1017 GIAC

GIAC
1017
1967

[illegible]

SOCIETY OF PETROLEUM ENGINEERS OF AIME
6200 North Central Expressway
Dallas, Texas 75206

PAPER
NUMBER SPE

THIS IS A PREPRINT --- SUBJECT TO CORRECTION

Migration of Reservoir Fluids

By

Wm. C. Gussow, Union Oil Co. of California, Brea, Calif.

ABSTRACT

The application of reservoir and production engineering experience to the problems of migration and accumulation of oil and gas is developed. The principle of differential entrapment is reviewed and updated, and geological evidence for selective trapping of oil and gas is illustrated. This theory, first published in 1953, explains why many good traps are dry while adjacent structures are prolific oil fields. It explains why some traps are gas fields and contain no oil, and why gas is trapped downdip in some areas while synclinal oil occurs in others. The law of gravity explains the gravity distribution of gas, oil, and water in a reservoir, but differential entrapment explains why some oil reservoirs are stratified, and why some oil accumulations are light-gravity condensates while others are medium or heavy crudes.

Under superimposed hydrodynamic conditions, oil and gas accumulations are modified in accordance with the hydrodynamic gradient, causing tilted interfaces, spilling, and remigration. When folding and faulting are superimposed on a basin with oil and gas accumulations, the oil and gas usually remigrate into the new structures in accordance with the principle of differential entrapment, and these new accumulations conform to the exis
hydrology.

How undersaturated oils are form
crudes have different GOR's, and the
significance of saturation pressures
these are used for determining the ti
accumulation are discussed.

References and illustrations at end of paper.

INTRODUCTION

Petroleum engineers are well awa
each oil and/or gas field has unique
istics all its own. The purpose of t
is to discuss the reasons for these d
and how they came about. Perhaps the
fundamentals, the physical laws gover
mulations of oil and gas, have been i
because of the ease with which petrol
been discovered in the past. There i
substance, so seemingly simple, which
intrinsic complexity offers such a ch
chemist, geologist, geophysicist, and
The challenge is that the oil and gas
accumulation have concentrated from s
and have left little trace of their s
petroleum geologists have an engineer
ground and yet this is becoming more
essential for a successful exploratio
The geologist and geophysicist are le

work together and realize the need for teamwork in applying their specialties. A similar and much greater effort of cooperation is needed between the reservoir engineer and the exploration geologist to find the remaining undiscovered oil and gas reserves. The engineer should carry his share of the burden and help the exploration geologist find more oil. This mutual understanding and cooperative effort is even more necessary as many engineers are now in management positions charged with making important exploration decisions.

The general application of the structural theory, together with migration, is now accepted by virtually all petroleum geologists. The so-called anomalous occurrences of oil and gas in interconnected traps had long baffled the petroleum industry throughout the world. Why are some apparently good structures gas fields rather than oil fields, while others are dry? This is explained by the principle of differential entrapment.[1-15] This simple principle explains why gas fields may occur in a downdip position and produce little or no oil, while structures further updip produce oil with little or no gas and others still further updip are dry. In reality, this carries the structural theory to its logical conclusion.

When we published our paper in 1954,[4] we learned of two earlier attempts to explain these apparently anomalous occurrences.[16] This, in spite of the fact that two 2-man years were spent searching the literature without discovering the slightest hint. A Russian geologist came the closest, but veered off.[17] In 1916, Loyal W. Trumbell, state geologist for Wyoming, set forth ideas almost identical with those developed by us nearly 35 years later, and yet Trumbell's idea lay dormant, except in the minds of a few of his associates [S. H. Knight] and received little attention. Trumbell was certainly on the right track. In 1932, T. Martin W. Strong of the former Anglo-Persian Oil Co. [British Petroleum--in a private report dated July 6], developed an explanation for the anomalous occurrences in the Middle East. This was based entirely on the effect of solution gas in the oil. He visualized saturated oil migrating updip without any free gas. With decreasing depth [and pressure] solution gas would be released from the oil. By this line of reasoning, every trap would contain a gas cap at the time of migration and these would be larger and larger the further downdip the trap because the further downdip, the more oil would have passed a specific trap. Strong then explained the absence of gas caps in the updip traps by selective leakage of gas from the shallower structures. Unfortunately, Strong was not permitted to publish his advanced ideas for obscure reasons practiced by too many oil companies. Wallace E. Pratt wrote that he had been made aware of Strong's idea many years earlier by George M. Lees;[19] and A. I. Levorsen [personal communication] also intimated that he had "bought leases based on the idea many years ago". The effect of solution gas in the oil is believed to be a secondary complication which obscures the underlying principle of differential entrapment and this is discussed later. Finally, in Dec., 1954, nearly simultaneously, another British geologist, G. D. Hobson, Imperial College of Science and Technology, published a book on petroleum geology in which he outlined nearly identical ideas, but with somewhat different emphasis.[20] Undoubtedly, the idea also existed in the minds of many others but was never thought out *a posteriori*.

MIGRATION OF OIL AND GAS

Primary migration refers to the movement of oil and gas in a finely dispersed state from the source beds into an aquifer or carrier bed. The movement of oil and gas in a carrier bed to the final positions of entrapment is known as secondary migration. Oil in a dispersed state or in small globules, cannot flow through a water-saturated reservoir rock or carrier bed. This has been proved in laboratory experiments and is also demonstrated by reservoir behavior: as long as the oil occurs as a continuous phase, a well will produce only oil; once the oil in the reservoir becomes the discontinuous phase, the well will produce only water. This knowledge is commonplace with all reservoir engineers. This is also the reason for the poor recovery of the oil in place in any oil accumulation, and is referred to as the irreducible minimum saturation when the accumulation has been depleted.

Evidence of Migration

The belief that oil can migrate seems fairly universal. Textbooks make reference in positive terms to movement through the pore space of rocks. However, some geologists believe in an in-situ or local origin. We are forced to conclude that it migrates for great distances, based on the geological evidence. Oil is produced by virtue of its migratory qualities. The fact that oil will move into the drill hole is axiomatic,[21] and it is known that a specific area of a reservoir can be drained by a well. Thus well spacing commonly varies from one well in 5 acres, to more than 2-mile spacing in some of the Persian fields.

According to Lees, ". . . the Persian fields are notable for their ready fluid communication throughout the extensive structures . . . Free reservoir connexion [sic] has been proved over long distances [up to 20 miles in the Persian fields and over 60 miles in the case of Kirkuk in Iraq] . . ."[22] In Arabia, common water drives have been proved over distances of 50 miles between several fields [Abqaiq, Ain Dar, and 'Uthmaniyah]. Good intercommunication over great distances is also demonatrated by ground-water hydrology and by generally good hydrostatic balance throughout large basin areas. The fact that petroleum fluids accumulate in structural culminations is proof of migration and is the very basis of the structural theory. Furthermore, abundant geological evidence of differential entrapment is evidence of distant migration.[1,4]

Tilted oil-water interfaces demonstrate that movement of the reservoir fluids can take place over considerable distances. At the East Coalinga Extension field in Fresno County, Calif., for example, there is a uniform northward tilt of 700 ft over a distance of 8 miles [Fig. 7], and further south at Kettleman North Dome field, a northwest tilt of more than 1,000 ft has been recorded over a distance of 12 miles. Many other examples of this phenomenon are known [Fig. 13].

The fact that many structural traps form very much later than the time of deposition of the reservoir rock can be explained only by the migration of oil and gas,[23] and finally, the presence in oils of microfauna foreign to the reservoir rock is strong evidence of migration and indicates the path it must have followed.[24] Accordingly, it is postulated that oil and gas continue to migrate in an aquifer as long as they occur in a continuous phase and until trapped.

