CHAPTER 1

INTRODUCTION TO SUBSURFACE MAPPING

TEXTBOOK OVERVIEW

This textbook begins where many others end. It focuses on subsurface structural and mapping methods and techniques and their application to the petroleum industry. These techniques are also important and applicable to other fields of study, and geologists, geophysicists, engineers, and students in related fields, such as mining, groundwater, environmental, or waste disposal, should benefit from this text as well.

The objectives of subsurface petroleum geology are to find and develop oil and gas reserves. These objectives are best achieved by the use and integration of all available data and the correct application of these data. This textbook covers various aspects of geoscience interpretation and the construction of subsurface maps and cross sections based upon data obtained from well logs, seismic sections, and outcrops. It is concerned with correct structural interpretation and mapping techniques and how to use them to generate the most reasonable subsurface interpretation that is consistent with all the data.

Subsurface geological maps are perhaps the most important vehicle used to explore for undiscovered hydrocarbons and to develop proven hydrocarbon reserves. However, the subject of subsurface mapping is probably the least discussed, yet most important, aspect of petroleum exploration and development. As a field is developed from its initial discovery, a large volume of well, seismic, and production data are obtained. With these data, the accuracy of the subsurface interpretation is improved through time. The most accurate interpretation for any specific oil or gas field can be prepared only after the field has been extensively drilled and most of the hydrocarbons have been depleted. However, accurate and reliable subsurface interpretations and maps are required throughout all exploration and development activities.

From regional exploration to a field discovery and through the life of a producing field, many management decisions are based on the interpretations geoscientists present on subsurface maps. These decisions involve investment capital to purchase leases, permit and drill wells, and work over or recomplete wells, just to name a few. An exploration or development prospect generator must employ the best and most accurate methods available to find and develop hydrocarbon reserves at the lowest cost per net equivalent barrel. Therefore, when preparing subsurface interpretations, it is essential to use all the available data, evaluate all possible alternate solutions, use valid structural interpretation methods, and use the most accurate mapping techniques to arrive at a finished product that is consistent with correct geologic models.

Subsurface geoscientists have the formidable task of mapping unseen structures that may exist thousands of meters beneath the earth's surface. In order to accurately interpret and map these structures, the geoscientist must have a good understanding of the basic principles of structural geology, stratigraphy, sedimentation, and other related geological disciplines. The geoscientist must also be thoroughly familiar with the structural style of the region being worked. Since all subsurface interpretations and the accompanying maps are based on **limited data**, the geologist, geophysicist, or engineer must use (1) his or her educational background, (2) field and work experience, (3) imagination, (4) an understanding of local structures, (5) an ability to visualize in three dimensions in order to evaluate the various possible alternate interpretations and decide on the most reasonable, and (6) correct subsurface structural and mapping methods and techniques.

There are many textbooks on structural geology, tectonics, stratigraphy, sedimentology, structural styles, petroleum geology, and other related geologic subjects. Since Bishop's classic work (1960), our original text published in 1991 was the only single-source textbook on applied subsurface mapping techniques. Many new developments occurred during the 1990s. In particular, the field of structural geology advanced to the extent that structural methods and techniques have enhanced subsurface interpretation and mapping. As we enter the 21st century, the objective of this second edition of *Applied Subsurface Geological Mapping* is to present a variety of subsurface structural, mapping, and cross-section methods and techniques applicable in various geologic settings, including extensional, compressional, strike-slip, and diapiric tectonic areas. The detailed structural and mapping techniques illustrated throughout the book are intended to expand your knowledge and improve your skills in preparing geological interpretations using a variety of maps and cross sections.

All energy companies expect positive economic results through their exploration and development efforts. Some companies are more successful than others. Many factors lead to success, including advanced technology, aggressive management, experience, and serendipity. A significant underlying cause of success that is often overlooked or taken for granted, however, is the **quality** of subsurface structural and mapping methods. The application of the numerous techniques presented in this book should improve the quality of any subsurface interpretation. This improved quality should positively affect any company's economic picture. This is accomplished by:

1. Developing the most reasonable subsurface interpretation for the area being studied, even in areas where the data are sparse or absent.
2. Generating more accurate and reliable exploration and exploitation prospects (thereby reducing associated risk).
3. Correctly integrating geological, geophysical, and engineering data to establish the best development plan for a new field discovery.

