2-1.3.1 From plug to core and well logs

A) Overview; typology of data acquired on cores

There are various types of core data, acquired at several scales and which must be reconciled:

– *Quantitative data,* either petrophysical, discussed at length in the first section of this book, or "geological", which must be considered in the same way. To process these data, it is essential to correctly distinguish between "point" type quantitative data (identified by a number: porosity, permeability, mineral content, etc.) and "function" type data (characterised by a series of X, Y pairs: capillary pressure, resistivity index curve, granulometric curve, etc.). We must mention in particular the quantitative data derived from image analysis (microscopy, digital photographs, scanner, etc.). The result is often expressed in the same terms as the true physical or chemical measurement (e.g. mineralogical contents, porosity, saturation) although it is only an estimation. Forgetting this simplifying convention may lead to contradictions, which are discussed in § 1-1.1.5, p. 26.

– *Descriptive qualitative data* must be included in the process. This is even one of the strong points of the "core-property log", provided that a clear distinction is made between the strict intrinsic description of the material (petrography, lithology, oil impregnations, etc.) and the analysis (e.g. sedimentological environments) whose qualification may vary over time according to the experience acquired.

One of the key points when studying cores is the comparison with the logging results (even if only to calibrate them). This comparison is only justified if the various results are reconciled; we will refer to this point repeatedly. The most efficient way of reaching this objective is to draw up a "Core Petrophysical Log" which includes the various observations.

This petrophysical log will be mentioned on a number of occasions in the following pages. We must emphasise the difference between this document, which results from an analysis, and the various core logs described below. To avoid terminology confusions, we will use the expression "Core Interpolated Petrophysical Log" to designate the summary document.

Before describing the principles used to produce this log, we will discuss below the data acquisition techniques implemented: continuous core logging, sampling, database, etc.

B) Drilling data recorded during coring

These data do not concern the core itself but the drilling conditions observed during the coring operation. Systematically recorded by the driller, these parameters include: the weight on bit, the torque on the pipe string, the drilling rate of the core barrel in the formation and any mud losses in a high-permeability reservoir. These data taken routinely by the driller are only very rarely taken into account by geologists, despite the fact that they are extremely useful to explain some coring incidents.

For instance, crossing a highly brittle "super K", lost during coring, like that shown on Figure 1-2.18, p. 151, is generally clearly visible on the weight on bit recording and on the instantaneous drilling rate.

Another extremely useful data is the depth at which even slight mud losses occur. This information is critical to detect the presence of an "open" fracture, which often causes core dislocation, leading to jamming in the core barrel and therefore loss of the interesting zone.

The amount of gas dissolved in the drilling mud is often recorded. Once again, this data is extremely valuable.

We can never over-emphasise the importance of these drilling parameters when interpreting the core results.

C) Continuous core logging

Various devices which offer continuous measurement of some physical properties along the core, are grouped under the denomination of "core logs" (which may sometimes lead to confusion with "Core Interpolated Petrophysical Log"). In the core logs described below, the first two are (or should be) employed for routine acquisitions, use of the others being less widespread:

a) γ ray core logging

Care must be taken during acquisition as regards background radiation in order to pick up a meaningful signal, but processing this measurement is relatively straightforward. This technique is sometimes implemented purely to carry out core depth matching with respect to core logs (see § G below). Obviously, we must not attempt to compare the absolute values. It is in fact recommended to weight the measurement by a volume index for the core investigated, especially in case of poor core recovery.

Currently, spectral analysis (K, Th and U) is often carried out in addition to this measurement. It is an extremely useful technique provided, once again, that the absolute values of the data are not considered in terms of elementary content in the strict sense.

Considering the volume investigated, the acquisition step of this core log is decimetric.

b) Apparent density core logging

This electron density measurement is quite similar to that implemented in well logging. The only difference is its acquisition by "transparency", the emitter and the receiver being positioned on opposite sides of the core.

The gamma radiation attenuation measured depends on the electron density of the medium between the emitter and the receiver.

$$I = I_0 \, e^{-C \rho_e L}$$

where: I: intensity of the γ radiation measured by the receiver.
- I_0: intensity of the γ radiation emitted by the source.
- ρ_e: electron density (number of electrons per unit volume) encountered on the path between source and receiver.
- L: distance between source and receiver.
- C: constant which depends on the device geometry, the detector type and the energy of the γ rays.

Provided that calibration is carried out regularly to readjust the value of C (standard materials are positioned systematically at the start and end of the acquisition sequence), conversion of the electron density into apparent density is quite straightforward.

In order to use this log correctly, therefore, the thickness crossed must be measured. Acquired by mechanical or optical sensors, this correction is of little value when the portion of core analysed is too fragmented.

Apparent density core logs (as well as mini-sonic) must be carried out with the virtual emitter/receiver axis in the bedding plane (i.e. parallel to the strike, see Fig. 2-1.14) so that acquisition occurs in this plane. The X-ray radiographs must also be positioned in the same way to obtain the best possible resolution on the bedding limits (this precaution is not required if a CT-Scanner is used, although the acquisition process is much longer; in addition, many laboratories are only equipped with the much less expensive X-ray radiography apparatus).

This type of core logging can be carried out for qualitative purposes on unconsolidated cores in rubber sleeve or fibre glass tube. Quantification is made extremely difficult, more due to the side effect of the variable thickness of mud remaining between the core and the sleeve than to the sleeve itself, whose effect can be calibrated.