Secondary Migration

Secondary migration is initiated by tilt and depends on buoyancy. Actual movement in the carrier beds begins when the buoyancy is sufficient to overcome the entry pressure in the carrier beds. This is a function of tilt and the height of the resulting oil column. In Fig. 1 the upper line is horizontal and oil globules, even though they have coalesced, remain in place. In the next illustration below, tilt is expressed as an angle, or h the height of the resulting oil column. It is seen that the greater the angle of tilt, the smaller the patch of oil required to give the minimum oil column x to initiate secondary migration. When the tilt is rather flat even a long accumulation may not move if the critical oil column is not attained. The critical height x may vary from six in. to five ft for average conditions. In the Mid-Continent areas migration has occurred with dips of only 1/4 to 1 1/4 degrees.

Secondary Migration Forms a Drainage Pattern

Oil and gas accumulate at the shale-sand interface where they wait for tilt. When it develops, the patches unite and begin to move. Slipping ever higher on top of the water which permeates the pore space of the rock, they stream along on the under side of a blanket-like impermeable interface. Their movement is normal to the contour lines but the very inverse of surface drainage - streams converging and filling culminations as surface water seeks declivities. The culminations are the traps in which the pools accumulate. Everyone should agree that petroleum having filled a trap, any overflow will take the form of a stream along a well defined path. A criterion that may be used to recognize a migration path along which oil has moved is that a well drilled into such a path will indicate oil saturation up to 50 percent, but will not produce. Many such wells have been drilled down the plunge of anticlinal folds, below the oil-water interface. Fig. 2 is an idealized drainage pattern illustrating how oil and gas migrate out of a supply basin along well defined migration paths.

As oil and gas migrate along a migration path, they fill all traps along the way until the supply is exhausted. Traps can be any size from a cup to many millions or even several billions of barrels.

Accumulation of Oil and Gas in a Simple Trap

Oil and gas accumulate in structural traps in reservoir rocks, displacing the reservoir water out of the trap. Fig. 3, stages 1 and 2, are textbook examples of the accumulation of oil and gas in a simple trap under hydrostatic conditions. Under such conditions, gas always occurs in the highest part of the trap and forms a gas cap above an oil column in accordance with the law of gravity. Water always occurs below the oil column and occurs throughout the aquifer. The fluids are bounded by gas-oil and oil-water interfaces.

Assuming that the supply of oil and gas is adequate, they will continue to accumulate until the oil-water interface reaches the spill point [Fig. 3, stage 2]. Thereafter, a trap for oil no longer exists and any additional oil entering the trap would cause oil to spill updip from the now filled trap. Gas, however, would continue to enter the trap, displacing more and more oil until, finally, all the oil has been displaced and flushed or spilled updip. Once the gas-oil interface has reached the spill-point level, it would, theoretically, coincide with the oil-water interface and become a gas-water interface as the last oil escapes from the trap [Fig. 3, stage 3]. The end point has how been reached and this represents the final stage in this specific trap unless the pressure is increased by further burial, or reduced by erosion. Any additional gas would now cause gas to spill updip while oil would continue to by-pass this gas-filled trap.

If the gas accumulated first, it would displace the water out of the trap. Some water would remain as a residue on the gas column but this would gradually reduce to a minimum by gravity drainage. The oil would then form an oil column below the gas, displacing more water from the trap. Oil cannot displace all the water in the oil column and this remains as an irreducible minimum water saturation in the oil column. The water in the oil column is not affected by gravity drainage. Note that no oil saturation would occur within the gas column.

If oil accumulated first, it would displace the water in the trap. Then when the gas accumulated, it would displace the oil in the highest part of the trap. The fluids [oil and water] left in the gas column would now drain down by gravity drainage until a minimum saturation is reached.

If the pressure in the trap is reduced by erosion at the surface, the gas will expand, displacing the oil still further. If the pressure is increased by greater burial, the gas cap will be compressed and more gas will also go into solution in the oil column. Eventually, the gas cap can disappear and go entirely into solution in the oil. This will result in a much higher gas-oil ratio in the upper layers of the oil column. It is also conceivable that this might result in an oil-wet reservoir in what was formerly the gas cap.

Wet Gas -- Dry Gas

Fig. 3, stage 3, is an example of a non-associated gas accumulation. That is, there is no oil column, and accordingly, the gas may be produced as soon as it can be tied in to a pipeline. This gas will probably be wet gas, and will have a specific gas-condensate ratio. If the accumulation is buried deeper and the gas volume is reduced by one half, the gas-condensate ratio is doubled. The deeper the burial, the higher the gas-condensate ratio. If the pressure on the gas is reduced by erosion, the gas is unable to hold as much condensate and this accumulates at the gas-water interface and is flushed out along with excess gas. Eventually, a dry gas will result. When a dry-gas reservoir occurs at depth, this is good evidence of accumulation before post-erosional deposition.

Migration in a Continuous Aquifer and Accumulation in a Succession of Traps

Oil and gas will now be moving in a well defined migration path. This will have its local tributary streams, and from time to time will be joined by larger branches. The path of migration will be generally up the regional dip out of a basin and, on reaching the crest of an anticline, along it at right angles to the regional dip, spilling from one culmination to another. It is rarely, if ever, in a straight line [Fig. 5]. The oil and gas will accumulate in traps along the migration path. When the lowest of these is filled, they will spill updip into the next highest trap and when the foregoing mechanics are applied to a series of interconnected traps [Fig. 4], at first [Fig. 4-A] oil and gas accumulate only in the lowest trap [Trap I] until this is filled to the spill point; all other updip traps would be water-bearing until the lowest trap is filled. Only when oil begins to spill updip from Trap I will any oil accumulate in Trap II. Note that there is no primary gas cap in Trap II at this stage. Traps III and IV are water-bearing.

Further stages in the selective trapping of oil and gas are illustrated in Fig. 4, B and C. Thus Fig. 4-B illustrates the conditions that might prevail when Trap I is completely filled with gas and all the oil has been flushed updip. Trap II might then be filled to the spill point with oil, and might be spilling oil updip into Trap III. Trap IV [and any other updip traps] would be filled with salt water. Fig. 4-C shows conditions at a still later stage. Trap I is filled with gas, and is spilling gas updip into Trap II; Trap II now has a gas cap, and is spilling oil updip into Trap III; Trap III is more or less filled with oil but still has no primary gas cap; Trap IV is filled with salt water.

Fig. 4, D and E indicate more or less the same stage of migration as 4-C but under different structural relationships. Note that the height of the culmination of succeeding traps is not necessarily higher than in the previous trap. The spill-point level is the controlling feature of selective trapping. The height of the culmination above the spill point determines the maximum oil and/or gas column in the trap.

The traps illustrated in Fig. 4 might represent a cross section through a series of parallel and contiguous anticlines or a longitudinal section [not necessarily a straight line--see Fig. 5] through a succession of culminations along one anticlinal axis, or they could represent a succession of culminations on a reef barrier or along a shoestring sand. Differential entrapment occurs also in migrating along a stratigraphic pinch-out edge of a sand. Only the simplest examples of the application of the principle of differential entrapment have been illustrated in Fig. 4. There are many examples of combinations of structural traps to be considered but in every case the fundamental principles govern. Many examples of this phenomenon were described in the literature of the world and they were passed up as beyond explanation. The principle of differential entrapment would appear to explain some of the relationships. From the foregoing, it is obvious that a trap filled with oil is still an effective gas trap but a trap filled with gas is not an effective oil trap. It is, therefore, necessary to consider the migration and trapping of oil and gas separately, and not collectively as has been the tendency in the past.

Fig. 5 represents a subsurface contour map of an anticlinal trend along the western margin of a large supply basin, and demonstrates the migration path that would be followed by any oil or gas migrating updip out of the geosynclinal area on the east. The heavy line indicates the regional migration path. The lighter broken lines represent minor local tributaries. First note that the migration path is not a straight line. When the lower culmination D has filled to the spill point at Saddle 1, oil and/or gas would stream updip at right angles to the contour lines into culmination C. Note that none would spill into Trap E; Traps A, B and C would have to be filled to about the 1,030-ft contour before any oil would back up across Saddle 2 and spill south into Trap E.

