CHAPTER 6

Reservoir Traps – General and Structural

The anticlinal theory. Classification of traps. Structural traps: caused by folding—by faulting—by fracturing.

THE FIRST essential element of a petroleum reservoir, you will recall, is the reservoir rock, and the second is the existence of connected pore spaces that are collectively capable of holding and storing petroleum. The third element is the oil, water, and gas—which are either in motion or are capable of moving—that occupy the connected pore spaces. The fourth element is the trap—the place where oil and gas are barred from further movement.

Since oil and gas are lighter than water, and since the reservoir rocks generally have a regional slope, though often slight, the petroleum moves through the water both vertically and laterally until it is barred by an impervious or less pervious rock. The impervious stratum that overlies the reservoir rock is called the *roof rock*.[*] A roof rock that is concave[†] as viewed from below prevents the oil and gas from escaping either vertically or laterally, thus localizing the pool of oil and gas. Such an external barrier is a *structural trap*. A lateral lessening of permeability due to facies changes, truncations, and other stratigraphic changes will, together with the roof rock, form an interior barrier, or *stratigraphic trap*.

Structural traps are the result of changes in the form of the reservoir rock; stratigraphic traps are the result of changes in the continuity of the rock. *Fluid barriers* occur where a difference in fluid potentials causes a down-dip

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[*] The term "cap rock" is also used, but it is better reserved for the cap rock of a salt plug.

[†] The term "concave" is used to describe the shapes of such structures as folds, domes, arches, and the intersecting planes that are peaked, or roof-shaped.

flow of water to oppose the up-dip migration of petroleum. Increased fluid potential gradients usually exist where the flow space is constricted; for example, where a formation thins or where permeability is reduced.

Reservoirs are infinitely variable in detail. Practically every sedimentary area has been deformed to some degree, and most areas have been deformed several times. Lateral change in the rock properties is the rule rather than the exception, and the direction of fluid flow has undoubtedly varied throughout geologic time owing to the continual change in the potentiometric surface. The relative importance of each of these elements in trapping a specific pool of petroleum may not be known until the field is completely developed and years of production history are available.

But the job of the petroleum geologist is to try to locate a favorable combination of these elements *before* a pool is found. His data are generally fragmentary: geophysical measurements are often inconclusive, well records for subsurface controls are lacking or widely scattered, fluid pressures are unknown, and outcrops are poor or distant. Small amounts of information must be combined and projected for long distances both vertically and horizontally. Of the essential elements, the most readily determined in advance of drilling is the presence of traps that result from the structural features of the reservoir rock. The structural geology may be mapped in a variety of ways, such as surface mapping, core drilling, subsurface mapping, and geophysical surveying. Since most reservoirs show at least some deformation, structural mapping adds information of value to most predictions; it becomes the basis of prediction where the trap is controlled by the deformation of the reservoir rock. Determination of the nature of the reservoir rock, on the other hand, including such characteristics as extent, porosity, and permeability, is more difficult; in fact, these characteristics cannot be fully determined without adequate subsurface data, which are obtained only from well records. Such data are based on studies of well logs, well cuttings, and cores, and on cross sections and subsurface maps that show the distribution of rocks, their correlations, and their unconformities. Several kinds of maps are needed to show the data upon which to base predictions of the position of favorable reservoir characteristics; these include areal-geology maps, structure maps, sand-distribution maps, formation-thickness (isopach) maps, subcrop and paleogeologic maps, productivity maps, isopotential maps, lithofacies maps, and other maps. They are discussed in more detail in the section on subsurface mapping, pages 591–618.

The simplest and commonest way for a permeable underground formation to become a trap is to be folded into an anticline. An anticline is the most readily mapped of the common traps and can frequently be mapped at the surface. The close association of oil and gas pools with anticlinal folds was noted early and led to what has long been known as the *anticlinal theory* of oil and gas occurrence. Geologists everywhere searched for anticlines and domes on which to drill—almost to the exclusion of any other kind of trap. Consequently the anticlinal theory has had such a predominant place in exploration that it warrants a brief review of its development and of its gradual change into the more modern *trap theory.*

THE ANTICLINAL THEORY

Although petroleum in various forms has been known since man made his earliest records, it was not until petroleum attained economic importance that much serious thought was given to why, how, and where it accumulated into pools. The discovery of oil by E. L. Drake in western Pennsylvania, in 1859, marked the beginning of the modern oil industry even though oil had previously been mined and obtained from wells at a number of places in various parts of the world. Drake demonstrated that drilling for oil could be successful, and the amount of oil he produced, though small compared with modern production, showed the world that drilling was the most effective way to obtain oil. From that time forth, the main question in the minds of every prospector for oil was where to put down the drill. Thought on this subject was greatly stimulated by the increasing demand for petroleum, and down to the present time it has constituted the core of petroleum geology.

A variety of theories have attempted to explain the conditions that result in an oil and gas pool in order to predict where such conditions may be found and where discoveries may be made. Of these the anticlinal theory[1] has received the most serious and continued attention. The development of the anticlinal theory in geologic thinking is itself an interesting subject, but it can only be touched on here. The theory was conceived even before Drake's discovery, and, having been modified and expanded through the years, it is fundamentally as true today as when first proposed.

One of the earliest references to a relation between oil and anticlinal folding was made before Drake's time, when oil seepages near Gaspé, at the mouth of the St. Lawrence River in eastern Canada, were visited by Sir William Logan in 1842 and were described in 1844 as occurring on anticlines.[2] Interest in the subject was greatly stimulated by Drake's discovery, and within a short period thereafter several geologists working independently arrived at a similar conclusion: anticlines are the place to look for petroleum.

I. C. White, one of many students of oil and gas accumulation, who had been an assistant on the Second Geological Survey of Pennsylvania (the Lesley Survey) since 1875, resigned in 1883 to engage in commercial work. An early assignment of his was to determine whether or not it was possible to predict the presence or absence of gas by a knowledge of the geologic structure. He had learned that gas wells in western Pennsylvania were located close to anticlines, and he inferred that there must be some connection between the position of the gas pools and the structure. His statement of the anticlinal theory, published in 1885, is as good even now as it was then.

"After visiting all the great gas-wells that had been struck in western Pennsylvania and West Virginia, and carefully examining the geological surroundings of each, I found that every one of them was situated either directly on, or near, the crown of an anticlinal axis, while wells that had been bored in the synclines on either side furnished little or no gas, but in many cases large quantities of salt water. . . . During the last two years, I have submitted it to all manner of tests, both in locating and condemning gas territory, and the general result has been to confirm the anticlinal theory beyond a reasonable doubt.

"But while we can state with confidence that all great gas wells are found on the anticlinal axes, the converse of this is not true; viz., that great gas-wells may be found on all anticlinals.

". . . The reason why natural gas should collect under the arches of the rocks is sufficiently plain, from a consideration of its volatile nature. Then too, the extensive fissuring of the rock, which appears necessary to form a capacious reservoir for a large gas-well, would take place most readily along the anticlinals, where the tension in bending would be greatest." [3]

Because of the wide attention this article on the occurrence of gas received from the oil operators of the time, I. C. White has often erroneously been called the "father of the anticlinal theory." He made no such claim for himself, but he did take credit for "the work which the writer has especially accomplished, and in the doing of it, so enforced the lessons of geology upon the minds of the men engaged in the practical work of drilling for oil, that the acceptance of the structural theory is now almost universal among them as well as among geologists. In this the writer has been ably assisted by Dr. Edward Orton." [4]

Many arguments for and against the anticlinal theory were published in the various scientific journals of the 1890's. But the practical success that White achieved in advising the drilling of wells for gas on anticlinal structures finally led him to state in 1892: "As is well known, it was formerly a popular saying among practical oil men that 'Geology has never filled an oil tank'; and to such a low estate had geology fallen that a prominent producer of oil and gas, disgusted with geology and geologists, was once heard to remark that if he wanted to make sure of a dry hole he would employ a geologist to select the location. It has been my pleasant task during the last eight years to assist in removing this stigma from our profession, so that with the valuable assistance of Ohio's distinguished geologist, Professor Orton, Dr. Phinney of Indiana, and others, the battle against popular as well as scientific prejudice has been fought and won and this long standing reproach to geology in great part removed." [5]

McCoy and Keyte recognized the importance of nonstructural accumulations and of traps that were not anticlines. In 1934 they used the term "structural theory" instead of "anticlinal theory," remarking that the term was "broad enough to include the occurrence of oil on the flanks of anticlines, in lenses, and in synclines, as well as the occurrence of oil on anticlines, domes, and noses." They summarized the structural theory as follows: ". . . commercial deposits of oil and gas are associated with structural irregularities in porous sedimentary rocks, the most important irregularity being the anticline or dome." [6]

Even though the term "anticlinal theory" may now have fallen into disuse, the fundamental principle upon which it was based—that oil and gas accumulate as high within the reservoir as possible—is as good today as it ever was. The only difference is that we now recognize a large number of conditions other than anticlines that will form a bounding rock surface that is concave as viewed from below.

The term "trap" was first introduced by McCollough in 1934 and applied to containers as diverse in character as those due to asphalt seals, lenses, local porosity variations, truncation, and overlap, especially in homoclinal dip areas, as well as to folding and faulting.[7] Continued recognition of the fact that structural deformation is only one of several ways in which a trap may be formed, and that a large number of pools have accumulated in traps formed in other ways, increases the desirability of using a more inclusive term than "anticlinal theory." The term "trap theory" is now more commonly used, and the geometrical configuration that holds in the oil is now commonly called a "trap," whatever its shape or cause may be. Its essential characteristic is that the oil and gas are capable of accumulating and being held in it.

The importance of the oil-water contact in defining the trap has led to some modification of former ideas that assumed the water table to be either level or nearly level. It is now recognized that in some regions, where there is a fluid potential gradient, the oil-water contact is distinctly tilted. This tilt affects the position of the pool with respect to the rock boundaries, displacing it varying distances in the direction of water movement, even to the point of flushing the pool completely out of the trap. The fundamental concepts of the effect of moving water on substances of less density are contained in the classic article by Hubbert[8] describing the physics of water movement. The effect of a tilted water table on the position of the pool was shown by Russell,[9] and his demonstration was expanded by Hubbert.[10] The whole idea was explored independently by Hill,* who arrived at the same conclusion as Hubbert—namely, that the trap for oil and gas in a reservoir rock is at the position of least potential energy, and that this position is determined by the difference in hydraulic head or fluid potential across the trap.

CLASSIFICATION OF TRAPS

Numerous classifications of reservoir traps have been proposed. Clapp's final classification contained the following main headings: (1) anticlinal structures, (2) synclinal structures, (3) homoclinal structures, (4) quaquaversal structures, or "domes," (5) unconformities, (6) lenticular sands, (7) crevices or cavities irrespective of other structure, (8) structures due to faulting.[11] Heroy classifies traps as (1) depositional traps, (2) diagenetic traps, (3) deformational traps.[12] Wilson classifies traps as (1) closed reservoirs: (a) reservoirs closed by local deformation of strata, (b) reservoirs closed because of varying porosity of the rock (no deformation of strata necessary other than re-

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* Gilman A. Hill in an unpublished manuscript, Stanford University, 1951.

gional tilting), (c) reservoirs closed by combination of folding and varying porosity, (d) reservoirs closed by combination of faulting and varying porosity; (2) open reservoirs (none of commercial importance).[13] Heald sets up two groups of reservoirs: (1) closed by local deformation of strata, (2) closed because of varying permeability of the rock.[14] Wilhelm's classification is quite detailed and attempts to take into account all trap-forming factors participating in the boundaries of petroleum reservoirs. His chief classification headings are: (1) convex trap reservoirs, (2) permeability trap reservoirs, (3) pinch-out trap reservoirs, (4) salt trap reservoirs, (5) piercement trap reservoirs.[15]

No classification is entirely satisfactory, for many traps are unique and would not fit readily into any but an extremely detailed classification. The following scheme, however, is believed to be as useful as any. Although simple, it includes a place for most kinds of traps known to contain oil and gas in commercial quantities. It is not all-inclusive, but the exceptions will be pointed out as they occur. The classification divides the traps broadly into three basic types: (1) structural traps, (2) stratigraphic traps, (3) combinations of these two.

1. 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.

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2. A *stratigraphic trap* is 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. The areal extent of a pool occurring in a stratigraphic trap is determined wholly, or in large part, by some stratigraphic variation associated with the reservoir rock. The pool may rest on an underlying water table, which may be either level or tilted, or it may completely fill the voids in the reservoir rock with no produceable underlying reservoir water. The flow of water down-dip through the restricted permeability that forms the stratigraphic barrier to up-dip movement of the petroleum probably is an important element in the trapping of petroleum in many stratigraphic traps. (See also Chap. 9.) due to Structu

3. *Combination traps.* Between these extremes—there is an almost complete gradation—traps are found that illustrate almost every imaginable combination of structure and stratigraphy. Traps in which structure or stratigraphy is clearly the most influential factor can readily be classified as structural or stratigraphic types. As the middle ground between a structural and stratigraphic trap is approached, however, it becomes increasingly difficult to decide the relative importance of each. Traps in this middle group—traps

formed by both structural and stratigraphic causes in roughly equal proportions—are best called combination traps.

