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Slim hole logging in shallow boreholes

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Abstract
While well logging, a continuous recording of the physical parameters down a borehole, is employed systematically in petroleum exploration, its application in environmental prospections, such as hydrogeology or civil engeering, has been very limited. This deficiency is partly due to the fact that logging probes used in this kind of boreholes are generally not calibrated and the results are more or less qualitative. The purpose of this lecture is to show that it is possible to calibrate these tools in order to obtain quantitative results, to make available to geologists, engineers and technicians engaged in shallow exploration, the information required for effectively applying the well-logging method.

Key words *environmental – logging – subsurface – density – porosity – elastic parameters – hydraulic parameters*

1. Introduction

1.1. *Principle*

Well logging is a continuous recording of variations in physical or chemical parameters *versus* depth.

Geophysical logging is conducted during a temporary halt or after the completion of a drilling operation.

The useful parameters of a particular investigation are measured by means of probes that are lowered into the borehole at the end of a cable. This cable allows the transmission of information to the recording instruments at the surface (Serra, 1979).

1.2. *Borehole conditions*

While in petroleum exploration the borehole diameters are of the order of 8 to 16″, in civil engineering and hydrology diameters are smaller, from 2 to 4.5″. This conditions the size of the probes to be used. In oil logging, probes are calibrated at the American Petroleum Institute and the units are standardized. In shallow boreholes, simple logging equipment can be obtained at reasonable cost but they are not calibrated or standardized.

Logs cannot provide values that are reliable, continuous and coherent unless the equipment is correctly calibrated.

Furthermore, in petroleum exploration, drilling is more often done using mud as drilling fluid, and the logs are run in open hole (without casing).

It is not the same in civil engineering or hydrogeology where drilling techniques could be water drilling or air drilling, and the logs are run in cased holes (metallic or PVC) to avoid any collapse risk of the hole.

Correction for environmental effects will thus be different according the application domain (Chapellier, 1992).

2. Environmental corrections for slim hole tools in shallow boreholes

2.1. *Resistivity logs*

Designed to measure the rock resistivity or its inverse, conductivity, there is a whole series

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of tools with different depths of investigation and vertical definition. This goes from the simple single-point, or mono-electrode, measurement of resistance in ohms, all the way to multiple-electrode focused tools, which measure resistivity at different depths of investigation.

Resistivity logs should be run in holes filled with conductive fluid.

They cannot be registered in Metallic (conductive casing) or in full PVC (resistive casing) cased holes. They can only be run in screened PVC casing as it is seen in fig. 1.

