

A New Approach for Interpreting Lithofacies and Sequence Stratigraphy using Borehole Image Data in Wells Drilled with Non-Conductive Mud Systems

ABSTRACT

The use of borehole image data is an increasingly critical component in evaluating the full potential of a field prior to initiation of the development phase. Over the years, a number of technological advances have significantly improved quality of the acquired micro-resistivity images in conductive mud systems. However, increasing use of oil and synthetic based mud systems, to limit drilling risks and improve efficiency, has produced an environment that precludes the use of conventional micro-resistivity imaging devices. Thus, it was imperative to develop a new micro-resistivity imaging technology that would operate in various oil, diesel or synthetic muds, allowing flexibility in the mud system design. This paper introduces the development and successful application of a new micro-resistivity imager (EARTH ImagerSM) that brings the well-accepted resolution and formation response characteristics of conventional micro-resistivity imaging technology to wells drilled with non-conductive mud systems.

Borehole image data provide high-resolution directional data sets, in addition to a wealth of information concerning sedimentary fabric and texture. In the past, the information derived from borehole image logs was typically used for structural dip determination, fracture identification, and for fault, and regional stress analysis. This paper aims to present a new approach for detailed description of lithofacies and depositional sequences, determination of paleo-current direction, and sand body geometry that ultimately provides detailed characterization of the depositional environment. We will present several field examples to demonstrate the instrument's functionality and applications throughout a range of geological environments and borehole conditions.

INTRODUCTION

Reservoir heterogeneity caused by structural complexity, stratigraphic stacking patterns or diagenetic alteration of pore system continuity may significantly hinder fluid production. Such heterogeneity, often manifested as compartments at the reservoir scale affects field economics at all stages. A new technology for borehole imaging in oil-base mud systems provides detailed sedimentological interpretation of lithofacies and sequence stratigraphic patterns. This increases our ability to predict reservoir compartmentalization and fluid distribution. Ultimately, this understanding will improve location of wells, allowing more efficient production of the reservoir.

In the past, much work has been done to verify and understand the similarities and differences between core and borehole images. Borehole imaging does not replace conventional core information, and tying images to a conventional core is still the most accepted mode of operation. Once borehole images are calibrated against core, borehole imaging can be used confidently without the core backup. The differences between the borehole images and core data should not be considered in terms of an inadequacy of any particular technique. Some differences clearly arise as a result of a fundamental conflict existing between features detected during analysis of core within the visible light spectrum, and those features recorded by the micro-resistivity imaging instrument. For example, where the visual appearance of the core is that of massive (structureless) sandstone, the EARTH Imager may detect subtle resistivity contrast indicative of relict lamination. Also, the larger surface area surveyed by the borehole image log compared to slabbed core surface may in some instances provide greater insight into the presence of certain fabric such as bioturbation, cementation, etc. Similarly, core description may allow direct observation of grain size, fabric, and lithological variation (mm scale) beyond the resolution of the borehole images (cm scale). Finally, interpretation conflicts may also arise as a result of poor borehole quality, and hence image log quality.

A NEW TECHNOLOGY FOR BOREHOLE IMAGING IN OIL-BASE MUD SYSTEM

The science of borehole data collection and interpretation has been constantly advancing with many exciting improvements in recent years. Each successive evolution attempted to refine resolution circumferentially and/or longitudinally. Prenskey (1999) provides an excellent bibliography of borehole imaging. Lovell et al. (1999) and Thompson (2000) document the main developments and applications to present. Lofts and Bourke (1999) detail the quality control necessary for interpretation of such images.

The growing popularity of oil-based mud systems has hitherto provided an environment that precluded the use of conventional micro-resistivity borehole imaging technology. As economics and drilling considerations associated with using oil-based mud often outweigh the benefits gained by running micro-resistivity-imaging tools, detailed reservoir characterization in the absence of core data becomes a major issue. Thus, the driving force behind the development of the oil-based mud micro-resistivity technology was the desire to create a logging instrument that would operate in various oil, diesel or synthetic muds, allowing flexibility in the mud system design for improved efficiency and reducing drilling risks.

