Characterization of heterolithic deposits using electrofacies analysis in the
tide-dominated Lower Jurassic Cook Formation (Gullfaks Field, offshore Norway)

Renu Gupta$^{1,2}$ and Howard D. Johnson$^2$

$^1$T. H. Huxley School of Environment, Earth Sciences and Engineering, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2 BP, UK
$^2$Present address: Schlumberger H-RT, Schlumberger House, Buckingham Gate, Gatwick Airport, West Sussex, RH6 0NZ, UK

ABSTRACT: A range of heterolithic facies, comprising thinly interbedded (millimetre–decimetre scale) sandstones and mudstones, characterizes the heterogeneous Lower Jurassic Cook Formation, including the productive Cook-3 reservoir in the Gullfaks Field. These heterolithic facies were deposited in a tide-dominated estuarine to deltaic setting and show up as massive ‘shaly-sands’ on conventional wireline logs. This makes the recognition and discrimination of different heterolithic facies types virtually impossible, which severely limits detailed reservoir geological and petrophysical predictions. This problem has been addressed by undertaking a high resolution electrofacies analysis using core facies as a ‘training set’ and applying this, through multivariate statistical techniques, to the interpretation of the conventional logs.

An electrofacies database was created comprising five genetically linked rock types (ranging from lenticular-wavy bedding, through flaser bedding and into clean/massive sandstones). This electrofacies scheme was validated with reference to c. 125 m of cored section from five wells using gamma-ray, density and neutron logs. Multivariate statistical techniques have enabled probabilistic discrimination of the different types of heterolithic facies down to intervals of only 0.25 to 0.5 m thick, which is considerably greater than could be achieved using conventional well-log evaluation techniques alone.

KEYWORDS: heterogeneous reservoir, tidal flat, sandstone reservoir, core analysis, well log interpretation, reservoir characterization

INTRODUCTION

Subsurface geological studies of tidal sandstone reservoirs are faced with several interpretational problems, mainly as a result of their often highly heterogeneous lithology. This is most notably reflected in the frequent millimetre to centimetre scale mud drapes and other high-resolution cyclicity, which results from the unique processes associated with tidal sedimentation (Reineck & Wunderlich 1968; Nio & Yang 1991). A fundamental obstacle to the interpretation of tidal deposits in the subsurface is the recognition of different facies types which, in traditional outcrop studies, is largely based on variations in sand–mud ratios and in the number, size and frequency of mud drapes (Allen 1982; de Boer et al. 1988; Yang & Nio 1989; Johnson & Levell 1995). A fundamental obstacle to the interpretation of tidal deposits in the subsurface is the recognition of different facies types which, in traditional outcrop studies, is largely based on variations in sand–mud ratios and in the number, size and frequency of mud drapes (Allen 1982; de Boer et al. 1988; Yang & Nio 1989; Johnson & Levell 1995). This aspect of tidal facies recognition is limited in the subsurface by vertical well-log resolution which, in the case of conventional well-logging tools, is typically in the range of 0.5–1 m. Traditional microresistivity devices, modern borehole imaging tools and the new electromagnetic propagation tool provide much higher vertical resolution (e.g. 1–4 cm) but are commonly only available in a limited number of wells. Consequently, in the absence of core, tidal sandstone reservoirs may be interpreted as intervals of massive shaly sand, which are not easily discriminated into their different sedimentary facies types using conventional well-logs. Such discrimination is necessary because (1) heterolithic facies display wide variations in reservoir quality, and (2) mud layer occurrence (e.g. thickness, extent and frequency) has a significant impact in predicting effective permeability and reservoir behaviour (Begg & King 1985). Facies recognition also influences formation evaluation, since tidal facies are one type of ’low resistivity, low contrast’ (LRLC) pay sands which can be difficult to recognize, evaluate and predict in terms of their reservoir properties (porosity, permeability and capillary pressure) and movable hydrocarbon saturation (Darling & Sneider 1993).

