservoirs, The Log Analyst, 9(4), 8-17.

Prepared by Richard Bateman

This paper reported on an exhaustive project undertaken by Turk Timur at the Chevron Research Center at La Habra, California, that established an empirical formula to predict formation permeability from porosity and irreducible water saturation.

One hundred fifty-five sandstone cores from three different fields covering a wide range of porosities, permeabilities and residual water saturations were painstakingly analyzed to measure Phi, K and Swr. (in today's nomenclature, we would write Swir). The result was an empirical fit between the measured parameters and permeability based on knowledge of porosity and irreducible water saturation. The iconic equation, still in use today is:

The paper concisely and logically reviewed the prior work by Leverett, Tixier, Wyllie and Rose. Purcell, and Koseny, all of whom had attempted to find. acceptable permeability predictors using different measurable parameters from drill cuttings and the like. Timur, who was also working on early nuclear magnetic resonance (NMR) logging tools, understood the vital link between the free-fluid index (FFI) that would later to become a readily available quantity from NMR logging tools, and the much sought-after permeability. Since the FFI is a direct link to the irreducible water saturation the Timur fit provided the industry with a predictor of 'permeability from logging measurements without the need for expensive core retrieval and lab analysis.

Almost without exception, modern computer-aided log analysis routines have a built-in option for the log analyst to generate a permeability curve from a pulldown menu that offers "the Timur permeability", a lasting tribute to this paper, the man and the work that generated it.

Waxman, M.H., and Smits, L.J.M., 1968, Electrical Conductivities in Oil-Bearing Shaly Sands, Paper SPE-1863-A, SPE Journal, 8(2), 107-122.

Prepared by Dr. E.C. Thomas

The most significant contribution made by this paper was to demonstrate that the mathematical analysis of water-bearing shaly sands in conductivity space results in a linear equation while the traditional analysis in resistivity space results in a nonlinear, power-law equation. Using conductivity, these authors present a simple, logical explanation for the observed behavior of shaly sands when exposed to an electrical field gradient, expressed as an imposed voltage drop. The explanation uses physical chemical principles supported by a large body of theoretical and experimental conductivity data. The paper introduces a new parameter, Qv, the cation exchange capacity per unit pore volume of a unit of rock, and explains how BQv is the correct parameter to explain and predict observed electrical behavior of shaly sands rather than Vclay or Vshale· An equation developed from data obtained at ambient temperature defines the parameter, B, the cationic equivalent conductance of the hydrated sodium ion in aqueous solutions of sodium chloride. Lastly, the authors propose a new equation using BQv to extend the water-bearing equation for shaly sands into one for hydrocarbon-bearing shaly sands.

One measure is the huge citation history of this publication. The equation is now programmed into every commercial digital well log evaluation package and is the standard evaluation for all shaly sands.

This paper spelled the death knell of all shaly sand equations using Vshale to correct for the extra conductivity of clay mineral hydrated sodium cations

This paper has experienced worldwide acceptance and application.

Until this paper was published the general belief was that Vshale was the parameter to use to make shaly sand resistivity corrections. Everyone now knows the correct parameter is BQv.

Wyllie, M.R.J., Gregory, A.R., and Gardner, L.W., 1956, Elastic Wave Velocities in Heterogeneous and Porous Media, Geophysics, 21(1), 41-70.

Prepared by Dr. John Doveton

This paper reported on results of laboratory measurements of acoustic velocity for a variety of rock samples with a focus on their relationship to porosity. Up to the time of this paper, the sonic velocity log had been recorded primarily as an aid to the interpretation of seismic surveys. While recognizing nonlinearities of the transit time (or velocity "slowness") at higher porosities due to a variety of factors, the authors concluded that a linear interpolation between matrix and fluid transit times was a good approximation in consolidated reservoir rocks. This relationship is expressed by the Wyllie time-average equation and provided the first log prediction of porosity other than inferences made from resistivity measurements.

The Wyllie time-average equation is today still the most widely used function to predict interparticle porosity from sonic velocity logs. Some improvements have been proposed by nonlinear models that consider the entire porosity range, of which, the most popular is the Raymer-Hunt-Gardner transform. However, the Wyllie equation should be considered as a robust first-order model for interparticle porosity estimation in reservoir formations that are not confounded unduly by significant issues of lack of consolidation, shaliness, or matrix mineral variability.

The introduction of a method to estimate pore volumes over extensive intervals that had limited core samples provided a new source of information to add to textural properties observed in drill cuttings. In carbonates, it was recognized that the time-average estimate was restricted primarily to interparticle pores, so that vuggy pores were not accounted for. However, when used in combination with density and/or neutron log measurements this limitation could be turned into an asset by allowing the subdivision of a dual-porosity system by pore type.

When first introduced, the sonic porosity transform was considered to be the principal method to estimate porosity from logs. However, density and/or neutron logs, particularly in combination, are now generally preferred in the evaluation of total porosity. Nevertheless, sonic velocity logs are still commonly recorded in connection with geophysical applications and the Wyllie time-average equation routinely used to predict interparticle porosity.

The paper demonstrated that a logging measurement that was introduced to aid geophysicists in their interpretation of seismic traces could be transformed easily into a viable measurement of porosity, and so with major geological implications.