RESERVOIR ROCKS AND STRATIGRAPHIC TRAPS IN NON-REEF CARBONATES

Abstract

Non-reef stratigraphic traps in carbonate rocks can seldom be detected geophysically, but certain common associations of facies can be used in searching for potential reservoir rocks.

Porosity in bedded limestones is of major importance in many petroleum reservoirs of the Middle East where much of their primary inter-grain pore-space remains uncemented. This condition appears to characterize undeformed areas of continuous miogeosynclinal carbonate sedimentation; an example is presented from the Lower Cretaceous Minagish Oolite of Southern Kuwait. In epicontinental regions where the sedimentary sequence is more frequently interrupted, and in folded areas, lime sediments tend to be tightly cemented by secondary calcite. In these conditions diagenetic-porosity is more important, dolomite being the chief carbonate reservoir rock. Numerous examples occur among the oil and gas fields of North America.

Microdolomites, probably formed in coastal salt flats (sabkhas), are poorly permeable but often highly porous, their intercrystalline and vuggy porosity being related to the process of dolomitization. Where they are sufficiently fractured they can contribute to effective reservoir porosity; but their common interbedded association with anhydrite (also a sabkha product) create impermeable cap rocks. Macrodolomites are less frequently anhydritic, and their similar but coarser porosity creates excellent permeable reservoir rocks.

Chalks also have a dual role. Under favourable conditions production is possible from coarser varieties, particularly where jointed or fractured; however, porous crypto-crystalline chalks commonly act as cap rocks.

Stratigraphically trapped oil-fields in the Mississippian carbonates of Saskatchewan and North Dakota illustrate the principles discussed.

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Résumé

On compare les rôles différents de la dolomitisation et de la cimentation par la calcite des roches calcaires pour amener le développement d'une porosité effective de réservoir.

On expose les facteurs stratigraphiques qui semblent devoir contrôler ces processus et on les compare en se servant des exemples du Mississipien du Canada Occidental et du Mésozoïque du Golfe Arabique.

INTRODUCTION

Stratigraphic traps depend on the occurrence of spatially limited porosity and permeability. Among carbonate rocks the facies-bounded reservoirs associated with reefs are the best known: we are here concerned with the more common but less spectacular development of localized porosity within non-reef carbonate rocks, where pore-space is not related to the essential reef-framework and binding activity of marine organisms. Along with all undoubted reef rocks, we exclude the related carbonate sediments of the "reef complex". Nevertheless, many borderline cases exist. Some, such as the development of porosity along the margins of carbonate banks, have affinities with reefs; modern seismic methods are often able to map such belts of lateral velocity contrast. Others include instances where the notoriously vexing algae play a role that could be construed either as sediment binding or as a source of clastic carbonate sediment.

The fundamental approach in searching for stratigraphic traps in any region is a careful study of its stratigraphy. This applies to carbonate rocks just as much as to shales and sandstone. Gone are the days when a rock was diagnosed simply as limestone.

Basically, the modern interpretation of carbonate rocks follows that of terrigenous rocks: we look for signs of high and low energy environments. But with carbonates we can go farther because these sediments are more susceptible to changes in such factors as salinity and water-depth than are sands and shales.[1] The carbonates contain little material derived from outside the basin of deposition, and are composed predominantly of material extracted by various agents from the overlying sea-water. These agents vary according to conditions. Sometimes, as with the lime-muds, the end products are distressingly similar regardless of the extracting agent, be it bio-chemical or physico-chemical precipitation, or simply a result of mechanical abrasion. Yet even in this intractable group careful microscopic[2] and isotopic[3] studies have proved that further discrimination is possible. Trace-element content has also proved of use, and the recent demonstration of the significance of the strontium content of carbonates promises to aid in their better understanding.[4]

When particle size exceeds the silt grade, the chances of recognizing individual grains are greatly enhanced and a variety of different types of sediment can be distinguished, depending on the nature of the dominant components. This has been well reviewed as a basis of classification by Folk[5, 6] and Dunham.[7]

POROSITY IN CARBONATE ROCKS

The one factor that is usually missing from such discussions is porosity. To some extent this is because porosity and lithology are only partly dependent on each other; other factors play an important part, notably cementation and diagenesis, and in some cases fracturing. Nevertheless, there exist close links between the distribution of porosity and the different types of carbonate sediment; Thomas[8] illustrated this among Palaeozoic carbonate producing areas of Western Canada, stressing the importance of adequate textural studies of the mud fraction—the matrix—of the rocks, rather than the more obvious carbonate grains. It is with this matrix that we are primarily concerned; for this is where most of the porosity develops.

To a petroleum geologist, pore-space is the most vital property of a rock. It is the part of the reservoir that oil or gas can occupy, and its geometry, scale and distribution determine whether petroleum can enter it and be extracted from it.

From a genetic point of view, porosity in carbonate rocks can be classified as primary, secondary and fracture. Primary porosity refers to pore space in the original sediment, whereas the secondary pores are those that are formed during the subsequent diagenetic history of the rock. But diagenesis begins at a very early stage, particularly in carbonates. As an idealized objective, we can restrict secondary processes to those that take place during and after lithification. Yet even here it is frequently impossible to tell how far primary pore space has been secondarily altered.

From a descriptive standpoint, separation of porosities into vuggy, inter-grain, inter-crystal and fracture types is found to be a workable system when used in conjunction with other observable parameters such as crystal and grain size. The vuggy group can be further broken down when the cause of the discrete cavities—leaching, inter- and intra-skeletal pores, etc.—is determinable.

Primary porosity

Immense oil reserves are trapped in the primary pore space of limestones in the Middle East. The oolith-pellet grainstones of the Minagish Oolite of Kuwait (described later in this section) and the pellet-bioclastic grainstones of the Jurassic Arab Formation of Saudi Arabia[9] are good examples.

In contrast, such primary porosity plays a relatively minor role in the non-reef carbonate reservoirs of North America. There are important Mississippian occurrences in the Mission Canyon of the Williston Basin[10] and the Fredonia oolite of Illinois[11]; also in the Smackover, Abra and other Mesozoic limestones in the Southern United States and Mexico; but on this continent as a whole most sediments deposited as porous lime-sands

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Fig. 1.—A Macrodolomite with good leached vuggy and intercrystalline porosity (filled with speckled plastic) (×55). Elkton Member of Turner Valley Formation, Mississippian, in Jumping Pound gas field, Alberta.

