SCA-9820

# IMPROVED CHARACTERISATION OF FINE SCALE STRUCTURE: INTEGRATION OF DOWNHOLE AND CORE ELECTRICAL IMAGE DATA

P. D. Jackson, M.A. Lovell*, P.K. Harvey*, C. G. Williams*, R.C. Flint,

G. Williamson* and D.A. Gunn

British Geological Survey, Keyworth, Nottingham, NG12 5GG

*Leicester University, University Road, Leicester, LE1 7RH

## Abstract

Downhole images provide detailed information of the textural and structural variation at the borehole wall, enabling the construction of the geological framework in which core is located. While it is widely accepted that these images provide quantitative dip and textural information, their use for deriving quantitative petrophysical properties is not yet established. In contrast, electrical core images provide quantitative resistivity values at a similar resolution to the downhole images which can then be used to evaluate traditional petrophysical properties with confidence.

We have compared electrical images of the borehole wall with corresponding electrical images obtained on core samples in the laboratory. Core-log matching was achieved utilising: core photographs, core gamma ray, downhole gamma ray logs, electrical logs and borehole wall images. Our results demonstrate that whilst there is often similarity in structure between core and downhole images, we have observed a difference in structure between downhole images and core images/photographs. More importantly we demonstrate that wide discrepancies can exist between resistivity values derived from core images and those derived from the downhole images, even when calibrated using conventional logs.

Evaluating the impact of fine sedimentary structure on reservoir behaviour requires high resolution quantitative petrophysical data. This cannot be achieved through the use of downhole measurements alone. Core can provide this high resolution data, but must be integrated within the geological framework constructed from downhole logs and images. Electrical images, of core and the borehole wall, provide a link between the two.

## Introduction

Small scale heterogeneity such as laminae or vugs are present in virtually all reservoir rocks, and exert major controls on the uncertainty associated with calculations of hydrocarbon reserves from downhole resistivity logs. The quantification of heterogeneity at this fine scale will enable resistivity data to be upscaled towards the reservoir model. Resistivity measurements, made downhole and in the laboratory cover scales from metres to millimetres, offering a tool for quantitative assessments of fine sedimentary structures; for example electrical imaging of the borehole wall has a resolution comparable with bedding descriptions obtained from core.

Downhole resistivity logging and electrical imaging of the borehole wall continuously measure the near-borehole region at varying depths of investigation and resolution; complete spatial sampling is generally achieved because, axially, the portion of the borehole region investigated by each measurement is designed to be greater than the measurement interval. Typically, this is not the case in the laboratory where core-plug measurements sample a tiny fraction of the recovered core and are averaged over intervals of at least 25 mm. Thus where fine scale structure is significant it can be difficult to reconcile core and log resistivity data.

### *Electrical imaging of the borehole wall*

On the mm scale, modern logging tools acquire multiple closely-spaced micro-resistivity logs simultaneously for presentation as visual images which reflect variations in the electrical conductivity of the rock, (Ekstrom, Dahan et al., 1987, Lloyd, Dahan et al., 1986, Boyeldieu and Jeffreys, 1988, Luthi and Souhaite, 1990, Bourke, Delfiner et al., 1989, Bourke, 1990). These electrical images, whilst not equivalent to optical images, provide the geologist with an opportunity to view subsurface formations in their complete state (Lovell, Harvey et al., 1998). Typically four pads containing overlapping rows of button-electrodes (5 mm diameter) are used to acquire these electrical images (e.g. Ekstrom, Dahan et al., 1987). The button-electrodes are held at a constant potential relative to a return electrode. The current flowing into the formation from each button-electrode is monitored continuously. The lower tool-body, including the pad faces, is held at the same potential as the button-electrodes (relative to the return electrode). This arrangement constitutes passive focusing where, in principle, current flows from the button-electrodes into the formation in a direction normal to the axis of the borehole, counteracting the short-circuiting effect of conductive mud and mud cake. Being at a fixed potential relative to the current return electrode, the current emanating from each button varies in response to the formation resistivity immediately adjacent to it (Ekstrom, Dahan et al., 1987; Williams, Jackson et al., 1998). Given a constant potential difference, the measured values can be seen to be directly proportional to the current flowing from each electrode.

