Formation Evaluation in Horizontal Wells

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ABSTRACT

The 1990s can be seen retrospectively as “the decade of the horizontal well”, because it was during this period that sharper seismic imaging, new drilling technology and reliable geosteering were recognized as leading to increased hydrocarbon production from extended-reach wells with correspondingly lower unit costs.

Subsequent advances in logging-while-drilling and in the deployment of wireline tools have allowed horizontal-well data broadly to match vertical-well databases in terms of the achievable range of along-hole measurements. However, tool environmental corrections in horizontal wells are more complex, particularly because of the 3D manifestations of differential invasion and formation heterogeneity. The technological advances in data acquisition have widened still further the gap between our ability to measure along hole and our ability to interpret the resulting log data.

The interpretation of environmentally-corrected, horizontal-well logs is far more difficult than for corresponding logs in vertical or even relatively high-angle wells. An overriding issue is the nature and scale of formation anisotropy. Key factors are intergranular anisotropy, laminar anisotropy and bedding anisotropy, all of which can co-exist. The situation is compounded by dipping beds and/or by undulating well trajectories. In the face of these problems, quality assurance of log analysis has drawn upon vertically-logged intervals within the same reservoir, for which groundtruthing core data are more likely to be available.

Key log-interpretation challenges are identified and possible remedial actions proposed. An important factor is how core-analysis practices should be modified in order to deliver an improved benchmarking facility for horizontal-well logs. The incorporation of the resulting petrophysical evaluation into a 3D integrated reservoir model remains an evolving issue.

INTRODUCTION

An early documented success of horizontal wells was in the karstified Rospo Mare (RSM) Field in the Adriatic Sea. The horizontal RSM-6 well resulted in a twenty-fold increase in heavy oil production for an approximate doubling of drilling costs relative to vertical producers (Bosio, 1986). Since then, the petroleum industry has enhanced the potential benefits still further through more comprehensive reservoir models, efficient drilling practices, and improved geosteering of wells towards target reservoirs in real time.

These developments have resulted in new downhole instrumentation that can function in horizontal wells, where borehole and environmental effects require even more sophisticated modelling of tool response. The recording and transmission of horizontal-well logging data has brought new advances in sensor engineering and telemetry. However, formation evaluation has not advanced at the same rate. Indeed, the emergence of a horizontal-well culture in the petroleum industry has widened still further the gap between our ability to measure and our ability to interpret the resulting petrophysical data (Fig. 1). This widening is mostly, but not exclusively, due to the various manifestations of formation anisotropy in the presence of a more complex borehole environment.

This paper examines the *status quo* in formation evaluation using horizontal-well data. The remit is to provide an overview rather than detail. The focus is on potential advances in open-hole interpretation and what is required to make progress. However, in a horizontal-well environment the integrity of the underpinning data is paramount and, as always, it represents a logical starting point.

LOG DATA ACQUISITION

A horizontal well has been defined as one with a deviation greater than 80 degrees (Passey et al., 2005). Under these conditions, standard wireline logging has given way to some other form of tool conveyance or to logging while drilling (LWD). The latter has been preferred because it also allows geosteering, the acquisition of data on a single run with consequent reductions in non-productive time, and the opportunity to bring the well on stream earlier (Rasmus et al., 2005). The drawback is that LWD programmes in horizontal wells have sometimes been designed solely with geosteering in mind, and this approach has restricted the database to gamma ray and resistivity logs, which are inadequate for comprehensive formation evaluation. Moreover, a complete well log is not achievable in any case, because the tool string sits behind the bit.

