

DRILLING SERVICES

LOGGING- WHILE-DRILLING TECHNOLOGY

Delivering Wide-Spectrum
Formation Evaluation for any
Drilling Environment



Weatherford[®]

ACQUIRE **ACCURATE** PETROPHYSICAL DATA WHILE DRILLING

Weatherford has an extensive selection of LWD sensors, with a broad array of hostile-environment logging (HEL™) tools, including the triple combo (directional, gamma ray, resistivity, azimuthal density and neutron porosity) toolstring. Designed and built in the 21st century, our fleet of LWD tools can operate in the highest temperatures and pressures in the industry. In addition to the triple combo service, the Weatherford Wave series of advanced tools and services complement our existing portfolio for obtaining accurate petrophysical measurements, even in extreme logging environments. Combining

spectral azimuthal gamma ray, deep-reading azimuthal resistivity, azimuthal sonic, high-resolution imaging, and formation pressure testing with traditional triple combo and drilling dynamics measurements, we can rapidly provide interpretations to facilitate your real-time drilling and completion decisions.

Our tools not only provide for operations under the most extreme downhole conditions; their system architecture also leads to enhanced reliability and fewer trips in more benign drilling environments.

GuideWave™ - Deep Reading Resistivity Tool



MFR™ Multi-Frequency Resistivity Tool



TNP™ Thermal Neutron Porosity Tool & AZD™ Azimuthal Density Tool



ShockWave™ & CrossWave™ Sonic Tools



PressureWave™ Formation Tester Tool



SpectralWave™ Spectral Azimuthal Gamma Ray Tool



SineWave™ Micro-Imager Tool



UltraWave™ Ultra-Sonic Imager



HEL™ Hostile Environment Logging MWD

Transmit logging data to surface in conventional or extreme environments

The HEL hostile environment logging MWD system lies at the heart of each Weatherford LWD tool. It enables downhole data to be transmitted to the surface at optimum data rates. The pulser can be reconfigured at the wellsite to optimize data transmission for various mud weight and flow rate conditions. The pulser is field-proven to transmit signals from depth in wells deeper than 35,000 ft (10,668 m) deep and mud weights higher than 18 ppg.

The pulser design has proved to be very robust, even in high concentrations of lost-circulation material (LCM). It has been put to the test, operating after LCM pills of 120 lb/bbl have been pumped through the tool.

EXAMPLE OF A BAP LOG, used to monitor bore and annular pressures, ROP, and hole cleaning to enhance performance drilling.

IDS Integrated Directional Sonde

Determine wellbore location precisely

The HEL collar also contains the IDS integrated directional sonde, which tracks the exact downhole location of the toolstring at all times. The system delivers a station-by-station survey of the wellbore and can make measurements “on the fly,” to produce high-quality data while drilling for more precise directional control and geosteering.

BAP™ Bore and Annular Pressure

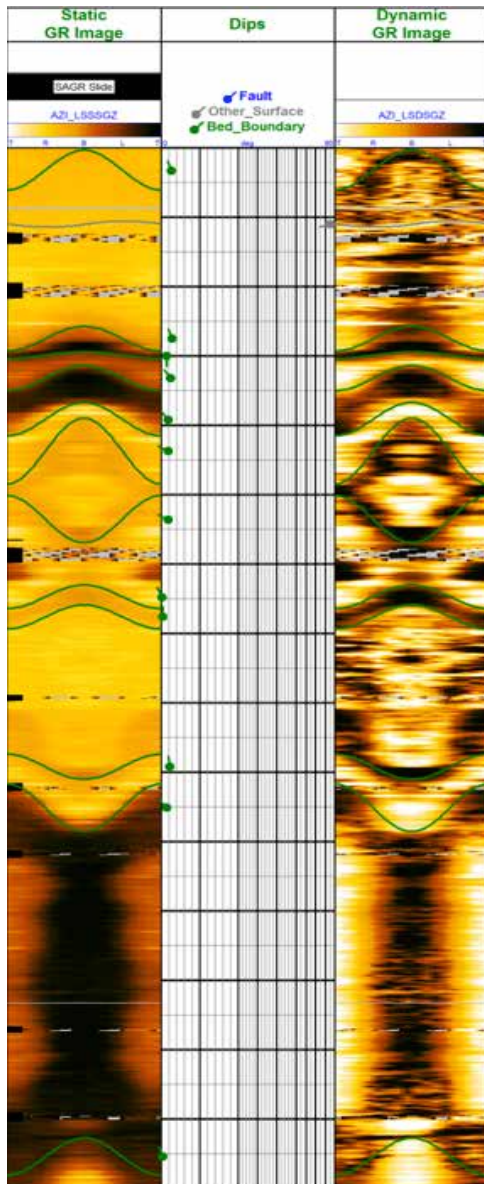
Monitor downhole pressures while drilling

The BAP bore and annular pressure sensor is an integral part of the HEL collar. This device uses highly accurate quartz transducers to monitor downhole well conditions while drilling, to help optimize the mud program and improve the rate of penetration (ROP). The BAP measurements may be presented in pressure units or equivalent circulating density (ECD) to help evaluate hole cleaning, control surge and swab pressures, and aid in rapidly identifying well control issues, cuttings pack-off, drillstring washouts, and lost circulation.



