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Chapter 13

Hydrocarbon Traps

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Abstract

Trap identification is a first step in prospect evaluation and an important part of any exploration or assessment program. Future success in exploration will depend increasingly on an improved understanding of how traps are formed and an appreciation of the numerous varieties of trap types that exist. We define a trap as any geometric arrangement of rock that permits significant accumulation of hydrocarbons in the subsurface. A trap must include a reservoir rock in which to store hydrocarbons, and a seal or set of seals that impede or stop migration out of the reservoir. Although it is the geometric arrangement of reservoirs and seals that determines if a trap is present, both reservoir and seal analysis should be an integral part of trap evaluation.

Traps can be divided into three broad categories: structural traps, stratigraphic traps, and combination traps, which exhibit both structural and stratigraphic elements. We have subdivided structural traps into fold traps, traps associated with faults, traps associated with piercement features, and combination traps that require elements of both faults and folds for effectiveness. Stratigraphic traps can be grouped into primary or depositional traps, traps associated with unconformities (either above or beneath the unconformity), and secondary or diagenetic stratigraphic traps. We note that although each trap has unique characteristics, early recognition of trap type will aid in mapping and evaluating a prospect.

INTRODUCTION

Trap evaluation is fundamental in the analysis of a prospect and an important part in any successful oil and gas exploration or resource assessment program. A *trap* can be defined as any geometric arrangement of rock, regardless of origin, that permits significant accumulation of oil or gas, or both, in the subsurface (modified from North, 1985). Although we define a trap as the geometric configuration that retains hydrocarbons, several critical components must be in place for a trap to be effective, including adequate reservoir rocks and seals, and each of these must be addressed during trap evaluation.

The oil and gas within a trap is part of a petroleum system, whereas the trap itself is part of one or more sedimentary basins and is evaluated as part of a prospect or play (see Chapter 1, Figure 1.1, this volume). The hydrocarbon-forming process and the trap-forming process occur as independent events and commonly at different times. The timing of the trap-forming process, as shown on the events chart (Chapter 1, Figure 1.5), is important in a petroleum system study because if the trap forms before the hydrocarbon-forming process, the evidence (oil and gas) that a petroleum system exists is preserved. The volume of oil and gas preserved depends on the type and size of the trap, which is important in the evaluation of the prospect.

The critical components of a trap (the reservoir, seal, and their geometric arrangement with each other) can be combined in a variety of ways by a number of separate processes. This variability has led to many different trap classifications (e.g., Clapp, 1929; Wilson, 1934; Heroy, 1941; Wilhelm, 1945; Levorsen, 1967; Perrodon, 1983; North, 1985; Milton and Bertram, 1992). Different authors have focused on various trap attributes as the key element or elements of their classification. Some have emphasized trap geometry, while others have concentrated on the mechanisms of trap formation. Others have considered reservoir or seal characteristics as the major parts of their classification. Space limitations preclude a thorough review of the various classifications

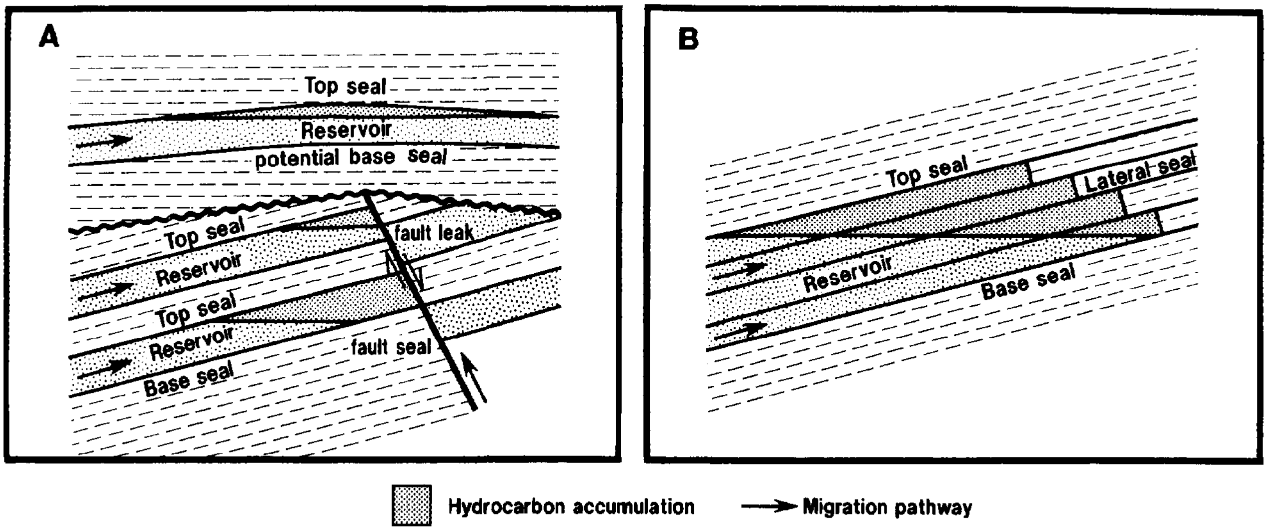

Figure 13.1. Key elements for (A) structural and (B) stratigraphic hydrocarbon traps.

here, but we note a general consensus on three broad categories of traps (Levorsen, 1967): those created by structural deformation, those formed by stratigraphic phenomena, and those that combine aspects of both. In addition, dynamic fluid conditions in the subsurface can modify the capacity of some structural and stratigraphic traps, or perhaps lead to hydrocarbon accumulations in unexpected locations. This chapter covers what we consider to be two critical components of a trap. It also describes the major structural and stratigraphic types of traps and provides suggestions for trap evaluation.

TWO CRITICAL COMPONENTS OF A TRAP

To be a viable trap, a subsurface feature must be capable of receiving hydrocarbons and storing them for some significant length of time. This requires two fundamental components: a *reservoir rock* in which to store the hydrocarbons, and a *seal* (or set of seals) to keep the hydrocarbons from migrating out of the trap (Figure 13.1). Both seal and reservoir are discussed in more detail elsewhere in this volume (see Morse, Chapter 6; Jordan and Wilson, Chapter 7; Downey, Chapter 8), but these are such basic parts of a trap that some of their aspects must also be covered here.

We do not consider the presence of hydrocarbons to be a critical component of a trap, although this is certainly a requirement for economic success. The absence of hydrocarbons may be the result of failure of other play or prospect parameters, such as the lack of a pod of active source rock or migration conduits, and it may have nothing to do with the ability of an individual feature to act as a trap. After all, "a trap is a trap, whether or not it has a mouse in it" (attributed to W. C. Finch, in Rittenhouse, 1972, p. 16).

Reservoir Rock

The reservoir within a trap provides the storage space for the hydrocarbons. This requires adequate porosity within the reservoir interval. The porosity can be primary (depositional), secondary (diagenetic), or fractures, but it must supply enough volume to accommodate a significant amount of fluids.

The reservoir must also be capable of transmitting and exchanging fluids. This requires sufficient effective permeability within the reservoir interval and also along the migration conduit that connects the reservoir with a pod of active source rock. Because most traps are initially water filled, the reservoir rock must be capable of exchanging fluids as the original formation water is displaced by hydrocarbons. As North (1985, p. 254) noted, "Traps are not passive receivers of fluid into otherwise empty space; they are focal points of active fluid exchange."

A trap that contains only one homogeneous reservoir rock is rare. Individual reservoirs commonly include lateral and/or vertical variations in porosity and permeability. Such variations can be caused either by primary depositional processes or by secondary diagenetic or deformational effects and can lead to hydrocarbon-saturated but nonproductive waste zones within a trap (Figure 13.2A). Variations in porosity and, more importantly, permeability can also create transitions that occur over some distance between the reservoirs and the major seals of a trap (Figure 13.2C and D). These intervals may contain a significant amount of hydrocarbons that are difficult to produce effectively. Such intervals should be viewed as uneconomic parts of the reservoir and not part of the seal. Otherwise, trap spill points may be mis-identified. Many traps contain several discrete reservoir rocks with interbedded impermeable units that form internal seals and segment hydrocarbon accumulations into separate compartments with separate gas–oil–water