Even where sufficient horizontal-well data have been acquired, the processes of quality assurance and environmental correction of the log measurements are far more complex than is the case with vertical and high-angle well logs. First, there is the mode of tool deployment, which can be on the drillstring (LWD), tractor-driven, conveyed by pipe or coiled tubing, or shuttle-conveyed. Second, the position of a tool in a horizontal well is more variable due to arching under compression or slumping under its own weight in the absence of compressive or tensile forces. Third, the horizontal wellbore itself may contain spurious matter in the form of cuttings accumulating on the bottom. Fourth, formation anisotropy gives rise to an elliptical invasion profile, which is further distorted by fluid segregation due to gravity. These effects make it more difficult to distinguish between bad logs, which fail to satisfy quality-assurance criteria, and environmentally-impacted good logs, which still need to be corrected on the basis of 3D models of tool response (Allen et al., 1995). Descriptions of tool responses and deployment in horizontal wells have been provided by Passey et al. (2005) and by Holden et al. (2006).

The problems are compounded by the fact that most logging tools were designed to be used in vertical wells that penetrate quasi-horizontal beds, not horizontal wells that penetrate quasi-horizontal beds (Fig. 2). This is particularly true with focussed or collimated tools, which are more affected by a horizontal-well environment than tools that average around the wellbore. These considerations raise key questions about what is actually sensed by a logging tool in a horizontal well. In a vertical or deviated well, there is the established concept of "shoulder" beds on the edges of the sensed volume, and therefore tool spatial resolution along the axis of the well is a key factor. Smudging effects on tool response are reduced by some form of signal enhancement that is achieved through either enhanced tool design or data processing. In a horizontal well, the concept of shoulder beds is replaced by one of "stacked" beds, which form an integral part of the sensed volume, and therefore tool geometric functions that govern radial depth of investigation become paramount. Here, there is no easy way in which the response of a particular bed can be processed out in order to enhance the manifestation of another, so recourse has been made to tools with multiple depths of investigation. Part of the problem is that unlike the vertical-well case, in a horizontal well we do not know the character of the stacked beds and where the bed boundaries are relative to the wellbore. This is a central issue for the interpreter. Up to now, it has been addressed through a combination of 3D forward modelling and inversion (e.g. Koelman et al., 1996).

CORE DATA ACQUISITION

Core data provide the groundtruth for log interpretation. Core sampling and measurement practices have not really changed in response to the emergence of horizontal wells. This is because most core is still acquired in (sub-)vertical wells, although the technology does exist to cut core in horizontal wells (e.g. Campbell et al., 2007). Moreover, cylindrical core plugs are often cut at places where the reservoir rock appears homogeneous, so that the measured data can be as representative as possible of a particular lithology. This means that directional core measurements are often concerned with anisotropy that is well below the centimetre scale. The industry culture remains with juxtaposed sister plugs, one horizontally oriented and one vertically oriented, with the underlying assumption that the constituent material is the same for both.

If core analysis is to contribute more fully to formation evaluation in horizontal wells, directional measurements will have to be made on the same piece of rock. This suggests that samples will have to be cubic rather than cylindrical (Fig. 3). Cubic samples have already been used for specialised applications. In the first instance, one might expect this to be done on core cut in vertical wells in the same formation as that drilled horizontally. The primary aim would be to characterise the directional properties of layers. However, the concept of core-plug sampling would also have to change. For example, the presence of millimetre-scale laminations in a cubic sample would allow important information to be gathered concerning average rock properties at the centimetre scale. The principal directionally-dependent core parameters are resistivity (including formation factor, resistivity index), permeability (air, brine and relative) and acoustic velocity (or its reciprocal, sonic transit time). Porosity and water saturation are scalar quantities, and therefore derived parameters such as porosity exponent m, saturation exponent n, and the regression terms in a porosity-permeability relationship, are also directionally dependent.

ANISOTROPY AND ITS IMPLICATIONS

The word "anisotropy" is derived from Greek. Its literal root means "unequal of turning". It is used to describe the character of formations whose physical properties are significantly different in two or three orthogonal directions. Many studies assume that there is isotropy in the "horizontal" plane (i.e. parallel to the bedding) but not in a "vertical" plane (i.e. perpendicular to the bedding).

An understanding of anisotropy is a prerequisite for formation evaluation in horizontal wells: in this latter context, the word "horizontal" does, of course, refer to well trajectory.

