ELECTRICAL RESISTIVITY IMAGING OF CORE SAMPLES

P.D. Jackson, M.A. Lovell*, C.Pitcher, C.A. Green, C.J. Evans, R. Flint and A. Forster
British Geological Survey, Keyworth, Nottingham.
* Borehole Research, Department of Geology, Leicester University.

Abstract High resolution imaging of the electrical resistivity of whole and half core is described. The technique aims to provide a calibration of downhole information on the resistance images that up to now provide only qualitative information on the formation resistivity structure. The resistivity imaging of core is shown to be sensitive to the same fabric and structural detail as available electrical image data and to provide a means of converting electrical resistance images into physical properties. Examples are presented for various lithologies from the BGS core archive, and also synthetic laboratory models. The measurement system is novel and it outlined along with the geophysical array required to produce the high resolution resistivity measurements. The measurement technique is able to provide an assessment of resistivity anisotropy in terms of constraining the electrical current flow either horizontally or vertically in the core sample. The core images are shown to be diagnostic of grain fabrics, and allow resistivity and resistance images to be understood in terms of sedimentary fabric. It should also prove of use in studies of climatic cycles, definition of mineral-filled fractures, and will provide better constraints on models of current conduction within formations in situ.

INTRODUCTION

Laboratory measurements have the traditional role of complimenting downhole measurements with a view to providing a calibration of downhole data in terms of petrophysical properties. For example laboratory derived parameters are required to derive porosities from electrical resistivity measurements. Laboratory investigations can also lead to a greater understanding of the fundamental relationships between geophysical processes and the petrophysics of core samples.

The Formation Micro Scanner (FMS; Schlumberger trademark) developed by Schlumberger (Ekstrom, 1986) has set new standards in the acquisition of borehole images. This technique uses multiple single point resistance measurements to assess fine changes in electrical resistivity at the surface of the borehole wall; many examples have been reported in the literature eg Pezard and Luthi (1988).

These downhole images represent the highest resolution of currently available technology with measurements on a vertical spacing of 0.1 inches. This is achieved using four rows of 0.2" diameter electrode buttons at 0.4" separation between nearest centres, with each of the four rows offset by 0.1" to provide even coverage. Thus it is feasible to produce high resolution electrical resistance images of the borehole wall.

FMS images may show fine bedding in sedimentary sequences, fractures, foliation, and property contrast to compare with visual inspection of the core. These images are of immense value in understanding geological processes and assessing qualitative petrophysical changes.

The resistance measurements are essentially relative and cannot be converted to resistivities with confidence. Furthermore each button is compensated by equalisation techniques to remove stripes from the data (see figure 4). This type of processing allows superb images to be produced but highlights the point that the technique is a relative non-quantitative one. Contrasts can be identified but, for example, the resistivity of a sealed fracture cannot be assessed with enough confidence to predict its porosity. Thus the need to convert downhole FMS images to quantitative resistivities is of considerable importance. Laboratory resistivity data at a similar resolution would allow FMS images to be interpreted in terms of porosity, foliation and fractures could be separated, and anisotropy could be assessed, in addition to enhanced fracture analysis where porosity and permeability could be assessed.

Laboratory investigations of electrical resistivity require relatively simple measurements that have been made for many decades. However, the simplicity introduces problems in that there is still no universally accepted common method. Electrical conductivities of fluids are normally measured using high frequency two-electrode methods in geochemical and hydrogeological investigations while geophysicists favour four-electrode methods which are inherently more accurate (Rust, 1952; Brace et al, 1965; Niininen & Kelha, 1979).

The objective has normally been to obtain an average value of the gross resistivity of core samples and plugs. This has the disadvantage of ignoring the smaller scale features and can be degraded by electrode effects (Jackson et al, 1978).

