CHAPTER

7

Traps and Seals

7.1 INTRODUCTION

In the early days of oil exploration in the United States, no specific legislation governed the exploration and exploitation of petroleum. Initially, the courts applied the game laws, which stated that oil and gas were fugacious (likely to flee away), moving from property to property, and ultimately owned by the man on whose land they were trapped (Dott and Reynolds, 1969).

The term trap was first applied to a hydrocarbon accumulation by Orton (1889): "…stocks of oil and gas might be trapped in the summits of folds or arches found along their way to higher ground." A detailed historical account of the subsequent evolution of the concept and etymology of the term trap is found in Dott and Reynolds (1969).

As discussed in Chapter 1, a trap is one of the seven essentials requisites for a commercial accumulation of oil or gas. Levorsen (1967) gave a concise definition of a trap as "the place where oil and gas are barred from further movement." This definition needs some qualification. Explorationists in general and geophysicists in particular search for hydrocarbon traps. Perhaps it would be more accurate to say that they search for potential traps. Only after drilling and testing is it known whether the trap contains oil or gas. In other words, a trap is still a trap whether it is barren or productive.

7.2 NOMENCLATURE OF A TRAP

Many terms are used to describe the various parameters of a trap. These terms are defined as follows and illustrated with reference to an anticlinal trap, the simplest type (Fig. 7.1). The highest point of the trap is the crest, or culmination. The lowest point at which hydrocarbons may be contained in the trap is the spill point; this lies on a horizontal contour, the spill plane. The vertical distance from crest to spill plane is the closure of the trap. A trap may or may not be full to the spill plane, a point of both local and regional significance. Note that in areas of monoclinal dip the closure of a trap may not be the same as its structural relief (Fig. 7.2). This situation is particularly significant in hydrodynamic traps. The zone immediately beneath the petroleum is referred to as the bottom water, and the zone of the reservoir laterally adjacent to the trap as the edge zone (Fig. 7.1).

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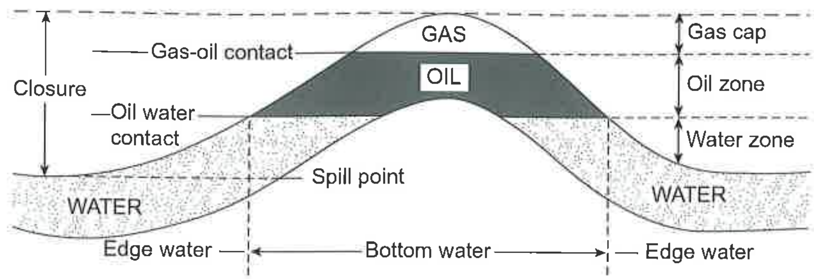


FIGURE 7.1 Cross section through a simple anticlinal trap.

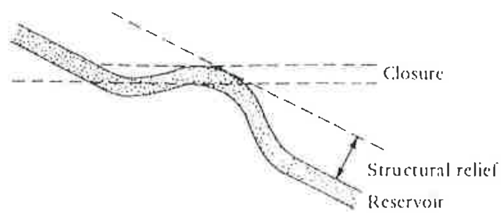


FIGURE 7.2 Cross section through a trap illustrating the difference between closure and structural relief.

Within the trap the productive reservoir is termed the pay. The vertical distance from the top of the reservoir to the petroleum/water contact is termed gross pay. This thickness may vary from only 1 or 2 m in Texas to several hundred meters in the North Sea and Middle East. All of the gross pay does not necessarily consist of productive reservoir, however, so gross pay is usually differentiated from net pay. The net pay is the cumulative vertical thickness of a reservoir from which petroleum may be produced. Development of a reservoir necessitates mapping the gross:net pay ratio across the field.

Within the geographic limits of an oil or gas field there may be one or more pools, each with its own fluid contact. Pool is an inaccurate term, dating back to journalistic fantasies of vast underground lakes of oil; nonetheless, it is widely used. Each individual pool may contain one or more pay zones (Fig. 7.3).

7.3 DISTRIBUTION OF PETROLEUM WITHIN A TRAP

A trap may contain oil, gas, or both. The oil:water contact (commonly referred to as OWC) is the deepest level of producible oil. Similarly, the gas:oil contact (GOC) or gas:water contact, as the case may be, is the lower limit of producible gas. The accurate evaluation of these surfaces is essential before the reserves of a field can be calculated, and their establishment is one of the main objectives of well logging and testing.

Where oil and gas occur together in the same trap, the gas overlies the oil because the gas has a lower density. Whether a trap contains oil and/or gas depends both on the chemistry and level of maturation of the source rock (see Chapter 5) and on the pressure and temperature of the reservoir itself. Fields with thick oil columns may show a more subtle

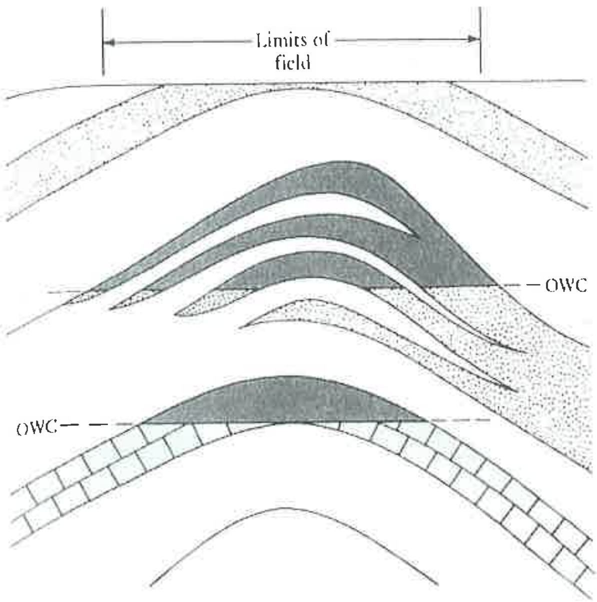


FIGURE 7.3 Cross section through a field illustrating various geological terms. This field contains two pools, that is, two separate accumulations with different oil:water contacts (OWC). In the upper pool the net pay is much less than the gross pay because of nonproductive shale layers. In the lower pool the net pay is equal to the gross pay.

gravity variation through the pay zone. Boundaries between oil, gas, and water may be sharp or transitional. Abrupt fluid contacts indicate a permeable reservoir; gradational ones indicate a low permeability with a high capillary pressure. Not only does a gross gravity separation of gas and oil occur within a reservoir, but more subtle chemical variations may also exist. The petroleum geochemistry of a trap is of concern to reservoir engineers trying to discover the most effective way of producing its petroleum. The petroleum geochemistry of a trap is of interest to petroleum explorationists, since it reveals its source and migration history, parameters that may point to the discovery of new adjacent fields (Cubitt and England, 1995).

Beyond the gross stratification of gas and oil, it is now known that petroleum layering may occur on a scale down to an order of some 10 m (Larter and Aplin, 1995). Particular interest focuses on vertical variations of the water saturation, since this obviously affects the producibility of the petroleum, and on establishing whether the water is free or bound, using tools such as NMR log discussed in Chapter 6.

7.3.1 Tar Mats

Some oil fields have a layer of heavy oil, termed a *tar mat*, immediately above the bottom water. Notable examples include fields such as Prudhoe Bay, Alaska, and Sarir, Libya (see Jones and Speers (1976) and Lewis (1990), respectively): Tar mats are also sometimes associated with late pyrite cementation. Wireline log interpretation of tar mats provides petrophysicists with some of their biggest challenges. Tar mats are very important to identify and understand because they impede the flow of water into a reservoir when the petroleum is produced.

Wilhelms and Larter (1994a,b) have given detailed accounts of tar mats in the North Sea fields and elsewhere. These studies show that tar mats are best developed at the most porous and permeable parts of the reservoir. The petroleum of the tar mat is genetically related to the supradjacent accumulation.

Traditionally tar mats are believed to have formed long after petroleum migration has ceased, and have been attributed to the bacterial degradation of oil. The bacteria were brought into contact with the petroleum accumulation by connate water flowing beneath the petroleum:water contact. Wilhelms and Larter (1994b, 1995) reject these ideas, together with the suggestion that tar mats form by the absorption of asphaltenes onto clays.

They propose two mechanisms for tar mat formation. They believe that tar mats are produced either by the thermal degradation of oils, causing the precipitation of asphaltenes, or by the increased gas solution in the oil column, leading to asphaltene precipitation. They also believe that tar mats form during petroleum migration, not long after, as previously supposed.

7.3.2 Tilted Fluid Contacts

Fluid contacts in a trap are generally planar, but are by no means always horizontal. Early recognition of a tilted fluid contact is essential for the correct evaluation of reserves. Correct identification of the cause of the tilt is necessary for the efficient production of the field. There are several causes of tilted fluid contacts. They may occur where a hydrodynamic flow of the bottom waters leads to a displacement of the hydrocarbons from a crestal to a flank position. This displacement can happen with varying degrees of severity (Fig. 7.4). The presence of this type of tilted OWC can be established from pressure data, which will show a slope in the potentiometric surface. Many, but by no means all, hydrodynamically tilted fields occur above sea level. Where these fields are shallow, the occurrence of tar mats is not unusual because of the degradation of oil due to the movement of water beneath the oil zone.

In some fields the OWC has tilted as a result of production, presumably because of fluid movement initiated by the production of oil from an adjacent field. This phenomenon has been recorded, for example, from the Cairo Field of Arkansas (Goebel, 1950). An alternative explanation for a sloping fluid contact is that a trap has been tilted after hydrocarbon invasion, and the contact has not moved. Considered on its own, this theory is unlikely because, within the geological timescale, the oil and/or gas have ample time to adjust to a new horizontal level.

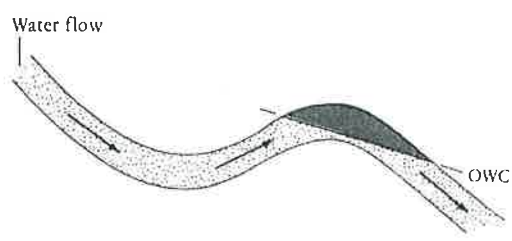


FIGURE 7.4 Cross section through a trap showing tilted oil:water contact (OWC) due to hydrodynamic flow.

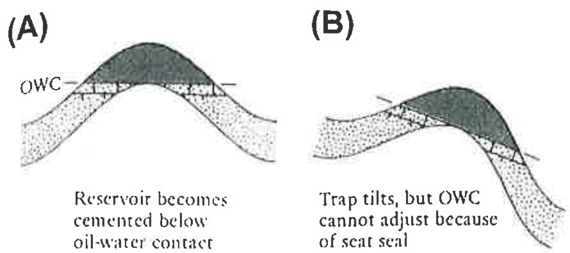


FIGURE 7.5 Cross section through a trap showing how a tilted oil:water contact (OWC) may be caused by (A) cementation of the water zone followed by (B) tilting.

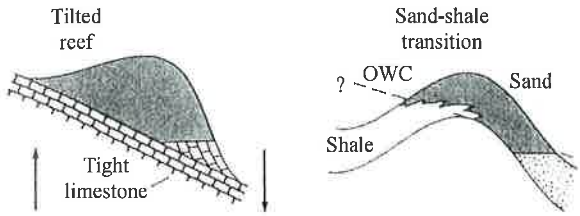


FIGURE 7.6 Cross sections through traps showing how apparently tilted oil:water contacts (OWC) may be caused by facies changes.

A tar mat may decrease permeability to such an extent that if a trap is tilted, the OWC may be unable to adjust to the new horizontal datum. Alternatively, cementation can continue in the reservoir beneath an oil zone while it is halted in the trap itself. This cementation seldom provides a seat seal sufficiently tight to restrain the hydrocarbons from later movement. It may, however, diminish permeability sufficiently to provide some interesting production problems: the updip edge of the field having anomalously low permeability, and the water zone on the downdip side having anomalously high permeability (Fig. 7.5).

A third possible cause of a tilted OWC may be a change in facies. Theoretically, a change in grain size across the reservoir causes a tilted contact. With declining grain size, capillary pressure increases, allowing a rise in the OWC. In practice, the effect of this rise is likely to be negligible, at the most only a few meters (Yuster, 1953). On the other hand, where the change is actually lithological, the lower contact of the field may be tilted. In this situation the underlying lithology, either a shale or basement, is generally impermeable. In such cases, the tilted lower surface of the reservoir is not truly an OWC, but a seat seal (Fig. 7.6).

7.4 SEALS AND CAP ROCKS

For a trap to have integrity it must be overlain by an effective seal. Any rock may act as a seal as long as it is impermeable (Downey, 1994). Seals will commonly be porous, and may in fact be petroleum saturated, but they must not permit the vertical migration of petroleum from the trap. Shales are the commonest seals, but evaporites are the most effective. Shales are commonly porous, but because of their fine grain size have very high capillary forces that prevent fluid flow.

The discussion on primary petroleum migration in Chapter 4 introduced Berg's (1975) concept of the capillary seal. Berg showed how shales may selectively trap oil, while permitting the upward migration of gas. Gas chimneys may sometimes be identified on seismic lines either by a velocity pull-down of the reflector on top of the reservoir, and/or by a loss in seismic character in the overlying reflectors. Indeed some petroleum accumulations, such as the Ekofisk Field, are sometimes identified because of their gas-induced seismic anomalies (Van den Berg and Thomas, 1980).

Several mechanisms allow the leakage of gas from a trap. These include the compressible Darcy flow of a free gas phase, the transport of dissolved gas in aqueous solution along adjacent aquifers under hydrodynamic conditions and the diffusive transport through the water-saturated pore space of the cap rock (Krooss et al., 1992).

For compressible Darcy flow of a free gas phase to occur, the reservoir gas pressure must exceed the capillary pressure in the cap rock (Berg, 1975). Diffusive transport through the water-saturated pore space of the cap rock is an ubiquitous, but probably least effective, method of gas transportation through a cap rock.

With increasing induration shales will tend to fracture when subjected to stress. Tectonic movements may thus destroy the effectiveness of a brittle shale seal, though the fractured shale may then, of course, serve as a petroleum reservoir in its own right (see the discussion of shale gas in Chapter 9).

7.5 CLASSIFICATION OF TRAPS

Hydrocarbons may be trapped in many different ways. Several schemes have been drawn up to attempt to classify traps (e.g., Clapp, 1910, 1929; Lovely, 1943; Hobson and Tiratsoo, 1975; Biddle and Wielchowsky, 1994). Most trap classificatory schemes are based on the geometry of the trap, but Milton and Bertram (1992) use the seal as the classificatory parameter. Two major genetic groups of trap are generally agreed on: structural and stratigraphic. A third group, combination traps, is caused by a combination of processes. Agreement breaks down, however, when attempts are made to subdivide these groups.

Table 7.1 presents a classification of hydrocarbon traps. The table is based on information previously cited in this chapter, and can only be regarded as a crude attempt to pigeonhole such truly fugacious entities as traps. The table has no intrinsic merit other than to provide a framework for the following descriptions of the various types of hydrocarbon traps.

Structural traps are those traps whose geometry was formed by tectonic processes after the deposition of the beds involved. According to Levorsen (1967), a structural trap is "one whose upper boundary has been made concave, as viewed from below by some local deformation, such as folding, or faulting, or both, of the reservoir rock. The edges of a pool occurring in a structural trap are determined wholly, or in part, by the intersection of the underlying water table with the roof rock overlying the deformed reservoir rock." Basically, therefore, structural traps are caused by folding and faulting.

A second group of traps is caused by diapirs, where salt or mud have moved upward and domed the overlying strata, causing many individual types of trap. Arguably, diapiric traps are a variety of structural traps; but since they are caused by local lithostatic movement, not regional tectonic forces, they should perhaps be differentiated.

TABLE 7.1 Crude Classification of Hydrocarbon Traps Based on Previous Schemes Cited in the Text

I	Structural traps—caused by tectonic processes
	Fold traps: Compressional anticlines; Compactional anticlines
	Fault traps
II	Diapiric traps—caused by flow due to density contrasts between strata
	Salt diapirs
	Mud diapirs
III	Stratigraphic traps—caused by depositional morphology or diagenesis (for detailed classification see Table 7.2.)
IV	Hydrodynamic traps—caused by water flow
V	Combination traps—caused by a combination of two or more of the above processes

Stratigraphic traps are those traps whose geometry is formed by changes in lithology. The lithological variations may be depositional (e.g., channels, reefs, and bars) or postdepositional (e.g., truncations and diagenetic changes). Hydrodynamic traps occur where the downward movement of water prevents the upward movement of oil, thus trapping the oil without normal structural or stratigraphic closure. Such traps are rare. The final group, combination traps, is formed by a combination of two or more of the previously defined genetic processes.

The various types of traps—structural, diapiric, stratigraphic, hydrodynamic, and combination—are described at greater length and illustrated with examples in the following sections.

7.6 STRUCTURAL TRAPS

As previously stated, the geometry of structural traps is formed by postdepositional tectonic modification of the reservoir. Table 7.1 divides structural traps into those caused by folding and those caused by faulting. These two classifications are now considered in turn.

7.6.1 Anticlinal Traps

Anticlinal, or fold, traps may be subdivided into two classes: compressional anticlines (caused by crustal shortening) and compactional anticlines (developed in response to crustal tension).

7.6.1.1 Compressional Anticlines

Anticlinal traps caused by compression are most likely to be found in, or adjacent to, subductive troughs, where there is a net shortening of the earth's crust. Thus, fields in such traps are found within, and adjacent to, mountain chains in many parts of the world.

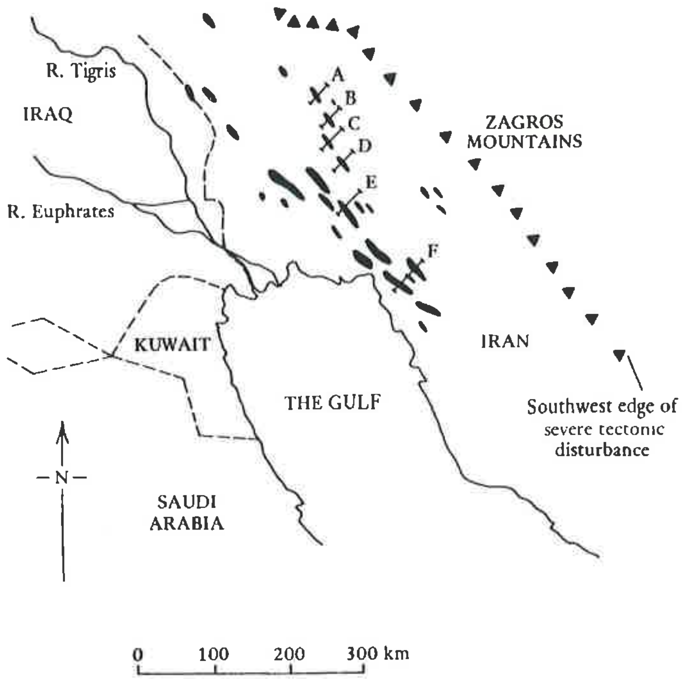


FIGURE 7.7 Map showing the location of the folded anticlinal traps of Iran. For cross section see Fig. 7.8.