These measurements can be seen to be two-electrode and as such will contain unknown contributions due to electrode polarisation and contact impedances. These contributions are unpredictable because they are controlled by electrochemical processes in addition to ohmic effects (Rust, 1952). Four electrode methods, as used in standard downhole resistivity logging tools, overcome these effects. Traces from adjacent button-electrodes often display similar character, while having different offsets and amplitudes. In order to display geological features the conductance-depth traces for each button are individually corrected for offset and amplitude. Thus while these measurements of the current flowing from each button-electrode can be used to produce images depicting geological structure, they do not represent quantitative estimations of formation resistivity.

The depth of investigation of Electrical Imaging Tools has been the subject of some debate, because while considering a homogeneous formation during computer modelling, the measurements can be shown to have a depth of investigation of approximately 0.25 m (e.g. Bourke, 1990). On the other hand there is a wealth of literature showing responses to geological features within a few mm. of the borehole wall (e.g. Badr and Ayoub, 1989; Lovell, Harvey et al., 1998; Ekstrom, Dahan et al., 1987). Thus, in the absence of large scale homogeneous layers, the depth of investigation is taken to be 1-5 cm because this near-pad region has the greatest current density and is thus controlled primarily by features near the surface of the borehole wall (e.g. Ekstrom, Dahan et al., 1987; Williams, Jackson et al., 1995). For example, it can be shown through numerical modelling that the depth of investigation for conductive fractures is typically 25 cm, whilst it is 1-2 cm for small conductive or resistive anomalies (Williams, Jackson et al., 1998). The maximum resolution for such devices has been achieved by offsetting the two rows of buttons, enabling measurements to be made every 2.5 mm.

### *Electrical imaging of core*

The development and use of electrical resistivity imaging of core using four-electrode technology at a resolution comparable to the diameter of the downhole button-electrodes (i.e. 5 mm) has been reported previously (Jackson, Lovell et al., 1990; Jackson and Lovell, 1991; Jackson, Lovell et al., 1992; Lovell and Jackson, 1991; Lovell, Harvey et al., 1994; Harvey, Lovell et al., 1995). The technology enables quantitative resistivities to be assessed on core in a form comparable with the corresponding downhole electrical images. Thus the resistivity responses of small scale sedimentary structures and heterogeneities seen in core should be mappable to the downhole image, and offer the possibility of constraining the quantitative analysis of downhole images for petrophysical purposes.

We have adapted methods originally developed for imaging geological structure for use on slabbed core samples. They enable independent control of current and obviate the degradation by electrochemical effects and contact impedances described above. The techniques utilise grids of over 500 electrodes to provide resistivity images of saturated half-round slabbed core and are described in detail elsewhere (Jackson, Lovell et al., 1990; Jackson, Lovell et al., 1995). The grid spacing is 5 mm, enabling an area of 6 by 24 cm to be imaged at a time. This size was chosen in response to the typical size of core expected, but could be increased. Current is introduced at the ends of the core and constrained to flow uniformly into the sample and measurements are made directly on the flat surface of the slabbed core. Images are based on apparent resistivity calculations which are close to true resistivity when current flow through the sample is uniform. Current gathering effects may cause image anomalies when the end of a core sample is not straight and vertical, and can be corrected as necessary (Jackson, Lovell et al., 1995).

In this paper we present results of electrical imaging both downhole and using corresponding core; they demonstrate major similarities, but also highlight major differences between core and downhole electrical images, showing the necessity of assessing the fine scale structure of core electrically as well as optically.

## Comparison of downhole images with core

Data and core were received from three wells in the North Sea (Wells A, B & C), in broadly similar lithologies consisting of sequences of sands and shales. Core samples were obtained with corresponding FMS data, but core samples suitable for core resistivity imaging were only available for short discrete depth intervals and thus precluded the examination of continuous lengths. The samples were in the form of half-round (or less) cores with lengths varying from approximately 100 mm to 300 mm. The overall profiles of the slabbed surfaces of the samples were flat, having irregularities at the grain scale.