When Trap C is filled to approximately the 1,055-ft level, oil would spill across Saddle 3 into Trap B, and B would have to be filled to approximately the 1,060-ft contour before any oil would spill across Saddle 4 into Trap A. Culmination D is shown as being filled with gas and has flushed all the oil updip. This would no longer be a trap for oil or more gas under existing conditions. Trap C is filled with oil and has a gas cap. Trap B is indicated as being filled to the spill point with oil [all primary gas is trapped downdip in Trap C]. Traps A and E are dry or at best would have showings of oil derived from local migration.

If a series of traps is filled with oil, any gas entering the lowest trap would form a gas cap and begin spilling oil updip. This would cause oil to spill updip, all along the line into a still higher water-filled trap. Eventually the lowest trap would become filled with gas and then gas would spill updip into the next trap, forming a gas cap in it. Conversely, if a series of traps is filled with gas, any oil migrating from below would bypass all the gas-filled traps and end up in a water-filled [or partly gas-filled] trap at the upper end. Thus it makes no difference which came first; the end result is the same.

When the supply basin is exhausted, secondary migration will cease and the reservoir fluids will come to rest so that, along the path of migration, the following general sequence will result. The deepest [downdip] traps will be filled to the spill point with gas. These will be followed by one or more traps containing oil and having a gas cap, and then by one or more traps filled with oil only [having no primary gas caps]. When the supply of oil is exhausted, all remaining updip traps will be filled with water. The number of traps that will be filled with gas only or with oil only, will depend on the size of the individual traps and on the supply of oil and/or gas.

It should be remembered that oil and gas are closely associated, the amount of gas dissolved in the oil or the amount of oil becoming volatile varying with the temperature and pressure. Thus, if the area of entrapment is subjected to deeper burial, the gas in filled reservoirs having an oil column and a gas cap, will go into solution in the oil, increasing the GOR. The size of the gas cap will also be further reduced due to compression of the gas remaining in the gas cap. [It is possible for the gas cap to disappear entirely.] As a result, the oil-water interface will no longer be at the spill point, making this an effective trap for oil again as well as for gas. Reservoirs filled with gas only will become effective traps again for oil and ga , but reservoirs filled with oil only will remain unchanged, so that the oil will now be undersaturated.

The important observation in Fig. 5 is the updip limit of gas flushing. This occurs between Traps D and C. It follows that if a line is drawn on a map along the updip limit of gas flushing in a specific zone, no oil will be found downdip from it and only solution gas will be found in updip oil accumulations.

Now, if a surface structural picture or seismic picture has been developed such as illustrated in Fig. 5, what is the procedure for testing with the drill? A move to the largest structure is obvious. If this is dry, the test is too far updip. However, in this case, a well drilled on the gas cap might determine the presence of gas only, depending on the thickness of the gas column. It is possible that a second test will be required further downdip to determine the presence of oil. When oil has been discovered in this structure the field can be developed by the production engineer and the exploration geologist moves on. Now the question is: Which structure to drill next? Since structure C has a gas cap, the next updip trap will probably contain oil. Should the next test be in Trap B or Trap E? This depends on the relative heights of the spill points. In Fig. 5, oil will migrate into Trap B and this is the structure to drill next. Undoubtedly, Trap E eventually will be drilled but at least a good explanation can be given if it is dry.

Examples of differential entrapment from all over the world are described in the original paper.[4] The Alberta Middle and Upper Devonian reefs and the gigantic Iranian fields are classic examples. The accumulations around the edges of the Central Basin Platform, West Texas, might be mentioned. These contain most of the oil while equally good structures of the interior are dry [T. S. Jones, personal communication]. Only two examples are illustrated and have been selected for discussion in the present paper.

Differential Entrapment in Bonnie Glen-Wizard Lake Reef Chain, Alberta, Canada[4]

This great barrier of Upper Devonian age has been traced more than 125 miles, extending 80 miles southwest from the Leduc field and more than 50 miles north of Leduc. Fig. 6 is a longitudinal section along the reef barrier south of the Leduc field, showing the fluid content of the various traps. It is visualized that oil and gas migrated updip out of the Rocky Mountain geosyncline along various tributary migration paths and, on entering the reef trend, migrated along it from south to north. Reef debris along the flanks of the reef trend forms an excellent pipeline or carrier for the migration of oil and gas along the barrier. All primary gas has been trapped in structures downdip from Wizard Lake. South Westerose, and Rimbey-Homeglen further south, are filled with wet gas to the exclusion of oil, while Westerose and Bonnie Glen reefs have large gas caps. Wizard Lake and Glen Park are filled to the spill point with oil and have no gas caps.

The fact that Westerose and Bonnie Glen both have gas caps might be pointed out as an exception. This, however, may be explained by assuming that gas must have been spilling updip from South Westerose into both Westerose and Bonnie Glen, simultaneously, just as a braided stream splits and comes together again. The gas caps may also have resulted from the solution solution gas evolved by the oil which has migrated updip into the large oilfields along the reef trend to the north. The small oil columns at Rimbey-Homeglen and South Westerose may be explained by oil which has drained down out of the gas cap after the oil content was flushed updip. These reefs were once filled to the spill point with oil and had no primary gas caps. Then gas caps appeared and, finally, all the oil was flushed updip. Then, during geologic time, oil drained down out of the gas cap. Another possible explanation is that more oil was trapped in these reefs after the gas was compressed due to deeper burial.

East Coalinga Extension Field, Fresno County, California[4]

A contour map of this field was published by L. S. Chambers[25] and is reproduced in Fig. 7. This indicates an oil field about 8 miles long, having two culminations and a common oil-water interface. Gas is trapped in the northern culmination [-7,400 ft], while there is no gas cap in the southern culmination [-5,800 ft]. Gas is thus trapped downdip, about 1,600 ft below the top of the structure. The oil accumulation is modified by a hydraulic gradient so that the oil-water interface is tilted north at about 90 ft/mile. The gas-oil interface, however, is horizontal. Apparently, gas was trapped in East Coalinga Extension north dome while oil was spilled updip into the higher culmination [south dome]. This relationship of oil and gas cannot be explained by the hydraulic theory, but is in accordance with the principle of differential entrapment.

Gas Flushing

The over-all effect of gas flushing will now be illustrated. Updip limits of gas flushing are important in evaluating petroleum possibilities of a basin area. A particularly good example of the limits of gas flushing is in Oklahoma and Arkansas where all traps in the Arkoma [McAlester] Basin are filled with gas to the exclusion of oil, the oil being found in northern Oklahoma and Kansas [Fig. 8]. A similar picture results from an analysis of Frio and Anahuac accumulations in the Gulf Coast area, and a structure map of the Sweetgrass Arch, Mont.,[7,8] explains why there is no oil at Pincher Creek, Alta., and why gas is trapped downdip at Pondera, Mont.

In 1954, we completed a detailed scientific study to evaluate the future possibilities of the Foothills belt of Alberta, Canada. The conclusions and deductions were controversial then, but have been substantiated by subsequent exploration. These findings were reported in a study of the accumulations of oil and gas in Western Canada presented in 1959,[15,26] and are repeated here. The conclusions are as true today as they were eight years ago. The Alberta Foothills might have been one of the most prolific oilfield areas of the world, had it not been for the fact that the upper 15,000 ft or so of the geological section are continental deposits and contain no source beds. It is also unfortunate that the Foothills belt lies almost entirely west of the limit of gas flushing in the Mississippian

Madison aquifer. Oil and gas in Foothills structures are essentially remigrated gas and/or oil which were originally trapped in buried topography at the post-Mississippian erosion surface or in stratigraphic sand pinch-outs associated with marine shales in the Mesozoic section. Accordingly, it was predicted that there would never be another Turner Valley field and that all future Mississippian Foothills discoveries would be gas-condensate fields. Furthermore, on account of the time sequence of migration of oil and gas and the folding, it was also predicted that most Foothills Mesozoic reservoirs would be filled with salt water, unless a stratigraphic or terminal trap had had Foothills structure superimposed on it. After more than 50 years of aggressive exploration and many millions of dollars, searchers in the Foothills have turned up no oil since Turner Valley.