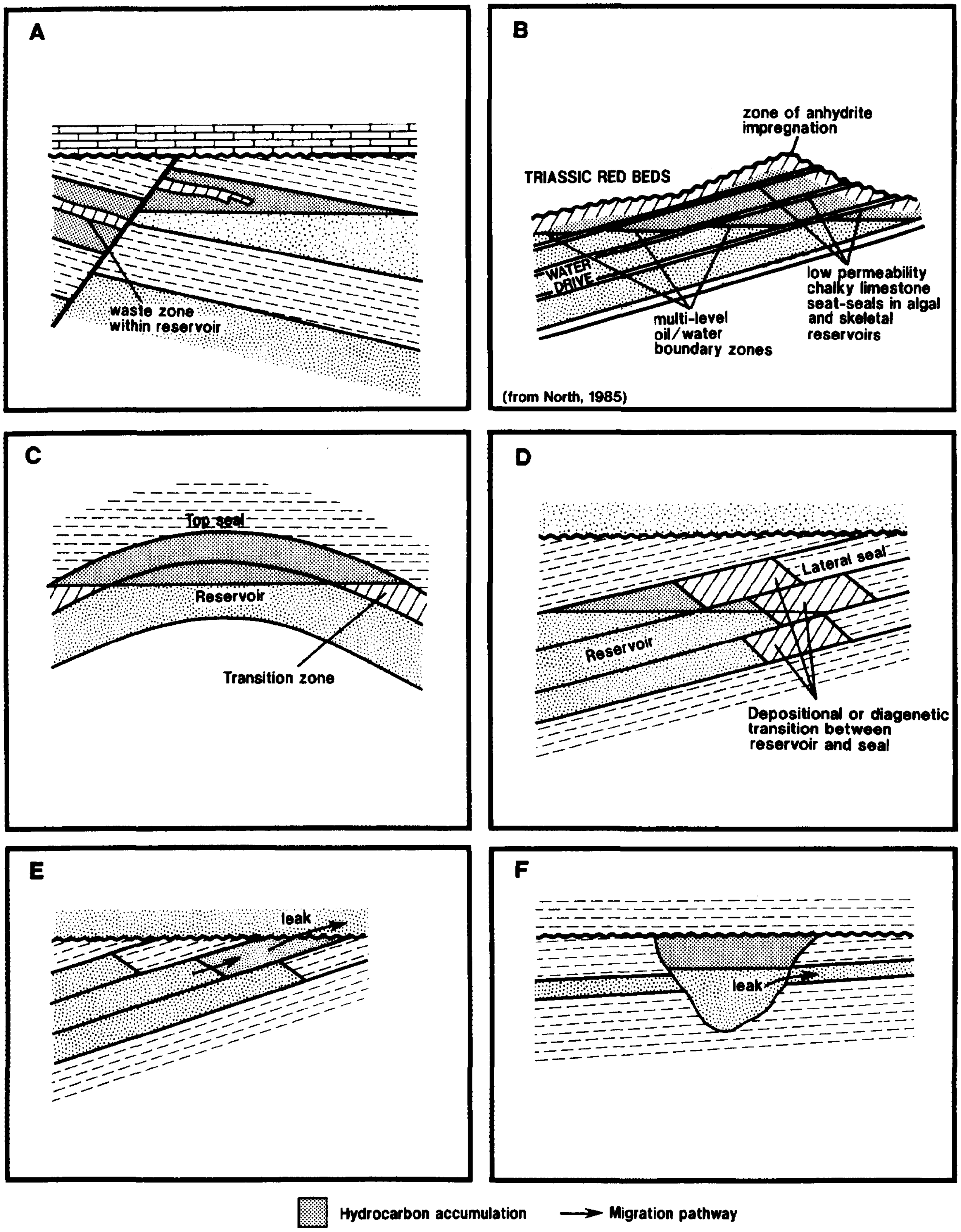

Figure 13.2. Common trap limitations. (A) Waste or nonproductive zones in trap. (B) Multiple impermeable layers in trap creating several individual oil–water contacts. (C) Non- to poorly productive transition zone (from reservoir to seal) rock above productive reservoir. (D) Lateral transition from reservoir to seal. (E) Lateral, stratigraphically controlled leak point. (F) Lateral leak point or thief bed.

contacts and different pressure distributions (Figure 13.2B). As illustrated, these are complications of a single trap and are not multiple traps.

Seal

The seal is an equally critical component of a trap (Milton and Bertram, 1992; Downey, Chapter 8, this volume). Without effective seals, hydrocarbons will migrate out of the reservoir rock with time and the trap will lack viability. Most effective seals for hydrocarbon accumulations are formed by relatively thick, laterally continuous, ductile rocks with high capillary entry pressures (Downey, 1984 and Chapter 8, this volume), but other types of seals may be important parts of individual traps (e.g., fault zone material, volcanic rock, asphalt, and permafrost).

All traps require some form of top seal (Figure 13.1). When the base of the top seal is convex upward in three dimensions, the contours drawn to represent this surface (called the *sealing surface* by Downey, 1984) close in map view). If this is the case, no other seal is necessary to form an adequate trap. In fact, some authors (e.g., Wilhelm, 1945; North, 1985) have used the basic convex or nonconvex geometry of the sealing surface as a way of classifying traps.

Many traps are more complicated and require that, in addition to a top seal, other effective seals must be present (Figure 13.1). These are the poly-seal traps of Milton and Bertram (1992). Lateral seals impede hydrocarbon movement from the sides of a trap (Figure 13.1B) and are a common element of successful stratigraphic traps. Facies changes from porous and permeable rocks to rocks with higher capillary entry pressures (Figures 13.1B and 13.2D) can form lateral seals, as can lateral diagenetic changes from reservoir to tight rocks. Other lateral seals are created by the juxtaposition of dissimilar rock types across erosional or depositional boundaries. Traps in incised valley complexes commonly rely on this type of lateral seal (Figure 13.2F). Stratigraphic variability in lateral seals poses a risk of leakage and trap limitation. Even thinly interbedded intervals of porous and permeable rock (thief beds) (Figures 13.2E and F) in a potential lateral seal can destroy an otherwise viable trap.

Base seals (Figure 13.1) are present in many traps and are most commonly stratigraphic in nature. The presence or absence of an adequate base seal is not a general trap requirement, but it can play an important role in deciding how a field will be developed.

Faults can be important in providing seals for a trap, and fault leak is a common trap limitation (Smith, 1966, 1980; Downey, 1984; Allan, 1989). Faults can create or modify seals by juxtaposing dissimilar rock types across the fault (Figure 13.1A), by smearing or dragging less permeable material into the fault zone, by forming a less permeable gouge because of differential sorting and/or cataclasis, or by preferential diagenesis along the fault. Fault-induced leakage may result from juxtaposition of porous and permeable rocks across the fault (Figure 13.1A) or by formation of a fracture network along the fault itself.

STRUCTURAL TRAPS

Structural traps are created by the syn- to postdepositional deformation of strata into a geometry (a structure) that permits the accumulation of hydrocarbons in the subsurface. The resulting structures involving the reservoir, and usually the seal intervals, are dominated by either folds, faults, piercements, or any combination of the foregoing (Figures 13.3A–D). Traps formed by gently dipping strata beneath an erosional unconformity are commonly excluded from the structural category (North, 1985) (Figure 13.3E), although as subunconformity deformation increases, this distinction becomes ambiguous (Figure 13.3F). Superposed multiple deformation may also blur the foregoing distinctions (e.g., Lowell, 1985).

Subdivisions of structural traps have been proposed by many authors based on a variety of schemes. For example, in his general trap classification, Clapp (1929) distinguished between anticlinal, synclinal, homoclinal, quaquaversal, and fault-dominated traps. Harding and Lowell (1979) based their classification of structural traps on the concept of structural styles, which emphasizes basement involvement or noninvolvement, inferred deformational force, and mode of tectonic transport. Levorsen (1967) divided structural traps into those caused by folding, faulting, fracturing, intrusion, and combinations of these processes. North (1985), under the category of convex traps, distinguished between buckle- or thrust-fold, bending fold, and immobile convexity traps. North (1985) appropriately pointed out that many convex traps are caused by faults (i.e., the folding is a response to the faulting rather than the other way around). However, the reverse is true under certain conditions in which prospect-scale faulting results from the folding process, such as in the development of chevron folds (Ramsey, 1974) or in keystone normal faulting above a rising salt diapir (Harding and Lowell, 1979).

The following sections discuss in more detail the two most important structural trap types: fold dominated versus fault dominated. In our experience, fold-dominated traps are by far the most important structural traps. We agree with North (1985) that purely fault-dominated traps (those on which the fault itself creates the trap without the presence of a fold) are relatively uncommon. Traps dominated by piercements (in which the reservoir is sealed by intrusion of salt or shale) and those resulting from combinations of faulting, folding, and piercement are treated by Harding and Lowell (1979), Lowell (1985), and North (1985).

