ELECTRICAL PROPERTIES OF ROCKS: EFFECTS OF SECONDARY POROSITY, LAMINATIONS, AND THIN BEDS

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Abstract: Pore geometries can be classified according to their electrical properties. Three main classes of conducting geometries are identified: 1) "Archie" rocks having a simple intergranular pore system similar to the rocks described by Archie (1942); 2) rocks with isolated porosity such as vugs, moldic pores, or microporous grains; and 3) rocks with components which have different capillary properties and which conduct as if the components were electrically parallel conductors. The electrical properties of the third category are often manifested as low resistivity pay.

Low resistivity pay can be encountered in a variety of geologic settings such as sandstones with diagenetic clay coatings, thin clean sandstones interbedded with shales, and aeolian sandstones. Any depositional or diagenetic environment which produces a rock fabric with a continuously connected system of small pores in addition to larger pores connected by proportionally large pore throats can result in low resistivity pay. In these types of bi- or polymodal pore systems, the capillary properties of the continuous systems of smaller pores results in a connected pore subsystem which is largely or completely water saturated. A coexisting system with larger pores may contain high hydrocarbon saturation. Such rocks can be modeled and understood using their capillary properties and a parallel conductor resistivity model. Using Archie's equation to evaluate hydrocarbon reserves in rocks of this class, low values of the saturation exponent *n* must be used, typically less than 1.5 and sometimes less than one.

Introduction

Wireline log analysis is the most commonly used method for the hydrocarbon-content evaluation of reservoirs. The accuracy of the evaluation depends on understanding not only logging tool response functions but also the effects of rock and pore geometry upon the conductivity distribution in a reservoir. In particular, some of the more subtle and interesting modes of water distribution in various "low resistivity pay" rocks have been understood only recently. This new insight helps to relate the effects of pore geometry on resistivity log interpretation.

Pore geometries can be classified according to their electrical properties. Three main classes of conducting geometries are identified: 1) "Archie" rocks having a simple intergranular pore system similar to the rocks described by Archie (1942); 2) rocks with isolated porosity such as vugs, moldic pores, or microporous grains; and 3) rocks with components which have different capillary properties and which conduct as if the components were electrically parallel conductors. The electrical behavior of the first two classes have been discussed previously; the relationship between water saturation, resistivity and porosity is accurately described by Archie's equation (1942) for Archie rocks; the electrical properties of rocks with isolated porosity have also been described previously (Herrick and Kennedy, 1995). The present paper concentrates on the electrical properties of the third category: rocks with conductive components differing primarily in their capillary properties.

Electrical Classification of Rocks

Sedimentary rocks can be classified by their low frequency electrical properties (Table 1). Archie's equation (1942) is used as the basis of the classification:

$$C_t = C_w S_w^n \phi^m, \qquad (1)$$

where C_t is the conductivity of the rock, C_w is the conductivity of the water in the rock, S_w is water saturation, ϕ is the porosity and n and m are fitting parameters determined experimentally. Rocks whose conductivity is accurately described by Archie's equation are classified as "Archie" rocks; others are "non-Archie" rocks (Herrick, 1988). Archie rocks are hydrophilic (water-wet) and have only simple intergranular or intercrystalline pore systems extending with similar geometric properties throughout the rock. Electrical conduction is exclusively through brine in the intergranular pore space. Non-Archie rocks differ from Archie rocks by having more complex pore systems, hydrophobic (oil-wet) pore surfaces, or multiple conduction mechanisms (e. g., conduction by exchangeable cations on clay mineral surfaces, or through conductive minerals such as pyrite, as well as through the intergranular pore water).

Electrical effects of large pores. Non-Archie rocks with complicated pore systems may be further classified by pore-type. Rocks with isolated moldic, vuggy, or other large pores distributed in a matrix with an otherwise Archie-like intergranular pore system exhibit non-Archie properties (Herrick and Kennedy, 1995). The dominant effect of large pores is to increase the bulk porosity over that of the matrix; bulk electrical properties are less affected and are controlled by the matrix (Figure 1a). When water-saturated, the water content of these rocks can be largely governed by the total volume of the large pores. Conversely, their conductivity is limited by the distribution and size of the pore-throats in the matrix; the high conductivity of the large pores is not effective in offsetting the resistance offered by the matrix pore throats. The result is less current flow than for Archie rocks having the same porosity. When described using Archie's formation resistivity factor relationship, such rocks exhibit a high value of the porosity exponent m (Figure 1b). Values as high as $m = 5$ are reported in the literature (Folke and Munn, 1985). In addition, in rocks having constant matrix properties but variable moldic porosity, the porosity exponent m varies with total porosity (Figure 1b).

