AN EXPLORATION AND DISCOVERY MODEL; A HISTORIC PERSPECTIVE - GULF OF MEXICO OUTER CONTINENTAL SHELF

G.L. Lore (Minerals Management Service, Gulf of Mexico Region, New Orleans, LA, 70123, USA)

ABSTRACT

The relatively mature Federal Gulf of Mexico Outer Continental Shelf (GOM OCS) with its abundance of available data and information can serve as a model for frontier or immature offshore basins in terms of the patterns, trends, and sequence of exploration and subsequent discoveries that may ultimately occur. It exhibits attributes that are characteristic of most hydrocarbon-producing basins. Lore (1992, 1994) reviewed the discovery and exploration history of the GOM OCS during the period 1947-1989. Exploration and ensuing development activities have gradually progressed seaward into the deeper waters of the GOM. The analysis of the empirical discovery record showed that during each ensuing decade the number of proved fields discovered increased. However, this was accomplished only through a significant increase in the number of exploratory wells drilled, which in turn was accompanied by a decline in the observed annual exploration success rate. Coincident with the increased maturity of the GOM OCS was a marked decrease in the mean size of new field discoveries. The observed efficiency of exploration activity on the GOM OCS, in terms of discovering with a minimum of effort the largest fields first, has been surprising. Not since 1976, however, has industry been able to discover fields containing quantities of hydrocarbons sufficient to replace production volumes.

INTRODUCTION

The GOM OCS has historically been a significant source of U.S. domestic oil and natural gas production. It has also long been on the leading edge in the application of innovative offshore exploration and development technologies. The initial field on the GOM OCS was discovered in 1947. Through 1991, 819 proved oil and gas fields had been established (figure 1).

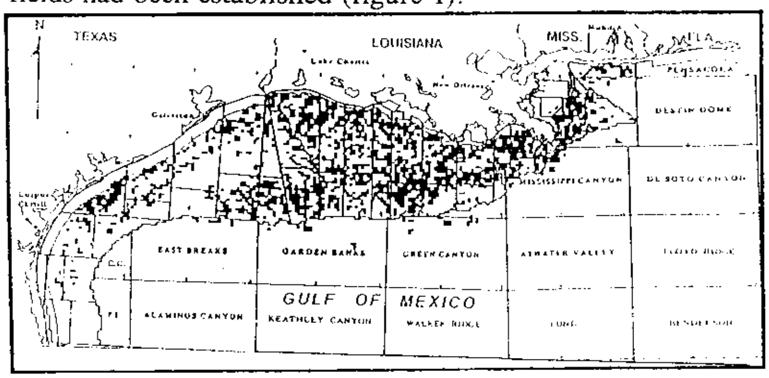


Fig. 1. Location of 819 proved fields, Gulf of Mexico OCS (Melancon and others, 1992).

An additional 70 fields were still in their initial delineation phase awaiting an operator determination of commercial viability. Many of these 70 fields are significant high-profile deep-water and subsalt discoveries and are exceptionally large when compared to other GOM OCS discoveries of the past 15 years. However, the inordinately high development costs and technological advancements required to bring these resources to market cloud their commercial potential. In the Minerals Management Service's (MMS) reserves classification scheme, these fields and their reserves are referred to as unproved (Melancon et. al., 1992). Original proved hydrocarbon reserves in the 819 fields were estimated to be 1.71 x $10^9 m^3$ of oil and 3.7 x 10^{12} m^3 of gas. Eighty-one of these fields have subsequently been depleted and abandoned. Remaining proved reserves recoverable from the 738 active proved fields are 370 x 10^6 m^3 of oil and 906 x $10^9 m^3$ of gas. The GOM OCS is primarily a gas-prone province with 676 (83 percent) of the proved fields classified as gas fields. The original proved reserves were present in 16,881 reservoirs, of which 9,473 were gas, 6,010 oil, and 1,398 combination reservoirs. Cumulative production through 1991 was 1.34 x 10^9 m^3 of oil and 2.79 x 10^{12} m^3 of gas, constituting on an energy-equivalent basis 68 percent natural gas.

Annual GOM natural gas production has fluctuated between 115 and 140 x 10^9 m^3 since 1978, peaking in 1981 and again in 1990 at 139 x 10^9 m^3 and averaging about 128 x 10^9 m^3 (figure 2). The oil production curve is also bimodal, peaking initially in 1971 at 59.7 x 10^6 m^3, and again in 1986 at 56.5 x 10^6 m^3. At year end 1991, the ratios of remaining proved reserves to production were 8.0 and 6.8 years for oil and gas respectively. Throughout the decade of the 1980's the GOM OCS contributed about 22 percent of the total annual U.S. domestic gas production. The oil share after rebounding from the influx of Prudhoe Bay production during the late 1970's remained relatively steady at about 10 percent during this period. Even though three-quarters of the estimated original proved reserves have been produced, the GOM OCS, as the U.S.'s premier natural gas producing province, will continue to have a pivotal role in determining its future gas supply.