Since this type of core logging is generally carried out on rocks of variable saturation state (core more or less dry), the density measured must be considered as "apparent". As with the other types of core logging, the most important point is to measure the relative density variation depending on the core depth. The acquisition step is centimetric.

c) Mini-sonic core logging

As for the density log, mini-sonic measurement is acquired by transparency, on a diametral plane of the core (Fig. 2-1.13a) and the operating conditions to obtain meaningful data are similar. An additional precaution is required: since measurement is taken with no

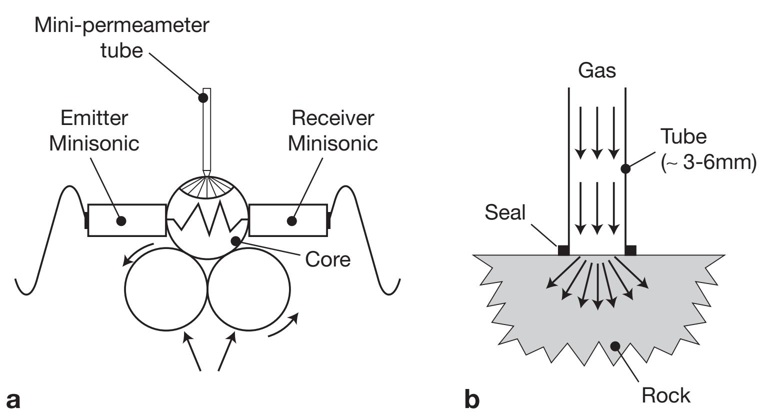


Figure 2-1.13 Schematic diagram of the mini-sonic and mini-permeameter devices
a) device simultaneously recording the two logs on several generators, using rollers to turn the core.
b) schematic diagram of the mini-permeameter, according to Jensen [1990].

confinement pressure, any cracks present have a considerable impact on the measurement. The sensors, and therefore the ultrasonic frequency implemented, are very similar to those used for acoustic measurements in laboratory, on sample (§ 1-3.2.3, p. 230). The most sophisticated devices can measure the compression and shear wave travel time. If the core is complete, acquisitions can be carried out along several generators.

The absolute values measured have little significance due to the uncertainty of the core saturation state but above all due to the possible effect of microcracks because the core is not under confinement. This type of logging, of centimetric acquisition step, is useful however:

– to carry out core depth matching (like the previous types of logging);
– to interpolate the isolated measurements acquired on samples (see § F below, core interpolated petrophysical log).

d) Mini-permeameter core logging

One or more permeability profiles are obtained along the core by a device (Fig. 2-1.13b) injecting gas (nitrogen) into the core.

The measurement is taken

– either by injecting nitrogen at constant rate:

$$Kg = \frac{2\eta MPe}{G_o a \rho_g (Pe^2 - Patm^2)}$$

where: M: nitrogen mass flow rate,
η: nitrogen viscosity,
ρ_g: nitrogen density,
a: probe radius,
Patm: atmospheric pressure (pressure of the gas in the core),
Pe: stabilised injection pressure,
G_o: geometric factor. This geometric factor depends on the assumption made regarding the shape of the current lines in the sample.

– or by connecting the probe to a known volume of nitrogen of pressure P decreasing with time as it flows through the sample. This is the drawn-down method, suitable for low permeabilities (§ 1-2.1.2B, p. 135).

The measurements may be corrected for the Klinkenberg and Forchheimer effects (§ 1-2.1.2A, p. 133) and calibrated on known samples. In spite of these precautions, it would be most unwise to consider the values supplied as absolute values (core surface state, unknown liquid saturation state, etc.). Consequently, there seems to be little point in making the corrections for the Klinkenberg and Forchheimer effects. These profiles are nevertheless extremely valuable to detect permeability variations which may occur very rapidly and which measurements on plugs, of average sampling frequency 25 or 23 cm, are unable to capture.

On complete cores, acquisition is carried out on several generators. However, the most reliable data are acquired on the sawn face of the core (in this case, acquisition is carried out after slabbing). Working on the sawn face improves the contact between the probe and the rock. The optimum sampling step is semicentimetric. Note that this technique is also used to acquire permeability maps on the surface of full size samples intended for relative permeability measurements.

e) Other types of core logging

Other types of non-destructive physical measurements are sometimes implemented as continuous (or high-resolution) core logging. For instance, a Formation Factor longitudinal profile could be relevant in carbonate rocks but too many experimental difficulties remain, the most important being to obtain perfect core saturation in brine of known resistivity.

Implementation of magnetic susceptibility profiles is technically possible, but this method is rarely used. In case of quite specific clay phase mineralogy, this profile is an indirect indicator of the clay content.

Infrared spectrometry measurement (§ 2-2.4) can also be used to obtain information on the mineralogical assemblage. This adaptation is still in its infancy however.

Concerning the mechanical properties, automated tests based on the old scratch method are also implemented (measurement of scratch width at constant load on the stylus, or instead controlling the scratch depth and recording the force to be applied on the stylus). This profile correlates well with the rock mechanical resistance variation profile, of interest to drillers.

From the operational point of view, the most readily available logs to date are data resulting from the more or less sophisticated processing of core images:

- pseudo-density profiles obtained from processing of X-ray plates or CT Scan;
- hydrocarbon index profiles obtained from processing of core photographs under UV light;
- lastly, although to our knowledge not yet operational, texture profiles (discontinuities, etc.) obtained from processing photographs taken under natural light or X-ray radiographs. X-ray absorption logging deduced from CT Scan measurement is being increasingly used. The CT scan method is described in § 2-2.3.

D) Core sampling procedures

a) Sampling sequence and conditions

The core is a valuable asset shared by several specialists who may implement contradictory procedures. This is particularly obvious when irreversible operations (sampling, slabbing, etc.) are involved. Sedimentologists can only work correctly on slabbed cores. Petrophysicists wanting to acquire initial saturation or relative permeability data (§ 1-2.3.4, p. 195) will need a piece of core "preserved" against any mechanical aggression and carefully protected from the ambient air as soon as it is brought to the surface. Similarly, optimum acquisition of a density log or mini-sonic on core requires unslabbed cores, whereas mini-permeability logging is more meaningful if carried out on a sawing plane. The sampling phases, whatever the sampling type (petrophysical or geological; thin section, mineral or organic geochemistry, micropaleontology, etc.) are irreversible operations. They must be part of the core acquisition sequence, while maintaining a satisfactory compromise for the other operations.