Furthermore there is often great confusion in the assessment of electrode effects, and equi-potential surfaces due to the complex nature of the electrolyte/ionic, and metal/electron interface where an electrochemical barrier to current flow exists. This

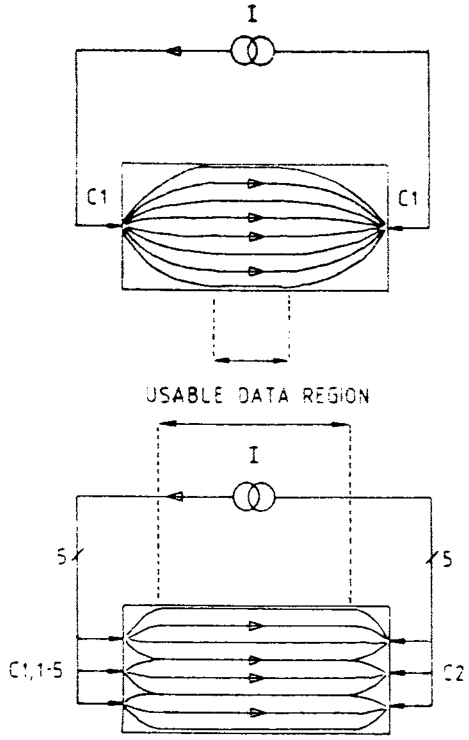


FIGURE 1 **The use of multiple current sources to provide a uniform electric field.**

effect has been documented by Guptasarma (1983) , where he identified problems in assuming Ohm's Law during tank modelling experiments using metallic conductors. Here the electrochemical component of the impedance to current flow was shown to be dependent on the magnitude of the current passed.

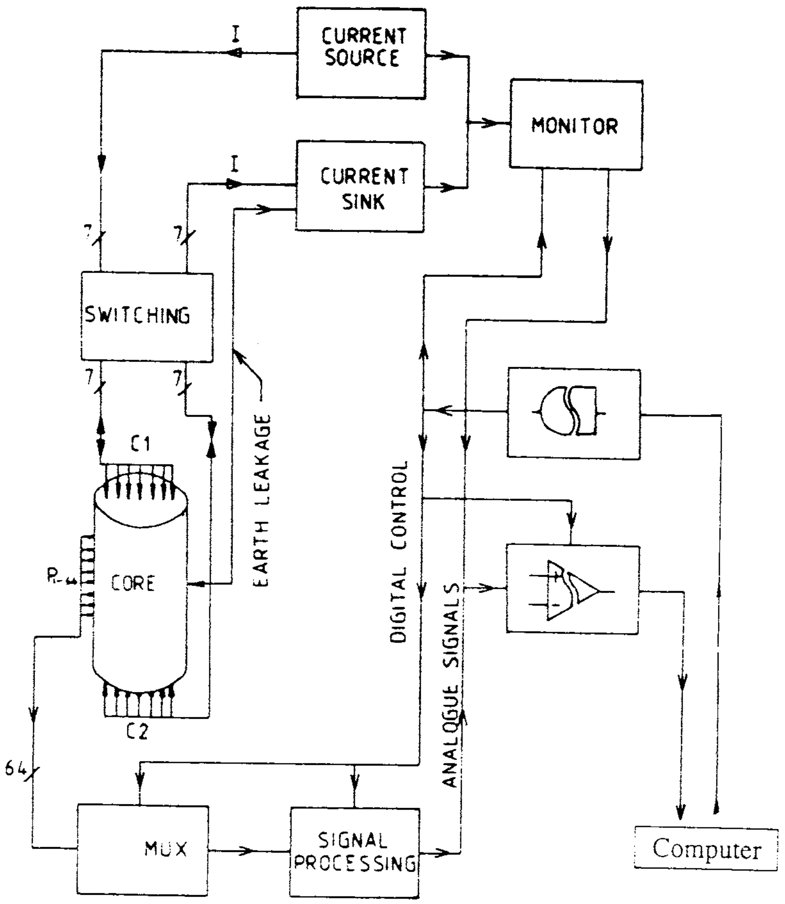


FIGURE 2 A schematic outline of the CORE-RES imaging system (pat. applied for).

