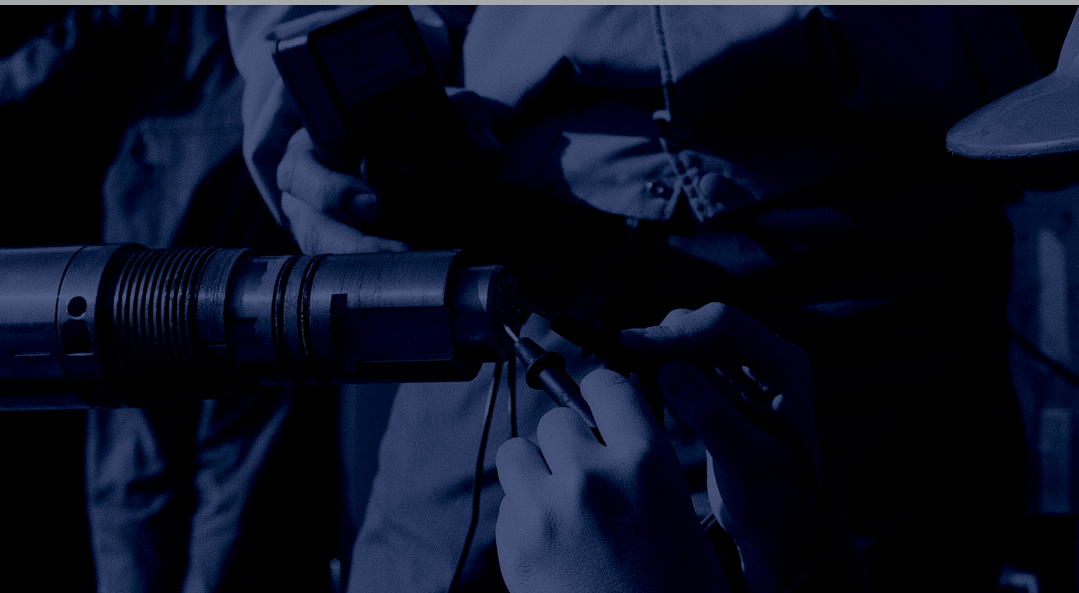




Schlumberger

FMI



Borehole geology,
geomechanics and
3D reservoir modeling

Applications

- Structural geology
 - Structural dip, even in fractured and conglomeratic formations
 - Faults
- Sedimentary features
 - Sedimentary dip
 - Paleocurrent direction
 - Sedimentary bodies and their boundaries
 - Anisotropy, permeability barriers and paths
 - Thin-bedded reservoirs
- Rock texture
 - Qualitative vertical grain-size profile
 - Carbonate texture
 - Secondary porosity
 - Fracture systems
- Complement to whole core, sidewall core and formation tester programs
 - Depth matching and orientation for whole cores
 - Reservoir description of intervals not cored
 - Depth matching for sidewall core samples and MDT* Modular Formation Dynamics Tester probe settings
- Geomechanical analysis
 - Drilling-induced features
 - Calibration for Mechanical Earth Modeling
 - Mud weight selection
- Geology and geophysics workflow
 - Deterministic reservoir modeling
 - Distribution guidance for stochastic modeling
 - Realistic petrophysical parameters

Overview

The FMI* Fullbore Formation MicroImager provides microresistivity formation images in water-base mud:

- 80% borehole coverage in 8-in. hole size
- 0.2-in. [5-mm] image resolution in vertical and azimuthal directions
- fully processed images and dip data in real time
- top combinable with other wireline tools such as the ARI* Azimuthal Resistivity Imager and AIT* Array Induction Imager Tool.

The FMI tool generates an electrical image of the borehole from 192 microresistivity measurements. Special focusing circuitry ensures that the measuring currents are forced into the formation, where they are modulated in amplitude with the formation conductivities to produce both low-frequency signals rich with petrophysical and lithological information and a high-resolution component that provides the microresistivity data used for imaging and dip interpretation. The depth of investigation is about 30 in., similar to that of shallow lateral resistivity devices. The image is normalized through calibration with low-frequency, deeper resistivity measurements from the tool signal or from another resistivity measurement tool.

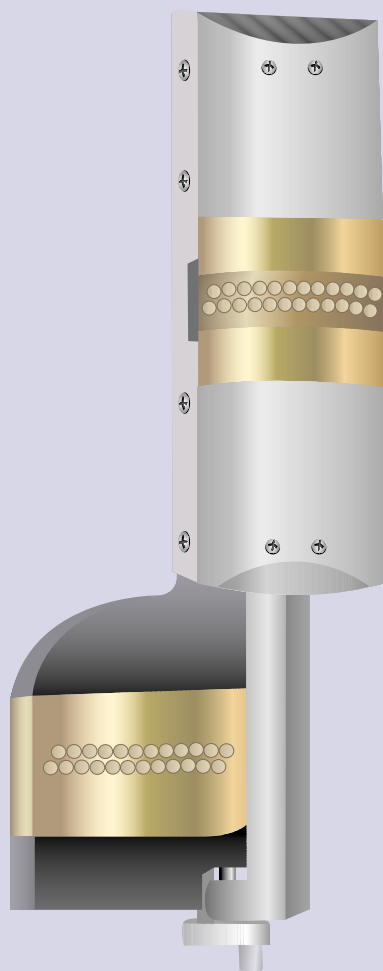
The spacing of the button electrodes, innovative pad and flap design, and high frequency of data transmitted by the digital telemetry system result in a vertical and azimuthal resolution of 0.2 in. This means that the dimensions of any feature that is 0.2 in. or larger can be readily estimated from the image. The size of features smaller than 0.2 in. can be estimated by quantifying the current flow to the electrode. Fine-scale details such as 50-micron fractures filled with conductive fluids are visible on FMI logs.

