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ELECTRICAL RESISTIVITY MEASUREMENTS ON UNCONSOLIDATED CORE.

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Abstract

Unconsolidated core is generally characterised by its lack of lithification or cementation. The gross material properties of the core are controlled, however, by the grain size; coarser sand-sized material is often difficult to sample intact due to its cohesionless nature while finer-grained material may be cohesive and retain its structure well. Consequently characterising unconsolidated samples in the laboratory varies with lithology.

The accurate measurement of electrical resistivity in unconsolidated sediments can be problematical. Changes to the physical state of the core can lead to determinations of the resistivity which are not representative of the insitu state. This variability in packing can, however, be used to advantage in allowing for the determination of an Archie 'm' value for that individual sample. Thus loose sediments provide a means of studying consolidation behaviour that is not possible using cemented rock samples where subtle changes in texture can mask the underlying process of interest. The soft nature of the unconsolidated material can also reduce electrode problems often associated with more competent rock. Such measurements have been used in the oceanographic field for several decades; this contribution reviews relevant experimental techniques previously applied in the study of seafloor sediments which may be appropriate for use in the hydrocarbons industry.

We demonstrate a range of different approaches for dealing with unconsolidated material in the laboratory. Using a variety of laboratory cells it is possible to investigate the relationships between electrical resistivity and both porosity and permeability, and to deduce Archie 'm' values. Furthermore it is possible to use the electrical resistivity to deduce the insitu porosity from insitu resistivity measurements. Using high spatial resolution resistivity measurements it is possible to produce laboratory images of unconsolidated sediments which relate to the degree of heterogeneity of the pore space (porosity). Introducing saline tracers provides a

means for assessing the variability of fluid flow pathways and a dynamic heterogeneity can be evaluated.

Introduction

In porous rocks electrical flow is generally considered to be dominated by electrolytic conduction through the pore fluid. Sundberg (1932) defined the Formation Factor (FF) as an intrinsic property of a fully saturated rock, independent of the nature of the pore fluid. This was shown by Archie (1942,1950) to be related to the porosity (Ø), and of course, in turn, to saturation (S). In real rocks, however, there are often clay minerals which offer alternative conduction mechanisms to the free-fluid conductivity. These increase the conductivity of the sample, consequently the measured or apparent Formation Factor is of lower magnitude than that described by Sundberg (see Worthington 1982 for an excellent summary of this problem). Deviations from Archie's Law were subsequently documented (e.g. Winsauer et al 1952) and numerous alternative formulae were derived (e.g. the Humble formula). This excess conductivity provides the peculiar boundary condition where a Formation Factor of unity corresponds to a porosity value less than 100%.

$$FF = a \text{ Ø } -m$$

With respect to Archie's Law and its derivatives, authors have attributed physical significance to the multiplier (a) and exponent (m) (e.g. Carothers 1968, Gomez-Rivero 1976, Lang 1976, Jackson et al 1978, Perez-Rosales 1982, Lovell and Pezard 1990).

Electrical resistivity measurements can be degraded by contact electrode effects and electrochemical phenomena. The use of 4 electrode measurements is designed to overcome these problems. Unconsolidated sediments can simplify the measurement through the use of penetrating electrodes which ensure adequate contact between the pore fluid and the electrode thus reducing the adverse effects sometimes seen with lithified formations. The techniques described here all use 4 electrode measurements in which the current and potential are measured independently.

The difficulties of using unconsolidated core have been considered for some time (Worthington et al 1987) and continue to be the subject of further study (Hjemeland et al 1998). The term *unconsolidated core* covers a wide range of physical states. The formation may be literally unconsolidated and thus the particle packing will be loose and generally exhibit a large proportion of space between the grains. This state relates to the mode of deposition of the formation and the energy level of the surroundings at that time. Deep sea clays and beach sands are classic examples of such unconsolidated material. Alternatively the term can include sediments which have been consolidated but which have undergone changing stress conditions and now exhibit a weak degree of structure. These may include clays and sands which have undergone stress relaxation and no longer retain their previous structure well. This category of sediment is generally characterised by little if any cementation or lithification. Typically the material properties of unconsolidated material are determined by the grain size distribution, although grain shape can also be important, as can mineralogy. In this contribution we consider three different types of sediments based on the manner in which they can be handled in the laboratory.

- Cohesive fine grained clays have an intrinsic structure which is retained through sampling; they can be readily sampled in an undisturbed state and transferred to a laboratory cell without too much difficulty.
- Disturbed, granular cohesionless sediments have no intrinsic structure which is retained on sampling. They therefore need to be redeposited in the laboratory and may display a range of packing states of which one may be similar to their insitu state.
- Intact, friable, poorly lithified sediments require careful sampling and handling; they may retain some semblance of their insitu structure. They are not easily redeposited but may be easily damaged.