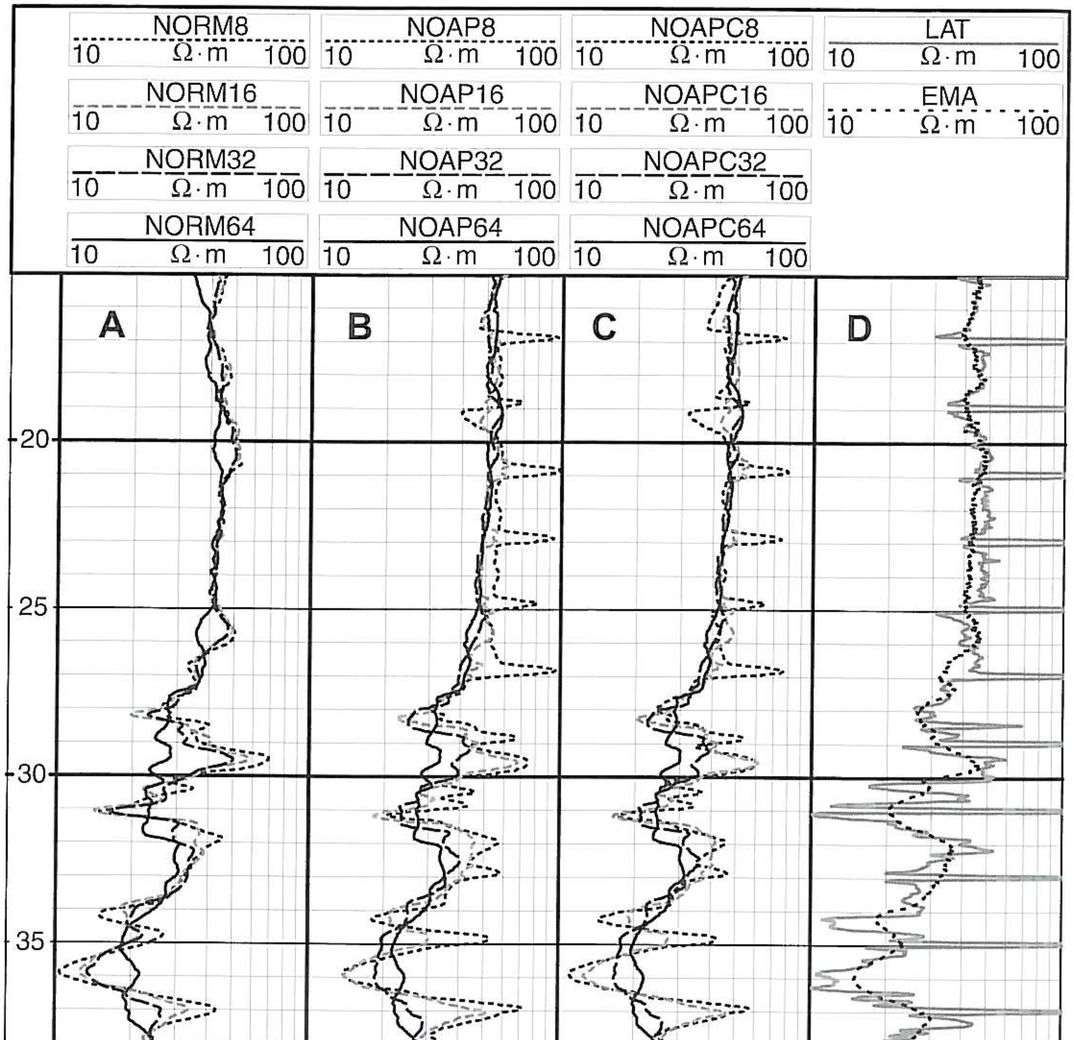

Fig. 1. Resistivity logs run in open hole (A) and screened PVC cased hole (B, C, D).

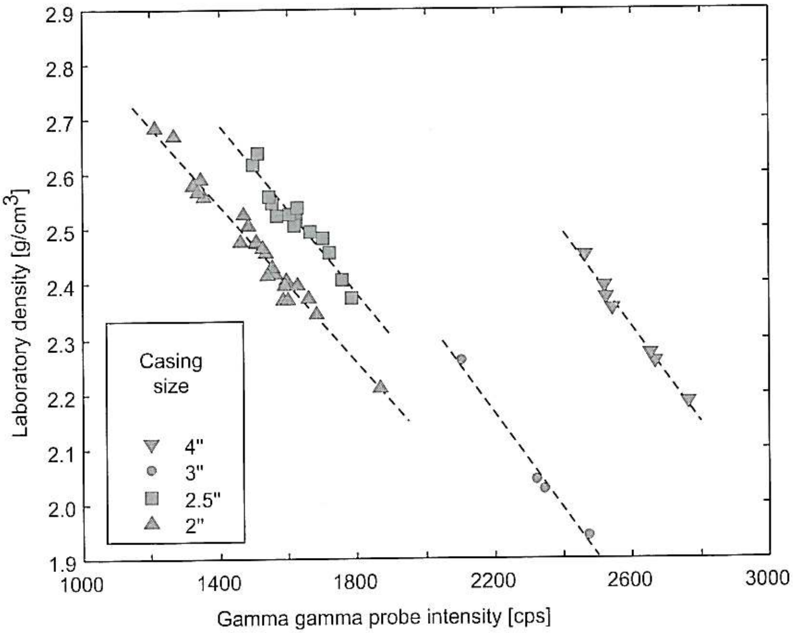

Fig. 2. Root mean square calibration for Gamma-Gamma probe.

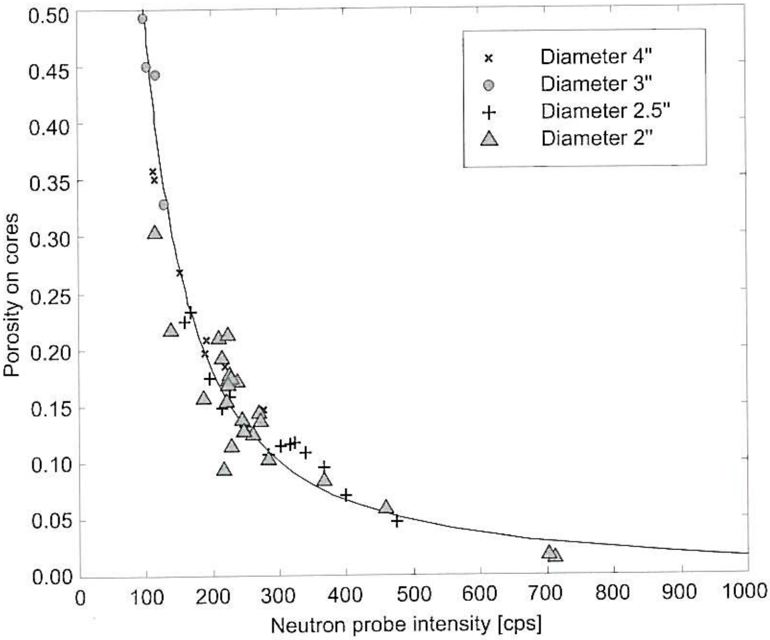

Fig. 3. Root mean square calibration for Neutron-Neutron probe.

In fig. 1, we can see in track A resistivity logs in open hole. In track B, the logs are registered in PVC screened cased hole. The casing joints are marked by resistive peaks on almost all the logs, which can also be a way to tie the various logs to one another.

