Petroleum System: Nature's Distribution System for Oil and Gas

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Glossary

active source rock A source rock that generates petroleum, either biogenically or thermally. If a source rock was active in the past, it is either inactive or spent in the present.

burial history chart A burial history curve or geohistory diagram constructed to show the time over which hydrocarbon generation occurs. Depicts the essential elements and the critical moment for the system.

critical moment The time that best depicts the generation-migration-accumulation of hydrocarbons in a petroleum system. A map and cross section drawn at the critical moment best shows the geographic and stratigraphic extent of the system.

essential elements The source rock, reservoir rock, seal rock, and the overburden rock of a petroleum system. Together with the processes, essential elements control the distribution of petroleum in the lithosphere.

events chart A chart for a petroleum system showing when the essential elements and processes took place as well as the preservation time and critical moment of the system.

generation-migration-accumulation One petroleum system process that includes the generation and movement of petroleum from the pod of active source rock to the petroleum show, seep, or accumulation. The time over which this process occurs is the age of the petroleum system.

geographic extent The area over which the petroleum system occurs, defined by a line that circumscribes the pod of active source rock as well as all the discovered petroleum shows, seeps, and accumulations that originated from that pod. The geographic extent is mapped at the critical moment. Also the **known extent**.

level of certainty The measure of confidence that petroleum from a series of genetically related accumulations originated from a specific pod of active source rock. Three levels used are known (!), hypothetical (.), and speculative (?), depending on the level of geochemical, geophysical and geological evidence.

overburden rock The sedimentary rock above which compresses and consolidates the material below. In a petroleum system, the overburden rock overlies the source rock and contributes to its thermal maturation because of higher temperatures at greater depths. An essential element of the petroleum system.

petroleum A mineral oil occurring in subsurface rocks and at the surface which is a naturally occurring mixture of hydrocarbon and nonhydrocarbon compounds. It may occur in the gaseous, liquid, or solid state depending on the nature of these compounds and the existent conditions of temperature and pressure. Common synonyms are **hydrocarbons** and **oil and gas**.

petroleum system The essential elements and processes as well as all genetically related hydrocarbons that occur in petroleum shows, seeps, and accumulations whose provenance is a single pod of active source rock. Also called **hydrocarbon system** and **oil and gas system**.

petroleum system age The time over which the process of generation-migration-accumulation of hydrocarbons in the system takes place on the events chart.

petroleum system name A compound name that includes the source rock in the pod of active source rock, the reservoir rock containing the largest volume of petroleum, and the level of certainty of a petroleum system; for example, the Mandal-Ekofisk(!) petroleum system.

petroleum system processes The two processes of trap formation, and the generation-migration-accumulation. The preservation, degradation, and destruction of petroleum is omitted as a process as it generally occurs after a petroleum system is formed (preservation time). Together with the essential elements, the processes control the distribution of petroleum in the lithosphere.

pod of active source rock A contiguous volume of source rock that is generating and expelling petroleum at the critical moment and is the provenance for a series of genetically related petroleum shows, seeps, and accumulations in a petroleum system. A pod of mature source rock may be active, inactive, or spent.

preservation time The time after generation-migration-accumulation of petroleum takes place and encompasses any changes to the petroleum accumulations up to the present day.

reservoir rock A subsurface volume of rock that has sufficient porosity and permeability to permit the migration and accumulation of petroleum under adequate trap conditions. An essential element of the petroleum system.

seal rock A shale or other impervious rock that acts as a barrier to the passage of petroleum migrating in the subsurface; it overlies the reservoir rock to form a trap or conduit. Also known as **roof rock** and **cap rock** an essential element of the petroleum system.

source rock A rock unit containing sufficient organic matter of suitable chemical composition to biogenically or thermally generate and expel petroleum. An essential element of the petroleum system.

stratigraphic extent The span of lithologic units that encompasses the essential elements within the geographic extent of a petroleum system. It can be displayed on the burial history chart and cross section drawn at the critical moment.

trap Any geometric arrangement of rock regardless of origin that permits significant accumulation of oil, or gas, or both in the subsurface and includes a reservoir rock and an overlying or updip seal rock. Types are stratigraphic, structural, and combination traps. Trap formation is one of the petroleum system processes.

A petroleum system encompasses a pod of active source rock and all related oil and gas, and it includes all the geologic elements and processes that are essential if a hydrocarbon accumulation is to exist. Petroleum here includes (1) high concentrations of any of the following substances: thermal and biogenic gas found in conventional reservoirs as well as in gas hydrate, tight reservoirs, fractured shale, and coal; and (2) condensate, crude oil, and asphalt found in nature. 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; whereas the two processes are trap formation, and the generation, migration (primary and secondary), and 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 into a petroleum accumulation. As used in this article, petroleum, hydrocarbons, and oil and gas are synonyms and are included under the term petroleum. Petroleum originally referred to crude oil, but was later broadened to include all naturally occurring hydrocarbons, whether gaseous, liquid, or solid. Geochemically, hydrocarbon compounds are those that contain only hydrogen and carbon, such as aromatic hydrocarbons and saturated hydrocarbons. Hydrocarbon compounds are in contrast to nonhydrocarbon compounds, or those that contain nitrogen, sulfur, and oxygen (N, S, O). Hydrocarbon and nonhydrocarbon compounds are both found in crude oil and natural gas, but hydrocarbon compounds usually predominate. Over the past 20 years, whenever the term hydrocarbons has been used without modifiers it is meant to be synonymous with petroleum. When oil and gas are used together, it collectively refers to crude oil and natural gas in any proportion. Condensate is a gas phase in the accumulation and in a liquid phase at the surface; either way it is considered petroleum as is solid petroleum (i.e. natural bitumen, natural asphalt, bitumenous sands, etc.).

1. IMPORTANCE OF THE PETROLEUM SYSTEM

Petroleum or oil and gas accumulations mostly occur in sedimentary rocks and less frequently in igneous and metamorphic rocks. These seemingly contradictory occurrences are easily explained when petroleum is viewed in the context of a subsurface fluid distribution network whose origin is an active source rock and whose destination is a trap or seep. An active source rock is sufficiently organic-rich that when heated high enough over sufficient time injects petroleum into the adjacent country rock. This largely thermal process of primary migration or expulsion gives way to the physical process of secondary migration outside the active source rock because of buoyancy and diffusion. Depending on the extent of lateral permeability of the country rock, the expelled petroleum will either stay near the site of expulsion or migrate up dip to the nearest trap. If the nearest trap is filled to the spill point, the spilled petroleum will continue to migrate up dip to the next trap and so on until migration ceases or it seeps to the earth's surface.