The next question was--where are all the oil and gas from this great supply basin? It was concluded that this is the explanation for the gigantic size and location of the Athabasca bituminous sands which occur at the highest culmination on the pre-Cretaceous unconformity and contain in excess of 625 billion bbls of oil. It was also predicted that Saskatchewan and Manitoba would never become great gas-producing provinces and that it was utter folly to base future gas and oil reserve estimates on a cubic-mile factor alone. Unfortunately, this was the basis of the estimates which were submitted on the future potential of oil and gas in Western Canada.

Terminal Traps and Synclinal Oil Pools[4]

Two types of synclinal oil pools are known: those in blanket-type sands in which the oil accumulatation is trapped far down the plunge of synclinal structures, and the shoestring sands, in which the oil lies in synclinal structures or in the downdip part of a lenticular sand body. When gas accumulates in a terminal trap such as a sand pinch-out or on a geanticline, gas displaces oil and water, backing them down the dip out of the culmination of the trap and into cynclinal positions and depressions below the gas cap. These are commonly referred to as synclinal oil pools and gave rise to the term dry sands in the Appalachian region. Before the gas and oil accumulated, the reservoir was filled with water, and the water now occurs down the plunge below the oil column. This is illustrated by Fig. 9, A and B. There are many examples of synclinal oil such as in the Hugoton-Panhandle field, Tex. [Fig. 11], the Carthage gas field in East Texas [Fig. 12], and the Appalachian gas fields [represented by the Griffithville pool, W. Va., Fig. 10]. Other good examples are the Dahlquist pool [16 oil wells] in the Cutbank field, Mont., in the Smiley field, Sask., the Monroe field, La., and in the Big Trenton gas fields in Indiana.

In every case, accumulation of oil and gas is in accordance with the structural theory of accumulation and the apparent absence of water in the sands is simply due to the fact that it has been displaced out of the anticlines and higher parts of the synclines by large quantities of gas. The absence of water in these sands seems no more puzzling than its absence in the gas cap of an anticlinal structure. There are thus no known exceptions to the structural theory.

MODIFYING FACTORS

Hydrodynamic Gradients

Hydrodynamic conditions causing tilt of interfaces and flushing of shallow traps are a fact and have been adequately proved. Tilts up to a maximum of 850 ft/mile are known. The average is about 100 ft/mile, and while much greater tilts and anomalous effects are readily demonstrated in the laboratory, they have so far not been found in nature. If hydrodynamic conditions actually existed such as to cause flushing of oil from a reservoir, the result would be to cause the oil to migrate downdip and accumulate in a downdip energy trap, leaving any gas caps in an updip position. This is exactly the reverse of the anomalous conditions found in nature.

Most hydrodynamic gradients measured today are downdip into the basin. These gradients are obviously superimposed. At the time of primary migration, and probably during secondary migration, hydraulic gradients must have been updip, due to the expulsion of large volumes of compaction fluids. Such gradients would augment buoyancy and help migration. Differential entrapment alone is thus responsible for the selective trapping of oil and gas. In most cases, present hydrodynamic tilts are superimposed on former hydrostatic accumulations. A strong gradient might cause an oil accumulation to move down plunge out of the culmination but this would always be revealed by the irreducible minimum oil saturation remaining in the former hydrostatic accumulation. In such cases, the hydraulic theory is not an exploration tool, but is a development tool. It is a valid and valuable concept, but has decided limitations which have not been recognized. If the culmination is dry and there are no oil shows, then there will be no oil in an energy trap downdip.

The importance of hydrodynamic entrapment as a development tool is illustrated in Fig. 13,[27] which shows oil accumulations in the

Stevens sand in the San Joaquin Basin, Calif. The age of the reservoir is Miocene; the age of the structure, post-Pliocene [Pasadenan orogeny]. Thus the oil is in all probability remigrated oil. All three accumulations occur in energy traps formed by a strong hydrodynamic gradient [in the order of 300 ft/mile], giving rise to highly tilted oil-water interfaces. North and South Coles Levee are filled to the spill point. As shown in Fig. 13, oil spilled updip from the Paloma field, southeast, where oil and wet gas are trapped downdip in accordance with the principle of differential entrapment. The oil entered South Coles Levee at A, filling it to the spill point at B. Oil spilled across into North Coles Levee and filled this energy trap to capacity. North Coles Levee has two spill points, C and D, causing oil to spill northeast into the Ten Section field and west into the east pool of the Elk Hills field. Just west of the map boundary is a saddle between the east and west pools of the Elk Hills field. Oil filled to the spill point in this saddle and spilled southwest into the west pool.

All three fields shown contain much more oil than the capacity of the structural trap in each field. Therefore the hydrodynamic gradients must have existed at the time of accumulation. The oil must have migrated updip and could not have been flushed downdip by a hydrodynamic gradient. Note that oil occurs at the culmination in all three structures, so that hydrology would not help in their discovery but would be valuable in their development. While records are incomplete due to their confidential nature, exploration to date would appear to substantiate the foregoing conclusions as only two oil fields [Sage Creek in Park County and North Tisdale in Johnson County, Wyo.] can be attributed to discovery by the application of hydrology.

Solution Gas

Up to this point, the effect of solution gas in the oil has purposely been disregarded as this complication tends to confuse presentation of the underlying principle of differential entrapment. Actually, the oil is saturated with gas and, in migrating updip, gas is constantly being evolved with decrease in hydrostatic pressure. Thus, at the time of migration every oil-filled trap beyond the updip point of accumulation of primary gas will have a secondary gas cap of solution gas. The size of these secondary gas caps is dependent on two physical requirements--first, the amount of oil passing a specific trap, and second, the height of its oil-water interface above the downdip spill point. In Fig. 14, the upper diagram shows an accumulation of oil in which the oil-water interface is at the downdip spill point. If primary gas was trapped downdip, this secondary gas cap is evolved only from the oil contained in the trap. Once filled, any more oil would cause oil to spill updip without loss of pressure, so the gas cap would not be further enlarged. In the lower diagram, however, the oil-water interface is at a specific height h above the downdip spill point. In this case the gas cap continually grows as more oil passes the trap and gas is evolved with the drop in pressure. The oil and gas are intimately associated and are in equilibrium for the reservoir temperature and pressure in each specific trap. If the area of entrapment is subjected to deeper burial with geologic time, many of these secondary gas caps disappear and with further burial, the oil becomes undersaturated. The point when the gas cap disappears is known as the saturation or bubble point pressure of the reservoir. As saturation pressures of undersaturated oil pools remain unchanged with deeper burial [increased pressure], they serve to date the geologic time when the secondary solution-gas gas caps disappeared.

Saturation pressures are the most accurate means of determining the time of final accumulation in a specific reservoir. Care must be exercised to be sure that all primary gas has been trapped downdip, and that no gas was evolved from oil that passed by. It must be either a terminal trap or one similar to the first example illustrated in Fig. 14, where h equals zero. The saturation pressure in such a trap corresponds very nearly to the hydrostatic pressure at the time of accumulation in this trap.

Other Possible Modifying Factors

Seepages are usually associated with excessive reservoir pressures [Norman Wells, NWT, Canada]. As erosion cuts down closer to an accumulation, the resulting pressure opens the fractures in the overlying rocks, permitting seepage. When the excess pressure has been dissipated, the fractures close. The vertical escape of oil and gas at depth is much rarer than surface evidence would suggest, seeps being largely superficial. Seepages themselves are not common--migration across coarse-fine rock interfaces is impossible, while fractures and faults are probably tightly closed at depth.

