Applications of High-Resolution Borehole Electrical Images to Sedimentary and Stratigraphic Analysis

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ABSTRACT

The recent introduction of high-resolution imaging techniques such as FMI has resulted in a breakthrough with a wide range of applications. Because the reservoir can now be more accurately imaged, it is possible to describe it in a greater detail as a three-dimensional package of subsurface geological objects. It has been demonstrated that the high-resolution borehole electrical images bring fundamental information which, when integrated with conventional open-hole log, core, seismic and test/ production data, contribute both qualitative and quantitative descriptions of reservoirs. This information may be used as input to a deterministic sedimentologic-stratigraphic modeling that can provide a more precise definition of reservoir volumes and reservoir petrophysical properties.*

INTRODUCTION

In many instances, subsurface geology is complex-structurally, stratigraphically and diagenetically. To adequately evaluate a prospect or field, it is necessary to derive the maximum information from data collected (i.e., conventional core) and measured (i.e., geophysical logs) during the drilling phase.

Borehole imaging tools provide a quantum leap in continuous observation of textural and structural variations and data analysis of subsurface formations. With the advent of these techniques, it is hoped that more prospects and reservoirs will be thoroughly investigated, tested and completed to produce more energy commodity from the subsurface more economically.

Electrical imaging tools have been in use in Indonesia for many years and the function and major applications of the tool have been explained and developed in several publications. This paper will briefly discuss the applications of the high-resolution electrical imaging tools mainly to sedimentary and stratigraphic analyses.

IMAGING TOOLS

Dipmeter logging, the precursor of the modern imaging tool, has its origins in the early 1940s. The first of the modern dipmeter tools (HDT*) for the purpose of stratigraphic analysis was introduced in 1969. More recently, the introduction of the four-pad Formation MicroScanner Tool (FMS*) at the start of 1989 further improved interpretation confidence, and the trend in increasing microresistivity-image borehole coverage continued in 1991 with the advent of an eight-pad, high-resolution tool, the fullbore Formation Micro Imager (FMI*) (Bourke, 1992; Cameron, 1992). The borehole coverage of this new tool, FMI*, is 80% in an 8-in. borehole, which represents an increase by a factor of two over previous generation tools such as FMS*. Such new electrical imaging tools must be run with high-speed telemetry and an acquisition computer system, such as the MAXIS 500*.

Present day imaging techniques employ two technologies: acoustic and resistivity. Both technologies are well documented (Serra, 1989; Griffiths and Worthington, 1992; Cameron, 1992; Sovich and Newberry, 1993). A comparison between resistivity/electrical and acoustic borehole image data has been discussed in the literature (i.e., Sovich and Newberry, 1993).

The observation and analysis of the images provide information that is related to changes in rock composition and texture, structure, or fluid content. The formation can be digitally "seen" through processing of the electrical currents re-

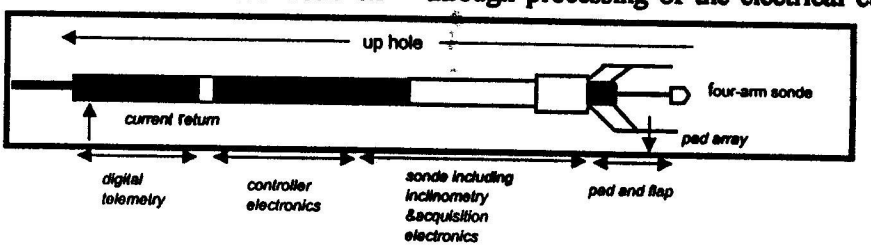


Fig. 1. Sketch of modern high-resolution imaging tool.

corded by microelectrodes that provide core-like images with the following features (Serra, 1989; Safinya and Le Lan, 1991):

•High vertical resolution (about 0.2 inches or 5 mm)
•Very large dynamic range – from less than 0.1 to more than 10,000 ohm-m
•High sensitivity, allowing detection of very thin events (fractures) which have an aperture on the order of a few microns or tens of microns, or with low contrasts in resistivity
•High sampling rate – one sample each 0.1 in. (2.5mm) vertical displacement

