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RECENT DEVELOPMENTS AND EMERGING TECHNOLOGY IN WELL LOGGING AND FORMATION EVALUATION -- WITH A SELECTED BIBLIOGRAPHY

by

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SUMMARY

Recent and near-term (1-3 years) developments in logging and formation evaluation consist primarily of evolutionary improvements in current technology. The current economics of the petroleum industry, expressed as a need for ever more cost-effective technology, combined with the need to evaluate thin-bed and non-conventional reservoirs serve as both the controlling factor and driving force respectively, in developing new logging technology. These developments include:

1. *Advances in wireline technology*
   - Improvements in downhole microprocessor-based technology and high-speed digital telemetry over conventional 7-conductor cable; makes possible (a) the use of high data-rate array and imaging tools, and (b) increased combinability of different tool types and can result in reduced rig time for logging.
   - Concurrent improvements in computer processing . New visualization and interpretation techniques have been introduced to facilitate the interpretation of these massive amounts of data.
   - The introduction of array-type tools that acquire (a) multiple independent measurements of electrical and acoustic parameters at different vertical resolutions and depths of investigation, (b) the complex parts of conductivity, and (c) shear-wave dipole components.
   - Improvements in acoustic and electric borehole imaging.
   - Development of (a) induction- and laterolog-array devices for improved thin-bed analysis and saturation imaging, (b) through-casing resistivity tools, (c) pulsed nuclear magnetic logging (NML) tools, (d) development of magnetic logging for geologic correlation and age dating.
   - Introduction of (a) neutron accelerators in neutron-porosity devices, (b) high-density gamma-ray detectors in spectroscopic logs, e.g. C/O tools, (c) increased use of neutron-activation logging, (d) improved elemental-analysis (geochemical) logging, (e) new developments in tracer logging and directional gamma-ray devices for evaluation of well stimulation.
   - Enhanced vertical resolution of traditional logging devices through new computer processing techniques.
   - Improvements in borehole gravity meters.
   - Development of wireline new formationtestersand extensometers for obtaining formation in-situ stress, modified DSTs, determining vertical and horizontal permeability, and recovering fluid samples.

2. *MWD (measurement while drilling) and logging horizontal wells*
   - Improvements in current resistivity and nuclear technology and introduction of additional services: (a) multiple depth of investigation resistivity, (b) borehole calipers, and (c) spectral gamma and density tools.

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- Prototype testing of acoustic sensors.
- Development of seismic while drilling
- Increased use of slimhole and coiled-tubing logging technology.

3. *Borehole geophysics*
   - Rapid advances in the theory and practice of acoustic and electric crosswell reflection imaging and tomography. Applications include (a) monitoring changes in fluid saturation during EOR, determinations of (b) reservoir lateral continuity, (c) interwell porosity and permeability, and (d) interwell geologic structure.
   - Development of nearwell acoustic and electrical imaging
   - Introduction of borehole radar systems for characterization of fractures and nearwell imaging.

4. *Surface Logging and Rock Characterization*
   - New techniques that enable accurate determination of formation oil concentrations while drilling, from core, or cuttings and formation gas concentrations while drilling.
   - Development of new techniques and adaptation of wireline techniques for making gamma-ray and acoustic logs at outcrop; advances in coring technology, core imaging, and determination of surface permeability.
   - Use of radial-drilling technology for obtaining full-diameter core, after drilling; development of coil-tubing coring systems; automate analysis of slimhole continuous core.
   - Advances in core imaging techniques; application of image-analysis techniques for core analysis; improved minipermeameter for rapid laboratory determination of surface permeability on core and thin sections.

INTRODUCTION

The purpose of this paper is to provide a broad overview of recent and emerging developments and trends in well-logging and formation-evaluation technology. It is my intention to discuss these developments in general terms rather than the specifics of tool design or comparison of the different versions offered by the logging service companies Several less familiar subjects are discussed in greater depth to provide background for the general reader. For additional information and details, readers are referred to the original technical papers cited in the bibliography.

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WIRELINE DATA TELEMETRY

A combination of new digital signal-processing microprocessors and existing techniques (e.g. use of adaptive digital filters) has produced a change from cable telemetry to digital telemetry. The resulting increase data capacity of conventional 7-conductor wireline, from 80 to 660 Kbits/sec , has , in turn, enabled the development of the current generation of array and imaging tools which have data rates one order of magnitude greater than the previous generation (see Figure 1). Systems capable of 700-1,000 Kbits/sec are on the horizon. The near-term (1-3 years) emphasis on expanding telemetry systems will be on the use of data-compression techniques to achieve data rates exceeding 5 Mbits/sec over 7-conductor wireline. Fiber-optic cable, capable of data rates above 10 Mbits/sec, has been developed but has been limited to use with downhole television (which requires the large bandwidth), in part because of cost and operational considerations.