A second pore geometry representing a variation in the behavior described above occurs where large pores (e. g. oomolds) are directly connected, or are close enough together to provide a preferential path for electric currents; such rocks conduct as Archie rocks if the large pores and their connections or electrical interactions are distributed isotropically. Non-Archie electrical behavior is observed when connected or electrically communicating large pores and the remainder of the pore space (i. e. intergranular pore space) are distributed into zones having different conductive and capillary properties. When such a rock is partially saturated with hydrocarbons, the differences in connectivity and capillarity among and between zones result in varying water saturation. In such cases, zones with higher water saturation conduct electricity better than hydrocarbon-rich zones; the rock conducts similarly to laminated and thinly bedded rocks (discussed below).

A third pore geometry having electrical properties similar to rocks with large isolated pores is exemplified by rocks with large volumes or nodules of low porosity poikilitic or "patchy" cement (e. g., anhydrite or calcite cement) or clasts that are significantly larger than the pores and grains of the rock matrix. Electric currents flowing through such rocks have to flow around the cement nodules or clasts (Figure 2). The effect is similar to the stagnant water upstream and downstream from a boulder in a river. The stagnant water does not contribute to the flow of the stream. Likewise the electrically stagnant pore water on the high and low potential sides of the cement nodule or clast does not contribute to electrical conduction. Hence, for rocks having this pore geometry, the electrical conductivity is lower than expected for a given water content. When these rocks are analysed using Archie's relationship, an abnormally high value of the porosity exponent m is required, usually with values significantly greater than the same rocks without the clasts or cement nodules (Figure 1b). As in the case of the first moldic pore geometry discussed above, m varies with porosity.

Electrical effects of microporosity: isolated microporous grains. Rocks containing dual pore-systems consisting of both macro- and micropores also exhibit non-Archie electrical behavior. Due to the difference in capillary properties between micro- and macropore systems, the micropores maintain a high water saturation and remain conductive when brine in the macropores has been displaced by nonconductive hydrocarbons. The micropore system may be discontinuous as it is in rocks containing isolated microporous grains such as partially dissolved feldspar or microporous chert grains separated from each other by numerous, non-porous grains of the rock matrix (Figure 1a). In these rocks, electrical connections between microporous grains are possible only through the intergranular macropore system. The main effect of the water bound in isolated microporous grains by capillary forces is to increase the water content of the rock beyond that of a similar rock containing no microporous grains.

The effect of isolated microporous grains on the conductive properties of a rock is small since electric current flow is controlled mainly by the geometry of the intergranular macropore system separating them. For a given water content, the conductivity of the rock is relatively low if a significant amount of water is bound in the microporous grains. The low conductivity results in a high value of the Archie porosity exponent m. The effect is similar to, but less pronounced than, identical rocks containing isolated moldic pores (Figure 1a) and m may similarly vary. For example, in rocks containing soluble grains such as feldspars, when the grains are intact, only intergranular porosity exists and the rock is a typical Archie rock. If the grains are partially dissolved so that they are microporous, then the conductivity is largely unaffected, but the porosity and water content are increased. Higher values of m are required to relate the higher porosity to the conductivity. When grains completely dissolve, m attains a maximum.

The presence of isolated microporous grains also affects the Archie saturation relationship. Since the capillary properties of the microporous grains tend to keep them water saturated, their main effect is on the water saturation. Water bound in isolated microporous grains is electrically connected only through the intergranular pore system of the matrix. When analyzed as Archie-rocks, the conductivity is unexpectedly low for a given water saturation leading to a high value of the Archie saturation exponent n. On the other hand, if the microporous grains are so numerous that they connect, or together with neighboring grains form highly conductive conduits, then two separate parallel conducting paths develop, one through the micropore system and the other through the intergranular pore system. The electrical properties of such rocks are similar to those with continuous microporous grain coatings as discussed next.

Electrical effects of microporosity: continuous microporous grain coatings. If the micropore system is continuous throughout the rock, as in the case of microporous authigenic clay grain-coatings, the rock then has dual pore systems; these tend to conduct in parallel (Figure 3a). The macropore system may have a highly variable conductivity depending on hydrocarbon saturation; the micropore system does not easily desaturate and maintains high conductivity. The result is a rock in which the micropore and macropore systems conduct in parallel. Regardless of high hydrocarbon saturation, the rock remains conductive since electric currents flowing through the micropores by-pass the resistive hydrocarbon-bearing macropores. The result of parallel conduction in continuous, microporous, clay grain-coatings is low conductivity contrast between water-saturated and hydrocarbon-bearing rocks. When these rocks are analyzed using Archie's equation, the value of n obtained is unexpectedly low, typically in the 1.3 to 1.5 range (Figure 3c). The conductivity contrast can be reduced even more if the grain-coating clay has exchangeable cations (e. g., illite), further contributing to the conductivity of the microporous clay system leading to yet lower n values, even $n < 1$.

