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Chapter 1

The Petroleum System

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Abstract

Sedimentary basins, petroleum systems, plays, and prospects can be viewed as separate levels of investigation, all of which are needed to better understand the genesis and habitat of hydrocarbons. *Sedimentary basin* investigations emphasize the stratigraphic sequence and structural style of sedimentary rocks. *Petroleum system* studies describe the genetic relationship between a pod of active source rock and the resulting oil and gas accumulations. Investigations of *plays* describe the present-day geologic similarity of a series of present-day traps, and studies of *prospects* describe the individual present-day trap. Except for the petroleum system, these terms are widely used by petroleum geologists. The procedure to identify, characterize, name, and determine its level of certainty is discussed.

A petroleum system encompasses a pod of active source rock and all related oil and gas and includes all the essential elements and processes needed for oil and gas accumulations to exist. The essential elements are the source rock, reservoir rock, seal rock, and overburden rock, and the processes include trap formation and the generation–migration–accumulation of petroleum. All essential elements must be placed in time and space such that the processes required to form a petroleum accumulation can occur.

The petroleum system has a stratigraphic, geographic, and temporal extent. Its name combines the names of the source rock and the major reservoir rock and also expresses a level of certainty—known, hypothetical, or speculative. Four figures and a table that best depict the geographic, stratigraphic, and temporal evolution of a petroleum system include a burial history chart to establish the age and critical moment of the system, a map and a cross section drawn at the critical moment, an events chart to summarize the formation of the petroleum system, and a table of related accumulations. The petroleum system can be used as an effective model to investigate discovered hydrocarbon accumulations.

INTRODUCTION

New ideas are constantly being developed and put to use in oil and gas exploration. Even more common than the development of new ideas is the revival of older concepts, which are then put to use in new ways. The concept of the petroleum system is one that many geologists are intuitively familiar with and may feel that they have been using all along. There are several reasons why we are now proposing to revive, expand, define, and formalize this concept. First, the ability to identify a petroleum system uniquely depends on geochemical techniques needed to map organic facies, to understand and map hydrocarbon shows, and to carry out petroleum–petroleum and petroleum–source rock correlations, some of which were put into widespread use only in the past 10–15 years. Second, the petroleum system approach is a way of organizing information that uniquely lends itself to efficient investigations for purposes of exploration, resource appraisal, and research. Third, the role of petroleum system investigations in basin analysis, play analysis, and prospect appraisal has never been adequately clarified.

In addition to providing an introduction to this volume, the purposes of this paper are as follows: (1) to define, compare, and contrast the different levels of petroleum investigations; (2) to describe the history of the petroleum system model; (3) to identify, name, and determine the level of certainty of a petroleum system; (4) to describe those figures that best depict the geographic, stratigraphic, and temporal extent of a petroleum system; and (5) to describe how a petroleum system study is implemented.

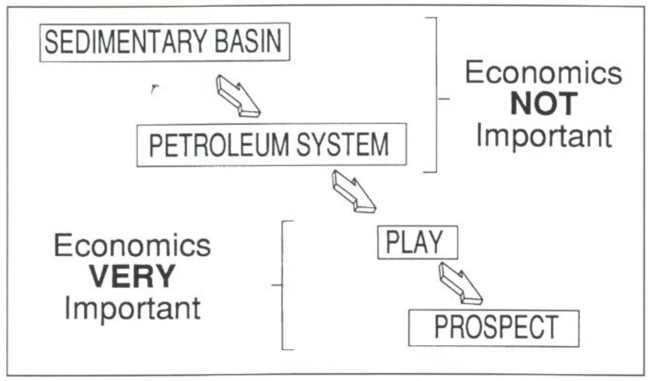

Figure 1.1. Four levels of petroleum investigation.

LEVELS OF PETROLEUM INVESTIGATIONS

Investigations of sedimentary basins, petroleum systems, plays, and prospects can be viewed as separate levels of hydrocarbon investigation, all of which are needed to better understand the genesis and habitat of hydrocarbons. Investigations of sedimentary basins describe the stratigraphic sequence and structural style of sedimentary rocks. Petroleum system studies describe the genetic relation between a particular pod of generating source rock and the resulting petroleum. Investigations of plays describe a series of present-day traps, and of prospects, an individual trap, and determine whether they have economic value and are exploitable with available technology and tools (Figure 1.1 and Table 1.1).

Economic considerations are unimportant in sedimentary basin and petroleum system investigations, but are essential in play or prospect evaluation. Whenever plays or prospects are discussed, economically producible hydrocarbons are implied or anticipated. Stated in another way, without favorable economics, a commercial petroleum play or prospect does not exist. In contrast, a sedimentary basin and a petroleum system exist regardless of economic considerations because these phenomena are based on natural processes. Proof of a sedimentary basin is sedimentary rock; proof of a petroleum system is the presence of hydrocarbons, even a puff of gas or a drop of oil (low volume but high concentration).

Historical aspects have differing importance for each level of investigation. Investigations of sedimentary basins and petroleum systems are relative to the geologic time when processes are occurring, that is, when sediments are being deposited and when hydrocarbons are migrating to their traps. In contrast, the present-day existence of a play or prospect is the important factor. There is little interest in a play or prospect that existed at the end of the Paleozoic but has since been eroded or destroyed. A prospect is conceptual because a successful prospect turns into an oil or gas field when drilled or disappears when the prospect is unsuccessful.

In addition, as the focus of investigation on hydrocarbon occurrence moves from the sedimentary basin to the prospect level, the cost of the investigation per unit surface area generally increases. Investigation of sedimentary basins requires a low-density information grid that covers a large area, such as widely spaced seismic lines, a few strategically placed exploratory wells, and small-scale geologic maps. In contrast, prospect evaluation requires a relatively high-density information grid that covers a small area, such as closely spaced seismic lines on a large-scale map. Eventually, the cost to acquire drilling rights and to drill wells must also be included in the economics of the prospect.

For the purpose of this volume, each level of petroleum investigation has its own descriptive term, such as basin *analysis* for the investigation of a sedimentary basin. Also, modeling has a similar set of terms, such as basin *modeling*. The difference between analysis and modeling is that in analysis, an existing item is dissected to determine how it functions, whereas in modeling, a hypothetical item is dissected to determine how it should function. For example, prospect modeling is used on a prospect to justify drilling, whereas a prospect analysis is carried out after drilling to understand why it lacked commercial hydrocarbons.

A historical summary of geologic models relevant to the different levels of petroleum investigations is outlined in Table 1.2. A descriptive comment for each reference is followed by eight items divided into two broad categories: geologic factors and evaluation criteria. These references discuss the eight items in the two categories at various levels of detail. Although this table is incomplete, it is shown to contrast and demonstrate the relationship of a petroleum system study with other levels of investigation.

Table 1.1. Factor Comparison in the Four Levels of Petroleum Investigation

Factor	Sedimentary Basin	Petroleum System	Play	Prospect
Investigation	Sedimentary rocks	Petroleum	Traps	Trap
Economics	None	None	Essential	Essential
Geologic time	Time of deposition	Critical moment	Present-day	Present-day
Existence	Absolute	Absolute	Conditional	Conditional
Cost	Very low	Low	High	Very high
Analysis and modeling	Basin	System	Play	Prospect

Table 1.2. Summary of Geologic Models That Incorporate Sedimentary, Structural, and Organic Geochemical Processes To Explain the Distribution of Petroleum in Nature[a]

		Geologic Factors[b]					Evaluation Criteria[c]		
Reference	Description	Geol	Gen	Mig	Acc	Tim	Nom	Crt	Cls
	Sedimentary basin analysis								
Weeks (1952)	Basin development	++	–	–	–	–	–	–	++
Knebel and Rodriguez-Eraso (1956)	Oil habitat	+	–	–	++	–	–	–	++
Uspenskaya (1967)	Accumulation categories	+	–	–	++	–	–	–	++
Halbouty et al. (1970a,b)	Basin classification	++	–	–	++	–	–	–	++
Klemme (1971a,b, 1975, 1986)	Basin classification	++	–	–	–	–	–	–	++
Bally (1975)	Geodynamic scenario	++	–	–	+	–	++	–	++
Huff (1978, 1980)	Basin type	++	–	–	–	–	–	–	++
Zieglar and Spotts (1978)	Reservoir and source bed	+	+	+	++	–	–	–	–
Bally and Snelson (1980)	Realms of subsidence	++	–	–	–	–	–	–	++
Welte and Yukler (1981)	Deterministic model	+	++	++	++	+	–	–	–
Bois et al. (1982)	Geotectonic classification	++	+	–	++	+	–	–	+
Kingston et al. (1983a)	Global basin classification	++	–	–	–	++	–	–	++
Demaison (1984)	Generative basin	+	++	+	+	+	–	–	–
Ungerer et al. (1984)	Deterministic model	+	++	++	++	++	–	–	–
Tissot et al. (1987)	Kinetic model	+	++	+	++	++	–	–	–
	Petroleum system study								
Dow (1974)	Oil system	+	++	+	++	+	+	–	–
Perrodon (1980, 1983a,b)	Petroleum system	++	–	–	–	–	–	–	–
Perrodon and Masse (1984)	Petroleum system	++	–	–	–	–	–	–	–
Meissner et al. (1984)	Hydrocarbon machine	+	++	+	+	+	–	–	–
Ulmishek (1986)	Independent petroliferous system	+	++	+	++	+	–	–	–
Magoon (1987, 1988, 1989a,b, 1992a,b)	Petroleum system	–	+	+	+	+	++	++	++
Demaison and Huizinga (1991)	Petroleum system	++	++	++	++	+	–	–	++
Perrodon (1992)	Petroleum system	++	+	+	+	+	–	–	++
	Play evaluation								
Bois (1975)	Petroleum zone	–	+	+	++	–	–	–	–
White (1980)	Facies cycle wedges	++	+	+	++	+	–	–	–
Kingston et al. (1983b)	Hydrocarbon plays	++	–	–	–	–	–	–	++
Dolton et al. (1987)	Play	+	+	+	+	+	–	–	–
Bird (1988)	Play appraisal method	++	+	+	+	+	+	–	–
Podruski et al. (1988)	Resource endowment	++	+	+	++	+	+	–	–
White (1988)	Play map	++	+	+	+	+	+	–	–
	Prospect evaluation								
Bishop et al. (1983)	Trapped hydrocarbon	–	+	+	++	–	–	–	–
Sluijk and Nederlof (1984)	Systematic appraisal	+	+	+	++	–	–	–	–
Callahan et al. (1987)	PRESTO	–	–	–	++	–	–	–	–
Mackenzie and Quigley (1988)	Geochemical appraisal	+	++	++	++	++	–	–	–

[a] ++, discussed in detail; +, only mentioned; –, not mentioned.

[b] Geol = geology, including structure, stratigraphy, and geologic history of sedimentary rocks; Gen = generation, including the necessary organic matter richness, type, and maturity to generate petroleum from a source rock; Mig = migration, including the movement of oil, gas, or other hydrocarbon through the country rock; Acc = accumulation, including the presence of a reservoir rock, seal, trap, and high concentration of hydrocarbons; Tim = timing, meaning trap formation relative to hydrocarbon migration.

[c] Nom = nomenclature or name; Crt = level of certainty; Cls = classification scheme.

Sedimentary Basin Investigations

Over the last several decades, investigations of sedimentary basins have emphasized plate tectonics or structural evolution. Basin classification schemes evolved from descriptive geology (Weeks, 1952; Knebel and Rodriguez-Eraso, 1956) to genetic interpretations (Halbouty et al., 1970a,b; Klemme, 1971a,b, 1975, 1986; Bally, 1975; Huff, 1978, 1980; Bally and Snelson, 1980; Bois et al., 1982; Kingston et al., 1983a) with the advent of plate tectonics theory. With increased understanding of organic geochemistry, work on the occurrence of oil and gas also has gone from the descriptive (Weeks, 1952; Knebel and Rodriguez-Eraso, 1956) to the deterministic (Tissot, 1969; Tissot and Pelet, 1971; Zieglar and Spotts, 1978; Welte and Yukler, 1981; Demaison, 1984; Ungerer et al., 1984; Tissot et al., 1987).

