CHAPTER

8

Sedimentary Basins and Petroleum Systems

8.1 BASIC CONCEPTS AND TERMS

A sedimentary basin is an area of the earth's crust that is underlain by a thick sequence of sedimentary rocks. Hydrocarbons commonly occur in sedimentary basins and are absent from intervening areas of igneous and metamorphic rocks (North, 1971). This fundamental truth is one of the cornerstones of the sedimentary–organic theory for the origin of hydrocarbons. (This theory is in opposition to the cosmic–igneous theory discussed in Chapter 5.) Therefore it is important to direct our attention not only to the details of traps and reservoir rocks but also to the broader aspects of sedimentary basin analysis. Before acquiring acreage in a new area, and long before attempting to locate drillable prospects, it is necessary to establish the type of basin to be evaluated and to consider what productive fairways it may contain and where they may be extensively located. This chapter describes the various types of basin with reference to examples from around the world and discusses the relationship between the genesis and evolution of a basin and its hydrocarbon potential.

First, however, some of the basic terms and concepts must be defined. A sedimentary basin is an area on the earth's surface where sediments have accumulated to a greater thickness than they have in adjacent areas. No clear boundary exists between the lower size limit of a basin and the upper limit of a syncline. Most geologists would probably take the view that a length of more than 100 km and a width of more than 10 km would be a useful dividing line. Most sedimentary basins cover tens of thousands of square kilometers and may contain more than 5 km of sedimentary fill. Note that a sedimentary basin is defined as an area of thick sediment, with no reference to its topography. A sedimentary basin may occur as part of a mountain chain, beneath a continental peneplain, or in an ocean. Conversely, a present-day ocean basin need not necessarily qualify as a sedimentary basin; indeed, many are floored by igneous rocks with only a veneer of sediment.

This distinction between topographic and sedimentary basins needs further elaboration. Both types of basin have a depressed basement. Sedimentary basins may or may not have

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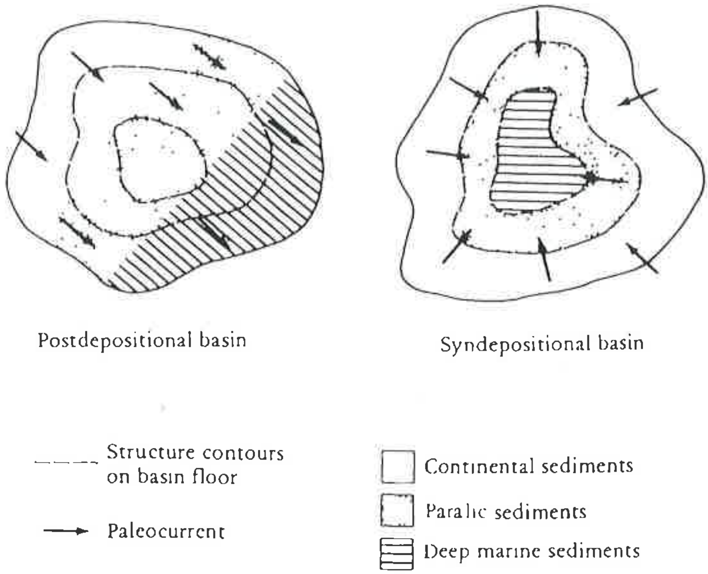

FIGURE 8.1 The differences between syndepositional and postdepositional sedimentary basins.

been marked topographic basins during their history. Many basins are infilled with continental and shallow marine sediments, and totally lack deep-sea deposits.

Similarly, a distinction needs to be made between syndepositional and postdepositional basins. Most sedimentary basins indicate that subsidence and deposition took place simultaneously. This simultaneous occurrence is shown by facies changes and paleocurrents that are concordant with structure. On the other hand, in some basins paleocurrent directions and facies are discordant with and clearly predate the present structure (Fig. 8.1). This is particularly characteristic of intracratonic basins, as is shown later. The distinction between these two types of basins is critically important in petroleum exploration because of the need for traps to have formed before hydrocarbon generation and migration. Stratigraphic traps are generally formed before migration, except for rare diagenetic traps. Structural traps may predate or postdate migration, and establishing the chronology correctly is essential.

A further important distinction must be made between topography and sediment thickness. When examining regional isopach or isochron maps, it is tempting to assume that they are an indication of the paleotopography of the basin. This is by no means always true. The depocenter (area of greatest sediment thickness) is not always found in the topographic nadir of the basin, but may frequently be a linear zone along the basin margin. This is true of terrigenous sediments, where maximum deposition may take place along the edge of a delta. Sediments thin out from the delta front both up the basin margin and also seaward. Similarly, in carbonate basins most deposition takes place along shelf margins, where organisms thrive in shallow, well-oxygenated conditions with abundant nutrients. Thus reefs and skeletal and oolite sands thin out toward basin margin sabkhas and basinward into condensed sequences of lime mud.

Many studies have shown that a depocenter may migrate across a basin. The topographic center of the basin need not necessarily move with it. Examples of this phenomenon have been documented from Gabon, the Maranhao Basin of Brazil, and Iraq (Belmonte et al., 1965; Mesner and Woodridge, 1964; Ibrahim, 1979; respectively). Note that the thickness of each of the formations measured at outcrop should not be added to determine the overall thickness of sediment within a basin. This measurement can only be made from drilling or geophysical data (Fig. 8.2).

Now that basins have been considered in time and profile, they may be viewed in plan. The term *basin* has two interpretations. In the broadest sense, as already defined, a sedimentary basin is an area of the earth's surface underlain by sediments. In a narrower sense basins may be subdivided into true basins; those that are subcircular in plan and those that are elongate (troughs). Embayments, lacking centripetal closure, are basins that open out into larger basins (Fig. 8.3).

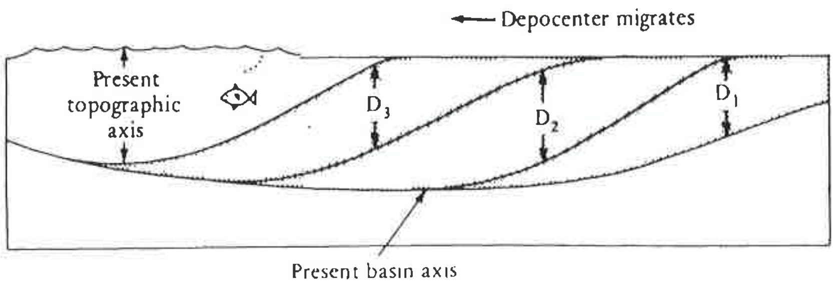

FIGURE 8.2 Cross-section illustrating migrating basin depocenters. Note how measuring the apparent thickness of each unit at the surface, and summing them, will give an erroneous overall thickness of the basin fill.

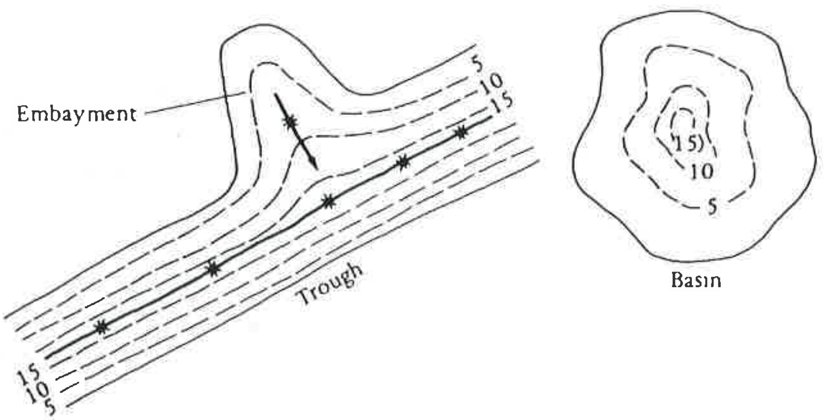

FIGURE 8.3 Basins, defined as areas of the earth's surface underlain by sediments, may be subdivided into true basins, embayments, and troughs. Contours are in kilometers.

8.2 MECHANISMS OF BASIN FORMATION

Sedimentary basins form part of the earth's crust, or lithosphere; they are generally distinguishable from granitic continental and basaltic oceanic crust by their lower densities and slower seismic velocities. Beneath these crustal elements is the more continuous subcrustal lithosphere. The crust is thin, dense, and topographically low across the ocean basins, but thick, of lower density, and, consequently, of higher elevation over the continents (Fig. 8.4). The lithosphere is made up of a series of rigid plates, which overlie the denser, yet viscous, asthenosphere.

The lithospheric plates drift slowly across the asthenosphere. Knowledge of plate tectonics is of fundamental importance in understanding sedimentary basins. Detailed exposition of this topic is beyond the scope of this text, but a brief summary is necessary before considering the mechanics of basin formation. Further details are found in Seyfert and Sirkin (1973), Fischer and Judson (1975), Tarling and Runcorn (1973), Davies and Runcorn (1980), Tarling (1981), and Allen and Allen (1990). A skeptical review of these ideas can be gained from Meyerhoff and Meyerhoff (1972).

The basic concept of plate tectonics can be stated as follows. Oceans are young (generally lacking rocks older than 200 million years), whereas continents are generally far older. Oceans are floored with basaltic volcanic rocks with a veneer of pelagic sediments. The oceans are cut by seismically active volcanic rifts, termed *midocean ridges*. Paleomagnetic

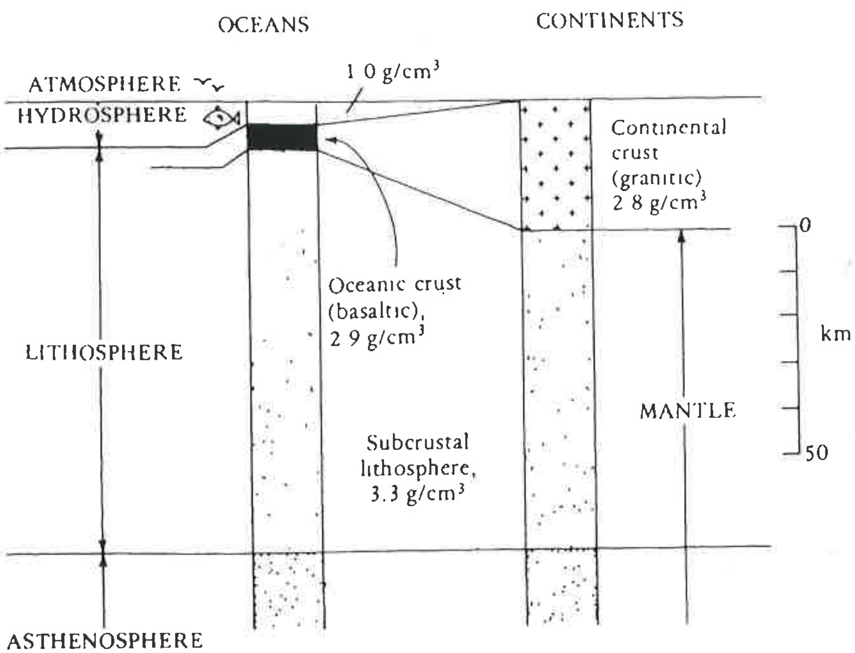

FIGURE 8.4 Comparative columns of oceanic and continental crust showing average densities.

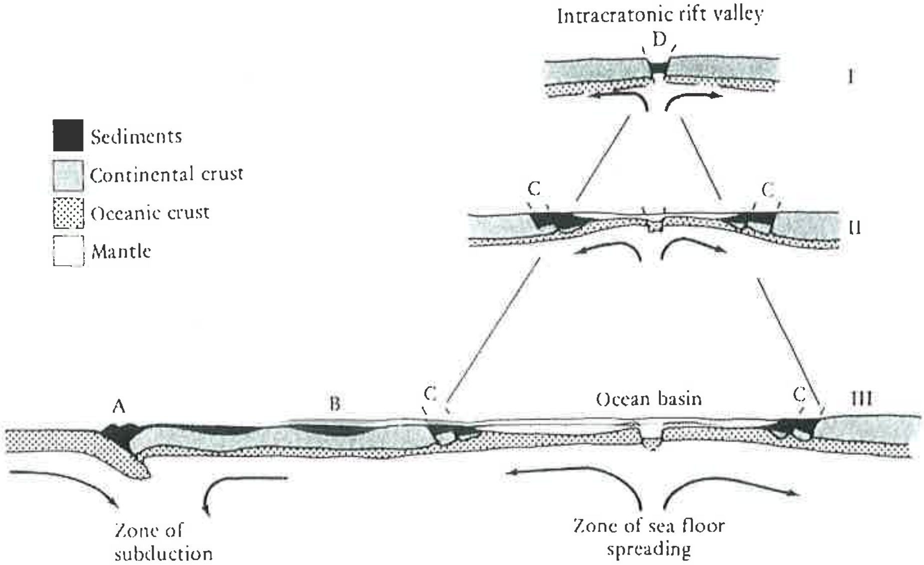

FIGURE 8.5 Cross-sections illustrating the basic concepts of plate tectonics, showing how basins form in response to crustal movement driven by convection cells in the mantle. (I) An axis of sea floor spreading develops, in this instance, beneath continental crust. Updoming occurs and a rift valley is formed (D). The East African rifts are a modern example. (II) Crustal separation causes the rift to split into two continental margin basins (C) separated by a widening ocean. (III) Concomitant with the formation of new oceanic crust at the spreading ridge, crust is drawn down into the mantle at zones of subduction (A). In these areas deep basins undergo extensive tectonism as their sediments are compressed by the converging plates. Intracratonic sag basins develop intermittently on areas of continental crust (B).

reversals and age dating show that rocks become progressively older away from the ridges and toward the continental margins. The midocean ridges can be traced landward into sediment-infilled rifts within continental granitic crust. The evidence suggests, therefore, that new crust, largely of basaltic composition, forms where tension and upwelling occur along these zones of sea floor spreading. Simultaneously, crust is drawn down into the asthenosphere at complementary linear features known as *zones of subduction*. These zones appear as folded troughs of sediment within or adjacent to continental masses and as volcanic island arcs within the oceans. Figure 8.5 shows the process of crustal gestation and digestion, and Fig. 8.6 shows the recognized plate boundaries of the earth.

Although there is general unanimity on the identification of the major plate boundaries, details of some of the smaller ones (microplates) are still somewhat unclear. Three types of plate boundaries are recognized: trailing, subductive, and transcurrent. Trailing, or rift, boundaries occur where new crust forms and plates diverge. Subductive boundaries occur where plates converge. Some plate boundaries are transcurrent where two plates move past each other. Transcurrent plate boundaries are marked by extensive transform faulting accompanied by deep basins and thrust belts of local extent but great complexity (Crowell, 1974; Dickinson and Seely, 1979).

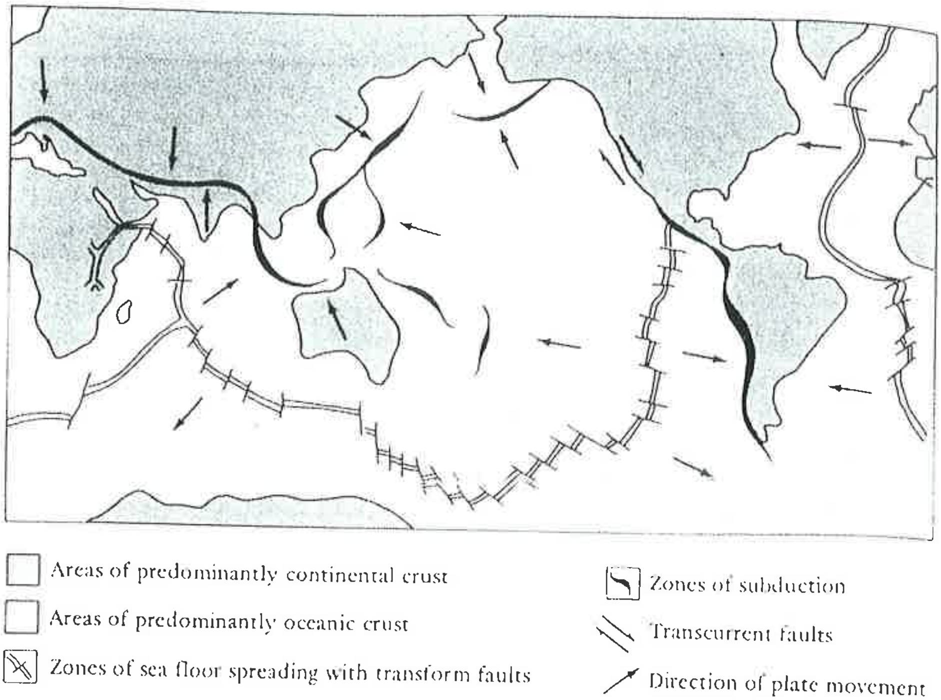

FIGURE 8.6 Map of the Earth showing approximate distribution of oceanic and continental crust and plate boundaries. *After Heirtzler (1968), Vine (1970), others.*

Basins can form in four main ways (Fischer, 1975). Three of these processes are summarized in Fig. 8.7. One major group of basins, the rift basins, forms as a direct result of crustal tension at the zones of sea floor spreading. A second major group of basins occurs as a result of crustal compression at convergent plate boundaries. A third type of basin can form in response not to lateral forces but to vertical crustal movements. For reasons not fully understood, phase changes can take place beneath the lithosphere. These changes may take the form of localized cooling, and therefore contraction, resulting in a superficial hollow, which becomes infilled by sediment. Conversely, the lithosphere may locally heat up and expand, causing an arching of the crust. Erosion of this zone will then occur. Sometimes this crustal doming is a precursor to rifting and drifting. Alternatively, subsequent cooling and subsidence result in the formation of an intracratonic hollow, which may be infilled with sediment.

A fourth mechanism of basin formation is simple crustal loading due to sedimentation. This process poses a "chicken-and-egg" problem, however. Basins of this type require an initial depression in the crust before deposition may begin. Thus, loaded basins characterize continental margins where a prograding delta can initiate and maintain the depression of adjacent oceanic crust.

Basins formed as a result of crustal thinning and rifting are of particular interest to the petroleum industry because they are an important habitat for petroleum. Many theories

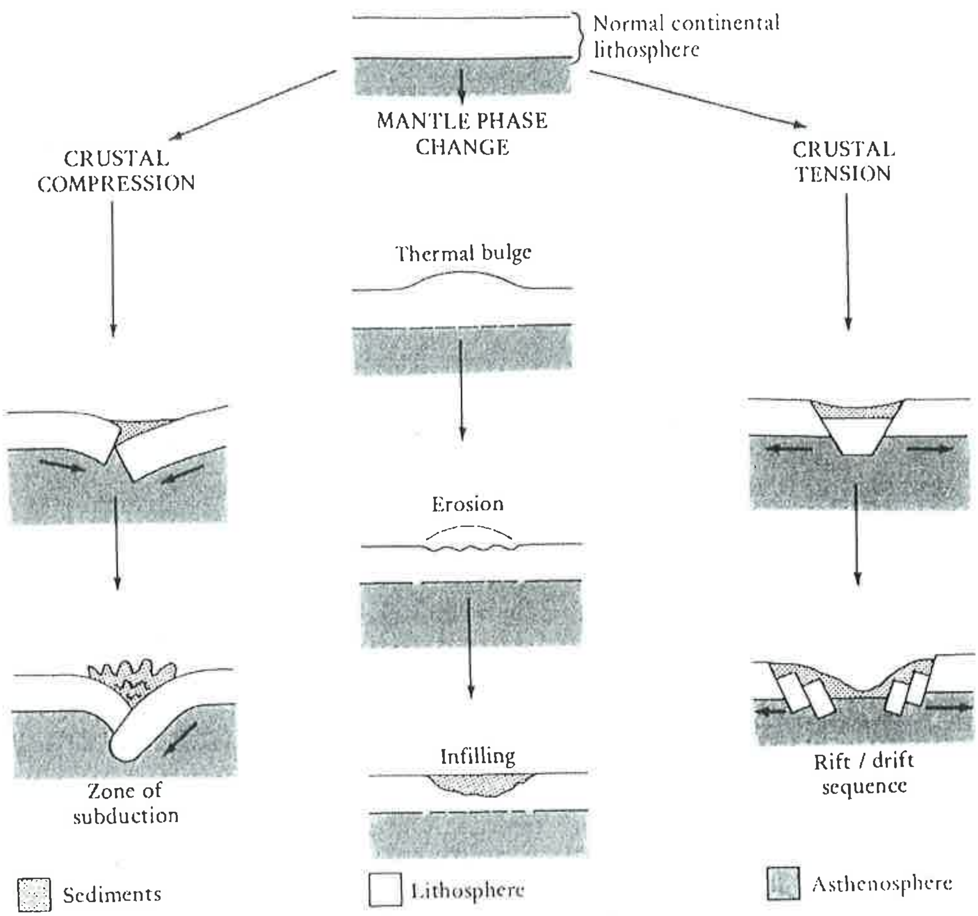

FIGURE 8.7 Cross-sections showing the various types of basin formation discussed in the text. *After Fischer (1975).*

have been advanced to explain their formation. A useful review of these can be found in Allen and Allen (1990). Of the many models proposed, three are particularly significant:

1. Salveson (1976, 1979) proposed a model of passive crustal separation, in which the continental crust was deemed to deform by brittle failure, while the subcrustal lithosphere is thinned by ductile necking. This model was largely based on studies of the Red Sea and Gulf of Suez rift system.
2. McKenzie (1978) proposed a model that assumed that both the crust and subcrustal lithosphere deformed by brittle failure. This model was largely based on studies of the North Sea Basin.
3. Wernicke (1981, 1985) proposed a model for crustal thinning by means of simple shear, in which a low-angle fault extends from the surface right through the lithosphere. This model was largely based on studies of the basin and range tectonic province of North America.

