High-resolution electrical resistivity measurements are made on saturated rocks using novel laboratory instrumentation and multiple electrical voltage measurements involving in principle a four-point electrode measurement but with a single, moving electrode. Flat, rectangular core samples are scanned by varying the electrode position over a range of hundreds of millimetres with an accuracy of a tenth of a millimetre. Two approaches are tested involving a contact electrode and a non-contact electrode arrangement. The first galvanic method uses balanced cycle switching of a floating direct current (DC) source to minimise charge polarisation effects masking the resistivity distribution related to fine scale structure. These contacting electrode measurements are made with high common mode noise rejection via differential amplification with respect to a reference point within the current flow path. A computer based multifunction data acquisition system logs the
current through the sample and voltages along equipotentials from which the resistivity measurements are derived. Multiple measurements are combined to create images of the surface resistivity structure, with variable spatial resolution controlled by the electrode spacing. Fine scale sedimentary features and open fractures in saturated rocks are interpreted from the measurements with reference to established relationships between electrical resistivity and porosity. Our results successfully characterise grainfall lamination and sandflow cross-stratification in a brine saturated, dune bedded core sample representative of a southern North Sea reservoir sandstone, studied using the system in constant current, variable voltage mode. In contrast, in a low porosity marble, identification of open fracture porosity against a background very low matrix porosity is achieved using the constant voltage, variable current mode. This new system is limited by the diameter of the electrode that for practical reasons can only be reduced to between 0.5 and 0.75 mm. Improvements to this resolution may be achieved by further reducing the electrode footprint to 0.1mm x 0.1mm using a novel high-impedance, non-contact potential probe. Initial results with this non-contact electric potential sensor indicate the possibility for generating images with grain-scale resolution.

Keywords: Electrical resistivity, imaging, instrumentation, porosity, rock, core imaging.
1. Introduction

The electrical resistivity of a porous rock depends primarily on the nature of any conducting pore fluid, the proportion of conducting fluid occupying the pore space, and the distribution of fluid (Archie 1942, 1950; equation 1).

\[ R_t = a R_w \phi^{-m} S_w^{-n} \]

(Equation 1)

Where \( R_t \) is the electrical resistivity of the rock, \( R_w \) is the resistivity of the conducting fluid (most commonly saline water or an aqueous solution), \( \phi \) is the porosity of the rock and \( S_w \) is the saturation (or proportion of pore space) occupied by the conducting fluid (water). The values of “\( a, m \) and \( n \)” are typically constant for a specific pore morphology and may commonly be determined by experimental laboratory methods or through numerical modelling. Archie assumed “\( a \)” is equal to one, while Winsauer et al. (1952) suggested it may deviate from this value. If the rock is fully 100% saturated with the conducting fluid (saline water) then the water saturation takes a value of unity and the equation reduces to:

\[ R_o = a R_w \phi^{-m} \]

(Equation 2)

where \( R_o \) indicates that the rock is fully water-saturated as in the experiments conducted here.

Electrical flow takes place primarily by ionic or electrolytic conduction through the pore fluid, in the absence of metallic conductors such as pyrite or clay minerals, although the pore fluid properties are affected by salinity, temperature and pressure. In siliciclastic rocks containing significant proportions of clay minerals the presence of a cation-rich
layer of electrochemically bound water at the mineral surface can add additional conductivity (e.g. Worthington 2011); this effect is due to the negative charge on silicate minerals attracting positive ions and water to the surface, but is negligible in so-called “clean” sandstones. In “shaly sands”, however, with a significant amount of clay minerals this effect can be large due to a large surface area to volume ratio, and can reduce the resistivity (e.g. Winsaeur et al. 1952; Waxman and Smits, 1968). There are two primary groups of so-called shaly sand models that can be used in these circumstances. Vshale models are based on shale volume fraction where the excess conductivity is represented by derived shale fraction, typically determined from downhole natural gamma ray or neutron-density log separation, together with the shale conductivity. Cation exchange models are based on ionic double layer or clay bound water where the excess conductivity is represented by cation exchange properties of clays and electrolyte conductivity. In both cases Archie’s equation is modified accordingly, but in each case the resulting equations reduce back to Archie where no additional conduction paths are available (i.e. there are insufficient clay minerals). Worthington (1985) provides an overview of the various models. Here we consider rock formations with relatively small surface conduction effects where Archie’s equation is applicable.