Fold-Dominated Traps

Structural traps that are dominated by folds at the reservoir–seal level exhibit a wide variety of geometries and are formed or modified by a number of significantly different syn- and postdepositional deformation mechanisms. Although usually considered to result from tectonically induced deformation, the term *fold* is purely descriptive and refers to a curved or nonplanar arrange-

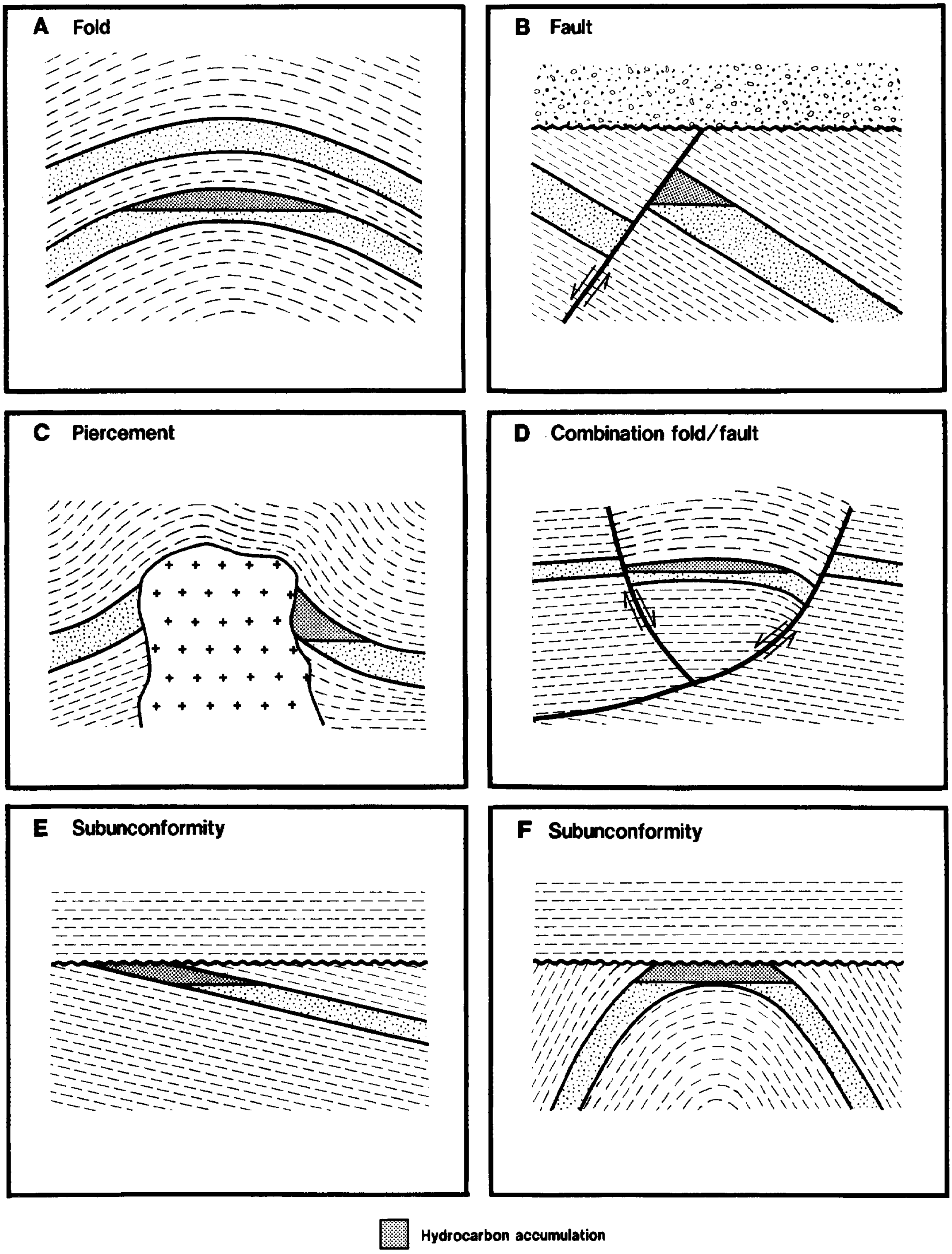

Figure 13.3. Major categories of structural traps: (A) fold, (B) fault, (C) piercement, (D) combination fold–fault, (E) and (F) subunconformities. The situation in (E) is commonly excluded from the structural category.

ment of geologic (usually bedding) surfaces (after Dennis, 1967). Therefore, folds include not only tectonically induced phenomena but also primary depositional features, gravity-induced slumping, compaction effects, and so on. It is convenient to divide prospect-scale folds into two categories—those that are directly fault related and those that are largely fault free.

Most fault-related folds result from bending above a nonplanar fault surface (Figures 13.4A and B). Crystalline basement may or may not be involved, and stratal shortening, extension, or transcurrent movements may have occurred. Common examples are *fault bend folds* (Figure 13.4A) (Suppe, 1983) and *fault propagation folds* (Figure 13.4B) (Suppe and Medwedeff, 1984) in detached fold and thrust belts. Fault bend folds are also common in extensional terranes. Other fault-related folds include *drag folds,* or folds formed by frictional forces acting across a fault (Figure 13.4C) (Suppe, 1985), and *drape folds,* those formed by flexure above a buried fault along which there has been renewed movement Figure 13.4D) (Suppe, 1985). These latter folds, however, are not caused by slip over a nonplanar fault surface. Also, drape folds do not involve significant stratal shortening or extension at the reservoir–seal level.

Fault-free, décollement, or *lift-off folds* (Figure 13.4E) (e.g., Namson, 1981) result from buckling caused by stratal shortening above a décollement, usually within a thick or very efficient (i.e., weak and ductile) sequence of evaporites or shale. Kink bands and chevron folds are special types of fault-free folds (Figure 13.4F). Other types of fault-free folds may form by bending above material that moves vertically or horizontally by flow without significant stratal shortening or extension at the reservoir–seal interval (Figure 13.4G). This would usually include folding related to flow and diapirism of salt and shale, although some prospect-scale folds are related to intrusive igneous activity. Drape folding can be caused not only by faulting, as previously mentioned, but also by differential compaction above buried topography, reefs, or other relatively immobile subsurface masses (Figure 13.4H). Initial depositional dips may also produce a drape fold geometry, but we would classify such features as a type of stratigraphic trap. Broad folding or warping of unknown genesis above basement arches and domes would fall into this latter category as well.

The distinction between fault-related and fault-free folds is somewhat artificial because the dominant fold generation mechanism may vary with time. For example, a fold may nucleate above a thick detachment horizon as a fault-free fold that is subsequently modified by fault propagation out of the detachment zone. Also, fold geometry may result from the action of more than one of the preceding mechanisms, such as extensional fault bend folding above a rising salt diapir.

In hydrocarbon exploration, it can be important to distinguish among the mechanisms of fold formation for a variety of reasons. These include predicting trap geometry where the subsurface is incompletely imaged by seismic data and untested by the drill bit, mapping migration pathways, and analyzing fracture distribution. In addition, the mechanism of fold generation in part controls secondary faulting, which can play a major role in trap segmentation and disruption even though the secondary faults are not integral to fold genesis.

Fold traps tend to change significantly in their geometry with depth. For example, detachments in fold and thrust belts, angular unconformities, primary stratigraphic convergence of reservoir units, and the tendency of parallel folds to die upward in synclines and downward in anticlines cause major vertical changes in trap capacity. In addition, regional tilting affects trap capacity because structural relief (the height that a reservoir unit rises above the regional slope) can become ineffective as a fold's crest in profile drops below the horizontal (Levorsen, 1967).

Fault-Dominated Traps

As already pointed out, faults can be extremely important to the viability of a trap by providing either seals or leak points. They are capable of acting as top, lateral, or base seals by juxtaposing relatively impermeable rock units against more permeable reservoir units (Figure 13.5), or by acting as sealing surfaces due to the impermeable nature of the material along the fault. In addition, they may act as leak points by juxtaposition of permeable units or by creation of a fracture network. The term *fault* is descriptive in that it refers to a surface across which there has been displacement without reference to the cause of that displacement (i.e., whether it is tectonically, gravitationally, diagenetically, or otherwise induced). Structural traps that are dominated by faults at the reservoir–seal level (the fault itself makes the trap by sealing the reservoir without an ancillary fold) can be divided into three categories based on the type of separation, or slip if it is known, that geologic surfaces exhibit across the fault (Dennis, 1967). These are normal, reverse, and strike separation or slip fault traps.

Normal fault traps are the most common fault-dominated structural traps. They are of two fundamentally different geometries and are most common in two different tectonostratigraphic settings. Normal faults involving the basement occur in areas of significant crustal extension, such as the Gulf of Suez and North Sea, and are characterized by tilted fault blocks that exhibit a zig-zag map pattern (Harding and Lowell, 1979). Probably the most important trap geometry is the trap door closure at fault intersections (Figure 13.6A). Syn- and postdepositional normal faults that are detached from the basement occur in areas of rapid subsidence and sedimentation, commonly on passive continental margins, such as the U.S. Gulf Coast or Niger Delta (Weber et al., 1978), and are characterized by a listric profile and a cuspate map pattern that is usually concave basinward (Figure 13.6B). On the downthrown side of major displacement normal faults in this setting, smaller synthetic and antithetic fault-dominated traps are typical. Keystone normal fault-dominated traps above deep-seated salt intrusions are also common (North, 1985).