Each new approach to the analysis of petroliferous sedimentary basins becomes more focused on the genesis of petroleum. Bally (1975) pointed out that sedimentary basin type does little to improve our ability to forecast the volume of petroleum from a particular type of basin. However, as more petroleum geochemistry is incorporated into the analysis of a sedimentary basin, the success ratio goes up (Demaison, 1984) and the forecast of petroleum occurrence becomes more certain (Tissot et al., 1987).

When sedimentary basins with uncomplicated geologic histories are studied, a basin analysis approach that promotes organic geochemistry works well. However, when similar studies are carried out in fold and thrust belts (such as in Wyoming, U.S.A.), in areas of complex geology (such as the Basin and Range of Nevada and Utah, U.S.A.), or in areas of uncommon heat source (such as in the mid-Pacific Ridge) (Kvenvolden et al., 1988), basin analysis techniques are more difficult to apply because the original sedimentary basin is severely deformed or incomplete. In fact, for maps that show oil and gas fields and basin outlines together, the petroleum accumulations occur within the basin outline as often as they occur on the adjacent highs or arches that are outside the basin outline (Vissides and Quirin, 1964; Wilkerson and Reed, 1982). Oil and gas fields usually (but not always) occur in sedimentary rocks, but not necessarily within the boundary of basins. Therefore, to understand the occurrence of these accumulations, at least two items need clarification. First, a working definition is needed for the sedimentary basin and what is being investigated, and second, a different type of investigation is needed that is separate from basin analysis and deals only with oil and gas.

First, the term *basin* has different implications to different specialties. A paleontologist uses the term in reference to where in the water column fossils live, such as benthic or planktonic. A petroleum geochemist visualizes the most anoxic part of a paleoocean or continental basin where organic matter accumulates and refers to that as the basin. Carbonate and siliciclastic stratigraphers refer to the sedimentary fill that was deposited sometime in the past as the basin. Structural geologists refer to the container that is created in response to a tectonic process, such as rifting, as a basin. On interpreting a seismic profile, a geophysicist refers to a thick package (measured in two-way time) of sedimentary rocks as a basin. Geologists frequently use the term geographically, that is, to name and locate a province, such as the Williston basin, which is separate from the genetic use of basin to mean any sedimentary basin. In some cases, the water column is implied as the basin, in others the sedimentary rock contents are the basin, and in yet others, the container is the basin. None of these meanings is incorrect, and specialists from different disciplines are usually aware that *basin* has more than one meaning.

For this volume, the *sedimentary basin* is a depression filled with sedimentary rocks. The depression, formed by any tectonic process, is lined by basement rock, which can be igneous, metamorphic, and/or sedimentary rock. The basin includes the rock matter, organic matter, and water deposited in this depression. In certain cases, such as with coal and some carbonate deposits, the sedimentary material is formed in situ. Basin used by itself refers to the sedimentary basin.

The term *basin* used with a proper noun refers to a petroleum province, such as the Williston basin. Sometimes basin is capitalized, such as in the Green River Basin, when it is a proper geographic name that usually refers to the present-day river drainage. A petroleum province is sometimes referred to as a petroleum basin, which is different from a petroleum system.

A sedimentary basin analysis investigates, in a myriad of ways, the formation and contents of this depression. Structural and stratigraphic studies are the most conventional way to study a sedimentary basin. More recent techniques include seismic stratigraphy and sequence stratigraphy. Sequence stratigraphy, for example, can be used to understand the distribution of sandstone and shale in a particular area as a package of related sedimentary rock. For the petroleum geologist, in certain areas the reservoir properties of this sandstone can be mapped as well as the organic facies of the shale. Sedimentary basin analysis includes all aspects of basin formation and the basin fill up to the time petroleum is generated, at which time a petroleum system investigation is required. Because petroleum is mobile, fragile, and responds to different physiochemical parameters than does basin fill, this second type of investigation, the petroleum system, is needed.

Petroleum System Investigations

Each investigative procedure has an appropriate starting point. For the prospect analysis, the starting point is the trap, for the play, a series of traps, and for a basin analysis, a tectonic setting and sedimentary rocks. Similarly, the investigative procedure for the petroleum system starts with discovered hydrocarbon accumulations, regardless of size. Because of this, shows or traces of oil and gas take on new importance. Petroleum geochemical analysis of oil and gas traces can provide critical information as to the nature of the responsible petroleum system. After the system is identified, the rest of the investigation is devoted to determining the stratigraphic, geographic, and temporal extent of the petroleum system. The bigger the petroleum system, the more likely it will have generated and accumulated commercial quantities of hydrocarbons. As indicated earlier, the petroleum system defines a level of investigation that usually lies between that of a sedimentary basin and a play.

The term *oil system* was first introduced by Dow (1974) and is based on the concept of oil–source rock correlation. The term *petroleum system* was first used by Perrodon (1980). Independently, Demaison (1984) devised the *generative basin*, Meissner et al. (1984) described their *hydrocarbon machine*, and Ulmishek (1986) identified an *independent petroliferous system*. All of these concepts are similar to Dow's oil system. Expanding upon previous work, Magoon (1987, 1988, 1989a,b) attempted to formalize criteria for identifying, naming, and determining the level of certainty for the petroleum system. This volume further refines the petroleum system concept and shows how the system is mapped and used to evaluate exploration opportunities (see later sections).

Play and Prospect Investigations

Beyond sedimentary basin and petroleum system analysis, the remaining levels of investigation are play and prospect analysis. *Prospects* were first used by exploration geologists to describe present-day structural or stratigraphic features that could be mapped and drilled. A series of related prospects is a *play*. As information about petroleum geochemistry increased, the definition of a play became broader. For example, Bois (1975) defined a *petroleum zone*, which he considered to be similar to a play (Bois et al., 1982), to include hydrocarbon mixtures of similar composition. More rigorous definitions of a play and a prospect have included a source rock as well as a migration path (White, 1980, 1988; Bishop et al., 1983; Sluijk and Nederlof, 1984; Dolton et al., 1987; Bird, 1988). The use of quantitative petroleum geochemistry (Mackenzie and Quigley, 1988) with play and prospect evaluation provides important volumetric information for economic analysis.

Plays and prospects are defined more traditionally in this volume, that is, to include present-day exploration potential for undiscovered commercial oil and gas accumulations (Table 1.1). The *play* is one or more prospects, and a *prospect* is a potential trap that must be evaluated to see if it contains commercial quantities of hydrocarbons. The presence of reservoir rock, seal rock, trap volume, hydrocarbon charge, and timing are usually involved in this evaluation. For example, if the reservoir rock in the play is eolian sandstone, then the distribution and quality of this sandstone is mapped from outcrop and well control so that it can be projected into the play area using seismic information. The probability that this eolian sandstone occurs in the play area can be evaluated in any aspect, e.g., thickness. Regardless of whether this sandstone is penetrated when the prospect is drilled, the existence of this eolian sandstone outside the play area is still valid. In the same way, already discovered oil and gas fields as well as other noncommercial quantities of hydrocarbons that are genetically related can be mapped as a petroleum system, which can then be projected into the play area as hydrocarbon charge. This hydrocarbon charge can then be evaluated with respect to the play or prospect.

PETROLEUM SYSTEM HISTORY

Dow's Oil System

The concept of an oil system was presented in 1972 at the AAPG annual meeting in Denver (Dow, 1972) and was later published (Dow, 1974). The oil system, as Dow (1974, p. 1254) presented it, was based on oil–oil and oil–source rock correlations

> to develop an understanding of the distribution of the three major oil types in the Williston basin . . ., and where each type is most likely to be found in the future. The focus of the paper is on geology and interpretation of geochemical data, not on the presentation of new geochemical data.

Dow (1974, p. 1254–1255) goes on to state that because the source rocks are isolated by evaporites,

> The distribution of oil in the basin therefore can be described in terms of three major source–reservoir oil systems. Each system contains a source rock and a group of reservoir rocks and is isolated from other oil systems by an evaporite seal.

He then names the oil systems. In Dow's (1974, p. 1261) summary section he states,

> The model developed in the Williston basin depends on the ability to (1) separate oils into genetic types, (2) relate each type to a specific source sequence, (3) understand the quantity of organic matter and the degree of thermal maturation required for generation and expulsion of oil in commercial quantities, and (4) map the distribution of both vertical and horizontal migration pathways and seals. The most likely distribution of each oil type in the subsurface can be mapped with the foregoing approach. Plays then can be made in these high-grade areas where the chance of finding oil is greatest.

Dow's (1974) paper is important for the following reasons: (1) oil–source rock correlation was the keystone to identifying the system; (2) the name included the source and reservoir rock separated by a hyphen; (3) the term *play* was used as a distinct concept; (4) in each oil system description, a mass balance comparison was carried out on the theoretical amount of oil generated and reserves (the calculations were left out of the paper); (5) the use of the term *oil system* excluded gas and condensate; and (6) the criteria for applying this concept beyond the Williston basin was only implied, not stated.

Perrodon's Petroleum System

Perrodon (1980, 1983a,b) and Perrodon and Masse (1984) first used the term *petroleum system*. Since Perrodon (1980, 1983b) are in French, and the same material is covered in a revised and updated version (Perrodon, 1983a) and in Perrodon and Masse (1984), which are in English, we quote these latter publications. Perrodon (1983a, p. 187) states that

> The geologic criteria governing the distribution of pools, and in particular, the combined presence of source rocks, reservoirs and seals, generally exhibit a certain geographic extension which is reflected by the formation of a family of pools, or even better, a petroleum system, a structured set of natural elements of the same species or having the same function. From the geographic standpoint, and according to their dimensions and complexity, these sets are reflected by the existence of a petroleum zone or province.

In Perrodon and Masse (1984), *petroleum system* is used in the title and they define it (p. 5) as follows:

> Therefore, a petroleum province can be considered as the final result of an organized set of geologic events (in space and in time) that can be called a petroleum system. In such a system, the sequence of subsidence movements and associated flows is just as decisive as lithologic and geometric factors in the formation of a group of pools. This concept of the succession of geodynamics and sedimentary processes which affect petroleum potential is developed, and specific examples of petroleum systems from the North Sea, the Arabian Platform and the Congo Basin are presented.

Concerning basin geodynamics, Perrodon and Masse (p. 5) go on to say that

> In a sedimentary basin it is not only the source rocks, reservoirs and seals, but the whole sedimentary column which plays an active and decisive role in the genesis, entrapment, and conservation of hydrocarbons. The formation of a petroleum system is the result of a succession of physical and chemical transformations (diagenesis, tectonic deformations, compaction, etc.) which affect these sediments and closely control the genesis, concentration and dispersion of hydrocarbons. Important factors which control these transformations and even initiate them are the movements of uplift and subsidence. We will stress the conditions which affect the genesis and growth of these movements, and note that together they conform to a small number of basic mechanisms: tectonics, heat flow and gravity.

Their paper then discusses thermotectonic areas, subsidence, sedimentation rates, and sedimentary and climatic factors. With regards to petroleum systems and provinces, Perrodon and Masse (1984, p. 18) state the following:

> The petroleum potential of a basin (the formation and preservation of hydrocarbon pools) is the result of the organization of the sedimentary volume and of its evolution in time. Furthermore, special attention must be paid to the characteristics and relationships of the flows passing through the sedimentary space: geothermal flows rising from the mantle and the crust, and flows of the different fluids circulating due to differences in pressure and available pathways. In the final analysis, all these transfers of energy and fluids themselves appear to be controlled by the geodynamics of the basin, i.e., by the characteristics of subsidence, whose mechanisms are reflected by different types of petroleum systems. Some examples follow.

