APPLICATION OF RESISTIVITY-POROSITY CROSSPLOT ANALYSIS TO NUCLEAR MAGNETIC RESONANCE LOGGING DATA

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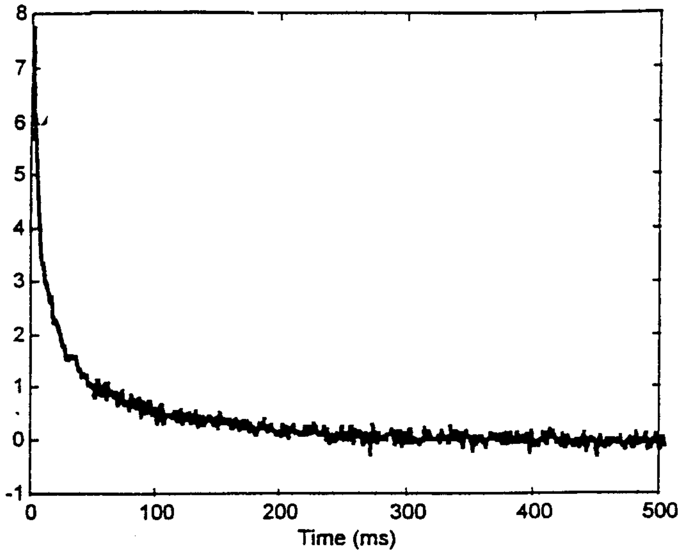
NUCLEAR MAGNETIC RESONANCE (NMR) LOGGING: PORE-SIZE AND FLUID TYPES

The recording of nuclear magnetic resonance by logging tools allows the measurement of the effective porosity independent of lithology type, the proportion of free fluid in the pore space, the irreducible water saturation, the amount of clay-bound water, as well as an improved estimate of permeability, the determination of wettability (water or oil), and a characterization of hydrocarbon type. Although NMR logging has been in operation for over twenty years, recent dramatic improvements in tool design have had a major impact on logging technology and interpretation.

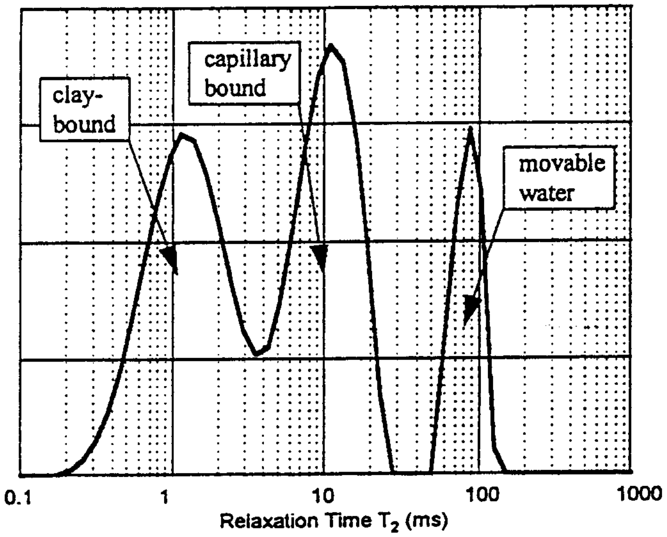
Many atomic nuclei have a magnetic moment which will be aligned with a magnetic field. Hydrogen nuclei (protons) have the strongest magnetic moment and occur in great abundance in the fluids of rock pore spaces . The NMR tool contains a large permanent magnet, so that hydrogen nuclei in the fluids (but not the solids) of the formation align themselves with the resulting magnetic field. The NMR tool transmits a radio frequency pulse train. The initial pulse causes the hydrogen protons at a known distance from the magnet to instantaneously tip themselves perpendicular to the direction of the permanent magnetic field. Immediately after the initial pulse, the protons begin to realign themselves with the magnetic field and generate a spin-echo signal as response to the remaining pulses that is measured by the tool. The decay of this echo train is a function of pore sizes and fluid types and their properties.

The total signal is proportional to the number of hydrogen protons in the fluid. However, the speed at which a hydrogen proton will realign itself depends on which of the fluid fractions it is located. Hydrogen protons in a large volume of water will realign in about 3 seconds. Hydrogen protons in oil, gas or water that is in the pore space of a rock will align much faster, in times measured in milliseconds, because of the additional relaxation caused by the interaction between the fluid and the pore wall. Hydrogen protons in clay-bound water will realign fastest, followed by hydrogen protons in capillary-bound water, and the slowest realignment will occur in the free fluid of the pore space.