Rock electrical properties are thus sensitive to the mineralogy and the pore morphological characteristics as well as the nature of the pore fluid, degree of saturation, temperature and pressure (e.g. Llera et al., 1990; Mualem and Friedman, 1991, Archie 1942). Most dry rocks are excellent insulators in vacuo, but even saturation with distilled water can decrease resistivity by several orders of magnitude due to the mobilisation of ions for
electrical conduction (e.g. Duba et al., 1978). Archie (1942) published the first quantitative use of electrical resistivity in a petrophysical context and developed a series of empirical yet quantitative relationships linking the resistivity of the water-saturated rock to the pore fluid resistivity through a formation factor previously defined by Sundberg (1932). Archie also related his experimentally-defined formation factor to porosity and in turn to saturation by incorporating the resistivity of the hydrocarbon bearing rock as well as the resistivity of the water-saturated rock. Today, some 70 years after Archie, these equations still form the generally accepted basis for the deterministic evaluation of water saturation using electrical methods within petrophysics (e.g. Archie, 1950; Burdine et al., 1950; Doll et al., 1952; Worthington and Griffiths, 1975; Spangenberg, 2001; Riedel et al., 2005, Worthington 2011). Archie’s equations rely on the rock matrix being non-conductive and the pore water being relatively saline. Where either of these conditions is contravened, then alternative methods can be employed, based on Archie but with modification to take account of the excess conductivity due to an additional, different mode of conduction beyond the ionic conduction we consider here (e.g. Worthington, 1985; Worthington, 1991; Worthington, 2010) while the combination of shale effects and low salinity may also lead to the electrical resistivity being frequency dependent. In this study we confine ourselves to water-saturated rocks and the relationship between pore fluid distribution as controlled by sedimentary fabric and stress-induced fractures. This understanding forms the basis of electrical resistivity investigations and monitoring at a range of scales, in the laboratory, in the field and in boreholes.
The electrical resistivity distribution is dependent on micro-scale (sub-millimetric) heterogeneity of properties such as porosity, controlled by grain size distribution and cementation, which are strongly related to sedimentological fabrics of millimetric geometries. Thus, small-scale heterogeneity controls the morphology of the pore space and in turn, fluid flow and migration within reservoirs, and this is reflected in the petrophysical properties such as electrical resistivity. Clennell (1997) published a classic paper on the tortuosity of electrical flow in rocks, while studies of electrical resistivity and heterogeneity include Bernabé et al and more recently Fitch et al. Downhole logging tools and techniques have been developed to evaluate and record the heterogeneity within the formation as part of subsurface formation evaluation. Conventional downhole logs use current focussing from multi-electrodes, and can identify bedding and fractures with vertical resolutions of about 600 mm (Rider and Kennedy, 2011) whereas, downhole electrical imaging devices comprising multi-electrode-button pads on several pads contained on radial arms provide images with approximately 5 mm resolutions (e.g. Gaillot et al., 2007). Images provided by the high resolution downhole tools, however, require quantitative calibration and while possible by integrating the borehole images with resistivity measurements made downhole using conventional resistivity logs, the latter often have a poor resolution and calibration can be problematical (e.g. Ekstrom et al., 1986; Boyeldieu & Jeffreys, 1988). Calibration may be feasible using laboratory measurements on core samples taken from the borehole. Thus, assessing the resistivity of core at the millimetre scale achieved in downhole image logs would be beneficial (Lovell et al., 1997; Lovell et al., 2006).
This paper concerns the development of laboratory techniques that are capable of making resistivity measurements with the required resolutions to capture the fine sedimentological fabric within reservoir rocks. Both galvanic or contacting and non-contacting techniques for high-resolution rock core resistivity measurements have been developed. By measuring the voltage gradient parallel to a switched DC current across fixed, multi-electrode grids Jackson et al. (1991, 1992, 1995) produced resistivity images with a 5 mm resolution of the fabric in samples of the Penrith Sandstone, building on earlier work developing multi-electrode grids (Jackson et al. 1990). These images were used within a study of the control of fine scale dune bedded structures on the flow of fluids through aeolian sandstone analogues to the Rotliegendes Formation of the Southern North Sea (Lovell et al., 1995; Harvey et al., 1995; Lovell et al., 2006). Using a primary and secondary coil pair, Jackson et al. (1997, 2006) also developed an electromagnetic, non-contacting technique based upon measurements of the secondary magnetic field induced by current flow within brine-saturated sandstone. These measurements were made at low induction numbers where the skin depth was far greater than the coil separation and the strength of the secondary magnetic field was controlled by the rock conductivity (reciprocal of resistivity). The coil separation of 40 mm enabled the method to be sensitive to resistivity changes over 15 mm axial resolution. Improving the resolution of the electromagnetic method would require re-engineering of small coils with closer separations, which would require miniaturisation of techniques. However, increasing the resolution methods based upon measurement of voltage or electric field gradients only requires a means of reducing the spacing within the electrode grid. The main system described here in this paper achieves this by replacing a fixed grid of
electrodes with a single robotically controlled electrode capable of very fine movements of as little as 100 microns; the increased scanning time required to move a single electrode is not considered to be a serious disadvantage. A key technical aspect of this paper, however, is the design of measures to overcome potential charge polarisation obscuring the fine detail in the resistivity image and also, to minimise spurious potentials associated with buffering the voltage measurements made with repeated contact of the single electrode. We also show how the system can be applied to optimise the resistivity imaging of fine scale, millimetric features determined by sedimentological fabric and fractures.

