Field Test Results of a New Oil-Based Micro-Resistivity Imaging Instrument in Canada

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ABSTRACT

The structural geology of the Western Canadian Foothills is dominated by a series of thrust faults, complex folds and steeply dipping formations. For many years, seismic imaging was used as an essential tool in the petroleum exploration of such complicated geology. Unfortunately, structural delineation in the deep, highly complex structures using only seismic data is challenging due to the deformed and/or overturned formations. Thus, borehole images were quickly accepted as an increasingly critical component in structural interpretation and analysis of the fractures patterns within the reservoir.

The growing popularity of non-conductive mud systems has hitherto provided an environment that precluded the use of conventional micro-resistivity borehole imaging technology. As drilling considerations associated with using oil-based mud often outweigh the benefits gained by running micro-resistivity imaging tools, detailed reservoir characterization became 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.

This paper introduces the development and successful application of a new micro-resistivity imager (EARTH Imager^{SM}) that brings well-accepted resolution and formation response characteristics of conventional micro-resistivity imaging technology to non-conductive mud systems. We present several field examples from the structurally complex, thrust belt setting of the Western Canada Foothills to demonstrate data accuracy, repeatability, and instrument reliability throughout a range of geological environments and borehole conditions.

Introduction

The key to successful exploration in the Western Canada Foothills play has been to predict where natural fracturing is abundant. Therefore, the use of micro-resistivity imaging devices to locate and determine the geometry of the existing fractures, lateral and vertical distribution of productive fractures, fracture quality, and hydrocarbon potential prior to setting casing is an essential element in evaluating the economics of any given well.

Naturally fractured reservoirs have always been difficult to describe and evaluate. The complex interaction of fractures, fault zones, matrix, and fluids is sufficiently variable to render each reservoir unique. There are many complex questions that must be answered for a satisfactory evaluation. Where are the fractured zones? What is the density of the fractures in the system, their distribution and orientation, and what is the anisotropy of the fracture system? Does the system contain open or closed fractures? And above all, is the fracture system capable of flowing hydrocarbons? Operators should have answers on those questions prior to committing to a sidetrack, horizontal completion.

Methodology of Fracture System Analysis

Numerous fracture analysis techniques have been developed over the past decade. These techniques can aid in the evaluation of naturally fractured reservoirs by statistically and quantitatively describing the fractures penetrated by the wellbore and thus estimate whether these fractures are important contributors to the reservoir storage capacity or permeability. For a single fracture the important attributes are type (natural or induced, open or mineralized), size (width, length, aperture, mechanical bed thickness), orientation, surface roughness, age, digenetic history, and fracture spacing. For fracture sets or systems, the important attributes are fracture distribution and connectivity (laterally or vertically), fracture spacing (density), and number of sets. Fracture connectivity plays a strong role in determining the degree and anisotropy of network permeability. For simplified model fracture-networks, the degree of connectivity is spatially uniform and may be computed from the fracture spacing and the distribution of length and orientation. Knowledge of these attributes can lead to idealized fracture-matrix block models for different parts of the reservoir that will help understand the potential performance of fractured reservoir. At the same time, the drilling-induced fracture analysis will provide insight as to the behavior of hydraulic fractures in well stimulation.

One approach to the fracture system analysis is to examine fractures in outcrop (care must be taken to recognize and discount fractures in outcrop that result from near-surface processes). Although conventional cores provide the premium sedimentological information and fracture pattern information, they are also expensive and therefore limited in availability. 2-D and 3-D seismic data have been used for subsurface structural determination. Unfortunately, structural delineation in these deep, highly complex structures with only seismic data is challenging due to the deformed and/or overturned formations. Therefore a comprehensive structural study and analysis of the fractures patterns within the reservoir requires data from conventional core and high-resolution 3D seismic integrated with high-resolution micro-resistivity borehole images.

Borehole imaging data were quickly accepted in and as measurements and data processing technology have improved, more detailed and descriptive images have evolved. Economics, time, method of acquisition, and urgency to obtain interpretive results all play very important role in the development and acceptance of both acoustic and resistivity imaging devices. The high-resolution borehole imaging devices have several advantages over the conventional core. The images are continuous and can be collected from any depth interval or intervals. The images are oriented in 3D space, allowing determination of different geological features. Image depth control is precise; a large advantage over conventional core data in partial recovery situations such as coring faulted or fractured reservoirs. Core observations, even though limited in extent, can be used to calibrate borehole images such that highly accurate geological interpretations can be made. After calibration with core, high-resolution geologic interpretation can often be carried out confidently without a conventional core backup.