Lofts et al., (2002) introduced a new device (EARTH ImagerSM) that allows micro-resistivity imaging to record high resolution formation detail previously not possible in non-conductive oil-based mud. A new borehole imaging technology brings the well-established and well-understood responses of existing micro-conductivity micro-lateral images to be recorded in non-conductive oil-based muds. The focusing and measuring currents flow along potential gradients established between the lower body of instrument and the “zero of potential”. These currents move and respond to the formation resistivity in the conductive portion beyond the non-conductive borehole and invaded zone after being induced there by the addition of the enabling technology of the recently introduced instrument (Fig. 1.).

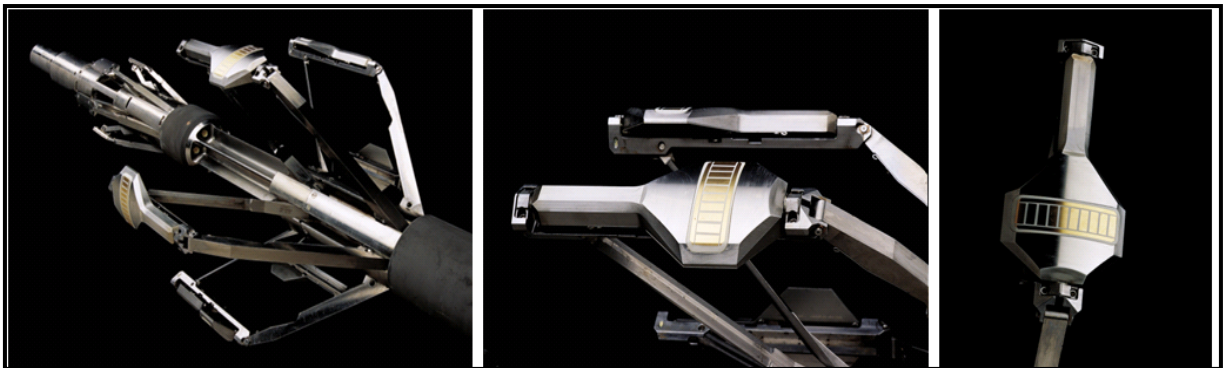


Fig. 1. The EARTH Imager Instrument

The EARTH Imager uses new micro-resistivity borehole imaging technology to provide significantly improved vertical resolution in non-conductive muds. A unique pad design allows significantly improved vertical resolution over other available instruments, suitable for acquiring detailed structural, fracture, and stratigraphic information. Finer resolution of azimuthal features is produced by a greater number of electrode pads than in conventional imagers and the greater number of traces per pad. The EARTH Imager's innovative focusing technology provides accurate, efficient, and cost effective high-resolution borehole image data and minimizes sensitivity problems that are commonly associated with irregular borehole geometry, mud-cake and mud invasion. The articulated six-arm carrier and powered standoff design of the EARTH Imager is based on the field-proven STAR ImagerSM carrier (Hansen and Parkinson, 1999). The highly successful six-arm carrier and powered stand-off ensures excellent data quality even in highly deviated and horizontal wells, with a significantly reduced pad pressure, thus eliminating stick-and-pull. The EARTH Imager 6-pad configuration provides 64.9% wellbore coverage in an 8-in borehole, approximately twice the borehole coverage compared to currently available four-arm instruments. Furthermore, small pad design gives an effective pad footprint of only 9-cm x 8-cm (3.5 in x 3.1 in) which provides the unique ability to operate effectively over a wide range of

borehole irregularities such as washouts and drilling-induced rugosity. This versatility contrasts with other oil-base imaging tools that are restricted to boreholes that are in-gauge and straight. The principal characteristics of the EARTH Imager instrument are listed in Table 1.

Table 1 - Instrument characteristics.

