GEOLOGICAL SURVEY CIRCULAR 767

Current Oil and Gas Production from North American Upper Cretaceous Chalks

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By Peter A. Scholle

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ABSTRACT

Production of oil and natural gas from North American chalks has increased significantly during the past five years, spurred by the prolific production from North Sea chalks, as well as by higher prices and improved production technology. Chalk reservoirs have been discovered in the Gulf Coast in the Austin Group, Saratoga and Annona Chalks, Ozan Formation, Selma Group, Monroe gas rock (an informal unit of Navarro age), and other Upper Cretaceous units. In the Western Interior, production has been obtained from the Cretaceous Niobrara and Greenhorn Formations. Significant, though subcommercial, discoveries of natural gas and gas condensate also have been made in the Upper Cretaceous Wyandot Formation on the Scotian Shelf of eastern Canada.

All North American chalk units share a similar depositional and diagenetic history. The chalks consist primarily of whole and fragmented coccoliths with subordinate planktonic and benthonic Foraminifera, inoceramid prisms, oysters, and other skeletal grains. Most have between 10 and 35 percent HCl-insoluble residue, predominantly clay. Deposition was principally below wave base in tens to hundreds of meters of water.

The diagenetic history of a chalk is critical in determining its reservoir potential. All chalk has a stable composition (low-Mg calcite) and very high primary porosity. With subsequent burial, mechanical and chemical (solution-transfer) compaction can reduce or completely eliminate pore space. The degree of loss of primary porosity in chalk sections is normally a direct function of the maximum depth to which it has been buried. Pore-water chemistry, pore-fluid pressures, and tectonic stresses also influence rates of cementation.

Oil or gas reservoirs of North American chalk fall into three main groups:

1. Areas with thin overburden and significant primary porosity retention (for example, Niobrara Formation of Kansas and eastern Colorado).
2. Areas with thicker overburden but considerable fracturing. Here primary porosity has been largely lost but secondary (fracture) porosity provides some storage capacity and greatly improves permeability (for example, Austin Group of the Pearsall field, Texas).
3. Areas with thick overburden in which marine pore fluids have been retained, or where hydrocarbons (including biogenically generated methane) were introduced early in the diagenetic history. In these settings, primary porosity is reduced to a lesser degree than in group two, and adequate reservoir properties can be maintained to depths approaching 2,000 m (6,600 ft) (for example, Scotian Shelf of Canada).

Continued small-scale oil and gas discoveries can be expected from these types of reservoirs in North America. The prolific production of oil and gas from North Sea chalk reservoirs will not be matched in North America unless deeply buried, overpressured chalks can be located. It is the early formation of overpressures and (or) early oil input into North Sea chalks that have preserved porosities as high as 40 percent at 3,000- to 3,500-m (9,800- to 11,500-ft) depths and provided the outstanding reservoir capacity of those chalks.

INTRODUCTION

Oil and gas have been produced from chalk reservoirs for at least four decades. The past 5 years, however, have seen a remarkable upsurge in exploration for, and discovery of, hydrocarbons in chalk. Study of North Sea fields such as Ekofisk, West Ekofisk, Tor, Albuskjell, Dan, and others have shown that, although the reservoir properties of chalk are generally poor, excellent production can be attained with sufficient fracturing and a sufficiently thick pay section. Production rates of 10,000 BOPD (barrels of oil per day) per well are common in these areas, and total reserves in North Sea chalk exceed 2.5 billion bbl (barrels) of oil and 8 trillion ft^3 (cubic feet) of gas (Tiratsoo, 1976).

Partly as a result of such exploration successes in North Sea and Middle Eastern chalk reservoirs and partly as a result of the rapid rise in crude oil prices over the past few years, exploration has increased dramatically in North American chalks as well. Significant oil and gas discoveries, for example, have been made in the Upper Cretaceous Austin Group of Texas. Indeed, the Austin drilling was the third most important exploration play in the United States in 1976 in terms of the number of exploration wells drilled (Petroleum Information Corporation, 1977). Commercial gas discoveries have been made from chalk reservoirs in the Niobrara Formation in several areas of Kansas and Colorado. In Louisiana, Mississippi, and Alabama, increased oil and gas production have been obtained from chalk facies of the Annona, Selma, Saratoga, and Ozan Formations, Monroe gas rock, and other Upper Cretaceous units. Finally, in the Scotian Shelf area of the Canadian Atlantic continental margin, several wells had promising, if subcommercial, shows of hydrocarbons.

This upsurge in exploration activity and the high potential for further hydrocarbon discoveries in North American chalks make it imperative that we gain a better understanding of the factors that control the reservoir properties of chalk. This paper will outline the production histories of chalks of North America and Europe and try to isolate those factors that improve or reduce the hydrocarbon potential of those units. It will also attempt to generalize from these relationships in order to provide a model for the prediction of subsurface reservoir properties of chalks. Those who are interested in greater detail about the depositional and diagenetic aspects of chalk are referred to other recent papers including Hancock (1976) and Scholle (1977), and to the extensive references contained in those papers.

ACKNOWLEDGMENTS

I would like to thank the following companies and individuals who kindly supplied samples and (or) data for this study: Shell Canada, Shell Development Co., Mobil Oil Canada, Exxon Co., Mountain Petroleum Corporation, Kansas-Nebraska Natural Gas Co., and T. S. M. Ranneft. Discussions with J. M. Hancock, Kelton Cloud, and D. E. Hattin were instrumental in formulating many of the ideas in this paper. R. B. Halley, G. L. Dolton, Kelton Cloud, C. W. Spencer, and J. P. Lockridge reviewed early versions of this paper and provided numerous suggestions and improvements for which I am grateful.

DEPOSITIONAL AND DIAGENETIC PATTERNS OF CHALK

The term "chalk" is restricted in this paper to include only those fine-grained carbonate sediments composed primarily of calcareous nannofossils (especially coccoliths) and calcareous microfossils (such as Foraminifera and calcispheres). Other components such as coarser calcareous skeletal grains, detrital quartz, glauconite, chert, phosphate pellets, and clay may be important in some units but are subordinate constituents overall. No limitation is placed on the degree of induration of a chalk, because this is an entirely artificial concept. Chalk can be found in all stages of lithification, ranging from a watery slurry (or "ooze") to very hard limestone.

The restricted, biologically defined meaning of the term "chalk" has several important implications. First, true chalk has existed only since the Jurassic or Early Cretaceous when coccoliths and planktonic Foraminifera first achieved widespread distribution.

Second, chalk forms only where calcareous nannofossils can live in the overlying water column. The accumulation rate of chalk is limited by the rate of production of the constituent organisms. Thus chalk normally forms only in areas where clastic terrigenous input is low enough that it does not overwhelm and mask the microfossil and nannofossil production. Coccoliths, in particular, have a remarkably broad range of salinity tolerance (one species is known to live in waters of as low as 11 ppt salinity) and can exist in abundance in very shallow inland seas or coastal zones. Therefore, the exclusion of diluting constituents such as clastic terrigenous debris, siliceous microfossils, or coarser carbonate skeletal grains is normally the critical factor in chalk deposition. Given the exclusion of dilutants, chalk can form in any water depth from tens to thousands of meters. In water depths greater than about 4,000 m (13,100 ft), extensive dissolution of $CaCO_3$ (compensation depth) reduces the probability of accumulating chalk.

Because of its pelagic origin, chalk deposition often marks the times of maximum transgression on continental shelves or interior seas. For example, during the Upper Cretaceous, a time interval of very high eustatic sea level stand, chalk deposition occurred across major portions of Europe, North America, and other areas. This type of widespread chalk sedimentation results from a combination of factors including the reduction of the exposed area of continental sources of terrigenous clastic sediment, raising of erosional base levels, and enlargement of areas of shelf sedimentation far removed from shorelines. These factors, in addition to depositional sites generally below wave base, also contribute to the lateral uniformity of chalk facies.

During times of lower eustatic sea level stand, chalk deposition does not cease; rather it retreats from the continental interiors and shelves to the continental slopes and deeper ocean basins. Chalk deposition was extremely widespread in the deep sea during the relatively low sea level stands of the Tertiary, as shown by the Deep Sea Drilling Project (DSDP) coring. Indeed, chalk accounts for about 67 percent of the total limestone deposited worldwide over the past 100 m.y. (million years) (Hay and others, 1976). Most of this chalk is in the ocean basins rather than on the continents.

A third consequence of the biological origin of chalk is reflected in its grain size and petrophysical properties. Coccoliths (and related groups of nannofossils) range in size from about 1 to 20 μm (micrometers) (Bukry, 1969). These organisms, in turn, are made up of individual crystal elements which are between 0.2 and 1 μm in size (Neugebauer, 1975a). Typical chalk, therefore, often has a polymodal grain-size distribution, with maxima in the 0.2-1, 1-20, and 62 μm ranges (Håkansson and others, 1974).

The very small average grain size of chalk has a major effect on its reservoir properties. Chalk may be deposited with as much as 70 or 80 percent porosity, but nearly half of this pore space is lost by dewatering during the first few tens to hundreds of meters of burial. Chalk that has never been buried deeper than a few hundred meters generally has between 35 and 45 percent porosity (Scholle, 1974, 1977). In areas where chalk has been deeply buried, porosity may be reduced to less than 1 percent by compaction and cementation. Yet even with 40 percent porosity, a pure chalk will have only between 2 and 10 md (millidarcies) permeability (Scholle, 1977). When porosity is reduced to 20 percent, matrix permeability ranges between 0.1 and 0.5 md. At values representing less than 10-percent matrix porosity, permeabilities are between 0.05 md and unmeasurably low values. Thus, it is apparent that any diagenetic reduction of porosity in chalk carries with it a commensurately large reduction in matrix permeability.

The extremely low permeability of chalk, a function of intergranular pore diameters primarily in the range of 0.1 to 1 μm (Price and others, 1976), implies very slow movement of fluids through the rock matrix. Because most of the fluid in matrix pores is held by capillary and molecular forces, gravity-induced drainage of fluids from chalks is a very slow and incomplete process except under unusual circumstances. Indeed, chalks often act as seals rather than as reservoirs where they are unfractured.

A fourth consequence of the nannofossil-microfossil origin of chalk is apparent during diagenesis. Coccoliths (and most other nannofossil groups) as well as planktonic Foraminifera are composed of low-Mg calcite. This is the most stable polymorph of calcium carbonate under near-surface temperature and pressure conditions. Even the coarser skeletal contributions to chalk (especially inoceramids and oysters) are often completely or partly composed of low-Mg calcite. In this respect, chalk differs radically from most shallow-water limestone which originally contains predominantly aragonite and high-Mg calcite.

This primary chemical stability is a very important factor in understanding the reservoir properties of chalk. It implies that, because generally few unstable components are susceptible to leaching, primary porosity is the only porosity likely in chalk except for fractures. The very low matrix permeability of chalk also contributes to this diagenetic stability, especially in deep subsurface settings. Large-scale water flow is largely confined to fractures, and the water that moves by means of matrix porosity normally is in equilibrium with calcite. Secondary porosity development, even at near-surface locations where chalk may be exposed to extensive freshwater input, is not an important factor in most chalk reservoirs. Fracturing is the only major exception to this rule. Indurated chalk is a brittle rock and secondary fracture porosity often plays a significant role in reservoir formation, especially through enhancement of overall permeability. Enlargement of fractures by subsurface dissolution may have had an effect on permeability relations in a few reservoirs (Woods, 1963), but this has not been fully demonstrated.

Primary chemical stability also implies that freshwater exposure alone, at near-surface conditions, will have little effect on the diagenesis of chalk. This situation is very different from that of most shallow-water limestones such as reefs, oolites, or lagoonal carbonate muds, which are highly susceptible to wholesale alteration by freshwater in both vadose and phreatic environments. Chalks can be found on outcrop today (in both North America and Europe) that have been exposed continuously to freshwater since the Late Cretaceous (approximately 70 m.y.). Yet, where these sediments have not been deeply buried, they show porosities of between 35 and 45 percent, with little or no evidence of significant secondary porosity formation by leaching.

The main factor controlling the degree of diagenetic porosity reduction in chalk is burial depth. The principles of this depth-related diagenesis have been extensively described by Matter (1974), Neugebauer (1973, 1974, 1975a), Schlanger and Douglas (1974), Scholle (1974, 1977, in press), and others and will not be elaborated on in detail here. Briefly, all chalk undergoes both mechanical and chemical compaction (pressure solution and reprecipitation) when subjected to sufficient differential stress. This stress is generally induced by addition of overburden but can also be influenced by tectonic effects and pore-fluid pressures. Differential intergranular stresses lead to dewatering and grain reorientation during early stages of diagenesis and then induce the formation of solution seams, embayed grains, and finally stylolites during later stages of compaction. Calcium carbonate dissolved at grain contacts and along solution seams is reprecipitated locally at sites of lower differential stress (such as open pores). In this manner a progressive, depth-related loss of porosity is effected.

The rate of porosity loss during burial is affected by a large number of secondary factors:

1. Pore-water chemistry--Although freshwater does not strongly influence porosity of chalk in outcrop or very shallowly buried sections, Mg-poor fluids (and most freshwater is Mg-poor) will greatly accelerate the rate of porosity loss when overburden is added (Neugebauer, 1973, 1974, 1975a).
2. Primary composition--Variations in grain size, clay content, or faunal composition can make individual beds more or less susceptible to diagenetic alteration. Beds having abundant coccoliths, for example, often are less cemented than those containing primarily Foraminifera. This can lead to significant bed to bed variation in porosity and permeability.
3. Tectonic stress--Tectonic deformation can be as effective as overburden load in generating intergranular stresses. Thus, in areas of intense faulting or folding the rates of porosity loss in chalks may be accelerated, as shown in the Isle of Wight area of England by Mimran (1975). Tectonic deformation can also lead to an increase in porosity and permeability through fracture development.
4. Presence of hydrocarbons--The early introduction of hydrocarbons into chalk can prevent porosity loss during subsequent burial, especially complete or nearly complete oil saturation is reached (Scholle, 1976; Wilson, 1977). These hydrocarbons may include biogenically generated natural gas formed within the chalk or adjacent units. Alternatively, the hydrocarbons may have formed in much deeper units with subsequent upward migration into the porous chalk reservoirs. In either case, prevention of porosity loss is largely accomplished by reduction of water flow through (or complete exclusion of water from) the reservoir.
5. Pore-fluid pressure--Compaction (either mechanical or chemical) depends on the expulsion of pore fluids and the generation of strong intergranular stresses. When pore-fluid escape is retarded and higher than normal pore-fluid pressures are developed, differential intergranular stresses are reduced and pressure solution and cementation are inhibited. This can have a major effect on chalk-reservoir properties (Harper and Shaw, 1974; Scholle, 1977).

The rates of chalk porosity loss as a function of burial depth are shown in figure 1. "Normal" rates are those produced with marine pore fluid, no major tectonic deformation, and normal pore-fluid pressure. The "maximum" rates apply to chalk that has had freshwater input before or during burial, has been exposed to major tectonic deformation, or has experienced both of these factors. No minimum rate is shown in figure 1, but with early introduction of hydrocarbons or early generation of abnormal pore-fluid pressure, porosities as high as 40 to 50 percent can be maintained to burial depths of at least 3,000 to 4,000 m (9,800 to 13,100 ft). This is illustrated by the North Sea chalk reservoirs plotted in figure 1.

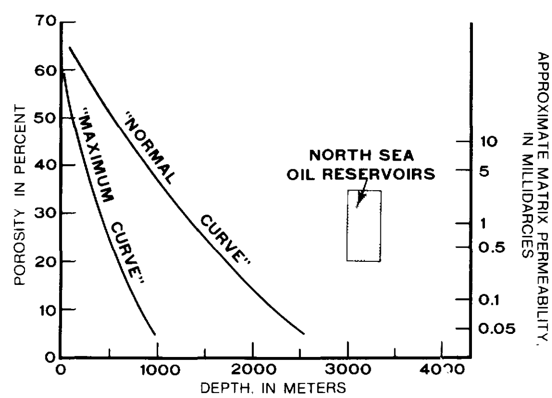


Figure 1.--Relationships between depth of burial, porosity, and matrix permeability in chalk. "Normal curve" represents units buried with marine (or Mg-rich) pore fluids; "maximum curve" represents units buried with freshwater (or Mg-poor) pore fluids or subjected to significant tectonic deformation. Approximate present-day porosity-depth data for overpressured North Sea chalk reservoirs are shown for comparison. Permeability relations taken from Scholle (1977).

REGIONAL GEOLOGIC STUDIES OF CHALK

Gulf Coast

Stratigraphy and sedimentology

Chalk is widely distributed in both outcrop and subsurface sections in the Gulf Coast area. Coniacian to lower Campanian chalk of the

Austin Group and its equivalents extends from northern Coahuilla in Mexico across Texas and into southwest Arkansas (Pessagno, 1969; Powell, 1970). Equivalent or slightly younger chalk is also present within the Selma Group, the Saratoga and Annona Chalks, the Monroe gas rock, and other units of Louisiana, Mississippi, and Alabama. A review of the stratigraphic relationships of these units is beyond the scope of this paper, but interested readers are referred to Cloud (1975), Durham (1957), Freeman (1961), Murray (1961), Pessagno (1969), Seewald (1967), and Smith (1973) for details of Austin stratigraphy, and to Bollman (1968), Braunstein (1959), Mellen (1958), Scott (1968), and Shreveport Geological Society (1968) for information on chalks of Louisiana, Mississippi, and Alabama. Generalized correlations of Upper Cretaceous chalks of the Gulf Coast are shown in figure 2.

In Texas, the Austin Group has been reported to be about 183 m (600 ft) thick in the Dallas area (Dallas Geological Society, 1965). It thins to less than 46 m (150 ft) over the Belton high (locality shown in fig. 3); thickens to as much as 168 m (550 ft) in the type area of the Austin in Travis County, thins again to the south to a minimum of about 30 m (100 ft) across the San Marcos arch, and finally thickens again to as much as 183 m (600 ft) in the Rio Grande embayment (Seewald, 1967;

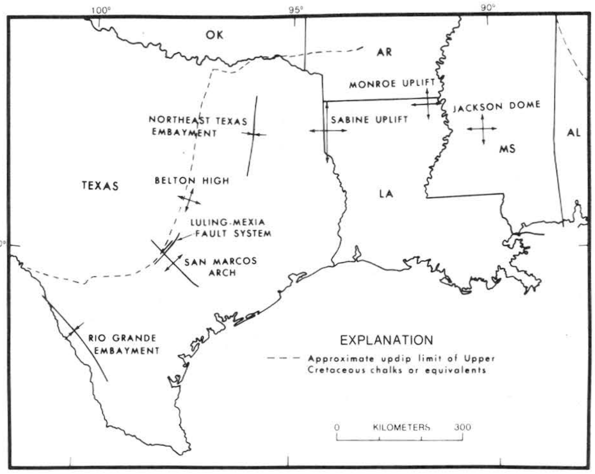
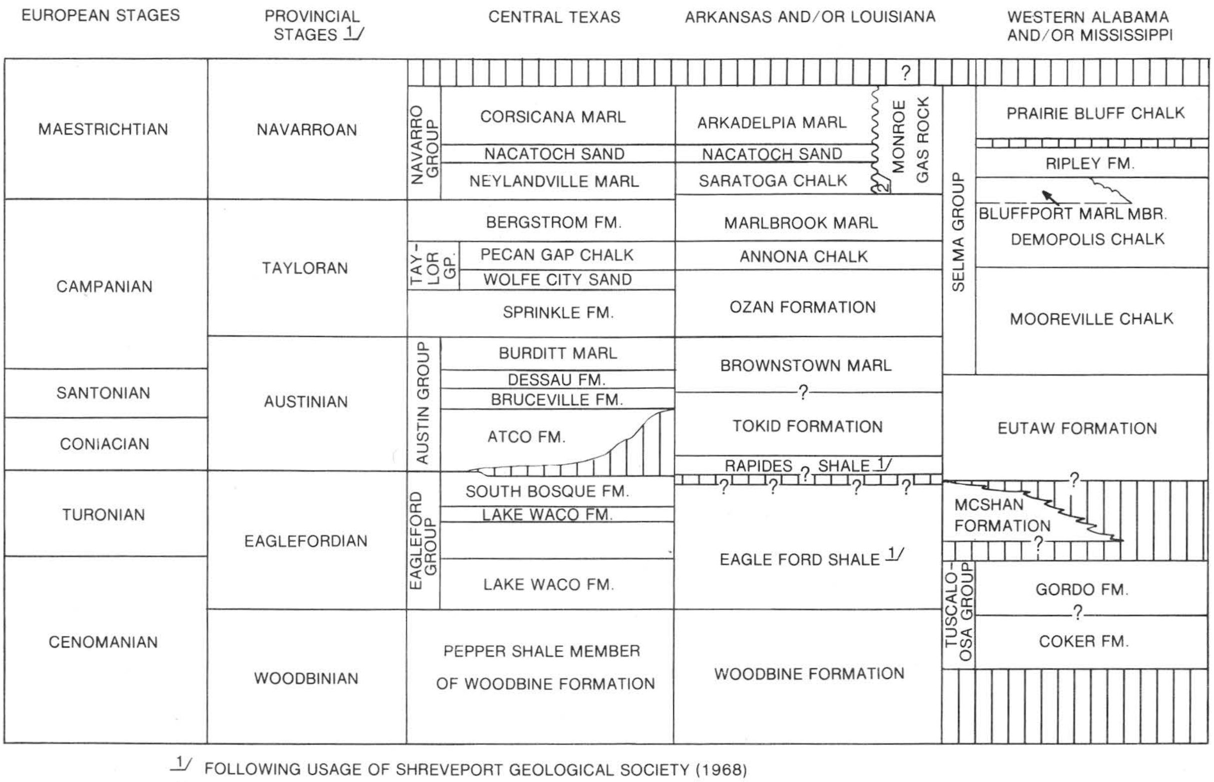


Figure 3.--Index map showing location of major paleogeographic features influencing the deposition and diagenesis of Upper Cretaceous chalk of the Gulf Coast.