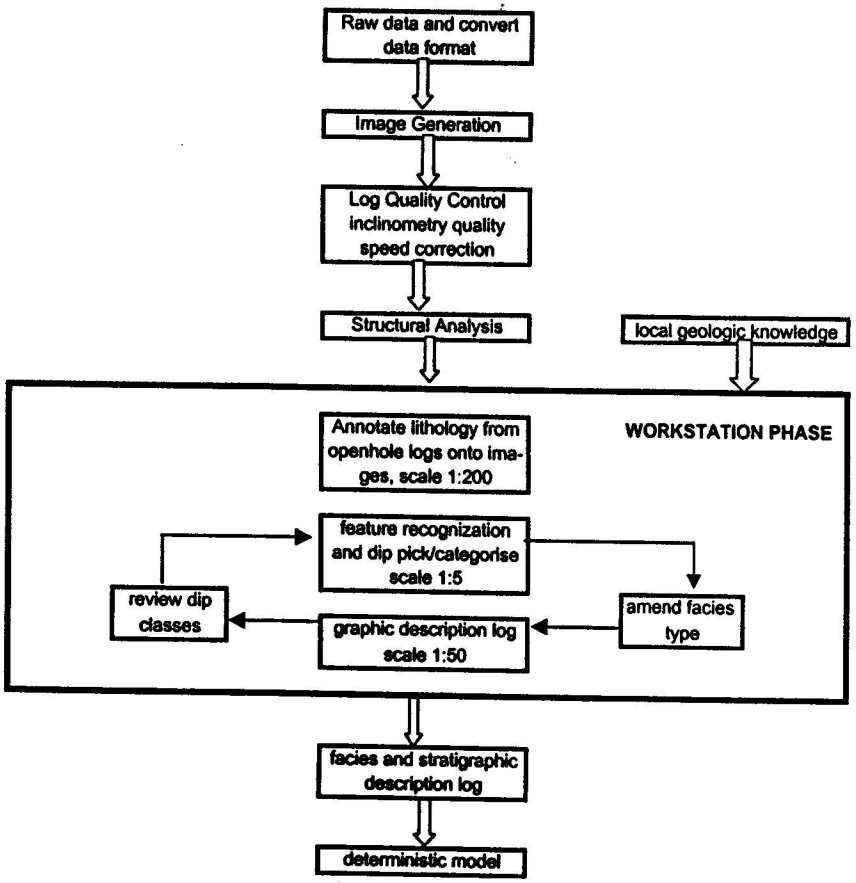


Fig. 2. Borehole imaging tool flow diagram (Bourke, 1992)

The high-resolution electrical imaging tool includes a general-purpose inclinometry cartridge which provides accelerometer and magnetometer data (Fig. 1), and it is best run in water-based mud. The triaxial accelerometer gives speed determination and allows recomputation of the exact position of the tool. The magnetometers determine tool orientation. During logging, each microelectrode emits a focused current into the formation. The button current intensity measurements, which reflect microresistivity variations, are converted to variable-intensity gray or color images. These microresistivity images provide a cylindrical view of the formation. This view can be considered two-dimensional (2D) by unwrapping the cylinder or by visualizing separately the stripes covered by each pad. The measurement resolution and spacing are small enough with respect to the size and spacing of formation heterogeneities that one can actually speak of imaging these local heterogeneities (Serra, 1989; Serra et al., 1993). Table 1 shows a comparison of the vertical resolution of laboratory and geophysical logging services for sedimentologic study.

These images can be displayed in many forms with the help of a workstation. Formats may include a core-like description log containing sedimentary and structural symbols and other annotations displayed along with the standard openhole logs (gamma ray, resistivity, neutron-density) and dipmeter data. Figures 3-6 show some examples of dipmeter interpretation, ranging from identification of syn-sedimentary structures in fluvial sandstone, stylolites in carbonate succession, paleo-current from cross-bedded sandstone, to fracture orientation in a carbonate reservoir. Dipmeter interpretations (e.g., structural dip and paleocurrent determination) are discussed in detail in several papers (e.g., Schlumberger, 1986; Gilreath, 1987; Enchecopar and Dubas, 1992; Cameron, 1992).