CORE IMAGING

Core imaging has been researched using hybrid electrode arrays over the last decade or so, but without real impact on petrophysics (Lytle et al, 1977; Lytle & Dines 1979). These methods tend to use hybrid electrode arrays that often combine the two and four electrode resistance measuring methods. As already mentioned the two-electrode methods suffer from variable electrochemical effects that can degrade large area electrodes, such as some of the so-called 'guard' electrodes that are designed to control where the electric current flows. In comparison the approach we have adopted is to apply computer controlled geophysical mapping techniques that have been developed for imaging geological structure (Jackson et al 1989, Jackson and McCann 1989; Jackson and Ogilvy, 1989).

The technique involves low frequency four-electrode resistance measurements where all electrodes are taken to be points as far as is possible. Thus the points in space where current emanates and potentials are measured are known precisely, in contrast to large area two electrode methods. The method adopted is a substantial development of the linear rectangle or 2-D gradient array (Kunetz, 1966). This array has many advantages in mapping geological structures based on high resolution and simple responses that are a direct indication of the underlying resistivity structure.

The overall arrangements adopted are shown in Figures 1 and 2 where the benefits of controlled distributed current sources are illustrated. The potential difference measurements are made via a pad of 64 sprung, gold plated electrodes spaced on a 4 by 16 grid of 0.2 inch spacing.

Each of the multiple current sources is individually fixed using a sophisticated feed back control system which enables the uniform current field to be generated using point electrodes. The potential differences are measured on the surface of the core as shown in Figure 3, which may be split if desired. The resolution is limited only by the number of electrode positions. This can be improved by increasing the number of electrodes or repeated offset measurements. The use of point electrodes for both potential and current allows control of the current field and very high resolution potential measurements which do not disturb the flow of current.

The technique (patent pending) is novel in that there is precise independent control of the current flow and voltage measurements which are not degraded by surface impedances and electrochemical effects. The computer

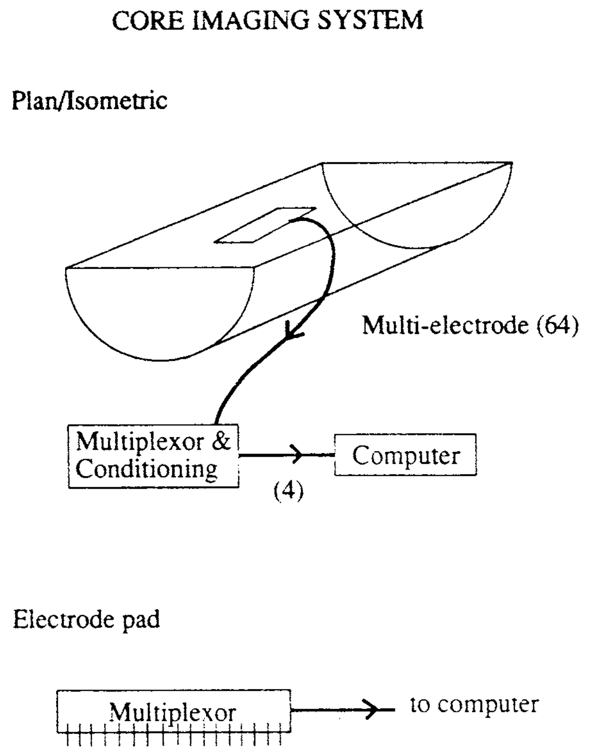


FIGURE 3 **Core imaging of split core; whole core can also be accommodated.**

controlled scanning system was developed specifically for core measurements but draws heavily on experience gained during the development of geophysical mapping techniques for geological structures (Jackson and McCann 1989; Jackson and Ogilvy 1989). Investigations of electrical anisotropy are possible by defining different directions of current flow by simulated offset line sources (eg Lytle and Dines 1979) derived from the controlled current field emanating from the constant-current point-sources.

