WELL LOGGING I—ROCK PROPERTIES, BOREHOLE ENVIRONMENT, MUD AND TEMPERATURE LOGGING

JAMES R. JORDEN AND FRANK L. CAMPBELL

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Well Logging I—Rock Properties, Borehole Environment, Mud and Temperature Logging

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Dedication

This Monograph is dedicated to Gus Archie and John Walstrom who blazed the trail we followed.

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SPE Monograph Series

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Acknowledgments

Dr. Samuel Johnson once said: ''A man will turn over half a library to make one book.'' Read we did, but it wasn't enough. Writing this monograph required the talented help and generous support of many people and we want to acknowledge them here.

This monograph had a gestation period longer than any living creature ever created. We outlasted several monograph coordinators and sorely tried the patience of the review committee. All these people are listed on the preceding page, and we gratefully acknowledge their contribution. Among this group we especially salute Chuck Konen, Amoco Production Co., whose gentle yet persistent persuasion did much to bring this project to a successful conclusion. Of all the SPE staff who helped develop this monograph, we particularly thank Pat Pate and Erin Stewart for their guidance as the authors struggled with policy issues on scope, structure, format, and deadlines.

Dresser-Atlas provided the graphics for this monograph. Among the several Dresser management staff who guided the firm's contributions for more than 7 years, Jim Anderson and Barbra Myers deserve special thanks. Most importantly, Debbie Schliesser created all the original illustrations and recreated all figures taken from the literature to provide a consistent nomenclature and format. Her ability to grasp engineering concepts and translate them into artistic images added substantially to this monograph's readability. Thanks go to Susan Burt for help in obtaining the photographs of the Dresser-Atlas tools. Ernie Finklea helped obtain the photographs of the Schlumberger tools.

Dr. Johnson after surveying the English language called it ''copious without order, and energetick without rules.'' This book is much less copious thanks to Charles Everett who applied 25 years of technical editing experience to improving the readability of this book. As the editing process evolved, our goal became: to have written a sentence that Charlie could not shorten and improve; we succeeded only occasionally. The order, with a minimum of rules, came from Kathleen Jun, SPE Asst. Editor, who coordinated the publication. Her thoroughness certainly improved the consistency of the highly interrelated components of this book.

We wish to thank Chevron Oil Field Research Co. and Shell Oil Co. for their many unheralded contributions to this monograph. Foremost among these is the technical insight we have gained through discussions with knowledgeable coworkers and access to proprietary technology. These opportunities have definitely improved the coherence of our review of the open literature. Whatever quality this monograph has as a comprehensive treatment of existing technology results in large part from the cooperation of the library science staff of both organizations. Aphrodite Mamoulides, Bernice Melde, and the other staff at Shell's Bellaire Research Center library were always willing to find ''just one more paper.'' Special thanks also to Elaine Spencer, Chevron.

In addition to the regular review process, we have asked numerous colleagues to challenge the scope, accuracy, and clarity of various chapters.

Chap. 1 contains log usage data furnished by Schlumberger. The project to gather these data turned out to be a larger task than originally expected. Nonetheless, Schlumberger stuck with it and produced log usage data available nowhere else in the well logging literature. In particular, Adam Perez and Bud Griswold devoted many of their own weekend hours to this chore.

Chap. 2 contains much geologic information outside the bounds of traditional petroleum engineering technology; Bob Sneider, consultant, and Don Harris, Exxon Production Research Co., brought a geologist's perspectives to their review. Bert Thomeer, Shell Oil Co., helped clarify several discussions of pore space properties and fluid distribution. E.C. Thomas, also with Shell, added a teacher's insight to the review.

Chap. 3 was built on an AAPG-sponsored short course presented by Ray Campbell of Schlumberger, Turk Timur of Chevron, and the authors. Many of the examples and explanations are from the notes of that course, especially Ray and Turk's sections on geometry, stress, and tool performance. Paul Hull, Al Brown, Bob Davis, and Chuck Haskin reviewed Chap. 3 and, as Chevron colleagues can, made many constructive suggestions. Jim Klotz, Union Oil Co. of California, reviewed this chapter and provided useful insights. Together their contributions significantly improved this chapter, which was fun but difficult to write because we tried to deal with real boreholes rather than the ideal world of test pits, computer models, and chart books.

Chap. 4 on mud logging was first reviewed by Fritz Reuter and Alun Whittaker of Exlog Inc. and John Spangler, Chevron. Their suggestions encouraged expanding the scope and revising the balance of the contents. Rich Mercer, EGG Continental Laboratories, shared his considerable experience and understanding by making many suggestions, which are now incorporated into the text. Carl Buchholz, Francis Crofton, Bill Zoeller, and Henry Potts of The Analysts were very helpful in clarifying some issues and obtaining some hard-to-find examples. Special thanks go to Exlog for the use of many examples from their fine training manuals. Mark Zetter, Delphian Corp., was an important source of information about gas detectors. The dialog with these experts raised Chap. 4 from what could have been simply an authors' perspective to an industry statement. Not to be forgotten when acknowledging contributions are those from the many dedicated logging crews with people like the late Al Lipphardt, whose patient teachings and strong convictions about the value of mud logging have influenced the authors' views that are presented in this chapter.

The long and lonely hours devoted to writing this were shared by Laurene Campbell and Shirley Jorden. They gave up many weekends and vacations needed to make that next deadline. If that wasn't enough, they were always ready to help with the typing, proofing, and editing. Our loving thanks to them.

We are grateful to all!

Foreword

While writing this, we struggled with several issues that eluded alternative solutions that will please everyone. Use of conventional options offered safe refuge from criticism but did not satisfy our objective to make this as readable as possible. Accordingly, we opted for some less conventional alternatives when dealing with scope, style, literature citations, and, especially, units.