Like other geophysical logs, electrical imaging techniques are subject to the influences of mud cake, invasion, borehole washouts, temperature changes and changing connate water resistivity, but they can still provide reliable quantitative information (Serra, 1989; Sovich and Newberry, 1993). Recognition of image artifacts/false images and the cause(s) is thus essential when dealing with image interpretation.

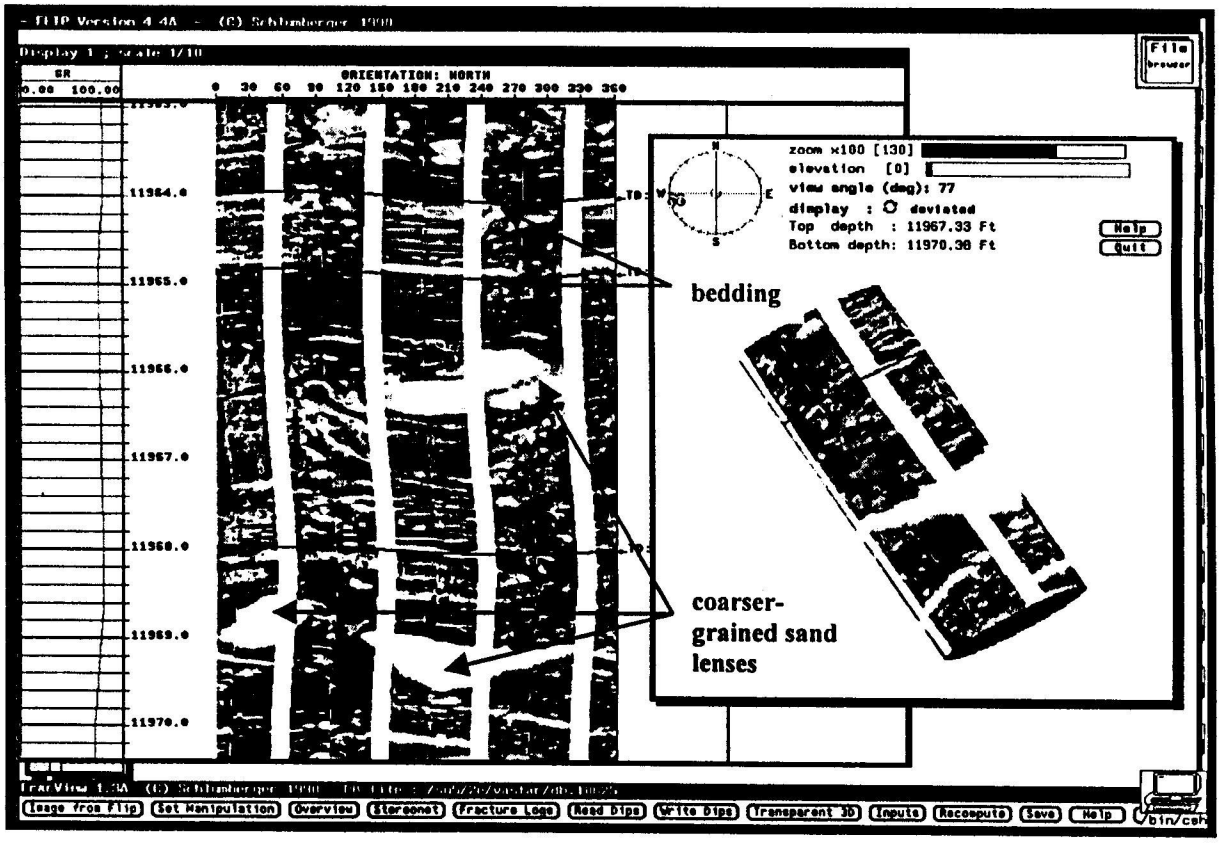


FIGURE 3. This example of electrical image shows fluvial sandstone interval containing syn-sedimentary deformation features (Grade 1). The sand lenses are ambiguous features (Grade 2). The three dimensional view of the image is also displayed.