From left to right, figures 1 to 3 contain downhole Formation MicroScanner (FMS) images, micro-resistivity images acquired on 3 core samples (one from each well) together with false coloured optical core photographs; in addition each figure has been expanded on the right to highlight small scale structure. In figures 1, 2, and 3 the FMS images correspond to statically normalised images, which have been re-scaled over a 2-3 ft window to emphasise local resistivity contrasts and enhance visual comparisons. Similarly, laboratory images were scaled independently.

Figure 1 shows Piece B5 from Well B where a good general depth match can be seen between the FMS and the false coloured core photograph on the left. At the higher magnification, the resistivity image of the core displays a change in resistivity which is consistent with a lithological change seen in the core photograph, whereas the downhole image displays a far more diffuse character.

Figure 2 shows Piece A4 from Well A. Fine scale dipping layers are visible in the core photo and can be seen on the electrical resistivity core image but not on the FMS record.

Figures 3 shows images for Piece C3 from Well C. The FMS image, the electrical resistivity core image, and the core photo, and show the same overall features. There is a high resistivity layer identified in all three images. Comparison of the FMS and electrical resistivity core image shows disagreement in the values attributed to either side of this high resistivity layer. The FMS indicates a higher resistivity on the lower side than the core image. Independent measurements of the resistivity of the core using a non-contact induction technique (Jackson, Gunn et al., 1997) confirm the electrical resistivity core image values and suggest the FMS values to be incorrect (Figure 4). The results show that while the FMS and core images are in general agreement, there are substantial disagreements in the quantitative values over particular intervals. Thus using FMS data alone to define resistivities of fine scale structures could be unsound.

## Conclusions

Variations in the electrical character of core images corresponding to features visible in core photographs are present in all samples. The electrical resistivity core images were thus seen to respond to fine scale sedimentary structure. The FMS images sometimes appear to respond to the fine scale sedimentary structure in the pieces examined but with some degree of inconsistency. Examples have been identified where very thin, optically invisible, thin layers have been present in the electrical resistivity core image. Using FMS data to define resistivities of fine scale structures may be subject to very substantial errors, making it unsuitable for assessing the impact of fine scale sedimentary structures on petrophysical properties and hence the reservoir model. Integration of downhole and laboratory resistivity data would be greatly facilitated if there was less discrepancy between the scale-rich data available downhole compared to that available for core.

## Acknowledgements

This research was supported by, Mobil North Sea Ltd., Shell UK ExPro, the Natural Environment Research Council (BGS) and Leicester University. Authors Jackson, Flint and Gunn acknowledge this paper is published with the permission of the Director (BGS).

## References

Badr, A. R. and M. R. Ayoub, Study of a complex carbonate reservoir using the Formation MicroScanner (FMS) Tool. *SPE Middle East Oil Technical Conference and Exhibition Proceedings*, Manama, Bahrain, 1989, paper 17977, 507-516

Bourke, L., P. Delfiner, J. C. Troullier, T. Fett, M. Grace, S. Luthi, O. Serra and E. Standen, Using Formation MicroScanner Images. *The Technical Review*, 1989, **37** (1): 16-40.

Bourke, L. T. Recognizing artifact images of the Formation MicroScanner. Borehole *Imaging Reprint Volume*. 1990. Society of Professional Well Log Analysts: 191-215.

Boyeldieu, C. and P. Jeffreys, Formation Microscanner--new developments. *11th European Formation Evaluation Symposium Transactions*, 1988, Norwegian Chapter, Society of Professional Well Log Analysts.

Ekstrom, M., C. A. Dahan, M. Chen, P. M. Lloyd and D. J. Rossi, Formation imaging with microelectrical scanning arrays. *The Log Analyst*, 1987, **28** (3): 294-306.

Harvey, P. K., M. A. Lovell, P. D. Jackson, A. P. Ashu, G. Williamson, A. S. Smith, J. K. Ball and R. C. Flint, Electrical Resistivity Core Imaging III: Characterisation of an Aeolian Sandstone. *Scientific Drilling*, 1995, **5** (4): 164-176.