The increased popularity of non-conductive muds provided an environment that precluded the use of conventional micro-resistivity borehole imaging technology. As economics and drilling considerations associated with using non-conductive muds often outweigh the benefits gained by running micro-resistivity-imaging tools, detailed fracture system characterization became a major issue.

A New Technology for Borehole Imaging in Non-Conductive Muds

The driving force behind the development of the new resistivity technology for borehole imaging in non-conductive muds was a 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 drilling efficiency and limiting borehole stability risks. Lofts et al., (2002) introduced a new device (EARTH Imager^{SM}) that allows micro-resistivity imaging to record high resolution formation detail previously not possible in non-conductive muds. This new borehole imaging technology brings the well-established responses of existing micro-resistivity images to be recorded in wells drilled with non-conductive 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.

The picture of the EARTH Imager instrument is presented on Figure 1.

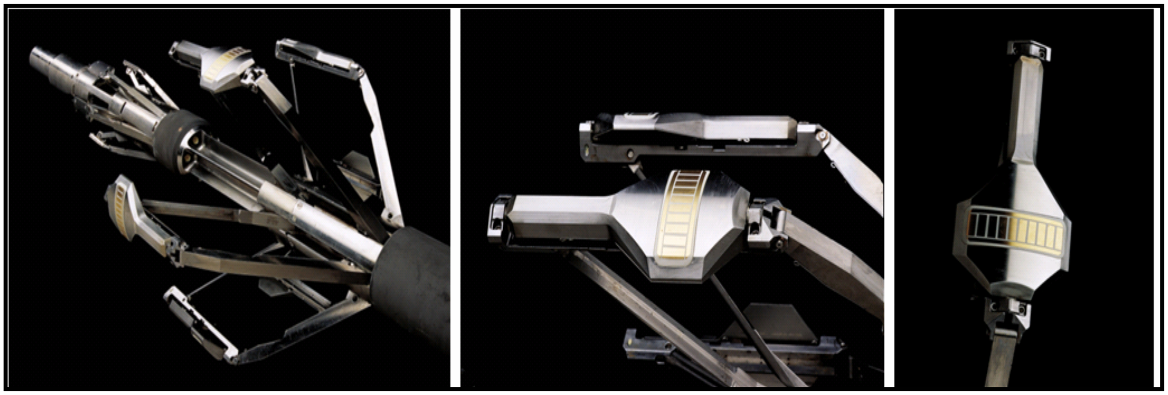

Fig. 1. The EARTH Imager instrument

The EARTH Imager uses patented micro-resistivity technology to provide significantly improved vertical resolution and borehole coverage in non-conductive muds. This new focusing technology provides accurate information and minimizes sensitivity problems commonly associated with borehole geometry irregularities such as washouts, drilling induced rugosity, and mudcake build-up. As a result, acquired borehole images are suitable for detailed structural, fracture, sedimentological, and petrophysical analysis.

The articulated six-arm carrier and powered standoff design is based on the field-proven STAR Imager^{SM} carrier (Hansen and Parkinson, 1999) and provides 64.9% wellbore coverage in an 8-in borehole (approximately twice the borehole coverage compared to currently available four-arm instruments). Small pad design gives an effective pad footprint of only 9-cm by 8-cm (3.5 in by 3.1 in) which provides the unique ability to operate effectively over a wide range of borehole irregularities and ensure excellent data quality in highly deviated and horizontal wells. This versatility contrasts with other oil-base imaging tools that are restricted to boreholes that are in-gauge and straight. Finally, the powered stand-off reduces the required pad pressure to maintain pad-to-wall contact and virtually eliminate stick-and-pull problems.

The EARTH Imager allows simultaneous acquisition of high-resolution resistivity and acoustic borehole image data. This unique capability provides a powerful interpretation perspective based on two sets of complimentary data. Data redundancy assures excellent data coverage in the wellbore and virtually eliminates loss of data due to the stick-and pull. In addition, the EARTH Imager can be run in combination with other Baker Atlas services, including RCI^{SM}, 3DEX^{SM}, and XMAC Elite^{SM}. The high-speed, multi tasking acquisition system allows for flexible combinations to meet the information needs, reduce uncertainties, and improve cost efficiency by minimizing data acquisition time. Wireline cable or drill pipe system can be used to convey the instrument in highly deviated or horizontal wells.