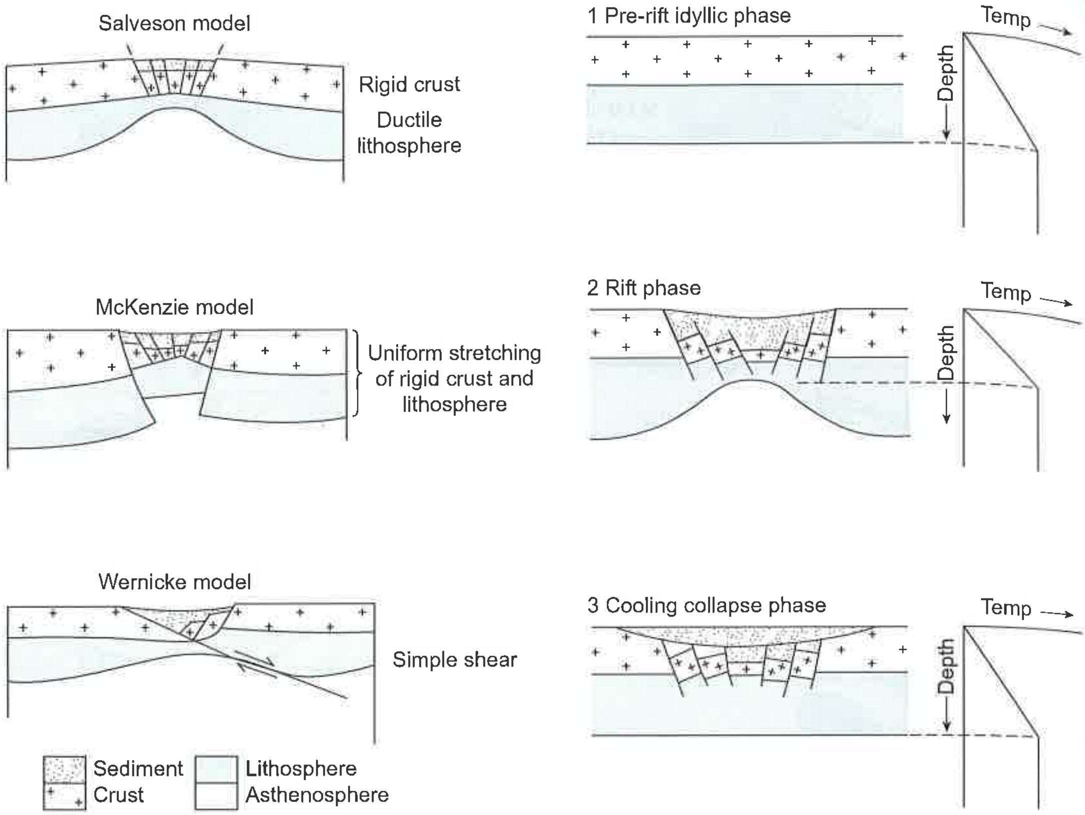

FIGURE 8.8 (Left) Geophantasmograms illustrating three popular explanations about how sedimentary basins are formed by lithospheric stretching. (Right) Geophantasmograms illustrating the McKenzie model for the formation of basins by lithospheric stretching. The sequence begins with the crust at rest and in thermal equilibrium. Crustal thinning and uplift of the asthenosphere are associated with high heat flow and the formation of a rift basin. Subsequent cooling and shrinkage causes the crust to collapse gently resulting in the "steer's head" basin form. Thermal equilibrium is finally reestablished.

These three models are illustrated in Fig. 8.8 on the left. The McKenzie model has received particular interest in the oil industry because it offers a means of predicting the history of heat flow in a sedimentary basin. This is a prerequisite to the accurate modeling of petroleum generation. In the McKenzie model rifting commences on a level surface that is in thermal equilibrium. As the crust thins and rifting develops, the heat flux increases and the temperature of the shallow rocks rises. After rifting has ceased, the crust cools, shrinks, and collapses. Sedimentation continues, but now infills a gently subsiding basin. Faults die out at the top of the syn-rift sediments. The crust returns to thermal equilibrium. The resultant basin is colloquially referred to as a "steer's head" basin, because it is reminiscent of a Texas Longhorn, or Highland Cattle (Fig. 8.8, right).

McKenzie demonstrated mathematically that the heat flow within a basin was related to the amount of crustal stretching, termed the β value. The higher the rate of stretching, the higher the heat flux during the initial phase of rifting (Fig. 8.9, upper). The β value for a basin

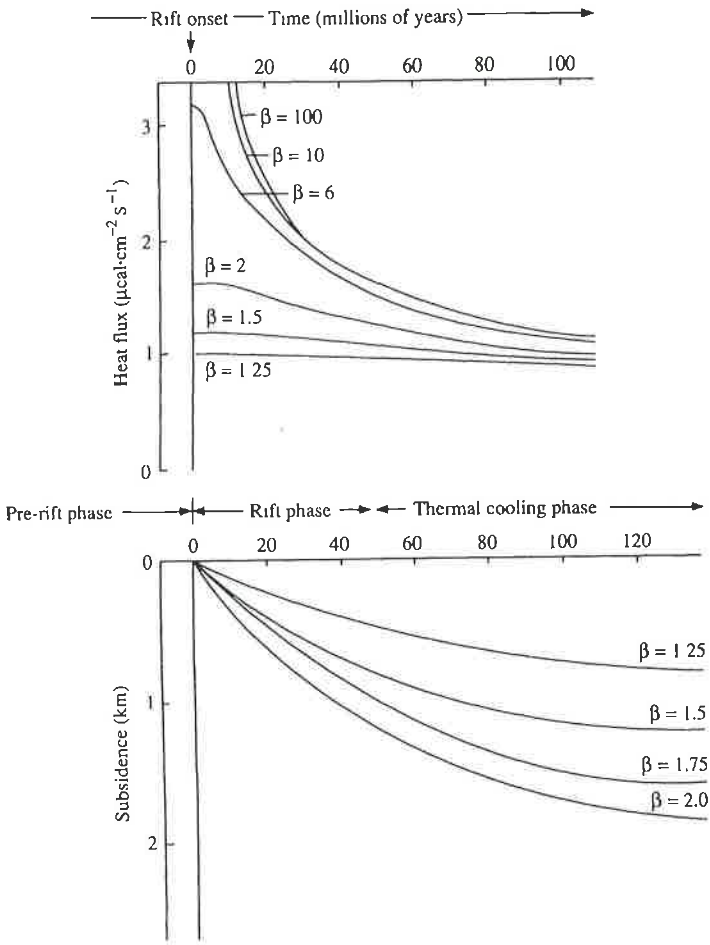

FIGURE 8.9 Illustration of the McKenzie model for basin formation by lithospheric stretching. (Upper) Graph of heat flux against time for various β factors. (Lower) Graph of subsidence against time for various β factors. *Developed from McKenzie (1978).*

may be discovered by constructing a burial history curve for the basin and comparing it with known curves calculated for given β factors (Fig. 8.9, lower). The accurate prediction of the history of heat flow in a sedimentary basin is a prerequisite to the accurate modeling of petroleum generation (Dore et al., 1991; Helbig, 1994).

8.3 CLASSIFICATION OF SEDIMENTARY BASINS

Many schemes have been proposed to classify sedimentary basins. The early schemes were largely descriptive. Today, with the current understanding of plate tectonics, it is now possible to devise schemes that are not only descriptive but also genetic (Busby and Ingersoll,

TABLE 8.1 Classifications of Sedimentary Basins Attempting to Relate Basins to Plate Tectonics

Scheme of Selley (2000)			Scheme of Halbouty et al. (1970) and Klemme (1975, 1980)
Cratonic suite associated with crustal stability	I basins	Intracratonic Epicratonic	Type I simple, saucer-shaped interior Type II intracontinental composite foreland shelf
Geosynclinal suite at convergent plate boundaries	II troughs	Miogeosuyncline Eugeosyncline Molasse	Type VI intermontane Type IV extracontinental downwarp Type VII intermontane
Transcurrent plate boundaries	III rifts	Strike-slip	Type III rifts
Rift-drift suite at divergent plate boundaries		Intermontane (postorogenic)	
		Intracratonic	Type IV coastal graben pull-apart
		Intercratonic	
	IV ocean margin basins (continental margin downwarp)		Type VIII Tertiary deltas

1995). Classifications have been proposed by Weeks (1958), Olenin (1967), Uspenskaya (1967), Halbouty et al. (1970), Klemme (1975, 1980), Perrodon (1971, 1978), Selley (2000), Allen and Allen (1990), and many others.

Table 8.1 attempts to synthesize the schemes of Halbouty, Klemme, and Selley. Sedimentary basins are difficult to classify because a basin may have had a complex history, during which it may have evolved from one type to another. Many basins could arguably be placed in more than one class. No great weight should be attached to Table 8.1. Its main merit is that it shows how basins can be linked to their genesis, providing a logical framework for the ensuing description of the various types of basins (Fig. 8.10).

8.4 CRATONIC BASINS

Cratonic basins are essentially subcircular basins that lie wholly or dominantly on granitic continental crust. The floors of such basins may be broken into a mosaic of horsts and grabens, but major rifting is absent. The genesis of circular sag basins, such as those of Africa, has long attracted attention. Several modes of origin have been postulated. One of the most popular mode proposes that thermal doming over a mantle "hot spot" generates doming of the crust, leading to the erosion of uplifted crustal rocks, followed by cooling and crustal collapse, initially into a rift, followed by gentle sag subsidence (Allen and Allen, 1990).

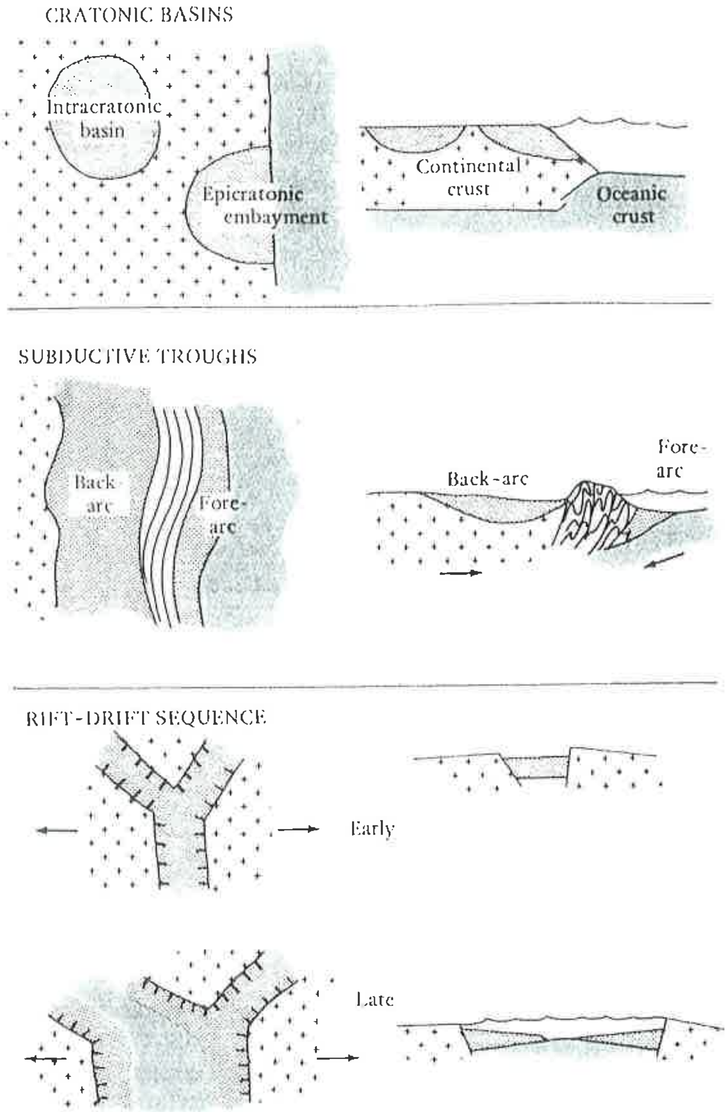

FIGURE 8.10 Geophantasmograms showing the geometry of the various types of basins. Beware of this figure. Note that transitions occur between the different categories and that a basin may evolve from one type to another.

More recently it has been suggested that crustal sags may result from "cold spots" due to mantle cooling, resulting in downwelling and a dignified sagging of the crust (Hartley and Allen, 1994). This model implies that sag basins may lack a precursor rift basin, and an early high heat flux, important considerations when modeling basins for petroleum generation studies.

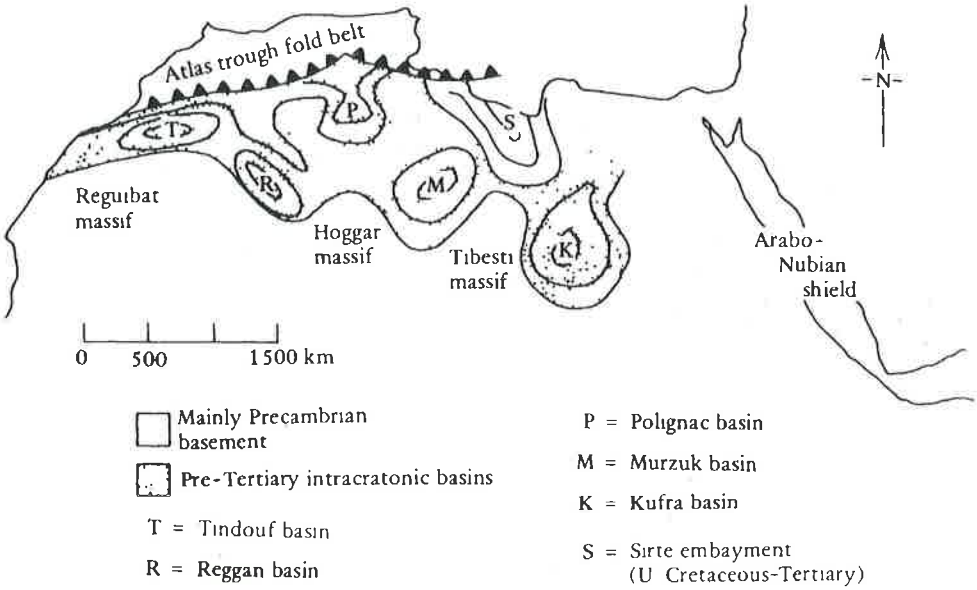

FIGURE 8.11 Map showing the distribution of North African sedimentary basins.

Cratonic basins can be subdivided into intracratonic basins, which lie wholly on continental crust, and epicratonic basins, which lie partly on continental crust and partly on oceanic crust. These classifications correspond to the type I and type II basins of Halbouty and Klemme (Table 8.1). This grouping is not based on artificial distinction. These two types of basins differ markedly in facies, structure, and hydrocarbon potential, as the following account shows.

8.4.1 Intracratonic Basins

Intracratonic basins are broad, shallow, saucer-shaped basins. A major division can be made between terrigenous and carbonate intracratonic basins. The former are dominated by continental clastics, with negligible or no marine shales; the latter are more marine, although they may also be evaporitic. Examples of these two types are described and discussed.

A series of intracratonic basins occurs in North Africa between the Atlantic Ocean and the Red Sea. These basins are separated from one another by ridges of Precambrian igneous and metamorphic basement and tend to plunge northward toward the Mediterranean (Fig. 8.11). These basins show a remarkably uniform Paleozoic stratigraphy, but their characters become distinctly different in the Mesozoic. The Murzuk and Kufra basins of southern Libya are examples of intracratonic basins (Fig. 8.12). They are both floored with the widespread Pan-Saharan Paleozoic sequence. Names vary from basin to basin, and facies' boundaries are diachronic, but the stratigraphy is remarkably uniform from Arabia to Africa (see Selley (1996, 1997a), respectively). A blanket of braided alluvial sands, several hundred meters

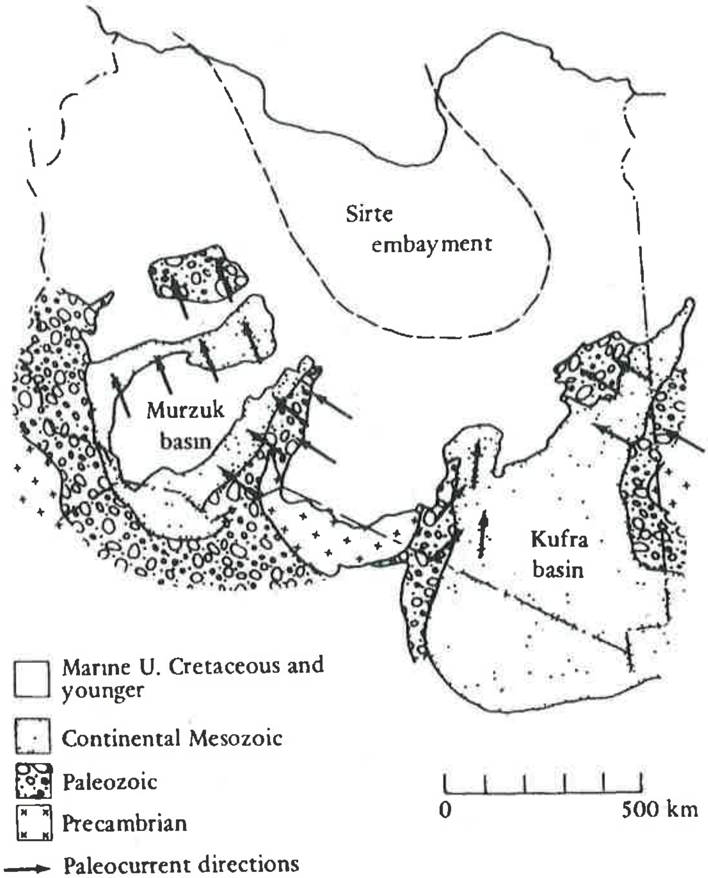

FIGURE 8.12 Map of Libya showing the Murzuk and Kufra intracratonic basins. Note how paleocurrent data show that basin subsidence postdated sedimentation.

thick, is overlain by a thinner, but still uniform, blanket of marine shoal sands. The precise age of these sands is uncertain because of a lack of fossils, but they are generally referred to the Cambro-Ordovician. These beds are succeeded by a marine graptolitic shale: the Tannezuft shale (Silurian) of Algeria and Libya and the Arenig shale of the Khreim Group in Jordan. This shale is an organic-rich oil source rock in northwest Algeria, but becomes thinner, siltier, and less organic when traced south and east toward the craton. A major regression then deposited the predominantly deltaic Acacus sandstone (Silurian) and the predominantly fluvial Tadrart sandstone (Devonian) in North Africa, and the equivalent Khreim Group and Al Jouf sandstone of Arabia. Overlying Carboniferous marine limestones and shales in Algeria and northwestern Libya pass southeastward into paralic sands and shales and finally to fluvial sands in the southeastern Kufra basin. After a major regression at the end of the Carboniferous, the sea has never again returned to the Murzuk and Kufra basins (Lestang, 1965; Klitzsch, 1970).

