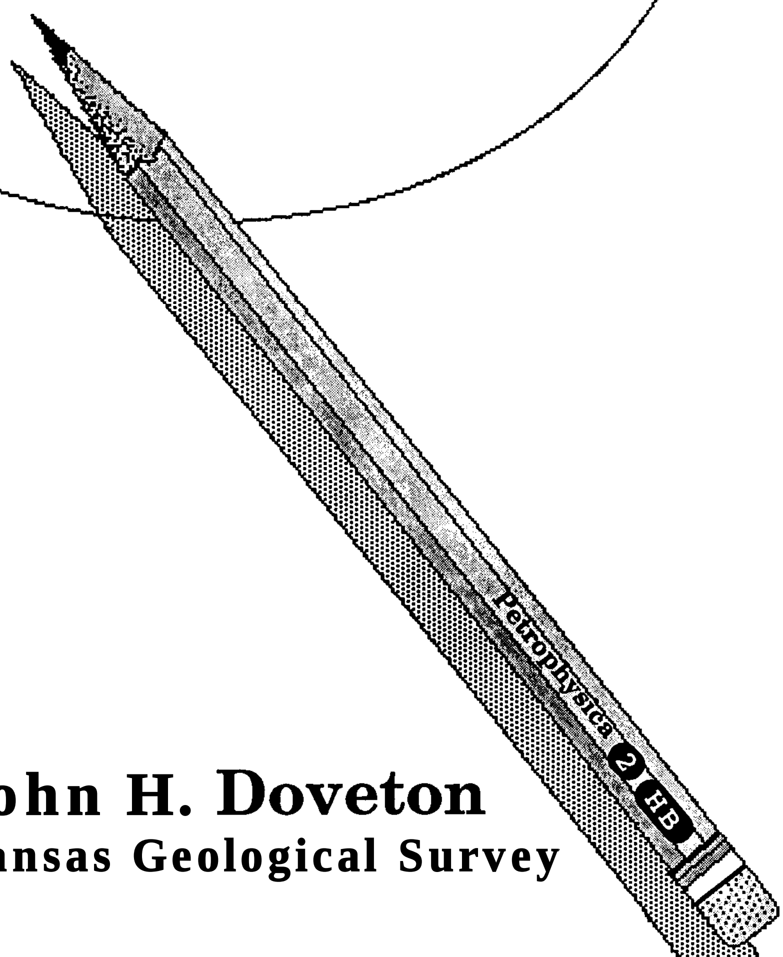
Basics of Oil & Gas Log Analysis



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RESISTIVITY LOGGING

In most runs of a resistivity tool, the major purpose is to obtain measurements of Rt, the true resistivity of the formation. However, there are a variety of complicating factors involved which may require corrections to be made to the recorded values in order to obtain good estimates of the true resistivities. All resistivity tools are to some extent "averaging" devices that record resistivities of zones rather than resistivities of discrete points. So, for example, the resistivity of a thin resistive horizon will generally be underestimated by most tools since its reading will be partly reduced by contributions of more conductive adjacent beds.

The process of drilling actually modifies the resistivities of formations in the vicinity of the borehole through the process of "invasion". In addition to its other functions, the drilling mud forms a mudcake seal on the borehole wall of permeable formations. In doing this, mud filtrate penetrates the formation, displacing formation water and oil or gas. In a zone immediately adjacent to the borehole the mud filtrate displaces all the formation water and any "moveable oil saturation" (the "flushed zone"). Beyond this, the mud filtrate displaces part of the formation water in a "transition zone" which ultimately peters out at a contact edge with the undisturbed formation. The relative depth of invasion is broadly a function of formation porosity/permeability properties, so that less porous formations (typical carbonates) are more highly invaded than moderately porous units (typical sandstones). Pore volume appears to be a major control on invasion depth, because this dictates the volume available to accomodate invading mud filtrate. Once the permeability of a formation exceeds a critical lower value (perhaps about 0.1 md), the formation will be invaded, but invasion depths appear to be insensitive to variations in permeability at higher values (Jorden and Campbell, 1984).