TEST RESULTS OF CORE IMAGING

Precambrian Charnian volcanoclastic

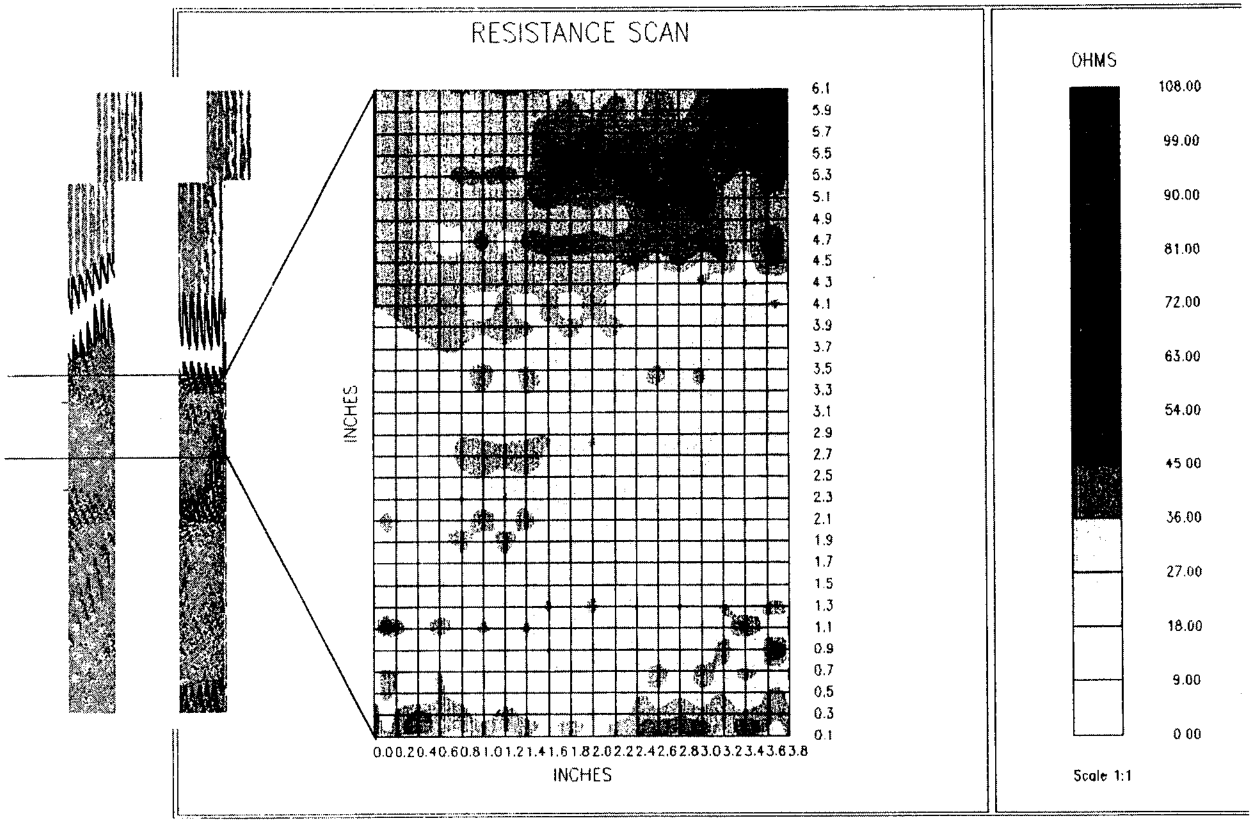
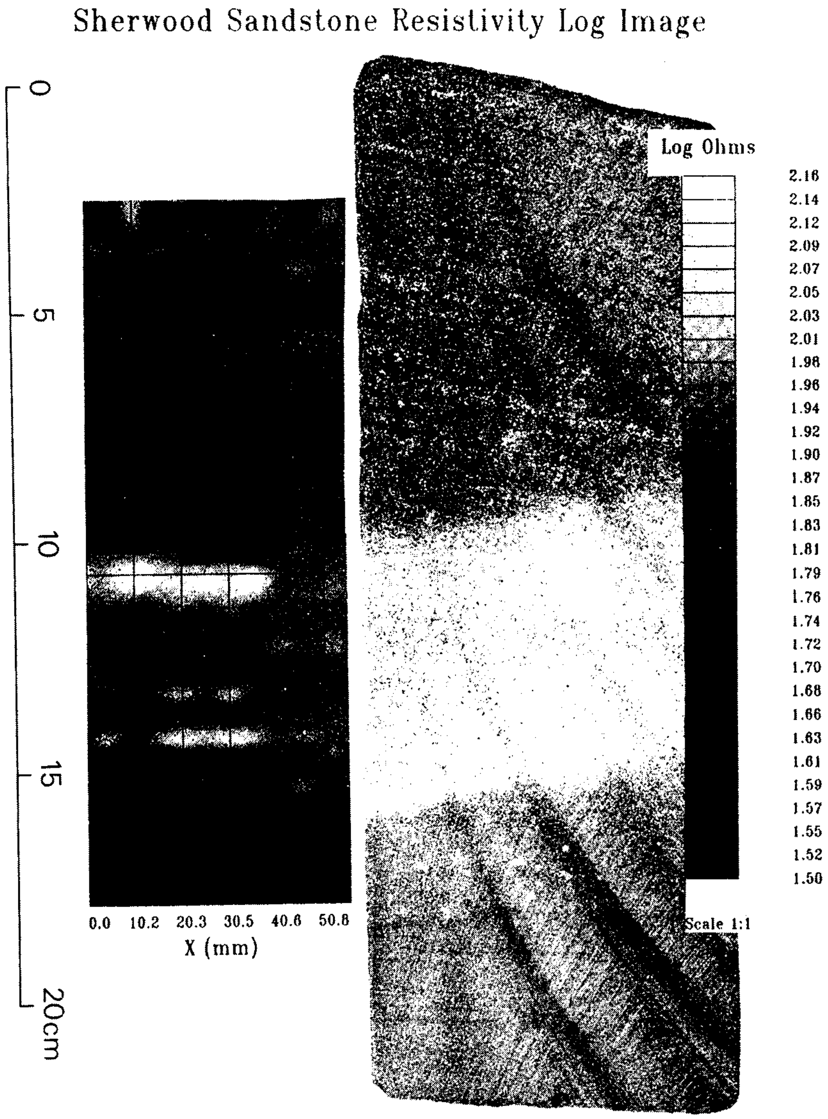