These examples include rift basins, platform basins, passive margin basins, and pull-apart basins.

Demaison's Generative Basin

In Demaison (1984, p. 1), the term *generative basin* is defined as follows:

> Areas underlain by mature source rocks are called "petroleum generative depressions" or "hydrocarbon kitchens." A "generative basin" is defined as a sedimentary basin that contains one or more petroleum generative depressions. Mapping generative depressions is achieved by integrating geochemical data relevant to maturation and organic facies with structural and stratigraphic information derived from seismic and deep wells.

Demaison (1984, p. 1) describes the success ratios in exploration of petroleum provinces:

> Locales of high success ratios in finding petroleum are called "areas of high potential," "plays," or "petroleum zones." A rapid worldwide review of 12 sedimentary basins, described in order of geotectonic style, reveals the following regularities:
>
> 1. The zones of concentrated petroleum occurrence ("areas of high potential") and high success ratios are genetically related to oil generative depressions or basins. These depressions are mappable by integrated methods (geology, geophysics, and geochemistry).
> 2. The largest petroleum accumulations tend to be located close to the center of the generative basins or on structurally high trends neighboring deep generative depressions.
> 3. Migration distances commonly range in tens rather than hundreds of miles and are limited by the drainage areas of individual structures. Thus the outlines of generative depressions commonly include most of the producible hydrocarbon accumulations and the largest fields. Unusual cases of long distance migration are documented on certain foreland basin plates where stratigraphy and structure permitted uninterrupted updip movement of oil.
>
> These three regularities provide powerful analogs for forecasting areas of high petroleum potential in undrilled or sparsely drilled basins.

Demaison (1984, p. 3) continues his discussion of the generative basin concept by stating that

> Recognition of generative depressions is achieved by overlaying organic facies maps and maturation maps of each key petroleum source horizon. Maturation maps are compiled from seismic depth maps, near the potential source horizons, and from maturation gradients derived from well data and calibrated time–temperature models. . . . Organic facies maps reflect the stratigraphic distribution of organic matter types within a given source rock unit. They are compiled by integrating kerogen type data in the known paleographic and paleooceanographic context.
>
> The geochemical approach, in prospect appraisal, begins by investigating whether mature source beds are present in the drainage area of a trap. A further step consists of mapping areas of mature source beds and calculating both mature source rock volumes and petroleum yield. Lastly, migration pathways can be modeled between the mature source-rocks and the trap. This type of geologic exercise permits a ranking of prospects by the criterion of degree-of-access to mature source rocks.
>
> The geochemical approach to basin evaluation consists of mapping oil generative depressions or basins and erecting a matrix of drilling success ratios, volumes of discovered hydrocarbons and "kitchen" potential. When these correlations have been established they may be used for comparative purposes and for future evaluation of geologic risk. Application of the "generative basin concept," leading to recognition and prediction of areas of high potential, is the object of this contribution.

Demaison (1984) makes the following points. First, the accumulated hydrocarbons whose provenance was the mature source rock is shown to apply for generative basins worldwide. Second, risk can be reduced by staying close to the mature source rock where the drilling success ratio is highest. Three, unlike the oil system, the generative basin can have one or more petroleum generating depressions as well as one or more source rocks.

Meissner's Hydrocarbon Machine

In Meissner et al. (1984, p. 1), the term *hydrocarbon machine* is defined as follows:

> Sequences which contain all of the elements involved in the process of hydrocarbon generation from source rock to consequent migration and accumulation constitute what may be termed natural geologic hydrocarbon machines.

They go on to say (1984, p. 1) that

> Use of this conceptual framework will allow the prediction of generation/migration/accumulation *cells* or *hydrocarbon machines* operative in certain portions of the stratigraphic section. This predictive ability, when used in conjunction with regional source rock distribution maps, will explain the distribution of hydrocarbon accumulations already found and lead to the further delineation of prospective areas.

Meissner et al. (1984, p. 1–2) expand on their definition of hydrocarbon machine in the explanation of a figure:

> The starting point of the diagram concerns the existence of a source rock from which the hydrocarbons originate, the factors controlling its deposition and composition, and the types of hydrocarbons it may generate under conditions of thermal maturity. The following parts of the diagram concern the controls that time, stratigraphy, structure, and fluid dynamics exert on the processes of hydrocarbon migration and accumulation.
>
> All of the factors which affect the processes of hydrocarbon generation, migration, and accumulation constitute elements of a total system which may be described as a *machine*. These elements are placed in their interdependent cause-and-effect context in the schematic diagram of Figure 2. The illustration of a plumbing system involving a typical hydrocarbon machine depicts the movement of fluids outward from their site of generation within an area of thermal maturity to carrier/reservoir beds in which they migrate and to sites of accumulation in traps.

Figure 2 of Meissner et al. (1984, p. 3) shows a diagram of the hydrocarbon machine, which is captioned as follows:

> Diagrammatic model of a hydrocarbon machine showing geometric arrangement of essential elements and fluid migration patterns characterizing the internal "plumbing" system. The function of such a machine is to turn organic matter in a source rock (raw material) into a hydrocarbon accumulation (finished product).

Meissner et al. (1984) make the following points. First, the "generation/migration/accumulation *cells* or *hydrocarbon machines*" are very similar to the oil systems of Dow (1974) (although they fail to reference his work) and to the petroleum system of Perrodon (1980, 1983a,b) and Perrodon and Masse (1984). Second, the processes of hydrocarbon generation, migration, and accumulation are distinguished from essential elements and are expressed as a single process. Last, the essential elements are shown in their figure 2 to be the source rock, reservoir rock, seal rock, and trap.

Ulmishek's Independent Petroliferous System

In Ulmishek (1986), the term *independent petroliferous system (IPS)* was used to describe the "stratigraphic aspects of petroleum resource assessment." In the abstract (p. 59), they state that IPS is

> . . . understood here as a body of rocks separated from surrounding rocks by regional barriers to lateral and vertical migration of fluids, including oil and gas. Stratigraphically, an IPS is essentially homogeneous. It includes source rocks, reservoir rocks, traps, and a regional seal, and thus, it is a suitable unit for comparative analysis of the factors and petroleum genetic studies. For oil and gas resource assessment in poorly known regions, an IPS has certain advantages over a basin or play as an assessment unit. The concept of an IPS can also be used in statistical methods of resource appraisal and can increase reliability of these results.

In expanding his definition, Ulmishek (1986, p. 61–62) goes on to say that

> It is evident that three of the four major factors controlling a region's petroleum richness (source, reservoir, and seal) contain much more stratigraphic than tectonic information. The fourth, the trap factor, tends to reflect both stratigraphy and tectonics depending on the type of trap. It seems reasonable, therefore, that a unit chosen for comparative assessment of petroleum resources should be more related to the stratigraphy of an area than to the tectonics. The analysis of factors of richness in such a unit will be an easier task than the analysis of these factors in any tectonic unit that is "heterogeneous" from a stratigraphic point of view. Because the four listed factors reflect the conditions for successive processes of generation, accumulation, and preservation of oil and gas, such a unit must meet two major requirements: (1) it must be a confined system in which these processes take place independently from surrounding rocks, and (2) it must be the simplest of these systems, to provide maximum internal geologic uniformity and to permit sufficient depth of analysis. Such an assessment unit is here called an independent petroliferous system (IPS), which is defined as a continuous body of rocks separated from surrounding rocks by regional barriers to lateral and vertical migration of liquids and gases (including hydrocarbons) and within which the processes of generation, accumulation, and preservation of oil and gas are essentially independent from those occurring in surrounding rocks.

At the end of this same section, he (1986, p. 62) states the following:

> The most important task in developing the proposed approach is the determination, for analog purposes, of IPSs in well-explored basins. At present, 40–50 well-explored basins worldwide certainly contain not less than 150–200 IPSs. These could provide an excellent file of analogs with most combinations of factor types. Volumetric yields of the well-studied IPSs could serve as a basis for the evaluation of undiscovered resources of the forecast IPSs.

In a discussion of an IPS as an assessment unit, Ulmishek (1986, p. 62) states that

> An IPS is purely an assessment unit; its application for other purposes is limited. As an assessment unit, however, it has significant advantages over two other such units that are widely used in practice: the play, or petroleum zone, and the basin.

He later observes (1986, figure 3D, p. 66) that when an analysis of drilling statistics is carried out by IPS, rather than by drilling depth in a basin, it becomes clear that poorly explored IPSs have potential for undiscovered commercial oil and gas accumulations.

Ulmishek's (1986) paper either states or implies several points. (1) The IPS is similar to the oil system of Dow (1974) and the hydrocarbon machine of Meissner et al. (1984) (although neither is referenced). (2) The major *factors* (source rock, trap, reservoir rock, and seal) are the same as the essential elements of Meissner et al. (1984). (3) All major factors are stratigraphic in nature except for trap, which is mainly structural. (4) Major factors are distinguished from *processes* (generation, accumulation, and preservation) when referring to the assessment unit (IPS). The process of migration is absent, and preservation is an addition when compared to Meissner et al. (1984). (5) The IPS is only considered an assessment unit. (6) The paper points to "two other such units that are widely used in practice: the play, or petroleum zone, and the basin." (7) Breaking out the drilling statistics so that new IPSs are more clearly identified is a sage observation.

Magoon's Petroleum System

Magoon (1987) first used the term *elements* to refer to source rock, migration path, reservoir rock, seal, and trap and explains that the elements "must be placed in time and space such that a petroleum deposit can occur." To identify a petroleum system, Magoon (1987) relied on oil–source rock correlation. The name of the petroleum system included the name of the source rock and major reservoir rock followed by the level of certainty. He classified the systems using certain criteria.

In Magoon (1988, table 1, p. 3), an attempt was made to put the petroleum system into historical perspective using a table that summarized the contribution of Dow (1974), Bois (1975), White (1980), Bois et al. (1982), Demaison (1984), Meissner et al. (1984), Ulmishek (1986), and Magoon (1987). The table specified the geologic parameters and evaluation criteria discussed by each author. Magoon (1988, p. 2) states that

> The petroleum system emphasizes the genetic relation between a particular source rock and the resulting petroleum accumulation; basin studies emphasize structural depressions and the included sedimentary rocks regardless of the relation to any petroleum deposits; and the play or prospect approach emphasizes whether the present-day trap is detectable with available technology or tools.

The most recent definition of a petroleum system and classification scheme can be found in Magoon (1989a). The definition incorporates previous contributions and adds new words where necessary to clarify a petroleum system. The levels of petroleum investigation (Magoon, 1989b) are introduced to distinguish the petroleum system from the sedimentary basin, play, and prospect.

Magoon and Dow's Petroleum System

The petroleum system is predicated on the synthesis of previous work (Table 1.2). The terms *sedimentary basin*, *play*, and *prospect* have been informally used by petroleum geologists prior to the advent of modern-day organic geochemistry to explain the habitat of hydrocarbons. Early work in organic geochemistry by Trask and Wu (1930), Triebs (1936), Hunt and Jamieson (1956), and Phillipi (1957) provided ways to measure and map source rocks and associated products. To understand a petroleum system, a working knowledge of petroleum geochemistry is essential.

Dow (1974) distinguished a play from the oil system based on geochemistry. Ulmishek (1986) recognized the (independent) petroliferous system as a separate unit distinct from the sedimentary basin and play. Magoon (1989b) identified the levels of petroleum investigation as basin studies, petroleum systems, plays, and prospects. The present volume refers to the sedimentary basin, petroleum system, prospect, and play.