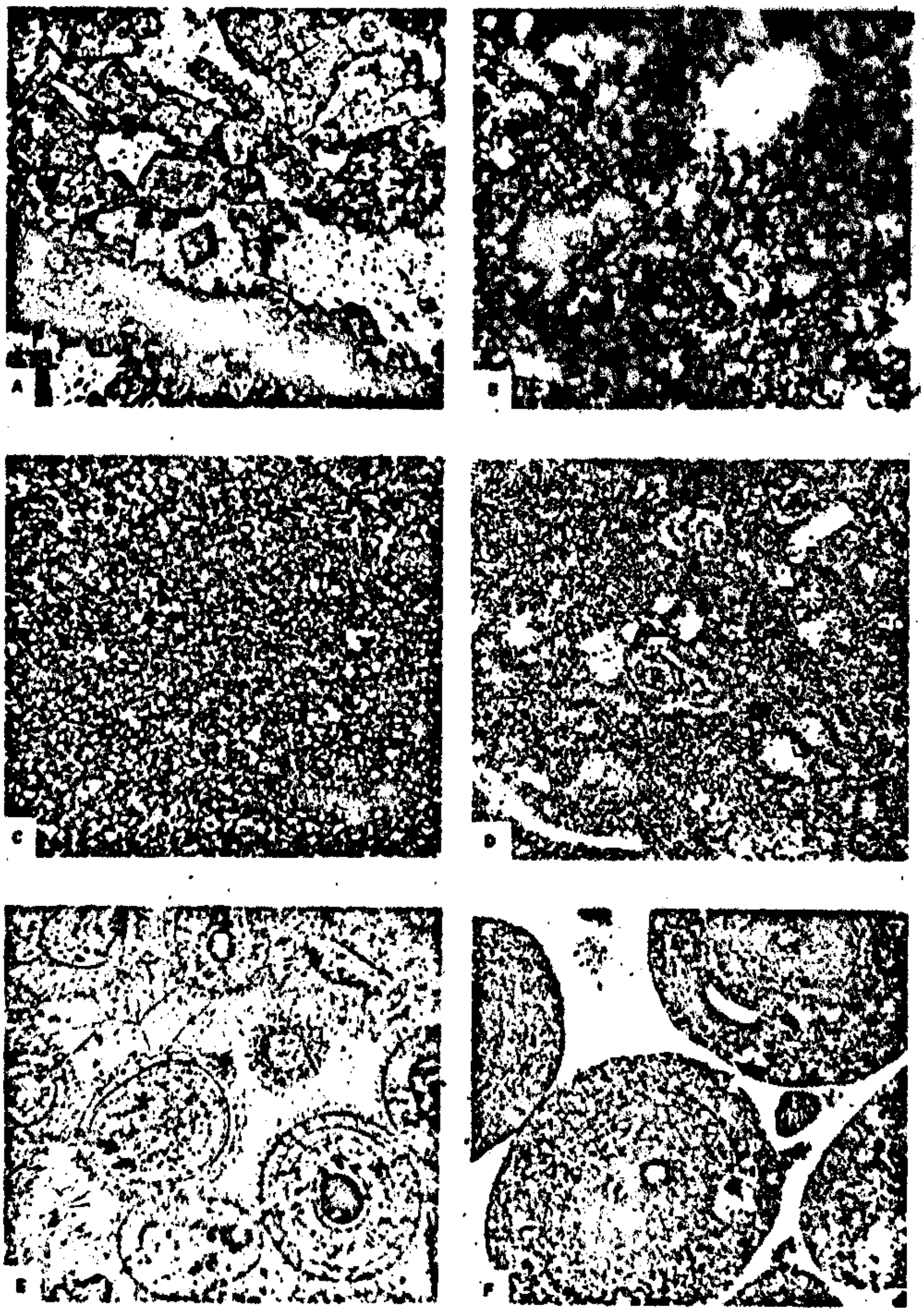
This is a particularly porous portion of a specimen of reservoir rock whose average porosity is 13%; the permeability is of the order of a Darcy. The stripe of turbid dolomite at bottom left is a skeletal relic[p] recognisable crinoid ossicles are common elsewhere. Jumping Pound 7–13–J, 9839 ft

B Microdolomite with leached vugs and remnants of fossil fragments (× 100). Porosity 20%, permeability 6md; Midale Beds., Mississippian, Saskatchewan. From the productive reservoir rock of the Steelman oil field; BA—Cdn Dev. Holmes 13-22-3-4 W2, 4658.6 ft. Photograph by British American Oil Co. Ltd

C Chalky limestone partly converted to microdolomite (× 100). Midale Beds, Mississippian, Saskatchewan.

The porosity is ineffective, and the permeability less than millidarcy. From a dry and abandoned well at the same stratigraphic level as the oil-bearing section of 1.B, 0·7 miles to the southwest. Imp. Frobisher 3–26–3–4 W2, 4651.2 ft. Photograph by British American Oil Co. Ltd

D Asmari Limestone (Oligocene-Miocene) from Kuh-e Asmari, Khuzestan, Iran (× 100). Lime-mudstone with "ghosts" of foraminifera. Although the matrix porosity and permeability are low, similar limestones in the nearby fields of Masjid-e Suleiman, Haft Kel and Naft Safid are highly productive as a result of their thick oil columns and extensive fracturing. BP field sample ANT 1704, 400 ft above base of Asmari section which is 1150 ft thick



E Ambléon Oolite (Bajocian) of Bas-Bugey, French Jura (× 55). The ooliths were surrounded by a fringe of radial calcite before the remaining pore space was filled with clear sparry calcite. From a peel loaned by Mr. D. J. Shearman

F Minagish Oolite (Lower Cretaceous) from Burgan Well 343, Kuwait (× 55). The primary inter-grain pore space is preserved with only a fine fringe of early radial calcite around individual ooliths. Porosity is in the order of 30%

have been tightly cemented by sparry calcite. Typical examples are the Devonian Palliser limestone of Alberta,[12] the crinoidal limestones of the Mississippian of the same area[13] and the common pellet limestones in the Cambro-Ordovician of the Appalachian belt. Only with the advent of fracturing can these rocks constitute commercial reservoirs for petroleum.

In addition to the factor of age—the older the sediment, the greater its exposure to cementation—two criteria appear to characterize the cemented limestones. Either, they have been subjected to appreciable burial and orogenic movement, the compression and compaction resulting in inter-particle solution and cementation; or, they belong to thin cratonic sequences laid down in areas of intermittent gentle epeirogenic warping. Such conditions existed around the margins of the Canadian Shield where the Devonian and Mississippian examples cited above were laid down. On the other hand, the Middle East examples were deposited in a miogeosynclinal environment; sedimentation was more-or-less continuous and the area suffered little compression. Similar conditions probably existed in Mesozoic times in Mexico and the Gulf Coast, and seem to have persisted to the present in the Bahamas.

Chalks

These rather puzzling rocks occupy a special place in petroleum geology; they can form either a reservoir or the cap rock to a reservoir, depending on geological circumstances. This arises from the special properties of chalk—high porosity (commonly close to 50%) and low permeability (characteristically less than 2 md). Though it is unlikely that they are all formed in the same way, it is commonly assumed that they accumulated as mud-sized particles of calcite. The omission of the aragonite-to-calcite change eliminated an important opportunity for cementation.

High entry pressures mean that chalks form effective reservoir rocks only under exceptional conditions. Coarser and more permeable varieties (7-15 microns; 20-40 md) are productive in the Arabian Gulf in the Nescomian Thamama Group of the Zakum Field and the Aptian Shu'aiba Formation of the Bu Hasa field, both in Abu Dhabi.

Some of the chalky carbonates associated with evaporatic conditions may have a different origin. Commonly they pass vertically or laterally into more permeable facies; many of the stratigraphic traps described later from the Williston Basin, Canada, are effectively sealed by such permeability barriers.

Limestone reservoirs of Iran

Although the nature of their porosity is complex, it is convenient to mention here some of the important limestone reservoir rocks of Iran. Beneath the perfect seal of the Fars salt-anhydrite cap rocks, the huge producing structures such as Agha Jari and Gachsaran have oil columns several thousand feet thick. The resulting buoyancy allows the oil to penetrate much finer pore space than is normally the case. Chalky porosity becomes filled with oil, and even such dense rocks as the famous Asmari limestone (Oligocene-Miocene) and the lime-mudstones and wackestones of the Bangestan limestones (Middle Cretaceous) become important oil reservoirs (Fig. 1.D). Yet the permeability of the matrix of the bulk of the Asmari is only a fraction of a millidarcy.[14] It is so tight that it would be impossible to extract the oil from these rocks by conventional method were it not for their very extensive network of joints and fractures.

The Minagish Oolite of Kuwait—an example of primary pore-space

The well developed primary porosity of the Oolite Member of the Minagish Formation (Lower Cretaceous) creates a very favourable non-reefal reservoir rock in the prolific oil fields of Minagish, Umm Gudair and Burgan in Southern Kuwait (Fig. 2). Its equivalent in Northern Kuwait is a deeper-water, dense, bioclastic wackestone-mudstone which is indistinguishable from the non-oolite or pellet intervals of the Minagish Formation above and below the productive horizon in the south.