Most acquisition types require precise orientation relative to the core diametral planes to obtain meaningful or highly accurate results: the strike of the bedding planes must be identified on each core or core section, either visually or by using an X-ray CT-Scan. By taking this preliminary precaution, there is no need to know the bed dip in advance or to allow for a possible deviation of the drilling angle from the vertical. A number of simple rules intended for the operators can therefore be defined:

– The core slabbing plane (observations of the lithology, sedimentary structures, etc. and photographs under natural and/or ultraviolet light) must be parallel to the dip (Fig. 2-1.14).
– The direction of the plug sampling axis must also be carefully chosen. By convention, "horizontal" plugs are sampled in the bedding plane, parallel to the strike. If we make the realistic assumption that the horizontal plane is virtually isotropic at the sample scale and with respect to the properties being investigated, applying this rule yields meaningful results irrespective of the dip of the reservoir horizons and the possible well deviation.
– The depth and well number should be marked on each plug to avoid losing any information (experience has shown the value of this apparently trivial remark!).

Apart from exceptions, most petrophysical properties must be acquired on these "horizontal" plugs. "Vertical" plugs (parallel to the core axis) are sometimes acquired in order to check for possible anisotropy. This is rarely justified.

We will take the example of routine permeability measurements. As illustrated above (§ 2-1.2.2Bb, p. 283), anisotropy is primarily a function of the scale and of the rock structure

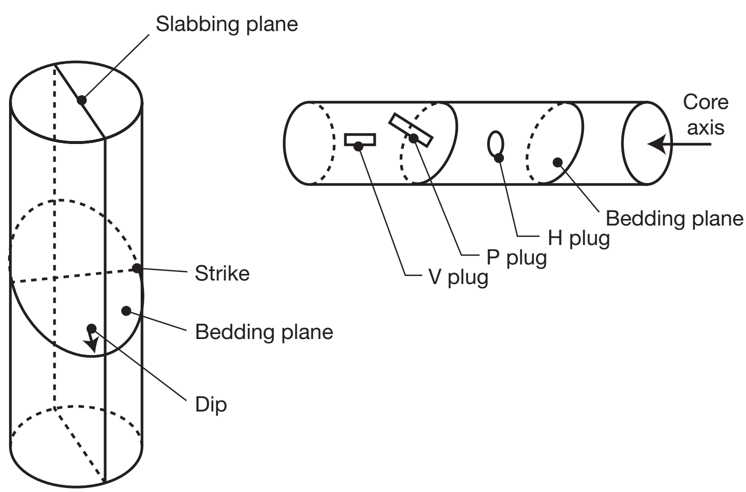


Figure 2-1.14 Orientation of core slabbing planes and plug axes

a) Slabbing plane parallel to the dip.
b) Orientation of various plugs: H parallel to the strike of the bedding plane; P perpendicular to the bedding plane; V parallel to the core axis (possible confusion with P). This terminology is not universally accepted and may lead to confusion.

organisation. We are more particularly interested in that concerning the scale of the model grid or of the volume investigated by the well test, …there is little likelihood of it depending on a possible "microscopic" anisotropy, meaningful at the scale of 1 inch plugs (oriented allochems, micas, etc.). This lack of meaning is further increased by another aspect: for practical reasons, "H" and "V" plugs are rarely sampled at the same depth (and spacing). Differences in measurement results are more often a sign of spatial variability in the property measured than true microscopic anisotropy. In addition, the notion of "vertical" is ambiguous: often taken to be the direction of the core axis, this direction may turn out to be oblique relative to the bedding, whether the well is deviated or the bed dip not horizontal. The sampling of "stratigraphically" vertical plugs must be carried out with extreme care.

In conclusion, as regards directional physical properties, the reference system used in practice is the local bedding plane. Measurements are usually taken in this plane. There are some exceptions:

– Compressibility measurements, when the experiment must be carried out under "œdometric" conditions (without lateral deformation, see § 1-1.1.6, p. 45) on samples taken along an axis parallel to the true geographic vertical.
– Relative permeability measurements whose results must be interpreted on a digital model (at least 1D), so that the vertical variability can be recreated along the laboratory sample.

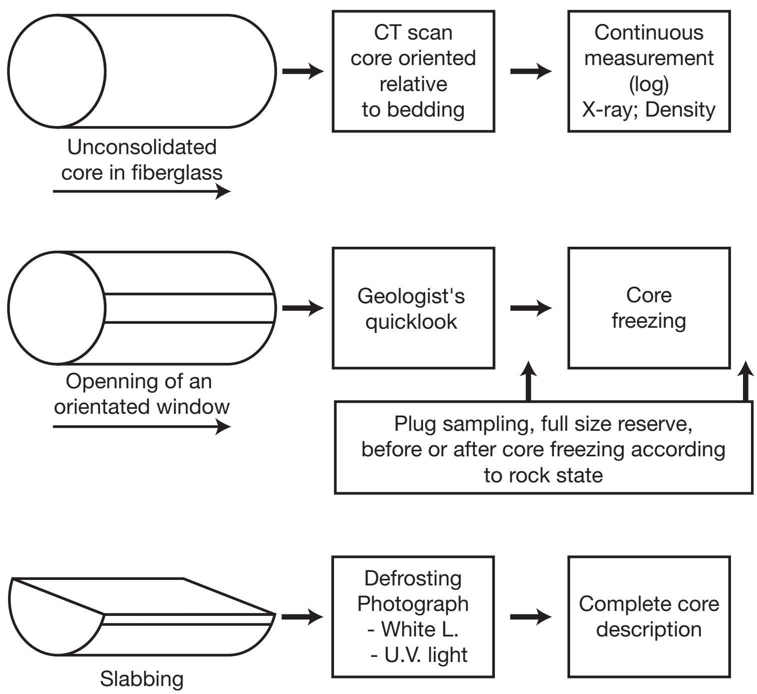


Figure 2-1.15 Example of unconsolidated reservoir core processing sequence

As an example, Figure 2-1.15 shows a preliminary unconsolidated reservoir core processing sequence, cores sampled and preserved in fibre glass or metal (steel, aluminium) tubes.