The replacement of formation water by mud filtrate involves a change of pore water resistivity from Rw to Rmf. In a typical logging operation, the mud is "fresh water" as contrasted with the formation waters encountered. The result of invasion is generally to create a more highly resistive annulus surrounding the borehole.

When the objective of most commercial logging is to evaluate the oil or gas potential of stratigraphic units, a resistivity tool is selected that will best estimate the true resistivity of the formation by taking into account borehole characteristics, drilling mud properties, formation lithologies, and degrees of invasion. There are two styles of resistivity tool for this purpose:

1) Induction

The focused induction tool was developed to measure conductivities deep within the formation with minimal disturbance by the invaded zone. The tool contains transmitter coils with a high frequency AC current which induce eddy currents in the adjacent section. Most of these eddy currents are focused beyond the diameter of the typical flushed zone and their magnitude is an approximation of the conductivity of the virgin formation. In turn, they induce voltages in the receiver coil which are translated to estimates of formation conductivity and, as a reciprocal, resistivity.

Since the induction tool actually measures conductivity directly, rather than resistivity, more reliable readings tend to be made within lower resistivity sections. As a result, the induction tool is ideally suited for sandstone sections, which typically have high porosities, but may not be a satisfactory first choice in highly resistive sequences such as low-porosity carbonates. Unlike other resistivity tools, the induction tool can be run in holes drilled with air or with oil-base muds since it does not require electrical contact with the mud or formation. The tool operates well in "fresh muds" but readings become strongly degraded in "salt muds" due to the greatly increased contribution of the borehole to the total conductivity reading.