This paper addresses the above issues in terms of tidal facies occurrence and recognition in the Lower Jurassic Cook Formation in the Gullfaks Field, northern North Sea (Erichsen et al. 1987; Petterson et al. 1990; Olaussen et al. 1993). The aim of this paper is to demonstrate how conventional logs, carefully calibrated with core-defined heterolithic facies, can be evaluated in a modern workstation environment to provide a much higher resolution electrofacies scheme than would be achieved through traditional methods. This electrofacies calibration
provides the basis for consistent interpretation of all uncored wells, which is a prerequisite to undertaking high-resolution stratigraphic analysis. This study may have wider application to similar heterogeneous tidal facies elsewhere, such as in the Lower Jurassic Tilje Formation, which is a widespread hydrocarbon-bearing reservoir in the Haltenbank area offshore mid-Norway. The approach used in this study could also be beneficial for the evaluation of other types of heterogeneous reservoirs, including other types of LRLC pay sands (Moore 1993).

SEDIMENTARY FACIES ANALYSIS

In the Gullfaks area, the Cook Formation is divided into three lithostratigraphic units that are arranged in a single, large-scale (120–160 m thick) coarsening-upward succession, comprising (from bottom to top) (Fig. 1): (1) Cook-1: 50 to 65 m of offshore mudstone with millimetre to centimetre scale lenses and thin beds of very fine-grained sandstone; (2) Cook-2: c. 50 m of fine-grained lower shoreface sandstones and siltstones of poor to moderate reservoir quality; and (3) Cook-3: 15–50 m of fine-medium-grained sandstone with abundant heterolithic facies (80–100%) displaying evidence of inshore/estuarine tidal deposition, including tidal bundles, double mud drapes and, more rarely, oppositely dipping cross-stratification (Dreyer & Wiig 1995; Marjanac & Steel 1997). Cook-1 and -2 form a single, gradational coarsening-upward facies succession resulting from forced regression, while the erosively bounded Cook-3 preserves a fluvially incised valley system that has been transgressively filled by a tide-dominated estuarine succession (Fig. 1; Dreyer & Wiig 1995; Marjanac & Steel 1997).

The present study is aimed at the identification and detailed characterization of the various heterolithic facies present in the cores through the Cook-3 unit and their recognition in conventional well-logs at a much higher resolution than has been described in previous studies. The overall geological and petrophysical characterization of core facies was initially determined from five cored wells, which provide good areal coverage across the field. The thickness variations of the various facies in these cores range from 5 cm to 10 m, most commonly on a scale of just a few metres. To account for the thin
alternations of the various facies, cores were originally described at a scale of 1:20 for detailed characterization of core facies in terms of sand–shale ratio, grain size, sedimentary structures, cementation and bioturbation. Subsequently, they were redrawn at 1:100 scale to facilitate their comparison with well-logs and core analysis measurements (Fig. 2). In addition to the facies description, detailed measurements of sand and shale layer thickness were also carried out using representative sections of each facies type in the cores (Figs 3 and 4), since this provides critical information on the internal heterogeneity of each of the heterolithic facies. For example, the effective permeability of these facies will be greatly influenced by the frequency and lateral extent of shale interbeds, which restrict the vertical movement of fluids and significantly increase the tortuosity of the flow path (Begg & King 1985).

Three types of heterolithic facies and one massive sandstone facies have been described in the cores (Fig. 3): (1) lenticular bedded; (2) wavy bedded; (3) flaser bedded; and (4) massive sandstones. The geological and petrophysical characteristics of these facies are summarized below.

**Lenticular bedded heterolithic facies**

This mud-dominated facies is characterized by millimetre to centimetre scale sand–shale alternations (sand content 10–30%; Figs 2 and 3a). The sand lenses are very fine- to medium-grained, laterally discontinuous and internally cross-laminated. Bioturbation is generally sparse and restricted to occasional single horizontal burrows. This facies occurs in 0.05 to 5 m thick intervals, which commonly occur in the basal part of coarsening-upward facies successions (Fig. 2).

The shale and sand layer thickness distributions directly measured from cores in the key well A indicate that 95% shale layers are millimetre-scale thick and 5% are centimetre-scale thick, with maximum thickness up to 4 cm (Fig. 4a). Routine core analysis measurements show that porosities lie in the range of 17–28% (mean 20%, mode 18%; Fig. 5a). The log transformed permeability distribution of probe permeameter measurements shows a bimodal distribution (Fig. 5a). The horizontal permeability, measured by probe permeameter, varies from 5 to 680 mD (mean 74 mD), whereas horizontal permeability measured on plugs ranges from about 0.5 to 300 mD (mean 83 mD; Fig. 2).