One of the best known oil provinces with production from compressional anticlines occurs in Iran (Fig. 7.7). Many such fields are found in the foothills of the Zagros Mountains. Sixteen of these fields are in the "giant" category, with reserves of more than 500 million barrels of recoverable oil or 3.5 trillion cubic feet of recoverable gas (Halbouty et al., 1970). These fields have been described in considerable detail over the years (Lees, 1952; Falcon, 1958, 1969; Slinger and Crichton, 1959; Hull and Warman, 1970; Colmann-Sadd, 1978). The main producing horizon is the Asmari limestone (Lower Miocene), a reservoir with extensive fracture porosity. Flow rates and productivity are immense, with some individual wells having flowed 50 million barrels (No. 7-7, Masjid-i-Suleiman Field). The cap rock is provided by evaporites of the lower Fars Group (Miocene), whose disharmonic folding makes it difficult to extrapolate from the surface to the reservoirs. The traps themselves lie to the southwest of the main Zagros Mountain thrust belt. Individual anticlines are up to 60 km in length and some 10–15 km wide (Fig. 7.8). The axial planes of the folds pass downward into thrust faults, which die out in a zone of decollement within the underlying Hormuz salt (Precambrian?).

A second major hydrocarbon province that contains compressional anticlinal traps occurs in the Tertiary basins of California. Here, a number of fault-bounded troughs are infilled by thick regressive sequences in which organic-rich basinal muds are overlain by turbidites capped by younger continental beds. These sediments have locally undergone tight compressive folding associated with the transcurrent movement of the San Andreas Fault system (Barbat, 1958; Schwade et al., 1958; Simonson, 1958). Many of the fields are associated with faulting:

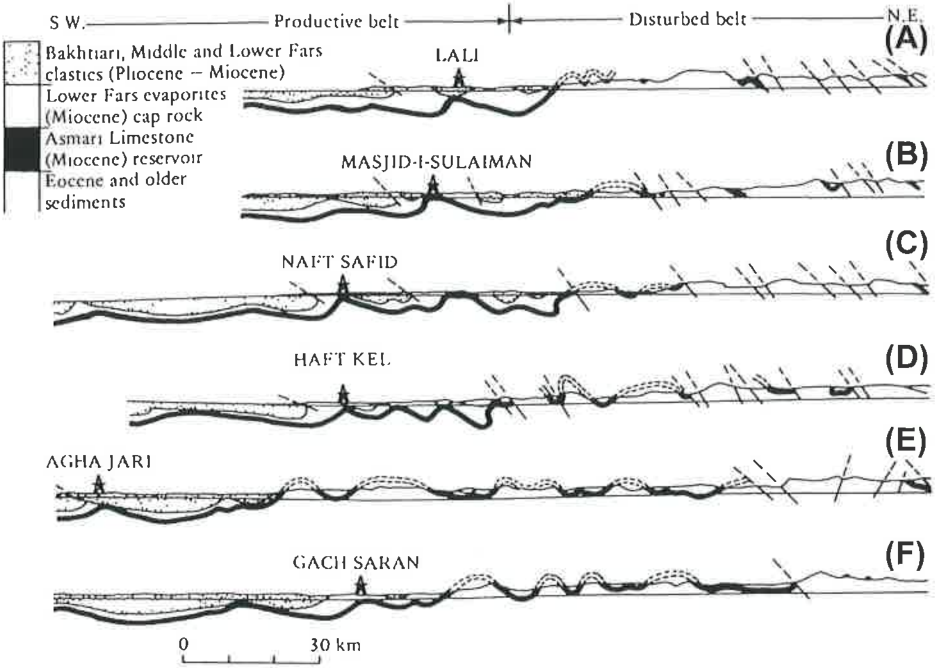


FIGURE 7.8 Southwest to northeast true-scale cross sections through some of the folded structures of Iran. Locations shown in Fig. 7.7. *After Falcon (1958), reprinted by permission of the American Association of Petroleum Geologists.*

normal, reversed, and strike slip (Fig. 7.9). The Long Beach-Wilmington Field of the Los Angeles Basin is a giant field in a compressional anticline, cross-cut by normal faults perpendicular to the fold axis (Mayuga, 1970).

Folds are often involved in thrusting within the mountain chains themselves. Hydrocarbons may be trapped in anticlines above thrust planes and in reservoirs sealed beneath the thrust. A major play of this type occurs in the eastern Rocky Mountains, including the Turner Valley field of Alberta and the Painter Valley Reservoir field of Wyoming (Fig. 7.10). Such fields are extremely difficult to find and develop because of the problems of seismic interpretation due to complex faulting and steeply dipping beds. With recent improvements in seismic technology, however, this task is becoming easier, opening up previously neglected areas to exploration.

7.6.1.2 Compactional Anticlines

A second major group of anticlinal traps is formed not by compression but by crustal tension. Where crustal tension causes a sedimentary basin to form, the floor is commonly split into a mosaic of basement horsts and grabens. The initial phase of deposition infills this irregular topography. Throughout the history of the basin, the initial structural architecture usually persists, controlling subsequent sedimentation. Thus anticlines may occur in the sediment cover above deep-seated horsts (Fig. 7.11). Closure may be enhanced both by compaction and sedimentation. Differential sedimentation of clays increases

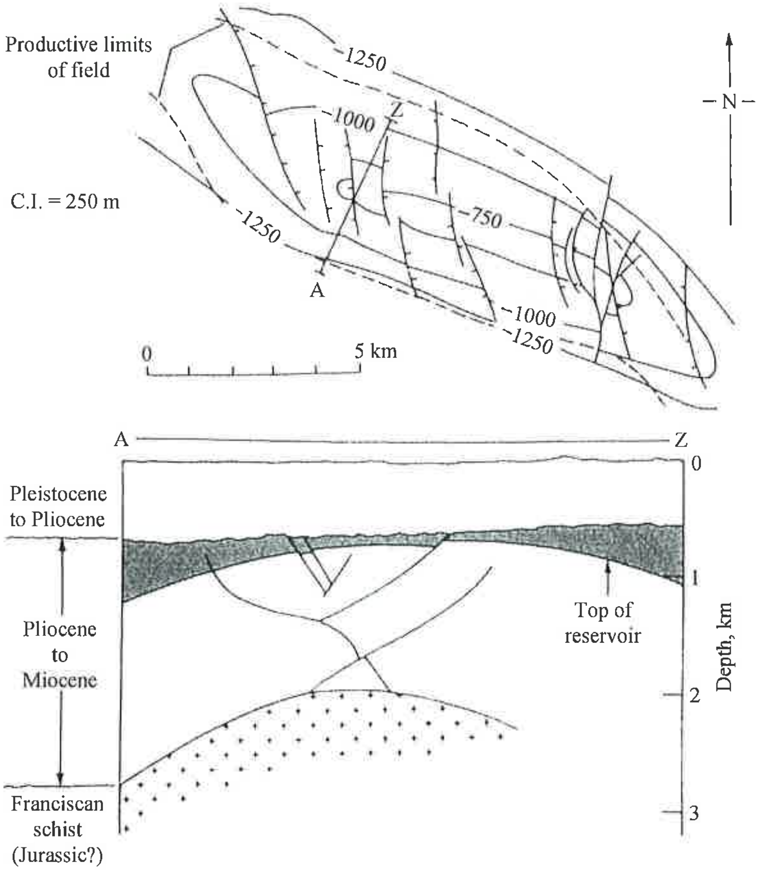


FIGURE 7.9 The Wilmington oil field, Long Beach, California. (Upper) Structure contour map on top of the Ranger Zone, just below the crest of the reservoir. (Lower) Southwest–northeast cross section along the line A–Z. *Modified from Mayuga (1970), reprinted by permission of the American Association of Petroleum Geologists.*

the amplitude of the fold because, although the percentage of compaction is constant for crest and trough, the actual amount of compaction is greater for the thicker flank sediment (Fig. 7.12).

Differential depositional rates also enhance structural closure. Carbonate sedimentation tends to be higher in shallow, rather than deep, water; so shoal and reefal facies may pass off-structure into thinner increments of basinal lime mud. Similarly, terrigenous shoal sands may develop on the crests of structures and pass down flank into deeper water muds. Thus, reservoir quality often diminishes down the flank of such structures.

Good examples of oil fields trapped in compactional anticlines occur in the North Sea. Here, Paleocene deep-sea sands are draped over Mesozoic horsts (Blair, 1975). These fields include the Forties, Montrose, Maureen, and East Frigg fields (Fig. 7.13).

The traps of compactional and compressional anticlines are very different. As just discussed, compactional folds may have considerable variations in reservoir facies across

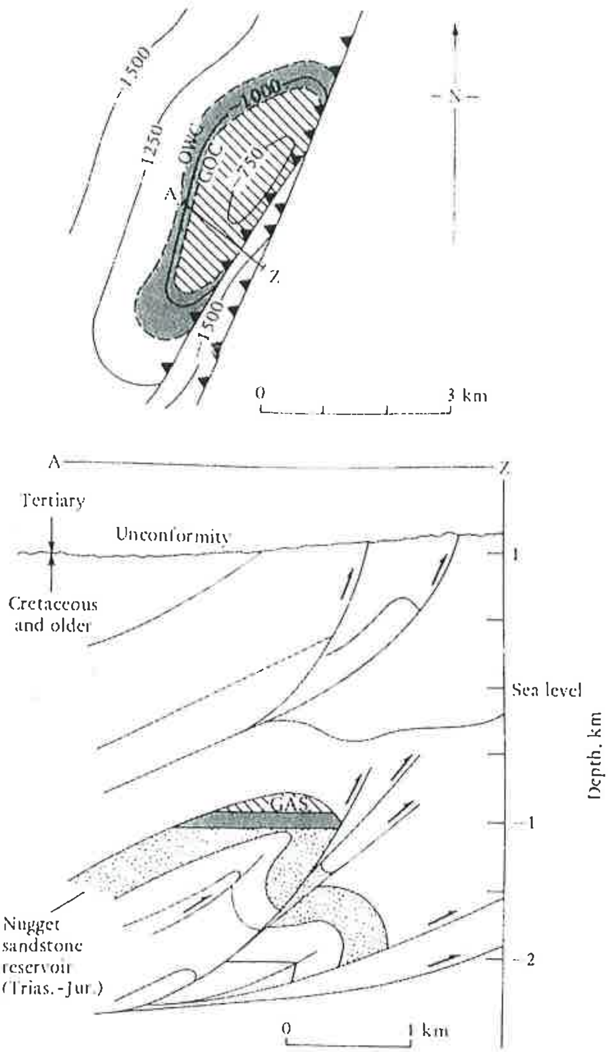


FIGURE 7.10 Map (upper) and cross section (lower) of the Painter Valley field of Wyoming. Thrust-associated compressional anticline traps such as this are becoming easier to find because of improving seismic data. *Modified from Lamb (1980), reprinted by permission of the American Association of Petroleum Geologists.*

structure. Not only can there be a primary depositional control of reservoir quality, but later diagenetic changes can be extensive, because such structures are prone to subaerial exposure, leaching, and, in extreme cases, truncation.

Whereas compressional folds are generally elongated perpendicular to the axis of crustal shortening, compactional folds are irregularly shaped, reflecting the intersection of fault trends in the basement. Compressional folds generally form in one major tectonic event,

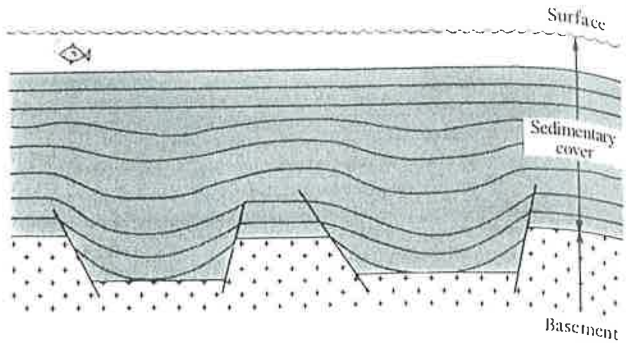


FIGURE 7.11 Cross section showing how basement block faulting causes anticlinal structures in sediments; closure decreases upward. These drape anticlines are caused by tension rather than compression.

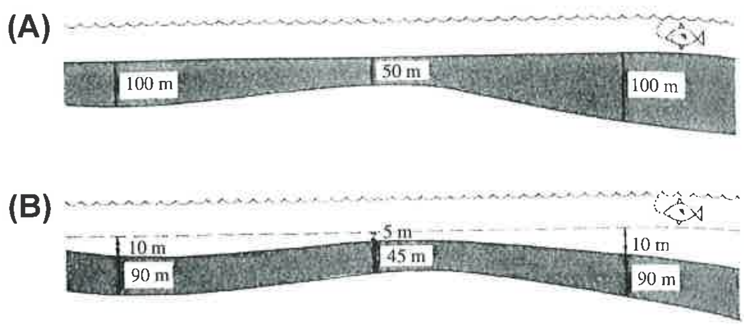


FIGURE 7.12 Cross sections showing how burial compaction enhances closure on drape anticlines. (A) Deposition and (B) after a uniform compaction of 10%.

whereas compactional folds may have had a lengthy history due to rejuvenation of basement faults as the basin floor subsided.

7.6.2 Fault and Fault-Related Traps

The identification of faults, and their significance as permeability barriers within petroleum reservoirs, was discussed at some length in Chapter 6. Faulting plays an indirect but essential role in the entrapment of many fields. Relatively few discovered fields are caused solely by faulting. A very important question in both exploration and development is whether a fault acts as a barrier to fluid movement (not only hydrocarbons but also water, which may be necessary to drive production) or whether it is permeable. The problem is that some faults seal, others do not.

Attempts to predict the nature of a fault ahead of the drill bit is a very active area of research. A few guidelines are available, but they are by no means foolproof. Where the throw of the fault is less than the thickness of the reservoir, it is unlikely to seal. Faults in brittle rocks are less likely to seal than those in plastic rocks. In lithified rocks faults may be accompanied by extensive fracturing, which may be permeable; indeed, some fields are caused solely by fracture porosity adjacent to a fault (refer back to Fig. 6.8). Sometimes, however, fractures may have undergone later cementation.

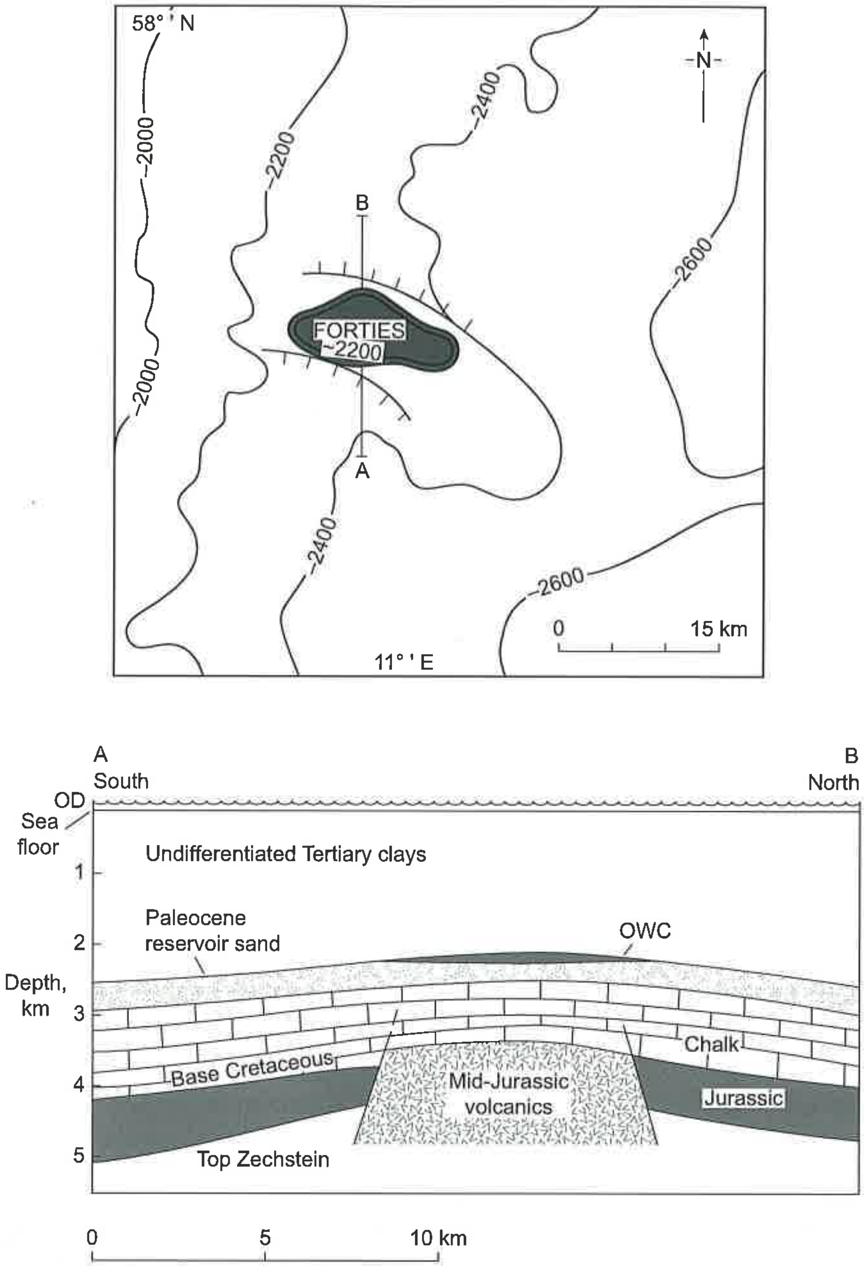


FIGURE 7.13 Map (upper) and cross section (lower) of the Forties field of the North Sea. This field is essentially a compactional anticline draped over an old basement high.

