PRACTICAL ENHANCED RESERVOIR ENGINEERING

Assisted with Simulation Software

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PREFACE

Practical Enhanced Reservoir Engineering—Assisted with Simulation Software is written to modernize and bring up-to-date petroleum reservoir engineering for college students. It is designed to prepare graduates to play an active and important role throughout the reservoir life cycle in the various phases of the reservoir management process with fellow geoscientists as members of the asset team. Teamwork is more important than ever, as we need to manage our reservoirs in a way that will make our projects profitable and our companies successful.

This book is not just a usual college textbook, but a modern and very practical guide with reservoir engineering fundamentals, advanced reservoir-related topics, and reservoir simulation fundamentals, problems, and case studies from around the world. The graduates can use these in their profession on a daily basis.

Reservoir engineering is the heart of petroleum engineering. In essence, reservoir engineering deals with the flow of oil, gas, and water through porous media, and the associated recovery efficiencies. Along with basic reservoir engineering, students will gain additional and advanced knowledge to play an active and important role throughout the reservoir life cycle, including discovery, delineation, development, production, and abandonment. Students will also be equipped to understand the various phases of the reservoir management process, including setting a strategy, developing a plan, and implementing, monitoring, evaluating, and completing it. In the digital age, petroleum fields are increasingly viewed as "digital fields," "smart fields," or "e-fields." This has occurred as wells have been transformed into next-generation "smart wells," coupled with robust information management systems. The vision is to attain real-time or near–real-time control on the assets, including continuous optimization of oil and gas production and maximization of recovery. Reservoir engineers are involved now not only in deterministic but also probabilistic methods, economics, recovery processes, and reserves estimation. Stand-alone studies in reservoir engineering and management are transitioned into integrated modeling.

In writing this book, the authors bring their lifelong experience and expertise in reservoir engineering and simulation techniques and practice. Reservoir simulation techniques play a very important role in enhancing basic reservoir engineering concepts and practice. Thus, applications of reservoir simulation methods are included throughout the various chapters of this book.

This practical book will consider the functions of reservoir engineers and how they analyze, think, and work in real-life situations. It presents the following:

- Rock and fluid properties, fluid flow principles, and reservoir performance analysis techniques; also, classical analyses in reservoir engineering, including volumetric, decline curve, and material balance studies. Most techniques are illustrated with the aid of software tools available in the industry.
- New topics such as well test analysis, reserves, reservoir economics, risk and uncertainties, probabilistic methods, and recovery processes, including waterflood and enhanced recovery processes such as thermal, chemical, and miscible floods. Recovery techniques from unconventional resources, such as oil sands, are also discussed.
- Fundamentals, applications, and value of reservoir simulation models.
- Probability analyses of hydrocarbons in place, well production, and petroleum reserves.
- Operational problems encountered by reservoir engineers and specific solution strategies to augment the recovery of oil and gas in a variety of circumstances, including marginal, matured, low permeability, stratified, and fractured reservoirs. Applications of smart well technology are also presented.
- Assignment of class projects in which the students have the opportunity to apply what they have learned to treat their problems.

Throughout the book, class exercises are designed to encourage the students to review published literature in order to learn about how real-life reservoirs are managed effectively. Furthermore, students are required to formulate strategies based on valid assumptions in the absence of necessary data, as frequently is the case in the reservoir engineering profession.

The book is designed to aid students and professionals alike in playing an active and important role throughout the reservoir life cycle in the various phases of the reservoir management process with fellow geoscientists and others as asset team members in the project.

We are confident this book will serve students and the industry well.

Abdus Satter, Ghulam Iqbal and Jim Buchwalter

1 · Introduction

Reservoir engineering is the heart of petroleum engineering. In the 1930s and 1940s, reservoir engineering evolved as a separate and important discipline of petroleum engineering. In essence, reservoir engineering deals with the flow of oil, gas, and water through porous media in rocks and also with the associated recovery efficiencies. Reservoir engineers play an active and important role throughout the reservoir life cycle and in the various phases of the reservoir management process.