Thin beds and laminations. A final class contains rocks that are thinly bedded or laminated (Figure 3b). Thin beds are taken to mean those which are sufficiently thin as to be unresolvable by a particular conductivity measurement process. For example, when a 6FF40 induction log is considered, beds less than a few feet in thickness are regarded as "thin"; when special core analysis measurements are considered, thin beds have thicknesses less than the diameter of a core plug. Much "low resistivity pay" can be attributed to thin or laminated beds. The electrical properties of rocks with thin or laminated beds is discussed in detail below.

Electrical Properties of Thin Beds and Laminations Having Differing Capillarity

Resistivity index of rocks with thin beds or laminations. A reduction in measured conductivity contrast between thinly-bedded, water-saturated, and hydrocarbon-bearing rocks occurs whenever the beds or laminations have differing capillary properties. Well-known examples are the thinly bedded sands and shales in the Gulf of Mexico comprising significant amounts of low resistivity pay. Less well known are the electrical properties of thinly-bedded sands which may have little or no shale, whether as beds, laminations, or authigenic clay coatings. These are typified by certain turbidites and aeolian dune sands.

During the 1980s, many reservoirs were discovered and developed in aeolian sandstones; e. g., the Dakota, Nugget, and Norphlet sandstones in the U. S. and Rotleigendes sandstones in the North Sea, U. K., and Europe. Early resistivity index measurements made on core from these reservoirs indicated that the Archie saturation exponent n was unusually low, often in the 1.3 to 1.6 range, with occasional values less than one (Figure 4). Initially these unusual values were regarded as erroneous; much work was done to discover the source of the error. Eventually the measurement procedures were validated and low n values were accepted as correct even though the cause was not understood. Petrographic studies revealed that the dune sands are not massively uniform as suggested by logs, but are bedded on an extremely fine scale, having "micro-beds" often less than one millimeter in thickness (Figure 5). Grain size varies considerably from micro-bed to micro-bed. The difference in grain and pore size engenders differences in capillary properties among micro-beds, implying that water saturation might vary appreciably from one micro-bed to the next (La Torracca, 1991, Beck, 1995).

The electrical effects of thin beds with different capillary properties can be illustrated using a simple model. Capillary pressure curves are given in Figure 6 for three rock types (numbered 1 through 3) which are subsequently used to create model rocks made from layers of each rock type. The grain and pore size of each rock type is in the order 1 > 2 > 3. Rock types 1 and 2 are Archie rocks which can be desaturated over the capillary pressure range of interest. Rock type 3 is so fine-grained that the entry pressure is not exceeded over the pressure range under consideration and represents a siltstone or shale. Thinly bedded model rocks can be constructed from the three rock types. The capillary properties of a model consisting of equal volumes of types 1, 2, and 3 are illustrated in Figure 7.

Poupon (1954) described the conductivity of interbedded sands and shales by assuming that the beds behave similarly to conductors in a parallel circuit. The contribution of each bed is assumed to be proportional to the volume fraction of each bed:

$$C_t = V_{ss}C_{ss} + V_{sh}C_{sh}, \qquad (2)$$

where V_{ss} and V_{sh} are the volume fractions of sandstone and shale, respectively, and C_{ss} and C_{sh} are the corresponding conductivities. Poupon's equation can be generalized to all layered conductive rocks:

$$C_t = \sum_i V_i C_i, \qquad (3)$$

where V_i is the volume fraction of each bed and C_i is its conductivity. For the purpose of modeling, the conductivity within each bed is assumed to be described by Archie's equation (1). Substituting Archie's equation in (3) gives the conductivity parallel to the layering of a composite model consisting of Archie laminations,

$$C_t = C_w \sum_i V_i S_{w_i}^{n_i} \phi_i^{m_i}. \qquad (4)$$

To model the conductivity of a thinly bedded rock, the water saturation of the ith bed is taken from the capillary pressure curves for a given value of capillary pressure (or hydrocarbon column height). The conductivity is determined by assigning values of V_i, C_{wi}, ϕ_i, n_i, and m_i for each bed.