ACOUSTIC LOGGING

Recent developments in acoustic logging are largely driven by the need to evaluate fractured reservoirs (low-permeability chalks, shales, and sandstones) and for improved seismic calibration. Developments in technology fall into two general classes, (a) transmission (full-waveform data) and (b) reflection (pulse-echo) imaging .

Full-waveform acoustic data consist of compressional, shear, and tube (Stoneley) waves. Table 1 summarizes well-log applications that use different components and attributes of the acoustic waveform.

Recent developments include:

1. **Tool design** - Improvements in (a) full-waveform tools (an array-type tool that can be used in open and cased holes), (b) ultrasonic pulse-echo tools (borehole-televiewer type) that measure acoustic reflectivity (time and amplitude) of the open borehole or the inside of casing, or cement outside of casing . These devices also have application to (a) borehole imaging (see below), (b) as borehole calipers, (c) dipmeters (in electrically non-conductive oil-based mud), (d) determination of cement bond (problems with channeling), and (e) evaluation of casing wear and corrosion..

2. **Dipole (and multipole) measurements** - Acquisition of the polarized components of the shear-wave velocity (shear-wave dipole tools) for improved measurement shear-wave data in a broader range of formations, particularly in soft formations, and also in hard formations, in both open and cased holes.

3. **Fractures** - Acquisition of new laboratory and field experience in the application of full-waveform data (shear, tube wave) to fracture identification and analysis.

4. **Well completion** - Use of full-waveform data for (a) full-borehole coverage in cement-bond evaluation, (b) measuring depth of perforating penetration and, (c) analyzing hydraulic fracture height (in combination with density and/or nuclear spectrometry tools).

5. **Wellbore resonance** - A technique to enhance otherwise weak acoustic signals in open and cased holes and for generating Q logs (a measure of seismic damping related to lithology) used in seismic modeling and formation evaluation.

6. **Downhole seismic** - Improved tools that produce better VSPs which are needed for improving the calibration of synthetic seismograms to surface seismic data.

7. **Behind-pipe flow** - Evaluation of "active listening", stationary time-lapse measurements of acoustic ampltiude and phase for detecting and measuring flow velocity behind casing. May offer an alternative to nuclear- activation logging.

ELECTROMAGNETIC LOGGING

The need for improved invasion profiles and better vertical resolutions for thin-bed analysis have served as the guiding factors in new technology. Recent developments include:

1. **Measurement** - Improved accuracy of measurement of basic parameters; improved processing.

2. **Vertical resolution** - Improved radial and vertical resolution through use of array-type tools. Induction-, laterolog- (both focused and unfocused (Shell MERT)). These tools use multiple coil spacings, multiple frequencies, and multiple receivers for obtaining independent measurements with different vertical resolutions and depths of investigations. The vertical resolution of induction array tools is 1 ft, and the focused laterolog, 8 in. A pad-mounted deep laterolog device has a vertical resolution of 2 in.

   Both the in-phase (R) and quadrature (X) components of the electromagnetic signal can be obtained. This results in more accurate determination of radial depths of investigation and these data can be used for imaging fluid saturations (e.g. invasion profiles) around the borehole. Microresistivity array tools (multipad, multielectrode, multifrequency) devices are in use for evaluating casing corrosion (cathodic protection) and casing wear (through measurement of casing thickness). Macro-array data can be combined with micro-array (borehole imaging) data for improved representation of resistivity in and around the borehole.

   Improvements in high-resolution dipmeters include increasing the number of arms from 4 to 6 and calibrating the resistivity measurements to permit quantitative use of the data (previously on qualitative in nature); data can be used for creating resistivity maps (images); microresistivity standard dipmeter data can be extracted from microresistivity imaging-tool data.

3. **Nuclear magnetic logging** - First available in the late 1960s and 1970s, a second generation of tools is now available. These tools use pulsed (spin-echo) NMR technology to measure free-fluid index and spin-lattice relaxation times. These values are related to pore sizes and hydrogen content, and can be used for quantitative determinations of lithology-independent porosity, permeability, effective bed thickness, irreducible water saturation (water-cut), and movable hydrocarbons. Doping the drilling mud to eliminate the influence of borehole fluid is no longer required.