The growth of the Minagish, Umm Gudair and Burgan structures started during the deposition of the Minagish Formation along a north-south trend, which persisted until after the Tertiary folding. Oolite accumulation kept pace with subsidence. The member is thickest along the crest of the structures, and its porosity and permeability decrease down flank. This has previously been attributed to increased cementation within the water zone, but detailed examination of samples indicates that the down-flank deterioration is caused by the higher proportion of interstitial matrix: these sediments accumulated in slightly deeper and quieter water and were less perfectly winnowed.

The Oolite Member can usually be subdivided into an upper unit of pellet grainstone and a lower unit of oolite grainstone (see Fig. 1.F). The pellets and ooliths are of the same order of size (about 0·4 mm). The concentric structure of the ooliths has been well preserved, suggesting that the aragonite-calcite conversion took place without any large scale solution and redeposition. In addition to small scale binding of pellets by encrusting algae, the only cementing agent is the thin fringe of acicular calcite on the margin of the pellets or ooliths. The porosity and permeability characteristics of these rocks are very similar to those of uncemented sandstones.

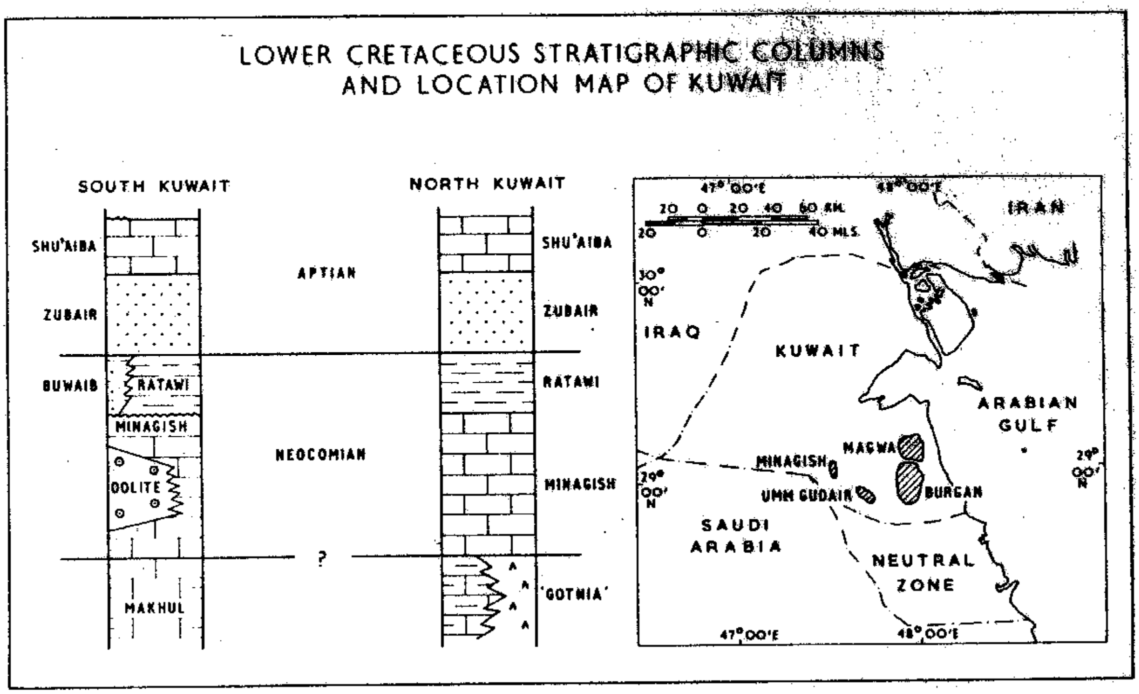


Fig. 2

Secondary porosity

We are here concerned with porosity that arises in a carbonate sediment as a result of diagenetic changes after burial. Some of the changes occur very soon after deposition; others follow much later. The distinction between early and late is as difficult to define as drawing a line between primary and secondary. The two principal diagenetic changes involved are the conversion of aragonite to calcite, and dolomitization.

Dolomitization

Microdolomite. Studies of recent carbonate sediments have demonstrated that they can be converted penecontemporaneously to dolomite. Conditions favouring the change involve intertidal and supratidal accumulations of carbonate sediments, usually aragonite mud, around the margins of protected lagoons in a hot dry climate. Evaporation from the supratidal surface concentrates the sea water contained in the pores of the sediment to a brine from which gypsum and possibly anhydrite precipitate. The brine thus becomes relatively enriched in magnesium (high Mg/Ca ratio) and is capable of dolomitizing the aragonitic sediment[15]). Extensive deposits of such dolomite are developing at the present time in the "sabkhas" (salt flats) along the Trucial Coast of the Arabian Gulf.[16] The dolomite is usually microcrystalline, porous but poorly permeable, and intimately interbedded with anhydrite. It is evident that equally extensive similar deposits have formed in the geologic record in many parts of the world by the same process.

The progressive textural and chemical changes that accompany this dolomitization conform to Murray's concept of "local source" diagenesis,[17] meaning that the extra carbonate ions necessary for the reaction are supplied by solution of the calcium carbonate itself. The process can be summarized as:

$$2CaCO_3 + Mg^{2+} + SO_4^{-} + 2H_2O \rightarrow CaMg(CO_3)_2 + CaSO_4.2H_2O.$$

In the early stages aragonite is replaced by microcrystalline dolomite, and the rate of the reaction is controlled by the rate at which the tiny isolated rhombs can form. It is only when the more reactive aragonite is nearing exhaustion that the calcite becomes significantly involved. At this stage the dolomite rhombs are likely to impinge on each other. Up to this point the sediment has remained plastic; further growth produces a loosely coherent sediment.

The literature has laid much stress on the creation of porosity by the theoretical 13% shrinkage in converting calcite to dolomite. In the present case the change would be far less, because it is chiefly the more dense aragonite that is being replaced. The main increase is not in porosity but in permeability, for as the dolomitization seeks out the more reactive carbonate muds it leads to a coarsening of texture.

Depending on the relative abundance and crystal size of the aragonite and calcite compared with that of the dolomite, a condition may be reached at which the reaction rate is limited by the rate of supply of carbonate ions. Dolomite nucleation ceases but the myriads of rhombs already formed continue to grow, and in the absence of an adequate external source, the necessary carbonate ions can only be provided by solution of the scattered remnants of calcium carbonate. This final leaching produces the familiar vuggy porosity associated with dolomites. The significance and inter-dependence of this sequence of changes has been described and illustrated by Murray[17] and Deffeyes, Lucia and Weyl.[18] It is repeated and elaborated here because it is fundamentally important to the interpretation of porosity in dolomites. Many authors have shown that the initial phases of dolomitization do little or nothing to improve the porosity and permeability of a carbonate sediment; it is only when the process is nearing completion that the dolomite becomes more permeable.[19, 20, 21, 9]

Peneprimary or penecontemporaneous or syngeretic microdolomites—all these mean the same—can thus show leached vuggy porosity[15]; and the creation of this porosity is part of the dolomitization process rather than being due to a subsequent independent leaching phase as was formerly believed.[13]

Macrodolomite. Secondary dolomites will be expected to involve a similar sequence of mineralogical and textural changes. Deffeyes and his colleagues[18] have demonstrated how this could occur in the subsurface. They have established that dense brines are forming today in and around a saline lake on the supratidal flats of Bonaire in the Dutch West Indies. The situation is analogous to that of the sabkhas of the Arabian coast, but the nature of the semi-permanent lake in which gypsum is precipitating indicates that the brine is refluxing out of the lake-bottom. It is a magnesia-rich brine, believed to be capable of dolomitizing limestones through which it passes.

