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1 Introduction

Overview

Introduction

Formation evaluation with wireline logs, for the purpose of estimating hydrocarbon pore volume (HPV), requires methods to accurately determine net-pay thickness, porosity, and hydrocarbon saturation. Traditional petrophysical algorithms, such as Archie's equation, need estimates of true formation resistivity (Rt) to calculate saturation and HPV, but many factors interfere with the ability to determine Rt. Resistivity modeling allows for accurate estimation of Rt from measured log data.

This chapter introduces the concepts of resistivity modeling for formation evaluation. The history of resistivity logs and modeling is reviewed briefly, and some fundamental concepts and terms, such as dimensionality of earth models and forward and inverse log modeling, are defined. The rationale for why and when resistivity modeling should be applied is introduced by a discussion of tool resolution and accuracy.

Contents

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The Quest for Rt

History of resistivity logs and modeling

Perhaps the most appropriate way to summarize the history of resistivity logs is to describe the subject as the quest for Rt, the true formation resistivity uncorrupted by borehole invading fluids. Such an endeavor implies the need for a resistivity tool that measures beyond the influence of borehole conditions, mudcake, caves, shoulder beds, and any other zones that give rise to anomalous signals leading instead to a measurement of Ra, the apparent formation resistivity. The quest for Rt has been ongoing in the logging industry ever since Conrad Schlumberger tipped his surface-electrical-prospecting array vertically to log down a wellbore, reasoning that the current from the electrodes spread out into the formation around the borehole (Schlumberger et al., 1934). An earth model was then assumed, and the laws of physics were used to predict analytically the response for a given electrode configuration (i.e., resistivity-tool-response modeling).

Historically, resistivity-tool-response modeling started with resistivity-logging-tool design. The primary effort in modeling resistivity tools was to design tools that measured Ra as closely as possible to formation Rt. Early experimental modeling used small electrodes in infinite-conductivity saltwater baths. Later, tool responses were studied using mock-up sondes in more realistic environments, created by using thin impermeable membranes to separate waters of different salinity.

Starting in the early 1950s, scale models and analog computers (resistor networks) were built to characterize tool responses in cases where complicated mathematical models do not yield analytical solutions.

H. Guyod (1955) discussed an approximate solution of Laplace's equation, $\nabla^2 V = 0$, where V = electrical potential, with proper boundary conditions, and a resistor network was designed to simulate tool response for a given formation and electrode arrangement. Sponsored by several major oil companies, Guyod designed a resistor network containing approximately 300,000 resistors. The innovative network consisted of a barrel with 2000 small mercury cups, arranged in a helical pattern on its inside surface, and a center rotor, bearing 1000 brass pins that can fit inside the cups in order to move the mud and formation networks into a new position relative to each other.

Until the late 1970s, a similar resistor network had been used at the Schlumberger-Doll Research Laboratory in Ridgefield, Connecticut (Figure 1.1). The network, consisting of nearly 500,000 resistors, led to predicting tool responses relative to true formation resistivity and to creating many of the early log-correction charts.

Despite the drawbacks to this kind of modeling, such as the difficulty in exchanging or reconfiguring thousands of resistors to build each new case, the scale modeling was successfully applied in studying galvanic tools. However, scale modeling was not readily adaptable to tools that have large depths of investigation, such as induction tools.

Large improvements in computing capability have introduced qualitative changes in the role of modeling since the 1980s. Direct numerical solutions of Maxwell's equation can be used to compute resistivity tool response in earth models with complex geometries. In these, the geometrical restrictions are much less severe than in analytical and scale models. Realistic problems can be formulated, and the solutions appear as simple and unthreatening numbers, rather than as arcane and difficult-to-compute mathematical functions. Computerized modeling has reduced from weeks to minutes the time required to calculate many borehole environmental effects on resistivity-tool

