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Full waveform acoustic logging

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Acoustic logging is the record of acoustic waves transmitted in a borehole between one or more sources and one or more receivers housed in the same logging tool. Full waveform acoustic logging is based on the analysis and processing of the various wave trains (refracted waves, guided waves, reflected waves) recorded by the tool. A geological formation can be simply defined by its acoustic parameters which are P and S velocities (VP and VS), density and Q factors of attenuation (QP and QS). Transmitters and receivers of the acoustic tool being in the borehole, a part of the acoustic energy propagates in the borehole fluid or mud. A geological formation is said a fast formation if the shear velocity (VS) of the formation is higher than the P-wave velocity in the mud (VP fluid). If it is not the case, the geological formation is said a slow formation.

Either monopole or dipole tools are used. Monopole tools are the most used. Transmitters and receivers are multidirectional. In the fluid, transmitters generate a compression wave, which creates in the formation a compression wave (P-wave) and a shear wave (S-wave) at the refraction limit angles. The full waveform acoustic data are composed of several coherent waves and noise. The coherent waves are:

- refracted compression wave.
- refracted shear wave, only in fast formations (VS > VP fluid).
- fluid wave.
- two dispersive guided modes, which are pseudo-Rayleigh waves (in fast formations) and Stoneley waves.
- reflected and converted waves. On constant offset acoustic sections, we can observe coherent slanted events. The slanted events, conventionally named criss-cross events, are refracted events reflected on the edges of geological discontinuities (acoustic impedance discontinuities), such as fractures.

Dipole acoustic tools are used to access the S parameters of slow formations and are equipped with polarized transmitters and receivers. Such tools generate polarized compression waves perpendicular to the borehole axis. These compression waves create flexure modes at the borehole wall that generate pseudo-shear waves in the formation that propagate parallel to the borehole axis.

Full wave field recordings mainly enable the determination of the propagation velocities of the different waves, using specific signal processing techniques such as velocity scan based on semblance criteria or picking of wave arrival times. The picking of wave arrivals can be based on the continuous tracking of a specific phase of wave, considering an acoustic section as a seismic section. The velocity logs, computed from picked arrival times of the different waves, have a higher vertical resolution than the velocity logs obtained by semblance analysis. Furthermore, a correlation coefficient, computed in short time windows for which the start time is given by the arrival picked times of the wave under consideration, allows to evaluate the quality of the picking and to edit the velocity logs. Continuous phase picking can be done by software's developed for the interpretation of seismic sections such as Earth Quick software (Mari, 2020) or by specific algorithms such as artificial intelligent technics. A picking algorithm based on A.I. technics (Mari and Coppens, 1992) gives both a slowness log (the inverse of propagation velocity) and an apparent frequency log for the picked wave, plus error logs which indicate the uncertainty of the measured parameter. In addition, error logs can evidence wave interferences such as criss-cross events fruitfully used for fracture detection (Gaudiani and Mari, 1993). The borehole may be an open hole, a cased hole (steel and/or PVC), or a cemented cased hole. In the latter type, acoustic logging is used to monitor the borehole cementation.

Acoustic logging has a vertical resolution of a few centimeters, and a lateral one of centimeters for interface modes (Stoneley waves), decimeters up to a meter for retracted modes, and up to ten meters for reflected modes. It provides detailed information of a borehole as a function of depth, in terms of acoustic wave velocities and rock petrophysical characteristics.

Stoneley waves are very useful in studying slow formations and fractured media in open hole. Stoneley waves can be used for the determination of slow-formation shear velocity and for the identification and characterization of fractures. The shear velocity estimate is based on the analysis of the dispersion curve of Stoneley modes, without a priori knowledge of the geological formation. The attenuation of Stoneley modes is used to determine a fracturation index. In a paper entitled "Geological formation characterization by Stoneley waves" (Mari, Delay, Gaudiani and Arens, 1997), both synthetic and field-data applications are presented and successfully compared with core analysis and well tests. In a first example, Stoneley waves are used to compute a Poisson's ratio log which reveals unconsolidated zones and the presence of gas in a reservoir. In a second example, Stoneley waves are used to a fractured medium and to identify potentially flowing structures.