Number of pads	6
Sensors per pad	8
Borehole coverage	64.9% in 8-in. hole
Log sampling rate	0.1 in (120 spf).
Sensors spacing	8.5 mm (0.31 in).
Depth of investigation	20 mm (0.80 in).
Resistivity range	0.2 to 10,000 ohm-m
Max. temperature	350°F (175°C)
Max. pressure	20,000 psi.
Max. logging speed	600 ft/hr
Borehole size range	6 to 21-in.

METHODOLOGY

The methodology described here presents an approach for interpreting lithofacies and sequence stratigraphy utilizing integration of core and oil-base micro resistivity image data. Examination of core as a continuous ‘core-photographic image log’ in the workstation environment has revealed that when displayed at appropriate scale core pictures contain a phenomenal amount of data. The procedure for creating continuous ‘core-photographic image log’ involved scanning of core photographs at a resolution of 200 DPI using a desktop scanner. Scanned images were saved in TIFF format, and subsequently loaded into the Baker Atlas Recall Software as RGB color data files. Once in the workstation environment, the core photographs can be depth-matched to the borehole image and other wireline data. Also, core photographs quality may be further enhanced by the application of various image filters, including ‘dynamic normalization’, in order to enhance features present within the core. These can then be displayed and interactively analyzed along with oil-base micro-resistivity images at high magnification on a workstation. The limit to the magnification that can be applied is dependant on core and borehole images quality (1:3 magnification is commonly used). An example of a borehole images and core display on the workstation is presented in Fig. 2.

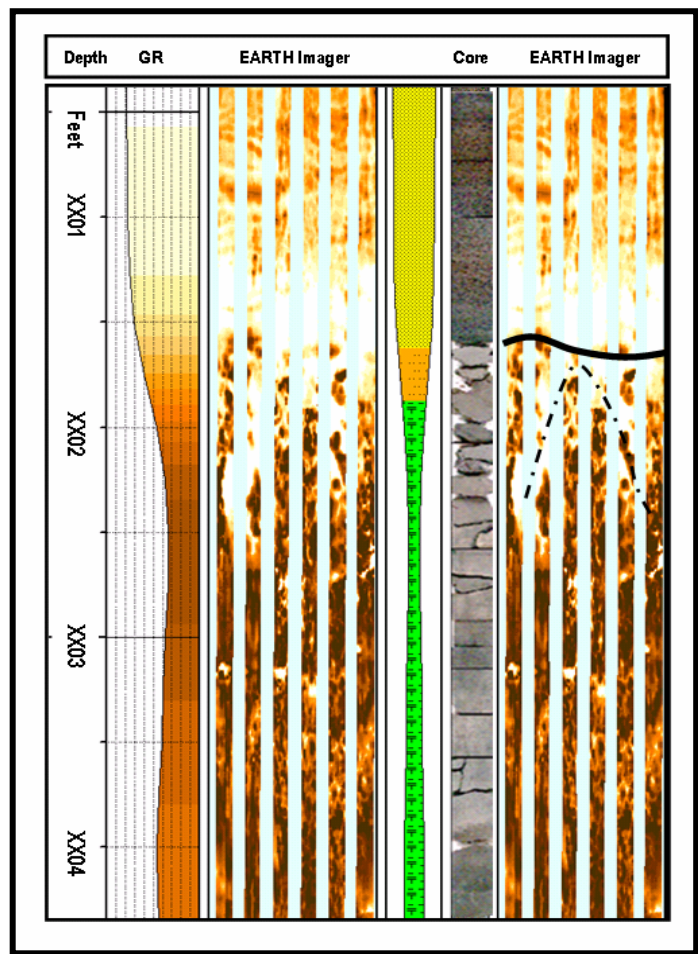


Fig. 2. Interactive oil-base image and core analysis.