Development of a non-contact electrical potential sensor has enabled further reduction of the scanning electrode footprint and led to images with even greater resolution. The Electric Potential Sensor (EPS), invented and patented by the University of Sussex (Prance et al., 2000), is a generic sensor technology, which can be configured to measure electric field, static charge or spatial potential, in a non-invasive, non-contact manner. Its use has been demonstrated in many areas of application, and include non-contact imaging of carbon composite structures (Gebrial et al., 2006, 2007), and the detection of electric field in rock, induced by uniaxial compression (Aydin et al. 2009). To image the resistivity distribution an alternating current (AC) is used to generate a spatial potential above the specimen that varies with the local resistivity of the rock structure. Using an appropriately fine electrode, the ultra-high input impedance of the EPS allows for the imaging of the surface potential through a raster scan. A preliminary scan of a sandstone sample is presented which offers complementary findings to that of the galvanic method.
A single line scan between the electrodes applying the current through the sample also confirms Ohm’s law.

2. Measurement Principles

The four-electrode measurement principle can be realised using a fixed, reference voltage electrode and a moving or scanning voltage electrode. Using a floating current source, the measurement and instrumentation can be simplified because the reference voltage electrode can be located at any position within the current loop, such as at the virtual earth point of the input buffers. The potential difference $\Delta V$, between voltage measurements at two positions of the moving electrode, a distance $\Delta l$ apart parallel to the flow of the current, $I$ can be related to the local bulk resistivity, $\rho$ by,

$$\rho = \frac{A}{I} \cdot \frac{\Delta V}{\Delta l}$$  \hspace{1cm} (Equation 3)

The current, $I$ is determined via independent voltage measurement across a reference resistor in series with the sample and the gradient $\frac{\Delta V}{\Delta l}$ by differentiating the potential field measurements parallel to current flow (Figure 1). $A$ is the cross-sectional area of the plane perpendicular to the current flow, and with carefully prepared samples, the geometric factor is accommodated by the ratio $\frac{A}{\Delta l^2}$.

Resistivity variation, and thus sedimentological structure, can be imaged via the localised potential gradient, with image resolution controlled by the increment $\Delta l$. Techniques to increase the region of uniform current flow include use of multiple, balanced electrodes (Jackson et al., 1995) in conjunction with small, saturating fluid reservoirs extending beyond the length of the sample (Figure 1). Use of a fixed reference and a single scanning electrode in galvanic methods leads to reduced settling times when compared to multiplexing between individual electrodes across a fixed grid. With both electrodes permanently connected to the buffer amplifiers and no multiplexing required, the input
bias current is only disrupted by making and breaking of contact between the rock and
the scanning electrode.

Figure 1. Current spreading at electrodes and distribution within a sample for different electrode
arrangements (after Jackson et al. 1991).

a) Fundamental four-electrode resistivity measurement.

b) Multiple current electrodes to extend uniform current flow within sample.

2.1 Instrumentation and Method

A system has been developed that can pass a uniformly distributed direct current through
each sample without developing charge polarisation due to net ionic migration. This is
achieved by balanced switching of a DC constant current source (0.5 – 50mA range) such
that equal cycles of current flow alternate in opposite directions along the sample. (Figure 1)
The complete system (Figure 2) comprises the following modules: (1) Timer, which
controls the current switching and measurement cycles; (2) Floating Constant Current
Source, which provides a constant current regardless of load impedance, (3) Signal
Conditioning Module, including differential amplification buffers for the current and
voltage measurements; (4) Sample & Hold to capture the peak DC levels; and (5)
Filter/Amplification of signals that are acquired by (6) PCMCIA PC Data Acquisition
(DAQ) Control card, which also manages the movement of (7) the Three-axis Robot that
carries the moving voltage electrode, P1. The overall operational procedure involves
current being driven into the saline fluid reservoirs at either end of the sample holder via electrodes C1 and C2, and through the saturated rock core sample, generating potentials that are measured at points along the rock surface via the scanning electrode, P1 relative to a fixed reference, P2 (c.f. Figures 1, 2). The robot is controlled in such a way that a moving phosphor bronze electrode is lifted and placed onto the surface of the sample where it is allowed to (electrically) settle before a measurement is made. A variable frequency clock driving a binary counter in the Timer (1 in Figure 2) ensures balanced cycle switching. A square wave signal controls the polarity of current flow through the sample by switching it in one direction and then in the opposite such that any net charge accumulation is eliminated. It also synchronises the timing between the current switching and the sampling of the measured voltages such that each measurement can be represented by a simple DC voltage level. Switching frequency was typically set at 25 or 30 Hz, which filters out any extraneously coupled mains noise. The timer also generates a series of pulses of widths 1/8th of the period of the current switching square wave that coincide with the third quarter portion of the low and high levels of every alternate cycle of the current switching wave. The synchronisation of these pulses ensures that the portion of the waveform sampled is free of any alternating current (AC) effects, e.g. associated with repeated sample re-contact of the moving electrode. Synchronising the measurement in this way provides an optimized measurement speed and S/N ratio.