Some corrections should be made for the influence of the casing on the values of the resistivity. In this case:

$$\begin{aligned}
R_{\text{Laterolog corrected}} &= 0.69{*}R_{\text{Laterolog measured}}\\
R_{\text{EM corrected}} &= 1.12{*}R_{\text{EM measured}}\\
R_{\text{Norm 8'' corrected}} &= 0.8{*}R_{\text{Norm 8'' measured}}\\
R_{\text{Norm 16'' corrected}} &= 0.9{*}R_{\text{Norm 16'' measured}}\\
R_{\text{Norm 32'' corrected}} &= 0.9{*}R_{\text{Norm 32'' measured}}\\
R_{\text{Norm 64'' corrected}} &= 0.9{*}R_{\text{Norm 64'' measured}}
\end{aligned}$$

These corrections, track C, do not suppress the resistive peaks. The EM alone does not show casing joints, track D.

2.2. *Radiometric logs*

Nuclear tools are of two types: one for the measurement of natural radioactivity (Gamma Ray), and the other for the measurement of induced radioactivity (Gamma-Gamma and Neutron-Neutron).

Nuclear logs offer an important advantage, they can be recorded in open or cased (PVC or Metallic) holes, empty or filled with any type of fluid.

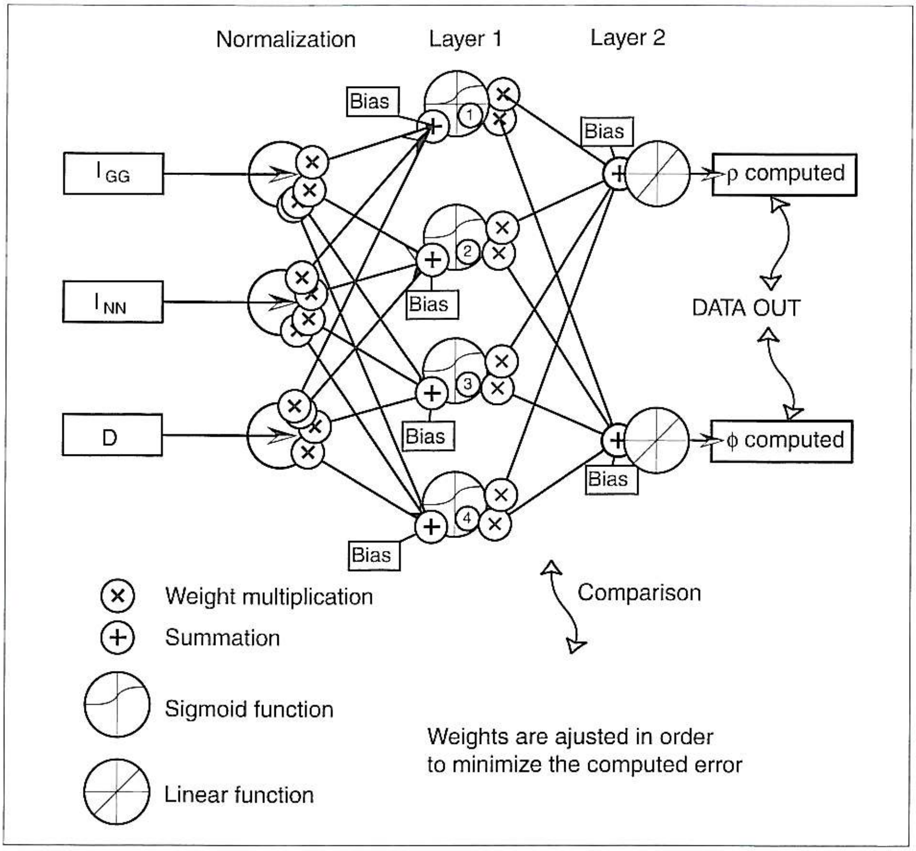

Fig. 4. Neural network calibration of nuclear tools.