The physics of the FMI measurement makes it a highly versatile geological and reservoir characterization tool that produces complete and reliable answer products. These real-time answers are used to characterize the rock tectonics, identify and evaluate sedimentary features, measure the rock texture and complement the information obtained from coring programs. FMI data are also used in geomechanical reservoir analysis to identify drilling-induced features such as breakouts. Stress field analysis of FMI data provides critical information for controlling wellbore stability problems through improved design of the mud program.

Real-time FMI answers help in making quick exploration, production and drilling decisions.



FMI pad and flap assembly with horizontally offset rows of electrode buttons.



Benefits

- Cost and time savings: complete interpretation with one image pass
- Data obtained in difficult environments, including deviated and horizontal wells
- Accurate and reliable interpretation of formation features
- Improved reservoir description
- Accurate pay estimate
- Wellsite answer products for on-site decision making

Features

- Borehole coverage of 80% in 8-in. borehole
- High-resolution measurement (nominal 0.2 in.)
- Image details to 50 microns
- Pad tilting for application in deviated and horizontal wells
- High-quality, real-time well-site image and Mean Square Dip (MSD) computation
- Multiple logging modes: fullbore image, four pad and dipmeter
- Top combinable with most services
- Excellent signal quality from focused electric currents
- Electrical images less affected by borehole rugosity and washouts

Measurement physics

The figure to the right illustrates the FMI measurement principle. An applied voltage causes an alternating current (AC) to flow from each electrode button in the lower pad section through the formation to the electrode on the upper cartridge housing.

As the current emerges from a button on the pad or flap, its path is initially focused on a small volume of the formation directly facing the button. The current path expands rapidly to cover a large volume of formation between the lower and upper electrodes. The current consists of two components:

- high-resolution component, modulated by the resistivity variations in the formation directly facing the button
- low-resolution component, modulated by the resistivity of the zone between the lower and upper electrodes.

Making the measurement in AC minimizes the effects of what are essentially direct currents created by the friction

of the pads against the borehole wall and by variation of the spontaneous potential (SP).

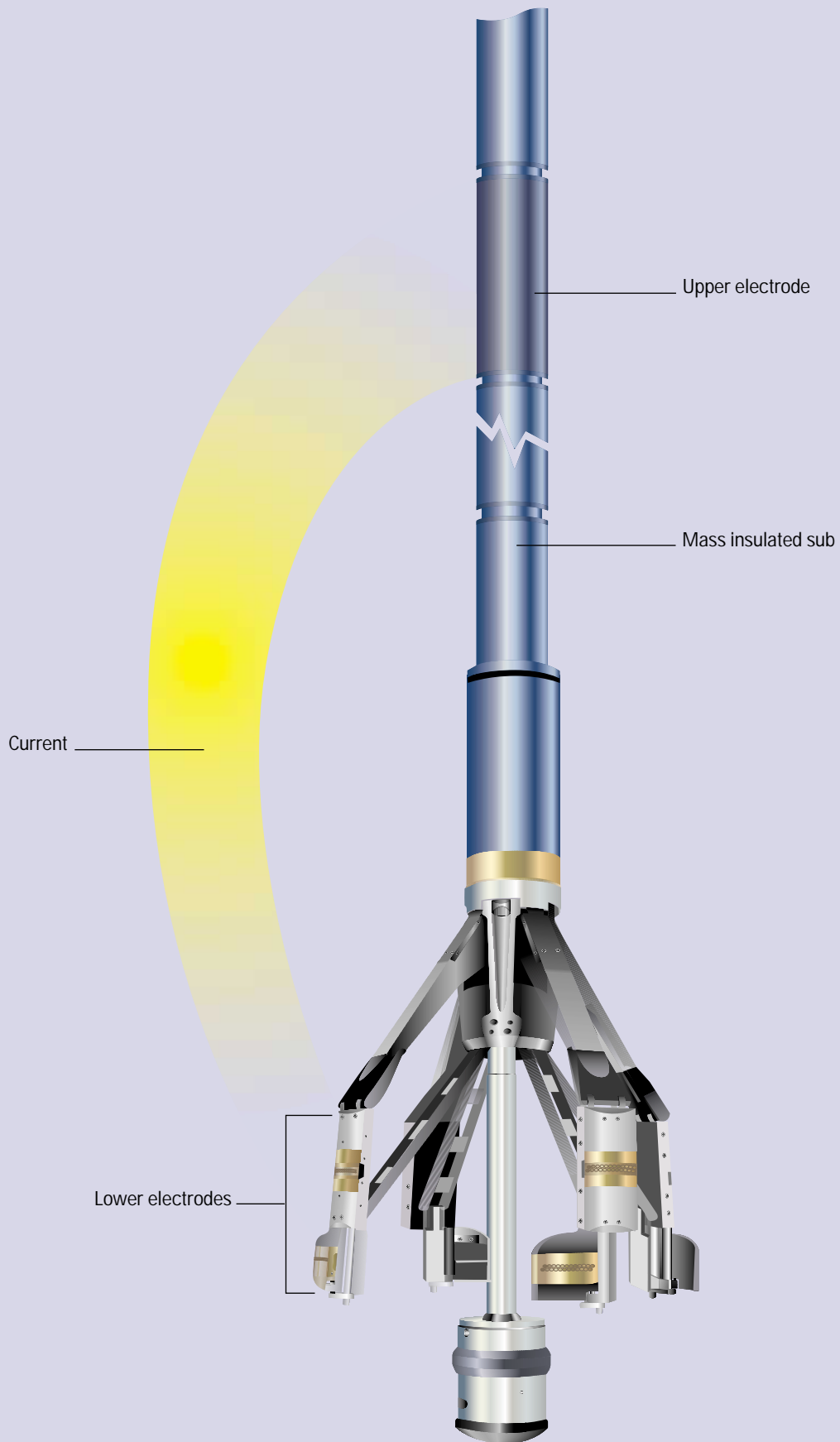
The microresistivity image of the borehole wall is created from the current measured by the array of buttons. The high-resolution component dominates the image because its value varies from button to button. The low-resolution component appears only as a gradually changing background. Microresistivity changes related to lithological and petrophysical variations in the rock, which are conveyed mainly by the high-resolution current component, are interpreted on the image in terms of rock texture, stratigraphic and structural features, and fractures.