GAMMA RAY LOGGING

Weatherford gamma ray tools provide a wide range of measurements from basic correlation to real-time borehole imaging, geosteering, and evaluation of reservoir organic content and clay volume.



STATIC AND DYNAMICALLY-NORMALIZED gamma ray borehole images, with interpreted formation dips.

HAGR™ Hostile Azimuthal Gamma Ray Tool

Obtain azimuthal GR data—even while sliding

The HAGR hostile azimuthal gamma ray tool is a rugged sensor, providing an accurate total gamma ray log, as well as real-time and recorded azimuthal gamma ray images. The HAGR tool contains a ring of Geiger-Müller tube detectors that acquire azimuthal gamma ray data in both rotating and sliding drilling modes. Furthermore, the HAGR sensor can be placed in different positions in the LWD string to obtain azimuthal gamma ray information near the bit. HAGR azimuthal gamma ray sensors are available in 4¾- to 9½-in. nominal tool sizes for logging boreholes ranging from 5.75 to 30 in. (146 to 914 mm) in diameter. This tool can operate in conditions up to 356° F (180° C) and 30,000 psi (207 MPa). Weatherford also offers scintillation detectors for improved image quality required in dip picking and well placement.

SpectralWave® Spectral Azimuthal Gamma Ray

Evaluate organic richness and clay content with the industry's only spectral GR LWD

The SpectralWave spectral azimuthal gamma ray sensor uses scintillation detectors mounted in pockets on the drill collar to provide:

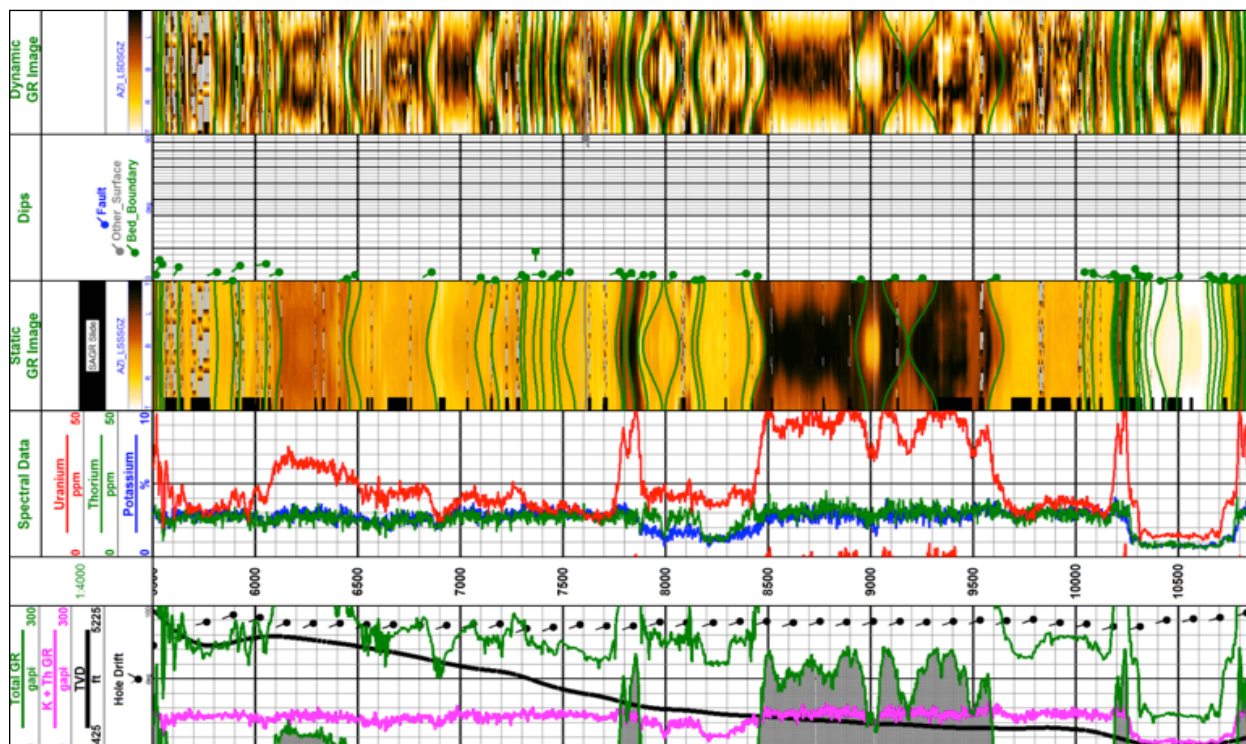
- high-precision total gamma ray measurements
- high-quality real-time and recorded 16-bin borehole image logs
- accurate measurements of potassium (K), uranium (U), and thorium (Th) content in the formation.