b) Sampling frequency for petrophysics

Full–size samples for special core analysis (SCAL)

A certain number of special measurements must be carried out on full diameter pieces (“full size”; typical cores have a diameter between 6 cm and 10 cm, reaching 12.5 cm for unconsolidated cores) which must be protected from ambient air to prevent drying and oxidation. Since the precise choice of the facies to be sampled is not determined in advance, and bearing in mind that apparently satisfactory pieces are often eliminated after the homogeneity study and that special measurements are often ordered at a late stage, or even during reservoir appraisal phases launched long after the drilling of the first appraisal wells cored, it is essential to anticipate by reserving enough full diameter pieces in order to protect them against future destructive operations: plugging, slabbing, etc. For information, a 30 cm long full size reserve should be made every metre in reservoir zones and every two or three metres elsewhere. As a precaution, these pieces must be “preserved”, i.e. carefully wrapped (good quality plastic film, paraffin, etc., but not aluminium foil which reacts with the impregnated rocks).

When reserving full size samples, we must always remember that preserved samples should also be used for measurements other than conventional SCAL (measurements of rock mechanical properties, measurements on shale: porosity, density, formation factor, salt content).

Plugs for routine core analysis

Since the plugs intended for routine measurements must allow vertical “scanning” of the basic petrophysical properties, they must be sampled at a relatively high frequency: typically 3 to 4 samples per metre of core.

A priori, the operator samples at regular intervals (every foot, or 1/4 or 1/3 m). Initially chosen for the simplicity of control, this practice is often justified *a posteriori* by statistical considerations. Experience has shown however, that this sampling mode is often biased in practice. Although the identifying depth is determined regularly: nn.00 m; nn.25 m; nn.50 m; nn.75 m; etc., the sampling is physically more or less shifted depending on the mechanical quality of the core at the planned point, or even to avoid a level considered to be of no interest (e.g. shale level). This initially well-meaning intention disturbs the data processing, often making the final analysis too optimistic. It represents a source of inconsistency when producing the Core Interpolated Petrophysical Log.

To control rather than suffer this sampling bias, the sampling can be adjusted according to lithological variations and/or, if necessary, according to the oil impregnation, always observing an average frequency of 3 to 4 samples per metre, with two at the ends of the preserved full size samples. Each plug is assigned a vertical representativeness coefficient defined by the upper and lower limits of the layer that the plug is supposed to represent (Fig. 2-1.16).

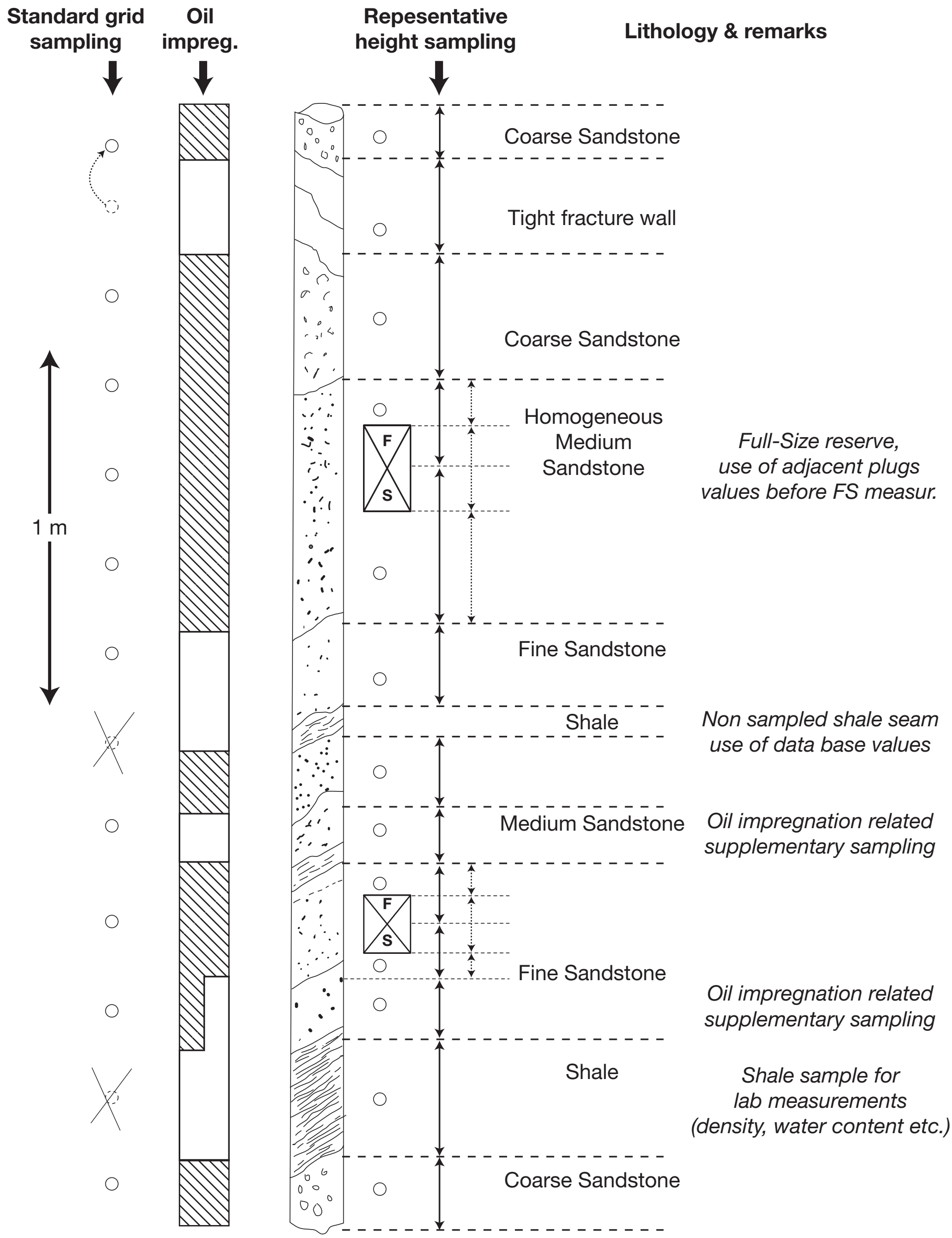


Figure 2-1.16 Routine sampling diagram, with estimation of a representative height (and therefore a weighting coefficient) for each plug

Experience has shown that this process is not an operational handicap if included rationally in the organisation of the initial core processing sequences. On the contrary, it ensures that the maximum amount of information can be extracted from the data during future analysis.