The scope of this monograph is confined primarily to formation evaluation. It was tempting to broaden the discussion to include production logging and subsurface modeling applications based on borehole gravity, vertical seismic profiling, ultralong-spaced electric logging, and dipmeters. The role of mud logging in drilling optimization is recognized but not systematically reviewed. These are important subjects but are considered beyond the scope of formation evaluation, as originally defined and from time to time reaffirmed by our review committee.

A single system of units is not always used for very carefully considered reasons. We started writing this using SI. However, our objectives were compromised by loss of visualization, uncertain precision, and difficulties in referring back to the original literature. So we chose to use units that are most commonly used in oilfield practice or, alternatively, are consistent with the particular reference that is being discussed. Equations are developed using units that allow an uncluttered view of the physical/chemical concepts and principles being expressed. Dual units were considered but seemed cumbersome and unenlightening. However, many figures are drafted with dual scales, SPE-preferred SI values for constants used in major equations are provided in the Appendix, and conversion factors for all quantities are presented in the Nomenclature.

The availability of the literature cited in some chapters remains a concern to us. We cited what seemed to be the best references, recognizing that some may not be available in every science library. We did not acknowledge all of the literature. The Selected Reading List on Page 157 contains what we found to be the most significant and helpful references. Computerized search services should provide adequate information about other sources.

We requested and accepted technical editing to make this monograph more readable—especially considering that English is the second language of many SPE members. Moreover, esoteric qualifications and details were omitted for clarity and brevity. We really tried to keep the readers in mind and hope it shows!

Preface

This monograph is the first of a four-volume set offering a comprehensive treatment of formation evaluation by well logging. The other volumes in this series are *Well Logging II—Electric and Acoustic Logging; Well Logging III—Radiation, Nuclear Magnetism, and Borehole Gravity Logging;* and *Well Logging IV—Formation Evaluation Methods.*

Well logging is one of the most dynamic areas in the oil industry. Data collection methods have been improved significantly by advances in microelectronics, computers, and computer processing methods. The advances over the past 50 years are shown clearly in this volume. At the time of publication, this monograph represents the state of the art. The authors, editor, and review committee have made every effort to eliminate erroneous information; however, it is inevitable that some of the material will be proved inaccurate in the future.

The ultimate objective of well logging is to evaluate subsurface formations. The form of the evaluation depends considerably on the information being sought, whether for hydrocarbon or mineral content, rock characteristics, or correlation. Wireline logging is by its very nature an indirect measurement of fluid and rock characteristics. Thus, the interrelations between rocks, fluids, and physically measurable parameters must be understood if the user of the data is to derive accurate interpretations. Wireline measurements, however, are influenced strongly by the environment of the wellbore even though significant efforts have been made to reduce these factors. This volume provides insight into both these areas.

Log interpretation often requires additional information to resolve discrepancies and conflicts. The required information is available from the mud log in many instances, as the log contains a history of drilling mud properties, hydrocarbon detection, and rock samples. A thorough discussion of mud logging is presented in Chap. 4.

Formation temperatures and temperature profiles are a very important component of modern log interpretation. Temperature logs have been recorded since the very early years of logging and remain an important source of information.

The authors, J.R. Jorden and F.L. Campbell, are well known in the well logging and petroleum industry. J.R. Jorden is manager of the Petroleum Engineering Research Dept. of Shell Development Co. and 1984 President of SPE. F.L. Campbell is vice president of the Exploration Research Dept. of Chevron Oil Field Research Co.

This monograph provides much basic information regarding log interpretation. As such, it is anticipated that the monograph will be used as a primary reference for petroleum engineers and for training purposes. Subsequent volumes will build upon this foundation.

Houston
December 1984

WELL LOGGING
REVIEW COMMITTEE

Contents

Chapter 1
Prologue

We made a sonde by connecting four metre-long sections of Bakelite tubing together. . . . The electrodes were wired to the Bakelite tubes. We contrived a weight . . . filling it with lead pellets like those used in duck shooting. . . . The whole assembly looked like a long black snake with five joints. . . . The cable, if you could call it that, was three lengths of rubber-insulated copper wire, like the kind used on spark plugs in cars. . . . We planned to take readings at intervals of one metre. . . . We made our measurements with a standard potentiometer mounted on a tripod like those we used in our surface exploration work ...

from the personal recollections of H.G. Doll,
who participated in recording the first wireline log.

1.0 Introduction. This chapter sets the stage for the monograph set by detailing the earliest history of well logging and well log analysis. Comment is given on the significance of these events to well logging development and to today's log user. The chapter also provides a perspective of how wireline and mud logging have grown. This overview illustrates current logging methods and their use relative to each other and to former methods.

The objective of this monograph set is to review and to summarize those aspects of mud and wireline logging that are pertinent to formation evaluation. It is written for log users interested in knowing what technical options are available as they use log data to evaluate formations. These include both the "generalist" log user and "specialist" log analyst. The monograph is formatted so that new data on logging tools and interpretive techniques can be added by the reader.

Skillful formation evaluation requires an understanding of several interrelated components, from fundamental reservoir properties through evaluation methods. This monograph set includes four books, of which this is the first, to treat these several topics adequately.

1.1 Early History of Well Logging and Log Analysis

For the first 70 years of oilfield development, the only well logs were written records (or logs) of formation cuttings and fluids exposed by the drilling process. The first wireline log of a borehole was obtained in the Pechelbronn oil field, France, on Sept. 5, 1927.[1] This survey, of electrical resistivity only (Fig. 1.1), was obtained by taking point-by-point measurements, essentially by hand. The methods were typical of those then used for surface geophysical prospecting, but ingeniously adapted for borehole surveying.