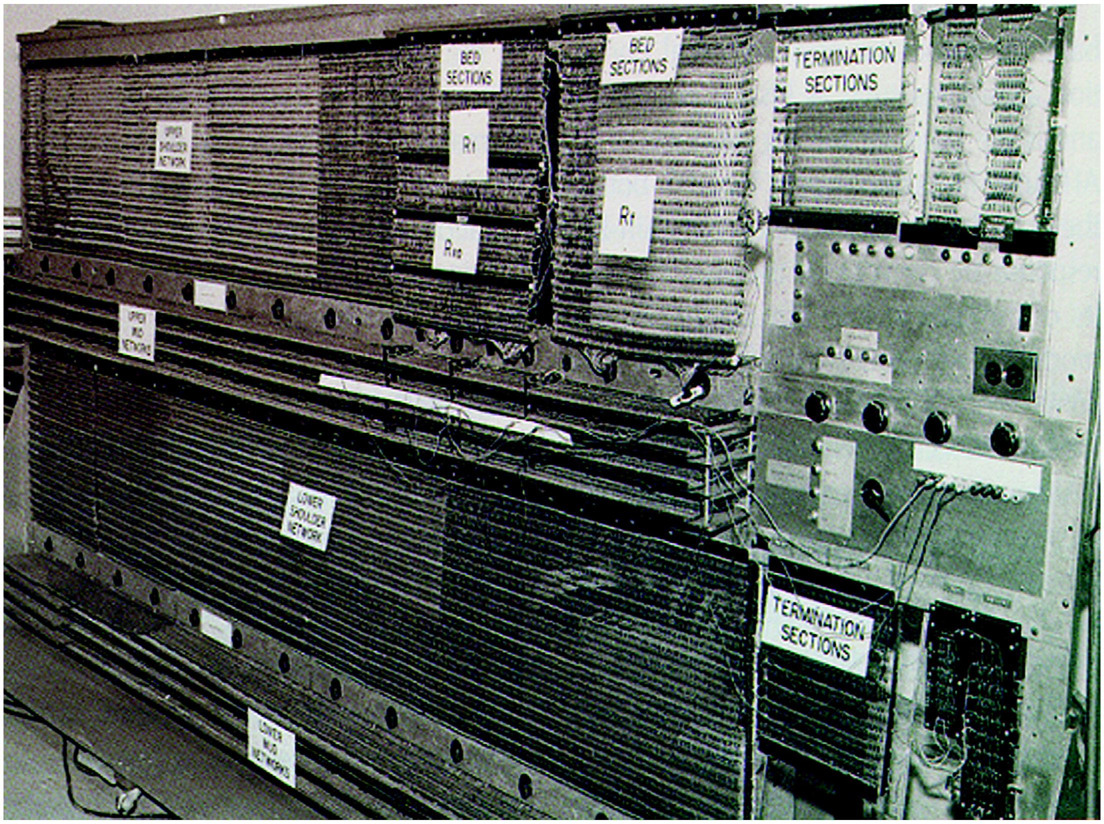

Figure 1.1. The resistor network as an analog computer for two-dimensional (2-D) resistivity-tool-response modeling. This last resistor network consisted of two racks, about 6 ft (1.8 m) tall and 12 ft (3.7 m) long, with nearly half a million resistors (Anderson et al., 1997, used with permission of Schlumberger).

responses. A systematic evaluation of the effects of such environmental conditions as borehole rugosity, caves, mud cake, invasion, dip, shoulder beds, and formation anisotropy on resistivity-tool response is now possible.

These theoretical simulations of tool responses to layered and invaded formation generated books of departure curves. In fact, most current resistivity-correction charts provided by service companies are the result of numerical computer simulation, rather than physical experimental scale modeling.