Lastly, lithological, mineralogical, mineral and/or organic geochemical determinations must be executed on scraps adjacent to the plugs (or on the plug itself, after analysis). Studies of "physics/lithology" correspondence are therefore relevant.

E) Creation and verification of the "core" database

Rational use of data acquired on cores requires a "petrophysical summary" designed to:

– check, and possibly guarantee, the overall consistency of petrophysical and analytical data;
– check, and if necessary determine the consistency of these data with other information acquired at well scale (lithological and sedimentological descriptions, core logs and images, etc.);
– analyse these data to present them in an integrated form which is, if possible, at the scale of the future application: in other words, creation of the Core Interpolated Petrophysical Log.

Typically, users only receive their petrophysical data a little at a time, following their requests for services. The information is distributed over a very long period of time: from the conventional "porosity-permeability" measurements generally taken immediately after drilling the well, up to the heavy "relative permeability" measurements which are often taken shortly before the reservoir modelling studies.

Consequently, petrophysical analytical studies on the same field rarely refer to each other. This effect is even greater when the measurements are carried out by different service providers. This implies a risk of inconsistency between the petrophysical data themselves and, often, a lack of correspondence between the acquisition of petrophysical measurements and the other information such as the lithological and sedimentological analyses. In the end, the onus is on the end user to reconcile all these data, even though he should not really have to.

a) Data validation

The data validation process must be carried out as soon as possible after data acquisition and therefore in the laboratory taking the measurements. The laboratory must be able to provide information on: the resolution of the test considered, the scale and the volume investigated, the measurement quality (i.e.: the precision, accuracy and bias).

This "quality control" must take place before data integration in the analysis process. Nevertheless, it is always recommended to check this information *a posteriori* by crossed validation between the different sets of data. A typical example concerning solid density and mineralogy was given in the first section (§ 1-1.1.5, p. 26).

Disagreement does not necessarily indicate a laboratory error. The sampling may have been badly supervised or be incoherent between several disciplines. Equally, the material may simply be heterogeneous with respect to the property considered. This is when it becomes essential to know the scale investigated by the measurement.

It is always a good idea to remember one basic rule: the first validation, calibration processes, etc. must be carried out set by set (in the typological meaning defined at the start of the paragraph: a set corresponds to an acquisition mode). Comparison, or calibration of one set by the other (typical example of calibration of porosities, densities and clay contents analysed in well logging on core measurements) cannot be carried out directly without prior scaling. Unfortunately, we observe all too frequently log analysis calibration validated simply by a graphical presentation of a porosity (or density) graph resulting from log analysis involving a vertical seeding of more or less well adjusted "core" measurements (see Fig 2-1.20a). The problem with this practice is that it damages the credibility of core measurements - thereby justifying their non-use - and develops the feeling that log analysis is systematically accurate compared with the direct measurement, given the small size of the core sample.

Continuing with the example of the log/core comparison: in the same way as the raw log data must be corrected for environmental effects, depth matched, etc., before being interpreted in terms of petrophysical quantities, the core data must be validated by crossed exploratory analysis (see § 1-1.1.5), corrected and recalculated under confinement conditions, then scaled to match the resolution of the logging tools before being compared with the log data.

b) Construction of data consistency

This first essential step is the most tedious. The data must be obtained then processed so that they can be mutually analysed:

Compile a first version of the petrophysical and analytical database

The other core data (mainly upstream "geological" information) must be added to the other petrophysical data on routine sampling, clearly identifying the measurement/observation scales:

- Those which are at the same scale as the petrophysical sampling (e.g. lithological description of plugs, full-size samples; microlithological analyses on petrographic thin sections, mineralogical analyses, etc.).
- Those which are at the scale of the layers, sedimentary units (descriptive analysis of cores) and whose scale must be reduced to the volumes investigated by the logs.

Good control of this first scale change will help us to understand the scaling of the petrophysical parameters discussed below.

Process the data:

For example:

- if necessary, correct the petrophysical values to return them to "confinement conditions" (mainly the effect of stress and fluids);
- depth match the various data acquired on cores, which may have been shifted during the numerous handling operations.

A reference datum must be chosen for the core depth. The most reliable reference datum is the earliest information taken: this could be the initial photograph or the first "quick-look" of the sedimentologist or the well-site geologist. When reconciling the various results, the data depth must be precisely identified. Full-size samples intended for relative permeability tests are generally identified by the core depth of the top of the piece considered. The layers described by the petrographer or the well-site geologist are identified by the top and bottom depths with an additional continuity requirement between these intervals (except for coring loss). These apparently secondary considerations are essential when processing the core property log.

Note that, unlike the case of the "log sample", this depth identification is not sufficient. Several physical samples may be taken at the same depth. In addition, and still by comparison with the log analysis, an entire section of the data processing is independent of the depth: the search for the laws and relations between physical properties and lithological type; their determination is one of the bases underlying upscaling in reservoir geology (rock typing § 2-1.4).