Similar creative adaptations have led to the automatically recorded, continuously operating, multifunctional tools of modern well logging. The principal events defining these creative adaptations and the technological evolution of well logging are summarized in numerous histories. The API history[1] traces well logging from its inception through 1958. The Natl. Petroleum Council study[2,3] looks at the growth of and improvements in well-logging technology from 1946 to 1965. Johnson[4] gives a complete chronology of the pioneer developments and improvements in well logging from 1927 through 1960, and also provides detail rich in human interest about the earliest days of wireline logging. Several World Petroleum Congress papers[5-12] review technological improvements in well logging over successive 4-year periods since 1951. Allaud and Martin[13] chronicle the story of the Schlumberger organization's evolution, from its beginning in 1920 to its status in the middle 1970's; they also explain the science-based techniques used in modern well logging.

Fig. 1.2 and Table 1.1 record the growth of wireline logging since 1927. During the decade following, logging was used mainly for picking formation tops and well-to-well correlation. Its use grew dramatically thereafter as analysts came to recognize that the measured parameters are interpretable in terms of useful reservoir properties. Early on, several qualitative correlations were noted among log data and reservoir characteristics,[1] as summarized in Table 1.2.

During the late 1930's, experimental programs were undertaken to define the relationship between electrical resistivity and oil saturation. Although the first results were summarized by Martin *et al.*[14] in 1938, the results reported in 1941 by Archie[15] were especially useful in two ways:

1. They provided the basic principles for quantitatively interpreting the electrical resistivity of rock in terms of oil saturation.

2. They demonstrated that wireline logs can be quantitatively interpreted if a relationship (or model) can be found between the measured log parameters and desired reservoir properties. Such modeling can be through empirical field observations, laboratory experiments, theoretical constructions, etc.

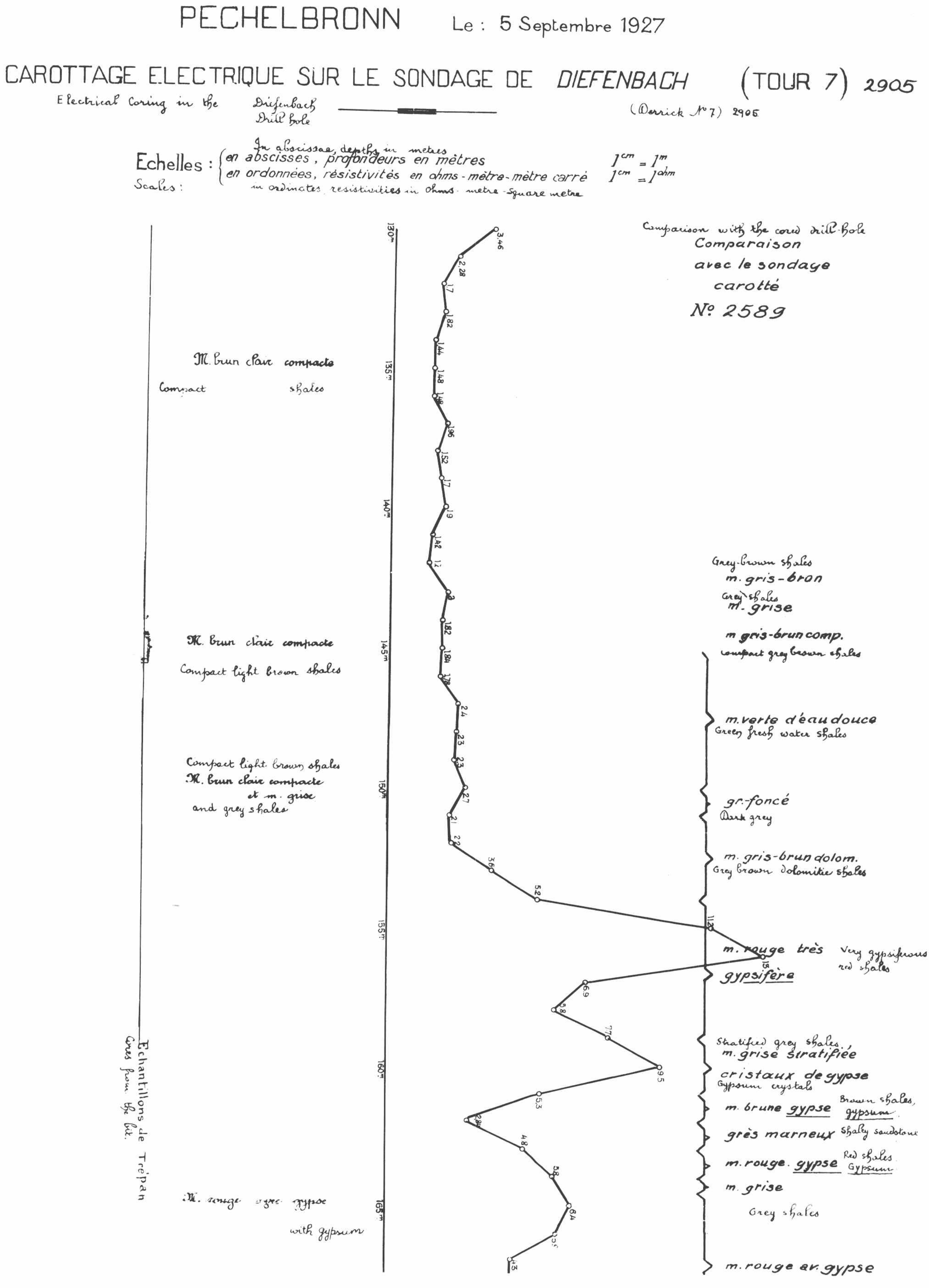

Fig. 1.1—First wireline log of a borehole (courtesy of Schlumberger Well Services).

