# SUBSURFACE GEOLOGY
# IN
# PETROLEUM EXPLORATION

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# PREFACE

It is the object of this symposium to acquaint the student, the practicing petroleum geologist, and the petroleum engineer with the tools and techniques used in the search for new oil and gas pools. The various facets of subsurface exploration fall into the following broad categories: analysis of well cuttings, cores, and fluids; well logging methods and interpretation; subsurface stratigraphic and structural interpretation; geophysical and geochemical prospecting; drilling, formation testing, and well completion; subsurface reports; and exploration planning. In executing the objective of the symposium there is, of necessity, some overlap into the areas of surface exploration and production engineering.

This symposium is a logical outgrowth of *Subsurface Geologic Methods* (1st edition, 1949; 2nd edition, 1950) compiled by L. W. LeRoy, which was made possible by the support and interest of many contributors in the petroleum industry. Because of rapid advances and refinements in subsurface geologic methods during the past 8 years, it was deemed necessary to reorganize and compile these new methods in the present volume. This volume will be sold by the Publications Department of the Colorado School of Mines.

Several of the papers that were printed in *Subsurface Geologic Methods* have been included in the present symposium with little or no revision; other papers from the former volume have been considerably revised in the light of recent developments in the particular field being considered. Some subjects treated in the former volume, namely those concerning mining methods and "hardrock" geology, have been dropped from the present compilation because of the change in primary objective. Many new subjects, not included in the former volume, have been added. It is hoped that these papers will be of value to geologists and petroleum engineers in the field as well as to educational institutions that offer formal courses in subsurface geology and petroleum geology.

The editors wish to thank the contributors to this symposium, without whose interest it would have been a much more difficult task. We would also like to acknowledge gratefully the assistance received from George W. Johnson, Professor of English at the Colorado School of Mines, for his many editorial suggestions. Special thanks go to Roger Hull, Hendrietta Jenson, and Doris Graham, of the Colorado School of Mines Publications Department, for their diligent work on this volume. We wish to extend our appreciation to John W Vanderwilt, President of the Colorado School of Mines, for his support of this symposium.

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Colorado School of Mines
Golden, Colorado
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# CONTENTS

# Subsurface Geology in Petroleum Exploration

a symposium

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# *Part One* | INTRODUCTION

# *Chapter 1*

# TRAINING THE PETROLEUM GEOLOGIST

**John D. Haun**

The primary objective of the petroleum geologist is to discover petroleum. This objective seems so obvious that it should not have to be stated. As a matter of fact, many petroleum geologists have lost sight of this major reason for their existence.

Many factors contribute to the success of an exploratory effort. Among these factors are the basic training of the geologist, the personnel and organizational framework of the company with which the geologist works, and perhaps most important, the facility with which the geologist is able to think independently and imaginatively. Charles F. Kettering often has said that the inventive ability of many young men has been weakened seriously by the rigidity of our present educational system. If this opinion is true, then we should endeavor to provide an educational atmosphere that will keep alive the innate curiosity, the excitement of new horizons, which is a part of nearly every young man in early childhood. Such an atmosphere is becoming more difficult to attain as our technology advances in complexity and requires an ever-increasing amount of time for mastery.

## TRAINING

This symposium is an effort to bring up-to-date many of the tools and techniques with which the subsurface geologist must be familiar if he is to be successful in the geological profession. More important than the learning and mastery of subsurface techniques, however, is the basic training of the geologist. A framework of knowledge in which these specific techniques are applied should include a thorough grounding in the physical processes of geology, the sequence of events of geologic history, the elements of structural geology, the significance of the paleontologic record, the principles of stratigraphy, the processes of sedimentation, and the principles of petroleum geology. Concurrent with the study of these branches of geology should be course work in crystallography, mineralogy, and petrology. The advanced student of geology should also be well-trained in the various techniques of field mapping and measurement of stratigraphic sections. There is an increasing necessity for a better grounding in mathematics, physics, and chemistry. The ability to write a concise geological report and to present a clear, well-organized oral report are necessary if the geologist is to sell his ideas to the men with whom he works. Further ramifications of the various areas of training and the part that these areas play in the work of the petroleum geologist will be considered.