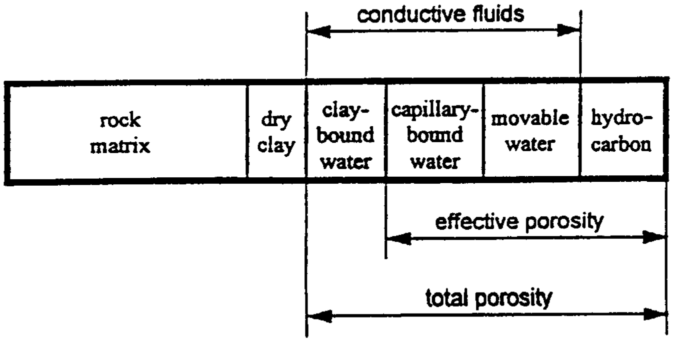
The speed of realignment is presented as a spectrum of transverse relaxation times (T2) determined from analysis of the pulse echo train measured in the time domain. Peaks on the spectrum differentiate clay-bound, capillary-bound, and free-fluid hydrogen protons. Typical values used for the T2 cut-offs in sandstones to differentiate these three classes of fluid are: clay-bound - below 3 ms; capillary-bound - between 3 and 33 ms; free-fluid - greater than 33 ms. However, reported values vary slightly in the NMR literature, as well as laboratory core NMR measurements, and they are also more difficult to establish satisfactorily for carbonates. The transverse relaxation time (T2) is a direct function of pore size from the equation:



Spin-echo data Acquisition Time Domain



T2 amplitude spectrum in Transverse Relaxation Time Domain



Standard Rock Porosity Model

BASICS OF NMR LOG DATA PROCESSING
From Prammer, Drack, Bouton, and Gardner (1996)

$$\left(\frac{V}{S}\right)=\rho_2 T_2$$

where (V/S) is the volume to surface area ratio of the pore and $\rho 2$ is the surface relaxivity which for quartz (sandstones) is about 10 microns per second, and for calcite (limestone) is about 3 microns per second.

The NMR data is presented on the log in a variety of ways. The basic curves are:

(i) the NMR porosity, which is the effective porosity as the sum of free fluid and capillary-bound fluid;
(ii) the Free-Fluid Index (FFI), which is the rock bulk volume of fluids which are free to flow out of the formation;
(ii) the Bulk Volume Irreducible (BVI), which is the rock bulk volume of fluids occupied by water immobilized by capillarity.

In addition, an estimated permeability curve is also presented, based on the fact that proton relaxation time is related to the internal surface area/volume (S/V) ratio and used in one of several variants of the Kozeny-Carman equation. The commonest form used in NMR logging is the "Coates equation":

$$k=\left[\Phi_{NMR}^2\left(\frac{FFI}{BVI}\right)\right]^2$$

although better estimates are given by partitioning the T2 spectrum into several bins and relating these to permeability (Curwen and Molaro, 1995).