Parametric Description

Anisotropy refers to a given parameter. The degrees of anisotropy can be different for different parameters that describe the same rock. It is quite feasible for a formation to be isotropic in terms of one directionally-dependent parameter and yet to be anisotropic in terms of another. For example, Fig. 4 contrasts (a) the isotropy of compressional wave velocity with (b) the anisotropy of formation resistivity factor for a consolidated sandstone measured at the core scale.

Mathematical Representation

The mathematical formulation of anisotropy has its foundations in the early analysis of resistivity measurements in the subsurface (Schlumberger et al., 1934). It is derived from the ellipsoidal nature of equipotential surfaces about a current source in a uniform anisotropic medium. A coefficient of anisotropy is defined:

$$\lambda = (R_v/R_h)^{0.5} \qquad (1)$$

where R_v is resistivity in the vertical plane, R_h is resistivity in the horizontal plane, and the two principal components of resistivity in the horizontal plane, R_{h1} and R_{h2}, are assumed to be equal.[1] Where this last assumption is not satisfied:

$$R_h = (R_{h1}R_{h2})^{0.5} \qquad (2)$$

Equations of the form of (1) and (2) have been extended to other parameters such as permeability. They can be applied at any scale. Electrical anisotropy has been extensively discussed by several authors (Moran & Gianzero, 1979; Worthington, 1981; Klein et al., 1995; Herrick & Kennedy, 1996; Schoen et al., 2001)

Scale of Occurrence

Anisotropy can vary with the scale at which it is considered. For petrophysical purposes, the following classification provides a useful reference framework.

•	Micro-anisotropy:	pores/intergranular ($10^{-6} – 10^{-3}$ m)
•	Meso-anisotropy:	laminations/thin layers ($10^{-3} – 10^{-1}$ m)
•	Macro-anisotropy:	bedding ($10^{-1} – 10^{1}$ m)

Fig. 5 shows a model system that is anisotropic in terms of resistivity at all three scales of occurrence. Table 1 indicates the increase in the coefficient of anisotropy with scale for this model.

Scale of Measurement

Anisotropy can only be reported at the scale at which it is measured.

- Micro-scale (coefficient of anisotropy = λ_{MICRO}): measured through core plug analysis.
- Meso-scale (λ_{MESO}): whole core analysis; high-resolution logs.
- Macro-scale (λ_{MACRO}): conventional logs.

Provided that the measurements are fully resolved at each scale, a composite or total anisotropy theoretically can be approximated as follows:

$$\lambda_T = \lambda_{MICRO} \text{ x } \lambda_{MESO} \text{ x } \lambda_{MACRO} \qquad (3)$$

where λ_T is a coefficient of total anisotropy.

Effect of Fluid Type

Anisotropy is generally greater in the partially water-saturated state than it is in the fully water-saturated state, all other things being equal. The parameters that are most affected are resistivity (Klein et al., 1995) and relative permeability (Iverson et al., 1996). This means that the degree of anisotropy of a reservoir can change during production because of a change in the interstitial

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[1] The literature refers to these conditions as "transversely isotropic", where the word "transverse" describes a plane within which there is isotropy of a given parameter, with anisotropy of this same parameter being evident in other directions. For a vertical well that penetrates horizontal beds, the *transverse* (isotropic) plane is also *orthogonal* to the direction of the logging traverse, and the terminology is therefore consistent. The transverse plane is horizontal. In the context of a horizontal well drilled through horizontal beds, the description "transversely" is potentially confusing, because the horizontal plane of isotropy is no longer orthogonal to the logging traverse but rather contains it. There is anisotropy in the vertical planes, one of which is the transverse plane in a literal sense. It would be far less confusing to refer to such a formation as "vertically anisotropic" and "horizontally isotropic", where the words "vertical" and "horizontal" refer to the bedding.

fluids. During reservoir depletion, an increased effective reservoir stress causes *in-situ* reductions in permeability, with consequent changes in the anisotropy of this parameter.