Earth Models

Definition

Resistivity-tool-response modeling may be categorized to the class of boundary-value problems. The earth model specifies the geometry and boundaries of earth regions of differing resistivity, and the resistivity within each region. A resistivity tool with its electric source(s) and detector(s), or transmitter(s) and receiver(s) located at specified points is introduced into the earth model. The source(s) or transmitter(s) excite the earth medium in some specific manner. With some assumptions made about the spatial distribution of resistivity, the solutions for resistivity tool response under a given earth model can take the form of simple formulas derived from Maxwell's equations, giving the electromagnetic (EM) field for any desired point in space. For more complicated cases, the EM fields cannot be expressed in terms of analytical functions, but must be laboriously computed at many points in space simultaneously. The degree of earth-model complexity may be summarized by referring to geometries of differing dimensionalities: one-dimensional (1-D), two-dimensional (2-D), or three-dimensional (3-D).

Consider the Cartesian coordinate system shown in Figure 1.2, specified by the coordinates x, y, and z.

1. One-dimensional: If the resistivity (R) varies in only one coordinate direction, then the geometry is referred to as a 1-D earth model. In a parallel-layered geometry of sedimentary rock with no borehole, the resistivity of the formation varies only in the z-coordinate direction; $R = R(z)$ (i.e., 1-D Vertical, when borehole is perpendicular to bedding plane. The relative dip is defined as the angle between the borehole and the normal of bedding plane). Or, in an infinitely thick homogeneous formation penetrated by a borehole with mud-filtrate invasion, the resistivity varies only in the radial direction around the borehole: $R = R(x) = R(y) = R(r)$ (i.e., 1-D Radial, when borehole is perpendicular to bedding plane).

2. Two-dimensional: If resistivity varies in the vertical and radial directions due to bedding, borehole conditions, and mud-filtrate invasion but is reasonably axisymmetric around the borehole, then the earth model can be adequately defined as 2-D, $R = R(x, z) = R(y, z) = R(r, z)$.

3. Three-dimensional: When $R = R(x,y,z)$, the earth model is said to be 3-D.

Applications of 1-D, 2-D, and 3-D modeling

Applications of 1-D, 2-D, and 3-D resistivity modeling are listed below. The associated earth-model geometries are illustrated schematically in Figure 1.2.

Table 1.1. Applications of 1-D, 2-D, and 3-D modeling

Modeling Dimension	Effects addressed
1-D	Bed thickness, shoulder beds, dipping beds
2-D	Borehole and caves, invasion
3-D	Heterogeneous Rt