## Physical Geology

Thanks to the Huttonian concept, we are able to gain more understanding of the processes of erosion, deposition, and deformation that were in effect in past geologic time by a study of these same processes that are reshaping the earth's surface today. The more complete the knowledge of the petroleum geologist of weathering processes, the movements of surface and subsurface waters, the depositional environments of lakes, swamps, and oceans, the better will be his interpretation of the nature and lateral extent of the various rock types encountered in both surface and subsurface studies.

## Historical Geology

The geologic history of a petroleum province holds the key to the origin, primary and secondary migration, and entrapment of the petroleum of that province. The knowledge of the geologic history of a closely drilled area is also an aid in the prediction of petroleum occurrences in a less developed nearby area which may have had a similar history. The student's knowledge of the geologic history of the various continents and broad subdivisions of the continents provides a frame of reference into which more detailed analyses of a provincial nature may be coordinated. In specific petroleum prospects, the changes in structural configuration that have taken place in recent geologic time should be separated, if possible, from the structural conditions that existed during earlier stages of geologic time.

## Paleontology

In addition to the more obvious uses of paleontology in petroleum exploration, such as age determination and regional correlation, branches of paleontology, especially micropaleontology, have been perfected as tools for the petroleum geologist. In the Gulf Coast, in California, and in Indonesia, species of foraminifera are used in structural contouring and in detailed local correlation. During the past 10 years, considerable advances have been made in the usage of fossils for determining sedimentary environments that are, in turn, related to the study of source beds for petroleum and to the more complete understanding of reservoir rocks.

## Structural Geology

Probably the most important facet of the geologic science used by the petroleum geologist is structural geology. A student must be versed thoroughly in the classification of folds and faults and in the types of local and regional forces that account for their development. The student also must be well acquainted with the methods of construction of maps and cross sections that are used to depict structural configuration in three dimensions. The part played by various logging and geophysical techniques in assembling structural data should be a part of the training of the petroleum geologist, either in school or in the early years of professional work.

## Stratigraphy and Sedimentation

The increasing importance of petroleum accumulations that are controlled in large part by stratigraphic factors has brought into greater focus the necessity for an understanding of the basic principles of stratigraphy and sedimentation. Here again, the methods of collecting data in the field and in the subsurface and the manner in which these data may be depicted on maps, as well as the significance of the data, should be made a part of every geologist's knowledge. An effort also should be made to acquaint the student with regional and systematic stratigraphy in order to instill a clearer understanding of the interrelationships between historical geology, structural geology, and stratigraphy. Petroleum exploration, from a strictly geological viewpoint, is primarily the application of the principles of stratigraphy and structural geology.

## Mineralogy and Petrology

The mineralogy of the grains, interstitial matter, and cement of detrital rocks can play a direct part in the migration and entrapment of petroleum. There is often a correlation between the mineralogy of chemically precipitated rocks and areas of high porosity and permeability. A knowledge of source areas and diagenesis is necessary to the complete understanding of the stratigraphy of sedimentary rocks; this knowledge then may be used in the delineation of areas and formations that are more favorable for the entrapment of petroleum. The techniques of optical mineralogy and petrography are sometimes necessary to the solution of problems of correlation as well as problems of origin and diagenesis of sedimentary rocks.

## Field Geology

Despite the recent downgrading of field geology by some educators and the lack of structural expression on the surface of some parts of the world, the fact remains that instruction in field geology is *one of the most important phases* of training for the geologist. It has been said that there is nothing more sobering than an outcrop. If the student has not been trained in the solution of structural problems in the field, he will find much more difficulty in visualizing three-dimensional complexities on the drafting board in the office. Field training develops observational powers and deepens understanding of the magnitude and nature of geologic problems. A background of field training is absolutely essential to a complete appreciation of the science of geology and to the most logical solution of many complex subsurface problems.