A log analyst unfamiliar with processing core data could be surprised by this strict requirement, since it might appear obvious that the depth should be clearly indicated on all core data automatically. In practice, various specialists carry out a number of operations and transfers on the core pieces as soon as they are brought to the surface: from the usual cutting into sections of practical length, generally 1 m, up to the more or less coordinated sampling by all the analysts: petrophysicists, sedimentologists, geochemists, micropaleontologists, etc. The successive handling operations to photograph the core under natural or ultraviolet light, or by X-ray radiography, must also be added to the list. The numerous risks of positioning the pieces incorrectly or inverting them are accompanied by the inevitable expansion of the most fragile or fractured levels.

Carry out an Exploratory Data Analysis

This analysis may be limited to the petrophysical data alone. It consists in:

- checking the possibly atypical individuals which might not have been detected during the laboratory analysis;
- checking the first petrophysical "standard relations" such as the "Porosity-Permeability" correlation or the Leverett-J functions or other capillary pressure curve processing operations (§ 1-1.2.5, p. 94).

By introducing geological type data at this stage, it is possible to:

- improve the check (e.g. verify the compatibility between the mineralogy and the solid density);
- specify the standard petrophysical relations by geological units.

These methods were described in the first section of this book. For a simple study, this first phase alone may be sufficient.

F) Identification of the organisation along the well: the Core Interpolated Petrophysical Log

The purpose of the Core Interpolated Petrophysical Log is to describe the isolated (depth) measurements produced in the laboratory as a virtually continuous log of petrophysical properties, along the core, and representative of the confinement conditions. It is therefore an interpolation process based on an exhaustive analysis of all information available on the core. We have already mentioned the possible terminology confusion with core logs, discussed in paragraph C. Consequently, we will systematically use this complete denomination.

We therefore obtain a continuous high-resolution description of vertical petrophysical variations, allowing:

- easy core depth matching compared with well logs;
- calibration of the quantitative log analysis, provided that unbiased scaling is carried out;
- more rigorous comparison of the permeability measurements with the well test results (h. K and Anisotropy);
- critical analysis of the petrophysical measurements, identifying anomalic samples.

The basic principle when establishing the Core Interpolated Petrophysical Log is to interpolate the validated petrophysical measurement, based on a continuous datum (or a combination of continuous data) acquired on the core, ideally a physical log on core, otherwise the lithological description. There are generally two cases:

- Core logs are available and the vertical variation of one of them or of a combination of them correlates with the vertical variability of the petrophysical property to be interpolated.
- No relevant core log is available, but the plug "representative heights" were carefully indicated during sampling. In addition, the geologist's description is available and is as detailed as possible, at a sufficient resolution (in the worst case, to within $^1/_2$ decimetre).

a) First configuration: one or more core logs are available

The method is based on the principle of kriging with external drift. Kriging (named after the South African statistician D. G. Krige) consists of interpolation which takes into account the spatial structure specific to the variable considered. It is one of the Random Function approximation applications we decided not to discuss in paragraph 2-1.2. From a property (micropermeability in the example of Fig. 2-1.17a) for which numerous measurement points are available and whose variation correlates with the property studied (intrinsic permeability on Fig. 2-1.17b), we define the spatial variability (in our example the external drift) to calculate a "petrophysical log" going through the validated/corrected measurement points and between these points fitting the shape of the support log.

The input variables must be preprocessed in order to use this procedure:

The measurements on plugs are:

- validated by the procedure described above and recalculated under confinement conditions, if possible;
- weighted, in case of obvious heterogeneity of the core section corresponding to where the plug was taken (nodules, pluricentimetric vugs, etc.);
- completed when significant levels have not been sampled (typical example of levels which are too thin or measurements considered to be not significant: shale, evaporite, etc.) by values from a database built specifically for the reservoir.