The term *petroleum system* was chosen because *petroleum* includes all forms of hydrocarbons (solid, liquid, or gaseous) (Levorsen, 1967) and *system* accounts for the interdependence of the essential elements (source rock, reservoir rock, seal rock, and overburden rock) and processes (trap formation and generation–migration–accumulation of petroleum). The term has been used before by Perrodon (1980, 1983a,b) and Perrodon and Masse (1984) in a way that is consistent with our use. The term *essential elements* originates from Meissner et al. (1984) and Ulmishek (1986), and *processes* are formalized in Meissner et al. (1984) and Ulmishek (1986).

The uniqueness of a petroleum system is based on petroleum–source rock correlation and is named according to Dow (1974), whereas the *level of certainty* is according to Magoon (1987, 1988, 1989a,b). The geographic and stratigraphic distribution as well as the preservation time of the petroleum system is specified by Magoon (1988). The definition of the petroleum system used in this volume is a refinement of previous work.

PETROLEUM SYSTEM DEFINITIONS AND CHARACTERISTICS

A *petroleum system* is defined here as a natural system that encompasses a pod of active source rock and all related oil and gas and which includes all the geologic elements and processes that are essential if a hydrocarbon accumulation is to exist. This once-active source rock may now be inactive or spent (depleted). *Petroleum* here includes high concentrations of (1) thermal or biogenic gas found in conventional reservoirs or in gas hydrate, tight reservoirs, fractured shale, and coal; or (2) condensates, crude oils, and asphalts found in nature.

Table 1.3. Oil and Gas Fields in the Fictitious Deer–Boar(.) Petroleum System, or the Accumulations Related to One Pod of Active Source Rock

Field Name	Discovery Date	Reservoir Rock	API gravity (°API)	Cumulative Oil Production (million bbl)	Remaining Reserves (million bbl)
Big Oil	1954	Boar Ss	32	310	90
Raven	1956	Boar Ss	31	120	12
Owens	1959	Boar Ss	33	110	19
Just	1966	Boar Ss	34	160	36
Hardy	1989	Boar Ss	29	85	89
Lucky	1990	Boar Ss	15	5	70
Marginal	1990	Boar Ss	18	12	65
Teapot	1992	Boar Ss	21	9	34

The term *system* describes the interdependent elements and processes that form the functional unit that creates hydrocarbon accumulations. The *essential elements* include a petroleum source rock, reservoir rock, seal rock, and overburden rock, and the *processes* are trap formation and the generation–migration–accumulation of petroleum. These essential elements and processes must occur in time and space so that organic matter included in a source rock can be converted to a petroleum accumulation. A petroleum system exists wherever the essential elements and processes occur.

Characteristics and Limits

The geographic, stratigraphic, and temporal extent of the petroleum system is specific and is best depicted using a table (Table 1.3) and the following four figures (Figures 1.2–1.5): (1) a burial history chart depicting the critical moment, age, and essential elements at a specified location; (2) a map and (3) a cross section drawn at the critical moment depicting the spatial relationship of the essential elements; and (4) a petroleum system events chart showing the temporal relationship of the essential elements and processes and the preservation time and critical moment for the system. The table lists all the oil and gas fields in the petroleum system.

The *critical moment* is that point in time selected by the investigator that best depicts the generation–migration–accumulation of most hydrocarbons in a petroleum system. A map or cross section drawn at the critical moment best shows the geographic and stratigraphic extent of the system. If properly constructed, the burial history chart shows that time when most of the petroleum in the system is generated and accumulating in its primary trap. For biogenic gas, the critical moment is related to low temperatures (Whiticar, Chapter 16, this volume). Geologically, generation, migration, and accumulation of petroleum at one location usually occur over a short time span (England, Chapter 12, this volume). When included with the burial history curve, the essential elements show the function of each rock unit and lithology in the petroleum system. In the example of Figure 1.2 (using fictitious rock units), the so-called Deer Shale is the source rock, the Boar Sandstone is the reservoir rock, the George Shale is the seal rock, and all the rock units above the Deer Shale comprise the overburden rock. The burial history chart is located where the overburden rock is thickest and indicates that the source rock started through the oil window 260 Ma in Permian time (time scale from Palmer, 1983) and was at its maximum burial depth 255 Ma. The critical moment is 250 Ma, and the time of generation, migration, and accumulation ranges from 260 to 240 Ma, which is also the age of the petroleum system.

The *geographic extent* of the petroleum system at the critical moment is defined by a line that circumscribes the pod of active source rock and includes all the discovered petroleum shows, seeps, and accumulations that originated from that pod. A plan map, drawn at the end of Paleozoic time in our example, includes a line that circumscribes the pod of active source rock and all related discovered hydrocarbons. This map best depicts the geographic extent or known extent of the petroleum system (Figure 1.3)

Stratigraphically, the petroleum system includes the following rock units or essential elements within the geographic extent: a petroleum source rock, reservoir rock, seal rock, and overburden rock at the critical moment. The functions of the first three rock units are obvious. However, the function of the overburden rock is more subtle because, in addition to providing the overburden necessary to thermally mature the source rock, it can also have considerable impact on the geometry of the underlying migration path and trap. The cross section of Figure 1.4, drawn to represent the end of the Paleozoic (250 Ma), shows the geometry of the essential elements at the time of hydrocarbon accumulation and best depicts the *stratigraphic extent* of the system.

The petroleum system *events chart* shows eight different events (Figure 1.5). The top four events record the time of deposition from stratigraphic studies of the essential elements, and the next two events record the time the petroleum system processes took place. The formation of traps is investigated using geophysical data and structural geologic analysis. The generation–migration–accumulation of hydrocarbons, or age of the petroleum system, is based on stratigraphic and petroleum geochemical studies and on the burial history

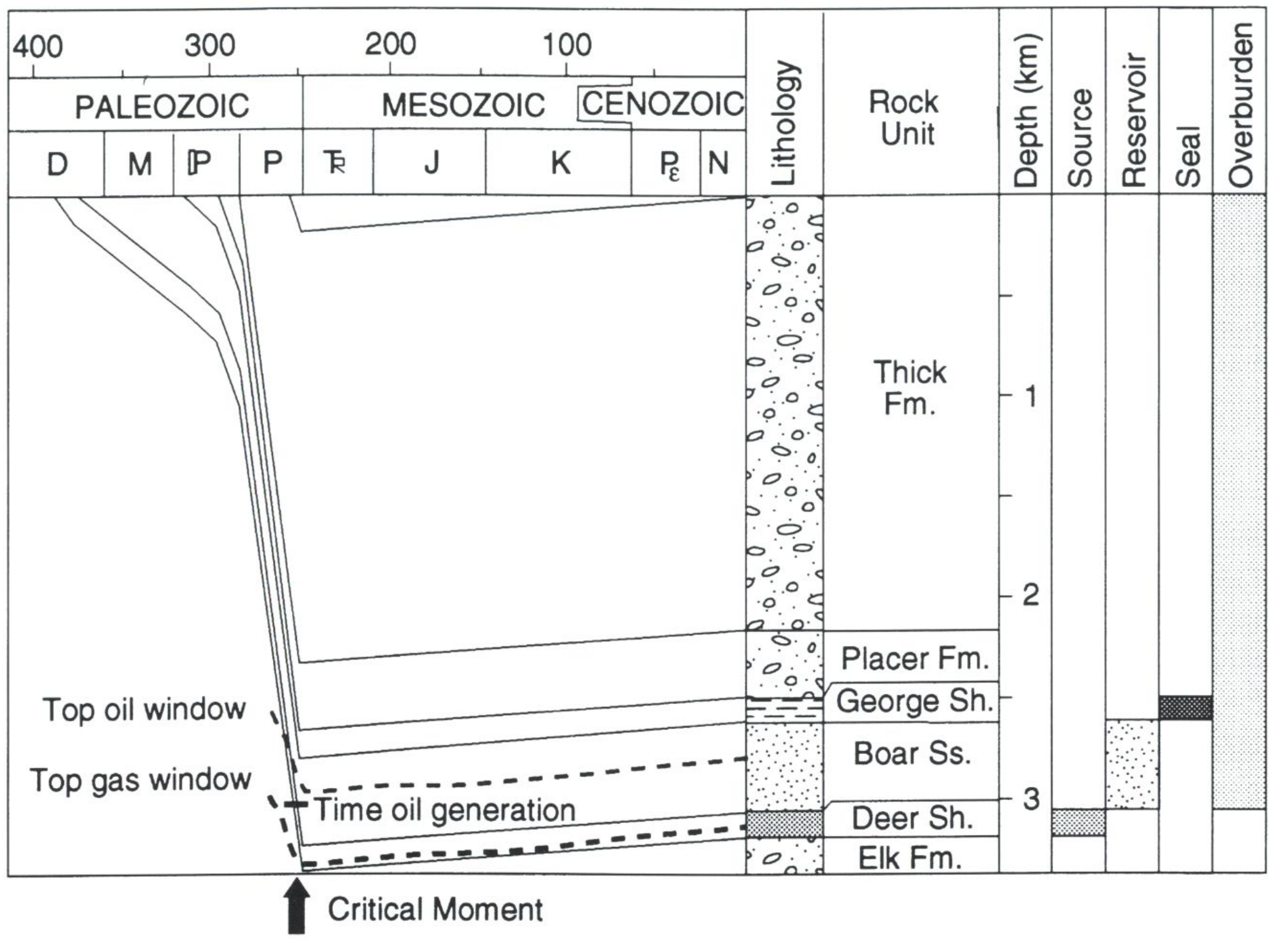

Figure 1.2. Burial history chart showing the critical moment (250 Ma) and the time of oil generation (260–240 Ma) for the fictitious Deer–Boar(.) petroleum system. This information is used on the events chart (Figure 1.5). Neogene (N) includes the Quaternary here. All rock unit names used here are fictitious. Location used for burial history chart is shown on Figures 1.3 and 1.4. (Time scale from Palmer, 1983.)

chart. These two processes are followed by the preservation time, which takes place after the generation–migration–accumulation of hydrocarbons occur, and is the time when hydrocarbons within that petroleum system are preserved, modified, or destroyed. When the generation–migration–accumulation of the petroleum system extends to the present day, there is no preservation time, and it would be expected that most of the petroleum is preserved and that comparatively little has been biodegraded or destroyed. The last event is the critical moment as determined by the investigator from the burial history chart, and it shows the time represented on the map and cross section.

Table 1.3 shows all the discovered accumulations included in the petroleum system, provides a basis for mass balance equations, and is a basis for ranking a system.

Level of Certainty

A petroleum system can be identified at three levels of certainty: known, hypothetical, or speculative. The level of certainty indicates the confidence for which a particular pod of active source rock has generated the hydrocarbons in an accumulation. In a *known* petroleum system, a good geochemical match exists between the active source rock and the oil or gas accumulations. In a *hypothetical* petroleum system, geochemical information identifies a source rock, but no geochemical match exists between the source rock and the petroleum accumulation. In a *speculative* petroleum system, the existence of either a source rock or petroleum is postulated entirely on the basis of geologic or geophysical evidence. At the end of the system's name, the level of certainty is indicated by (!) for known, (.) for hypothetical, and (?) for speculative (Table 1.4).

Petroleum System Name

The name of the petroleum system includes the source rock, followed by the name of the major reservoir rock, and then the symbol expressing the level of certainty. For example, the Deer–Boar(.) is a hypothetical petroleum system consisting of the Devonian Deer Shale as the oil source rock and the Boar Sandstone as the major reservoir rock. The major reservoir rock contains the largest volume of hydrocarbons in the petroleum system (see, e.g., La Luna–Misoa(!) petroleum system in Talukdar and Marcano, Chapter 29, this volume).