The second achievement was probably the more important. As is repeatedly emphasized in this monograph set, reliable wireline log analysis and formation evaluation require that models be developed relating measured log data and desired reservoir properties. Archie's research started the industry on an evolving technology that developed interpretive models for wireline log analysis and formation evaluation.

Mud logging (defined in Chap. 4) has been practiced almost since the inception of the petroleum industry; drill-cuttings logs were made during the 1870's.[1] However, the work of J.T. Hayward[16] in the late 1930's marks the beginning of mud logging as a coordinated and coherent tool for formation evaluation. Fig. 1.3 shows an early mud log. Fig. 1.4 shows that, like wireline logging, mud logging has grown steadily, both commercially and technologically.

1.2 Relationship of Well Logging to Formation Evaluation

Formation evaluation, as applied to subsurface petroleum reservoirs, has historically been defined as the practice of determining reservoir thickness, lithology, porosity, hydrocarbon saturation, and permeability, using information obtained from a borehole. This definition probably represents a consensus from the statements in Table 1.3, which is a summary of quotations on the definition, scope, and objectives of formation evaluation from experts on the subject.[3,17-23]

Formation evaluation can be more generally defined as the practice of determining the physical and chemical properties of rocks and their contained fluids.

Four major classes of tools and techniques are available for formation evaluation: (1) *mud logging*, (2) *coring and core analysis*, (3) *drillstem testing*, and (4) *wireline logging*.

To many log users, "well logging" means "wireline logging." Actually, *well logging* is the creating of a record (a log) of some engineering or geologic parameter vs. borehole depth or time. This includes wireline logs, mud logs, core-analysis plots, stratigraphic sample logs, drilling parameter logs, and many others.

This well-logging monograph set deals only with mud logging and wireline logging. Excluded are drillstem testing, coring and core analysis, and production logging (now a sophisticated and widely used branch of wireline logging). Thus, this monograph set is not a complete treatment of either formation evaluation or well logging, except for those aspects of mud and wireline logging pertinent to formation evaluation. To simplify terminology, "well logging" is used synonymously with "wireline logging" and "mud logging."

1.3 Objectives and Scope of This Monograph Set

Well logging has been discussed in many papers and texts. Thus, readers might ask why this monograph set is needed and how it can be useful. The prime objective is to review and to summarize completely those aspects of mud and wireline logging pertinent to formation evaluation. Readers of this monograph are perceived as log users interested in knowing the available technical options in the use of log data to evaluate formations. This publication set should give "generalist" log users, who have not had time to master completely all the details of logging tools and interpretive techniques, a quick yet comprehensive summary of the technology and its applications. At the same time, it should provide "specialist" log analysts with a retrospective overview that will deepen their perception of their profession. This objective is achieved by (1) reviewing as thoroughly as possible the entire body of technical literature, (2) identifying and referencing the truly significant technical work, and (3) unifying and interpreting the current state of technology to achieve a comprehensive treatment of log analysis and formation evaluation. This monograph set is not addressed to beginning students nor to those engaged in research and development of new logging tools or interpretive techniques.

Well logging is based on well-established principles of physics and chemistry. Although these principles are completely developed in other texts and reviews, they are restated and summarized here for ready use on future novel problems.

Log users who apply these principles to well-log interpretation and formation evaluation soon encounter dilemmas created by a rapidly improving technology. There is a continuous stream of improvements in geologic and petrographic concepts, logging-tool electronics, and computer-processing capabilities, as well as the opening of new geologic provinces. All of these combine to add quickly to the knowledge available and required to evaluate formations. How then could any well-logging review, once completed, have any lasting value in such a rapidly changing technological environment?

This monograph set attempts to minimize the problem through a format that can be easily updated. Specifically, existing knowledge is summarized in tables and graphs. Further, preformatted blank tables and graphs are provided for adding new knowledge as it becomes available. These concepts are particularly emphasized in the accompanying loose-bound chart collection. This scheme permits the new to be compared with the old, and allows the various logging tools and interpretive techniques to be put in a time frame.

1.4 Organization of This Monograph Set

Skillful formation evaluation requires an understanding and mastery of several somewhat sequential yet highly interrelated components: (1) the fundamental (primary) properties of reservoirs (i.e., thickness, lithology, porosity, permeability, and fluid distribution) and the relationships among them; (2) the borehole environment; (3) the secondary reservoir properties (such as electrical resistivity and acoustic velocity) and their relationships with the primary reservoir properties; (4) the methods used to measure these properties (i.e., mud logging, coring and core analysis, drillstem testing, and wireline logging); and (5) the interpretation methods used in formation evaluation. The monographs in this set (Table 1.4) present topics in approximately this order.

This first monograph, *Rock Properties, Borehole Environment, Mud and Temperature Logging*, reviews the fundamental properties needed to evaluate a hydrocarbon reservoir. Emphasis is placed on the basic geologic and petrographic characteristics that control these properties,