In practice, when we speak of a "trap," we commonly mean its rock boundaries, and we use such a term as "structural trap," "stratigraphic trap," "anticlinal trap," or "combination trap" when we wish to indicate its cause. The position of the pool within the trap may depend in part on the movement of the formation water. Where there is no movement, the pool is as high as possible in the trap; if the water is in motion, the pool may be displaced for varying distances down the side of the trap. The movement of the water is determined by the fluid potential gradient in the reservoir rock unit that contains the trap. (See Chap. 9.) A trap, therefore, though present, may be ineffective because of particular fluid, temperature, and pressure conditions of the present or of the geologic past.

Cause by faulting N. Strikeslip

STRUCTURAL TRAPS

Cause by folding

Traps that are formed chiefly as a result of folding and faulting are the ones that are most apparent from surface mapping and most readily located underground; they are also the ones that give the most help to the discovery of oil and gas. Consequently, structural traps have received the most attention by geologists, as indicated by the persistent use of the term "anticlinal theory" and the general custom of designating any trap resulting from deformed rocks as a "structure." Nearly all of the surface mapping, shallow core drilling, and geophysical mapping, and most of the subsurface mapping, has as its objective the location of traps that result wholly or in part from deformation of the reservoir rock.

One important aspect of structural features such as anticlines is that the structure generally extends vertically through a considerable thickness of sedimentary formations, thereby causing traps to form in all of the potential reservoir rocks affected by them. For this reason the drilling of structural traps involving a good thickness of sediments is considered good prospecting, even though specific reservoir rocks or other features of subsurface stratigraphy may not be known in advance. It is reasoned that, if the geologic section to be explored contains any reservoir rocks, they are most likely to produce where they are deformed into traps. One of many possible examples in which folding affects a great thickness of strata is the Santa Fe Springs field, of Los Angeles County, California, where a smooth, nearly circular dome fold extends down to form traps in twenty-five or more reservoir rocks, each of which contains an oil pool.[16] A section through the field is shown in Figure 6-1.

The deformation of the reservoir rock may be determined in several ways. Some folds and faults extend from the reservoir rock to the surface of the ground, where they may be mapped by ordinary surface mapping methods. A modification of surface mapping is the use of shallow core drilling, to

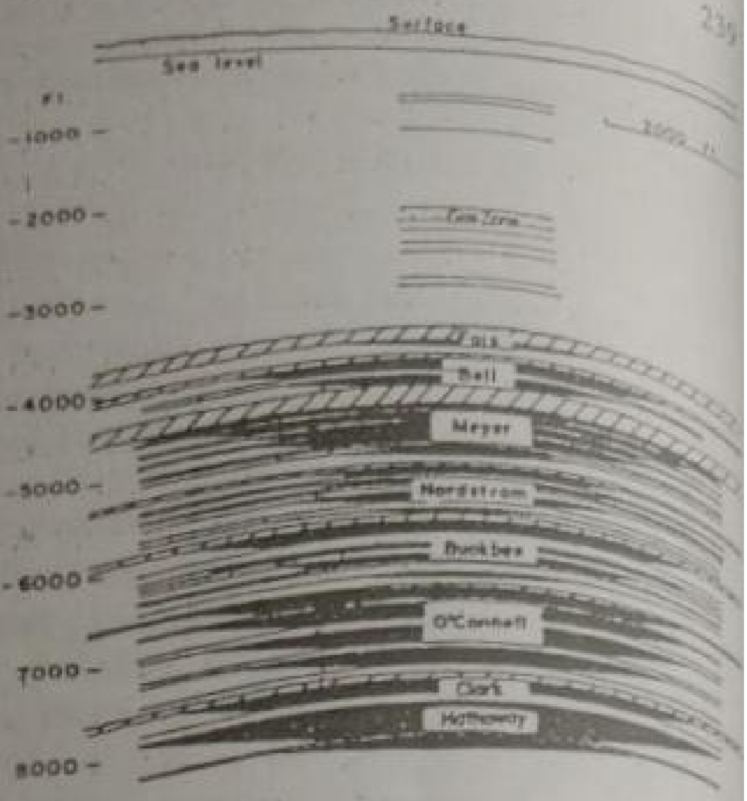


FIGURE 6-1

Section through the Santa Fe Springs oil field, California, an example of how many separate traps, holding many separate pools, are formed by one fold. The lack of connection between the different reservoirs is shown in the different water-oil contact level for each productive sand. [Redrawn from Winter, Bull. 118, Calif. Div. Mines (1943), p. 345, Fig. 142.]

depths of one or two thousand feet, for example, by means of which structur mapping is extended below the surface. Core drilling is especially useful regions where the stratified rocks are covered with alluvium and other uncon solidated materials, which not only conceal the structure but also interfere wi geophysical measurements. Still deeper mapping—called subsurface mappin —is done with the data available from various kinds of well logs. (See p 75–85.) How detailed the resulting map will be depends on how close t ★ gether the wells are drilled and how much information there is on the logs. Sub surface mapping of geologic structure is also done without logs, by interpreta tion of geophysical data. These data include measurements of various physic properties of the rocks, such as their elasticity, magnetic susceptibility, and den sity; all of these physical properties are measured at the surface, but the surfac measurement determines them down to depths of several miles, often with gre accuracy. In this way it is possible to map the structure of formations at near the anticipated reservoir formation. Since the trap *must be in the rese voir rock*, mapping on or close to the reservoir formation is most desirabl for it eliminates many of the errors that come from projecting shallow defo mation down to the producing formation. If the folding of the reservoir ro does not extend far above the reservoir horizon, as where it is terminated by a unconformity surface, the first evidence of deformation may be found tho sands of feet below the surface. Where this occurs, both well data a geophysical surveys may be required for a mapping of the reservoir rock. Th location of such hidden traps is often very difficult to predict.

Some deformation of the reservoir rock has been involved in the formatio of nearly all petroleum traps (there are some exceptions among traps of th lens and reef types). Since deformation is commonly associated in so manner or other with nearly all kinds of traps, structural mapping is of prime importance as a method of searching for oil and gas pools. The structure alone may be enough to form a trap, or it may be combined with favorable stratigraphic and fluid conditions. The standard exploration procedure is to aim the first test well at what is believed, on the basis of structural mapping, to be the highest part of the potential reservoir rock.

The great hazard in all structural mapping of deep-seated rocks is inadequacy of the data; the data recorded on the maps, whether geological, geophysical, or geochemical, are frequently indefinite, hazy, or inconclusive. Geologic reasoning and predictions are no better than the validity of the evidence upon which they are based. Another hazard is that the structure of the reservoir rock may be quite different from that of the overlying formations. It may shift laterally, or it may lose closure with depth and thereby become ineffective as a trap; or the pool may be displaced down the lee flank of the fold by moving water in the reservoir rock. Prospective traps that develop these unforeseen shifts in position are sometimes facetiously described as "rubber structures" or "structures that have slipped out from under." For reasons such as these, a second or third test well is often justified in the attempt to discover a pool in a trap, the new location being determined by the information obtained from the first hole.

Underground traps formed chiefly by structural deformation result from nearly all of those types of folding, faulting, and other deformation that can be observed at the surface of the ground. These structural features can be combined in a great variety of ways; when structural and stratigraphic phenomena are combined, the number of possible variations is almost infinite. Through the growing accumulation of geophysical surveys, through close drilling, accurate sampling, improved logging, and careful study of stratigraphy and paleontology, geologists have become increasingly aware of the innumerable ways in which traps can differ. Reservoir structure is as complex in places as any surface structure. The problem is to predict, in advance of drilling and from whatever data are available, the nature and character of the deformation. The geologist's predictions are based on the coordination and piecing together of many kinds of surface, subsurface, and geophysical information, which differ in value and whose relative value is one of the things that have to be judged.

Traps that are predominantly structural in origin may be classified, according to the chief kinds of deformation involved, as caused by (1) folding; (2) faulting, both normal and reverse; (3) fracturing; (4) intrusion of a plug, usually of salt; (5) combinations of the preceding.

Traps Caused by Folding

Structural traps that result chiefly or altogether from folding are of widely varied shapes; they include everything from low domes essentially circular

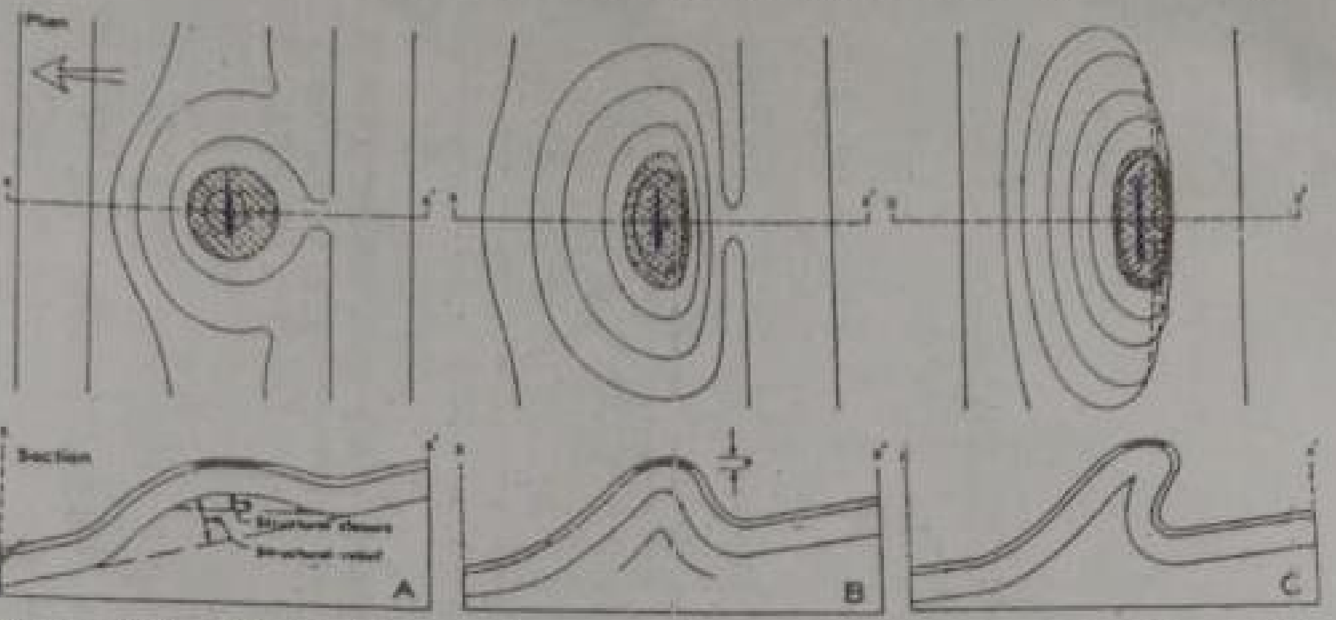
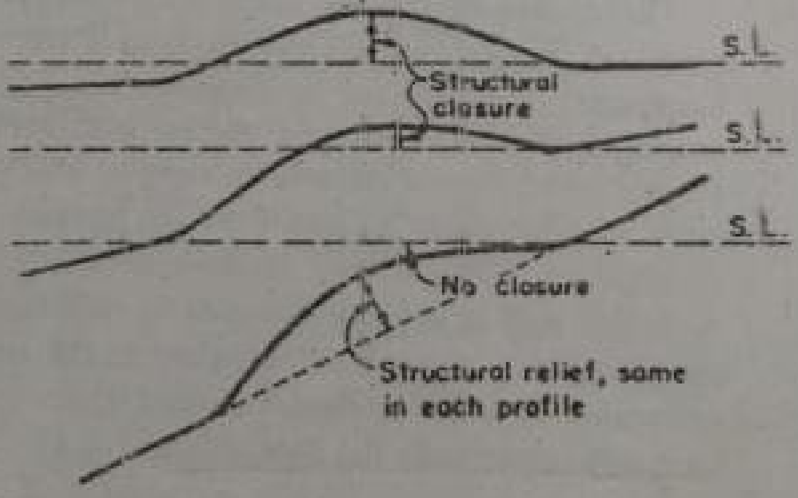


FIGURE 6-2 *Idealized structural maps and sections of typical anticlinal dome folds; such folds are characteristic of many traps containing oil and gas pools (oil, shaded and black). (Arrow shows direction of dip.)*

in plan (Fig. 6-2, A) to long, narrow anticlines (B), which may be symmetrical or asymmetrical or even overturned (C). The amount of *structural closure*—the vertical distance from the highest point down to the lowest closed contour—may range from a few feet up to thousands of feet. The *structural relief* of a fold, which is generally greater than the structural closure, is the height to which a folded bed rises above the regional slope, and is measured from the highest point to the projection of the regional slope below. (See Fig. 6-2, A.) The structural closure of a trap is referred to sea level as a datum. It does not necessarily represent the structural relief, as may be seen in the profiles in Figure 6-3, where the same fold may have different amounts of structural closure, depending on the regional dip of the formation. The capacity of a fold trap to hold oil and gas depends chiefly on the structural closure, the thickness of the reservoir rock, the rock's effective porosity, the reservoir pressure, and the conditions of fluid flow through the

FIGURE 6-3

Diagrammatic profiles showing how the same amount of structural relief will have differing amounts of structural closure according to the rate of the regional dip (i.e., the angle with a horizontal reference plane).