INTERPRETATION CHALLENGES

The following discussion looks beyond environmental corrections. Horizontal wells are drilled to improve access to the reservoir and thence to increase production either as producers or as injectors. The objectives of formation evaluation in horizontal wells overlap only partially with those in vertical wells. The commonality is the evaluation of reservoir properties, including permeability and pressure profiles. Beyond this, the evaluation of vertical-well data seeks fluid contacts and free fluid levels, whereas that in horizontal wells is concerned with the location of (sub-vertical) fractures, proximity to layers such as cap rocks, and the degree of lateral heterogeneity. A key issue with horizontal wells, vis-à-vis vertical and high-angle wells, is that it is much more difficult to contain the effects of water or gas breakthrough in an oil reservoir or of water breakthrough in a gas reservoir. This emphasises the need for the best possible reservoir description along with quality-controlled measurements of depth. In these respects, petrophysics has an important role to play.

Using Data from Vertical Well(s)

Since most logging tools were designed for use in vertical wells, it is appropriate to consider vertically-drilled intervals as a reference for the interpretation of logs in horizontal wells, especially where the vertical well has been fully cored in the same target reservoir (Bonnie, 1993; Radtke et al., 2006). The most important deliverables of this exercise are:

- Core measurements of key reservoir parameters.
- Assessment of anisotropy at the core scale (micro- or meso-anisotropy).
- Identification of laminated intervals (meso-anisotropy).
- Quantification of bed thickness (macro-anisotropy).
- Evaluation of formation dips.
- Determination of reference signatures of conventional logs.

It is important that conventional logs resolve the beds rather than merely detect them. Logs in vertical wells are tied back to core. This opens the door for reconciling a log in a horizontal well with a groundtruthed log in a vertical well. In isotropic reservoirs, data differences are largely environmental. In anisotropic reservoirs, they are compounded according to the scale of anisotropy. *Whatever the degree of complexity, it is imperative that as much information as possible be obtained from vertical wells about the geological and petrophysical character of the unit that is to be drilled and logged horizontally.*

Volumes Sensed by Logs

Different logging tools have different depths of investigation, which are determined by tool design, environmental conditions, wellbore direction relative to bedding, and formation properties (Yin et al., 2006). A major challenge for the interpreter is to effect an evaluation where formation properties are changing in directions of tool measurement and where, unlike the assumed vertical-well situation, these variations co-exist with the perturbing effects of invasion. The primary concern is whether a bounding shale is manifest in the response of a deeper-sensing log. If it is, only the shallower readings should be used for formation evaluation. The second issue is whether a reservoir unit that is bounded by shales is lithologically heterogeneous and to what extent. In these situations, special care must be taken concerning differential depths of investigation (Fig. 6). The third question is whether the reservoir unit is isotropic or shows micro-anisotropy, meso-anisotropy or macro-anisotropy, or perhaps all three forms of anisotropy. These cases are considered separately in the following subsections, which focus on resistivity as a key reference parameter.

Micro-anisotropy

The context is a reservoir unit that is sufficiently thick for the cap rock to be beyond the depth of investigation of logging tools. Anisotropy at the grain-grain scale is manifest in core measurements. This is the only anisotropy that would be evident in a homogeneous tank. Fig 7 shows how a formation can be (b) heterogeneous and isotropic and (c) homogeneous and anisotropic, at the micro-scale. Fig. 8 illustrates schematically log resistivity measurements in formations that show only micro-anisotropy in both vertical and horizontal wells. Even after full and appropriate environmental corrections, the measurements could be very different. Therefore, directional dependence has to be taken into account in formation evaluation. In the presence of micro-anisotropy, resistivity tools in vertical and horizontal wells read as per Table 2.