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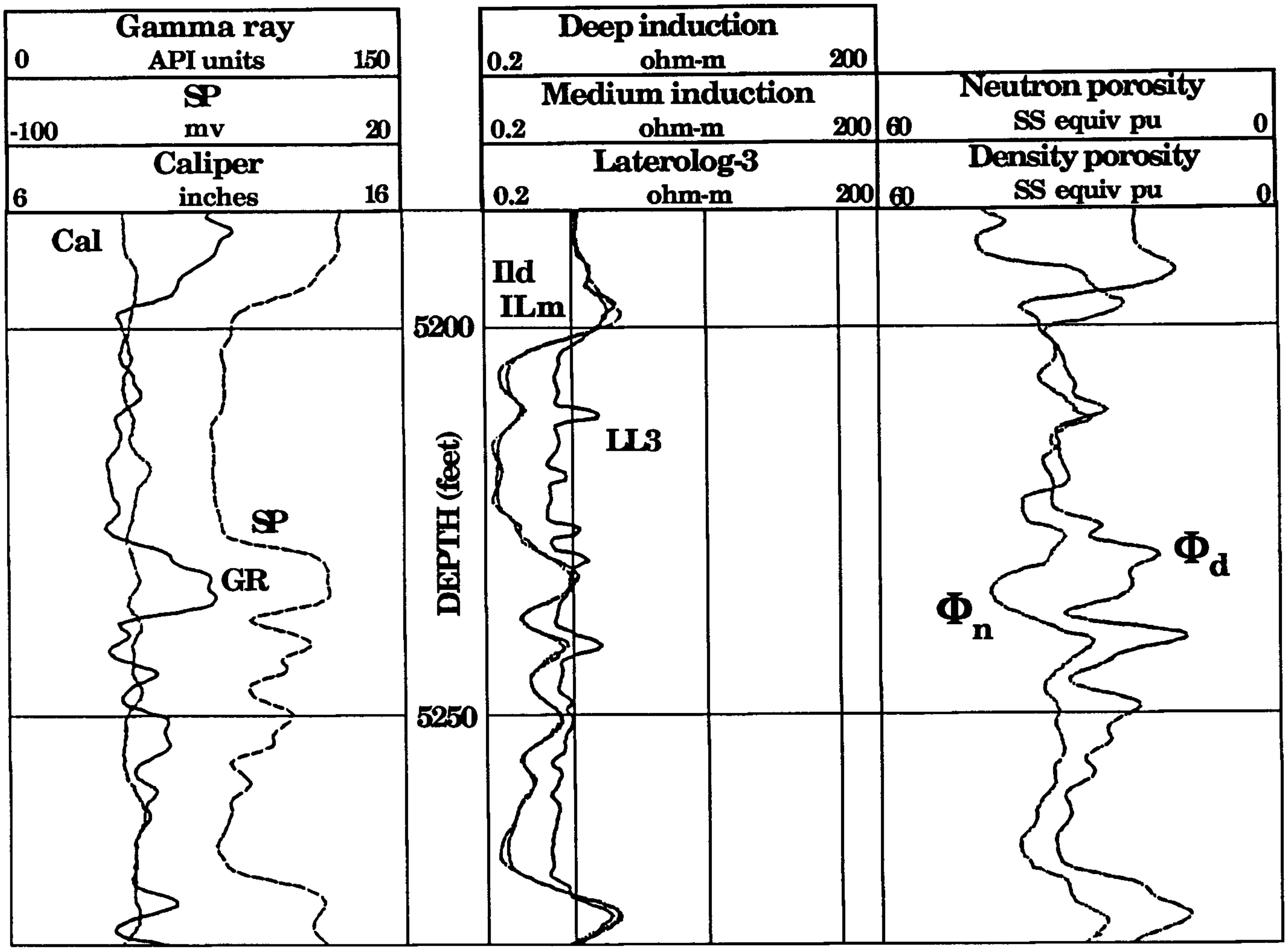
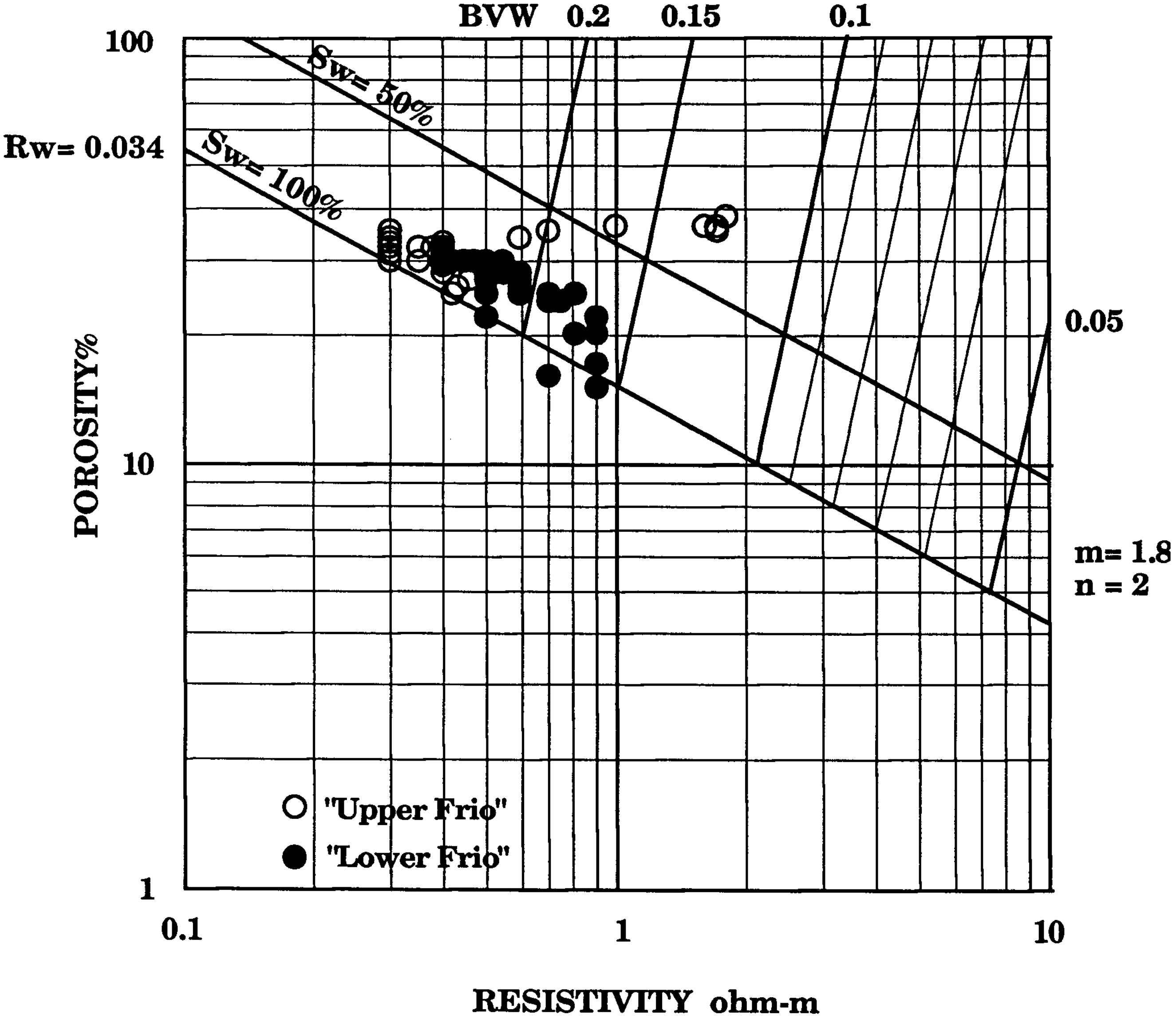
Example of an NMR log analysis in a productive sandstone

A simple example of NMR log analysis is shown for a Frio Sandstone section from the Miocene of the Texas Gulf Coast (Coates, Gardner, and Miller, 1994). In the plots that follow, the section is subdivided between an "Upper Frio (5197-5227) and a "Lower Frio" (5237-5272). Both neutron and density logs were run and are shown overlaid on a common sandstone porosity scale. These two logs coincide in zones of clean sandstone, but the neutron log is drawn to higher values in zones with shale contents because of clay effects. The resistivity log, considered in conjunction with the porosity logs and the associated Pickett plot suggest some hydrocarbon in the section, with the best show just above 500 feet depth. (The neutron-density porosity curve crossover suggests that the hydrocarbon is gas, as will be discussed later in this manual.) Zones of the "Lower Frio" form a trend of high water saturations that parallel the water line. These probably reflect residual hydrocarbon saturation and would likely produce only water. The "Upper Frio" shows a good indication of a transition zone that peaks at a BVW of about 0.12 at the top. This value implies either that the top zone would produce water as well as hydrocarbons, or that the zone is rather fine-pored. When tested, would this zone produce water-free hydrocarbons?