The FMI buttons produce only a profile of the conductivity—the response correlates with the formation conductivity, rather than an actual conductivity/resistivity measurement. This is because the high- and low-resolution components are generally similar in magnitude and impossible to separate. The button response is typically scaled to present

a resistivity curve that coincides with the shallow laterolog over distances that are large in comparison with the FMI electrode spacing. Over comparatively short distances, the scaled curve provides a high-resolution, but approximate, resistivity log.

The resolution of the FMI tool is the button size at 0.2 in. In theory, this means that an object larger than 0.2 in. appears as its true size. An object smaller than 0.2 in. may be visible, depending on the resistivity contrast with the background rock. If it is visible, it may appear to be as large as 0.2 in. In conformance with sampling theory, the FMI image is sampled at one-half the resolution (0.1 in.) vertically and horizontally so that the theoretical resolution is not compromised. To achieve 0.1-in. sampling horizontally for the button diameter of 0.2 in., the buttons are arranged on the pad and flap in two horizontally offset rows.

FMI measurement current path.

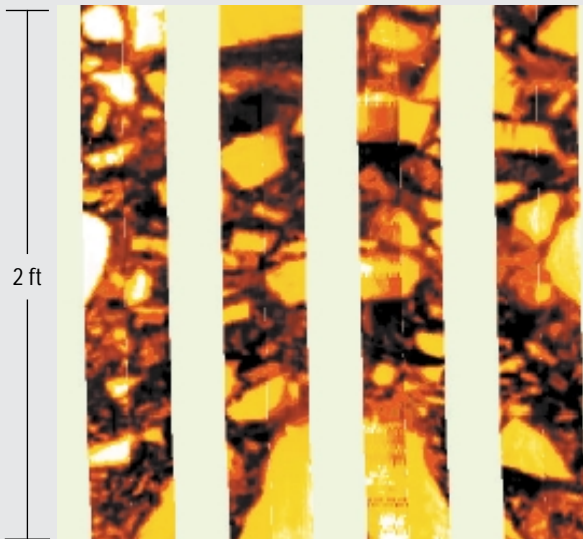


Characterization of rock structure

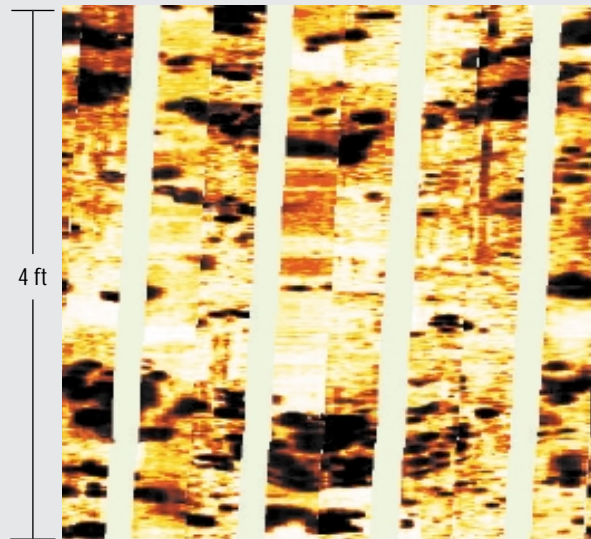
FMI images provide critical information if the rock structure and sedimentary features are significant determinants of formation productivity. The figure below shows paired carbonates and sandstones with the same porosity but completely different permeabilities and hence production capabilities.

FMI images differentiate the structures that result in vastly different production potential for formations with the same porosity.

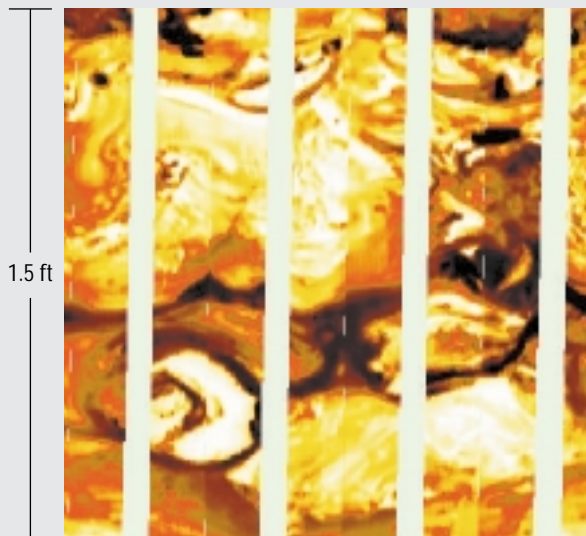
Collapse Breccia
(14% porosity, 6000 BOPD)



