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ADVANTAGES AND DISADVANTAGES OF ACOUSTIC LOGGING. TRENDS OF THEORY AND PRACTICE IN THE NEAR FUTURE

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Digital technology significantly extended acoustic logging capabilities. Separate recording of basic information waves such as longitudinal and shear (head) waves propagating in the rock in case of open and cased holes, Lamb waves in borehole liquid and casing, Stoneley waves became practically achievable. At the same time, the theory of generalized waves formation and propagation that dominates in acoustic logging proves that most problems cannot be solved. Well logging with variable length sondes that give – without operator's intervention - hodographs of waves recordable in a complex wave train, suggests that the generalized waves do not exist. New results in well logging and mathematical modeling confirm that the dominating theory is waning and should be changed. This would expand the list of geologic and technical problems solvable by acoustic logging.

Digital recording of raw acoustic logs and their multi-variant digital processing considerably expanded the capabilities of the method for solving geologic and technical problems. The existing digital data processing programs can extract information-reach waves (such as longitudinal P- and shear S- head waves, Lamb L-waves and Stoneley St-waves) from a complex signal recorded. Researchers begin to achieve success in using parameters (such as propagation velocity v, amplitude A, effective attenuation á) of these waves in order to evaluate (in case of open or cased hole) elastic properties of the rock, mineral composition, capacity and current hydrocarbon saturation of reservoirs, detect permeable intervals in complex-structure shaly or compacted sections. In cased holes they are also used in order to evaluate casing string cementing quality, which means to evaluate what portion of the annular space is filled up with the cement stone and how strong the latter adheres to the casing string and rock.

The theory of formation and propagation of generalized waves (including head ones) in complex media where each layer thickness is less than the wave length predominates in the current (Russian) field acoustic logging [1,2, etc.]. In the cased hole this wave propagates in the system of media such as "casing – cement stone - rock" or "casing – cement stone". The propagation velocity of this wave is to change from its rock value to its casing one [2, p.153]. In the open hole the generalized wave can be represented by a "Lamb-Stoneley wave" with its velocity monotonously changing from surface (?) Lamb wave velocity to Stoneley (also surface) one [2, p.144]. In wave physics they call Lamb waves (there are two ones: symmetric and asymmetric) normal waves which propagate in a single medium limited relative to the wave length [3], and this medium (with certain provisos) can be called a waveguide.

The dominating theoretical treatment of principles of acoustic logging excludes the solution of the most of the above geologic and technical problems. In cased holes, it denies an opportunity to record rock velocities of P- and S- (head) waves (v_p and v_s respectively) through the casing string and cement annulus, as if the latter distort the results. There also exists even more radical opinion that one can record a P-wave only when v_p exceeds wave velocity in the casing [4, p.343]. From the point of view of the existing theory, both Russian and foreign companies, when solving problems of cementology, over fifty years record wave amplitudes and attenuation along casing in the fixed time window (Ät = 184-185 mcs/m or 57 mcs/foot) *incorrectly*, without paying due attention to the changing velocity of the generalized wave.

An objective information about the parameters of the elastic waves propagating in and around the hole can be presented by wave hodographs constructed without any operator's intervention (see Figure). They can be obtained, for example, with the help of a changeable length measurement sondes tool [5]. The tool completely reproduces the geometry of acoustic logging; when it stops in the hole, there starts a movement of an elastic oscillation receiver (in a vinyl plastic tube); it is excited by two transmitters with a spacing of 0.4 to 0.5 m between them. The minimum distance between the receiver and near transmitter is 0.35 m (it is caused by the tool's design philosophy). If the hole is cased with a string of 140 to 168 mm, the minimum sonde length provides recording a wave when starting in the borehole fluid, with first arrivals (see Fig. b, low left-hand corner) as that length is insufficient to form a head P-wave along the column.