4. Optimizing hydrocarbon recoveries through accurate volumetric reserve estimates.
5. Planning a more successful exploration or development drilling program, or preparing a recompletion and workover depletion plan for a mature field.
6. Accurately evaluating and developing any required secondary recovery programs.

THE PHILOSOPHICAL DOCTRINE OF ACCURATE SUBSURFACE INTERPRETATION AND MAPPING

The philosophical doctrine of accurate subsurface interpretation and mapping presented here is designed to provide geologists, geophysicists, and engineers with the tools necessary to prepare the most reasonable subsurface interpretations. In our quest for hydrocarbons, we are always searching for excellence. The material contained in this book can serve as a teaching medium, as well as a source of reference for conducting subsurface investigations beginning with the initial stages of exploration, continuing through field development, and ending with enhanced recovery and field depletion.

Have you ever wondered what makes the difference between a great, successful oil and gas prospector and one who is mediocre or below average? Have you ever wondered why one geoscience team has a much greater success rate than others working within the same area? When you place your investment dollars into exploration or development prospects or in the purchase of a producing field, do you ask or even consider what methodology or philosophy was used by the generating geoscientist or team (Tearpock 1998)? Remember, people, not computers or workstations, find oil and gas!

Is the methodology or philosophy used by geoscientists an important factor? Well, decades of research, observation, and analyses indicate the primary reason why some individuals, teams, or companies are more successful than others is the direct result of the philosophy and methods used. It is not serendipity, luck, or guesswork that finds hydrocarbons. It is solid scientific work.

The Philosophical Doctrine of accurate subsurface interpretation and mapping presented here provides the best-proven process for finding and developing hydrocarbons. It requires common sense, a certain technical background, experience, logic, and the application of proven scientific methods. The key points of this philosophy are:

1. All subsurface interpretations must be geologically and geometrically valid in three dimensions.
2. An interpreter must have a fundamental, classic education in geology and a strong background in structural geology for the tectonic setting being worked.
3. Sufficient planning, time, and detail are required to generate reliable prospects. Haste makes waste.
4. All subsurface data must be used to develop a reasonable and accurate subsurface interpretation.
5. Accurate correlations (well log and seismic) are required for reliable geologic interpretations.
6. The use of correct mapping techniques and methods is essential to generate reasonable and correct subsurface interpretations.
7. All important and relevant geologic surfaces must be mapped and the maps integrated to arrive at a reasonable and accurate subsurface picture.
8. The mapping of multiple horizons is essential to develop reasonably correct, three-dimensional interpretations of complexly faulted areas.

9. Balanced cross sections are required to prepare a reasonably correct interpretation of complexly deformed structures.
10. All work should be documented.

The following text provides more detail, defining the ten points of the Philosophical Doctrine.

1. All subsurface interpretations must be geologically and geometrically valid in three dimensions. Subsurface data are either one-dimensional (well log) or two-dimensional (well log cross sections and conventional seismic sections); however, these data are used to generate a three-dimensional depiction of the subsurface. Even though it is intuitive that all interpretations must be valid in three dimensions, too often subsurface structure maps, cross sections, and seismic interpretations are made without much consideration given to establishing a three-dimensional framework or verifying that the interpretation is even possible in three dimensions (Tearpock et al. 1994). There are a number of methods and techniques that can be used to validate an interpretation before investment dollars are committed to a prospect, lease, concession, or field purchase. Management should require that such work be done prior to investment decisions.

2. An interpreter must have a fundamental, classic education in geology, including field experience, and a strong background in structural geology for the tectonic setting being worked. When an interpretation is made in a particular tectonic setting, the interpreter must know as much as possible about the geology of the area so that the interpretation represents geology that is known to fit the style of the area. This places the requirement on an interpreting geoscientist initially to have a fundamental, classic education in geology. Without knowledge and understanding of geology, the applications of geophysics, petrophysics, workstation activities, or even computer mapping will be questionable and potentially inconsistent with geologic principles.

Of special interest is the area of structural geology. With few exceptions, interpreters are working in tectonic areas where a knowledge of structural geology is important. A limited understanding of structural geology is one of the shortcomings in numerous geologic interpretations that result in unrealistic or even impossible interpretations in three dimensions.