The principal characteristics of the EARTH Imager instrument are listed in Table 1.

Table 1. - EARTH Imager Specifications.

Length:	30.7 feet (9.7 m.)
Weight:	680.9 lb. (309.5 kg.)
Tool Outside Diameter:	5.25 in. (133.35 mm.)
Hole Size Range:	6.0 – 21.0 in. (152.4 – 533.4 mm.)
Max. Temperature:	350°F (175°C)
Max. Pressure:	25,000 psi (172.4 Mpa)
Numbers of Pad:	6
Sensors per pad:	8
Hole Coverage:	64.9% in 8-in. hole
Log Sampling Rate:	120 spf (393 samples per meter)
Max logging speed:	900 ft/hr (274.2 m/hr)
Combinability:	Top and Bottom

Review of the Field Test Results from Canada

As a part of extensive field testing, the EARTH Imager has been run in several wells that penetrated structurally complex thrust belt setting of the Western Canada Foothills. Data accuracy, repeatability, and tool reliability were of great importance. Herein we are presenting two separate passes (main & repeat pass) of the EARTH Imager over a ~10 feet (~3 m.) interval. While acquired resistivity images provided high-resolution information previously available only in water-based mud environments, excellent agreement between main and repeat pass provided evidence of excellent repeatability.

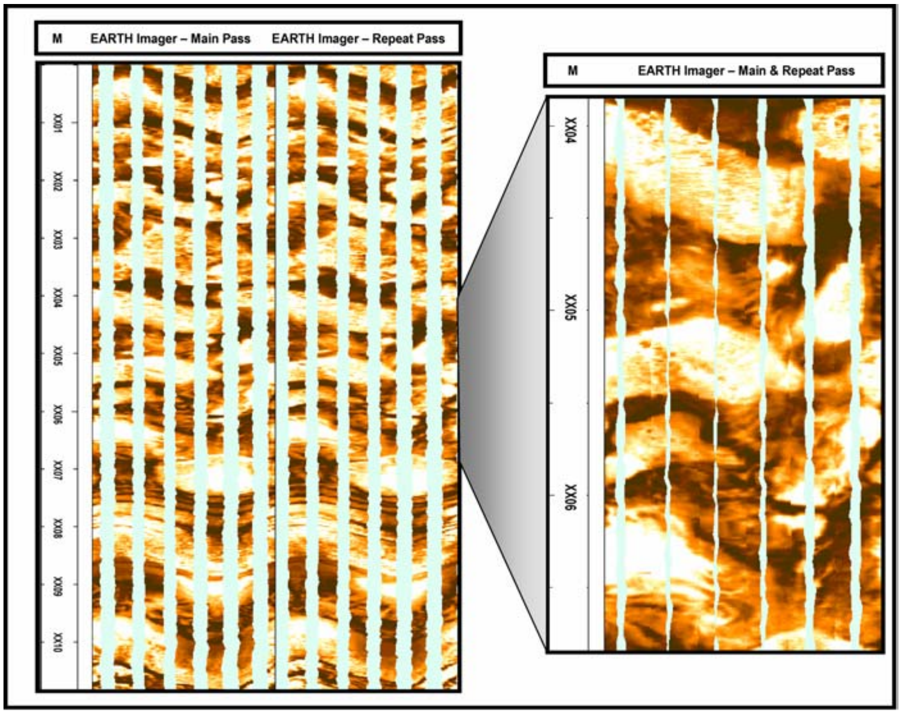

Fig. 2. Two separate passes of the EARTH Imager showed excellent repeatability.

For the last 10 years a combination of CBIL^{SM} acoustic images and pseudo-resistivity images, created from the Hex-Diplog button traces, has been extensively used throughout the Western Canada Foothills for detailed structural and fracture system analysis. In some cases, pseudo-resistivity images from Hex-Diplog provided reliable structural information, while CBIL Images were traditionally used for detailed fracture analysis. Unfortunately, interpretation of lower resolution Hex-Diplog and CBIL data is not unique and quite often operators didn't get the right answers on many important questions. In order to address this very important aspect of borehole image applicability, it was decided to conduct a field test to provide a direct comparison of the EARTH Imager data against traditional oil-based borehole imaging services (Fig. 3.)