4. **Cased-hole resistivity logging -** Casing conductivity is 7 orders of magnitude greater than formation conductivity and the problem is to measure current leakage off the casing into the formation. Prototype tools are in development and testing and early results agree with openhole laterolog-3 measurements. Potential applications are in (a) MWD, (b) evaluating old wells for by-passed pay, and (c) monitoring production and flooding.

5. **Borehole magnetometer -** There has been much interest recently in applying these tools, commonly used for ore mineral exploration in crystalline rocks, in sedimentary and petroleum environments. These tools provide a continuous log of magnetic susceptibility, a measure of the iron minerals present in the rock. Magnetic minerals can be products of various diagenetic and alteration processes and their presence can be used to infer depositional environment. Also, magnetic susceptibility can be use for determining the natural remnant magnetization polarity, a means of stratigraphic dating. Applications in sedimentary rocks include (a) lithostratigraphic correlation, (b) formation age dating through magnetostratigraphy, (c) examination of formation alteration (diagenesis), and (d) analysis of depositional environments.

BOREHOLE IMAGING

Borehole-imaging devices, both acoustic and electrical, provide a partial or full image (map) of the borehole wall or casing. The acoustic-imaging devices use a rotating, focused ultrasonic transducer (borehole-televiewer-type devices) to measure reflectivity times and amplitude of the pulse-echo from the borehole wall or from inside the casing . While these devices are not affected by the type of borehole fluid they are not used in high-weight mud because of signal attenuation. Electrical-imaging devices evolved from dipmeter design and use pad-mounted microelectrical arrays and are limited to holes with conductive mud. A doubling of sensor pads and an increase in the number of sensors from 64 to 192 has doubled the effective borehole coverage. The application of 2-D and 3-D computer visualization techniques are applied to both electric and acoustic imaging data for enhanced interpretation.

The very fine resolution (0.2-in. vertical resolution) of these tools makes them extremely valuable for obtaining positive identification and analysis of (a) natural and induced fractures, (b) borehole breakouts, (c) thin beds, (d) geologic structure (strike, dip, faults) in ,and near the borehole, (e) improved core orientation and core-log correlation, (f) sedimentary features and interpretation of depositional environment, (g) for casing inspection (corrosion, wear, or damage), (h) use as borehole calipers.

NEARWELL AND CROSSWELL REFLECTION IMAGING AND TOMOGRAPHY

Rapid advances have been made in both the technology and processing used for nearwell and crosswell imaging and many field-tests are in progress. While these geophysical methods are related to surface-seismic reflection imaging, the receivers and sources (electrical or acoustic) are placed in the boreholes of adjacent wells. Borehole techniques provide a wider viewing angle than surface techniques as well as higher resolution since the highly attenuating surface layer is avoided. Pseudo-logs derived from tomograms correlates with wireline acoustic logs. Applications include (a) improved reservoir characterization, (b) monitoring fluid movement in producing fields, and (c) to aid in the remediation of underground contamination.

Electrical or seismic sources and receivers are placed along the borehole in adjacent wells and a seismic signal or low-frequency electrical current is recorded by each receiver/electrode in each well. Displacement of formation fluids and changes in temperature produce changes in reservoir rock properties (saturation, resistivity, pressure, and velocity) that are detectable by both electrical and acoustic (seismic) methods. The resulting data are processed into images and tomograms that can be used for visualizing fixed or time-lapse sequences of fluid movement. In order to monitor the progress of EOR flooding (water, miscible, and thermal), it is necessary to know the vertical and horizontal distribution of flood fronts between wells that may be hundreds of feet apart. Well logs, even the newest generation of array tools (both electrical and acoustic) can image formations only a few feet away from the borehole. Electrical resistivity tomography is being explored as a means for detecting and evaluating underground contamination within the vadose zone.

The effective distance for these techniques is dependent on the source strength and is generally less than 2000 ft. Vertical resolution can be several feet. Cross-well continuity logging is a specialized form of crosswell seismography that can be used for determining lateral reservoir continuity between wells. Geologic structure and stratigraphic heterogeneity can also be imaged with these techniques.

Borehole radar - A developing form of crosswell imaging, different versions of borehole radar systems (an electromagnetic method) are available or currently under development. The vertical resolution of the currently available system ranges from 3 to 10 ft and has range of investigation (depending on operating mode) from 300 to 1000 ft in crystalline rock. In sedimentary rocks, the investigation range is lower because the presence of pore fluids results in signal attenuation. The receiving antenna registers the electromagnetic pulse as a function of time which allows the system to operate in single-well or crosswell reflection mode and crosswell tomography mode. Current applications include (a) characterization of fractures, and (b) obtaining quantitative values of dielectric permeability and conductivity.