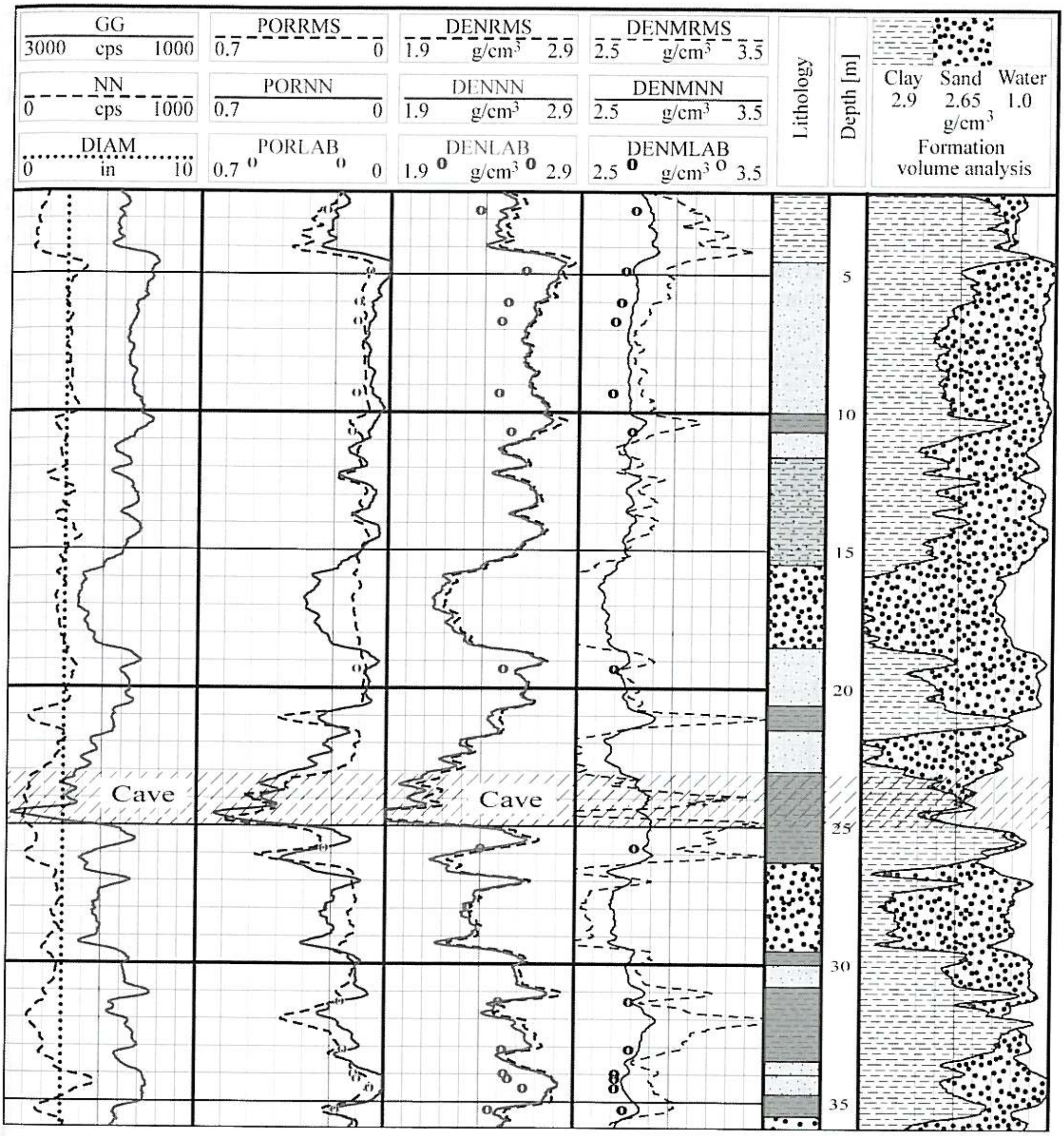

Fig. 5. Example of computation of density and porosity using the two approaches. RMS = Root Mean Square approach; NN = Neural Network approach; LAB = Laboratory values; DENM = Matrix Density.

They are mainly used to provide:

- Shadiness for Gamma-Ray.
- Density for the Gamma-Gamma.
- Porosity for the Neutron.

Processing of the log data from these radioactive tools consists of (Baron and Chapellier, 1998):

- Borehole effect correction (diameter, casing).
- Transformation of cps in g/cm^3 for Gamma-Gamma (Tittman *et al.*, 1965, 1966).

– Transformation of cps in porosity units for the Neutron.

Generally done in oil exploration, using calibration wells (American Petroleum Institute), this processing is seldom performed for slim hole tools. It is however possible as is shown in the following examples.

Gamma-Gamma calibration – Calibration of the probe was first performed by a root mean square approach, comparing between values in cps recorded by the probe in different conditions in a borehole and laboratory data obtained on samples. As seen, diameter effect (4″, 3″, 2.5″ and 2″) cannot be neglected (fig. 2).

Neutron-Neutron calibration – Using the same approach, calibration was done for the Neutron probe. Diameter effect is less significant due to larger depth of investigation of the Neutron-Neutron probe (fig. 3).