Meso-anisotropy

The context is one of laminations or thin beds that cannot be resolved by a logging tool, i.e. there is no place where a tool sees a given layer and nothing but the layer (Fig. 2). To simplify the immediate discussion, the individual layers are presumed to be isotropic. Resistivity tools in vertical wells that penetrate horizontal beds record resistivity in the horizontal plane as follows:

$$R_h = H\,(\Sigma\,(h_i/R_i))^{-1} \qquad (4)$$

where $1 \leq i \leq p$, and p denotes the number of laminations or thin beds of thickness h_i within the spatial resolution H of the tool. The contribution of each layer represented in Equation (4) should strictly be weighted using an axial tool-response function.

Resistivity tools in horizontal wells read a combination of R_h and R_v. Here R_h is written as before but the physical significance of p is not the same because the sensed volume of laminations has changed. R_v is written:

$$R_v = (1/D)\,\Sigma\,(h_i\,R_i) \qquad (5)$$

where $1 \leq i \leq p$, and p denotes the number of laminations or thin beds (above and below the well) within the vertical range of investigation of the tool D, which is twice the depth of investigation as measured from the axis of a centred tool. The contribution of each layer represented in Equation (5) should strictly be weighted using a radial distribution of tool geometric factors.

Here there is no clear approach to the adoption of values of m and n for the evaluation of water saturation. The best reference is the depth-distribution of these exponents in a vertical well. This would call for a fit-for-purpose approach to sampling for special core analysis. It also calls for a clear insight into the physical character of the sedimentary succession and a reliable knowledge of where the horizontal well is in that succession. This latter requirement reiterates the need for accurate depth control during drilling.

Macro-anisotropy

The context is one of thick beds that can be resolved by a logging tool in a vertical well, i.e. there are places where a tool sees a given layer and nothing but the layer. In this situation, the anisotropy due to layering is beyond the petrophysical scale. The individual layers may themselves be anisotropic, as illustrated in Fig. 8. If they are, the vertical well problem reduces to one of micro-anisotropy.

The horizontal-well case is more complex. Much depends on the position of the wellbore relative to bed boundaries and the depth of investigation of a given tool. In some places, shallow tools will see a single bed (the micro-anisotropy problem if the layer is anisotropic) while deeper tools will see more then one bed (a simplified form of the meso-anisotropy problem).

An undulating quasi-horizontal wellbore can provide useful information, especially where the beds are fairly thick (Fig. 9). Note, however, that the comparatively small angle between the well axis and the dip will cause bed boundaries to be unclear.

TECHNICAL RESPONSE

The technical response to the above challenges is summarized in Table 3. Essentially, a vertical well that penetrates the horizontally-drilled interval is used to determine the degree of complexity of the reservoir unit. The information obtained provides the basis for modelling tool response in a horizontal well in that particular geological setting. The vertical well also furnishes groundtruthing data to which the horizontal-well log analysis can be compared. Interpretative procedures are very much dependent upon the type of anisotropy that is present. In the case of meso-anisotropy, as defined here, depth of investigation becomes crucial in terms of different tools sensing different groups of layers and, at the limit, certain tools sensing a cap rock or basal shale. Porosity is addressed through azimuthal nuclear tools. Resistivity is approached through differential depths of investigation with the same tool. All the characterising parameters required for interpretation are more difficult to define in a horizontal-well setting, yet interpretation practices continue to evolve.

CONCLUSIONS

In horizontal wells, the biggest measurement issue is the need to sense directionally with controlled depths of investigation. The biggest interpretation issue is how to handle stacked beds. These matters come together when dealing with the more complex borehole environment that horizontal wells present to the tool engineer and to the petrophysical interpreter. Some longer term benefits will be forthcoming from the availability on the drillstring of tools such as electrical imaging devices and magnetic resonance logs.

One thing is certain – horizontal wells are here to stay. It is therefore especially important to derive the maximum benefits from horizontal-well data in terms of production enhancement and ongoing reservoir evaluation and management.