The acoustic refracted waves can be analyzed using the intercept time method. The method gives the slowness of the refractor (geological formation) and the delay time at the source and receiver positions. The delay times are related to the thickness and velocity of the borehole altered zone. Examples of slowness and delay logs derived from acoustic data recorded in both a sandstone reservoir and a carbonate reservoir show that the delays are borehole consistent and correlated to the geology (Coppens and Mari, 1995). On a first example of a reservoir consisting of shale and sandstone, the delay time increases in shaly zones. In the sandstone porous zones, the increase of the delay time is related to the presence of unconsolidated sands. A second example is a carbonate reservoir consisting of dolomite with a few limestone layers. In this reservoir, the delay time increases are related to fissured or fractured zones and, the comparison of the porosity and of the altered zone extension can help to discriminate the zones of secondary porosity from fissured zones.

After wave separation (Gavin and Mari, 1992 and 1994), the processing of the reflected modes can provide an image comparable to a time micro seismic section which, in favorable cases such as near horizontal boreholes (Mari, Gavin and Coppens, 1994), allows the tracking of layer boundaries and an estimation of their dip (Gavin and Mari, 1992 and 1994).

In a paper entitled "Characterization of geological formations by physical parameters obtained through full waveform acoustic logging (Mari, Gaudiani and Delay,2011), it is shown through a field example that full wave form acoustic logging allows a quantitative evaluation of geological formations. For that purpose, conventional logs, and their associated standard deviation (Std) must be computed (formation velocities, amplitudes, frequencies, etc.) since the Std is used to estimate the uncertainties associated with the log and to edit other logs. The missing values are then reconstructed by geostatistical interpolation (ordinary kriging and co-kriging). The shear velocity and density of the formation are also estimated to obtain mechanical parameters such as Poisson's ratio or shear modulus. Since the converted refracted shear waves can be recorded in fast formations, a joint method based on the local measurement of the shear velocity by picking the arrival times of the refracted S wave and interpolation by co-kriging with P-wave velocity log has been used to compute a continuous shear velocity log. The Analysis of the dispersive properties of the Stoneley modes has then been used to estimate density variations and build iteratively a density log from an a priori density model. Furthermore, we will show that a dimensionless shape index can be used as a qualitative acoustic attribute to detect the presence of interfering waves, anomalic zones and to obtain a measurement of the attenuation. We will also show that P-wave attenuation, P-wave frequency, and acoustic porosity logs can be fruitfully used to compute an acoustic permeability log.

Carbonate reservoirs are characterized by strong permeability heterogeneity mainly linked to the predominant pore type. In a paper entitled "Petrophysical characterization of carbonates (SE of Spain) through Full Wave Acoustic data" (Benjumea, Lopez, Mari, and Garcia-Lobon, 2018), a field case in carbonate formation is presented. The case study is focused on a shallow borehole (160 m depth) located at the in eastern end of the Betic Cordillera, SE of Spain. This borehole sampled a marly seal (deep marine marls rich in planktonic organisms from Messinian – upper Tortonian) on top of a carbonate reservoir (algae limestone from Miocene - upper Tortonian). Laboratory analyses show that most of the samples from the reservoir correspond to grainstone and packstone limestone types, and that the quality of this reservoir is controlled mainly by its detritic composition and a high content of bioclasts. The aim of this work is to show the suitability of using standard geophysical logging to assess permeability supported by laboratory and Lugeon tests. Two approaches have been used based on Kozeny's equation (pseudo-k log) and Mari et al. (2011) work (IK-Seis log). Both ways require obtaining specific surface which is an indicator of pore type. This calculation is based on porosity and Vp/Vs relations. Porosity has been obtained from resistivity and sonic logs constrained by laboratory measurements. Shear wave velocity has been inferred from Stoneley wave velocity since this formation is considered as slow (Vs lower than 1500 m/s). Pseudo-K and IK-Seis logs have been scaled using the Lugeon tests results. Both logs reproduce the heterogeneities found in the in-situ test. Finally, an analysis of the dependence of different seismic attributes to the specific surface has been performed to check the suitability of using solely sonic measurements to assess permeability. This can be useful for boreholes were laboratory or field tests are not available.