Before 1970, reservoir engineering was considered to be the most important technical function in reservoir management. Since then, the value of synergism between engineering and the geosciences—geology, geophysics, petrophysics, and geostatistics—has been recognized. Furthermore, in recent years, integration and teamwork involving multidisciplinary professionals, tools, technologies, and data are considered essential for successful reservoir management.[1,2]

Many reservoir engineering books have been published in the past 50 years.[3–18] In addition, several reservoir simulation books have been published since the 1970s with the advent of digital computing.[19–26]

In writing this book, the authors intend to share their lifelong experience and expertise in reservoir engineering, including reservoir simulation techniques and reservoir management practices. The goal is to present a comprehensive book, starting from basic principles and leading to real-life reservoir management aided by simulation and other software tools. This practical book will consider the functions of reservoir engineers and how they analyze, think, plan, and work in real-life situations. It will present the following:

- Rock and fluid properties, fluid flow principles, well test analysis, and reservoir performance analysis techniques
- New topics such as reserves, reservoir economics, risk and uncertainties, probabilistic methods, and recovery processes
- The role of reservoir simulation models in enhancing basic reservoir engineering concepts and practice

Computer-based tools, including reservoir simulators and related software tools, are used extensively in this book to illustrate various concepts in reservoir engineering.

The learning objectives of this chapter are:

- Elements of petroleum reservoirs
- Composition of petroleum
- Origin, accumulation, and migration of petroleum
- History of reservoir engineering
- Reservoir life cycle
- Reservoir management goal
- Reservoir management process
- Reservoir engineers' functions

The scope, objectives, and organization of this book will be presented in the following sections.