Sedimentological interpretation of the EARTH Imager data was carried out with the aid of gamma ray, density, neutron porosity, sonic, and resistivity logs. Where core calibration was possible, a series of log cutoffs were identified, which were used to help guide interpretation of lithologies. Identified lithofacies types were classified according to a simple scheme using mnemonics based upon interpreted lithology and contained fabric, the latter being determined from borehole image log and associated dip data. Although the lithofacies nomenclature, and bioturbation index is based upon qualitative visual image inspection, it was found that lithofacies could be assigned with a high degree of consistency, even for examples where several image geoscientists were integrating data from different wells. Finally, comparison of the results of dip trend analysis with the core data has indicated the subtle, though consistent variations in shale bed dip azimuth corresponded closely with location of sequence boundaries. This has provided increased confidence in unconformity recognition in un-cored well sections.

DISCUSSION OF RESULTS

The recently acquired data presented in this paper are from the large, overpressured, basin-centered, compartmentalized gas accumulation in the continental US. These units are composed of fluvial-channel sandstones and siltstones, floodplain shales, and minor coals that were deposited on a broad alluvial plain. Sediment transport was generally to the south-west and east. Individual sandstone units average 25 ft. thick, with some amalgamated sandstone packages more than 100 ft. thick. Reservoirs are typified by tight (porosity in pay zones ranges from 8% to 12%), low permeability (3-20 microdarcys) sands. Based on core data, fracture stimulation pressures and production profiles they appear to be naturally fractured. As fracture network connectivity plays a significant role in gas deliverability, all wells require successful application of stimulation and completion techniques to achieve economic flow rates. Most of the successful wells have high initial production rates that rapidly decline but continue to produce for long periods of time.

Structure plays an important role in controlling field geometry and viability as most of the wells drain a limited area, possibly less than 40 acres. Recently acquired 3-D seismic and wellbore data confirm existence of complex fault system that bound and compartmentalize the productive zones. Reservoir compartmentalization also occurs on much smaller scale and it is caused by reservoir heterogeneity. Producing intervals in many wells are interrupted by horizontal shale beds that form baffles or barriers to vertical fluid flow. While those shale beds are easily recognized in core or borehole images, they are practically invisible for conventional wireline logs. As continuous coring is non-economical, the operators are relying on high-resolution micro-resistivity images acquired in oil-base muds to provide necessary information to fully characterize lithofacies and predict reservoir compartmentalization, shale barriers, and fluid distribution (Fig. 3.).



Fig. 3. Top of the reservoir (shale barrier?)

Sharp basal contacts, strongly fining upward character, interbedded mudstone and carbonaceous mudstones, rooted intervals and poorly developed paleosols indicate that the sandstones were deposited in small meandering fluvial channels. Sandstone bodies consist of stacked deposits of amalgamated pint bars and channel levees. Most of the sandstones are fine-grained, well sorted, light gray, trough, massive and ripple cross laminated, with wavy and locally contorted bedding. Conglomerates and medium-grained sandstones were deposited in the basal portion of channel-fill deposits. Channel lag, containing a large percentage ripped-up clasts of overbank muds, are also common in the basal portions of channel fill units. These channel-lag horizons can be mistaken for shale beds when examining a gamma ray log across the interval.