Facies analysis shows that throughout the Paleozoic the Murzuk and Kufra basins lay on a more or less uniform northerly dipping shelf. Paleocurrent analysis shows that the basins were separated by northerly plunging ridges. This morphology continued while the continental Mesozoic sandstones ("Nubian," Messak sandstone) were deposited (McKee, 1965; Klitzsch, 1972; Van Houten, 1980). These sandstones include the deposits of a wide range of continental environments: dominantly fluvial, but including fanglomerate, lacustrine, and eolian deposits. Again paleocurrent analysis shows essentially a northerly paleoslope across both basins. The Murzuk and Kufra basins only became structurally enclosed basins, as opposed to embayments, after the deposition of the Continental Mesozoic. This deposit is largely barren of fossils and is considered to range in age from ? Triassic to Lower Cretaceous (Wealden). On regional grounds the closure of the basins by uplift of their northern edges would seem to have occurred toward the end of the Cretaceous period.

The Murzuk and Kufra basins thus provide good examples of intracratonic basins. Their main characteristics are subcircular shape and thin sediment fill (probably of the order of some 2 km for the Murzuk Basin and 3 km for the Kufra Basin). They show a remarkable intrabasinal and interbasinal uniformity of stratigraphy. Their facies are predominantly nonmarine sands, with minor volumes of marine sands, shales, and limestones. There is a shortage of organic-rich source beds, which partly reflects the shortage of marine shales, and also reflects the predominantly arid Mesozoic climate unfavorable for lacustrine oil shale deposition. The basin floors show a fairly uniform dip, and structural anomalies are largely absent. Geothermal gradients are low over the old, undisturbed granitic crust.

Intracratonic basins of this type are relatively poor prospects for hydrocarbon exploration. They contain adequate potential reservoirs, but have a shortage of mature source rocks and structure. The hydrocarbons that may be generated may come from lacustrine source beds and be trapped stratigraphically around the basin margin. This situation is illustrated by the Green River Formation Tertiary basins of Wyoming and Utah (Picard, 1967; Eugster and Surdam, 1973; Surdam and Wolfbauer, 1975).

The second type of intracratonic basin is dominated by carbonate sedimentation. This variation is not due to an underlying structural difference, but rather due to climatic and other factors, and transitions between the two types are present. The Williston and Michigan basins of North America are good examples of carbonate intracratonic basins. The Williston Basin occupies parts of Saskatchewan, Montana, and North Dakota. It has a diameter of some 400 km and contains some 3 km of sediment, ranging in age from Cambrian to Tertiary (Darling and Wood, 1958; Smith et al., 1958; Dallmus, 1958; Harding and Lowell, 1979).

The Paleozoic sequence begins with a basal Cambrian marine shoal sand, followed by largely marine shales and shallow water limestones, with sabkha evaporites and red beds in the Devonian and Lower Carboniferous. A more or less uniform Paleozoic stratigraphy becomes regionally varied in the Mesozoic. Triassic and Jurassic sediments pinch out toward the basin margin, and a major sub-Cretaceous unconformity cuts across earlier rocks down to and including basement. This process plays a major part in the sealing of subcrop truncation traps. More than a kilometer of Cretaceous and Tertiary shales and clastics was then deposited in shallow marine and continental environments (Fig. 8.13). These beds, although not themselves significantly petroliferous, played an important part not only as a seal but also as a blanket cover, which enabled the Paleozoic source shales to mature and generate oil and gas.

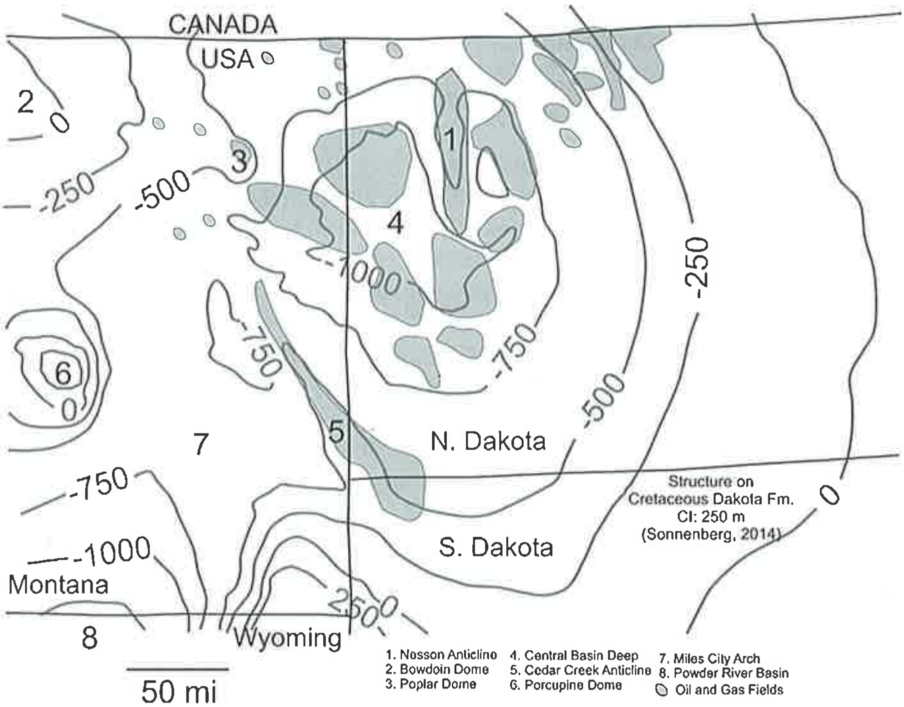

FIGURE 8.13 Structure contour map on the top of the Cretaceous Dakota Formation of the Williston Basin (contours in 250-m intervals). This basin is a good example of a closed intracratonic basin, with a fill of more than 3 km of shallow marine and continental sediments.

The Williston Basin is a major oil province and contains giant oil or gas fields in the Late Devonian—Early Mississippian Bakken Formation. Prior to the Bakken play which started in 2000, it produced oil and gas from numerous relatively small accumulations. The Bakken play production occurs mainly in the basin center. Traps are of three main types: (1) a number of broad regional arches, such as the Miles City arch and Porcupine dome; (2) several positive trends, which are related to basement faults, such as the Cedar Creek and Nesson anticlines; and (3) basin center continuous (discussed in Chapter 9). Warps and faults trend north—south or northwest—southeast. Oil emigrating from the source beds in the deeper part of the basin has been trapped in pre-Cretaceous reservoirs in anticlinal, truncation, and combination traps (structural closure plus unconformity) beneath both the Cretaceous and Jurassic erosion surfaces. The basin center area is a continuous unconventional accumulation in the Bakken and Three Forks formations.

Another good example of an intracratonic carbonate basin is the Michigan Basin to the southeast of the Williston Basin (Cohee and Landes, 1958; Delwig and Evans, 1969; Mesolella et al., 1974). This basin is also subcircular in plan, with a sediment thickness of some 5 km. Unlike the Williston Basin, the section consists largely of Lower Paleozoic rocks, with a veneer of Devonian to Jurassic strata. Facies are largely shallow marine with a basal Cambrian shoal sand overlain by shales, carbonates, and evaporites (Fig. 8.14). Particular

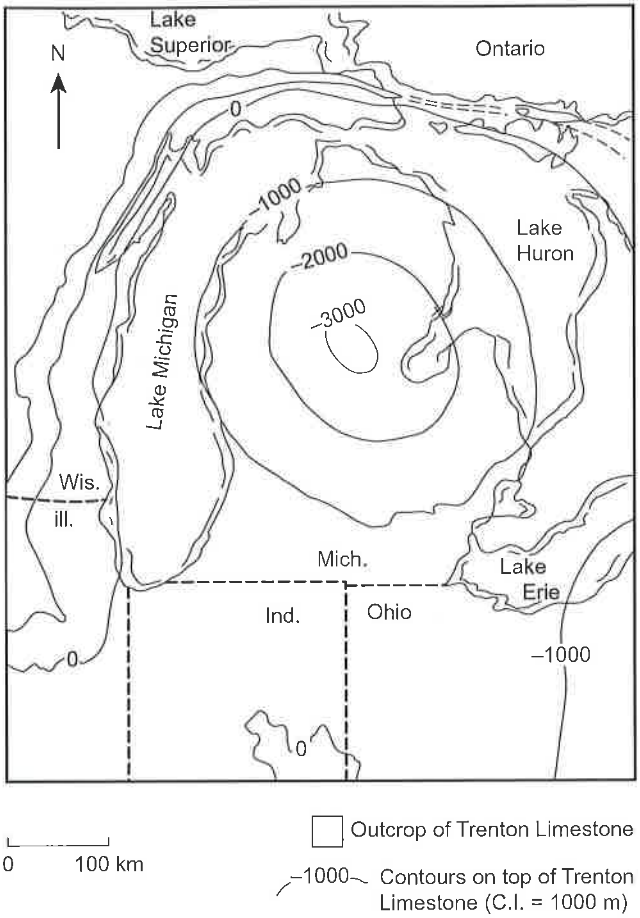

FIGURE 8.14 Structure contour map on the top of the Trenton Limestone (Ordovician) showing the shape of the intracratonic Michigan Basin of the Great Lakes region of North America. *Modified from Cohee and Landes (1958); reprinted by permission of the American Association of Petroleum Geologists.*

interest has centered on the Silurian rocks. These consist of basinal carbonates rimmed by, in turn, pinnacle reefs on the platform slope, a barrier reef, and platform backreef carbonates. This depositional topography was infilled with Upper Silurian evaporites and minor carbonates.

Like the Williston Basin, the Michigan Basin is not a major hydrocarbon province, and does not contain a single known giant oil or gas field. Similarly, however, it contains many hundreds of small oil and gas fields. These are mainly trapped on the myriad pinnacle reefs and on culminations on the concentric barrier reef. Smaller reserves have also been found, ranging from the Ordovician Trenton limestone to the basal Upper Carboniferous (Pennsylvanian) sands.

8.4.2 Epicratonic Embayments

Epicratonic embayments are basins that lie on the edge of continental crust. They are not true closed basins, but plunge toward major oceanic areas floored with basaltic crust. Epicratonic embayments correspond broadly to type II intracontinental composite foreland shelf basins of Halbouty et al. (1970). As with intracratonic basins, a major distinction can be made between dominantly terrigenous and dominantly carbonate-filled embayments. The Tertiary Gulf Coast of the United States and the Niger Delta embayment illustrate a terrigenous basin, and the Sirte embayment of Libya illustrates a carbonate-filled basin.

The Gulf Coast embayment of the southern United States is a major embayment containing some 15 km of sediment (Fig. 8.15). Basement is overlain by the Louann salt of Jurassic age (?) (Murray, 1960; Wilhelm and Ewing, 1972; Antoine, 1974; Dow, 1978). This salt is succeeded by a series of prograding wedges, which range in age from Cretaceous to Recent. Each wedge is composed of a thin up-dip section of fluvial sands, which thickens seaward into deltaic sands and muds. These deltaic sands and muds thin seaward, in turn, into deep marine clays of the Gulf of Mexico. These sediments contain major reserves of oil and gas (21.5 billion barrels of recoverable oil and 17,000 ft^3 of recoverable gas, according to Ivanhoe (1980)). These reserves occur in a series of fairways that become young toward the Gulf (Fig. 8.16). Within each fairway, production occurs where the oil window intersects the breakup zone of interfingering slope mud source beds and deltaic sands. Hydrocarbon generation has been aided by rapid sedimentation and hence overpressuring. This process has resulted in abnormally low geothermal gradients over the gulf depocenter as heat builds up in the "devil's kitchen" far below (Jones, 1969). Within the productive fairways hydrocarbons occur in a variety of traps. These traps include the rollover anticlines associated with the Vicksburg flexure (Section 7.5.1.2), rollover anticlines associated with local growth faults originating in the overpressured clays, and diapiric traps due to both Louann salt domes and younger mud diapirs.

The Niger embayment of West Africa is in many ways analogous to the Mississippi embayment. It, too, plunges from continental to oceanic crust, but the subsidence that initiated sedimentation is clearly related to rifting of the African craton as the Atlantic ocean developed. The embayment merges up-dip into the Benue and Chari rifts, which extend into Niger and Chad (Fig. 8.17). Like the Mississippi, the Niger embayment contains a series of prograding clastic wedges, which range in age from Upper Cretaceous to Recent. Three diachronous formations are recognized: the predominantly fluvial Benin Formation, the deltaic sands and shales of the Agbada Formation, and the slope muds of the Akata Formation (Short and Stauble, 1967; Weber and Daukoru, 1975; Evamy et al., 1978; Avbobo, 1978; Reijers, 1997). Like the Mississippi delta the clays are overpressured, giving rise to growth faults and rollover anticlines, which form the major traps (Section 7.5.1.2). The Niger delta does not show a series of seaward younging productive fairways, although oil and gas are regularly distributed within each major growth fault structural unit. Abnormally low geothermal gradients are again encountered over the depocenter, the top of the oil window rising from some 5 km in the middle to 3 km around the edge. The Mississippi and Niger embayments are both characterized by high gas:oil ratios and waxy low-sulfur crudes. These characteristics probably reflect the high humic content of their kerogen.

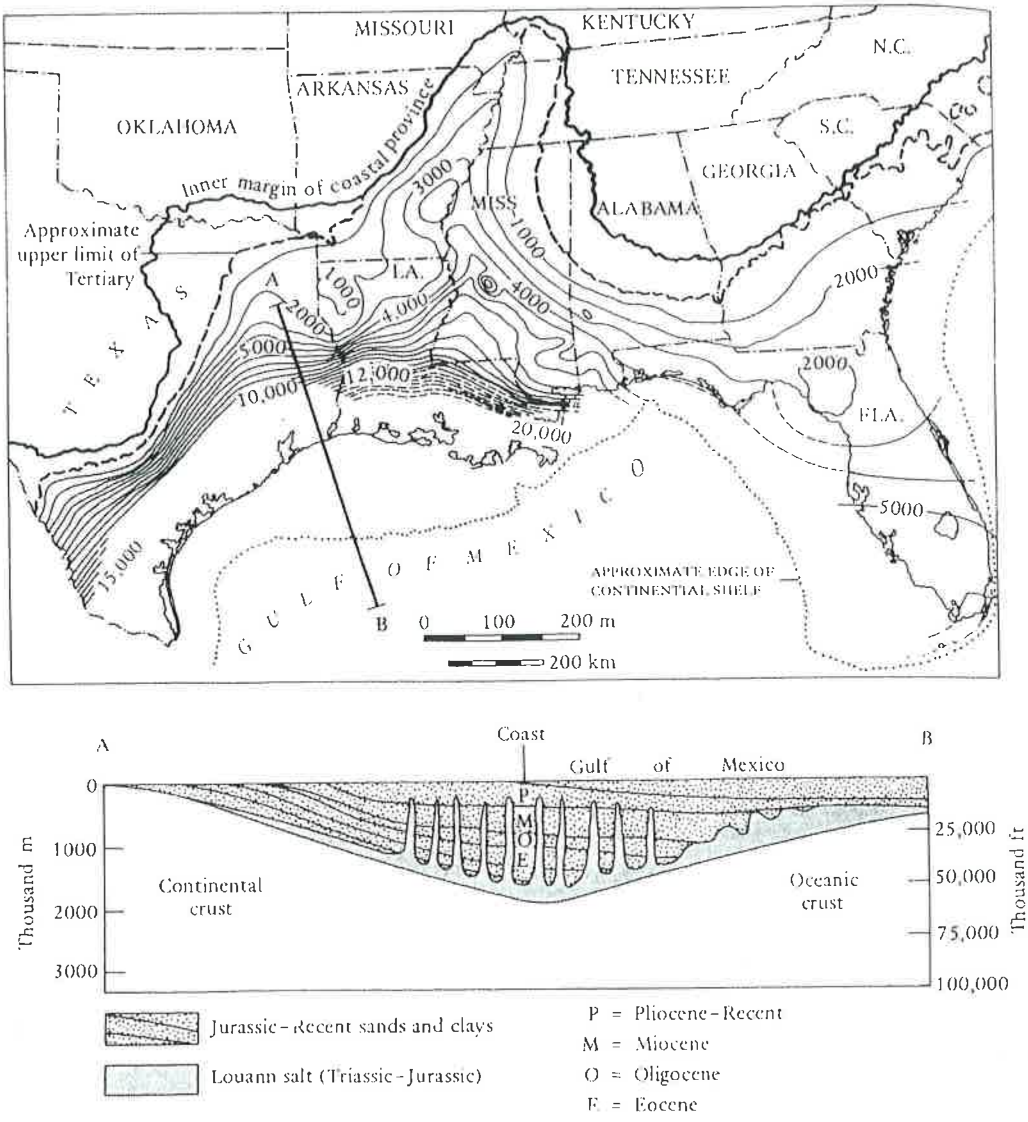

FIGURE 8.15 Map and cross-section of the northern Gulf of Mexico coastal basin. *Modified from Murray (1960); reprinted by permission of the American Association of Petroleum Geologists.*

Many other clastic epicratonic embayments occur around the world, especially in southeast Asia and the Canadian Arctic (Bruce and Parker, 1975). However, few are as well documented and apparently prolific as those just described.