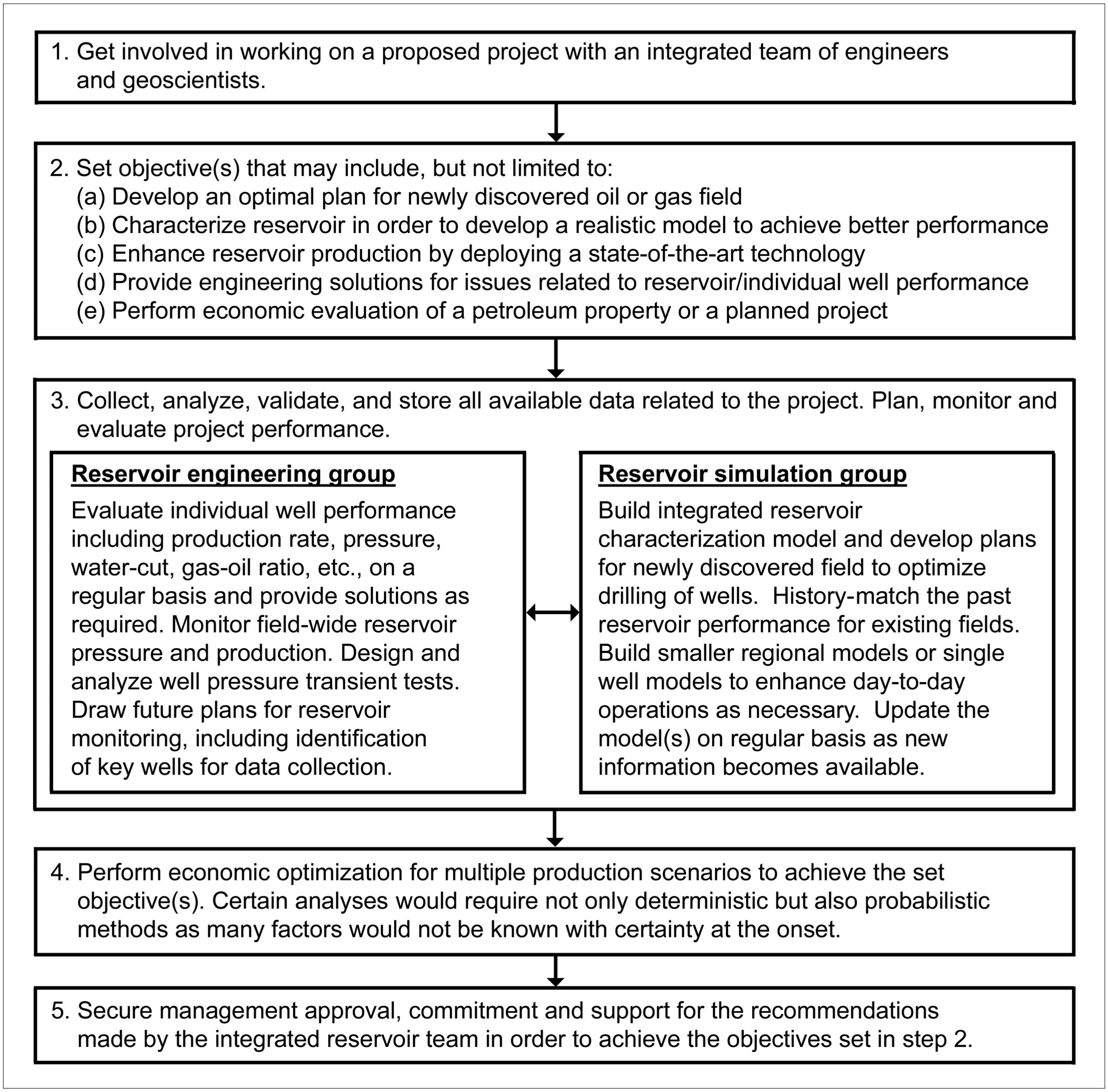

Fig. 1–7. Example workflow of reservoir engineers' functions

Organization of the Book

Reservoir engineering is the heart of petroleum engineering. It plays a very important role in reservoir management. This book presents the following:

- Chapter 1: Introduction. Introduces petroleum reservoirs, petroleum composition, origin, accumulation, and migration, the history of reservoir engineering, reservoir life cycle and management, and functions of reservoir engineers.
- Chapters 2 and 3: Rock Characteristics, Significance in Petroleum Reservoirs, and Applications; Fundamentals of Reservoir Fluid Properties, Phase Behavior, and Applications. Reservoir rock and fluid properties: definitions and significance in reservoir performance.
- Chapter 4: Fundamentals of Fluid Flow in Petroleum Reservoirs and Applications. Steady and unsteady state.

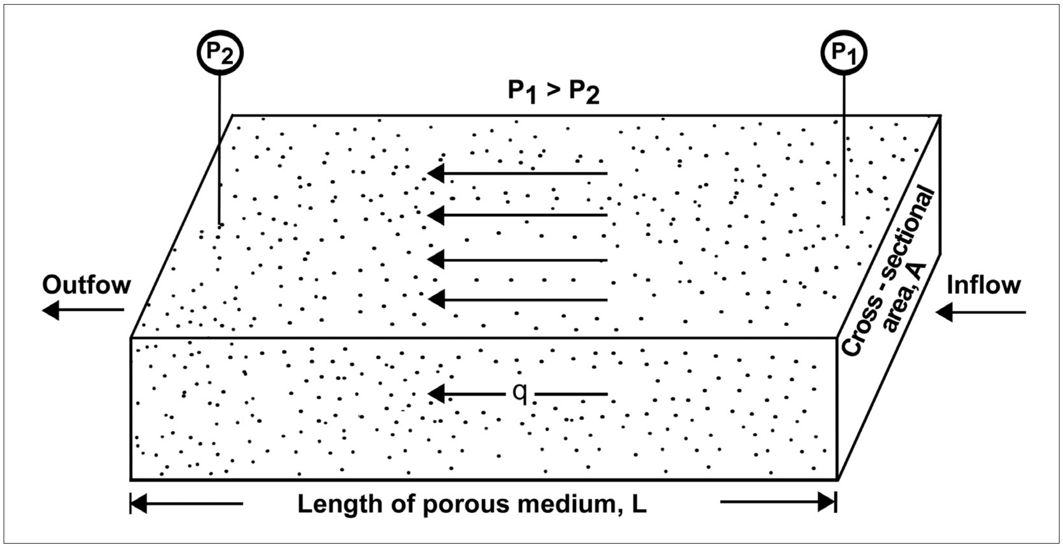

Fig. 2–3. Linear flow of fluid through porous media

Linear fluid flow through porous media

This review of Darcy's equation begins by considering the simplest case first, i.e., 1-D linear horizontal flow in homogeneous porous media. Rearranging Equation 2.10, and integrating between the limits of fluid pressure (p_2, p_1) over the length of flow path (L, 0) and noting that α=0, a relationship between the observed pressure drop and resulting flowrate for a linear flow system (fig. 2–3) can be obtained as follows:

$$q\int_0^L \partial L = -\frac{kA}{\mu}\int_{p_1}^{p_2} \partial p$$

$$qL = \frac{kA}{\mu}(p_2 - p_1) \quad \textbf{(2.11)}$$

$$q = \frac{kA}{\mu L}\Delta p \quad \textbf{(2.12)}$$

where

L = length of linear flow path, cm, and

Δp = pressure drop ($p_1 - p_2$) of flowing fluid over length L, atm.