To the general training in field mapping procedures and in the measurement of stratigraphic sections, some instruction in surveying and photogeology should be added. Photogeology recently has gained importance as a tool of the petroleum geologist. It is quite obvious that the most logical interpretation of the geology on photographs in the office can be made by a geologist who has had considerable experience in field mapping.

## Mathematics, Physics, and Chemistry

Many geologists are striving to make their science more precise than it has been in the past. In order to bring this about, a more thorough understanding must be gained of the forces and processes that bring into being, and that react upon, the rocks of the earth's crust. Many of the basic problems of petroleum geology such as the origin of petroleum and the mechanics of migration of petroleum can be attacked only in the light of the physical and chemical principles that bear on the problems. Rather glaring errors in reasoning have been made by geologists who have tried to answer some of these problems without adequate knowledge of the basic sciences. The more common problems facing the petroleum geologist—such as the interpretation of electric logs and drill-stem tests; cementation, solution and recrystallization phenomena; and variations in salinity of subsurface waters—are understood more readily if the geologist has a working knowledge of areas of chemistry and physics that relate to these problems.

Course work in the aforementioned branches of geology and allied sciences, plus course work in the humanities or liberal arts (English, foreign languages, history, political science, etc.), should form the program of undergraduate study leading to the profession of petroleum geology. As in the other science departments, geology departments are increasingly faced with the problem of turning out graduates skilled in the complex technology of their profession and concurrently turning out "well-rounded" graduates who are prepared to face their responsibilities as world citizens.

The training of the petroleum geologist does not end with the granting of an academic degree. Many companies maintain formal six-month to two-year training programs that are designed to round out the new employee's general education in geology and to acquaint him with company organization and objectives. In addition, it is the responsibility of the geologist throughout his career to become acquainted with the geology of the area in which he is working and to keep abreast of new concepts and advancements in geologic science. In a sense, the new graduate's training in geology has just begun. There is a constant overlap between the training and the duties of the petroleum geologist.

## DUTIES

Two probable channels into which the duties of young petroleum geologists will be directed are field mapping and/or well sitting. For the adequately trained geologist, field work will not be new, but the specific company-approved techniques must be mastered. The duties of a well-site geologist are primarily sample and core examination, selection of coring and testing intervals, recommendations regarding the mud program, logging, and completion methods.

The end product of most company assignments is a report, which may consist of a sample log and a written description of the samples and cores obtained from a wildcat well, or it may consist of a map and a written description of the structural geology and stratigraphy of an area and an estimation of the possibilities of petroleum entrapment. Wildcat prospect reports will contain information regarding depths to possible pay horizons, thickness of formations that will be encountered, distances from nearby production, gravity of oil expected, accessibility of drill site, and water availability. In addition, information may be required regarding distance from piplines, price of oil, land acquisition, and drilling costs.

From field and well-site duties, it is only a short step to the compilation of local or regional structural maps and formation correlations. In addition to the stratigraphic and structural work, the geologist may be required to keep abreast of the activities of other companies in a particular area (leasing, geophysical activities, wildcat locations, etc.).

As a geologist advances in a company, he will become involved with exploration planning, budgeting problems, hiring and coordinating personnel, and myriad administrative duties. The geologist's day-to-day problems tend to divert his mind from his basic duty and responsibility to his company: *finding more* *oil.* Ultimately, the geologist must contribute his share to the teamwork that brings about the discovery of a new field; this contribution will justify his existence as a petroleum geologist. Of all the characteristics that are desirable in an exploration geologist, the one most likely to contribute to the discovery of new fields is imagination tempered by sound reasoning, and this quality may be as much an inherent trait as an acquired skill.