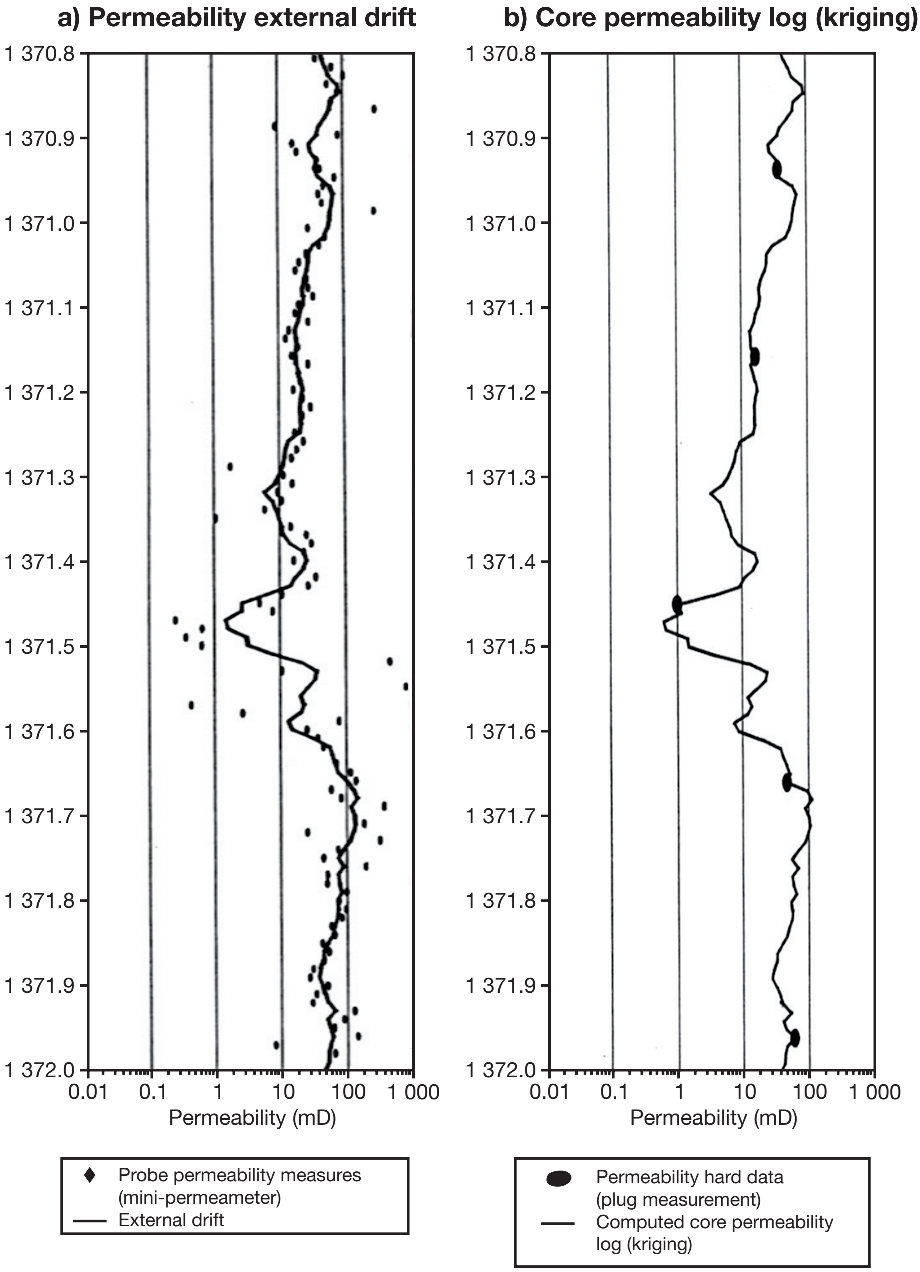


Figure 2-1.17 Example showing the construction of a core permeability log (**b**), by kriging, from the permeability spatial structure information (external shift) obtained using a minipermeameter (**a**). *In* [Greder *et al.*, 1994]

Similarly, core logs are also:

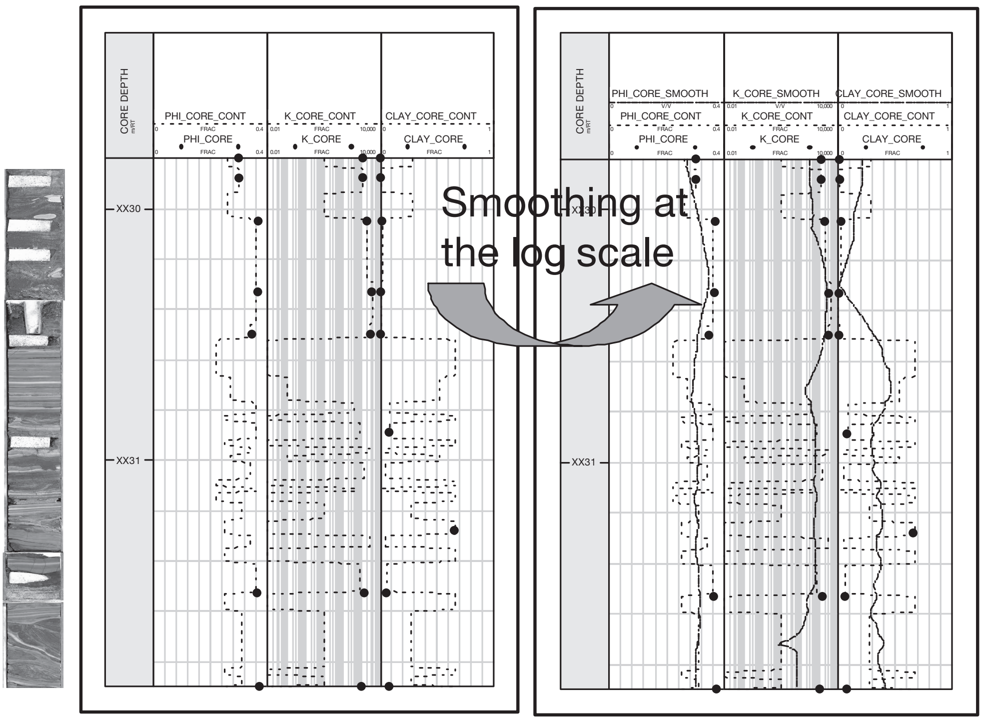
– validated/cleaned (artefacts, lack of material, etc.);
– possibly completed from more or less sophisticated processing of images acquired on cores (typical and simple example of X-ray plates processed in terms of density index log);
– recalculated with a centimetric resolution, either by resampling (natural radioactivity log) or by smoothing (minipermeameter of semicentimetric acquisition frequency).

Obviously, all these data are depth matched on the basis of well identified reference depth.

b) Second configuration: no relevant core logs are available (Figure 2-1.18)

The method is based on the plug representative heights defined during sampling (Fig. 2-1.16), after processing the measurements on plugs as previously.

The segmentation by representative heights is sometimes too basic and the sedimentological analysis is often too approximate at the required scale (centimetric



Core measurements (points) and continuous core log at sample resolution (dotted line)

Smoothing of the continuous core log with a window of 60 cm to get a smooth core log (continuous line)

Figure 2-1.18 Example showing the construction of a Core Interpolated Petrophysical Log from the core description, in the absence of any relevant core logs. *In* [Levallois, 2000] resolution). It must then be repeated by direct observation on core or, if the core is inaccessible, by analysing all the photographs available: natural light, UV light (the impregnation variations are sensitive indicators) and X-rays.

The concerned parameter value of the plug is assigned to each level identified in this way. The missing values are rebuilt as above. In this case, the data base is systematically created for each well. We therefore obtain a petrophysical log by high resolution step. Clearly, the better the coring (recovery) quality, the better the accuracy.

G) Depth matching

This obviously essential process must be carried out very carefully. Too often, this operation is carried out on an individual basis and repeated for the same well as the core data becomes available, without too much discussion between the independent disciplines: geologists sedimentologists on the one hand, petrophysicists or log analysts on the other. At the end of the studies, it is not uncommon to observe a number of conflicting depth matching analyses, leading to errors and lost time when building the reservoir models. This operation is carried out in two stages:

a) Harmonisation of the various core depths

The same process must be applied to the core data and the various well log runs. By convention in log analysis, one run is chosen to be the "depth" reference. Typically, it could be the "natural radioactivity/neutron log" combination, acquired almost systematically. A natural radioactivity probe (γ-ray) is then associated with each tool combination.