Note that fluid pressure decreases along the flow path, and the negative sign in Equation 2.11 is eliminated. Finally, an expression for permeability can be obtained by rearranging the above equation:

$$k = \frac{q\,\mu\,L}{A\,\Delta p} \quad \textbf{(2.13)}$$

The above equation is frequently used in the laboratory to estimate the permeability of a core sample. The important assumptions are that the fluid is incompressible and flow is steady state. In addition, the following conditions must be met:

1. Fluid flow occurs in a horizontal direction.
2. Flow occurs in a laminar regime without any turbulence effects.
3. Only one fluid is present in the system occupying the entire pore space.
4. There is no chemical reaction between the rock and the fluid.

In oilfield units, Equation 2.13 takes the following form:

$$q = 1.127 \times 10^{-3}\frac{kA}{\mu L}\Delta p \quad \textbf{(2.14)}$$

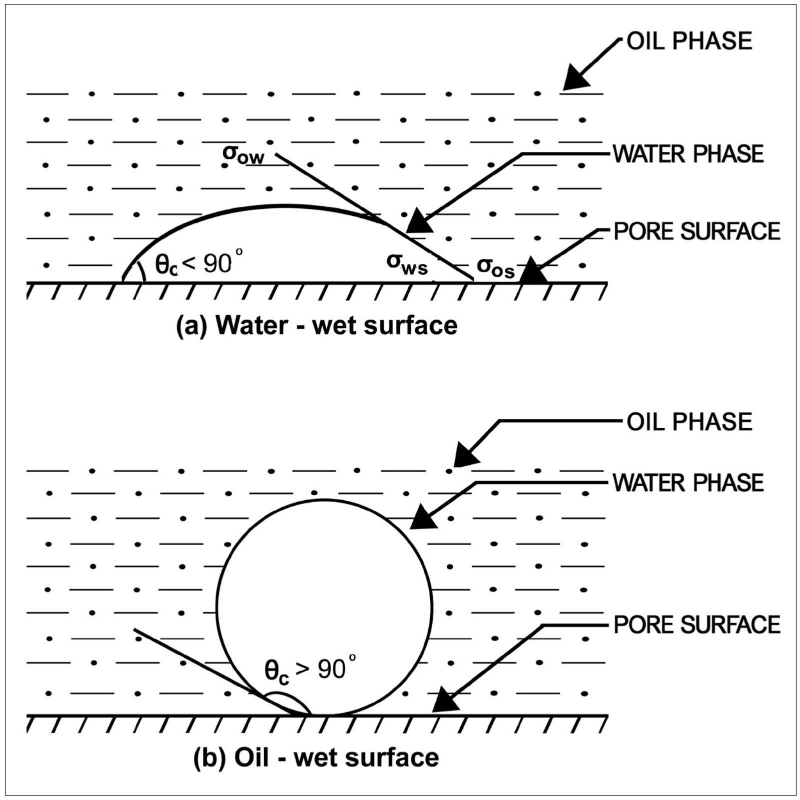

Fig. 2–11. Conceptual depiction of wettability. In an oil-wet porous medium, water droplets are less likely to adhere to the pore walls.

The contact angle is measured through the water phase as shown in Figure 2–11. It is observed that the angle of contact differs significantly depending on the wettability characteristic of the rock. When the surface of the rock pore is strongly water-wet, water droplets spread out at the periphery due to greater affinity between the water phase and the solid surface, leading to a contact angle significantly less than 90°. In contrast, a strongly oil-wet rock tends to have a contact angle significantly greater than 90°. Rock samples of intermediate wettability are also encountered, having a contact angle around 90°.