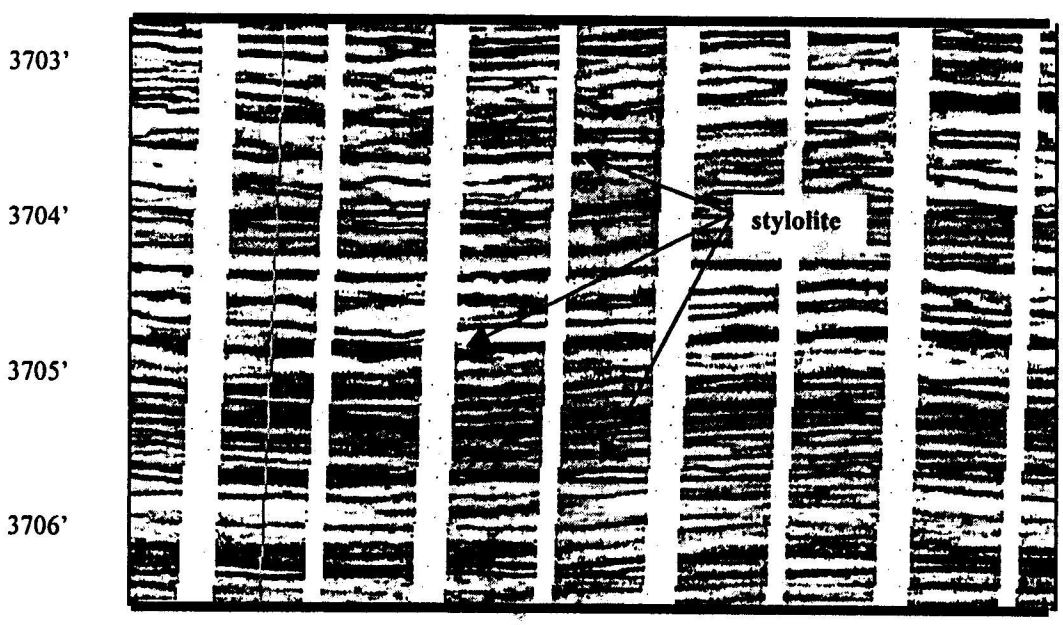


FIGURE 4. Electrical image of carbonate rock containing rhythmically layered stylolites. These stylolites have high-amplitude peaks and can be considered as self-interpretable features (Grade 1).

INTERPRETATION METHODOLOGY

PRINCIPLE OF SEDIMENTARY/STRATIGRAPHIC ANALYSIS

Interpretation and reconstruction of ancient depositional environments depend upon identifying physical, chemical, and biological characteristics of sedimentary rocks that can be related to environmental parameters. In general the physical criteria (i.e. gross lithology, facies associations and sedimentary geometry and structures) and the biological properties (i.e. fossil content and type) for environmental interpretation are more important than chemical properties of sedimentary rocks. No single criterion, however, can generally be relied upon to provide unequivocal environmental interpretation; geologists commonly must make use of all available properties of the sedimentary rocks and only when several independent criteria yield the same interpretation can the environment be confidently assigned (Selley, 1985; Serra, 1989; Boggs, 1995). Facies models are commonly based on modern sedimentary environments but common sense and good judgement must be exercised in the use of facies models. Geologists must be careful not to ignore or subordinate facts that do not fit in order to force interpretation of depositional environments on the basis of a particular model (Boggs, 1995). Geologists are warned by this Reading's statement (Boggs, 1995): "The conviction that one's own hypothesis is right is frequently the mark of one who is poorly informed about alternatives".

SEDIMENTARY/STRATIGRAPHIC INTERPRETATION FROM ELECTRICAL IMAGES AND PITFALLS

Electrical images can be classified into three main categories for the purpose of sedimentary-stratigraphic interpretation (Serra, 1989; Salimullah and Stow, 1992. These are summarized in Table 2 with some modifications presented in this paper.

- *Grade 1* (self-interpretable): The features are easily interpretable due to their shape, length and patterns. A trained analyst need only refer to memory and experience to interpret the images with confidence. The Grade 1 features include bedding surfaces, laminations and cross-beds, erosional surfaces and penecontemporaneous/ synsedimentary deformation features. Any planar surface such as bedding and faulting, that crosses the borehole will be represented as a sinewave on a two dimensional plot.
- *Grade 2* (ambiguous): A conceptual model or other log data are necessary to interpret the images correctly and completely (such as gravel, graded bedding, sorting, and some aspects of diagenesis).
- *Grade 3* (core calibration needed): Images are used to complement core interpretation. These include bioturbation type and degree, some trace fossils, rootlets and glauconite.