If necessary, this depth is corrected for side effects (catching, partial sticking, etc.), using the accelerometers connected to the tool combinations.

Equally, for the cores, a reference datum must be chosen as indicated above since, as soon as they are brought to the surface, the cores undergo a number of operations and manipulations which inevitably disturb their sequencing.

b) Harmonisation of core/log depths

Depth matching consists in adjusting these two references: the logger depth on the one hand and the driller depth on the other hand. For the latter, the best support is the Core Interpolated Petrophysical Log defined above, which offers the fundamental advantage of being able to display the parameters recalculated at the scale of the volume investigated by the logs, including simulating their resolution.

The Core Interpolated Petrophysical Log is therefore produced at two scales, one at high resolution to refine the physical and geological interpretations and the other, where the information is degraded to match that of the logs, intended for calibration of the log analyses.

We must remember that choosing, at the end, the "logger depth" as the "true depth" is a pragmatic convention based on the fact that not all wells are cored. The logger depth is no more "true" than the driller depth.

On the contrary, experience has shown that in a correctly cored well, the driller depth may be closer to the true value, since the length of the pipe string can be measured directly, the coring losses are taken into account knowing the core barrel dimensions. The comparison between well images and core sections must be strictly calibrated on the "driller depth" of each end of the core.

c) Terminology remark on depths in deviated wells

With deviated wells, various terminological conventions must be respected to unambiguously characterise the bed depths and thicknesses. Some definitions are schematised in Figure 2-1.19, the standard abbreviation *Z* representing the depths:

ZKB or ZRT Apparent depth (in fact, the well length) measured from the Kelly Bushing or the rotary table (there may be a difference of 1 or 2 feet between the two). It is the depth driller in the common meaning.

ZTVD: True Vertical Depth. Vertical depth, calculated from the well trajectory logs, relative to a "geographical" reference, generally mean sea level (TVDMSL) (TVDSS, for sub sea).

TVDT: TVD Thickness: Bed thickness calculated by subtracting the ZTVD values of the bed top and bottom (note that this thickness is far from being "true").

TVT: True Vertical Thickness. Vertical thickness, measured vertically through the wellbore entry point.

TST: True Stratigraphic Thickness. Thickness calculated perpendicular to the bed. The TST is the closest to the "geological" thickness.

DT: Drilled Thickness: Bed length measured along the well.

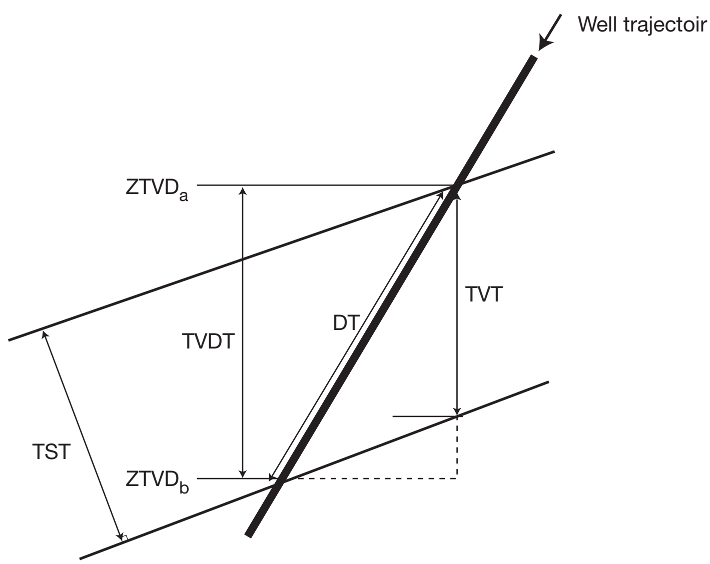


Figure 2-1.19 Diagrammatic representation of the terminological conventions used when defining bed depths and thicknesses in deviated wells

H) Conclusion: comparison of the "core log" and the well logs

One of the main applications of the Core Interpolated Petrophysical Log, after reintegration of missing data (shale levels are systematically omitted during standard procedures) is calibration of the quantitative log analysis.

To compare the two data types, the Core Interpolated Petrophysical Log must be brought to the scale of the well log. Initially, to simplify matters, this consists in calculating a sliding mean, more or less weighted, on a vertical window whose height is of the order of magnitude of the log depth resolution. Experience has shown that the resolution of the logs interpreted is rarely less than 0.5 m and even much larger, e.g. for saturations interpreted using resistivity logs.

The type of mean to be used depends on the petrophysical property considered. The arithmetic mean is always used for porosity, the solid density and mineral contents. For the total saturation, an intermediate variable ($\phi \, . \, S_w$) is required to homogenise the fluid volume with respect to the total volume. An arithmetic mean of this parameter is then used. For permeability, although the problem of comparison with a log does not arise, it may be worthwhile producing a log at the same scale. To allow for the fact that fluids mainly flow "horizontally" towards the well, the arithmetic mean is generally used in stratified formations. With "non stratified" rocks (non-sedimentary rocks but also reef limestone, etc.), it is best to use the geometric mean.

For comparison, the log analysis must also be calculated in variables of the same type as those of the Core Interpolated Petrophysical Log, e.g.: total porosity, total saturation, mineral contents by weight, etc. If all these precautions are taken, the log/core comparison is a valuable tool. Figure 2-1.20 illustrates the benefit of this method: while a crude comparison of log results and isolated plug data (Fig. a) is extremely disappointing, comparison of the well log and the "core petrophysical" log is excellent.

Ideally, the Core Interpolated Petrophysical Log should be "completed" with the corresponding core rock type. However, this sorting operation is difficult and is described in § 2-1.4, p. 317.