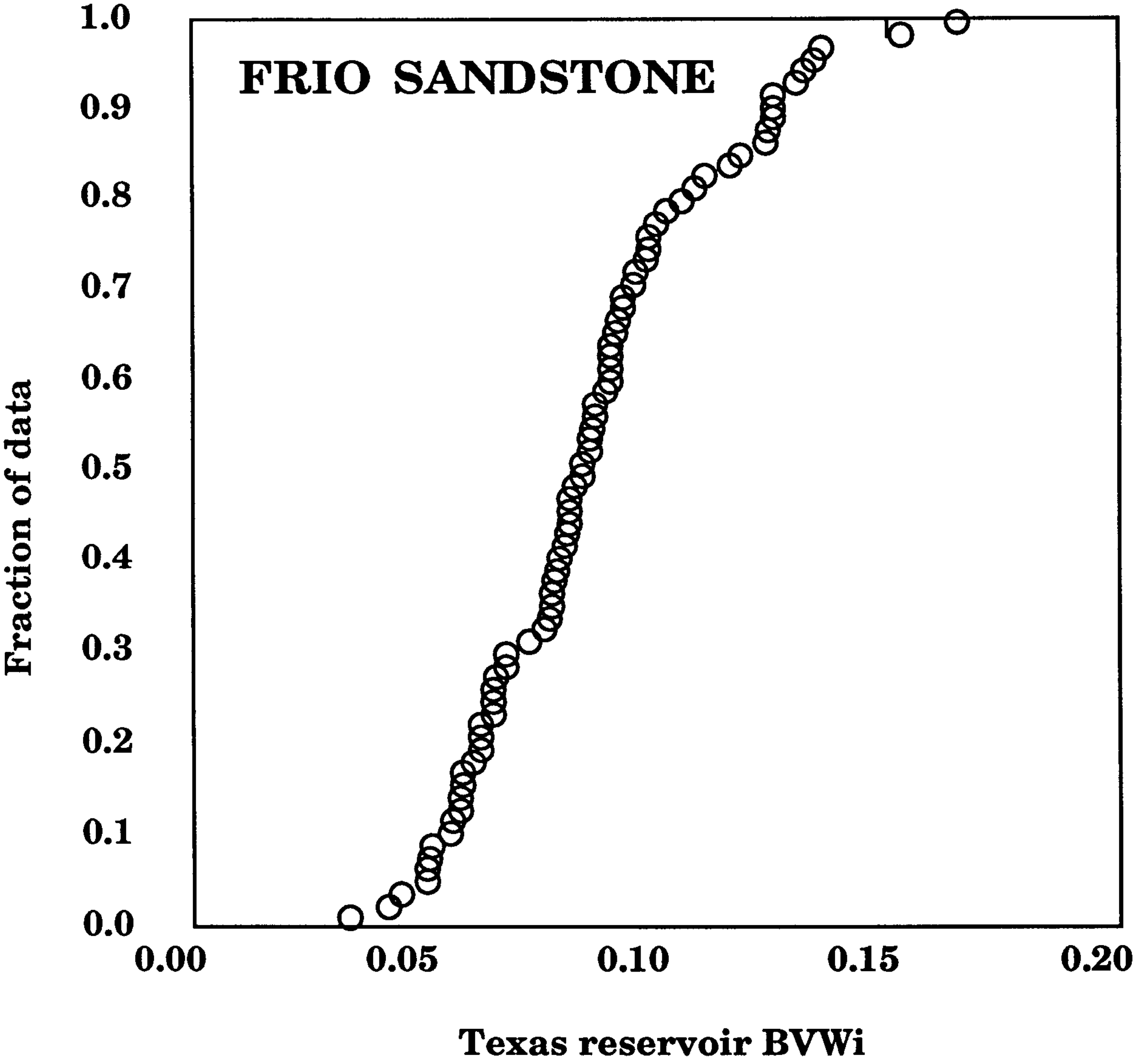


Adapted from Coates, Gardner, and Miller (1994)

THE "TRADITIONAL" RESISTIVITY-POROSITY LOG VIEW OF A FRIO SANDSTONE (MIOCENE, TEXAS) SECTION



PICKETT PLOT OF THE FRIO SANDSTONE SECTION
("UPPER FRIO" = 5197-5227 ; "LOWER FRIO" = 5237-5272 FEET DEPTH)