An absolute rule in image interpretation is never to attempt analysis of an image without first categorizing both the lithology and the sequence of sedimentary features. If cores are available, they should be described in detail. Comparing sedimentary features between cores and images permits assessment of lateral variation of thin beds and other features on the scale of the borehole. Images, however, provide better visualization of minor-scale features (e.g. faults and slumps) that are ambiguous or absent on dipmeter logs or may be too large to interpret from core data alone (Roestenburg, 1988; Serra, 1989; Bourke, 1992).

The benefits of workstation input to image analysis greatly aids in interpretation in terms of data manipulation, speed and accuracy. It must be stressed, however, that the use of a workstation is not a substitute for the skills and knowledge of the interpreter, but an additional aid to the interpretation process (Bourke, 1992).

OTHER APPLICATIONS

Since electrical images are related to lithology, texture, sedimentary features, and some aspects of diagenesis, the electrical images, therefore, can serve as a valuable source of data for precise and accurate facies description and determination, and as a consequence they can be fully utilized in sequence-stratigraphic analysis.

With regard to this fact, the practical methodology outlined by Posamentier and Allen (1999) with an emphasis on borehole data for sequence-stratigraphic analysis of single or multi-well study is clearly benefited by the existence of borehole imaging data. The scheme of the sequence stratigraphic procedure is reiterated below to underline the important position of precise and accurate subsurface data which validate all the steps necessary in the sequence stratigraphic analysis. The procedure is as follows:

- Step 1: establish the paleogeographic setting
- Step 2: interpret depositional systems and facies