For example, the model given in Figure 7 has equal volume fractions of rock types 1, 2 and 3, and has identical petrophysical properties in each lamination: $\phi_i = 10\%$, $V_i = 1/3$, $m_i = 2$ and $n_i = 2$. Values of C_t are computed from (4) for a range in S_w including the water saturated state ($C_t = C_0$ at $S_w = 1$, where C_0 is the conductivity of a water-saturated rock). Rock type 3 remains water saturated over the range of capillary pressures considered. The resistivity index $I = C_0 / C_t$ is related to water saturation by Archie's second relationship,

$$I = S_w^{-n}. \qquad (5)$$

The saturation exponent of the laminated model is determined from the slope of a line fitted to the log I vs. log S_w relationship as indicated by equation (5) (Figure 8). The saturation exponent for the example model is $n = 1.3$, despite each layer having $n = 2.0$.

That $n = 1.3$ for a composite model of laminated rock components, each of which has $n = 2$, is startling; however, it is consistent with laboratory data from laminated and thinly bedded rocks such as aeolian dune sandstones (Figures 4 and 5), and is a direct result of the parallel conduction of beds with different hydrocarbon saturations and conductivities. The more similarity there is between the capillary properties of the components, the closer the composite n value is to the arithmatic average of the components. Conversely, the more diverse the capillary and conductive properties and the greater the range in water saturation between components, the more the composite n value is reduced.

It is important to point out that if beds are thick enough to be resolved by some high vertical resolution logging tool, then the conductivity of each bed may frequently be determined separately by modeling the deep resistivity log response. This analytical technique is becoming routine for the 6FF40 induction log and may soon be generally available for most resistivity devices. If the beds or laminations are unresolvable, then an appropriately low value of n determined by application of (4) and (5) is required to calculate the average water saturation of the unresolved laminated unit.

Electrical properties of thin dipping beds. If thin or laminated beds are not perpendicular to the wellbore, then there is a series component to electrical conduction in addition to the parallel conduction described above.

The series component can be computed for the model rock as a function of water saturation. Figure 9 gives the resistivity index-water saturation relationship for series conduction perpendicular to the laminations of the model rock as well as the relationship for conduction parallel to the laminations.

The effect of measurement direction is dramatic and reflects the series or parallel measurement of a set of beds varying in hydrocarbon content due to differences in capillary properties. The value of the saturation exponent n, needed for Archie analysis for the case in which the electrical measurement currents flow parallel to bedding, is $n = 1.3$ as determined above. The average n value for the series case, however, is much higher, $n = 6.8$. In the parallel case, the conductivity is dominated by rock type 3 which remains water saturated and conductive. The resistive hydrocarbon-bearing beds 1 and 2 control the conductivity in the series case. Figure 10 illustrates that n values between 1.3 and 6.8 result when electrical measurements are made at selected intermediate angles with respect to bedding.

As an example of one important log-derived electrical parameter, the effect of formation dip on the apparent conductivity C_a of both conventional electric logs (e.g., normals and laterals) and the induction log response is (Moran and Gianzero, 1979),

$$C_a = C_p \sqrt{\cos^2 \theta + \left(C_s / C_p\right) \sin^2 \theta}, \qquad (6)$$

where θ is the dip angle, C_p is the conductivity parallel and C_s is the conductivity perpendicular to the beds. When there is no dip ($\theta = 0$) C_a reduces to C_p; i.e., the case of parallel conductivity discussed above. Conversely, C_a never reduces to C_s, even at $\theta = 90°$. When $\theta > 0$ the apparent conductivity is influenced by the dip angle as well as both perpendicular and parallel components of conductivity. The tool response averages the thin bed conductivities and an appropriately low value of n is required to calculate the average water saturation.

C_p and C_s can be estimated from conventional core resistivity measurements if the laminations or beds are thick enough so that a representative core plug can be obtained from each bed. When the beds are very thin (e.g., in the case of aeolian dune sandstones) then non-standard core analysis methods are required to obtain C_s. Laboratory methods for measuring C_s of anisotropic laminated samples have been described by Sprunt et al. (1990), Givens and Kennedy (1992) and Kennedy and Givens (1992). In favorable cases, the component conductivities can be estimated from wireline log measurements (Moran and Gianzero, 1979; Hagiwara, 1994), or from LWD logs (Hagiwara, 1995). C

The resistivity index-water saturation relationship for 45° and 90° dip of the wellbore relative to bedding were computed from (6) and plotted in Figure 10 along with the relationship for parallel and series conductance. Note that the resistivity indices for 90° dip are less than those for the series conduction case. The induction log cannot respond to the series component of conductivity alone. Even at 90°, there are both parallel and series components in the response. The value of n required to calculate the correct average water saturation for the model rock depends strongly on the angle between the thin beds and the wellbore, or measurement axis. For example, if the average porosity of the model rock is 20%, the porosity exponent is $m = 2$, and the average value of C_a/C_w is 0.0084, then the calculated S_w lies in the range of 30% ($n = 1.3$) to 68% ($n = 4$) depending on dip. Whether the calculated water saturation is correct depends on accurate knowledge of the relative dip between the bedding and the wellbore.