Chapter 2

# THE FUTURE OF SUBSURFACE PETROLEUM EXPLORATION

**A. I. Levorsen**

The usefulness of subsurface geological methods in petroleum exploration and production problems has increased steadily since the beginning of the petroleum industry. As more subsurface understanding is called for, more and more geologists become specialized in this type of work, until in many areas practically all of the exploration geology is based on subsurface interpretations.

## PETROLEUM EXPLORATION

Petroleum exploration in most regions has followed a logical sequence in that it has proceeded from the known and obvious to the less known and less obvious, from surface geology toward subsurface geology. Once the anticlinal theory of oil and gas accumulation was accepted, it was only natural that all anticlines that could be observed at the surface should be mapped and tested by the drill. This was followed by structure mapping at shallow depths by core drilling, by subsurface mapping within the reach of the drill, and at all depths by geophysical methods. The search for structural traps may be called Phase I in the orderly sequence of exploration.

As favorable closed structures in a region become increasingly difficult to locate by any available means, attention is directed to traps in which local structure is but a part of the reason for a trap, the other part being some stratigraphic anomaly that combines with the structure to form the trap. It is in this phase, or Phase II of the sequence, that half domes, open anticlines, terraces, noses, and any irregularity in the regional dip become important, because such structure, combined with any one of the many kinds of stratigraphic anomalies, may form one of a wide variety of traps in which oil and gas pools have accumulated.

The stratigraphic evidence for Phase II develops only as wells are drilled and logs and subsurface data become available. Consequently most of the drilling for stratigraphic traps is close to wells that have tested the crests of dome folds, for it is only there that stratigraphic information is available by which combination traps can be predicted. It is around the flanks of dome folds, moreover, that arching or half domes occur down the pericline so that half of the trap is known; then it becomes necessary to locate only the other half—the stratigraphic half—of the combination.

For several reasons wells are sometimes drilled and pools discovered where there is no local structure. One reason is that an error has been made in the structural mapping, and no local fold or fault occurs where it is mapped. Another is that a permeable lens or reef is suspected. Leasing problems cause many wells to be drilled without regard to structure, as for example where leases are about to expire and no definite geological information can be worked out to evaluate the lease even though the location is generally favorable. Large lease ownerships, likewise, may justify drilling random wildcat wells to satisfy lease requirements or to gain the stratigraphic information needed to proceed with the exploration program. Each of such wells, even though nonproductive, adds subsurface data that can be integrated with other data to work out combination trap prospects or purely stratigraphic traps.

Finally, after all structural anomalies that combine with stratigraphic features to form traps have been tested, the purely stratigraphic traps remain. This may be called Phase III. These traps require little or no local structural anomaly to complete the trap and consist of such phenomena as sand patches and lenses; shoestring, channel, and bar sands; coquina lenses; dolomitization patches; irregularities along an up-dip wedge-out of permeability; variations in the permeability; and a variety of permeable lenses surrounded by impermeable rocks. Pools of this kind are discovered either by random drilling or by drilling based on interpretations of precise subsurface stratigraphic data.

The three phases and the kind of mapping called for may be listed as:

Phase I—Structural traps. Surface, subsurface, and geophysical mapping.
Phase II—Combination traps. Subsurface and geophysical mapping.
Phase III—Stratigraphic traps. Subsurface mapping.

A sequence such as this does not have sharp time boundaries, and all three phases may be operating to a varying degree in every region simultaneously. Each phase, however, is seen dominating the exploration effort at some time during the life of nearly all regions, and generally in the order listed above. Different companies and different geologists, each with a different background of training and experience, will attack the exploration of a region differently, and some phase may be omitted. If there are no outcrops, for example, surface mapping may be omitted, and geophysical mapping may begin at once. If a purely stratigraphic trap-pool is discovered early, more attention will be given to stratigraphic exploration in the early stages. On the whole, however, the more exploration there has been, the higher will be the proportion of effort devoted to subsurface mapping, both structural and stratigraphic.