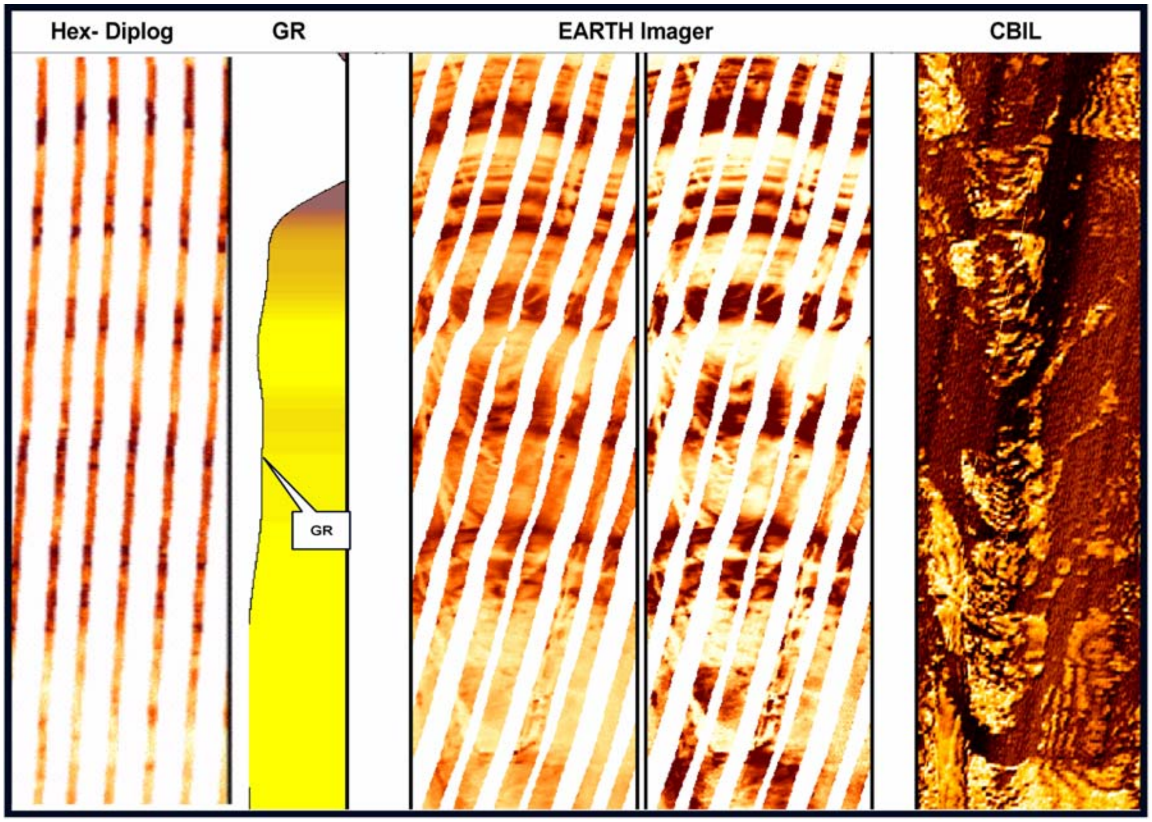

Fig. 3. Comparison of the EARTH Imager, CBIL, and Hex-Diplog images over a fractured section in Western Canada Foothills.

The well was drilled with an 8.5" (159 mm) bit and for the most part it was in very good conditions. Over the zone of interest, the well was slightly deviated at approximately 16°. It is not only bedding and rock texture that is clearly defined on the oil-base resistivity images. For the first time, we are able to provide detailed fracture system classification and to determine the lateral and vertical distribution of productive fractures. This information allowed operator to better understand fracture distribution and the inherent relationships between the fracture systems, lithofacies, and reservoir structure.

Simultaneous acquisition of oil-base resistivity and acoustic images is another feature of the new instrument. It is not only significant cost savings in “rig time”, but acquired images are “on-depth”. Data redundancy assures excellent data coverage in the wellbore and virtually eliminates loss of data due to the stick-and pull. This unique capability provides a powerful interpretation perspective based on two sets of complimentary data. Most of the time oil-base resistivity and acoustic images are very similar. While resistivity image logs have natural tendency to better resolve stratigraphic details (i.e. bedding, erosion surfaces, and texture), acoustic images are more used for fracture and borehole breakout analysis. However, in some cases two different physical measurements provide completely different image of the same some formation. Combining different tools, which operates on different physical principles provides unique perspective in data interpretation (Fig. 4.).