Discussion: Resistivity Interpretation of Rocks with Laminations and Thin Beds

Rocks with thin beds or laminations having different capillary properties, as well as rocks having authigenic clay coatings, are difficult to analyze for hydrocarbon saturation. When they contain hydrocarbons, their resistivity can nevertheless be very low, engendering the description "low resistivity pay". Successful analysis of such rocks depends on knowledge of the presence of laminations or thin beds, the capillary properties of the individual beds, and whether the beds dip relative to the wellbore or measurement axis. When rocks have authigenic clay coatings, knowledge of the amount of microporosity associated with the clay is required along with the cation exchange properties of the clay.

Rocks with thin beds or laminations unresolved by the conductivity measurement employed and those with clay coated grains behave electrically as a system of parallel conductors. Poupon's equation (2) can be generalized to quantify the conductivity of these rock types (equation 3). If the conductivity measurement method cannot resolve the beds, laminations, or grain-coatings then a volume average of conductivity is measured. Average water saturation corresponding to such average conductivity can be computed using Archie's equation if an appropriate value of the saturation exponent n is used. For example, Figure 11 gives the resistivity index-water saturation relationship for a rock unit with resistivity index $I = 7$. If the rock is an Archie rock, then a value of $n = 2.0$ may be appropriate to calculate the true water saturation. If the rock is laminated, the laminations differing in capillary properties, then water saturation varies among the laminations. The bulk conductivity of the rock is relatively high, even with significant hydrocarbon saturation, since beds with high water saturation dominate the conductivity. Accurate determination of the average water saturation of the rock unit requires a low value of the saturation exponent; e.g., $n = 1.3$ for the example in Figure 11 is determined by modeling using (4). If the grains are clay coated, the value of n required for accurate calculation of S_w is further reduced due to the continuous conductive water phase in the clay micropores. When the clay has exchangeable cations also contributing to the conductivity, the value of n required to correctly evaluate S_w is reduced yet again, sometimes taking on values less than one. If the specific example in Figure 11 is considered to be laminated, with authigenic clay-coated grains, the very low saturation exponent $n = 1$ gives a (true) water saturation $S_w = 14\%$ for the resistivity index $I = 7$. If the rock were instead assumed to be an Archie rock with $n = 2$, then the calculated S_w would be 38% rather than the actual value of 14%.

When thin beds or laminations are inclined relative to the borehole or measurement axis, then a series conductive component is combined with the parallel component; the resulting bulk conductivity is described by (6). The effect of inclined beds is to increase the value of n required to calculate the correct average water saturation. For the example given in Figure 11, $n = 4$ is required to calculate the correct water saturation of 61% if the beds are steeply dipping and I = 7.

Conclusion

In general, for thinly bedded or laminated rocks that may also contain clay-coated grains, the value of the saturation exponent n required to calculate the correct average water saturation can vary widely from less than 1 to in excess of 4. Determination of the value of n required to correctly calculate S_w depends on an understanding of the scale of bedding, the variability in the capillary properties among the beds and various laminations, and the relative dip between the bedding and the measurement device.

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Archie Rocks	Non-Archie Rocks
Simple homogeneous pore system • only intergranular porosity	*Complex or heterogeneous pore system* • moldic / vuggy porosity - isolated - connected e. g., oomoldic carbonates • microporosity - discontinuous e. g., microporous chert - continuous e. g., authigenic clay coatings • laminations or thin-beds • patchy cement / large grains or clasts
Hydrophylic (water-wet)	*Hydrophobic* (oil-wet)
Single conduction mechanism • through intergranular pore water	*Multiple conduction mechanisms* • cation exchange on clay minerals • metallic conduction on sulfide minerals e. g., pyrite

Table 1: Rock classification according to electrical properties (modified from Herrick, 1988).