Full wave acoustic logging (FWAL) and vertical seismic profiles (VSP) are currently used to transform seismic block in impedance block and to perform the time to depth conversion. A 3D seismic survey has been done on a near surface karstic reservoir located at the Hydrogeological Site (HES) of the University of Poitiers (France). The processing of the 3D data leads to obtain a 3D velocity block in depth. The velocity block has been converted in pseudo porosity for reservoir model building (Mari and Delay, 2011). The resulting 3D seismic pseudo-porosity block reveals three high-porosity, presumably-water-productive, layers, at depths of 30-40, 85-87 and 110-115 m.
Full wave acoustic logging (Mari, Porel. and Delay, 2020) can be used to validate the results obtained from the 3D seismic if the karstic body has a lateral extension over several seismic cells. If karstic bodies have a small extension, FWAL in open hole can be fruitfully used to:

- detect highly permeable bodies, thanks to measurements of acoustic energy and attenuation.

- detect the presence of karstic bodies characterized by a very strong attenuation of the different wave trains and a loss of continuity of acoustic sections.
- confirm the results obtained by vertical seismic profile (VSP) data.

The field example also shows that acoustic attenuation of the total wavefield as well as conversion of downward-going P-wave in Stoneley waves observed on VSP data are strongly correlated with the presence of flow.

Tying full wave acoustic results to other measurements carried out in the same borehole or on surface, can be illustrated in the shallow geotechnical subsurface by examples collected in the following open access book, by Jean Luc Mari and Christophe Vergniault (2018):

Well seismic surveying and acoustic logging

https://www.edp-open.org/well-seismic-surveying-and-acoustic-logging

Mari J.L., Coppens F., 1992, Application de techniques issues de l'intelligence artificielle au pointé des diagraphies acoustiques, Revue de l'Institut Français du Pétrole, vol. 47, no 1, jan.-fév. 1992, p. 3-28.

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Dip measurement based on acoustic data, In: Full waveform acoustic data processing, 1994, Editions Technip, Paris, ISBN 2-7108-0664-9.

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Mari J.L., Coppens F., Gavin Ph., Wicquart E., 1994, Full waveform acoustic data processing, Editions Technip, Paris, ISBN 2-7108-0664-9.

Mari J.L., Gavin Ph., Coppens F., 1994, An example of acoustics and very high-resolution seismic in a near-horizontal borehole, First Break, vol 12, no 1, January 1994, p 21-29.

Coppens F., Mari J.L., 1995, Application of the intercept time method to full wave form acoustic data, First Break, vol 13, no 1, January 1995, p 11-20.

Mari J.L., Delay J., Gaudiani P., Arens G., 1997, Geological Formation Characterization by Stoneley waves, European Journal of Environmental and Engineering Geophysics, 2, 15 – 45.

Mari J.L., Gaudiani P., Delay J., 2011, Characterization of geological formations by physical parameters obtained through full wave form acoustic logging, J. Phys. Chem. Earth, doi: 10.1016/j.pce 2011.07.011

Mari, J.L., Delay F ,2011, Contribution of Seismic and acoustic methods to reservoir model building, in " Hydraulic Conductivity / Book 1", ISBN 978-953-307-288-3, InTech- Open Access Publisher, DOI: 10.5772/22051, available from http://www.intechopen.com/articles/show/title/contribution-of-seismic-and-acoustic-methods-to-reservoir-model-building

Mari J.L., Vergniault C, 2018, Well seismic surveying and acoustic logging, EDP Sciences, DOI: 10.10051/978-2-7598-2263-8, ISBN (e-book): 7598-2263-8. https://www.edp-open.org/well-seismic-surveying-and-acoustic-logging

Benjumea B., Lopez A.I., Mari J.L., Garcia-Lobon J.L., 2018, Petrophysical characterization of carbonates (SE of Spain) through full wave sonic data, Journal of applied geophysics, 160,1-14, https://doi.org/10.1016/j.jappgeo.2018.10.024

Mari J.L., Porel G., Delay F., 2020, Contribution of Full Wave Acoustic Logging to the Detection and Prediction of Karstic Bodies, *Water* **2020**, *12*(4), 948; doi:10.3390/w12040948

Mari J. L. 2020. Processing of full wave form acoustic data, white paper, Earth-Quick, www.earth-quick.com https://www.earth-quick.com/images/EQ_Images/Paper%20Acoustic%20EarthQuick.pdf