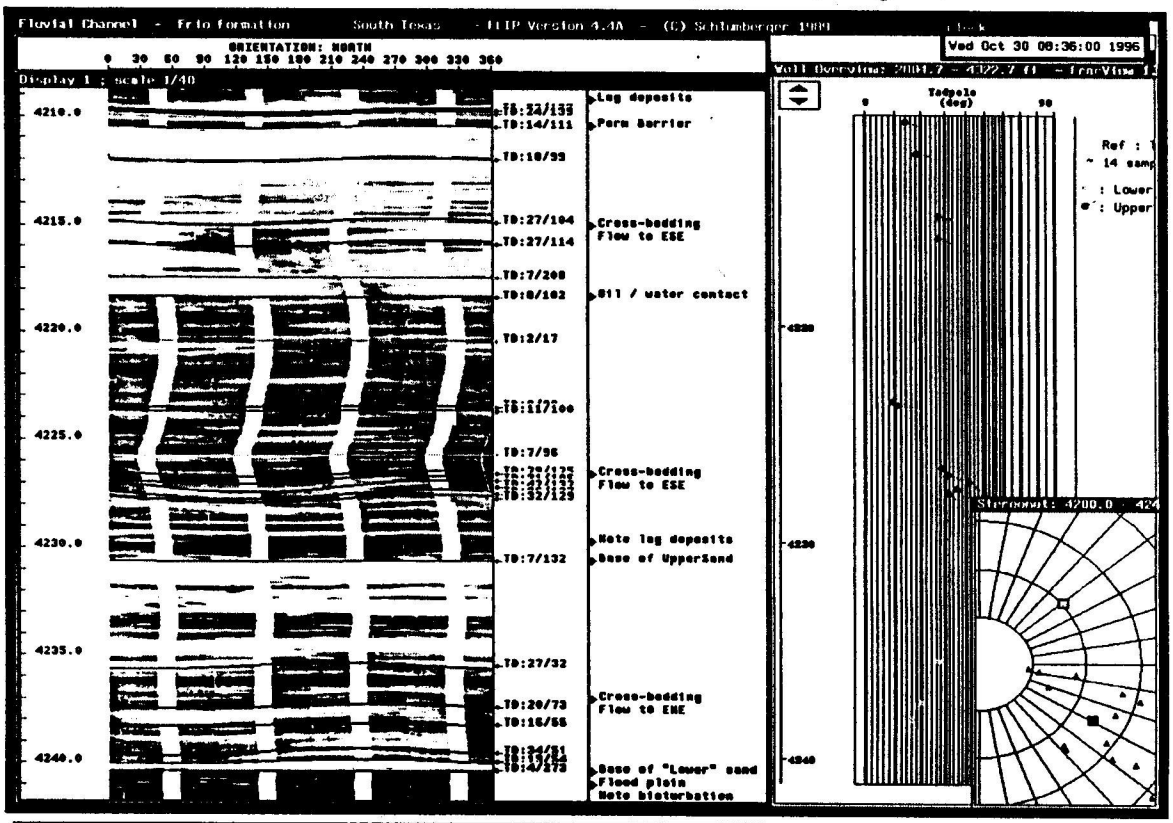


FIGURE 5. Electrical image of cross-bedded fluvial sandstone. The right-hand side is the tadpole plot of dipmeter log that shows a 'red' pattern indicating the paleoflow being to ESE.

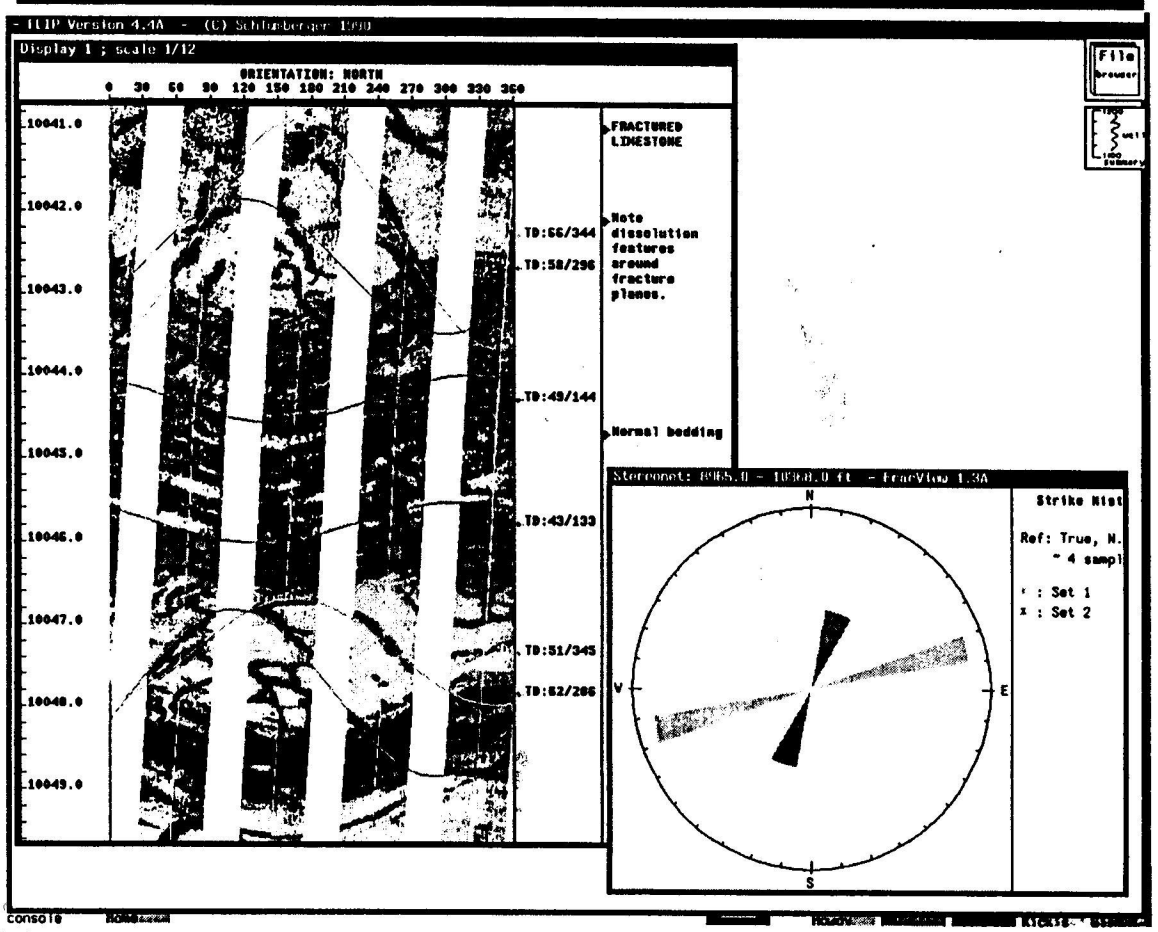


FIGURE 6. Electrical image of intensively fractured carbonate rock. All the fractures (shown as sinewaves)are of unfilled type, striking NE-SW and NNEE-SSWW.