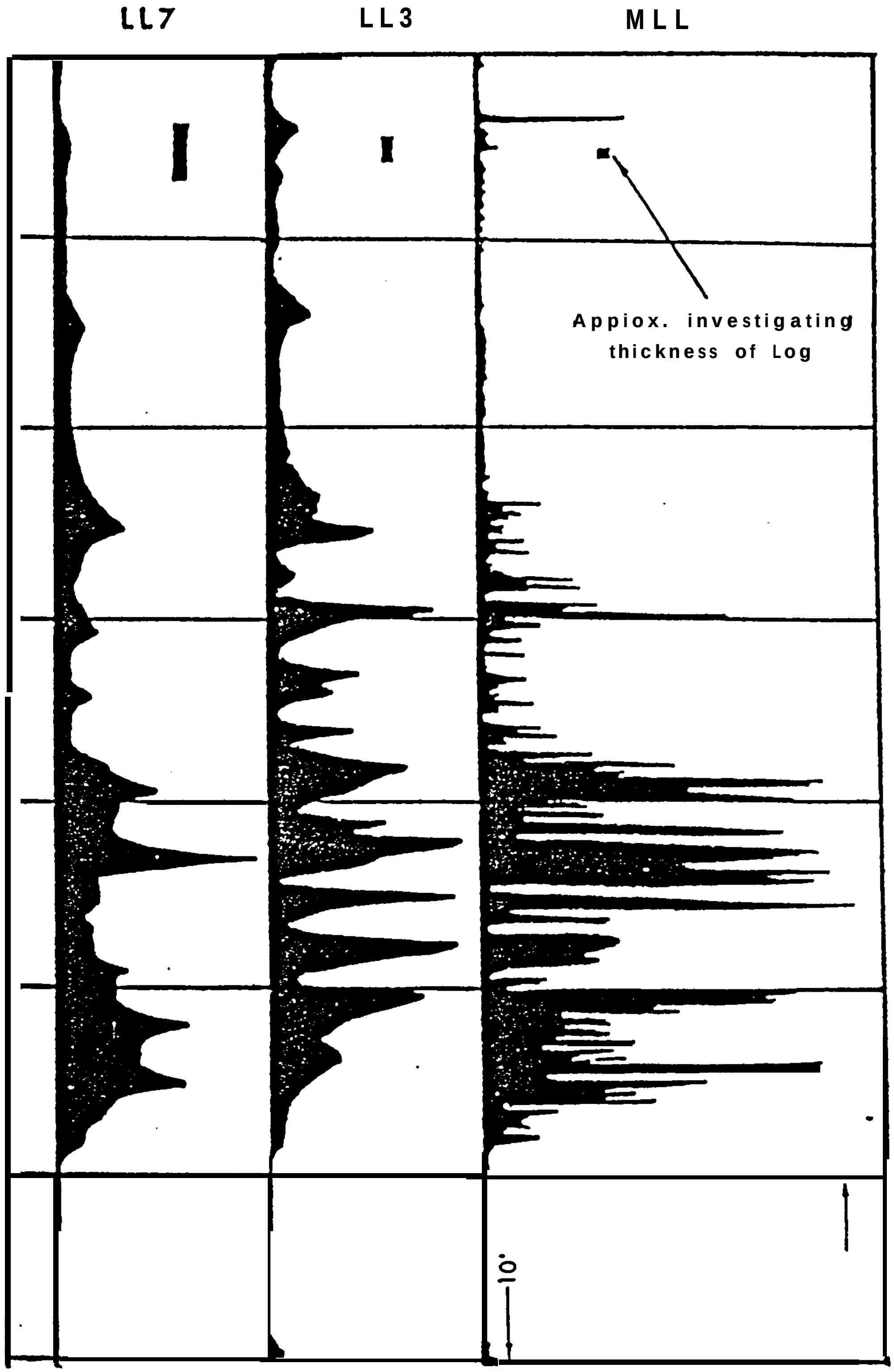
(2) Laterolog

The laterolog (or guard log) was developed to provide accurate readings of formation resistivity in holes drilled with salt water muds. There are various designs of laterolog tools but the central principle of operation is a three electrode arrangement in which a current supply of constant intensity is supplied to the central electrode. A variable current intensity is transmitted to the two surrounding ("guard") electrodes whose magnitude is adjusted so that there is a zero potential with the central electrode. As a result, current in the central electrode is constrained to flow radially outwards as a "current disc" into the surrounding formation. The thickness of the disc is determined by the spacing of the guard electrodes while the current density at any lateral distance from the central electrode is inversely proportional to this distance times the spacing. The drop in potential of the current disc radiating into the formation is monitored by a remote return electrode. As a result, an apparent resistivity is deduced which is the summation of resistivity contributions by the mud, invaded zone and virgin formation. In situations where the mud is relatively conductive, degree of invasion restricted and resistivity of the formation is fairly high, this apparent reading is a close approximation of the true formation resistivity.

Vertical resolution and radius of investigation

The ideal resistivity tool would obviously be one that had extremely good vertical resolution (thereby defining very thin beds) and a large radius of investigation (giving reliable readings deep in the formation). These two criteria are almost impossible to meet in the design of a practical resistivity device, since it requires the vertical component to be extremely small (effects of adjacent beds) and the lateral component to be very large. As a result, different resistivity tools are run for different purposes and several types may be run in the same hole.

A comparison of three different laterologs run the same section (Mississippian carbonate, Saskatchewan) is shown overleaf. Moving from left to right (across log types) there is a progressive increase in vertical resolution, but, at the same time, a reduction in the radius of investigation, with increasing resistivity contributions from