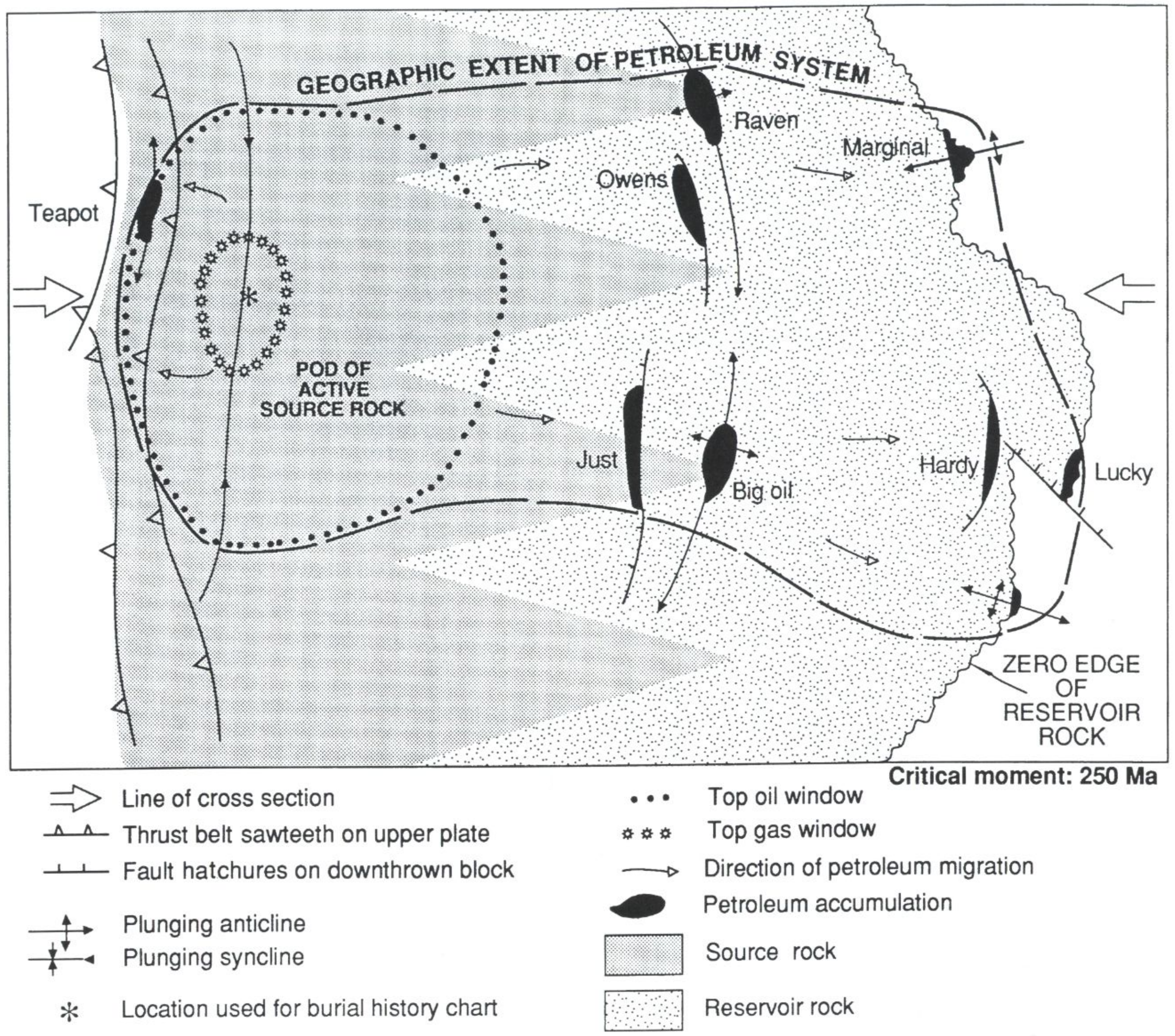

Figure 1.3. Plan map showing the geographic extent of the fictitious Deer–Boar(.) petroleum system at the critical moment (250 Ma). Thermally immature source rock is outside the oil window. The pod of active source rock lies within the oil and gas windows. (Present-day source rock maps and hydrocarbon shows are shown on Figures 5.12 and 5.13, Peters and Cassa, Chapter 5, this volume.)

Discussion

Because our description here of a petroleum system attempts to incorporate previous work, it is written in a way that gives some words specific meanings, so that all petroleum types and occurrences are included in the definition. These specific meanings are purposely chosen to address the so-called exceptions in petroleum occurrence, such as biogenic gas and immature oil. The reader is referred to other chapters in this volume and to the glossary for clarification of terms. Here, terms important to the petroleum system definition are discussed.

Pod of Active Source Rock

A pod of active source rock indicates that a contiguous volume of organic matter is creating petroleum, either through biological activity or temperature, at a specified time. The volume or pod of active source rock is determined by mapping the organic facies (quantity, quality, and thermal maturity) considered to be the presently active, inactive, or spent source rock using organic geochemical data displayed as geochemical logs (Peters and Cassa, Chapter 5, this volume). Organic matter generates petroleum either biologically (Whiticar, Chapter 16, this volume) or thermally (Lewan, Chapter 11). From the time a petroleum phase is created, a

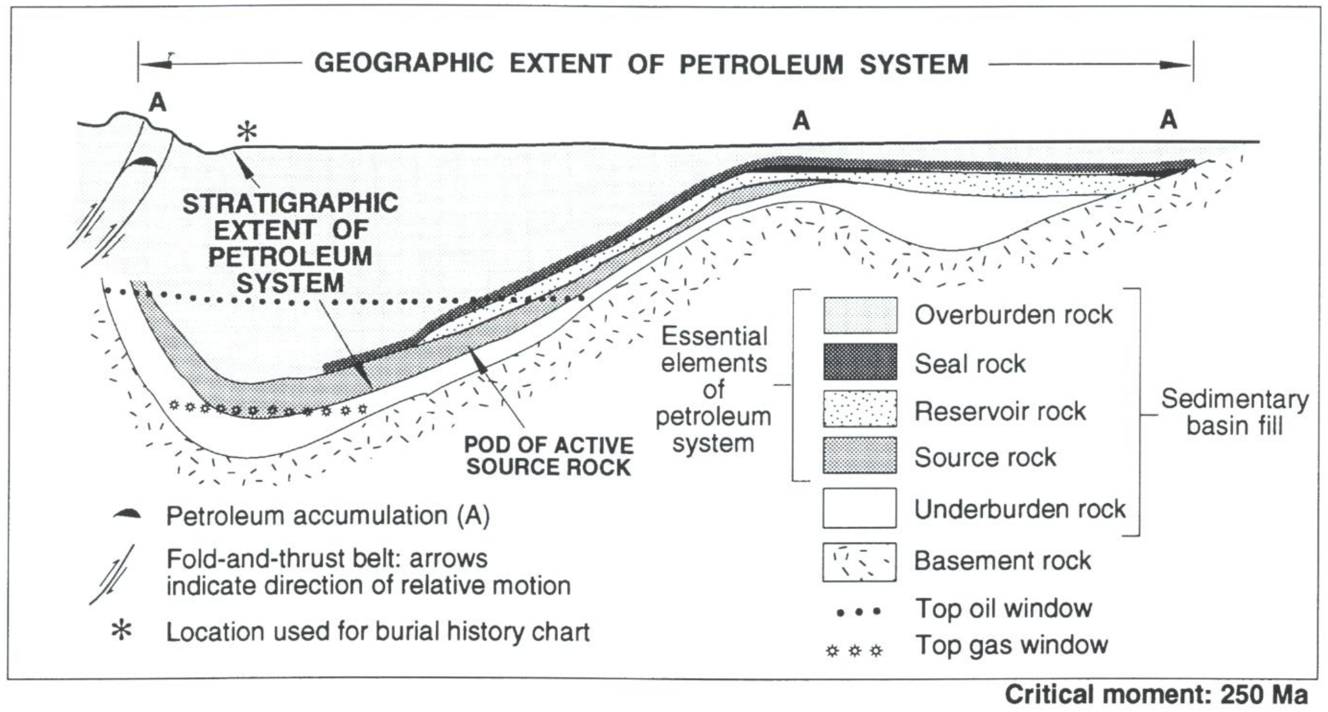

Figure 1.4. Geologic cross section showing the stratigraphic extent of the fictitious Deer–Boar(.) petroleum system at the critical moment (250 Ma). Thermally immature source rock lies updip of the oil window. The pod of active source rock is downdip of the oil window. (The present-day cross section is shown in Figure 5.12F, Peters and Cassa, Chapter 5, this volume.)

petroleum system exists. A source rock is active when it is generating this petroleum, whereas an inactive or spent source rock was at some time in the past an active source rock. For example, the Deer Shale source rock was an active source rock in Late Paleozoic time, but is presently an inactive source rock. The *pod of active source* rock is that contiguous volume of source rock that is generating gas biologically or oil and gas thermally. The active time can be present day or any time in the past.

Petroleum Synonyms

As used in this volume, the terms *petroleum, hydrocarbons,* and *oil and gas* are synonyms. Petroleum originally referred to crude oil, but its definition was broadened by Levorsen (1967) to include all naturally occurring hydrocarbons, whether gaseous, liquid, or solid. Geochemically, hydrocarbon compounds are those containing only hydrogen and carbon, such as aromatic or saturated hydrocarbons. Hydrocarbon compounds are in contrast to nonhydrocarbon compounds, or those containing nitrogen, sulfur, and oxygen. Hydrocarbon and nonhydrocarbon compounds are both found in crude oil and natural gas, but hydrocarbon compounds usually predominate. Over the past 10–15 years, whenever the term *hydrocarbons* has been used without modifiers, it is usually meant to be synonymous with petroleum. When *oil and gas* are used together as a term, it collectively refers to crude oil and natural gas in any proportion. *Condensate* is in a gas phase in the accumulation and in a liquid phase at the surface, but either way it is considered petroleum, as are solid petroleum materials such as natural bitumen, natural asphalt, and bituminous sands.

Major and Minor Reservoir Rocks

Major and minor reservoir rocks are determined from the percentage of in-place petroleum that originated from a particular pod of active source rock. If the volume of in-place petroleum is unavailable, recoverable hydrocarbons are the next best volume. All the discovered oil and gas fields included in a petroleum system are listed and the original in-place (recoverable) hydrocarbons are determined by stratigraphic interval. The volumes of in-place hydrocarbons for each stratigraphic interval are added up, and the percentage for each is determined. Reservoir rocks that contain minor amounts of in-place hydrocarbons are the minor reservoir rocks. Usually one stratigraphic interval contains most of the in-place hydrocarbons, so this interval is the major reservoir rock. The name of this unit is the one used in the second part of the petroleum system name.

The major reservoir rock indicates the optimum migration path for the petroleum between the pod of active source rock and the traps that include the major reservoir rock. The minor reservoir rock indicates the least effective migration path or one that should be studied for overlooked prospects. Major and minor reservoir rocks should be included on the events chart.

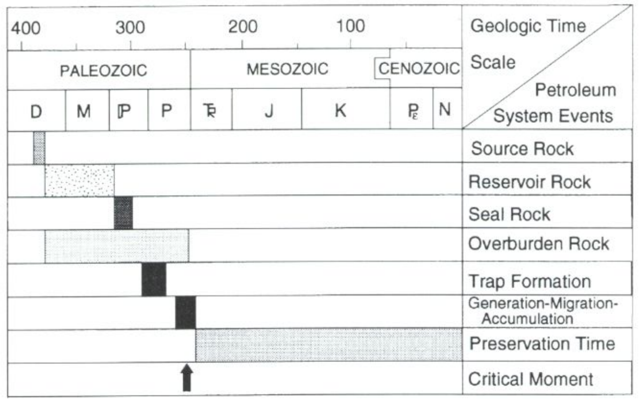

Figure 1.5. The events chart showing the relationship between the essential elements and processes as well as the preservation time and critical moment for the fictitious Deer–Boar(.) petroleum system. Neogene (N) includes the Quaternary here. (Time scale from Palmer, 1983.)