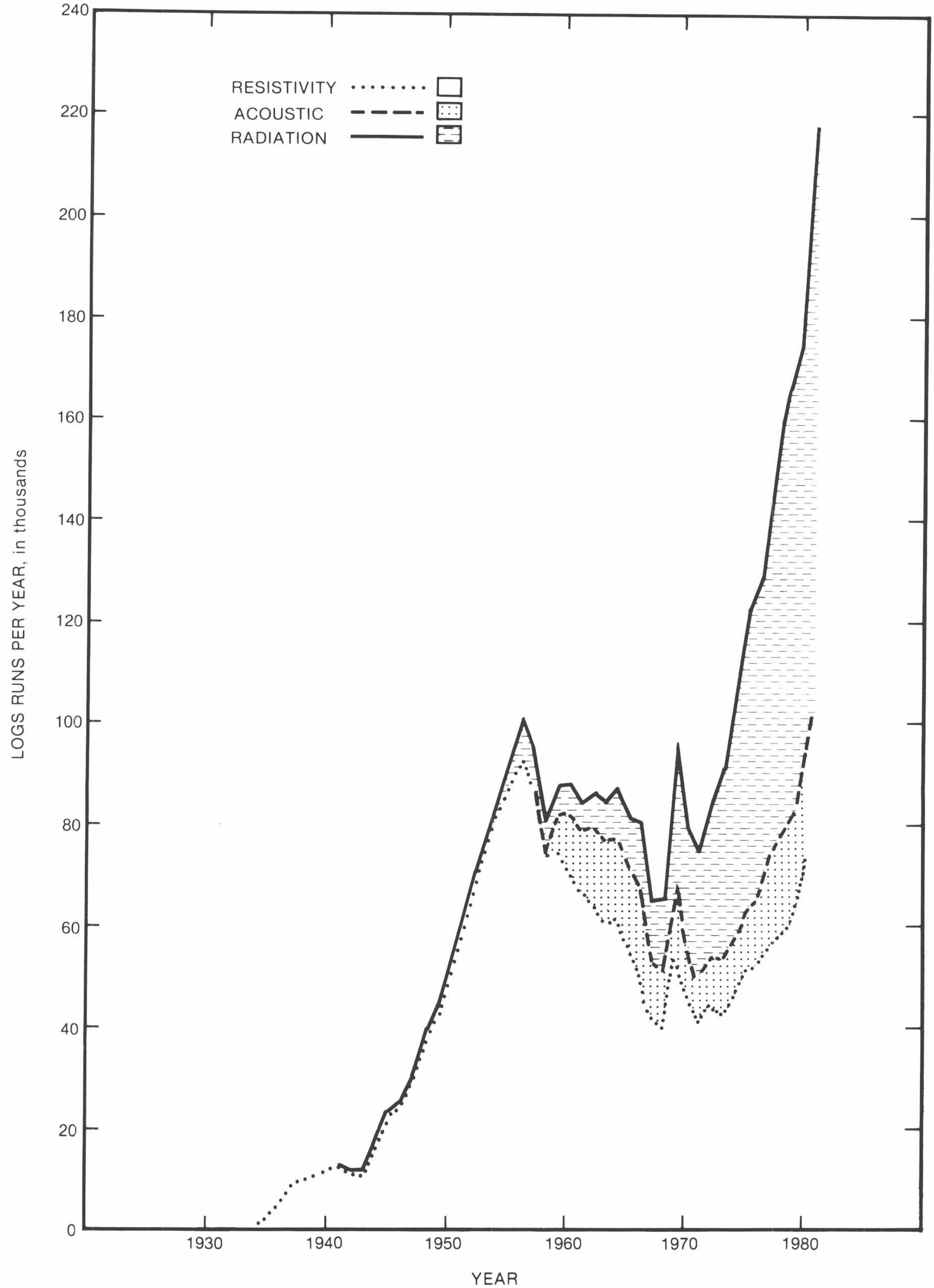

Fig. 1.2—Historical growth of wireline logging (data courtesy of Schlumberger Well Services).

TABLE 1.1—GROWTH OF WIRELINE LOGGING, NUMBER OF LOGS RUN PER YEAR, 1927–1980*

	Electrical				Acoustic	Radiation				
Year	Conventional	Focused	Micro	Induction	Interval Transit Time	Natural Gamma Ray**	Steady-State Neutron	Pulsed Neutron	Gamma-Gamma Density	Total
1927	10									10
1928	20									20
1929	160									160
1930	216									216
1931	384									384
1932	27									27
1933	243									243
1934	580									580
1935	2,790									2,790
1936	5,180									5,180
1937	8,930									8,930
1938	10,170									10,170
1939	10,810									10,810
1940	11,720					200				11,920
1941	12,470					400	200			13,070
1942	11,100					600	200			11,900
1943	10,960					800	300			12,060
1944	16,730					1,000	400			18,130
1945	22,040	100				1,200	500			23,840
1946	23,490	200				1,400	600			25,690
1947	27,840	300				1,600	700			30,440
1948	35,070	400	500			1,700	800			38,470
1949	38,910	600	2,000			1,500	900			43,910
1950	42,020	1,200	6,000			1,600	1,000			51,820
1951	44,130	1,800	12,000	400		1,800	1,200			61,330
1952	49,060	2,400	16,000	600		2,000	1,400			71,460
1953	53,020	2,600	18,000	1,000		2,200	2,000			78,820
1954	55,030	4,000	20,000	2,500		2,500	3,000			87,030
1955	54,320	5,000	24,400	3,500		2,800	4,000			94,020
1956	52,920	6,000	27,200	6,100		3,000	5,400			100,620
1957	41,160	5,000	26,800	13,750	50	3,000	5,000			94,760
1958	34,430	3,500	22,000	14,000	1,820	1,300	4,800			81,850
1959	29,150	4,600	22,000	18,300	7,760	1,000	4,700		200	87,710
1960	27,630	4,000	19,000	20,000	11,300	1,000	4,500		500	87,930
1961	24,470	4,000	15,000	23,000	12,550	900	4,000		600	84,520
1962	17,310	5,100	14,300	28,000	15,100	800	3,900		2,100	86,610
1963	16,250	4,300	11,200	29,000	16,100	600	4,200		2,950	84,600
1964	15,040	3,700	10,100	32,500	15,800	500	4,500		4,800	86,940
1965	11,550	3,200	8,100	33,100	15,900	500	2,800		6,480	81,630
1966	11,660	2,530	6,100	30,500	16,800	500	3,600		8,810	80,500
1967	5,090	1,820	4,400	30,700	11,300	500	2,900		8,570	65,280
1968	5,540	1,690	3,600	28,800	11,900	500	3,600		10,030	65,660
1969	4,700	2,030	13,000	34,390	13,970	500	9,800	490	15,000	93,880
1970	3,900	1,710	11,000	30,140	9,830	200	9,500	910	13,000	80,190
1971	3,300	1,690	8,000	28,180	9,080	200	9,700	1,330	14,000	75,480
1972	3,000	2,370	8,000	30,810	10,050	200	12,600	1,560	16,000	84,590
1973	2,800	3,290	6,000	30,340	11,050	100	13,700	1,650	22,000	90,930
1974	2,800	3,740	6,000	33,520	11,850	100	20,000	2,020	27,000	107,030
1975	2,500	4,950	6,000	38,060	12,590	100	25,400	2,350	30,000	121,950
1976	2,000	4,120	4,000	41,820	14,370	100	27,560	2,470	31,860	128,300
1977	1,500	5,620	2,000	47,160	18,710	100	34,310	2,490	38,570	150,460
1978	1,000	6,060	1,200	50,220	20,900	200	40,210	2,680	42,930	165,400
1979	700	6,540	1,200	53,380	21,420	300	43,190	2,660	44,400	173,790
1980	500	9,320	1,200	63,670	25,620	100	56,110	3,410	57,600	217,530