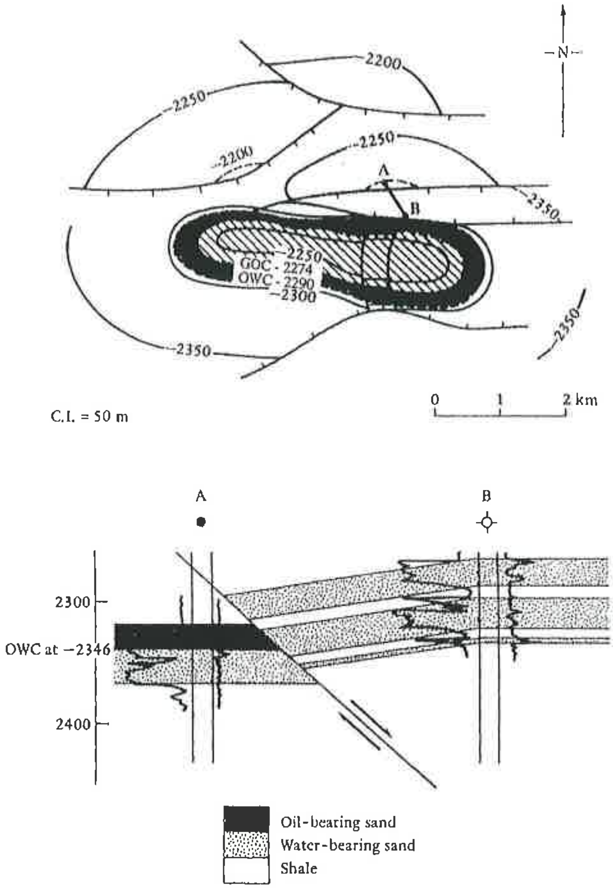


FIGURE 7.14 Map (upper) and cross section (lower) of the West Lake Verret Field, Tertiary, Louisiana. This field provides an example of a sealing fault in which oil has not moved across the fault plane, even though permeable sands are juxtaposed. *Modified from Smith (1980), reprinted by permission of the American Association of Petroleum Geologists.*

In unlithified sands and shales faults tend to seal, particularly where the throw exceeds reservoir thickness. Examples are known, however, where clay caught up in a fault plane can act as a seal even when two permeable sands are faulted against each other. This phenomenon is known from areas of overpressured sediments, such as in Trinidad, the Gulf of Mexico, and the Niger Delta, where Gibson (1994), Smith (1980), Weber and Daukoru (1975), and Berg and Avery (1995) have studied the role of faults as seals and barriers. Smith (1980) noted that in the Gulf Coast where sands were faulted against each other, the probability of the fault sealing increased with the age difference of the two sands. Figure 7.14 shows cross sections of the West Lake Verret Field in which hydrocarbon and water-bearing sands are faulted against one another. The faults do not separate sands of different facies or capillary displacement pressure, so Smith (1980) concluded that the faults sealed by virtue of impermeable material smeared along the fault planes. Particular attention is paid to the

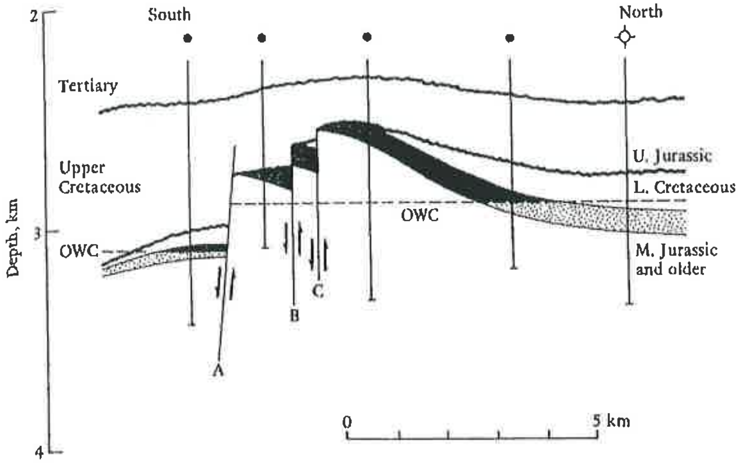


FIGURE 7.15 Cross section through the Piper Field of the North Sea showing how within the same field (A) some faults seal and (B and C) others do not. *After Williams et al. (1975).*

sand:shale ratio of the section that is faulted. This may be used in probabilistic estimations of whether faults are open or closed (Gibson, 1994). Figure 7.15 shows a complexly faulted field in which the OWCs indicate that some faults are conduits, whereas others are seals.

Because of the importance of predicting the extent to which permeable reservoir beds are juxtaposed or offset by faults, sophisticated computer packages are now available to image such scenarios (Fig. 7.16).

Bailey and Stoneley (1981) have shown that there are eight theoretical geometries for fault traps, assuming that faults do not separate juxtaposed permeable beds (Fig. 7.17). Six of these geometries may be valid traps provided that there is also closure in both directions parallel to the fault plane. Although many fields are trapped by a combination of faulting and other features, pure fault traps are rare. Figure 7.18 illustrates one example of a simple faulted trap. Fault and fault-related traps may be conveniently categorized according to whether transverse or tensional forces operate.

7.6.2.1 Traps Related to Transverse Faults

Transverse faults give rise to several distinctive types of petroleum traps (Wilcox et al., 1973). Transverse movement of basement blocks takes place along wrench faults. These movements are expressed in the overlying sediment cover in a trend of en echelon folds. Fold axes are oblique to the wrench fault and indicate its direction of movement. In some instances, fold axes may be offset by faults (Fig. 7.19). In cross section, wrench faults split upward into low-angle faults. This phenomenon is sometimes referred to *as flower structure* (Gregory, in Harding and Lowell (1979)). The Newport-Inglewood fault in the Ventura basin of California provides a classic example of petroleum entrapment in en echelon folds developed along a wrench fault (Harding, 1973).

Few wrench faults have no vertical movement. Indeed, sedimentary basins often form by rapid subsidence of one side of a wrench fault. In such settings, the folds may be present only on the basinward side of the fault and may form structural noses where they are truncated (Fig. 7.19). Examples of this type of trap occur where the southwestern flank of the San Joaquin Basin is truncated by the San Andreas Fault, California (Harding, 1974).

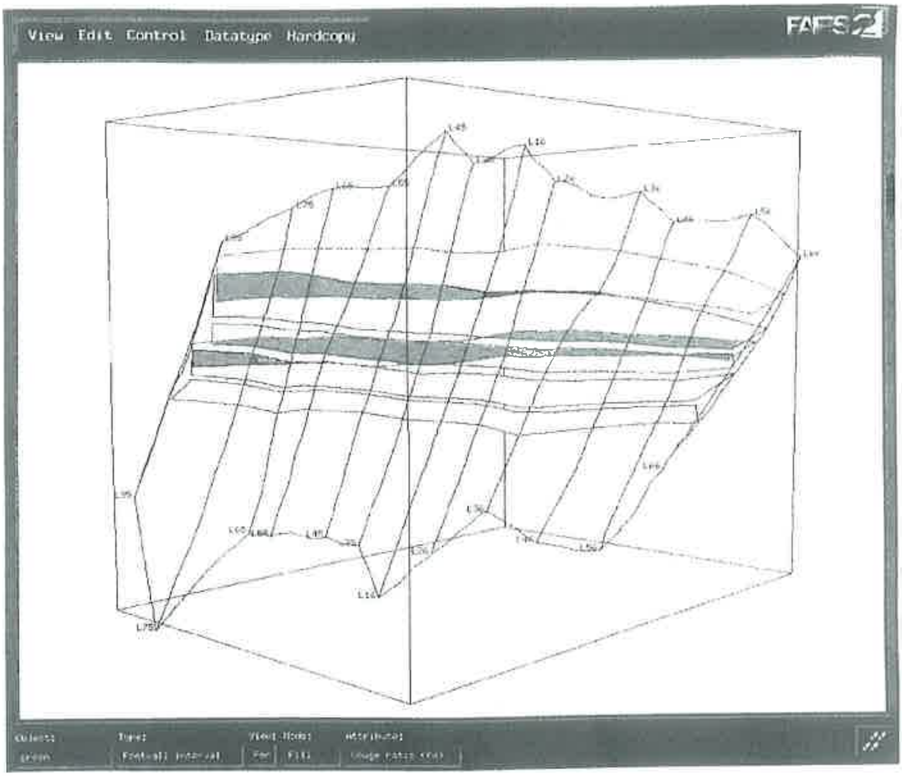


FIGURE 7.16 Computer-generated illustration to show where permeable beds are in communication across a fault plane. This is an example of the FAPS software used for the 3D display and analysis of faults developed by Badley Earth Sciences Ltd. in collaboration with the Fault Analysis Group, University of Liverpool, United Kingdom.

7.6.2.2 Traps Related to Tensional Faults

A particularly important group of traps is associated with tensional faults. In some faults the throw increases incrementally downward. This demonstrates that fault movement was synchronous with deposition. Such faults are thus termed growth faults. In plan view the fault trace is frequently curved and when viewed from the downthrown side, it is concave. Similarly, in profile the fault angle diminishes downward.

There are two types of growth fault. One type is basement-related and tends to be long in plan view and to have had a lengthy history controlling facies and sedimentation rate (Shelton, 1968). A good example of this type occurs on the flank of the Sarir Field in Libya (Fig. 7.20). One of the best known large-scale growth faults is the Vicksburg flexure, which extends for some 500 km around the Gulf Coast of Texas. The maximum increase in sediment across the fault is of the order of 1500 m near the Mexican border. Most of this thickening occurs in the Vicksburg Group (Oligocene); considerably less thickening occurs in the overlying Frio Group (Miocene).

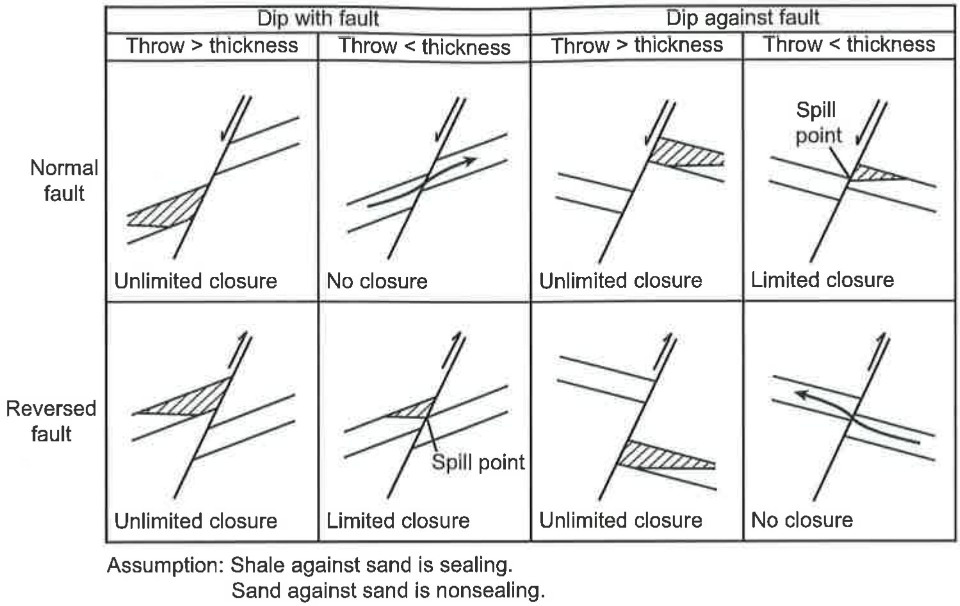


FIGURE 7.17 The eight theoretical configurations of petroleum traps associated with faulting. These configurations are drawn on the assumption that oil can move across, but not up, the fault plane when permeable sands are juxtaposed. *After Bailey and Stoneley (1981), reprinted with permission from Black-well Science Ltd.*

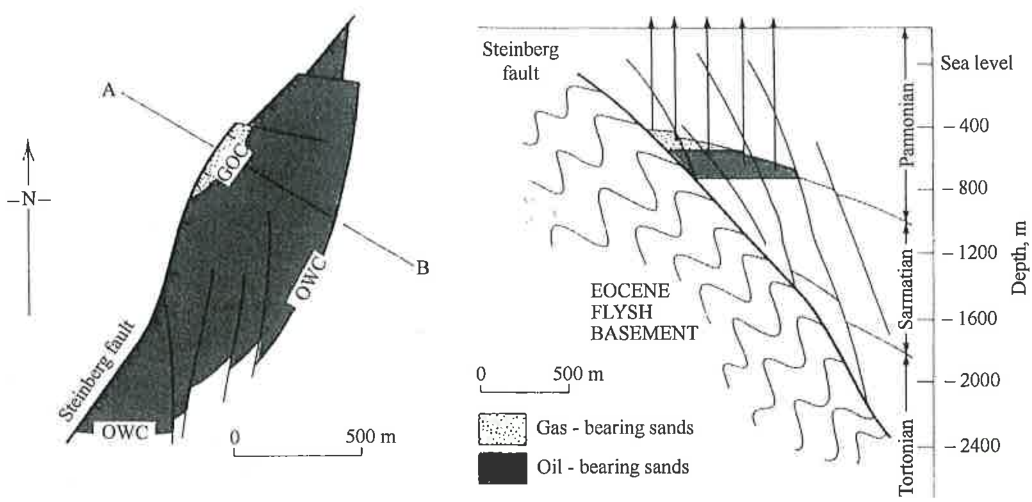


FIGURE 7.18 Map (left) and cross section (right) through a fault trap in the Gaiselberg Field, Austria. *Modified from Janoschek (1958), reprinted by permission of the American Association of Petroleum Geologists.*

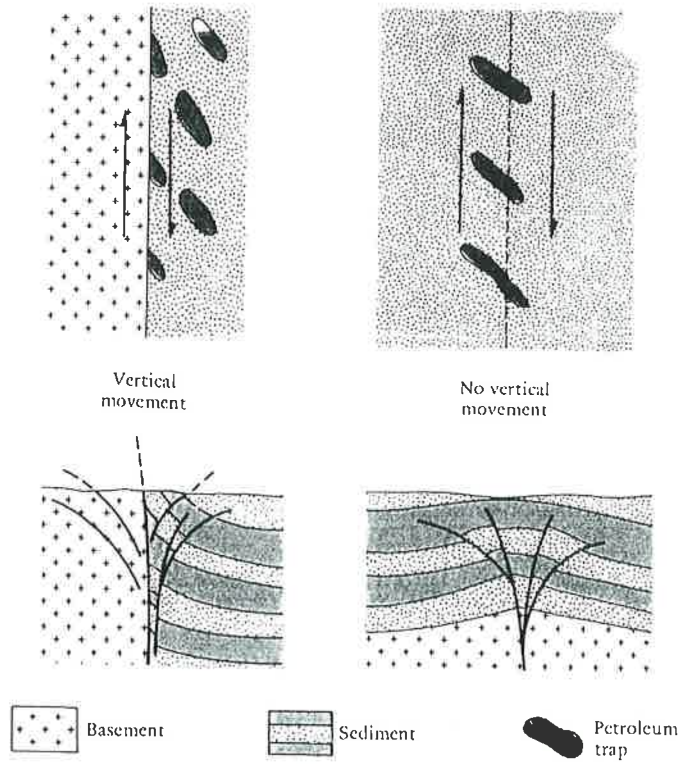


FIGURE 7.19 Maps (upper) and cross sections (lower) showing the types of petroleum traps associated with wrench faults. For examples and explanation see text.

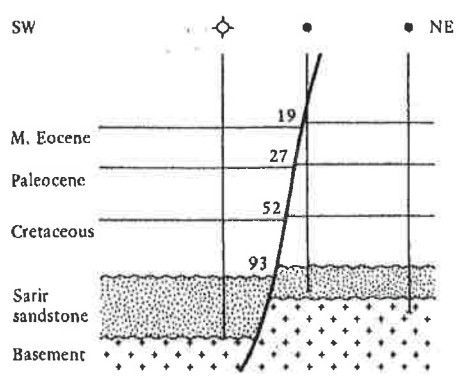


FIGURE 7.20 Cross section through a basement-related growth fault in the Sarir Field, Libya. The numbers show the throw (in meters) of the fault for various markers and demonstrate an incremental increase downward. *Modified from Sanford (1970), reprinted by permission of the American Association of Petroleum Geologists.*

Not only do formations thicken across the fault toward the Gulf but the percentage of net sand increases too. This suggests that subsidence on the downthrown side of the fault formed a natural sediment trap. Characteristically, there is a local reversal of the easterly regional dip of strata adjacent to the fault plane, with rollover anticlines developed on its downthrown side (Fig. 7.21). The strata dip toward the fault to fill the space caused by separation along the plane of the fault. The dip reversal of the anticlines is often enhanced by antithetic faults downthrown and dipping in toward the major fault.

Oil and gas are trapped both in the rollover anticlines and in sand pinchout stratigraphic traps on both upthrown and downthrown sides of the Vicksburg Fault (Halbouty, 1972). It has been estimated that some 3 billion barrels of oil and 20 trillion cubic feet of gas are trapped adjacent to the Vicksburg flexure, partly in pure fault traps, but more commonly in rollover anticlines and pinchouts.

Traced eastward into Louisiana, the Vicksburg Fault disappears beneath the clastic wedge of the Mississippi Delta. Growth-fault-related traps dominate this hydrocarbon province too, but they are different in scale and genesis. Individual faults are seldom more than a few kilometers in length; although with their curved traces, scalloped fault patterns can also occur. These faults are not basement-related, but pass downward to die out as horizontal shear planes either in overpressured shales or in the deeper Louann Salt (Triassic—Jurassic).

Similarly, in the Tertiary sediments of the Niger Delta, growth faults play a major role in the migration and entrapment of oil and gas (Evamy et al., 1978). A detailed analysis by Weber et al. (1980) was based on observation of the fault-associated fields and laboratory experiments. They concluded that in most instances growth faults were not sealing because they were associated not only with clay gangue but also with slivers of permeable sand. Migration of hydrocarbons appears to occur both up the fault plane and across it, from overpressured mature source shales into normally pressured (or at least lower-pressured) sands. In the upper part of a rollover anticline, traps may be filled to the spill point; but where sands are faulted against overpressured shale, traps may be filled to below the spill point (Fig. 7.22).

7.6.3 Relationship between Structural Traps and Tectonic Setting

The classification and account of structural traps just given are essentially descriptive and static; that is, the traps were not examined in their tectonic context. Structural traps do not occur at random. The types and distribution of structural traps are closely related to the regional tectonic setting and history of the region in which they are found.

A genetic classification of structural traps has been developed by Harding and Lowell (1979). They note that structural traps can be grouped according to the tectonic forces operating, according to whether the basement or only the detached cover is involved, and according to their habitat with respect to tectonic plates. This last classification is covered in Chapter 8. Table 7.3 presents a genetic grouping of structural traps. It shows that a major distinction is made between regions where basement and cover are attached and regions where basement and cover are detached (generally because of the presence of intervening evaporites or overpressured clays). Compressive and tensional forces can operate in both situations; the former occur at convergent plate boundaries, the latter at divergent ones. This type of genetic grouping of structural traps is more useful than a purely descriptive one. It is an exploration tool that predicts the type of structural trap to be anticipated in any given tectonic setting.