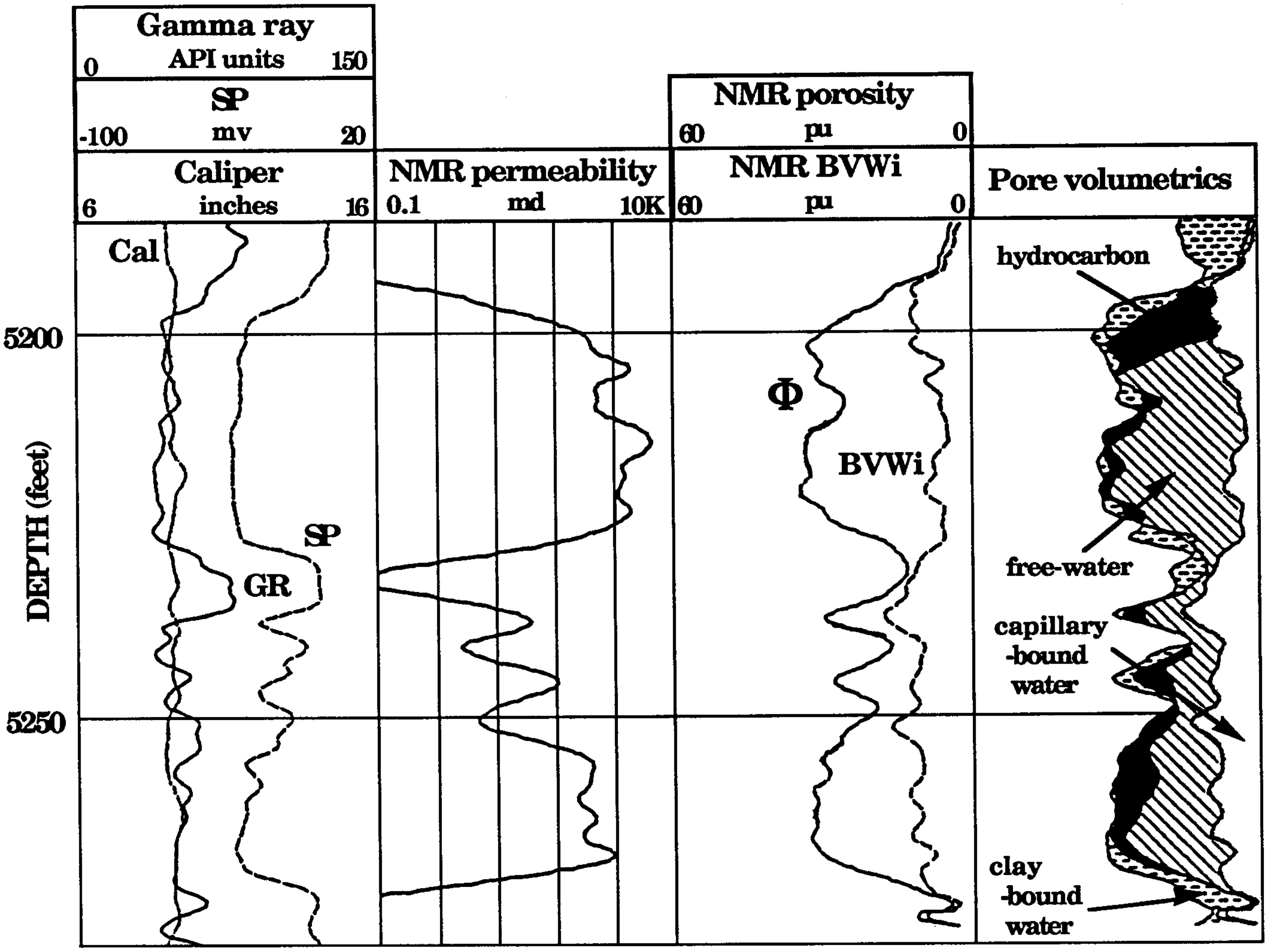


CUMULATIVE FREQUENCY PLOT OF BULK VOLUME WATER IN 76 TEXAS
FRIO SANDSTONE OIL RESERVOIRS CALCULATED FROM DATA
REPORTED BY GALLOWAY et al (1983)

As an aid in our decision, we could consider the cumulative frequency plot of irreducible bulk volume water (BVWi) values shown for Frio Sandstone oilfields. The data for this plot are based on the porosities and water saturations of 76 Frio fields tabulated by Galloway et al (1983). The cumulative plot shows that the Frio Sandstone tends to be fine-pored with a median BVWi value of 0.084. Almost all the zones in the logged section are beyond the range of the field data, so that water-free hydrocarbon production is unlikely except for zones at the very top of the section.