Jackson, P. D., D. G. Gunn, R. C. Flint, D. Beamish, P. I. Meldrum, M. A. Lovell, P. K. Harvey and A. Peyton, A non-contacting resistivity imaging method for characterising whole round core at the well site. *Developments in Petrophysics*, 1997, M. A. Lovell and P. K. Harvey. London, Geological Society Special Publication. **122**: 1-10.

Jackson, P. D. and M. A. Lovell, The correspondence of electrical current and fluid flow in rocks - impact of electrical resistivity core imaging. *THAMES*, 1991, SPWLA Symposium, London, , December 9th to 11th 1991.

Jackson, P. D., M. A. Lovell, P. K. Harvey, J. K. Ball, C. Williams, P. Ashu, R. C. Flint, P. I. Meldrum, G. Reece, et al., Electrical Resistivity Core Imaging:- theoretical and practical experiments as an aid to reservoir characterisation. *Society of Professional Well Log Analysts 33rd Annual Logging Symposium*, 1992, Oklahoma OK, Paper VV, 7pp 1992.

Jackson, P. D., M. A. Lovell, P. K. Harvey, J. K. Ball, C. Williams, R. C. Flint, D. A. Gunn, A. P. Ashu and P. I. Meldrum, Electrical Resistivity Core Imaging I: A new technology for high resolution investigation of petrophysical properties. *Scientific Drilling*, 1995, **5** (4): 139-151.

Jackson, P. D., M. A. Lovell, C. Pitcher, C. A. Green, C. J. Evans, R. C. Flint and A. Forster, Electrical resistivity imaging of core samples. *Advances in core evaluation, accuracy and precision in reserves estimation*, 1990, Proceedings of the European Core Analysis Symposium (Eurocas I), Society of Core Analysts, London, P. F. Worthington, Gordon & Breach Science, **1** 555 1990.

Lloyd, P. M., C. Dahan and R. Hutin, Eds., Formation imaging with micro electrical scanning arrays--a new generation of stratigraphic high resolution dipmeter tool. *10th European Formation Evaluation Symposium Transactions*, 1986. Aberdeen Chapter, Society of Professional Well Log Analysts.

Lovell, M. A., P. K. Harvey, T. S. Brewer, C. G. Williams, P. D. Jackson and G. Williamson, Application of FMS images in the Ocean Drilling Program: an overview. *Geological Evolution of Ocean Basins: Results from the Ocean Drilling Program.* 1998, A. Cramp, C. J. MacLeod, S. V. Lee and E. J. W. Jones. London, Geological Society Special Publication. **131**: 287-303.

Lovell, M. A., P. K. Harvey, P. D. Jackson, J. K. Ball, P. Ashu, R. C. Flint and D. A. Gunn Electrical resistivity core imaging : towards a 3-dimensional solution. *Society of Professional Well Log Analysts 35th Annual Logging Symposium*, , 1994. Tulsa OK , II Paper JJ, 5 pp

Lovell, M. A. and P. D. Jackson, Electrical flow in rocks; the application of high resolution electrical resistivity core measurements. *Thirty-second Annual SPWLA Symposium*, 1991, Midland, Texas, June 16-19th, 1991.

Luthi, S. M. and P. Souhaite, Fracture apertures from electrical borehole scans. *Geophysics*, 1990, **55** (7): 821-833.

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

Williams, C. G., P. D. Jackson, M. A. Lovell and P. K. Harvey, Assessment of and interpretation of electricalborehole images using numerical simulations. *The Log Analyst*, 1998, **38** (6): 34-44.

Williams, C. G., P. D. Jackson, M. A. Lovell, P. K. Harvey and G. Reece, Numerical simulation of downhole electrical images. *Scientific Drilling*, 1995, **5** (2): 93-98.