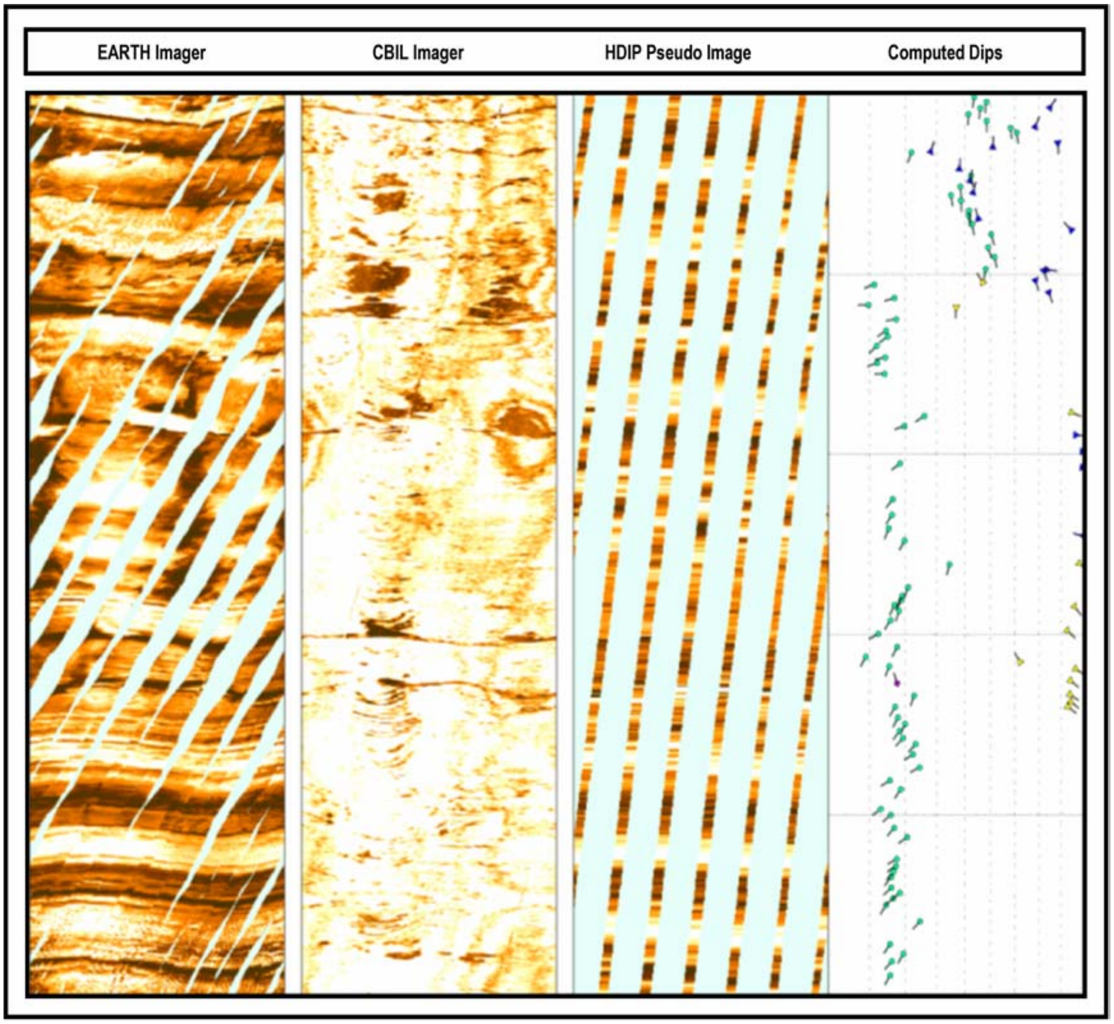

Fig. 4. Simultaneous acquisition of resistivity and acoustic images in wells drilled with non-conductive muds provides powerful interpretation perspective based on two sets of complimentary data.

Fracture System Characterization – Case Study

The structural geology of the Western Canadian Foothills is dominated by a series of thrust faults, complex folds and steeply dipping formations. Horizontal compression deformed the sedimentary bedding so that thin thrust sheets ride over each other forming complex fold structures which results in many repeat sections. For many years seismic imaging is used as an essential tool in the petroleum exploration of such complicated geology. However, due to structural complexity and steep dips seismic images often provide an obscure picture of the subsurface (Fig. 5.)