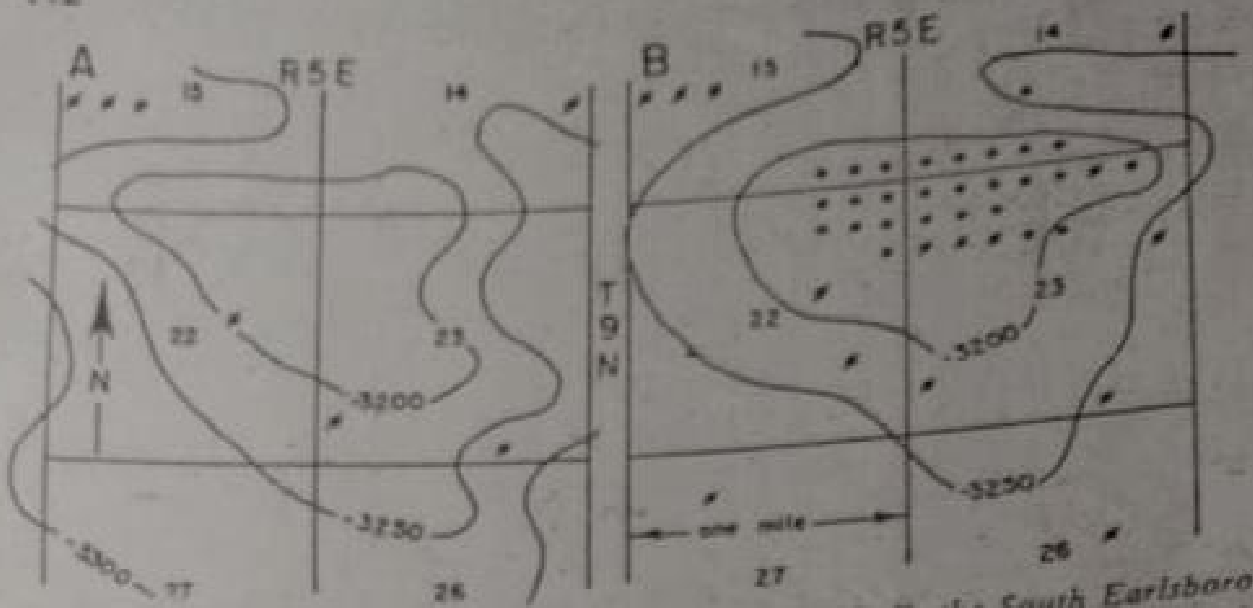


FIGURE 6-4 A, *A seismic map and the dry holes of 1929;* B, *the South Earlsboro pool, Seminole County, Oklahoma, following discovery in the Wilcox sand, and the structure on the Viola limestone (Ordovician) that overlies the pay formation.* [*Redrawn from Weatherby,* Geophysical Case Histories, *Soc. Explor. Geophysicists* (1949), *p.* 289, *Fig.* 4, *and p.* 290, *Fig.* 5.]

rock. The actual volume of the reservoir is that of the effective pore space between the underlying water table and the overlying roof rock. It is useful, in stating the size of the pool, to give the height of the *oil column* or the *gas column* or the *oil and gas column*. This is the vertical distance from the underlying oil-water or gas-water contact to the highest point to which either the oil or the gas extends in the trap. It is, in other words, the maximum vertical thickness of the oil, of the gas, or of the combined oil and gas in the pool. (See *a*, Fig. 6-2, B.)

Folding, as evidenced by some bending or tilting of the reservoir rock, is present to a greater or lesser extent in practically every trap, whether stratigraphic or structural. A trap in which folding is the predominant trap-forming factor is classed as a folded trap even though faulting and stratigraphic factors may have helped in some degree to form the closure.

The causes of folding are, of course, the same for reservoir rocks as for rocks at the surface. They include such varied mechanisms as horizontal compression, tangential or couple pressures, drag folding (possibly on a large scale), initial dips around buried hill, settling around buried hills, diapiric folding, and domes caused by deeply buried intrusive salt plugs. The folding may all take place at one time, or it may be an aggregate result of a series of episodes, each causing the fold to become more acute with increasing depth. A folded trap is seldom completely free from faulting. A reservoir may be cut by a fault that cannot be observed at the surface of the ground, and it is often extremely difficult to detect such a fault by subsurface methods unless a test well actually crosses the fault plane.

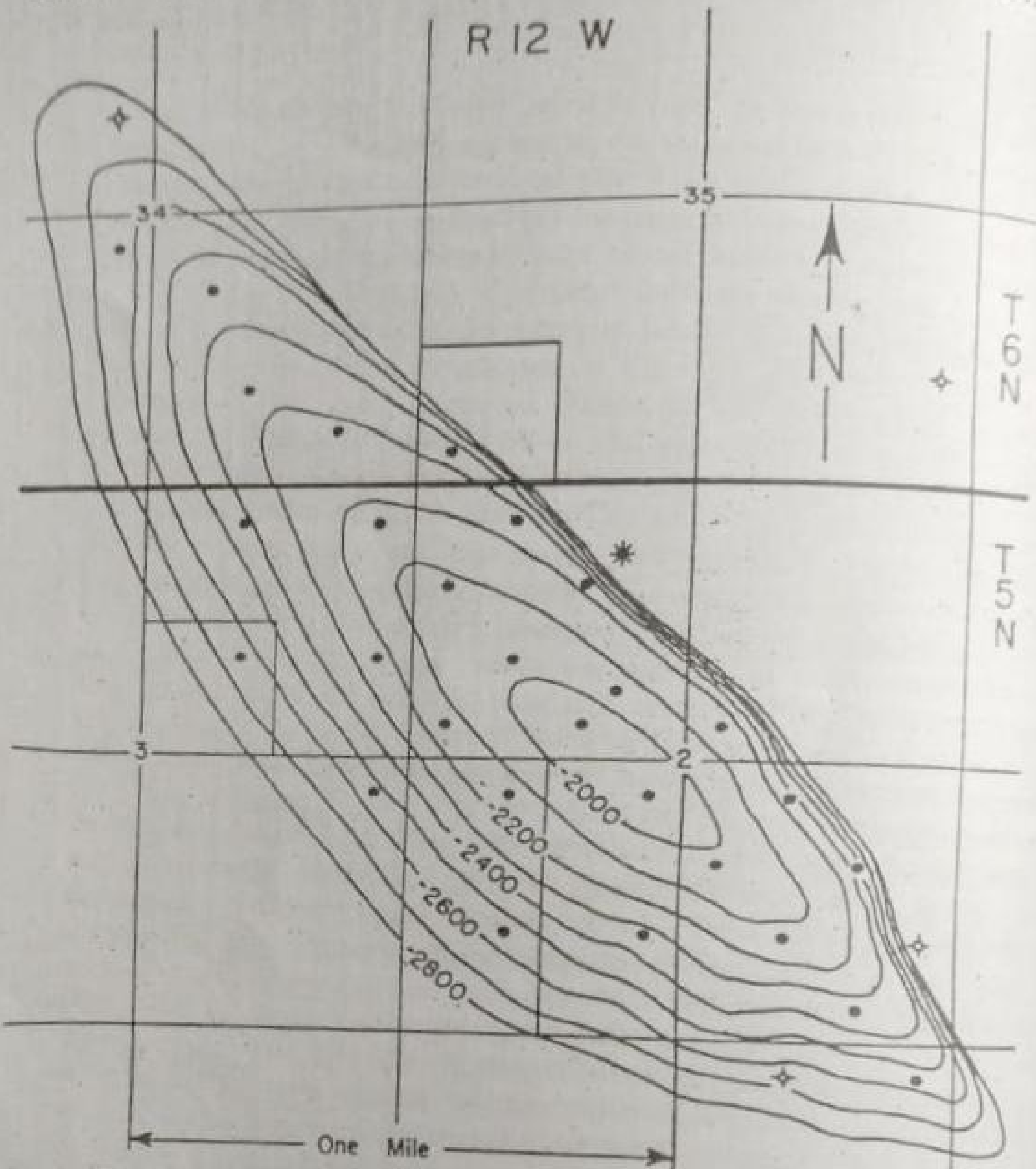


FIGURE 6-5 *Structure on top of the Bromide sand (Ordovician) in the Apache pool, Caddo County, Oklahoma. The contour interval is 100 feet. This fold formed at some time after the Caney (Mississippian) was deposited and before the Permian was laid down. The evidence is shown in Figures 6-19 and 13-12. [Redrawn from V. C. Scott, Bull. Amer. Assoc. Petrol. Geol., Vol. 29, p. 103, Fig. 3.]*

Some traps that are chiefly the result of folding are shown in the accompanying figures. Figure 6-4 illustrates the structure of the South Earlsboro pool, Oklahoma. This is one of the early discoveries made by seismic mapping of the characteristic low-relief, nearly circular dome folds found throughout the Mid-Continent region. The producing "Wilcox" sand (Ordovician) is a blanket sand through this area, and the fold determines the trap. The struc-

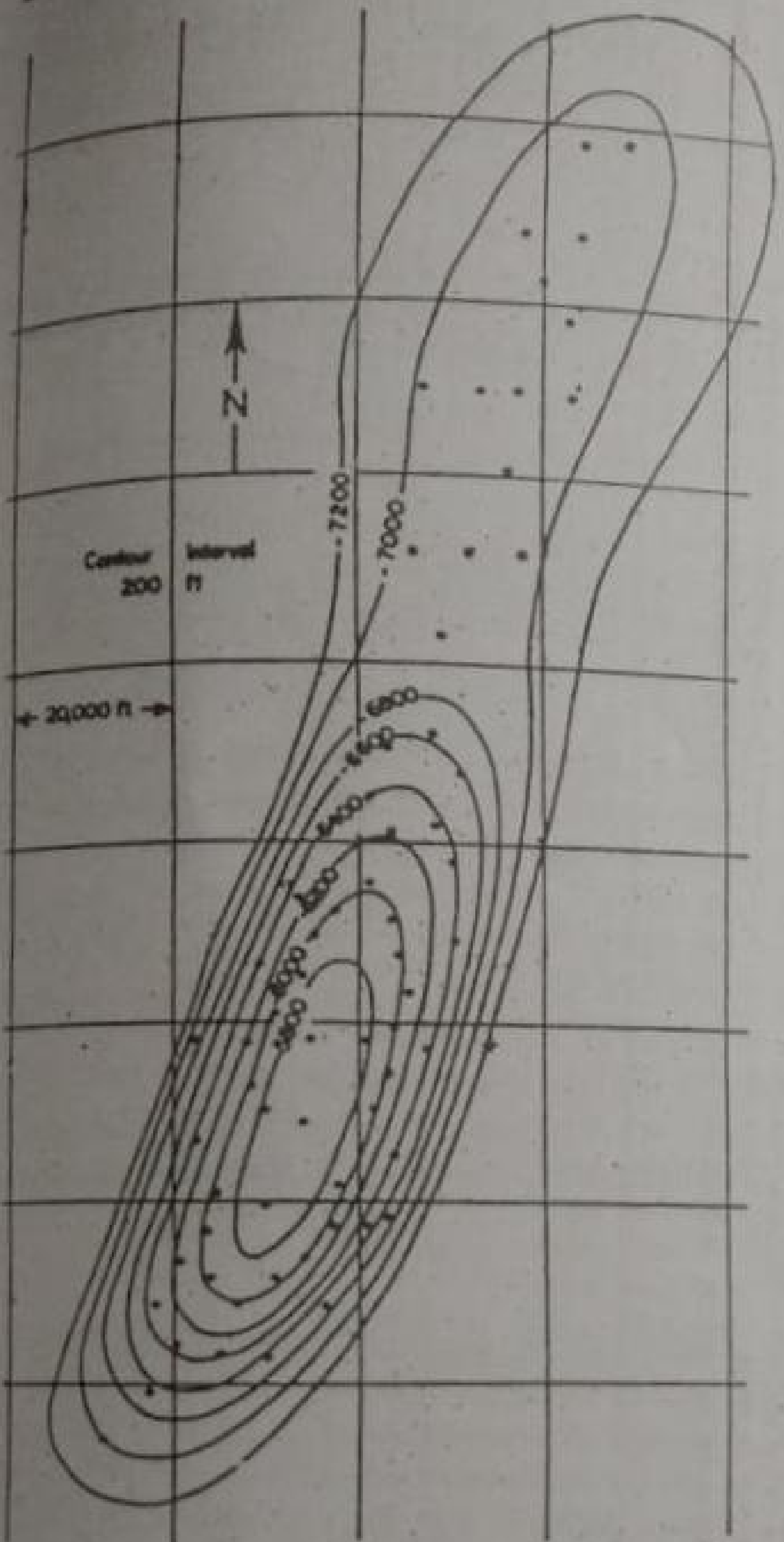


FIGURE 6-6

Structure of the Jurassic oolitic and dolomitic producing formation, the Arab zone, in the Abqaiq pool of Saudi Arabia. This great pool is 30 miles long and 6 miles wide and has a maximum oil column of over 1,500 feet; the average initial production of each of the sixty-six wells was 17,000 barrels per day. [Redrawn from McConnell, O. & G. Jour., December 20, 1951, p. 199.]

ture of the Apache field, in Caddo County, Oklahoma, is shown in Figure 6-5. (See also Figs. 6-19 and 13-12 for structural section and paleogeologic map of the Apache field.) Figure 6-6 is a section of the elongated dome fold containing the Abqaiq pool, in Saudi Arabia, which is typical of many traps in the Near East, although some are overlain by complexly folded incompetent formations. (See Figs. 6-12, p. 248, and 6-21, p. 254.) The structure of the Vallezza field, in northern Italy, is a faulted, overturned, and recumbent anticline. Such a fold is unusual as a trap, but it does show the extent to which overturning can go and still form a trap. A section through the field is shown in Figure 6-7.