1/ FOLLOWING USAGE OF SHREVEPORT GEOLOGICAL SOCIETY (1968)

2/ AN INFORMAL NAME

Figure 2.--Stratigraphic correlations of the chalk-bearing Upper Cretaceous rocks of the Gulf Coast. Data modified from Hazel and others (in press), Owens and others (1970), Pessagno (1969), Shreveport Geological Society (1965).

Smith, 1973). Much of the Austin Group consists of chalk facies, especially the basal Atco Formation which constitutes about one-third the total thickness of the Austin Group.

In Louisiana, the Annona Chalk is about 30 m (100 ft) thick, the Marlbrook Marl (consisting of chalk and calcareous shale) is about 53 m (175 ft) thick, and the Saratoga Chalk is about 6 m (20 ft) thick (Shreveport Geological Society, 1965). In western Alabama, the Demopolis, Mooreville, and Prairie Bluff Chalks of the Selma Group consist predominantly of chalk. The Demopolis is 128-151 m (420-495 ft) thick, the Mooreville is 79-183 m (260-600 ft) thick, and the Prairie Bluff is 3-21 m (10-70 ft) thick (Scott, 1968). All three units interfinger with sand and shale to the east.

Most of the chalk in the Austin, Annona, and Selma is massive-bedded, with regular alternations of thin marls or calcareous shale seams and thicker, less clayey chalks. Similar cyclic deposition of chalk has been noted in England (Kennedy, 1967), France (Cayeux, 1935) and Italy (Arthur and Fischer, 1977). Using average sedimentation rates, these cycles appear to reflect 20,000- to 100,000-year fluctuations in the input of the carbonate components (Arthur and Roggenthen, 1976; Arthur and Fischer, 1977).

Figure 4 shows averages of insoluble residues for chalk beds in the Atco Formation. The data indicate that clay and silt-sized terrigenous material were contributed to the Austin sea mainly from the north and that the Atco Formation in the south Texas area is a relatively pure limestone. Chalk and marl of the Selma Group in western Alabama, although not plotted on figure 4, generally have insoluble residues of 20 to 50 percent.

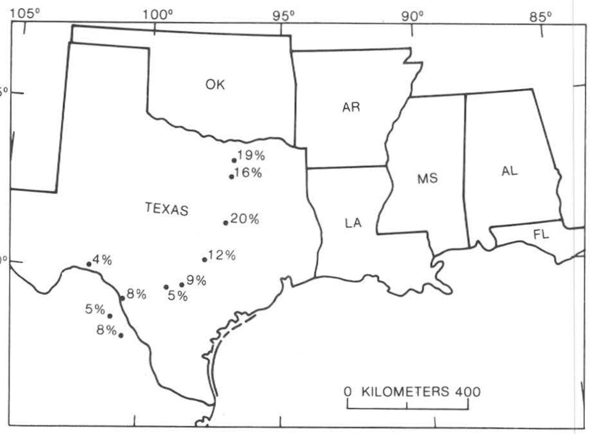


Figure 4.--Percent HCl-insoluble residue in outcropping chalk of the lower part of the Austin Group in Texas and equivalent units in northern Mexico. Each data point represents an average of a number of analyses for that locality.

Few primary sedimentary structures are seen in the Austin and other Gulf Coast chalks because most of the sediment is intensely bioturbated. However, the rarity of wave or current-generated, large-scale structures (such as channels or cross bed sets), the uniform preservation of the meter-scale bedding across wide areas, and the general absence of bioherms indicate deposition below wave base. Exact water depths cannot be determined, but deposition of most Gulf Coast chalk probably occurred in 30-300 m (100-1,000 ft) of water. Exceptions occur locally, as on the San Marcos arch and in

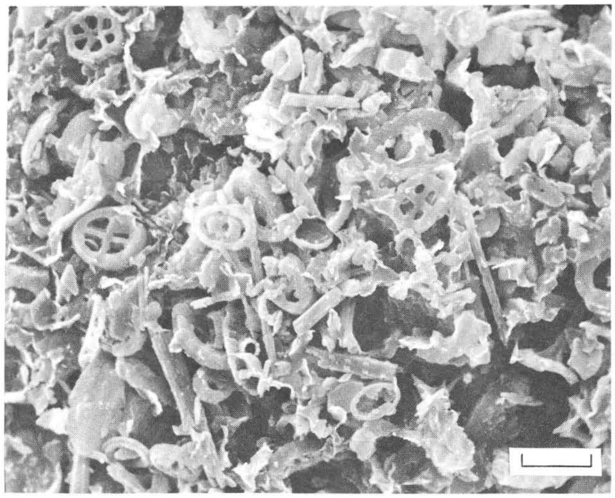


Figure 5.--SEM photomicrograph of Coniacian chalk in the basal part of the Atco Formation of the Austin Group from the Atlas Cement Co. quarry, southwest of Waco (McLennan County), Tex. Coccolith plates and rhabdolith spines constitute the major portion of the sediment. Sediment has 32 percent insoluble residue and about 25 percent porosity. Scale bar is 3.3 µm.

association with small volcanoes within the Austin sea. In these areas, calcarenitic limestone, significant unconformities within the Austin, and biohermal accumulations are indicative of shallower water deposition (McNulty, 1971; White, 1960).

Although faunal diversity is not as great as in English chalk of equivalent age, it is sufficient to indicate probable normal marine salinity throughout the depositional area. Gulf Coast chalks are generally rich in coccoliths and planktonic Foraminifera (Clark and Bird, 1966; Pessagno, 1969; Smith, 1973) and, the comments of Scott (1977, p. 201) notwithstanding, these pelagic chalks are very similar in overall composition and texture to those of England and the North Sea. SEM (scanning electron micrography) (figs. 5 and 6) often shows a sediment composed almost exclusively of coccolith plates and fragments.

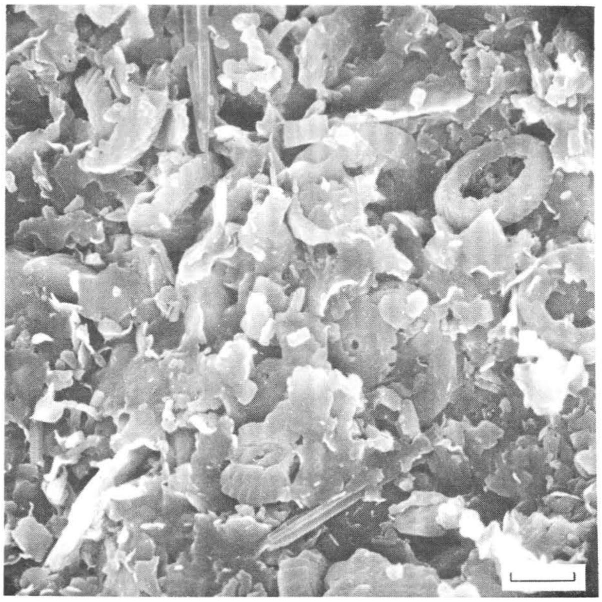


Figure 6.--SEM photomicrograph of chalk from the Bluffport Marl Member of the Demopolis Chalk of the Selma Group in Marengo County, Ala. Sample has abundant coccoliths and rhabdoliths, 29 percent insoluble residue, and 33 percent porosity. Scale bar is 2 µm.

Petrophysical properties and diagenesis

There is considerable variation in porosity and permeability of Gulf Coast chalks, both along outcrop and into the subsurface. Figure 7 illustrates outcrop porosity values for chalks of the Austin and Selma Groups. The significant loss of porosity south and west of the San Marcos arch is presumably related to a number of factors including possible deeper burial, higher paleogeothermal gradients, and greater tectonic deformation in the Rio Grande embayment in conjunction with development of the Sierra Madre structural front of northern Mexico. The high porosities reported for chalk from the Northeast Texas embayment may be due, in part, to the very small number of samples analyzed from that area. Porosity of Gulf Coast chalk also consistently decreases in a downdip direction as a direct consequence of increased overburden.

The loss of porosity noted above involves solution transfer of calcium carbonate from zones of high stress to zones of lower stress (generally open pores). This process is marked in the Austin Group by the appearance of corroded and embayed grains and stylolites (Cloud, 1975). It can also be traced by a progressive shift in bulk oxygen isotopic values of the chalk as cementation takes place. (For an explanation of this process and the isotopic data, see Scholle, 1977 and references provided therein.) Figure 8 shows oxygen isotopic data for outcropping Gulf Coast chalks. The least negative values (indicating minimum alteration) are located on the San Marcos arch, on the Sabine uplift, and in western Alabama. Areas of deeper burial or more tectonism, such as the Rio Grande embayment or the Northeast Texas embayment, have more negative oxygen isotopic values, indicative of greater diagenetic alteration.

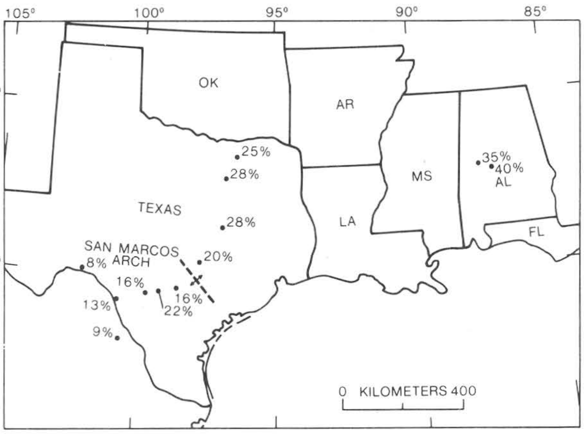


Figure 7.--Porosity in percent, of outcropping chalks of the Gulf Coast area. Samples are from the San Vicente Formation in northern Mexico, the lower half of the Austin Group in Texas, and the Selma Group in Alabama. Each data point represents an average of a number of analyses for that locality. Samples were collected in deep roadcuts or quarries to minimize weathering effects.

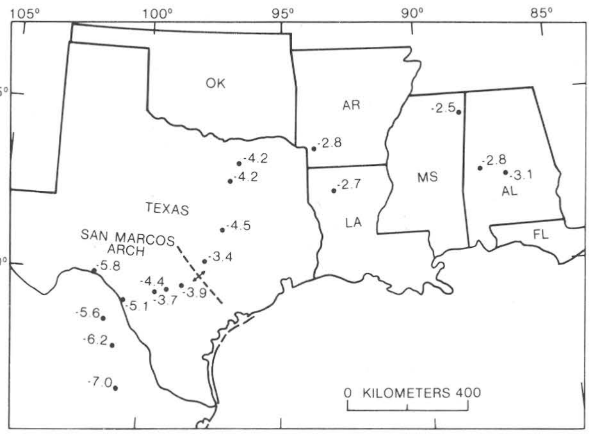


Figure 8.--Stable oxygen isotopic analyses of outcrop samples of Gulf Coast chalks. Samples are from the San Vicente Formation in northern Mexico, the lower half of the Austin Group in Texas, the Annona and Saratoga Chalks of Arkansas, and the Selma Group in Alabama. Samples were collected from deep roadcuts or quarries to minimize weathering effects. Data are reported as permil deviation from the PDB standard (δO^{18} PDB). Each data point represents an average of a number of analyses for that locality.

Similar results are seen in figure 9, which shows analyses of cuttings from the Austin Group in nine wells in south-central Texas. The strong correlation between depth of burial and oxygen isotopic values implies progressive cementation and reequilibration of the chalk as burial depth increases. The shift in oxygen isotopic values probably is due to elevated subsurface temperatures at which the solution-reprecipitation processes take place, but it may also reflect isotopically light interstitial waters in the chalk. The depth-oxygen isotopic correlation also implies, as was shown in figure 1, that Gulf Coast chalks will have very low matrix porosities and permeabilities at depths below about 1,500-2,000 m (4,900-6,600 ft).

Although oxygen isotopic and petrophysical analyses provide quantitative data on the diagenetic alteration of chalks, the same effects can be seen qualitatively by SEM. Figure 10*A-C* illustrates some typical fabrics of the Austin at various stages of diagenesis. Cementation is noted to have been accomplished largely by overgrowth of primary grains. Different types of grains have different susceptibilities to overgrowth cementation; planktonic Foraminifera readily receive overgrowths whereas many types of coccoliths do not (Matter, 1974; Neugebauer, 1975a; Wise, 1973). Yet even coccoliths are eventually incorporated into an interlocking framework of angular, euhedral crystal overgrowths which increase average grain size, reduce overall pore space, and drastically reduce permeability by narrowing pore throats. The process is a continuous one that can proceed to the stage of virtually complete elimination of porosity.

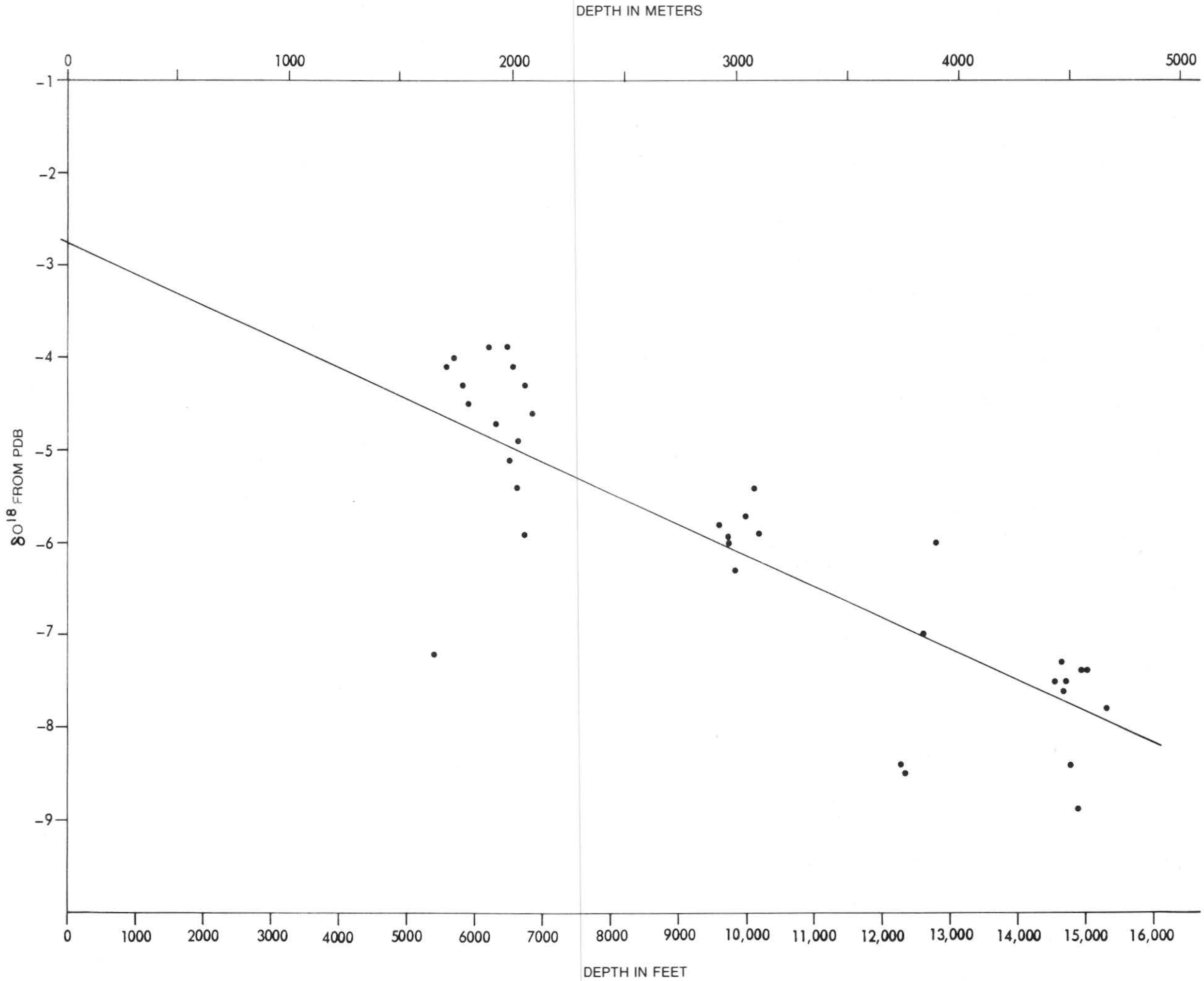


Figure 9.--Trend of 34 stable oxygen isotopic analyses of cuttings of chalks of the Austin Group from nine wells in central and south-central Texas as permil deviation from the PDB standard (δO^{18} PDB) versus depth. Trend line is a least squares fit to the data. Some of the sample scatter may be related to caving of cuttings from overlying units or to analysis of calcite from sources other than the chalk matrix.

Figure 10.--SEM photomicrographs of chalk of the Austin Group in various stages of diagenetic alteration. *A*, Sample from the basal part of the Atco Formation, Austin Group from the Atlas Cement Co. quarry, southwest of Waco (McLennan County), Tex. Note presence of coccoliths, coccosphere, and rhabdolith spines with virtually no cement (porosity 27 percent). Most grains have primary biogenic outlines. Scale bar is 3.3 µm. *B*, Sample from Atco Formation, Austin Group at Austin (Travis County), Tex. Sample shows intermediate stage of alteration with coccoliths still visible, but most grains have euhedral outlines produced by overgrowth cementation. Crystals are only partly interlocking and sample retains 19 percent porosity. Scale bar is 1 µm. *C*, Sample from the Austin Group in Shell Oil Co. # 1 Jackson well (Washington County, Tex.) at 4,465 m (14,650 ft) depth. Most traces of original biogenic grains have been obliterated by cementation. Matrix crystals are completely interlocking and porosity is estimated to be less than 5 percent. Scale bar is 3 µm.

Hydrocarbon production

The patterns of diagenetic alteration of Gulf Coast chalks has had a major effect on the distribution of oil and gas reservoirs in those units. Production of hydrocarbons from chalk in the Gulf Coast was established nearly 70 years ago. In Texas, Alta Vista field (Bexar Co.) was discovered in 1912, Luling-Branyon (Guadalupe Co.) in 1922, and Darst Creek (Guadalupe Co.) in 1929. The Pearsall Field (Frio Co.), the largest chalk reservoir in Texas, was discovered in April 1936 by the Amerada and Rycade 1, Tract 6 McWilliams well (Scott and Prestridge, 1977). In northern Louisiana, commercial production began in the Zwolle Field (Sabine Parish) in November 1928 (Woods, 1963). During the seven decades of production, at least 30 million bbls of oil and 5 billion ft^3 of gas have been produced from chalk in Texas; more than 50 million bbls of oil have been extracted to date from chalk in Louisiana. Available data on lithology of producing horizons in Alabama and Mississippi are too poor to provide reliable production totals.

Oil and gas production data from chalk of Texas, Louisiana, Mississippi, and Alabama are shown in tables 1-4. The data are shown by county (or parish) and by field. Fields that overlap two or more county boundaries are listed only under the first county alphabetically. The data are incomplete for a number of reasons. In many fields, especially those in Louisiana or those discovered before 1940 in Texas, no data have been kept on the amount of production from each producing unit in a multiple-pay field. Thus, for example, in the Luling-Branyon field of Texas, although most of the hydrocarbon production is from the Lower Cretaceous Edwards Limestone, significant production is also obtained from the Austin Group. No data are available on how much of the total field production is from the Austin, however.

In the case of the Pearsall field and other areas of intense current exploration interest, the data do not necessarily reflect the increases in production subsequent to late 1976. Although the Austin exploration in Texas is often economically marginal (with average completed well costs of about $250,000), 347 wells were drilled in the Pearsall area alone during 1976 (Petroleum Information Corporation, 1977). These wells are expected to have an average ultimate recovery of about 80,000 bbl per well where drilled on 80-acre spacing (Stewart-Gordon, 1976), and thus eventually will add several million barrels to the total production figures.