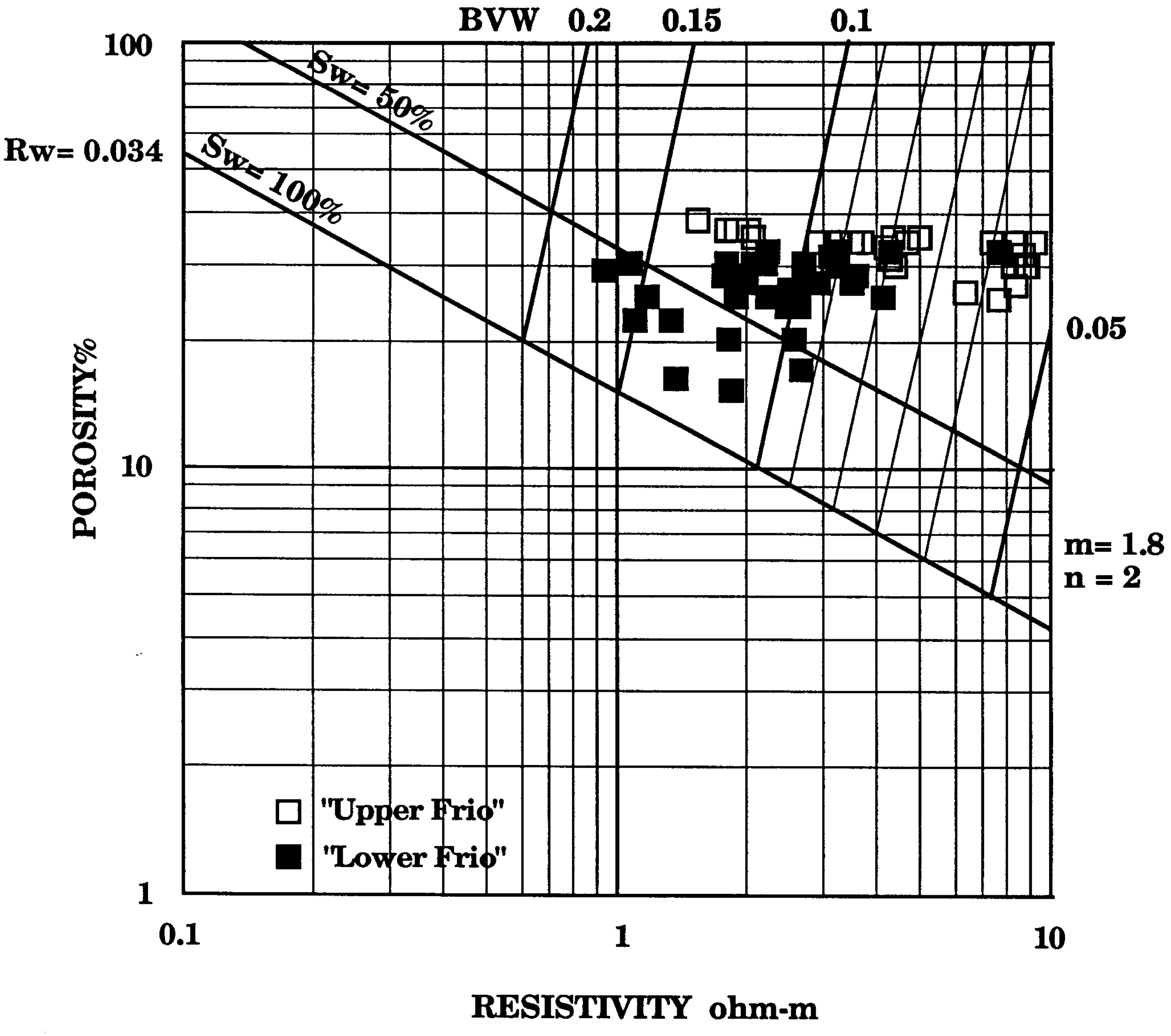
The results of the NMR logging run are shown together with the SP, caliper, and gamma-ray curves. The NMR permeability is computed from the "Coates equation". The NMR porosity is subdivided between Bulk Volume Irreducible (to the right) and Free-Fluid Index (FFI) (to the left) by the BVWi curve. In the "pore volumetrics" track, density porosity, NMR porosity, bulk volume water (from resistivity-porosity calculations), and irreducible bulk volume water are superimposed. Notice that the NMR porosity either equals or is slightly less than the density porosity, because it registers the effective porosity, and the difference reflects clay-bound water. The Free-Fluid volume can be made up of either water, hydrocarbon, or a mixture of both, so a computation of the bulk volume water (BVW) from the resistivity-porosity data by the Archie equation, allows the discrimination of hydrocarbons. The superimposition of the BVWi curve on the other logs now shows the porosity content in terms of free fluid and bound water. The only significant hydrocarbon is at a depth of 500 feet, where water content is at irreducible and indicates water-free hydrocarbon production. In reality, this zone was tested for production and made 600 MCFPD of gas for thirty days, then 50 BOPD and 20 BWPD, and finally leveled at 40 BOPD and 100 BWPD (Coates and Howard, 1992).

The BVWi readings from the NMR log can also be crossplotted directly on a Pickett plot against density porosity, as shown. The information on depth is lost (although it could be retained by color-coding the plotted symbols as depth). However, the broad relationship between porosity and BVWi is shown by the location and spread of the cloud at different porosity levels. More importantly, the use of this Pickett plot allows NMR information from this well to be used for other Frio Sandstone wells in the area that were NOT logged by an NMR tool. The Bulk Volume Irreducible (BVWi) values could be applied as production boundaries on conventional Pickett plots as aids in deciding whether crossplotted resistivity-porosity points came from either a transition zone, or if they signified water-free production. Notice that in the example well, the BVWi is noticeably higher in the lower sandstone than the higher sandstone, reflecting both finer pore sizes and lower permeabilities. Therefore, when applying these data to neighboring wells, some consideration would have to be made of likely changes in pore-size and their trends both laterally and vertically.