Figures

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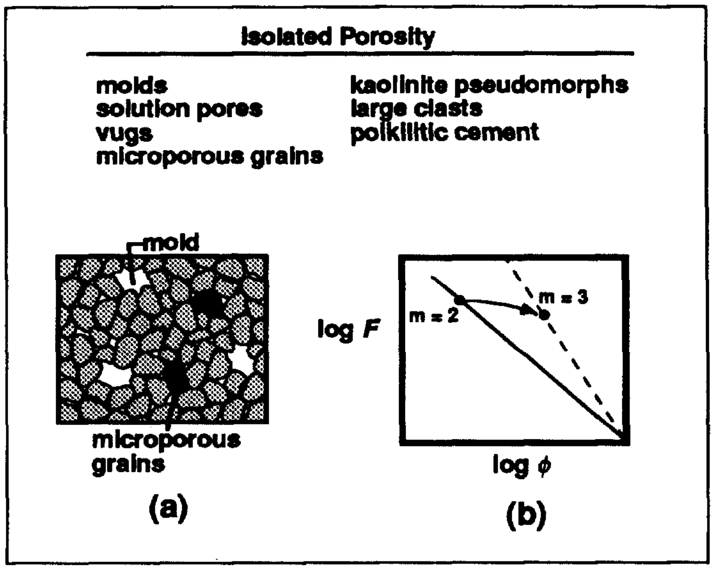

Figure 1. Examples of isolated porosity and its effect on the F-ϕ relationship. The presence of isolated porosity generally increases the value of m.

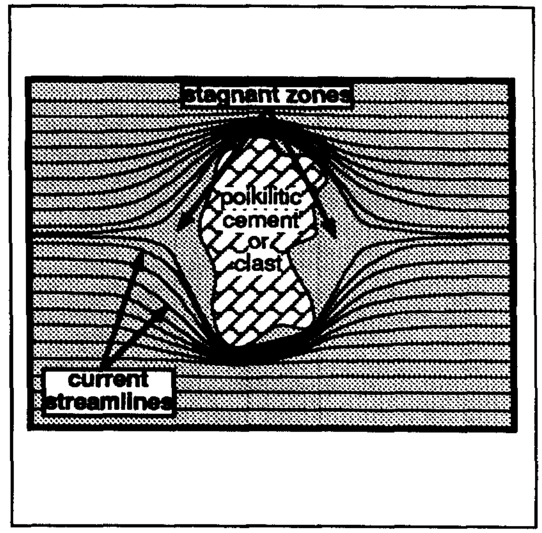

Figure 2. Large clasts or volumes of poikilitic cement generate significant volumes of electrically stagnant water.

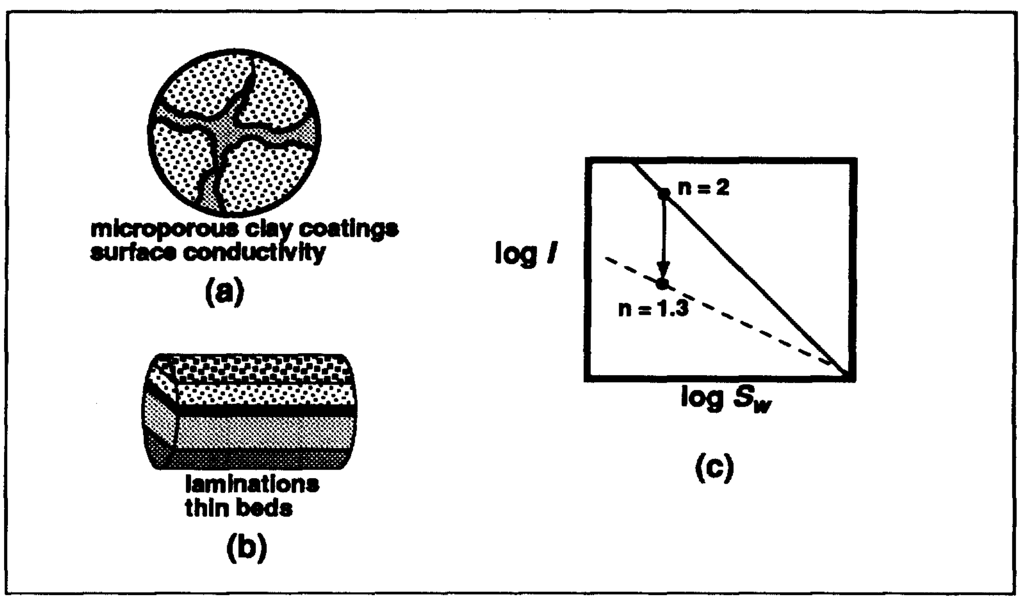

Figure 3. Parallel conduction paths with different capillarity occur in rocks with laminated beds and authigenic clay grain-coatings. The electrical effect of these parallel paths is to reduce the saturation exponent.