using all available data
•Step 3: identify maximum flooding surfaces and sequence boundaries
•Step 4: analyze facies stacking patterns and identify systems tracts

The electrical imaging method also has been applied to thin laminated sands where it can be used to estimate the sand volume present and to differentiate rock type in complex lithologies. For a petroleum engineer, images provide information on the internal organization of the reservoirs (homogeneous or not), the presence of permeability barriers (cemented beds or fractures, stylolites, shale laminations, etc.) or paths (open fractures, vuggy-fenestral porosity, etc.). This helps to optimize the reservoir model and completion design. Imaging data provide answers to many fracture attributes, such as vertical or horizontal (horizontal wells) distribution, fracture size (width, length, aperture), orientation, spacing and type (Serra, 1989, Sovich and Newberry, 1993, Standen et al., 1993). Image interpretation will help in the selection of the saturation equation and associated parameters such as cementation factor (m) and is also useful for selecting zones for sidewall cores, fluid sampling or for pressure measurements (Serra, 1989).

BOREHOLE IMAGING STUDIES IN INDONESIA

Imaging tools have been in use in Indonesia for many years, both in oil and geothermal fields. Roestenburg (1988) presented a paper discussing the use of the FMS* (first-generation high-resolution imaging tool) in subsurface structural and stratigraphic analysis. This paper exhibits some electrical images of salient sedimentary and stratigraphic features compared to those identified in slabbed core. Komaruddin et al. (1992) and more recently Wathan et al. (1996) discussed the applications of the imaging tool techniques in the evaluation of the geothermal fields. Gumilar et al (1996) discussed an analysis of low-contrast pay using several methods and data including electrical image. Nabasir et al (1999) presented the integrated reservoir study that utilized the imaging tool techniques to determine detailed sedimentary facies and fracture orientation, stress and strain system to identify the optimum direction of frac-job in a shaly formation.

It is perhaps true, as also being stated by Sidi et al. (1999) that the energy sectors (i.e., petroleum and geothermal businesses) will remain the major users of technology-based subsurface methods including high-resolution imaging and others (3D seismic, 3D visualization). These are required by the industry not only to find and produce supplementary reserves from mature fields, but also to explore frontier areas and technologically as well as geologically complex zones.

SUMMARY

Electrical images provide geologists with information that is related to lithology, texture, sedimentary and structural features, and some aspects of diagenesis. They are conclusively a valuable source of data for precise and accurate facies description and determination of depositional environments, and the excellent resolution of the tool makes it possible to discriminate features that are not seen using conventional logs. As with sedimentological analysis of core data, the systematic description of borehole images can provide a detailed graphical sedimentary interpretive log. Electrical images are also used for fracture study and well-to-well stratigraphic correlation. However, clear and reliable interpretation of electrical image data should not only be supported by an accurate and detailed analysis of measured log data, but it must also be based on a solid knowledge of tool and measurement principles and correct geological concepts.