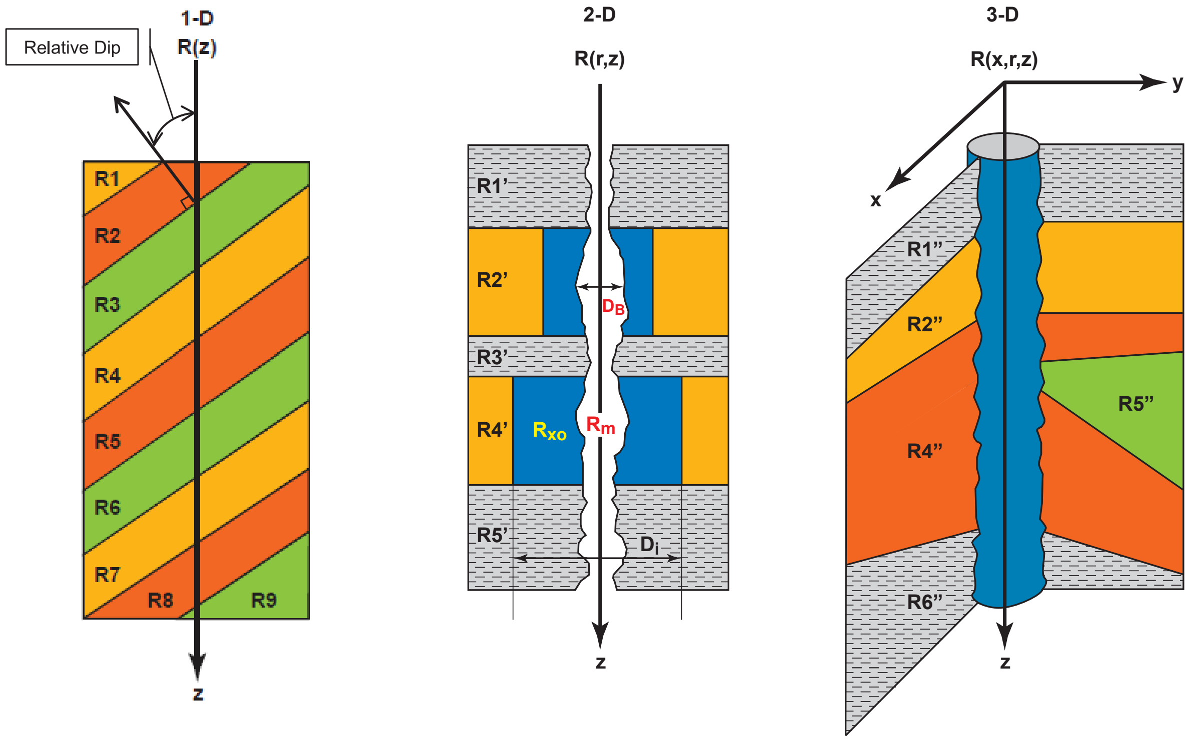

Figure 1.2. Schematic resistivity profiles for earth models in one dimension (1-D) if the resistivity varies in borehole axial direction (R = R[z]); two dimensions (2-D) if resistivity varies in the vertical and radial directions (R = R[x,z] = R[y,z] = R[r,z]) axisymmetric around the borehole (where R_{xo} = resistivity of invasion zone, R_m = borehole mud resistivity, D_i = diameter of invasion zone, and D_B = diameter of borehole); and three dimensions (3-D) if resistivity varies in all major axes (R = R[x,y,z]).

Forward and Inverse Modeling

Forward modeling

The numerical process of reconstructing a resistivity log for a given earth model is often referred to as forward modeling. Forward modeling typically results in a unique and robust solution for the modeled resistivity log.

Forward modeling entails the analytic or numerical solution of Maxwell's equations in a mathematical boundary-value problem, where the earth model specifies the boundaries and shapes of earth regions of different resistivities. The resistivity logging tool is introduced into the earth model by locating its transmitter(s) and receiver(s) at specified points. The transmitters excite the physical medium of the earth model in a mathematically defined manner. For a 1-D earth model, the solutions of Maxwell's equations can take the form of simple formulas, giving the EM field for any desired point in space. For 2-D or 3-D cases, the EM fields cannot be expressed in terms of analytical functions, but must be laboriously computed at many points in space simultaneously. The mathematical and numerical techniques used in forward modeling have been the subject of many publications, and discussion of these techniques is outside the scope of this volume. See, for example, Anderson and Gianzero (1983); Anderson et al. (1996); Chew et al (1984); Gianzero et al. (1985).

A schematic representation of 1-D forward modeling is shown in Figure 1.3. On the left is the earth model. It assumes no borehole washout or ellipticity and no invasion. Simplified tool-response functions with three different depths of investigation (shallow, medium, and deep) are shown in the middle. In principle, the depth of investigation of an induction tool is proportional to the spacing between the transmitter and receiver coil pairs (i.e., the longer the spacing, the deeper the tool measures). The right-hand side shows the true resistivity of the formation (orange), and the shallow (blue), medium (green), and deep (red) resistivity logs. The deep resistivity tool reads the lowest values over the interval, because the thicknesses of the beds are below the vertical resolution of the deep tool, whereas the shallow tool reads nearly the true Rt here in the absence of invasion.