Microdolomite is forming at the supratidal surface. Plio-Pleistocene macrodolomites that outcrop further north on the Island are interpreted as having been formed in the subsurface by heavy brines sinking down from higher salt flats now eroded away. Averaging about 75 microns in crystal size, they are in every way representative of the type of dolomite which we are accustomed to interpret as secondary or late diagenetic. They are sucrosic and vuggy in keeping with being formed by "local source" dolomitization, the refluxing brines being poor in carbonates.[18,4]

Only where there is some external source of both Mg and CO_3^2 ions (Murray's[17] "distant source") would we expect dolomitization to fill existing pore space by further crystal growth. Such dolomites as the Leduc of Alberta, in which although the permeability is high (because of the coarse crystallinity) the porosity is commonly low (4 to 8%), may be examples of this. Indeed many parts of the Leduc consist of a tightly interlocking mosaic of subhedral crystals, and such non-porous macrodolomite is commonly encountered elsewhere. Dolomites can form excellent reservoir rocks: but not all dolomites are porous.

Interbedded microdolomite and anhydrite is a common occurrence. On the other hand, macrodolomite is seldom found in this association. If it is formed by a reflux mechanism as suggested, it seems that the sinking magnesian brines had been stripped of their sulphate ions. Recent geochemical studies of the Trucial Coast sabkhas support this.[4, 22]

Deffeyes and his colleagues do not claim that all secondary dolomites are formed by a reflux mechanism. Nevertheless, it is believed that their elegant synthesis and model satisfactorily explains very many of the dolomites in the geologic column. Pointing to the present equatorial distribution of Pacific atolls with evaporitic lagoons, Schlanger[23] has made a good case for a reflux origin for their Tertiary dolomites. This includes those of the famous Funafuti cores, which figure so prominently in early discussions of dolomitization[24] reflux origin and was invoked by Newell and his colleagues[25] to explain the dolomitization of the Goat Seep and Capitan reefs of the Guadalupe Mountains in New Mexico. They point to the evaporitic dolomites of the lagoons and salt flats to the west from which highly magnesian brines sank down and dolomitized the reefs in escaping through them eastward to the deep Delaware Basin. A similar conclusion was reached by Adams and Rhodes[26] in discussing equivalent Permian rocks in the subsurface further east on the other side of the Basin. In both areas the dolomite shows extensive leaching of skeletal fragments that resisted conversion, producing vuggy and intercrystalline porosity and high permeability.

Numerous examples of this sucrose type of lithology can be given. It is "quantitatively, the most important North American carbonate pore type in terms of oil and gas production",[17, p.66] producing prolifically in such diverse fields and formations as the Trenton, the Ellenburger and the Arbuckle limestones, the Niagaran-Cayugan of the Michigan Basin, the Andrews South Devonian field in West Texas, and the Cretaceous Tamabra of Poza Rica, Veracruz.

Elkton dolomites. As a further example that may have resulted from brine reflux, we mention the porous Elkton dolomites of the Turner Valley Formation, the main Mississippian producing horizon of Alberta (Fig. 3). Evaporitic dolomites occur above and below the Elk-

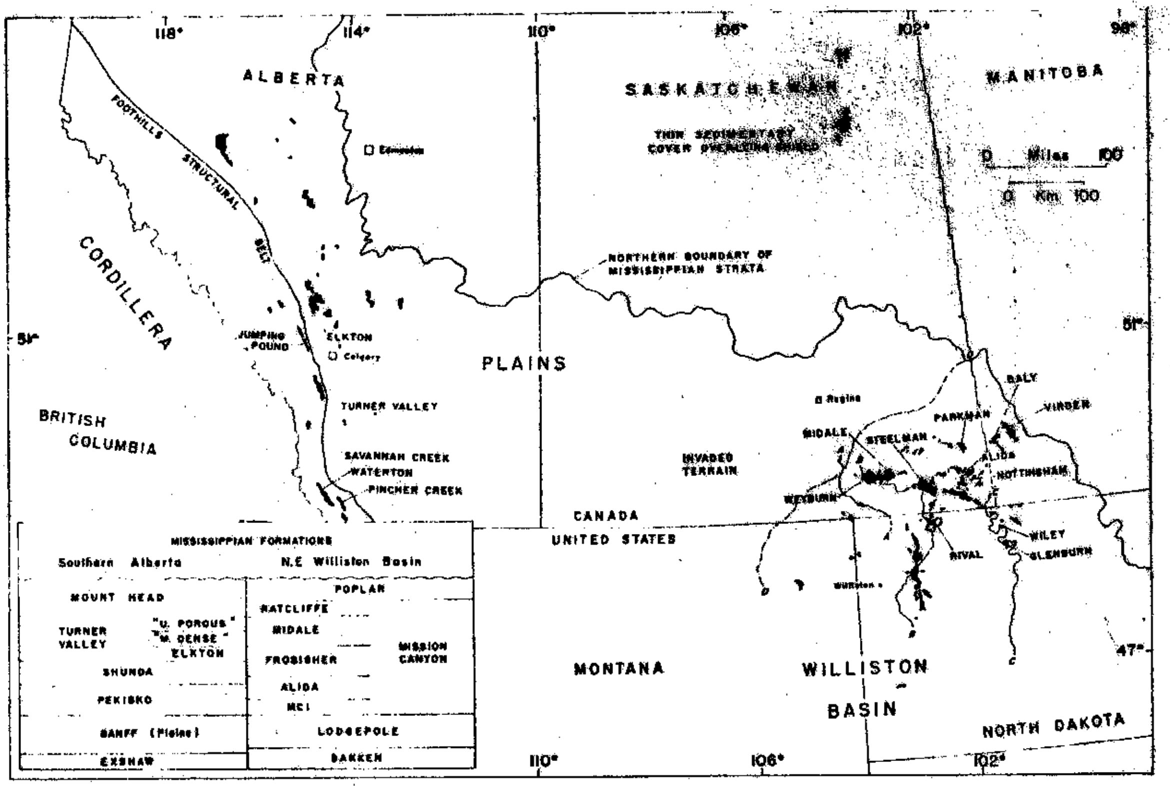


Fig. 3.—Principal Mississippian oil and gas fields producing from carbonate reservoirs in southern Alberta and the north-eastern part of the Williston Basin area; named fields are mentioned in the text. Most of the Mississippian formations shown in the table (inset) have more than one name in current use; formation thicknesses are not represented to scale.

Lines A, B, C, *in the Williston Basin area indicate the southwestern extent of fringing anhydrite sheets associated respectively with lower Ratcliffe, lower Midale and upper Alida sabka deposits. Line* D *represents the boundary between the oil-field province and the invaded terrain*

ton, and become more important as the whole sequence thins on to the Canadian Shelf to the north-east. Boundaries are probably diachronous. Compaction fluids from the underlying Shunda evaporites may have contributed to the process,[13] but it seems likely that the dolomitization was effected mainly by heavy magnesia-rich brines sinking down from sabkhas of the over-lying Middle Dense member or the Mount Head Formation.[27] Much of the evidence of these formerly extensive evaporites has been removed in the east by pre-Mesozoic erosion. All we have left in the Middle Dense are beds of cherty micro-dolomite, sometimes anhydrite, which lose their identity westwards within the thicker sequences of crinoidal limestones of the Foothills and Front Ranges of the Rockies.

Large gas reservoirs have been discovered in these variably dolomitized carbonates in the foothills at Pincher Creek, Savannah Creek and Waterton, where extensive fracturing enables some of the less permeable limestones and microdolomites to contribute to the effective porosity. But the best reservoir rocks, such as those of the Turner Valley and Jumping Pound fields and those in the Elkton district in the plains, are sucrose macrodolomites (Fig. 1.A). All the known foothills fields are structurally controlled. The oil fields in the plains are trapped in gently and uniformly dipping strata truncated by the post-Palaeozoic inconformity.

Calcitization

Under this heading we discuss the replacement of aragonite and high-magnesian calcite and the infilling of pore space by calcite. These common processes have a very important bearing on the porosity of limestones. We are not here concerned with the replacement of dolomite by calcite, which though interesting is far less important in the present context.