The high-precision total gamma ray log increases certainty in well-to-well correlations and shale volume calculations, while the gamma ray borehole images guide real-time geosteering decisions and provide formation

structural dip information. The spectral K, U, and Th measurements are used in shale reservoir evaluation, clay typing, evaluation of uranium-bearing carbonates, and assessing sandstone reservoir quality.

The SpectralWave tool is ideal for high-ROP drilling applications, where the high count rate (up to 50 times higher than typical MWD gamma ray detectors) from large scintillation detectors provides high-quality gamma ray logs at drilling speeds up to 1,000 ft/hr (300 m/hr). The SpectralWave sensor is particularly valuable in shale reservoir development, where the real-time

borehole images facilitate geosteering and provide formation structural information, while the K, U, and Th data can provide information on organic richness, clay content, and formation brittleness. Empirical correlations between uranium and total organic carbon (TOC) facilitate the evaluation of organic content. In cases where organic-associated uranium affects the total gamma ray measurement, clay content can be evaluated from potassium and thorium values; this may be important in reservoirs where clay content controls formation brittleness and fracturing behavior.



IN THIS SPECTRALWAVE LOG from the Marcellus Shale, the high uranium readings (red curve in Track 2) indicate organic-rich zones. The relatively constant potassium and thorium curves indicate that clay volume is fairly constant, despite the wide variation in total gamma ray activity. The azimuthal gamma ray image log provides information about formation dip and indicates when the wellbore is drilling stratigraphically up or down.

RESISTIVITY MEASUREMENTS

Weatherford state-of-the-art resistivity tools provide high-resolution data that deliver precise formation evaluation and well placement.

MFR™ Multi-Frequency Resistivity Sensor

Achieve highly accurate resistivity measurements, even in high formation resistivities

The MFR multi-frequency resistivity device, with its fully compensated antenna array and digital electronics, obtains highly accurate formation resistivity measurements over a range of 0.1 to 2,000 ohm-m, and in any mud system—from fresh water to salt water, oil-base muds, or air-field holes. The MFR device can transmit real-time measurements for R_t , D_i , R_{xo} , and R_v/R_h anisotropy inversion, or record the data for later symmetrical retrieval.

The MFR sensor measures resistivity from electromagnetic wave propagation phase shift and attenuation measurements. It operates at 2 MHz and 400 KHz with antenna-receiver spacings of 20, 30, and 46 in. All measurements are symmetrically compensated for maximum accuracy, with antennas integrated into the drill collar to increase reliability and simplify maintenance. The MFR device provides 12 fully compensated resistivity measurements at unique radial distances from the borehole, and can attain 6-in. vertical resolution at logging speeds up to 300 ft/hr.

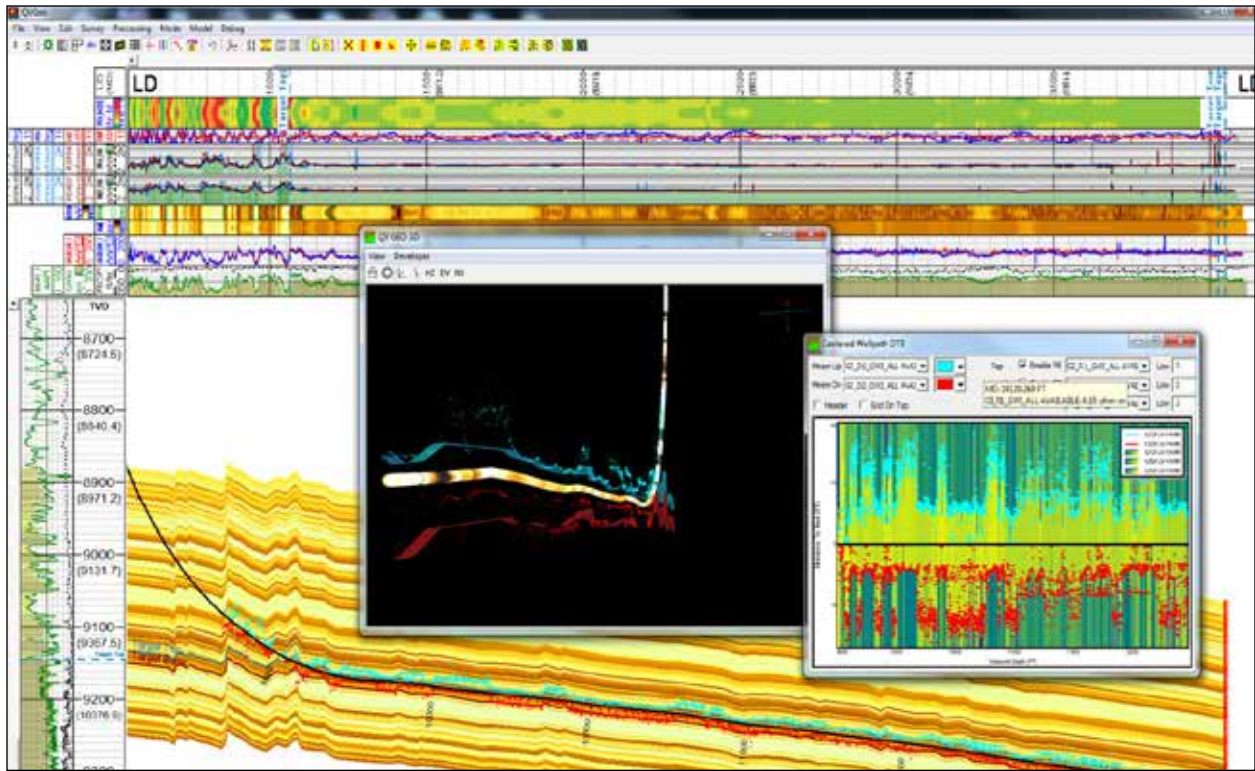
GuideWave® Deep Reading Resistivity Tool