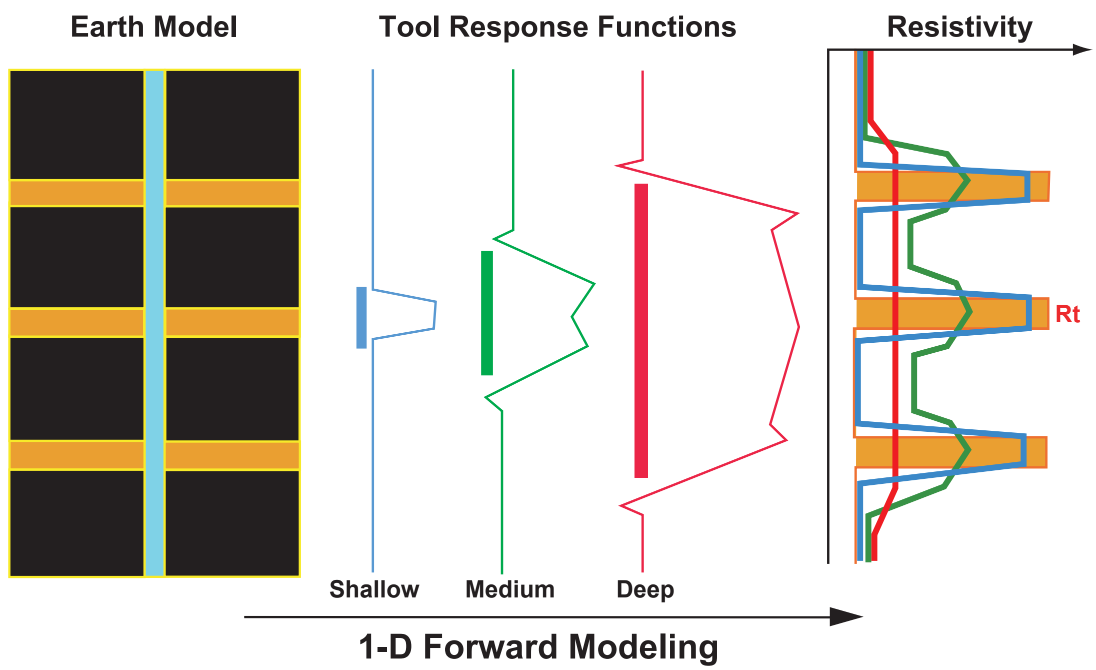

Figure 1.3. Schematic representation of 1-D forward modeling of resistivity in ohm m of an earth model where the sands are not invaded. Rt = true resistivity.

Inverse modeling

The process of deriving an earth model including an Rt profile from a set of given field logs with appropriate resistivity-tool-response functions is referred to as inverse modeling. Inverse modeling entails iteratively adjusting the formation resistivity (Rt), bed boundaries, and (for a 2-D model) invasion depth and invasion-zone resistivity (Rxo) in each layer of the earth model, and repeating the forward-model calculation, until an acceptable replication of the observed field logs is achieved. Inverse modeling may not yield a unique solution.

Figure 1.4 is a schematic representation of 2-D forward and inverse modeling. The sand layers have been invaded by mud filtrate. The tool-response functions for the shallow, medium, and deep resistivity tools are shown in the middle. The right-hand side shows the true resistivity of the formation Rt, resistivity of the invaded zone Rxo, and the respective shallow, medium, and deep tool readings. In this case, the shallow resistivity log is significantly lower than true resistivity (Rt) but closely agrees with the invaded zone resistivity Rxo because of invasion (contrast with Figure 1.3).