Regional tilt superimposed on accumulations also modifies them by decantation. But regional tilt if shown in true scale cross-section is relatively slight and little spilling would occur. Regional orogenic movements, however, might cause remigration and a redistribution of oil and gas. An example is the gas and condensate fields in the Foothills of Alberta and the Rocky Mountain states [Fig. 13].

TIME OF ACCUMULATION

It will be quite apparent to anyone that if no trap exists at the time of migration, there can be no accumulation of oil or gas. The relative time of migration and the time of formation of traps is most important for oil or gas accumulation to occur. Traditionally, two factors have been prerequisite to any geological search for accumulations of petroleum: source beds, and structure. They are fundamental, but time is a fourth dimension of equal importance. Formation of structure must have preceded migration for accumulation to result; obviously, those structures formed after the oil and gas have passed will be dry.

The time of formation of traps dates the earliest time of any accumulation. It is the age of the structure, rather than the age of the reservoir rock that limits the time of accumulation. Stratigraphic traps, reef traps, marine shoals, and depositional draping and onlap on buried topography are traps that occur early in the history of the reservoir rock. Traps formed below an unconformity or by differential compaction and draping form somewhat later in the history of the reservoir rock. Structures formed by tectonic deformation may be formed, by comparison, very much later.

While the time of formation of traps does not in itself date the exact time of accumulation, at least it fixes the time before which there could be little or no accumulation. By pure a priori reasoning, based on a study of these three--compaction, tilt, and structure--the time may be worked out without reference to the actual content of the accumulations. However modifications in the oil and gas, both during and after migration, give effective evidence on which to base more accurate dating.

Time of Accumulation Based on Capacity of Traps to Hold Gas

TIME of accumulation

Changing depth, either by deposition or erosion at the surface has a marked influence on the gas capacity of the trap. This capacity varies directly as the pressure and inversely as the temperature, and is a function of depth. For instance, Levorsen demonstrated that the Oklahoma City field, at a depth of 6,200 ft, holds 200 times the volume that it could at sea-level and, since it was almost full when discovered, accumulation must have occurred when its capacity for gas was comparable to that at the present time.[23] As Permian strata are exposed at the present erosion surface, Permian is the earliest time of final accumulation--it might have been even later.

The application of each of these principles has been discussed in detail as applied to oil and gas accumulation in Alberta.[5] It was concluded that the rapid twofold increase in regional tilt following the Nevadan orogeny probably abruptly initiated secondary lateral migration. Time of formation of traps in the Nisku by differential compaction over the Leduc reefs was probably not effective until mid-Upper Cretaceous time. This was also the time of accumulation in the Leduc reefs, based on an analysis of their gas capacity.

Time of Accumulation Based on Saturation Pressures

This is one of the most exact methods for determining the time of migration and accumulation of oil and gas. However, it is fraught with pitfalls. To use this method successfully, it is necessary to have a clear understanding of the principle of differential entrapment and the other factors involved, such as the behavior of hydrocarbons and their phase relationships. We became aware of this phenomenon in 1953 and developed the method of application. The idea, however, is not entirely new. In regard to the East Texas field, M. G. Cheney suggested that undersaturation is related to depth of burial, and he interpreted this to represent the reservoir pressure at the time accumulation ceased.[28] A small gas cap occurs in the southeast part of the East Texas field, in a separate downdip closure, isolated from the main reservoir, and there is a "great abundance of gas" in various Woodbine structures at the southwest. This appears to indicate that the East Texas field is a terminal trap and that no primary gas entered the East Texas reservoir. If it can be demonstrated that this is the case, then Cheney's computation of the time of accumulation was correct. This places the time of migration and final accumulation near the top of the Navarro, or at the close of the Mesozoic.

Lees used similar reasoning in discussing the Zubair field in Iraq.[29] He pointed out that the Third Pay [Lower Cretaceous] is undersaturated with gas to the extent of about 2,000 psi and concludes that the present saturation pressure possibly represents the hydrostatic head at the time of migration [actually, at the time of disappearance of the solution gas cap], when there was only a Middle and Upper Cretaceous cover, and that migration coincided with Upper Cretaceous movement.

An analysis of saturation pressures in several of the Leduc and Misku accumulations of Upper Devonian age demonstrated that these did not accumulate until about mid-Cretaceous time.[5] Saturation pressures at Redwater, which is a very large updip accumulation with 1-1/2 billion bbl of oil in place, probably indicate that flush migration and accumulation occurred about the close of Lower Cretaceous time [mid-Viking] and the saturation pressure at Wizard Lake, the farthest downdip undersaturated reservoir, probably indicates that essentially all migration ceased by mid-Upper Cretaceous [mid-Belly

River] time. In summary, flush migration and accumulation in Leduc and Misku reservoirs must have occurred during early Colorado [Viking] time. This fell off rapidly during Upper Colorado time and appears to have ended by Lea Park time.

Based on saturation pressures at Lloydminster [Alta.-Sask.], oil in these basal Cretaceous reservoirs accumulated about mid-Upper Cretaceous [Lea Park] time and this is also likely the time of accumulation of the bitumen in the giant Athabasca deposit. At the time of accumulation, this was a normal oil field with an oil-water interface at +700 ft and a gas-oil interface at about +1,000 ft above sea-level. It is now exposed by erosion by the Athabasca River. Saturation pressures at Norman Wells also indicate an early Cretaceous time of accumulation. Saturation pressures thus serve to date the time when final accumulation ceased. A large accumulation [such as East Texas] would give the best indication of the time of flush migration, while the farthest downdip undersaturated oil accumulation would indicate the approximate time when final accumulation ended.

STRATIFIED OIL COLUMNS

Formerly, segregation of oil gravities was the explanation offered for stratification in a reservoir. The light ends were believed to separate from the oil by buoyancy. But miscible liquids cannot separate in this way. At Kettleman Hills in California, for example, 68.3°API oil occurs at the top and this grades down to 34.2°API oil at the bottom. One way in which stratified reservoirs might result is illustrated in Fig. 15. As already mentioned, changes of pressure have an important effect on phase relationships: the greater the pressure the more gas will go into solution; as pressure reduces gas is evolved. A similar mechanism governs the condensates in gas: the greater the pressure, the richer the condensates in the gas phase. With reduction of pressure, the condensate condenses out of the gas until eventually it becomes a dry gas. The condensate is flushed updip by the simple mechanics of differential entrapment and gas flushing.

Fig. 15 shows condensate accumulating below a gas cap in the lowest trap. Due to expansion of the gas, some condensate has spilled updip into the next trap, explaining accumulations of white oil, or condensate in some pools. The highest trap shows a layer of condensate beneath a gas cap and above an oil column. If there was any oil in the second trap, it would have been spilled updip by the condensate. Different gravities of oil must accumulate in a reservoir according to their gravity and this appears to be the logical explanation of stratified oil reservoirs. A tar mat is shown in the highest trap. This is probably caused by bacterial cyclization.[6,9] If this had been present before the condensate accumulated, the condensate would have accumulated below the seal.

HOW CAN THE PRINCIPLE OF DIFFERENTIAL ENTRAPMENT BE USED?

Differential entrapment is reviewed in Fig. 16. The simplest succession is non-associated wet gas in the deepest structure, followed by a structure having an oil column with a gas cap, then one or more traps filled with oil and no gas, and, finally, water. Note the updip limit of gas flushing shown by the open arrow [all downdip traps will be filled with gas]. Note also the updip limit of oil shown by the solid arrow. Beyond this point, all updip traps are dry.

Let us assume that the exploration people have discovered a beautiful, large structure. It looked like a sure bet but drilling resulted in a dry hole! It is unfortunate that the test was dry but has all the money been wasted? No! Valuable new geological information is always obtained. Why was the test dry? Was it located too far updip? --beyond the updip limit of oil migration? As shown in Fig. 17, it is necessary to move downdip to find oil.