Aragonite—calcite changes and solution porosity. Both high-magnesian calcite and aragonite are metastable in normal shallow sea water, but tend to convert to normal calcite by solution and redeposition in the deep oceans or in a fresher water environment.[28] The process is governed by the same criteria of solubility and rates of reaction, nucleation and ionic movement as the conversion of calcium carbonate to dolomite discussed earlier, and leads to a similar end-phase in which the few remaining stout resistant aragonite (or high-magnesian calcite) particles are dissolved leaving a leached vuggy texture. Much of the vuggy porosity in limestones commonly ascribed to solution is of this nature. Solution occurs but it is only part of the story, for precipitation of calcite goes on at the same time, resulting in a redistribution of the porosity. Usually this leads to a coarsening of the texture and hence to an increase in permeability. The leached vuggy Pleistocene cay-rock of the Bahamas and Florida are good examples.[29]

Sometimes, solution alone is suspected, particularly at erosion surfaces flushed by fresh waters. An Iranian example has been studied by Wood from the Sarvak Limestone of Khuzestan where the micritic matrix of a bioclastic pelletoid wackestone has been leached out at the post-Turonian unconformity. The porosity extends some sixty feet below the unconformity, but it is significant that in the uppermost ten or fifteen feet it has been reduced by sparry calcite cementation.

Where aragonitic sediments escape early diagnetic conversion they may persist to a considerable depth. Ultimately they change to calcite by solution-cum-deposition on a sub-microscopic scale preserving details of sedimentary structure.[30] Though the change to the less dense paramorph must involve an expansion, there is little evidence that it leads to extensive infilling of porosity. As we have seen, pelletoid sands and oolites from the Arab D zone of Saudi Arabia and the Minagish Oolite of Kuwait are sometimes so lacking in cement as to be easily crumbled between the fingers. (Fig. 1.F).

Cementation and the generation of sparry calcite. The thin fringe of acicular calcite shown on the grains in Fig. 1.F is a fairly common feature. It may represent either a primary aragonite cement formed close to the intertidal zone, or it may have been precipitated from fresher pore waters involved in the recrystallization of aragonite to sparry calcite nearby: a patch of such calcite is visible within the same grain. These early diagenetic fringes can usually be differentiated from later, coarser, and more equant sparry calcite when the latter fills the remaining pore space (Fig. 1.E).

It is this later calcite that has destroyed the porosity in so many North American limestones. Its source is debatable. The early fringes are usually pure, but it is commonly observed that the sparry calcite carries appreciable ferrous iron.[31, 32] This may indicate an external source of calcium and carbonate ions, possibly carried by iron-bearing fresher meteoric waters during periods of uplift. On the other hand, it may be a purely internal change in the physico-chemistry of the pore water. Bathurst[33, 34] has argued that a great deal of calcium carbonate is released to form sparry calcite by solution of the aragonitic components of the carbonate sediment itself. He points to pressure welding of grains and to collapsed "micrite envelopes" outlining the relics of molluscan shells that have gone into solution. Similar features are not uncommon in some of the Mesozoic rudist grainstones and packstones of Mexico and the Middle East. Bathurst believes that a significant portion of the aragonitic sediment is destroyed without trace in this way.

However, the aragonite-calcite conversion, involving simultaneous solution and redeposition, would be expected to proceed in a piecemeal fashion similar to the sabkha dolomitization already discussed. Unless there is overall solution by acidic waters, cavities would only be formed when the last of the aragonite was being used up. The 8% expansion in converting to the less dense paramorph would readily account for the commonly observed fringes of early diagenetic calcite cement. At any stage in the process the sediment would be self-supporting, and collapse would only be likely under appreciable loading where pressure could induce solution at points of contact. It is hard to see how collapse could occur near the sediment surface; but at a depth of some tens of perhaps hundreds of feet—which, if fresh waters are involved, implies similar uplift above sea-level to allow their deep penetration—the process of solution and redeposition would be expected to involve a measure of redistribution, leading to compaction and cementation by sparry calcite.

STRATIGRAPHIC TRAPS IN MISSISSIPPIAN CARBONATES OF WILLISTON BASIN, CANADA—U.S.A.

Having discussed the two main factors governing the occurrence of effective-porosity in the non-reef carbonates, we turn to the role of porosity in stratigraphic traps among these rocks, selecting the Mississippian of the northeastern Williston Basin as an example of a North American producing area that exhibits particularly well how sedimentary, diagenetic, structural and fluid conditions have combined in several ways to create leak-proof traps for oil.[35, 36, 37, 38, 39]

Carbonate rocks 1500 ft thick form most of the lower half of the Mississippian deposits in the basin, a roughly circular sedimentary arena about 400 miles in diameter. For the Mississippian carbonates (unlike other parts of the Palaeozoic) the centre of maximum accumulation was near the present-day structural centre. This condition played a major role in primary trap generation because the Mississippian sedimentary strike-lines often run parallel to present-day regional strike. Furthermore, from the basin-centre outwards a pre-Mesozoic unconformity cuts into the Palaeozoic column, bringing first Triassic red-beds and then younger deposits into contact with the wide tract of bevelled Mississippian carbonates, thus forming a secondary suite of unconformity traps.

The carbonate column breaks into three nearly equal 500-ft divisions, of which the middle division (Mission Canyon—Fig. 3) is of chief interest in our present context. It consists of marine limestone, partly dolomitized and rhythmically interbedded with microdolomite and beds of anhydrite. The evaporitic rocks (locally including halite) fringe the basin margin and pass inward through lateral facies changes into algal-pellet limestones and shelly crinoidal limestones; in their lithologies, associations and fringing position the sediments of the evaporite rhythms have all the attributes of sabkha-environment deposits. Three main rock types are found among them: (*1*) pelletoid and bio-calcarenites with lime-mud matrix, characteristic of the lower part of a rhythmic unit and increasingly dolomitic toward the top; (*2*) microdolomite with fossil fragments; and (*3*) anhydrite, as pockets or stringers in "earthy" microdolomite, grading into massive anhydrite with dolomite veins.

Due to general regression of the marine environment, each successive evaporite layer encroached farther toward the basin centre, thus forming in the sedimentary column at the side of the basin a set of overlapping or louvred repetitions of porous dolomitized limestone and impermeable evaporite layers. From the standpoint of later fluid movement the impermeable layers (either anhydrite or cryptograined carbonates) formed a set of baffle-plates angled into the pre-Mesozoic unconformity (itself sealed by the Triassic red-bed cover), trapping any buoyant fluid moving up-dip toward the edge of the basin.

Traps and pool boundaries

Three distinct types of stratigraphic trap are found in the Mississippian carbonate formations, as follows:

(*1*) in sabkha carbonates overlain by anhydrite;
(*2*) in down-dip pellet-limestone shoals at sabkha margins; and
(*3*) at sealed terminations of unconformity-bevelled aquifers.

They are shown diagrammatically in Fig. 4a, b, c. We shall consider the distinctive characters of each in turn.

(1) Oil-filled traps exist in dolomitized areas of fossil sabkhas in the evaporite rhythms of the basin margin, where up-dip escape of hydrocarbons was blocked by lateral permeability deterioration in the carbonate. The main reservoir rock is micro- to very finely crystalline dolomite (porosity 20-35%, permeability 5-50 md), or fragmental and pelletoid limestone with a variably dolomitized matrix (10-20%, 0·5-10 md; Fig. 1.B). The reservoir passes up-dip with decreasing dolomitization into comparatively impermeable crypto-crystalline chalky limestone (15-25%, 0·3-3 md; Fig. 1.C) or fragmental limestone with lime-mud matrix. These less dolomitic rocks may represent a lagoonal indentation in the coast line or they may be the result of arrested early-diagnetic alteration in the sabkha itself. Lateral boundaries to the reservoirs are of the same kind, accentuated by structural position, and barren areas between fields are also characterized by sediments having a high lime-mud content. Whether all the dolomitization in these reservoirs can be classed as early diagenetic is arguable, but their dependence on dolomitization processes to reach an effective porosity-permeability condition seems certain.