Four wave types can be determined in the hodographs of the waves recorded in a cemented casing interval, in a low-velocity section (in this case v_p = 3300 m/s). In the first arrivals it is a longitudinal (head) wave propagating in the casing material (steel). If we consider real relationships of wavelengths at acoustic log frequencies (8 to 40 kHz) and casing thicknesses (7 to 15 mm), this wave can be only normal longitudinal Lamb wave L_c of zero order. In the literature on acoustic cementology such wave is called "a wave along the string". This wave's interval travel time (Ät = 1/v) equals 184 to 185 mcs/m.

The second by its arrival time is a longitudinal (head) wave P_r propagating in the rock. There is no shear head (converted) S_r wave in this example because the ratio v_s / v_f does not favor to formation of a refracted S-wave sliding along the borehole wall. There are no other waves (including a wave along the cement) between the first arrivals of the L_c and P_r waves, which suggests that both the waves do not contribute to generalized waves formation in the "casing – cement - rock" systems, etc.

On the background of P_r wave slowing down, there appear a P_f wave that propagates in the fluid or (which is the same) a L_f (Lamb) wave in fluid. They have the highest frequency in the wave train (however, the theory in force [2, p.145] suggests the opposite). The wave front of the normal zero-order wave in fluid is flat and coincides with the borehole cross-section (strictly speaking, an annular gap between the borehole walls and tool), and the phase velocity is independent of frequency and equal to the wave velocity v_f in bulk. The zero-order wave in fluid is not typical of the waveguide propagation [6], so it slows down with distance soon (see Fig. 1 a). In a higher-velocity section where a shear head wave can form, the L_f time interval is occupied by an intense shear wave.

The last phase lines in Fig. 1 (a, b) belong to an intense low-frequency Stoneley wave that propagates along the fluid – solid (casing or open hole's rock wall) boundary within the limits of the same wavelength in each medium. The propagation velocity of this wave – v_{st} – depends on the properties of the two contact media. If one of them is a fluid and the second is a solid, then $v_{st} < v_f , v_s , v_p$. The wave velocity, amplitude and attenuation depend significantly on rock permeability. In contrast to the dominating theory [2, p.145] the wave parameters do not depend at all on the presence of a hydraulic connection between the rocks and fluid in the borehole. Mathematical modeling did prove [7] that the dynamic change of the stresses near the well (that are approximately one wavelength deep) leads to appearance of a radial component of formation pressure gradient and fluid redistribution near the well. That is, one can evaluate rock permeability from acoustic logs in not only open, but also cased holes. Actually, there are two Stoneley waves traceable on phase-correlation acoustic logs. The parameters of the first (poorly differentiated) wave depend on borehole fluid and casing characteristics. The second wave's lines configuration corresponds to the elastic and reservoir properties of the rock.

The extraction of different wave types from a recorded complex acoustic logging signal and evaluation of the wave parameters allow active using of digital acoustic logs in solving the following new geologic and technical problems:

- evaluation of true P- and S-wave velocities in open and cased holes, evaluation of the mineral composition and capacity of intergranular, fractured and cavernous reservoirs, elastic properties evaluation and acquiring input data for hydrofracs;
- evaluation of reservoirs' current oil and gas saturations using the same parameters;