Evolution of a Petroleum System

The time of hydrocarbon generation for a petroleum system can span considerable time and cover a large area. The time span over which petroleum generation occurs can be determined for a series of locations to show how the petroleum system evolves in time and space. At given time increments within this time span, maps and cross sections can be drawn to show the kinematic evolution of the petroleum system. Knowing the age of various horizons within the overburden rock is the key to determining when and where a source rock first starts generating petroleum and when and where it finishes generating petroleum.

For example, for a petroleum system whose overburden rock has been deposited over a broad area (such as a prograding deltaic sequence), the time span over which petroleum generation–migration–accumulation occurs is quite large. If this deltaic sequence, which is the overburden rock, has prograded over a 50-m.y. period from west to east, then the underlying source rock in this petroleum system will generate petroleum first on the west and last on the east. The geologist knows that it is not always practical to show from start to finish the kinematic development of this petroleum system in 5-m.y. increments, as it would require up to 11 maps and cross sections. However, one map and cross section can be drawn to represent the time when the west end of the cross section shows the source rock at maximum burial depth, and an other map and cross section can be drawn to represent the time when the east end of the cross section shows the source rock at maximum burial depth. If more detail is required to better understand how the system evolved, then additional maps and cross sections can be drawn. The critical moment is defined as a single moment because, in most instances, the exploration geologist has only enough time to construct and present one map and cross section to depict a petroleum system.

Table 1.4. Definitions of Levels of Certainty

Level of Certainty	Symbol	Criteria
Known	(!)	Oil–source rock or gas–source rock correlation
Hypothetical	(.)	In absence of petroleum–source rock correlation, geochemical evidence indicates the origin of the oil and gas
Speculative	(?)	Geologic or geophysical evidence

Preservation Time

The preservation time of a petroleum system starts after oil and gas generation, migration, and accumulation processes are complete. Processes that occur during the preservation time are remigration, physical or biological degradation, and/or complete destruction of the hydrocarbons (Blanc and Connan, Chapter 14, this volume). During the preservation time, remigrated petroleum can accumulate in traps formed after hydrocarbon generation has ceased in the petroleum system. If insignificant tectonic activity occurs during the preservation time, accumulations will remain in their original position. Remigration occurs during the preservation time only if folding, faulting, uplift, or erosion occurs. If all accumulations and essential elements are destroyed during the preservation time, then the evidence that a petroleum system existed is removed. An actively forming or just completed petroleum system is without a preservation time.

Comparison with Sedimentary Basin and Play

Aspects of the petroleum system can also be compared with the sedimentary basin and the play. If the critical moment of 250 Ma used in our example (Figure 1.4) was instead present-day, then two sedimentary basins, three plays, and one petroleum system would be shown on the map and cross section. The interface between the sedimentary rock and the basement rock on the cross section would show two lenticular bodies of sedimentary rock or two basins. The three plays that would be shown on the map and cross section are (1) a series of suspected traps along an anticlinal trend, (2) a series of suspected traps along a stratigraphic pinch-out trend, or (3) suspected traps within a stratigraphic interval. However, if all these accumulations were discovered, there would be only one petroleum system on the cross section because one pod of active source rock generated all the hydrocarbons in the discovered accumulations.

EXAMPLES OF PETROLEUM SYSTEMS

One way to better understand what is meant by a petroleum system is to categorize or classify as many systems as possible. Magoon (1989b) classified petroleum systems in the United States based on the complexity of the overburden rock (purebred versus hybrid), reservoir lithology (siliciclastic versus carbonate), and kerogen type (type I, II, and III kerogen). Later, these same petroleum systems were classified according to the age of their source rock (Magoon, 1992b). Demaison and Huizinga (1991; Chapter 4, this volume) classified 38 petroleum systems found throughout the world by hydrocarbon charge (supercharged, normally charged, and undercharged), migration drainage style (vertically versus laterally drained), and entrapment style (high versus low impedance).

Another way to classify petroleum systems is to designate them as either typical or atypical. A *typical* petroleum system is an oil system whose source rock is thermally matured during deep burial by the overburden rock. Most the case studies in this volume are of typical petroleum systems. An *atypical* petroleum system is one in which hydrocarbons were generated in other ways. For example, a petroleum system can occur when an immature source rock within a thin sequence of sedimentary rocks that overlays continental crust is intruded by a dike (Figure 1.6). The dike's heat thermally matures the source rock and generates oil that seeps into the adjacent sedimentary rock and river valley. Another example is the oil generated from the heat related to the ridge vent in the Escanaba trough (Kvenvolden et al., 1988). Yet another example is biogenic gas generated at a shallow depth through biological activity (Whiticar, Chapter 16, this volume), such as the gas in the shallow Tertiary sedimentary rock in the Cook Inlet, Alaska (Claypool et. al, 1980; Chapter 22, this volume).

Typical petroleum systems are shown on Figures 1.7 and 1.8 using maps and cross sections that are each drawn at the critical moment. Notice that the source rock in each case has been deposited in a much larger sedimentary basin than the overburden rock. Although all the essential elements and a trap are included in Figure 1.7A, a petroleum system is absent because hydrocarbons have not been generated. Given the same situation in Figure 1.7B but with a source rock now generating hydrocarbons, you have one petroleum system (Cornford, Chapter 33, this volume). If two or more source rocks are superimposed on one another and are both thermally mature by the same overburden rock within the same basin fill (Figure 1.7C), then more than one petroleum system occurs in the same basin fill (Dow, 1972; Talukdar and Marcano, Chapter 29, and Kockel et al., Chapter 34, this volume). If each source rock expels hydrocarbons with unique compositions, then an analysis of these hydrocarbons from seeps or accumulations will indicate how many systems are in the area. At this point, the investigator should map the stratigraphic and geographic extent of the seeps and accumulations of the same composition as a halo of hydrocarbons that encase a pod of active source rock, which also should be mapped (Peters and Cassa, Chapter 5, this volume).

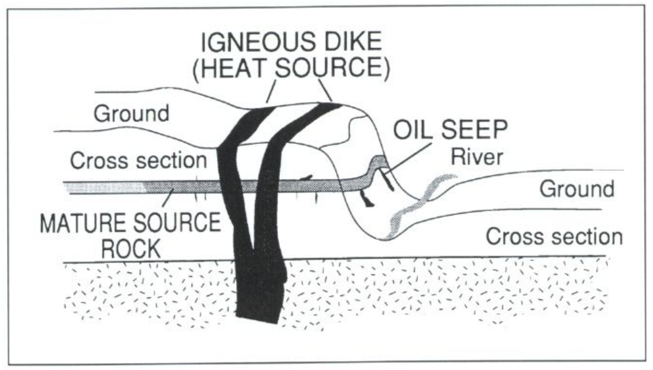

Figure 1.6. An atypical petroleum system whose oil originates from a source rock that is thermally matured by an igneous dike.

A corollary to the area with stacked or multiple active source rocks that form more than one petroleum system is the one source rock that extends over a wide area and has sufficient overburden rock in more than one area to form pods of active source rock (Klemme, Chapter 3; Buitrago, Chapter 30; and Mello et al., Chapter 31, this volume).

Upper Devonian of United States

More than one petroleum system can form when a source rock extends beyond one package of overburden rock to another package (Figures 1.8B and 1.9). For example, when the sedimentary basin of a source rock is on the scale of a continent, such as the Upper Devonian of the United States, that one organic-rich interval can be the source rock for more than one petroleum system. However, the stratigraphic nomenclature for this Upper Devonian source rock is different depending on the location (in parentheses): Ohio Shale and Devonian black shale (Appalachian basin), Antrim Shale (Michigan basin), New Albany Shale (Illinois basin), Woodford Shale (mid-Continent provinces), Aneth Formation (Paradox basin), Pilot Shale (Great Basin), Bakken Formation (Williston basin), and Exshaw Formation (Sweetgrass arch). Wherever this Upper Devonian source rock is buried enough by overburden rock (basin) to generate hydrocarbons, a petroleum system exists.

What eventually matures the Upper Devonian organic-rich interval is increased heat from additional burial by overburden rock deposited in smaller post-Devonian sedimentary basins (successor basins) located on or along the edge of the North American craton. Sedimentary basins on the craton are sags or rifts, whereas basins at the edge of the craton are foreland basins. Unless the sediments are created in situ (e.g., carbonate rocks, evaporites, and coals), the provenance for the sediments deposited in all three basin types is the craton (as well as the fold-and-thrust belt for the foreland basin). The reservoir and seal rocks are either in the Upper

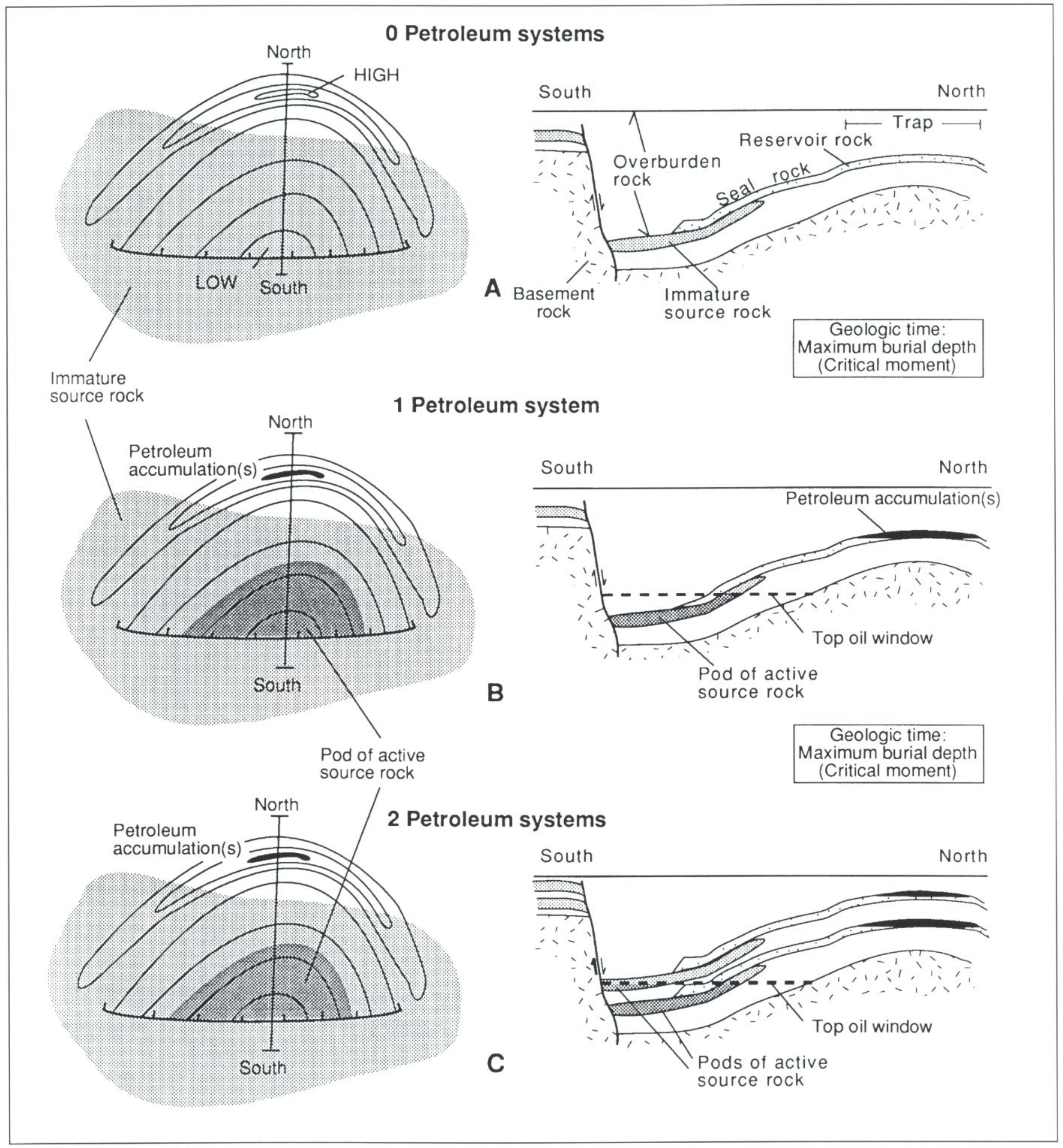

Figure 1.7. Three examples of partial or complete petroleum systems at the critical moment. (A) The essential elements are present, but the system is incomplete (thus no petroleum system); (B) one petroleum system; and (C) two petroleum systems. Notice that the overburden rock creates the geometry of the most recent sedimentary basin and that the source rock was deposited in a larger, older sedimentary basin.