Major petroleum accumulations trapped in this way occur for example in the Weyburn, Midale and Steelman fields along the "Midale" trend in Saskatchewan (Fig. 3). As a measure of their size, the original oil in place in these three fields is estimated to be respectively 1121, 482 and 627 million barrels. All were initially produced by solution-gas drive.

(2) The anhydrites and associated microdolomites of the basin-margin evaporite rhythms pass down-dip into banks of algal-pellet limestones which have porosities in the 5% to 17% range and permeabilities ranging from 5 md to 50 md. They are thought to represent shoals at the seaward edges of sabkhas, and are not dolomitized, though porosity has been modified by calcite and anhydrite cementation. Reservoirs of this kind augment the sabkha reservoirs of the Weyburn and Steelman fields referred to above, and form smaller independent fields at several stratigraphic levels in North Dakota, for instance at Rival, Wiley and Glenburn. The oil in these reservoirs is produced by edge-water drive, and the barrier to up-dip leakage is provided by the impermeable anhydritic sabkha deposits occupying the same stratigraphic levels.

(3) A third group of stratigraphic traps occurs in the basin where the pre-Triassic unconformity surface cuts across porous and permeable beds in the carbonates. In some instances the reservoirs are dolomitized sabkha

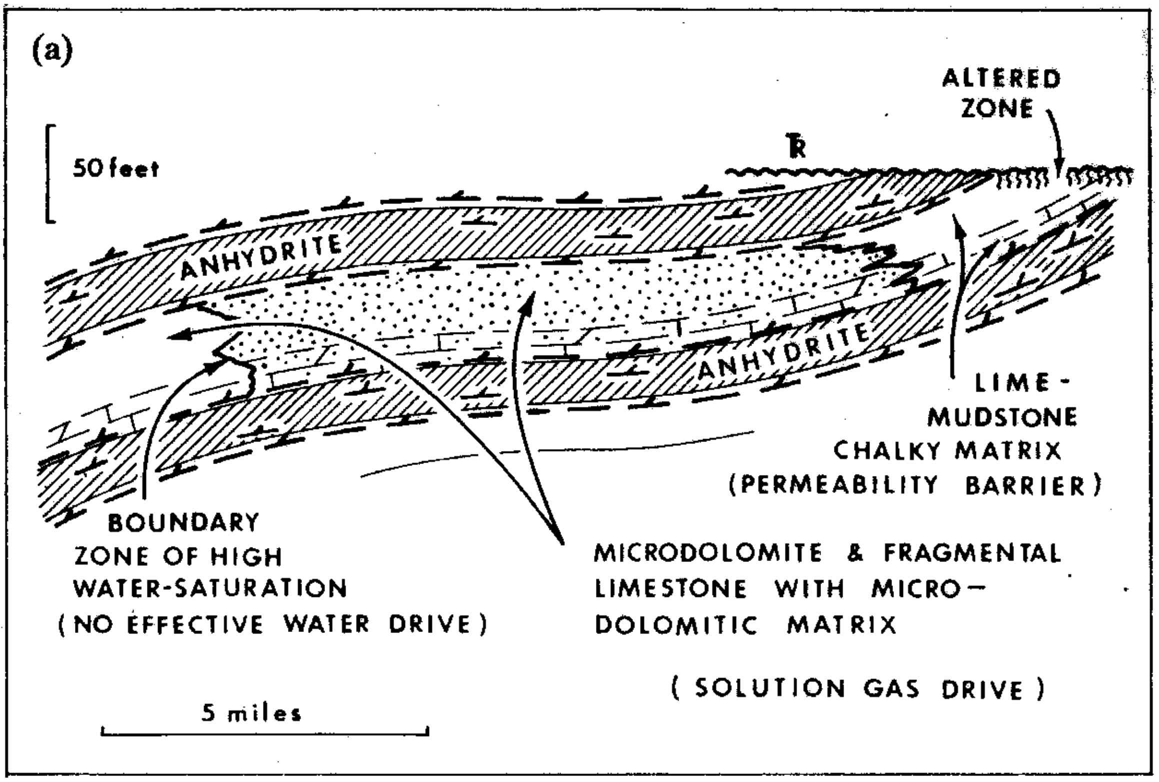


Fig. 4.—Diagrams illustrating the three principal kinds of stratigraphic trap in the Mississippian strata of Saskatchewan and North Dakota. Effective oil-bearing reservoirs are shown stippled.

a *Trap in dolomitized carbonates associated with fossil sabkha deposits.*

b *Trap in off-sabkha pellet-limestone shoal.*

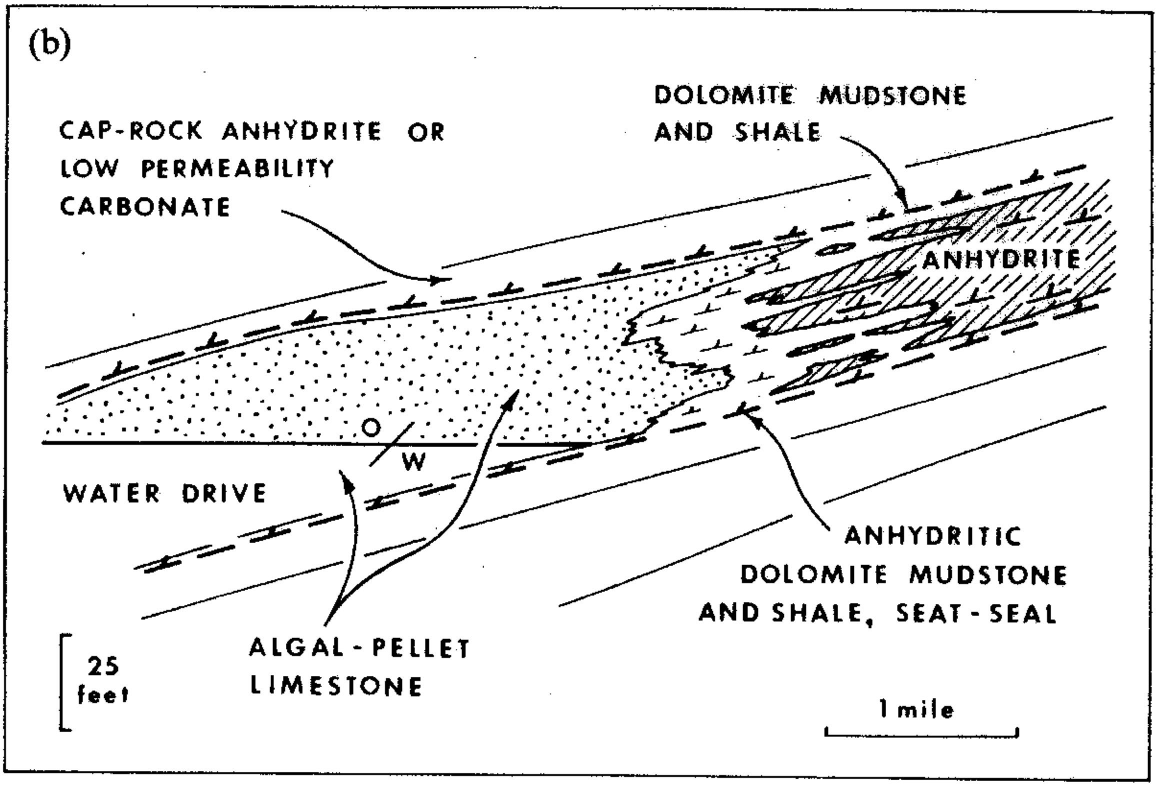
c *Trap in unconformity-sealed reservoir.*