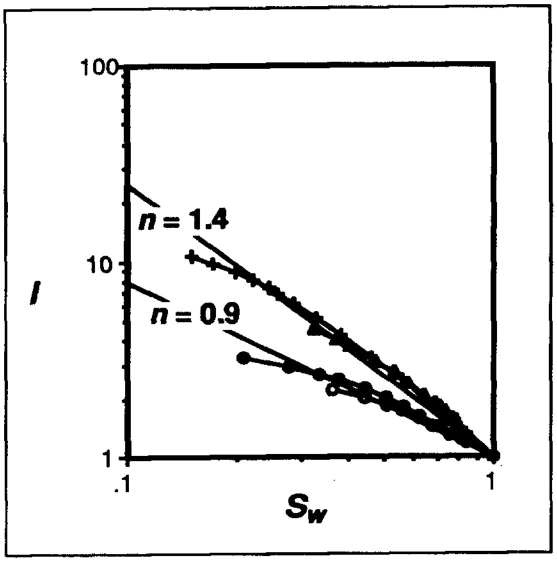

Figure 4. Measured resistivity-index curves for four aeolian dune sandstone samples.

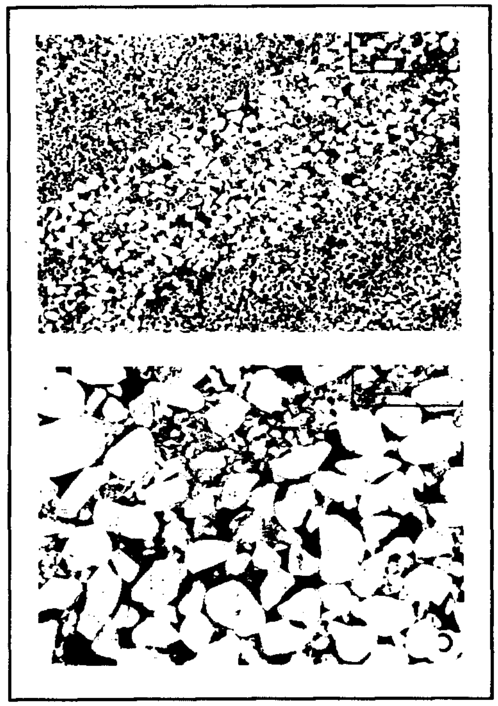

Figure 5. Thin section of an aeolian dune sandstone at high and low magnification. The difference in grain size between micro-laminations causes different capillary properties and varying water saturation between laminations.

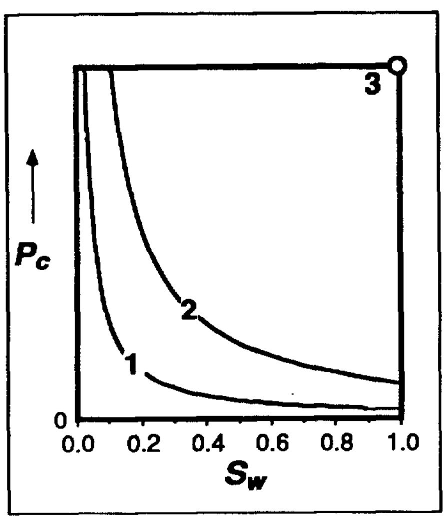

Figure 6. Model capillary pressure curves. Rock type 3 does not desaturate over the pressure range of the example and this is represented by a vertical line at $S_w = 1.0$; Rock type 3 is representative of a shale or siltstone.

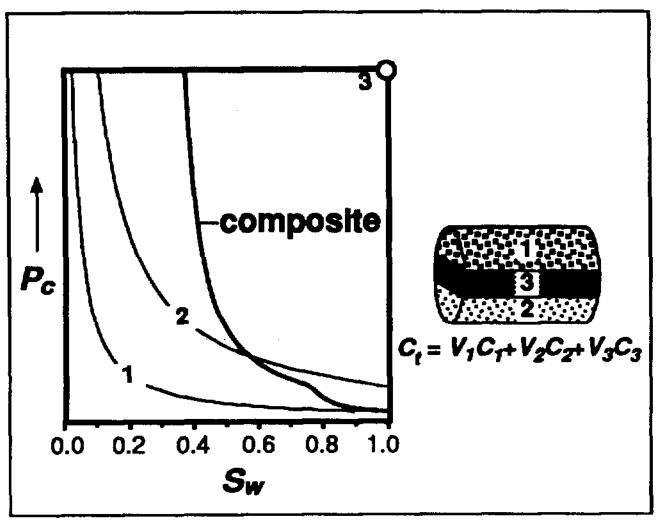

Figure 7. Capillary properties of a model rock. The conductivity of the model conducting parallel to bedding is the volume-weighted sum of the conductivites of the beds.