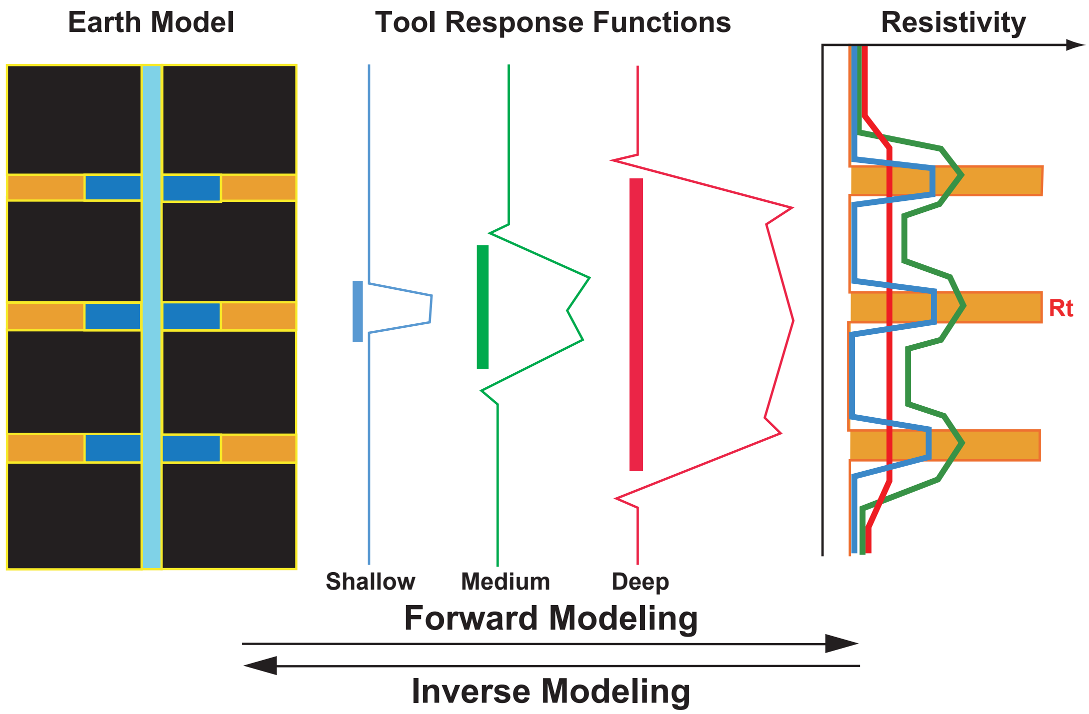

Figure 1.4. Schematic representation of 2-D forward- and inverse-modeling process of resistivity in ohm m for an earth model where the sands are invaded.

Acceptable error

In this volume, resistivity-tool-response modeling, when applied for formation evaluation, involves replicating the observed field log by numerically solving the mathematical boundary-value problem of the electromagnetic fields generated from a specific resistivity tool under a pre-defined earth model on trial. To the degree that the field-log and the modeled-log responses are in acceptable agreement, the underlying earth model can be considered one possible representation of the formation's true-resistivity profile. If the assumption in the defined earth model (1-D, 2-D, or 3-D) is close to the reality where the field log data were obtained, such an acceptable agreement can be defined by the tool-sonde error in many cases.

Non-uniqueness in inversion

Resistivity modeling may not yield a unique solution. Multiple acceptable replications of the observed field log may be achieved through resistivity modeling by variation of the formation resistivities, bed boundaries, and invasion depths. Hence, the derived earth model may not be the true formation-resistivity profile, but one possible representation that yields a similar observed response.

Non-uniqueness is particularly problematic in formations where the bedding frequency (inversely related to bed thickness and spacing) exceeds the so-called blind frequency of the logging tool. The blind frequency is the maximum spatial frequency below which individual beds can be distinguished on the log. For bedding above the blind frequency (and thinner than the corresponding minimum thickness and spacing), individual beds cannot be distinguished, and non-uniqueness becomes a major factor in inversion. As an example, the blind frequency of the dual induction log is in the range of one bed per foot (0.3 m). See Chapters 3 and 6 for more details.

To minimize non-uniqueness, it is essential to integrate logs with different depths of investigation and vertical resolution, and to employ constraining data from all possible sources in the application of resistivity modeling for formation evaluation. For example, core images or borehole-image logs may be utilized to identify bed boundaries and thicknesses. Petrophysical limits from porosity logs or core data may be used to derive possible maximum and minimum resistivity values. Knowledge of tool physics, local geology, and offset well data may lead the resistivity modeler to a more realistic earth profile of formation resistivity.

Why Model Resistivity for Formation Evaluation?