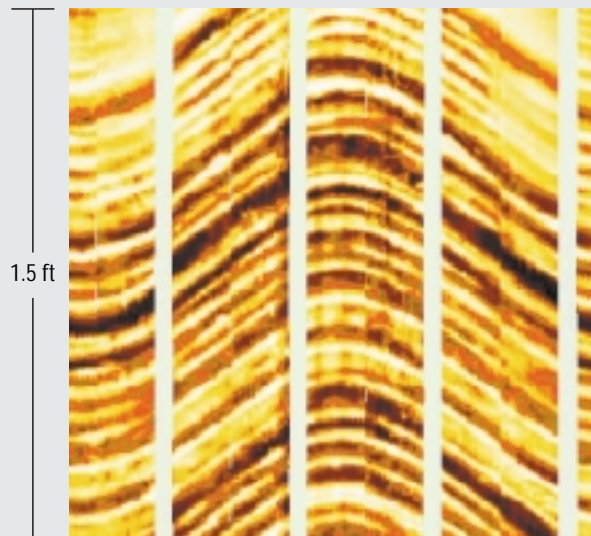
Vuggy Limestone
(14% porosity, 0 BOPD)



Slumped Sandstone
(18% porosity, 0 BOPD)



Turbidite Levee Deposit
(18% porosity, 5000 BOPD)

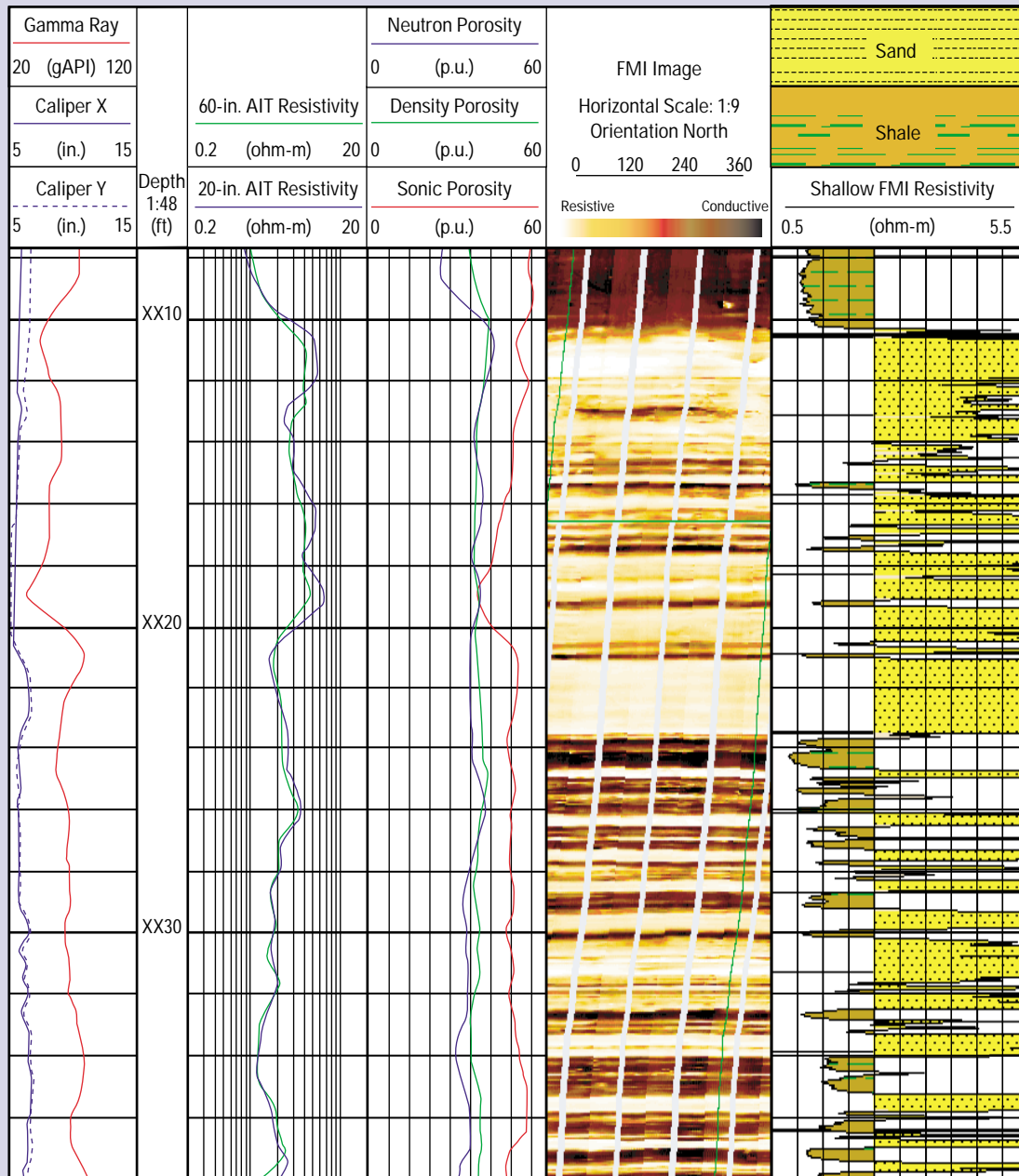


Net pay determination in laminated sediments

The FMI tool is the preferred approach for determining net pay in the laminated sediments typical of fluvial and turbidite depositional environments. The method for obtaining an accurate sand count is to compute an average resistivity curve from the FMI measurements and apply a cutoff that

distinguishes sand from shale. Laminations as thin as 0.2 in. can be resolved. Sections with laminations thinner than this intrinsic resolution are analyzed by calibrating FMI lithofacies with the sand count from core. The resulting sand-shale curve can be analyzed for the bed-thickness distribution and used to derive mappable parameters.