Figure 2. Schematic representation of the core imaging system. A microprocessor generates timing signals which control the current switching polarity and ADC measurement cycle. A constant current is injected into the sample under test via the constant current source and electrodes C1 and C2. A potential reference, P2 is fixed at one end of the sample, whilst P1
moves around the surface of the sample in order to measure the local potential at each position.

Signal conditioning allows the potentials to be measured via the ADC.

The system is capable of acquiring a two-point (electrode) measurement; a moving electrode, however, offers flexibility and higher single point resolution to image structures in low resistivity rocks with very high primary porosity, such as a dune-bedded sandstone. The same is also true in highly resistive rocks where open fractures contribute to the secondary porosity against a low matric porosity. In either case, resistivity images aid interpretation of pore space connectivity, and, in turn, qualitative permeability and flow patterns, by identifying sedimentological fabric as delineated by changes in porosity, or by distinguishing between open or closed (i.e. cemented) fractures.

Electrode-probe designs can be adapted to match the requirements of the measurement; for example a solid 1 mm diameter phosphor bronze tip enables high resolution measurements with very low voltage offsets on low resistivity, high porosity, rocks, while a fibre-tipped probe maintains an ionic pathway when imaging conductive fractures in very low porosity, high resistivity, rocks.

3. Results

3.1 Calibration Tests

Three machines were tested in order to reveal the accuracy contour of the measured resistance versus the drive current (Table 1). Resistive test loads were chosen to a tolerance of 0.5%. In order to average out any interference effects from the mains AC supply, tests were undertaken with the current switching frequency below 50 Hz (UK mains frequency). A four point measurement was carried out across the load at a constant
temperature. The results shown (Table 1) in black indicate the optimised operational
load-current range of the instrument, i.e. of the order of 0.1V – 20V over the test load.
Results shown in blue indicate that the voltage across the load has reached 20V, which
represents the maximum potential difference available and results in a limiting of the
current flowing through the test load. The readings in red indicate where the instrument is
either under or over-voltage, which leads to poor reading accuracy.

Table 1. Calibration data for Core Imaging system. All values expressed in Ohms, unless
otherwise stated. Results shown in blue indicate that the voltage across the load has reached 20V,
which represents the maximum potential difference available and results in a limiting of the
current flowing through the test load. The readings in red indicate where the instrument is either
under or over-voltage, which leads to poor reading accuracy.

3.2 Constant Current – Imaging Sedimentary Structure
The set-up in Figure 1 was used for measurements on low resistivity rocks, typically of
the order of kilo ohms, where the sample can be considered as a distributed network of
resistors and the resistance between more porous bands is lower than the resistance
throughout less porous bands. In this set-up, a constant current flows through the total
resistance of the network and thus, by taking the gradient of the voltage measurements
along the y-axis (Δl in Equation 2), an image of the structure of the core can be generated.
Single potential measurements were taken over the surface of a flat rectangular
(nominally 250 mm x 60 mm) core sample (25 mm thick) and resistivities derived from
the differences between neighbouring measurement points along the y-axis. A gradient
was not calculated with respect to the x-axis as this was aligned parallel to the structural
lamination. Contact resistances were measured and found to be small and of the order of
< 2 kΩ, and therefore no additional measures were required to correct for these. Steps
could have been taken to reduce this; such as using a higher conductivity saturating fluid.
The sample was wetted throughout the tests with aqueous solution of lab grade NaCl and
never allowed to dry out, as this could affect the pore water properties and the surface
conductivity. The experiment was maintained at a constant temperature of 20°C
throughout the tests. During the tests, the y-incremental electrode spacing was varied
from 6 mm to 0.5 mm and the current was varied from 10 – 30 mA in order to find
optimum minimum and maximum operating parameters. In the studies here it is assumed
that there is a constant resistivity structure throughout the height of the rock, and to this
dend the rock is prepared so the current flow is orthogonal to the sedimentological
structure (and the x-axis). Image resolution can be improved through increasing the
spatial resolution by reducing the y-incremental electrode spacing. Best results were
found when reducing the y-incremental electrode spacing was accompanied by an
increase in the current, which is considered to be related to increasing the amplitude of
the voltage difference measurements above the system noise floor. Figure 3 shows the
improved resolution gained by reducing the y-incremental spacing from 4 mm to 1 mm
combined with an increase in current from 12 mA to 30 mA, where structure within fine
laminations appears only at the highest resolution. The photograph of the sample surface
is also presented for comparison.

