ELECTRICAL RESISTIVITY ANISOTROPY DUE TO PORE SCALE STRUCTURE

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ABSTRACT

Electrical resistivity measurements are used to estimate the water saturation in hydrocarbon reservoirs. For clean rocks the interpretation methods are based on Archie's equations, but these equations do not consider directly any heterogeneity or anisotropy of the porous media. Electrical anisotropy is the variation of electrical resistivity with the direction of measurement; i.e., the resistivity varies in different directions (tensor). This paper studies both experimentally and theoretically the electrical anisotropy in clean, fully saturated porous media due to the pore level structure characteristics. Systematic packs of spheres of known structure and morphology have been built, their pore space saturated with brine and the resistivity measured in orthogonal directions. The pore space structure of these packs were determined and mathematically reduced to an equivalent network and the electrical formation resistivity factor calculated using these pore space dimensions. The calculated resistivity in perpendicular directions gave good agreement with the experimental results. These studies show that anisotropy within a bed plane can exist due to the tensor characteristics of the electrical resistivity. This resistivity characteristic has importance in log interpretation, not only for vertical wells, but also and especially for deviated and horizontal wells.

INTRODUCTION

Electrical resistivity logging gives essential information about the water saturation within reservoir rocks needed to evaluate the oil-in-place. Interpretation methods are based on modification of Archie's equations[1, 2]. Archie proposed in 1942 a relationship between porosity and resistivity for a rock fully saturated with brine:

$$F = \frac{Ro}{Rw} \quad ; \quad F = \frac{1}{\phi^{m}} \qquad \qquad (1)$$

where F is the formation factor, Rw is the brine resistivity, Ro is the resistivity of a rock fully saturated with brine, ϕ is the porosity and m is an empirical constant. However, reservoir rocks normally have complex characteristics at different scales (pore scale, core scale and log scale). One of the effects of this complex structure is that the rock has electrical anisotropy, i.e., the resistivity is different in different directions of measurement.

Electrical anisotropy has been known for a long time[3] but it has not been studied in depth and usually (almost) ignored in resistivity log interpretation. The **total** anisotropy is the combination of both the **macroscopic** and **microscopic** contributions. The macroscopic anisotropy (beds of different resistivities) is usually caused by a sequence of parallel (and homogeneous) layers with different resistivity, whilst the microscopic anisotropy (within a single bed) is caused in part by the shape and orientation of the grains in an apparently homogeneous rock. The scale of anisotropy depends on the characteristics of the rock and the resolution of the resistivity measuring tool. The recent increase in the number of deviated and horizontal wells and their log interpretation has highlighted the problem of anisotropy[4, 5]. If the existence of anisotropy is not considered in log interpretation then the water saturation and hence the oil-in-place calculated may be in error. Some effort has been given to the macroscopic anisotropy, due to this practical importance in wells[6, 7 8].

The existence of microscopic electrical anisotropy in cores has also received some attention[9, 10, 11]. The measured anisotropy can be considered as microscopic anisotropy as there is no mention to the existence of layers within the cores, and they were probably homogeneous (at least to the eye because no X-ray or CAT scanning was available at the time). Sawyer et al.[10] found that cores from the Bradford and Gordon sands have vertical and horizontal anisotropy. The resistivity of a fully saturated sample, measured perpendicular to the faces of a cubic rock specimen with the four electrode technique, showed differences in different "horizontal directions" which was also reflected in permeability measurements. Wyllie and Spangler[9] also reported differences in permeability and resistivity in three directions, measured perpendicular to the faces of a cubic rock specimen described as shale free and from the Pennsylvanian age.

This work studies the electrical microscopic anisotropy in fully saturated media with intergranular pore space so that the conduction is due only to the ions in the water phase. We focus on the pore scale structure elements and we have used packs of spheres as porous media where we can control the geometry precisely so allowing us to study the influence of the pore structure. Four systematic packs of spheres were built and their resistivity measured in two perpendicular directions.

PORE SPACE CHARACTERISTICS OF THE PACKS OF SPHERES

The packs will first be defined and then their pore space described. A **systematic pack** is an arrangement of uniform **layers** on top of each other. A **uniform layer** is a group of spheres of uniform diameter, **d**, in contact with each other. In this work the limiting cases of square (90°) and rhombic (60°) layers are considered, Figure 1.