NUCLEAR TOOLS

Recent developments in nuclear logging (open and cased hole) have been largely evolutionary, i.e. incremental improvements in current technology and processing. More of the newer tools use spectral measuring systems rather than discrete windows. Significant advances include:

1. **Pulsed-neutron logging**

   Neutron porosity tool- A high-energy neutron accelerator (previously used in pulsed-neutron-capture (PNC, decay-time) and C/O tools) has been used in place of a radioactive source in a new dual-neutron (epithermal and thermal) tool. This change provides (a) a more accurate measurement, (b) a higher vertical resolution, and (c) operation in a pulsed mode to obtain thermal- and epithermal-neutron porosity and neutron slowing-down time. These data can be used to derive the capture cross section (sigma).

   Improved detectors - (a) Use of higher-density materials , i.e., bismuth germinate (BGO), gadolinium oxyorthosilicate (GSO), in scintillation detectors in place of NaI (sodium iodide). in gamma-ray induced-spectrometry tools (PNC and C/O). The denser material results in a doubling of detector efficiency which can be translated into improved precision at previous logging speeds (1-2 ft/min) or a doubling of logging speed (approximately 5 ft/min) or a reduction in detector size to achieve statistics similar to previous tools. (b) A C/O tool using a cryogenically cooled germanium direct detector has recorded two 4,000-channel spectra, versus the standard 256-channel currently recorded. However, the expense of the germanium crystals and the electronic hardware combined with the operational limitations (hole-size limitations - the bulky Dewar-type enclosure needed to maintain critical temperature results in only larger-diameter tools; logging-speed limitations - although germanium has a high-resolution than scintillation detectors, its lower intrinsic efficiency means more time is needed to obtain usable statistics) and the perception in the petroleum industry that elemental measurements of minor and trace elements are of little value has so far limited this device to a few experimental and research wells and prevented commercial development. (c) Use of lithium-6 glass scintillation detectors in place of helium-3 in MWD neutron sensors to meet the needs for robust measurement in a rugged environment.

2. **Spectral logging**

   Carbon/Oxygen logging - New tools that use the higher-density detectors for improved measurements of behind-casing fluid saturations, e.g., residual-oil saturation and monitoring reservoir flooding (water, miscible, and thermal), and that permit faster logging speeds (approximately 5 ft/min). One version is a small-diameter, dual-detector (for borehole compensation) through-tubing tool that can make continuous measurements in flowing wells.

   Elemental analysis (geochemical) logging - In geochemical logging, natural and induced-gamma spectrometry methods are used to measure elemental abundances. These values are transformed into mineralogical concentrations using a rock model and these in turn, are related to grain size, porosity, permeability, and cation exchange capacity for improved rock and clay typing. The new C/O tools are being used to obtain relative concentrations of 7 elements. A new version of the current multisonde device that measures 10 elements (generally run in openhole to avoid complications introduced by casing and cement) is in field testing. This new tool will be smaller and provide generally improved statistical precision at twice the previous logging speed.

   Neutron-activation logging - The need to detect flow behind casing in producing wells and recent requirements by EPA to confirm mechanical testing of hydraulic well integrity (zonal isolation) in injection wells, has generated renewed interest in neutron-activation techniques first developed in the late 1960s. A burst (pulse) of high-energy neutrons activates oxygen nuclei (occurring primarily in water both inside and outside of casing). Variation in the predictable exponential decay of thermal neutrons (measured by emitted gamma rays) indicates water movement (e.g., in cement channels, or tubing annulus). This is a stationary measurement that can determine both the volume and velocity of fluid movement. New methods and modified PNC (TDT-type) tools, permit (a) direct detection of water movement (oxygen activation), and (b) a new application, evaluation of gravel-pack quality (silicon activation).

Tracer logging - Well stimulation materials tagged with different radioisotopes are detected by natural spectrometry (KUT-type) tools with high spectral resolution. The depth, height, radial, and azimuthal distribution of hydraulically induced fractures can be determined and the effectiveness of well stimulation projects can be evaluated. The addition of a directional gamma-ray device allows determination of fracture-plane orientation.