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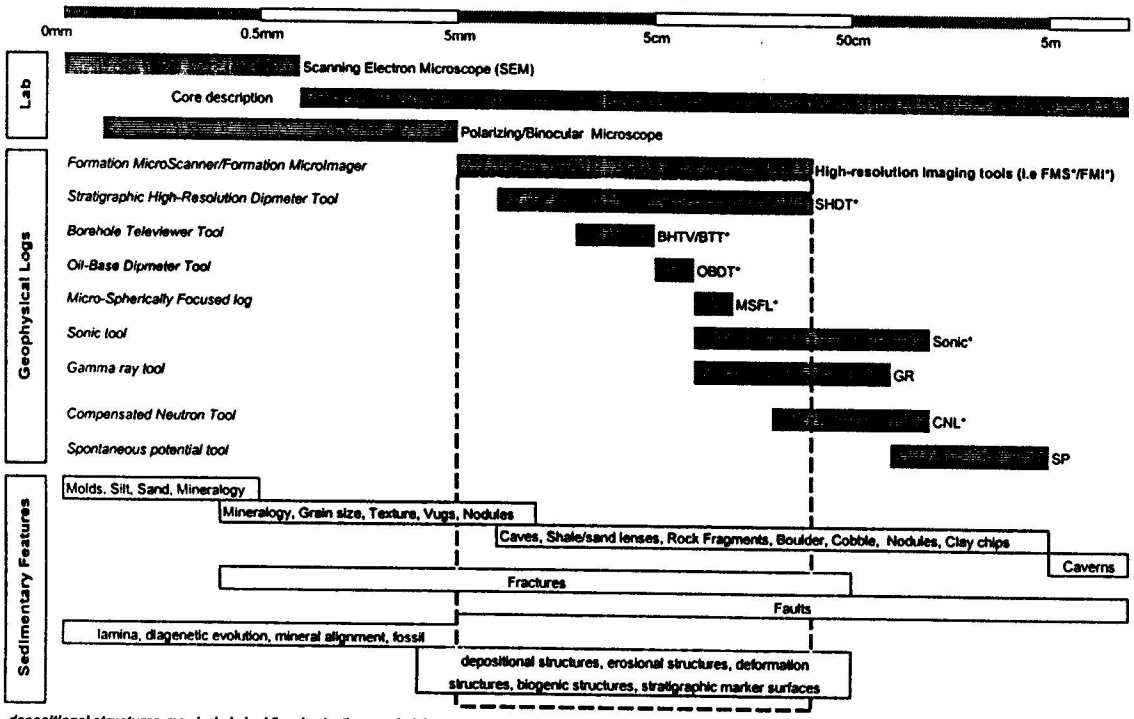
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TABLE 1: COMPARISON OF VERTICAL RESOLUTION OF LABORATORY AND LOGGING SERVICES FOR SEDIMENTOLOGIC STUDY
(modified from Serra, O., 1993)



depositional structures may include bedding, lamination, graded, hommocky and x- bedding, massive, ripple, flaser and lenticular bedding
erosional structures may include scour marks, channel lag, flute cast
deformation structures may include load cast, flame structure, synsedimentary fold and fault
biogenic structures may include horizontal and vertical burrows, bioturbation (in general), ichnofossils (with core verification)
stratigraphic marker surfaces may include hardgrounds, channel/conglomeratic base, ichnofossils (i.e Glossifungites)
** mark of Schlumberger*

TABLE 2: CLASSIFICATION OF IMAGE FEATURES (modified from Serra, O., et al, 1989)

TECTONIC FEATURES	SEDIMENTARY FEATURES	DIAGENETIC FEATURES
GRADE 1: Self-Interpretable Features		
Structural dip Fracture (unfilled/filled) (oblique or vertical) Faults Folds	Bedding surfaces Laminations Cross-bedding Grain size (general category) and shape Erosional surfaces (scour mark, channel lag, flute cast) Synsedimentary deformation features (slump, dragfolds, overturned, convolute, load cast)	Stylolites (high amplitude peaks)
GRADE 2: Ambiguous features (interpretable with the help of other log data and association with Grade 1 images)		
	Cobbles, pebbles, breccias Detrital shale (clay chip, flaser, clay gall, clay drape) Graded bedding Sorting Carbonate rock texture (grainstone, mudstone) Shell, fossil debris/lineation Sand/pebble lineation Pebble imbrication Parasequence boundaries	Calcareous concreations Cemented layers Chert Vugs, caverns Sulfate nodules (pyrite)
GRADE 3: Core calibration/local geologic data needed		
Small fractures Horizontal fractures Angular unconformity Disconformity Paraconformity Nonconformity	Bioturbation (vertical and horizontal burrows) Some trace fossils Thin and close laminations Boundstone, Wackestone, Packstone Rootlets/ carbonaceous drape and debris Glauconitic layers/concentrations Sequence boundaries, flooding surfaces	Stylolites (low amplitude peaks) Caliche Fenestral structure Fossil ghosts/vugs