Fig. 2. Annual production 1947-1991, Gulf of Mexico OCS.

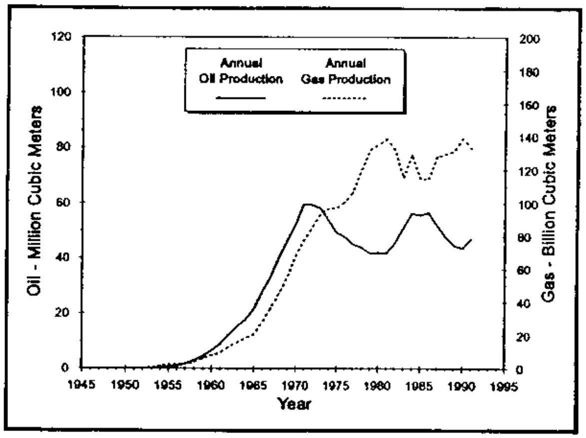
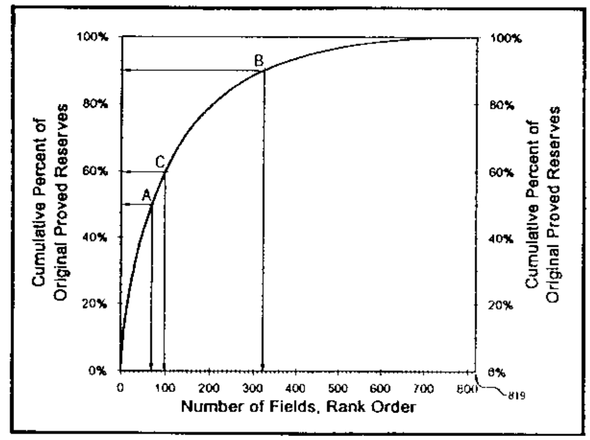


Figure 3 is the field size distribution expressed as a plot of the cumulative percent of original proved reserves versus the rank order of field size (the largest field is 1, next largest 2, etc.). Fifty percent of the original proved reserves were contained in the 69 largest fields (point A), only 8 percent of the total number of proved fields, and 90 percent in the 323 largest fields (point B), 39 percent of the total number of proved fields. The 98 large fields with proved reserves exceeding 15.5 x 10^6 m^3 of oil-equivalent, represent 12 percent of the proved fields and contain 59 percent of the original recoverable proved reserves (point C). A characteristic often observed in petroleum-producing basins is a rapid drop-off in size from the largest known field to the smaller ones. Hydrocarbon accumulations are the result of complex geological processes. The actual quantities of producible reserves are further defined on the basis of technological and economic considerations. As a consequence of these independent influences and the multiplicative nature of the factors affecting the size of a hydrocarbon accumulation, field size distributions in producing plays, basins, or provinces are typically highly skewed.

Fig. 3. Field size distribution, Gulf of Mexico OCS.

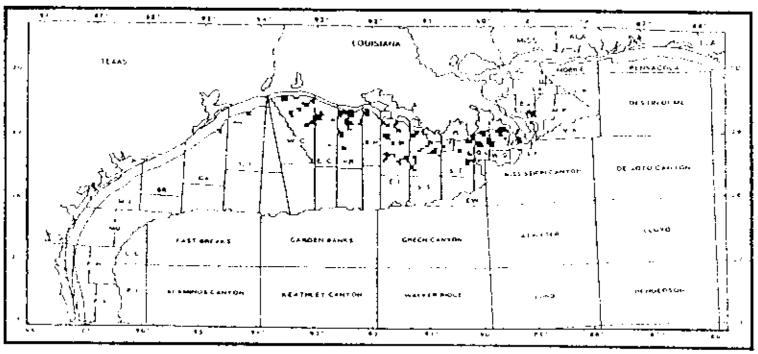


This paper will review the results of past exploration and production activities, examine industry's performance in terms of the results that have emerged from the discovery process and identify historical patterns and trends, many of which are applicable models for other offshore basins. All estimates of original and remaining proved reserves, cumulative production, and numbers of proved and unproved fields are as reported in Melancon et. al. (1992) and are current as of December 31, 1991.