Not all epicratonic embayments are terrigenous; some have a predominantly carbonate fill. The Sirte embayment is an example of this type (Conant and Goudarzi, 1967; Grey, 1971; Salem and Busrewil, 1981; Selley, 1997b). Paleocurrent analysis shows that from the Cambrian

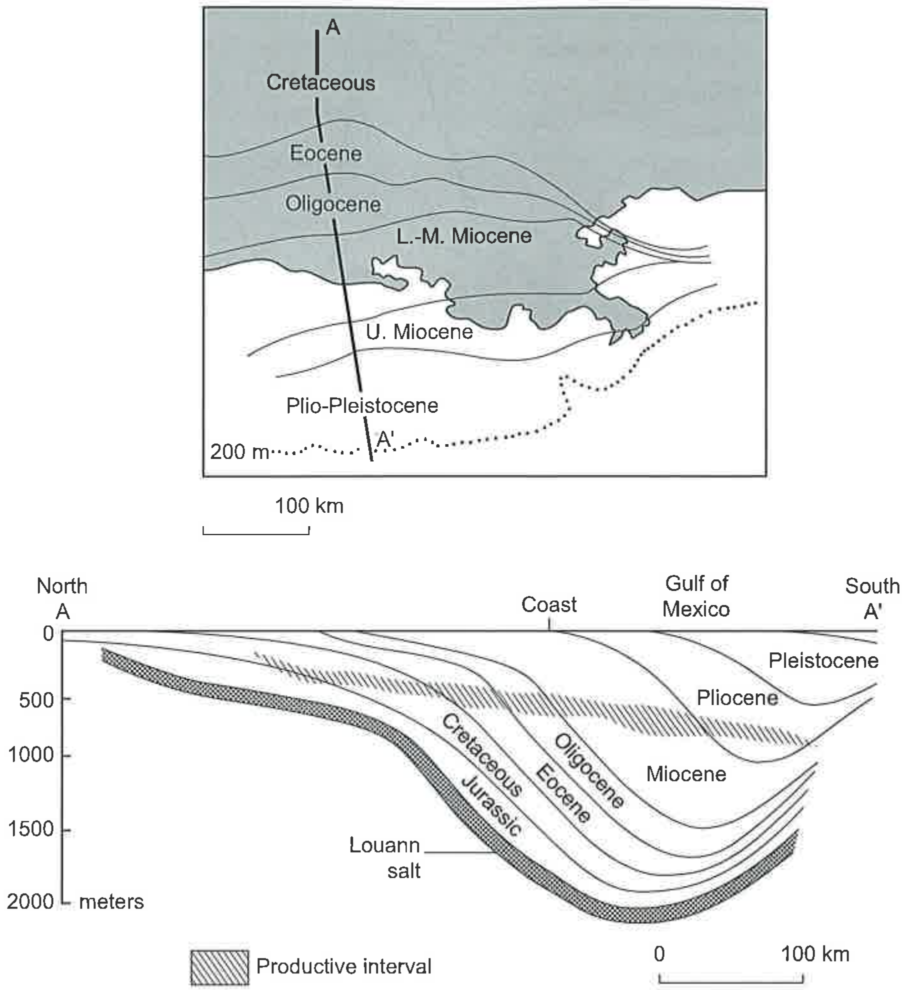

FIGURE 8.16 (Upper) Map showing the productive fairways of the Gulf Coast embayment. (Lower) Cross-section showing the progradational nature of the basin fill and its relation to hydrocarbon production. *Modified from Dow (1978); reprinted by permission of the American Association of Petroleum Geologists.*

to the early Cretaceous the area now occupied by the Sirte embayment was a northerly plunging ridge that separated the Murzuk and Kufra embayments, as they then were. This arch collapsed in the mid-Cretaceous. The Sirte unconformity directly overlies Precambrian basement in the center of the embayment and progressively younger rocks away from the basin axis. A locally developed basal sand is overlain on tilted fault blocks by Upper Cretaceous to Paleocene reefs and, in the troughs, by organic-rich shales that locally onlap and overlie the highs. The Lower Eocene consists of up to a kilometer of interbedded evaporites and carbonates. Carbonate sedimentation continued in the Middle Eocene, to be succeeded by shallow marine and fluvial sands and shales from the Oligocene to Recent (Fig. 8.18).

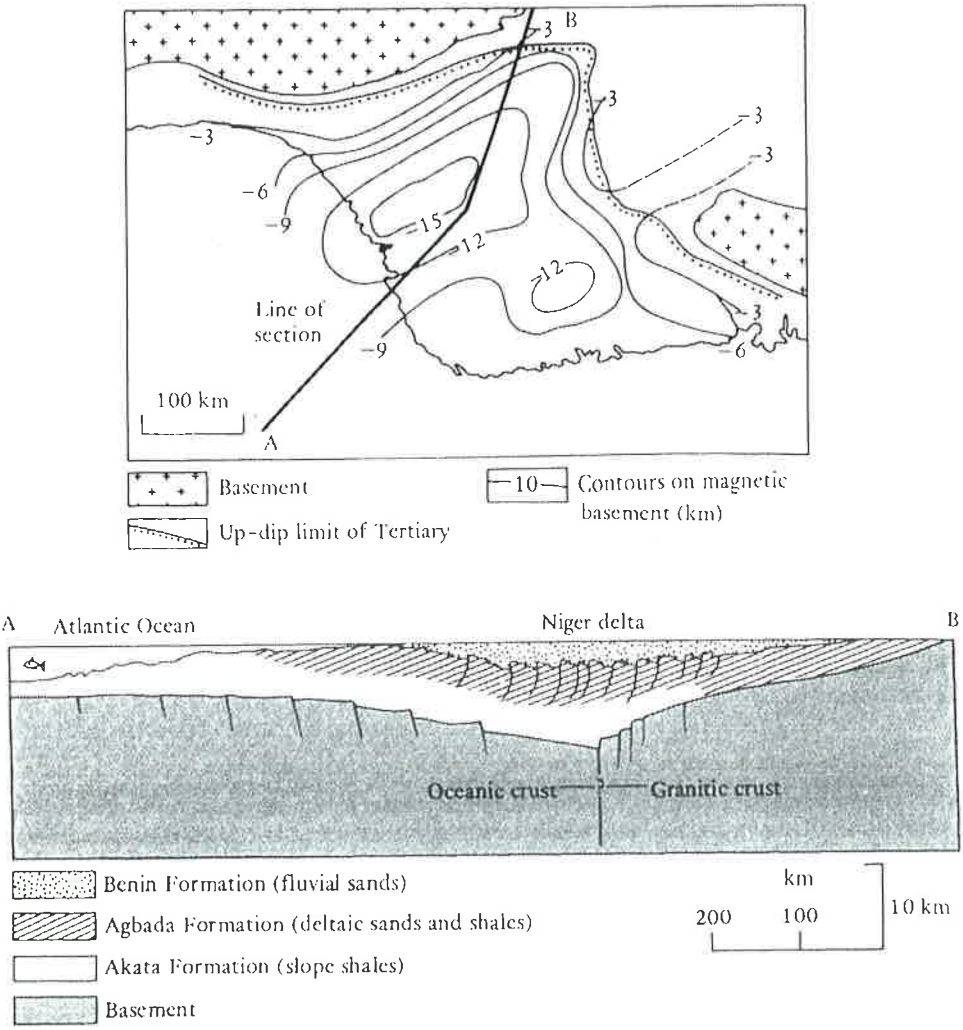

FIGURE 8.17 (Upper) Map of the Niger Delta showing depth to magnetic basement. (Lower) Cross-section along the line A–B. *Modified from Evamy et al. (1978); reprinted by permission of the American Association of Petroleum Geologists.*

The Sirte embayment contains three main productive horizons. Many fields are combination traps on structural highs sealed by the Sirte unconformity. Reservoirs range in age, from Precambrian granite (Aguila) through various sandstones that range in age from Cambrian to Lower Cretaceous (Messla and Sarir). The second and most important play involves production from Upper Cretaceous and Paleocene reefal carbonates on the crests of fault blocks (Zelten, Waha, Dahra, etc.). A third, minor play occurs in the Oligocene sands, where the Gialo field is in the giant category (Fig. 8.19). Overall reserves of the Sirte embayment have been estimated at 30 billion barrels of recoverable oil and 32 trillion cubic feet of gas (Ivanhoe, 1980). It contains more than 13 fields in the giant category (Halbouty et al., 1970).

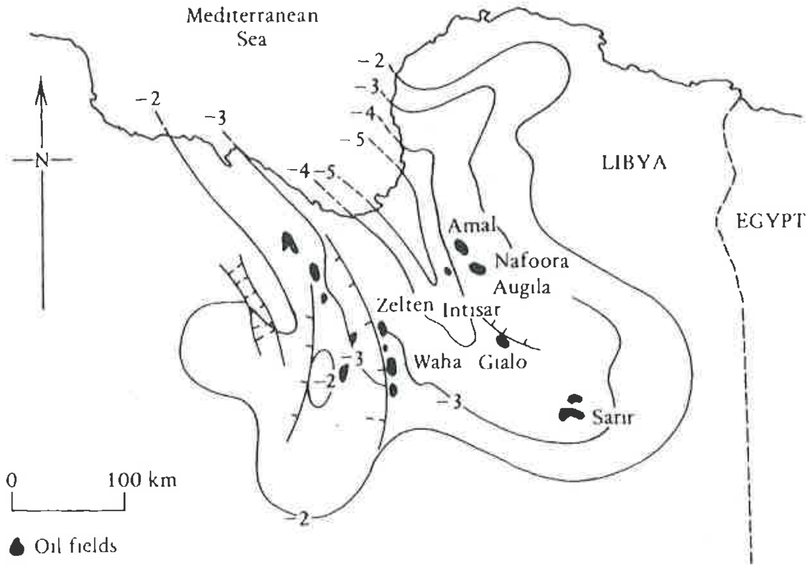

FIGURE 8.18 Map of the Sirte embayment showing distribution of oil fields (black) and structure contours (kilometers) on the Sirte unconformity (pre-Upper Cretaceous). *Modified from Sanford (1970); reprinted by permission of the American Association of Petroleum Geologists.*

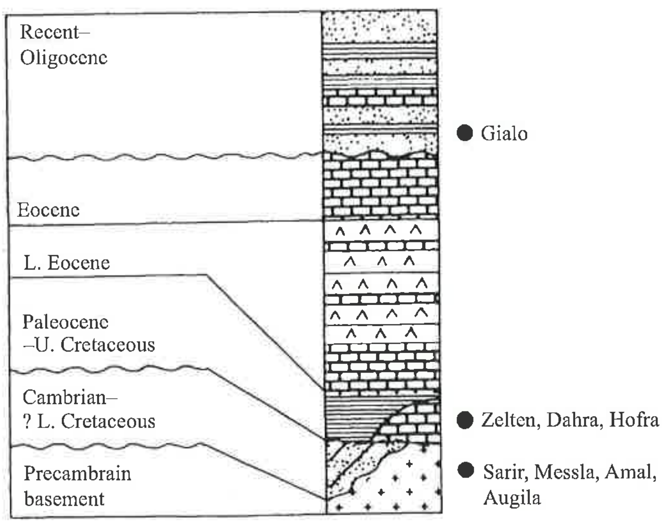

FIGURE 8.19 Summary stratigraphy of the Sirte embayment showing the main reservoir formations. The Upper Cretaceous–Paleocene shales provide the main source rock.

These three types of subduction zone may form part of an evolutionary sequence in which an ocean closes as plates of oceanic crust converge, finally resulting in the juxtaposition of continental crustal blocks. Figure 8.20 illustrates these different types of subduction zones. Note the change in terminology: back-arc, arc, and fore-arc broadly correspond to the old miogeosyncline, geanticline, and eugeosyncline, respectively.

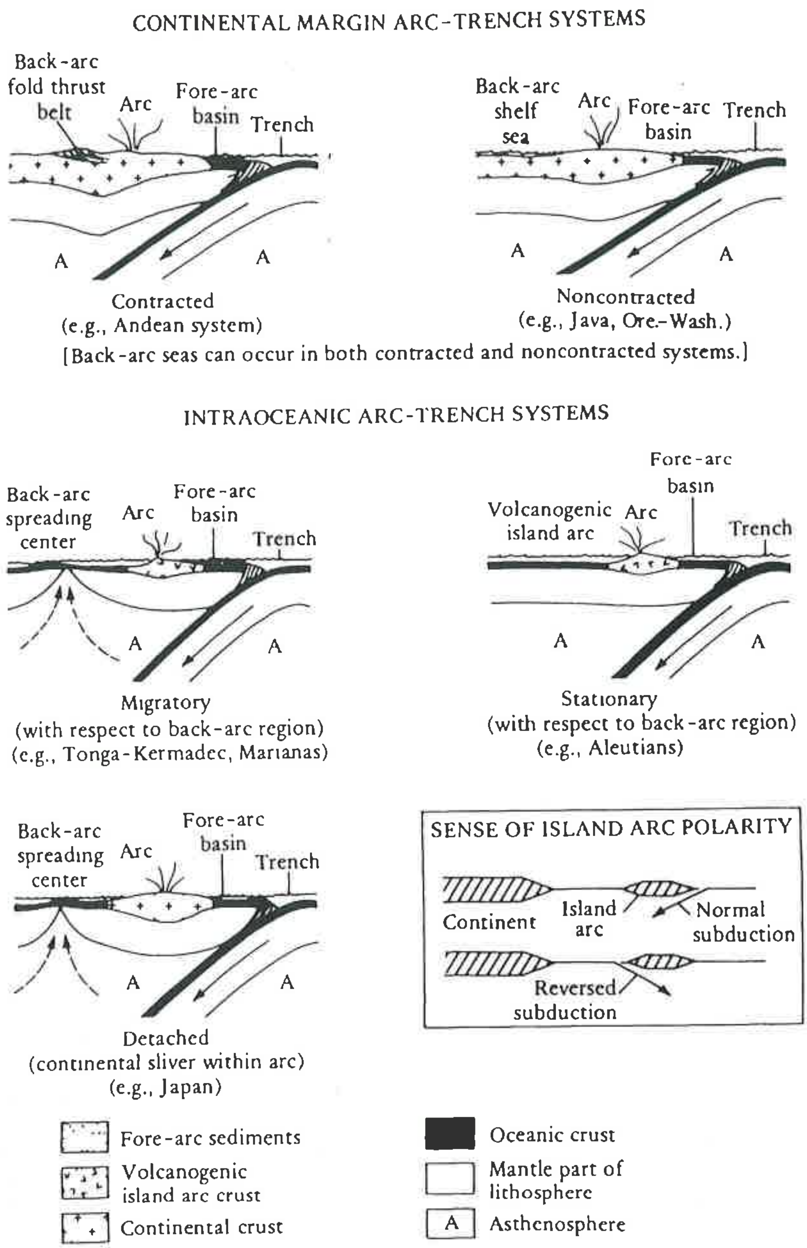

FIGURE 8.20 Cross-sections illustrating the various types of zones of subduction and their associated sedimentary troughs. *From Dickinson and Seely (1979), namely Fig. 1, p. 4.*

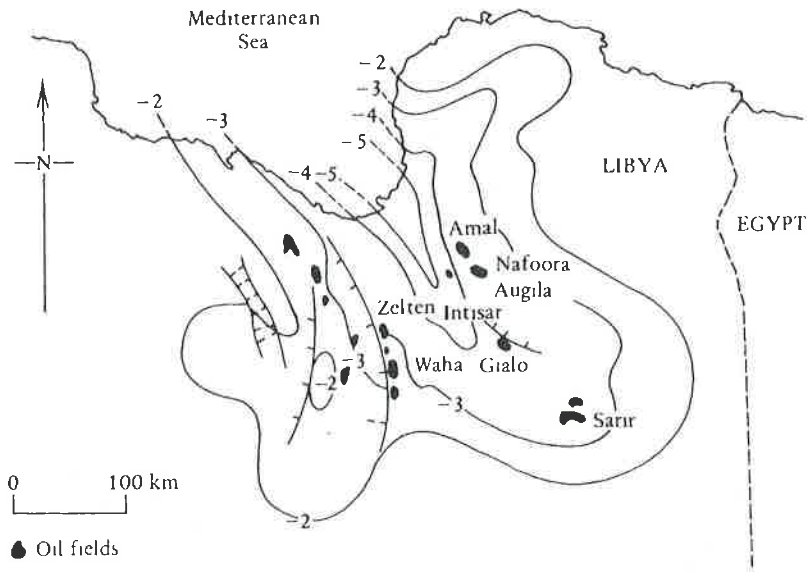

FIGURE 8.18 Map of the Sirte embayment showing distribution of oil fields (black) and structure contours (kilometers) on the Sirte unconformity (pre-Upper Cretaceous). *Modified from Sanford (1970); reprinted by permission of the American Association of Petroleum Geologists.*

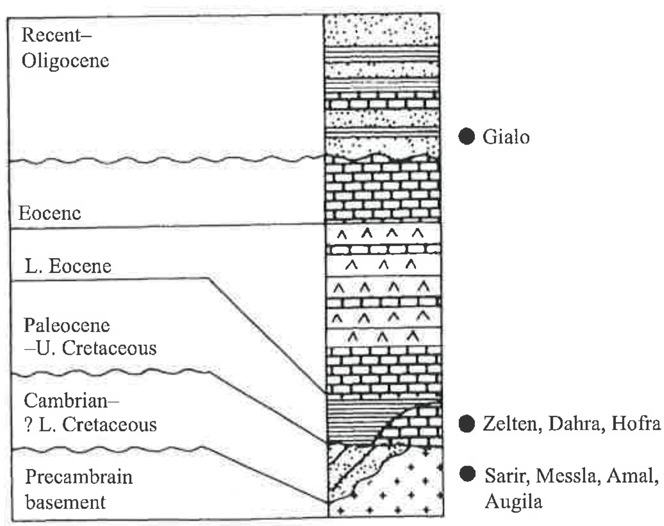

FIGURE 8.19 Summary stratigraphy of the Sirte embayment showing the main reservoir formations. The Upper Cretaceous–Paleocene shales provide the main source rock.

This review of epicratonic embayments shows that they are far more prospective than intracratonic basins. This statement is true of both terrigenous and carbonate embayments. Not only do they contain more marine sediments and, therefore, better source potential but they also occur where continental crust is thinner and less stable. Thus heat flow is high, which favors hydrocarbon generation in areas of high geothermal gradients due to overpressure. Crustal instability also favors structural entrapment of oil, as well as stratigraphic (reefal) unconformity and growth-fault-related traps.

8.5 TROUGHS

8.5.1 Geosynclines and Plate Tectonics

The second major type of basin to consider is the troughs. These are linear basins far larger and far more complex in structure and facies than the basins discussed thus far. These troughs were long termed *geosynclines*, a concept defined by Hall (1859) and elaborated on by a series of workers, including Dana (1873), Haug (1900); Schuchert (1923), Kay (1944,1947), and Glaessner and Teichert (1947), before reaching its apotheosis in the mighty work of Aubouin (1965). At that time—the dawn of the plate tectonic revolution—the concept of the geosyncline could be summarized as follows. Geosynclines consist of two parallel troughs. One, the miogeosyncline, which lies on continental crust and consists of an oceanward-thickening wedge of shallow marine limestones, sandstones, and shale. This trough is separated from the second trough, the eugeosyncline, by the miogeanticlinal ridge. The eugeosyncline is deeper than the miogeosyncline and is infilled largely by deep-water sediments. Initially, these sediments may be bathyal muds, but as the geosyncline evolves, turbidite sands infill it from a rising arc of islands on its oceanward side. This wedge of clastics has been referred to as *flysch* (Hsu, 1970). Compression of the flysch trough is accompanied by igneous intrusion, regional metamorphism, folding, and thrusting. Each phase of compression, or orogenesis, initiates isostatic adjustment, causing the sediments of the trough to rise and form a mountain chain. The adjacent miogeosyncline persists and is filled by a postorogenic wedge of predominantly continental sediments, referred to as molasse (Van Houten, 1973). This process, the classic geosynclinal cycle, was epitomized for European geologists by the Alps, in which it was easy to envisage the mountains being formed from a trough of sediments squeezed between the European and African cratons. Continental margin geosynclines, like the Appalachians, were harder to envisage, since one side of the vice was apparently absent. With the development of the concepts of sea floor spreading and crustal subduction, geologists rapidly reappraised classic geosynclinal theory (Ahmad, 1968; Mitchell and Reading, 1969; Coney, 1970; Schwab, 1971; Reading, 1972). Geosynclines are now interpreted as zones of subduction where plate boundaries converge, and the term has fallen into disuse.

There are three types of subduction zones. One type occurs between areas of continental crust, as, for example, in the Alps, Zagros, and Himalayas. In the second type the trough develops at the boundary between oceanic and continental crust. The Cordillera of North America, the Andes, and the Banda Arc of Southeast Asia illustrate this type. The third type is where subduction occurs between two plates of essentially oceanic crust, as, for example, in the Japanese and New Zealand arcs.

These three types of subduction zone may form part of an evolutionary sequence in which an ocean closes as plates of oceanic crust converge, finally resulting in the juxtaposition of continental crustal blocks. Figure 8.20 illustrates these different types of subduction zones. Note the change in terminology: back-arc, arc, and fore-arc broadly correspond to the old miogeosyncline, geanticline, and eugeosyncline, respectively.