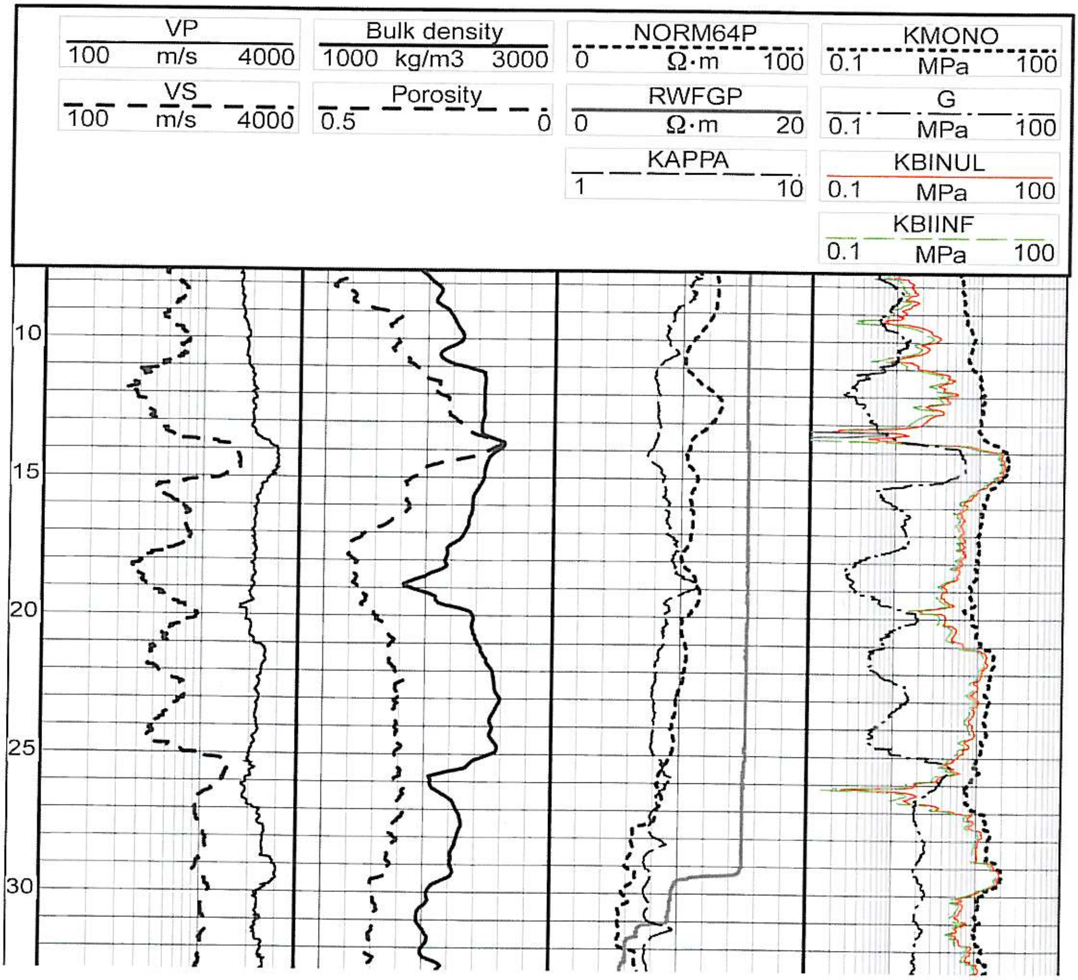

Fig. 6. Example of elastic moduli. Kappa = coupling factor; KMONO = classical Gassmann formulae; KBINUL = eq. (3.3), with Kappa infinite; KBINF = eq. (3.3); *G* = this curve is the same for GMONO eq. (3.4) with kappa infinite, GBINUL eq. (3.4) with kappa infinite, GBINF eq. (3.4).

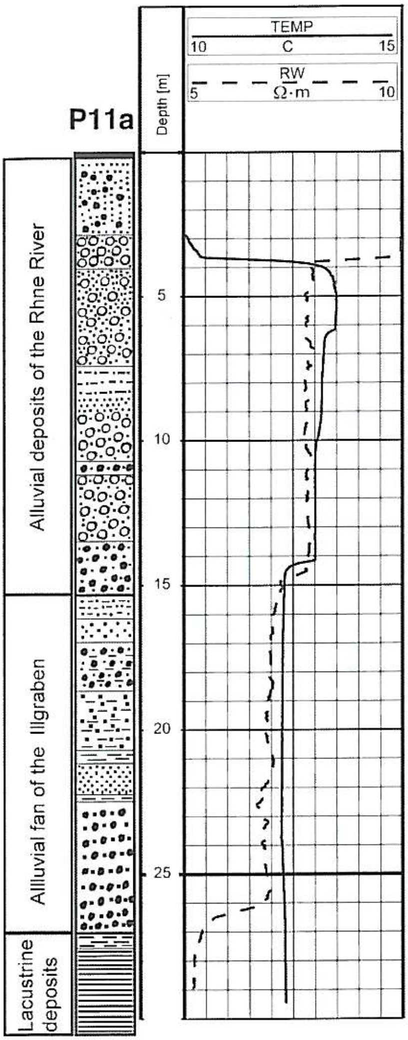

Fig. 7. Fluid resistivity and fluid temperature in the P11a - Finges - Valais (Switzerland).

Neural network approach – For better calibration it is possible to use the neural network approach with parameters adjusted from learning data (Rumelhart and Hinton, 1986).

In our example (Baron and Chapellier, 2000), input data are the caliper (diameter of the borehole, D) and Gamma-Gamma and Neutron-Neutron intensities (IGG and INN in cps).

Output data will be density and porosity (ρ and ϕ). Each group obtained at the same depth is a learning point (fig. 4).

Figure 5 shows the computation of density and porosity using two approaches. Calibration was performed using a nominal diameter in the absence of caliper log. Comparison with laboratory data shows a better calibration for porosity than for density due to the high diameter influence on the Gamma-Gamma tool.

Density matrix value is more accurate with the neural network approach. From these data it is possible to compute the different mineral proportions assuming that we have only two matrix components.

3. Application to civil engineering: determination of mechanical parameters

Logs allow us to determine elasticity parameters in unconsolidated formations using velocity V_p, velocity V_s, density and porosity (Mari *et al.*, 1999).