HISTORICAL EXPLORATION AND DISCOVERY PATTERNS AND TRENDS

It is informative to review the historical exploration and development activities that resulted in the world class hydrocarbon producing province that is the GOM OCS. Each of the four decades of activity will be examined by reviewing the status of exploration and development activity and the number of fields and quantities of proved reserves discovered during each decade.

Fig. 4. Location of proved fields discovered 1947-1959, Gulf of Mexico OCS.



The Fifties (1947 - 1959)

Figure 4 depicts the locations of the proved fields discovered prior to December 31, 1959. As expected, initial development was in shallower, nearshore waters concentrated mainly in the areas off central and western Louisiana. This development primarily reflected the gradual extension of existing inland drilling and development technologies into the open-water marine environment and the infancy of marine seismic acquisition activities. Early exploratory drilling in very shallow water on the shelf utilized barges and platforms constructed for exploratory drilling. The mid-1950's witnessed the introduction of submersible and jack-up drilling rigs.

Table. Exploration activity and results by decade.

	Number of			Mean Water Depth	Original Proved Reserves			Mean Field Size
	Exploratory Wells	Total Wells	Proved Fields	meters	Oil million cubic meters	Gas billion cubic meters	Oil Equivalent million cubic meters	Oil Equivalent million cubic meters
1947 - 59	442	1,325	70	16	638	882	1,520	22
1960 - 69	2,377	6,779	119	36	485	936	1,420	12
1970 - 79	3,356	9,288	265	59	414	1,305	1,718	6
1980 - 89	4,356	10,222	334	55	169	557	725	2
Total	10,531	27,614	788	50	1,706	3,680	5,383	7

During this period, 442 exploratory wells were drilled, culminating in the discovery of 70 proved fields (table). These fields contained original proved reserves estimated at 638 x 10^6 m^3 of oil and 882 x 10^9 m^3 of gas (37 and 24 percent, respectively, of the original proved reserves discovered on the GOM OCS through 1991). For purposes of this analysis, all reserves in a field are credited to the year in which the well indicating a commercial discovery was drilled. Seven of the eight largest fields were discovered during this period. The mean size of all fields discovered was a robust 21.7 x 10^6 m^3 of oil-equivalent. The median field size was 11.4 x 10^6 m^3 of oil-equivalent and the smallest 314 x 10^3 m^3.

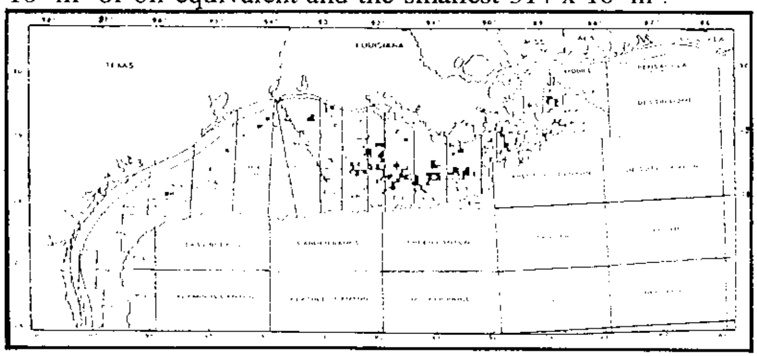


Fig. 5. Location of proved fields discovered 1960-1969, Gulf of Mexico OCS.

The Sixties (1960 - 1969)

With a few notable exceptions off Texas, proved fields discovered between 1960 and 1969 were still concentrated offshore central and western Louisiana (figure 5). They had, however, advanced seaward into deeper waters, although still on the continental shelf (areas with water depths less than 200 meters). The introduction of drillships and semisubmersibles as floating platforms for exploratory drilling operations provided the basis for deep-water exploratory drilling techniques in use today. During the decade, 2,377 exploratory wells were drilled and 119 proved fields discovered. These fields contained original proved reserves of 485 x 10^6 m^3 of oil and 936 x 10^9 m^3 of gas.

This near doubling of cumulative original proved reserves was accomplished only through considerably more effort than was required for prior discoveries. During this period there was more than a fivefold increase in both the number of exploratory wells and in the total number of wells drilled, and a 70 percent increase in the number of fields discovered. However, the mean size of the fields discovered decreased by 45 percent from the previous period (1947 through 1959) to 11.9 x 10^6 m^3 of oil-equivalent. The smallest commercial field discovered was 80.5 x 10^3 m^3. Even more significant is that, by the end of the decade, fields estimated to contain original proved reserves of 1.12 x 10^9 m^3 of oil and 1.82 x 10^{12} m^3 of gas (approximately 65 and 49 percent, respectively, of the total proved reserves discovered through 1991) had been found.