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Table 1 Anisotropy of resistivity as a function of scale for the model of Fig. 5

Scale	R_v (Ωm)	R_h (Ω m)	Coefficient of anisotropy, λ
MICRO	24	20	1.1
MESO	36	26.7	1.2
MACRO	14.9	7.2	1.4

Table 2 Electrical parameters for vertical and horizontal wells in micro-anisotropic formations

Parameter	Type of well	2D anisotropy (vertical plane)	3D anisotropy
Log-derived resistivity	Vertical	R_h	$(R_{h1}R_{h2})^{0.5}$
	Horizontal	$(R_hR_v)^{0.5}$	$(R_{h1}R_{h2}R_v)^{0.5}$
Archie porosity exponent	Vertical	m_h	$(m_{h1} + m_{h2})/2$
	Horizontal	$(m_h + m_v)/2$	$(m_{h1} + m_{h2} + m_v)/3$
Archie saturation exponent	Vertical	n_h	$(n_{h1} + n_{h2})/2$
	Horizontal	$(n_h + n_v)/2$	$(n_{h1} + n_{h2} + n_v)/3$

Table 3 Summary of technical responses needed for formation evaluation in horizontal wells

Technical Challenge	Technical Response
Consistent terminology	Expanded glossary
Geosteering requirements	Non-exclusive subset of LWD toolstring
Complex borehole environment	3D modelling of tool responses 3D departure corrections Enhanced borehole depth control
Asymmetrical measurement domain	Azimuthal and multi-depth tools Tools that can see further but in a controlled manner
Micro-anisotropy	Identified using core data from vertical well Orthogonal core measurements of directionally-dependent parameters Directionally-dependent petrophysical algorithms
Meso-anisotropy	Identified using whole core or image logs in vertical well Characterise layers and quantify dips Identify layer sequences Accurate wellbore positioning in the column Manage stacked beds Quantify radial geometric functions
Macro-anisotropy	Identified using conventional logs in vertical well Tool-specific criteria for effective constancy of log data to be classified as a bed Elements of micro- and/or meso-anisotropy responses according to local conditions
Need for an interpretation workflow	Make maximum use of vertical wells as a reference Generate a catalogue of archetypal tool responses for different along-hole situations Collate literature to extract commonalities of approach
Greater uncertainty in formation evaluation (FE)	Rank environments in terms of degree of petrophysical complexity Evolve a look-up uncertainty for each set of horizontal-well conditions
Reservoir description between vertical wells	Investigate ways of controlling the populating of geocellular models Identify lead model realisations Especially useful where beds show highly significant dips
Core data in horizontal wells	Paradigm shift away from not coring development wells
Net pay	Quantify along hole for completions and in true vertical space for volumetric analysis Demonstrate the value of FE in horizontal wells

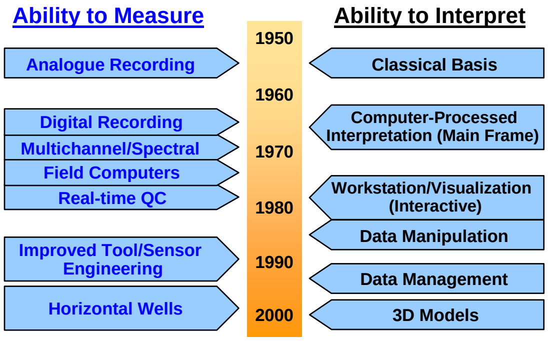

Fig. 1 History of technological developments in petrophysics.