It is generally believed that reservoir rocks are more likely to be water-wet than oil-wet, since porous rocks are originally occupied by formation water through geologic times. During migration of the oil into the water-saturated formation, only a part of water is expelled from the rock's pores. The remaining portion is left behind, adhering to pore walls and overcoming the forces of oil migration. However, oil-wet or mixed wettability reservoirs are not uncommon.

Water-wet reservoirs are considered to be better candidates for improved oil recovery by water injection into the reservoir. Oil is expected to flow through the pore channels with relative ease, as it has little or no tendency to adhere to the rock surface. In contrast, the oil phase exhibits a greater affinity for remaining in the pores in oil-wet reservoirs. Consequently, residual oil saturation following water injection is relatively high, and ultimate recovery is lower. Laboratory core studies indicate that the wetting fluid tends to occupy the smaller pores and does not flow through pore channels during drive by a nonwetting fluid.

Key points—wettability

In conclusion, the following points are summarized:

1. Rocks exhibit a characteristic known as wettability, where one fluid preferentially adheres to the pore surface over the other. The phenomenon occurs due to the existence of interfacial tension between immiscible fluids, as well as between fluids and the pore surface.
2. The wettability of a hydrocarbon-bearing rock has a profound impact on preferential flow of one fluid over another. The wetting fluid phase tends to occupy smaller pores in the rock and remains there under dynamic reservoir conditions.
3. All factors being the same, water-wet rock is expected to perform better when water is injected in the reservoir to displace in-situ oil, as the latter has little or no tendency to adhere to the rock surface.
4. Studies indicate that reservoir rocks may exhibit intermediate wettability characteristics, in addition to being either water-wet or oil-wet. Moreover, rock wettability may alter with time as certain liquids come in contact with the pore surface.

Triangular diagrams can be generated to depict three-phase relative permeabilities for porous media. The three axes in the plot represent oil, gas, and water saturations in a scale of 0 to 100%, and relative permeability values are shown as contours. In addition to the above, familiar three-phase relative permeability correlations include the equations proposed by Stone as follows:[28]

$$k_{ro} = (k_{row} + k_{rw})\,(k_{rog} + k_{rg}) - (k_{rw} + k_{rg}) \tag{2.90}$$

where

k_{row} = relative permeability to oil in oil-water system ($S_g = 0$)

k_{rog} = relative permeability to oil in gas-oil system ($S_w = 0$)

Relative permeability ratio

The relative permeability ratio of a two-phase fluid system in porous media is defined as in the following:

I. Oil-water system:

$$\frac{k_{ro}}{k_{rw}} \tag{2.91}$$

II. Gas-oil system:

$$\frac{k_{rg}}{k_{ro}} \tag{2.92}$$

In a gas-oil system, the relative permeability ratio is low when the gas saturation is low. However, with an increase in gas saturation, the ratio may increase by several orders of magnitude, as gas is significantly more mobile. A semilog plot is used to show the significant increase in the gas-oil relative permeability ratio as the gas saturation increases. A similar trend is observed in an oil-water system where water displaces oil during waterflooding. The oil-water relative permeability ratio decreases markedly as water saturation increases. Values of the relative permeability ratio readily indicate the dominance of one fluid phase over another as a function of phase saturation in porous media. These values are utilized in multiphase fluid flow studies.

Pseudorelative permeability

Absolute permeability as well as relative permeability usually differ from layer to layer in a petroleum reservoir. Pseudorelative permeability values can be derived from layer-specific relative permeability values by considering permeability-thickness weighted averages.

I. Pseudorelative permeability of wetting phase:

$$\frac{\Sigma\,(kh)_i\,(k_{r,w})_i}{\Sigma\,(kh)_i} \tag{2.93}$$

II. Pseudorelative permeability of nonwetting phase:

$$\frac{\Sigma\,(kh)_i\,(k_{r,nw})_i}{\Sigma\,(kh)_i} \tag{2.94}$$

These equations for pseudorelative permeabilities under dynamic flow conditions find widespread application in reservoir simulation studies. In certain instances, a multilayered reservoir can be viewed as a single-layer system when pseudorelative permeability values are employed along with weighted averages of other layer properties. Such properties could include absolute permeability, porosity, and saturation. This aids in building a relatively simple reservoir model and increases computing efficiency without sacrificing the desired accuracy in results.