Find distance and direction to bed boundaries and fluid contacts

Geosteering engineers use azimuthal resistivity measurements for well placement in clastic or carbonate reservoirs that exhibit a resistivity contrast between the pay zone and adjacent beds. We acquire the resistivity data using the GuideWave azimuthal tool, and incorporate that data into a pre-well model. Our geosteering engineers use a sophisticated inversion algorithm developed by Weatherford to calculate the direction and distance to a formation boundary (DTB) or an oil-water contact (OWC). Using this well-placement tool to avoid the water zone while drilling, operators may delay the subsequent onset of coning when they produce the well.

In challenging applications, the GuideWave tool activates additional 100-kHz azimuthal resistivity long-spaced measurements to detect boundaries and contacts at a radius of up to 35 ft (10.2 m), and obtain additional raw curves to correlate with the model. The depth of investigation, directionality of the azimuthal signatures, and 360° bed-boundary detection combine to aid in geosteering laterals through the sweet spot, regardless of complex formation geometries. Our fully compensated array delivers dynamic resolution and extremely accurate measurements in reservoirs with R_t as high as 4,000 ohm-m.





GUIDEWAVE, DENSITY, AND GAMMA RAY MEASUREMENTS
used in multilayer inversion to obtain distance-to-bed boundaries

The GuideWave tool is used extensively by Weatherford experts in providing InZone™ well placement services. Our highly experienced personnel provide real-time, instantaneous information and guidance to optimize steering and drilling.

Our well placement experts use QVGeo proprietary software for real-time streaming and 2D and 3D visualization. The 3D window enables drillers and geoscientists to visualize wellbore trajectories, interpreted

surfaces, log curves, and operator-imported 3D surfaces. The link between 2D and 3D visualization is dynamically updated and connected by WITSML data streaming. This enables the geosteering team to instantaneously visualize all real-time data as it is received in the 3D windows and associated structure map.



DENSITY AND NEUTRON POROSITY LOGGING

Our tools help determine formation lithology and porosity, and the fluids within.

Neutron Porosity and Azimuthal Density

Measure formation density and porosity for lithological parameters at faster ROPs