The extent, connectivity, and type of the conduits and traps radiating up dip from the active source rock determine the nature and area over which these hydrocarbon fluids migrate. This hydrocarbon distribution network is an integral part of the petroleum system; it can be mapped in space and time using geochemical, geological, and geophysical information.

Even though the petroleum system was introduced in 1972, the concept was largely overlooked until the early 1990s. In the past decade, many petroleum systems have been studied and results published in journals, magazines, and presented at scientific meetings. Petroleum geologists now recognize that the sedimentary basin provides the rock framework in which a hydrocarbon fluid distribution network resides (Fig. 1). It is this fluid system that petroleum geologists need to understand if their exploration of the play and prospect are to be successful.

2. *ESSENTIAL ELEMENTS AND PROCESSES OF THE PETROLEUM SYSTEM*

2.1 Source Rock

A source rock contains sufficient organic matter of suitable chemical composition to biogenically or thermally generate and expel petroleum. Only one active source rock interval occurs in each petroleum system. The two important elements in organic matter are carbon and hydrogen; the carbon provides the skeleton on which the hydrogen is attached. The oxidation of hydrogen provides the energy so the more hydrogen per unit of carbon, the better quality the source rock.

The higher the concentration of carbon in organic matter, the richer is the source rock. Carbon is measured in weight-percent of rock matrix. A source rock needs at least 2 wt % of organic carbon before it can expel petroleum. Organic carbon content (TOC) for a petroleum source rock commonly exceeds 3 wt % and can get as high as 10 wt % or more.

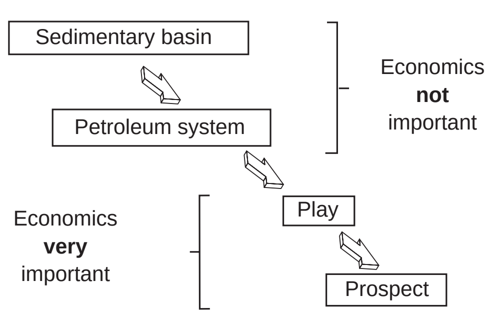

FIGURE 1 Four levels of petroleum investigation. From Magoon, L. B., and Dow, W. G. (1994). The petroleum system—From source to trap. Memoir 60, p. 4 (as Figure 1.1). AAPG © 1994. Reprinted by permission of the AAPG whose permission is required for further use.

Hydrogen content is measured in hydrocarbons per unit of organic carbon (mg HC/g TOC) and is a measure of source rock quality, the higher the hydrogen index (HI), the better the quality. In addition, the HI indicates the type of hydrocarbon fluid expelled. For example, HI greater than 300 (mg HC/g TOC) and less than 900 expel mostly oil with some gas, HI between 200 and 300 expel some light oil but mostly gas, and HI between 50 and 200 is just natural gas. As a source rock thermally matures and expels petroleum, the HI is reduced to below 50 so the difference between the immature HI and HI of the depleted source rock is a measure of the amount of hydrogen or petroleum expelled. For example, if an immature source rock has an HI of 500 and the HI of the spent source rock is 100, the 400 mg HC/g TOC of oil and gas was expelled as compared to an immature HI of 200 and the spent HI is 100, the amount of expelled gas is 100 mg HC/g TOC.

The presence of porphryns from plant chlorophyll as well as other complex molecules that are the building blocks of single and multicellular plants and animals are proof that the organic matter in source rocks originates from the biosphere. These so-called biomarkers indicate the origin and sometimes the age of the source rock and the origin of the petroleum.

2.2 Overburden Rock

Overburden rock is the sedimentary rock above which compresses and consolidates the material below. In a petroleum system, the overburden rock overlies the source rock and contributes to its thermal maturation because of higher temperatures at greater depths. The age and thickness of the overburden rock determines the burial rate and thereby influences the heating rate. Frequently, the reservoir and seal rocks immediately overly the source rock and are thus included within the overburden rock. The close proximity of the source and reservoir rocks allow the expelled petroleum immediate access to a migration conduit. The deposition and erosion of the overburden rock through time determines the slope and form of the burial history curve of the source rock through petroleum expulsion. Rapid burial with little erosion is best for the preservation of the petroleum system.

2.3 Reservoir Rock

A reservoir rock is a subsurface volume of rock that has sufficient porosity and permeability to permit the migration and accumulation of petroleum under adequate trap conditions. Porosity is a measure in percentage of pore volume or size of holes or vugs per unit volume of rock. For example, a well-sorted sand in a 300 ml container will hold about 100 ml of water in its pore space, or a porosity of 33%. If petroleum is present, it can also occupy this pore space. During burial of this sand, compaction reduces this porosity substantially to where only a small percentage of porosity is left.

Permeability is a measure of the connectivity of pores in the subsurface. The sand in the container has narrow pore throats between the large pores that allows fluid to pass from one pore to another. Permeability is measured in millidarcies (md) or Darcy (1000 md) of these narrow throats. Commonly, permeability in the range of 100 to 500 md are reasonable values for a petroleum reservoir rock. Values over a Darcy are exceptional. Fractures have infinite permeability.

Any lithology can have porosity and permeability. Siliciclastic sandstone is most likely to have vertical and lateral porosity and permeability over a relatively large distance. Frequently, carbonate rock has the most complex patterns of porosity, frequently vuggy porosity with little or no permeability, but dolomitized zones can have lateral porosity and permeability. Volcanic rock can be vuggy where hot gases bubble from molten rock. Metamorphic and other sedimentary rocks can acquire secondary porosity because of weathering or groundwater movement. All these rock types can be shattered so that unconnected pores can be connected with fractures.

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, the volume of recoverable hydrocarbons are used. All 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 of in-place hydrocarbons by stratigraphic interval is determined. Usually, one stratigraphic interval contains most of the in-place hydrocarbons, so this interval is the major reservoir rock. Reservoir rocks that contain minor or lesser amounts of in-place hydrocarbons are the minor reservoir rocks. The major reservoir rock is the second name used in the name of the petroleum system. The major reservoir rock indicates the optimum migration path 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 it indicates a migration path that should be studied for overlooked prospects. Major and minor reservoir rocks should be included on the petroleum system events chart.

2.4 Seal Rock

Seal rock is a shale, evaporite, or other impervious rock that acts as a barrier to the passage of petroleum migrating in the sub-surface; it overlies the reservoir rock to form a trap or conduit. The seal rock is also known as roof rock or cap rock. A dipping reservoir rock overlain by a seal rock provides a migration path for petroleum.