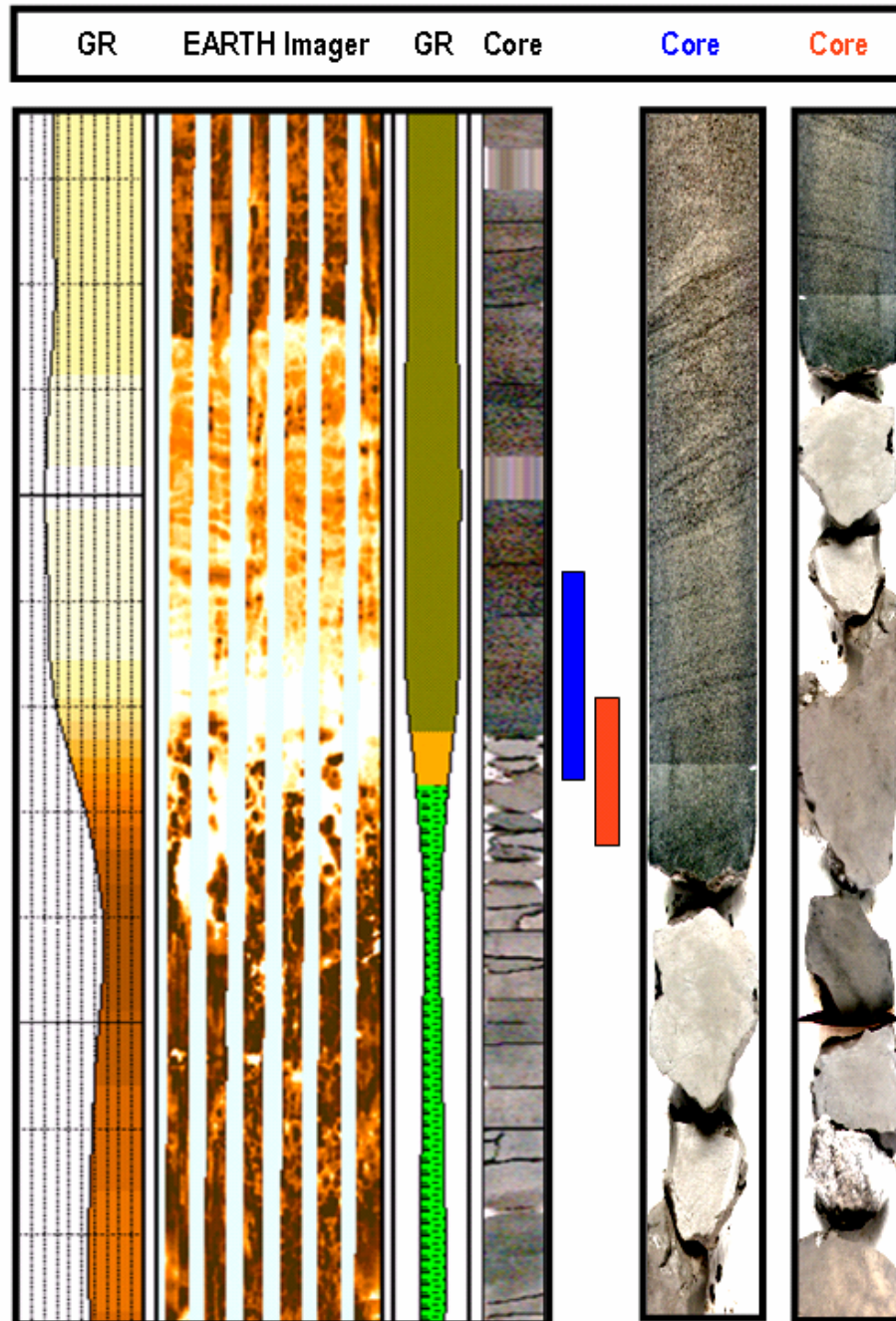


Fig. 4. Basal portion of a channel fill unit is composed of fine to medium grained, well sorted, cross-laminated sandstone bedding). Channel lag contain large percentage of rip-up clasts from overbank muds.

Fine to very fine-grained sandstones were deposited in upper point bars and channel levees. Soft sediment deformation (contorted and slumped beds) that were observed in very fine to fine-grained sandstone is characteristic of collapsing caused by falling water level. Overbank splays are encased in mudstone, and for the most part finer grained and thinner bedded. Shale, silty mudstone and siltstone are dark gray to medium olive gray, moderately to poorly sorted, bioturbated, rooted, locally carbonaceous, with common plant impressions. Shale beds range from 0.5 feet to more than 10 feet thick (Fig. 5).