3. Sufficient planning, time, and detail are required to generate reliable prospects. Haste makes waste. Do not be too anxious to drill that next dry hole. There are not many shortcuts to good prospecting. Initially, it is essential to develop a program or project plan designed to meet the objectives and provide the needed deliverables. With limited time available to complete a project, alternate solutions may not be analyzed, all the data may not be used, unjustified shortcuts might be taken, or incorrect techniques may be applied. When you consider the cost of a dry hole, an unsuccessful exploration program, or the loss of investor confidence, the time taken to ***do the project right the first time*** is time well spent. Remember Murphy's Law: "If something can go wrong, it will."

Management must also realize that each project is in some ways unique. Therefore, the detail required for any given project to achieve the objectives should be specific to that project. Consider two projects: one on a simple four-way closure and the other on a complex compressional duplex. It is obvious that these studies will require different plans, timetables, and technical details. Use common sense in evaluating the time, plan, and detail required.

4. All subsurface data must be used to develop a reasonable and accurate subsurface interpretation. The data available for interpretation are limited and are typically one- and two-dimensional (including a seismic section displayed on a 3D conventional workstation). A body of data itself can be confusing with respect to true subsurface relationships. For example, cross sections and seismic sections can misrepresent true three-dimensional subsurface relationships by the simple nature of their orientations. All data (well log, seismic, production, paleontologic, etc.) must be integrated into an interpretation if it is to be considered sound and viable.

Important thoughts to keep in mind while compiling and using subsurface data are the physical limits and accuracy of these data. A degree of confidence must be built into any final interpretation, but the end result can be only as good as the data that are used. The reasons for failing to recognize inaccuracies of data can range from blindly accepting auto-correlations to not investigating questionable directional surveys, mud logs, electric logs, core reports, velocity functions, production data, and so on. Inclusion of incorrect data may be unavoidable due to inaccuracies inherent in tools and procedures that generate data or to historical methods of record keeping. Many times, however, it is possible to determine whether the data are out of date, incomplete, or subject to error.

Questionable data may represent the only data that are currently available. In other cases, more reliable data are available and should be sought. The physical limits and possible inaccuracies of the data should always be noted when presenting completed work. Always acknowledge questionable findings and possible discrepancies in a final interpretation. Also, all data used must be used correctly in order to ensure accuracy in any interpretation.

5. Accurate correlations (well log and seismic) are required for reliable geologic interpretations. An interpretation that properly integrates all data, such as well log, seismic, and production data, is always more accurate than an interpretation that ignores one of these sources (Tearpock and Bischke 1991). Likewise, the correlations must be accurate because geologic interpretations have their foundation in correct correlations. Consider that all aspects of subsurface interpretation and prospecting are based on correlations. These correlations are used to prepare cross sections and fault, unconformity, salt, structure, and isochore/isopach maps. Workstations have given geoscientists the ability to work immensely large databases in a relatively short time. They have also provided, however, a method of auto-picking correlations. These correlations are at times blindly accepted and therefore not verified by the interpreter before plunging into map generation. This can be a blessing as well as a curse to the less knowledgeable.

Eventually, a geoscientist's correlations, right or wrong, are incorporated into the final interpretation. Incorrect correlations can be costly; they can result in a dry hole, an unsuccessful workover or recompletion, the purchase of an uneconomic property, or the sale of a producing property that has significant, unrecognized potential.

6. The use of correct mapping techniques and methods is essential to generate reasonable and correct subsurface interpretations. Maps and cross sections are in most cases the primary vehicles used to organize, interpret, and present available subsurface information. The reliability of any subsurface interpretation presented on maps and cross sections is directly related to the use of accurate and correct mapping methods and techniques.

Geoscientists who have a good understanding of the mapping methods applicable in the area of study prepare the most accurate geologic interpretations. There is no substitute for correct mapping techniques. A poor understanding of mapping techniques can result in incorrect procedures, unjustified short cuts, and costly inaccurate interpretations. We illustrate interpretive contouring as an example of the use of a correct mapping technique. Interpretive contouring is the most acceptable method of contouring subsurface features (Bishop 1960). Unlike other contouring methods, interpretive contouring allows the geoscientist to use knowledge of the structural and depositional style in the tectonic setting being worked, the ability to think in three dimensions, field and work experience, imagination, and geologic license to generate an interpretation that is geologically sound.

In today's world of computer-contoured maps, can you, as a geoscientist, define which gridding or triangulation procedure should be used to generate a map that honors the data and reflects a mapped interpretation in a way similar to a hand-contoured map made by an experienced geoscientist? This is one example of a technique with which a geoscientist must be familiar in order to generate a good subsurface interpretation.