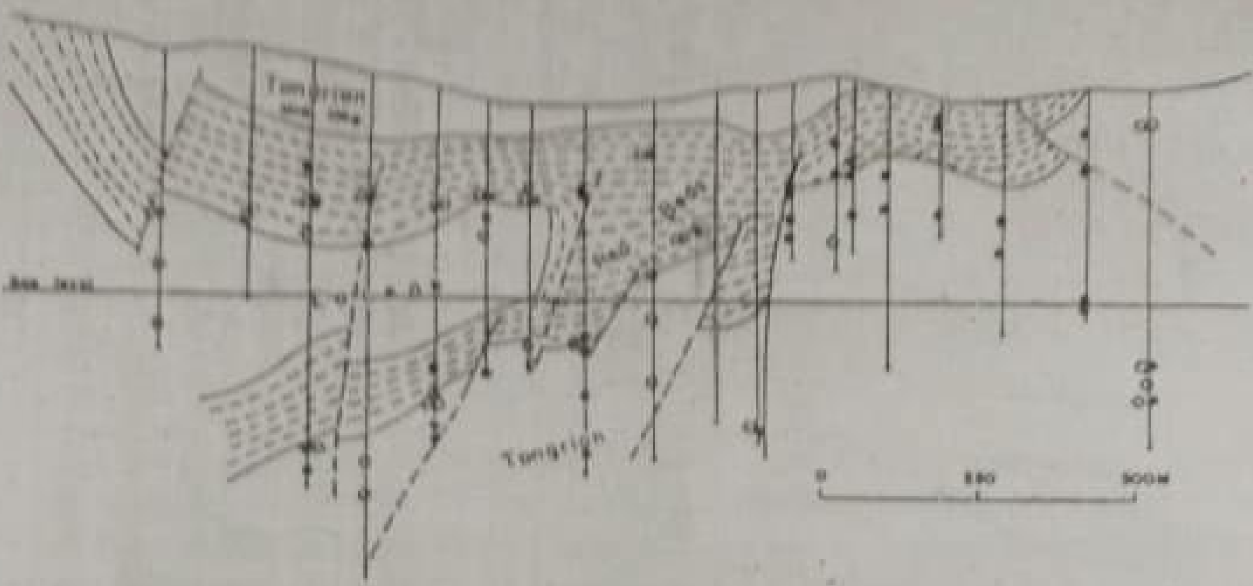
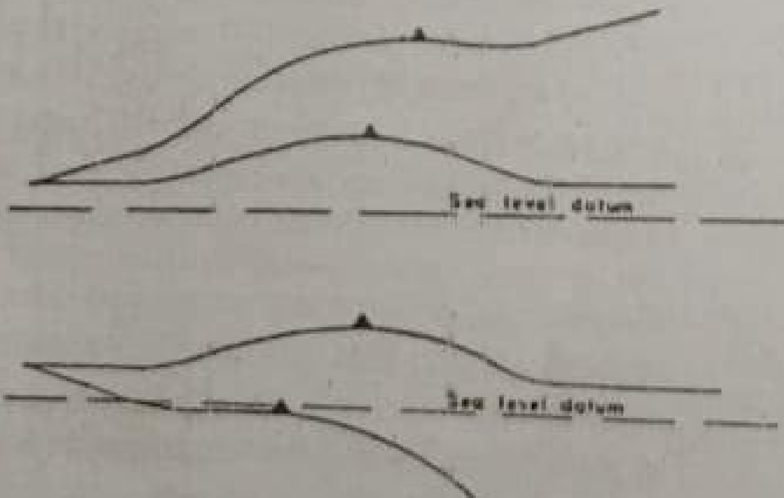


FIGURE 6-7 *Section through the Vallezza oil field, northern Italy, showing the surface occupied by a syncline, which overlies a recumbent fold of Eocene and Oligocene formations. Oil production occurs at the solid circles and gas at the hatchured circles. This is an extreme example of an overturned fold forming a trap.* [*Redrawn from Reeves, Bull. Amer. Assoc. Petrol. Geol., Vol. 37, p. 612, Fig. 4 (1953), from section by Grieg.*]

Changes with Depth. Many folds and other structures change in shape, size, or amplitude, or shift their position laterally, in passing from the surface or shallow depths down to the reservoir rock. Folding at the surface or at shallow depth is therefore not always a reliable guide in searching for petroleum pools that are trapped in reservoir rocks at great depths; for it frequently does not parallel the deeper folding. Seismic mapping in advance of drilling, applied to the prospective reservoir rock or to some formation close to it, may show the deep structure to be completely out of harmony with the known shallow structure. Or a test well located on the crest of a surface fold may

FIGURE 6-8

Diagrammatic sketches showing the gain or loss of structural closure and the shift in position of the crest of a fold when projected through converging strata. The fold has the same amplitude in all profiles. Black triangles mark the crest of the structure in different positions.



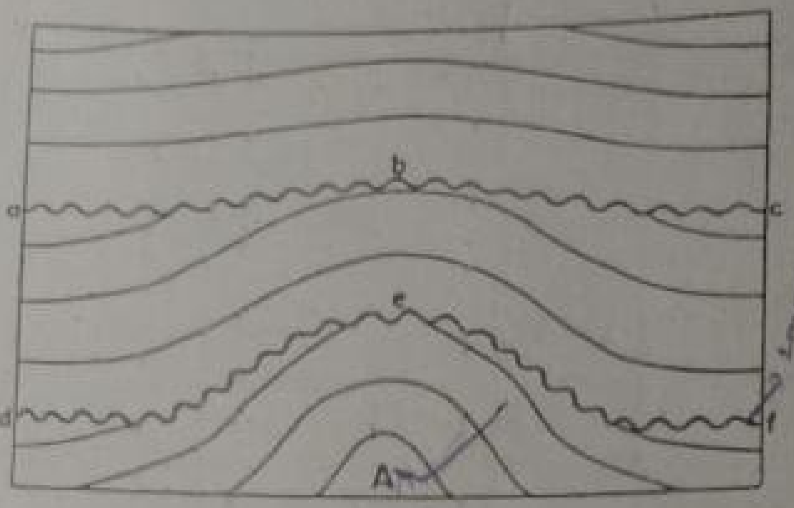


FIGURE 6-9

Diagrammatic sketch showing the increase in structural relief with depth as a result of superimposed, repeated folding. The evidence is in the thinning over the crest of the deep fold. In the example shown, three periods of folding add up to make the final fold, A: one period of folding before unconformity surface def, a second period after def and before unconformity abc, and a third period after the deposition of the youngest formations shown.

Unconformity

find no evidence of folding at the level of the reservoir rock. In either case doubt is thrown on the accuracy of the data, and many such differences are not necessarily due to the poor quality of the geophysical measurements or the well records; they are sometimes due to actual downward changes of structure. Many discrepancies between shallow and deep structure cannot be foretold, but some can be anticipated, or at least suggested as probable, if the geologic history of the region is known.

The discrepancies between the shallow and the deep folding, and therefore in the position of the pool, may result from various causes, such as (1) convergence of the intervening strata; (2) repeated folding; (3) parallel folding; (4) discordant and diapiric folding; (5) buried hills, anticlines, or fault blocks; (6) asymmetric folding; (7) shallow and surface weathering phenomena—deposition, solution, slumping; (8) pre-unconformity deformation; (9) overriding thrust faults; (10) displaced pool.

Convergence of the Intervening Strata. Where the strata between a shallow or surface formation and the reservoir rock are converging regionally,[17] the deep folding on the reservoir rock may be expected to shift its crest with depth in the direction of the convergence, and either to increase or to decrease the amount of structural closure with respect to sea level, depending on the direction of regional dip compared with the direction of the convergence. For example, a fold that is mapped as a terrace at the surface may become a closed dome at the reservoir, or a fold mapped as a dome at the surface may lose its closure at depth and therefore not be a trap. The diagrams in Figure 6-8 show how the structure may change and shift its crest with depth, even where the amount of deformation is actually the same in both the shallow and the deep strata.

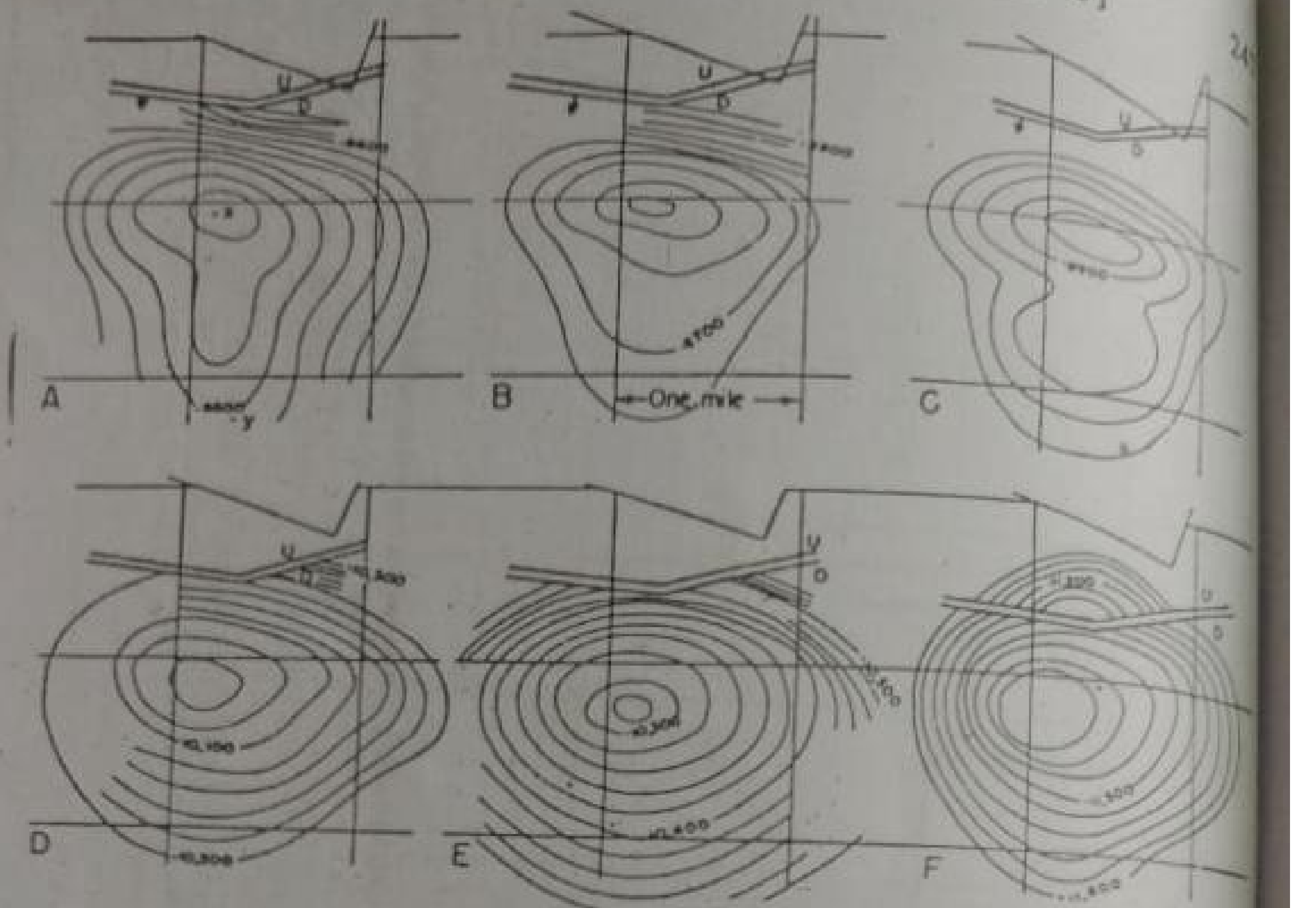


FIGURE 6-10 *Structural maps of various producing formations in the Erath oil field, Louisiana, showing the growth of the deep fold by recurrent periods of folding. The approximate amounts of closure between comparable points, as* x *and* y, *are:*

A	*8,500-foot sand*	*45 feet of closure*
B	*8,700-foot sand*	*71 feet of closure*
C	*8,900-foot sand*	*83 feet of closure*
D	*10,100-foot sand*	*153 feet of closure*
E	*10,400-foot sand*	*155 feet of closure*
F	*11,600-foot sand*	*172 feet of closure*

Isopach maps of these sands would show 17 feet of closure between F *and* E, *70 feet of closure between* D *and* C, *12 feet of closure between* C *and* B, *26 feet of closure between* B *and* A, *and 45 feet of closure after* A, *or a total of 170 feet (actually 172 feet) of closure on the 11,600-foot sand.* [*Redrawn from Steig* et al., *Bull. Amer. Assoc. Petrol. Geol., Vol. 35: Figs. 8, 11, 13, 15, 17, and 27.*]

Repeated Folding. Some folds have grown in intensity during the geologic life of the reservoir rock.* Such folds become increasingly more acute downward; that is, they show more and more structural relief with increasing depth. Under these conditions, formations commonly become thinner on the crest of the fold than on the flanks; the thinning may occur intermittently at several

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* The geologic life of the reservoir rock is the time between its origin, such as its diagenesis or lithification, and the present.