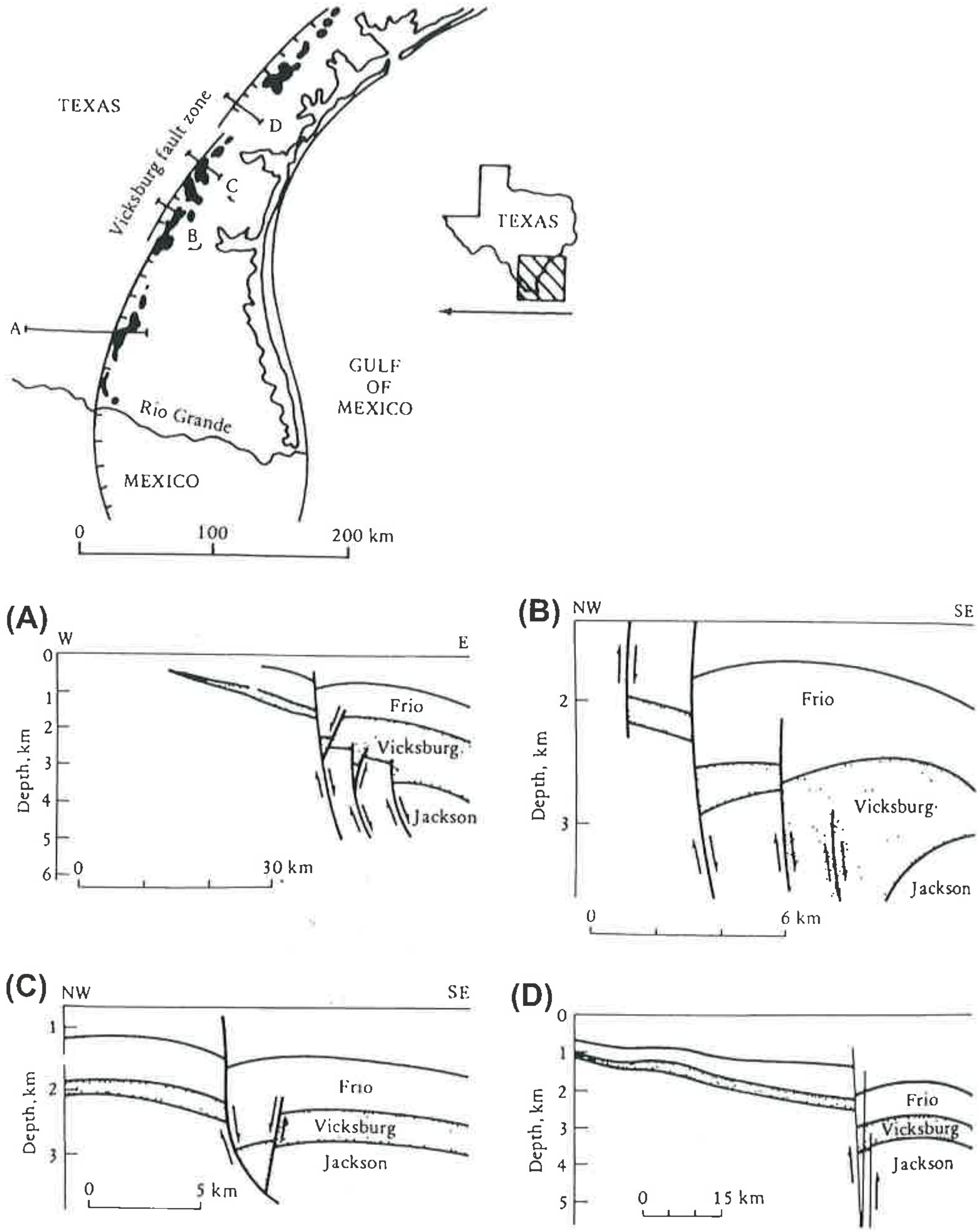


FIGURE 7.21 Map (upper) of and cross sections (lower) through the Vicksburg growth fault of South Texas. Traps associated with this structure contain estimated reserves of 3 billion barrels of oil and 20 trillion cubic feet of gas. Note how formations thicken basinward across the fault, the rollover anticlines and antithetic minor faults dipping toward the major fault. Production comes from sands in both the Vicksburg (Oligocene) and Frio (Eocene) Groups. The locations of cross-sections A, B, C & D are shown on the map. *Modified from Stanley (1970), reprinted by permission of the American Association of Petroleum Geologists.*

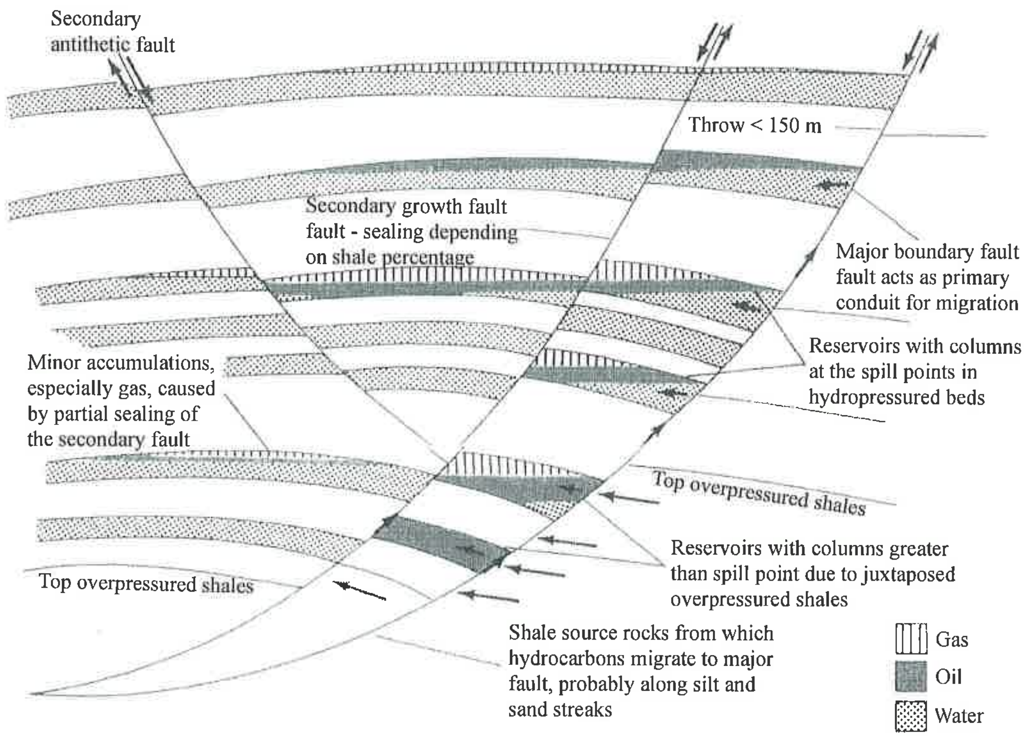


FIGURE 7.22 The mode of accumulation of oil and gas in Niger Delta growth fault traps. Unlike basement-related growth faults, this type shears out horizontally into overpressured shales. *After Weber et al. (1980).*

7.7 DIAPIRIC TRAPS

Diapiric traps are produced by the upward movement of sediments that are less dense than those overlying them. In this situation the sediments tend to move upward diapirically and, in so doing, may form diverse hydrocarbon traps. Such traps cannot be regarded as true structural traps, since tectonic forces are not required to initiate them (although in some cases they may do so). Similarly, diapirically related traps are not initiated by stratigraphic processes, although in some cases they may be caused by depositional changes across the structure. Diapiric traps are generally caused by the upward movement of salt or, less frequently, overpressured clay.

7.7.1 Salt Domes

Salt has a density of about 2.03 g/cm^3. Recently deposited clay and sand have densities less than that of salt. As the clay and sand are buried, however, they compact, losing porosity and gaining density. Ultimately, a burial depth is reached when sediments are denser than salt. Depending on a number of variables, this point may occur between about 800 and

TABLE 7.2 Genetic Grouping of Structural Traps Based on Basement—Cover Relationship, Structural Style, and Dominant Force

	Structural Style	Dominant Force
Basement involved	Wrench Fault	Couple
	Regional paleohigh	Mantle processes
	Thrust blocks and reversed faults	Compression
	Extensional fault blocks and drape anticlines	Tension
Cover detached from basement	Growth faults and rollover anticlines	
	Decollement-related structures	Compression
	Diapirs (salt and clay)	Density contrast

From Harding and Lowell (1979), reprinted with permission.

TABLE 7.3 Classification of Stratigraphic Traps

I.	Unassociated with unconformities	Depositional / Diagenetic	Pinchouts, Channels, Bars, Reefs
			Porosity and/or permeability transition
II.	Associated with unconformities	Supraunconformity / Subunconformity	On lap, Strike valley, Channel
			Truncation

From Rittenhouse (1972), reprinted with permission.

1200 m (Fig. 7.23). When this point is reached, the salt will tend to flow up through the denser overburden. This movement may be triggered tectonically, and the resultant structures may show some structural alignment. In other instances, however, the salt movement is apparently random. The exact mechanics of diapiric movement has been studied by observation, experiment, and mathematical calculation over many years (e.g., Halbouty, 1967; Berner et al., 1972; Bishop, 1978; Alsop et al., 1995; Jackson et al., 1996).

In some salt structures the overlying strata are only updomed, whereas in others the salt actually intrudes its way upward; the latter are referred to as piercement structures. In some instances the salt may actually reach the surface, forming solution sinks in humid climates and salt glaciers in arid climates (like Iran) (Kent, 1979). Salt movement, or *halokinesis*, plays an important role in the entrapment of oil and gas in the US Gulf Coast, Iran, and the Arabian Gulf and the North Sea. Oil and gas may be trapped by salt movement in many ways (Fig. 7.24). In the simplest cases subcircular anticlines may trap hydrocarbon over the crest of a salt dome. Notable examples of this type include Ekofisk and associated fields of offshore

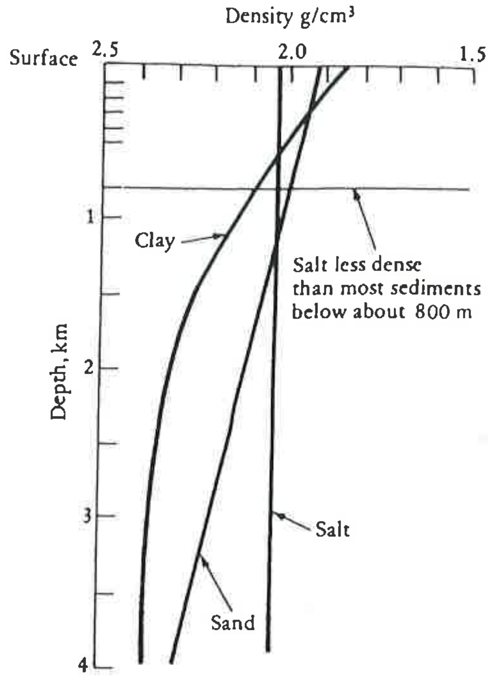


FIGURE 7.23 Density–depth curves for sand, clay, and salt. The graph shows that salt is less dense than other sediments below about 800 m, and salt movement may therefore be anticipated once this burial depth has been reached.

Norway and Denmark (Fig. 7.25). The crestal dome may be complicated by radial faults or a central graben. Around the flank of the dome, oil or gas can be trapped by faults, both sediment against sediment and sediment against salt, and by stratigraphic truncation, pinchout, and onlap. Some salt domes are pear or mushroom shaped in cross section, and petroleum is trapped beneath the peripheral overhang zone.

As the salt moves upward, a cap of diagenetically produced limestone, dolomite, and anhydrite often develops (Kyle and Posey, 1991). This cap may contain oil and gas in fractures. When a salt dome moves up close to the earth's surface, its crest may be dissolved by groundwater. Overlying sediments may collapse into the space thus formed, so giving rise to solution-collapse breccias. Ultimately, these too may act as petroleum reservoirs.

In the Arabian Gulf today coral atolls grow above salt domes (e.g., Das Island), and analogues containing oil and gas are present in the subsurface. When a salt dome moves upward, a concentric rim-syncline may form where the adjacent salt once was. In some instances the rim-syncline may be infilled by sand. Subsequent salt movement and shale compaction may result in structural closure of the sand. This phenomenon is sometimes referred to as a sedimentary anticline (i.e., of atectonic origin) or turtle-back (Fig. 7.26). These structures are essentially residual highs caused by adjacent salt moving into domes. The Bryan Field of Mississippi is one example of a turtle-back trap (Oxley and Herliny, 1972).

From the preceding account it is apparent that traps associated with salt domes can be very complex indeed. Not only are there many different trap situations but any one salt

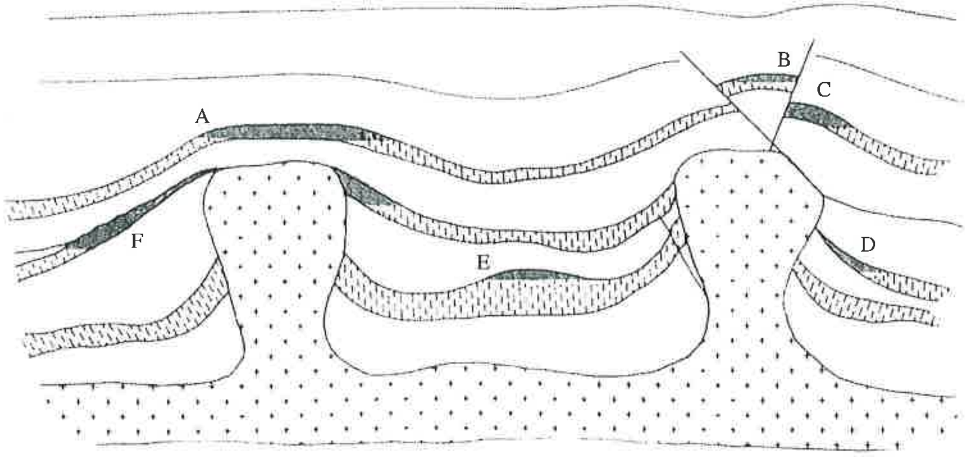


FIGURE 7.24 Crustal cross section illustrating the various types of trap that may be associated with salt movement: (A) domal trap; (B and C) fault traps; (D) pinchout trap; (E) turtle-back or sedimentary anticline; and (F) truncation trap.

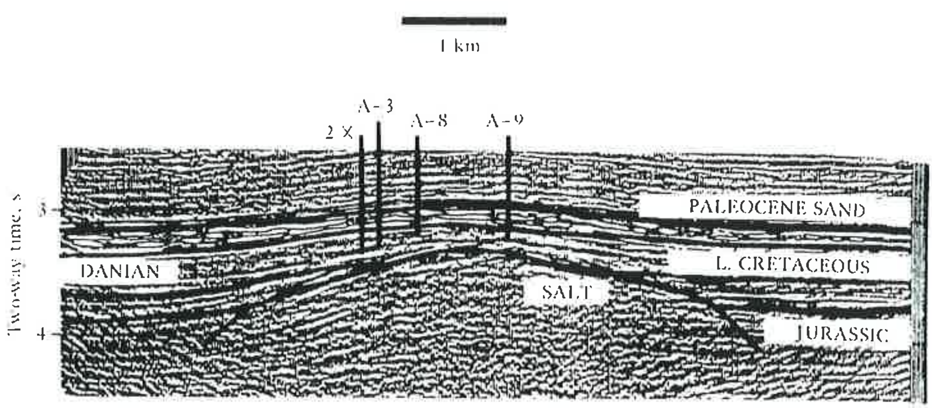


FIGURE 7.25 Seismic cross section through the Cod Field in the Norwegian sector of the North Sea. This structure is an example of a salt dome trap. Production comes from Paleocene deep-sea sands. *From Kessler et al. (1980).*

dome may host many separate traps of different types. Although the total reserves pertaining to one diapir can be vast, they may be contained in many separate accumulations. Each accumulation may have its own fluid and pressure characteristics. Individual oil columns may be high because of steeply dipping beds; individual pressures may be high because of the forces set up by the salt movement itself. A salt dome can be easily located by gravity or seismic methods. Once found, however, the associated traps may be too small to be delineated by present-day seismic resolution.

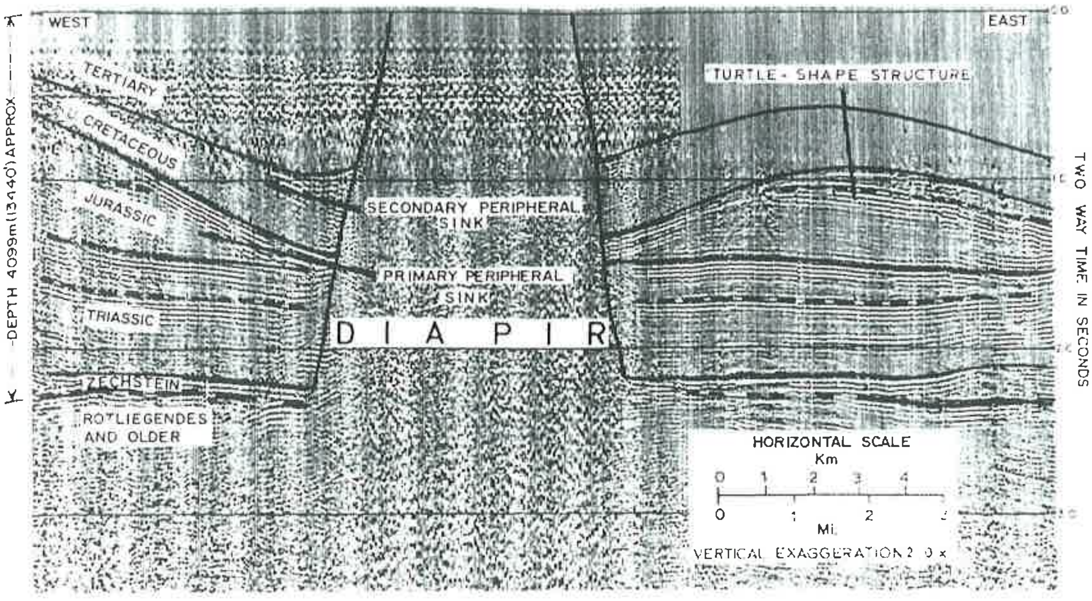


FIGURE 7.26 Seismic line through a Zechstein (Upper Permian) salt dome in the southern North Sea, showing rim-syncline due to salt withdrawal and associated turtle-back structure. *From Christian (1969).*

7.7.2 Mud Diapirs

The foregoing account deals largely with diapirs formed by salt. Diapiric mud structures also exist, and they too may generate hydrocarbon traps. Overpressure and overpressured shales were discussed earlier. By its very nature, an overpressured shale has a higher porosity and therefore a lower density than does normally compacted clay.

As already discussed, prodelta clays may be overpressured because of rapid burial beneath an advancing prism of deltaic sediment. This sediment thus becomes unstable, tending to slump seaward over the clays beneath it. This slumping is associated with growth faulting.

Sometimes diapirs of overpressured clay intrude the younger, denser cover, and, like salt domes, these mud lumps may even reach the surface. Mud diapirs are known from the Mississippi, Niger, Mackenzie, and other recent deltas and are less common, but not absent, from pre-Tertiary deltas (Fig. 7.27). Many of these mud diapirs have hydrocarbons trapped in ways analogous to those previously described for salt domes (e.g., the Beaufort Sea of Arctic Canada).

7.8 STRATIGRAPHIC TRAPS

Another major group of traps to be considered are the stratigraphic traps, whose geometry is due to changes in lithology. Such changes may be caused by the original deposition of the rock, as with a reef or channel. Alternatively, the change in lithology may be postdepositional, as with a truncation or diagenetic trap.