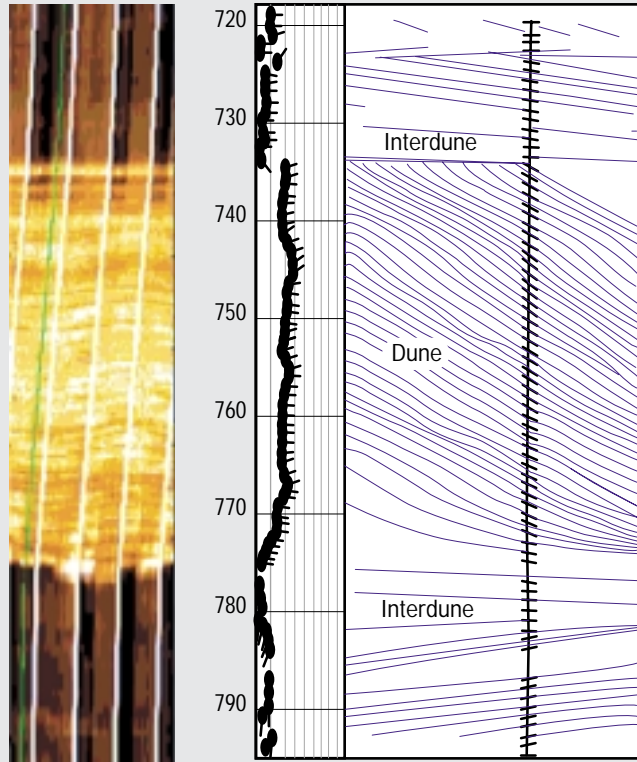
In highly laminated sediments, the FMI log clearly shows the net pay zones that can contribute to production.



Visualization of sedimentary features

The interpretation of image-derived sedimentary dip data enables the visualization of sedimentary structures that define important reservoir geometries and petrophysical reservoir parameters. The figure to the right shows eolian dunes separated by interdune deposits.

FMI images and dip data clearly differentiate the dune and interdune deposits. The data were acquired from an 8½-in. diameter borehole.

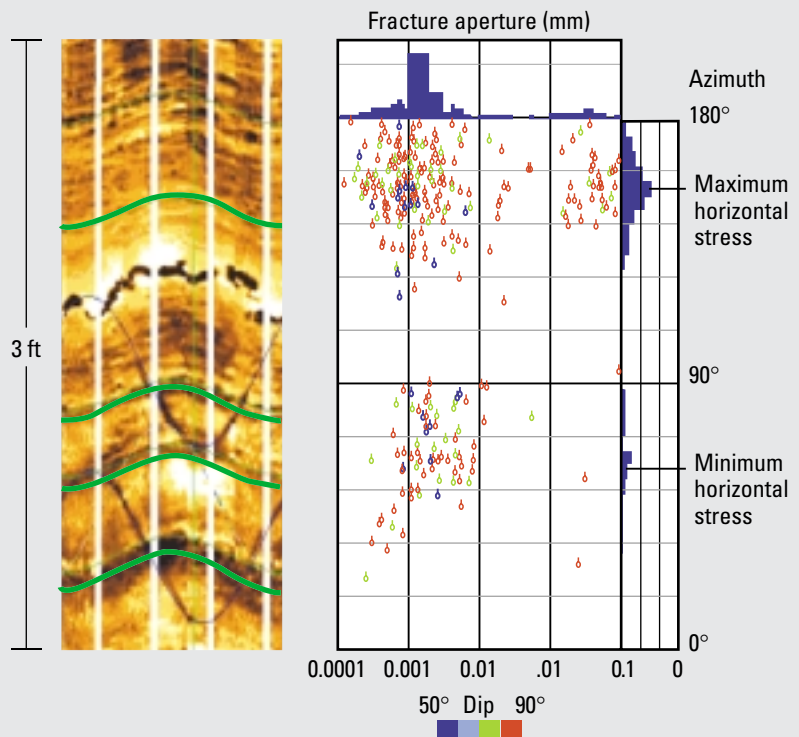


Fracture permeability direction

The principal stress azimuths obtained from borehole image analysis define the maximum permeability direction in fractured reservoirs. The fracture set that is aligned with the maximum horizontal stress contains the widest fracture apertures and dominates the direction of fracture permeability.

The stylolite that appears as a dark, irregular feature in the center of the image to the right acts as a vertical permeability barrier.

FMI data analysis identifies the maximum permeability direction in a fractured reservoir, which is important information for designing a completion for optimal production.