2.5 Trap Formation

Any geometric arrangement of rock regardless of origin that permits significant accumulation of oil or gas, or both, in the subsurface and includes a reservoir rock and an overlying or updip seal rock is a trap. Types are stratigraphic, structural, and combination traps. The formation of traps by deposition, tension or compression is one of the processes needed to create a petroleum system. Trap formation must occur before or during petroleum migration in order to have an accumulation.

2.6 Generation-Migration-Accumulation

One petroleum system process that includes the generation and movement of petroleum from the pod of active source rock to the petroleum show, seep, or accumulation. The time over which this process occurs is the age of the petroleum system. Even though each increment of this process can be studied separately, it is the petroleum in the accumulation, seep, or show in a well that is proof that a petroleum system exists.

3. PETROLEUM SYSTEM FOLIO SHEET

The petroleum-system folio sheet is a graphical way to depict the geographic, stratigraphic, and temporal evolution of the petroleum system (Fig. 2; Table I).

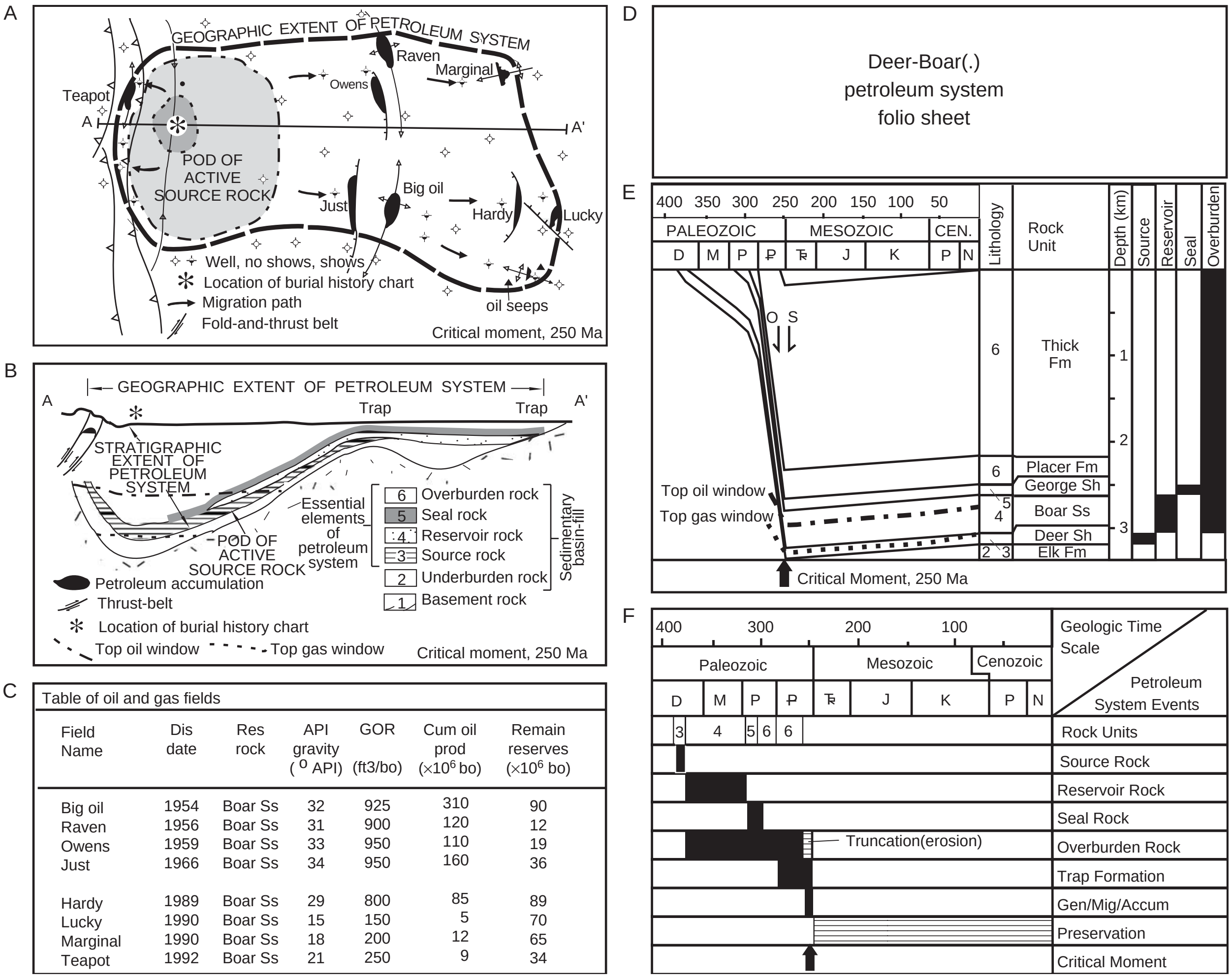

Table of oil and gas fields

Field Name	Dis date	Res rock	API gravity (° API)	GOR (ft3/bo)	Cum oil prod (×10⁶ bo)	Remain reserves (×10⁶ bo)
Big oil	1954	Boar Ss	32	925	310	90
Raven	1956	Boar Ss	31	900	120	12
Owens	1959	Boar Ss	33	950	110	19
Just	1966	Boar Ss	34	950	160	36
Hardy	1989	Boar Ss	29	800	85	89
Lucky	1990	Boar Ss	15	150	5	70
Marginal	1990	Boar Ss	18	200	12	65
Teapot	1992	Boar Ss	21	250	9	34

FIGURE 2 (A) Map showing the geographic extent of the so-called Deer-Boar(.) petroleum system at the critical moment (CM, 250 Ma). Thermally immature source rock is outside the oil window. The pod of active source rock lies within the oil and gas windows. (B) Cross section showing the stratigraphic extent of the so-called Deer-Boar(.) petroleum system at the critical moment (250 Ma). Thermally immature source rock lies up dip of the oil window. The pod of active source rock is down dip of the oil window. (C) Table of oil and gas fields in the Deer-Boar(.) petroleum system, or the accumulations related to one pod of active source rock. (D) The name of the petroleum-fluid system. (E) Burial history chart shows the critical moment (250 Ma) and the time of oil generation (260-240 Ma) for the so-called Deer-Boar(.) petroleum system. This information is used on the events chart. All rock unit names used here are fictitious. (F) Events chart shows the relationship between the essential elements and processes as well as the preservation time and critical moment for the so-called Deer-Boar(.) petroleum system. (G) The text and other figures needed to describe the petroleum system. From Magoon, L. B., and Dow, W. G. (2000). Mapping the petroleum system—An investigative technique to explore the hydrocarbon fluid system. Memoir 73, p. 55 (as Figure 1). AAPG © 2000. Reprinted by permission of the AAPG whose permission is required for further use.