The type section of this facies in the key well A (∼4 m thick) shows a coarsening/cleaning-upward gamma-ray profile (Fig. 6). The density/neutron separation is 13–18 pu (limestone porosity units) with similar coarsening/cleaning-upward trends as seen on the gamma-ray log and core.

**Wavy bedded heterolithic facies**

This sand-dominated facies is characterized by laterally continuous millimetre-centimetre scale rippled sandstone layers which are intercalated with thinner (mainly millimetre-scale) mud drapes (sand content 50–75%; Figs 2 and 3b). The sands are characterized by current ripple cross-lamination with distinctive tidal features, such as double mud drapes and oppositely dipping foresets. Bioturbation is sparse and this facies occurs in intervals ranging from 0.4 to 6.0 m thick. Occasional carbonate-cemented zones (10–20 cm thick) are present. This facies is typically gradational with both the underlying lenticular bedded facies and with the overlying flaser bedded facies.

The analysis of sand and shale layer thickness measurements in the key well A indicates that c. 65% of the sand layers are millimetre-scale thick and c. 35% are centimetre-scale thick, whereas 90% of the shale layers are millimetre-scale thick and 10% are centimetre-scale thick (Fig. 4b).

Excluding the tight cemented zones, core porosity ranges from 20 to 30% (mean 21%, mode 27% in well A; Fig. 5b). The
log transformed permeability distribution of probe permeameter measurements shows a bimodal distribution (Fig. 5b). The horizontal permeability measured from a probe permeameter varies from 5 to 2000 mD (mean 180 mD), whereas horizontal permeability measured on plugs ranges from about 2 to 1000 mD (mean 272 mD; Fig. 2).
The c. 6 m thick interval of this facies in the key well A is characterized by a lower gamma-ray (53–41 GAPI) and reduced density/neutron separation (32–37 API in type well A) and density/neutron cross-over (Fig. 6). The density/neutron separation is 3 to – 3 limestone pu. The core porosity varies from 25–35% (mean 34%, mode 34%). The horizontal permeability measured on core plugs ranges from 200–4000 mD and the vertical permeability ranges from 50–1000 mD. In the type well A the probe permeameter measurements give a permeability range of 10–1297 mD (mean 456 mD), whereas plug measurements give a permeability range of 5–1880 mD (mean 708 mD; Fig. 2).

Facies successions and genetic sandbody types

The cored section in the key well A shows an overall coarsening-upward succession. The main sandbodies identified in this section, within the framework of existing depositional models for the Cook-3 unit, are: (1) tidal sand bar; (2) tidal distributary channel; and (3) transgressive shallow marine sand sheet (Fig. 2).

Tidal sand bars show a coarsening/sandier-upward (C/SU) trend, comprising a gradual vertical succession from lenticular, through wavy and into flaser bedded facies. Reservoir quality increases progressively upwards in these deposits. Similar vertical facies and reservoir quality trends have been documented in modern, elongate tidal sand bars in the Colorado delta (Meckel 1975) and in the Gironde estuary (Allen 1991). Tidal distributary channels are dominated by the flaser bedded facies, they fine upwards and occasionally contain calcite cement at the base. The frequency of clay interbeds gradually increases upwards but overall reservoir quality is higher in the channel sandbodies as compared with the tidal bars (cf. Allen 1991). The transgressive shallow marine sand sheet is restricted to the southwestern and central part of the field. It is dominated by the massive sandstone facies, which is relatively homogeneous and forms the best quality reservoir within the Cook-3 unit.

**CORE–LOG CALIBRATION**

The calibration of log shape by core is particularly important to establish the suite of logs that would be most suitable for the recognition and discrimination of the various types of facies and facies successions seen in cores before quantitative electrofacies analysis is carried out. During the core–log calibration process in the key well A with a 35 m thick continuous cored section, the core-defined heterolithic facies could be best discriminated on the gamma-ray log and the separation between density and neutron logs. When density and neutron logs are displayed on a compatible scale (limestone porosity units) in the same track, the separation between the two porosity logs is
attributed to lithology or to the presence of gas in the formation. On this compatible scale, the density log is displayed in $g \, cm^{-3}$ but scaled to be equivalent to density porosity in limestone units with the theoretical limits shown in Table 1.