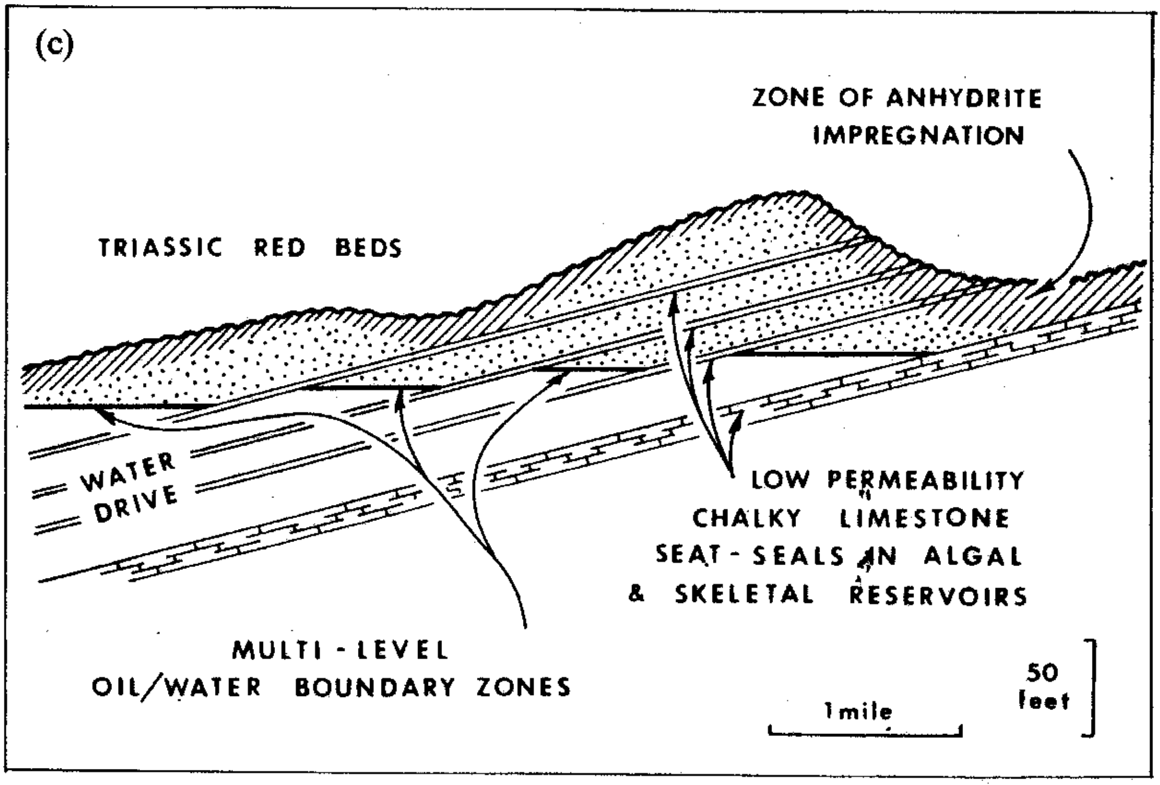
Either of the two anhydrite deposits shown in (a) *when traced down dip is found to break up into anhydrite stringers and pockets closely associated with microdolomite, which in turn passes into algal-pellet limestone. This is illustrated in* (b). *The complete facies change spreads over little more than a mile*

deposits, as for instance in the eastern "Midale" trend; in others they are shelly, crinoidal, algal-pellet or oolitic limestones comparatively unaffected by early dolomitization. Thin bands of anhydrite form excellent caprocks and seat-seals to most of the truncated sabkha units; chalky cryptograined limestones with high entry-pressures (permeability $<0{\cdot}1$ md) effectively seal the less evaporitic reservoir rocks in a similar way (Fig. 4c). The barrier obstructing up-dip escape of fluids from the truncated face of a reservoir bed in such a trap is stratigraphically part of the reservoir material itself, dolomitized, and impregnated and cemented by anhydrite to depths up to 50 ft below the Triassic unconformity. In general, the "stratigraphic" component of the trap, which chiefly determines the seat-seal, and hence the up-dip extent of a field, is reinforced by topographic or structural relief on the unconformity. Fields characteristic of this kind of trap have active water-drives, and are exemplified by Alida, Nottingham and Parkman in Saskatchewan (with 107, 254 and 148 million barrels of oil in place); and by Daly and Virden in Manitoba.

Trap failure

The term "stratigraphic accumulation" covers the fields described in this account. But only the rock, not the fluid, in a reservoir is strictly "stratigraphic" for what fluid a reservoir now holds is a question relating more to its subsequent structural history. In the sector of the Williston Basin that we have been considering the formations are comparatively undisturbed and formation-water salinities are high (20 M–200 M ppm Cl^-). Outside the known oil-field province, though "stratigraphic" potential exists, the strata have undergone extensive dislodgement due to solution-subsidence of


(b)
DOLOMITE MUDSTONE AND SHALE
CAP-ROCK ANHYDRITE OR LOW PERMEABILITY CARBONATE
ANHYDRITE
O
W
WATER DRIVE
ANHYDRITIC DOLOMITE MUDSTONE AND SHALE, SEAT-SEAL
ALGAL-PELLET LIMESTONE
25 feet
1 mile


(c)
ZONE OF ANHYDRITE IMPREGNATION
TRIASSIC RED BEDS
WATER DRIVE
LOW PERMEABILITY CHALKY LIMESTONE SEAT-SEALS IN ALGAL & SKELETAL RESERVOIRS
MULTI-LEVEL OIL/WATER BOUNDARY ZONES
50 feet
1 mile

deep-lying salt beds. Successful invasion of reservoirs by meteoric water occurred, and its extent determined the present-day boundary of the oil-bearing part of the stratigraphic trap terrain.

POROSITY IN MIDDLE EAST AND NORTH AMERICAN CARBONATES COMPARED

North American examples have been discussed to demonstrate the importance of dolomitization in creating effective porosity in carbonate rocks. In the Middle East, such reservoirs play a relatively minor part. Isolated examples occur in the Middle Arab D zone of the Ghawar field in Saudi Arabia,[9] and sucrose dolomite forms the main Arab/Darb reservoir rock of the Umm Shaif field, Abu Dhabi.[40, 41] It is likely that some of the production from the Asmari reservoirs in Iran comes from dolomites. But, both here and elsewhere in the Middle East, it is overshadowed by the much greater production from limestones, particularly from extensive developments of calcarenites with primary porosity that has not been filled by later cementation.

How are we to explain this difference in behaviour of carbonate reservoir rocks in different parts of the world? Is it purely a matter of geologic age, depth of burial and tectonic history; or is there also, as we believe, a tendency for carbonate sands deposited discontinuously in epicontinental regions to undergo greater cementation than similar sediments in thicker uninterrupted carbonate sequences?

Clearly such broad generalizations have many exceptions: witness the poorly cemented Jurassic oolites and pelletoid limestones of Southern England. Others have already been mentioned. Nevertheless there is sufficient evidence indicating a difference in diagenetic history to demand an explanation.

The vast majority of carbonate sediments are formed and accumulate in shallow marine water. To a large extent they are part of a self-regulating mechanism. They are not dependent on currents to transport them to the basin of deposition, but are extracted by various agencies from the sea water itself. If the sea bottom subsides they form and accumulate to compensate; and if there is a still-stand permanent accumulation temporarily ceases. Local exposure above the intertidal level can bring the sediment within reach of fresher ground waters, changing the stability fields of its carbonate minerals. Aragonite and high magnesian calcite are converted to normal calcite. But it seems that only where fresh water penetrates to considerable depths can overall compaction and cementation by calcite occur.

In the absence of large eustatic sea-level changes, such as those which led to the widespread cementation of Pleistocene limestones, extensive cementation by sparry calcite should therefore be more common in epi-continental areas of repeated uplift and downwarp than in miogeosynclinal belts of continuous subsidence.