The folio sheet includes (1) the petroleum system map (Fig. 2A), (2) the petroleum system cross section (Fig. 2B), (3) a table of genetically related accumulations (Fig. 2C), (4) the petroleum system name (Fig. 2D), (5) a burial history chart located over the pod of active source rock (Fig. 2E), and (6) an events chart to summarize the history of the petroleum system (Fig. 2F). In the ideal case, this folio sheet summarizes the detailed work of many specialists and provides the supportive information for the petroleum system map needed to evaluate the play and prospect.

3.1 Petroleum System Map

The petroleum system map (Fig. 2A; Table I) shows (1) the geographic extent of the petroleum system; (2) the pod of active source rock; (3) the genetically

TABLE I

Components of a Complete Petroleum System Study

Figure or table	Information required	Purpose
Petroleum system map	Locate petroleum fields included in system; Indicate whether oil or gas; Indicate surface and subsurface oil or gas shows included in system; Indicate direction of petroleum migration; and Indicate distribution of pod of active source rock.	*Geographic extent of a petroleum system* at critical moment shown by circumscribing the pod of active source rock and the outer limit of migrated hydrocarbons; *Source rock name* from pod of active source rock; and *Petroleum system burial history chart* location.
Petroleum system table	List all oil or gas fields by petroleum system; Indicate discovered reserves and in-place petroleum by stratigraphic unit; trap type; reservoir rock name, age, and lithology; and seal rock name, age, and lithology; For oil field indicate GOR, API gravity, sulfur content, and Pr/Ph ratio; and For gas field indicate GOR, $\delta^{13}C$, and gas wetness $[(C_1/C_1{-}C_4) \times 100]$.	*In-place petroleum* for mass balance calculation; *Reservoir rock name* from that reservoir rock with the highest percentage of in-place petroleum; *Seal rock* most commonly occuring in trap; and *Oil or gas province* from average GOR.
Petroleum system cross section	Structural and stratigraphic information such as deformation style and rock units; Indicate oil window and gas window; Indicate petroleum shows and accumulations; Draw at critical moment; and Indicate direction and conduits for petroleum migration.	*Stratigraphic extent of petroleum system* at the critical moment by identifying the base of the pod of active source rock or base of hydrocarbon column, whichever is deeper; *Geographic extent of petroleum system*; *Pod of active source rock* shown; *Overburden rock* shown; and *Petroleum system burial history chart* location.
Petroleum system burial history chart	Stratigraphic units penetrated in well; Time rock-units were deposited; Thickness of rock units; Names of rock units; Lithology of rock units; Present day thermal maturity profile; Present day geothermal gradient; Computer program to determine time and depth for oil window and gas window; and Indicate essential elements of petroleum system.	*Petroleum system events chart information* determined from chart, such as onset and end (at uplift) of petroleum generation, and critical moment; *Essential elements of petroleum system* shown; *Oil window* depth for cross section at critical moment; and *Gas window* depth for cross section at critical moment.
Petroleum system events chart	Age of essential elements of petroleum system; Onset and end of trap formation; Onset and end of petroleum generation, migration, accumulation; Preservation time of petroleum system; and Critical moment.	*Petroleum system events chart* summarizes in one diagram the essential elements and processes of the system, as well as the preservation time and critical moment.
Petroleum-petroleum correlation	Geochemical evidence, such as bulk properties, biological markers, and isotopic data to show that more than one petroleum accumulation came from the same source rock (but not necessarily the same pod of active source rock).	*Geographic and stratigraphic extent of a petroleum system* is established with this geochemical correction in concert with the structure and stratigraphy of the pod of active source rock and the adjacent traps.
Petroleum-source rock correlation	Geochemical evidence, such as biological marker and isotopic data, to indicate a certain petroleum originated from a specific source rock.	*Level of certainty* is established using geological and geochemical evidence and indicates the confidence that a specific source rock expelled a given petroleum.
Mass balance calculation	TOC and Rock-Eval pyrolysis; Source rock density; and Volume of pod of active source rock.	*Mass of petroleum generated* to determine petroleum system generation-accumulation efficiency (GAE).

Source. From Magoon, L. B., and Valin, Z. C. (1994). Overview of petroleum system case studies. Memoir 60, p. 332 (as Table 20.2).

related oil and gas accumulations, shows, and seeps; (4) the location of the burial history chart; and (5) the location of the petroleum-system cross section. Usually this map is drawn at the present day, but may be refined later to depict the critical moment or that time when most of the hydrocarbons were generated and accumulating, especially if the petroleum system is old. This map is in contrast to a geologic map which depicts rock units and geometry at the surface or an oil and gas field map.

3.1.1 Accumulations, Shows, and Seeps

The genetically related oil and gas fields or petroleum accumulations, by inference, originated from the pod of active source rock. So start with an oil and gas field map of the petroleum province. The accumulations shown on an oil and gas field map need to be grouped into one or more possible petroleum systems based on their geographic and stratigraphic locations, and the bulk and geochemical properties of the fluids in each accumulation (Fig. 2A). For example, the accumulations in the fictitious Deer-Boar(.) petroleum system include Teapot in the thrust belt; Raven, Owens, Just, and Big Oil in the anticlines adjacent to the foreland basin; and Marginal, Hardy, and Lucky, the most distal accumulations. These widely spaced accumulations are in the same stratigraphic interval, the Boar Sandstone, and all have similar geochemical properties, as known from wells that sample these accumulations.

The exploratory wells indicate that some of the wells have oil shows in the Boar Sandstone. One surface seep occurs in the southeast portion of the map where the Boar Sandstone crops out. These oil occurrences have geochemical similarities with the oil accumulations. Based on this information, these oil occurrences are judged to belong to the same petroleum system.

3.1.2 Pod of Active Source Rock

The pod of active source rock is a contiguous volume of source rock that generated and expelled petroleum at the critical moment and is the provenance for a series of genetically related petroleum shows, seeps, and accumulations in a petroleum system. A pod of mature source rock may be active, inactive, or spent. There is only one pod of active source rock for each petroleum system.