Both early and recent drilling in the Big Horn basin was unsuccessful because shallow updip structures around the margins of the basin were dry. They never had any oil in them. They were beyond the limits of oil migration. They were not flushed by a hydrodynamic gradient. Other examples are the Burns Dome in Kansas, the Kevin-Sunburst dome in Montana, Sage Creek in Wyoming, Bunker Hill in Wyoming, and the Artesia dome in New Mexico.

When a wildcat results in an oil discovery, it is most important to determine if the trap is filled to the spill point. Fig. 18-A shows that it is necessary to move downdip if the structure is not filled and Fig. 18-B shows that oil should be trapped updip, if the discovery is filled to the spill point, and that oil, with or without a gas cap, may be expected in a downdip trap.

Any time a wildcat makes a gas discovery, it is essential to establish whether the gas is associated or non-associated before the gas is shut in or put on production. That is, is there an oil column? Time and again, oil companies have discovered large gas fields and have either shut the well in before establishing a gas-water interface, or have produced the gas for its condensate, flaring the dry gas for lack of a market. A classic example is the Turner Valley field in Alberta. In 1924, Royalite No. 4

discovered a large gas-condensate field and 12 years elapsed before oil was discovered below the gas cap in 1936. By this time many billions of cubic feet of gas had been wasted and irreparable damage had been done to the oil accumulation. Turner Valley has a 3,000-ft gas cap and a 2,100-ft oil column.

Fig. 19-A shows an oil column. This means that in all probability only gas will occur downdip, and updip traps can be expected to contain only oil. It is also necessary to keep in mind that there may have been a gas cap which has gone into solution with increased pressure [Fig. 19-B]. If this is the case, then the trap will not be filled to the spill point and the interval between the oil-water interface and the spill point will have an irreducible minimum oil saturation.

Fig. 20 illustrates a gas discovery in which a gas-water interface has been established. Then, all downdip traps will be filled with gas; to find oil, it is necessary to move updip. The next updip trap may be all gas or will probably have a gas cap if oil is discovered. The gas-water interface need not be at the spill point [Fig. 20-B], as further burial may have decreased the volume of the gas.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the help of the Union Oil Co. of California for drafting and typing, and for permission to publish.

REFERENCES

1. Gussow, Wm. C.: "Differential Trapping of Hydrocarbons", Jour., ASPG [1953] 1, 4-5.
2. ______: "Physical Behavior of Hydrocarbons in Interconnected Reservoirs", Cdn. Oil and Gas Ind. [June, 1953] 41-43.
3. ______: "Differential Trapping of Hydrocarbons", Oil and Gas J. [Sept. 7, 1953] 168-169.
4. ______: "Differential Entrapment of Oil and Gas: A Fundamental Principle", Bull., AAPG [1954] 38, 816-853.
5. ______: "Time of Migration of Oil and Gas", Bull., AAPG [1955] 39, 547-574.
6. ______: "Evolution of Asphaltic Oils", Bull., AAPG [1955] 39, 1626-1631.
7. ______: "Oil and Gas Accumulation on the Sweetgrass Arch", Guide Book, Billings Geol. Soc., 6th Ann. Field Conf. [1955] 220-224.
8. ______: "Oil and Gas Accumulation on the Sweetgrass Arch", Oilweek [Nov. 25, 1955] 20-23, and back cover.
9. ______: "Evolution of Asphaltic Oils and Genesis of Athabasca Bituminous Sands", Oil in Canada [Dec. 26, 1955] 22, 24, 26.
10. ______: "Differential Entrapment and Migration of Oil", Cdn. Oil and Gas Ind. [Jan., 1956] 9, 51-53.
11. ______: "Migration of Oil", World Oil [Aug. 1, 1956] 79-83.
12. ______: "Time Accumulation and Evolution of Hydrocarbons", World Oil [Sept., 1956] 113-115.
13. ______: "Athabasca Bituminous Sands, Alberta, Canada", Oil and Gas Symposium, XX Intern. Geol. Congress, Mexico [1956] 3, 68-70.
14. ______: "Interventi sulla relazione Costipamento dei sedimenti argillosi nel bacino padano", I Giacimenti Gassiferi dell'Europa Occidentale, Accademia Nazionale dei Lincei, Roma [1959] II, 537-542.
15. ______: "Fundamental Principles Controlling the Accumulation of Oil and Gas in Western Canada", Paper 1, Session 1, 10th Annual Technical Meeting, CIM, Pet. and Nat. Gas Div. [May, 1959]. Discussion in Oilweek [May 22, 1959] 30-31.
16. Personal Communications: Geo. M. Lees, British Petroleum [Retired] [Jan. 31, 1954]; Peter T. Cox, British Petroleum [March 19, 1954]; J. V. Howell [July 30, 1955].
17. Brod, I. O.: "Geological Terminology in Classification of Oil and Gas Accumulations", Bull., AAPG [1945] XXIX, 1738-1755.
18. Trumbull, L. W.: "The Effect of Structure upon Migration and Separation of Hydrocarbons", Bull., Sc. Ser., Wyo., 1, 17-27.
19. Pratt, Wallace E.: Personal Communication [Aug. 2, 1954].
20. Hobson, G. D.: Some Fundamentals of Petroleum Geology, Oxford U. Press, London [1954].
21. Clark, Frank R.: "Origin and Accumulation of Oil", Problems of Petroleum Geology, AAPG [1934] 309-335.
22. Lees, G. M.: "Persia", in "The World's Oil Fields--The Eastern Hemisphere", Science of Petroleum [1953] VI, Pt. 1, 73.
23. Levorsen, A. I.: "Time of Oil and Gas Accumulation", Bull., AAPG [1945] 29, 1189-1194.
24. Sanders, J. McConnell: "The Microscopical Examination of Crude Petroleum", J. Inst. Pet. Tech. [1937] 23, 525-573.
25. Chambers, L. S.: "Coalinga East Extension Area of the Coalinga Oil Fields", in "Geologic Formations and Economic Development of the Oil and Gas Fields of California", Bull., Calif. Dept. Nat. Resources, 118, Pt. 3, 486-490.
26. Anon.: "No More Turner Valley Fields?", Oilweek [May 22, 1959] 30-31.
27. Hoots, H. W., Bear, T. L. and Kleinpell, W. D.: "Stratigraphic Traps for Oil and Gas in the San Joaquin Valley", in "Geology of Southern California", Bull. 170, Calif. Div. Mines, 1, 29-32.

28. Cheney, M. G.: "The Time of Origin and Accumulation of Petroleum", Quar. Colorado School of Mines [1941] 36, No. 2, 80.

29. Lees, G. M.: "The Middle East", in "The Worlds Oil Field--The Eastern Hemisphere", Science of Petroleum [1953] VI, Pt. 1, 69, 71.

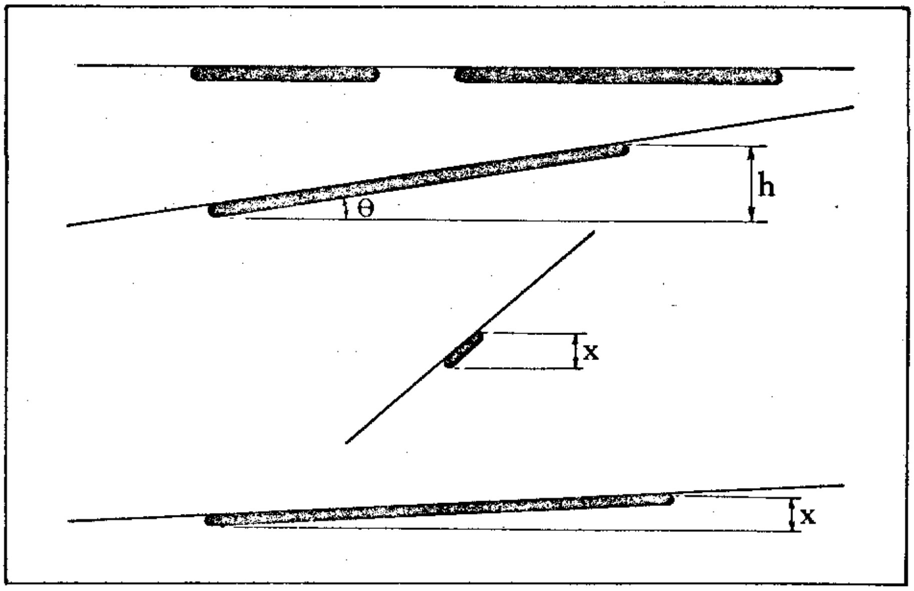


Fig. 1 - Tilt is required for secondary migration. (After Gussow,[10] Fig. 2.)