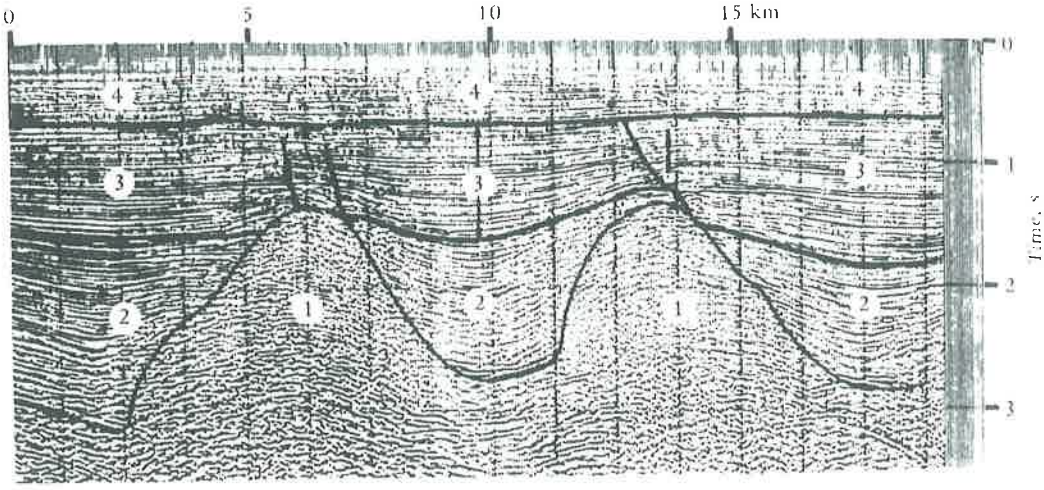


FIGURE 7.27 Cross section illustrating overpressured clay diapirs in a regressive deltaic sequence. *From Dailly (1976), with permission from the Canadian Society of Petroleum Geologists.*

The concept of the stratigraphic trap was first enunciated by Carll (1880) when he realized that the entrapment of oil in the Venango sands of Pennsylvania could not be explained by the then-prevailing anticlinal theory. Clapp (1917), in his second classification of oil fields, included lenticular sand and pinchout traps. The term *stratigraphic trap* was first coined by Levorsen in his presidential address to the American Association of Petroleum Geologists at Tulsa in 1936. He defined a stratigraphic trap as "one in which the chief trap-making element is some variation in the stratigraphy, or lithology, or both, of the reservoir rock, such as a facies change, variable local porosity and permeability, or an up-structure termination of the reservoir rock, irrespective of the cause" (Levorsen, 1967). For reviews of the evolution of the term and concept of the stratigraphic trap, see Dott and Reynolds (1969) and Rittenhouse (1972).

Stratigraphic traps are less well known and harder to locate than structural traps; their formation processes are even more complex. Nonetheless, as with structural traps a broad classification of different types can be made. Table 7.2 shows a scheme based on that of Rittenhouse (1972). Like most classifications it has its limitations, since many fields represent transitional steps between clearly defined types. It does, however, provide a convenient framework for the following account of stratigraphic traps. Major sources of data on stratigraphic traps are found in King (1972), Busch (1974), and Conybeare (1976).

7.8.1 Stratigraphic Traps Unrelated to Unconformities

Table 7.2 shows that a major distinction can be made between stratigraphic traps associated with unconformities and those occurring within normal conformable sequences. This distinction itself is somewhat arbitrary, since some types of trap, such as channels and reefs, occur both at unconformities and within conformable sequences. Those traps that do not necessarily require an unconformity are considered in this section. In this group the major distinction is between traps due to deposition and traps due to diagenesis. The depositional traps (the facies change traps of Rittenhouse) include channels, bars, and reefs. Diagenetic traps are due to porosity and permeability changes caused by solution and cementation. These various types of traps are discussed and illustrated as follows.

7.8.1.1 Channel Traps

Many oil and gas fields are trapped within different types of channels. Before examining examples of these fields, some background information is necessary. A channel is an environment for the transportation of sand, which may or may not include sand deposition. Thus, whereas a barrier island will always be made of sand, channels are frequently clay plugged. This situation is not necessarily bad, because the channel fill may act as a permeability barrier and thus trap hydrocarbons in adjacent porous beds. Therefore, finding a channel is not a guarantee of finding a reservoir. Also, channels occur both cut into unconformities and within conformable sequences (although it could be argued that, by definition, a channel is a *prima facie* case for the existence of some kind of depositional break).

Many good examples of channel stratigraphic traps occur in the Cretaceous basins along the eastern flanks of the Rocky Mountains, from Alberta down through Montana, Wyoming, Colorado, and New Mexico (Harms, 1966). These traps occur both cut into a major sub-Cretaceous unconformity and within the Cretaceous beds. The South Glenrock oil field of Wyoming serves as a typical example illustrating many of the characteristics of these fields (Curry and Curry, 1972). The South Glenrock field occurs in a syncline, which partly underlies a thrust block of Precambrian basement. The field contains oil trapped in both barrier bar and fluvial channel reservoirs. Only the latter is considered here. The channel has a width of some 1500 m and a maximum depth of some 15 m. It has been mapped for a distance of more than 15 km and shows a meandering shape (Fig. 7.28). The channel is partly infilled by sand and partly clay plugged. The SP curve on some wells suggests upward-fining point bar sequences. The channel is cut into the marine Skull Creek shale and is overlain by the marine Mowry shale. Immediately above the channel sand are thin, marine bar sand reservoirs. There can be no doubt about the channel origin of the lower reservoir, and, with its meandering geometry, there can be little argument as to its fluvial environment. This example demonstrates two main points. First note the scale: With a thickness of 15 m and a width of 1500 m, such reservoirs are not the hosts to giant oil accumulations. Second, because of the partial clay plug, only part of the channel is actually reservoir.

Oil is also trapped in channels other than fluvial ones. Perhaps, one of the best examples is Busch's (1961, 1971) illustration of oil fields in the deltaic distributary channels of Oklahoma (Fig. 7.29).

In the old days, channel traps could only be found by serendipity because it was so hard to predict the geometry and trend of sands in the subsurface. With modern seismic surveys, however, channels can be mapped on 2D and 3D surveys. Figure 7.30 illustrates a channel subtly imaged on a 2D seismic line. 3D examples are much more dramatic (see, for example, Brown, 1985; Rijks and Jauffred, 1991).

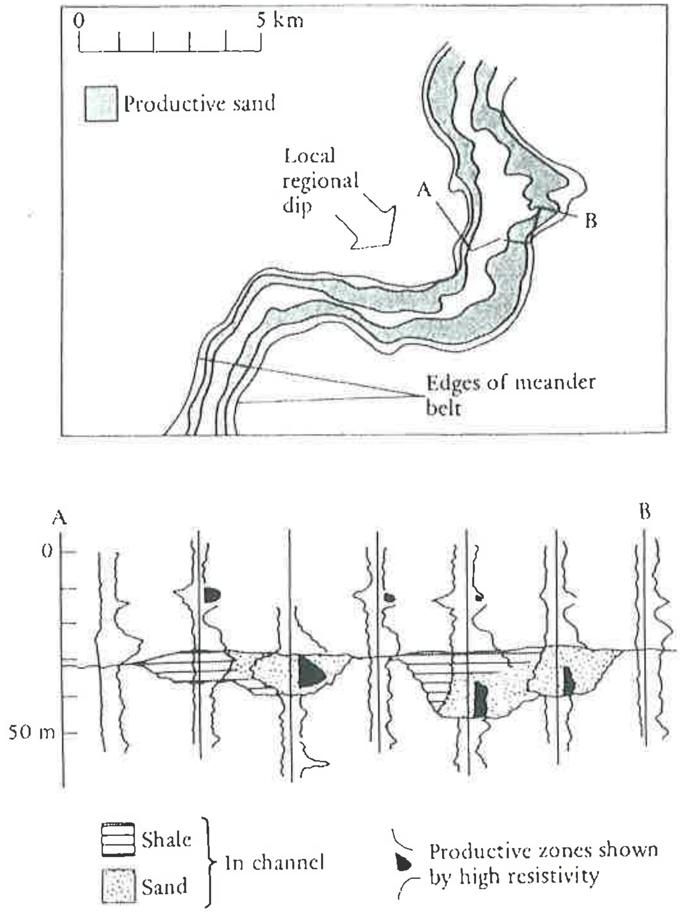


FIGURE 7.28 Map and cross section of the Cretacous South Glenrock oil field, Powder River Basin, Wyoming. Note the small dimensions of the reservoir and that not all of the channel contains sand. *Modified from Curry and Curry (1972), reprinted by permission of the American Association of Petroleum Geologists.*

7.8.1.2 Barrier Bar Traps

Marine barrier bar sands often make excellent reservoirs because of their clean, well-sorted texture. Coalesced barrier sands may form blanket sands within which oil may be structurally trapped. Sometimes, however, isolated barrier bars may be totally enclosed in marine and lagoonal shales. These barrier bars may then form shoestring stratigraphic traps parallel to the paleoshoreline. Many examples of this type of trap are known, but one of the classics is the Bisti field described by Sabins (1963, 1972). This field occurs in Cretaceous rocks of the San Juan Basin, New Mexico. Three stacked sand bars, with an aggregate thickness of only about 15 m, occur totally enclosed in the marine Mancos shale. The field is about 65 km long and 7 km wide. In some wells the three sands merge totally and cannot be

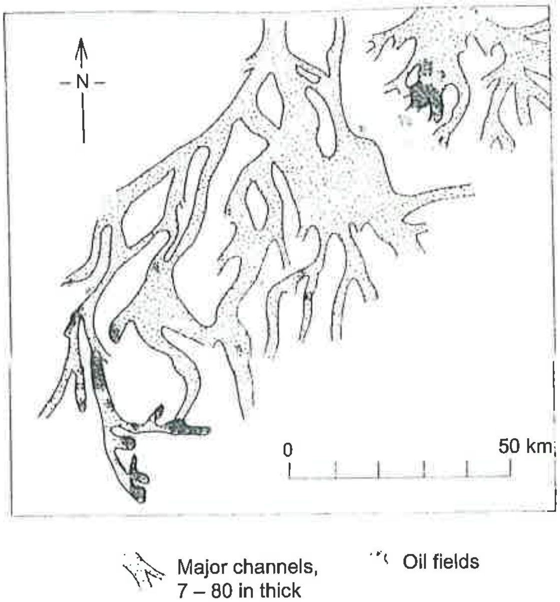


FIGURE 7.29 Map of the Booch delta, Seminole Country, Oklahoma. This celebrated study shows how oil is stratigraphically trapped in the axes of a major Pennsylvanian (Upper Carboniferous) delta distributary channel system. This type of map can only be constructed with imagination and ample well control. *Modified from Busch (1961), reprinted by permission of the American Association of Petroleum Geologists.*

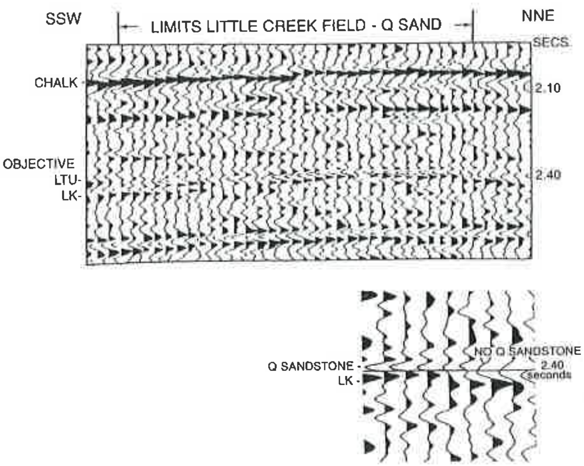


FIGURE 7.30 Seismic lines through the Little Creek Field, Mississippi. The discovery well was located to test a closure at the stippled Lower Tuscaloosa horizon (LTU) on the upper line. It located the Little Creek Field serendipitously. The extent of the field was subsequently determined by carefully mapping one negative amplitude event (seismic line lower right). *(From Werren et al. (1990), with permission from Springer-Verlag.)* This is a subtle trap. 3D seismic surveys show channels more dramatically (e.g., Brown, 1985; Rijks and Jauffred, 1991).

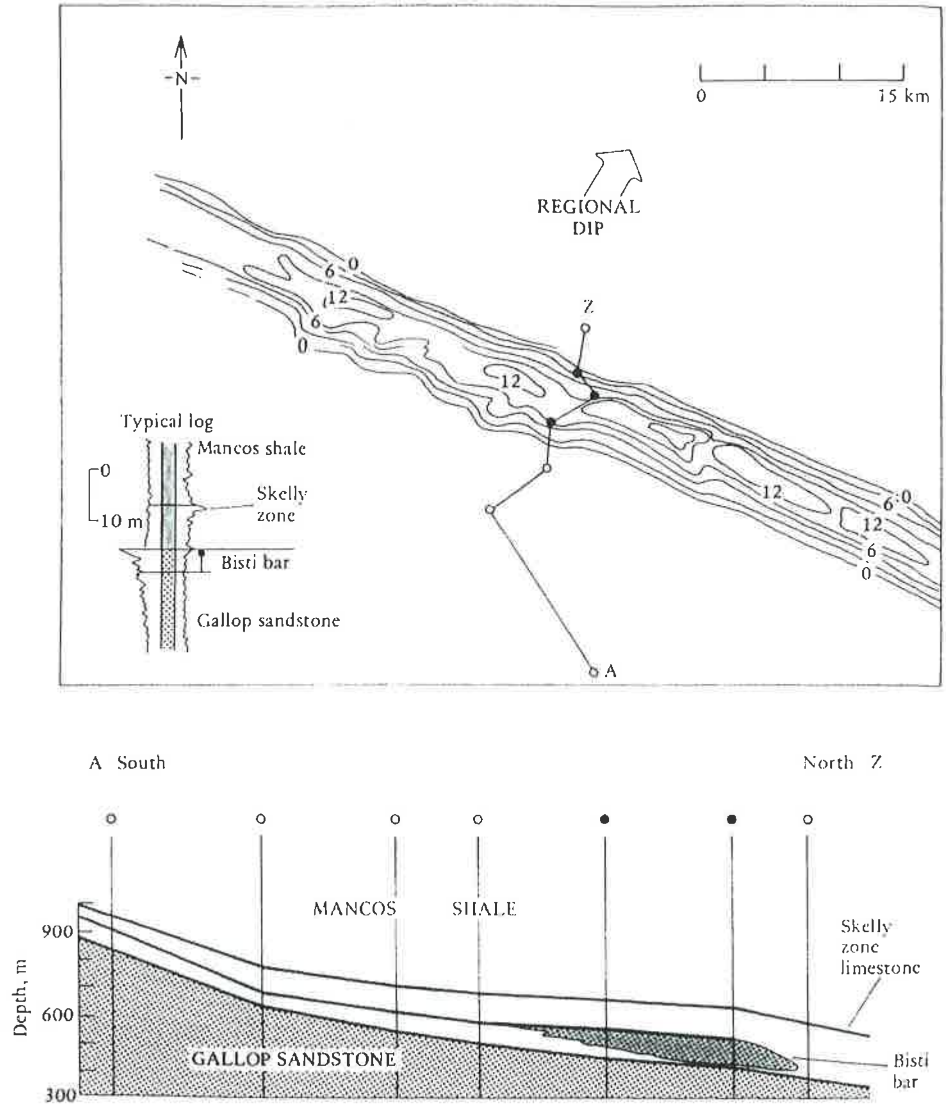


FIGURE 7.31 Isopach map of typical log and cross section of the Bisti field (Cretaceous) of the San Juan Basin, New Mexico. This field is a classic example of a barrier bar stratigraphic trap. Note the regressive upward-coarsening grain-size motif shown on the SP curve. *Modified from Sabins (1972), reprinted by permission of the American Association of Petroleum Geologists.*

separated. SP logs show typical upward-coarsening bar sand motifs in some of the wells (Fig. 7.31).

Barrier bar sand traps occur in many of the Rocky Mountain Cretaceous basins, ranging from the Viking sands of Alberta and Saskatchewan in the north (Evans, 1970; Cant, 1992, p. 13), via the Powder River Basin of Montana and Wyoming (Asquith, 1970; Woncik, 1972),

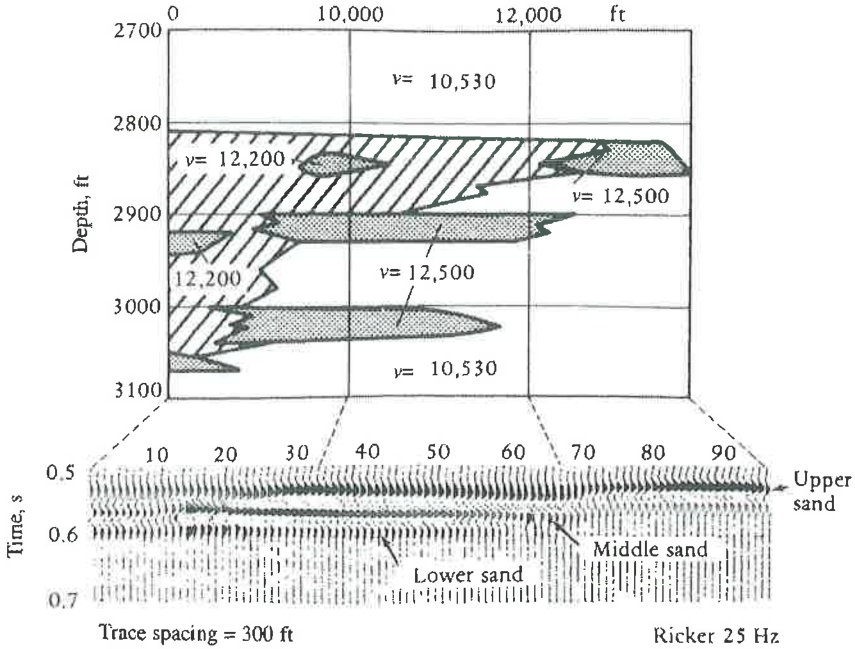


FIGURE 7.32 Geological model (upper) and computer-simulated seismic lines (lower) for regressing coastal barrier island sands. *From Meckel and Nath (1977), namely Fig. 27, p. 434.*

to the Denver Basin, Colorado (Tobison, 1972; Weimer and Davis, 1977) and the San Juan Basin of New Mexico (Hollenshead and Pritchard, 1961; Sabins, 1963, 1972).

As with channel traps, in the old days barrier bar fields were normally only found by serendipity. Today, however, cunning seismic techniques can be used to locate such subtle features (Fig. 7.32).

7.8.1.3 Pinchout Traps

Isolated barrier bar shoestring stratigraphic traps like those of the Bisti field are rare. Generally, a regressing barrier island deposits a sheet of sand. This sand may form a continuous reservoir, although in some instances shale permeability barriers may separate successive progradational events. Where these sheet sands pass updip into lagoonal or intertidal shales, they may give rise to pinchout, or feather edge, traps. Note that for these traps to be valid, they also need some closure in both directions along the paleostrike. This closure may be stratigraphic (where, as shown in the example in Fig. 7.33, the shoreline has an embayment) or structural, in which case the field should more properly be classified as a combination trap, rather than a stratigraphic trap.

Barrier bar sands, sheets, and shoestrings often occur as an integral part of major regressive–transgressive cycles. Sands are thickest and best developed in the regressive phase, and tend to occur only as discrete shoestrings during the transgressions. Examination of the Rocky Mountain Cretaceous basins shows that the transgressive sands tend to make the best traps.