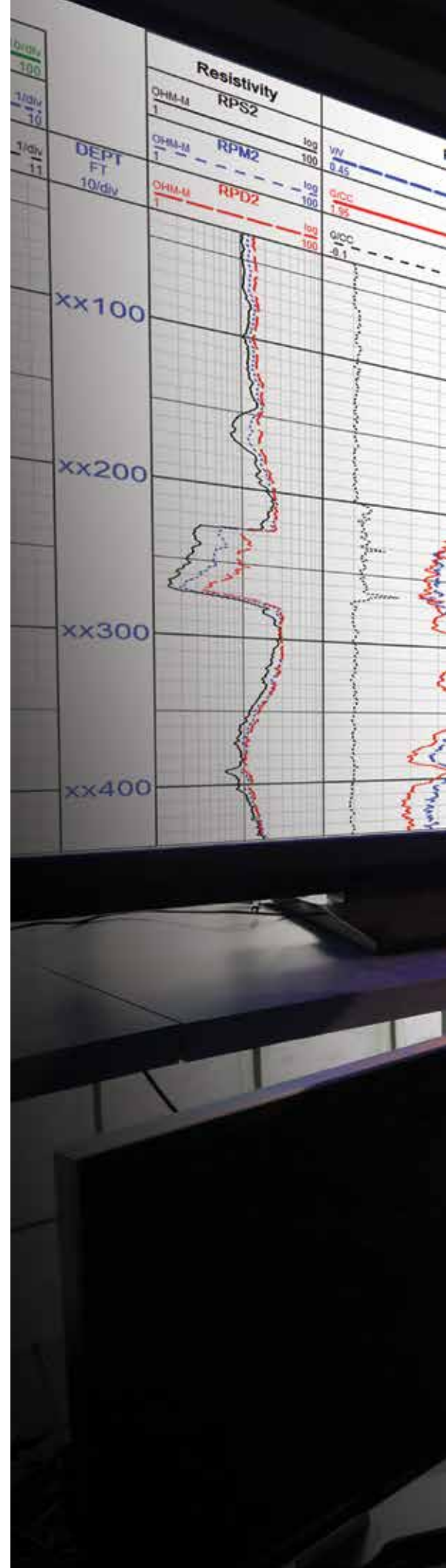
The Weatherford formation density/neutron porosity tool combines measurements from two primary sensors: the AZD™ azimuthal density sensor and the TNP™ thermal neutron porosity sensor. This combination tool delivers high accuracy and statistical repeatability at logging speeds up to 400 ft/hr (122 m/hr). The AZD and TNP sensor detector configurations are optimized separately for each tool size, resulting in industry-leading accuracy and precision, with minimal borehole effects.

The AZD sensor provides highly accurate bulk density, photoelectric capture (Pe), standoff, and caliper logs in real time. For real-time geosteering and borehole monitoring, it can transmit 16-bin azimuthal density and standoff images.

The TNP sensor uses multiple He³ thermal neutron detectors at two spacings for a highly accurate, compensated neutron-porosity measurement. The size, number, and position of the detector tubes are optimized for each tool size to maximize formation sensitivity and statistical precision. Environmental corrections can be applied for hole size, standoff, mud weight, mud salinity, pressure, and temperature.

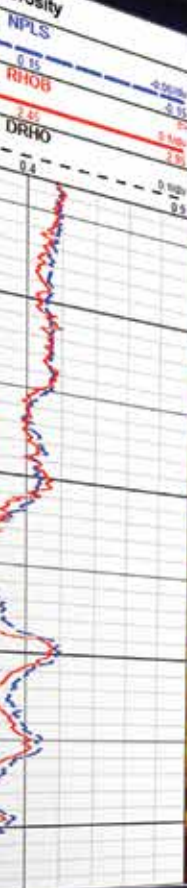
Individually, the AZD and TNP sensor each obtain accurate, precise, measurements—but combined, they are a powerful tool for porosity, lithology and fluid information. Neutron-density crossplots provide both porosity and lithology information in dual-mineral systems, while lithology can also be interpreted from Pe log values or Pe-bulk density crossplots. Gas-bearing formations can be identified by neutron-density crossplots, or through separation of neutron porosity and density porosity log curves.

LWD TRIPLE COMBO LOG AND DENSITY IMAGE, with data from HAGR, MFR, AZD, and TNP sensors.





Porosity



Density image



Image Cylinder Plot



SONIC LOGGING

Weatherford sonic LWD tools provide critical measurements for porosity evaluation, geophysical correlations, and geomechanical analyses.

ShockWave® Sonic Measurement

Gather sonic measurements in real time

The ShockWave sonic tool provides robust, real-time LWD sonic data for porosity evaluation, seismic time-depth correlation, pore pressure determination, gas detection, and borehole geomechanics. Our ShockWave tool is a next-generation acoustic device—being the first LWD sonic tool to deliver clear, accurate, and reliable compressional and shear wave travel-time data in real time—without the requirement for significant post processing and correction.

Its high-output transmitter and unique attenuator design combine with advanced acquisition modes and real-time downhole processing techniques for accurate, reliable data in downhole conditions up to 30,000 psi (207 MPa) and temperatures to 329°F (165°C).

The ability to gather sonic data in real time allows better seismic depth correlation, to facilitate interpretation and target adjustment while drilling. Real-time transmission of full-semblance projections provides accurate and reliable compressional, shear, and Stoneley slowness logs while drilling. This data facilitates reliable pore pressure evaluation, as well as real-time estimates of formation mechanical properties to ensure wellbore stability. Combining compressional and shear slowness data (e.g., V_p/V_s ratio) can identify gas-bearing formations and provide lithology information, by using sonic data alone, or by combining it with neutron and density data. And the final recorded logs are delivered from the field, just hours after the bit run.