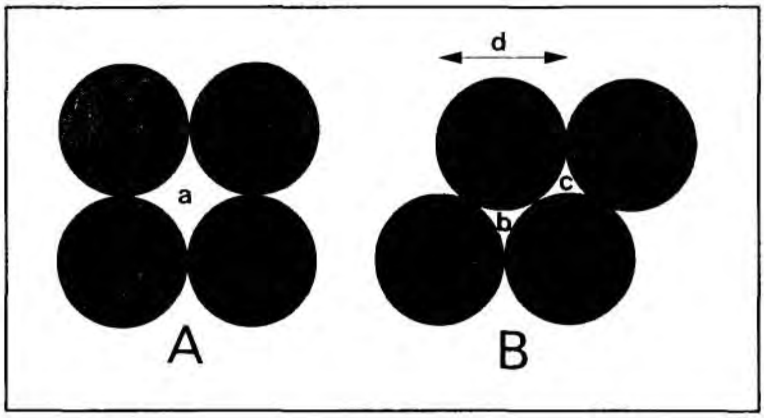

Figure 1- Plan structure of a layer. A- square. B-rhombic.

The layer is the basic building block needed to obtain different packs. Different types of packs can be obtained by displacing the alternate layers. A schematic representation of the theoretical packs used in this work and their pore space are shown in Figure 2:

Pack 1 (orthorhombic): Here the basic structure of this pack is the "square" layer (spheres in a square lattice, Figure 1-A) but the successive layers are displaced a distance **d/2** from the layer below. Thus the angle formed between layers is 60^0. The pack has a porosity of 39.54%.

Pack 2 (rhombohedral or face-centered): The square layer is also the basis of this pack but the successive layers are located over the central point of the diagonal of the lower layer (point **a** in Figure 1-A). Thus the vertical distance between the centre of the layers is 0.707 **d**. This pack has the minimum porosity of the sphere packs with a square layer (25.95 %).

Pack 3 (tetragonal): This pack has rhombic layers (Figure 1-B) and the successive layers are displaced a distance **d/2**. The layers form an angle of 60^0 and generate a rhombic structure in two planes and a square structure in the third. The distance between layers is 0.866 **d** The pack has a porosity of 30.19 %.

Pack 4 (hexagonal): The rhombic layer is also the basis of this pack but the second layer is placed so that the spheres are located above position **b** (Figure 1-B), giving the distance between layers of 0.816 **d**. It is important to notice that if a sphere is in position **b** then position **c** will remain empty (a sphere will not fit in it because it will be surrounded by spheres in a rhombic arrangement) which creates two types of paths. The rhombic structure is present in all directions. This pack also has a porosity of 25.95 %, and its composite nature is of special importance for our study of electrical resistivity behaviour because it has the same porosity as pack 2 but a different structure.