3.1. *Biot bi-phase approach*

$$V_{Pb} =$$

$$= \left\{ \frac{1}{\rho_b} \left[K_{Sk} + \frac{4}{3} G_{Sk} + \frac{(1-\beta)^2}{(1-\phi-\beta)/K_M + \phi/K_f} \right] \right\}^{\frac{1}{2}} \tag{3.1}$$

Equation (3.1) at 0 frequency.

$$V_{Pb} =$$

$$= \left\{ \frac{1}{\rho_b} \left[K_{Sk} + \frac{4}{3} G_{Sk} + \frac{\frac{\phi\rho_b}{\kappa\rho_f} + (1-\beta)\left(1-\beta-\frac{2\phi}{\kappa}\right)}{(1-\phi-\beta)/K_M + \phi/K_f} \right] \right\}^{\frac{1}{2}} \tag{3.2}$$

Equation (3.2), at infinite frequency.

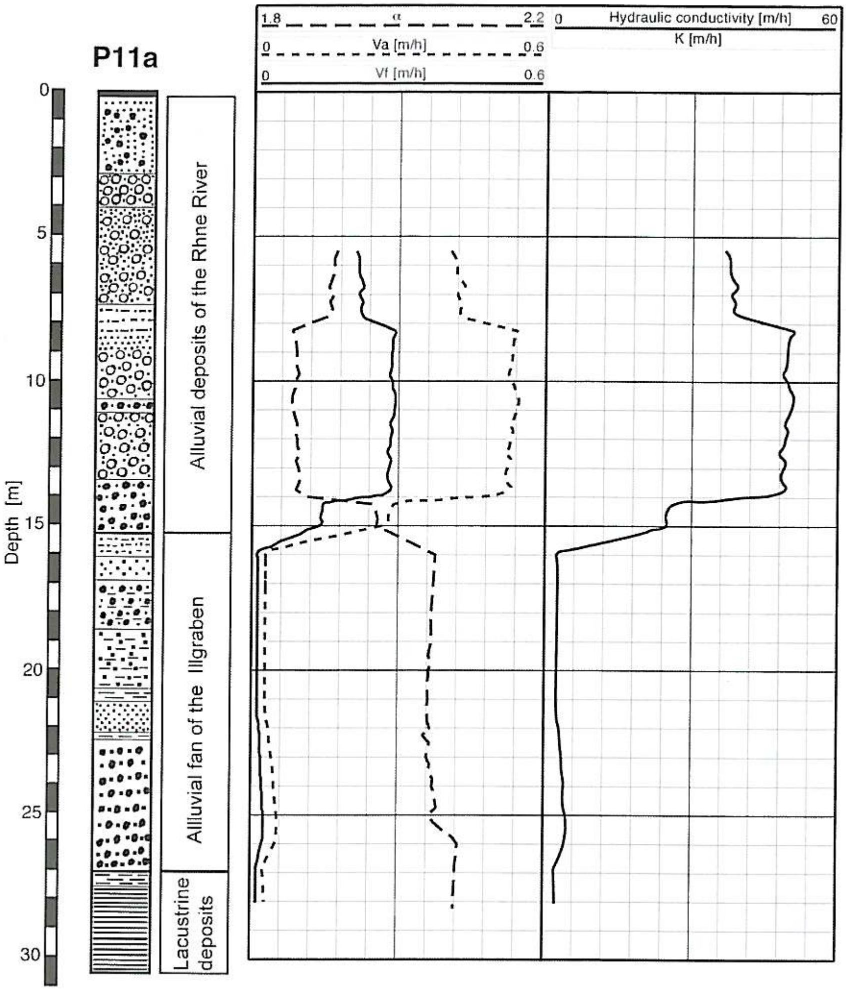

Fig. 8. Dilution technique in the P11a. α = hydrodynamic field distortion coefficient; V_a = apparent filtration velocity; V_f = filtration velocity; K = hydraulic conductivity.

3.2. *Elastic moduli*

$$K_{Sk} = \frac{\rho_b\left(1-\frac{\rho_f\phi}{\rho_b\kappa}\right)\left(V_{Pb}^2-\frac{4}{3}V_{Sb}^2\right)\left(K_f-\phi\left(K_f-K_M\right)\right)+K_M K_f\left(\frac{\phi}{\kappa}\left(2-\frac{\rho_b}{\rho_f}\right)-1\right)}{\rho_b\left(1-\frac{\rho_f\phi}{\rho_b\kappa}\right)\left(V_{Pb}^2-\frac{4}{3}V_{Sb}^2\right)\frac{K_f}{K_M}+\phi K_M+K_f\left(\frac{2\phi}{\kappa}-1-\phi\right)} \qquad (3.3)$$

Equation (3.3), at infinite frequency.