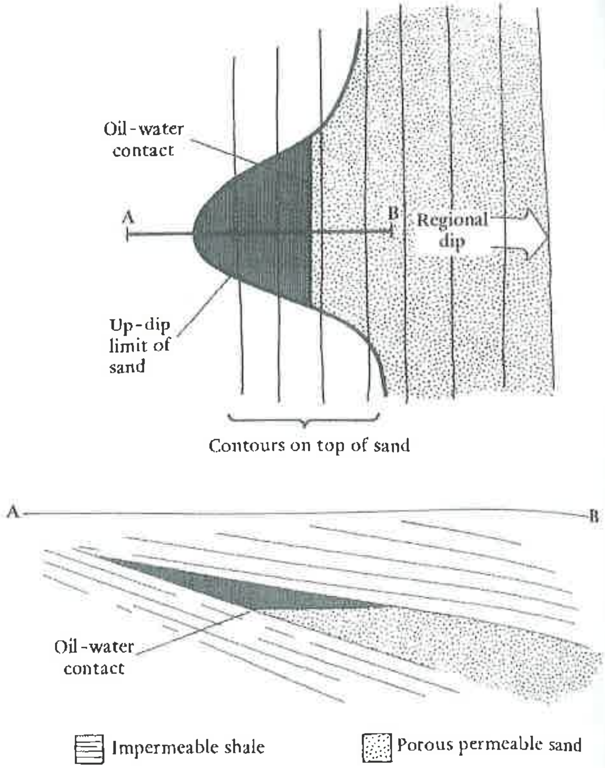


FIGURE 7.33 Cross section and map showing a stratigraphic pinchout trap. Note that this example is a pure stratigraphic trap because of the embayment of the coast. Usually, some structural closure on top of the sand forms a combination trap.

The regressive sands tend to lack updip seals as they pass shoreward into channel sands. The transgressive sands, by contrast, pass updip into sealing lagoonal and tidal flat shales (Mackenzie, 1972) (Fig. 7.34).

More complex pinchout traps can occur where both barrier bar and channel sands are in fluid communication with one another. The Bell Creek field (Cretaceous) of the Powder River Basin is an example of this type of trap (Berg and Davies, 1968; McGregor and Biggs, 1972). It lies on a basin margin where stratigraphic traps can be mapped in fairways of fluvial channels, and deltaic and bar sands (Fig. 7.35). The Bell Creek field is one of the few stratigraphic traps of "giant" status, with reserves of over 200 million barrels. It occurs at the mouth of the major river estuary in a complex of productive channel and barrier bar sands that interfinger with nonproductive marsh and lagoon muds and sands (Fig. 7.36). This complexity of reservoir geometry has lead to the occurrence of several GOC and OWC.

7.8.1.4 Reefs

Reefs, or carbonate buildups (to use a nongenetic term), have long been recognized as one of the most important types of stratigraphic traps. Modern reefs have been intensely studied by biologists and geologists (e.g., Maxwell, 1968; Jones and Endean, 1973), and accounts of ancient reefs are found in most sedimentology textbooks (see also Laporte (1974)).

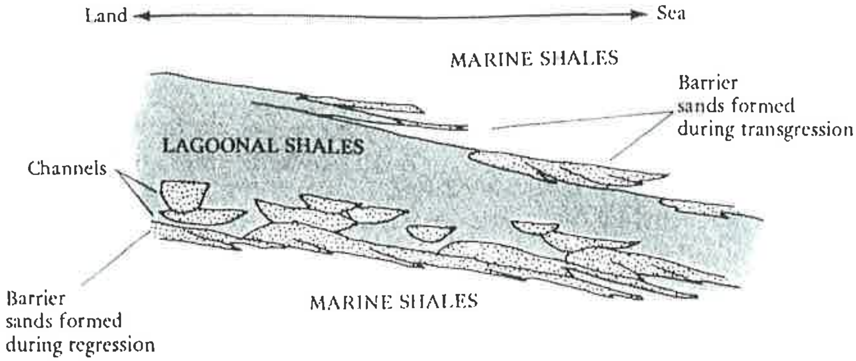


FIGURE 7.34 Cross section of regressive–transgressive shoreline deposits showing how barrier sands deposited during transgression can form stratigraphic traps due to updip lagoonal shale seal. Barrier sands formed during regressions lack updip seals, being in communication with channel sands. *Modified from Mackenzie (1972), reprinted by permission of the American Association of Petroleum Geologists.*

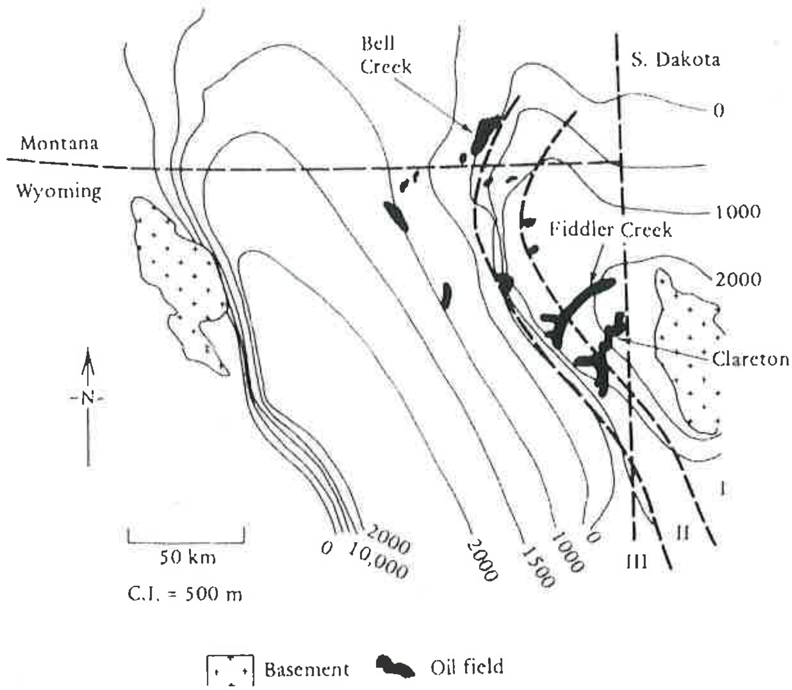


FIGURE 7.35 Map of the Powder River Basin of Wyoming and Montana, USA, contoured on top of the Fall River Sandstone (Cretaceous) showing productive fairways of stratigraphic traps: (I) fluvial channels, (II) deltaic distributary channel systems, and (III) marine bar sands. *Modified from Woncik (1972) and McGregor and Biggs (1970), reprinted by permission of the American Association of Petroleum Geologists.*

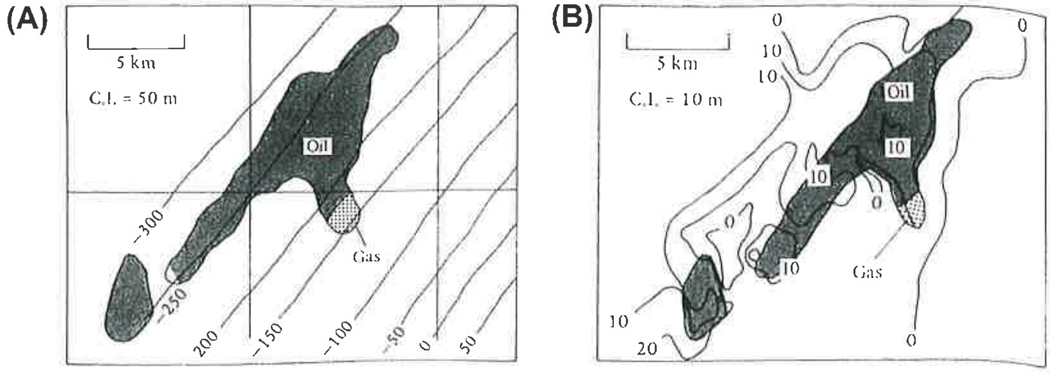


FIGURE 7.36 Maps of the Bell Creek giant stratigraphic trap (for location, see Fig. 7.30). (A) Structure contour map on top of the Muddy sand (the main reservoir) showing lack of structural control on the field boundaries. *(Modified from McGregor and Biggs (1970), reprinted by permission of the American Association of Petroleum Geologists.)* (B) Gross sand isopach. Basically an up-dip pinchout trap, the Bell Creek reservoir consists of a complex of marine shoreface and fluviodeltaic channel sands with multiple fluid contacts.

Reefs develop as domal (pinnacle) and elongated (barrier) antiforms. They grow a rigid stony framework with high primary porosity, and they are frequently transgressed by marine shales, which may act as hydrocarbon source rocks. Small wonder, then, that few identified reef traps have been left undrilled. To show the characteristics of this type of stratigraphic trap, some examples of reef fields are examined as follows.

Many reef fields occur in the Sirte Basin of Libya, although not all of these have been published. One group, the Intisar (formerly Idris) fields, has been described by Terry and Williams (1969) and Brady et al. (1980). Five pinnacle reefs were located in a concession of 1880 km^2. Each reef is only about 5 km in diameter, but up to 400 m thick; that is, the reefs build up in thickness from 0 to 400 m in a distance of about 2500 m. Of the five reefs located and tested, only two were found to contain oil (Fig. 7.37).

Figure 7.38 shows the "A" reef in cross section, demonstrating how the reef began to form as a biostrome of algal—foraminiferal wackestone on a platform of tight nonreef limestone. A reef (largely made of corals and encrusting algae) began to grow at one point on the biostrome. It first grew upward and then prograded over a coralline biomicrite, which had formed as a forereef talus of its own detritus. Now compare the upper and lower halves of Fig. 7.38. There is little obvious correlation between facies and petrophysics. As discussed in Chapter 6, extensive diagenesis is characteristic of carbonate reservoirs. Therefore, it is common to find secondary porosity whose distribution is unrelated to the primary porosity with which the sediment was deposited.

Thus the Intisar reefs demonstrate the two main problems of reef stratigraphic traps: (1) Not all reefs contain hydrocarbons and (2) those that do may have reservoir characteristics unrelated to depositional facies. Nonetheless, many reef hydrocarbon provinces exist around the world, notably in the Arabian Gulf, Western Canada, and Mexico.

In common with sandstone stratigraphic traps, reefs were very hard to locate in the subsurface until the advent of geophysics. Gravity surveys were an early effective exploration

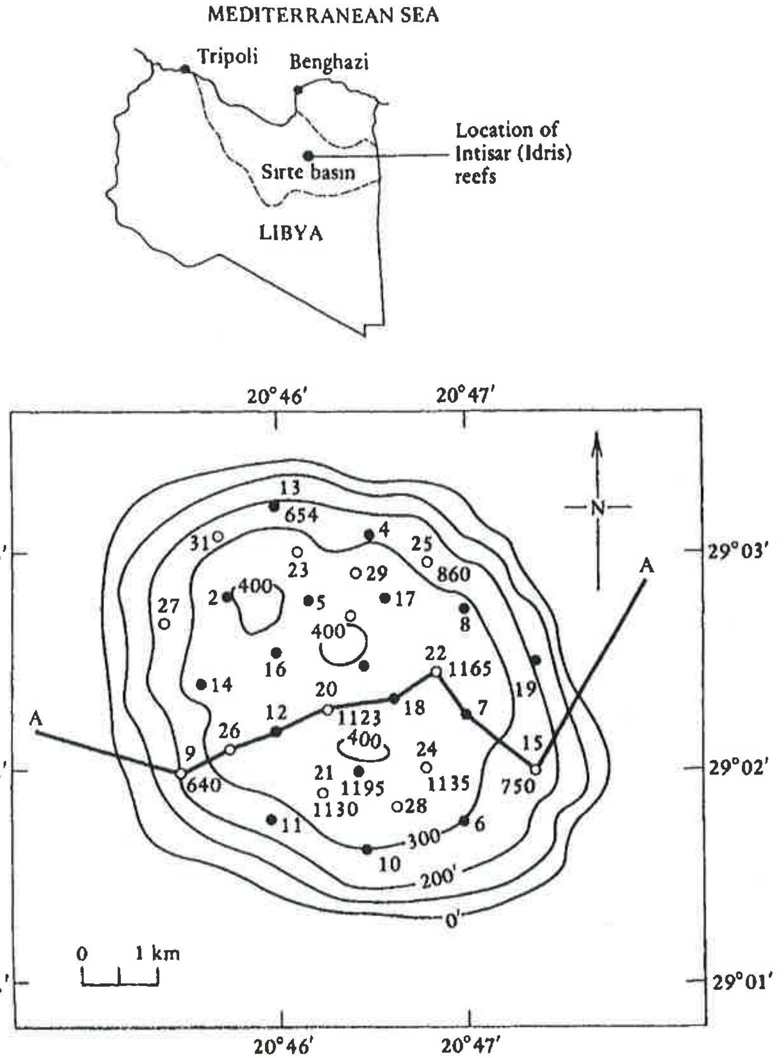


FIGURE 7.37 Isopach map of the Idris "A" reef, Sirte Basin, Libya. *After Terry and Williams (1969).*

tool (e.g., Ferris, 1972), but are now surplanted by 2D and 3D seismic surveys (see Fig. 7.39 and Plate 3).

7.8.1.5 Diagenetic Traps

Diagenesis plays a considerable role in controlling the quality of a reservoir within a trap. As discussed in Chapter 6, solution can enhance reservoir quality by generating secondary porosity, whereas cementation can destroy it. In some situations diagenesis can actually generate a hydrocarbon trap (Rittenhouse, 1972). Oil or gas moving up a permeable carrier

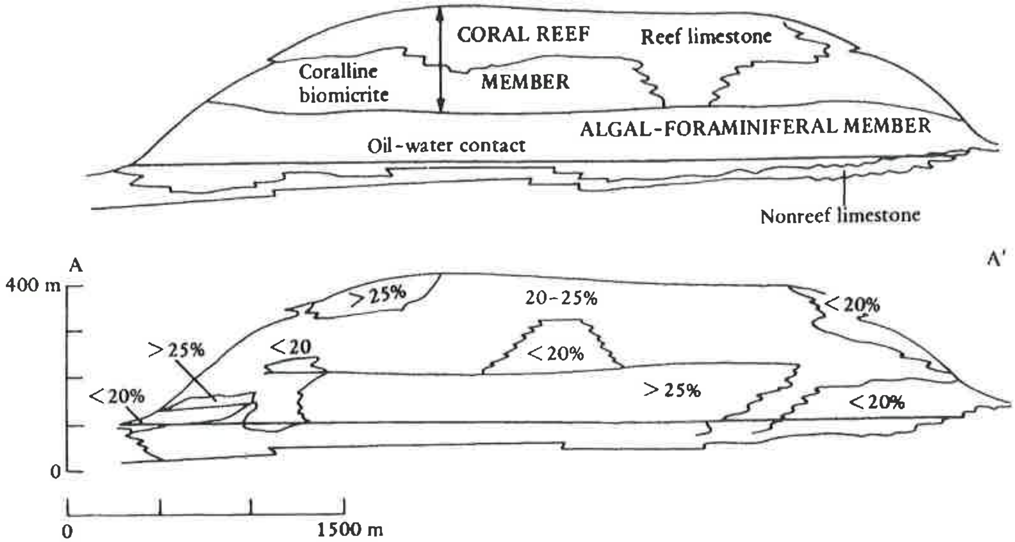


FIGURE 7.38 Cross sections of the Idris "A" reef showing facies (upper) and porosity distribution (lower). Note the lack of correlation between the cross sections, a common problem of carbonate reservoirs. *After Terry and Williams (1969).*

bed may reach a cemented zone, which inhibits further migration (Fig. 7.40(A)). Conversely, oil may be trapped in zones where solution porosity has locally developed in a cemented rock (Fig. 7.40(B)). Secondary dolomitization can generate irregular diagenetic traps as the dolomite takes up less space than the original volume of limestone.

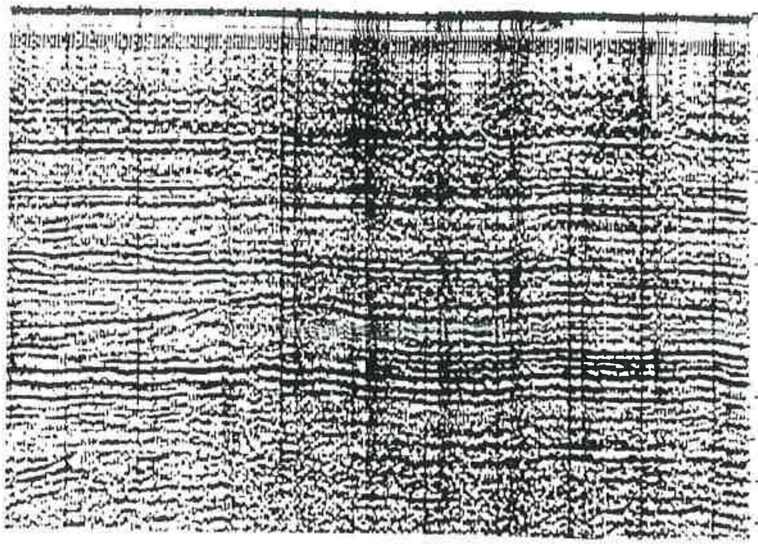
Diagenetic traps are not formed only by the solution or precipitation of mineral cements. As oil migrates to the surface, it may be degraded and oxidized by bacterial action if it reaches the shallow zone of meteoric water. Cases are known where this tarry residue acts as a seal, inhibiting further updip oil migration (Fig. 7.40(C)). The Shuguang oil field in the Liaohe Basin is an example of a diagenetic trap caused by shallow-oil degradation (Ma Li et al., 1982).

Traps that owe their origin purely to diagenesis are rare, although there are probably a number of diagenetic traps around the world whose origin has gone unrecognized, and many are yet to be found (Wilson, 1977). Many traps, however, are due to a combination of diagenesis and one or more other causes. This type of origin is particularly true of the subunconformity traps discussed in the next section.

7.8.2 Stratigraphic Traps Related to Unconformities

The channel, bar, reef, and diagenetic traps just described can occur both in conformable sequences and adjacent to unconformities. The first three types often overlie unconformities, whereas diagenetically assisted traps underlie them.

The role of unconformities in the entrapment of hydrocarbons has been remarked by geologists from Levorsen (1934, 1964) to Chenoweth (1972) and Bushnell (1981). Unconformities



Seismic line through a limestone reef or buildup, clearly visible as a characterless lense at
regular reflectors of back reef lagoonal sediments to the east, and basinal reflectors onlapping the
ıt. *From Fitch (1976).*

ıxtaposition of porous reservoirs and impermeable shales that may act as source rge percentage of the known global petroleum reserves are trapped adjacent to ꞉ unconformities and source rocks of Late Jurassic to mid-Cretaceous age. Many ·es are held in structural and combination traps, as well as the pure stratigraphic ıre described as follows. As already shown (Table 7.2), unconformity-related ivided into those that occur above the unconformity and those that occur below types of unconformity traps are now described in turn.

ɜunconformity Traps

ic traps that overlie unconformities include reefs and various types of terrige- hese traps may be divided into three classes according to their geometry: sheet, ıtrike valley. Shallow marine or fluvial sands may onlap a planar unconformity. c trap may occur where these sands are overlain by shale and where the sub- rocks are also impermeable. In many ways, therefore, these onlap traps are pinchout traps described previously. Note, in particular, that both traps require ɔermeability changes or structural closure in both directions along the paleo- rap to be valid. The Cut Bank field of Montana is an example of an onlap strat- (Fig. 7.41). Here the Lower Cretaceous Cut Bank sand unconformably onlaps ; and is itself onlapped by the Kootenai shale (Shelton, 1967). It contains recov- s of more than 200 million barrels of oil and 300 billion cubic feet of gas. In this voir is a fluvial sand, but in other onlap traps the reservoir is of marine origin.