**POWERFUL
TRANSMITTER** | **EFFECTIVE
ATTENUATOR** | **SENSITIVE
RECEIVERS**

HIGH SIGNAL TO NOISE RATIO

CrossWave® Azimuthal Sonic Measurement

Obtain azimuthal shear wave data for geomechanical evaluation of anisotropic formations

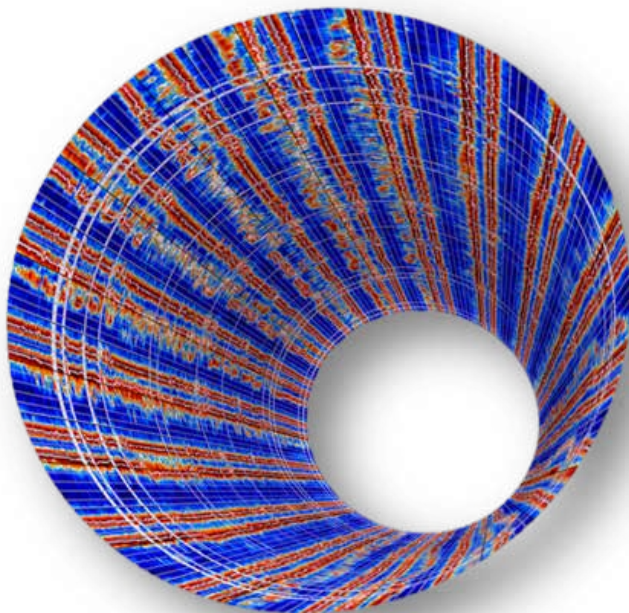
The CrossWave azimuthal sonic tool provides conventional sonic measurements and 360° azimuthal sonic borehole images. As the drillstring rotates, the azimuthally focused transmitter fires acoustic waves into the formation. These waves are refracted back to the receivers and stored in 16 fixed-orientation azimuthal bins. Processed in bins, the waveforms yield azimuthally oriented borehole images of compressional and refracted shear images.

While both compressional and shear images show bedding features similar to density or gamma ray borehole images, the azimuthal shear wave measurements also reveal shear anisotropy, such as stress-induced HTI anisotropy in vertical wells, and intrinsic VTI anisotropy in horizontal shale wells. Understanding the orientation and magnitude of shear wave anisotropy is critical in planning horizontal shale

development wells, modeling hydraulic fracturing performance, and optimizing frac stage placement.

Combining data from azimuthal density, compressional slowness, and shear slowness images provides information to compute 3D borehole images of key geomechanical parameters such as Poisson's ratio and Young's modulus.

Combining the Weatherford wireline CDX™ cross-dipole logs from vertical wells with LWD CrossWave data from horizontal wells provides three-dimensional compressional and shear velocity data for enhanced seismic interpretation. Vertical compressional slowness and horizontal plane HTI shear anisotropy is obtained from the vertical well, while horizontal compressional slowness and vertical plane VTI shear anisotropy data can be measured by the CrossWave tool in horizontal wells. This data also provides the geophysicist with an accurate three-dimensional velocity model for optimal seismic processing and interpretation, including AVO analysis and attribute modeling.



SIXTEEN INDIVIDUAL "BINS" OF DATA are reconstructed around the borehole to establish the shear acoustic semblance minimum and maximum orientation and evaluate the ratio of minimum to maximum.