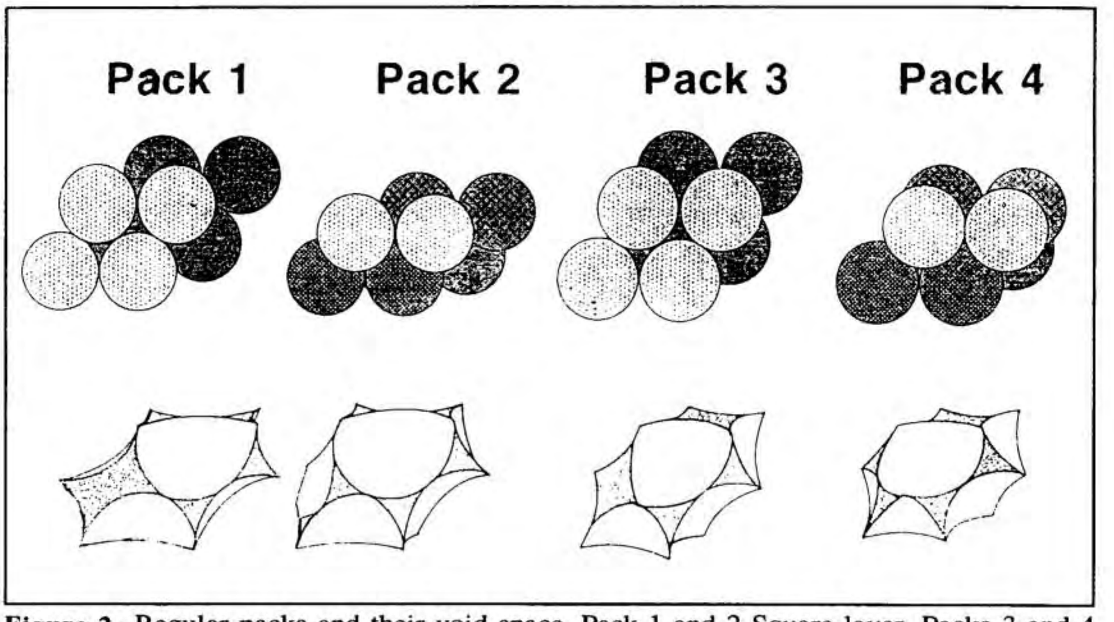

Figure 2- Regular packs and their void space. Pack 1 and 2 Square layer. Packs 3 and 4 rhombic layers. Modified from Gratton and Fraser[12].

The basic structure for each pack is called the **unit volume cell** and can be defined as the minimum portion of a systematic pack which gives a complete representation of the pack and the void contained in it (unit void cell, Figure 2). The unit volume cell is bounded by the planes which intersect the centres of the adjacent spheres, forming a rectangular parallelepiped (6-sided body of square or rhombic base and rectangular sides). The main characteristics of the packs studied are presented in Table 1.

Table 1 - Basic characteristics of the systematic pack of spheres.

	Pack 1	**Pack 2**	**Pack 3**	**Pack 4**
Type of Layer	Square	Square	Rhombic	Rhombic
Layer Spacing	$d.\sqrt{3/4}$	$d.\sqrt{2}$	$d.\sqrt{3/4}$	$d.\sqrt{2/3}$
Volume of Unit Cell	$0.87\ d^3$	$0.71\ d^3$	$0.75\ d^3$	$0.71\ d^3$
Porosity (%)	39.54	25.95	30.19	25.95

The throat planes (which separate adjacent pores) also intercept the centres of adjacent spheres and so the throats are located on the faces of the unit volume cell. There are two types of throat: i) concave-square formed by four adjacent spheres, ii) concave-triangle formed by three adjacent spheres, Figure 2 shows the faces clearly. For example, the rhombic layers form a double concave-triangular throat connected by the corners and the square layer form a concave-square throat. Thus all the packs studied here have a combination of concave-triangular and concave-square throat shapes in different directions. Also in these packs of spheres the porosity is proportional to the distance between layers, and the voids are interconnected so producing a succession of throats and pore bodies. The systems with square layers (packs 1 and 2) have a larger porosity than the ones with rhombic layers (packs 3 and 4) for the same way of stacking thus we can compare the packs by the way of stacking or by porosity changes.

EXPERIMENTAL MEASUREMENTS

The packs of Figure 2 were constructed in the laboratory using plastic balls of 2.0 cm of diameter. An example is shown in Figure 3. The packs were constructed with four balls per basic layer and 2 or 3 layers. The assembled layers were carefully placed inside perspex boxes (with the correct shape: square or rhombic). Whenever necessary, the balls were cut to fit into the box, according to the pack requirements, to avoid wall effects. Such wall effects can affect the flow and resistivity behaviour and could occur if there is a change of pore morphology between the balls and the container[12].

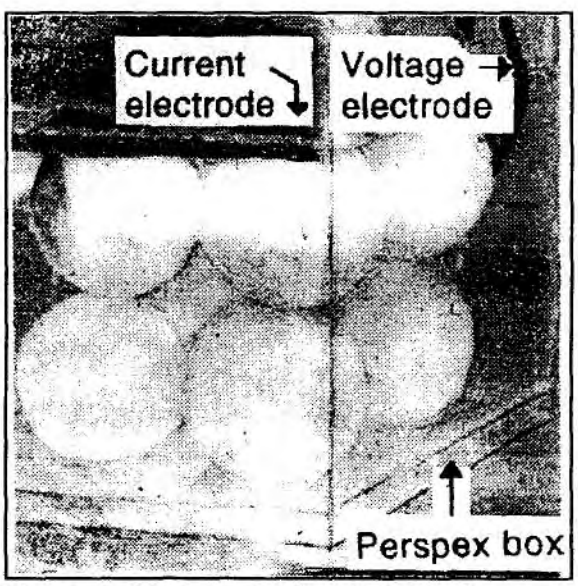

Figure 3- Photograph of pack 3 into the perspex box.