FIGURE 4 A core image compared to FMS data over a 1 meter interval - Morley Quarry 791-792m depth.



'IGURE 5 A resistivity core image of a sandstone showing higher values in a chemically altered zone.

A very low porosity precambrian sample which had been heavily metamorphosed, showing schistose foliation, was investigated as corresponding FMS data was available (see Figure 4). The method of measurement is illustrated in Figure 3 where a split core is seen with the electrode pad. The core was held within a plastic membrane and care was taken to reduce electrical current flow within surface water layers.

The results are shown in Figure 4 where a relatively complex image is displayed indicating there are substantial local variations that would be averaged out by conventional measurements. There is some correspondence with the rock fabric, but greater variability than had been expected. The resistivity values ranged from 20 to 120 ohm-m using saturating water of 12 ohm-m.

The weakness in the experiment is the unknown degree of saturation. Although the sample was saturated under vacuum and then allowed to take up water by surface tension, the sample is unlikely to be uniformly saturated. However, the results do indicate the small scale resistivity structure that is possible within crystalline rock core samples.

Sherwood Sandstone

A high porosity sandstone was used as a test core in order to remove any doubts over saturation, although no downhole FMS image was available. The sandstone is medium grained with a porosity of 25% and contains a light coloured band as can be seen in Figure 5. This feature is thought to be a zone of hydrochemical alteration.