In other cases, production from chalks may have been overestimated. Some fields in the Austin are associated with volcanic plugs and surrounding contemporaneous calcarenitic limestone facies. Some of the hydrocarbon production listed from the Selma, Saratoga, Monroe, Annona, or Ozan may be from sand, shale, or other limestone facies rather than from chalk. The Eutaw Formation of Alabama and Mississippi, in particular, contains both sand and chalk facies. Little information is generally available about the subsurface facies distribution within these units in many producing fields.

Even with these constraints on the quality of the data, some interesting relationships are brought out by plotting the data by region. Figures 11-14 illustrate the area distribution of oil and gas in Gulf Coast chalks by number of fields and by cumulative production. It is apparent that oil and gas production is concentrated in the areas of the San Marcos arch, the Sabine uplift, the Monroe uplift, and the Jackson dome. Oil reservoirs, both in terms of number of fields and of cumulative production, are located mainly at shallow depths (2,000 m; 6,600 ft or less). Gas production, while concentrated at a depth of about 2,000 m (6,600 ft), extends to depths as great as 4,500 m (14,800 ft). These relationships between depth of burial, total production, and type of production are shown more clearly in figures 15-17.

These regional and depth relationships of hydrocarbon production fit the patterns predicted from an understanding of the principles of chalk diagenesis. Production from paleotopographically positive areas may be related to both depositional and diagenetic factors. Paleohighs may have been sites of winnowing and deposition of more calcarenitic chalk. These areas also were subjected to thinner accumulations of overburden and thus underwent less diagenetic porosity loss. In these uplift areas optimal reservoir characteristics are found. Fields at depths of less than 1,000 m (3,300 ft) often have porosities as great as 25-30 percent. For example, along the Luling-Mexia trend in central Texas, matrix porosities of as much as 24 percent have been reported, along with as much as 40 percent oil saturation of matrix pore space (Doyle, 1955). In fields located at greater depth, porosity is much lower. In the Pearsall field, at about 1,800 m (5,900 ft) of depth, matrix porosity averages 6-8 percent with an average permeability of 0.0 to 0.4 md (Doyle, 1955). In most of these areas, present burial depths closely approximate maximum depths.

Fracturing is the second major factor involved in the location of hydrocarbon reservoirs in chalks. Production from chalk reservoirs of the Austin Group, as well as other Gulf Coast chalks, would be entirely uneconomic at depths below about 1,500 m (4,900 ft) were it not for imporved permeability related to fracturing. In many fractured chalk-reservoir fields, initial production rates are quite high, commonly as much as 370 BOPD in modern wells that have had massive hydraulic fracture treatment using sand-oil-gel mixtures (Long, 1976a, 1976b; Stewart-Gordon, 1976). This initial production declines rapidly, in most cases, to average values of 60-70 BOPD, and the wells need to be pumped after about 6 months (Long, 1976a and b). The rapid decline rates, coupled with the long-term, low-level productivity of many wells, indicate that while initial production is largely from fracture porosity, slow drainage of oil from the rock matrix into the open fractures often occurs. The initial discovery well in the Pearsall field, for example, still produced 239 bbl of oil during May 1976, over 40 years after the well was completed (Scott and Prestridge, 1977). Similarly, farther east, many fields such as Pendleton-Many and Fort Jessup in Sabine parish, Louisiana, have had long histories of production, chiefly from fracture porosity.

Fracturing is important in production at all depths. In fields at shallow depths, fracturing enhances the effective permeability of the chalk and efficiently channels oil or gas from the matrix pores to the well bore. Thus, many of the most productive shallow fields are associated with major fracture zones. The Dunlap, Fentress, Salt Flat, Tenney Creek, Staples, Luling-Branyon, Darst Creek, Day, Jayeddie, Jayeddie South, United, Wolf Creek, Zoboroski, LaVernia, Saspamco, Philtop, and other fields are all associated with the Luling-Mexia fault system (Doyle, 1955). In deeper fields, fracturing not only enhances production but often provides the major porosity for hydrocarbon storage. Where matrix porosity is less than about 20 to 25 percent, fracturing is essential for hydrocarbon production. The Pearsall field and its extensions, the largest single producing field in the Austin Group, is productive only because of development of fractures on the crest of the Pearsall anticline. Artificial fracturing of the chalk in modern wells in this area improves both long- and short-term production, because it allows connection of more open fractures with the well bore and because it provides a larger surface area of fractures for very slow drainage of oil from the rock matrix.

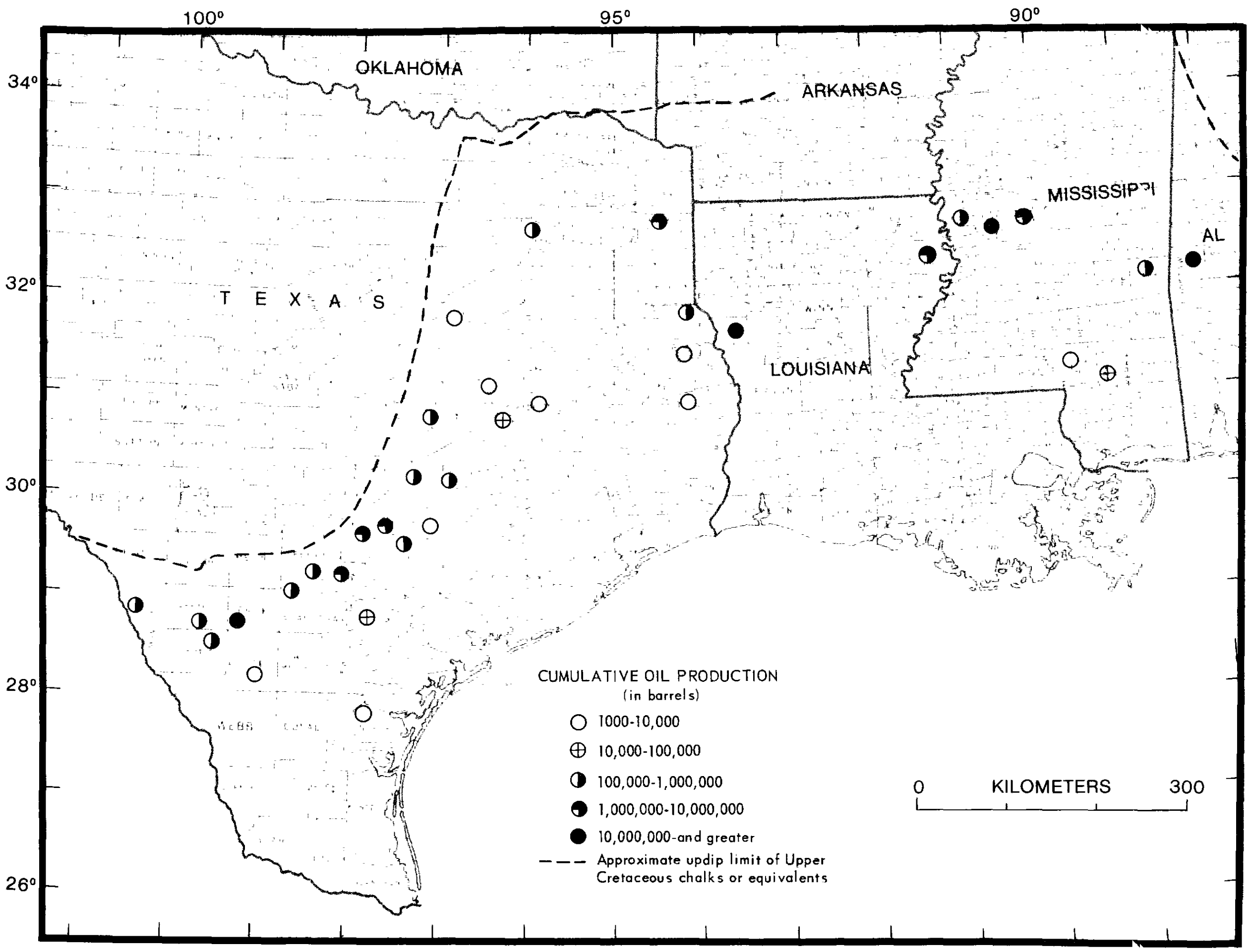


Figure 11.--Regional distribution of cumulative oil production from Gulf Coast chalks, plotted by county or parish. Data are taken from tables 1-4.

Table 1.--*Oil and gas production, by county, from Upper Cretaceous chalk reservoirs in Texas*

[Data taken from International Oil Scouts Association (1976), University of Oklahoma Petroleum Data System (M. Atkins, written commun., 1977), and Texas Railroad Commission records. Leader (---) indicates information not available; N.A., data column not applicable; A.C., Austin Chalk; Seg, segment; Mcf, 1,000 ft^3]

Field or pool	Stratigraphic unit	Average top of producing formation		Average API[1] gravity (degrees)	Total wells	Cumulative oil (bbl) (through 1976[8])	Cumulative gas (Mcf) (through 1974)	Current oil (bbl) (1976[8])	Current gas (Mcf) (1976)
		Feet	Meters						
Atascosa County									
Charlotte A.C.	Austin Group	6,435	1,961	38	3	141,700	---	0	0
Charlotte A.C. Seg A.	---do------	6,345	1,934	37	1	1,599	4,008	0	0
Coughran A.C.	---do------	6,330	1,929	23	10	248,511	---	[5]8,194	33
Coughran South A.C.	---do------	6,385	1,946	27	2	13,267	38	0	0
Coughran West A.C.	---do------	6,265	1,910	23	1	2,236	---	0	0
Horn A.C.	---do------	6,203	1,891	34	5	128,458	---	480	45
Horn Seg B Austin.	---do------	6,450	1,966	37	1	92,047	---	0	0
Horn Seg C	---do------	6,703	2,043	39	3	192,919	151,918	0	0
Jourdanton A.C.	---do------	6,506	1,983	32	1	1,309	3,526	0	0
Pleasanton A.C.	---do------	7,726	2,355	N.A.	1	0	2,190	0	0
Poteet	---do------	3,567	1,087	41	3	99,983	---	1,466	[5]13
W.P. Holloway A.C.	---do------	6,100	1,859	---	2	[6]44,186	56	[7]2,005	12
Total--						966,215	161,736	12,145	103

Bastrop County									
Bastrop A.C.	Austin Group	2,496	761	28	1	4,236	---	0	0
Bateman A.C.	---do------	2,139	652	39	3	19,617	---	685	24
Elgin	---do------	2,855	870	36	---	3,565	---	0	---
Paige Austin	---do------	6,792	2,070	33	1	3,043	---	0	0
Paige NE A.C.	---do------	6,143	1,872	---	1	---	0	---	0
Peg A.C.	---do------	1,549	472	37	3	16,060	---	---	0
Peg N A.C.	---do------	1,559	475	38	3	58,696	---	636	11
Red Rock W A.C.	---do------	2,208	673	42	1	1,406	---	0	0
Total---						106,623	0	1,321	35
Bexar County									
Alta Vista	Chalk	1,180	360	---	---	56,494	---	---	---
Leon Creek	Austin Group	1,100	335	18	1	0	0	0	0
Losoya A.C.	---do------	1,855	565	17	4	32,797	---	0	11
Philtop	---do------	1,100	335	23	---	8,171	---	---	0
Rinehart A.C.	---do------	1,163	354	20	67	625,754	---	6,479	31
Total---						723,216	0	6,479	42
Brazos County									
Ferguson Crossing A.C.	Austin Group	11,016	3,358	47	1	15,403	---	---	0
Burleson County									
Northeast Clay	Austin Group	11,436	3,486	N.A.	---	---	0	---	0

Table 1.--*Oil and gas production, by county, from Upper Cretaceous chalk reservoirs in Texas*—Continued

Field or pool	Stratigraphic unit	Average top of producing formation: Feet	Meters	Average API[1] gravity (degrees)	Total wells	Cumulative oil (bbl) (through 1976[8])	Cumulative gas (Mcf) (through 1974)	Current oil (bbl) (1976[8])	Current gas (Mcf) (1976)
				Caldwell County					
Bob Rose	Austin Group	1,975	602	39	22	48,859	---	0	0
Drummond 1400 Austin.	---do------	1,382	421	36	6	32,496	15,692	1,945	340
Dunlap	---do------	2,123	647	36	292	4,660,040	---	135,850	5,905
Fentress	---do------	1,608	490	---	---	---	---	---	---
Fentress East	---do------	1,615	492	36	1	---	---	---	---
Joliet 2000	---do------	1,901	579	---	1	353,817	---	---	0
Lane A.C.	---do------	1,609	490	41	1	1,427	---	---	0
Luling-Branyon.	Austin Group and Edwards Limestone.	1,834	559	36	1,752	---	---	---	---
O'Leary A.C.	Austin Group	1,932	589	37	3	10,546	---	---	0
Salt Flat	Austin Group and Edwards Limestone.	2,250	686	36	61	---	---	---	---
Staples	Austin Group	695	212	23	23	30,496	---	441	18
Tenney Creek	---do------	2,335	712	36	75	1,608,124	---	37,308	363
Total------						6,745,805	15,692	175,544	6,626
				Dimmit County					
Espantosa Lake	Austin Group	---	---	---	1	34,234	---	34,234	7
Evergreen Farms.	---do------	---	---	---	1	6,322	---	6,322	9,658
Fitz A.C.	---do------	5,374	1,638	44	1	720	---	---	0
Thirteen Austin.	---do------	5,808	1,770	34	1	77,219	---	999	54
Total------						118,495	---	41,555	9,719

				Fayette County					
Monument Hill Austin.	Austin Group	10,633	3,241	47	1	3,402	---	---	0
				Frio County					
Dilley	Austin Group	---	---	---	9	86,437	---	86,437	5,932
Divot	---do------	5,533	1,686	---	---	6,003	---	---	---
Doering Ranch	---do------	5,500	1,676	---	---	4,522	---	---	---
East Derby	---do------	---	---	---	8	45,776	---	45,776	2,047
Frio Town	---do------	2,600	792	---	---	666	---	0	---
Hindes A.C.	---do------	7,106	2,166	25	1	2,475	---	---	0
Pearsall A.C.	---do------	5,350	1,631	35	[7]232	11,756,510	---	4,759,850	1,701,635
Pearsall South.	---do------	---	---	---	9	107,841	---	107,841	58,286
Sand Hollow 3700 SD.	---do------	4,934	1,504	---	---	2,381	---	---	---
Schattel	---do------	5,300	1,615	---	---	[2]633	---	[3]0	0
Stacy	---do------	---	---	---	3	38,655	---	38,655	8
Total--						12,051,899	---	5,038,559	1,767,908
				Gonzales County					
Austin Pierce	Austin Group	10,838	3,303	43	2	119,176	---	3,341	83
Cheapside NW A.C.	---do------	10,108	3,081	39	1	15,979	7,455	---	0
Cosmopolitan	---do------	6,824	2,080	---	---	2,306	---	2,306	2
Ottine	---do------	3,790	1,155	32	---	12,000	---	0	---
Mag	---do------	---	---	---	1	67,354	---	67,354	27,109
Pilgrim	---do------	---	---	---	1	17,060	---	17,060	3,270
Total--						233,875	7,455	90,061	30,464

Table 1.--*Oil and gas production, by county, from Upper Cretaceous chalk reservoirs in Texas*—Continued

Field or pool	Stratigraphic unit	Average top of producing formation: Feet	Average top of producing formation: Meters	Average API[1] gravity (degrees)	Total wells	Cumulative oil (bbl) (through 1976[8])	Cumulative gas (Mcf) (through 1974)	Current oil (bbl) (1976[8])	Current gas (Mcf) (1976)
				Guadalupe County					
Alderman	Austin Group	1,748	533	23	1	1,360	---	135	12
Berlin New	---do------	1,650	503	---	---	[2]387	---	---	---
Carver-Kallison.	---do------	2,450	747	34	1	57,169	---	47	0
Chas. N. Jones	---do------	2,402	732	14	2	4,045	34	---	1
Clark	---do------	2,360	719	34	---	424,471	---	---	0
Darst Creek	---do------	2,240	683	33	769	---	---	---	0
Day A.C.	---do------	2,554	778	38	4	1,834	---	---	0
Geise-Springs 1900.	Austin Group and Buda Limestone.	1,912	583	137	1	1,040	---	0	0
Jayeddie	Austin Group	2,015	614	29	7	72,670	---	---	0
Jayeddie South.	---do------	1,970	600	25	3	89,891	---	---	0
John Deering	---do------	---	---	---	---	17,684	---	33	2
La Vernia A.C.	---do------	1,716	523	17	3	65,792	---	2,878	24
Luling-Branyon 1700	---do------	1,713	522	---	3	---	---	---	0
Luling-Branyon 1600	---do------	1,608	490	1	1	---	---	---	0
Manford	---do------	2,290	698	37	2	434,825	---	---	0
Maple Hughes 1500 Burton	---do------	1,552	473	16	2	3,715	72	---	0
Mill Creek	---do------	2,182	665	33	3	35,956	---	---	0
Sal Mar	---do------	2,040	622	---	---	[2]11,427	---	---	---
United	---do------	2,582	787	39	---	17,364	---	---	0
Wolf Creek	---do------	2,041	622	36	8	35,497	---	---	0
Zoboroski	---do------	2,200	671	35	30	387,460	---	---	0
Total-----------						1,662,587	106	3,093	39

Hays County									
Schubert A.C.	Austin Group	741	226	25	1	---	---	---	0
Hill County									
Mt. Calm	Austin Group	607	185	31	6	1,084	---	---	0
Jasper County									
Turpentine 10390 Lime.	Austin Group	10,390	3,167	49	1	1,760	10,712	---	0
Jim Wells County									
Stratton A.C. West Lower.	Austin Group	6,595	2,010	62	1	---	330,909	---	0
Stratton A.C. West Middle.	---do------	---	---	---	5	---	---	---	231,739
Stratton A.C. West Upper.	---do------	---	---	---	6	---	---	---	862,660
Total--						---	330,909	---	1,094,399
Karnes County									
Falls City A.C.	Austin Group	10,258	3,127	40	2	16,795	---	0	0
Labus Austin	---do------	10,053	3,064	41	1	1,729	4,299	---	0
Total--						18,524	4,299	0	0
Kleberg County									
Stratton A.C. Lower.	Austin Group	6,880	2,097	57	1	[2]0	1,390,699	0	152,058

Table 1.--*Oil and gas production, by county, from Upper Cretaceous chalk reservoirs in Texas*—Continued

Field or pool	Stratigraphic unit	Average top of producing formation		Average API[1] gravity (degrees)	Total wells	Cumulative oil (bbl) (through 1976[8])	Cumulative gas (Mcf) (through 1974)	Current oil (bbl) (1976[8])	Current gas (Mcf) (1976)
		Feet	Meters						
				La Salle County					
Millet West	Austin Group	---	---	---	1	1,146	---	1,146	7
Ronnie SW A.C.	---do------	8,218	2,505	30	1	676	640	---	0
Total						1,822	640	1,146	7
				Lee County					
Giddings A.C.	Austin Group	7,480	2,280	40	3	610,186	---	158,072	250,914
Giddings A.C. East.	---do------	8,190	2,496	37	1	78,242	63	12,035	24
Total						688,428	63	170,107	250,938
				Madison County					
Halliday A.C.	Austin Group	8,174	2,491	39	2	5,500	16,358	---	0
				Marion County					
Caddo	Saratoga Chalk	1,400	427	---	---	---	---	---	---
Potter	Austin and Navarro Groups.	2,470	753	40	100	3,660,139	---	15,869	1,328
Total						3,660,139	---	15,869	1,328

Maverick County									
Burr, North	Austin Group	---	---	---	1	14,138	---	10,710	12
Chittim A.C.	---do------	1,440	439	17	5	149,707	---	---	0
Four Aces A.C.	---do------	4,040	1,231	37	1	39,968	---	40	0
Jay-Boy	---do------	ca. 4,300	1,310	---	1	1,688	---	1,688	1,241
Robert Cage	---do------	---	---	---	3	2,791	---	2,791	13
Sacatosa 2780 Austin.	---do------	2,780	847	31	1	4,873	1,676	---	0
Total---						213,165	1,676	15,229	1,266
Milam County									
Cherokee A.C. Lower.	Lower pt., Austin Group.	5,652	1,723	33	6	159,525	8,613	48,991	83
Nueces County									
Agua Dulce Austin L. 6850.	Austin Group	6,850	2,088	N.A.	2	---	---	0	0
Agua Dulce Austin L.	---do------	---	---	---	6	---	---	---	473,808
Agua Dulce Austin U.	---do------	---	---	N.A.	3	5,184	---	5,184	235,014
Total--						5,184	---	5,184	708,822
Robertson County									
Maggie Austin	Austin Group	6,814	2,077	34	1	5,229	[4]1,339	2,561	1,339
San Augustine County									
Macedonia Chalk.	Austin Group	6,380	1,945	38	2	2,435	---	---	0