In the absence of any light hydrocarbons in Cook-3 reservoir (API gravity of oil 29°; formation water salinity 43000 mg l$^{-1}$), the separation between the density and neutron logs could be directly related to the lithology. The progressively higher sand–shale ratio characterizing the core-defined facies succession is clearly reflected in the decreasing positive separation between these two logs (Fig. 6). This separation has been quantified in porosity units (pu) and named as a new curve DIFF, where DIFF = NPHI – DPHI (NPHI being the neutron porosity and DPHI being the density porosity, both in limestone porosity units). In the cored interval of the key well A, the shapes of the gamma-ray and DIFF curves are mirrored and show an overall funnel-shape profile characteristic of the overall C/SU facies succession (Fig. 6).

## ELECTROFACIES ANALYSIS

Electrofacies analysis in this study is based on the linear discriminant function analysis (Davis 1986; Serra 1986; Doveton 1994; Tabachnick & Fidell 1996), which is a supervised multivariate statistical technique and involves two steps for facies classification: (1) creation of an electrofacies database with reference to the core-defined facies; and (2) assigning electrofacies to the unknown depth levels with reference to the electrofacies database and a linear discriminant function.

The database of electrofacies was created by examination of log cross-plots (RockClass*) and depth plots for clusters that were corresponding to the sedimentary facies identified in cores. The correspondence between the clusters on the log cross-plots and the core-defined facies was established by using depth vs. gamma-ray log as one of the plots in the multiple cross-plot display window. When the depth interval corresponding to a particular core-defined facies on the depth vs. gamma-ray plot is picked up, the data points corresponding to that interval are highlighted on all other cross-plots allowing generation of electrofacies corresponding to the sedimentary facies or vice versa. The distinct electrofacies correspond to different and separated clusters. They can possibly overlap in one or more dimensions of the $n$-dimensional space. The electrofacies volumes can be represented as ellipsoids in $n$-dimensional space ($n$ being the number of logs) with data points concentrating in the centre and diffusing in density towards the margin. The ellipsoids are constructed from their projections in two-dimensions (cross-plots), which are ellipses. These ellipsoids can generally be represented adequately by a set of multivariate normal parameters for each electrofacies (e.g. multivariate mean and the matrix of variances and covariances between the logs). The vector of mean values gives the location of the centre of the cloud while the variance–covariance matrix gives its relative degree of dispersion and

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<tr>
<th>Neutron (porosity units)</th>
<th>All porosity ($H_2O$)</th>
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<td>1.0</td>
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Table 1. Theoretical limits for density and neutron logs compatible scale

Firstly, the electrofacies volumes are represented as ellipsoids in $n$-dimensional space; secondly, the computed probability density function is used to assign electrofacies to unknown depth levels. The electrofacies are assigned to the unknown depth levels with reference to the electrofacies database through a linear discriminant function.

Once the database of electrofacies was created with reference to the cored intervals and was validated by comparing predicted electrofacies with the core facies against these cored intervals, this database was used for prediction of electrofacies in the other uncored intervals. The assignment of an electrofacies to a depth level is guided by the Bayes’ decision rule (DeLinger et al. 1984; Serra et al. 1985; Doveton 1994). The principle is to attach a probability distribution of log values to each electrofacies and then to identify from which population the given set of log readings is most likely to originate. The electrofacies selected as the answer at a given depth level is simply that which maximizes the probability. The computed probability provides an index of confidence in the result and can be displayed together with the electrofacies classification. A point falling outside of all ellipsoids is classified as unidentified.

The major steps used in the electrofacies classification of the Cook-3 unit are as follows (Fig. 7): (1) data preparation; (2) electrofacies creation (single well); (3) electrofacies database (multiwell); and (4) electrofacies-based correlation. These steps are described in more detail below.

### Data preparation

Application of the multivariate statistical techniques requires that a common suite of logs should be available in all the wells under study. The common suite of logs available in most of the wells in the Gullfaks Field included gamma-ray, density, neu-
Electrofacies creation (single well)

Electrofacies were first created for the cored interval (35 m) of the key well A, which contains the most complete set of core-defined sedimentary facies. The gamma-ray (gr), density (rhob), neutron (nphi), sonic (dt) and neutron minus density porosity (diff) curves were used to generate various cross-plots which could best discriminate these sedimentary facies. Five electrofacies (M, S1, S2, S3 and S4) could be created corresponding to four core-defined facies using diff vs. gamma-ray and rhob vs. nphi cross-plots (Fig. 8). Calcite-cemented zones were excluded in the electrofacies creation process by using the cut-off, rhob >2.35.