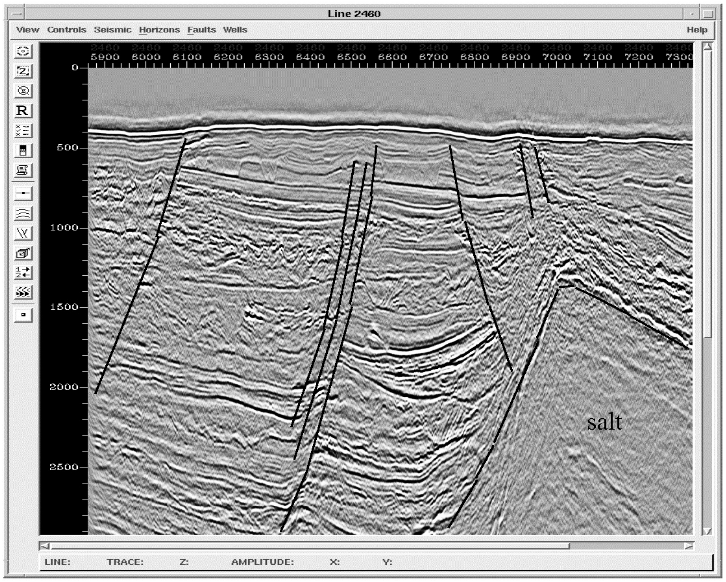

Fig. 2–26. Seismic interpretation. *Source: A. Satter, J. Baldwin, and R. Jespersen. 2000.* Computer-Assisted Reservoir Management. *Tulsa: PennWell.*

Figure 2–26 shows the same data with some faults interpreted and the outline of a salt dome indicated. By correlation with well logs (if available), the interpreter will determine which of the seismic events corresponds to the reservoir. The interpreter will then follow it throughout the 3-D volume, producing a structure map of the top of the reservoir.

Geostatistics

Geostatistics started gaining popularity in the mid-1980s. It provides a major tool for reservoir characterization, which accounts for vertical and horizontal variations of rock and fluid properties.

Computerized mapping is a simple extension of the maps drawn by hand contouring. Statistics provides an alternative procedure for measuring statistical variations of the data points and then creating maps having similar statistical properties throughout.

Like conventional mapping, geostatistics seeks to answer the question, "What are the reservoir property values between the wells?" (See fig. 2–27.) Analysis of the statistical distribution of the data values can lead to more detailed estimates of the map values between the measured points. It offers the following:

- Statistical variation of the data points and creation of maps having similar statistical properties throughout
- Better description of reservoir heterogeneity using statistical distribution of data values
- Means for displacing uncertainty of the interpolated values

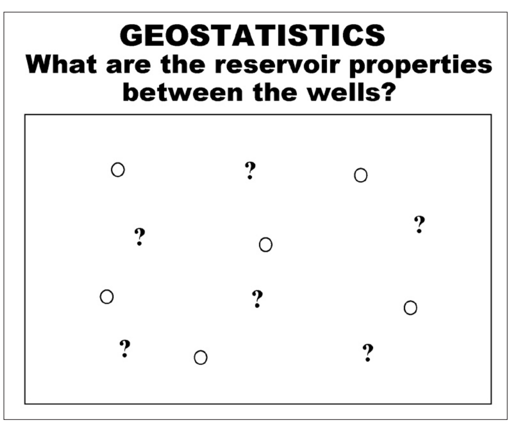

Fig. 2–27. The actual reservoir information is limited to drilled well locations only (shown as circles). *Source: A. Satter, J. Baldwin, and R. Jespersen. 2000.* Computer-Assisted Reservoir Management. *Tulsa: PennWell.*

The usual measure of this statistical variation is called a variogram. It is a mathematical expression involving the measured data points and represents how the data values change from one location on the map to another. The amount of change is measured as a function of the distance between data points, sometimes as a function of direction. The variogram serves as a tool for interpolating the map property between known points, while preserving the degree of variation seen in the data.

Some fundamentals of geostatistics, with example results, are presented in the following sections.