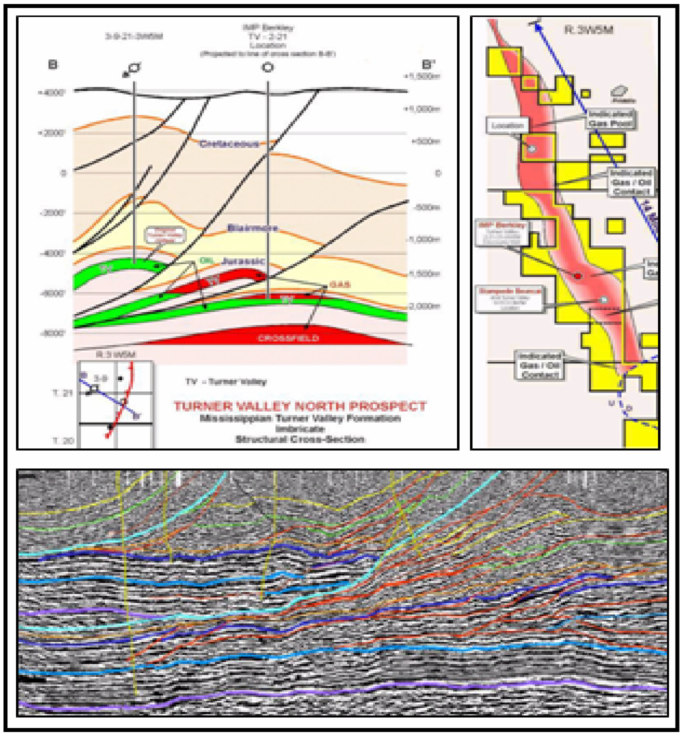

Fig. 5. Typical example of the structural setting In the Western Canada Foothills.

The primary zones of interest in the Western Canadian Foothills are found mostly in formations of Mississippian and Devonian age. In general, the productive formation consists of medium to coarse crystalline crinoidal limestone and medium crystalline dolomite in the Upper Porous and Lower Porous intervals, separated by the intervening Middle dense unit of finely crystalline, nonporous carbonate. The entire Turner Valley Formation is dolomitized over much of southwestern Alberta. Porosity normally is less than 10% and permeability ranges from 0.1 to 10 md. In the Western Alberta, the Turner Valley sediments rests on the Shunda Formation and it this particular case they are overlain by the dark grey to black, cherty and phosphate limestone (40-90% chert occurring as layers exhibiting pinch and swell, lenticular beds and nodules).

Herein we are presenting fracture system characterization case study from a recently drilled exploration well in the Canadian Foothills. A full standard logging suite was acquired (i.e. gamma ray, caliper, array induction, density, neutron, array acoustic, 6-arm Oil-Base Hex-Diplog, and CBIL acoustic images). In addition, the EARTH Imager was ran to provide structural framework (linear NW-SE trending structure has been indicated by the seismic data) and detailed fracture system characterization and classification.

Results of a fracture system analysis are presented in Figure 6. Gamma ray, array induction and density neutron data are presented in the first three tracks. Calculated fracture intensity from oil-base resistivity image, acoustic image and combined fracture density is presented in track number four. Oil-base resistivity and acoustic image are presented side-by-side in the tracks five and six. Computed dips, fractures, borehole breakouts, and rose diagrams are presented on the far right. We used red color for geological features symbols that have been identified from the acoustic image. In blue color we presented the data interpreted from the oil-base resistivity image. Dips are uniform (~9^o) and in general oriented toward W indicating an N-S structure trend. Computed dips from oil-base resistivity images showed excellent agreement with dips computed from acoustic images or Hex-Diplog data. Slight dip azimuth rotation from SW to NW may indicate the structure plunge. Natural fractures are concentrated in the upper part of the reservoir. Most of the fractures are nearly vertical and mainly open. Fracture strike orientation is almost parallel to the present-day maximum horizontal stress (NE-SW). Excellent agreement between oil-base resistivity and acoustic image data was observed. Computed fracture density correlates very well with density derived porosity and it may serve as relative indicator of fracture intensity. Drilling-induced fractures are almost parallel to the natural fractures and perpendicular to the borehole breakout direction.