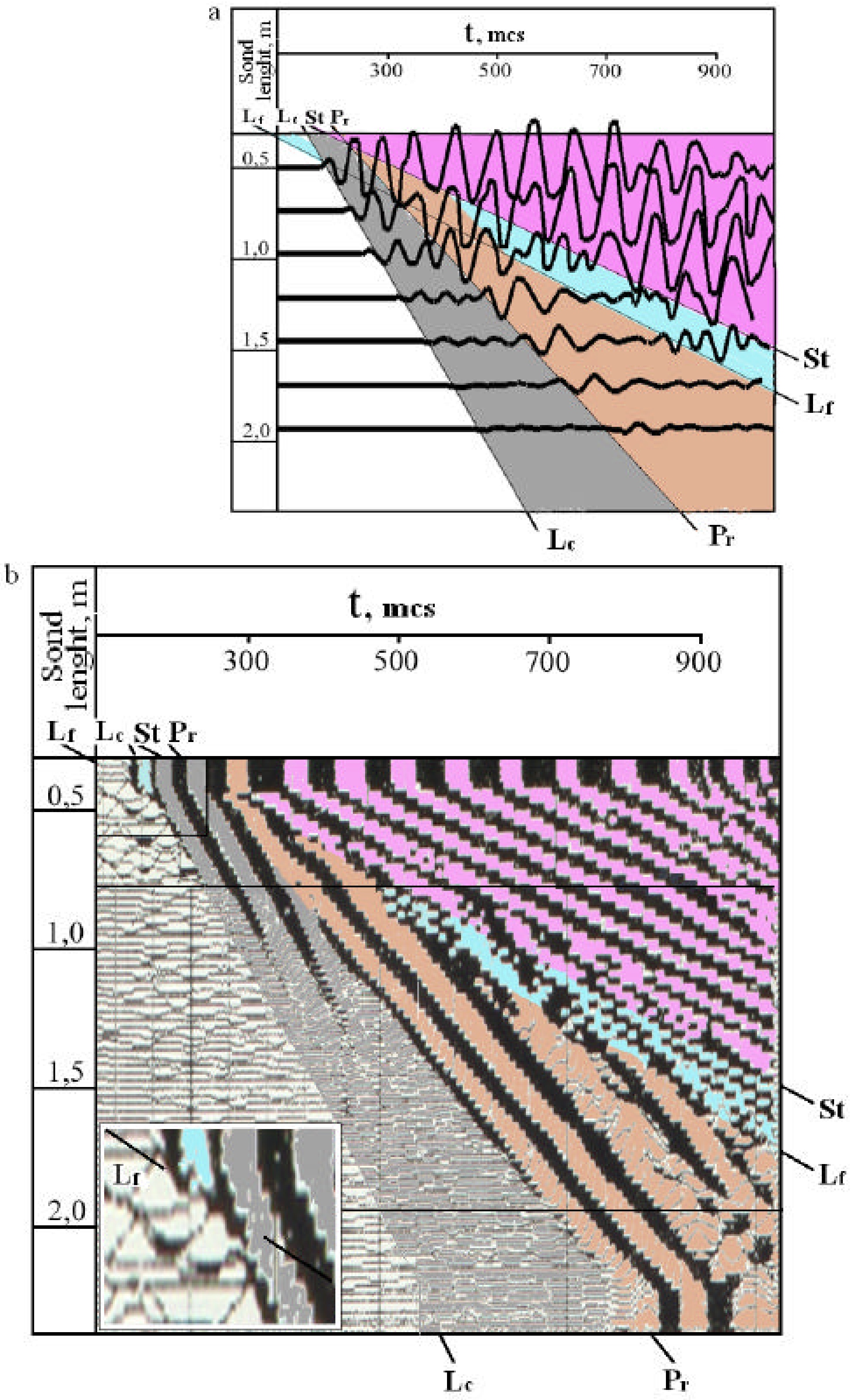

Figure. Wave trains (a) and hodographs (b) of elastic waves determined in cemented interval of a cased well by a variable length measurement sondes tool (raw data provided by V.G.Rafikov).

- detection of permeable differences in complex-structure sections (including cased holes) from Stoneley wave parameters;

- detection of stressed-state rock and casing intervals;
- evaluation of casing cementation quality including grading of “partial setting” intervals using L_c (at different frequencies), P_r , S_r wave parameters;
- detection of unsealed collars and intervals with annular gaps between the casing and cement stone using L_c , P_r , S_r , St wave parameters.

Solving the problems is illustrated with examples. To explain the accompanying effects requires developing a new acoustic logging theory.

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