The kerogen type for the thermally mature source rock has been shown by numerous investigators to control the type and volume of petroleum expelled. Other investigators have provided explanations of the tools and techniques to characterize and map the pod of active source rock. The pod of active source rock (also referred to as the kitchen or oil and gas window) is a required feature of the petroleum system map because of its genetic control on petroleum accumulations.

For the fictitious Deer-Boar(.), the pod of active source rock is in the western part of the map area and is mapped using a dashed line (long and short dashes, Figs. 2A and 2B). The Deer Shale is considered the most likely source rock because it is geographically near and stratigraphically below the Boar Sandstone, the reservoir rock for the accumulations, shows, and seep. Thermal maturity data for the Deer Shale indicate it is thermally mature in the foreland basin, but immature in the thrust belt toward the west and on the craton toward the east. The dashed lines correspond to the thermal maturity contours for the top of the oil window (long and short dashes) and the top of the gas window (short dashes) (Figs. 2A and 2B).

3.1.3 Geographic Extent

The geographic extent of the petroleum system at the critical moment is described 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. The critical moment is a snapshot of the petroleum system at the time when most of the hydrocarbons were generated and migrating. A map of the Deer-Boar(.) petroleum system, drawn at the end of the Paleozoic time (250 Ma), includes a line that circumscribes the pod of active source rock and all related, discovered hydrocarbons. This area represents the geographic extent or known extent of the petroleum system (Fig. 2A).

To draw this petroleum system map, we assume that all the petroleum occurrences emanate from the same pod of active source rock. The pod of active source rock is shown as a shaded area, and the depth to the source rock is assumed to be close to the thickness of overburden rock which is contoured in thousands of meters. Based on the locations of the accumulations, drill-stem tests, and exploratory wells with and without oil shows the geographic extent of the petroleum system is drawn. Using the guidelines discussed earlier, the location of the cross section and the burial chart are indicated. This petroleum system map emphasizes the short migration path of the discovered oil fields and that the long migration path to the northwest lacks an oil field. This map strongly suggests that the most likely place to find undiscovered oil is above or close to the pod of active source rock and along the preferential migration paths as expressed by the geographic extent of the petroleum system.

3.1.4 Location of Cross Section
The cross section is placed on the map so that it passes through the largest accumulations, thickest overburden rock, and extends over the entire geographic extent of the petroleum system (Figure 2B). If possible, start with an available present-day cross section unless the petroleum system is so old or structurally altered that a restored cross section representing a previous time is required to depict the time when most of the hydrocarbons migrated and accumulated. Here, a cross section at the end of the Paleozoic (250 Ma) was used (Fig. 2B). The largest accumulations are included because they are usually located on the simplest, most efficient migration path from the pod of active source rock. A transect through the thickest overburden rock shows the most likely area where the source rock is thermally mature and, therefore, the provenance of the hydrocarbons. The cross section should transect the entire the petroleum system so that the basis for the geographic extent can be demonstrated.

3.1.5 Location of Burial History Chart
The location of the burial history chart is along the cross section line within the pod of active source rock (Fig. 2B, E). At this location, the source rock must be thermally mature (active or spent) otherwise petroleum would be absent in the conduits or migration paths. The reconstruction of the burial history provides the basis for the times of the onset (O) of generation-migration-accumulation, the depletion (D) of the source rock, and the critical moment (CM).

3.2 Table of Fields

The table showing all the oil and gas accumulations included in the folio sheet provides important information about the petroleum system (Fig. 2C; Table I). First, the discovery dates and sizes of the fields are useful for field-size distributions and discovery-rate modeling. Second, the complexity of the hydrocarbon plumbing system is suggested by the number of reservoir rocks. One reservoir rock for all fields indicates a simple plumbing system, whereas many reservoir rocks indicates a more complicated system. Third, the size of the petroleum system and the generation and expulsion efficiency can be determined by using the total volume of recoverable oil and gas for all fields. Finally, the reservoir rock with the highest percentage of oil or gas reserves is to be used in the petroleum system name. For example, if all the oil is in the Boar Sandstone, it is included in the name (Fig. 2D).

For example, the Deer-Boar(.) is a 1.2 billion barrel petroleum system with a simple plumbing system. This size designation using recoverable petroleum is most useful to the explorationist who is interested in (1) comparing the sizes of different petroleum systems to rank or plan an exploration program and (2) comparing the field-sizes in a petroleum system to determine the most likely prospect size and what volumes can be produced. However, the size (volume of recoverable petroleum) of the petroleum system needed for material balance equations is quite different. Here, three additional types of information are estimated: the in-place petroleum for each field, what is left behind along the migration path, and what was lost in surface seeps and exhumed accumulations. These estimates are made by the investigator. This volume of petroleum can then be compared to the estimated volume of petroleum generated in the active source rock.

3.3 Cross Section

The petroleum system cross section (Fig. 2B; Table I), drawn at the critical moment, or time when most of the hydrocarbons were generated, shows the geographic and stratigraphic extent of the petroleum system and how each rock unit functions within the system to distribute the oil and gas. Stratigraphically, the petroleum system includes a petroleum source rock, reservoir rock, seal rock, and overburden rock. This cross section is in contrast to structural or stratigraphic cross sections.

The presence of adequate overburden rock in the correct geometry provides (1) the burial needed to thermally mature the source rock, (2) the up dip vector needed for oil and gas to migrate to shallower depths, (3) the burial depth variations needed to form traps for petroleum accumulations, and (4) the burial depth of accumulations that allow for the preservation or biodegradation of oil. If the history of the petroleum system is to be correctly modeled, the age, thickness, and erosional history of the overburden rock is required. The cross section, drawn to represent the end of the Paleozoic (250 Ma), shows the geometry or structural style of the essential elements at the time of hydrocarbon accumulation, or critical moment, and best depicts the stratigraphic extent of the system (Fig. 2B).

3.4 Petroleum System Name

The name of a petroleum system labels the hydrocarbon-fluid system or distribution network (Fig. 2D) in the same way the name Colorado River designates an aqueous distribution system, the river and its tributaries. The name of the petroleum system includes the geological formation names of the source rock followed by the major reservoir rock (Fig. 2C) and then the symbol expressing the level of certainty. For example, the Deer-Boar(.) is the name of a hydrocarbon fluid system whose source rock, the Deer Shale, most likely generated the petroleum that charged one or more reservoir rocks, which in this case is the Boar Sandstone. It is the major reservoir rock because it contains the highest percentage by volume of hydrocarbons in the petroleum system.