The core sample was saturated at ambient temperature and pressure and water was allowed to flow into the sample from below by surface tension. The wetting front was observed to move through the sample ahead of the saturating fluid level. Once saturated the electrode pad was moved over the sample in stages and an image built up. The results in Figure 5 show the sample to have a complex resistivity structure where the calcium carbonate rich band is seen as a higher resistivity. This is consistent with hydrochemical alteration where any clay particles have been washed out and the iron oxides cement has been replaced with calcium carbonate. It was also noted that the central portion of this band was coarser and less well cemented at the position of the resistivity lows in Figure 5 (within the band).

The unaltered sandstone also can be seen to display a variable resistivity structure which changes rapidly in

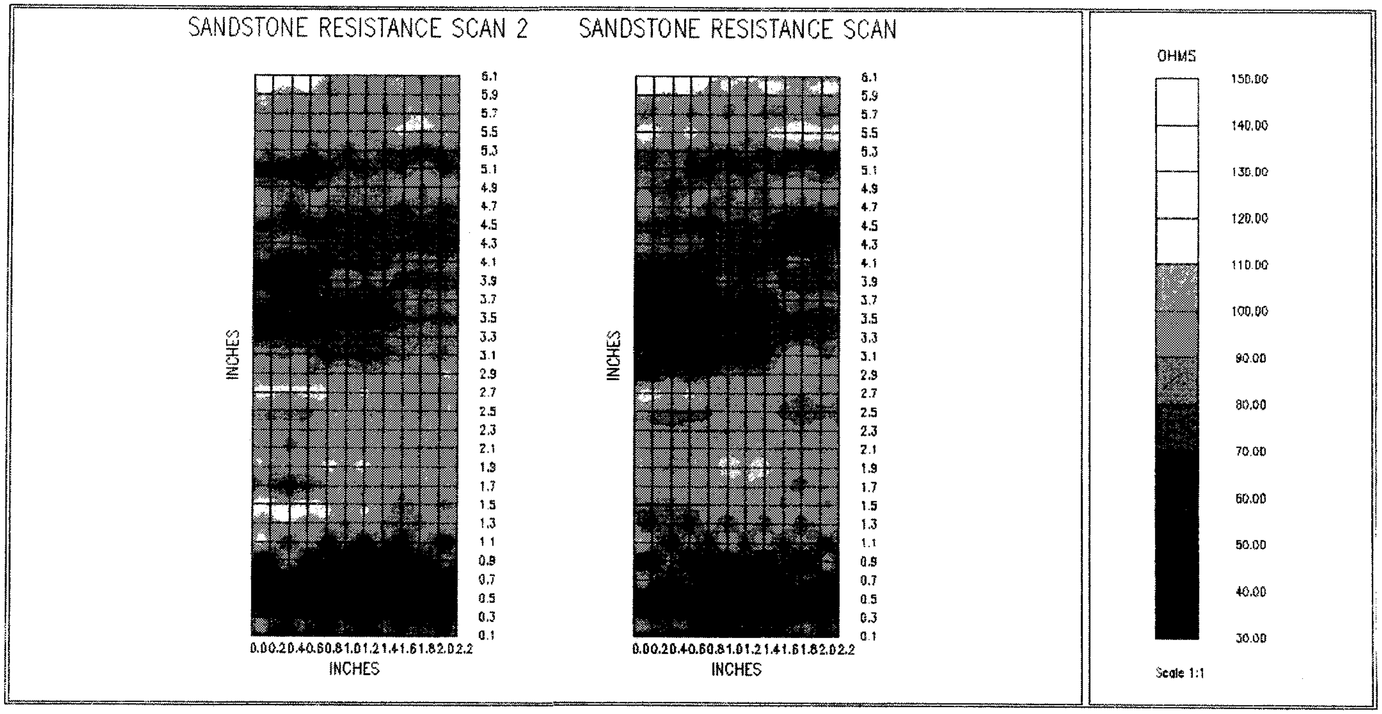


FIGURE 6 A comparison of repeated measurements of Figure 5.