Figure 3. Sedimentological fabric detail within electrical images of a dune-bedded sandstone,
taken from the Penrith Sandstone gathered from the Stoneraise Quarry, NW England. The
variation in resistance is due to the contrast in resistance between more porous bands (lower) than and less porous bands (higher):

a. Photo of rock surface;
b. Δy 4 mm / I 12 mA, scanned data;
c. Δy 1 mm / I 30 mA, scanned data;

The samples are taken from the Penrith Sandstone gathered from the Stoneraise Quarry, NW England. This sandstone is described by Lovell et al., (2006) as having an orange/red colour, comprising well-rounded, highly spherical quartz grains, often showing euhedral overgrowths of quartz. Chemically, the rock is predominantly SiO2 (>95%), with no evidence of carbonate cements. There is no evidence of the presence of clay minerals. The Penrith Sandstone is a typical clean sandstone characterised by moderate porosity (12%) and Archie ‘a’ value of 1.0 and an 'm' exponent less than 2, suggesting a reasonably clean 'Archie' rock with no excess conductivity associated with clays or bound water. This sandstone sample comprises 85% quartz grains with minor lithic fragments (gneiss), feldspar, mica and opaques. The grain size across heterogeneous zones varies from very fine (100 µm) to coarse sand (700 µm). The grain size range has an overall bimodal distribution, predominately falling within 25 to 250 µm and 0.5 to 1 mm. Greater resistivity structures in the upper half of the sample are generally associated with the smaller grain size distributions ranging from coarse silt to fine sand in a relatively densely packed structure. In contrast, the lower half of the sample, the denser fabric, are narrower and are inter-laminated with more loosely packed bands of well-rounded coarse sand. Typical resistivity of the saturating fluid was measured to be 0.25 Ω.m and the scale bar (Figures 3 & 4) is graduated as a multiple
factor, which in this case equates to resistivities from 10 Ω.m to 30 Ω.m. Increasing current flow to 30 mA appeared to improve signal to noise ratios by increasing the measured voltages over the core surface. Again, this improvement can be seen in better delineation of the fabrics within the image. Note how the banding in the lower section is better resolved and also how more distinct banding in the central section is developing the resistivity of bands of more loosely packed, thinner laminations. By combining the benefits of increased signal to noise ratio and improved spatial resolution, it can be observed that a far more complex structure to the lower, banded section of the core sample emerges (Figure 4). These images have been interpreted as showing grainfall lamination and sandflow cross stratification found in dune-bedded Permo-Triassic sandstones within the Eden Valley and Carlisle Basins of the UK (Reading, 1981; Walker, 1984; Benton et al., 2002). The grainfall laminae result from wind transportation and deposition from suspension of well-sorted, well-rounded millimetre-sized grains in a high porosity, loose packing. The sandflow laminae result from minor slippages along the leeside of the dune along laminations of coarse silt, producing a denser packing with a more poorly-sorted grain size range from silt to sand classes (Harvey et al., 1995).

Figure 4. Constant current measurements, with 20mA of injected current, 1mm x-axis and 0.5mm y-axis resolution. Sandstone sample, taken from the Penrith Sandstone gathered from the Stoneraise Quarry, NW England.

a. Photo of sandstone rock surface;

b. Δx: 1mm, Δy: 0.5mm, 20mA, scanned data. (Δy is equivalent to Δl in Equation 2);

c. Photo of thin section depicting sandflow lamination and grainfall lamination features;
3.3 Constant Voltage – Fracture Mapping