FIGURE 6-11

Parallel folding may be important as a cause of increased structural closure over anticlines with depth, especially in areas where the reservoir rock is several miles below the surface. With sufficient depth, anticlines that result from parallel folding will eventually disappear.

periods, or it may be continuous through a part of the geologic column. Sudden increases in amount of folding commonly appear just below unconformities. The time at which the increased folding occurred is readily shown by cross sections and by isopach maps (maps that show variation in stratigraphic thickness by means of thickness contours), the evidence of the folding being the thinning of the rocks over the fold. (See also pp. 596–598.) Figure 6-9 shows some of the evidence of repeated folding that is found at depth. The fact that the unconformity surface *def* shows more of a fold than surface *abc* shows that folding occurred during the time interval represented by the intervening rocks. Furthermore, the folding of *def* took place after the

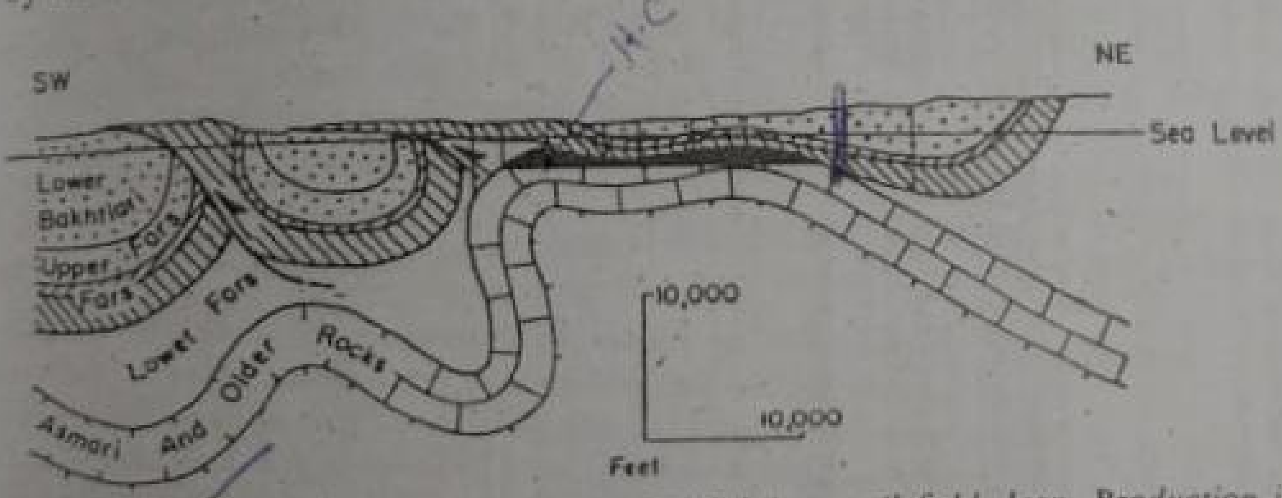

FIGURE 6-12 *Section through the Masjid-i-Sulaiman oil field, Iran. Production is from the Asmari limestone (Lower Miocene and Upper Oligocene). The section shows the great discordance in structure between the incompetent, shallow sands, shales, and evaporites of the Upper Fars (Miocene-Pliocene) and the underlying, competent Asmari limestone. More than one billion barrels of oil has been produced from this reservoir. [Redrawn from Lees, in* The Science of Petroleum, *Vol. 1, p. 147, Fig. 4.]*

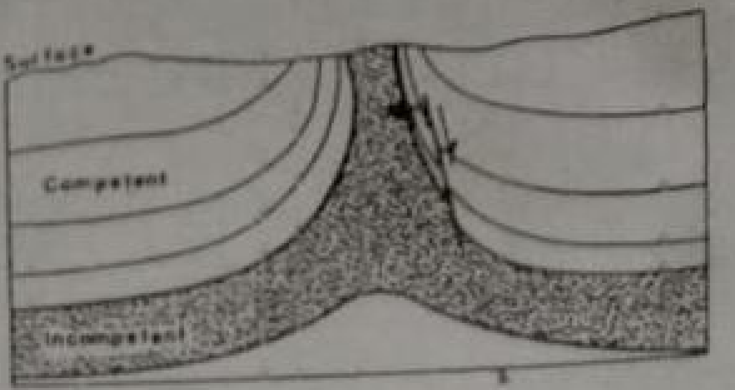

FIGURE 6-13

Diagrammatic section through a diapir fold showing how the incompetent formations below are squeezed up and out in the folding of the overlying competent formations. Contrast this type of folding with the folding in Iran shown in Figures 6-12 and 6-21.

youngest of the rocks below it were folded, later truncated by erosion, and finally overlapped by the succeeding formation. The intermittent downward increase of folding shown here is common to a great many folded traps. The Oklahoma City fold, in Oklahoma[18] (Fig. 14-7, p. 644), and the Hawkins fold, in Texas,[19] are examples of folds that have grown repeatedly since the time the reservoir rock was formed. Several repeated periods of folding may be seen in the dome structure of the Erath field, Louisiana, by comparing structure maps on progressively deeper producing formations. (See Fig. 6-10.)

Parallel Folding. Thick sections of sedimentary rocks, especially of shales that are folded into low-relief anticlines and domes, may be expected to fold normally—that is, in such a way that the fold in the reservoir rock is virtually parallel to that at the surface and to those in the intervening formations. Parallel folding means that the thickness of the beds did not change materially during folding and that the folding becomes more acute with depth.[20] The effect of parallel folding is shown in Figure 6-11. In areas where the reservoir rock is two or three miles below the surface, the folding on it from this cause is likely to be considerably sharper than on the shallow rocks.

Discordant and Diapiric Folding. The nature of folding depends, in part, on whether an incompetent formation underlies or overlies a competent for-

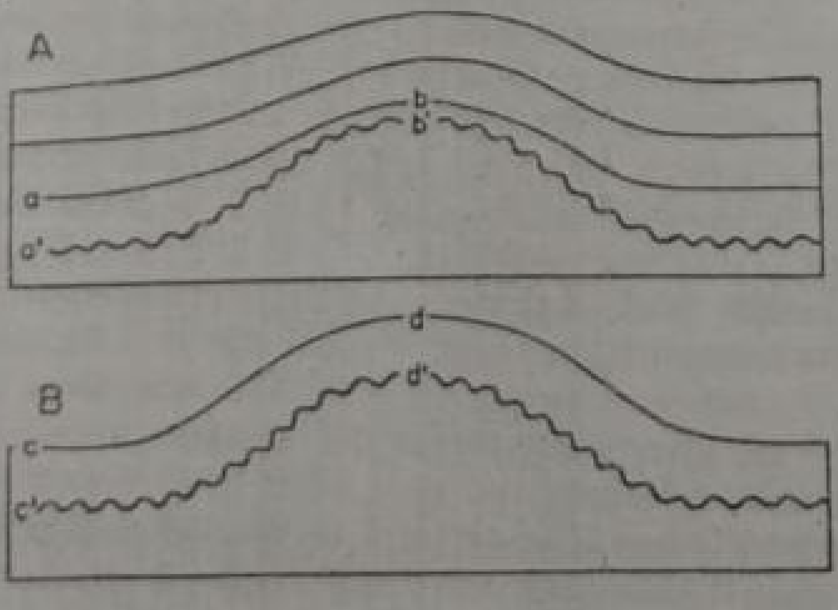

FIGURE 6-14

The difference between a buried hill, A, and no buried hill, B. The difference between aa' *and* bb' *in* A *is a measure of the topographic relief of the unconformable surface, or the height of a buried hill, which localized the folding of the younger formations. In* B *the thicknesses* cc' *and* dd' *are the same, showing no topographic relief of the unconformable surface.*

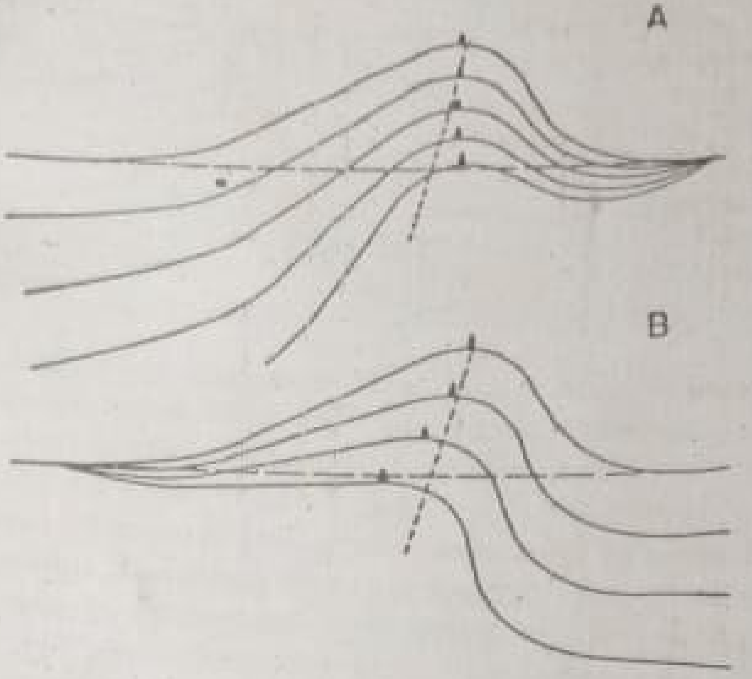

FIGURE 6-15

Diagrammatic sections showing the effect of converging formation thicknesses when added to an asymmetrical folding. The dashed line is the axis of the asymmetrical fold if the formations are of equal thickness. In A the formations are thinning in the direction of the steep-dip side of the fold, and the crest of the fold shifts in the direction of thinning. In B the beds are converging toward the low-dip side of the asymmetrical fold, and the crest of the fold shifts in the direction of thinning.

mation. Where a competent reservoir rock is *overlain* by a great thickness of soft, incompetent rocks, there may be a great discrepancy between the folding at the surface or at shallow depths and the folding on the reservoir rock. Conspicuous examples are some of the anticlinal folds containing the great oil pools of the Middle East. (See the cross section in Fig. 6-12.) The competent Asmari limestone reservoir rock (Miocene and Oligocene) is overlain by a series of interbedded evaporites and shales, which are extremely incompetent and whose deformation is entirely discordant with that of the Asmari limestone. Similar relations are found in the foothill belt of the Carpathians, where the oil pools occur in flysch sediments of Cretaceous-to-Oligocene age, and in the Polish oil fields. Here the oil is trapped in folds that are completely out of harmony with those in the shallower formations,[21] and the shallow structure gives little help to one who is trying to predict the deep structure.

Where the incompetent formations *underlie* the competent formations, a different kind of fold develops—one characterized by a central core of older, incompetent material, which has been squeezed or injected up through the crest of an anticline. Such folds, which are called *diapir folds* or *piercement folds* (see Fig. 6-13), are common in Europe in Aquitaine and the Carpathian region and in the USSR in the Caucasus.[22]

The fold through which the underlying material is extruded is generally tightly compressed and has vertical or nearly vertical dips near its axis. Where the extruded material is salt, as it commonly is in Romania, these structures are sometimes called "salt anticlines." Where the extruded material is mud, they sometimes form mud volcanoes and mud flows. (See Fig. 2-5, p. 23.) Other injected material includes sands and clays, anhydrite, mud breccias, and bitumen or asphalt. The oil associated with diapir folding is generally trapped in the gently dipping formations alongside the steeply dipping axial rocks. It was formerly believed that the oil was squeezed out of the central core and deposited in the flanking reservoirs. It is now thought, however, that diapir folding is only a manifestation of the deformation of a combination of competent and incompetent rocks, and has no genetic relation to petroleum. Diapir folding may form traps, and that is its important relation to petroleum.