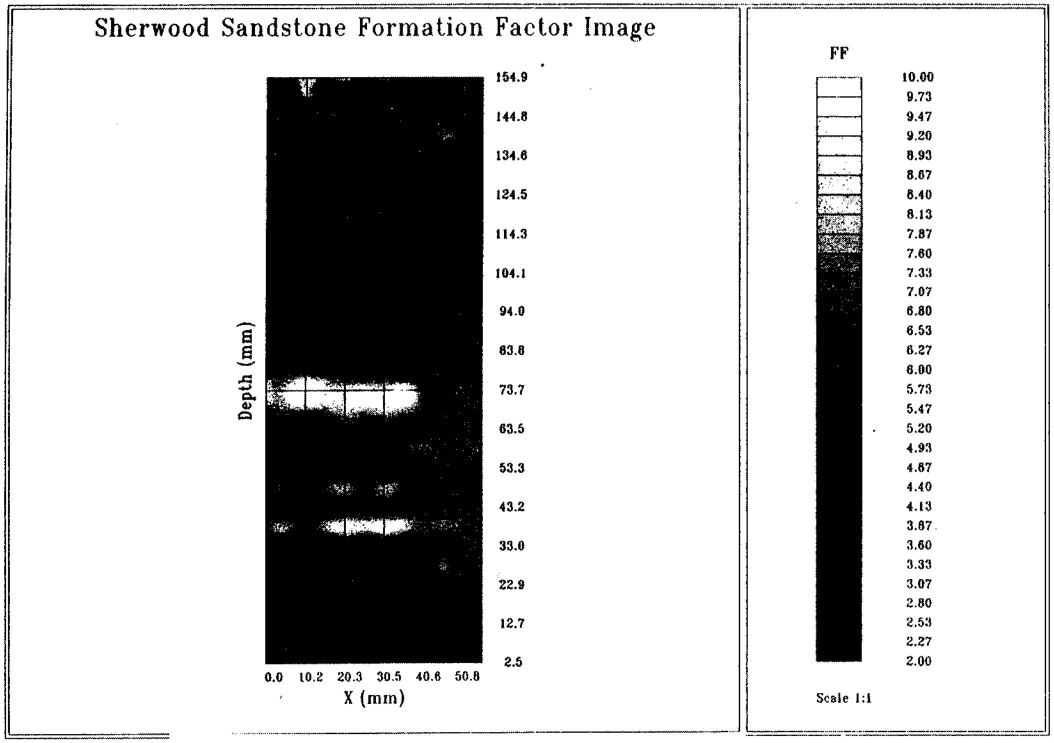


FIGURE 7 A Formation Factor image of Figure 5 showing very great variability.

some instances. Thus again a simple core specimen exhibits a complex geological structure that cannot be observed by traditional laboratory measurements.

The repeatability of the technique is illustrated in Figure 6 where the measurements in Figure 5 have been repeated. As the system is under computer control, the facility exists to average the data by repeated measurements which would reduce the random errors in the data. The results indicate good agreement in terms of the position and values of the major features but show some small variations in the fine detail. The major component of the variability is thought to be introduced by variability in positioning the electrode pad. However this aspect is being improved in the next stage of the work.

The apparent resistivity data has been converted to Formation Factor in Figure 7 to illustrate the large changes in petrophysical properties that the resistivity structure in Figure 5 implies. It should be noted that this imaging system does not incorporate mathematical artefacts due to inversion processes, it accurately reflects the resistivity distribution in two dimensions with averaging over the third.

As mentioned in section 2 the facility exists to pass a uniform current across a core sample by creating a line source and line sink current electrodes using the multi-source balanced system described above. The core sample contains bedding planes which are sub-horizontal and substantial layering is apparent. Thus it is likely that this macro-anisotropy will create a difference in resistivity between axial and corresponding perpendicular current flow. The effect of the particle alignment on a microscopic scale could also be studied.