List of Figures

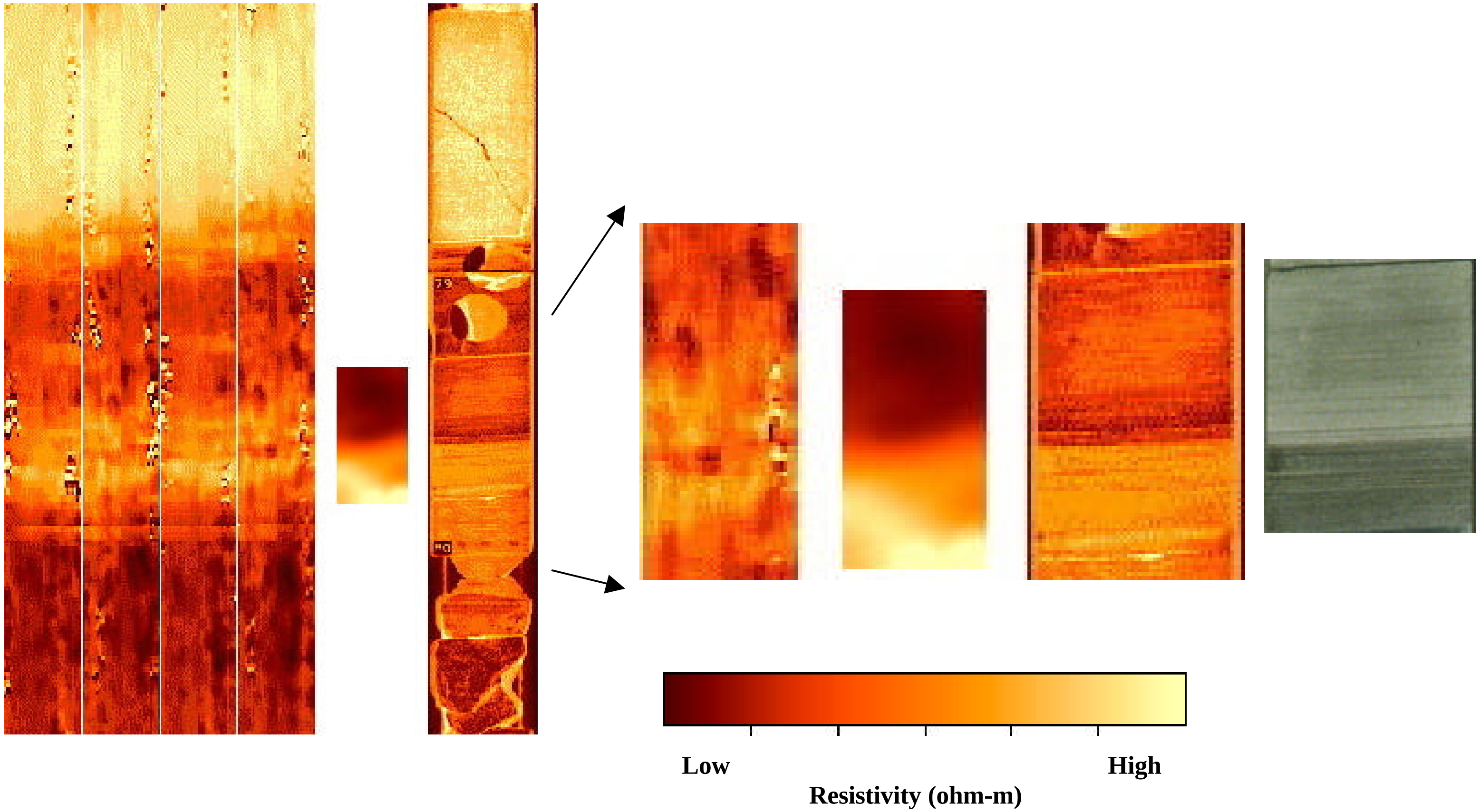



Figure 1. Piece B5 Well B (from left to right): FMS image (four pads), resistivity core image and false coloured core photography; followed by a blown up version of the centre section including core photograph.