MEASUREMENT-WHILE-DRILLING LOGGING

Although there is increased drilling of horizontal wells, advancements in MWD technology have been largely incremental (improvements to existing technology). Acoustic sondes eagerly awaited by industry, are currently in prototype development and testing. Recent developments include:

1. **Electrical devices** - (a) Use of electromagnetic phase shift as an MWD caliper, (b) an increased number of measurements from 2 to 4 (phase shift and amplitude) to provide additional independent depths of investigation. Data presentation for these tools is similar to a dual-induction log.

2. **Nuclear devices** - Improvements to current measurements (gamma-ray, density, neutron porosity, and spectral gamma-ray and spectral density)

3. **Acoustic devices** - Introduction of ultrasonic pulse-echo caliper devices; other acoustic devices are in field-test phase.

4. **Electronics and telemetry**- improved microprocessors for storing data and increased rates of data transmission. Locating sensors closer to, or immediately behind the bit, provides better "real-time" data needed for (a) drill-bit guidance ("geosteering") used to optimize drilling, particularly in horizontal wells, and (b) detection of overpressuring, and (c) for formation analysis before invasion. Research on high data-rate tools for improved vertical resolution at typical rates of bit penetration, is in progress.

The general feeling in industry is that MWD has matured to where it can replace conventional wireline logging in many situations, both in exploratory and production wells and the introduction of acoustic devices will further secure the role of MWD.

SLIMHOLE AND COILED-TUBING LOGGING

During the past few years, there have been significant improvements in slimhole-drilling technology. Because of the large reductions in cost that may result from using slimhole drilling (up to 50 percent, in some cases), particularly in exploration drilling and especially in high-cost remote locations, there has been great interest in this technology. There are presently four methods of drilling slimhole wells (a) rotary, (b) continuous coring, (c) downhole-motor drilling with drill rods, and (d) drilling with coiled tubing. Wells depths exceeding 12,000 ft have been achieved with these methods. Concurrent improvements in MWD and coiled-tubing logging have resulted in the development of a new class of logging methods and slimhole tools. Many of the recent developments in logging technology that discussed elsewhere in this paper, have been adapted for use in slimhole conditions.

BOREHOLE GRAVITY LOGGING

A new tool design provides improved vertical resolution. A movable gravity sensor can be vertically adjusted within the sonde, while on station, to obtain readings with a resolution up to 1 mm. Previously the vertical resolution was limited to 10 ft, due to depth uncertainty resulting from cable stretch (a 1 in. error in 10 ft creates an uncertainty of 0.012 g/cm^3 in the density measurement). This wireline device measures the vertical component of the acceleration due to gravity with extreme accuracy thereby enabling direct determination of formation bulk density and porosity. Using a large station interval makes the borehole gravimeter an excellent tool for measuring density in very rugose (especially karstic carbonates) and cased hole, conditions where standard wireline open- and cased-hole porosity logs, that have very shallow depths of investigations, were limited. Advantages of using a large measurement spacing are (a) a very large radius of investigation that results in an average density value for a more representative volume of formation than other logging devices, and (b) tool insensitivity to hole size, washout and rugosity, number and size of casing strings, mudcake, mud invasion, cement, acidization effects, and lithology. Additional applications include (a) use old cased wells where no density or saturation log data are available, (b) for determining gas saturation and monitoring saturation changes during field production. If a baseline survey is made prior to, or at the beginning of production, time-lapse measurements (log-produce-log method) can be used for analyzing changes in residual oil saturation.

WIRELINE FORMATION TESTING

New wireline formation testing tools using a modular-design have been introduced. These toolscan be configured to meet different operational needs, e.g., bottomhole testing, single- or multiple-probe testing, and use of multiple sampling chambers. In a multiprobe configuration, direct in-situ determination of both vertical and horizontal permeability can be made (unlike a single-probe device) and over a larger range of permeabilities. Other improvements include (a) new sensors that provide more accurate measurements in less time reducing the time needed for each test, (b) improved real-time surface control that allows for point-by-point pressure tests which can be used to determine gas, oil, and water contacts, (c) ability to pump formation fluid for an extended period of time until a representative reservoir fluid sample is obtained (as measured by a flow-line resistivity device). A new downhole extensometer uses 12 caliper arms to measure borehle delections before, during, and after fractuing to determine in-situ stress and formation properties.