CONCLUSIONS

A resistivity core imaging technique has demonstrated that it is possible to obtain high resolution images of borehole core. These images are in terms of apparent resistivity which can readily be related to core resistivity if they can be considered to be 2-D.

The generation of resistivity data for core samples at a comparable resolution to the downhole Formation MicroScanner opens the way to petrophysical interpretation of these high resolution downhole images. It should now be possible to infer the porosity of sealed fractures and to distinguish between foliation and small scale fractures.

Furthermore the technique opens up new possibilities in laboratory measurements where there are substantial small scale structure within one core sample. It is absolutely necessary to assess this intermediate scale structure in order to reduce the errors in petrophysical relationships and to identify constraints for theoretical investigations of petrophysical processes within porous media.

ACKNOWLEDGEMENTS

This work is published with the permission of the Director of the British Geological Survey (NERC) and was part funded through the NERC ODP Special Topic Initiative.

REFERENCES

BRACE, W.F., ORANGE, A.S. and MADDEN, T.R. (1965) The effect of pressure on the electrical resistivity of water saturated crystalline rocks. *J. Geophys. Res.*, 70, 5669-5678.

EKSTROM, M., DAHAN, C.A. CHEN, M., LLOYD, P.M. and Rossi, D.J. (1986) Formation imaging with microelectrical scanning arrays. *Society of Professional Well Logging Analysts Transactions, Paper BB. Houston.*

GUPTASARMA, D. (1983) Effect of polarisation on resistivity modelling. *Geophysics*, 48, No.1, 98-106.

JACKSON, P.D., TAYLOR SMITH D., and STANFORD P.N., 1978 Resistivity-porosity- particle shape relationships for marine sands: *Geophysics*, Vol.43, **No.6**, pp.1250-1268.

JACKSON, P.D. and McCANN, D.M. (1989) Electrical Resistivity surveying to detect concealed geological structures during site investigations. The second International Conference on Foundations and Tunnels 19-21 September. University of London.

JACKSON, P.D. and OGILVY, R.D. (1989) The application of the gradient array of electrical resistivity prospecting for near surface engineering studies. In 'Curso sobre tecnicas geofisicas aplicadas al reconocimiento geotecnico', Ministerio de Obras Publicas y Urbanismo, 23-27 October, Madrid, Spain.

JACKSON, P.D., HALLAM, J.R., RAINES, M.G., RAINESBURY M.P., GREENWOOD P.G. and BUSBY, J.P. 1989 Reconnaissance Geophysics to locate major faults in clays. Report of the Geological Survey. WE/89/32.

KUNETZ, G. (1966) Principles of direct current resistivity prospecting. *Geoexploration Monographs, series 1, No. 1, Berlin: Gerbruder Borntaeger*,103pp.

LYTLE, R.J. and DINES, K.A. (1979) An impedance camera: A system for determining the spatial variation of electrical conductivity. Lawrence Livermore Laboratory Report UCRL-52413, 11pp.

LYTLE, R.J., DUBA, A.G. and WILLOWS, J.L. (1977) Surface methods for determining the electrical conductivity of core samples. Lawrence Livermore Laboratory Report UCRL-52311, 21pp.

NIININEN, H. and KEHLA, V. (1979) Construction of a wide-range specific resistivity meter with logarithmic output. *J.Phys. E: Sci. Instrum.*, **12**, 261-263.

PEZARD, P.A. and LUTHI, S.M. (1988) Borehole electrical images in the Basement of the Cajon Pass scientific drill holes, California; fracture identification and tectonic implications. *Geophysical Research Letter*, 15, 9,1021-1024.

RUST, C.F. (1952) Electrical resistivity measurements on reservoir rock samples by the two-electrode and four-electrode methods. *Transactions of the American Institution of Mining and Metallurical Engineers*, 195, 217-224.

WATER SATURATION