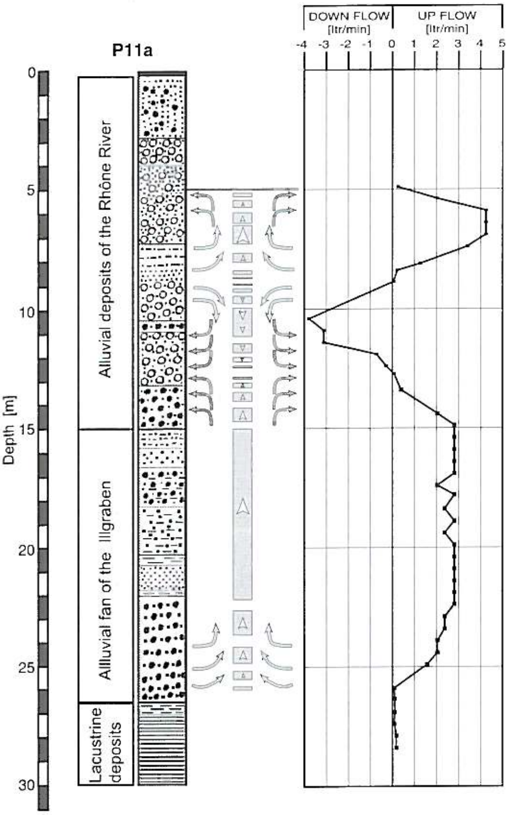

Fig. 9. Heat pulse flowmeter in the P11a.

$$G = \rho_b V_{Sb}^2 \left(1 - \frac{\rho_f \phi}{\rho_b \kappa}\right) \qquad (3.4)$$

Equation (3.4), at infinite frequency.

These bulk moduli obtained by these equations are functions of:

- Matrix elasticity parameters (KM and GM) and fluid (KF).
- Skeleton elasticity parameters.

Skeleton parameters are those needed by civil engineers as they are comparable to the one obtained in three axial cells in drained conditions.

In unsaturated non-consolidated formations, determination of mechanical properties needs complementary logging data and a well adapted deterministic model.

In fig. 6, logs of the P and S wave velocities (V_P and V_S) are obtained with acoustic logging at frequencies from 5 up to 20 kHz.

Porosity and density logs were computed using Gamma-Gamma and neutron-neutron logs with an appropriate calibration method. The main result is that the K modulus is over estimated by the classical Gassmann formulae (KMONO) especially in front of unconsolidated formation (from 7 to 14 m) where eq. (3.3) should be used. G is quite the same using different equations.

4. Application to hydrology: determination of hydraulic parameters

4.1. *Temperature log*

This log provides useful information. First it is used to correct the resistivities for the temperature effect. Further, the curve anomalies allow the zones of water circulation to be determined.

4.2. *Fluid resistivity log*

This log permits the determination of the zones with high permeability, and the anomalies of the curve are an index of inflow or losses of water, especially in fractured aquifers (fig. 7).

4.3. *Dilution technique*

The fluid resistivity tool is also used to carry out the dilution technique (see fig. 8.). After recording the fluid resistivity, a tracer injection is performed. The tracer is often NaCl, as it has an influence on fluid resistivity, lowering it. New recordings are then performed.

The examination of the variations of fluid resistivity *versus* time yield the hydraulic parameters such as (Monnet *et al.*, 1998):

- Horizontal filtration velocity.
- Horizontal hydraulic conductivity.

4.4. *Heat pulse flowmeter*

Always aiming to quantify the hydraulic parameters, a heat pulse flowmeter can be used.