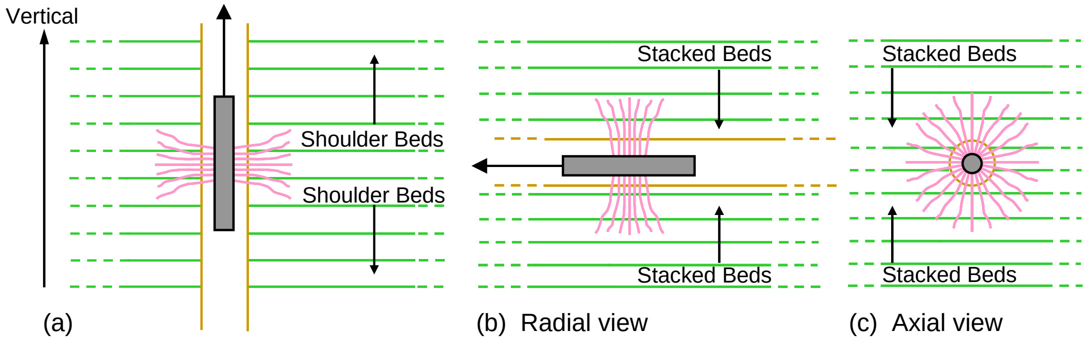

Fig. 2 Concepts of (a) shoulder beds in a vertical well and (b,c) stacked beds in a horizontal well, at the meso-scale.

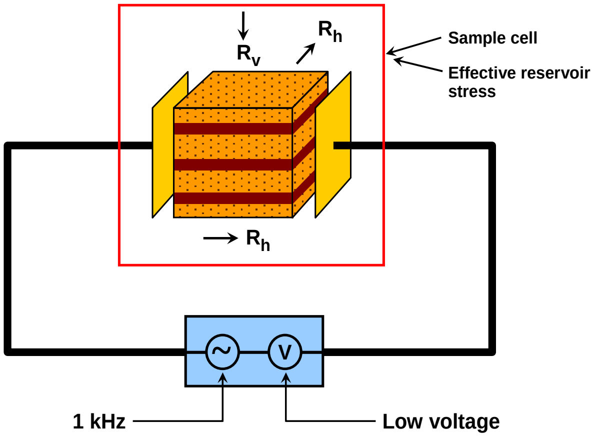

Fig. 3 Schematic measurement of cubic core samples.

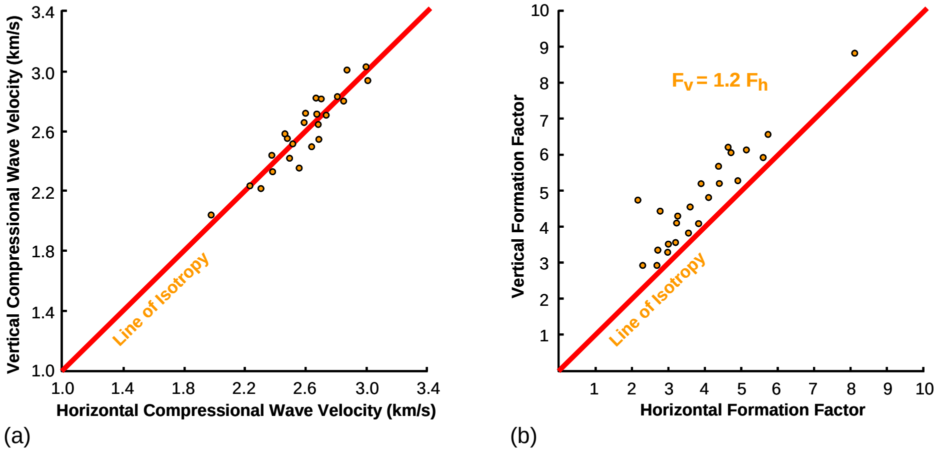

Fig. 4 Contrast between (a) isotropy of compressional wave velocity and (b) anisotropy of formation factor at the core scale for a consolidated sandstone.

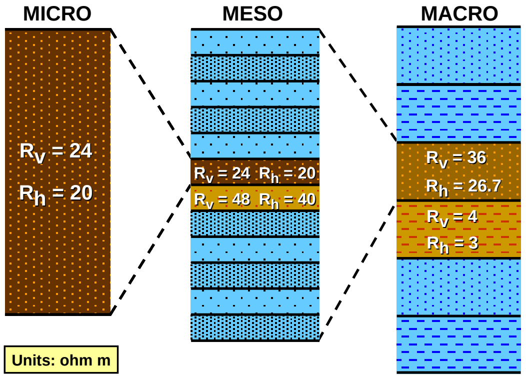

Fig. 5 Anisotropic model as the basis for Table 1.