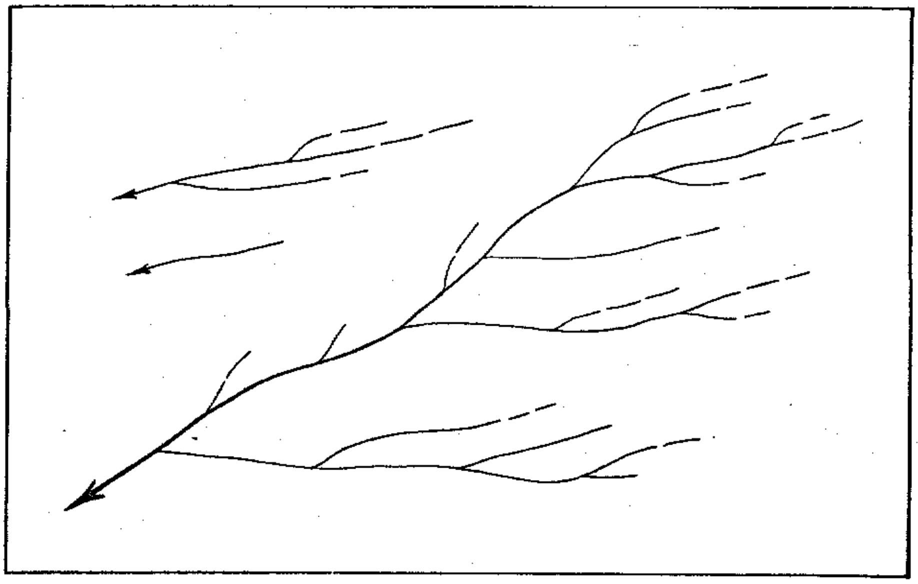
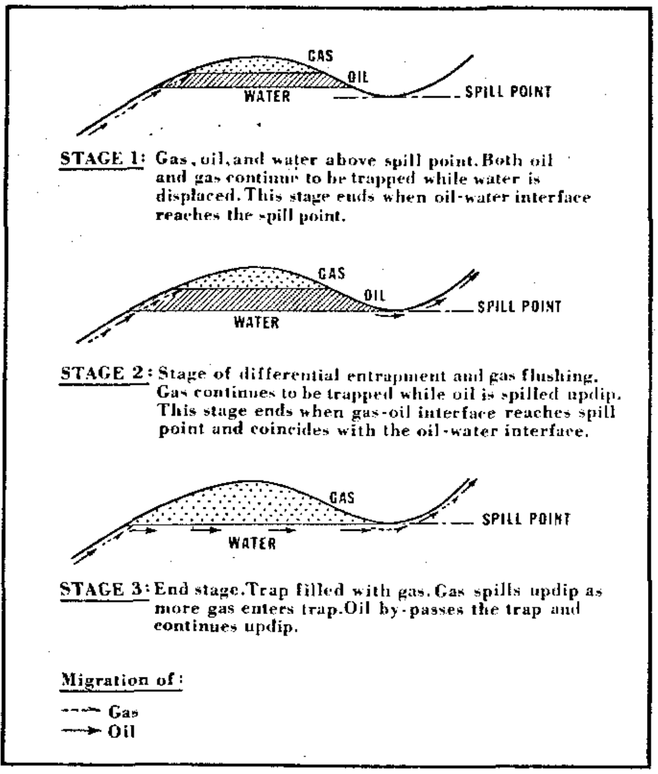


Fig. 2 - Migration pattern out of a supply basin.
(Slightly modified after Gussow,[10,11] Fig. 3.)



STAGE 1: Gas, oil, and water above spill point. Both oil and gas continue to be trapped while water is displaced. This stage ends when oil-water interface reaches the spill point.

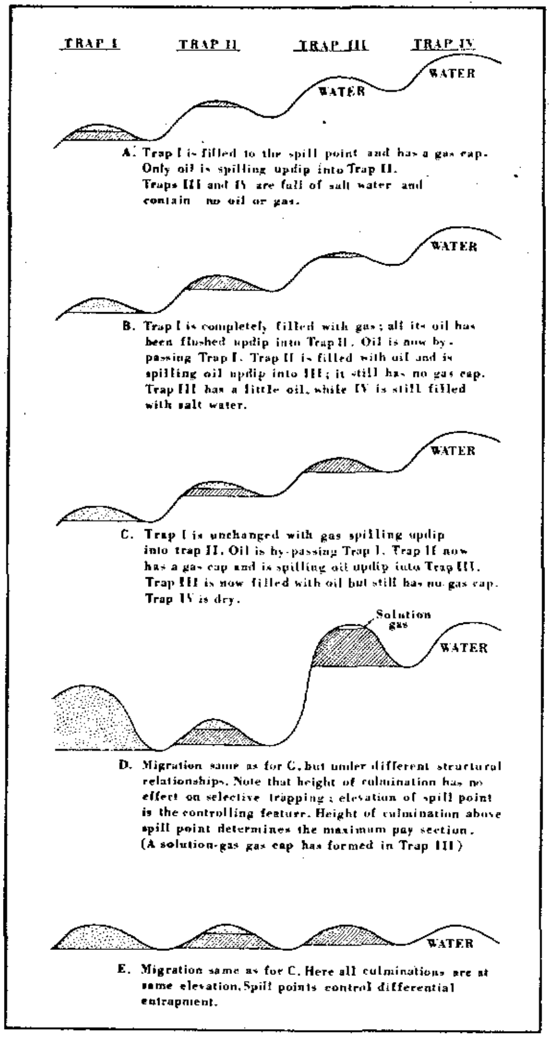
STAGE 2: Stage of differential entrapment and gas flushing. Gas continues to be trapped while oil is spilled updip. This stage ends when gas-oil interface reaches spill point and coincides with the oil-water interface.

STAGE 3: End stage. Trap filled with gas. Gas spills updip as more gas enters trap. Oil by-passes the trap and continues updip.

Migration of:

⇢ Gas
→ Oil

Fig. 3 - Accumulation of oil and gas in a simple trap under hydrostatic conditions. (Redrawn after Gussow, 1,2; 4 Fig. 1.)



A. Trap I is filled to the spill point and has a gas cap. Only oil is spilling updip into Trap II. Traps III and IV are full of salt water and contain no oil or gas.

B. Trap I is completely filled with gas; all its oil has been flushed updip into Trap II. Oil is now by-passing Trap I. Trap II is filled with oil and is spilling oil updip into III; it still has no gas cap. Trap III has a little oil, while IV is still filled with salt water.

C. Trap I is unchanged with gas spilling updip into trap II. Oil is by-passing Trap I. Trap II now has a gas cap and is spilling oil updip into Trap III. Trap III is now filled with oil but still has no gas cap. Trap IV is dry.

D. Migration same as for C, but under different structural relationships. Note that height of culmination has no effect on selective trapping; elevation of spill point is the controlling feature. Height of culmination above spill point determines the maximum pay section. (A solution-gas gas cap has formed in Trap III)

E. Migration same as for C. Here all culminations are at same elevation. Spill points control differential entrapment.

Fig. 4 - Differential entrapment. Three stages (A, B, and C) in the migration and accumulation of oil and gas in interconnected traps. C, D, and E represent the same stage in migration but under different structural relationships. (Redrawn after Gussow, 1,2; 4 Fig. 2.)