Table 1.--*Oil and gas production, by county, from Upper Cretaceous chalk reservoirs in Texas*—Continued

Field or pool	Stratigraphic unit	Average top of producing formation		Average API[1] gravity (degrees)	Total wells	Cumulative oil (bbl) (through 1976[8])	Cumulative gas (Mcf) (through 1974)	Current oil (bbl) (1976[8])	Current gas (Mcf) (1976)
		Feet	Meters						
				Shelby County					
Center Saratoga.	Saratoga Chalk	2,204	672	42	2	136,349	[4]37,148	85,083	37,148
				Van Zandt County					
Van A.C.	Austin Group	2,662	811	34	6	203,574	26,057	29,739	6,053
				Washington County					
Brenham	Austin Group	14,800	4,511	N.A.	---	---	[4]95,373	---	44,974
				Webb County					
Melinda-Mag	Austin Group	9,752	2,972	---	1	[2]0	27,082	[3]0	0
				Wilson County					
Dismukes A.C.	Austin Group	4,913	1,497	32	1	45,551	---	---	0
Donoho Ch. Upper.	Upper Chalk	4,341	1,323	32	1	1,016	22	0	0
Floresville E A.C.	Austin Group	4,885	1,489	32	2	56,751	---	0	0
Higgins	---do------	5,612	1,711	40	6	178,078	---	---	0
La Vernia A.C. Crevice.	---do------	2,812	857	33	6	137,244	---	---	0

McLain	---do------	---	---	---	1	[6]8,798	---	[7]8,798	3
Pawlelek	---do------	---	---	---	1	18,887	---	18,887	7,576
Poth N A.C.	---do------	6,157	1,877	34	1	39,414	---	---	0
Poth E A.C.	---do------	7,255	2,211	30	1	14,884	5,963	0	0
Saspamco	---do------	2,833	863	24	50	1,217,796	---	328	6
Stockdale A.C.	---do------	4,882	1,488	31	4	285,985	---	---	0
Stockdale E Chk L.	---do------	4,826	1,471	34	5	200,913	---	---	0
Stockdale E Chk U.	---do------	4,755	1,449	33	1	93,399	---	---	0
Stockdale N Chk U.	---do------	4,848	1,479	36	1	43,300	---	---	0
Stockdale W Chk U.	---do------	4,768	1,453	34	2	41,248	1,319	1,477	47
Sutil	---do------	---	---	---	1	545	---	545	8
Total--						2,383,809	7,304	30,035	7,640
Zavala County									
Goodwell	Austin Group	---	---	---	1	5,162	---	5,162	8
Jeune	---do------	---	---	---	---	9,115	---	9,115	3,645
Leta AC-A	---do------	---	---	---	2	129,944	[6]40,570	86,481	49,042
Leta AC-B	---do------	---	---	---	---	3,883	---	1,489	673
Loma Vista	---do------	---	---	---	2	8,022	3,627	8,022	6,486
Total--						156,126	[6]44,197	110,269	59,854
Texas total--						30,270,173	2,187,458	5,882,970	4,180,845

[1]API, American Petroleum Institute.
[2]Cumulative production to December 31, 1974.
[3]Production from January 1, 1974 to January 1, 1975.
[4]Cumulative production to December 31, 1976.
[5]Production from January 1, 1976 to January 1, 1977.
[6]Cumulative production to June 1, 1976.
[7]Production from June 1, 1975 to June 1, 1976.
[8]Includes condensate.

Table 2.--*Oil and gas production, by parish, from Upper Cretaceous chalk reservoirs in Louisiana*

[Data taken from International Oil Scouts Association (1976).
Leader (---) indicates information not available; Mcf, 1,000 ft^3.]

Parish	Field or pool	Stratigraphic unit	Average top of producing formation		Average API[1] gravity (degrees)	Total wells	Cumulative oil (bbl) (through 1975[2])	Cumulative gas (Mcf) (through 1974)	Current oil (bbl) (1975[2])	Current gas (Mcf) (1974)
			Feet	Meters						
Bossier-Caddo.	Millers Bluff	Annona Chalk	2,300	701	---	11	---	---	---	---
Caddo	Caddo-Pine Island.	---do-------	1,400	427	---	---	---	---	---	---
E & W Carroll.	Epps	Monroe gas rock	2,300	701	---	29	---	---	0	---
Desoto	Logansport	Annona Chalk	1,545	471	---	---	---	---	---	---
	Oxford	Saratoga Chalk	1,807	551	42	---	---	---	---	---
	Red River-Bull Bayou	Saratoga and Annona Chalks.	850	259	42	---	---	---	---	---
	Spider	Annona Chalk	1,626	496	41	---	---	---	---	---
Morehouse-Ouachita-Union.	Monroe	Monroe gas rock	2,145	654	---	4,100	---	---	---	---
Sabine	Pendleton Many.	Saratoga Chalk	2,840	866	41	803	19,774,705	3,489,342	94,662	0
	---do----	---do---------	2,771	845	42	---	---	---	---	---
	---do----	Annona Chalk	3,074	937	42	---	---	---	---	---
	Blue Lake	Chalk	2,100	640	45	18	161,510	---	0	---
	Converse	Annona Chalk and Ozan Fm.	1,500	457	23	512	5,612,981	814,794	55,947	170,540
	---do---	Saratoga Chalk	1,716	523	47	---	---	---	---	---
	Fort Jessup	---do---------	3,017	920	42	200	7,571,179	2,243,453	36,851	0
	Many New	Annona Chalk	3,074	937	47	---	---	---	---	---
	---do---	Saratoga Chalk	2,771	845	42	---	533	---	0	---
	Pleasant Hill	Annona Chalk	1,974	602	43	---	---	---	---	---
	Rattan	Austin equivalent.	6,890	2,100	62	3	---	---	---	---
	---do---	Saratoga Chalk	5,566	1,697	60	---	564,150	89,393	93,339	2,632
	Zwolle	---do---------	2,230	680	---	431	16,325,485	---	---	---
	---do--- and Ozan Fm.	Annona Chalk	2,100	640	42	---	---	---	---	---
Louisiana Total							50,010,543	6,636,982	280,799	173,172

[1]API, American Petroleum Institute.
[2]Includes condensate.

Table 3.--*Oil and gas production, by county, from Upper Cretaceous chalk reservoirs in Mississippi*

[Data taken from International Oil Scouts Association (1976). Leader (---) indicates information not available; Mcf, 1,000 ft^3.]

County	Field or pool	Stratigraphic unit	Average top of producing formation: Feet	Average top of producing formation: Meters	Average API[1] gravity (degrees)	Total wells	Cumulative oil (bbl) (through 1975[2])	Cumulative gas (Mcf) (through 1974)	Current oil (bbl) (1975[2])	Current gas (Mcf) (1974)
Clark	Junction City	Selma Group	2,950	899	18	---	119,108	21,779	4,575	0
	Langsdale West Selma Chalk Oil.	---do------	3,421	1,043	19	14	368,160	119,473	0	0
Total							487,268	141,252	4,575	0
Forest-Pearl River.	Piston Ridge	Selma Group	6,340	1,932	45	1	20,200	4	3,460	0
Hinds-Rankin.	Jackson	---do------	2,420	738	---	157	---	117,777,195	---	23,907
Jasper	Heidelberg	---do------	3,921	1,195	---	---	353	440,669	12	90,224
Jones-Jasper.	Sharon	---do------	4,430	1,350	59	---	137	123,034	0	0
Jefferson Davis-Simpson.	Gwinville	---do------	6,700	2,042	52	2	362	94,610	111	22,469
Lamar-Marion.	Baxterville	---do------	6,560	1,999	54	---	6,672	1,931,441	432	151,242
Madison	Flora Selma Gas Rock Oil.	---do------	4,357	1,328	26	33	5,113,652	6,340	269,551	0
Rankin	Pearl Selma Gas Rock.	---do------	2,480	756	16	1	---	91,227	---	2,860
Sharkey	Cary Selma Gas Rock Oil.	---do------	3,270	997	25	7	153,458	---	0	---
Yazoo-Madison.	Pickens	---do------	4,434	1,351	38	---	1,432,894	293,655	17,116	9,765
Yazoo	Tinsley	---do------	4,400	1,341	---	---	189,199,274	93,225	1,208,287	0
Mississippi Total							196,414,270	120,992,652	1,503,544	300,467

[1]API, American Petroleum Institute.
[2]Includes condensate.

Table 4.--*Oil and gas production, by county, from Upper Cretaceous chalk reservoirs in Alabama*

[Data taken from International Oil Scouts Association (1976). Leader (---) indicates information not available; Mcf, 1,000 ft^3.]

Field or pool	Stratigraphic unit	Average top of producing formation: Feet	Average top of producing formation: Meters	Average API[1] gravity (degrees)	Total wells	Cumulative oil (bbl) (through 1975[2])	Cumulative gas (Mcf) (through 1974)	Current oil (bbl) (1975[2])	Current gas (Mcf) (1974)
				Choctaw County					
Gilbertown	Selma Group	2,578	786	20	118	10,627,933	---	157,530	---
---do-----	Eutaw Formation	3,480	1,061	20	---	---	---	---	---
Gilbertown South.	---do----------	3,423	1,043	17	4	55,887	---	8,190	---
Langsdale	---do----------	3,742	1,141	19	3	151,988	---	---	---
Langsdale East	---do----------	3,794	1,156	19	1	204,159	---	2,975	---
Total						11,039,967	---	168,695	---
Alabama total						11,039,967	---	168,695	---

[1]API, American Petroleum Institute.
[2]Includes condensate.

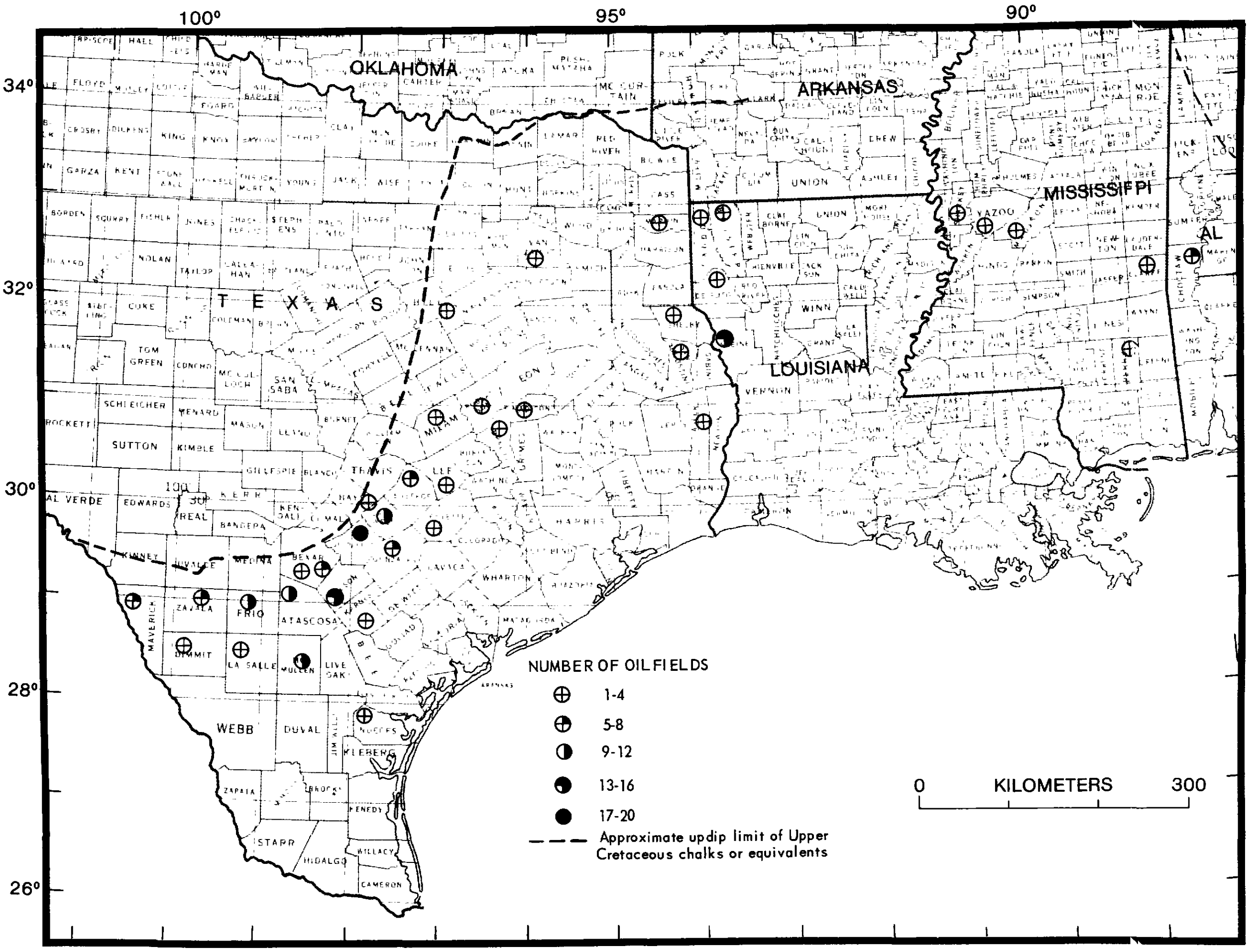


Figure 12.--Regional distribution of oil fields producing from Gulf Coast chalks, plotted by county or parish. Data are taken from tables 1-4 and are based, in part, on state classification of fields as oil or gas producers.

Gas production can be extended deeper than oil production because of the greater ease of getting gas to move through the extremely small pore throats and overall low permeability of deeply buried sediments. Yet, even here, fracturing is critical for the economic viability of any given well.

Fracture or fault systems may also be important as conduits for migrating hydrocarbons into chalks. Much of the oil in the Luling-Branyon, Darst Creek, and other associated fields may have migrated up from the underlying Edwards Limestone through faults within the Luling-Mexia system (McCallum, 1933). In other areas, oil may have been generated in the Eagle Ford Group which underlies the Austin Group. Upward migration of hydrocarbons would have been maximized in areas of intense fracturing of the Austin. In Louisiana as well, upward migration of oil through fractures from the Ozan and other units into overlying chalks has occurred in a number of important fields (Woods, 1963).

Fracture systems can be enlarged through solution (Woods, 1963), so that in some areas, despite very low matrix permeabilities, chalk sections are major zones of fluid movement. Indeed, in England the chalk is a major aquifer supplying about 15 percent of all the potable water in the country (Price and others, 1976). Water-flow rates as much as 2 km/day have been measured in this unit (Atkinson and Smith, 1974), and exchange of fluids between the matrix pores and fractures is considered to be insignificant as a result of the extremely small pore sizes (Price and others, 1976).

On the other hand, fracture systems can undergo cementation with calcite and other minerals and can therefore also be rendered ineffective as fluid conduits. Thus, some areas that might be expected to have reservoir potential because of structural deformation and fracturing may, in fact, be virtually impermeable owing to later cementation of the open fractures. Prediction of these conditions prior to drilling is very difficult.

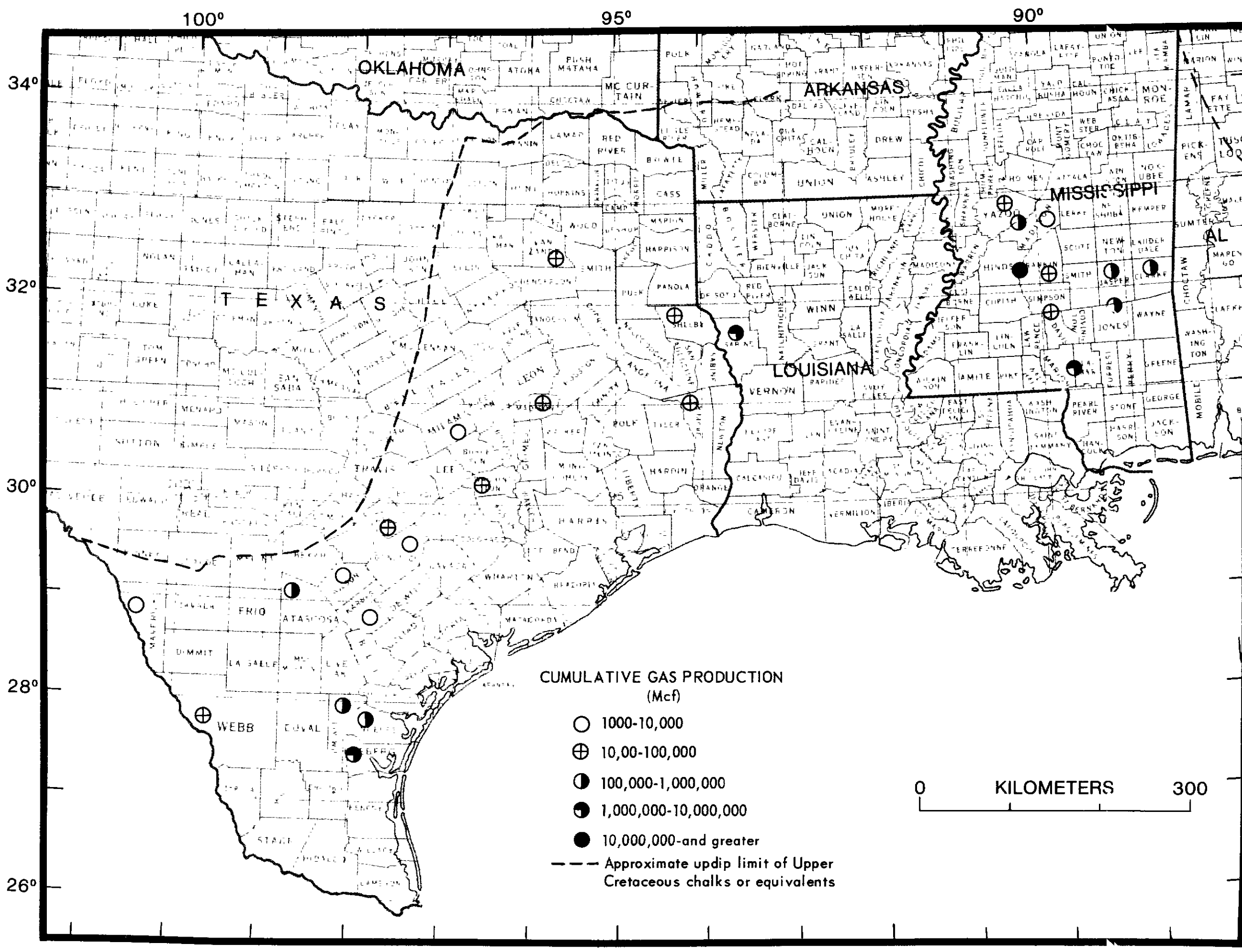


Figure 13.--Regional distribution of cumulative gas production from Gulf Coast chalks, plotted by county or parish. Data are taken from tables 1-4.

Thus, oil and gas production from Gulf Coast chalks to date has depended on the presence of a number of factors. Shallow burial (and paleoburial) allow retention of significant matrix porosity and hydrocarbon storage capacity of the formation. Fracturing greatly increases the effective permeability of the sediment and often provides pathways both for migration of the hydrocarbons into the chalk and later for withdrawal of them during production. Effective exploration in Gulf Coast chalks maximizes one or both of these factors.

U.S. Western Interior

Stratigraphy and sedimentology

Chalk deposition was widespread, both in time and space, in the Upper Cretaceous seaway of the U.S. Western Interior. Chalk facies were particularly extensive during transgressive intervals of the late Cenomanian-middle Turonian and Coniacian-Campanian (Kauffman, 1967, 1973; Hancock, 1975). Although the discussion in this section will focus mainly on the Niobrara Formation, significant thicknesses of chalk are present, both in outcrop and in the subsurface, in the Greenhorn Limestone (especially the Hartland Shale and Jetmore Chalk Members) and in the Carlile Shale (particularly the Fairport Chalky Member) (stratigraphy shown in fig. 18). The regional extent and thickness of chalk and associated carbonate facies of the Greenhorn and Niobrara Formations are shown in figures 19 and 20. Toward the west, both units grade progressively into calcareous shales, noncalcareous shales, and sandstones; to the east, facies equivalents have been removed by erosion.

Details of the stratigraphy and facies distribution of the Upper Cretaceous strata of the Western Interior have been described by many authors and will be only briefly reviewed here. For further information, readers are referred to papers by Cobban and Scott (1972), Hancock (1975), Hattin (1962, 1965, 1975a), Kauffman (1967, Reeside (1944), Scott and Cobban (1964), and Weimer (1960).