## SUBSURFACE GEOLOGY

Subsurface geology increases in usefulness as more drilling is done in a region principally because (1) the more exploration there has been the more difficult it is to find new structural features to drill, and more attention is given to stratigraphic anomalies that can be determined only by subsurface mapping, and (2) the more exploration, the more data there are available for study and comparison with past data.

The emphasis in subsurface geology changes with time. As the exploration of any region develops, more attention is given to subsurface methods for mapping structure than is given to surface and geophysical techniques. Once a structure is located and mapped, there is seldom a need for complete remapping. The emphasis then shifts to any of a variety of stratigraphic features associated with the structure that might form traps, and these require a revaluation as every new log in the vicinity becomes available. Finally, an accurate understanding of the geologic history of a region calls for mapping every imaginable phenomena and episode that can be located until the history is unravelled.

There is also a need for subsurface geology during the development of a pool. The subsurface geologist is accustomed to working with all kinds of well logs and well data, and his interpretations and thinking are essential to the petroleum engineer's understanding of the geological conditions associated with the reservoir. After all, much of the development and production of a pool are but extensions of principles that the geologist uses in his daily thinking during the search for a pool.

The well log is the basic source of information in subsurface mapping. Significant and useful facts are continually being squeezed out of the old logs, and development of new ways of logging are almost an annual occurrence. No area has been mapped completely until the most modern logging methods have been applied to it. Even where the logs are old, one modern log may help considerably in deciphering the old log. The sample log, the paleontologic log, the time log, the electric log, and the continuous-velocity log add new data to the stratigraphic record. These data, after being evaluated, can be applied frequently to the drillers' logs to make them more useful than before.

All analyses of stratigraphic methods in exploration point to the increasing need of greater precision. The direction is toward better logs; more accurate correlations, contacts, facies changes, unconformities, and truncations; to more data on porosities and permeabilities; and to better fluid and reservoir characteristics such as saturations, pressures, and temperatures.

The relationships between structural and stratigraphic phenomena in the formation of a trap are shown in Figure 2-1. The gradation from 100 percent structural causes to 100 percent stratigraphic causes is shown diagramatically.

## THE SUBSURFACE GEOLOGIST

The first objective of the petroleum geologist is to discover oil and gas; this is the chief reason for his existence. As long, then, as there is a need for more petroleum discoveries, there will be a need for the petroleum geologist—first for his ability to work geology at the surface, then, and probably more important, his ability to work geology below the surface.

Subsurface geology, like other kinds of geology, is dynamic. New ways are continually being found for obtaining subsurface information, or interpreting data, and for predicting the position of a favorable prospect. The subsurface geologist must, therefore, be alert to change and be ready to use new kinds of information, to re-examine his old data for new meanings, and to put his findings together in new ways. Not only are new techniques continually being discovered but, once discovered and found to be practical, there is a steady advance in their interpretation and in the construction and operation of the equipment.

Geophysical surveys are an integral part of any modern exploration program. A geophysical survey is, in fact, a subsurface geological survey conducted from the surface without drilling. The records might be thought of as logs of the rocks below the surface, and they require geological interpretation exactly as do well logs. It is essential that any geologist working on subsurface problems should be familiar with the advantages and the limitations of the different geophysical methods of surveying.

Geophysical data should be fitted into other subsurface data and all of the information synthesized into a complete picture. This procedure becomes more and more important as the structural closure diminishes, for less and less reliability can be placed on minor structural features, especially where the measurements are near or below the limits of error of the instruments, and more and more reliance must be placed on stratigraphic anomalies. Geophysical surveys of all kinds are steadily improving in accuracy, however, and areas that could not be precisely mapped even in the recent past may suddenly become mappable.

One corollary of an increase in subsurface mapping is that it requires more geological imagination than surface or geophysical methods. The reason is that the data are frequently widely scattered, insufficient, or inconclusive; and unless