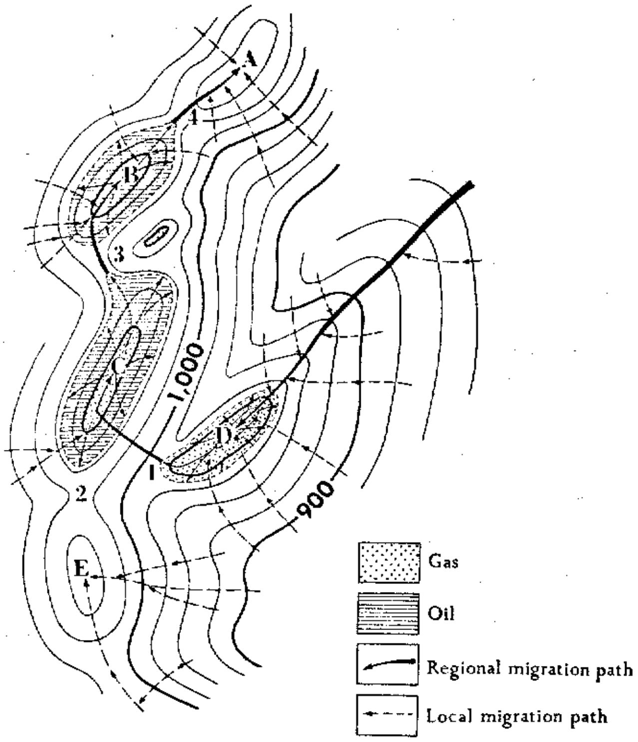


Fig. 5 - Subsurface structure map showing migration path of oil and gas entering an anticlinal trend along west margin of large supply basin. Contour interval, 25 ft. (Redrawn after Gussow,[4] Fig. 3.)

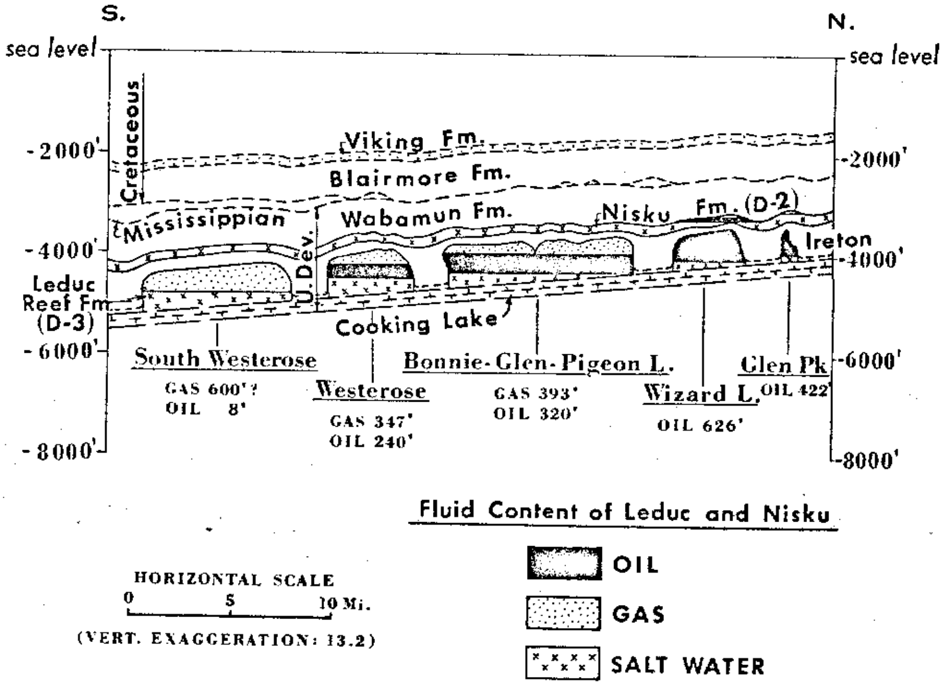


Fig. 6 - Oil and gas accumulations in leduc reefs on the Bonnie Glen - Wizard Lake Reef Trend, Alta., Canada, showing fluid content of leduc (D3) and nisku (D2) traps. Maximum pay sections are indicated for leduc reservoirs. (Redrawn after Gussow[4] Fig. 4.)

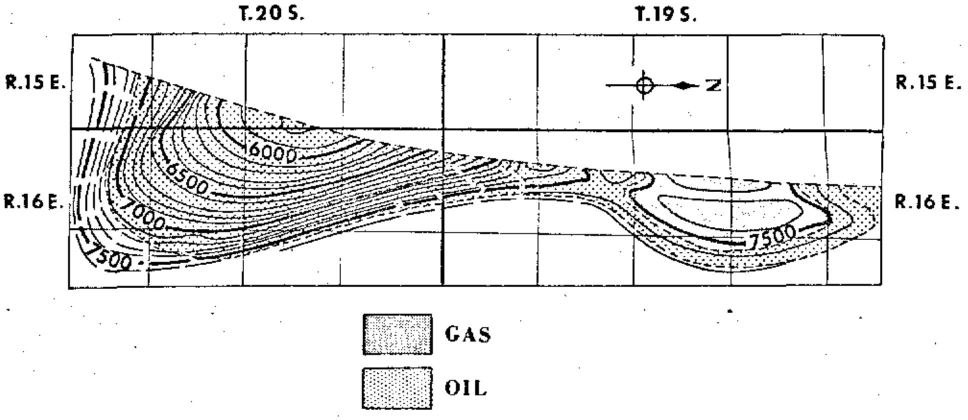


Fig. 7 - East Coalinga extension field, Fresno Co., Calif. (Redrawn after L. S. Chambers[4] Fig. 15.) Gas is trapped downdip in northern culmination; and no gas cap 1,000 ft. higher in southern culmination. Scale: sections are 1 mile sq.

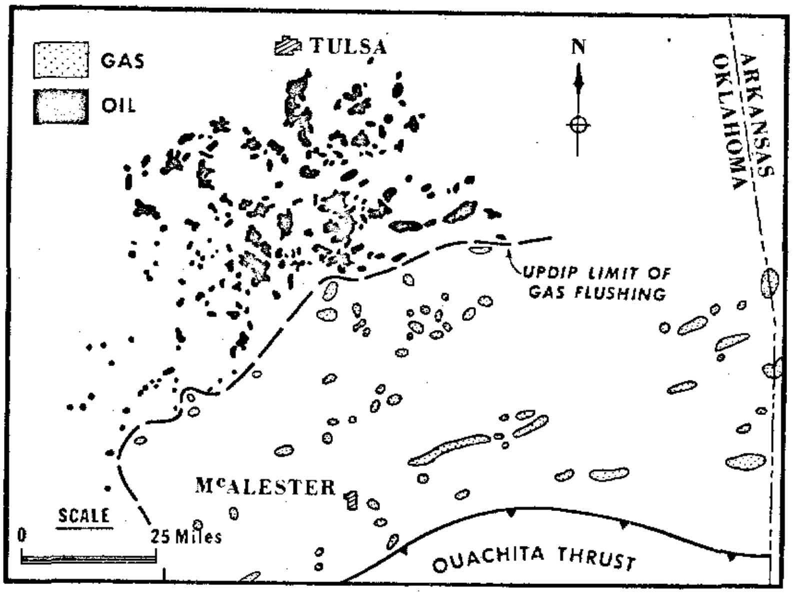


Fig. 8 - Gas flushing in the Atoka sands, Arkoma Basin, Okla. Gas only occurs downdip in the basin; oil occurs updip north of the updip limit of gas flushing. (Redrawn and updated, after Gussow[14] Fig. 4.)