The Lincoln Limestone Member of the Greenhorn Limestone is composed predominantly of shaly chalk in beds ranging in thickness from 3 cm to 2 m (0.1-6.7 ft). The unit reaches a maximum thickness of 10 m (33 ft) in Kansas (Hattin, 1975a) and 11 m (37 ft) in south-central Colorado (Cobban and Scott, 1972). The Hartland Shale Member of the Greenhorn Limestone has been reported to range from 3-21 m (9-68 ft) in thickness in Kansas (Hattin, 1975a) and is 18 m (59 ft) near Pueblo, Colo. (Cobban and Scott, 1972). Although primarily a calcareous or chalky shale, the Hartland has several thick beds of burrowed, lithified chalk (Hattin, 1971, 1975a). The overlying Jetmore Chalk Member of the Greenhorn Limestone contains numerous beds of chalk that have been traced for hundreds of kilometers. The Jetmore varies from 4 to 7 m (13-23 ft) in thickness in Kansas (Hattin, 1975a), while in Colorado it is part of the more inclusive Bridge Creek Limestone Member of the Greenhorn. Chalk and lithified chalk also form a significant part of the Pfeifer Member of the Greenhorn, some in the form of concretionary or lenticular beds. The Pfeifer ranges from 5 to 8 m (15-25 ft) in thickness in central and western Kansas (Hattin, 1975a). Equivalents of this unit are also part of the Bridge Creek Member in south-central Colorado, where the total Bridge Creek is 17 m (57 ft) thick (Cobban and Scott, 1972). The total Bridge Creek section (which includes the upper part of the Hartland Shale Member and all of the Jetmore Chalk and Pfeifer Shale Members) thins to only 10 m (34 ft) at Huerfano Park, Colo. (Kauffman and others, 1969); thickens rapidly to 40 m (130 ft) near Littleton, Colo. (Scott, 1962) and thins again northward to 25 m (83 ft) near Lyons, Colo. (Cobban and Scott, 1972).

The Fairport Chalky Member of the Carlile Shale contains a significant volume of chalk

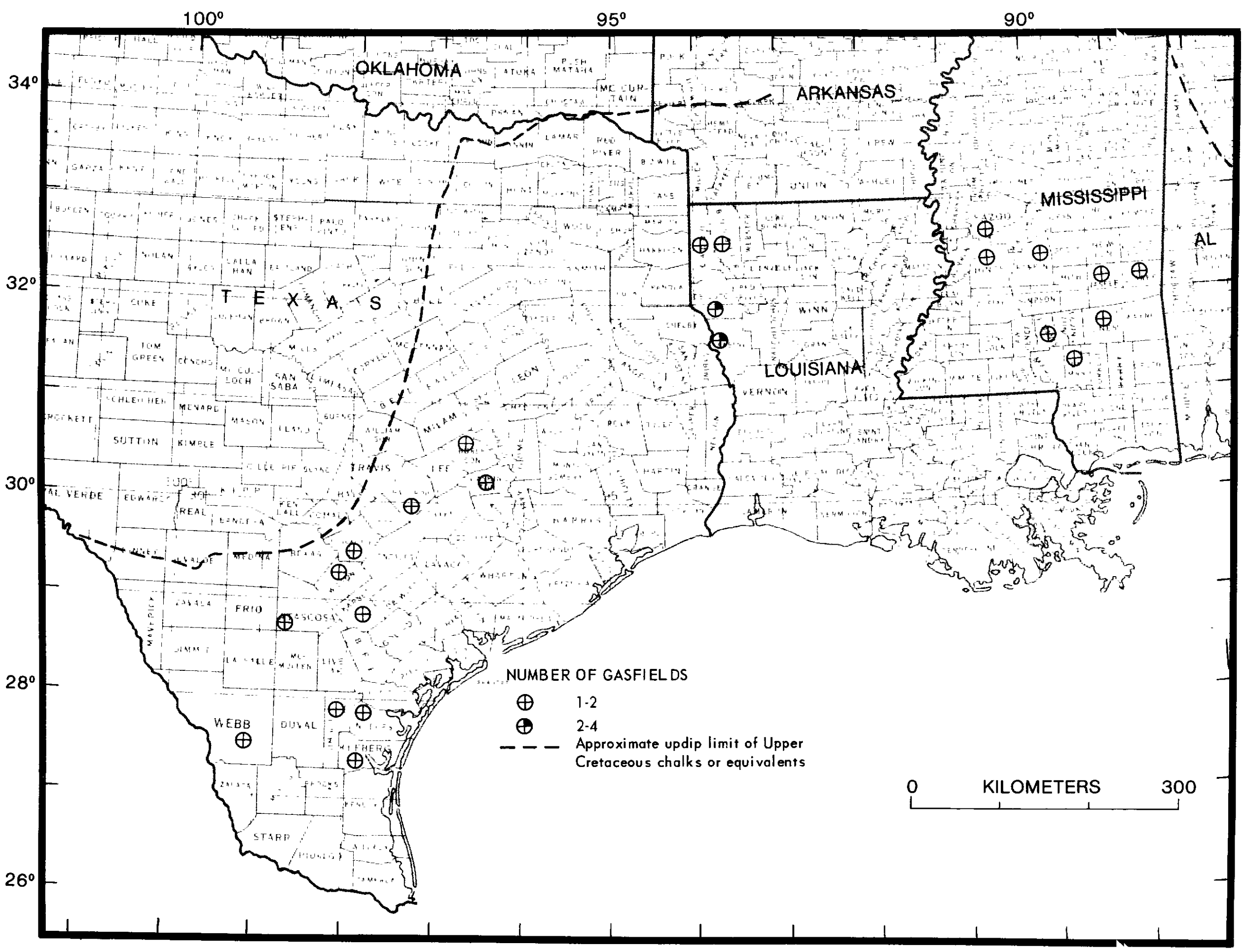


Figure 14.--Regional distribution of gas fields producing from Gulf Coast chalks, plotted by county or parish. Data are taken from tables 1-4 and are based, in part, on state classifications of fields as oil or gas producers.

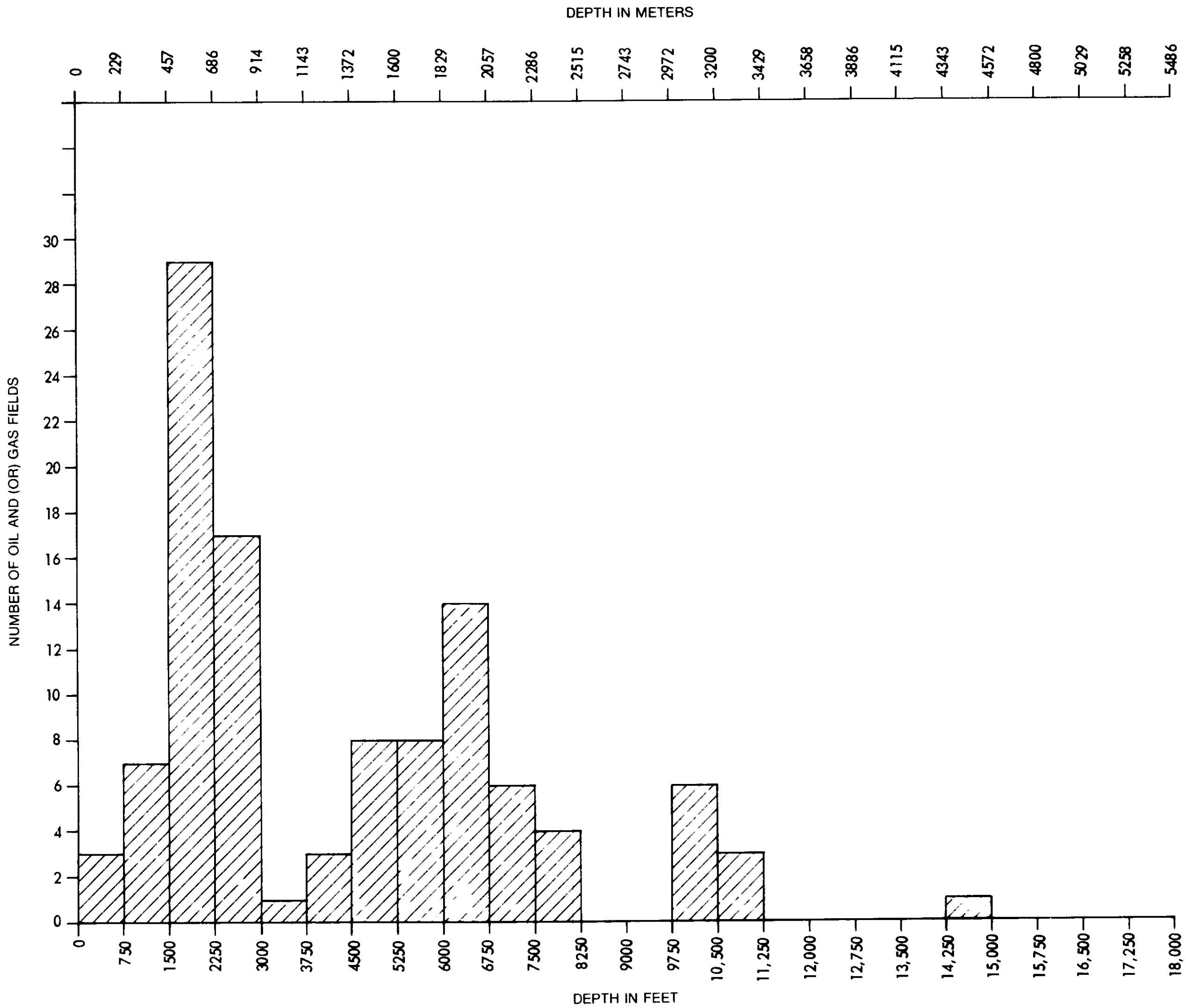


Figure 15.--Histogram showing number of oil and (or) gas fields producing from the Austin Group in Texas as a function of burial depth. Data are taken from table 1.

and shaly chalk and reaches a thickness of 18-24 m (60-80 ft) in Nebraska (Condra and Reed, 1959), 17-21 m (55-70 ft) in central Colorado (Mann, 1958; Dane and others, 1937), and 23-37 m (90-122 ft) in central and western Kansas (Hattin, 1962).

The basal member of the Niobrara Formation, the Fort Hays Limestone, contains some of the purest chalk in the Western Interior. It has virtually no shale interbeds and is 12 m (40 ft) thick in the Pueblo, Colo. area (Scott and Cobban, 1964) and 17-23 m (55-75 ft) thick in central and western Kansas (Hattin, 1965). The overlying Smoky Hill Chalk Member of the Niobrara contains shaly chalk in most areas and is 171-189 m (560-620 ft) thick where present in Kansas (Hattin, 1965) and 213 m (700 ft) thick near Pueblo, Colo. (Scott and Cobban, 1964).

Although many different chalk units are found in the Western Interior, they show a number of unifying elements. Many are uniformly bedded with bedding thickness in the 10-cm to 1-m (4- to 39-in.) range. In fresh outcrops many are dark gray, but they weather to a light-gray, tan, or cream color. Chalk of the Smoky Hill Chalk Member of the Niobrara Formation and parts of the Greenhorn Limestone shows well-preserved lamination consisting of millimeter-scale alternations of clay-rich and clay-poor chalk. Many of these laminated sediments also contain small white specks which have been shown by Hattin (1975b) to be fecal pellets containing abundant coccoliths. In other units, however, extensive burrowing has obliterated any traces of primary depositional fabrics (Frey, 1972).

Most chalk of the Western Interior area

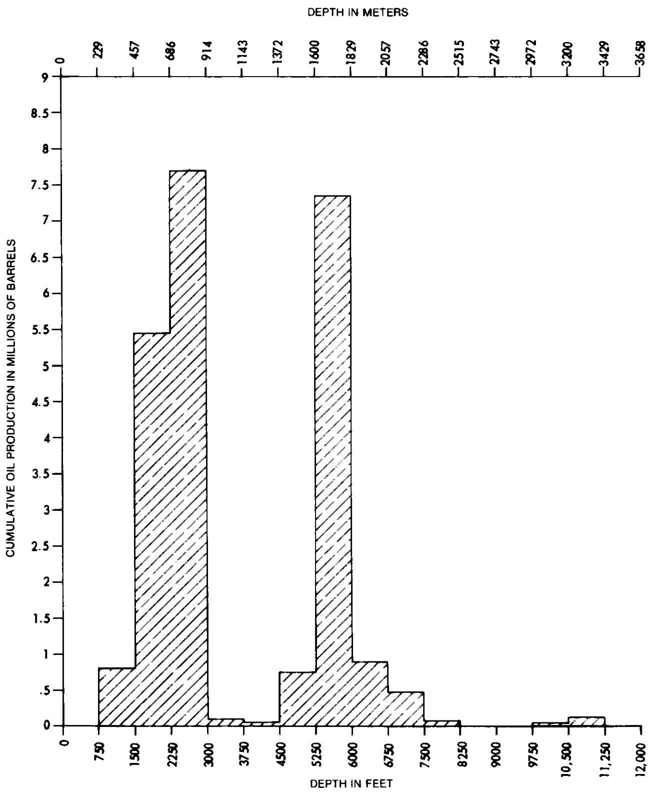


Figure 16.--Histogram showing cumulative oil production in millions of barrels from the Austin Group in Texas as a function of burial depth. Data are taken from table 1, but only include production from 1974 and earlier years.

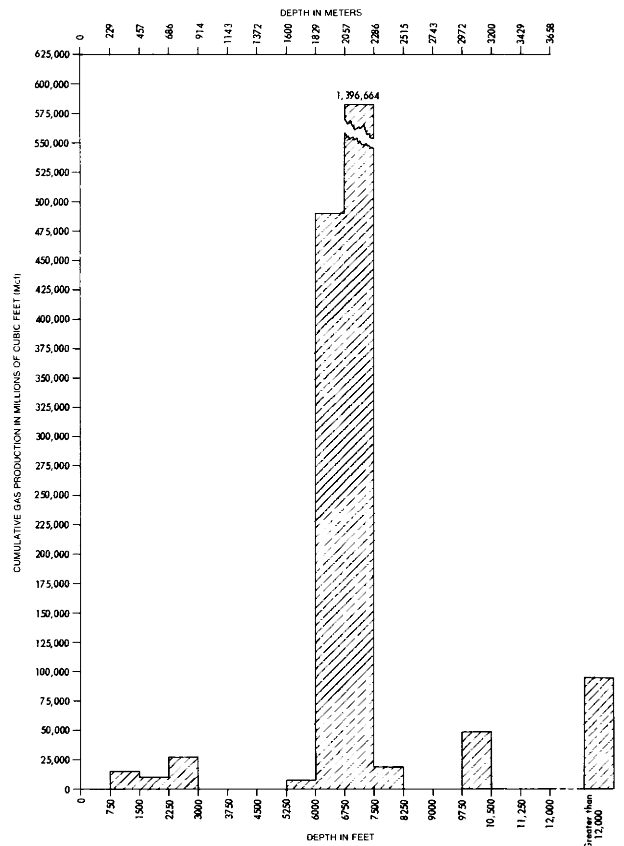


Figure 17.--Histogram showing cumulative gas production in millions of cubic feet (Mcf) from the Austin Group in Texas as a function of burial depth. Data are taken from table 1.

contains appreciable quantities of HCl-insoluble detrital terrigenous material. Insoluble residues of the Greenhorn Limestone in Kansas range from 9.5 to 56.6 percent (by weight) and average 31.9 percent (Hattin, 1975a, p. 73). Insoluble residues of five samples of Greenhorn chalk from the Pueblo, Colo. area, analyzed during the present study, average 15 percent and range as high as 45 percent. Runnels and Dubins (1949, p. 17) reported 2 to 12 percent insoluble residue in the Fort Hays Limestone Member of Kansas. Three samples of the same unit from Pueblo, Colo. examined in the present study, average 18 percent insoluble material. Samples from the Smoky Hill Member of the Niobrara Formation average 30 percent insoluble residue in south-central Colorado and 28 percent in central and western Kansas. The vast bulk of this HCl-insoluble material has been shown by X-ray analysis to consist of clay minerals, detrital quartz, pyrite, hematite, and gypsum. Phosphate is important in some local areas.

Coccoliths are the predominant constituent of Western Interior chalks. Hattin and Darko (1971) discovered as many as $6x10^9$ coccoliths per cm^3 in shaly chalk of the Greenhorn Limestone. SEM photographs of Western Interior chalks (figs. 21-24) show that coccoliths are abundant in other units as well. Subordinate to coccoliths, but still important rock-forming constituents in many Western Interior chalk samples, are planktonic Foraminifera, inoceramid prisms, and oyster shell fragments.

Reconstruction of depositional environments of Western Interior chalks is a complex problem. Estimates of water depths have ranged widely from tens of meters to nearly 1,000 m (3,300 ft) (Eicher, 1969). The problems of comparing faunas from warm interior seas with modern species makes paleoecological determinations of water depths very difficult. The preservation of thin lamination, the common absence of burrowing, restricted benthonic faunas (Eicher and Worstell, 1970), and specialized adaptations of organisms to poorly oxygenated conditions (Hattin, 1965, p. 21) all indicate that bottom-water oxygen content, salinity, or temperature conditions may often have been inhospitable for most organisms. In addition, isotopic and faunal studies (Kauffman and Scholle, 1977; Scholle and Kauffman, 1977) indicate that salinities lower than normal marine and temperatures far higher than the average for modern oceans may have prevailed at times in the restricted Western Interior seaway. All these factors make water-depth interpretations difficult. Deposition was apparently below wave base and below the photic zone, so that most depth interpretations fall in the 50- to 300-m (150- to 1,000-ft) range (Hancock, 1975). Detailed paleoecological interpretations are published in Frey (1972), Hancock (1975), Hattin (1965, 1975a), and Kauffman (1967).

Petrophysical properties and diagenesis

Despite significant bed-to-bed variations in porosity, which may be related to primary depositional differences (for example, grain size, faunal composition, or primary aragonite content), porosities in Western Interior chalks are primarily a function of burial depth. Figure 25 is an isopach map of the Upper Cretaceous Pierre Shale, in most areas the thickest single unit overlying the chalk section.

In areas where thin Pierre and younger units were deposited, underlying chalks have high porosity. In Kansas, for example, outcrop samples of the Smoky Hill have an average of 40 percent porosity, Fort Hays samples have 39 percent porosity, and Fairport samples have 37 percent porosity. In wells in western Kansas and easternmost Colorado, where the Smoky Hill is buried to a present depth of less than 550 m (1,800 ft), the chalk retains 35-40 porosity (with 2.8 md permeability).

In areas where the Pierre and younger sediments are (or were) thicker, porosities in underlying chalks are significantly reduced. Outcrop samples of the Niobrara near Pueblo, Colo., have an estimated 10-15 percent porosity. These samples, although at the surface now, probably were once buried by more than 1,400 m (4,500 ft) of overlying sediments (fig. 25). Outcrop samples of chalk from the Niobrara at Fort Collins, Colo. have an estimated 5 percent porosity or less and were once overlain by approximately 3,050 m (10,000 ft) of total overburden. Within the Denver Basin, subsurface samples of the upper part of the Smoky Hill from 1,655 to 1,667 m (5,429-5,470 ft) in depth have an average of 9.2 percent porosity (0.03 md permeability) in the Excelsior A. G. Nay No. 1 well, Weld County, Colo. (T. Smagala, written commun., 1977). In general, these porosity versus depth relationships hold for all chalk units examined in the Western Interior, and they agree with the predicted porosities shown in figure 1. Porosities of Greenhorn samples are generally significantly lower than those of the Niobrara from the same area. This may be due to the significantly greater overburden thickness over the Greenhorn; it may be related to primary compositional differences (especially in aragonite and clay content) between the two units; or it may be a product of sea-floor cementation during Greenhorn deposition.

Isotopic analyses of Western Interior chalk samples are more difficult to interpret than those from the Gulf Coast because of the variable water temperatures and salinities in the Western Interior seaway (Kauffman and Scholle, 1977). Yet, even in this setting, progressive shifts in oxygen isotopic values, which can be related to the stage of burial diagenesis, are observable. In the Fort Hays Limestone Member of the Niobrara Formation, for example, average oxygen isotopic values vary from -4.9 permil (relative to the PDB standard) in western Kansas; to -6.2 at Pueblo, Colo.; and -7.0 at Fort Collins, Colo. This shift to more negative oxygen isotopic values with increased burial can be demonstrated for most other units in the Western Interior as well, and it parallels the loss of porosity through progressive cementation which is seen in SEM.