HIGH-RESOLUTION IMAGING

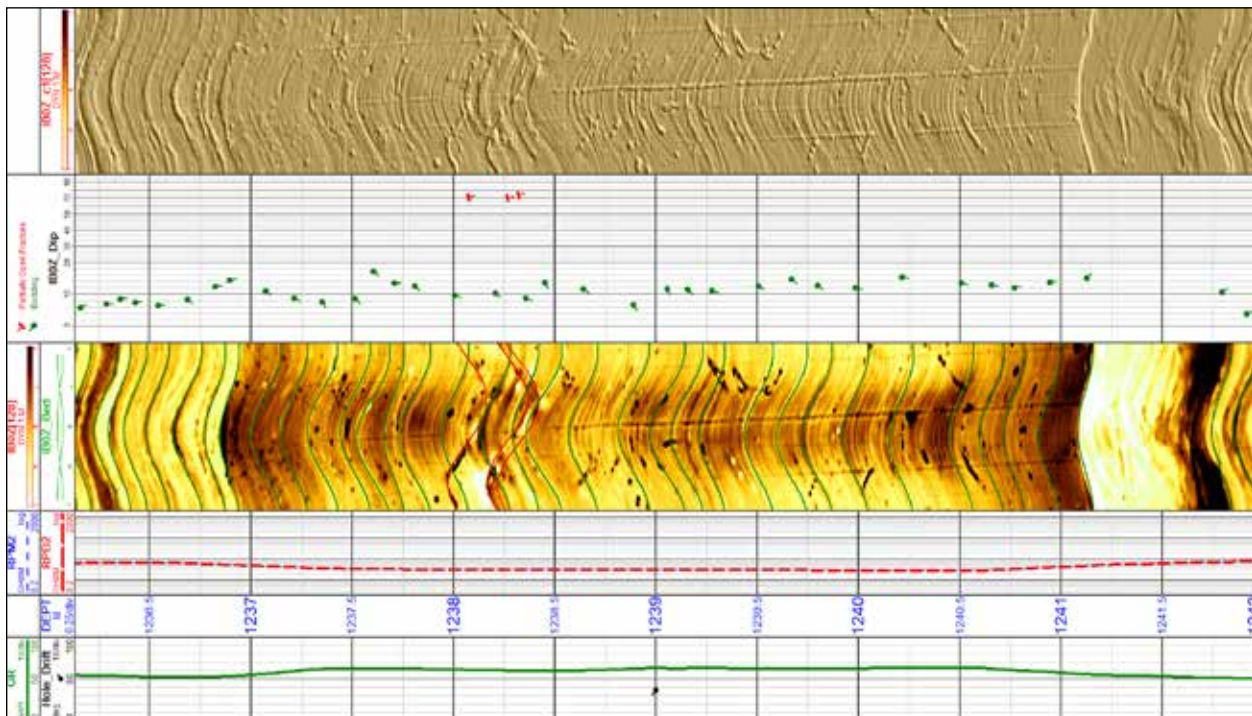
Through high-definition formation imaging, geoscientists obtain important information for analyzing wellbore shape, fracture orientation, formation dip, and stratigraphic features.

SineWave® Microimager

Visualize the formation in detail while drilling

The SineWave microimager uses two electrodes to obtain azimuthal measurements from the rotating drillstring in water-based drilling fluids. The data is recorded in 128 azimuthal sectors on a continual basis while drilling, and can be processed downhole into 16 or 32 real-time

bins for transmission of images to the surface. These high-resolution electrical images help geoscientists interpret structural and stratigraphic characteristics of the formation, as well as geomechanical properties and wellbore stability. Through high-definition imaging, the customer can visualize the formation that has been drilled to assess the fabric of the reservoir on a millimeter to centimeter scale, as if it was presented in a core. With this enhanced level of detail, geoscientists can determine formation dip, characterize net-to-gross in thin-beds, evaluate well placement, identify fractures and evaluate their orientation, aperture, stress, and sealing capabilities, and more.



HIGH-RESOLUTION SINEWAVE IMAGES can provide detailed structural and stratigraphic information to reveal natural and induced fractures, faults, vugs, and fine-scale bedding features. Advantages of the SineWave microimager include full 360-degree borehole coverage and real-time images for proactive geosteering and early formation evaluation.

UltraWave™ Ultra-Sonic Imager

Image the formation in oil- or water-based muds

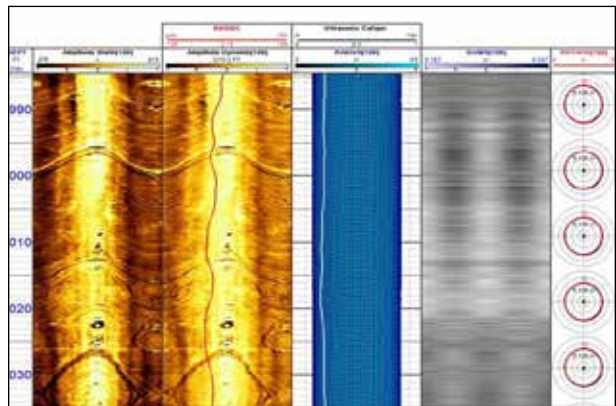
The UltraWave ultra-sonic imager provides high-resolution borehole images and borehole caliper measurements while drilling in oil- or water-based mud systems.

This imager records the amplitude and travel time of ultrasonic acoustic waves reflected from the borehole wall. These measurements are recorded in 128 azimuthal sectors around the circumference of the borehole, providing high-resolution, 360 degree, borehole images while drilling.

The reflected amplitude image reveals formation structural and stratigraphic features such as bedding, natural fractures, and vugular porosity, as well as geomechanical features such as induced fractures and borehole breakout.

The travel time image produces high-resolution standoff and borehole caliper images, showing the size and shape of the borehole.

Imaging can be used while drilling to optimize the placement and completion of wellbores in unconventional reservoirs. In addition to providing formation dip and geomechanical information, images help determine tectonic stress orientation based on natural- and stress-induced fractures, and enhance petrophysical evaluation of thinly-bedded and fractured reservoirs. Similarly, caliper displays can be used for borehole stability analysis and monitoring.