Reverse fault traps may be associated with detached or basement-involved thrust (low angle) or high-angle

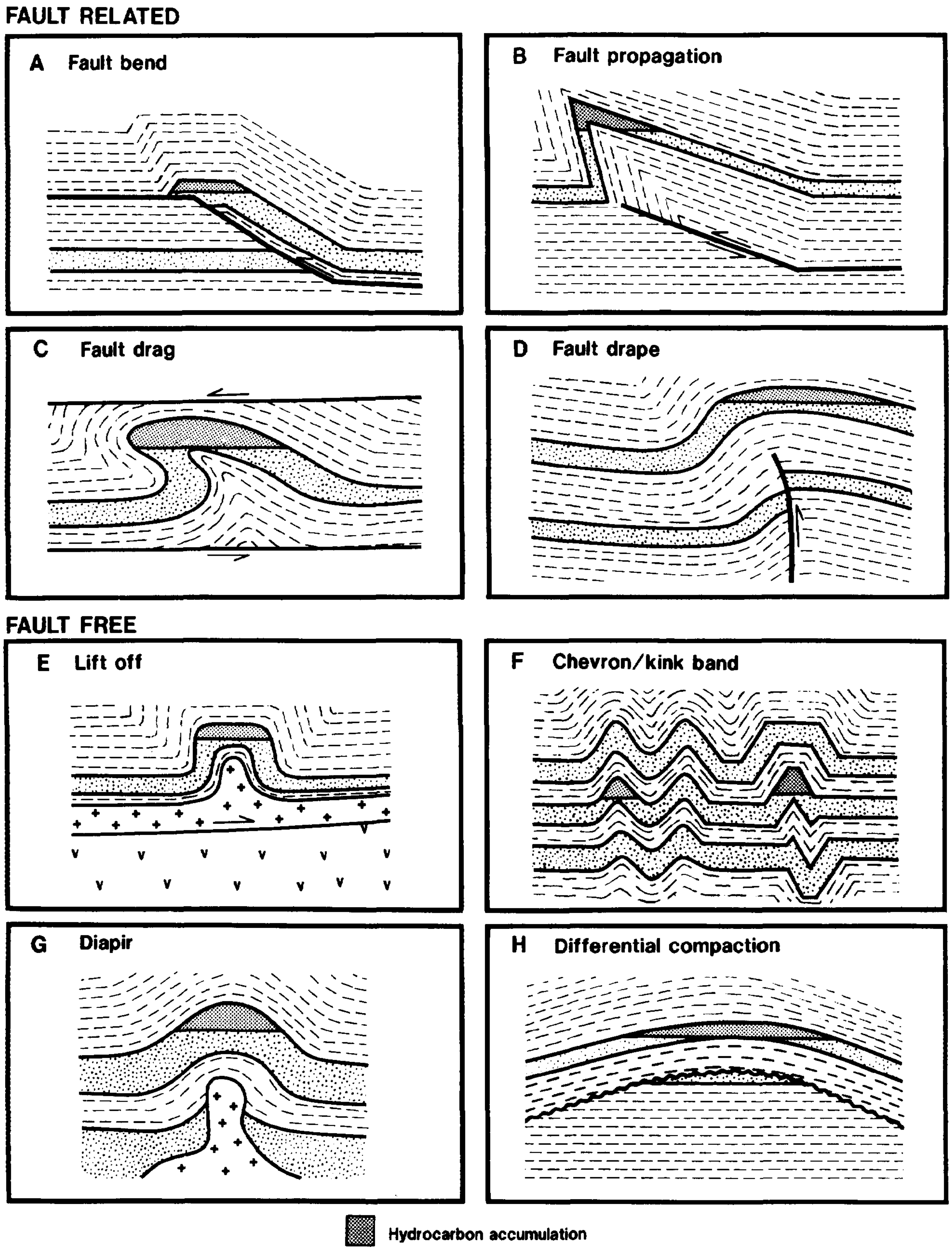

Figure 13.4. Types of traps in which folding dominates the reservoir–seal interval. Fault-related types include (A) fault bend, (B) fault propogation, (C) fault drag, and (D) fault drape. Fault-free types include (E) lift off, (F) chevron/kink band, (G) diapir, and (H) differential compaction.

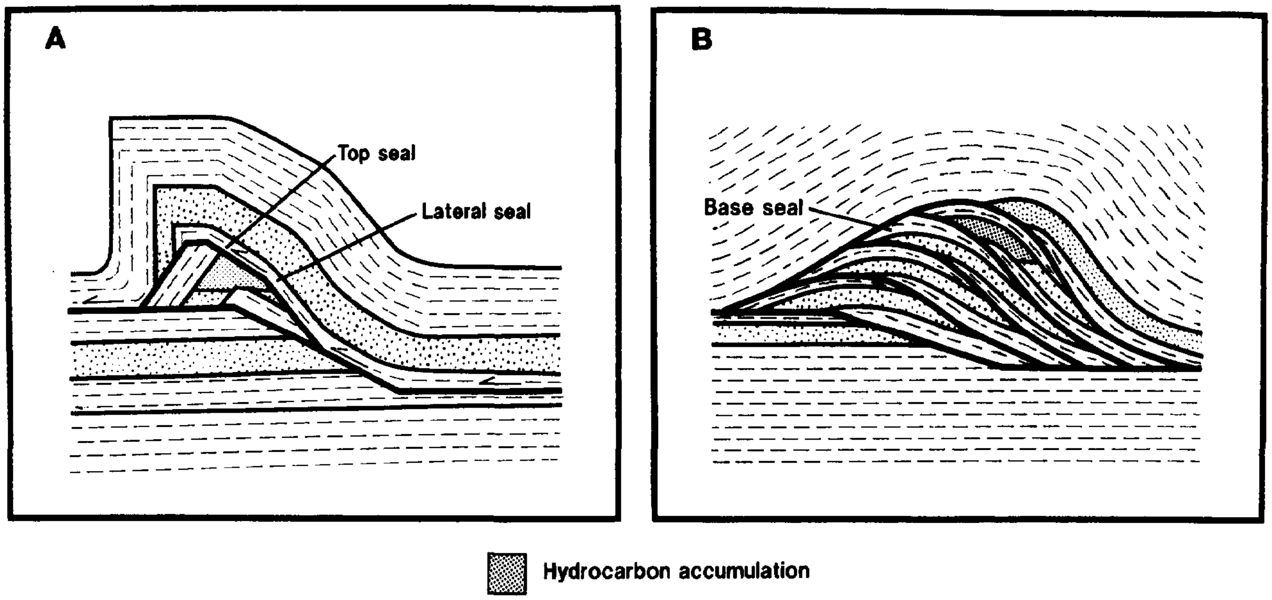

Figure 13.5. Combination fold and fault traps in which both are critical to trap viability. (A) Complex fault-bend fold showing associated sealing fault. (B) A duplex structure with a thrust fault forming an element of the base seal. Selected fault sealing properties are also illustrated.

reverse faults. These structures tend not to produce pure fault-dominated traps because of attendant folding. However, Figure 13.6C shows how regional dip plus thrusting can produce a viable reverse fault-dominated trap without folding at the relevant reservoir–seal interval and how minor footwall drag can provide a viable trap sealed by an overlying thrust fault.

Figure 13.6D is an example of a *strike-slip fault* trap in the Los Angeles basin of the United States (Harding, 1974). Folding and a tar seal also play a significant role in this trap.

STRATIGRAPHIC TRAPS

In 1936 (p. 524), Levorsen proposed the term *stratigraphic trap* for features "in which a variation in stratigraphy is the chief confining element in the reservoir which traps the oil." The existence of such nonstructural traps has been recognized since at least the late 1800s (Carll, 1880). Today, we would define a stratigraphic trap as one in which the requisite geometry and reservoir-seal(s) combination were formed by any variation in the stratigraphy that is independent of structural deformation, except for regional tilting (modified from North, 1985).

Many attempts have been made to classify types of stratigraphic traps. Early efforts, while not specifically using the term *stratigraphic,* led to broad categories of traps that were "closed" because of varying porosity within rock (e.g., Wilson, 1934). Later work recognized that considerable variability exists among such traps (e.g., Levorsen, 1967), and subdivisions became more numerous. A number of treatments of stratigraphic traps provide information on different approaches to classification and supply abundant examples of types of stratigraphic traps (e.g, Levorsen, 1936; Dott and Reynolds, 1969; King, 1972; Busch, 1974; Halbouty, 1982; Foster and Beaumont, 1988, 1991). Here, we generally follow Rittenhouse (1972) and divide stratigraphic traps into primary or depositional stratigraphic traps, stratigraphic traps associated with unconformities, and secondary stratigraphic traps.

Primary or Depositional Stratigraphic Traps

Primary or *depositional stratigraphic traps* (Figure 13.7) are created by changes in contemporaneous deposition (see MacKenzie, 1972). As described here, such traps are not associated with significant unconformities. Two general classes of primary stratigraphic traps can be recognized: those formed by lateral depositional changes, such as facies changes and depositional pinchouts (Figure 13.7A), and those created by buried depositional relief (Figure 13.7B).

Facies changes (Figure 13.7A) may juxtapose potential reservoir rocks and impermeable seal rocks over relatively short lateral distances in either siliciclastic or carbonate settings. The lateral transition from reservoir to seal is generally gradational, leading to possible noneconomic segments within the reservoir. Particular care must be taken to identify strike closure in this type of trap. *Depositional pinchouts* (Figure 13.7A) may lead to reservoir and seal combinations that can trap hydrocarbons. The transition from reservoir to lateral seal may be abrupt, in contrast to facies change traps. Strike closure is also a risk for pinchout traps.