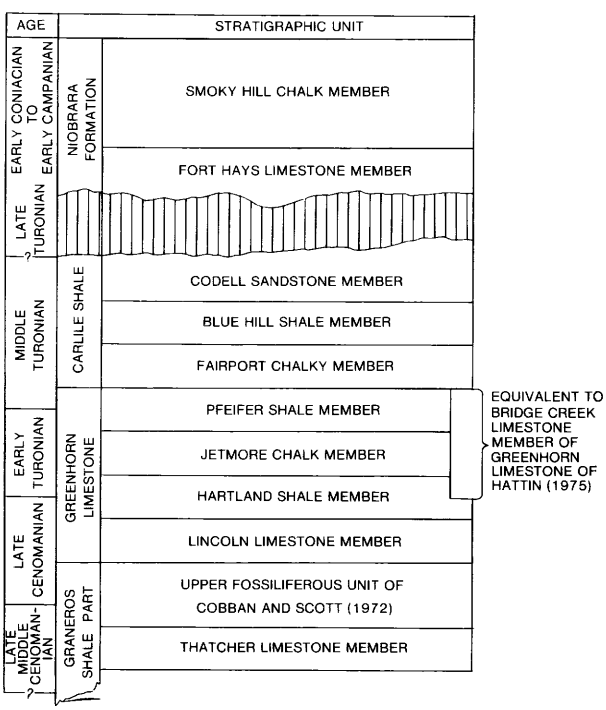


Figure 18.--Stratigraphic section of the Upper Cretaceous Colorado Group of Kansas and eastern Colorado. Modified from Hattin (1975a), Smith (1975), Cobban and Scott (1972), and Scott and Cobban (1964).

Hydrocarbon production

Oil production was discovered as early as 1916 in the Niobrara Formation of the Big Muddy field in Wyoming. Subsequently, a large number of additional fields have been discovered that

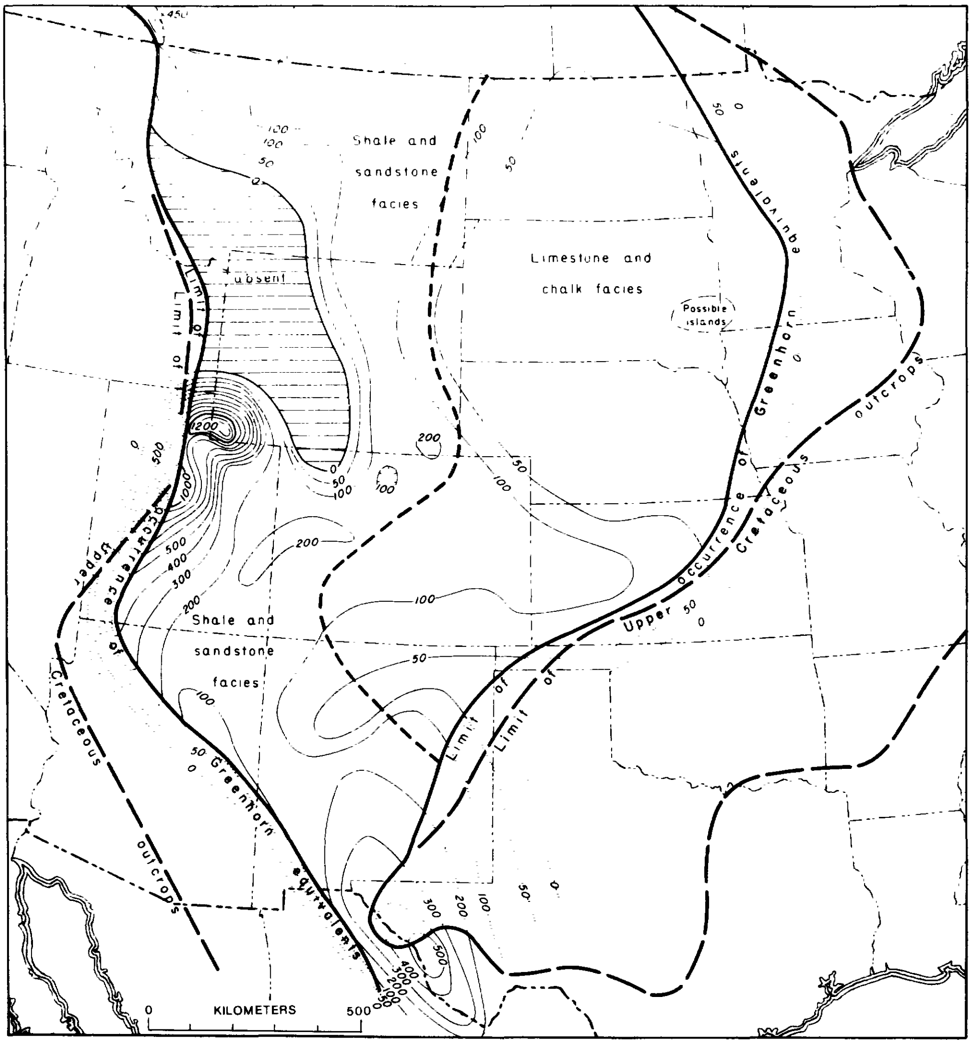


Figure 19.--Thickness and regional distribution of facies in the Greenhorn Limestone and lateral equivalents. Map taken from Reeside (1944).

have oil or gas production from the Niobrara or Greenhorn chalk. None of the fields is large, and cumulative oil production from chalk reservoirs of the Western Interior totals only about 7-8 million bbl. Production figures for the states of Colorado, Wyoming, and New Mexico, broken down by county and field, are presented in tables 5-7. The data are subject to the same qualifications as those listed in the discussion of the Gulf Coast data (tables 1-4). In some cases non-chalk reservoirs may have been included in the tables if they are part of a formation consisting dominantly of chalk. Likewise, some chalk reservoirs undoubtedly have been excluded when no detailed lithologic information was available and they were part of dominantly non-chalk formations.

The regional distribution of production, shown in figures 26-29, indicates that production is not strongly concentrated in any one area. Furthermore, as shown by comparison with figures 19, 20, and 25, the production is largely from areas that have been buried below 1,525 m (5,000 ft) and from areas where the chalk interfingers with thick marine shales. In these fields production is primarily from fracture porosity in calcareous shales or hard shaly chalks (McAuslan, 1959); it is generally associated, therefore, with anticlines, arches, fault zones, or other areas of concentrated structural deformation and fracture development. Cumulative production has been very low, largely because of the burial-related loss of matrix porosity and the associated lack of large-scale hydrocarbon storage capacity of the rock in many of the explored areas. The widespread distribution of production may reflect the fact that Niobrara oil and gas may be indigenous to

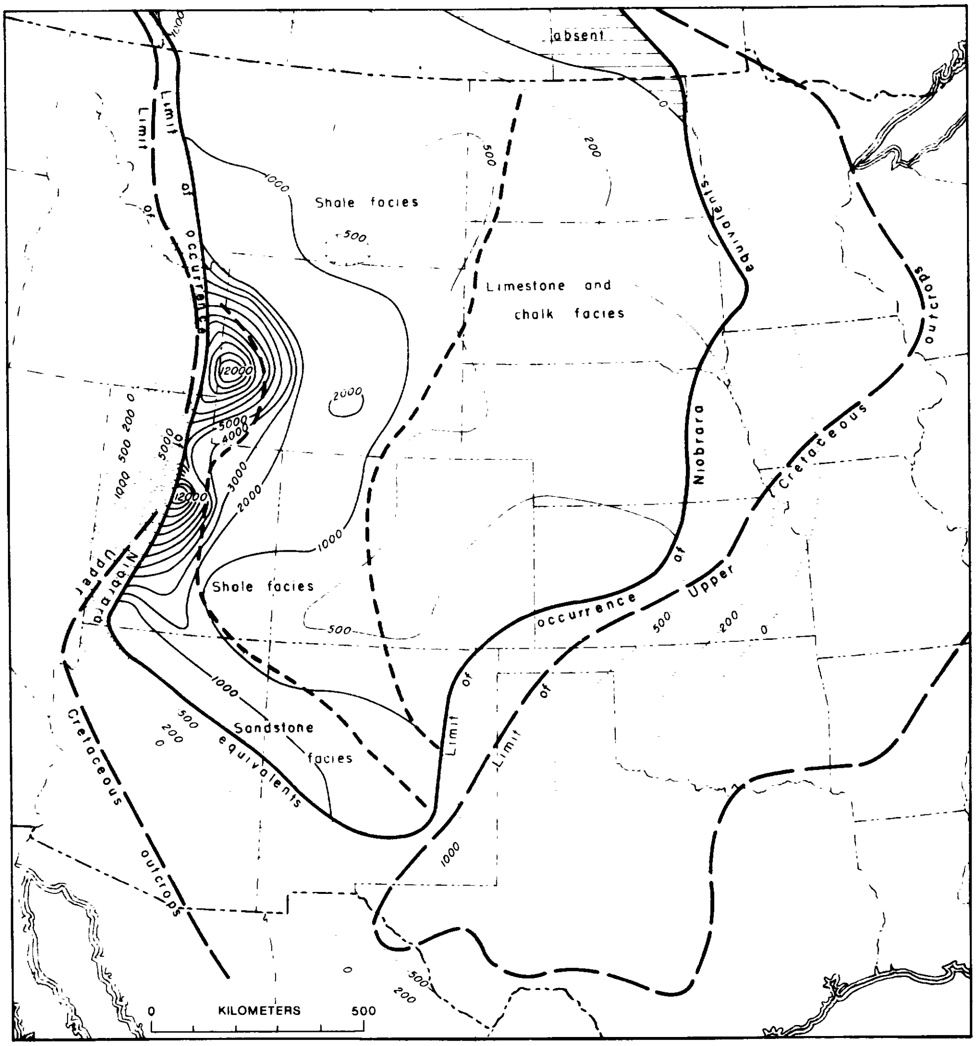


Figure 20.--Thickness and regional distribution of facies in the Niobrara Formation and lateral equivalents. Map taken from Reeside (1944).

that unit; assays reported by McAuslan (1959) indicate the presence of 10-12 gallons of oil per ton of rock in the Niobrara.

The past 5 years have seen a resurgence of exploration in the Niobrara Formation in particular. This exploration has centered in the Beecher Island field of Yuma County, Colo., initially discovered in 1919, and in the Goodland area (Sherman County, Kans.), where natural gas has been produced for local consumption since 1939. More than 60 wells have been drilled over the past 5 years to test the Niobrara in western Kansas and eastern Colorado along a northwest-trend. Currently, exploration is extending into northern Colorado and western Nebraska. Approximately 40 wells, shown in table 8, have resulted in gas production. Although none of these wells has been a major discovery, increased prices for natural gas and modern techniques of well stimulation by hydraulic fracturing have made continued exploration financially attractive for small, independent producers. Most of this recent exploration is in areas where the Niobrara is buried to about 305-762 m (1,000-2,500 ft). At these depths, completed wells cost an average of about $50,000, and wells will presumably pay out in about 2 years.

The bulk of the new gas production is from the top of the Smoky Hill Member of the Niobrara Formation. Figure 30 illustrates typical FDC-CNL (Compensated Neutron Formation Density) log response indicative of a gas-bearing zone at the top of the Niobrara. The characteristic crossover of the neutron and density porosity curves is, however, seen only when logs are run within a short time interval after penetration of the chalk interval. Longer time intervals

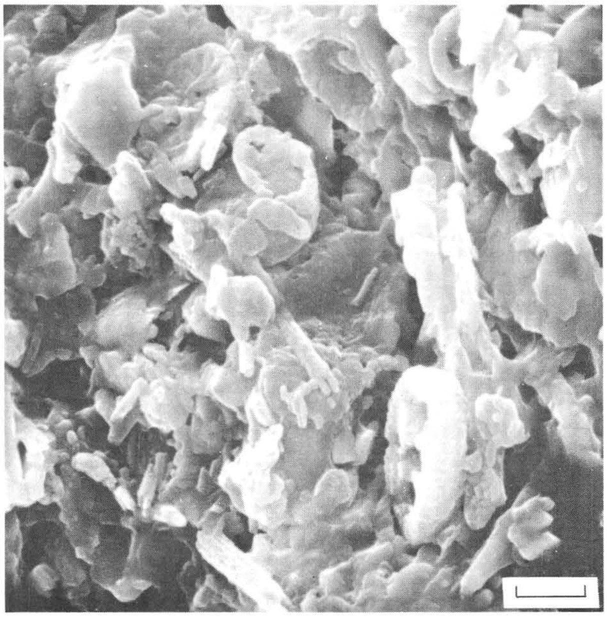


Figure 21.--SEM photomicrograph of a shaly chalk from the lower Turonian, middle part of Hartland Shale Member of the Greenhorn Limestone. Sample is from an outcrop about 5 km (3 mi) north of Bunker Hill (Russell County), Kan. Numerous coccoliths are welded together in an interlocking calcite-cement framework. Sample contains 27 percent insoluble residue. Scale bar is 2 μm.

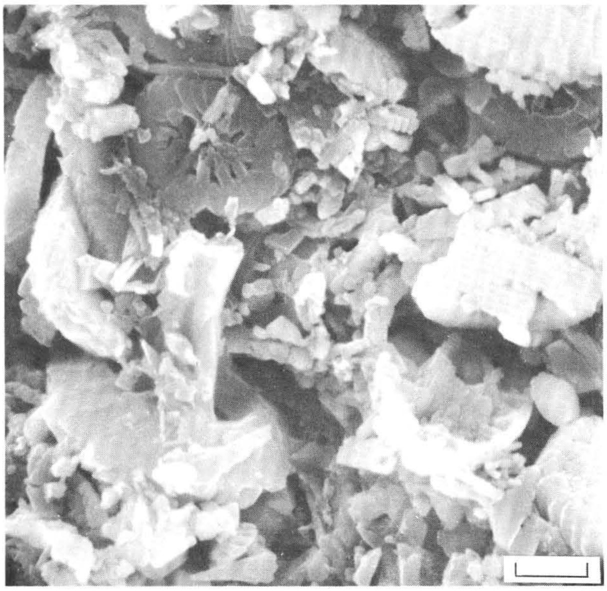


Figure 22.--SEM photomicrograph of a chalk from the Turonian Fairport Chalky Member of the Carlile Shale. Sample is from an outcrop 6 km (4 mi) west of Fairport (Ellis County), Kan. A typical coccolith- and rhabdolith-rich chalk with 15 percent insoluble residue and an estimated 30 percent porosity. Scale bar is 2 μm.

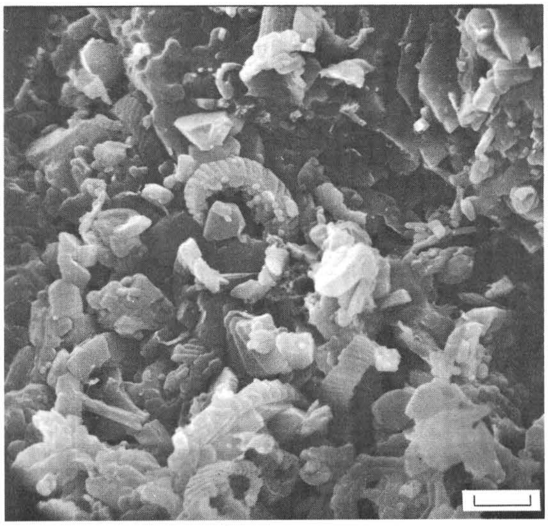


Figure 23.--SEM photomicrograph of a chalk from the Coniacian-Santonian Fort Hays Limestone Member of the Niobrara Formation about 10 m (33 ft) above the base of the unit. Sample is from bluffs along Smoky Hill River, southwest of WaKeeney (Trego County), Kan. Numerous coccoliths and early stages of euhedral overgrowth cementation are visible. Note nonuniform orientation of grains. Sample has 8 percent HCl-insoluble residue and an estimated 35-40 percent porosity. Scale bar is 2 μm.

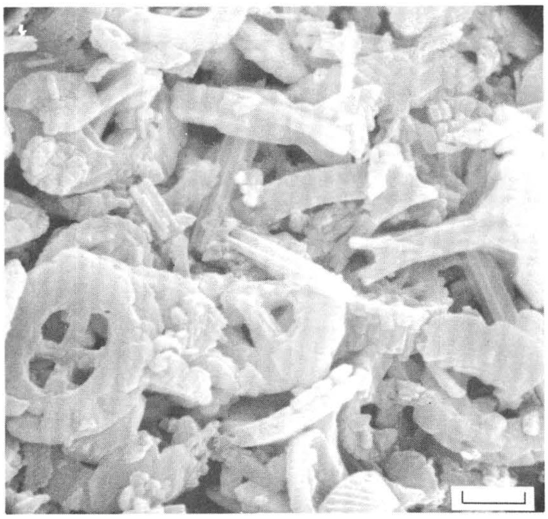


Figure 24.--SEM photomicrograph of a shaly chalk in the Campanian Smoky Hill Chalk Member of the Niobrara Formation. Sample is from within a gas-producing interval of Mountain Petroleum Ltd. No. 1-16 State well (515 m or 1,690 ft in depth), Beecher Island field, Yuma County, Colo. Note abundant coccoliths and rhabdoliths having random orientation and virtually no cementation. Estimated overall porosity of sediment is 40 percent. Scale bar is 2 μm.

Table 5.--*Oil and gas production, by county, from Upper Cretaceous chalk reservoirs in Colorado*

[Data taken from International Oil Scouts Association (1976). Leader (---) indicates information not available; Mcf, 1,000 ft^3.]

Field or pool	Stratigraphic unit	Average top of producing formation		Average API[1] gravity (degrees)	Total wells	Cumulative oil (bbl) (through 1975[2])	Cumulative gas (Mcf) (through 1974)	Current oil (bbl) (1975[2])	Current gas (Mcf) (1974)
		Feet	Meters						
				Archuleta County					
Chromo Greenhorn.	Greenhorn Limestone.	---	---	---	1	1,083	---	0	---
				Jackson County					
Canadian River Niobrara.	Niobrara Formation.	408	124	---	1	3,147	176	0	0
Carlstrom	---do-----	6,457	1,968	---	1	4,026	2,293	1,161	661
Coalmont Niobrara.	---do-----	---	---	---	3	39,166	23,061	24,169	20,641
Total						46,339	25,530	25,330	21,302
				Larimer County					
Berthoud Niobrara.	Niobrara Formation.	240	73	---	---	---	1,164,459	---	0
Kelim Niobrara.	---do-----	7,000	2,134	38	1	653	---	0	---
Loveland Dakota-Niobrara.	---do-----	---	---	---	1	5,555	---	0	---
Loveland Niobrara.	---do-----	4,578	1,395	---	---	377,958	658,546	17,516	4,786
Loveland Niobrara-Timpas.	Fort Hays Limestone Member, Niobrara Formation.	---	---	---	3	63,607	140,862	1,123	0
Total						447,773	1,963,867	18,639	4,786

Moffat County									
Buck Peak Niobrara.	Niobrara Formation.	6,868	2,093	37	---	[3]2,607,167	[3]2,039,606	[3]220,324	[3]277,960
Moffat Niobrara.	---do-----	2,405	733	---	---	86,786	14,031	954	0
Waddle Creek Niobrara.	---do-----	2,076	633	41	6	314,062	---	8,121	---
Total						3,008,015	2,053,637	229,399	277,960
Morgan County									
Bijou Greenhorn.	Greenhorn Limestone.	5,875	1,791	---	1	1,261	900	0	0
Empire	---do-----	6,114	1,864	---	---	5,037	---	0	---
Total						6,298	900	0	0
Routt County									
Bear River	Niobrara Formation.	---	---	36	---	14,779	---	---	---
Curtis Niobrara.	---do-----	3,795	1,157	36	3	210,734	90,376	3,074	576
Dill Gulch Niobrara.	---do-----	---	---	---	1	1,467	---	1,467	---
Fish Creek Niobrara.	---do-----	---	---	---	---	9,313	2,791	2,958	885
Grassey Creek Niobrara.	---do-----	4,750	1,448	---	10	458,982	50,845	28,364	0
Hidden Valley Niobrara.	---do-----	3,691	1,125	39	1	18,986	5,650	0	0
Sage Creek Niobrara.	---do-----	2,418	737	39	4	73,830	---	0	---
Sage Creek North Niobrara.	---do-----	4,944	1,507	---	3	414,388	---	14,822	---
Tow Creek Niobrara.	---do-----	2,600	792	35	42	2,908,936	338,899	7,935	0
Total						4,111,415	488,561	58,620	1,461

Table 5.--*Oil and gas production, by county, from Upper Cretaceous chalk reservoirs in Colorado*—Continued

Field or pool	Stratigraphic unit	Average top of producing formation		Average API[1] gravity (degrees)	Total wells	Cumulative oil (bbl) (through 1975[2])	Cumulative gas (Mcf) (through 1974)	Current oil (bbl) (1975[2])	Current gas (Mcf) (1974)
		Feet	Meters						
Baxter Lake Niobrara.	Niobrara Formation.	5,249	1,600	36	1	963	629	0	0
Lost Creek Niobrara.	---do-----	---	---	---	1	119	---	0	---
Total						1,082	629	0	0
Yuma County									
Beecher Island Niobrara.	Niobrara Formation.	---	---	---	---	---	[3]598,000	---	74,329
Colorado total						7,622,005	4,640,211	331,988	379,838

[1]American Petroleum Institute.
[2]Includes condensate.
[3]As of December 31, 1976 (J. P. Lockridge, written commun., 1977).