The pore space was then saturated with brine of 5 to 10 % (by weight) of NaCl. The resistance was measured using a four electrodes technique at 2000 Hz[13,14]. Two metal screens were located at the top and bottom of the pack (current electrodes) to introduce a uniform current across the pack. The voltage electrodes were installed at positions within the pack by passing wires through the balls and locating the electrodes (silver wires) in the throats. In this way the measured resistance corresponds to the known distance between layers and the transverse section is of one unit volume cell. The resistivity in a direction parallel to the layers was measured by setting the electrodes in an orthogonal direction. The mean experimental formation factor values (F_{exp}) are presented in Table 2.

Table 2 - Main characteristics of the ball-packs used.

PACK		Porosity %(ϕ)	Coordination Number (Z)	Aspect Ratio (PAR)	Throat Type	Experimental F_{exp}	Experimental σ	F_{calc}
1	X	39.5	7	1.2	s	3.62	0.29	3.44
	Y	39.5	7	6.7	t	2.82	0.09	2.92
2	X	26.0	8-3-8	1.0	s	5.51	0.42	5.20
	Y	26.0	8-3-8	5.4	t	3.52	0.07	3.41
3	X	30.2	7-6	5.1	t	3.15	0.04	3.02
	Y	30.2	7-6	5.1	t	3.35	0.29	3.34
4	X	26.0	8-4	6.6 1.0	t	2.55	0.18	2.62

X = perpendicular to the layer plane, Y = parallel to the layer plane, s= square throat, t= triangular throat, σ= standard deviation, F_{calc}= calculated with the equivalent network model.

EQUIVALENT NETWORKS AND MATHEMATICAL MODEL

The systematic packs generate a 3-D networks of pores and throats in which the shape, size of pores and throats are uniquely defined by each pack. These pore spaces can be drawn out and their structure reduced to their equivalent network. Figure 4 shows the equivalent networks for the four packs and Table 2 gives the main characteristics; the full methodology is described in reference 14. The topology and structure of the unit volume cell and its equivalent network can show the isotropic or non-isotropic nature of the packs. Thus, the observation of the equivalent network can give an indication of the directional behaviour that can be expected for the electrical resistivity.

Examining the void space (Figure 2) and the networks (Figure 4), Pack 1 can be seen to have two types of path in perpendicular directions. The coordination number, **Z**, is the number of connections that a pore has to the neighbouring pores and is equal to seven, with five branches on one plane and the other two perpendicular to it. Therefore, the electrical resistivity of the pack will depend on the direction of measurement (vertical/horizontal). Packs 2, 3 and 4 have very complex topologies with two types of pore in each void cell: one of large size and highly interconnected (**Z**, seven or eight) and another smaller and less interconnected (**Z**, three, six and four respectively). Additionally pack 4 has two types of path perpendicular to the layer plane; one directly connected to the upper and lower layers and the other restricted within the layer. This shows that the electrical resistivity will be non-isotropic due to the structural characteristics of the pore space.

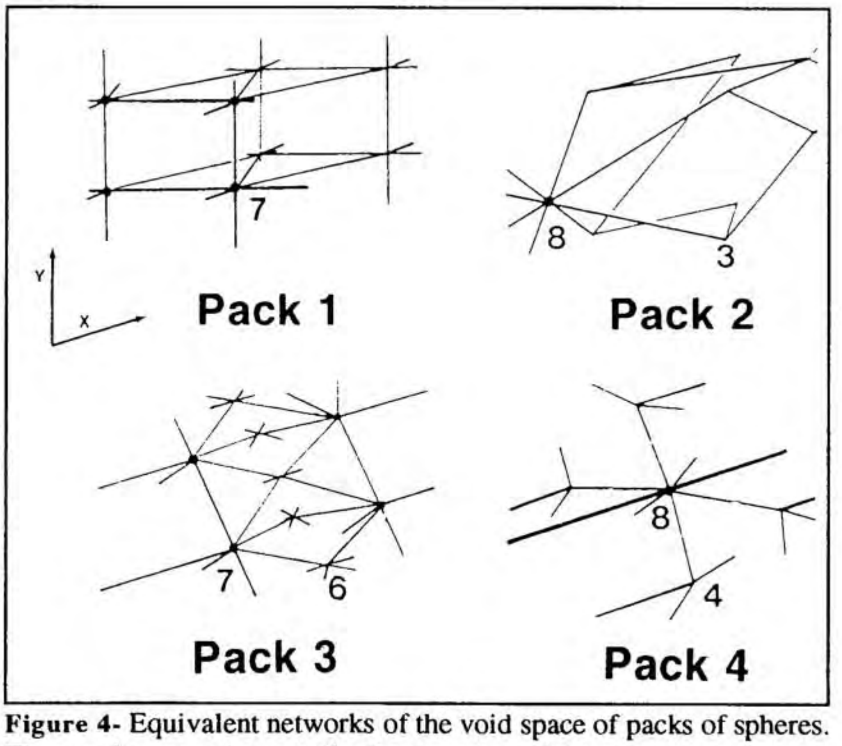

Figure 4- Equivalent networks of the void space of packs of spheres. The numbers are the coordination number of the pores.