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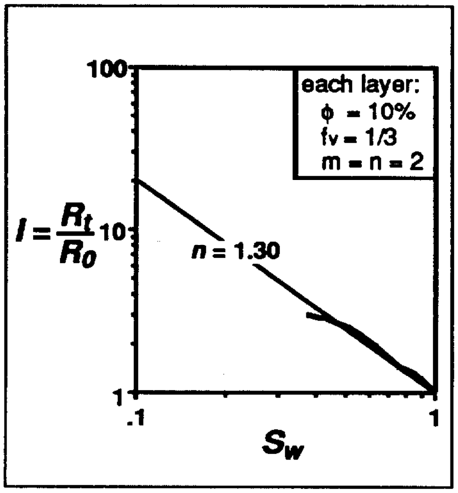

Figure 8. I-S_w relationship for layers 1, 2, and 3. Despite each layer having n = 2, the composite n = 1.3.

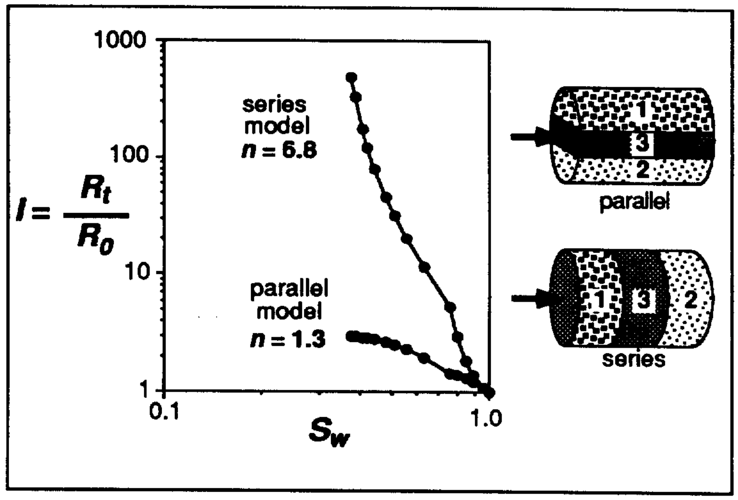

Figure 9. Model rock samples conducting in series or parallel result in very different n values.

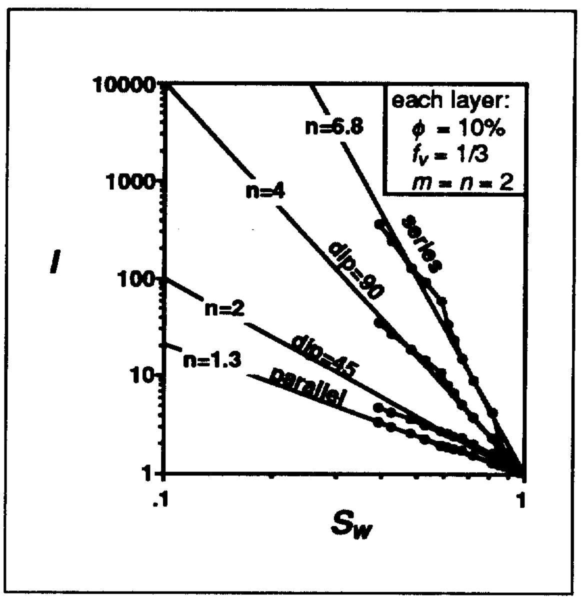

Figure 10. The saturation exponent varies widely as a function of dip angle for a model rock consisting of three layers (1, 2, 3: Figure 6).

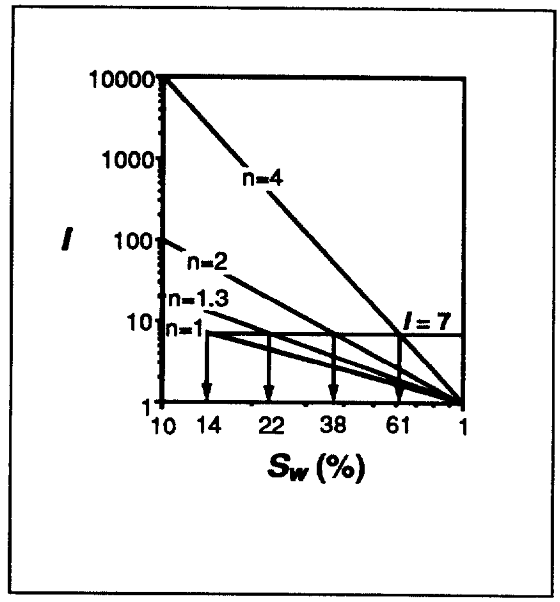

Figure 11. n may vary greatly due to layering, dip, clay coatings, capillary properties or other causes. The accuracy of calculated water saturations depends on understanding these factors.