Both lateral facies change and depositional pinchout traps generally require a component of regional dip to be effective. Both types are common elements of combina-

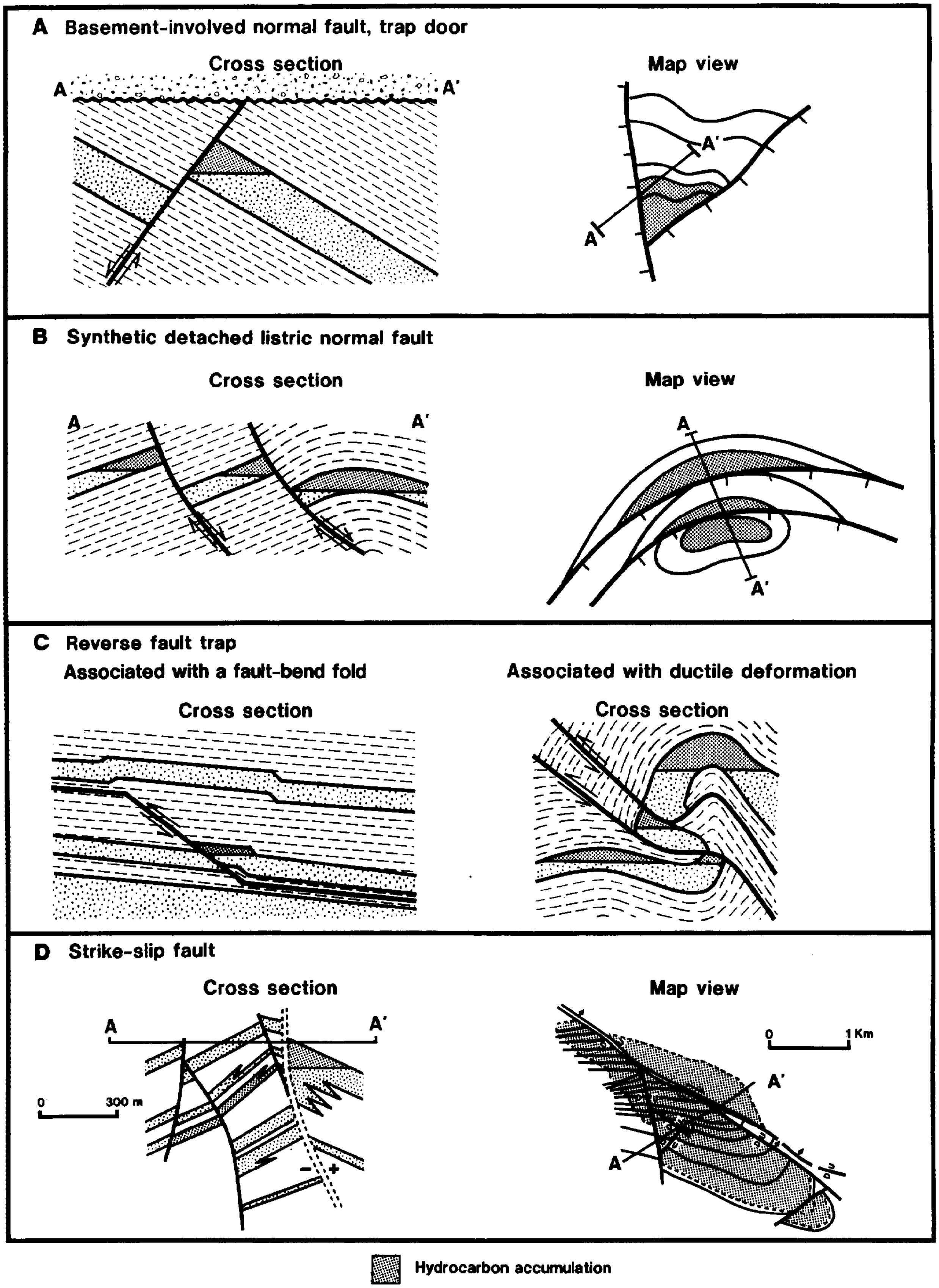

Figure 13.6. Types of traps in which faulting dominates the reservoir–seal interval. (A) Basement-involved normal fault trap and trap door. (B) Synthetic detached listric normal fault traps. (C) Two types of reverse fault traps. (D) Strike-slip fault traps.

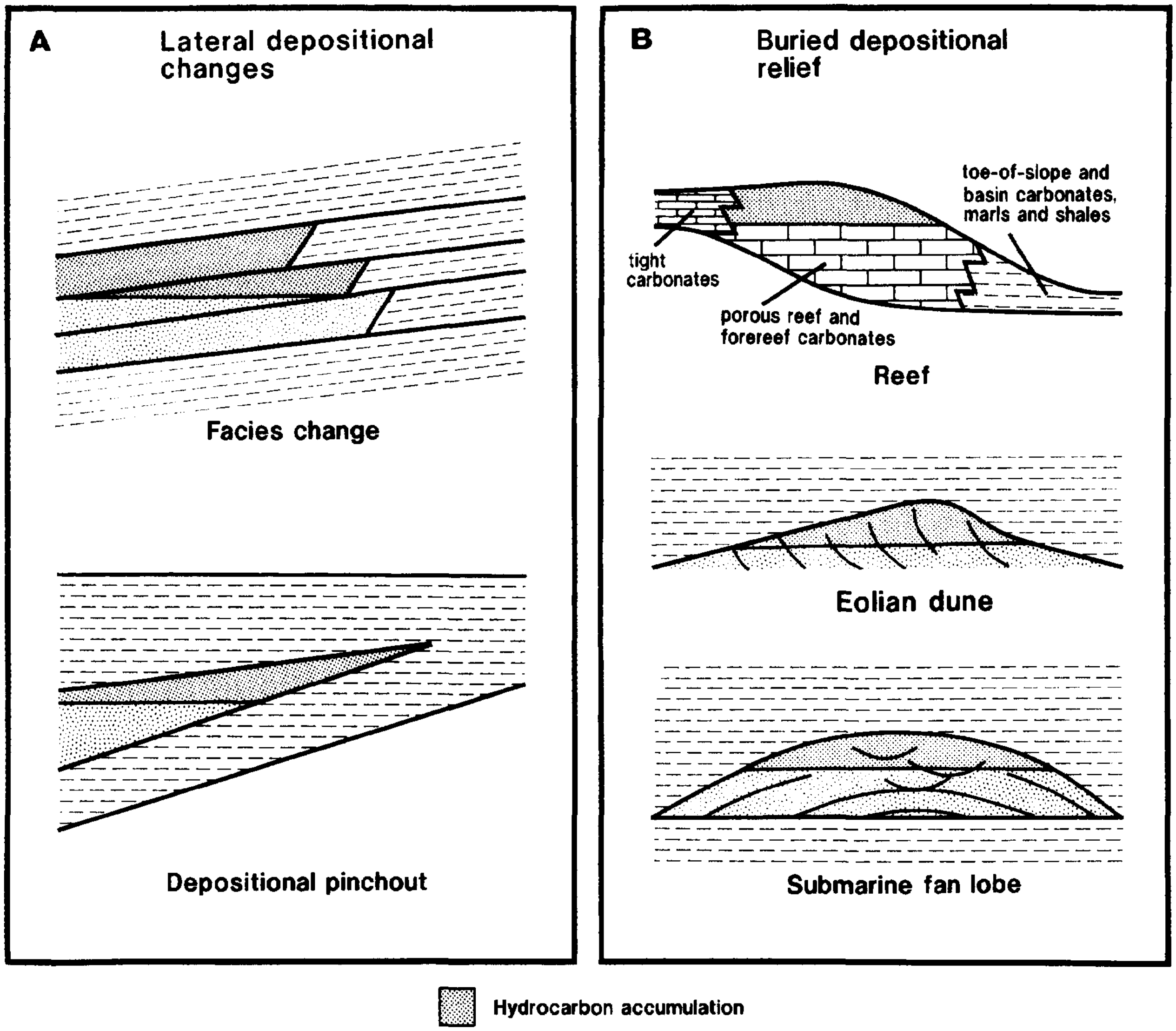

Figure 13.7. Primary or depositional stratigraphic traps. (A) Traps created by lateral changes in sedimentary rock type during deposition. Top: juxtaposition of reservoir and seal caused by lateral facies changes. Bottom: reservoir termination due to the depositional pinchout of porous and permeable rock units. (B) Traps formed by buried depositional relief. In each example, sedimentary processes form a potential trapping geometry, but require burial by younger impermeable section to create the required top seal.

tion structural–stratigraphic traps, particularly if the structure was growing during deposition of the reservoir and seal rocks.

The second general class of primary stratigraphic traps is associated with *buried depositional relief*. These traps are equivalent to the constructive paleogeomorphic traps of Martin (1966). There are many different types of such traps, a few of which are illustrated in Figure 13.7B. Each of these has distinct characteristics and attendant trap risks.