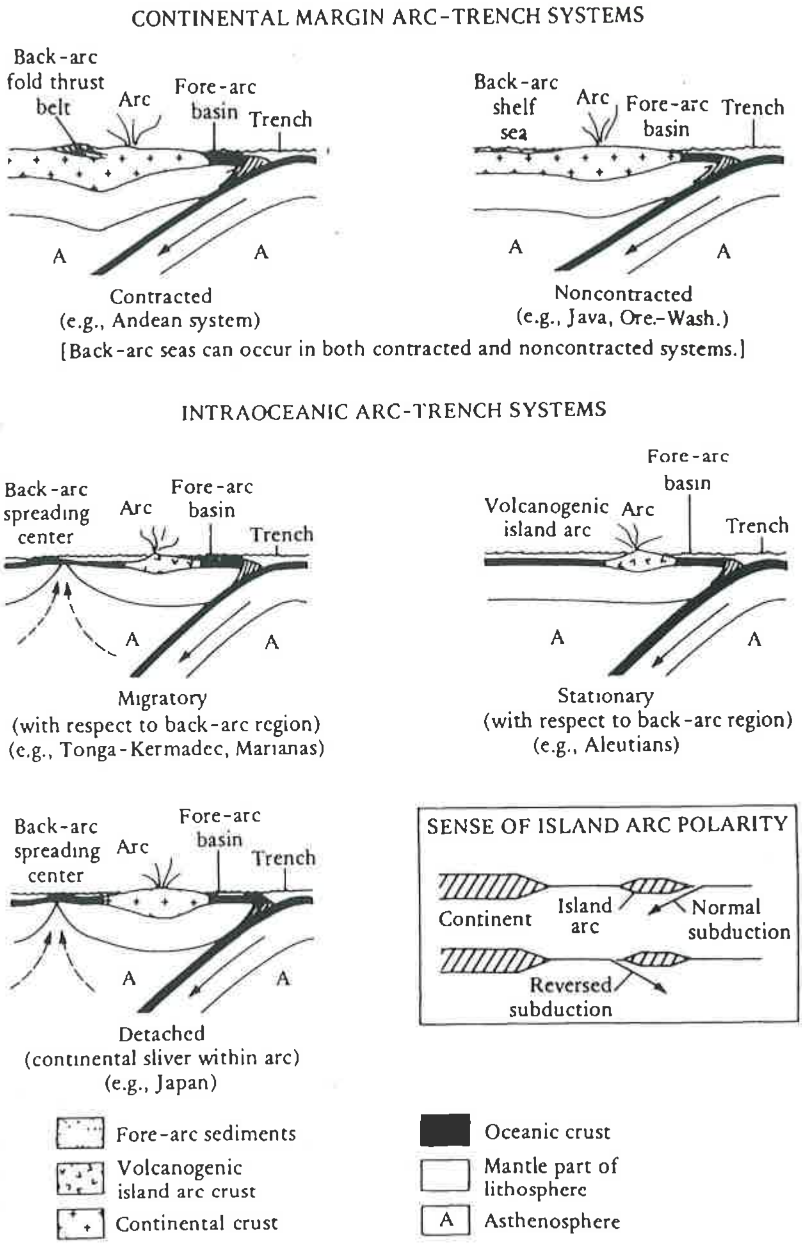

FIGURE 8.20 Cross-sections illustrating the various types of zones of subduction and their associated sedimentary troughs. *From Dickinson and Seely (1979), namely Fig. 1, p. 4.*

This later reinterpretation of sedimentary troughs has been complicated by the fact that some troughs that should theoretically be zones of subduction actually contain rifts with flat-lying sediments, which suggests a lack of compression, if not tension. The Peruvian trench is one such embarrassing example (Scholl et al., 1968). This phenomenon has led to the idea that plate movement may occasionally reverse, so that subductive zones become divergent, albeit for intermittent periods. The Alps have been interpreted in such a way by Wilson (1966, 1968), as shown in Fig. 8.21.

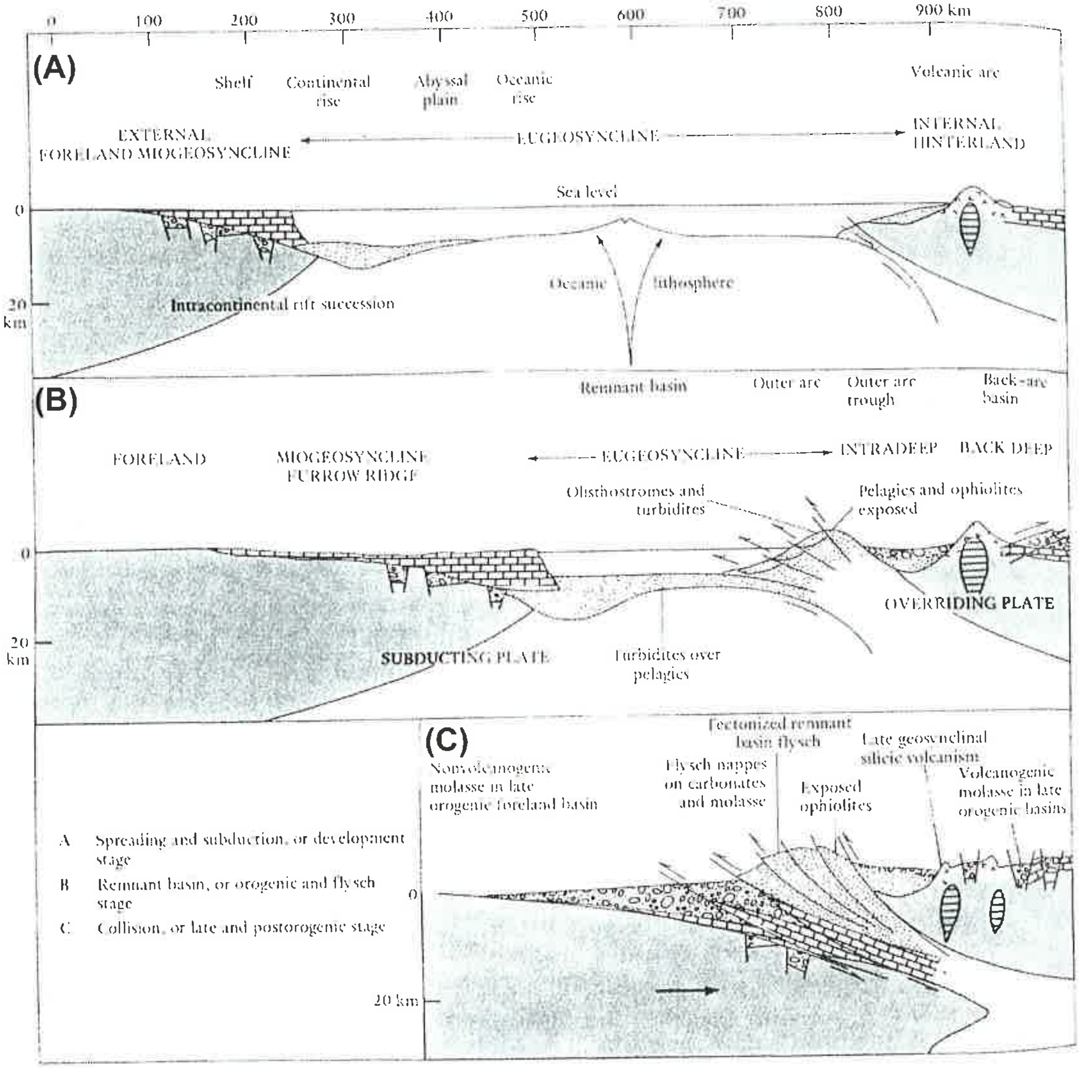

FIGURE 8.21 Cross-sections illustrating Wilson's (1968) interpretation of the evolution of the Alps. An original sea-floor-spreading phase (A) reverses to become a zone of subduction (B), leading to the collision of continental plates (C). *After Mitchell and Reading (1978), with permission from Blackwell Science Ltd.*

8.5.2 Back-Arc Troughs

The complexity of facies, structure, and history makes it difficult to generalize about the petroleum potential of subductive troughs. Consider first the back-arc, or miogeosynclinal, troughs. These troughs are asymmetric shelves whose sediments thicken toward the arc. This type of basin can also be regarded as an elongated epicratonic embayment and is more or less synonymous with Klemme's extracontinental downwarp. The deposits of these basins are largely shallow marine shales, carbonates (often reefal), and mature tidal shelf sands, with perhaps a feather edge of nonmarine sediments. Between major subductive phases, extensive source rocks may be deposited along the basin's seaward margin. Orogenic movements leave these back-arc basins terminated on their outer side by a thrust belt.

The Arabian Gulf, Sumatra, and Western Canada illustrate this type of basin. A map and cross-section of the Arabian Gulf is shown in Fig. 7.8. For further details see Kamen-Kaye (1970) and Murris (1980,1981).

Figure 8.22 illustrates the salient features of the Western Canada Basin. This basin contains a wedge of sediments that thickens westward to some 5 km until it is abruptly truncated by the Rocky Mountain thrust belt. The earlier Paleozoic sediments include sands, carbonates (with spectacular Devonian reefs), organic-rich shales, and evaporites. Major oil and gas production occurs in the Devonian reefs (Illing, 1959; Barss et al., 1970; Evans, 1972; Klovan, 1974) and in the Viking and Cardium (Cretaceous) shallow marine sands. Recoverable reserves are estimated at 16.3 billion barrels of oil and 94 trillion cubic feet of gas (Ivanhoe, 1980).

The source of terrigenous detritus is important in basins such as the Western Canada Basin. For most of the time the sands are produced by the slow weathering of the craton, followed by extensive reworking and deposition mainly in high-energy marine environments. These sands are thus mineralogically and texturally mature and have good porosity and permeability. As the arc rises, however, it begins to shed detritus into the back-arc basin. These later sands are often mineralogically immature, especially if derived from volcanic rocks. Rapidly deposited in fluviodeltaic environments, their mineralogical and textural immaturity may render them poorer reservoirs than the earlier shelf-derived sands.

Southeast Asia provides another example of back-arc basins and their relationship to fore-arc basins and plate boundaries (Schuppli, 1946; Haile, 1968; Crostella, 1977; Ranneft, 1979; Bowen et al., 1980; Wood, 1980). Here the continental crust of the Sunda Shelf moves westward toward the Indian Ocean plate, forming a convergent subductive plate boundary. Simultaneously, northward movement of the Australian plate is causing subduction on the southern margin of the Sunda plate. A number of back-arc basins separate the shelf from a volcanic arc (Fig. 8.23). These basins are infilled with a series of Eocene–Recent prograding clastic wedges in the Sumatra and Borneo basins and with carbonates over the more stable southeastern part of the shelf. These basins contain more than 10 fields with recoverable reserves in excess of 8 billion barrels of oil and 24 trillion cubic feet of gas (St. John, 1980). The back-arc basins are separated from the fore-arc basins by a volcanic arc. The latter are infilled with marine sediment, derived largely from the volcanic arc. The fore-arc basins are gradually being subducted between the Indian and Sunda plates. Thrust slices thus appear locally as an outer nonvolcanic island arc (e.g., the Andaman and Nicobar Island chains). Hydrocarbon production from the fore-arc basins is negligible for several reasons,

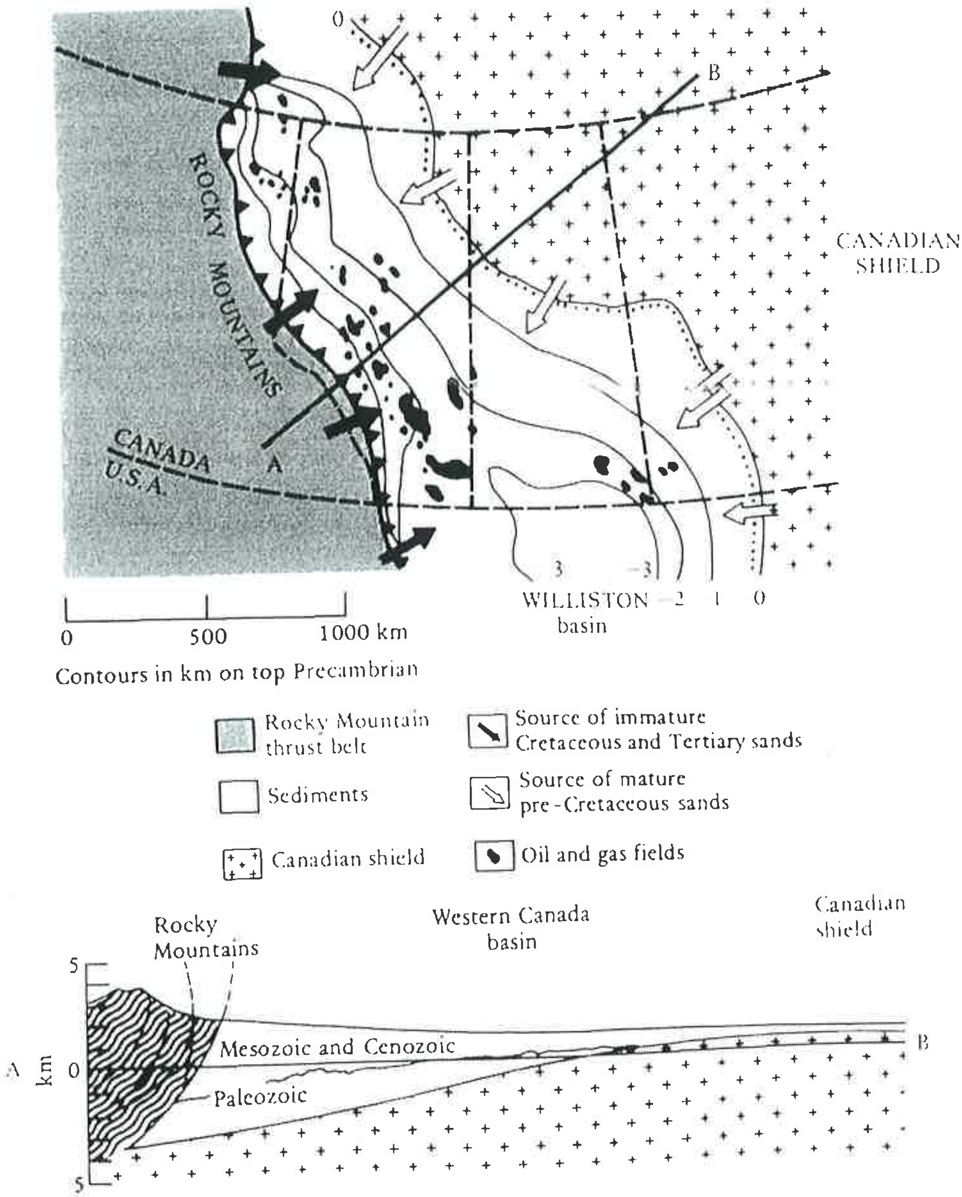

FIGURE 8.22 Map and cross-section of the Western Canada (Alberta) trough, a major hydrocarbon province in a back-arc setting.

including the volcaniclastic nature of the sediments, which causes poor porosity preservation. Geothermal gradients are low and structure complex (Kenyon and Beddoes, 1977).

Back-arc basins have a good potential for favorable source rock sedimentation. An extensive marine shelf can have clay blankets deposited during marine transgressions. When these

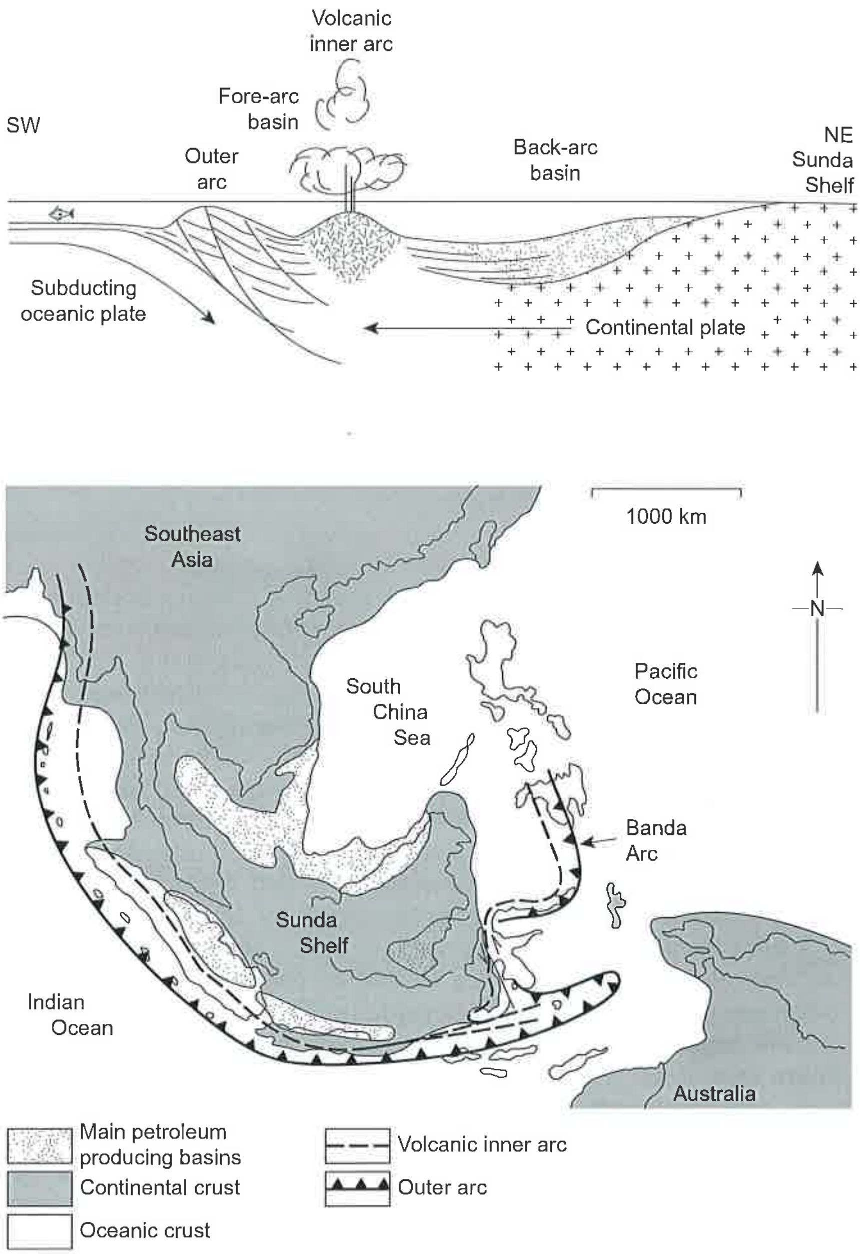

FIGURE 8.23 Cross-section and map of Southeast Asia showing the relationship between fore-arc and back-arc troughs. The back-arc troughs are the main oil-producing basins. *After Haile (1968), Crostella (1977), Ranneft (1979), Bowen et al. (1980), Wood (1980).*

clay blankets coincide with uplift of the arc to form a barrier, restricted anaerobic conditions may occur because of poor circulation. The Cretaceous shales that were deposited in the great seaway extending from the Arctic to the Gulf of Mexico in the back-arc basins of the Rocky Mountains illustrate this point.

Traps in back-arc basins are numerous and varied. Classic anticlines may develop adjacent to the mountain front, as was already discussed in connection with Iran (Section 7.6.1.1). Traditionally, the thrust belts have been ignored in hydrocarbon exploration, both because of possible poor prospects and because of problems of seismic acquisition and interpretation. With improved technology, however, thrust belt exploration is increasing, as, for example, in the Appalachians, the Rockies, and the Alps (see McCaslin (1981), Anonymous (1980), Bachmann (1979); respectively). Away from the thrust belt, entrapment may be stratigraphic, including reef and shoestring sand plays as well as onlap and truncation traps. Fairways for these prospects may parallel the basin margin or form halos around regional arches.

With this combination of favorable reservoir rocks, source rocks, and trap diversity, it is not surprising that back-arc basins are commonly major hydrocarbon provinces.