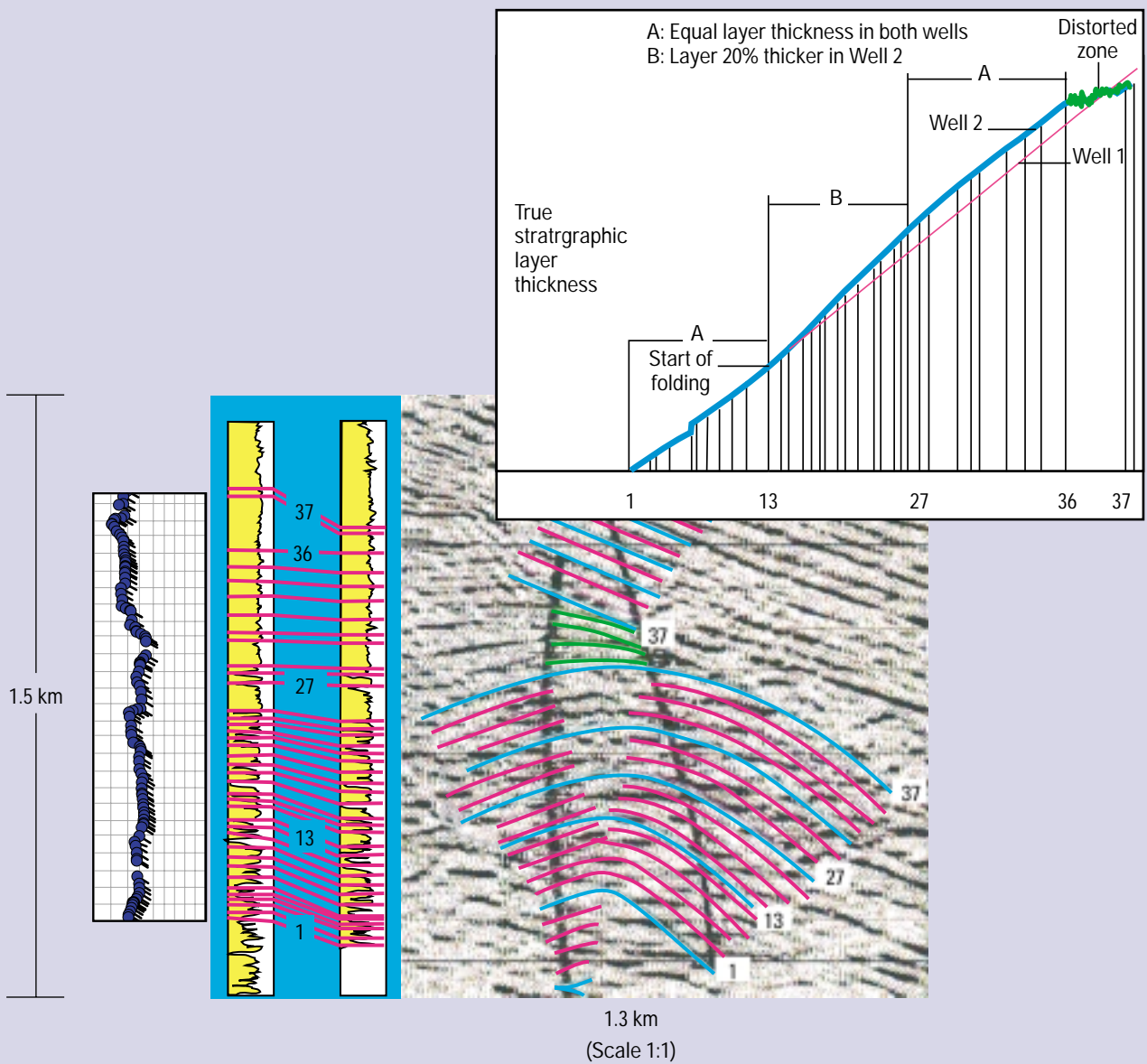
Structural interpretation

Well-to-well correlation is difficult in deviated wells with sections of steep and varying structural dip. The structural interpretation of seismic sections is greatly improved by the use of high-quality bedding dips to compute accurate logs of the true stratigraphic thickness (two well logs

second from left in the figure below). The two correlated wells are plotted on the seismic section using structural dip (magenta lines) and stratigraphic markers (cyan lines). The ramp anticline is well defined by the well data compared with the seismic section. The far-right plot in the figure compares the thickness of strati-

graphic intervals 1 through 37 in both wells. The thicknesses are the same in interval A, but from stratigraphic marker 13 to marker 27, the layers in Well 2 show increasing thickness in comparison with the layers in Well 1, indicating a syntectonic sedimentation differential.

FMI images and dip data are an independent complement for structurally interpreting seismic sections. The ramp anticline is better defined by the dip data than the seismic surface data.