Carbonate reefs provide a classic example of potential traps associated with buried depositional relief. Reef growth with time enhances depositional relief, and the transition from tight lagoonal rocks to porous and permeable backreef–reef–forereef rocks may provide a good reservoir–lateral seal combination. The relationship between the forereef rocks and adjacent basinal deposits (potential source rocks) can create excellent migration pathways. Formation of a top seal requires that reef growth is terminated and that the reef is buried beneath a cap of low-permeability material. A key risk for this type of trap is accurate prediction of porosity and permeability within the reef complex. The Devonian reef fields of the Western Canada sedimentary basin are excellent examples of this type of trap (Hemphill et al., 1970; Barss et al, 1970).

Another type of buried depositional relief is associated with some submarine fan deposits (Figure 13.7B). In such depositional settings, sand-rich depositional lobes may be encased in shale. The Balder oil field in the Norwegian section of the North Sea is an example of this type of trap (Sarg and Skjold, 1982).

Other types of buried depositional relief exist (e.g., the eolian dune example in Figure 13.7B), and most of these are capable of producing potential traps for hydrocarbons. Exploration for these traps requires good knowledge of depositional models and careful attention to potential reservoir and seal limitations.

Stratigraphic Traps Associated with Unconformities

The important relationship between many types of stratigraphic traps and unconformities has been recognized for a long time (e.g., Clapp, 1917; Levorsen, 1954; Chenoweth, 1972; Rittenhouse, 1972). In 1972, Rittenhouse proposed that traps associated with unconformities can be grouped into two major categories: those occurring *beneath* an unconformity and those located *above* an unconformity (Figure 13.8).

Truncation of tilted strata beneath an unconformity (Figure 13.8A) can lead to the formation of a classic type of subunconformity stratigraphic trap. Rocks immediately above the unconformity provide the top seal and subunconformity units stratigraphically above and below the reservoir provide elements of lateral seal. Lateral seal in the strike direction can be created by variations in the subcrop pattern beneath the unconformity. The presence of permeable material just above the unconformity surface may seriously degrade the top seal and is a risk for this type of trap. Some of the largest stratigraphic traps discovered to date are of this type, such as the super giant East Texas field (Halbouty, 1991). Loma de la Lata, a super giant gas–condensate field in the Neuquen basin of Argentina is another giant field that produces from a subunconformity truncation trap. There, however, the truncation is on the flank of a large structure in the basin, and trap formation is clearly tied to the evolution of the structure. This trap is best viewed as a combination structural–stratigraphic trap.

Another type of subunconformity trap is set up by the truncation of reservoir-quality strata along the flanks of *incised valleys* or canyons (Figure 13.8A). These traps require that the fill of the incised valley forms part of the necessary lateral seal. Sinuosity of the incised valley along its strike can complete the lateral seal. Rittenhouse (1972) further subdivided this type of trap into valley-flank traps and valley-shoulder traps, depending on the position of the reservoir beds and the erosional surface of the valley.

A third type of subunconformity trap is created by *buried landforms* or erosional relief (Figure 13.8A). Many of Martin's (1966) paleogeomorphologic traps are of this type. There are numerous different subtypes of potential traps associated with buried erosional relief (Martin, 1966; Rittenhouse, 1972). The geometry of such traps depends on the geometry of the erosional surface and of the underlying beds. Key risks are the identification and distribution of reservoir beneath the unconformity and the effectiveness of seal above the unconformity. The buried hills oil and gas fields in the North China basin provide a broad spectrum of examples from buried erosional features, such as the Rengin field, to combination normal fault–eroded structures, such as the Xinlungai field (Zhai and Zha, 1982).

Deposition above unconformities can also form trapping configurations, several of which are illustrated in Figure 8B. *Onlap* onto an unconformable surface may lead to the areally widespread deposition of reservoir and seal rocks. Strike closure can be provided by the geometry of the underlying unconformity, but may be hard to define.

A common type of stratigraphic trap above an unconformity is created by deposition within incised valleys or canyons (Figure 13.8B). The incised feature itself defines much of the geometry of the potential trap, although pinchouts and facies changes within the valley fill can greatly complicate trap geometry. In fact, many incised valleys are relatively easy to map, but predicting reservoir and seal rock distribution within the incised valley fill is a significant challenge. Many of the fields in the Powder River basin of Wyoming that produce from the Muddy Formation are examples of traps within the fill of incised valleys.

Onlap of erosional relief (Figure 13.8B) is the last illustrated example of possible stratigraphic traps above an unconformity. This type of trap forms rims or halos around the buried erosional feature and may be associated with so-called bald-headed highs.

Secondary Stratigraphic Traps

Another major category of stratigraphic traps results from *postdepositional alteration* of strata. Such alteration may either create reservoir-quality rocks from nonreservoirs or create seals from former reservoirs. Two examples are shown in Figure 13.9. The first (Figure 13.9A) shows updip porosity loss caused by cementation in previously porous and permeable carbonate rocks. Although the example used is taken from a carbonate setting, similar diagenetic plugging can occur in just about any rock type under the proper circumstances. Porosity occlusion is not limited to only diagenetic mineral cements. Asphalt, permafrost, and gas hydrates are other possible agents that may form seals for this type of stratigraphic trap. Unfortunately, it is often diffcult to predict the position of cementation boundaries in the subsurface before drilling, and this type of trap can be a challenging exploration target.

The second type of secondary stratigraphic trap is associated with *porosity enhancement* that improves reservoir quality in otherwise tight sections. Dolomitization of limited-permeability limestones is a good example (Figure 13.9B). Dissolution of framework or matrix material is another porosity- and permeability-enhancement mechanism. Porosity enhancement associated with dolomitization and dissolution potentially can create traps on its own. Commonly, though, porosity enhancement is associated with other types of traps as a modifying element. The dolomitized reservoirs of the Scipio–Albion trend in Michigan are a good example of porosity and permeability enhancement along a structural trend (Harding, 1974).

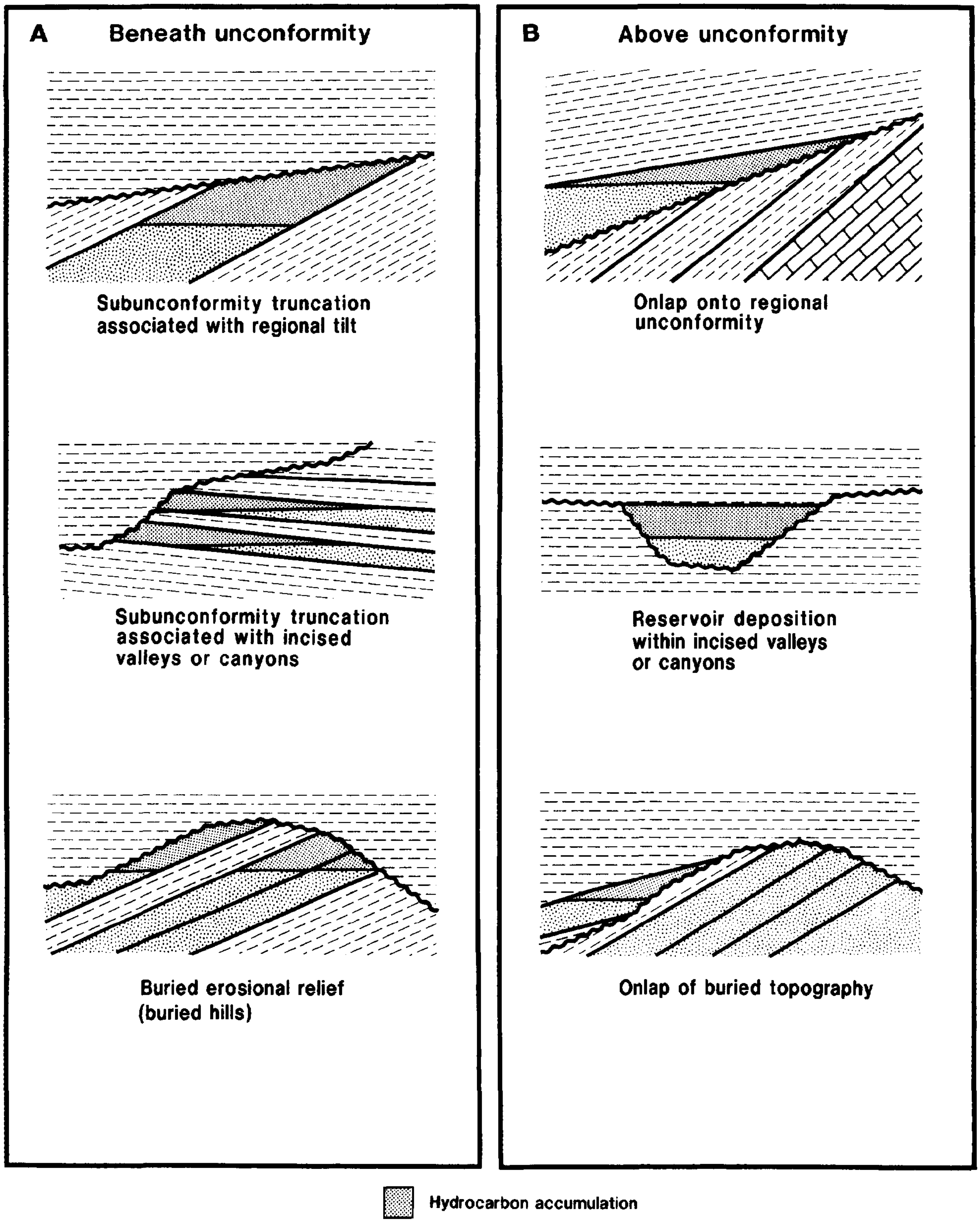

Figure 13.8. Stratigraphic traps associated with unconformities. (A) Traps beneath an unconformity. (B) Traps above an unconformity.