In this mode, superior results to that of the phosphor bronze method were obtained by introducing the current at the contact point between a fibre tipped voltage measuring probe and the rock surface via ionic flow within fluid absorbed in the porous fibres. Voltage measurements were made between the base of the fibre from an electrode, P1 positioned just above the core sample surface and the reference point C2 (Figure 2). Total current flow was monitored via a voltage measurement across a standard resistor network (between I1 and C2) that is in series with the load provided by the core sample (Figure 5a). Current flow in this set-up would be limited mainly because of the highly resistive rock, typically of the order greater than tens of kilo-ohms, as the voltage is kept constant. A variable current style of measurement would therefore be made. Figure 5c shows the result of constant voltage, variable current measurements carried out on a highly resistive, fractured rock sample using the constant current probe configuration described above. Note from the image of the core surface (Figures 5b and 5c) that the more conductive area is following the path of the fracture and other smaller, interconnected fractures. The fracture generally appears less resistive, which is measured via the greater current that flows via the fracture pathway while the system maintains a constant voltage. The sample is from the Apulian platform foreland carbonates in the Southern Apennines, Italy. As part of the Southern Apennines fold-thrust belt, the sample is a carbonate rock characterized by the development of both primary (matrix) and secondary (fracture) porosity. The fracture porosity is particularly important in that it is not homogeneously distributed and is often accompanied by microfractures and fissures against a background porosity. The rock is predominantly composed of calcite with minor proportions of
dolomite; the sample selected did not contain any significant clay minerals. The constant voltage method therefore appears to be ideal for fault or fracture detection and analysis where fractures are either open and fluid filled, or closed and cemented with a non-conducting mineral such as quartz or calcite. In this case, the lower resistance of the fracture is an indication that it is open and fluid filled, rather than a closed, cemented fracture. The surfaces of very low permeability rocks can be analysed with this system to assess the proportion of open to closed fractures on the basis of thresholds within the conductance or resistivity images, although the presence of clay-filled fractures may give similar responses to open fractures depending on the nature of the clays and the conductivity of the pore fluid. It may be feasible to develop a series of indices relating to the fracture flow potential within the rock on the basis of these analyses.

Figure 5. Constant voltage measurement set-up and image on high resistivity, fractured core sample taken from the Apulian platform foreland carbonates in the Southern Apennines, Italy. 

a. Modified core imaging system including porous fibre probe and ground reference;

b. Photo of carbonate rock surface;

c. Δx: 1mm, Δy: 0.5mm, 20mA, scanned data;

3.4 Electric Potential Sensor surface and line scans

The techniques described above concern measurements made with an electrode in contact with the rock surface. In this section we demonstrate an innovative non-contact method where the electrode does not contact the surface of the rock. This technique again utilises the precision control of the sensor movement involving a single scanning electrode to
provide rapid, high-resolution images. The Electric Potential Sensor (EPS or EP sensor) is an ultra-high input impedance integrated active electrode capable of sensing spatial potential through weak capacitive coupling. Typically, the input impedance is >100 GΩ with an associated capacitance <1 pF. This level of performance is achieved through a combination of guarding and bootstrapping feedback techniques, together with a circuit to provide a stable DC input bias current, as illustrated in figure 6a (Gebrial et al. 2006, 2007). The operational bandwidth may be configured to be anywhere between quasi DC to 100 MHz. Unlike laboratory electrometer instruments EPS is intrinsically DC stable with no adjustments required at any stage during manufacture, setup or use. The technology is scalable and for this application the electrode takes the form of a guarded coaxial probe with a measurement tip diameter of 0.2 mm. EPS can be configured to measure electric field, static charge or spatial potential, in a non-invasive, non-contact manner. To infer the resistivity an AC current is used to generate a spatial potential above the specimen that varies with the local resistivity of the rock structure.

Figure 6. EPS line scan through length of sandstone specimen and EPS surface scan of sandstone specimen taken from the Penrith Sandstone gathered from the Stoneraise Quarry, NW England;

a. Modular elements of a typical Electric Potential Sensor (EPS) showing the probe electrode, feedback, guard, and input bias circuits of the electrometer amplifier.

b. EPS line scan through length of sandstone specimen, showing the output voltage and phase variations.

c. Very high resolution surface scan of sandstone specimen using data from EPS.
Figure 6b shows the results for a line scan of the sandstone sample, taken from the Penrith Sandstone gathered from the Stoneraise Quarry, NW England, through its central axis from the input to the grounded electrodes. The data for the EPS output amplitude over the single line are shown. The overall voltage amplitude drop across the length of the sample is caused by the whole resistance presented by the sample. The voltage at each measurement position represents a proportional, potentiometric drop along the complete scan, where the voltage difference between adjacent points is controlled by local resistivity structure. A 0.2 mm electrode probe was used to scan a central area of 25.2 mm x 25.2 mm. The probe was not in contact with the formation but is in very close proximity, smaller than the electrode diameter. The step increment size was 126 µm, scanned in a raster fashion. The very fine movement control combined with the small footprint of the EPS probe enables very high resolution imaging of the sedimentary structures within the sample. The two images in figure 6 depict (b) the EPS output voltage response and (c) a high resolution surface scan of the Penrith sandstone core sample.