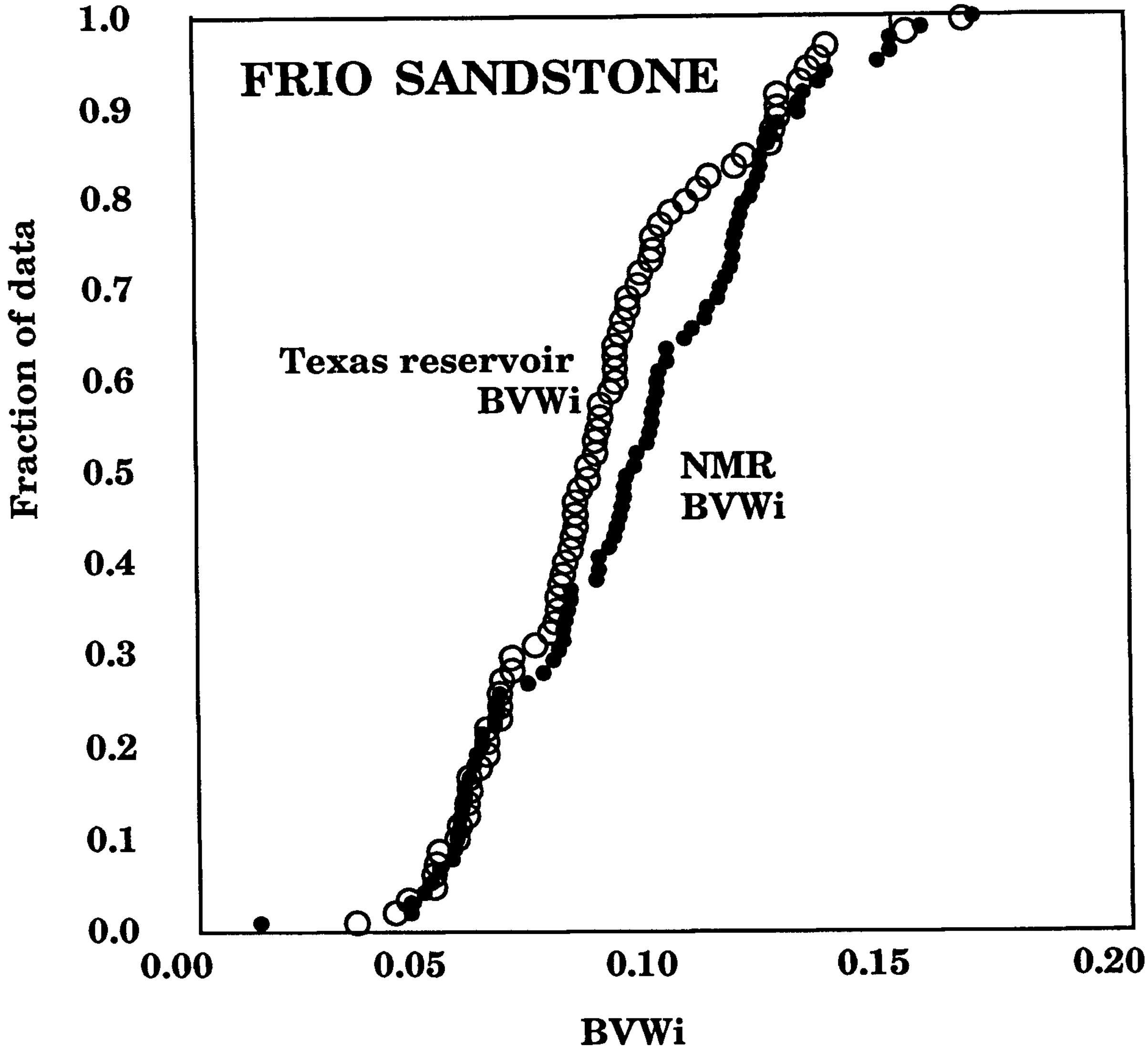
Adapted from Coates, Gardner, and Miller (1994)

APPLICATION OF THE NMR LOG TO IMPROVE THE RESISTIVITY-POROSITY LOG VIEW OF A FRIO SANDSTONE (MIOCENE, TEXAS SECTION)



PICKETT PLOT OF NMR BULK VOLUME IRREDUCIBLE (BVWi) VALUES IN THE FRIO SANDSTONE SECTION
("UPPER FRIO" = 5197-5227 ; "LOWER FRIO" = 5237-5272 FEET DEPTH)

Finally, the cumulative frequency plot of irreducible bulk volume water (BVWi) values from the NMR log of the Frio Sandstone section are shown superimposed on that for Frio Sandstone oilfields. The overall similarity shows that (at least for the Frio) there is a good match between reservoir summary statistics and NMR logging data. While NMR logs are always preferable, because they are site-, section-, and depth-specific, the broad match confirms that empirical data can still be applied in useful interpretations and that their "meaning" can be understood in terms of the latest models of pore geometry and the most recent NMR logging technology.