SONIC IMAGING DISPLAY shows borehole and formation features while drilling. Track 1 depth; 1:100 log scales. Track 2 static acoustic amplitude image, Track 3 dynamic acoustic amplitude image and bulk density, Track 4 borehole radius wireframe and ultra-sonic caliper, Track 5 borehole diameter image from travel time measurement and Track 6 potato plot showing borehole conditions

PRESSURE TESTING

Real-time formation pressure measurements characterize the reservoir and enable safe, efficient drilling through precise, real-time overbalance or underbalance pressure data.

PressureWave® Formation Pressure Tester

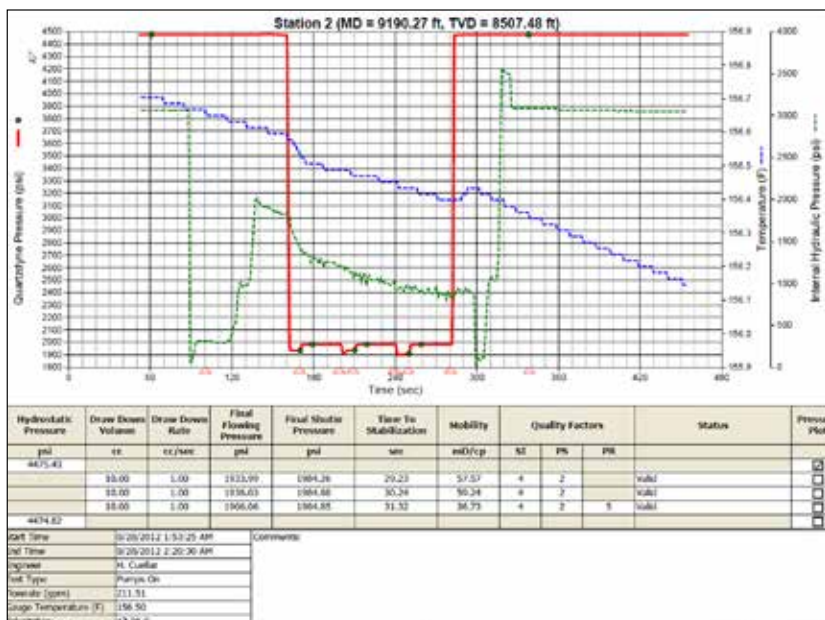
Obtain formation pressure and overbalance while drilling

The PressureWave LWD formation tester takes direct measurements of formation pore pressures. When used with the HEL-LWD suite, the PressureWave formation tester delivers mission-critical formation pressure and fluid-mobility information, to maintain well integrity while drilling. In addition to measuring pore pressure in real time, the PressureWave data provides a permeability indication and aids in confirming formation mechanical properties.

This tool takes fast, reliable formation pressure measurements with pumps either on or off. While testing with pumps on, data can be transmitted as fast as one pressure measurement every four seconds, with 1/2-psi resolution. High-resolution 32-bit pressures are recorded into memory at five samples per second.

The system is set up with external modules for enhanced reliability and easy maintenance. Included in the tool architecture is a fully mechanical drawdown device rather than a hydraulic device. Because it is not affected by changes in temperature downhole, the PressureWave tester takes precise volumes on drawdown for identifying fluid gradients and boundaries in real time.

REAL-TIME DATA from the PressureWave™ LWD formation tester compares well with memory recorded data stored in the tool. Real-time data can be reliably used to evaluate formation pressure while drilling ahead.





HEATWAVE EXTREME LWD service provides gamma ray, bore and annular pressure, resistivity, neutron porosity, and bulk density measurements in a Gulf of Thailand well.

EXTREME LOGGING

Our triple combo data lets you evaluate the formation in extreme temperatures and pressures.

HeatWave™ Extreme LWD service

Reliable, real-time triple combo data in 392°F (200°C)

The HeatWave Extreme service brings reliable LWD measurements to the most challenging drilling environments on Earth. The service acquires high-quality LWD data in temperatures up to 392°F (200°C) and pressures up to 30,000 psi (206.8 MPa).

Each HeatWave Extreme service component—from electronics to elastomers—has been completely redesigned for optimal reliability and robust resistance to ultra-high temperatures, high pressures, and vibration. The result is the first LWD service to reliably acquire gamma ray, resistivity, neutron porosity, bore and annular pressure, and density data at high temperatures without wireline runs, extra trips, or temperature mitigation.



REDUCE RESERVOIR UNCERTAINTY

All basins pose their own unique challenges—
at Weatherford, we have the people and the
technology to help you drill, evaluate and
complete your wells.

WEATHERFORD.COM/LOGGINGWHILEDRILLING

CONNECT WITH WEATHERFORD



© 2018 Weatherford. All rights reserved. 12782.00