*Data for 1927–1931 are worldwide; data for 1932–1980 are North America only. Data courtesy of Schlumberger Well Services.

**Natural gamma ray logs are counted only when run singly; "combination gamma ray" logs began being run in about 1958.

TABLE 1.2—EARLY INTERPRETATION OF WIRELINE LOGS (after Leonardon[1])

Resistivity Log	SP Log	Probable Conclusion
Low resistivity	no SP	shales
Low resistivity	large SP	saltwater sand
High resistivity	low SP	freshwater sand
Good resistivity	moderately large SP	possible oil sand
Very high resistivity	no SP	hard rock; very compact sand with sweet water

and less discussion concerns the diagenetic processes that modify the properties. Perhaps the most important characteristic of a rock is its pore-size distribution, which strongly influences porosity, permeability, and fluid distribution (basic definitions of these are given). Discussion includes the pore-distribution differences for both clastics and carbonates. The use of capillary pressure curves to infer pore-size-distribution characteristics is introduced. The principles of capillarity are used to explain and to quantify further the concepts of fluid distribution. Also presented are the petrophysical relationships that exist among various fundamental rock properties (such as porosity/permeability and porosity/water saturation), and examples are given from the literature. Reviews are given of the chemical nature of subsurface formation waters and methods of measuring and relating water compositions.

This monograph discusses the actual borehole environment for well logging, which can be very different from that in the idealized models used to formulate tool response and formation-evaluation methods. Included are reviews of (1) wellbore geometry; (2) the impregnation and infiltration processes (with their resultant influences on porosity and saturation) during and after drilling; (3) the temperature distribution in the borehole during and after drilling; (4) the stress disturbances induced by drilling; (5) chemical alteration effects; and (6) example tool performance in nonideal environments and recommended practices.

This book also deals with the techniques of mud and temperature logging. The organizational scheme is similar to that described next for the more conventional wireline logging methods.

Chapters in the second and third monographs in the set, *Electric and Acoustic Logging* and *Radiation, Nuclear Magnetism, and Borehole Gravity Logging,* deal with a specific wireline logging method in this order: (1) the relevant principles of physics and chemistry; (2) the use of models to relate measurable secondary reservoir properties to required primary reservoir properties; (3) the instrumentation and operation of the logging tools; (4) the problems that can arise in measuring true secondary properties (i.e., the perturbations caused by the borehole, invaded zone, and thin beds); (5) the limitations of existing logging-tool designs and tool-response models for accurately portraying the heterogeneous and anisotropic properties of natural rock; and (6) the methods of deriving true secondary properties from recorded log responses.

Example logs and pertinent interpretation charts are used. Emphasis is on summarizing, through tables and graphs, the characteristics of past and present logging tools. These books, particularly the companion chart inserts, are formatted so that readers can conveniently update the summaries as new and improved tools become commercially available—which will assuredly happen.

The fourth monograph in this set, *Formation Evaluation Applications,* covers the methods that can be applied through the use of well logging data. The opening chapter reviews principles and general techniques, including crossplots, "quick-look" logs, and digitized well log processing by computer. Subsequent chapters deal with estimating primary formation properties from

WELL-LOGGING SERVICE

Location of Well — Company; Well; Field, Goldsmith; County, Ector; State, Texas

Elevation

	From	To	Casing Record:	Observers:
Date logged	5/18/40	5/26/40	$5\frac{1}{2}$-in. outside-diameter at 4,105 ft	
Depth logged	3,800 ft	4,173 ft		

From (Feet)	To (Feet)	Remarks
3,800	4,085	$7\frac{7}{8}$-in. hole drilled.
4,085	4,105	$7\frac{3}{4}$-in. core head; $3\frac{1}{2}$-in. core.
4,105	4,125	$4\frac{3}{4}$-in. core head; $2\frac{1}{8}$-in. core.
4,125	4,155	$4\frac{3}{4}$-in. hole drilled.
4,155	4,173	$4\frac{3}{4}$-in. core head; $2\frac{1}{8}$-in. core.