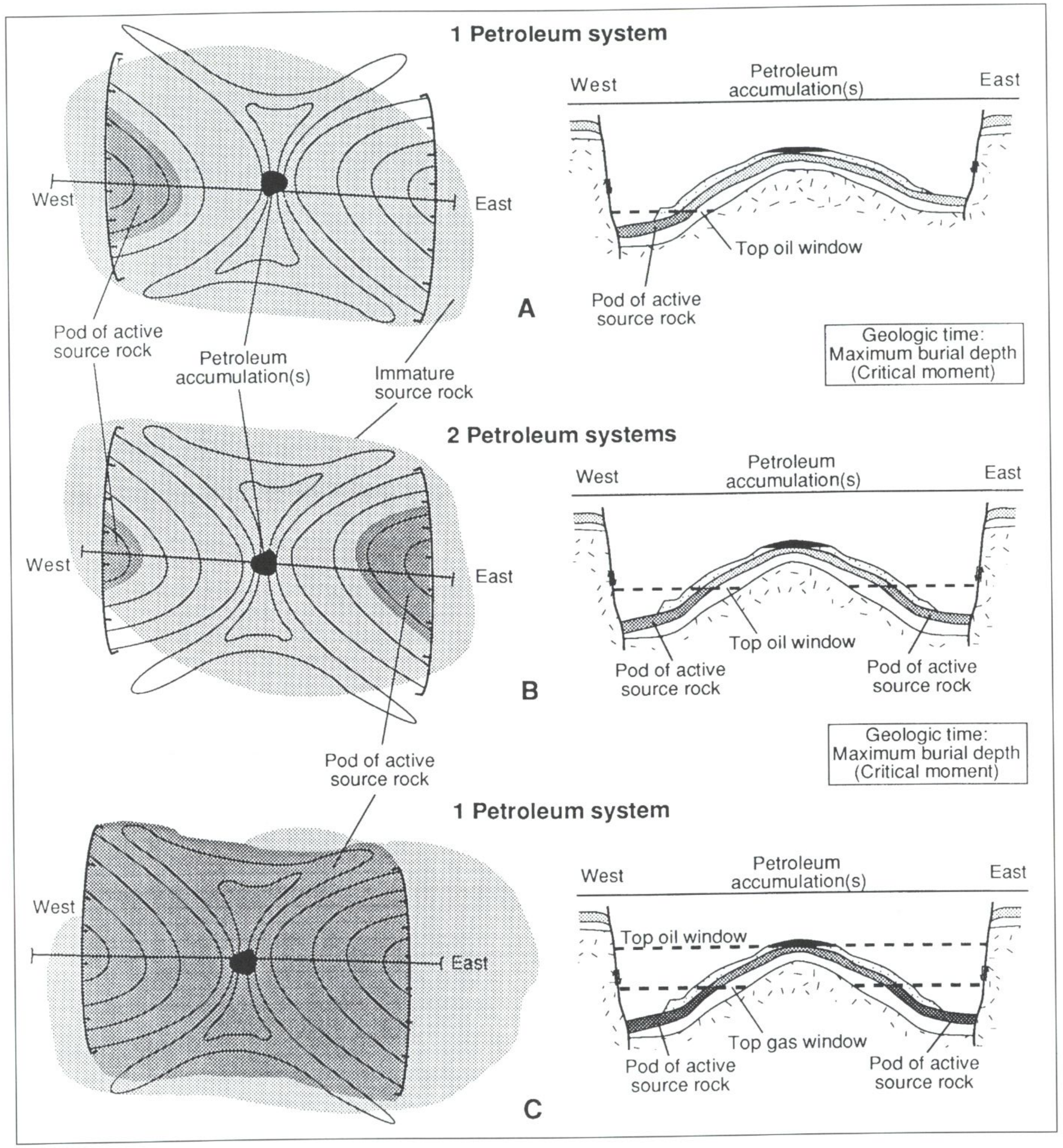

Figure 1.8. The number of petroleum systems is determined by the number of pods of active source, as shown by these three examples. Petroleum accumulation is charged by (A) a single pod of source rock, or one petroleum system; (B) two pods, or two petroleum systems; and (C) one pod, or one petroleum system.

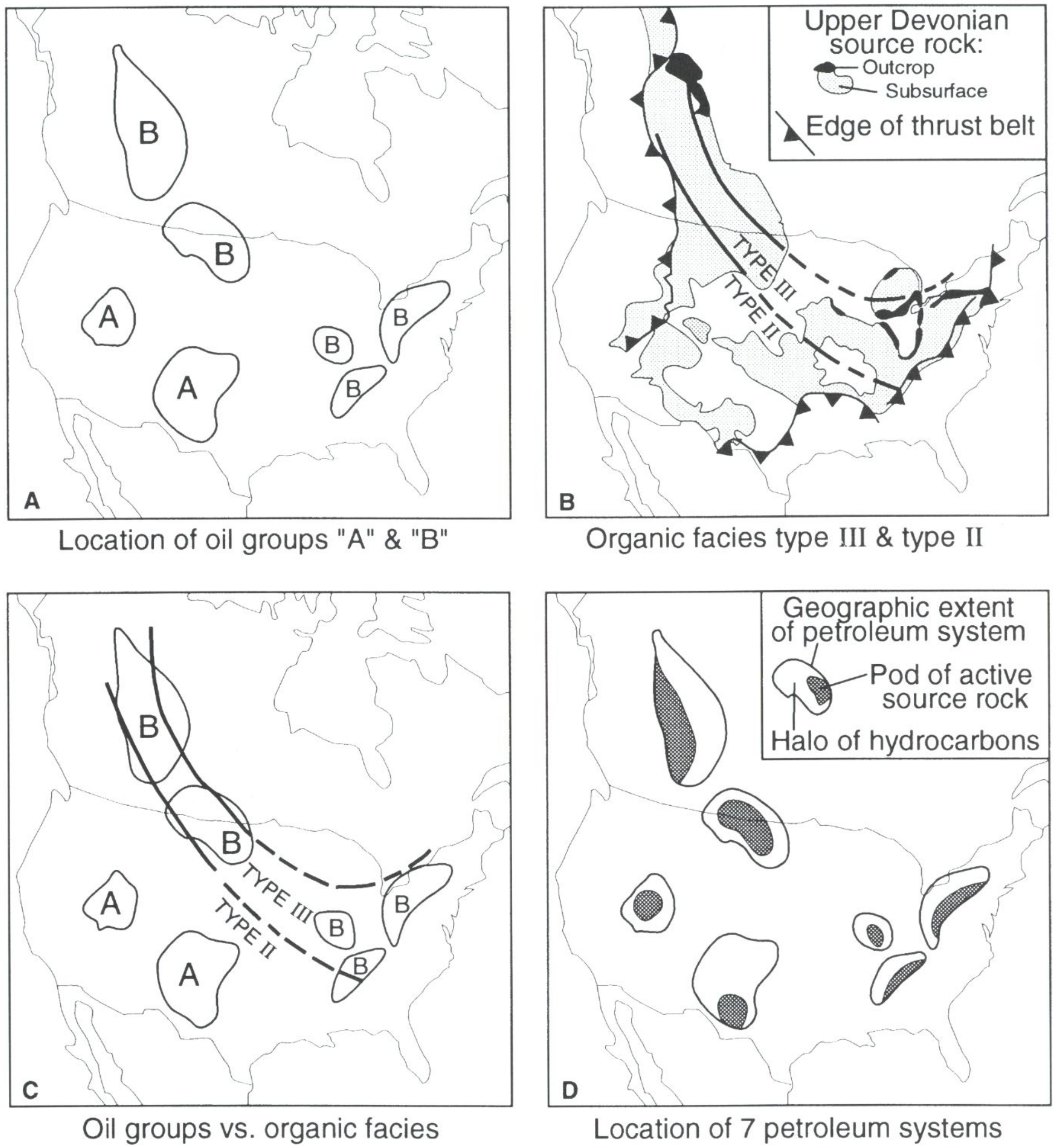

Figure 1.9. Fictitious example #1, in which one source rock deposited over a continent (North America) forms seven different petroleum systems where the overburden rock is thick enough to form a pod of active source rock. Using oil–oil and oil–source rock correlations, geochemical logs, and petroleum accumulations and shows, seven petroleum systems can be mapped.

Devonian strata or are within the overburden rock. The trap and petroleum forming processes occur during deposition of the overburden rock.

Over the area of the North American continent, the age of these petroleum systems that have Upper Devonian source rocks varies with the location of the system. Along the eastern and southern edge of the North American craton, these late Paleozoic foreland basins (including the Appalachian, Warrior, and Anadarko basins) received only minor amounts of post-Paleozoic sediments. Since the present-day petroleum accumulations must have generated and migrated around the end of Permian time or earlier (when maximum burial was achieved), the age (generation–migration–accumulation) of these petroleum systems having Upper Devonian source rocks ranged from Mississippian to Permian time. The preservation time extended through the Mesozoic and Cenozoic. In contrast, the western edge of the craton includes foreland basin sedimentary rocks as young as Cretaceous or early Tertiary, and one of the cratonic interior basin sags may be as young as Tertiary. The age of these systems ranged from the Cretaceous to Tertiary.

Miocene of California, U.S.A.

Another organic-rich interval that is involved in many petroleum systems is the Miocene of California. In California, numerous strike-slip basins formed in the Miocene and continue to develop to the present day. At first, conditions in the basins were conducive to the formation and preservation of organic matter along with abundant biogenic silica and relatively little siliciclastic material. Deposition of coarser siliciclastic material became progressively more rapid during Pliocene–Pleistocene time. This sediment provided the necessary overburden that heated the source rock to generate hydrocarbons that formed petroleum systems within the Los Angeles basin, Ventura basin (Santa Barbara offshore), Santa Maria basin, San Joaquin basin, and several other coastal basins. Again, what started out as organic-rich deposits over a large area eventually developed into smaller sedimentary basins that acquired sufficient overburden rock to generate hydrocarbons, thus forming separate petroleum systems.

INVESTIGATIVE TECHNIQUE

A petroleum system investigation should begin with hydrocarbons (Smith, Chapter 2, this volume), such as a show of oil or gas. In the same way that sedimentary rock requires a sedimentary basin, an oil or gas show requires a petroleum system. With this line of investigation, it is necessary to understand the smallest accumulations or shows because they are clues to whether commercial accumulations are possible. In addition, the petroleum system investigation approach requires that the focus of work is on the stratigraphic and structural studies of the essential elements and processes. If an exploratory well penetrates and successfully tests the plumbing of the petroleum system (within the stratigraphic and geographic extent), the chance of finding commercial hydrocarbons is improved.