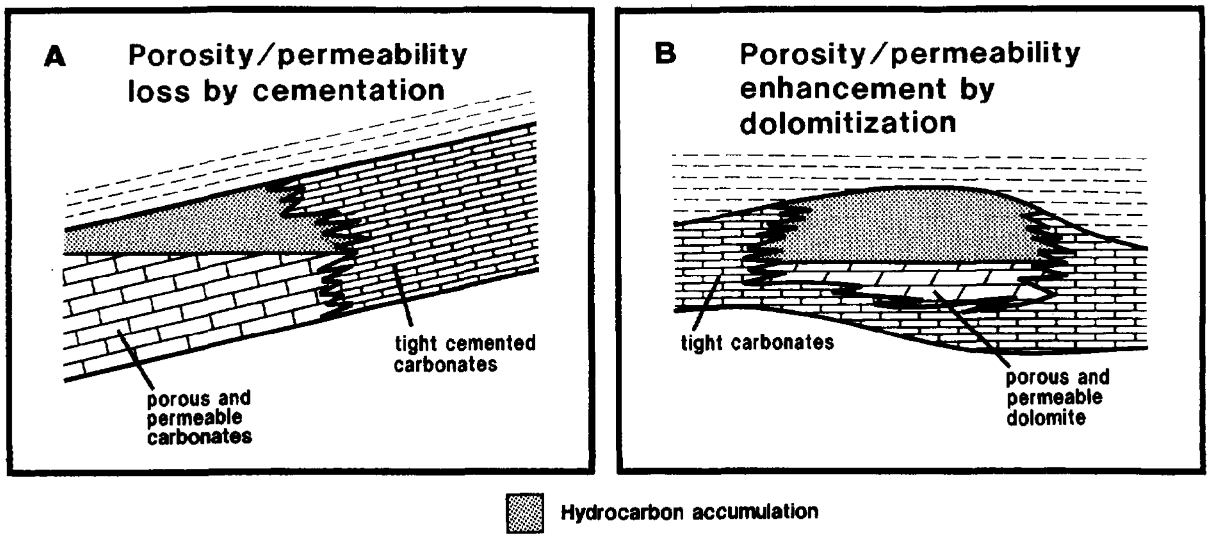

Figure 13.9. Secondary diagenetic stratigraphic traps. (A) Traps created by postdepositional updip porosity occlusion. (B) Traps created by postdepositional porosity and permeability enhancement.

COMBINATION TRAPS

Many of the world's hydrocarbon traps are not simple features but instead combine both structural and stratigraphic elements. Levorsen recognized this in his 1967 classification of traps. He noted that almost a complete gradation exists between structural and stratigraphic end-members and that discovered traps "illustrate almost every imaginable combination of structure and stratigraphy" (Levorsen, 1967, p. 143). Levorsen restricted the use of the term *combination trap* to features in which neither the structural nor the stratigraphic element alone forms the trap but both are essential to it (Levorsen, 1967). Two examples of combination structural–stratigraphic traps are illustrated in Figure 13.10. In both cases, part of the trap is formed by an updip depositional pinchout of porous and permeable rock. Fault seal forms a required part of the trap in Figure 13.10A, while folding of the permeability pinchout creates the required strike closure in Figure 13.10B.

Many people now use the term *combination trap* in a less rigorous way and apply it to any trap that has both structural and stratigraphic elements, regardless of whether both are required for the trap to be viable. Strict adherence to definitions does not necessarily find hydrocarbons, but early recognition of stratigraphic complications associated with structural traps or structural modification of dominantly stratigraphic traps can help eliminate exploration or development surprises.

HYDRODYNAMIC TRAPS

Explorationists have known since about mid-century that oil–water contacts in many hydrocarbon-bearing traps are tilted (see Levorsen, 1967; North, 1985). In other cases, traps that have no static closure contain hydrocarbons, and traps that do have static closure and should reasonably contain hydrocarbons do not (North, 1985). An explanation that is commonly proposed for these observations is that reservoir conditions are hydrodynamic rather than hydrostatic. In general, dips of oil–water contacts seldom exceed a few degrees, but higher dips have been reported (up to 10°) (North, 1985). If the dip (or tilt) of the oil–water contact exceeds the dip of the trap flanks, the trap will be flushed (generally, if trap flank dips exceed 5°, there is little risk of flushing). Therefore, in the evaluation of structural traps with relatively gently dipping flanks, consideration should be given to hydrodynamic conditions (see Dahlberg, 1982). It is important to note that tilted oil–water contacts may be related to phenomena other than hydrodynamics (e.g., variations in reservoir characteristics and neotectonics), and that present-day hydrodynamic conditions may not reflect those in the past.

It is possible to calculate the theoretical change in trap capacity and therefore the risk associated with trap flushing in a strongly hydrodynamic situation. Hubbert (1953) showed that the tilt of the oil–water contact in the direction of flow is a function of the hydraulic gradient and the densities of both hydrocarbons and water. The lower the oil density and greater the water flow, the more easily the oil is displaced. Figure 13.11A illustrates one type of hydrostatic trap, and Figure 13.11B demonstrates the qualitative effect of a hydrodynamic situation. If water flow rate is increased with a constant oil density, or oil density is increased with a constant water flow rate, the situation in Figure 13.11C will arise. In Figure 13.11D, a trap is created in a flexure without static closure due to downdip water movement. Figure 13.11E illustrates the effect of updip water movement for static conditions under the same structural situation. Figures 13.11F and G show the qualitative effect of downdip and updip water movement on the capacity of a fold-dominated trap to store hydrocarbons. As can be seen, downdip water flow tends to promote hydrocarbon entrapment and updip flow tends to impede it.

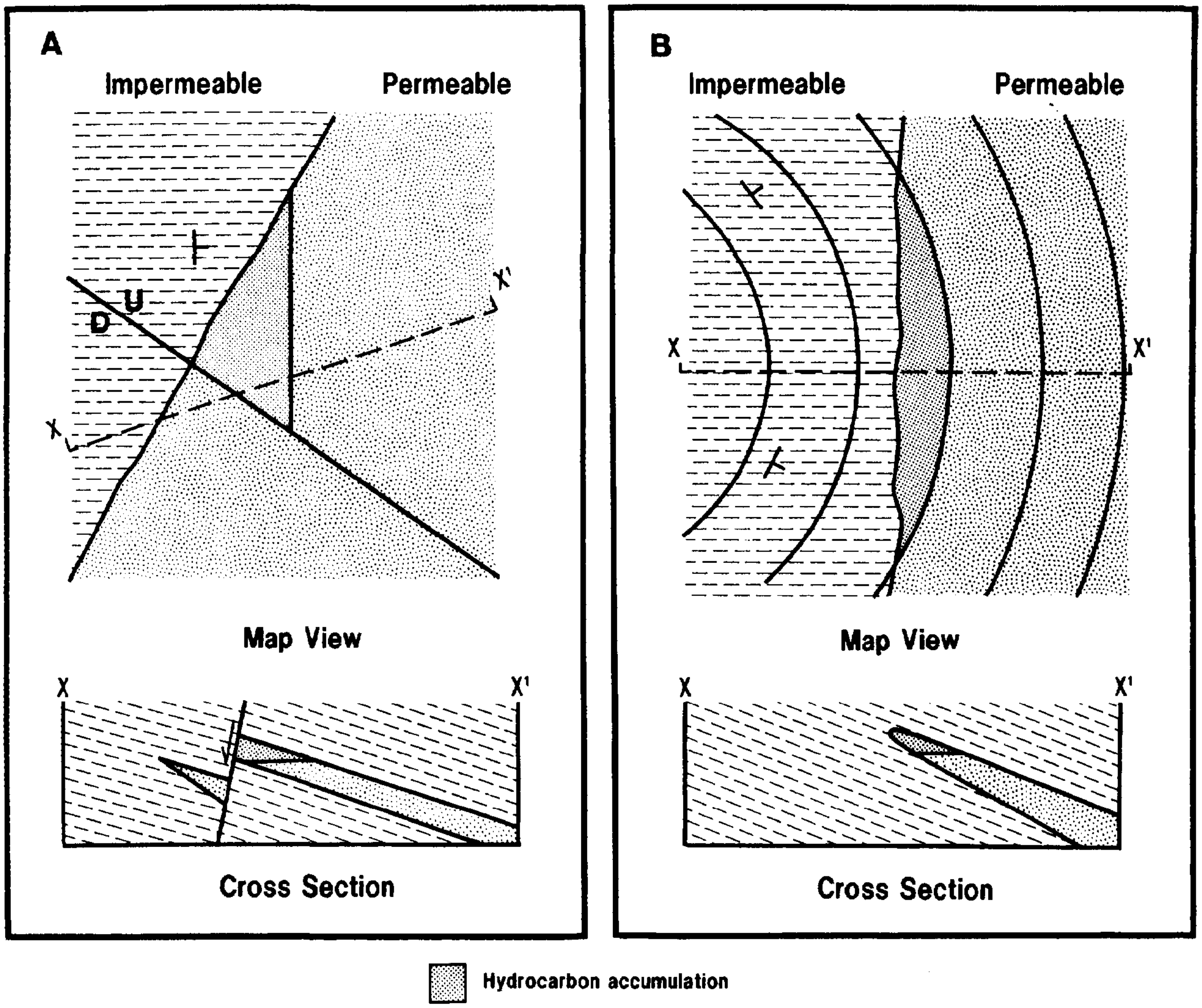

Figure 13.10. Combination traps. (A) Intersection of a fault with an updip depositional edge of porous and permeable section. (B) Folding of an updip depositional pinchout of reservoir section. In these examples, both the structural and stratigraphic elements are required to form a viable trap. (After Levorsen, 1967.)