SURFACE FORMATION EVALUATION AND ROCK CHARACTERIZATION

Recent developments can be classified by methods related to evaluation of outcrop and of core:

Surface logging (mud logging) - New technique determine oil and gas concentrations while drilling, from core or cuttings, providing an accurate means of direct, quantitative identification of oil and gas zones at the surface. A portable fluorometer is used to measure intensity of oil fluorescence in samples. Plots of oil intensity versus depth (oil-concentration profiles) can be used to identify missed oil zones, verifying log analysis, select DST intervals, and to identify source rocks. A new continuous gas-extraction device enables a determination of formation gas while drilling that is more accurate than determinations from either wireline or MWD.

Hand-held techniques and outcrop evaluation

1. <u>Gamma-ray logging of outcrops</u> - The novel use of truck-mounted wireline tools for obtaining continuous gamma-ray logs of formation outcrops provide (a) correlation with subsurface (wireline and MWD) logs, (b) improved interpretation of these logs, and (c) determination lateral continuity of reservoir rocks.

2. Hand-held velocity probe - Used to obtain rapid measurements of ultrasonic velocity on outcrop, core, and hand samples. The data can be used for porosity determination, correlation with wireline acoustic data, calibration of downhole data, estimation of rock mechanical properties. Smoothed data show good correlation with wireline data.

3. Hand-held minipermeameter - Development of a portable, hand-held mechanical minipermeameter for rapid, in-situ determination of surface permeability at outcrop or on core. This equipment is capable of making 400-500 measurements per day.

Coring and core imaging

1. Core acquisition and analysis - (a) Improvements in mechanically drilled sidewall core plugs. (b) Development of sidetrack coring--the use of radial-drilling technology--to obtain full-diameter sidewall cores up to 50 ft in length, *after* completion of drilling and logging. This results in less rig time and better targeting of desired intervals and the larger samples can provide more representative reservoir analyses. (c) Development of techniques for core acquisition in horizontal wells, including coiled-tubing coring systems. (e) Slimhole coring system s and rapid analysis of continuous core ("inverse logging").

2. Core imaging techniques- Development of new techniques for non-destructive determination of fluid saturations, pore distribution, and petrophysical properties (porosity, relative permeability, capillary pressure), mineral distributions, and depositional textures. These techniques include improvements in (a) X-ray computer tomography (CT scanning), and (b) nuclear magnetic resonance, and a new technique (c) thermal neutron imaging. New electrical imaging techniques and acoustic techniques compliment and calibrate data obtained from wireline logs (electric imaging and full-waveform acoustic logs).

3. Petrographic image analysis - Rapid, automated, quantitative analysis of images obtained by the techniques described above, and by convention SEM (backscattering electron) techniques for rock characterization of core, cuttings, and thin sections. The analyses are used in determination of (a) mineralogy, (b) grain textures (shape and size), (c) pore structure and distribution, (d) very high-resolution sand-shale ratios in thin beds, and (e) log-core calibration.

4. Surface permeability - Introduction of a new probe minipermeameter, that uses an unsteady-state pressure-decay method to obtain rapid and more accurate measurements of surface permeability on core and thin sections.

ENHANCED VERTICAL RESOLUTION AND THIN-BED EVALUATION

Recent exploration and reservoir characterization efforts have concentrated on thin-bed, laminated reservoirs (both clastic and complex lithologies) where vertical resolutions of less than 1 ft, and preferably on the centimeter scale, are necessary for accurate evaluation. Newer tools, e.g., array-type induction and laterolog, can measure data at this scale and still provide invasion profiles; existing dipmeters and borehole imaging devices can resolve beds down to the millimeter range. Concurrent with development of these new tool designs have been efforts to enhance the vertical resolution of older nuclear and resistivity tools as well as old data, through new computer processing techniques. Recent developments include new processing techniques for enhanced tool resolution and for thin-bed analysis.

OUTLOOK

The economics and resulting restructuring of the petroleum industry, in general, over the past seven years and the continuing unsettled state of the U.S. domestic industry, in particular, have and will continue to exert a chilling effect on the development of new logging technology. Near-term and future advances will continue to be largely incremental, i.e., evolutionary rather than revolutionary.

1. **Factors affecting future developments in logging technology.**

   (a) Virtually all the major producers have eliminated their in-house research efforts in logging technology. These groups played a major influence in the development of new technology during the past 40 years. Table 2 lists some of the significant advances in well-logging technology generated by these groups.

   (b) There is now a heavy, almost total, reliance on the logging service companies to generate new hardware and software technology. Since development costs are extremely high and the payoff increasingly uncertain in the current economic climate, these companies have sought to spread the risk by developing joint research efforts and partnerships with operating companies. The operators in turn, have a vital interest in exerting an influence on the direction and pace of development of new technology. It is likely that economics, not the needs of reservoir geoscientists will play the primary role in determining what technology is developed.