Electrofacies M corresponds to the lenticular bedded facies and is characterized by low sand–shale ratio and very thin laminations of sand and shale. Most of the sand laminae are very fine to fine grained and millimetre-scale thick. A few relatively thicker sand laminae (up to 3 cm thick) are medium grained with good horizontal permeability (up to 300 mD). However, the effective vertical permeability will be very low due to the dominance of shale and these facies can be considered as non-reservoir from a production standpoint. Electrofacies S1 corresponds to the wavy bedded heterolithic facies with 50–75% sand proportion. The sands are mostly medium grained with good horizontal permeability (up to 1000 mD). The effective vertical permeability will be dependent on the proportion and dimensions of the shale layers (Begg & King 1985). From a reservoir production performance point of view this facies has qualitatively been considered to be of moderate reservoir quality, mainly based on the intermediate range of sand–shale ratio with reference to the non-reservoir lenticular bedded facies and the good reservoir quality flaser bedded facies. Electrofacies S2 and S3 both correspond to the flaser bedded facies. Electrofacies S2 is distinguished from electrofacies S3 on the basis of the higher frequency of mud drapes and the presence of mica and coal fragments. Electrofacies S4 corresponds to massive or clean sandstone facies which has the best reservoir quality.

The validation of the database for well A was carried out by predicting electrofacies in the cored interval of this well and again comparing them with the core-defined sedimentary facies that were originally used as a training set to create this database. This comparison involved rigorous matching of each predicted electrofacies with the detailed core description (original description at 1:20 scale) and continuous core photographs. The match was very good with probability values for each predicted facies being more than 70% (Fig. 9). In the electrofacies classification, the lenticular bedded facies at the bottom shows the presence of a few intervals of wavy bedded facies. Similarly, the overlying wavy bedded facies shows a few intervals of lenticular bedded facies. These intervals (10–50 cm thick) were checked on the continuous core photographs and their presence was confirmed. Once it was established that rhob vs. nphi and diff vs. gamma-ray cross-plots are best suited for electrofacies classification, electrofacies databases were created and validated for each of the remaining four cored wells.
following the similar procedure as used in well A. The cores of these four wells contained either one or more of the four sedimentary facies, but none of them had as complete a ‘training set’ as the key well A.

**Electrofacies database (multiwell)**

A total of 15 electrofacies were created from the five cored wells, which were lumped together to create a composite database containing five electrofacies (M, S1, S2, S3 and S4). This kind of lumping has been useful to account for the lateral variations in the characteristics and associated log responses of each sedimentary facies across the field. For example, if the lenticular bedded facies was present in the cores of four wells, the corresponding electrofacies M was created in each of these wells with reference to their respective cored intervals. In the database of each single well this electrofacies is stored as a set of multivariate parameters derived from four log curves. In the composite or multiwell database these four sets of multivariate parameters would correspond to the same electrofacies M. When electrofacies are predicted in a well with reference to this multiwell database, the electrofacies M would be assigned to a depth level if any of these four sets maximizes the probability. Thus lumping of electrofacies from individual wells leads to a more robust and versatile electrofacies database for field-wide application. The validation of the multiwell database was

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**Fig. 9.** Validation of single well and multiwell electrofacies database by comparison of the predicted electrofacies with the core-defined facies in the key well A. Electrofacies were computed using gamma-ray, diff (neutron minus density porosity in limestone porosity units), density and neutron logs. The match between electrofacies and core facies is very good with probability values for each predicted facies being more than 70% in most of the intervals.

**Fig. 10.** Core–log calibration in a cored well with thin facies alternations in the Cook-3 reservoir. Conventional wireline logs do not show a distinct log-motif for the coarsening/sandier-upward facies successions that are observed in the core. However, these C/SU successions can be readily picked up on the electrofacies classification.