Laboratory techniques

Cohesive sediments

Fine grained cohesive sediments can be studied using a modified consolidation (oedometer) cell (Lovell, 1984). The cell (Figure 1) is based on a standard soil mechanics apparatus which allows static loads to be added in increments simulating the loading of sediments insitu. As the axial load is increased pore fluid is expelled from the sediment and escapes through the porous discs which bound the sample’s upper and lower faces. The lateral boundary to the sample is a fixed (non-electrically conducting) PVC ring. The measurement of electrical resistivity is accomplished through a four electrode measurement (2 current electrodes are plates mounted behind the porous discs; 2 potential electrodes are circular wires on the sample -side faces of the porous discs). In addition the cell allows for the measurement of P-wave and S-wave velocities simultaneously during the loading cycle, although this aspect of the work is not discussed here.

Figure 2 shows a set of results on a log-log plot for a single sample undergoing a loading cycle; the initial porosity is close to 85% and reduces to almost 65% by the end of the test. The straight line relationship between formation factor and porosity represents the Archie m value for this sample and is determined through the ability to reduce the porosity of the sample during the test through axial loading. Extrapolation of the line would demonstrate further that this clay has an excess conductivity associated with it; thus the equation follows the form proposed by Winsauer et al (1952) for shaly sands in which Archie's a is not equal to unity. Similar results for a range of deep sea clays demonstrate the viability of this technique for isolating the a and m values where the sediment is cohesive (Lovell 1984, Lovell and Ogden 1984).

Disturbed, granular sediments

Loose material consisting of individual particles can be redeposited in the laboratory. Kolbuszewski (1948a,b) studied the packing of sands by various depositional techniques. He demonstrated that by pouring a sand in fluid without any entrapped air the sample achieved a loose packing state whereby the porosity exhibited a maximum porosity value. Using such a depositional technique Jackson (1975a,b) developed a novel porosity cell which enabled a deposited sand to be compacted through a known series of porosity values from its maximum towards its minimum value. The cell (Figure 3) differed from previous cells (Kermabon et al 1969, Erchul and Nacci 1972) in that it contained electrical resistivity electrodes and enabled staged settling of the sample such that a sequence of porosity-resistivity data could be obtained as the sand became increasingly dense. This technique was later adapted to consider the variability of permeability for a given sand sample undergoing densification through packing (Lovell 1984). Figure 4 shows an outline drawing of a constant head permeameter with electrode plates enabling resistivity-permeability data to be obtained for one sample as it is compacted from a maximum towards a minimum porosity.

Jackson et al (1978) report the results of an experimental investigation of cohesionless beach sands of varying shape and size distributions using the cell in Figure 3. A similar set of results for 4 clean sand samples is shown in Figure 5a with each sample following Archie's original equation and adhering to the condition (FF=1 at Ø=100%). Note that all of the sand samples in Figure 5 are composed of similar sized grains; the only variable is their shape. The effect of variation in grain size distribution has also been studied by Jackson et al (1978); the distribution affects the receptivity and porosity values (larger distribution of sizes providing reduced porosity and increased resistivity) but does not affect the exponent m in the Archie equation. Thus the exponent m is seen to have a clear relationship with particle shape; m increasing with decreasing particle sphericity. Figure 5b shows the resistivity relationship with permeability for each of the same sand samples. Again the particle shape is seen to control the magnitude of the exponent. Further work (Lovell 1984) demonstrates that, in examining the relationship between fluid flow and formation factor, uniquely definable trends existed for any one sample of either clean sands, deep sea clays, or shaly sands. These individual empirical relationships cannot, however, be contained within any single generalised model or predictive equation.

Extensive experiments using the porosity and permeability cells (Figures 3 and 4) have demonstrated that for unconsolidated clean sands there are relationships between the electrical resistivity and both porosity and permeability which are reproducible. Using the cells in Figures 3 and 4 to obtain results such as those in Figures 5a and 5b enables estimates of the insitu porosity and permeability to be made from insitu measurements of resistivity (Jackson 1975b).