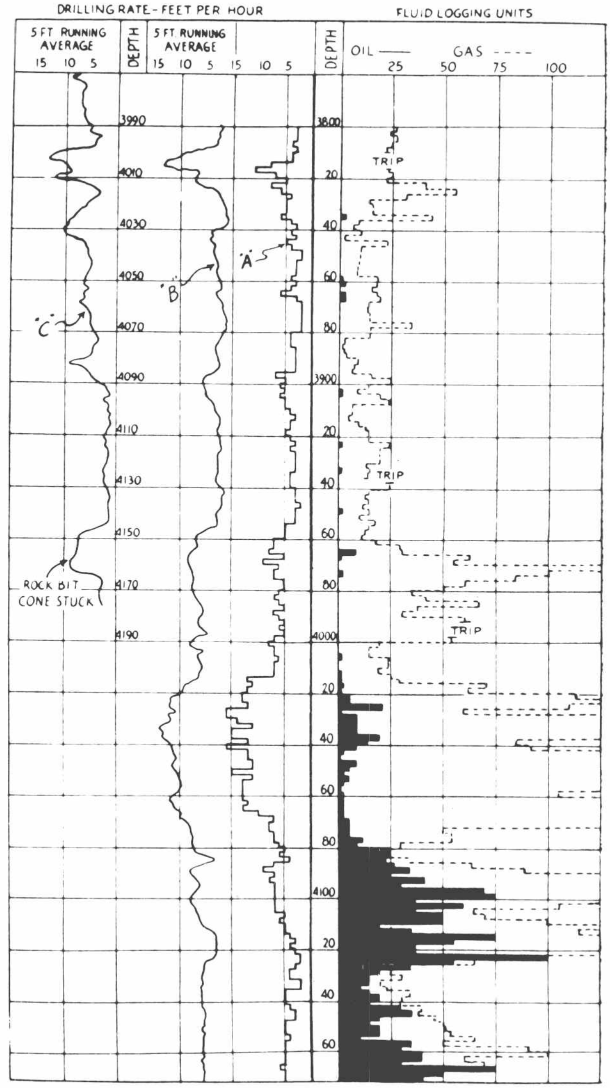

Fig. 1.3—Example of an early mud log of a borehole (after Hayward[16]).

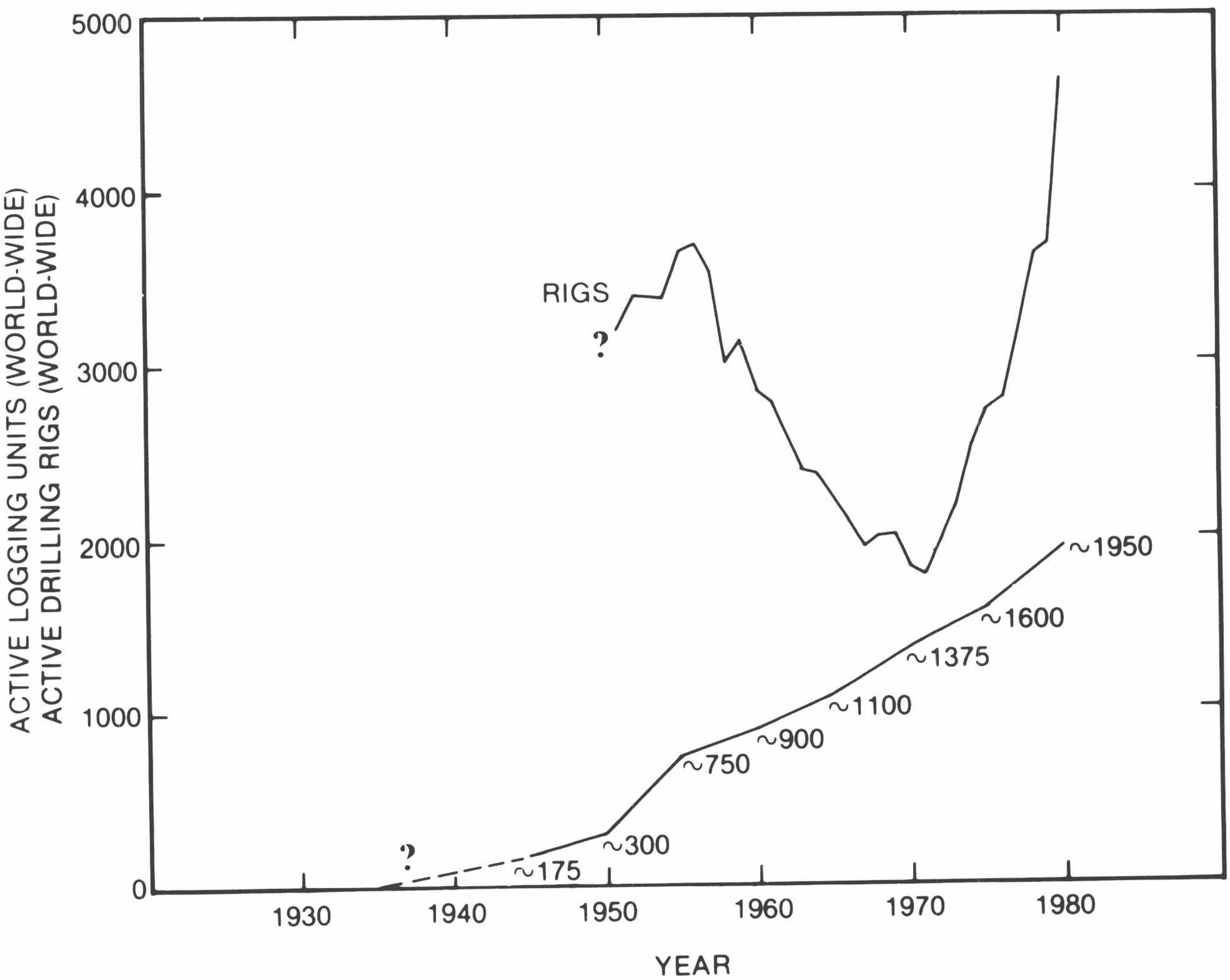

Fig. 1.4—Historical growth of mud logging (data courtesy of Exploration Logging Inc.).

log responses for one or more of those properties: (1) lithology; (2) porosity, permeability, and fractures; (3) water composition; and (4) saturation. Chapters on the use of well log data for correlation and abnormal pressure analysis also are included.