8.5.3 Fore-Arc Troughs

In contrast with back-arc basins, fore-arc basins are more complex in structure and facies. They are therefore more diverse in the nature and extent of their petroleum productivity. The fore-arc basins of the northeast Indian Ocean have already been noted. Dickinson and Seely (1979) have given a detailed analysis of fore-arc basins and have reviewed their petroleum potential. Figure 8.24 shows the basic structural elements of a fore-arc. Terrigenous sediments may be deposited in the trough in a wide range of environments, ranging from continental to deep marine. Initially, sands are derived from the igneous rocks of the volcanic arc. They thus tend to be mineralogically immature and lose porosity rapidly upon burial. Dickinson and Seely note that fore-arcs may have shelved, sloping, terraced, and ridged topographies. Broad shelves enable sands to mature, both mineralogically and texturally, before deposition. Narrow shelves, by contrast, favor rapid sedimentation of immature sand with minimal reworking. As the oceanic plate subducts, wedges of fore-arc sediments are thrust up to form an outer nonvolcanic island arc. This arc will be composed of the distal edge of the fore-arc sedimentary prism, which is largely made up of ocean floor deposits. These thrust slices thus contain metamorphosed serpentinites, cherts, pelagic limestones, and turbidites. As this outer arc rises, it too will shed sediment into the fore-arc trough. The mineralogical immaturity and rapid sedimentation of these sands may diminish their reservoir quality, as was the case for those derived from the volcanic arc.

Fore-arc basins make less productive hydrocarbon provinces than do back-arc basins. As just described, sands are generally of poorer quality, lacking the polycyclic and reworked history of back-arc sediment. Carbonate reservoirs are generally absent.

Source rocks may be abundant and of good quality because of the prevalence of deep and often restricted sea floor conditions. However, locating the main area of oil generation may be difficult. Geothermal gradients are often low in fore-arcs because the cool sediment is subducted, which depresses the isotherms. Those hydrocarbons that are generated are more commonly trapped in structural fold and fault traps than in stratigraphic ones. Extensive structural deformation may cause traps to be small and hard to develop.

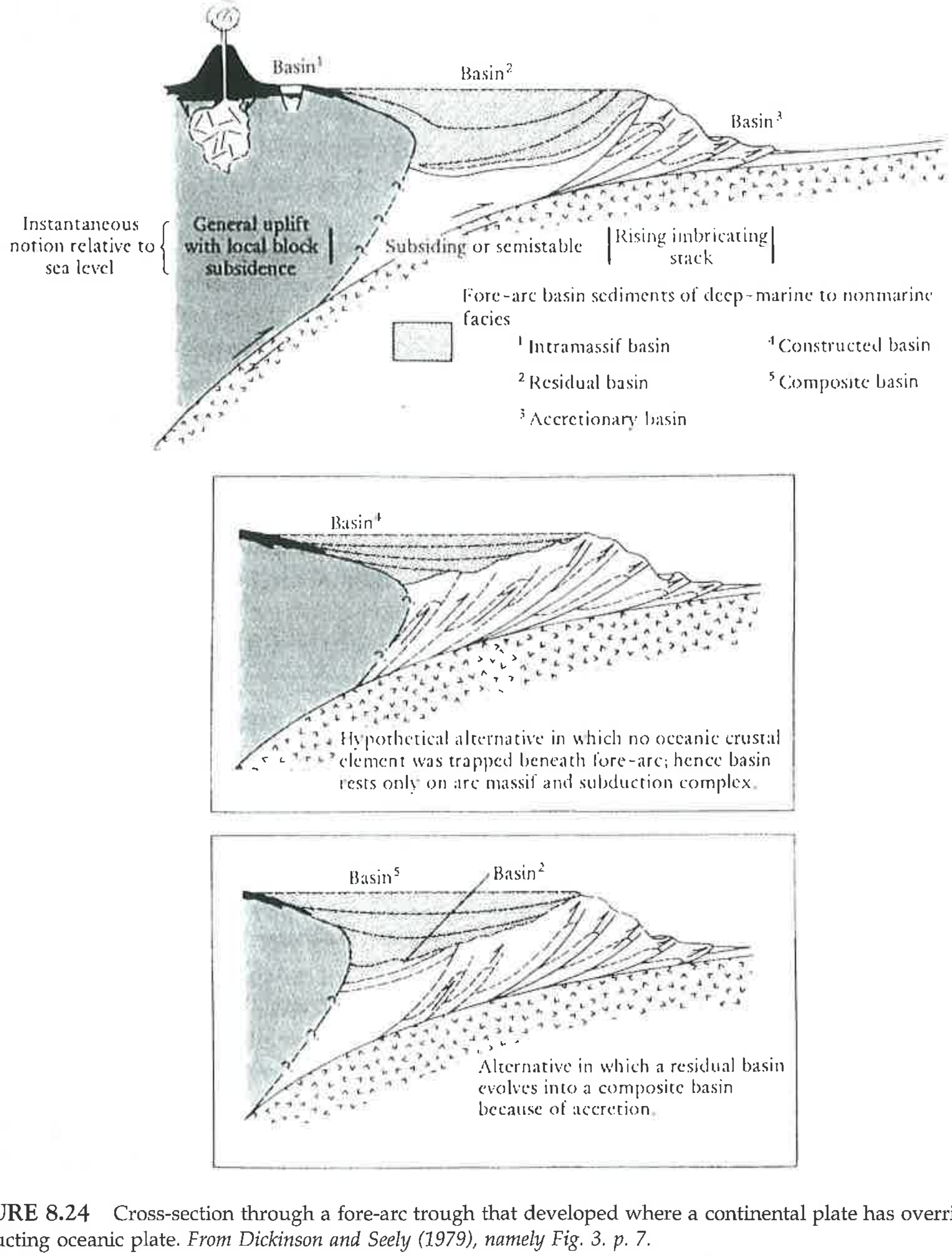

FIGURE 8.24 Cross-section through a fore-arc trough that developed where a continental plate has overriden a subducting oceanic plate. *From Dickinson and Seely (1979), namely Fig. 3. p. 7.*

Those fore-arc basins that are productive tend to have fairways on their continental side and to have had broad shelves. The Cook Inlet Basin of Alaska and the Peru coastal basin are examples of productive fore-arc basins with giant fields (Magoon and Claypool, 1981). The Kenai field in the Cook Inlet has more than 5 million cubic feet of recoverable gas. The La Brea, Parinas, and Talara fields of Peru have aggregate reserves of 1.0 billion barrels of recoverable oil (St. John, 1980).

Thrust belts, themselves, used to be avoided in petroleum exploration because of the problems of interpreting seismic data in areas of structural complexity, and also because reservoirs were not anticipated beneath metamorphic nappes. The first problem has largely been resolved with the help of modern high-resolution seismic surveys. The second problem is now known to be a misconception in many cases. Petroleum exploration in the thrust belts of the Alps, the Rocky Mountains, and the Appalachians has been rejuvenated in recent years. In all these areas wells have penetrated metamorphic nappes and encountered sediments with potential reservoirs and remarkably low levels of kerogen maturation (Anonymous, 1980; Lamb, 1980; Bachmann et al., 1982; Picha, 1996; Wessely and Liebl, 1996).

A specific famous example of this occurrence is the Vorderiss No. 1 well, in Austria. This well penetrated nappes with R_o values of up to nearly 2.0, before drilling through to sub-nappe sediments with R_o values of 0.5–0.6 at depths of some 5 km (Bachmann, 1979). Thrust belts are thus explored with more vigor today than in the past.

8.6 THE RIFT-DRIFT SUITE OF BASINS

A rift basin is bounded by a major fault system. Symmetric rifts, or grabens, are bounded by two sets of faults; asymmetric rifts, or half-grabens, are bounded by one set of faults. The introduction to this chapter discusses how rifts characteristically occur along the crests of regional arches on continental crust and along the crests of the midoceanic ridges, which are axes of sea floor spreading. Asymmetric rift, or half-graben, basins occur along the edges of many continents, notably those that border the North and South Atlantic Oceans. The concept of plate tectonics shows how all these basins are genetically related in what may be termed the rift-drift suite. This concept is described in its evolutionary sequence in the following section.

8.6.1 Rifts

Rifts occur today along the midoceanic ridges, which are now interpreted as zones of sea floor spreading. These rifts are formed in response to tension in the crust as the plates separate. The resultant troughs are infilled with basaltic lavas interbedded with pelagic clays, limestones, and cherts. Because of their fill and geographic location, the rift basins of midocean ridges are not attractive areas for hydrocarbon exploration.

A number of rift basins occur on continental crust, including the Rhine Valley of Germany and the Baikal rift of Russia (Illies and Mueller, 1970; Salop, 1967). Both of these basins crosscut areas of arched crust and show a tendency to radiate into minor rifts at both ends of the main rift. They are infilled with up to 5 km of sediment and have igneous extrusives associated with them (Fig. 8.25). Equally well known, and in many ways similar, are the great rift valleys of Africa. Central Africa is now known to be crossed by rifts that, extending inland

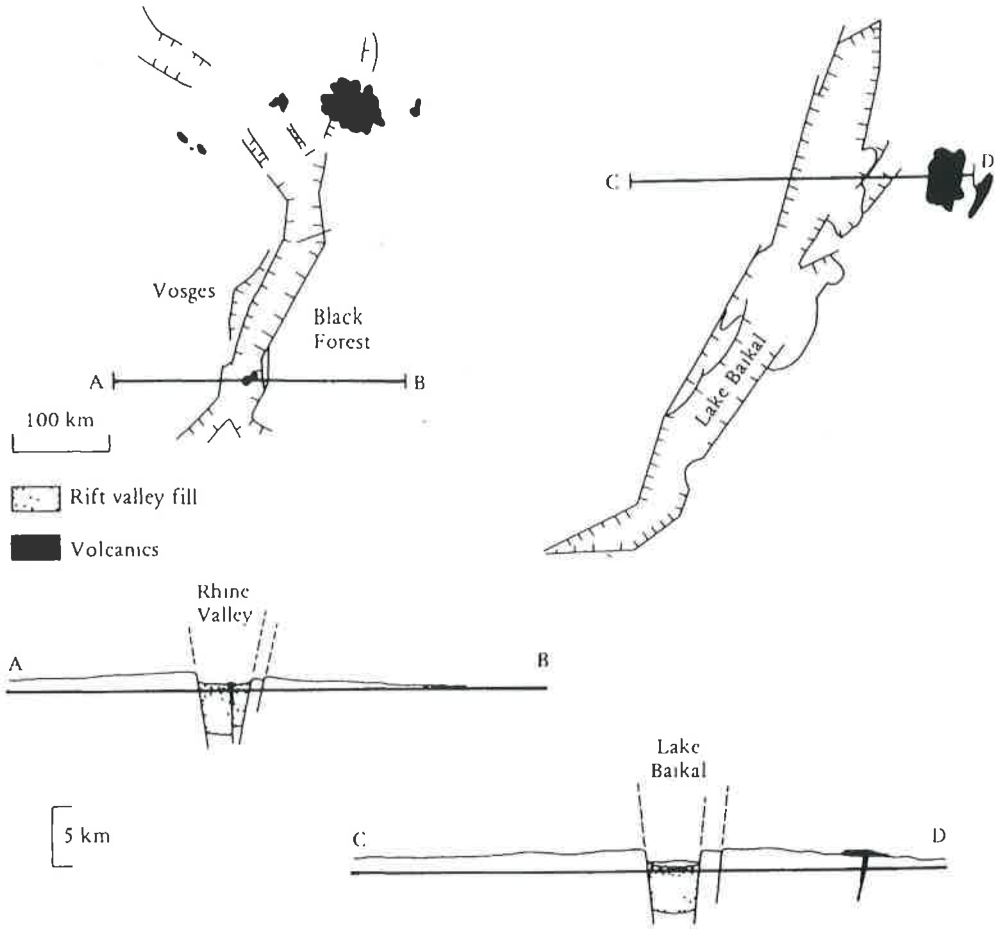

FIGURE 8.25 Maps and cross-sections of the Rhine rift of Germany (left) and the Lake Baikal rift of the Soviet Union (right). *After Selley (2000).*

from Nigeria, Mozambique, and Somalia, intersect in Sudan, Chad, and Niger. These rifts are of Cretaceous and early Tertiary age. Largely blanketed by younger sediments, they have only recently become known as a result of petroleum exploration in these countries. More conspicuous is a series of younger rifts that occur in eastern Africa (Unesco, 1965; Baker et al., 1972; Darrcott et al., 1973; Veevers, 1981). These rifts are very similar to the Rhine and Baikal rifts. They show crustal doming with local reversal of drainage. Major rifts bifurcate at their terminations, are volcanically and seismically active, and are infilled with volcanic, fluvial, and lacustrine sediments of Miocene to Recent age. As rifts are traced northeastward toward the Omo Depression on the Ethiopian coast of the Red Sea, rift initiation began earlier (Eocene), basaltic lava outpourings are more extensive in time and space, and the sediments include extensive evaporite deposits (Fig. 8.26).

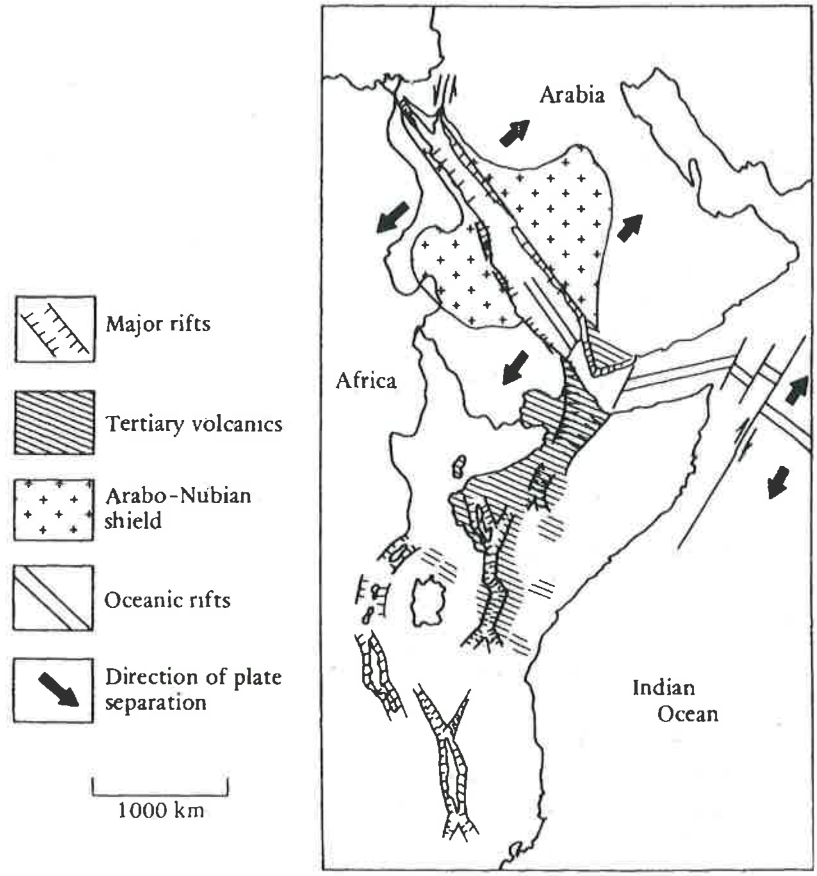

FIGURE 8.26 Map of East Africa and Red Sea area illustrating the transformation from intracratonic rifts in the south to oceanic rifts in the north.

The Red Sea is itself a complex rift that provides a genetic link between the intracratonic rifts just discussed and the ocean margin rifts (Heybroek, 1965; Lowell and Genik, 1972; Lowell et al., 1975; Thiebaud and Robson, 1979). The margins of the Red Sea are two parallel-sided half-grabens, whose major faults downthrow seaward. On the upthrown sides of the faults the granites of the Arabo-Nubian shield crop out with occasional veneers of basaltic lavas (Fig. 8.27). Within the coastal basins Paleozoic Nubian sandstones and Cretaceous and Eocene limestones are locally truncated on numerous fault blocks. This horst and graben floor to the coastal basins is onlapped by Miocene evaporites, reefal limestones, and younger sands. Many oil fields have been discovered in Tertiary carbonates and sandstones and in Nubian sandstone reservoirs in the fault blocks of the Gulf of Suez (Fig. 8.28).

The deeper central part of the Red Sea consists of basaltic oceanic crust with a veneer of young deep marine deposits. It contains a longitudinal axial rift, which can be traced, offset by many transform faults, into a midoceanic rift in the Indian Ocean. The Red Sea thus

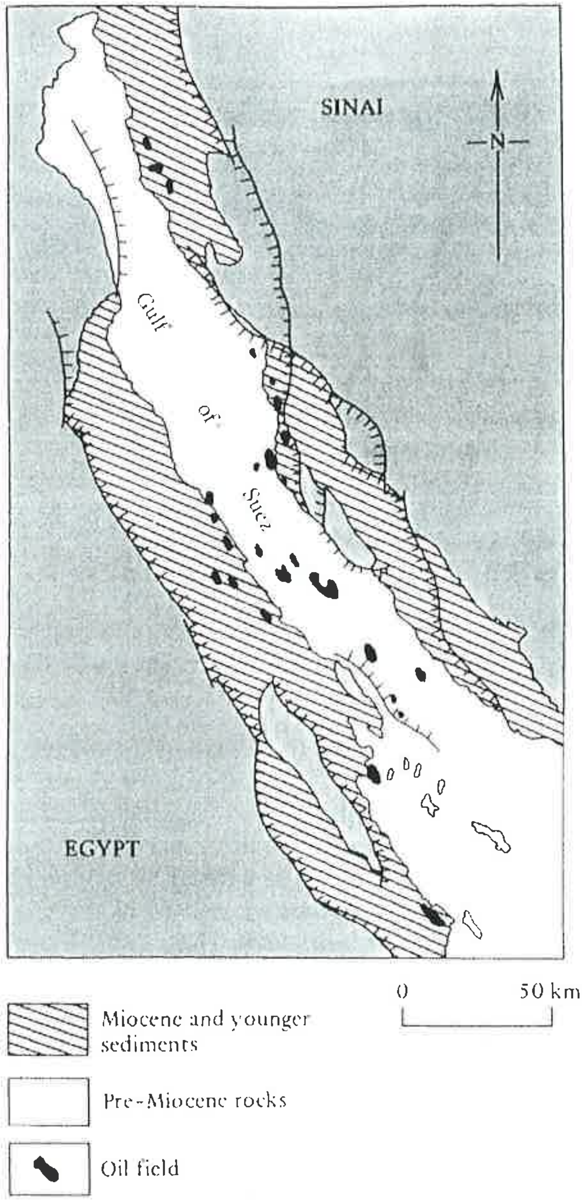

FIGURE 8.27 Map of the Gulf of Suez rift basin showing location of faults and oil fields. *After Thiebaud and Robson (1979).*

provides the link between the intracratonic rifts of East Africa and the oceanic rifts of the mid-ocean ridges. The Red Sea may be regarded as an incipient ocean basin in which a rift in the Arabo-Nubian shield separated into two half-graben basins, between which new oceanic basaltic crust is now forming.

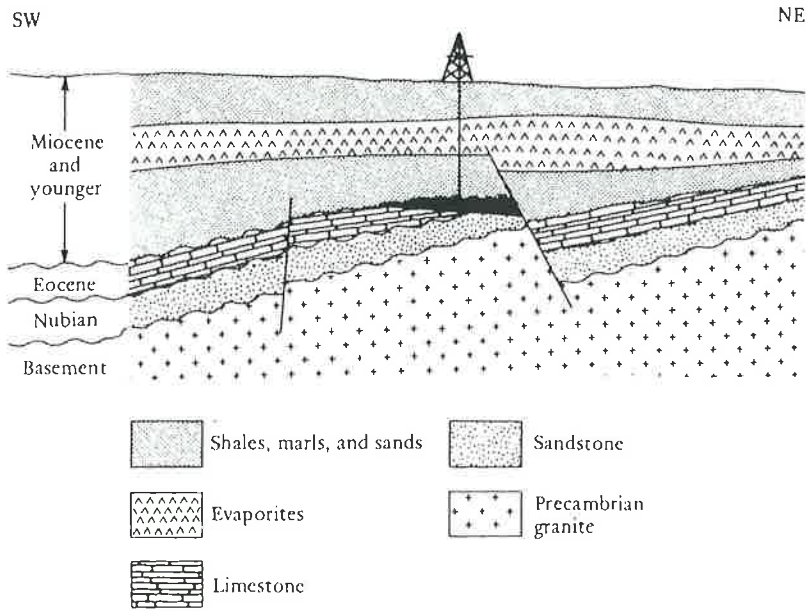

FIGURE 8.28 Cross-section illustrating a typical fault block trap in the Gulf of Suez.