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Electrofacies were predicted in the cored section of these wells using this database and were compared with the core-defined facies. The match between the predicted electrofacies and the core-defined facies was found to be reasonably good in all the wells. This comparison for well A is shown in Fig. 9.

To further check the validity of electrofacies classification for sandbody interpretation, the vertical facies successions and interpreted sandbodies in cores were calibrated with the electrofacies classification. The tidal sand bars are represented by C/SU facies successions that are clearly identified, not only in the type well A, with its thick and well-developed facies successions (Fig. 9), but also in other cored wells, where the C/SU facies successions are much thinner (c. 1–2 m). The latter could be distinctly resolved in the electrofacies classification, although on conventional logs they would have been overlooked (e.g. Fig. 10). In well A, a distal to proximal trend through a prograding, or laterally migrating, tidal bar sandbody is clearly represented by the electrofacies transition from M, through S1, to S2 and S3 (Fig. 9). The tidal distributary channels are dominated by electrofacies S3. The gamma-ray log shows a blocky to slightly fining-upward vertical profile, with a lower value at the base due to the presence of calcite cement (Fig. 9). The transgressive shallow marine sand sheet at the top of the Cook-3 unit, is mainly composed of massive sandstone facies, calibrated with electrofacies S4.

The multiwell electrofacies database was used to predict electrofacies in uncored intervals/wells. In each well, facies successions and sandbody types were interpreted based on the electrofacies classification. This provided the basis for detailed well-to-well correlation and reservoir architecture prediction.

Electrofacies-based correlation

The electrofacies classification provides a high resolution facies correlation scheme, with simultaneous display of associated reservoir quality in the heterogeneous Cook-3 unit, which is not possible from conventional log signatures alone (Fig. 11). The sandbody interpretation, in conjunction with an understanding of their geometry from a review of tidal depositional environments (e.g. Nio & Yang 1991; Dalrymple 1992; Dalrymple et al. 1992; Reading & Collinson 1996; Johnson & Baldwin 1996) and a study of one ancient (Lower Cretaceous) outcrop analogue on the Isle of Wight, southern England (Gupta 1998), has been used to guide possible interpretation of the interwell volume (Fig. 11c). This correlation predicts the distribution of sandbodies and reservoir architecture at a very fine scale (0.5 to 1 m) and can be used to build a detailed 3D reservoir model (Fig. 11d). The distal tidal bars which are dominated by lenticular bedded facies form non-reservoir layers. Distributary channels, with their dominance of flaser bedded facies and relatively lower fre-
quency of mud drapes, are better quality reservoir facies than the proximal tidal bars. The transgressive shallow marine sand sheet, although restricted only to the southwestern and central part of the field, is comprised of massive sandstone facies and forms the best reservoir facies.

The electrofacies classification scheme not only provides a basis for a high resolution facies correlation but also a simultaneous display of the reservoir quality trends at the same level of detail. These subtle, but potentially significant, vertical and lateral variations in reservoir quality cannot be visualized by conventional correlation schemes based on log shapes alone.

CONCLUSIONS

An electrofacies approach based on linear discriminant function analysis (RockClass®), has been successfully applied to the recognition and discrimination of different types of tidal heterolithic facies on conventional logs (density, neutron and gamma-ray logs). These heterolithic facies were deposited in a tide-dominated deltaic/estuarine environment and show up as massive shaly-sands on conventional logs. The database of electrofacies was created and validated with reference to c. 125 m of cored section from five wells. The facies analysis involved two steps: (1) sedimentary facies were first determined from detailed core description; and (2) electrofacies were then created by grouping distinct well-log clusters corresponding to these sedimentary facies on multiple log cross-plots.

In the electrofacies classification, different types of heterolithic facies have been resolved down to intervals of 0.25 to 0.5 m thick. The database of electrofacies can be used for a probabilistic prediction of electrofacies in the Cook-3 unit in other uncored wells and provides a high resolution facies classification. The two main types of sandbodies present in the cores of the Cook-3 reservoir (tidal sand bar and tidal distributary channel) can be interpreted using the electrofacies classification with the simultaneous display of their reservoir quality and heterogeneity. The electrofacies classification allows a genetic interpretation of each well and forms the basis for building high resolution 3D reservoir geological models of the Cook Formation and, perhaps, other heterolithic tidal sandstone reservoirs.

*Mark of Schlumberger.

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