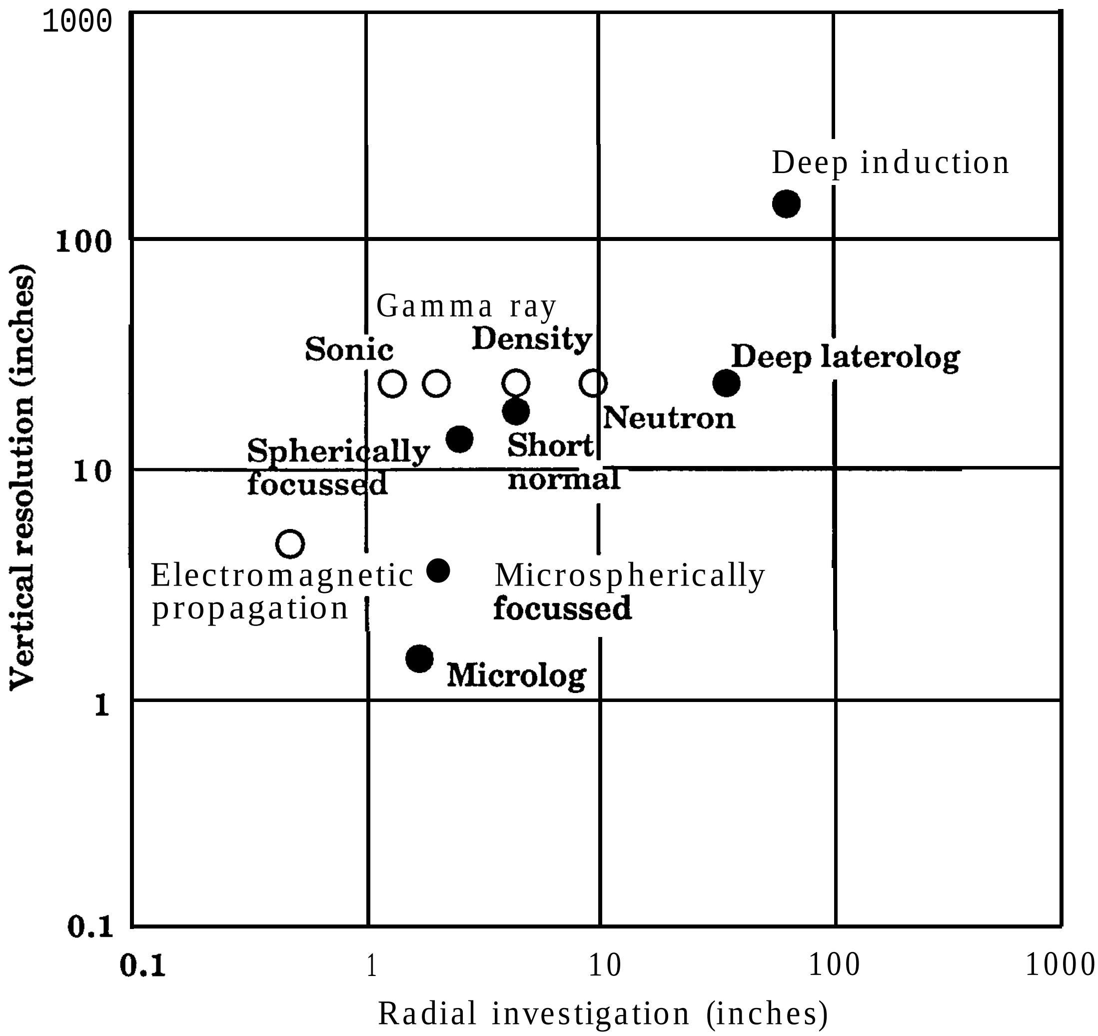


Laterolog-7, Laterolog-3, Microlaterolog resistivity profiles of a Mississippian carbonate section in Saskatchewan (after Jeffries, 1965) the flushed zone. If a stratigrapher wished to use one of these logs for bed correlation purposes, the microlaterolog (MLL) would be his choice. If a petroleum geologist required a reservoir analysis of the formation, he would use the laterolog LL7, since the readings are the best estimate of the virgin formation resistivity.