Intact, friable sediments

Unconsolidated friable sediments may be sampled with care such that their structure remains intact on transfer to the laboratory. Such material cannot be redeposited as above and necessitates an alternative approach. Figure 6 shows a cylindrical cell with a series of equi-spaced circular potential electrodes. The current is passed vertically through the cell from porous plate sintered bronze electrodes. This cell has a uniform cross section and thus an intact sample of sediment can be introduced into it. The potential electrodes can be used to determine the resistivity of the sample between them, or to assess the heterogeneity of the sample. An average porosity value can be obtained using the total volume of the sample and the volume of fluid introduced to saturate the sample. The total volume can be measured with the aid of the potential between the two potential electrodes bounding the upper surface of the sample. This cell can also be used to determine the resistivity-porosity relationship where the sediment is composed of loose grains but contains fine grained material; in this case the sample is not redeposited but can be placed semi-intact in the cell and compacted to produce a series of porosity states.

More recently a core imaging technique using high resolution electrical resistivity measurements has been developed by Leicester University and the British Geological Survey (Jackson et al 1990); individual surface electrodes are mounted on a 2.5 mm x 2.5 mm grid. The variability of electrical resistivity in a poorly consolidated sand is shown in Figure 7a (Lovell et al 1995). In the case of a poorly consolidated sand of more or less constant particle shape, and thus lacking any significant cementation, this variability in resistivity is attributable to changes in porosity, the Archie m exponent remaining constant. Figure 7b shows the same sample as a resistive tracer is introduced from one end (top). The migration of the fluid through the sample is shown in the three time slices (increasing time from left to right). Note the higher permeability zone in the middle right of the image which corresponds with the higher porosity zone (lower resistivity) identified in Figure 7a. Introducing saline tracers provides the means for assessing the variability of fluid flow pathways and a dynamic heterogeneity can be evaluated.

Discussion

Various techniques have been developed within the oceanographic and, more recently, ocean drilling disciplines. Their application to unconsolidated core in the oil industry is not necessarily straight forward since it depends both on the precise nature of the core and the specific parameters that are desired. There are, however, substantial amounts of work already completed in this field which could have impact on future developments in the increasingly important study of unconsolidated core. We welcome open discussion as to how these techniques may be applied to current problems.

Conclusions

1. Many of the techniques presented here were developed within oceanography and demonstrate the need for communication between different scientific and technical disciplines in addressing apparently novel problems.
2. We have demonstrated a range of different approaches for dealing with unconsolidated material in the laboratory.
3. Using a variety of laboratory cells it is possible to investigate the relationships between electrical resistivity and both porosity and permeability, and to deduce Archie 'm' values.
4. It is possible to use the electrical resistivity to deduce the insitu porosity from insitu resistivity measurements.
5. Using high spatial resolution resistivity measurements it is possible to produce laboratory images of unconsolidated sediments which relate to the degree of heterogeneity of the pore space (porosity).
6. Introducing saline tracers provides the means for assessing the variability of fluid flow pathways and a dynamic heterogeneity can be evaluated.

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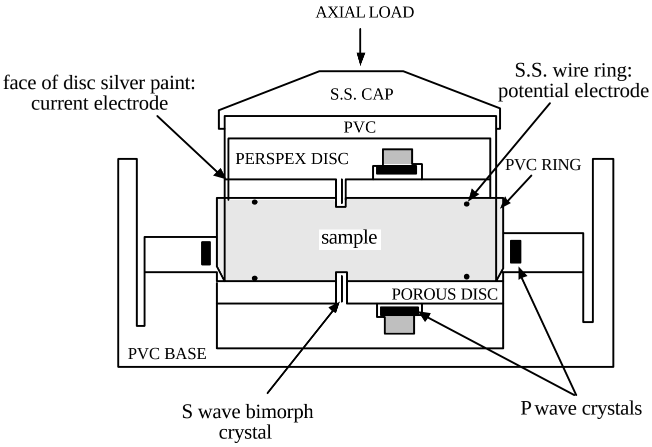