Each of the chapters presents methods for evaluating the major rock types encountered in petroleum reservoir exploration and development. Actual example problems and pertinent interpretation charts are included.

Interpretation charts are included in the monograph texts to illustrate how to correct apparent log responses to true rock properties, or how to derive fundamental (primary) rock properties from secondary rock properties. In addition, a separate, loose-bound chart collection is provided. It contains (1) a complete indexing system providing a framework for organizing a collection of charts into a system compatible with the monograph text discussion and (2) a few actual charts, which illustrate the types of charts intended for each "pigeonhole" in the framework. Generally speaking, these are the universal (or basic) charts necessary for rudimentary log interpretation. Beyond this, readers can add to their chart collection as they wish.

This monograph set presents a cross-reference system within the four books (Fig. 1.5 shows one example of this system). This guide is given in each monograph text and the separate chart collection as an outline of how to use the monograph set and where to find related topics in the four books.

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TABLE 1.3—FORMATION EVALUATION—ITS DEFINITION, SCOPE, AND OBJECTIVES

Author(s)	Reference	Definition, Scope, and Objectives
Pirson	17	"... reservoir engineers and ... oil and gas property appraisers ... use logs for the evaluation of structural or stratigraphic closure, effective pay, porosity, fluid saturation, calculation of oil and gas originally in place, expected ultimate recovery, and present reserves .... In the oil and gas industries, the main purpose of well log analysis is the evaluation of reservoir rock properties in situ ...."
Archie	3	"The process of using information obtained from a borehole to determine the physical and chemical properties of the rocks and their fluid content, especially hydrocarbons, is known as formation evaluation. The complexity and importance of formation evaluation have led to the establishment of a new technical position in many companies — the formation analyst or petrophysical engineer .... Evaluation of a reservoir involves defining its areal extent and determining its thickness, porosity, permeability, and oil saturation. Accurate determination of the last four of these parameters at a reasonable cost is the goal of the formation analyst or petrophysical engineer .... Formation evaluation methods can be divided into two categories: ... Analyses of cores, cuttings, and drilling fluids are the methods that constitute the first category. The second category includes drill-stem testing and all the tools run in the hole on wireline to measure natural electrical potential, electrical resistivity, radioactivity, acoustic velocity, and other physical parameters which provide an indirect measure of rock and fluid properties."
Lynch	18	"...the duty of the wellsite geologist or engineer to locate those formations that contain hydrocarbons and to evaluate their commercial significance ... comprises the field known as Formation Evaluation .... Included in the formation evaluation methods are logging from drill returns, coring and core analysis, formation testing, and various wireline services .... The value of an oil reservoir is defined by its areal extent, its thickness and permeability, its fractional porosity, and the fraction of porosity that is saturated with oil. The objective of good formation evaluation is the quantitative determination of these items."
Guyod and Shane	19	"... the objectives of geophysical well logging may be said to be: the location of petroleum reservoirs, the estimation of the ability of a well to produce petroleum, the mapping of the reservoir shape, the estimation of the petroleum reserves, the determination of the best well completion procedure."
Evans and Pickett	20	"... the field of formation evaluation ... includes: estimates of in-place and recoverable hydrocarbon volumes, lithology determination, identification of geological environments, derivation of initial versus residual oil saturation relations, evaluation of water flood feasibility in early wells, location of reservoir fluids contacts, reservoir 'quality' mapping, determination of water salinity, determination of fluid pressures in reservoirs during the drilling of wells, detection of fractures, derivation of parameters required for reservoir engineering studies, prediction of probability of interzone fluid communication in casing-formation annulus, determination of porosity and pore size distribution, monitoring of fluid movement in reservoirs."
Jorden	21	"An intelligent system of formation evaluation requires a complete understanding of the primary reservoir properties and the relationships among them, then an understanding of the secondary reservoir properties and the relationships both among them and with the primary properties. Next the methods used to measure the properties—the data-gathering phase, the core and fluid analysis and well logging aspects of formation evaluation—must be thoroughly understood. Finally, the interpretation methods used in formation evaluation must be mastered."
Walstrom	22	"The evaluation of subsurface formations ... includes all coring, logging, mud logging, testing and sampling procedures. It includes log interpretation methods and laboratory analyses related to subsurface evaluation of the formations including an analysis of their contained fluids. ...The principal objectives of formation evaluation are to evaluate the presence or absence of commercial quantities of hydrocarbons in formations penetrated by, or lying near, the wellbore and to determine the static and dynamic characteristics of productive reservoirs. Another objective of formation evaluation is to detect small quantities of hydrocarbons which nevertheless may be significant from an exploratory standpoint. A further objective is to provide a comparison of an interval in one well to the correlative interval in another well."
Jennings and Timur	23	"In a general sense, formation evaluation can be defined as the science and the art, in that order, of economic evaluation of natural resources occurring in earth formations. For the purposes of this paper, however, the definition will be confined to the evaluation of petroleum reservoirs. In this context, formation evaluation may be considered to include all coring, well logging, mud logging, testing, and sampling."

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