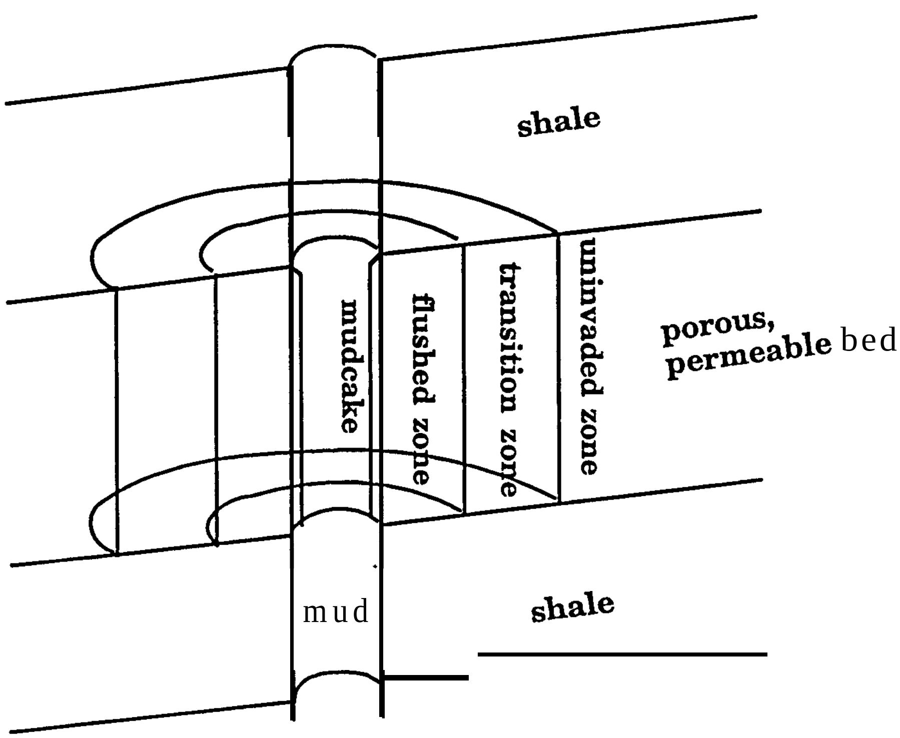
The preceding remarks on vertical resolution apply to all logging tools so that analysis by hand is most rationally done after zoning the logs as an initial step. As a general rule of thumb, the vertical resolution of the induction and larger laterologs runs at about 3-5 feet; the vertical resolution of the porosity tools is in the order of 1-2 feet. Variations of these figures are introduced by different design features in any tool series and the magnitude of contrast between adjacent beds.

In carbonates, situations frequently occur when the depth of invasion is great enough to adversely affect all conventional resistivity tools to a marked degree so that good direct estimations of Rt are precluded. Deep invasion is generally associated with low porosity or underpressured zones. It would be possible to develop a tool with sufficiently high radius of investigation to register a major resistivity contribution beyond deeply invaded perimeters. However, the price would be an exceedingly gross vertical resolution and consequent large-scale averaging of zones of interest. There are some cases, where invasion exceeds the reach of standard commercial resistivity tools, such as the Chase Group in the giant Hugoton gas field, where holes are sometimes drilled with air or foam to minimize invasion and so allow resistivity tools to obtain good readings for saturation calculations (Olson and others, 1997).

Cases of moderate invasion are resolved by running three different resistivity tools simultaneously (for a small slam) or four (for a grand slam). By utilizing the differing response characteristics of the tools, which are defined by the hardware design, the unknowns of the invasion profile may be deduced, namely the resistivities of the flushed zone and virgin formation, and the diameter or diameters of invasion. The small slam is usually made with a "dual induction-laterolog" (older) or "dual induction-spherically-focused log" (newer) combination which are common logging runs in Midcontinent boreholes, which penetrate thick platform carbonate sections. The three resistivity traces are recorded simultaneously on a logarithmic scale. The relative disposition of the traces gives an immediate impression of the degree of invasion in any zone. When the traces are almost coincident and the resistivity reading is low to moderate, invasion is virtually negligible and the resistivity is approximately Rt. With increasing invasion, the LL8 trace peels away to a higher value and is followed sluggishly by the IL_m trace and, to a lesser degree, the IL_d trace. Ultimately, if the depth of invasion is extraordinarily deep, the three traces will again roughly coincide in a common estimate of R_{xo}. Since the resistivities are recorded on a logarithmic scale, the resistivity reading ratios used in the tornado chart correspond directly with horizontal displacements on the log. As a result, a logarithmic rule to the same scale may be used to read the ratio values directly from the log.