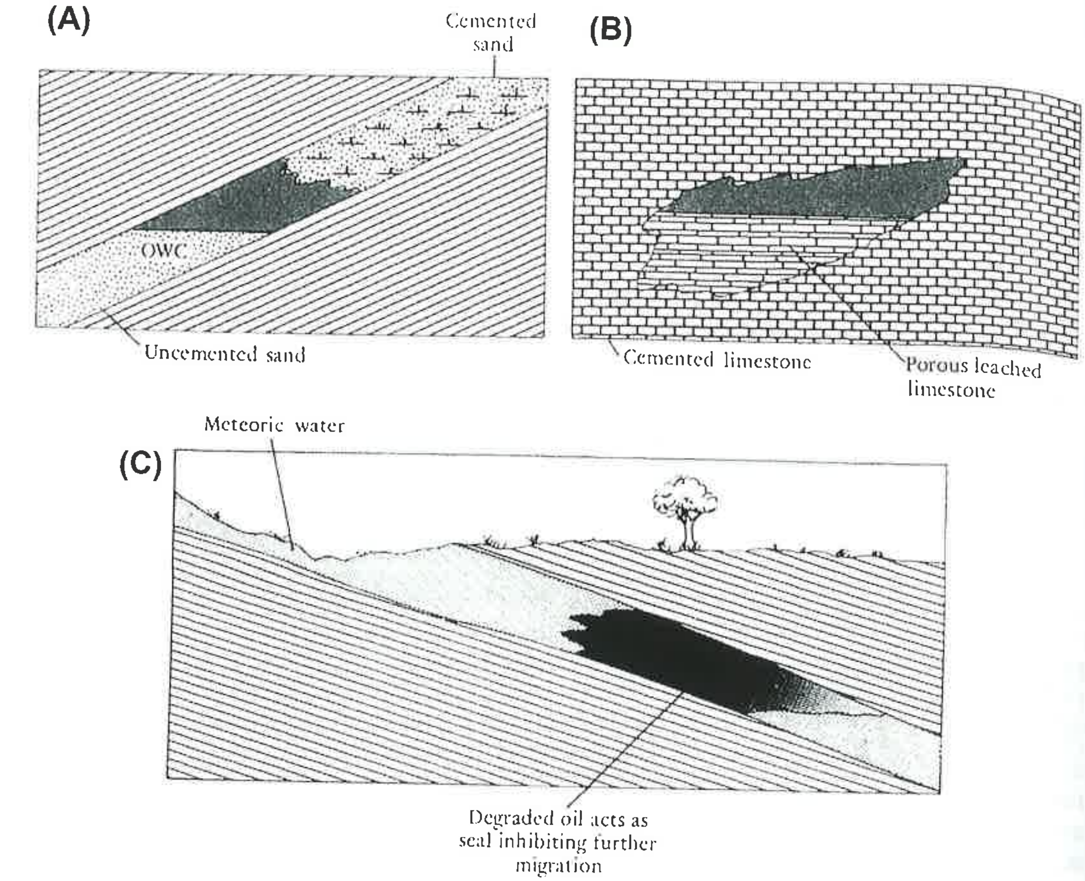


FIGURE 7.40 Configurations for diagenetic traps caused by (A) cementation, (B) solution, and (C) shallow-oil degradation.

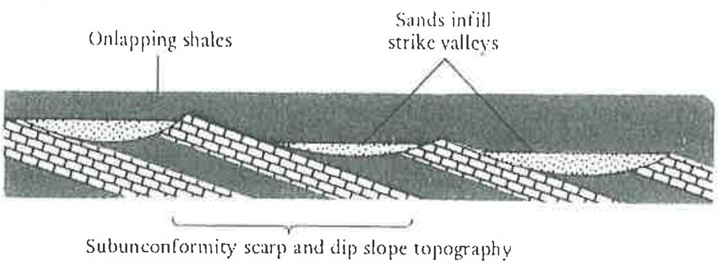


FIGURE 7.41 Cross section showing the occurrence of strike valley sands. Examples of oil trapped in these sands are known from the Pennsylvanian of Oklahoma and the Cretaceous of New Mexico.

Where an unconformity is irregular, sand often infills valleys cut into the old land surface (valley fill traps). The location and trend of these valleys may be related to the resistance to weathering of the various strata that once cropped out at the old land surface, basement tectonics, or other causes. This process gives rise to paleogeomorphic traps (Martin, 1966; Wood and Hopkins, 1992). The two main groups of paleogeomorphic traps are valley fill (channel) and strike valley. Rivers draining a land surface may incise valleys into the bedrock, and these valleys may then be infilled with alluvium (both porous sand and impermeable shale). Pinchouts and facies changes within the valley fill can make predicting of reservoir facies difficult (Biddle and Wielchowsky, 1994). The Glen Rock field, Wyoming, has already been described as an example of a fluvial channel stratigraphic trap. There is little difference between valleys cut in unconformities and those within conformable sequences. The Fiddler Creek and Clareton fields (Fig. 7.35) are examples of paleogeomorphic channel traps. Many of the Cretaceous Muddy Formation fields in the Powder River Basin and Pennsylvanian Morrow Formation of the Mid-Continent produce from incised valleys. There are many other such traps, ranging from fluvial channels to deep submarine ones like those of Miocene age in California (Martin, 1963).

Where alternating beds of hard and soft rocks are weathered and eroded, the soft strata form strike valleys between the resistant ridges of harder rock. Fluvial, and occasionally marine, sands within the strike valleys may be blanketed by a transgressive marine shale. Oil and gas may be stratigraphically trapped in the strike valley sands (Fig. 7.41). This type of trap was first described from the sub-Pennsylvanian unconformity of Oklahoma. Some of these sands are 60–70 km in length, yet only 1 or 2 km wide. Local thickening of the reservoir occurs where primary consequent valleys intersect strike valleys (Busch, 1959, 1961, 1974; Andresen, 1962). Other examples have been identified in the basal Niobrara (Upper Cretaceous) sands of the San Juan Basin, New Mexico (McCubbin, 1969). These sands are shorter and wider than the Oklahoma sands. In both cases, however, the sand bodies are generally less than 30 m thick.

7.8.2.2 Subunconformity Traps

Stratigraphic traps also occur beneath unconformities where porous permeable beds have been truncated and overlain by impermeable clay. In many instances a seat seal is also provided by impermeable strata beneath the reservoir. As with pinchouts and onlaps, some closure is needed in both directions along the paleostrike. This closure may be structural or stratigraphic, but for many truncation traps it will be provided by the irregular topography of the unconformity (Fig. 7.42).

Most, if not all, truncation traps have had their reservoir quality enhanced by epidiagenesis. This secondary solution, porosity induced by weathering, is particularly well known in limestones, but also occurs in sands and basement. Weathering of limestones ranges from minor moldic and vuggy porosity formation to the generation of karstic and collapse breccia zones of great reservoir potential. One noted example is the Casablanca field of offshore Spain (Watson, 1982). Figure 6.38 shows a Zechstein dolomite collapse breccia due to pre-Cretaceous weathering of the Auk field in the North Sea (Brennand and Van Veen, 1975). Subunconformity solution porosity is important in many sandstone reservoirs, such as the Sarir Group of Libya and the Brent Sand of the North Sea.

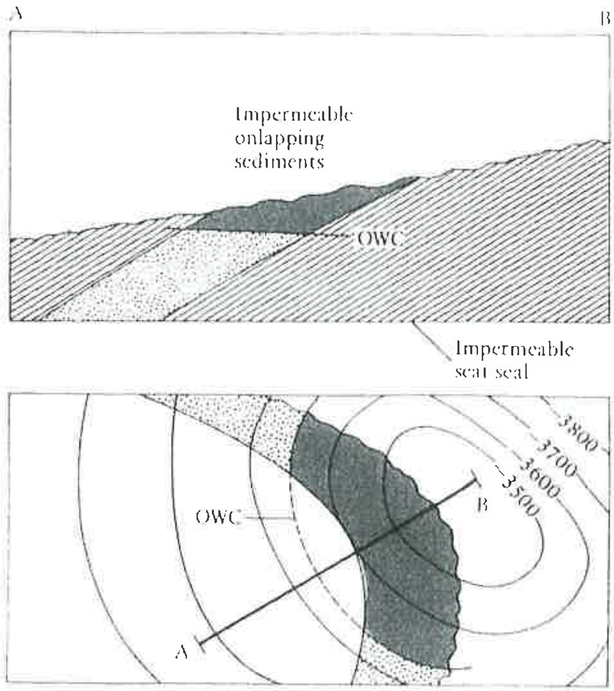


FIGURE 7.42 Cross section (upper) and map (lower) illustrating the geometry of a truncation trap. The contours drawn on the unconformity surface of the map define a buried hill.

As discussed earlier, a number of fields produce from basement rocks, notably in Vietnam and China. In almost every case the reservoir is unconformably overlain by shales that have acted as source and seal. Production comes from fractures and solution pores, where unstable minerals (generally mafics and occasionally feldspar) have weathered out. A notable example of this type of trap is the Augila field of Libya, where one well produced 40,000 bopd from granite (Williams, 1968, 1972). This remarkable stratigraphic trap also produces from sands and carbonates that onlap a buried granite hill (Fig. 7.43).

7.8.2.3 *Unconformity-Related Traps: Conclusion*

The preceding sections describe the various ways in which unconformities may trap hydrocarbons. It must be stressed that few traps are simple and monocausal. The number of combination traps in which an unconformity is combined with folding or faulting far outweighs simple unconformity traps. Many unconformity traps produce from both onlapping and subcropping reservoirs, as in the Augila field just noted. Similarly, as unconformities converge and merge upstructure, reservoirs that are both onlap and subcrop traps form. The East Texas field is one such example (Fig. 7.44). This giant field, with estimated recoverable reserves of 5600 million barrels, has a length of some 75 km and a maximum width of 25 km. It produces from the Cretaceous Woodbine sand, which unconformably overlies the Washita Group and is itself truncated by the Austin Chalk (Halbouty, 1994).

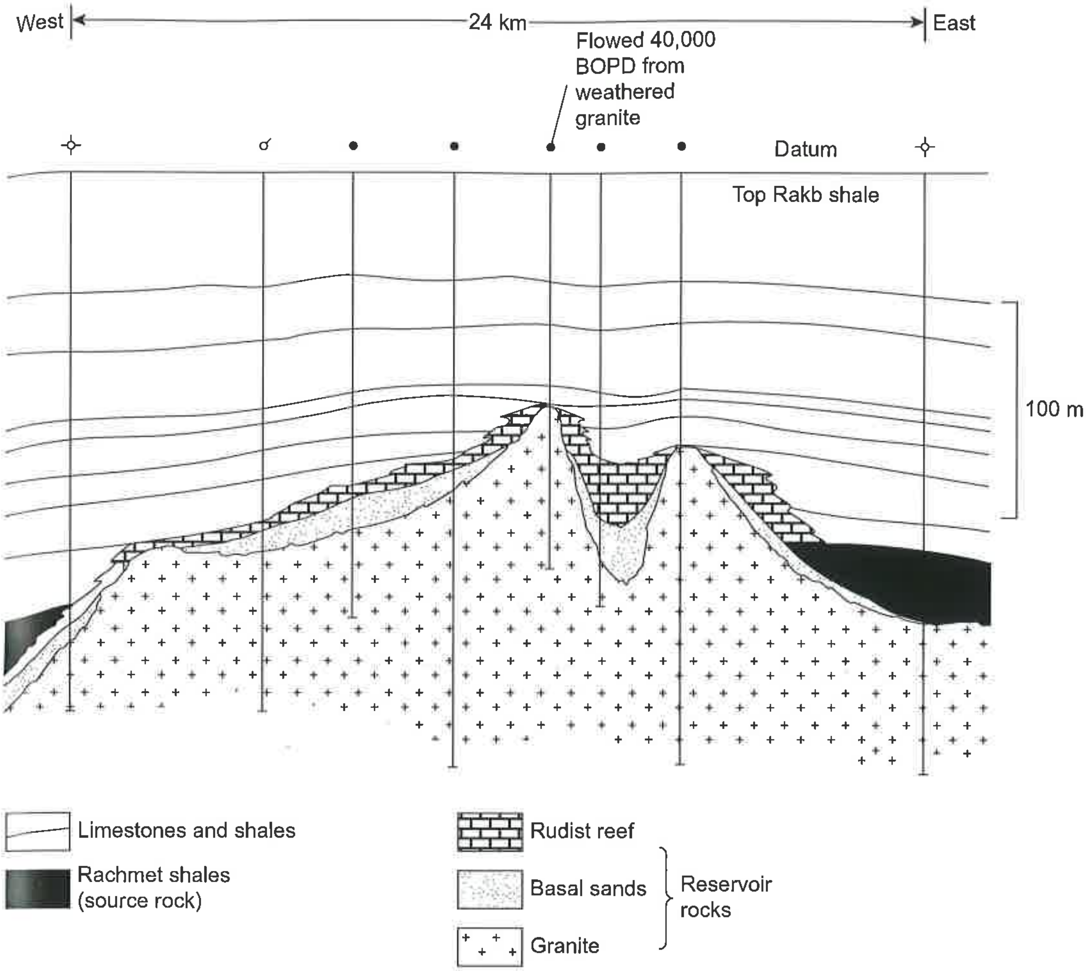
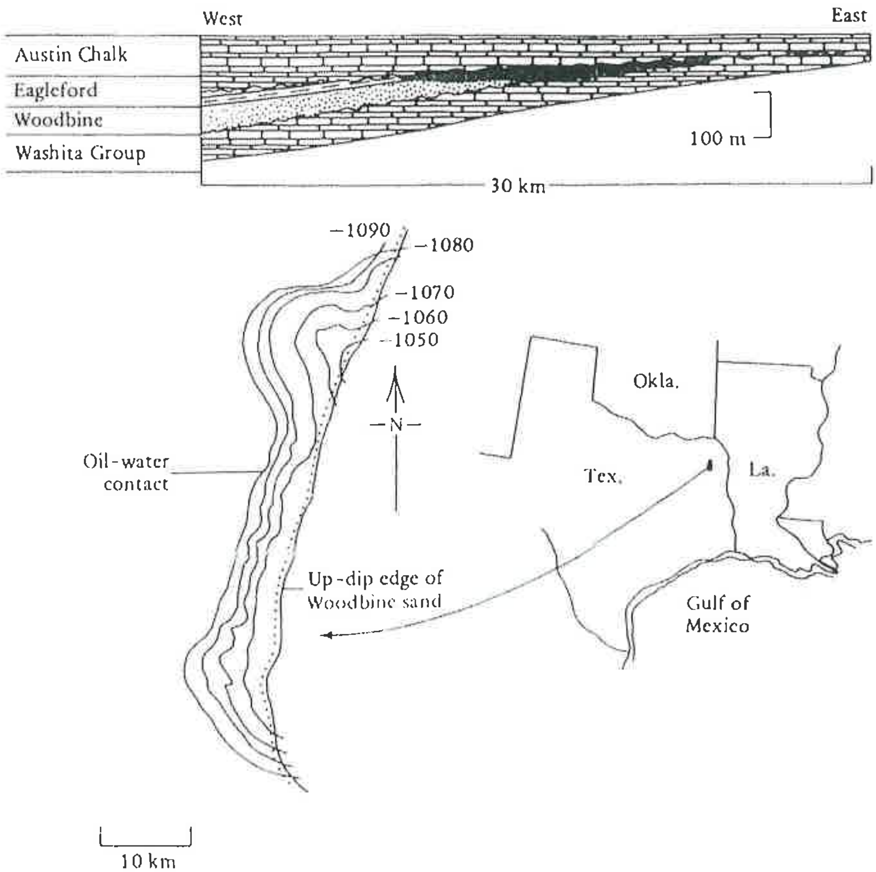


FIGURE 7.43 Cross section through the Augila field of Libya. This field is a complex trap that produces partly from sands and reefal carbonates and partly from fractured and weathered granite. *Modified from Williams (1968, 1972).*

There has been considerable debate as to whether shales above or below an unconformity provide the oil for adjacent reservoirs. With modern geochemical techniques of matching crudes and their parent kerogen, this problem can generally be solved. In some cases the source rock is clearly beneath the unconformity. A notable example of this condition is the Hassi Massaoud field, in which Cambro-Ordovician sands contain oil derived from the Tannezuft Shale (Silurian) on a large paleohigh sealed by Triassic evaporites (Balducci and Pommier, 1970). Another example is the Brent field and its associates in the North Sea. Here the early Cretaceous Cimmerian unconformity seals many traps ranging in age from Jurassic to Devonian. All are sourced by the Upper Jurassic Kimmeridge clay.



JRE 7.44 Map and cross section through the East Texas field, a supra- and subunconformity giant strati-ic trap. Contours in meters. *Modified from Minor and Hanna (1941), reprinted by permission of the American iation of Petroleum Geologists.*

onversely, in many fields shales above an unconformity act as source and seal. This sit-on occurs, for example, in Prudhoe Bay, Alaska (Morgridge and Smith, 1972; Jones and rs, 1976) and Sarir field, Libya (Sanford, 1970). That an impermeable shale should act oth source and seal may seem incomprehensible at first. Actually, two explanations account for this phenomenon. The oil trapped in a structural culmination need not neces-y have moved downward in a physical sense, but may have moved up the flank of the ture from adjacent lows, and in so doing moved downward only in a stratigraphic sense. , any good engineer can prove mathematically that fluid can move downward if there is fficient pressure differential.

3 Relationship between Stratigraphic Traps and Sedimentary Facies

the same way that structural traps are related to tectonic style, stratigraphic traps are related to sedimentary environments. A genetic grouping of stratigraphic traps and

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TABLE 7.4 Relati
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Coastal
Deep marine

facies may be more useful as an aid to prospect prediction than the formal classification used for the preceding descriptive section. This approach needs to be qualified. As discussed in Chapter 6, the distribution of porosity is often unrelated to facies in carbonate reservoirs. Thus, apart from the obvious environmental control of reefs, carbonate stratigraphic traps are seldom facies related. Diagenetic processes and the position of unconformities are generally more significant than earlier environmental controls.

Turning to sandstones, Chapter 6 noted that reservoir quality is generally facies related and the effects of diagenesis are usually less significant. Pinchout traps, whether due to onlap or truncation, can occur in a blanket sand deposited in any environment. All they require is the necessary structural tilt and an adequate seal. Many varieties of sandstone stratigraphic trap have distributions that are largely facies related, as shown in Table 7.4. Channel traps may, of course, be found in almost any environment from fluvial to deep marine, as already noted. Strike valley sands are generally of continental origin. Growth-fault-related traps, such as rollover anticlines, and clay diapir traps are not stratigraphic in origin, but their occurrence is closely related to environment. They are restricted to rapidly deposited regressive wedges of deltaic sands and overpressured clay. Diapiric traps are commonly present to the basinward side of growth faults. In deep basinal settings stratigraphic traps may occur in submarine channels and in submarine fans. The latter include updip pinchouts as well as closed structures where fan paleotopography is preserved.

This brief review shows that many stratigraphic traps are related to depositional environment. This correlation obviously aids the prediction of the type of trap to be anticipated in a particular sedimentary facies.