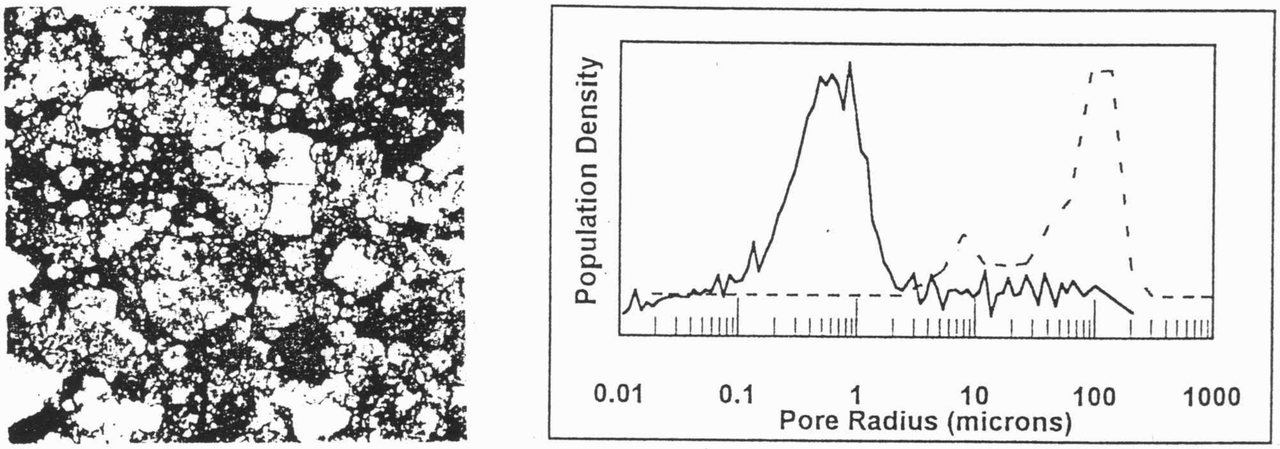


CUMULATIVE FREQUENCY PLOT OF IRREDUCIBLE BULK VOLUME WATER FROM LOGGED ZONES IN A FRIO SANDSTONE SECTION (COATES et al, 1994) SUPERIMPOSED ON CUMULATIVE FREQUENCY PLOT OF BULK VOLUME WATERS IN 76 TEXAS FRIO SANDSTONE OIL RESERVOIRS CALCULATED FROM DATA REPORTED BY GALLOWAY et al (1983)

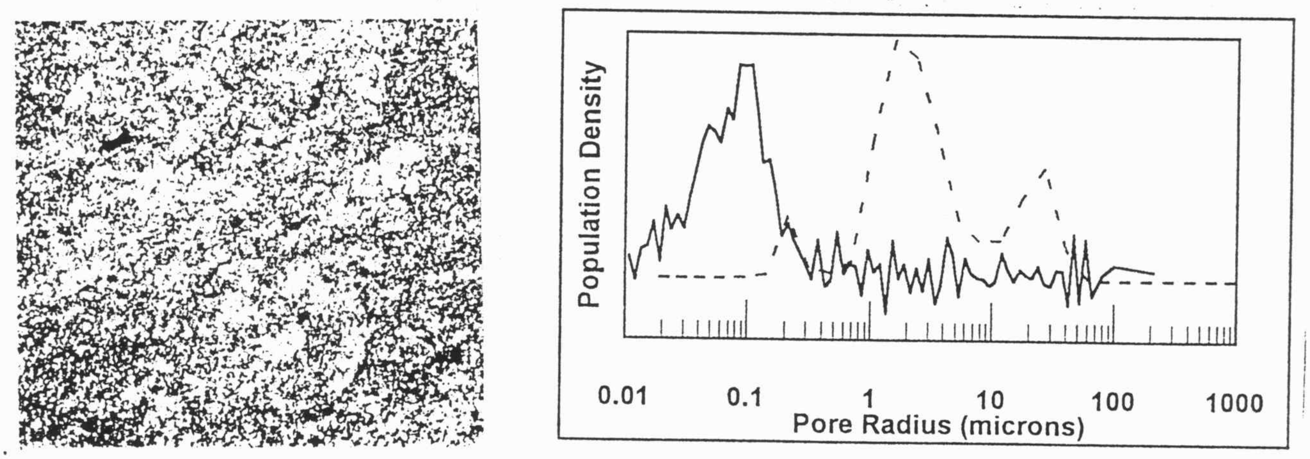
PORE SIZE VERSUS PORE THROAT SIZE

Notice that the NMR measurement generates a distribution of *pore* sizes, rather than *pore-throat* sizes that results from mercury porosimetry. However, there is generally a sympathetic relationship between them in any given rock, particularly if the aspect ratio does not change much within the total pore system. In the illustration on the next page, the pore sizes and pore-throat sizes in two reservoir rocks are contrasted:

(A) Good-quality reservoir rock.
Subtidal dolograinstone with average crystal size 128 microns.
NMR (dashed line): Intercrystalline pores 8-10 microns that surround 100 microns grain-moldic pores.
Hg porosimetry (solid line): Pore-throat average radius = 0.8 microns
Result: High permeability (14 md) and large hydrocarbon displacement efficiencies.
(B) Poor-quality reservoir rock.
Fine-grained dolomudstone with average crystal size 16 microns.
NMR (dashed line): Intercrystalline pores, 1-16 microns ; grain-moldic pores, 25 microns ; very small pores, 0.2 micron s.
Hg porosimetry (solid line): Pore-throat average radius = 0.08 microns
Result: Low permeability (0.01 md) and low hydrocarbon displacement efficiencies.



(A) Good-quality reservoir rock



(B) Poor-quality reservoir rock

COMPARISON OF PORE SIZES MEASURED BY NMR (DASHED LINE) AND PORE-THROAT SIZES (SOLID LINE) MEASURED BY MERCURY POROSIMETRY IN TWO CARBONATE RESERVOIR ROCKS

From Siemers et al (1996)

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