7. All important and relevant geologic surfaces must be mapped and the maps integrated to arrive at a reasonable and accurate subsurface picture. These include surfaces such as tops of formations, stratigraphic markers, faults, unconformities, and salt. For example, in faulted areas it is typically the faults that form the structures, such as rollovers, fault bend folds, and fault propagation folds. To develop a good understanding of any faulted structure, one must analyze, interpret, and map the faults. We cannot overemphasize the importance of mapping faults. In addition, faults play an important role in both the migration and trapping of hydrocarbons. Therefore, a reasonable structural interpretation in most faulted areas is dependent upon an accurate three-dimensional understanding of the faults in the area.

The next step in the interpretation process is to integrate the faults with the structure to arrive at an accurate interpretation. If you want to drill more than your share of dry holes, don't map faults.

8. The mapping of multiple horizons is essential to develop reasonably correct three-dimensional interpretations of complexly faulted areas. It allows the interpreter to establish a three-dimensional structural framework prior to generating prospects. The mapping of at least three horizons (shallow, intermediate, and deep) allows the geoscientist to determine if the interpretation is plausible and fits at all levels from shallow to deep. Remember, almost any set of fault and structural data can be forced to fit on one horizon. The true test of an interpretation is to have the data fit at all structural levels. Therefore, *no prospect should be accepted for review without verification that multiple levels have been interpreted and mapped.* The multiple horizon mapping must show that the interpreted structural framework is geologically sound and that it conforms to three-dimensional spatial and temporal relationships.

9. Balanced cross sections are required to prepare a reasonably correct interpretation of complexly deformed structures. In complexly deformed areas the application of sound structural methods and the generating of structurally balanced cross sections are necessary to prepare admissible interpretations. Structural interpretations are not cast in stone. Any given structure was not always as it is today. If an interpreted structure does not volume-balance or a cross section does not area-balance, then the interpretation cannot be correct from a simple geometric point of view. Thus, balancing can direct the interpreter toward the correct interpretation. Structural balancing provides a better understanding of the present configuration of structures, how structures form, how, when and where fluids may have entered the structures, and where hydrocarbons may presently exist. Structural balancing should be an integral part of geologic interpretations in complex areas.

10. All work should be documented. Significant volumes of data are collected, evaluated, used, and manipulated during a project. Good, accurate recording of data and a description of procedures taken by an interpreter make everyone's work go more smoothly and accurately. The documentation of work is an integral part of that work. All subsurface projects will provide better results if the data collected and generated are recorded in some format that can easily be referenced, used, or revised. These data include information on formation tops and bases, faults, unconformities, net sand counts, correction factors, and more. All completed work needs to be supported by all the raw data, whether obtained from commercial services or internally generated.

Many persons, including the interpreter, supervisors, managers, other members of an organized study team, or persons inheriting the area of study, may at some time need to review the subsurface data. Numerous types of data sheets are available for documenting geological activities. Everyone should become familiar with the forms used in their company and use them on a regular basis.

The Philosophical Doctrine presented here has been employed by many successful geoscientists. Hydrocarbons are not found by luck, serendipity, or guesswork, but instead by solid scientific work. Historical data show that those geoscientists who practice this philosophy on a regular basis are more successful finders and developers of hydrocarbons than those who do not. Workstations and computers have enabled geoscientists to evaluate more data in a short amount of time and to apply the philosophy and methods faster than by hand. However, we must remember that people, not workstations, find oil and gas, and the philosophy and methods used have a great impact on success.

TYPES OF SUBSURFACE MAPS AND CROSS SECTIONS

When conducting any detailed subsurface geologic study, a variety of maps and cross sections may be required. The numerous techniques available to use in the preparation of these maps and sections are discussed in subsequent chapters.

As mentioned earlier, the primary focus of this book centers on structural and mapping methods and the maps and cross sections used to find and develop hydrocarbons. However, the techniques are applicable to many other related geologic fields. The following is a list of the types of maps and sections discussed in this book.

SUBSURFACE MAPS. Structure, structural shape, porosity top and base, fault surface, unconformity, salt, net sand, net hydrocarbon, net oil, net gas, isochore, interval isopach, facies, and palinspastic maps.

CROSS SECTIONS. Structure, stratigraphic, problem-solving, final illustration, balanced, and correlation sections. Conventional and isometric fence diagrams and three-dimensional models are also presented.