The resistance of the packs can be calculated using these equivalent networks and the dimensions of each branch. The basic equations of the network are based on Ohm's law for each branch (current flowing between two neighbour pores or junctions) and Kirchoff's current law for each node (conservation of current and no accumulation of charge at a pore). The basic equations can be written as nodal current equations creating a linear system of equations. This system can be solved numerically to calculate the resistivity, Ro_{calc}, and the formation factor, $F_{calc}=Ro_{calc}/Rw$, of the saturated pack (full details appear in reference 14).

RESULTS

The experimental measurements and the calculated values of resistivity are reported as formation factors (obtained as ***Ro/Rw***) and are given in Table 2. As can be seen the agreement between experimental (F_{exp}) and calculated (F_{calc}) values is very good. The difference in the formation factor in different directions (i.e, **X** and **Y** in Table 2) shows the non-isotropic behaviour of these packs as was predicted by the equivalent networks. A measure of the anisotropy is given by the anisotropy coefficient, λ, defined as :

$$\lambda = \sqrt{F_X / F_Y} \qquad (2)$$

where F is the formation factor and the subscripts **X** and **Y** denote two normal directions respectively. The values of the anisotropy coefficient for our packs are shown in Table 3. Pack 3 has the resistivities reversed with respect to packs 1 and 2 due to the topology of the internal pore structure (see network of pack 3 in Figure 4).

Table 3 - Experimental and calculated anisotropy coefficients.

	Pack 1	Pack 2	Pack 3
λ experimental	1.13	1.25	0.97
λ calculated	1.08	1.23	0.95

It has also been found that the packs 2 and 4 which have the same porosity and size of spheres have very different values of the formation factor. Thus internal pore structure differences have a definitive influence on resistivity. These results show that the microscopic electrical resistivity anisotropy occurs due to the internal pore structure of the porous media (mainly topology), even though the porous media is homogeneous on a bulk scale. Different amounts of anisotropy can be observed even for spherical particles with the same size.

PORE SPACE PARAMETERS: The characteristics of the packs studied have a systematic variation but the influence of the pore space parameters such as ϕ, **Z**, length and cross sectional area of the unit cell, etc. are more difficult to identify and interpret.

From a comparison of the results of our packs, Table 2, the following patterns can be observed:

- A decrease of F is associated with an increase in pore-to-throat aspect ratio, decrease in distance between layers and mean pore transverse area (packs 1 and 2).
- Comparing F in perpendicular directions shows that the topology is responsible for producing the anisotropy (packs 1, 2 and 3).

The understanding of the influence of the different parameters (e.g., the role of coordination number or topology) is not yet fully clear in order to confidently extrapolate their influence to real systems. For instance, the effect of coordination number on the directional resistivity is not certain because of the joint effect of different factors. Finally, there are also some variables that cannot be changed independently such as mean cross sectional area (pores-throats) and length.

CONCLUSIONS

The microscopic electrical anisotropy behaviour is caused by the pore structure effects. The implications in core analysis and well log interpretation is so significant that the influence of the direction of measurement in cores should be studied in detail in order to quantify the resistivity tensor. Commonly it is assumed that the principal axes of the tensor are parallel and perpendicular to the bedding planes. This cannot always be true and plugs should be taken to study the microscopic resistivity anisotropy. If the principal directions are not confidently known a more complicated procedure to measure the resistivity tensor is necessary. To obtain this tensor a minimum of six resistivity values in different directions are needed, so that the principal directions orientation and the moduli of the components of the tensor are known. Even so, the resistivity of natural rocks is likely to be inaccurate and the true values of the tensor may be difficult to determine. The non isotropic resistivity characteristics has importance especially for deviated and horizontal wells, where this effect should be considered in log interpretation especially in sensitive oil-in-place estimations.

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