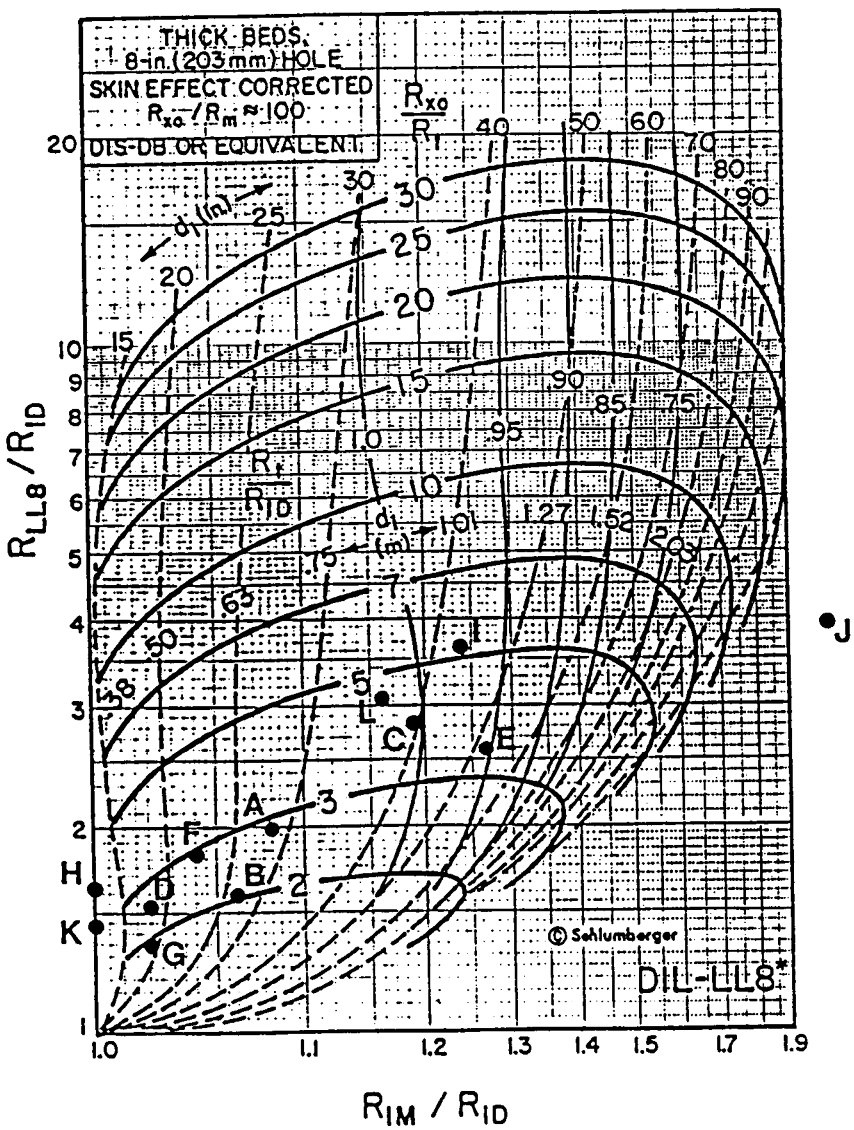


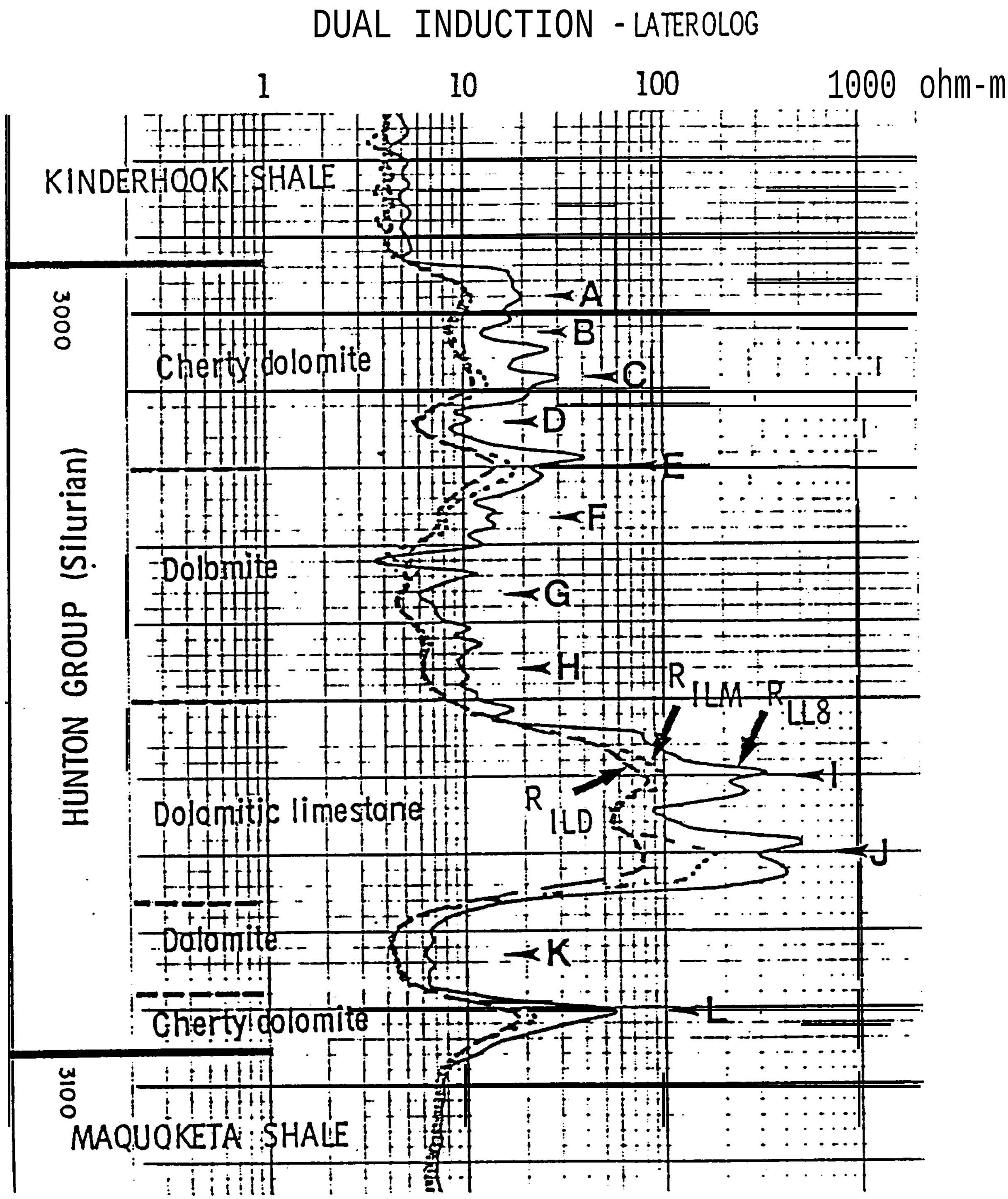
1000
100
10
1
0.1
Vertical resolution (inches)
Deep induction
Gamma ray
Sonic
Density
Deep laterolog
Neutron
Spherically focussed
Short normal
Electromagnetic propagation
Microspherically focussed
Micrulog
0.1
1
10
100
1000
Radial investigation (inches)



shale
mudcake
flushed zone
transition zone
uninvaded zone
porous, permeable bed
mud
shale

A dual induction - laterolog resistivity combination is shown of a water-saturated Hunton Group section in central Kansas. The resistivity variability is therefore regulated by the pore network brine content, with the primary control being the volume of pore space. High resistivity zones have relatively low porosities; low resistivity zones have high porosities. Notice the greater separations between the curves in the lower porosity zones, indicating greater invasion. By crossplotting the three resistivity readings as two ratios on a tornado chart, the true formation resistivity, Rt, the resistivity of the flushed zone, Rxo, and the diameter of invasion, di, can be estimated. Inspection of the plotted points shows that many of these do not need a correction to be applied to the deep induction resistivity - it appears to be reading the formation resistivity, Rt. However, the crossplotted point of one zone falls outside and to the right of the tornado, suggesting that in this case, invasion is so deep that the deep induction tool does not read beyond the flushed zone.





Dual induction - laterolog resistivity combination in the Hunton Group (Silurian) in the borehole USGS-KGS Geis #1, 32-13S-2W, Saline County, Kansas.