Three-dimensional reservoir modeling

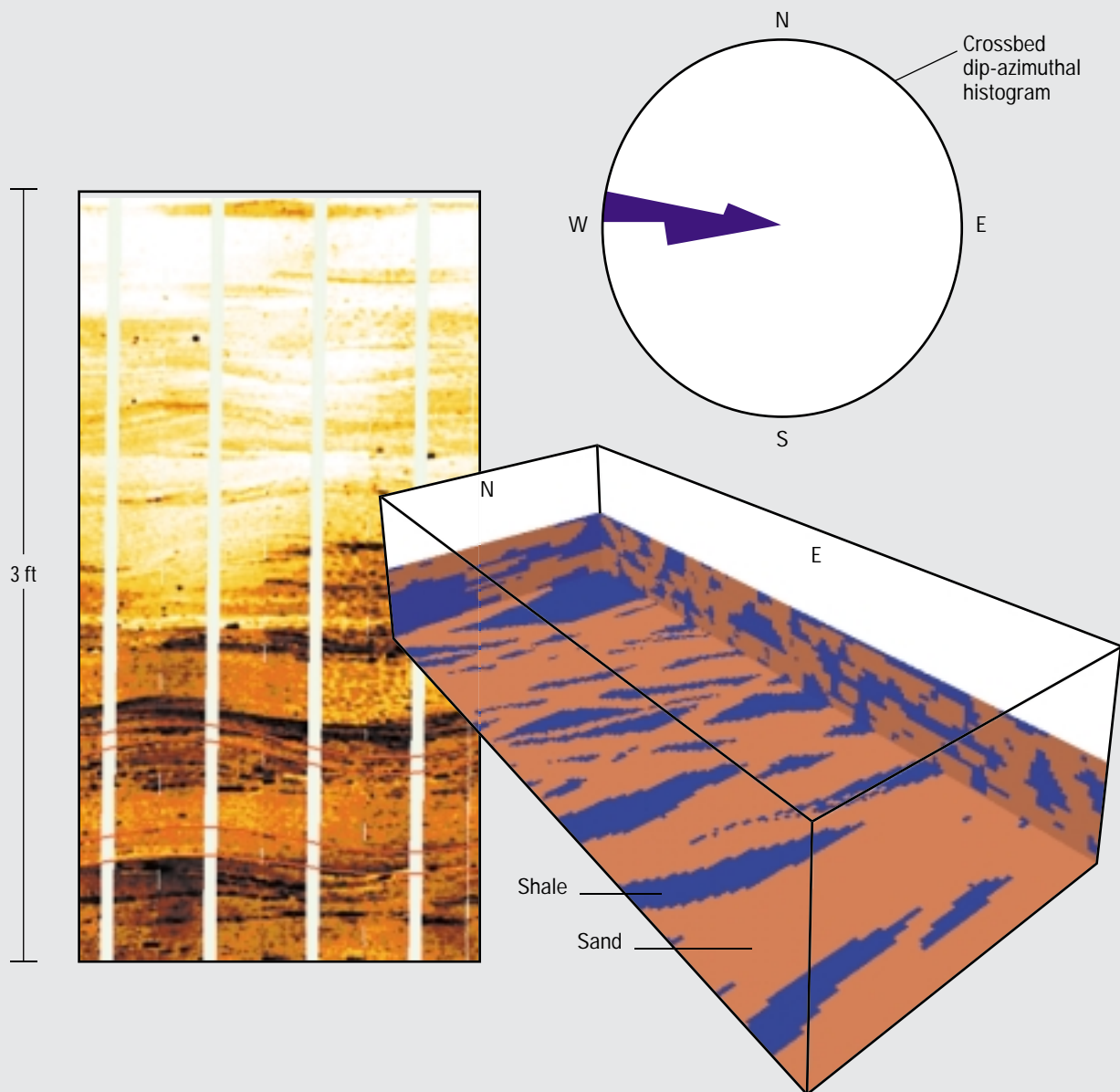
Once the structural framework is established within the geology and geophysics workflow, the reservoir is divided into lithologic units, which are then populated with properties such as porosity, permeability and water saturation to support reservoir simulation. The lithologic units are created deterministically or stochastically. The latter approach is shown

in the figure below and employs the Fluvial Simulation (FLUVSIM) methodology.

Sand-shale logs can be derived from wireline and logging-while-drilling (LWD) logs from vertical as well as horizontal wells. Critical guidance for stochastic modeling of the sand-shale distribution is provided by the geological information derived from FMI borehole images. Crossbedding translates

into channel directions, and FMI images superbly define channel heights in amalgamated units. Other variables, such as the channel width and channel sinuosity, can be estimated using geological analogs based on detailed sedimentological analysis of FMI image data in conjunction with other logs and core data.

The three-dimensional display shows the distribution of sand (orange) and shale (blue) as modeled for a fluvial reservoir using FMI-derived sedimentological information in an 8½-in. well.