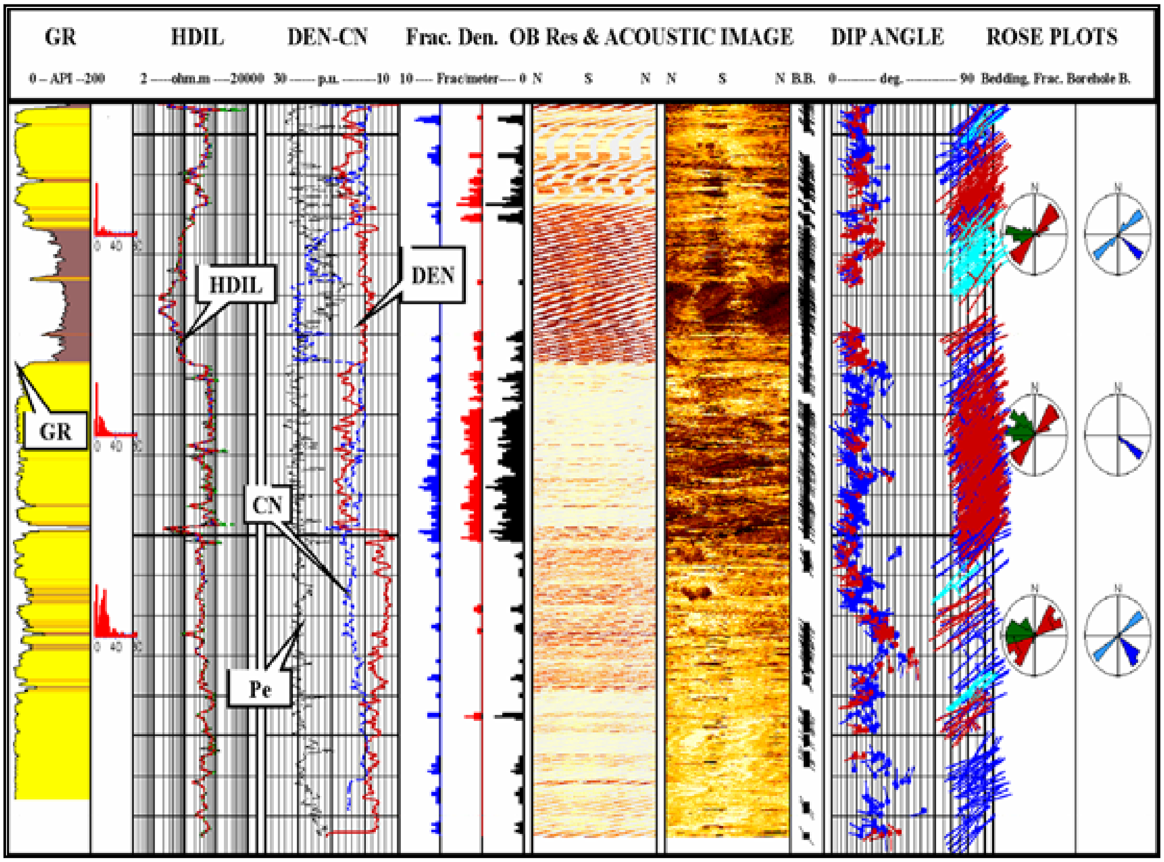

Fig. 6. Results of the fracture system characterization study

Conclusions

A new borehole imaging technology brings the well-understood responses of existing micro-resistivity images to the non-conductive mud arena. The EARTH Imager provides efficient borehole image data acquisition in non-conductive muds and establishes a new level of performance in borehole image data interpretation through significantly improved vertical resolution and borehole coverage. The focusing design provides high-resolution borehole images and minimizes sensitivity problems commonly associated with borehole geometry irregularities. The field-proven, six-arm carrier and powered stand-off design of the EARTH Imager provides a unique ability to operate effectively in difficult borehole geometries as highly deviated and horizontal boreholes.

Several field test examples from the Western Canada Foothills provide evidence of resistivity image data accuracy, repeatability, and reliability throughout a range of geological environments and borehole conditions. Presented images showed excellent repeatability and allowed evaluation of geological features down to a fraction of inch in thickness. These images have been successfully used for structural, stratigraphic, and detailed fracture system analysis.

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References

Hansen T. and Parkinson N., 1999, Insights from simultaneous acoustic and resistivity imaging, Borehole Imaging: Case Histories. Geol. Soc. Spec Publ. 159, 191-201.

Lofts J.C., Evans, M., Pavlovic, M., and Dymmock, S. 2002, A new micro-resistivity imaging device for use in oil-based mud. Transactions of the SPWLA, Vol 43, Paper II, Oiso, Japan.