TRAP EVALUATION

In this chapter, our illustration of various trap types has focused on cross-sectional views. This is because cross sections provide diagnostic images of many of the various trap types. Map views of traps are equally important, although sometimes not as visually distinctive of trap type. Those involved in trap evaluation should develop a detailed understanding of the various map patterns associated with different styles of traps. This can guide mapping during the early stages of evaluation or in cases where only limited data are available. Examples of map patterns for the types of traps discussed here can be found in many of the references that we have cited (e.g., King, 1972; North, 1985; Foster and Beaumont, 1991). Useful mapping techniques are described by Tearpock and Bischke (1991).

Regional trap evaluation should concentrate on placing potential traps in the context of the operating petroleum system. Plate tectonic setting, basin type, and structural evolution (sedimentary basin study) can be used at this stage to predict the possible styles of structural and stratigraphic traps that should be expected in an area (Harding and Lowell, 1979). Regional seals and their relation to potential traps should be established early in the evaluation. Particular attention should be paid to the timing of trap formation and its relation to the timing of generation, migration, and accumulation of hydrocarbon. Traps that form after hydrocarbon migration has ceased are not attractive targets unless remigration out of earlier formed traps has occurred.

Detailed evaluation of individual traps, once identified, should begin with the selection of the mapping surface. Ideally, this would be the sealing surface of the trap. Identification of the actual sealing surface requires that both seal and reservoir characterization are integral

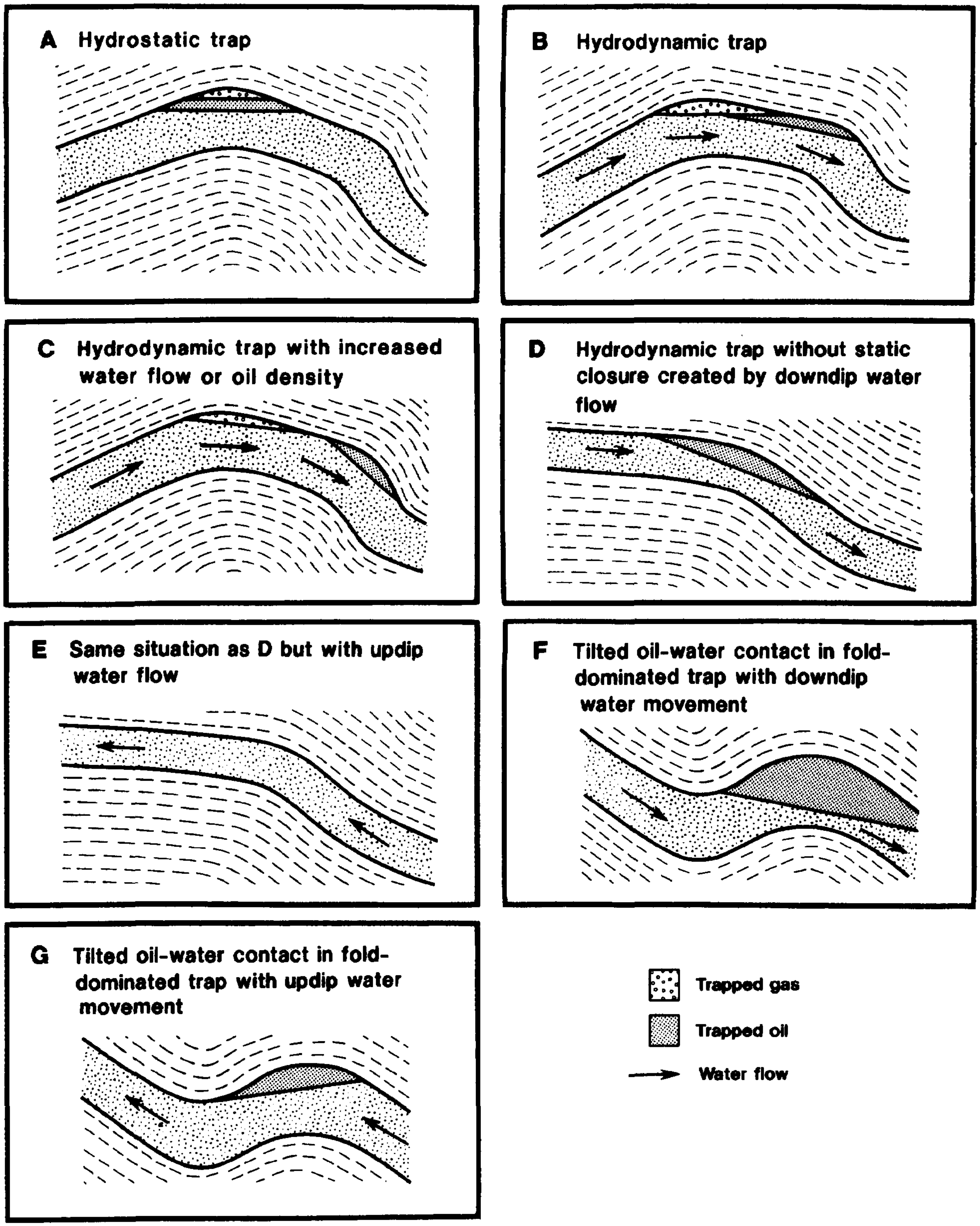

Figure 13.11. Illustrations of the qualitative effect of the amount and direction of water flow and oil density on hydrocarbon trap configuration. (A) Generalized hydrostatic trap. (B) Generalized hydrodynamic trap. (After Hubbert, 1953; North, 1985.) (C) Hydrodynamic trap with increased water flow or oil density. (D) Hydrodynamic trap without static closure created by downdip water flow. (E) Same situation as in (D) but with updip water flow. (F) Tilted oil–water contact in fold-dominated trap with downdip water movement. (G) Tilted oil–water contact in fold-dominated trap with updip water movement.

parts of the trap evaluation. Also, if the sealing surface of the trap is not correctly identified, trap leak points may be missed. A common flaw in trap evaluation results from ignoring the transition (or waste) zone, if present, between an economic reservoir and its ultimate seal.

Before drilling, reservoir and seal characteristics can be predicted by combining regional and local paleogeographic information, sequence stratigraphic concepts, and detailed analyses of seismic facies and interval velocities. If well data are available, detailed log analysis and incorporation of pertinent drill-stem test data will greatly improve predictions. Petrophysical measurements from downhole samples are also useful, but because of small sample sizes, such information may not characterize either reservoir or seal properties throughout the trap and should be extrapolated with caution.

We have defined a trap as any geometric arrangement of rock that permits significant accumulation of hydrocarbons in the subsurface. We do not consider the presence of hydrocarbons in economic amounts to be a critical element of a trap. The absence of oil or gas in a subsurface feature can be the result of failure or absence of other essential elements or processes of a petroleum system and may have nothing to do with the viability of the trap.

Although we use the geometric arrangement of key elements to define a trap, trap evaluation must include much more than just mapping the configuration of those elements. Reservoir and seal characteristics are so important to trap viability that their evaluation must be an integral part of any trap study. Timing of trap formation is also critical. No trap should be viewed out of context but rather should be evaluated in concert with all of the other elements of a petroleum system.

Traps can be classified as structural, stratigraphic, or combination traps. In addition, hydrodynamic flow can modify traps and perhaps lead to hydrocarbon accumulations where no conventional traps exist. The trap classification discussed here is a useful way to consider traps during the early stages of prospect evaluation. An understanding of end-member trap types can help guide data acquisition strategy and mapping efforts, but there is an almost bewildering array of documented and potential hydrocarbon traps, many of which may be subtle or unconventional. As more and more of the world's hydrocarbon provinces reach mature stages of exploration, such traps may provide some of the best opportunities for future discoveries.

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