Key input for Mechanical Earth Models

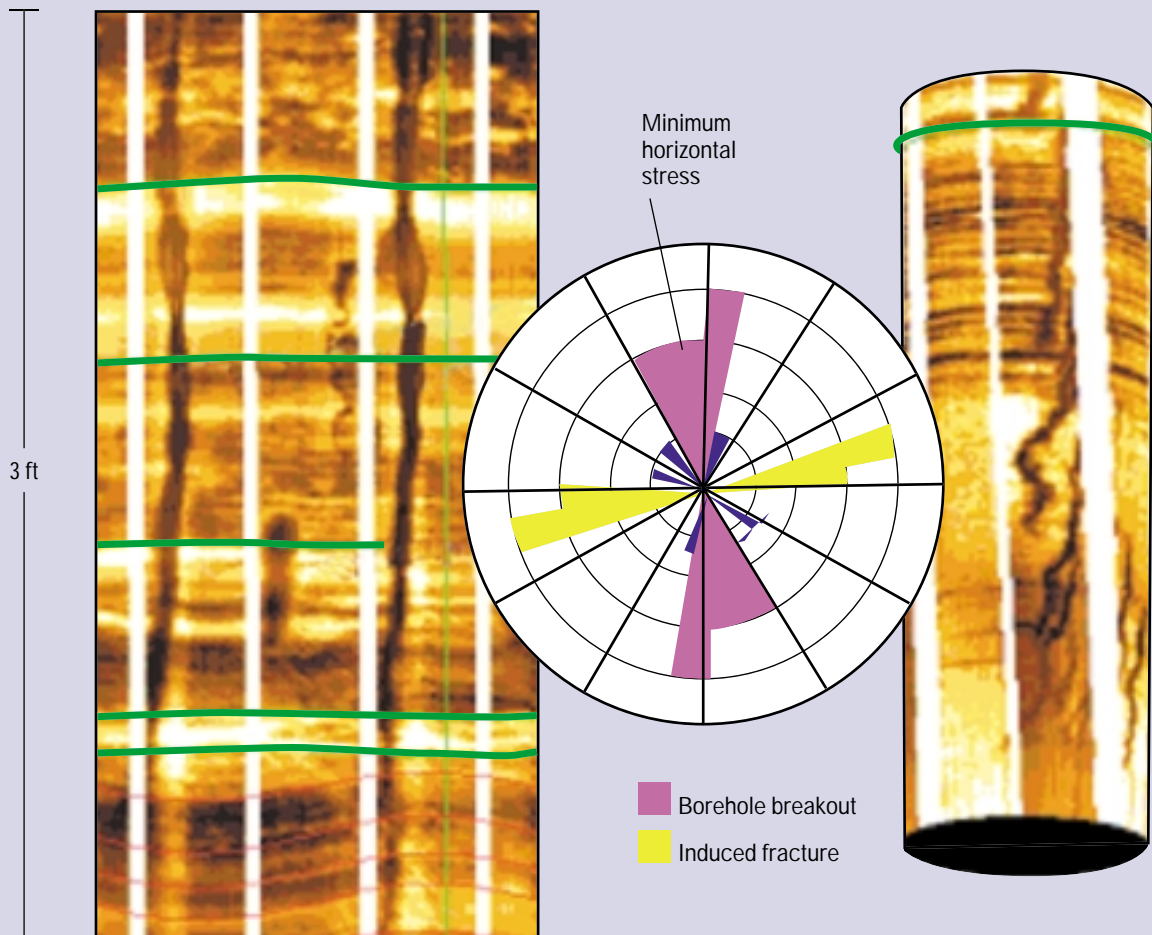
A growing application for borehole images is providing input and verification data for the Mechanical Earth Model (MEM) used to optimize well construction. Better understanding of borehole stability can save operators millions of dollars by shortening

the learning curve during the initial field development.

The example below shows the borehole breakout and hydraulic fractures and their relationship to the horizontal stresses. An MEM can predict the type and position of induced features on borehole images. Disagreement

between modeled and observed features on the borehole images is used to tune the assumptions made in the MEM, such as changing the azimuth or relative magnitude of the principal stresses.

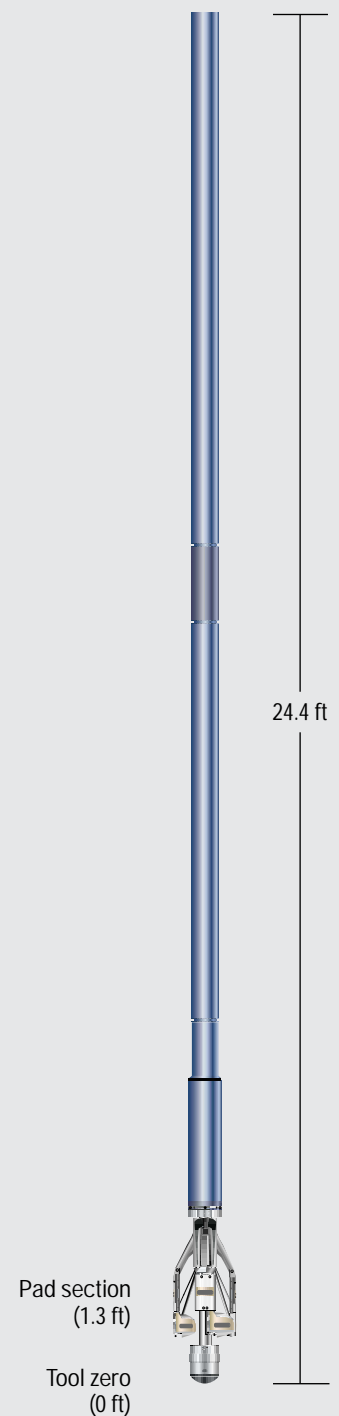
A Mechanical Earth Model can be used to predict the type and position of drilling-induced features in the borehole. Knowledge of the directions and relative magnitude of the principal stresses is needed to optimize a drilling program.



FMI Specifications

Applications	Structural geology, stratigraphy, reservoir analysis, heterogeneity, fine-scale features, real-time answers
Vertical resolution	0.2 in. with 50-micron features visible
Azimuthal resolution	0.2 in. with 50-micron features visible
Measuring electrodes	192
Pads and flaps	8
Coverage	80% in 8-in. borehole (fullbore image mode)
Max pressure	20,000 psi
Max temperature	350°F [175°C]
Borehole diameter	
Min	5⅞ in.
Max	21 in.
Max hole deviation	90°
Logging speed	
Fullbore image mode	1,800 ft/hr with real-time processed image
Four-pad mode	3,600 ft/hr with real-time processed image
Dipmeter mode	5,400 ft/hr with real-time dip processing
Inclinometer mode	10,000 ft/hr
Max mud resistivity	50 ohm-m
FMI tool	
Max diameter	5 in.
Makeup length	24.4 ft
Makeup length with flex joint	26.4 ft
Weight in air	433.7 lbm
Compressional strength (TLC* operations)	12,000 lbf (safety factor of 2)
Max pad pressure	44 lbf
Combinability	Top combinable with openhole wireline tools

FMI tool string.



Maximum tool diameter 5 in.