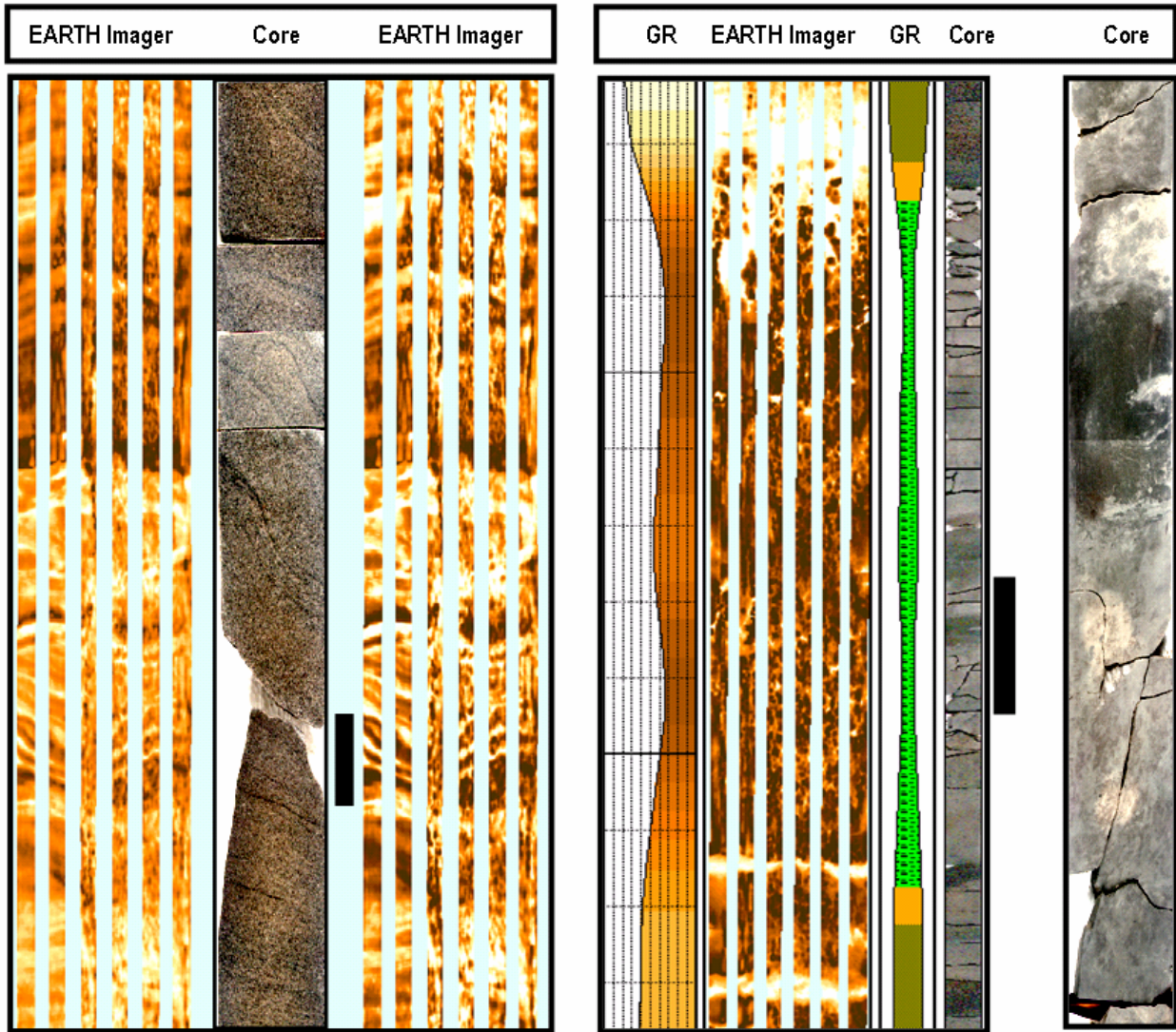


Fig. 5. An example of soft sediment deformation and shale sediments on the OBM resistivity images and core

CONCLUSIONS

- A new technology for borehole imaging in oil-base mud system provides detailed sedimentological interpretation of lithofacies and sequence stratigraphic patterns.
- Once borehole images are calibrated against core, borehole imaging can be used confidently without the core backup.
- Integrated analysis provides insight in reservoir heterogeneity and increases our ability to predict reservoir compartmentalization occurrence, distribution, and fluid distribution.
- This understanding will improve location of wells, allowing more efficient production of the reservoir.