   (c) Because of the high costs of running the latest technology and the unwillingness or inability of operators to pay the price, especially since many remain unconvinced of the cost/benefits, service companies are offering tiered service to avoid pricing themselves out of the domestic market: customers can choose to run just a basic suite of logs using the older technology or the newer, advanced services. This serves to inhibit the acceptance dissemination of new technology throughout industry. The latest generation of tools may not become the next de facto industry standard.

   (d) Many recent developments are the end-product of a development process initiated 5 to 10 years earlier. Because of the cash-flow crises of the past seven years, many promising research and development efforts were canceled (this is apparent in the reduced offerings in new technology by some companies in the past few years).

2. **Data interpretation and application lag data acquisition.** Future advances will be weighted towards the interpretation side: development of user-friendly software that not only integrates all forms of log data but includes advanced new interpretation techniques.

3. **Education on advanced technology needed.** To avoid having tools viewed as optional luxuries, the users of logging technology, from the geologist/engineer up through managers, must be better informed of the benefits derived from all logging devices and especially the more recent "exotic" tools. There must be a fundamental shift away from viewing logging data only in the context of fluid saturations. This process should start at the advanced college undergraduate and university graduate levels in both geology and engineering courses. Emphasis should be placed on developing integrated models for use in exploration and reservoir management using data and information derived from the entire range of logging devices, especially the latest and most advanced technology. Logging service companies who once provided seminars for college faculty, must become re-involved, as a matter of self interest, since the knowledgeable student now, may become tomorrow's customer of advanced technology.

4. **Return of the generalist.** The current climate, where cost-effective operation is foremost, places a high degree of reliance on the integration of geology, geophysics, petrophysics, engineering and on computer processing to effect this integration. The geologist, geophysicist, or engineer necessarily becomes a data generalist. There is a concern that a future lack of specialists who are able to apply the advanced processing and interpretation techniques needed to get the most out of the advanced tools may inhibit the acceptance and wider use of new technology by many companies.

5. **New markets for well-logging and formation technology.** Environmental assessment and remediation is a promising new market for developing logging technology.

Table 1. Acoustic-Wave Propagation and Summary of Well-Logging Applications

Property	Wave component (velocity and amplitude)	Application
Transmission		array tools used in open and cased hole
	full waveform	seismic calibration and VSP near-borehole and crosswell imaging (offwell structure; fracture ID; flood monitoring) cement-bond evaluation
	compressional wave	porosity and lithology (delta t) hydrocarbon content geopressure detection cement-bond evaluation calibrate surface seismic synthetic seismic
	shear wave	mechanical properties fracture detection and evaluation permeability determination shear/compressional ratio for lithology determination and gas detection
	tube (Stoneley) wave	permeability determination crosswell imaging and lateral continuity fracture characterization
Property	**Wave attribute**	**Application**
Reflection (ultrasonic pulse-echo)		for use in open- and cased hole (a) fixed transducers (helical arrays) (b) rotating transducer (BHTV-type)
	velocity	borehole imaging caliper for borehole and casing ID (casing wear and scale buildup)
	amplitude	imaging borehole detection and orientation of vugs and fractures (shear) sedimentology cement-bond evaluation casing evaluation
	resonant frequency	casing thickness (indirectly, OD, corrosion)
	time-lapse (amplitude and phase)	"active listening" for detecting and measuring flow velocity behind casing (stationary measurement)

Table 2. Significant advances in logging technology developed by major E&P research labs

Decade	Device	Company
1950s	Acoustic log Nuclear magnetism log (NML) Borehole gravity meter (BHGM) Dielectric tool	Mobil; Shell Chevron Shell Shell
1960s	BHGM Borehole televiewer (BHTV) Ultra-long spaced electric log (ULSEL) Compensated neutron log (CNL) Carbon/oxygen log (C/O)	Exxon Mobil Chevron Mobil Exxon
1970s	Dielectric Natural gamma-ray spectral log	Texaco Exxon
1980s	Long-space and shear-wave acoustic logs (LSAL/SWAL) Circumferential acoustice log (CAD) High-resolution induced polarization log Pulsed-neutron porosity log (PNP) Rotary sidewall tool	Mobil Shell Shell Mobil Amoco
1990s	Multiple-electrode resistivity tool (MERT)	Shell