Rt for HPV

The accuracy of hydrocarbon saturation calculated from well logs is fundamentally dependent upon accurate determination of Rt. True formation resistivity is an essential input into hydrocarbon-resource assessments in petrophysics. If the apparent resistivity (Ra) measured by a resistivity tool is used directly to estimate hydrocarbon saturation and hydrocarbon pore volume (HPV), errors in HPV will generally result.

Tool resolution and accuracy

Because of tool physics and borehole conditions, formation resistivity measured by a logging tool, Ra, is not equal to Rt in most logging environments. All deep-reading resistivity tools are influenced by the resistivity distribution in a large volume surrounding the sonde. For example, the deep induction resistivity tools may not resolve beds less than 2 ft (0.6 m) thick even after resolution-enhancement processing, because their vertical resolution is limited by induction-tool physics and the spacing of the deep-reading coils.

Chart book vs. computer modeling

Traditional environmental correction charts usually do not provide satisfactory remedies for estimating environmental effects on resistivity logs. The charts that are provided by the service companies have limiting assumptions that seldom match real-world examples. Computer modeling can be done to convert apparent resistivity from logs into a response profile that may be closer to reality. In fact, any modern environmental correction chart provided by a service company is the result of computer modeling.

High-resistivity anomalies may not correspond to resistive beds, but rather to the interface between two beds, each with lower Rt than the Ra indicated on the log. Such an anticorrelation may often be mistaken as depth mismatch, and only modeling may resolve the correct depth and resistivity of each bed.

With the advent of modeling codes (computer programs) to simulate resistivity-tool response, and with significant increases in computing power, resistivity modeling has become a feasible alternative to chart books for formation evaluation. When appropriately used, resistivity modeling can reduce uncertainty in resistivity-based reserve estimates.

When Should Rt Modeling be Considered?

Practical considerations

Although resistivity modeling is becoming practical with the continual increase in computing power, resistivity-tool-response modeling may still be quite time consuming, especially in 2-D and 3-D modeling. Whether resistivity-tool-response modeling is practical for a given well should be objectively judged, based on project requirements and available information from field logs.

When accurate resistivity-based HPV calculation is required, resistivity modeling should generally be applied when the chart-book-specified environmental conditions do not approximate the borehole conditions in which the logs were collected.

"Strange" resistivity log interpretation

Wells are often not ideal for logging. Resistivity logs from deviated and horizontal wells, drilled to optimize productivity, often appear counter-intuitive, and are not correctable by chart books. The physical principles embodied in Maxwell's equations of resistivity tools are well understood, and with modeling capable of honoring enough details of the tool physics and borehole environment, such responses are predictable. Tool response artifacts such as polarization horns, which appear as large transient overshoots in the resistivity response at bed boundaries in deviated wells, can be readily understood through modeling.

When does resistivity modeling have high risk?

Defining resistivity for beds thinner than the vertical resolution of deep-reading resistivity tools is highly uncertain without additional constraints, such as core-plug saturation data to define bed resistivity and high-resolution log or core images to rigorously define beds and bed thicknesses. This is due to the tools' physical limits in accuracy and sensitivity for beds thinner than the vertical resolution of the tool. The vertical resolution of today's array induction tools is about 2 ft (0.6 m), and that is also about the vertical resolution of most porosity logs. Because of limited resources for modeling porosity logs, resistivity modeled for beds thinner than 2 ft (0.6 m) may not completely address the uncertainty in HPV calculation, except when the well has core-plug porosity. Moreover, when beds are thinner than the vertical resolution of deep-reading resistivity tools, other techniques may work well and be more economical, such as the parallel-conductivity model and/or volumetric laminated sand analysis (VLSA) (Passey et al., 2006).

Flowchart for applicability of resistivity modeling

The following flow diagram summarizes when and where resistivity modeling should be considered.