Armed with this concept, it is now time to examine the Atlantic Ocean. A well-defined ridge with an axial rift extends from the Arctic, through Iceland, and down through the northern and southern Atlantic Oceans before running east into the Indian Ocean (Fig. 8.6). Both sides of the Atlantic Ocean, from Labrador to the Falkland Islands and from the Barents Sea to the Agulhas Bank, are flanked by asymmetric half-graben basins, whose major bounding faults downthrow to the ocean (Drake et al., 1968; Burk and Drake, 1974; Lehner and Dc Ruiter, 1977; Pratsch, 1978; Hoc, 1979; Emery, 1980). These basins show a remarkable similarity of stratigraphy and symmetry of structure (Fig. 8.29). The Gabon Basin is well known and will be used as a specific example (Belmonte et al., 1965; Brink, 1974; Vidal, 1980). It is typical of these basins geologically, but unusual in that it is a modest hydrocarbon province (Figs. 8.30 and 8.31). Seismic lines of the Atlantic coastal basins show that they are half-grabens. Two major unconformities may be discerned. One, generally the lowest mappable reflection, is considerably faulted. This marks the onset of rifting. Below this unconformity, basement and rare prerift sediments occur.

The overlying sediments were laid down during active rifting. They consist largely of continental clastics, but, as the fault blocks subside progressively toward the continent, a barrier develops between the rift and new oceanic crust. Behind this barrier sapropelic lacustrine shales may form in humid climates. Within the Cocobeach Group of the Gabon Basin these shales have generated oil. In arid climates, however, evaporites may form in the back basin; these evaporites are common in the Atlantic coastal basins. As the ocean opened from north to south, the onset of evaporite development becomes young southward: Permian in northern Europe, Triassic in the Georges Bank and Senegal basins, Jurassic in the

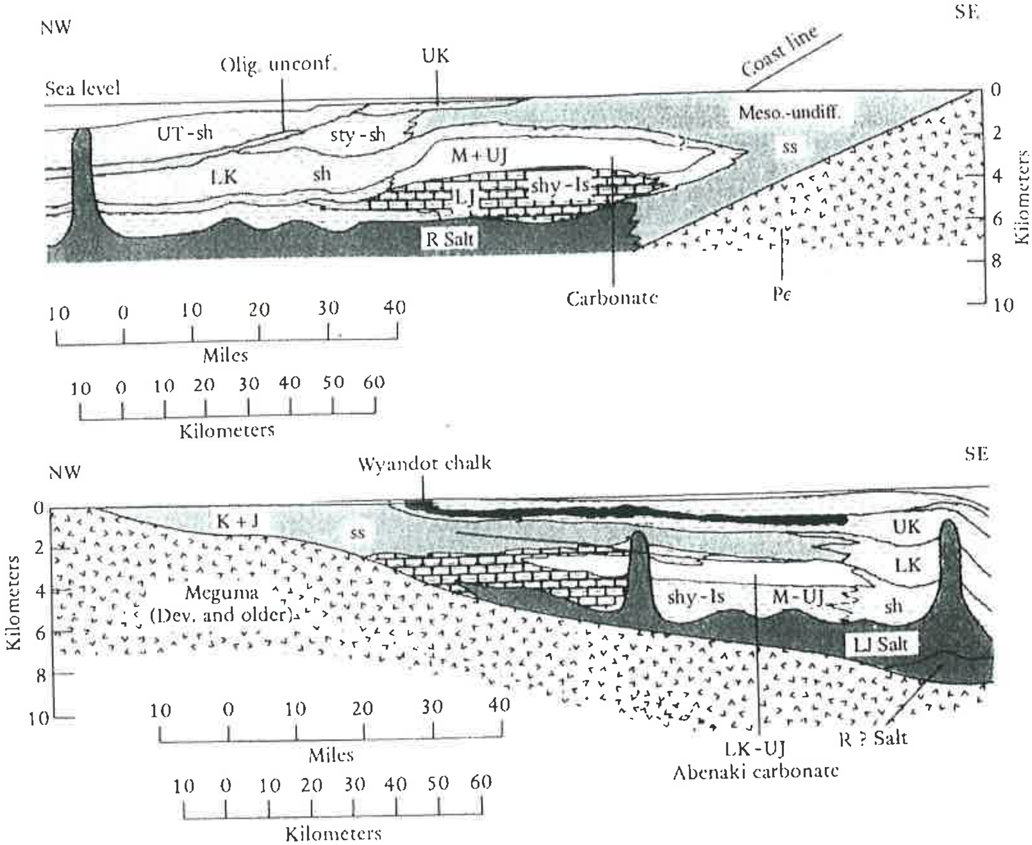

FIGURE 8.29 Cross-sections through the Moroccan (upper) and Scotian (lower) continental shelves showing the symmetry of structure and similarity of stratigraphy of these two Atlantic margin half-graben basins. *After Bhat et al. (1975) with permission from the Canadian Society of Petroleum Geologists.*

Gulf of Mexico, and Aptian in the Brazilian, Gabon, Cuanza, and Congo basins (Evans, 1978).

The second major unconformity overlies the evaporites. It marks the end of the rifting phase and the onset of drifting as the Atlantic Ocean widened. Rift faults generally die out at this surface, except at the basin margin. The overlying sediments start with an organic-rich shale, deposited as the sea invaded the incipient Atlantic Ocean. This shale is then overlain by a major regressive wedge. Sometimes this wedge is composed of carbonates, with marked thinning from a reefal shelf edge into basinal marls. Alternatively, there are terrigenous progrades in which basinal shales pass shoreward and upward into turbidites and paralic and continental deposits.

Basins of this half-graben type, with rift-drift sequences similar to those just described, are not unique to the Atlantic Ocean, but also occur around other opening oceans. The Exmouth Plateau of northwest Australia is such an example (Exxon and Wilcox, 1978). Collectively,

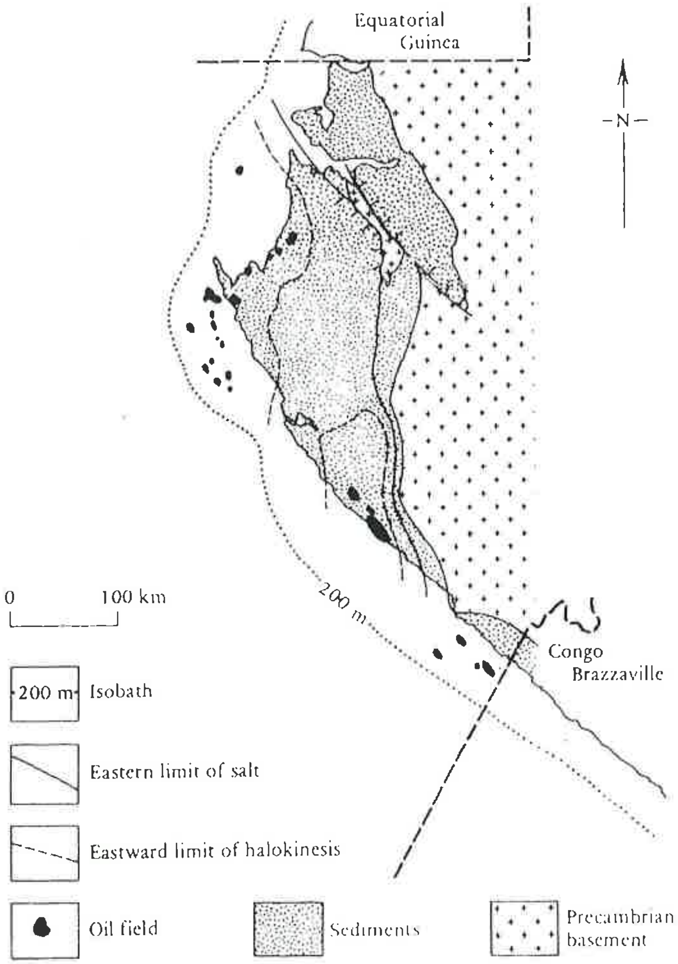

FIGURE 8.30 Geological map of the Gabon basin, compiled from various sources.

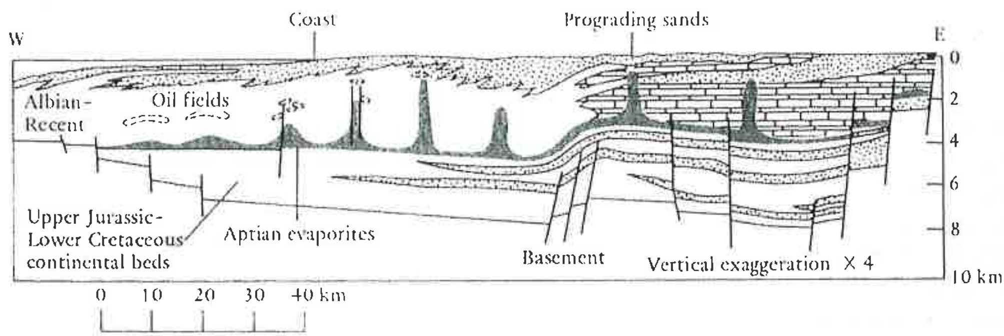

FIGURE 8.31 Cross-section of the Gabon basin. *Modified from Brink (1974) reprinted by permission of the American Association of Petroleum Geologists.*

such coasts are referred to as passive, or trailing, continental margins, in contrast to the active, or Pacific, continental margins where subductive arcs occur.

The preceding review shows that the Atlantic coastal basins evolved from intracratonic rifts, which were initiated on axes of crustal divergence and incipient sea floor spreading. For many years Atlantic-type coastal basins could only be explored along their less prospective up-dip edges. Within recent years offshore exploration has shown that many of these edges contain considerable reserves of oil and gas. Traps include tilted fault blocks (sealed by evaporites or the drift-onset unconformity), salt domes, and anticlines draped over basement horsts. For reasons still not clear, most of the productive basins appear to be in the Southern Hemisphere.

8.6.2 Failed Rift Basins: Aulacogens

There is one last type of rift basin to consider. Earlier, intracratonic rifts were noted to develop a triradiate pattern, often with triple-rift, or triple-R, junctions at the end of each major rift. As the crust draws apart, only two rifts out of each triple-R junction actually separate and become ocean margin half-grabens. One rift has failed to open. These aborted rifts, also called *failed arms* or *aulacogens*, are prime targets for petroleum exploration and deserve to be examined closely. The Benue Trough of Nigeria, which has already been mentioned, is the failed arm of a triple-rift junction that developed on the site of the present Niger Delta. When the old Pangean southern continent began to break up, rifts developed from the Benue trough north into Niger and Chad. Simultaneously, rifts developed along the Tibesti-Sirte Arch, which separated the Murzuk and Kufra basins (Section 8.4.1). The Sirte embayment, which was introduced earlier as an epicratonic embayment, developed along this axis and could therefore be regarded as a complex failed rift.

One of the best known failed rifts occurs in the North Sea of Europe. When the European, Greenland, and North American plates began to separate, a triple-R junction developed somewhere to the northeast of Scotland. Two of these arms opened to form the Norwegian Sea and the Atlantic Ocean, which are both flanked by half-graben basins. The southeastern branch of the triple-R junction subsided but failed to open, providing the North Sea oil province. This province is described in many papers in volumes edited by Woodland (1975), Finstad and Selley (2000,1977), Illing and Hobson (1981), Brooks and Glennie (1987), Glennie (1990), and Parker (1993). Short reviews are given by Ziegler (1975) and Selley (1976).

Figures 8.32 and 8.33 illustrate the main structural features of the North Sea as seen in plan and sections. Rifting began in the Permian and continued throughout the Triassic, with the deposition of fluvial and eolian sands and evaporites. A major transgression in the Jurassic resulted in the deposition of organic-rich shales and paralic sands. As rifting continued, submarine fault scarps along the rift margins poured conglomerates and turbidites onto the basin floor. At the end of the Jurassic a major unconformity, the Cimmerian event, marked the end of rifting and the onset of drifting as the Atlantic Ocean opened to the west. Lower Cretaceous sands and shales onlap pre-Cimmerian fault blocks. These blocks have considerable structural relief and locally underwent crestal erosion. Quiescence in the Late Cretaceous allowed the widespread deposition of coccolithic chalk. Renewed rifting in the Paleocene caused chalk turbidites and melanges to be shed into the Central Graben, following which a major delta complex prograded east and southeastward from Scotland. Submarine channel

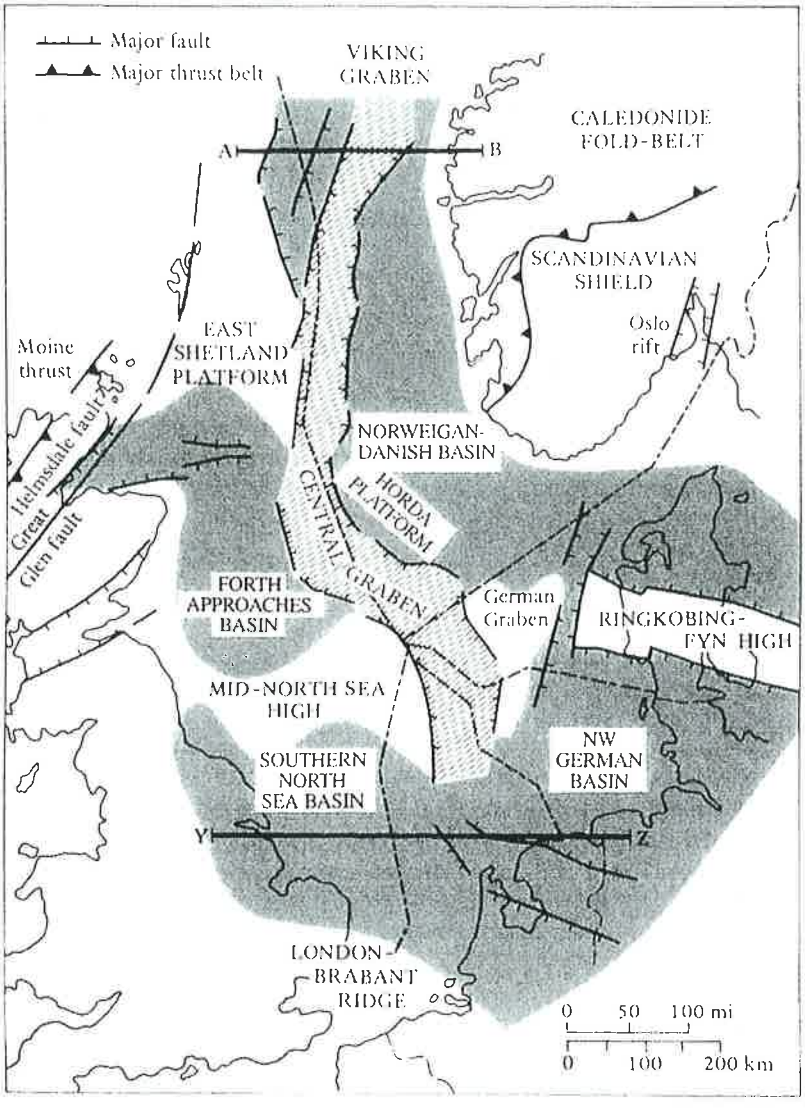

FIGURE 8.32 Map of the North Sea showing the main structural elements. This major hydrocarbon province is a classic example of a failed rift system.

sands and turbidite fans were deposited at the foot of the delta complex. The basin continued to be infilled by marine clays and occasional shallow marine sands up to the present day.

The North Sea contains four major hydrocarbon plays. In the southern North Sea Basin gas occurs in block-faulted anticlines beneath the Upper Permian Zechstein salt. Lower Permian eolian dune sands are the reservoir, and underlying Carboniferous coal beds provide the source for the gas. This play contains several gas fields in the giant category, including

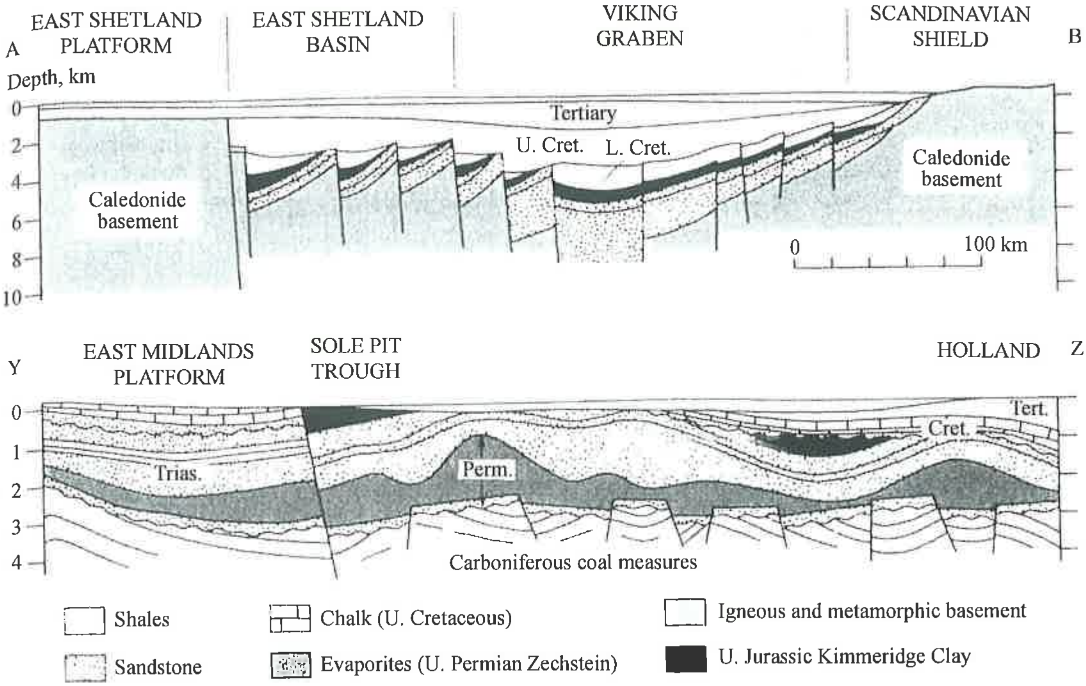

FIGURE 8.33 Cross-sections of the North Sea. Locations shown in Fig. 8.32.

Groningen, Hewett, Leman, and Indefatigable. The second major play occurs in Jurassic sands in tilted fault blocks sealed by Cretaceous shales and limestones that onlap the Cimmerian unconformity. The Brent, Statfjord, Piper, and Heather fields are of this type (refer back to Figs. 7.15, 7.48, and 7.49). The third major play occurs in southwestern offshore Norway. Here Ekofisk and associated fields produce from fractured, overpressured Cretaceous chalk reservoirs domed over Permian salt structures (refer back to Fig. 7.25). Finally, production comes from Paleocene deep-sea sands draped over pre-Cimmerian horsts. The Montrose, Frigg, and Forties fields are of this type (refer back to Fig. 7.13).

The Jurassic, Cretaceous, and Paleocene oil and gas fields are all believed to have been largely sourced from Jurassic shales. Estimates of North Sea reserves vary widely, but Ivanhoe (1980) cites recoverable reserves of 20 billion barrels of oil and 40 trillion cubic feet of gas.