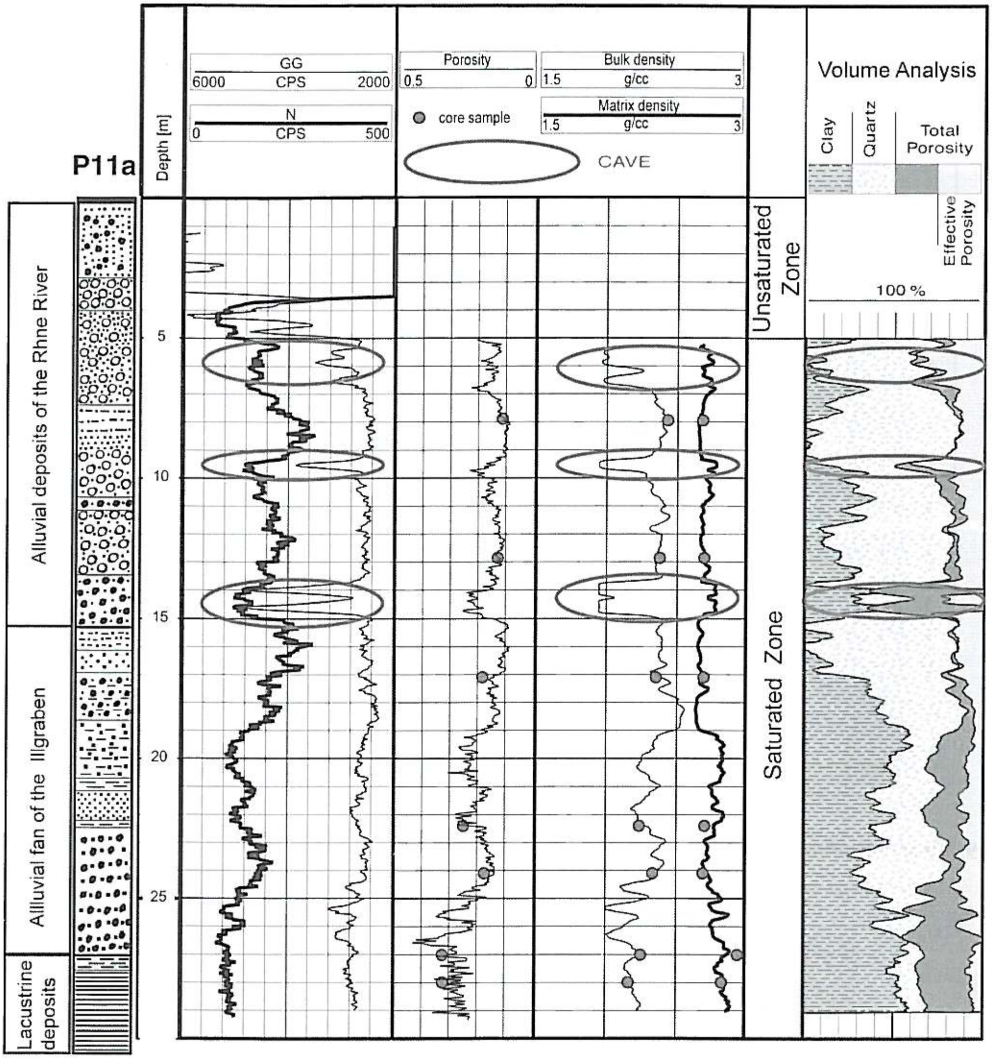

Fig. 10. Porosity, bulk density, matrix density and volume analysis in the P11a.

This tool measures the time used by a thin layer of heated water to reach a thermometer, which after calibration, allows the vertical velocities of fluids in the borehole to be obtained (Monnet and Chapellier, 1999). Knowing the borehole section it is possible to calculate vertical velocities (fig. 9).

Finally, combining all the logs, we can see in figs. 10 and 11 that borehole logging methods provide:

– K, ϕ_{Eff} and V_f at very precise scale in the borehole.

5. Conclusions

All these calibrations are only valid for our probes and cannot be extrapolated to another

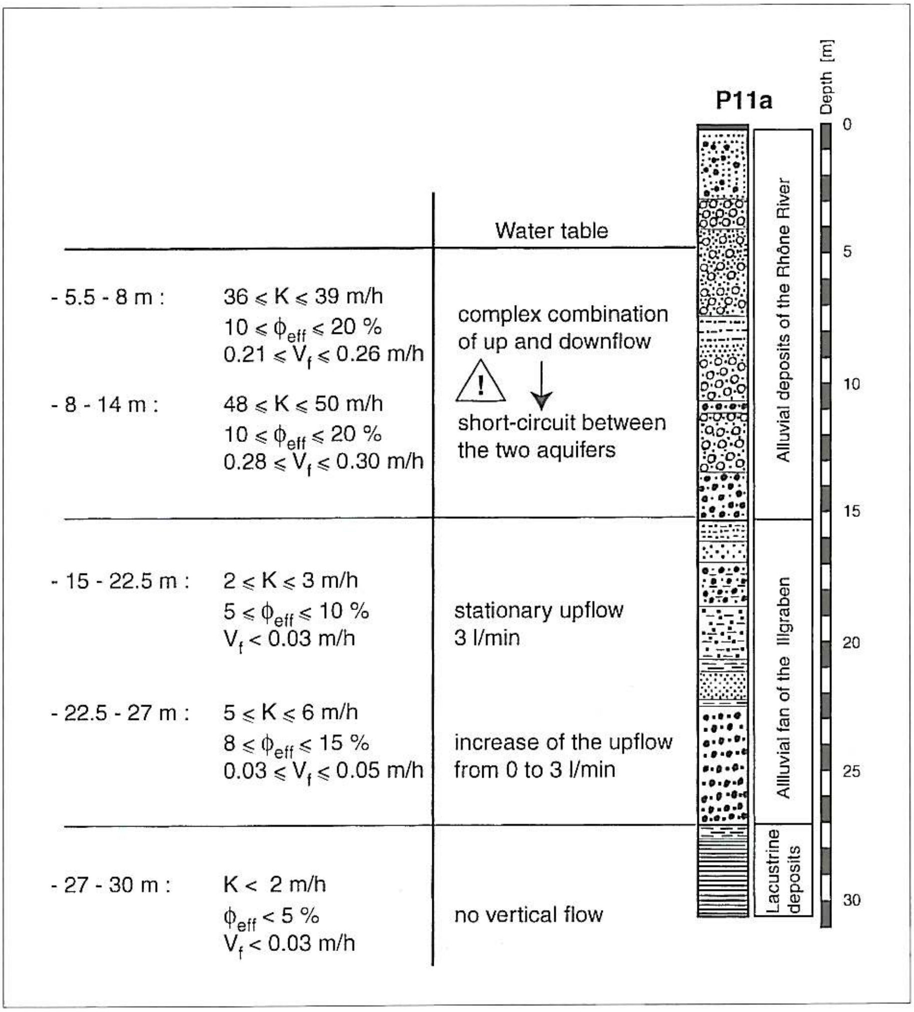

Fig. 11. Results provided by borehole logging methods. P11a.

tools. They are valid for shallow borehole conditions (PVC, screened or not, 2″ to 4″).

Nevertheless, this research shows that it is now possible to obtain quantitative results in civil engineering as in hydrogeology but it is important to:

- have a certain number of logs available,
- calibrate the tools in order to obtain quantitative results,
- be in position to make borehole corrections.

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