Table 6.--*Oil and gas production, by county, from Upper Cretaceous chalk reservoirs in Wyoming*

[Data taken from International Oil Scouts Association (1976). Leader (---) indicates information not available; Mcf, 1,000 ft^3.]

County	Field or pool	Stratigraphic unit	Average top of producing formation: Feet	Average top of producing formation: Meters	Average API[1] gravity (degrees)	Total wells	Cumulative oil (bbl) (through 1975[2])	Cumulative gas (Mcf) (through 1974)	Current oil (bbl) (1975[2])	Current gas (Mcf) (1974)
Carbon	Espy	Niobrara Formation.	4,013	1,223	43	---	497,377	---	13,720	---
	G P Dome	---do-----	3,000	914	---	3	203,031	---	1,162	---
	Overland	---do-----	3,819	1,164	---	1	11,916	---	1,988	---
Total							712,324	---	16,870	---
Converse	Big Muddy and Big Muddy East.	Niobrara Formation.	2,100	640	---	---	---	---	---	---
Crook	Thornton	Carlile Shale	600	183	---	21	38,516	---	705	---
	Wakeman Flats	---do--------	505	154	---	5	987,965	---	810	---
Total							1,026,481	---	1,515	---
Natrona	Smokey Gap	Niobrara Formation.	705	215	38	21	487,889	---	25,570	---
	Teapot Outside Reserve.	---do------	2,440	744	---	20	179,784	---	0	---
Total							667,673	---	25,570	---
Sweetwater	Buster Basin	Niobrara Formation.	13,216	4,028	---	---	---	---	---	---
	Teepef	---do------	848	254	---	1	0	---	0	---
Wyoming Total							2,406,478	---	43,955	---

[1]API, American Petroleum Institute.
[2]Includes condensate.

Table 7.--*Oil and gas production data, by county, from Upper Cretaceous chalk reservoirs in New Mexico*

[Data taken from International Oil Scouts Association (1976). Leader (---) indicates information not available; Mcf, 1,000 ft^3.]

County	Field or pool	Stratigraphic unit	Average top of producing formation		Average API[1] gravity (degrees)	Total wells	Cumulative oil (bbl) (through 1975[2])	Cumulative gas (Mcf) (through 1974)	Current oil (bbl) (1975[2])	Current gas (Mcf) (1974)
			Feet	Meters						
Rio Arriba	Puerto Chiquito West Mancos.	Greenhorn Limestone.	3,419	1,042	38	---	---	---	---	---
	Stephenson (T)	---do-----	2,931	893	---	1	366	---	0	---
	Not Named Greenhorn Gas.	---do-----	---	---	---	1	2,496	255,652	0	0
Total							2,862	255,652	0	0
New Mexico Total							2,862	255,652	0	0

[1]API, American Petroleum Institute.
[2]Includes condensate.

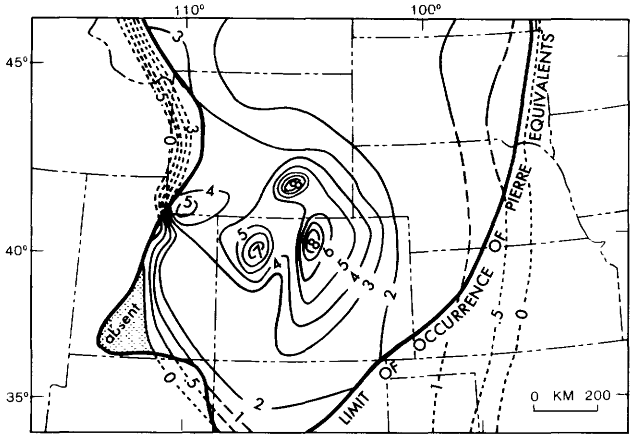


Figure 25.--Isopach map of the Pierre Shale and its lateral equivalents (contour interval in thousand feet). In most areas of chalk deposition the Pierre forms the major part of the total overburden. Adapted from Reeside (1944).

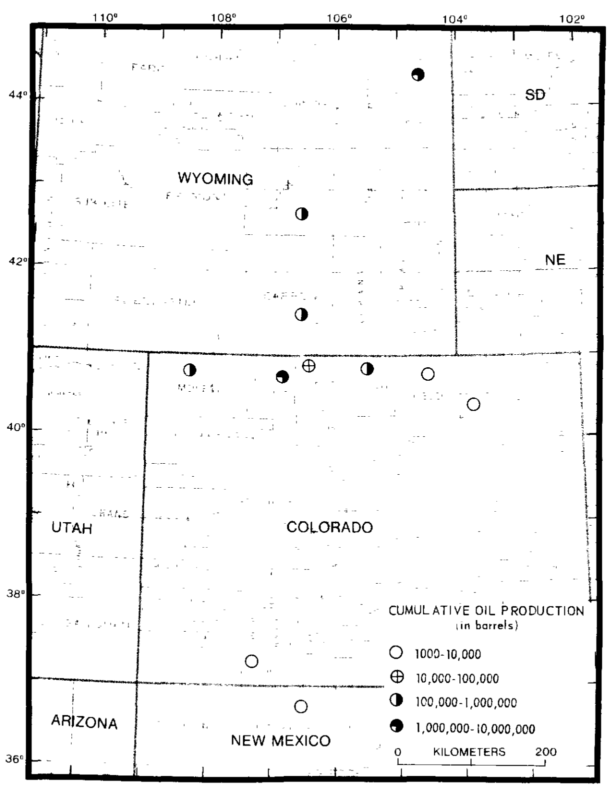


Figure 26.--Regional distribution of cumulative oil production from Western Interior chalks, plotted by county. Data are taken from tables 5-7.

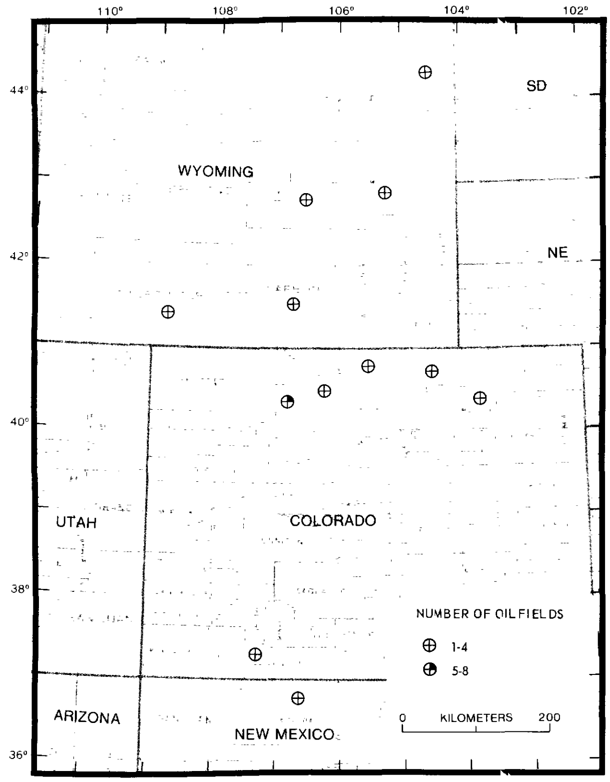


Figure 27.--Regional distribution of oil fields producing from Western Interior chalk, plotted by county. Data are taken from tables 5-7.

between drilling and logging allow invasion of the formation by mud filtrate and make evaluation of gas-bearing zones more difficult. The gas saturated zones range from 8 to 18 m (25-60 ft) in most productive wells. The porosities (as much as 40 percent) and permeabilities (as much as about 5 md) of the productive intervals are typical of much of the Niobrara Formation. Hydrocarbon entrapment at the top of the formation apparently is related to the presence of low relief structures, the fracturing of the Smoky Hill, and the presence of an unfractured, overlying Pierre Shale seal. The presence of fractures, here, as in the Gulf Coast, is instrumental in making these extremely low permeability chalk zones commercially productive. Fortunately, indurated chalk is a brittle sediment that fractures readily, even where affected only by minor deformation.

The gas in these fields, which have never been deeply buried, is presumably derived from organic matter in the Niobrara Formation itself. Carbon isotopic analyses of natural gas samples from the Niobrara of eastern Colorado clearly indicate that the gas, more than 92 percent methane at Beecher Island field (Yuma County, Colo.), is of biogenic (bacterial) origin (D. D. Rice, oral commun., 1977). Thus, burial

Table 8.--*Recent gas-producing wells in Niobrara Formation, eastern Colorado and western Kansas*

[Data from Kansas-Nebraska Natural Gas Company (Written commun., 1977); summarizes wells drilled up to February 22, 1977. Leader (---) indicates information not available; Mcfpd, 1,000 ft^3 per day; IP, initial production.]

Operator	Well name	Location Sec.	Location T.	Location R.	Completion date	Status
Beecher Island field, Yuma County, Colorado						
Kansas-Nebraska	Whomble 1-5	5	3S	43W	9-10-76	IP 473 Mcfpd.
Mountain Petroleum	Whomble 1-6	6	3S	43W	---	Incomplete.
Kansas-Nebraska	Bruder 1-7	7	2S	43W	8-25-76	IP 455 Mcfpd.
Kansas-Nebraska	Bruder 1-8	8	2S	43W	8-24-76	IP 445 Mcfpd.
Kansas-Nebraska	Herbert 1-9	9	2S	43W	---	Complete.
Mountain Petroleum	State 1-16	16	2S	43W	3-11-72	IP 435 Mcfpd.
Mountain Petroleum	New 1-A	17	2S	43W	1-11-75	IP 716 Mcfpd.
Kansas-Nebraska	Rose 1-18	18	2S	43W	8-26-76	IP 980 Mcfpd.
Mountain Petroleum	Rose 1-19	19	2S	43W	2-20-75	IP 839 Mcfpd.
Mountain Petroleum	Strangeways 1-A	20	2S	43W	1-11-75	IP 519 Mcfpd.
Mountain Petroleum	Beecher Island #1	21	2S	43W	3-31-72	IP 68 Mcfpd.
Mountain Petroleum	Eckberg 1-22	22	2S	43W	9-10-76	IP 863 Mcfpd.
Kansas-Nebraska	Cranmer 1-27	27	2S	43W	2-21-75	IP 818 Mcfpd.
Mountain Petroleum	Gracie Chase #1	28	2S	43W	4-10-72	IP 120 Mcfpd.
Mountain Petroleum	State 1-29	29	2S	43W	4-03-74	IP 675 Mcfpd.
Mountain Petroleum	State 2-30	30	2S	43W	5-19-75	IP 1598 Mcfpd.
Mountain Petroleum	State 1-31	31	2S	43W	5-19-75	IP 1203 Mcfpd.
Kansas-Nebraska	Whomble 1-32	32	2S	43W	9-10-76	IP 587 Mcfpd.
Kansas-Nebraska	Eckberg 1-33	33	2S	43W	2-18-75	IP 1287 Mcfpd.
Kansas-Nebraska	Simmons 1-24	24	2S	44W	8-27-76	IP 410 Mcfpd.
Republican field, Yuma County, Colorado						
Kansas-Nebraska	Stone 1-26	20	1N	45W	---	Incomplete.
Kansas-Nebraska	Fonte 1-27	27	1N	45W	2-10-76	IP 304 Mcfpd.
Kansas-Nebraska	Toner 1-28	28	1N	45W	9-10-76	IP 82 Mcfpd.
Shout field, Yuma County, Colorado						
Kansas-Nebraska	Neuhaus 1-34	34	3N	47W	4-07-76	IP 640 Mcfpd.
Kansas-Nebraska	Pioneer Farms 1-3	3	2N	47W	---	Incomplete.

Vernon field, Yuma County, Colorado

Kansas-Nebraska	Allison 1-29	29	1S	44W	3-11-76	IP 260 Mcfpd.
Mountain Petroleum	Allison 1-32	32	2S	44W	---	IP 344 Mcfpd.

Whisper field, Yuma County, Colorado

Kansas-Nebraska	State 1-16	16	3N	47W	5-08-76	IP 700 Mcfpd.

Cherry Creek field, Cheyenne County, Kansas

Mountain Petroleum	Schauer 1-12	12	3S	41W	---	IP 260 Mcfpd.
Murfin	Zyegardt 1-1	1	3S	41W	---	Tight-hole.

Unnamed fields, Yuma-Phillips County, Colorado

Mountain Petroleum	Chapman 1-10	10	5N	46W	---	Tight-hole.
Mountain Petroleum	Ferguson 1-26	26	6N	46W	---	Tight-hole.

Wildcat fields

Kansas-Nebraska	Lippert 1-8	Yuma County, Colo. 8 1S 44W	---	Incomplete.
Kansas-Nebraska	Engel 1-10	Cheyenne County, Kansas 10 3S 42W	---	IP 132 Mcfpd.
Kansas-Nebraska	O'Brian 1-31	Cheyenne County, Kansas 31 4S 41W	---	Incomplete.
Shakespear Oil	Walter #1	Cheyenne County, Kansas 9 3S 41W	---	IP 100 Mcfpd.
Kansas-Nebraska	State 1-16-436	Yuma County, Colorado 16 3N 46W	---	Incomplete.
Kansas-Nebraska	Stulp 1-1	Yuma County, Colorado 1 1N 47W	---	IP 329 Mcfpd.
Murfin	Walz #1	Yuma County, Colorado 3 5S 42W	---	Tight-hole.
Federer	Leach #1	Cheyenne County, Kansas 29 4S 39W	---	Tight-hole.

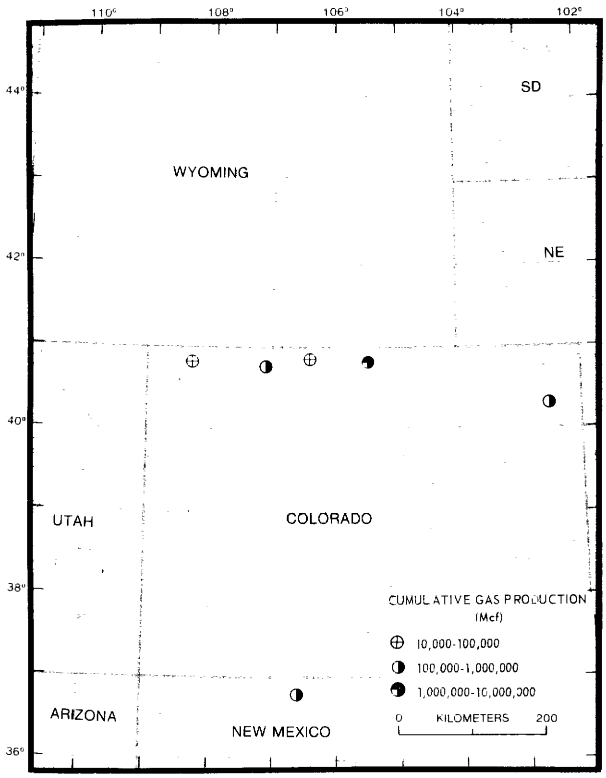


Figure 28.--Regional distribution of cumulative gas production from Western Interior chalks, plotted by county. Data are taken from tables 5-7.

depth is not a critical factor in the origin of the gas.

With increasing gas prices, future increases in gas production can be expected from the Niobrara. The regional extent of chalk facies, the high porosity, and the susceptibility of the Niobrara to fracturing insure at least adequate reservoir properties over broad areas where the unit has not been deeply buried. Even where more extensive burial has taken place, such as in the Denver-Julesburg basin, fractured oil or gas reservoirs, similar to the Loveland or Tow Creek fields of Colorado and the Pearsall field of Texas, may be found. The moderately high kerogen content of much of the Niobrara and the biogenic production of gas even at shallow depths indicate that source beds and conditions suitable for hydrocarbon generation will normally not be limiting factors in exploration. Furthermore, the thick overlying section of Pierre Shale insures adequate seals in most regions. Although considerable additional production can be expected from the Niobrara, it is unlikely that the fields will be more prolific than the ones discovered to date. There is no indication that the conditions responsible for the remarkable chalk reservoirs of the North Sea (discussed later in this paper) are present in the Western Interior. New fields will be small but numerous and will probably be of economic interest mainly to independent operators.

Many areas of potential Niobrara production may already have been drilled. Historically, tens of thousands of wells have penetrated the Niobrara section but only rarely was the chalk interval cored, immediately logged, or tested. Undoubtedly considerable potential production has therefore been overlooked. Increased production from the Niobrara, as well as from Gulf Coast chalks, is augmenting awareness of the potential of chalk reservoirs and should insure more adequate evaluation in the future.

It should be noted that, although the Niobrara is undergoing very active current exploration, a number of other potentially interesting chalk units continue to be unstudied and untested. The Fairport Chalky Member of the Carlile Shale, for example, has interesting features. It is quite porous on outcrop in central and western Kansas (as much as 38 percent pore space), has a section thick enough to be of commercial interest in many areas, and is overlain by the thick Blue Hill Shale Member of the Carlile Shale, an excellent seal. Likewise, the Fort Hays Limestone Member, the

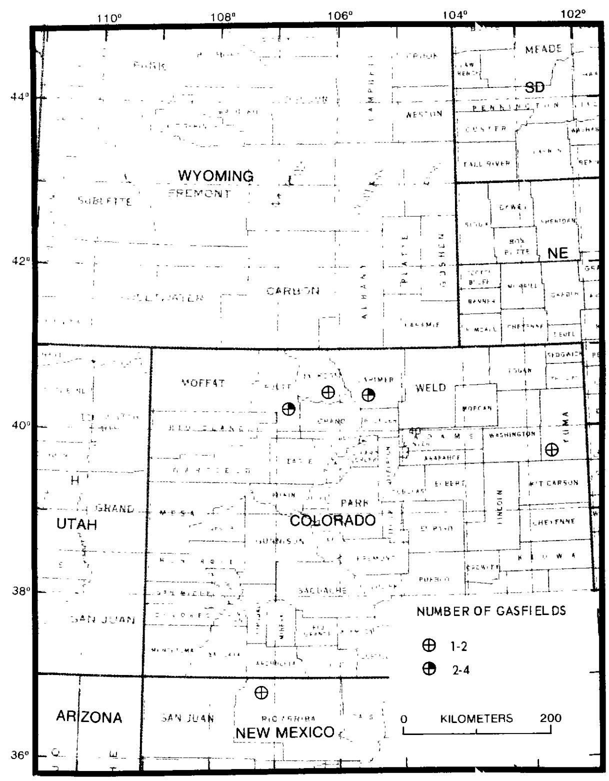


Figure 29.--Regional distribution of gas fields producing from Western Interior chalks, plotted by county. Data are taken from tables 5-7.

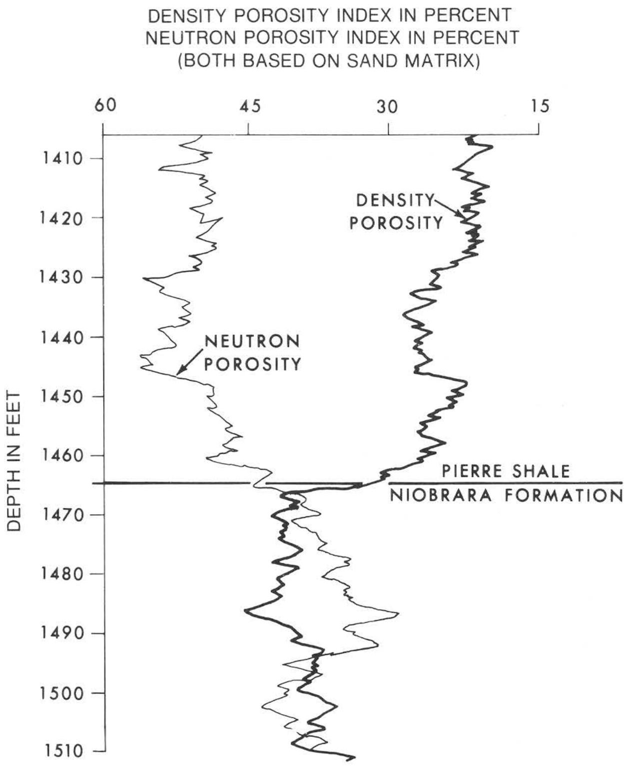


Figure 30.--Redrawn Schlumberger FDC-CNL (Compensated Neutron-Formation Density) log showing typical response in a gas-saturated zone (shaded area) at the top of the Niobrara Formation. Note characteristic crossover of neutron- and density-porosity curves in gas zone. Data from Mountain Petroleum Ltd. State No. 1-29 well, Yuma County, Colo., provided by J. P. Lockridge, Mountain Petroleum Corp.

lower part of the Smoky Hill Chalk Member of the Niobrara Formation, as well as the Hartland Shale, Jetmore Chalk, and Pfeifer Shale Members of the Greenhorn Limestone could be locally prospective sources and reservoirs.