Several conditions have made the North Sea rift basin a major hydrocarbon province. Excellent reservoirs are provided by polycyclic sands, often with subunconformity-leached porosity. Thick, rich source beds within the rift axis interfinger with and underlie the reservoirs. Traps are many and varied, including horsts, combination fault block truncations, salt domes, and compactional anticlines. Geothermal gradients, although now near average, were once abnormally high, enhancing hydrocarbon generation and migration.

This shows why rift basins in general, and failed rifts in particular, may be major petroleum provinces (Lambiase, 1994). Schneider (1972) has shown that a regular sequence of

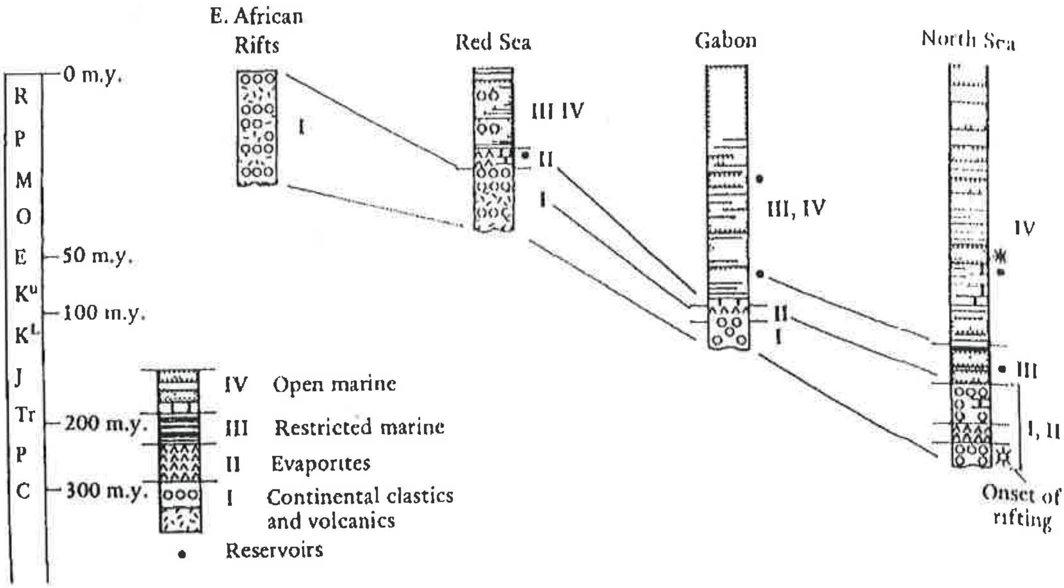

FIGURE 8.34 Comparative sections of various rift basins showing characteristic sedimentary sequences and distribution of source rocks.

facies tends to occur within the rift-drift suite of basins. Stage one, when the rift was still above sea level, consists of continental clastics, which are often associated with volcanics. The subsiding rift floor ultimately reaches sea level. This condition favors evaporite formation as the trough surface oscillates above and below the sea. As the rift floor is finally submerged, evaporites are overlain by organic-rich marine muds deposited in the restricted trough. Finally, as the rift dilates into an open sea, carbonate shelves and prograding clastic wedges build out over the old rift floor onto oceanic crust. Figure 8.34 shows how this ideal sequence applies to the examples of the rift-drift sequence of basins just described.

8.7 STRIKE-SLIP BASINS

We have now reviewed the different types of basins associated with convergent and divergent plate boundaries. Some plate margins are transcurrent and develop a particular type of rift basin. Transcurrent plate margins are defined by major wrench faults. Where plates move past one another, however, the movement is seldom wholly parallel; an oblique component commonly causes crustal compression. Similarly, compressive phases may alternate with phases of separation. These changes occur both in time and space. Thus, for example, the divergent plate boundary of the Red Sea can be traced northeastward to the Dead Sea rift. The transcurrent nature of the Dead Sea faults has been understood from biblical to recent times (see Zechariah 14.4 and Quennell (1958); respectively). By contrast the San Andreas transverse fault system of California passes into compressive plate boundaries at both ends (Fig. 8.6).

Transform fault systems give rise to very distinctive types of rift basin. These rift basins are generally very deep, subside rapidly, and have rates of high heat flow. The Dead Sea rift is such an example. It is some 15 km wide and 150 km long. Left lateral displacement has been estimated in the order of 70–100 km (Wilson et al., 1983). More than 6 km of subsidence has occurred since the Miocene period. The Dead Sea valley has long been noted for its petroleum seeps, occasionally giving rise to floating blocks of asphalt (Nissenbaum, 1978). Commercial quantities of oil have yet to be found within the margins of the rift.

By contrast the strike-slip basins associated with the transcurrent fault systems of California are very petroliferous (Fig. 8.35). These rifts are mainly of late Tertiary age. They are characterized by thick sequences (more than 10 km) of rapidly deposited clastics in which abyssal shales (source rocks) pass up through thick submarine fans (reservoirs) into paralic and continental deposits. The basins are often asymmetric, with alluvial and submarine conglomerates developed adjacent to the active boundary faults (Crowell, 1974. Petroleum is trapped in

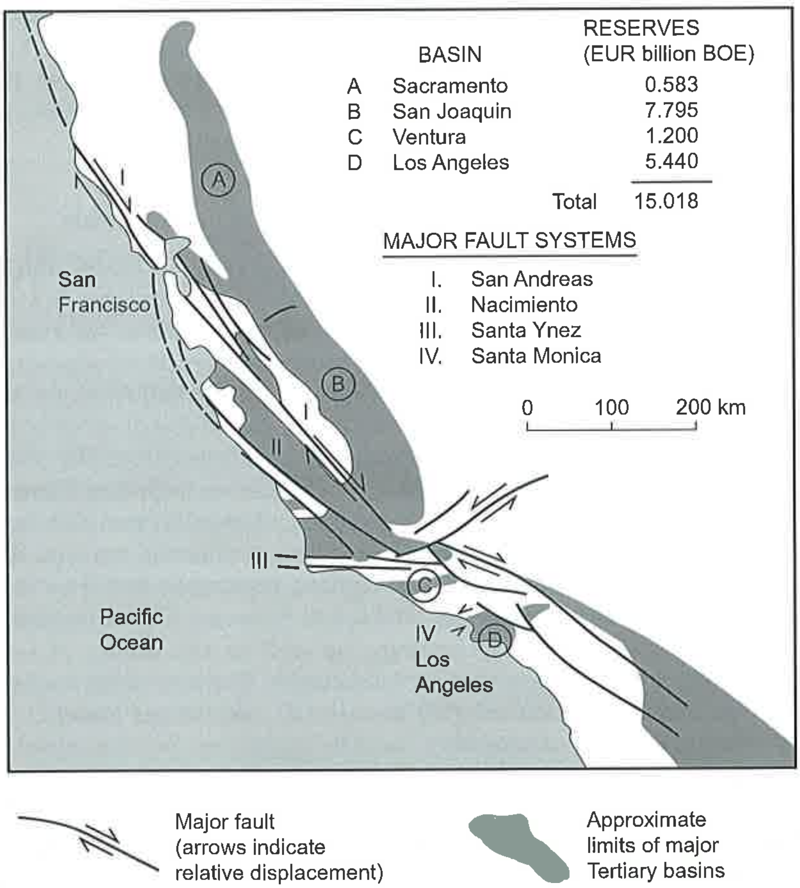

FIGURE 8.35 Map of part of California showing major strike-slip basins and their associated faults.

en echelon and flower-structure faulted anticlines (see Section 7.6.2); examples are given in Weeks (1958). Stratigraphic entrapment in submarine channels and fans is less common (Section 7.6.2). Estimated ultimate recoverable reserves for the Californian basins is in excess of 15 billion barrels of oil equivalent (St. John, 1980). Additional information on strike-slip basins can be found in Allen and Allen (1990), pp. 115–138).

8.8 SEDIMENTARY BASINS AND PETROLEUM SYSTEMS

The concept of the petroleum system was introduced in Chapter 5, where it was discussed in terms of how petroleum systems were related to the volumes of petroleum generated from source rocks. Recall that a petroleum system was defined as "a dynamic petroleum generating and concentrating physico-chemical system functioning in geologic space and time" (Demaison and Huizinga, 1994). It is now appropriate to integrate the concept of the petroleum system with sedimentary basins, a topic that has been intensively studied in recent years (Demaison and Murris, 1984; Magoon and Dow, 1994). The mathematical modeling of petroleum generation within a computer was discussed in Section 5.5.2, and illustrated in Plate 5. Further accounts can be found in Dore et al. (1991), and Helbig (1994). First it may be useful to consider the distribution of petroleum in the various types of basins, and then to consider the vertical distribution of petroleum within basins.

8.8.1 Distribution of Hydrocarbons in Different Types of Basins

The preceding part of the chapter reviewed the various types of basins and analyzed the conditions affecting their potential for being major hydrocarbon provinces. Several geologists have quantitatively reviewed the global distribution of hydrocarbon reserves. This review may provide guidance to future exploration by establishing the relative productivity of the different types of basins (Halbouty et al., 1970; Klemme, 1975,1980).

Figure 8.36 presents data from Klemme's study of the global distribution of hydrocarbons in different basins. His basin classification is somewhat different from the one used in this chapter, and it does not precisely correspond to his earlier version (see Table 8.1), but the figure does show many interesting features. Note particularly that the Arabian Gulf, which has 38% of the world's reserves (Ivanhoe, 1980), has a major effect on the type IV Continental borderland downwarp class. In studying these figures, remember that they do not indicate the distribution of actual reserves but only of known reserves. Thus they reflect factors of geography, economics, politics, and technology, as well as our ability as explorationists. Note particularly that the percentage of reserves found in Tertiary deltas and coastal basins will increase as offshore exploration extends into deeper and deeper water.

8.8.2 Distribution of Hydrocarbons within Basins

Oil and gas tend to occur in sedimentary basins in a regular pattern. Considered vertically, oil gravity decreases with depth. Heavy oils tend to be shallow and, with increasing depth, pass down into light oils, condensate, and finally gas, until the point at which hydrocarbons and porosity are absent. Hunt (1979) took all the API data from the 1975 International

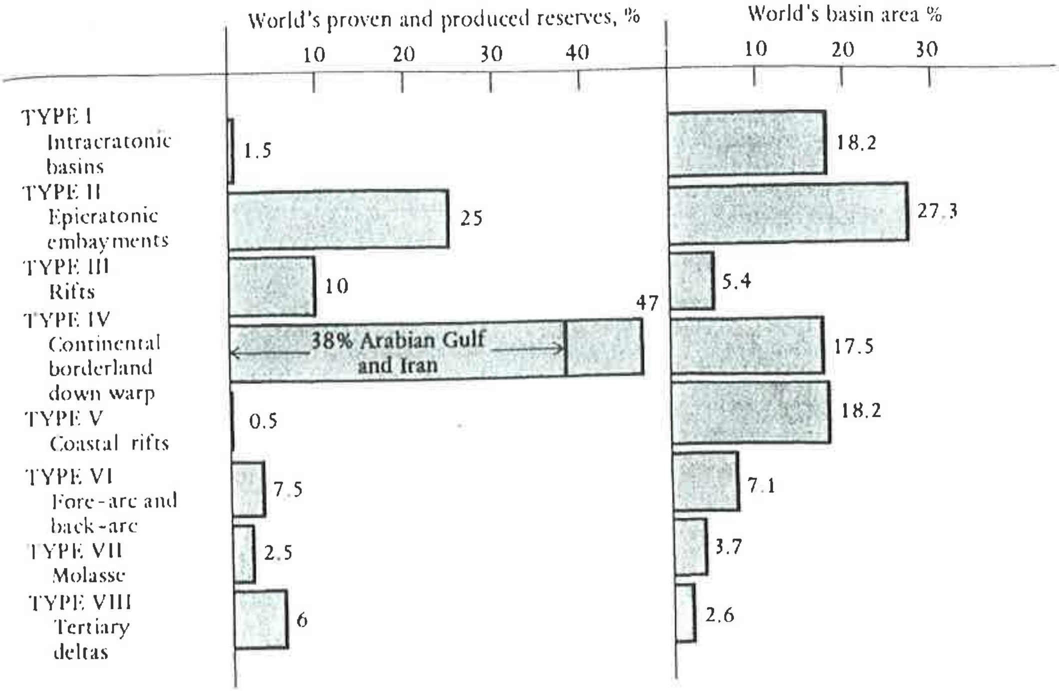

FIGURE 8.36 Histograms comparing the surface area of different types of sedimentary basins and their currently known petroleum reserves. *Based on data from Klemme (1980).*

Petroleum Encyclopedia to produce the graphs shown in Fig. 8.37. These graphs bear out the statement just made. Although oil API generally increases with depth (density decreases), many local conditions may disrupt this pattern, for example, the existence of several source beds in a basin, hydrocarbon flow along faults, flushing and degradation, and uplift and erosion. A noted anomaly is provided by the Niger Delta, where gas commonly occurs at shallower depths than oil (Unomah, 1993).

Oils tend to become lighter not only downward but also laterally toward a basin center. Typically, heavy oils occur around basin margins, and condensate and gas in the center. The cause, or causes, of these vertical and lateral variations of oil and gas are of considerable importance.

An ingenious explanation was advanced by Gussow (1954) and has since gained wide acceptance as Gussow's principle. This theory may be stated briefly as follows. Consider a sedimentary basin, up whose flanks extend continuous, permeable reservoir beds that contain many traps. Consider also that the hydrocarbons, oil and gas, emigrate from the "devil's kitchen" in the deep center of the basin up the flanks. On reaching the first trap, gas may displace all the oil, which will be forced below the spill point and up to the next trap, where the process will be repeated. Finally, all the gas will be retained, so there will be a trap with a gas cap and an oil column. The trap will be full to spill point, and oil forced below the spill point will emigrate up, filling trap after trap until all the oil is contained. The

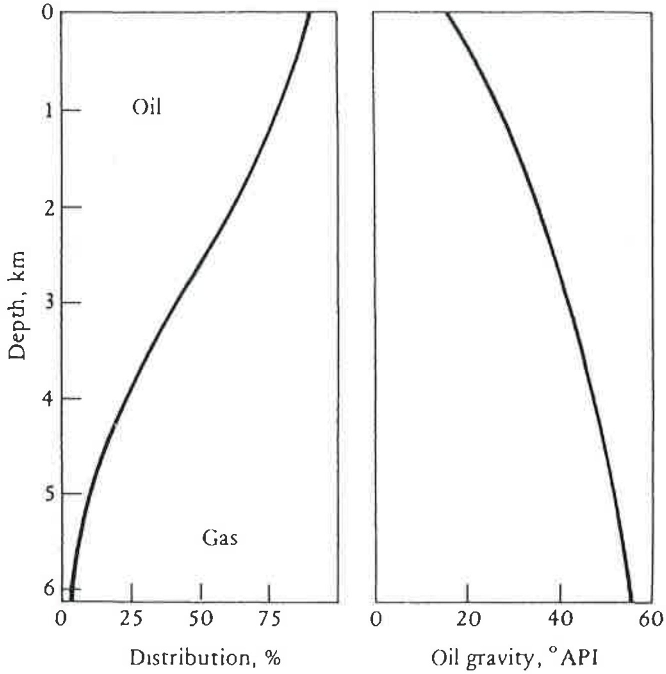

FIGURE 8.37 Vertical variation in the distribution of oil and gas and in oil gravity. These curves were calculated from data in the 1975 International Petroleum Encyclopedia. These global trends have many local exceptions. *From Hunt (1979), used with permission.*

final trap will not be full to spill point, and any additional traps that may be structurally higher will be barren (Fig. 8.38).

It has already been pointed out that some fields show a gravity segregation of oil (Section 7.2.1). Therefore it is not hard to envisage Gussow's principle explaining not only the gross distribution of oil and gas in a basin but also the less obvious variations in oil gravity. Gussow established his principle from work on the Bonnie-Glenn-Wizard Lake Devonian reef complex of Alberta, across a distance of about 160 km. Other excellent examples of differential entrapment have been noted from the Niagaran reefs of Michigan (Gill, 1979) and from the Mardin Group of Anatolia (Erdogan and Akgul, 1981).

There are problems, however, in applying Gussow's principle over large distances and in basins with discontinuous reservoirs. Thus Bailey et al. (1974) showed how oil and gas distribution can be mapped with great continuity right across the Alberta Basin, where many reservoirs are isolated reefs and where unconformities provide regionally extensive permeability barriers. The zonation of gas, light oil, and heavy oil from basin center to margin may be due to a combination of thermal maturation and degradation by meteoric water.

Many other basins around the world exhibit a regular gravity zonation of hydrocarbons, yet lack continuity of reservoir from trap to trap. The chalk fields of the Ekofisk area of the North Sea, for example, show an increase in API gravity toward the Central Graben, yet lack any regional permeability.

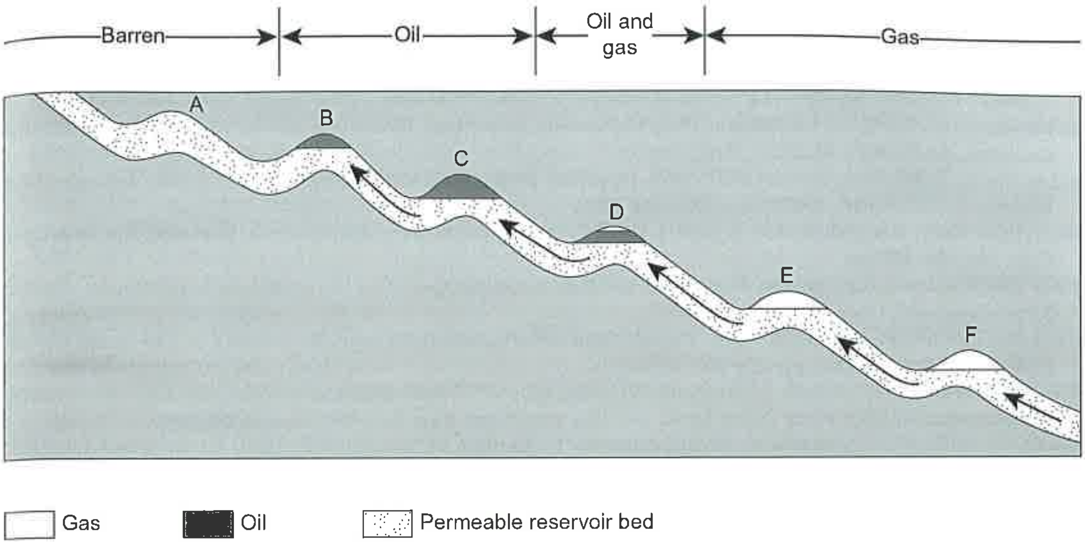

FIGURE 8.38 Cross-section through a hypothetical sedimentary basin with a laterally continuous permeable stratum folded into a multitude of traps. This figure illustrates Gussow's principle.

Thus the differentiation of oil and gas found in a basin is related to two factors. One factor is the level of thermal maturation of the source beds: gas being generated at higher temperatures and therefore at greater depths than oil (see Section 7.3.3). The shallowest traps around a basin rim are likely to have been flushed by meteoric water, as can be checked from their salinity. The shallowest oil is likely to be heavy where oil moving up from the basin center has been degraded by contact with meteoric water. The second factor is the regional distribution of permeable carrier formations, a factor that is termed the "impedance" of the petroleum system as discussed earlier.

Thus Gussow's principle must be applied with care when considering the basinwide distribution of oil, condensate, and gas. It is particularly useful, however, when trying to understand local variations in the distribution of different gravities of petroleum. This is illustrated by Fig. 8.38. If trap C was the first to be drilled and it was full to spill point, then both traps B and D will be prospective. It may be anticipated that trap D will be full to spill point, but one can only speculate about the thickness of the oil column in trap B. Consider, on the other hand, that trap B had been drilled first and had been found not to be full to spill point. It would be sound policy to drill trap C, but trap A should be farmed out at the earliest opportunity, since it is unlikely to have received any oil.

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