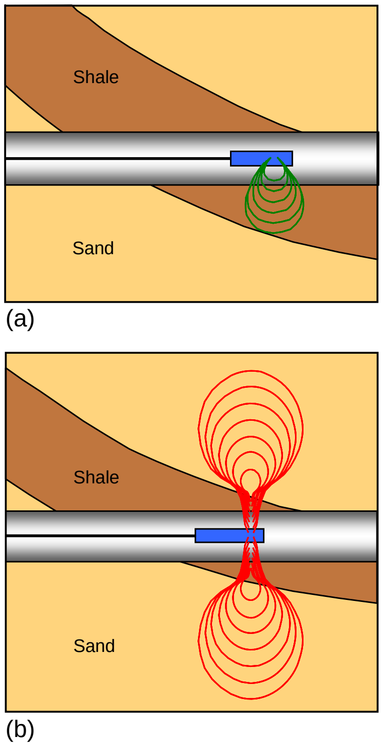

Fig. 6 Schematic illustration of differential depths of investigation for (a) porosity and (b) deep resistivity tools.

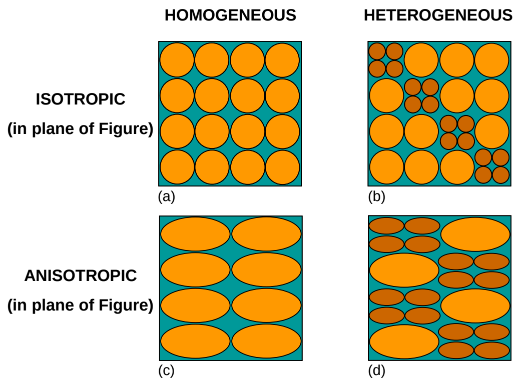

Fig. 7 Micro-scale examples of coexisting:
(a) homogeneity/isotropy;
(b) heterogeneity/isotropy;
(c) homogeneity/anisotropy;
(d) heterogeneity/anisotropy.

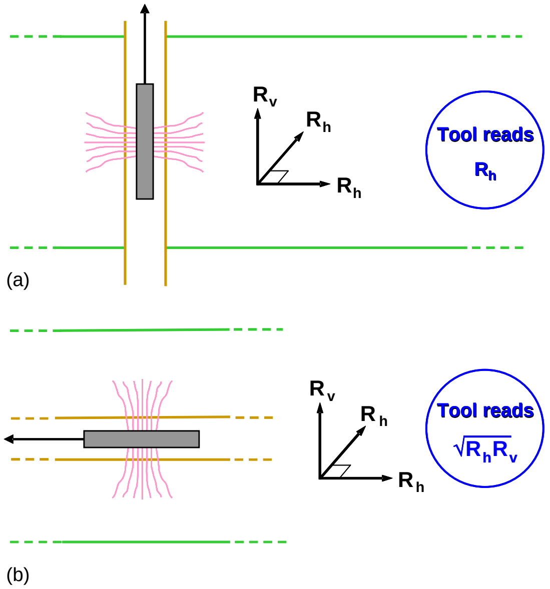

Fig. 8 Schematic tool deployments in (a) vertical and (b) horizontal wells, in the presence of micro- and macro-anisotropy. The beds are sufficiently thick that tool response is unaffected by adjacent beds.

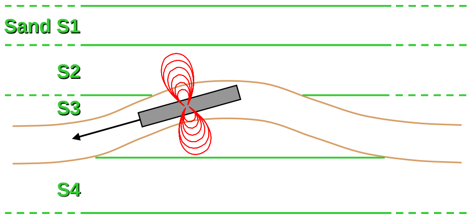

Fig. 9 Illustration of effect of drifting wellbore on tool response. Where the wellbore drifts through different reservoir layers, this can provide important information for tying back to vertical well data, provided that the physical character of the sedimentary succession has been established at the vertical well.