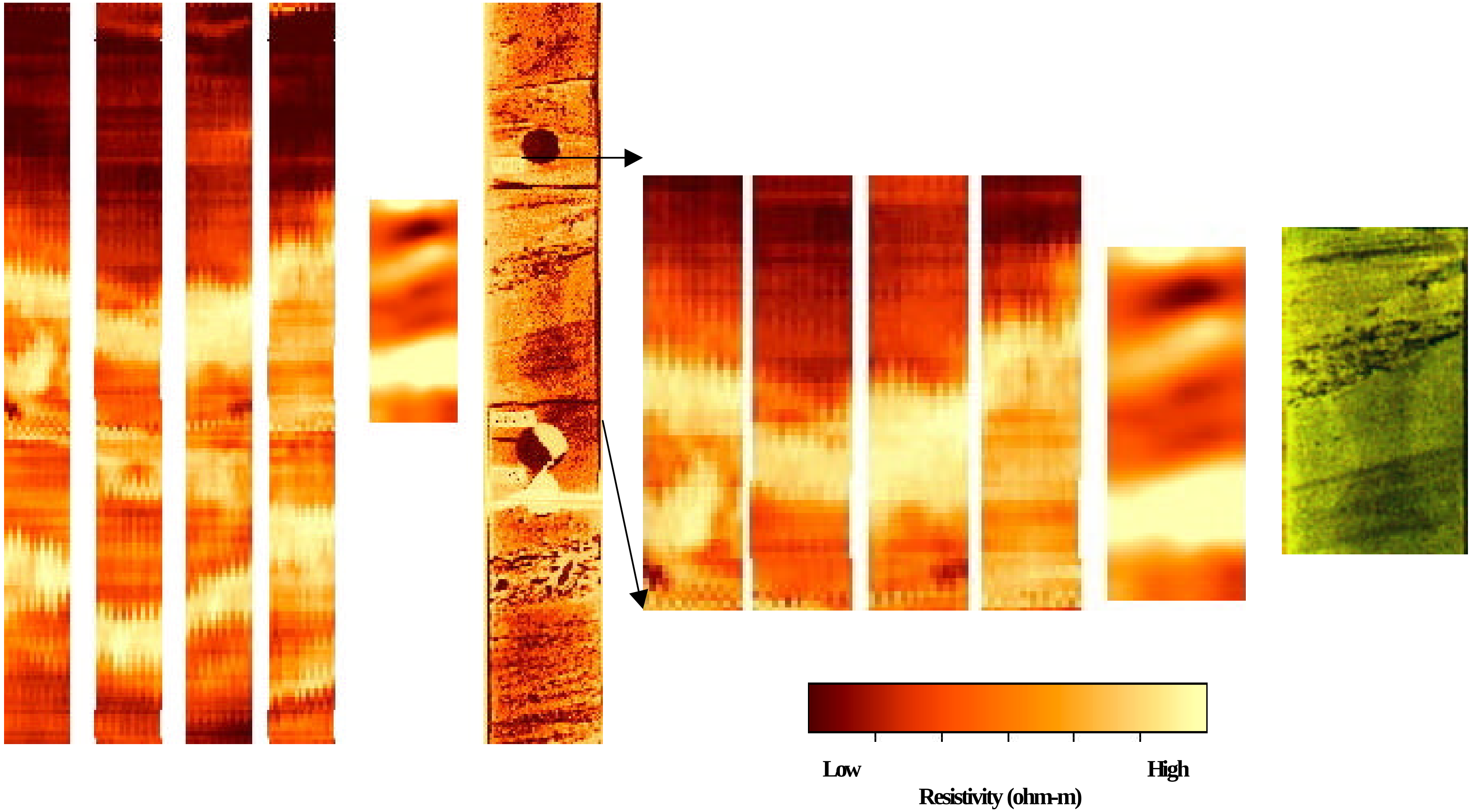



Figure 2. Piece A4 Well A (from left to right): FMS image (four pads), resistivity core image and false coloured core photography; followed by a blown up version including core photograph.