TABLE 7.4 Relationship between Stratigraphic Traps and Sedimentary Environments of Sandstone Reservoirs

Environment		Trap Type
Continental	Eolian	Pinchout
	Fluvial	Channel
		Strike valley
Coastal	Barrier bar	Shoestring
	Delta	Channel
		Crevasse·splay and mouth bar
		Growth-fault-related
		Diapir-related
Deep marine		Submarine fan pinchout or paleotopographic closure
		Submarine channel

7.9 HYDRODYNAMIC TRAPS

The third group of traps to consider, in addition to structural and stratigraphic ones, is the hydrodynamic traps. In these traps hydrodynamic movement of water is essential to prevent the upward movement of oil or gas. The concept was first formulated by Hubbert (1953) and embellished by Levorsen (1966). The basic argument is that oil or gas will generally move upward along permeable carrier beds to the earth's surface except where they encounter a permeability barrier, structural or stratigraphic, beneath which they may be trapped.

When water is moving hydrodynamically down the permeable beds, it may encounter upward-moving oil. When the hydrodynamic force of the water is greater than the force due to the buoyancy of the oil droplets, the oil will be restrained from upward movement and will be trapped within the bed without any permeability barrier. Levorsen illustrated this concept by using the analogy of corks in a glass tube below which water was flowing. The corks would tend to accumulate where the tube was restricted, causing a local increase in the fluid potential gradient.

In the real world this increase might occur where there was a local reversal of dip or facies change, or even a local fluctuation in the potentiometric gradient (Fig. 7.45). Hubbert (1953) expounded the theory behind the concept of the hydrodynamic trap. The role of the hydrodynamic flow in causing tilted OWCs was discussed earlier in this chapter. Although this phenomenon occurs in many fields, pure hydrodynamic traps are very rare. One such example, however, is the Wheat field of the Delaware Basin, West Texas, described by Adams (1936). This field occurs in a gentle flexure in monoclinally dipping beds, which have closure but not vertical relief (Fig. 7.46). Other examples have been described from the Paris Basin, France, from Poland (see Heuillon (1972); Zawiska (1986); respectively), and from Canada (Eremako and Michailov, 1974).

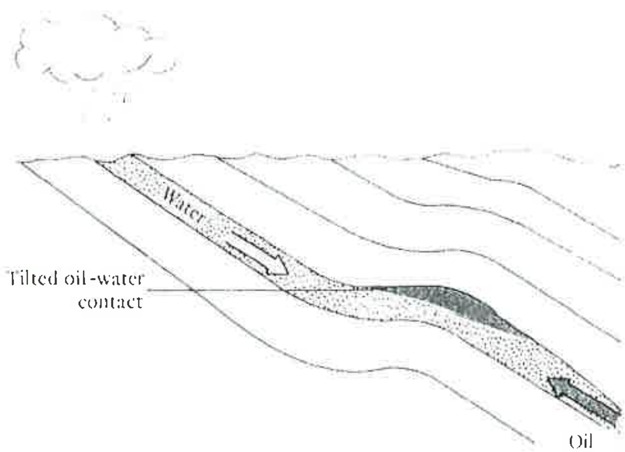

FIGURE 7.45 Crustal cross section showing a pure hydrodynamic trap. There is no vertical structural relief. Oil migrating upward is trapped in a monocline by the downward flow of water.

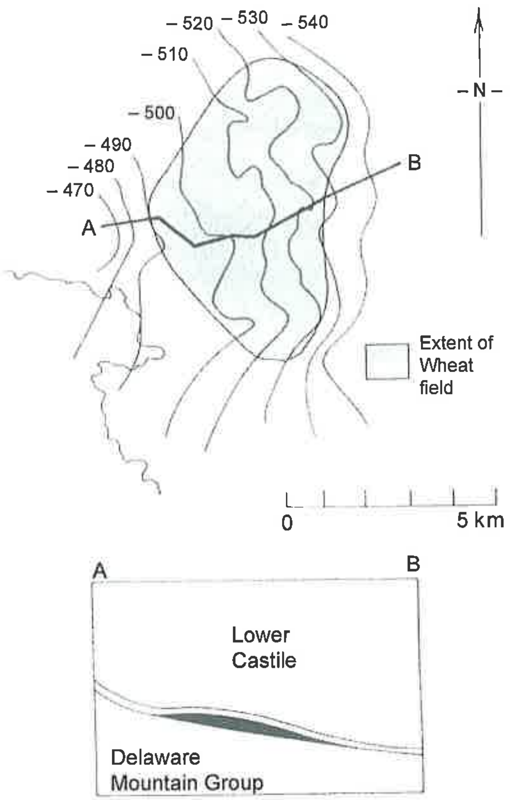

FIGURE 7.46 Map (upper) and cross section (lower) through the Wheat field, Delaware Basin, Texas. This field is an example of a hydrodynamic trap. The structure contours on the map are drawn on top of the Wheat field reservoir. *Modified from Adams (1936), reprinted by permission of the American Association of Petroleum Geologists.*

An obvious tilted oil/water contact points to the role of hydrodynamic flow. If there was no flow and pressures were hydrostatic, oil could not be trapped because the trap lacks four-way structural closure. Traps like the Wheat field are very rare and are not regarded as a prime target for exploration, although the significance of hydrodynamic flow in shifting fields down the flank of structures must always be remembered.

7.10 COMBINATION TRAPS

Many oil and gas fields around the world are not due solely to structure or stratigraphy or hydrodynamic flow, but to a combination of two or more of these forces. Such fields may properly be termed *combination traps*. Most of these traps are caused by a combination of structural and stratigraphical processes. Structural–hydrodynamic and stratigraphic–hydrodynamic traps are rare. Examples are known from the Rocky Mountain Cretaceous basins where Hubbert developed his theories of hydrodynamic flow, and from Indonesia

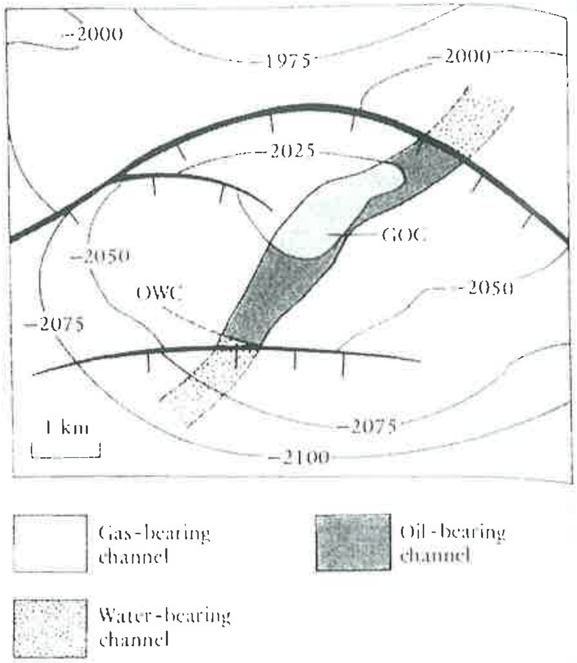

FIGURE 7.47 Combination channel rollover anticline trap, the Main Pass Block 35 field, offshore Louisiana. Contours are drawn on top of "G" sand (CI = 25 m). *Modified from Hartman (1972), reprinted by permission of the American Association of Petroleum Geologists.*

(Cockroft et al., 1987). Because of the multiplicity of different types of combination traps, discussing them in groups or any logical order is impractical. One or two examples must suffice.

On a small scale, oil may be trapped in shoestring sands (channels or bars) that cross-cut anticlines (Fig. 7.47). As pointed out earlier, pinchout, onlap, and truncation traps all require closure, which is very often structural, along the strike. Likewise, folded and/or faulted beds may be sealed by unconformities to form another group of traps. Examples of folded and faulted unconformity traps are now discussed in turn.

The Prudhoe Bay field on the North Slope of Alaska is a fine example of a combination trap (Morgridge and Smith, 1972; Jones and Speers, 1976; Jamison et al., 1980; Bushnell, 1981). Here a series of Carboniferous, Permian, Triassic, Jurassic, and basal Cretaceous sediments were folded into a westerly plunging anticlinal nose. This structure was truncated progressively to the northeast and overlain by Cretaceous shales, which act as source and seal to the trap. Oil and gas are trapped in the older beds, which subcrop the unconformity. The main reservoir is the fluvial Sadlerochit Sandstone (Triassic). Additional closure is provided by major faults on the northern and southwestern side of the structure (Fig. 7.48).

Fault unconformity traps characterize the Jurassic Brent province of the northern North Sea. The reservoir is the Middle Jurassic deltaic Brent Sandstone Group, which is overlain by Upper Jurassic shales. These include the Kimmeridge clay formation, which is the source rock. Late Jurassic—Early Cretaceous Cimmerian movement created numerous fault blocks, which were tilted, truncated, and unconformably overlain by Cretaceous shales. The resultant traps, which include fields such as Brent, Statford, Murchison, Hutton, Thistle, and Piper

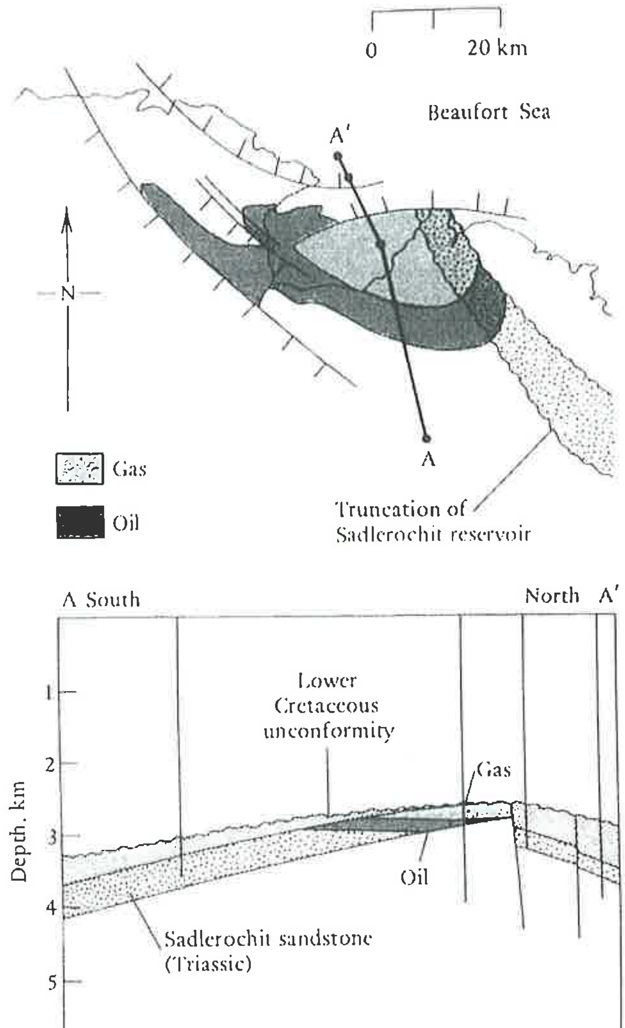

FIGURE 7.48 Map (upper) and cross section (lower) of the Prudhoe Bay field of Alaska. *Modified from Jamison et al. (1980), reprinted by permission of the American Association of Petroleum Geologists.*

(Fig. 7.15), are thus all combination fault unconformity traps with varying degrees of truncation of the reservoir. Such combination traps can normally be found by seismic surveys since both the fault and the truncating unconformity are usually detectable (Fig. 7.49).

7.10.1 Astrobleme Traps

Finally, mention must be made of one very rare, but spectacular, type of combination trap, namely, the astrobleme, or meteorite impact crater. Gold's theory for the origin of petroleum

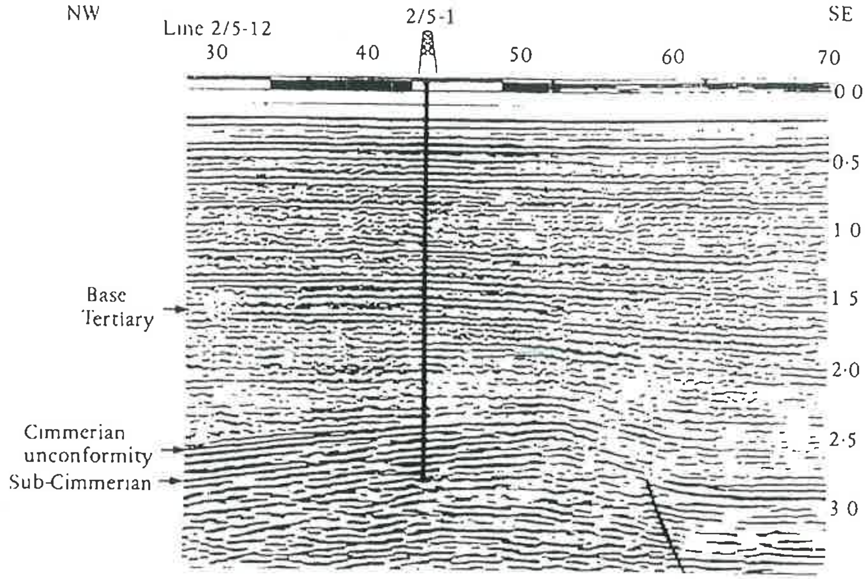

FIGURE 7.49 Seismic line to illustrate a combination trap, the Heather field from the Northern North Sea *(from Gray and Barnes (1981))*. This is a combination of a tilted fault block that has been truncated by the Cimmerian unconformity. The reservoir is a Jurassic sand beneath the truncating unconformity.

by earthquake outgassing, and the significance of crustal fractures due to meteorite impact was discussed earlier. Ancient meteorite impact craters are well documented around the globe, both on the surface and buried beneath younger sediments, in the subsurface (Jenyon, 1990, pp. 363–368).

Numerous geologists have, over the years, argued that ancient subcircular structures are of meteoritic origin. In some cases petroleum is trapped within and adjacent to them. Notable examples include the Lyles Ranch field in south Texas (LeVie, 1986), the petroliferous Avak structure in Alaska (Kirschner et al., 1992), and the Red Wing Creek Field of the Williston Basin (Parson, 1974). No doubt there is a multiplicity of combination traps that might be associated with astroblemes, where organic-rich source rocks pre- or postdate the impact structure. This type of prospect may be particularly appealing to adherents of Gold's theory of the origin of petroleum.

Thus the list of combination traps is endless. The preceding examples illustrate some of their variety and complexity.

7.11 TRAPS: CONCLUSION

7.11.1 Timing of Trap Development Relative to Petroleum Migration and Reservoir Deposition

The time of trap formation relative to petroleum migration is obviously extremely important. If traps predate migration, they will be productive. If they postdate migration, they will be barren. Questions concerning a prospect should include these: Which horizons are known or presumed to be source rocks? Can time–burial depth curves be used to determine the time of petroleum generation? If the prospect is structural, did the fold or fault form before or after migration? In the case of truncation traps the source rock may underlie or overlie the unconformity (as in Hassi Messaoud and Prudhoe Bay, respectively). It is important, though, to establish that a truncation trap was thoroughly sealed before petroleum generation began.

Postmigration structural movement may also be relevant. Faults can open to allow petroleum to undergo further migration. Structural closure may tighten. This tightening is not harmful by itself, unless it is accompanied by crestal fractures, which increase the permeability of the seal. Uplift and erosion may breach the crests of traps. Regional tilting may trigger extensive secondary migration of petroleum because the spill points of traps may be altered.

The time factor is also important, although less so, when considering the relationship between the deposition of the reservoir and the formation of structural traps. At its simplest level syndepositional structural growth will affect sedimentation and hence reservoir characteristics; postdepositional structures, on the other hand, may not correlate with facies variations within the reservoir. In a terrigenous basin with synchronous structural growth, channels and fans of fluvial, deltaic, or submarine origin will develop in the lows. Simultaneously, winnowed marine shoal sands may be present on the structural highs, although, where too high, truncation may be present. In carbonate basins oolite shoals and reefs may be anticipated on structural highs, but, for reasons already discussed, porosity is often unrelated to facies in carbonate sediments.

The situation may be rather different in areas where structural traps postdate sedimentation. Once sediments are lithified, they respond to stress by fracturing. Thus in both sandstone and carbonate reservoirs, porosity and permeability due to fractures may be closely related to structure. Fracture intensity, and thus reservoir performance, may be enhanced over the crests of folds and the apices of diapirs, as well as adjacent to faults.

This review of the timing of trap formation relative to reservoir deposition and petroleum generation emphasizes its importance. Generally, the relationship between structural movement and petroleum migration is more important than whether structures are syn- or postdepositional.

7.11.2 Relative Frequency of the Different Types of Traps

This chapter has covered a great deal of ground. Therefore, it is appropriate to close with an attempt to arrange the various types of traps in some sort of order of importance. A great aid to this classification has been a global analysis of the trapping mechanisms of known giant oil fields by Moody (1975). His study showed that by far the majority of giant oil fields are anticlines, followed, a long way behind and in order of decreasing importance, by combination traps, reefs, pinchouts, truncations, salt domes, and faults (Fig. 7.50).

These interesting data deserve careful analysis. They only concern giant fields, which are defined as those with more than 500 million barrels of recoverable reserves. This chapter has shown that stratigraphically trapped oil tends to occur in small fields because of the limited extent of channel, bar, and reef reservoirs. Also, these data pertain to oil fields, not gas fields, although, intuitively, they would probably be similar.

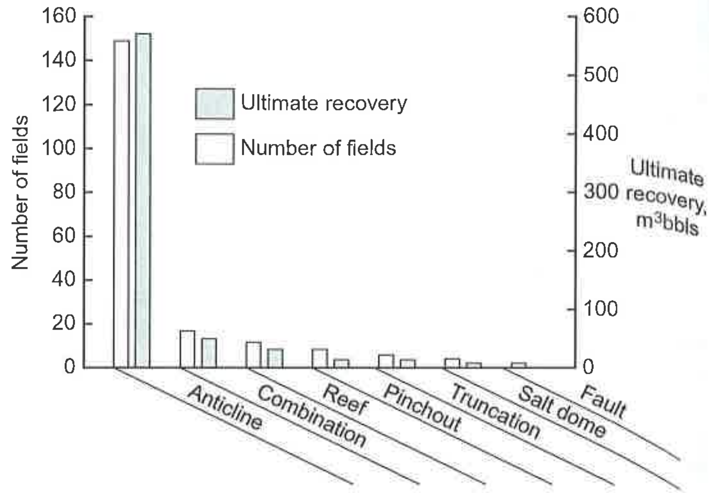

FIGURE 7.50 Histograms showing the mode of entrapment of giant oil fields around the world. *After Moody (1975).*

Note also that these figures were compiled some time ago. With the steady improvement in seismic geophysics, the percentage of known subtle stratigraphic traps may now have increased in proportion to anticlines. Most importantly, these figures record the entrapment of known giant oil fields. The various percentages of the different types of giant trap that actually exist under the earth might be completely different.

These figures, therefore, reflect mankind's ability to find oil, not the total number of fields in the world. Finding oil in anticlines is easy. They may be mapped at the surface or detected seismically in the subsurface. The concept of the anticlinal trap is a simple one to grasp for the managers, accountants, engineers, and farmers who may actually make the decision to drill, or not, based on a geologist's recommendation.

Stratigraphic traps, on the other hand, are harder to locate. Few can simply be picked off a brightly colored seismic section; most require an integration of seismic, log, and real rock data with sophisticated geological concepts. An explorationist would therefore find it harder to develop a stratigraphic trap prospect, and harder still to explain it to the lay audience, which may hold the purse strings. Pratt (1942) spoke very truly, though now politically incorrect, when he said that "oil is found in the minds of men."

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