4. Discussion

These novel measurements produce fine scale images of the samples with millimetric resolution. The contact measurement, for example identifies the fabric associated with bimodal grainsize-porosity distributions resulting from scour, granule lags and cross-lamination caused by wind driven dune deposition and slumping in a desert environment (Figure 3). These resistivity images enable high-resolution evaluation of the rock porosity within a porous, permeable reservoir and reveal fine scale detail of fining up sequences. Features such as these are often associated with the deposition processes whereby wind-
blown, aeolian deposits of varying grain size have been deposited sequentially. Coarser
deposition bands relate to greater porosity and therefore lower resistivity while finer
bands, often with greater quartz cementation, have a lower porosity and a greater
resistivity (Lovell et al., 2006). As Figure 4 illustrates, there has been some success in
imaging these fabrics, with $\Delta y$ resolutions as low as 0.5 mm being used in order to
achieve these results. The disadvantage of the system, however, is the physical limit
imposed by the phosphor bronze electrode, which equates to approximately 0.5 mm.
Further improvements on resolution could be made by reducing, in turn, the physical size
of the probe tip and the $\Delta y$ resolution, or the development of a non-contact probe that
would totally eliminate issues such as contact resistance.
The existing system may be further improved, for example, with the elimination of high
voltages presented to the instrumentation amplifier input stage whilst injecting current
into highly resistive rocks. Currently, the divider network at this point reduces the
common mode rejection ratio (e.g. the rejection of common signals coupled onto both the
reference and scanning voltage electrodes) via the imbalance of the low tolerance
network resistors and also introduces input offset voltages caused by the input bias
current of the instrumentation amplifier. These input offsets are further amplified down
the chain. It also has the effect of reducing smaller signals to the point at which they
could be masked by noise, hence the need to apply higher injection currents in our
experiments. At present however, the input offsets were measured and found to be larger
than the noise floor of the system, but it is possible to calibrate this effect out of the
system. Detection and automatic adjustment of the input signal and conditioning it to a
suitable level, prior to the instrumentation amplifier, is a possible improvement, using the
raw signal without reducing the quality of the signal prior to amplification. At present the system is capable of sourcing 0.5 – 50mA of current at 20V. This yields a sample test range of approximately 400 Ω to 40 kΩ. Further improvements have been made to the current source to allow lower currents (typically 50 µA) to be injected and allow further testing of existing samples at lower currents and to allow higher resistivity samples to be investigated.

The preliminary electric potential measurements using the EPS clearly provide an additional non-contact advance on scanning the sandstone, which evidently follows expected Ohmic laws. The EPS offers far more rapid, higher resolution resistivity scanning of those achievable using non-galvanic approaches. The added benefit of having a non-contact system is that ultimately it may be possible for a cylindrical core sample to be imaged through its plastic core liner and remain uncontaminated. The challenges to this approach include overcoming the loss of signal strength that occurs as the area of the electric potential sensor is reduced and as the offset distance between the sensor and the rock surface is increased. But if these challenges are overcome, the EPS offers the potential for sub-millimetric image resolution and better imaging of fine scale detail of fining up sequences. The EPS results clearly show structure at high spatial resolution, however further work is required to explore this approach and seek to calibrate and comprehensively compare it with the galvanic contact technique.

Wider application of these core imaging approaches to hydrocarbon reservoirs has yet to be demonstrated, but where conductive paths exist in the rock it may yield useful additional core imaging on which to base further research and special core analysis, even in shale gas and shale oil plays if the formation water is highly conducting and the rock
5. Conclusions

We have successfully developed and demonstrated novel electrical resistivity measurements for use on water-saturated core with high spatial and measurement resolution. Current is injected into the core sample and the electric field measured by rapidly scanning the probe at very fine increments along the core surface. By increasing the resolution of the scanned probe over a fixed grid, and improving the signal to noise ratio, it is possible to build up a resistivity map that is fine enough to resolve sedimentological features. Four-electrode measurements effectively allow electrical resistivity images to be acquired that result from resistivity variations associated with sedimentological fabrics associated with deposition and diagenesis processes in the form of primary and secondary porosity. Image fidelity is improved via balanced, floating DC current source switching that minimises charge polarisation effects masking fine-scale structure. Using constant current flow a range of fabrics resulting from depositional and diagenetic processes can be identified in a fully brine-saturated dune bedded sandstone. When operated in variable current mode, the system can image relatively high resistivity, fractured rocks to differentiate conducting fractures from non-conducting fractures (as higher current flow, lower relative resistivity features). Movement increment, repeatability and electrode diameter impose limitations on the system capability, both of which could be improved via improved precision engineering. Other limitations include settling times of the measuring amplifiers associated with galvanic voltage measurements. These limitations can be overcome and imaging time significantly
reduced by using non-galvanic (non-contact) methods of electric field measurement that
draw virtually zero current. Resolutions greater than those of existing down-hole logging
tools, and comparable to or greater than existing downhole electrical imaging devices can
be achieved with the possibility of logging undisturbed, cylindrical core samples, as
extracted from wells, through their core liner. These methods have been shown in brief,
but require further investigation.