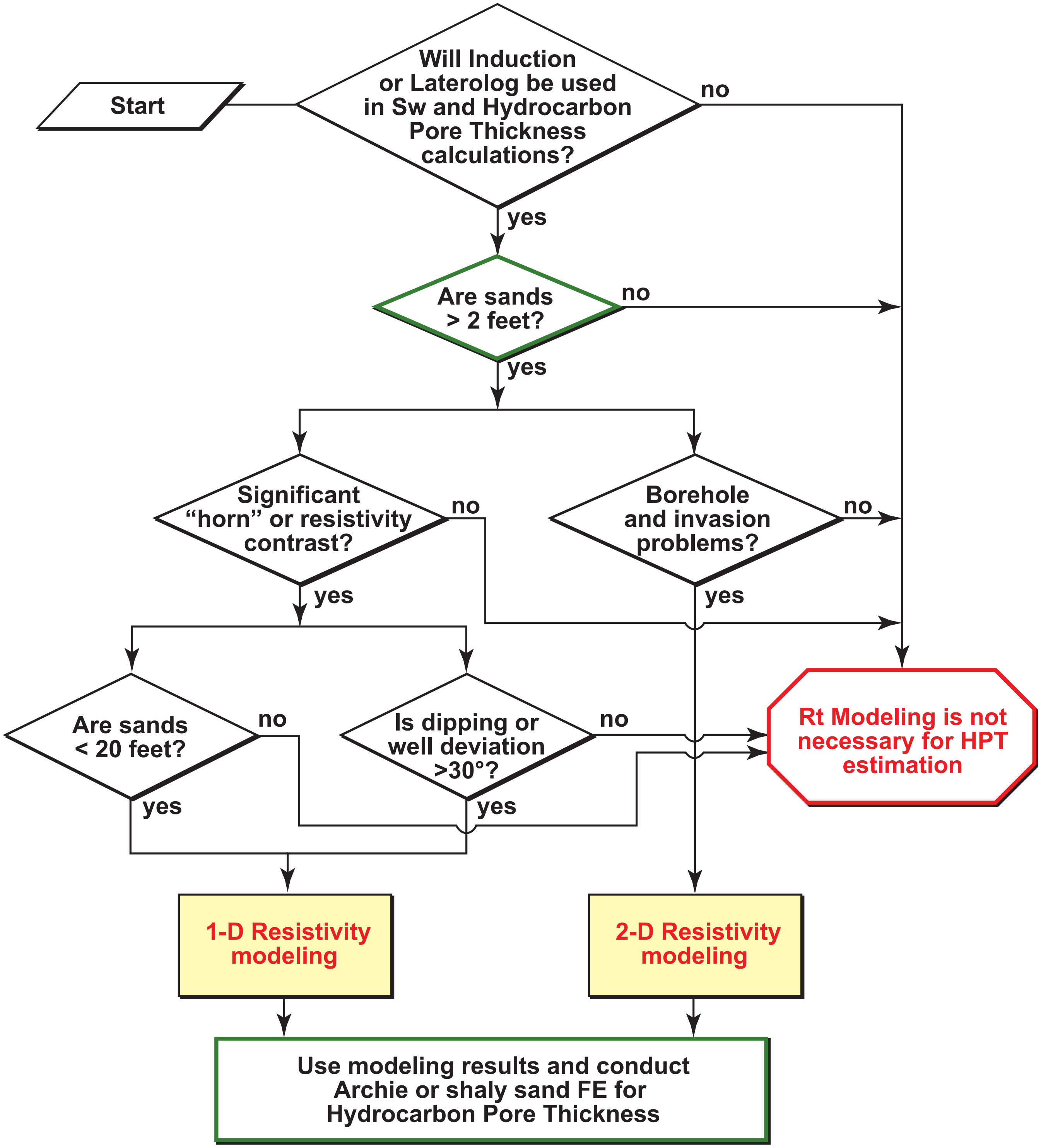

Figure 1.5. Flow diagram summarizing when and where to apply resistivity modeling. Sw = water saturation