A petroleum system can be identified at three levels of certainty: known, hypothetical, and speculative. At the end of the system's name, the level of certainty is indicated by (!) for known, (.) for hypothetical, and (?) for speculative. The symbol indicates the level of certainty that a particular pod of active source rock has generated the hydrocarbons on the table of accumulations (Fig. 2C). In a known petroleum system, a well-defined geochemical correlation exists between the source rock and the oil 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 link between a source rock and petroleum accumulations is postulated entirely on the basis of geological or geophysical evidence.

In certain frontier areas of the world, especially in the offshore, the stratigraphic units are poorly understood and frequently undesignated. Here, the judgment of the investigator is required. The geologist should avoid using ages, such as Jurassic, in the name because it fails to uniquely identify the petroleum system. Other situations arise where it is difficult or confusing to follow the naming rules. For example, when a rock unit that includes both the source and reservoir forms more than one petroleum system, the same name might be used more than once, such as Monterey(!) petroleum systems. Here, a geographic modifier can be used to differentiate the systems. Another naming problem arises in frontier areas where formal rock units are lacking, so only ages or geophysically mapable units are used. A geographic name or the name of an accumulation in the petroleum system may be used. If it is impossible to follow the formal designation of a petroleum system, the investigator should select a unique name that identifies the fluid system, not the rock units.

3.5 Burial History Chart

The purpose of the burial history chart is to show the essential elements, and three important hydrocarbon events, which are (1) the onset (O) of generation-migration-accumulation, (2) the partially spent or depleted (D) active source rock, and (3) the critical moment (CM) of the petroleum system (Fig. 2E; Table I). The top of the oil and gas windows, and the lithology and name of the rock units involved should also be shown. This chart uses sedimentologic and paleontologic evidence in the overburden rock to reconstruct the burial or thermal history of the source rock. The onset of generation-migration-accumulation usually occurs when the source rock reaches a thermal maturity at a vitrinite reflectance equivalence of 0.6% R_o and ends when the source rock is either uplifted before all the hydrocarbons can be expelled or is depleted as the source rock is more deeply buried. The location of the burial history chart is shown on the petroleum system map and cross section.

In this example, the Deer Shale (rock unit 3) is the source rock, the Boar Sandstone (4) is the reservoir rock, the George Shale (5) is the seal rock, and all the rock units above the Deer Shale (4, 5, 6) comprise the overburden rock. The burial history chart is located where the overburden rock is thickest, and indicates that the onset of generation-migration-accumulation started 260 Ma in Permian time and was at maximum burial depth 255 Ma. Oil generation ended about 240 Ma because the source rock is depleted. The critical moment as judged by the investigator is 250 Ma because modeling indicates most (>50%) of the hydrocarbons have been expelled and are accumulating in their primary traps. However, the investigator would be correct to have chosen anytime between 250 and 240 Ma, but 250 Ma was chosen because the best geologic information is available to reconstruct the map and cross section. The time of generation-migration-accumulation ranges from 260 to 240 Ma and is the age of the petroleum system.

As mentioned in the cross section discussion, knowing the age and thickness for each increment of overburden rock is crucial for any modeling exercise. Each increment needs to be bounded by time lines whose dates are supported by paleontologic dates, isotopic age dates, or other means of dating strata. As the number of increments in the overburden rock increases, the details of the burial history of the source rock will be better understood. For instance, in the previous example, the overburden rock is Permian, undifferentiated. Suppose, however, that paleontologic dates indicate that 95% of the overburden rock is Early Permian and that the rest is Late Permian. This increase in increments in the overburden rocks will change the time when the underlying source rock becomes thermally mature. In this example, the change in time that the source rock becomes mature might be considered insignificant, but in other examples the difference could be significant.

3.5.1 Location of Burial History Chart

The burial history chart chosen to show the three hydrocarbon events for a petroleum system should be located in the pod of active source rock where, in the judgment of the investigator, much of the oil and gas originated. Usually this location is down-dip from a major migration path to the largest fields.

Petroleum systems are seldom so simple that only one burial history chart adequately describes the same three hydrocarbon events for every location in the pod of active source rock. The investigator chooses the burial history curve that best suits the purpose. If the investigator is presenting (oral or written) a petroleum system investigation, he or she would use the burial history curve down-dip from a major migration path to the largest fields. However, if the subject is a play or prospect, the burial history curve would be down-dip on a suspected migration path to the area of the play or prospect.

3.5.2 Critical Moment

The generation, migration, and accumulation of oil and gas in a petroleum system never starts when the source rock is being deposited and seldom extends into the present day. If a source rock is deposited in the Paleozoic, it may be the Mesozoic before it becomes thermally mature and charges adjacent traps, and by the Cenozoic, this source rock is probably depleted. The time over which the process of generation-migration-accumulation takes place could be tens of millions of years. This is a long period of time to chose from if an investigator needs to select the most appropriate moment during this process to make a map and cross section that shows the petroleum system when most ($>50\%$) of the hydrocarbons were migrating and accumulating. To help the investigator with this important exercise, the critical moment was introduced and incorporated into the petroleum system folio sheet.

Geologists use the concept of the critical moment for other exercises. Whenever a map, such as an isopach map, is constructed, it is frequently reconstructed to its original thickness at the moment of deposition. The kinematic development of a fold-and-thrust belt occurs over many millions of years, but it is frequently represented by one cross section, or a snapshot in time. A structural cross section of a fold-and-thrust belt reconstructed at the end of the Cretaceous, for example, utilizes the critical moment concept.

The critical moment is the time that best depicts the generation-migration-accumulation of hydrocarbons in a petroleum system. This definition needs an explanation and an example to be better understood. A moment is a brief, indefinite interval of time that is of particular importance. For a camera to take a picture, a moment is less than a second. In geology, the further one goes back in time, the interval becomes thousands or even millions of years. For the petroleum system, moment relates to the shortest measurable time. Critical refers to the moment that best shows, in the judgment of the investigator, the process of generation-migration-accumulation.

Best is a keyword in this definition. Best contains the criteria the investigator should use to select the appropriate moment. The best time needs to fulfill several criteria: (1) it must be within the age of the petroleum system; (2) it must be when most, or more than half, of the hydrocarbons are migrating and accumulating; and (3) it must be shown as an arrow, not an interval, on the burial history and events charts.