Buried Hills. Some folds arch over buried topographic highs, called "buried hills."[28] These buried hills have been investigated by many geologists, and the part they play in the formation of the overlying dome fold or anticline

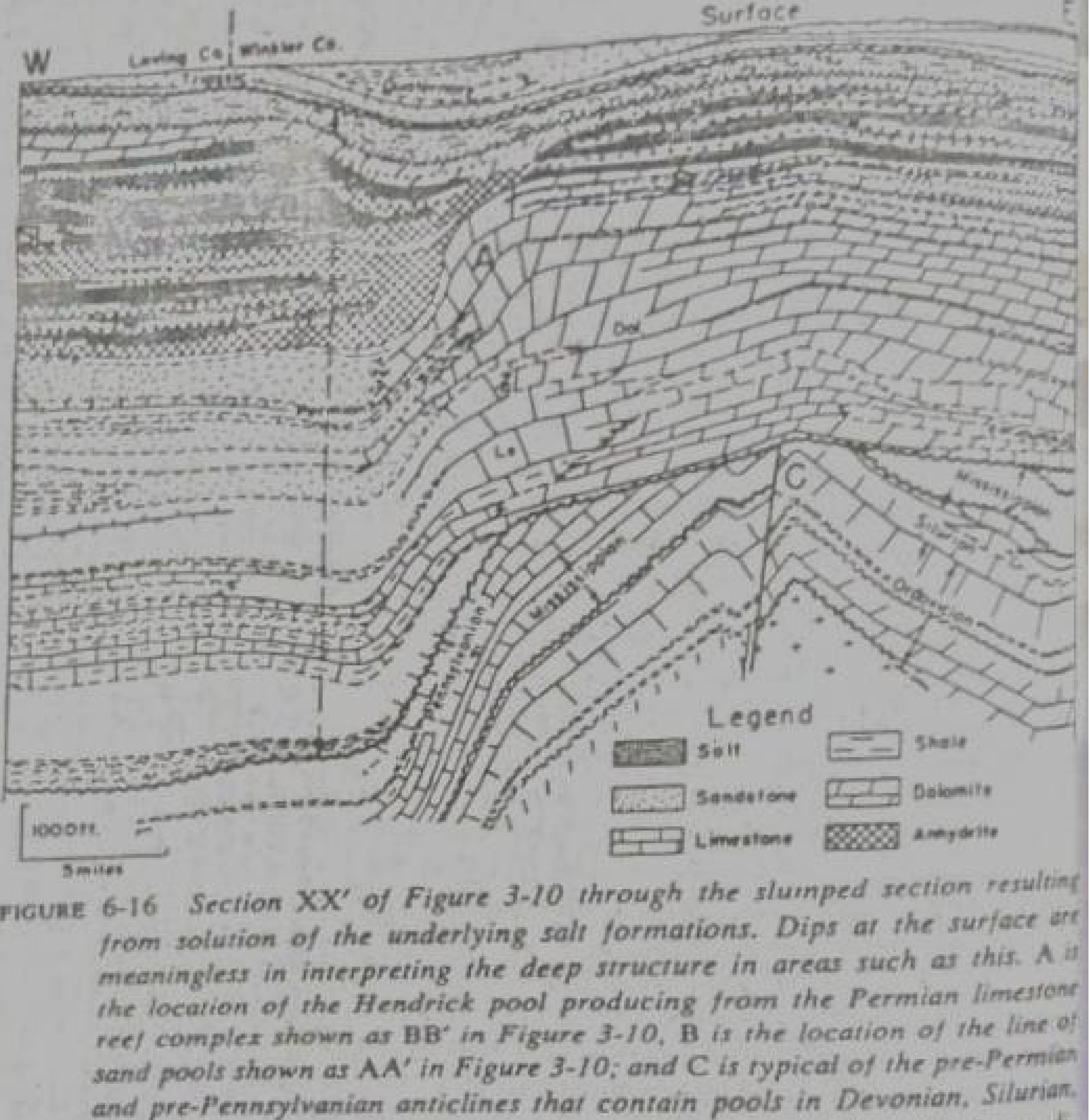

FIGURE 6-16 *Section XX′ of Figure 3-10 through the slumped section resulting from solution of the underlying salt formations. Dips at the surface are meaningless in interpreting the deep structure in areas such as this. A is the location of the Hendrick pool producing from the Permian limestone reef complex shown as BB′ in Figure 3-10, B is the location of the line of sand pools shown as AA′ in Figure 3-10; and C is typical of the pre-Permian and pre-Pennsylvanian anticlines that contain pools in Devonian, Silurian, and Ordovician formations. This section is typical of the geologic conditions that occur in the province of western Texas and southeastern New Mexico shown in Figure 3-10, p. 73. [Redrawn from West Texas Geol. Soc. (1949).]*

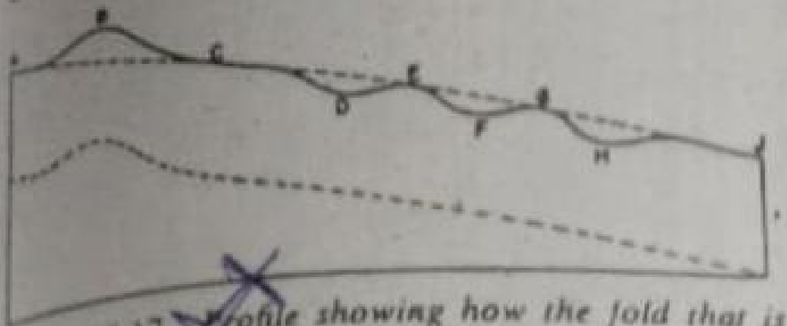

FIGURE 6-17 *Profile showing how the fold that is present at depth in the stratigraphic section, ABC, rises above the regional dip, whereas the superficial folds, DEF and FGH, do not. These superficial folds are probably the result of shallow solution and slumping.*

has been variously explained. It has commonly been supposed that the overlying sediments have become differentially compacted or drape down over their sides, thus giving rise to a shallow fold overlying a sharper fold in the deeper potential reservoir rock.[24]

Many of the "buried hills" were actually not hills or topographic highs when the overlapping sediments were being deposited. They may appear from casual examination to have been at one time elevated areas around which the sediments were compacted into domes, but they are frequently, in fact, merely folded surfaces of unconformity. When the beds are flattened out and placed on a stratigraphic section (see Fig. 6-14), the hills vanish. Many are buried anticlines, which were eroded and left little or no topographic relief to be covered by the succeeding formation, and were later refolded along with overlying formations.

A true buried hill may consist of a topographic high, a bioherm, or organic reef, or a resistant lens composed of some such material as a sand or gravel, surrounded by clays and shales. Where a fold overlies a buried hill or an uncompactable lens of sediments in the stratigraphic section, the folding may be explained in one of two ways:

1. It may be due to more compaction around the edges of the hill, where the shales are thicker, than over the top of the hill, where the shales are

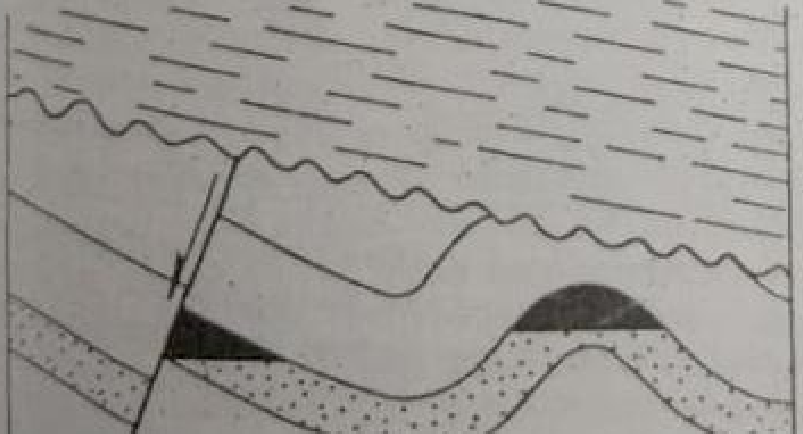

FIGURE 6-18

Idealized section showing characteristic pre-unconformity traps that are obscured by post-unconformity formations.

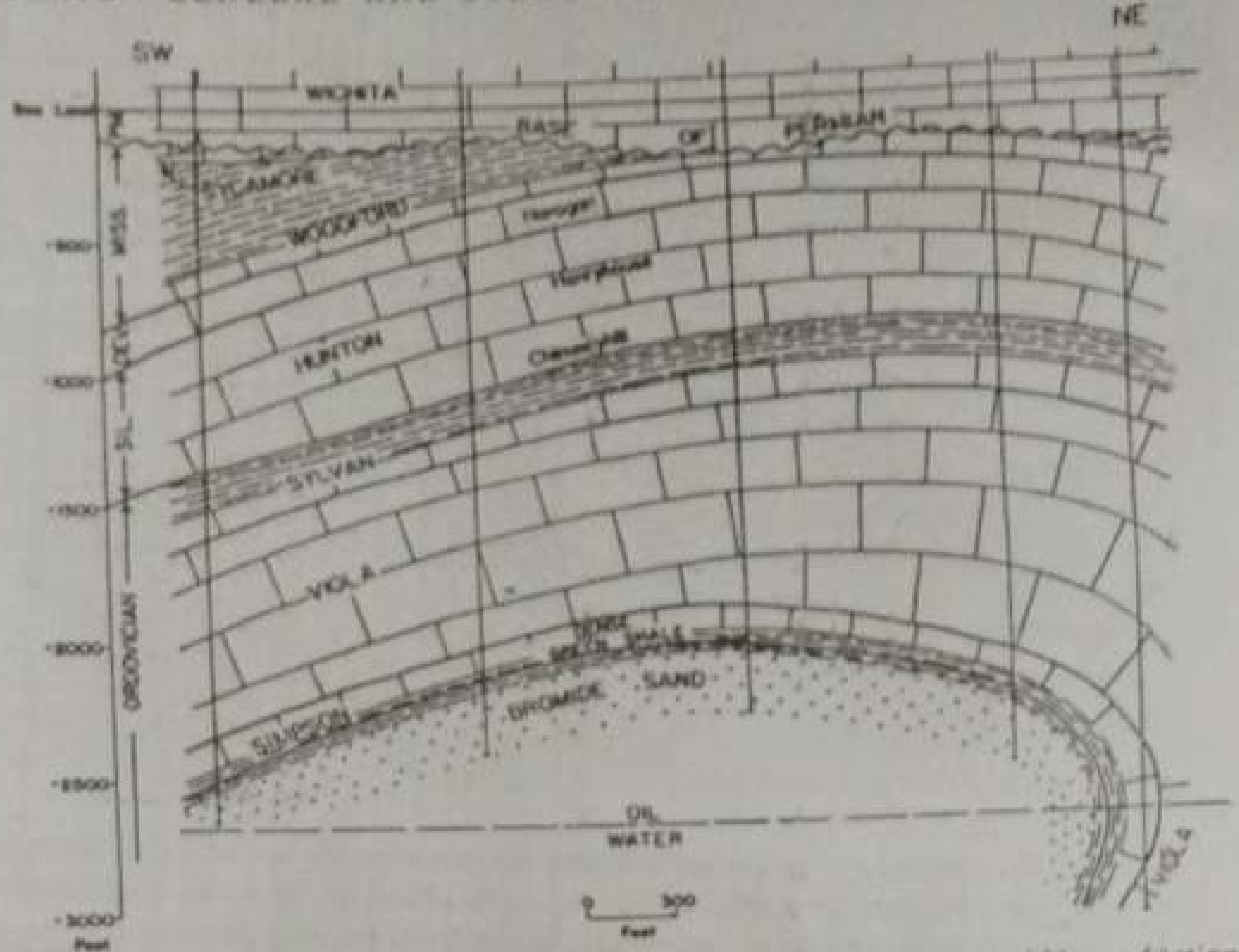

FIGURE 6-19 *Section across the Apache pool, Oklahoma, showing (1) production from a trap that is an overturned anticline, and (2) an example of a wide discordance between the structure of the shallow and that of the deep formations. The area distribution of the pre-Permian rocks below the unconformity is shown in Figure 13-12, page 605, and the structure of the Bromide sand is shown in Figure 6-5, page 243. [Redrawn from V. C. Scott, Bull. Amer. Assoc. Petrol. Geol., Vol. 29, p. 101, ig. 1.]*

thinner. This would cause the overlying sediments to drape over the edges of the hill and thereby form a dome or anticline. It is difficult to see how this folding could extend vertically much beyond the immediate overlying and surrounding shale formations, for diagenesis would be expected to lithify and solidify the clays into shales, and erosion would probably bevel off any uplifted areas, so that later formations would be of uniform thickness and would consequently compact uniformly.

2. The hill may have localized later folding in the region. This localization of folding may be the result of initial dips surrounding the hill or the bioherm, which could cause the overlying sediments to dip as much as 30° away from the center or core of the hill.[28] Where the buried hill is caused by a buried anticline or fault, it may be expected to localize later folding and cause a fold to extend vertically upward into much younger formations.