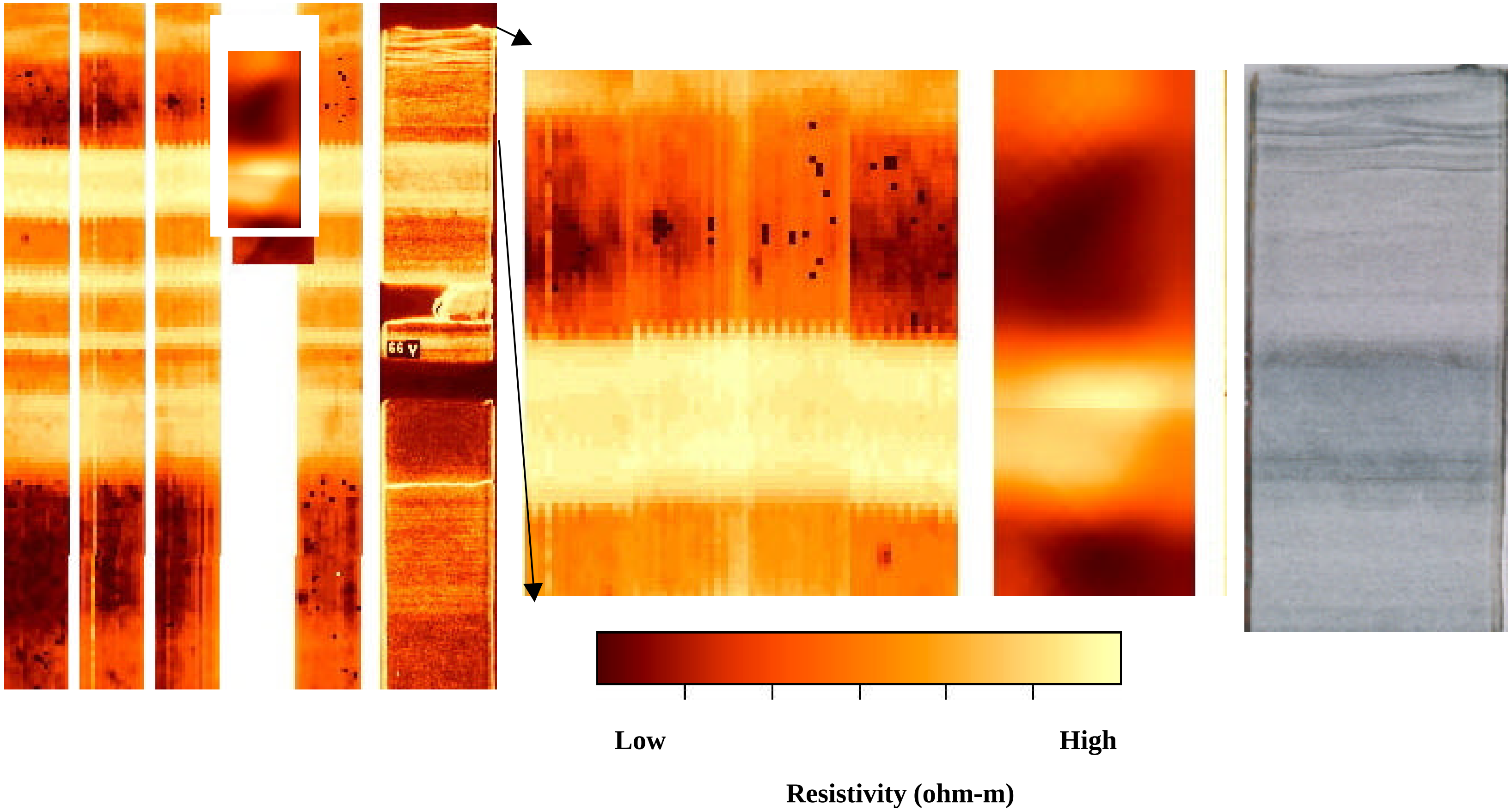
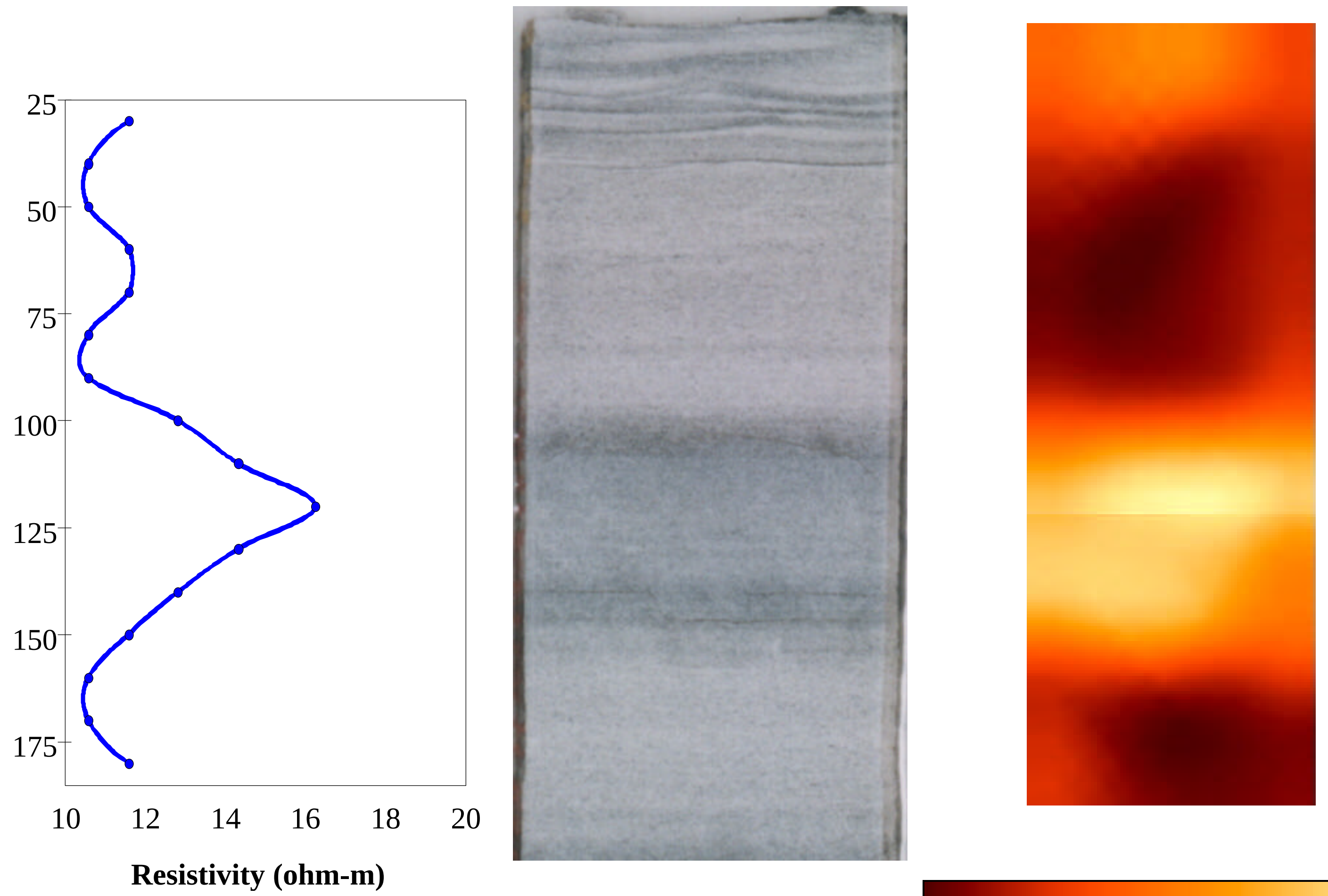



Figure 3. Piece C3 Well C (from left to right): FMS image (four pads), resistivity core image and false coloured core photography; followed by a blown up version including core photograph.



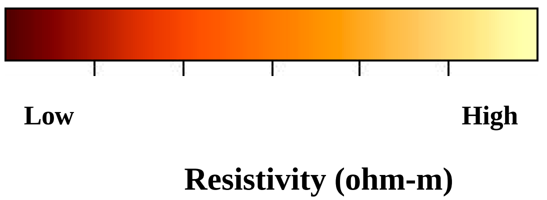




Figure 4. Piece C3 Well C (from left to right): Core non-contact resistivity log, core photograph, core resistivity image.