Scotian Shelf

Stratigraphy and sedimentology

A thick chalk section was described by McIver (1972) from the Upper Cretaceous of the Scotian Basin of the Canadian Atlantic outer continental shelf. On the basis of extensive drilling in the area, it has been established that the entire Santonian-Campanian interval and part of the lower Maestrichtian consist ot chalk with interbedded calcareous mudstone and marl (Jansa and Wade, 1975). This unit was termed the Wyandot Formation by McIver (1972).

The Wyandot reaches a thickness of 397 m (1,302 ft) in the Dauntless D-35 well, thins westward to 104 m (340 ft) in the Naskapi N-30 well (Williams and others, 1974), and is entirely absent on the southwestern part of the LaHave Platform (localities shown in fig. 31). The Wyandot is also absent in wells on the Avalon Uplift to the east and north, but equivalent chalks have been found at JOIDES site 111 (Orphan Knoll) (Jansa and Wade, 1975; Ruffman and van Hinte, 1973). Contacts with overlying units are generally conformable (Williams and others, 1974).

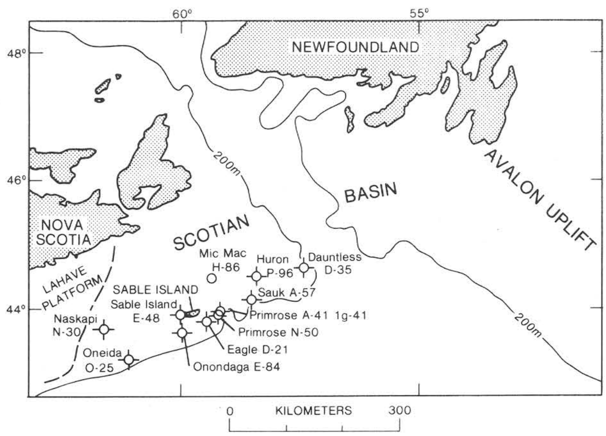


Figure 31.--Map of Scotian Shelf area showing major structural features, location of exploration wells mentioned in text and 200 m isobath.

The Wyandot, although predominantly composed of chalk, becomes progressively more calcarenitic toward the landward portions of the basin and progressively marlier toward the present-day shelf edge (Jansa and Wade, 1975). Wyandot chalk intervals are extremely rich in coccoliths (fig. 32), but can also contain significant quantities of inoceramid prisms and shell fragments, planktonic Foraminifera, sponge spicules, and other skeletal grains. Clay minerals and cristobalitic lepispheres are major constituents of the marls.

Primary sedimentary structures have not been described from the Wyandot Formation because it is rarely cored. Bioturbation is the most predominant feature in the chalk observed in conventional cores from the Shell-Mobil-Tetco Eagle D-21 well (Jansa and Wade, 1975).

Paleoecological data based on planktonic-benthonic foraminiferal ratios and other features lead to the determination of "outer neritic to upper epibathyal" (120-450 m; 400-1,500 ft) water depths for Wyandot deposition (Jansa and Wade, 1975; McIver, 1972; Ruffman and van Hinte, 1973). Wyandot equivalents which may be found beneath the present-day continental slope most likely were deposited in even deeper waters.

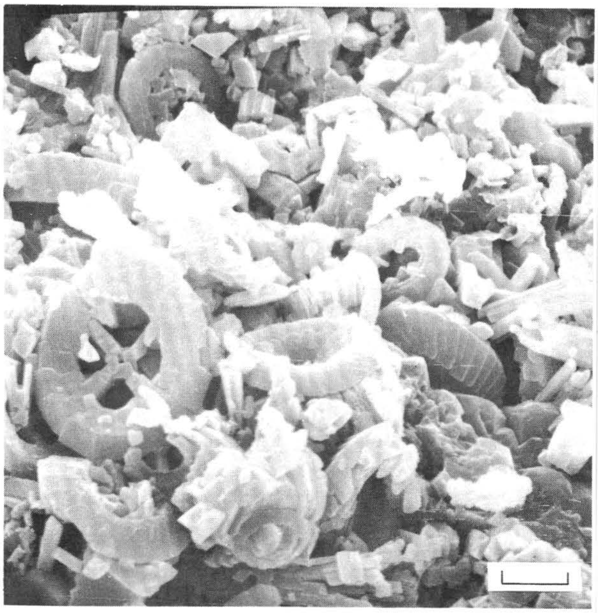


Figure 32.--SEM photomicrograph of chalk from the Wyandot Formation at 1,676 m (5,500 ft) of depth in the Shell-Mobil-Tetco Eagle D-21 well in the Scotian Basin of Canada. Sample is composed almost exclusively of whole and fragmented coccoliths. Porosity is estimated to be about 25 percent. Scale bar is 2.5 μm.

Petrophysical properties and diagenesis

Information on the distribution of porosities and permeabilities of the Wyandot Formation is sparse. Porosities (determined from electric logs) are as high as 35-38 percent in the 946- to 1,039-m (3,105- to 3,408-ft) interval of the Huron P-96 well, and 38-40 percent in the Mic Mac H-86 well at 713-832 m (2,340-2,730 ft) of depth. Where the unit is more deeply buried, porosities decrease significantly. In the Onondaga E-84 well, porosity is about 34 percent at 1,350-1,420 m (4,428-4,658 ft), whereas in the Sauk A-57 it is about 23 percent at 1,476-1,578 m (4,842-5,178 ft).

This porosity-depth relationship fits that shown in figure 1 as the "normal curve." It implies that diagenetic alteration took place in the presence of marine pore fluids, a reasonable inference considering that the Wyandot is conformably overlain by a thick section (as much as 1,220 m or 4,000 ft) of marine shales of the Upper Cretaceous-Tertiary Banquereau Formation (Jansa and Wade, 1975). The data also imply that diagenetic porosity loss is produced by pressure solution due to overburden loading rather than by structural deformation. Horsetail solution seams, microstylolites, and other solution features were mentioned by Jansa and Wade (1975) as indicative of intrastratal dissolution.

As with Gulf Coast and Western Interior chalk units, this progressive depth-related cementation is visible in SEM photographs and evident from oxygen isotopic analyses. These data will not be presented here because of their similarity to those shown for the Gulf Coast and Western Interior.

Hydrocarbon production

No commercial production has been obtained to date from the Wyandot Formation. A number of significant gas shows have been found, however, and these are summarized in table 9. Two of these wells, the Shell-Mobil-Tetco Eagle D-21 and the Shell Primrose 1a-41 were completed in the Wyandot interval (although presently shut-in), anticipating possible future production.

Potential is high for future production from the Wyandot Formation. The absence of freshwater displacement of marine pore fluids accounts for the unit having lost porosity during burial at a significantly slower rate than that of Gulf Coast or Western Interior chalks. Even samples buried as deeply as 1,525-1,825 m (5,000-6,000 ft) retain primary porosities of 20-25 percent. With section thicknesses of 400 m (1,300 ft) or greater and fracture enhancement of permeability, significant fields could be discovered both on the present-day shelf and on the modern continental slope.

COMPARISONS WITH THE NORTH SEA

The total cumulative hydrocarbon production from all North American chalk reservoirs equals less than 10 percent of the estimated recoverable reserves from North Sea chalks, shown in table 10. Wells in the Ekofisk area produce an average of about 10,000 BOPD (Byrd, 1975; World Oil, 1971). What makes these fields so prolific? Are North Sea chalk facies similar to North American ones in terms of original lithology and diagenetic history? Does any potential exist for equivalent prolific production from North American chalks? The answers to these questions are neither obvious nor easily obtainable, but studies conducted to date have provided at least some partial answers.

It is beyond the scope of this paper to fully cover the deposition, diagenesis, and petroleum production history of North Sea chalks. Byrd (1975), Childs and Reed (1975), Hancock and Scholle (1975), Harper and Shaw (1974), Mapstone (1975), Rickards (1974), and Scholle (1977) have provided extensive data on North Sea chalks; and Kent (1975) and Ziegler (1975) have discussed the overall geologic framework of the area. The North Sea chalk section spans the approximately 30-m.y. time interval from Cenomanian to Danian. Chalk deposition covered about 30 percent or more of Europe during that time interval, and over 1,400 m (4,600 ft) of chalk was deposited in the central part of the North Sea (Hancock and

Table 9.--*Gas shows from the Wyandot Formation on the Scotian Shelf, Canada*

[Data compiled from open-filed well reports by D. J. Taylor (written commun., 1976). Leader (---) indicates data not available; Cfpd, ft^3 per day; Bopd, bbl of oil per day.]

Well name	Location	Depth		Shows	Initial production
		Feet	Meters		
Shell-Mobil-Tetco Eagle D-21	43°50'00.000" N. 59°34'09.210" W.	---	---	Gas	1.58 million Cfpd.
Shell Huron P-96	44°35'47.035" N. 58°28'50.688" W.	2,570- 3,400	783- 1,036	Gas	---
Shell Primrose A-41	44°00'06.000" N. 59°06'14.000" W.	4,960- 5,020	1,512- 1,530	Gas	Not tested.
Shell Primrose 1a-41	44°00'06.000" N. 59°06'14.000" W.	4,672- 5,120	1,424- 1,561	Gas and condensate	3.3 million Cfpd and 2.5 Bopd of condensate after acidizing.
Shell Primrose N-50	43°59'48.430" N. 59°06'51.630" W.	4,500- 4,594	1,372- 1,400	Gas	---
Mobil-Tetco Sable Island E-48	43°57'20.500" N. 60°07'23.900" W.	3,720- 3,847	1,134- 1,173	Gas	---

Table 10.--*Estimated recoverable reserves of oil and gas in Upper Cretaceous and Tertiary (Danian) chalk of the North Sea area*

[Modified from Tiratsoo (1976, p. 99-100). Leader (---) indicates data not available.]

Country	Field name	Crude oil (millions of bbl)	Condensate (millions of bbl)	Associated gas (billions of ft^3)
Norway	Ekofisk	1,030	200	3,500
	West Ekofisk	340	165	2,500
	Tor	105	20	250
	Cod	20	30	700
	Edda	50	10	200
	Eldfisk	180	40	950
	S.E. Tor	25	5	60
Denmark	Dan	300	---	---
Total		2,050	470	8,160

Scholle, 1975). Oil and gas production, to date, has been limited to the upper Maestrichtian and Danian part of the section. Production has also been limited to the area within that portion of the Central Graben of the North Sea which has the thickest overlying section of Tertiary sedimentary rocks (fig. 33). In this area the top of the chalk section is buried at a depth between 2,000 and 3,500 m (6,600-11,500 ft). No production is known from shallower chalk sections within the North Sea or from chalks in surrounding onshore regions.

This pattern is opposite from that seen in the Gulf Coast and Western Interior areas where oil and gas production generally decrease as a function of burial depth. However, in the North Sea area much higher porosity values are found in the chalks of the Central Graben than would be predicted by theoretical or observational studies. (See fig. 1.) Porosities as high as 40 percent (and averaging 30 percent) were reported for much of the hydrocarbon

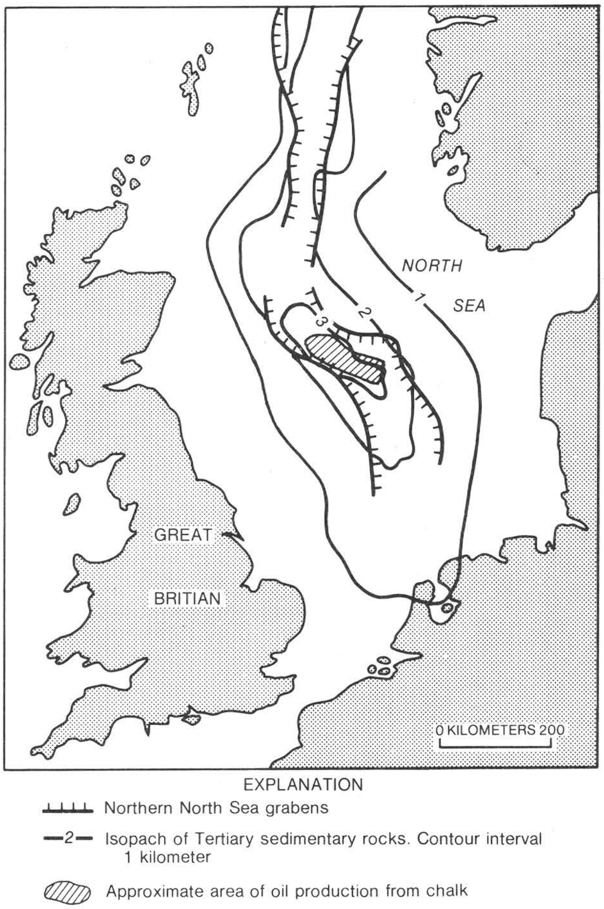


Figure 33.--Isopach map of Tertiary sedimentary rocks of the North Sea in relation to chalk oil and gas reservoirs. Adapted from Scholle (1977).

productive section in the Ekofisk field (Owen, 1972; Rickards, 1974), despite burial depths in excess of 3,000 m (9,900 ft). SEM studies have indicated that the bulk of this pore space is primary and that the North Sea chalks are extremely similar petrographically to those in the Gulf Coast and Western Interior. Figure 34 illustrates a typical porous chalk from Ekofisk and shows remarkable compositional and textural analogies between North Sea and North American chalks. What is unusual about North Sea chalk, then, is not its primary composition but its subsequent diagenetic history.

The major factor that sets the North Sea chalk reservoirs apart from all other chalk fields is overpressuring. Harper and Shaw (1974) reported pore fluid pressures of 7,100 psi at a depth of 3,050 m (10,000 ft) in the Ekofisk area (normal pressures at that depth would be about 4,300 psi), and T. D. Eames (oral commun., 1974) indicated that such overpressures are common in wells throughout the deep Central Graben area. Overpressures are restricted to the graben, however, and do not extend beyond the border faults. The overpressuring is presumably related to the retardation of water expulsion due to extremely low permeabilities of the chalk and thick overlying shale. Overpressuring may also be related to early generation of biogenic gas which accumulated in structural highs, expelling original pore waters and preserving porosity. Areas laterally adjacent to these structures would have retained pore fluids and may have undergone considerable porosity loss during burial. This would provide a lateral seal for maintaining geopressures in the chalk reservoirs. Oil may have entered the reservoirs late in the burial history, moving downsection from the even more overpressured overlying Tertiary shales (Byrd, 1975). Alternatively, oil derived from a deeper part of the section may have entered the structures early in their burial history and the oil itself may be responsible for much of the porosity preservation.

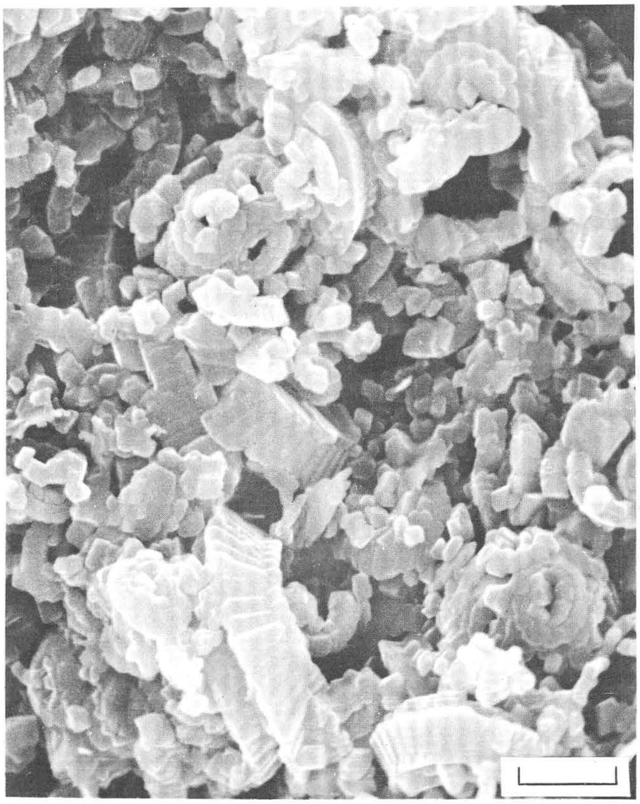


Figure 34.--SEM photomicrograph of Danian chalk from Phillips Petroleum Co. Ekofisk 2/4-2X well (3,127 m or 10,258 ft in depth) in Norwegian sector of the North Sea. Abundant coccoliths show only the earliest stages of overgrowth cementation in spite of deep burial. Sample has 31 percent porosity. Scale bar is 2 μm.

Overpressuring has such a profound effect on chalk diagenesis because it reduces differential intergranular stresses (Scholle, 1977). The chalk of the Ekofisk area, for example, is subjected to an effective overburden stress equivalent to only about 1,000 m (3,300 ft) of burial, despite an actual burial depth of 3,050 m (10,000 ft). The stress difference between these two values is borne by the pore fluids and therefore does not cause the pressure solution-reprecipitation or mechanical-compaction phenomena responsible for chalk cemention. The early (pre-deep burial) establishment of abnormally high pore-fluid pressures or the early introduction of oil and (or) gas into the reservoir can significantly retard the cementation of chalk, and one or both of these mechanisms have clearly acted in the North Sea reservoirs.

A number of other factors also are involved, however, in making the North Sea fields as prolific as they are. Fracturing improves overall permeability (calculated from oil flow rates) to about 12 md (World Oil, 1972) as compared with measured chalk matrix permeabilities of less than 2 md. Very thick pay sections (as much as 223 m or 731 ft thick), high gas-to-oil ratios (ratios of 1,000-2,000 were noted by Harper and Shaw, 1974), low viscosity oil (36° gravity), and oil saturation of 70-100 percent all contribute to the high production rates from sediments with apparently poor reservoir properties. The oil is thought by some to have been derived from overlying, thick Tertiary marine shales which are even more overpressured than the chalk (Byrd, 1975), or it may have been generated, in part at least, within the chalk section. It is quite possible, however, that the oil migrated from underlying Jurassic or Lower Cretaceous source beds very early in the burial history, before overpressures were initiated. How one achieves oil saturation of such extremely low permeability sediments is still a largely unsolved problem.

This type of production could potentially be found in North American chalk areas as well. Overpressuring depends largely on the rapid deposition of thick sections of low-permeability sediments. These criteria could be met in a number of areas in the Gulf Coast, particularly in downdip areas not yet extensively tested by drilling. With the maintenance of overpressures, burial depth is no longer the controlling factor in chalk diagenesis and excellent reservoirs could be found at very considerable depths. Chalk-density data presented by Scholle (1977) indicate that such deep overpressured reservoirs could be located by seismic techniques.

SUMMARY AND EXPLORATION MODELS

North American chalks have produced an estimated 100 million bbl of oil and significant quantities of gas. These discoveries all occur in one of three geological situations:

1. Where chalks have never been deeply buried (less than 1,000 m or 3,300 ft) and thus retain considerable primary porosity (for example, shallow Niobrara gas production from western Kansas and eastern Colorado).
2. Where chalk has been buried to intermediate depths (1,000-2,000 m or 3,300-6,600 ft) with marine pore fluids. The Mg-content of the pore waters inhibits pressure solution-reprecipitation and thereby maintains significant amounts of primary pore space (for example, Wyandot gas on the Scotian Shelf).
3. Where chalk has been buried to depths of 1,000 m (3,300 ft) or more with Mg-poor pore waters and extensive loss of primary porosity has taken place. In these areas production is mainly from secondary fracture porosity (for example, the Pearsall field of Texas).

Future discoveries of these types will undoubtedly continue to be made. All three situations can be commercially profitable as a result of sharply increased prices for crude oil and natural gas and of improved well-stimulation techniques.

None of these types of fields will achieve even a small fraction of the potential of the North Sea chalk reservoirs, which have reserves of 2.5 billion bbl of oil and 8 trillion ft^3 of gas. The key to this prolific production is early overpressuring (and (or) early oil input) into the reservoirs prior to deep burial. Overpressuring and oil saturation dramatically reduce diagenetic porosity loss and maintain porosities of 30-40 percent at depths of 3,000-3,500 m (9,900-11,500 ft). Fracturing, low-viscosity oil, low water saturations, and a high gas-oil ratio further improve production characteristics.

Outstanding production will be obtained from North American chalks only if similar overpressured reservoirs can be found in downdip, deeply buried areas of the Gulf Coast or the Atlantic continental margin. Without early formation and subsequent maintenance of overpressures, however, production from chalks in such deeply buried sections will be minimal.

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