CONCLUSION

This paper has evolved from a request by Mr Falcon, Chairman of this session, for a discussion on how to find stratigraphic traps in non-reefal carbonate rocks. This is a very broad and difficult topic. We have concentrated on certain aspects of the problem, notably what types of carbonate are commonly sufficiently porous and permeable to be potential reservoir rocks, and how does this porosity arise. We have not covered all types of effective porosity; for such, we refer the reader to Murray's more comprehensive discussion.[17] Our concern has been with what we regard as the most widespread and important types: primary porosity, and secondary porosity through dolomitization. The rarer solution of interstitial lime-mud has also been mentioned. To these must be added a third major group, the fractured reservoirs, in which matrix porosity that would otherwise be ineffective because of lack of permeability, is enabled to produce via a network of ramifying hairline cracks and joints.

The limitation of primary porosity by secondary cementation is too complex and varied a topic to be fully covered in these few pages. We have presented certain generalizations involving the redistribution of material within bodies of carbonate sediment. However, these and other cements may be introduced in solution on a large scale, and there is a close parallel between the stratigraphic factors that localize their deposition and those that create traps for hydrocarbons. Some potential stratigraphic traps are obliterated by such cementation; others are fortified by the extra sealing provided. Still other examples are known where a later cement encloses a reservoir already filled.

We do not claim to have answered the question of where to drill to find stratigraphic traps. Every case is different; each area requires the unravelling of its stratigraphic history in minutest detail. The most we can do here is to offer such generalizations as arise out of the commonly observed spatial relationships of porous and non-porous carbonates. To make a stratigraphic trap, rocks with effective porosity must be sealed by impermeable strata. Examples have been presented from the Mississippian of the northeastern part of the Williston Basin; these demonstrate but a few of many possible configurations that can form a trap, but they illustrate some of the important likely sedimentary relationships, particularly the lateral passage of porous carbonate into impervious anhydritic microdolomites.

In other circumstances, notably where they are sufficiently fractured and not anhydritic, these microdolomites can form reservoirs in their own right. Further, we have traced a connection between these evaporitic dolomites and porous permeable secondary dolomites. Spatial relationships here are probably too unpredictable to be used as a direct exploratory tool, but the association is sufficiently clear for the occurrence of one type of dolomite to suggest the proximity of the other.

The above refers in the main to carbonate reservoir rocks formed in epicontinental seas, most of the examples having been taken from the North American Continent. In more strongly basinal carbonate areas such as the Arabian/Persian Gulf and other parts of the Tethyan geosyncline, much primary porosity remains and major reservoirs occur in uncemented lime-sands. In such conditions stratigraphic traps are likely to exist where such clean sands pass laterally into more muddy carbonates, as on the flanks of pelletoid and oolite shoals.

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REFERENCES

1. HAM, W. E., and PRAY, L. C., Amer. Ass. Petrol. Geol., 1962, Mem. 1, 2-19.
2. MATTHEWS, R. K., J. Sedimentary Petrology, 1966, 36 (2), 428-454.
3. LOWENSTAM, H. A., J. Sedimentary Petrology, 1955, 25 (4), 270-272.
4. KINSMAN, D. J. J., Ph.D. thesis London University, 1964.
5. FOLK, R. L., Bull. Amer. Ass. Petrol. Geol., 1959, 43 (1), 1-38.
6. FOLK, R. L., Amer. Ass. Petrol. Geol., 1962, Mem 1, 62-84.
7. DUNHAM, R. C., Amer. Ass. Petrol. Geol., 1962, Mem. 1, 108-121.
8. THOMAS, G. E., Amer. Ass. Petrol. Geol., 1962, Mem. 1, 193-223.
9. POWERS, R. W., Amer. Ass. Petrol. Geol., 1962, Mem. 1, 122-192.
10. THOMAS, G. E., and GLAISTER, R. P., Bull. Amer. Ass. Petrol. Geol., 1960, 44 (5), 569-588.
11. GRAF, D. L., and LAMAR, J. E., Bull. Amer. Ass. Petrol. Geol., 1950, 34 (12), 2318-2336.
12. BEALES, F. W., Bull. Amer. Ass. Petrol. Geol., 1956, 40 (5), 848-870.
13. ILLING, L. V., Proc. Fifth World Petrol. Cong., 1959, Sect. 1, 23-52.
14. GIBSON, H. S., J. Inst. Petrol., 1948, 34 (294), 374-398.
15. ILLING, L. V., WELLS, A. J., and TAYLOR, J. C. M., Soc. Econ. Pal. and Min., 1965, spec. pub. 13, 89-111.
16. CURTIS, R., EVANS, G., KINSMAN, D. J. J., and SHEARMAN, D. J., Nature, 1963, 197 (4868), 697-680.
17. MURRAY, R. C., J. Sedimentary Petrology, 1960, 30 (1), 59-84.
18. DEFFEYES, K. S., LUCIA, F. J., and WEYL, P. K., Soc. Econ. Pal. and Min., 1965, spec. pub. 13, 71-88.
19. LANDES, K. K., Bull. Amer. Ass. Petrol. Geol., 1946, 30, 305-318.
20. BARNETCHE, A., and ILLING, L. V., The Tamabra Limestone of the Piza Rica Oilfield, Mexico, XX Congreso Geológico Internacional, 1956.
21. WEYL, P. K., J. Sedimentary Petrology, 1960, 30 (1), 85-90.
22. BUTLER, G. P., M.Sc. thesis London University, 1965.
23. SCHLANGER, S. O., Sci. Rep. Tohoku Univ., 2nd Ser. (Geol.), 37 (1), 15-29.
24. CULLIS, C. G., Atoll of Funafuti, Royal Soc., 1904, Coral Reef. Comm. Rept., 392-420.
25. NEWELL, N. D. *et al.*, The Permian Reef Complex of the Guadalupe Mountains Region, Texas and New Mexico. San Francisco, Freeman & Co., 1953.
26. ADAMS, J. E., and RHODES, M. L., Bull. Amer. Ass. Petrol. Geol., 1960, 44, 1912-1920.
27. MACQUEEN, R. W., Edmonton Geol. Soc., 1966, 8th Ann. Field Trip Guidebook, 39-59.
28. FRIEDMAN, G. M., Bull. Geol. Soc. Amer., 1965, 76, 1191-1196.
29. FRIEDMAN, G. M., J. Sedimentary Petrology, 1964, 34 (4), 777-813.
30. BANNER, F. T., and WOOD, G. V., Geol. Jour., 1964, 4 (1), 21-34.
31. EVAMY, B. D., and SHEARMAN, D. J., Sedimentology, 1965, 5, 211-233.
32. DICKSON, J. A. D., J. Sedimentary Petrology, 1966, 36 (2), 491-505.
33. BATHURST, R. G. C., *in* Approaches to Paleoecology, edited by Imbrie and Newell, 357-376, John Wiley, 1964.
34. BATHURST, R. G. C., Geol. Jour., 1966, 5 (1), 15-32.
35. FULLER, J. G. C. M., Saskatchewan Dept. Mineral Resources, 1956, Rept. 19, 72 pp.
36. FULLER, J. G. C. M., *in* Williston Basin Symposium, 1956, Bismarck, N. Dak., 29-35.
37. EDIE, R. W., Bull. Amer. Ass. Petrol. Geol., 1958, 42 (1), 94-126.
38. Steelman Main Midale Beds Unit, Operators Committee Report to the Oil and Gas Conservation Board, Saskatchewan, 1960.
39. McCABE, H. R., Manitoba Mines Branch, 1963, Publication 60-5, 50 pp.
40. ELDER, S., J. Inst. Petrol., 1963, 49 (478), 308-315.
41. BANNER, F. T., and WOOD, G. V., Bull. Amer. Ass Petrol. Geol., 1964, 48 (2), 191-206.

7th World Petrol. Congress
Mexico, April 1967