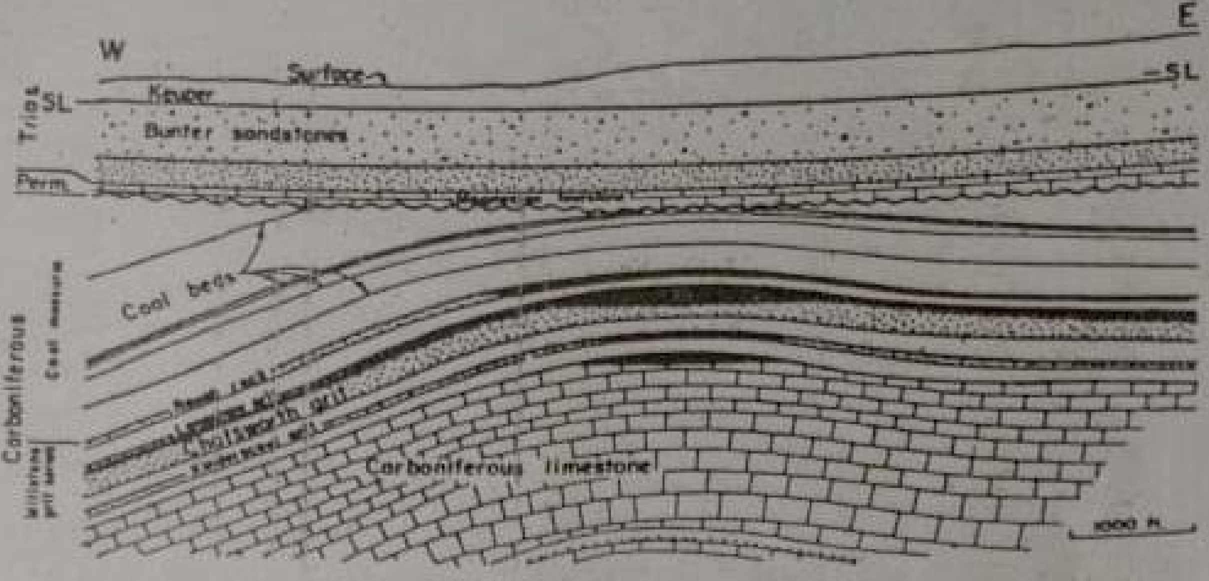

FIGURE 6-20 *Section through the Eakring oil field, Nottinghamshire, England. This is a multiple-pay field with the traps formed by an anticline completely masked by flat-lying Permian and Triassic formations. [Redrawn from Kent, in* The Science of Petroleum, *Oxford University Press (1953), Vol. 6, Part I, p. 56, Fig. 2.]*

The presence of a buried hill can be revealed by an isopach map showing the interval between the surface of unconformity and the first marker bed above it. In some places, as shown in Figure 6-14, B (where *dd'* is as thick as *cc'*), little or no evidence is found of any appreciable topographic relief on surfaces of unconformity. The topographic relief is shown, as in Figure 6-14, A, as the difference between *aa'* and *bb'*. Buried hills, as the cause of folding by compaction and draping over the sides, have probably been overemphasized. It seems more reasonable to regard many of the folds associated with such buried topographic features as due chiefly to normal folding processes that were localized by the irregularities in the rocks, such as folds, faults, initial dips, and igneous intrusions.

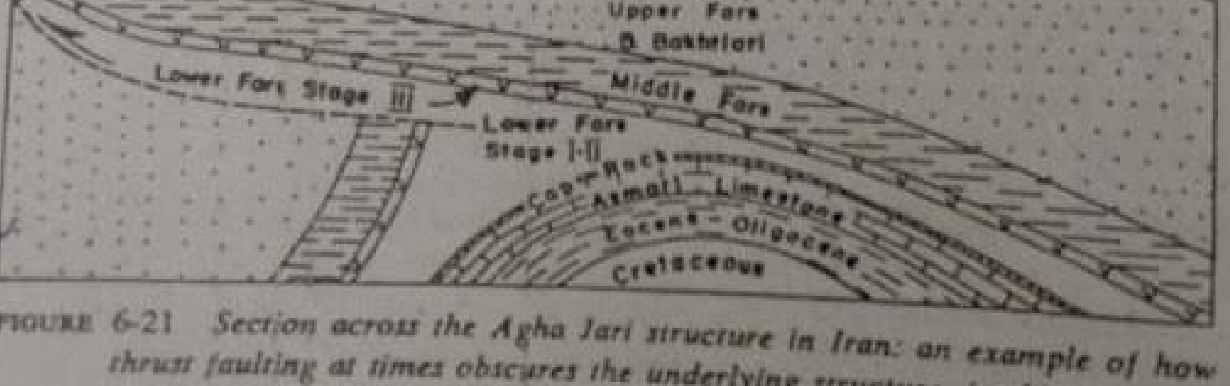

FIGURE 6-21 *Section across the Agha Jari structure in Iran: an example of how thrust faulting at times obscures the underlying structure, in this case containing one of the world's great oil fields. [Redrawn from Lane, O. & G. Jour., August 4, 1949, p. 57, Fig. 2.]*

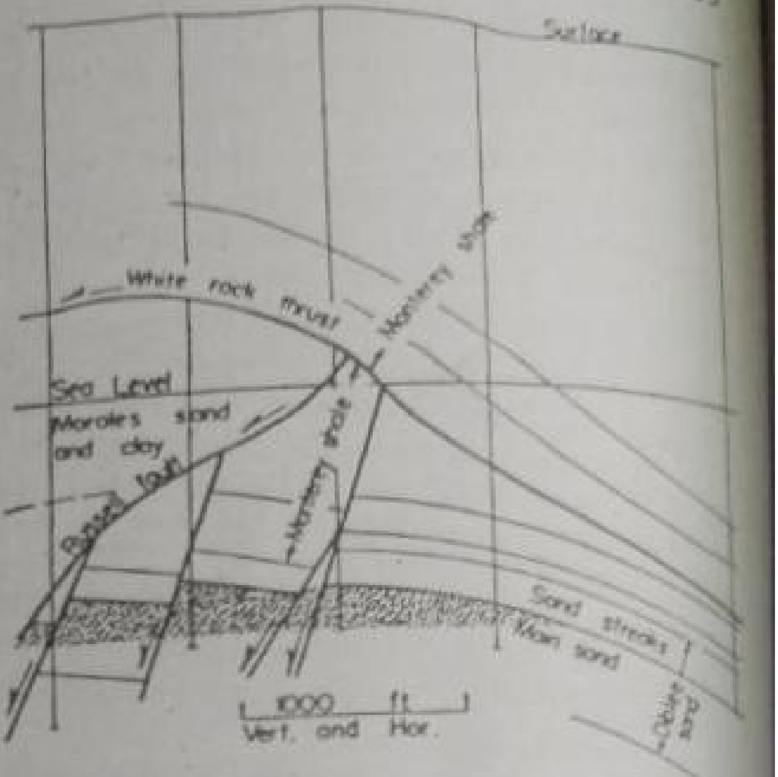

FIGURE 6-22

Section across the Russell Ranch field, in the Cuyuma Valley, California. The trap is formed by a faulted fold, which was later covered by an overthrust sheet. Oil pool shaded. [Redrawn from Eckis, AAPG Guidebook *(1952), Los Angeles, p. 91.]*

Asymmetric Folding. Asymmetric folding causes a shift of the crest of an anticline with depth, in the direction of the flank with the lower dip. The shift may be considerable where the depth to the potential reservoir formation is two or three miles and there is a large difference in dip between the opposing flanks. The position of the crest at depth may be calculated[26] from the shallow or surface evidence, or it may be determined by seismic surveys. Where asymmetric folding occurs in an area of rapid convergence of the formations involved in the folding, the two factors may combine to cause a much greater

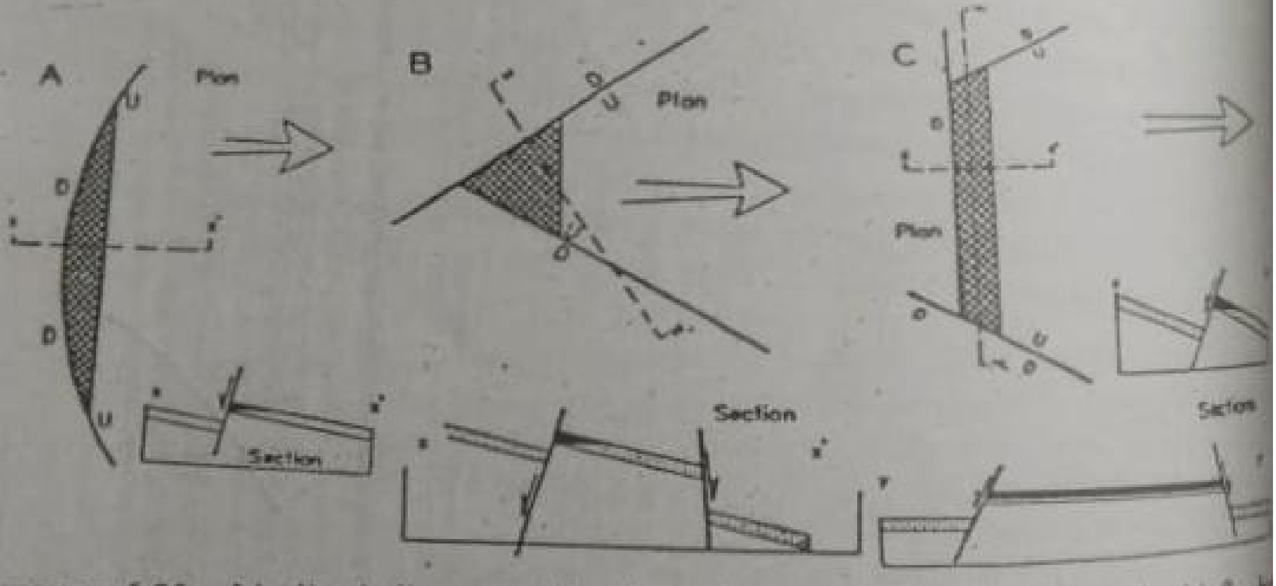

FIGURE 6-23 *Idealized diagrams showing characteristic traps formed chiefly b normal faulting, coupled with regional homoclinal dip: A, a trap form by a single curved fault; B, a trap formed by two intersecting faults; C a trap formed by several intersecting faults. Arrows show dip.*

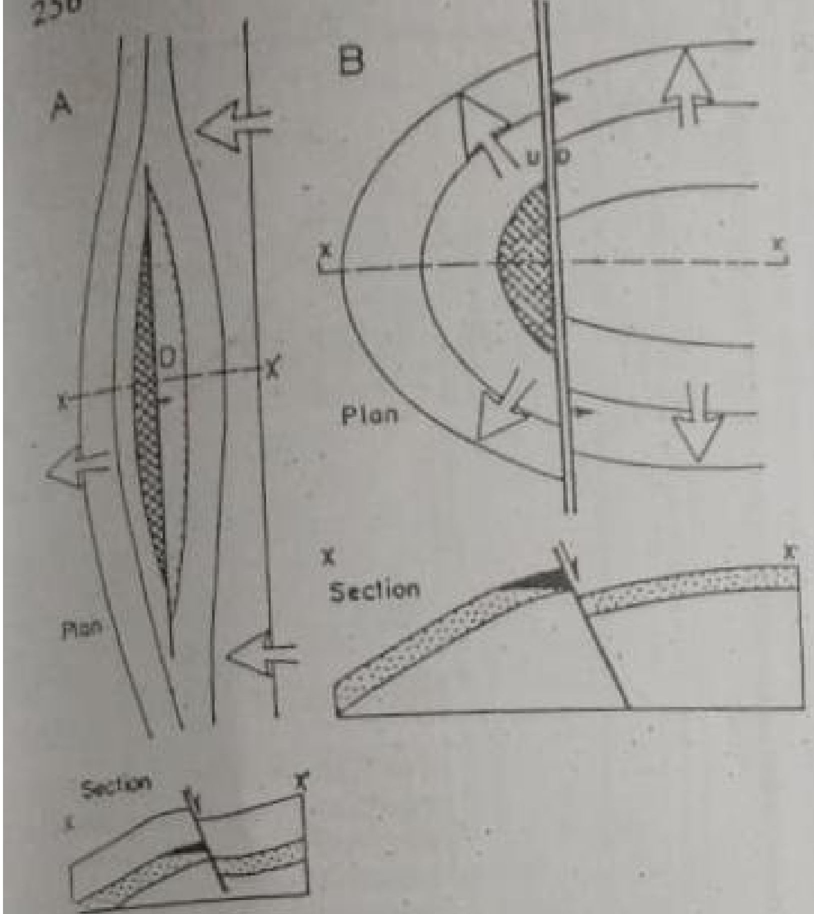

FIGURE 6-24

A, trap formed by intersection of a low fold with a normal fault; B, trap formed by intersection of a normal fault with a more acute fold (Arrows show direction of dip.)

shift than would normally be calculated from either one, or they may nullify each other. These two effects are shown diagrammatically in Figure 6-15.

Shallow and Surface Weathering Phenomena. Wherever highly soluble formations are exposed by erosion or come within the zone of circulating ground water, the resultant surface structure is often completely at variance with the deeper structure.[27] Solution of salt and other evaporites may throw the rocks at the surface into a jumbled mass of high dips, irregular folds, and erratic structures that have no meaning in relation to the deeper structure. Several large areas of salt solution, slumping, and collapse, for example, occur in western Texas, and the shallow structure is entirely unrelated to that of the underlying rocks. A section through the collapse over the Hendrick pool is shown in Figure 6-16. Because of the wide distribution of evaporites,[28] fossil slumps may occur in some areas, and some of the thinning, now ascribed to original causes, of the salt beds found at the edges of depositional basins may well be due to solution by surface waters circulating during the time interval represented. The swelling of bentonitic and montmorillonite clays also may give rise to misleading surface folds. Surface dips in caliche have been mistaken for true formation dips and have caused structures to be mapped—and drilled—that do not affect the deeper formations.[29] At times the fold that carries down may be distinguished from the superficial fold by plotting a profile. The true fold, *ABC* in Figure 6-17, rises above the regional dip; the superficial folds, *DEF* and *FGH*, do not—they are, in fact, more like residual folds between two synclines. Folding such as *CEGJ* is sometimes spoken of as "pan-of-biscuit" folding.