Acknowledgements

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Jackson, P. D., M. A. Lovell, J. A. Roberts, P. J. Schultheiss, D. A. Gunn, R. C. Flint, A.


Figure Captions (note colour figures 3, 4 & 5 below)

Figure 1. Current spreading at electrodes and distribution within a sample for different electrode arrangements (after Jackson et al. 1991).

a. Fundamental four-electrode resistivity measurement.

b. Multiple current electrodes to extend uniform current flow within sample.

Figure 2. Schematic representation of the core imaging system. A microprocessor generates timing signals which control the current switching polarity and ADC measurement cycle. A constant current is injected into the sample under test via the constant current source and electrodes C1 and C2. A potential reference, P2 is fixed at one end of the sample, whilst P1 moves around the surface of the sample in order to measure the local potential at each position. Signal conditioning allows the potentials to be measured via the ADC.

Figure 3. (Colour) Sedimentological fabric detail within electrical images of a dune-bedded sandstone, taken from the Penrith Sandstone gathered from the Stoneraise Quarry, NW England. The variation in resistance is due to the contrast in resistance between more porous bands (lower) than and less porous bands (higher):

a. Photo of rock surface;

b. Δy 4 mm / I 12 mA, scanned data;

c. Δy 1 mm / I 30 mA, scanned data;
Figure 4. (Colour) Constant current measurements, with 20mA of injected current, 1mm x-axis and 0.5mm y-axis resolution. Sandstone sample, taken from the Penrith Sandstone gathered from the Stoneraise Quarry, NW England.

a. Photo of sandstone rock surface;

b. Δx: 1mm, Δy: 0.5mm, 20mA, scanned data;

c. Photo of thin section depicting sandflow lamination and grainfall lamination features;

Figure 5 (Colour) Constant voltage measurement set-up and image on high resistivity, fractured core sample taken from the Apulian platform foreland carbonates in the Southern Apennines, Italy.

a. Modified core imaging system including porous fibre probe and ground reference;

b. Photo of the carbonate rock surface;

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Figure 6. EPS line scan through length of sandstone specimen and EPS surface scan of sandstone specimen taken from the Penrith Sandstone gathered from the Stoneraise Quarry, NW England;

a. Modular elements of a typical Electric Potential Sensor (EPS) showing the probe electrode, feedback, guard, and input bias circuits of the electrometer amplifier.

b. EPS line scan through length of sandstone specimen, showing the output voltage and phase variations.

c. Very high resolution surface scan of sandstone specimen using data from EPS.
Table 1. Calibration data for Core Imaging system. All values expressed in Ohms, unless otherwise stated. Results shown in blue indicate that the voltage across the load has reached 20V, which represents the maximum potential difference available and results in a limiting of the current flowing through the test load. The readings in red indicate where the instrument is either under or over-voltage, which leads to poor reading accuracy.

Equation 1.

\[ R_t = a R_w \phi^{-m} S_w^{-n} \]  

(Equation 1)

Equation 2.

\[ \rho = \frac{A \Delta V}{I \Delta l} \]  

(Equation 2)

Figures
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Tables

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Figure 1
Click here to download high resolution image

a. Region of uniform current density
   Equi-potentials $\Delta V$

b. Fluid Reservoir
   Extended region of uniform current density
   $\Delta V$
Figure 5

Click here to download high resolution image

a. Diagram showing a schematic of a testing apparatus with components labeled as follows:
- C1
- C2
- 100 R
- Current Ref: 11
- Porous Fibre
- Fractured Rock
- Metal Substrate

b. Image showing a cross-sectional view of a material with labeled axes x (mm) and y (mm)

c. Image showing a color-coded representation of resistance (kΩ) with a legend indicating resistance values from 10 to 1.7 kΩ and conductance (Siemens) values from 0.1 to 0.6 Siemens.
Figure 6

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b. EPS line scan showing the output voltage variations across the length of the sandstone specimen.

c. Very high resolution surface scan of sandstone specimen using data from EPS