Figure 1: The modified consolidation cell for cohesive sediments

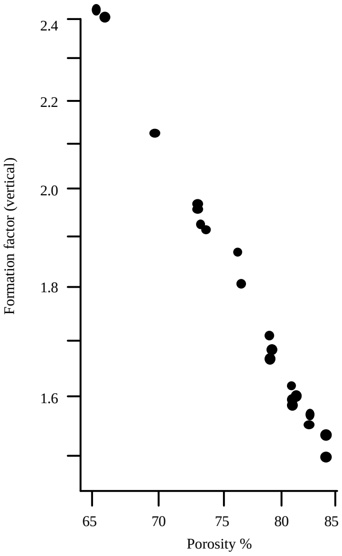

Figure 2: Archie ‘m’ determination for a cohesive sample during consolidation

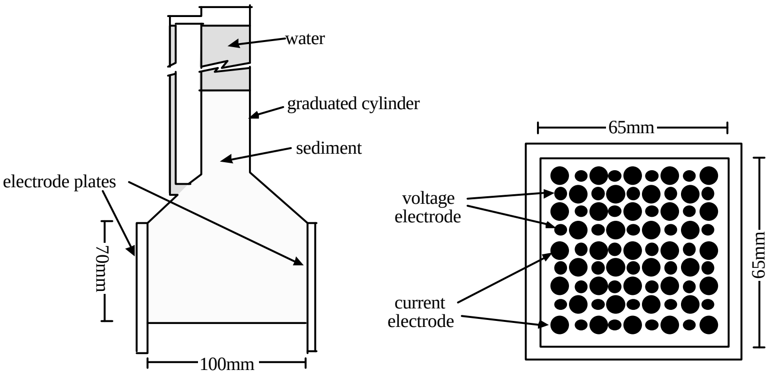

Figure 3: Electrical resistivity -porosity cell for unconsolidated sands

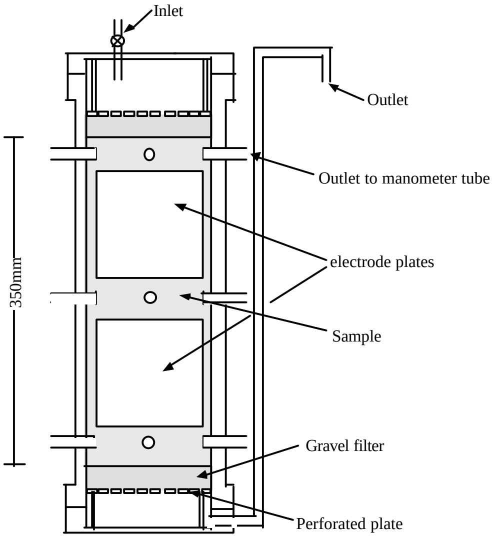

Figure 4: Electrical resistivity -permeability cell for unconsolidated sands

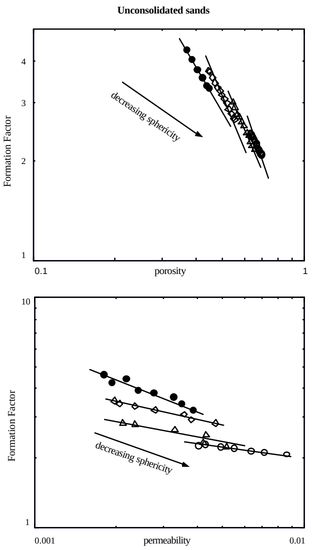

Figure 5

(a) Archie ‘m’ value varies with grain shape for unconsolidated sands

(b) Grain shape also affects the electrial and fluid flow observations

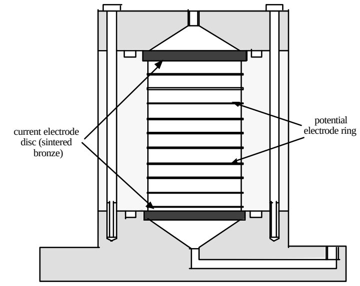

Figure 6:A cylindrical cell for porosity and heterogeneity determination in intact friable sediments

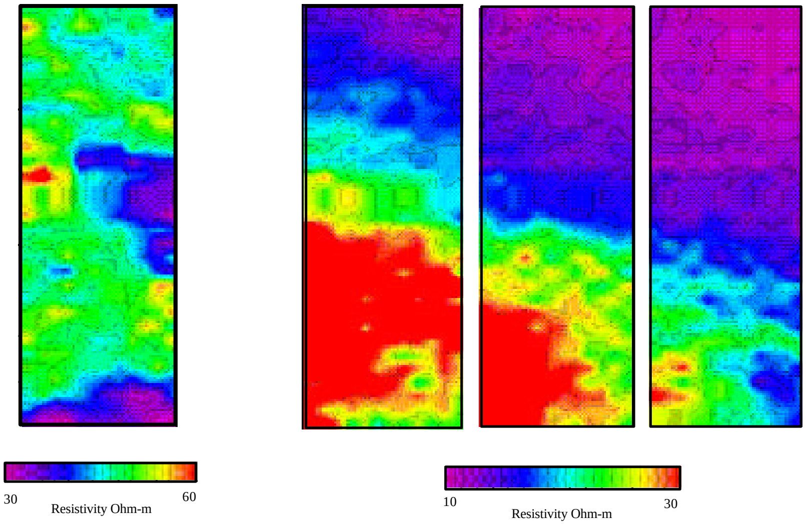

Figure 7:

(a) Resistivity image of a poorly consolidated sand lacking significant cementation (left).

(b) The same sample displayed in three time slices as a tracer is passed through the sample from top to bottom (right).