The critical moment of a petroleum system can vary depending on its purpose. If the purpose is a petroleum system case study, then the critical moment should be representative of the entire system. However, if the purpose is related to an exploration play or prospect, then the critical moment should be for that part of the pod of active source rock most likely to charge the traps in the play or prospect. Depending on the size, thickness, and variation of the thermal maturity of the pod of active source rock and the objective of the investigator, these could be different best times, none of which are incorrect. In fact, the investigator may need to make numerous burial history charts of a large, thick pod of active source rock that has a wide range of thermal maturity to determine which best moment properly depicts generation-migration-accumulation for the intended audience.

The burial history chart omits important information available in most modeling software packages that explains the critical moment from a different perspective (Fig. 3). This graph shows cumulative volumes of generated or expelled oil and gas.

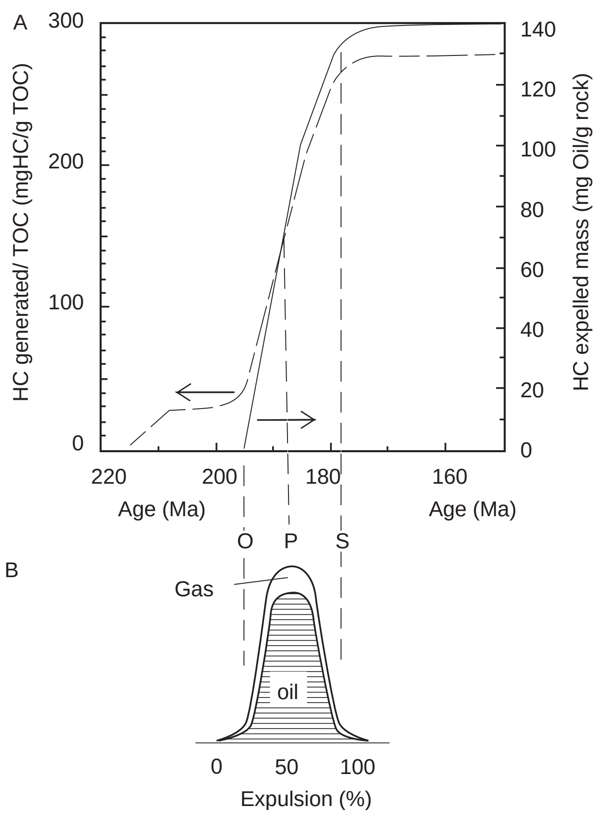

FIGURE 3 (A) Cumulative curves showing the time over which hydrocarbons (HC) are generated and expelled. (B) Distribution curve for oil and gas (HC) expulsion using the same information and showing the onset (O) of expulsion, peak (P) expulsion, and depletion (D) of the source rock. The critical moment (CM) is selected to be any time between P and D. From Magoon, L. B., and Dow, W. G. (2000). Mapping the petroleum system—An investigative technique to explore the hydrocarbon fluid system. Memoir 73, p. 64 (as Figure 7). AAPG © 2000. Reprinted by permission of the AAPG whose permission is required for further use.

Wherever the curves are horizontal, no volume is being added. This graph shows the onset of generation (dashed line) precedes expulsion (solid line) by almost 20 million years. According to this graph, most expulsion occurs more than 15 million years from 195 to 179 Ma. When this cumulative expulsion curve is transformed to a curve showing the distribution of expulsion, it shows peak expulsion at 187.5 Ma (Fig. 3). At this time, at least half of the petroleum is migrating so the critical moment can be selected by the investigator as any time between 187.5 to 179 Ma.

3.6 Events Chart

The petroleum-system events chart shows the temporal relationship of the rock units, essential elements, processes, preservation, and critical moment for each petroleum system in bar graph form (Fig. 2F; Table I). The events chart concept is flexible and is used as a risk chart to evaluate plays and prospects

The events chart shows the following items (Fig. 2F). The rock units include those that are within the stratigraphic extent of the petroleum system. On a certainty scale, the ages of the four essential elements (source, reservoir, seal, and overburden rocks) are usually better established from paleontology or radiometric age dates than those associated with the two processes (trap formation and generation-migration-accumulation). Determining the times over which the traps form and hydrocarbons accumulate (generation-migration-accumulation) is more interpretive because there is less precise temporal information about these processes. Therefore, risk or uncertainty with regard to the times over which the two processes takes place is higher or less certain than for the better established times of development of the four essential elements. This certainty relationship is important if a similar chart is constructed for a complementary play/prospect or assessment unit.

When an events chart is constructed for a complementary prospect, it becomes a risk chart. The risk chart is derived from the petroleum-system events chart which, in turn, is derived from the summation of the events chart for each oil and gas field in the petroleum system. These oil or gas fields are successful prospects. Unsuccessful prospects are dry holes. For example, if a risk chart for a prospect is similar to the petroleum-system events chart, then it can be concluded that this prospect is more likely to contain petroleum than one that has a dissimilar risk chart. Conversely, if an events chart is constructed for each dry hole within a petroleum system, they should be dissimilar from producing fields. This dissimilarity indicates where the greater uncertainty lies. Used this way, the events chart is a useful analytical tool to deal with uncertainty or risk.

One important issue this simple bar graph addresses is as follows: For an evolving petroleum system to effectively trap migrating hydrocarbon fluids, the trap forming process must occur before or during the generation-migration-accumulation process in order for petroleum to accumulate.

When constructing an events chart, these rules should be followed. First, there is only one pod of active source rock for each petroleum system. Second, every effective reservoir rock needs a seal, no matter how thin. Third, show only reservoir rocks

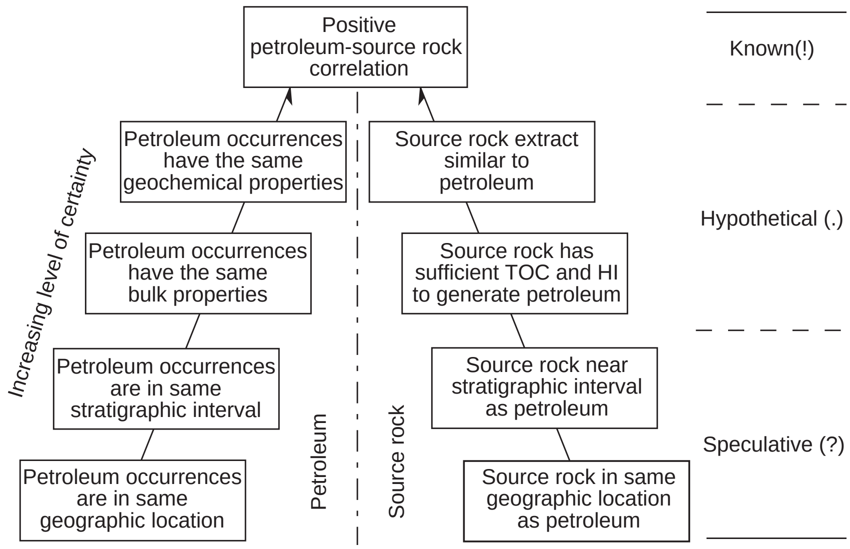

FIGURE 4 The logic sequence used for the levels of certainty from guessing to knowing. From Magoon, L. B., and Dow, W. G. (2000). Mapping the petroleum system—An investigative technique to explore the hydrocarbon fluid system. Memoir 73, p. 56 (as Figure 2). AAPG © 2000. Reprinted by permission of the AAPG whose permission is required for further use.