Ideally, a petroleum system analysis begins with an oil and gas (show) map. Geochemical analyses of those hydrocarbon shows are needed to understand the origin of the oil or gas (biogenic versus thermal). Comparing oil to oil and gas to gas can indicate whether more than one petroleum system is involved. The line of inquiry can be expanded to include the type of organic matter responsible for those shows and the overburden rock required to thermally mature the source rock. To determine the geographic, stratigraphic, and temporal extent of the petroleum system, the investigator will need to acquire specific information to make the burial history chart, map, cross section, and events chart that define the system (Figures 1.2–1.5) (see also Peters and Cassa, Figures 5.12 and 5.13, Chapter 5, this volume).

Fictitious Example #1

To explain the investigative technique more graphically, two fictitious examples are provided (see also Smith, Chapter 2, this volume).

From the United States and Canada, 300 oils were collected and analyzed. The oils were collected from rocks that range in age from Precambrian to Holocene, from a depth range of 0–3000 m, and from many lithologies, such as fractured granite and shale, sandstone, and dolomite. Many different types of analyses were carried out on the oils. Oil–oil correlations indicate two groups, A and B, that form clusters in seven areas (Figure 1.9A).

A geochemical profile (Peters and Cassa, Chapter 5, this volume) of a well in each area indicates that each well penetrated more than one source rock and that an Upper Devonian source rock was common to all seven areas. Reexamining the vertical distribution of the oils indicates that one-third of the oils are from Carboniferous reservoirs. Using kerogen studies from the literature and other data, an organic facies map indicates two kerogen types, type II and III, in the Upper Devonian source rock (Figure 1.9B). In areas where the Upper Devonian source rock was eroded across the transcontinental arch, regional mapping allowed the organic facies to be mapped where it was absent or too deeply buried.

By use of hydrous pyrolysis (Lewan, Chapter 11, this volume) on immature source rock samples, oil–source rock correlations indicate that the two organic facies in the Upper Devonian are responsible for the two oil groups. Furthermore, the two clusters of group A oil are within the type II kerogen, and the four clusters of group B oil are within the type III kerogen (Figure 1.9C).

Additional well and outcrop control and burial history diagrams can be used to map the the thermal maturity of the Upper Devonian source rock. A pod of active source rock occurs with each of the seven oil clusters. Computerized exploratory well and field files are used to map the distribution of oil, which is found to be within the oil clusters, further confirming the geographic and stratigraphic extent of these seven petroleum systems.

This example shows the use and limitations of oil–oil and oil–source rock correlations. First, if two oils are identical, they may not necessarily be in the same petroleum system even though the oil–source rock correlations indicate that they are from the same source rock. Second, if two oils are different, they can still be from the same source rock. For example, if the organic facies changes within a pod of active source rock, the oils may be from the same petroleum system. Finally, to identify a petroleum system uniquely, the extent of hydrocarbon shows must be mapped relative to the pod of active source rock. This example also shows why the distribution as well as the quality, quantity, and thermal maturity of source rock should be mapped worldwide at the time of deposition (Klemme, Chapter 3, this volume).

Fictitious Example #2

The previous example identified and mapped the geographic and stratigraphic extent of seven petroleum systems. The next example investigates and describes one petroleum system (see Peters and Cassa, Chapter 5, this volume).

To demonstrate how the four figures and one table work together to characterize a petroleum system, we illustrate a petroleum system study with a specific example. Figures 1.2–1.5 and Table 1.3 depict a fictitious petroleum system, the so-called Deer–Boar(.) petroleum system. The oil accumulations and shows prove the existence of at least one system, but if there is more than one group of oils, there could be two or more systems present. To identify and name each system, oil and source rock samples were collected and analyzed for the following reasons: (1) to establish oil families, (2) to determine which family originated from which source rock, (3) to map the quantity and type of organic matter in the source rock, and (4) to map the thermal maturity of the source rock. On a map, we have shown the present-day location of each oil accumulation attributed to each group (Table 1.3) and have indicated the pod of active source rock. Much of this information is included in Figures 1.3 and 1.4.

In our fictitious example, sufficient information was collected to identify and map the thermal maturity of the Deer Shale as the most likely source for the oil accumulations in the Boar Sandstone (Peters and Cassa, Chapter 5, Figure 5.12, this volume). However, because of a lack of thermally mature samples of the Deer Formation, an oil–source rock correlation was inconclusive (see Lewan, Chapter 11, this volume, for solution). Therefore, our level of certainty is hypothetical because we are unable to demonstrate geochemically that the oil originated from the Deer Shale. However, geographic and stratigraphic evidence is sufficient to assign a name and level of certainty—the Deer–Boar(.) petroleum system.

At the location of the most thermally mature source rock, a burial history chart has to be made to determine the critical moment (Figure 1.2). The critical moment, in this case, is when the source rock is at maximum burial depth and is near the time when most hydrocarbons migrated into primary traps. (If the critical moment were the present day, the source rock would presently be at maximum burial depth; see Magoon, Chapter 22; Cole and Drozd, Chapter 33, this volume.) Various articles and computer programs exist to model petroleum generation and migration; most use the burial history curve or geohistory chart (Waples, Chapter 17, this volume). The essential elements of the system should be shown on the burial history chart.

Next, a map and cross section are drawn for the critical moment (Figures 1.3 and 1.4), and all accumulations are itemized (Table 1.3). The critical moment is important because the geometry of the migration paths and traps are reconstructed for about the time the oil and gas accumulated. If the critical moment is prior to present-day, then the location of present-day traps on a play or prospect map (not shown) can be compared to the location of traps at the critical moment to determine if oil and gas have remigrated. If the traps have shifted from the critical moment to the present day, the shifted trap or prospect would have to be charged with remigrated oil or gas. These maps can also be compared to determine if physical or microbial alteration (or destruction) occurred during the preservation time. A table of accumulations for this petroleum system indicates its size and is the basis for further calculations and comparisons carried out in the case studies.

Last, a petroleum system events chart is constructed to summarize the essential elements, processes, preservation time, and critical moment (Figure 1.5). In our fictitious example, the description is as follows. The Deer Shale, a Devonian (390–380 Ma) source rock is buried by Devonian–Permian (380–250 Ma) rocks to its maximum depth in the Late Permian (250 Ma). The process of generation–migration–accumulation of hydrocarbons occur during the Permian (260–240 Ma), and the critical moment is 250 Ma. These hydrocarbons accumulated under the George Shale (300–286 Ma) and in the Boar Sandstone, reservoirs of Pennsylvanian age (315–300 Ma) that formed into traps during the Late Pennsylvanian–Early Permian (290–270 Ma). The preservation time is 240 m.y. (Figures 1.3 and 1.4).

The events chart can be viewed as a team organizational tool. For example, geologic time is studied by the paleontologist and stratigrapher, the reservoir by the petrophysicist and stratigrapher, and trap formation by the structural geologist and geophysicist.

These four figures and table are simplified to make important points about a single petroleum system. Each figure could be drawn to include additional information unique to a particular petroleum system. Once a petroleum system is named, mapped, and described, it can be analyzed in many ways. For example, this volume contains case studies that describe petroleum migration from the pod of active source rock to a trap.

SUMMARY

Sedimentary basins, petroleum systems, plays, and prospects can be viewed as separate levels of petroleum investigations, all of which are needed to better understand the genesis and habitat of hydrocarbons. Investigations of sedimentary basins describe the stratigraphic sequence and structural style of sedimentary rocks. Petroleum system studies describe the genetic relationship between a pod of active source rock and an accumulation. Investigations of plays describe the present-day geologic similarity of a series of traps, and of prospects, describe individual traps. Except for the petroleum system, these terms are widely used by petroleum geologists.

A petroleum system encompasses a pod of active source rock and all generated oil and gas and includes all the elements that are essential for an oil and gas accumulation to exist: petroleum source rock, reservoir rock, seal rock, and overburden rock. All essential elements must be placed in time and space such that the processes required to form a petroleum accumulation can occur. These processes include trap formation and generation–migration–accumulation of hydrocarbons. The petroleum system has a stratigraphic limit, geographic extent, and an age. Its name combines the names of the source rock and the major reservoir rock with a symbol that expresses a level of certainty—known (!), hypothetical (.), and speculative (?). Along with its name, four figures and a table best depict the geographic, stratigraphic, and temporal evolution of the petroleum system: a burial history chart to establish the age and critical moment for the system, a map and cross section drawn at the critical moment, an events chart to summarize the formation of the petroleum system, and a table listing the accumulations in the system.

A petroleum system investigation is different from the other three levels of investigation in at least three ways. First, every petroleum system investigation commences with hydrocarbons regardless of amount. Second, hydrocarbons of a particular composition are related back to a pod of active source rock. Third, the pod of active source rock and related hydrocarbons are mapped. In addition, investigating each essential element of a petroleum system individually prevents the investigator from overemphasizing basin, play, or prospect analysis before the plumbing of the petroleum system has been unraveled.

This chapter describes the petroleum system; how it is used is limited only by the readers imagination. Some of the ways to characterize and use the petroleum system are shown in the remainder of this volume.

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Chapter 2

Petroleum System Logic as an Exploration Tool in a Frontier Setting

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Abstract

Petroleum system logic is the thought process required to develop an integrated interpretation of the processes of petroleum generation, migration, and accumulation. It is illustrated here in frontier area exploration with examples taken from three offshore sales. Details of the application of petroleum system logic vary widely depending on the nature of the exploration problem and the data available. The application of petroleum system logic often allows the explorer to reduce the evaluation problem to the careful assessment of a single factor. The first two examples are of this type. The third example is a comprehensive evaluation illustrating the quantitative treatment of the processes of hydrocarbon generation, migration, and accumulation.

The critical problem in the first example (1986 Offshore Texas) was the prediction of petroleum type in a new growth fault trend. The presence of gas in the new trend was correctly predicted using petroleum system logic to extrapolate information bearing on hydrocarbon type from adjacent previously explored areas. In the second example (1976 Baltimore Canyon), the critical problem was predicting a petroleum charge in a previously unexplored area. Reservoirs, seal, trap, and ease of migration from a thick, mature stratigraphic section were ensured for the Schlee dome. An adequate petroleum charge was predicted to be available because favorable environments for source rock deposition were inferred from a geologic model derived from reflection seismic data. Postsale drilling discovered no petroleum and demonstrated the risk inherent in this mode of prediction.

The third example was taken from the 1983 Norton Sound sale. In part I of this example, the critical problem was determining the likelihood of an oil charge in the area. A reliable answer was anticipated because the determination was based on analyses of samples obtained from favorably located wells that penetrated the whole sedimentary section at a thermally mature location. The most useful evidence was Rock-Eval pyrolysis measurement of the amount of oil generated in the thermally mature section and oil shows in porous rocks in the thermally mature section. These indicated that a negligible volume of oil had migrated out of the mature section. This prediction has been confirmed by drilling. Part II of this example is a comprehensive evaluation of the Stuart subbasin, where the processes of hydrocarbon generation, migration, and accumulation were quantified using rock data from a COST well. The failure of five exploratory wells drilled on four prospects around the Stuart subbasin to find any gas accumulations is explained by this evaluation.

These examples demonstrate that all pertinent data should be considered and that proper interpretation of hydrocarbon shows is often important. When there is a possibility of a limited petroleum charge, quantitative evaluation of the processes of hydrocarbon generation, migration, and accumulation should be considered to aid in prospect or play evaluation.

INTRODUCTION

This chapter illustrates the use of petroleum system logic in frontier area exploration by describing three examples taken from the author's experience as a geochemical consultant to Shell Oil Company. These examples are from the following offshore sales: 1968 Offshore Texas, 1976 Baltimore Canyon, and 1983 Norton Sound. In each case, the conclusions drawn from the application of petroleum system logic played a major role in Shell's evaluation. The characteristics assigned to each example and the ensuing interpretation based on petroleum system logic were derived from Shell's work carried out in preparation for the particular offshore sale. In each case, the postsale drilling results are compared to the presale predictions.