Pre-unconformity Deformation. Folding and faulting that occur belo buried unconformities are frequently not indicated at the surface, as t idealized section in Figure 6-18 shows. That is so over the Apache pool Caddo County, Oklahoma, for example, and the reason is apparent from structural section through the pool. (See Fig. 6-19.) A structural map of t overturned fold in the producing formation is shown in Figure 6-5, page 24 and a paleogeologic map of the pre-Pontotoc surface of unconformity Figure 13-12, page 605. In the Eakring field of England, also, several tra containing oil and gas pools are concealed below an unconformity surfac (See Fig. 6-20.)

Overriding by Thrust Faults. Thrust faults may obscure the underlyi structure, and a number of pools have been trapped in structures conceal by overriding sediments. An example is the Agha Jari anticline in Iran, shov in Figure 6-21, where the almost homoclinal dip above the overthrust fa gives no evidence of the underlying anticline. The Russell Ranch field, in t Cuyama Valley of California, is another example. (See Fig. 6-22.) The p thrust, normal faulting and folding, which localize both the trap and the po are completely hidden by the overriding sediments.

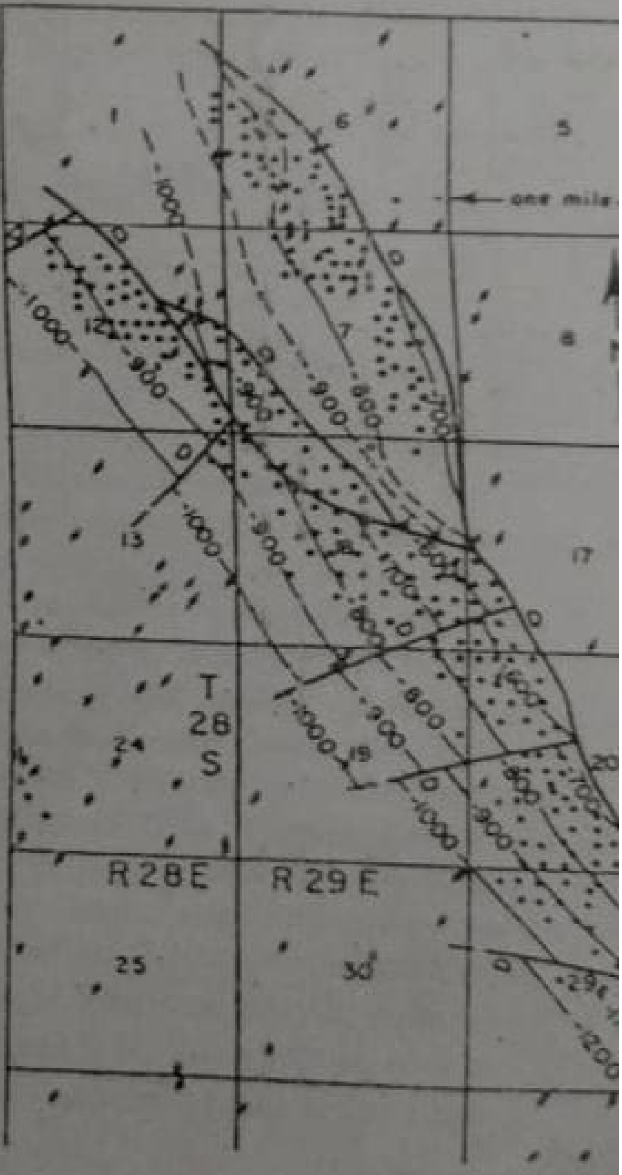

FIGURE 6-25

Structural map of the Vedder sand (Lower Miocene) of the Round Mountain field, Kern County, California. This is an example of a trap formed by a curved fault intersecting a homoclinal dip. [Redrawn from Brooks, AAPG Guidebook (1952), Los Angeles, p. 148.]

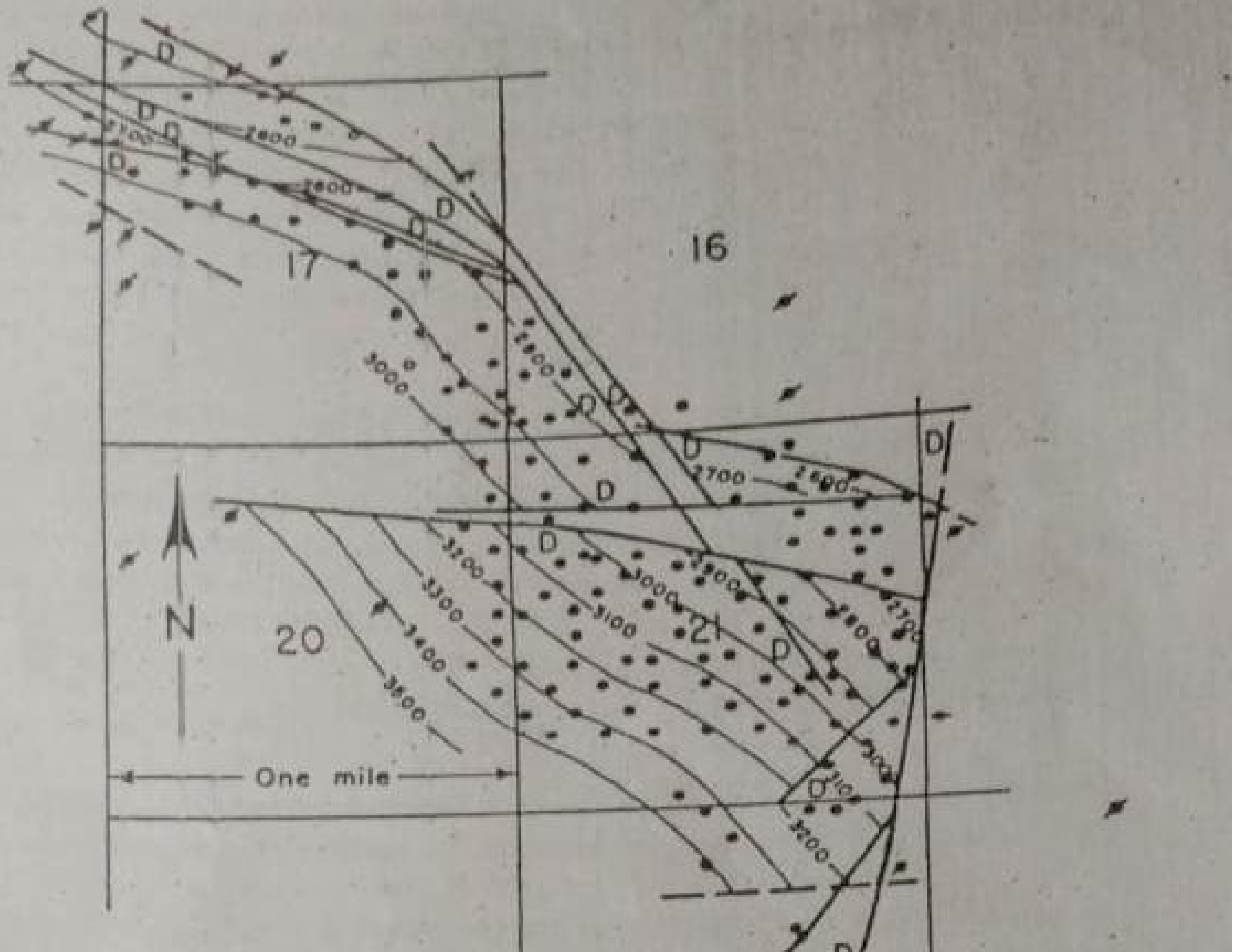

FIGURE 6-26

Structural map of a phantom horizon in the Chanac formation (Plio-Miocene) of the West Edison oil field, Kern County, California. This is an example, typical of many pools in the region, of traps formed chiefly by intersecting faults superimposed on a homoclinal dip. [Redrawn from Sullwold, Bull. Amer. Assoc. Petrol. Geol., Vol. 37 (1953), pp. 802, 803.]

Displaced Pool. In most traps, if a pool of oil or gas is present, it wi occupy the structurally highest position in the reservoir rock, as the crest a fold or the peak of a fault trap. There are some exceptions, however, whe the pool is displaced for varying distances down one side of the trap. In mo

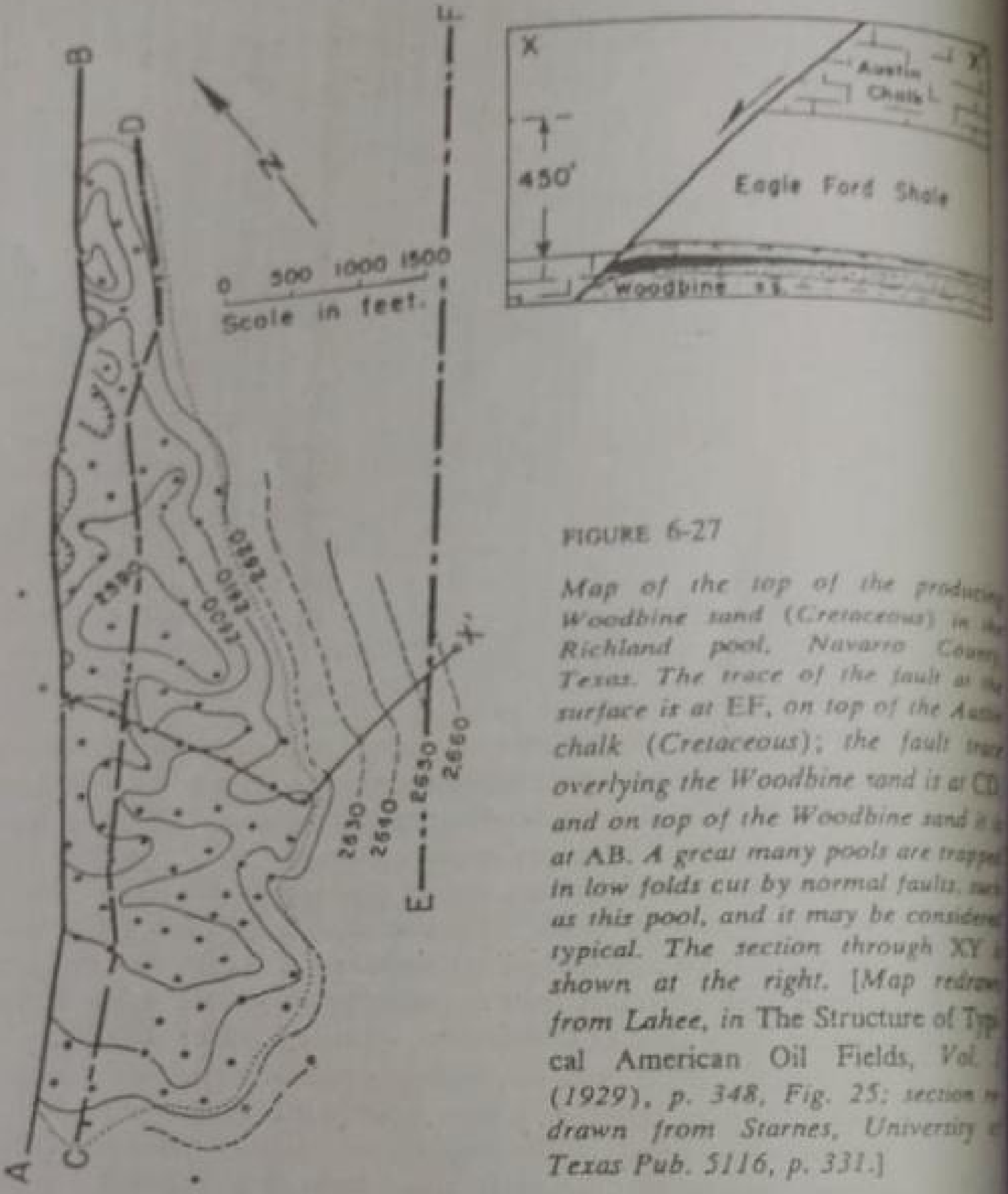

FIGURE 6-27

Map of the top of the produci Woodbine sand (Cretaceous) in th Richland pool, Navarro Coun Texas. The trace of the fault at th surface is at EF, on top of the Aust chalk (Cretaceous); the fault trac overlying the Woodbine sand is at CD and on top of the Woodbine sand i at AB. A great many pools are trappe in low folds cut by normal faults, suc as this pool, and it may be consider typical. The section through XY shown at the right. [Map redraw from Lahee, in The Structure of Typical American Oil Fields, *Vol. (1929), p. 348, Fig. 25; section drawn from Starnes, University Texas Pub. 5116, p. 331.]*

cases the crest of the structure will still be productive, and drilling into th highest point of the trap will make a discovery, but occasionally the displacement is enough to leave the crest of the structure barren. Displacement o pools is generally due to fluid potential gradients that result in the movemen of water through the reservoir rock; if this condition is suspected, the flui potential gradients of the area and the densities of the water and the expecte oil should be studied, and the test well should be drilled where the shape of th trap indicates the pool will be trapped under these conditions. The subject i considered in more detail in Chapter 12.