that contain petroleum accumulations, shows, or seeps. Fourth, show eroded overburden rock with hatcher lines so that it can be incorporated in the modeling exercise. Fifth, the best information for timing of trap formation comes from oil and gas fields. Sixth, the best information for generation-migration-accumulation comes from geological and geochemical information about the source rock that are then incorporated into the burial modeling and kinetics. This information indicates the onset, peak, and end of generation-migration-accumulation or when the active source rock is depleted (spent) or uplifted (inactive source rock). This process takes place over a relatively short period of time. Seventh, preservation time, by definition, starts when generation-migration-accumulation ends and continues to the present. Some petroleum systems have no preservation time. Last, when the critical moment occurs is, as discussed earlier, in the judgment of investigator, but modeling software packages are useful tools as they show the time over which expulsion from the pod of active source rock occurs.

4. THE PETROLEUM SYSTEM AS A WORKING HYPOTHESIS

A petroleum system investigation starts with a working hypothesis for generation, migration, and entrapment of petroleum in a province, based on available geological and geochemical data, which evolves as more data becomes available (Fig. 2A, B). The investigator starts with an oil and gas field map and related field data for the petroleum province of interest. The geographic location of the accumulations is important because accumulations located close together are more likely to have originated from the same pod of active source rock (Fig. 4). Accumulations that occur in the same or nearly the same stratigraphic interval are also likely to be from the same active source rock. In contrast, accumulations separated by barren rock sections are presumed to have originated from different pods of active source rock. Accumulations of widely differing bulk properties, such as gas versus oil, API oil gravity, gas-to-oil ratios, and sulfur contents, may also be presumed to originate from different pods of active source rock. Detailed geochemical data on oil and gas samples provide the next level of evidence for determining whether a series of hydrocarbon accumulations originated from one or more pods of active source rock. Last, comparing the geochemistry of oils and gases to possible source rocks provides the highest level of certainty as to which active source rock generated which oil or gas type.

By acquiring and organizing information that addresses these issues of location, stratigraphic position, and geochemistry, an investigator can take a working hypothesis of how a particular petroleum system formed to increasing levels of certainty (Fig. 2; Table I). The investigator organizes the information on the oil and gas accumulations into groups of like petroleum types on the oil and gas field map, cross section and table (Figs. 2A, 2B, and 2C).

With this step completed, the investigator then locates all surface seeps on the oil and gas field map, which now becomes the petroleum system map. The seeps with the same geochemical composition as the subsurface accumulation provides geographic evidence for the end point of a migration path. The stratigraphic unit from which the fluid emanates can be compared to the stratigraphic unit in which oil and gas accumulations are found to determine the complexity of their migration paths. If the stratigraphic units are the same, then the migration paths are simple. If they are different, migration may be more complex. Geochemical information from seeps can be compared with that of discovered accumulations in order to link the seep fluid to the proper petroleum system.

Oil and gas shows in exploratory wells are added to the petroleum system map and cross section to better define the migration paths. As this map and cross section evolve, the investigator is encouraged to anticipate how the final map will look based on the framework geology and petroleum fluid information. Intuitively, exploration risk is high if the petroleum system is complicated and hence less predictable; risk is lower if the petroleum system is simple and thus more predictable.

After similar hydrocarbon fluids in the petroleum system have been mapped individual oil and gas accumulations are tabulated to better understand the size (by volume) and complexity of the petroleum system. The petroleum system table is organized by stratigraphic interval in each field (Fig. 2C). These stratigraphic intervals are zones, members, and formations that produce or contain measurable amounts of oil and gas. The table should include age of the stratigraphic interval, API gravity and sulfur content of the oil, gas-to-oil ratio (GOR), cumulative amount of oil and gas produced, and the remaining amount of oil and gas that can be produced. Other information the investigator may chose to include are lithology, gross and net thickness, porosity and permeability of the reservoir rock, geometry, closure, and area of the trap, and detailed geochemistry of the oil and gas. The information included in the table will depend on what is available and the objectives of the investigation. The required information is used to determine the size (by volume) of the petroleum system, which reservoir rock name is to be used in the name of the petroleum system, and to evaluate the complexity of the migration path.

Now the provenance or origin of the petroleum is mapped as the pod of active source rock. Only one pod of active source rock occurs in each petroleum system. A pod is a contiguous body of source rock that has or is expelling oil and gas. Because this pod has thickness and area, it can be mapped using well, outcrop, or geophysical data. When an organic-rich rock is in close, or reasonably close, proximity, both stratigraphically and geographically, to oil and gas accumulations, shows, or seeps, it is tentatively correlated with those fluids. Based on seismic, well, or outcrop data, the likelihood of correlation increases when the source rock's burial depth is known to reach 3 km, which in the experience of the authors is a reasonable minimum burial depth for thermal maturity or when burial depth modeling indicates a source rock is in of below the oil window. The correlation gains certainty if the source rock, by vitrinite reflectance or some other analytical technique, is established as being thermally mature. If the kerogen type of the source rock is consistent with that of the oil and gas, then confidence increases that the source rock is correctly correlated. If the geochemical composition of the organic matter in the source rock compares favorably with the migrated petroleum, the oil-source rock correlation is considered a match. Using seismic, well, and outcrop data, the suspected or confirmed active source rock is mapped as a contiguous, three-dimensional body, or pod, on the petroleum system map and cross section.

In this manner, the petroleum system map and cross section evolve, as the working hypothesis is taken to successive level of certainty. To further refine this work, a burial history chart and events chart are constructed and the petroleum system is named. This article discussed each of these petroleum system components in sequence, but they are frequently developed in parallel, and their relationship to each other is considered so that the petroleum system can be properly mapped. To organize these components, the petroleum system folio sheet is used.

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Further Reading

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