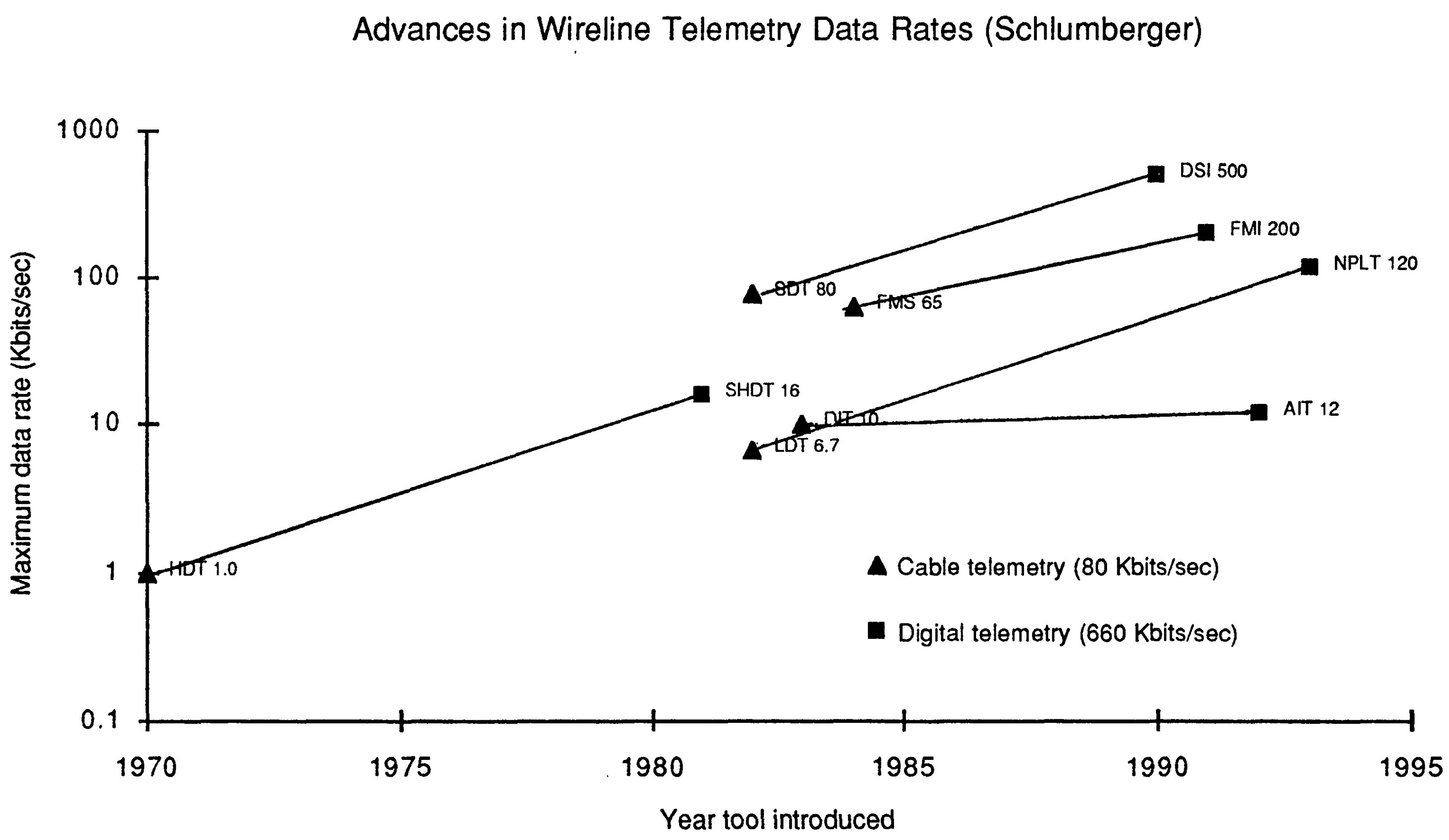

Figure 1. Telemetry rates for selected Schlumberger tools showing the increase in data rates between previous generation of cable systems and the current generation of digital systems (data courtesy of Steve Kush, Schlumberger). HDT, High Resolution Dipmeter; SHDT, Stratigraphic High Resolution Dipmeter; FMS, Formation MicroScanner; FMI, Formation MicroImager; SDT, Ditigal Sonic Tool; DSI, Digital Sonic Imager; LDT, Lithodensity Tool; NPLT, Neutron Porosity Logging Tool; DIT, Digital Induction Tool; AIT, Array Induction Tool.

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