The Seventies (1970 - 1979)

Figure 6 identifies the location of all proved fields discovered during 1970-79. Development on the seaward edge of the continental shelf was more extensive than previously, reflecting the results of intensive exploration activity in the prolific Pleistocene depocenter. Most of the emphasis continued to remain on the shelf, but increased activity is evident on the upper slope, with the first fields established in what is now known as the Flexure Trend. Technology stretched the factors limiting deep-water exploration through the introduction of dynamic positioning systems in the 1970's. During this period, 3,356 exploratory wells were drilled, resulting in the discovery of 265 fields containing original proved reserves of 414 x 10^6 m^3 of oil and 1.31 x 10^{12} m^3 of gas, the peak decade in terms of the volume of hydrocarbons discovered. This increase in original proved reserves appears modest, however, considering that it was achieved only through drilling more exploratory wells and discovering more fields than during the entire period between 1947 and 1969. The mean size of the fields discovered during this decade was 6.48 x 10^6 m^3 of oil-equivalent, and the minimum size decreased to 1820 m^3. By year end 1979, a total of 6,175 exploratory wells had been drilled and 454 proved fields discovered. These fields contained original proved reserves of 1.54 x 10^9 m^3 of oil and 3.12 x 10^{12} m^3 of gas (90 percent of the oil and 85 percent of the gas total proved reserves discovered through 1991).

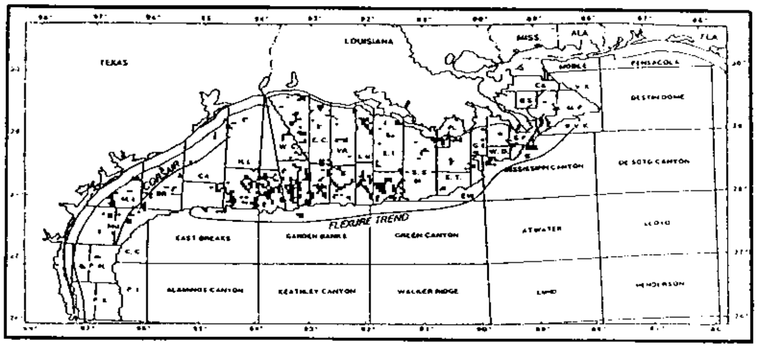


Fig. 6. Location of proved fields discovered 1970-1979, Gulf of Mexico OCS.

The Eighties (1980 - 1989)

As can be seen in Figure 7, during this decade development activities occurred over practically the entire central and western GOM shelf, as well as on the upper slope. In addition, the first fields representing extensions of the prolific Norphlet Trend and a Miocene shallow bright spot play were discovered in the eastern GOM. The development of improved buoyant riser and riser coupling systems, electrohydraulic blowout preventer controls, and advanced motion compensating systems permitted exploratory drilling to progress onto the slope in water depths of greater than 2,100 meters. Major development activity occurred on the upper slope, where 15 proved fields were established. By the end of the 1980's, industry had drilled 10,531 wells and discovered 788 fields. Original reserves in the 788 proved fields were 1.71 x 10^9 m^3 of oil and 3.68 x 10^{12} m^3 of gas.

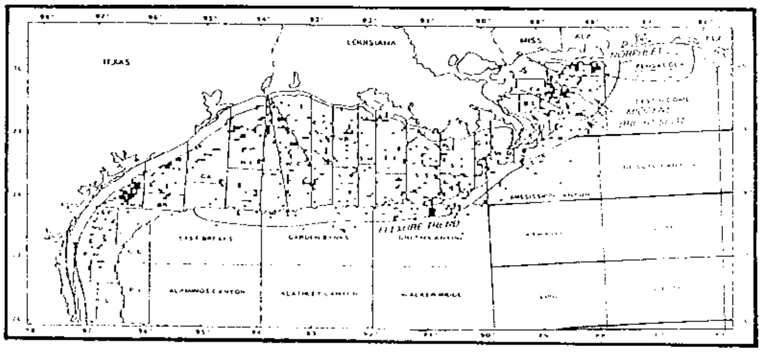


Fig. 7. Location of proved fields discovered 1980-1989, Gulf of Mexico OCS.

Estimates of original proved reserves increased only 16 percent over the decade in spite of a 70-percent increase in the number of exploratory wells drilled and a 74-percent increase in the number of proved fields. The mean size of fields discovered during the 1980's decreased to only 2.17 x 10^6 m^3 of oil-equivalent. It should be noted that aggregate estimates of proved reserves for fields discovered during this period are considered conservative and are subject to substantial growth for two reasons. First, fields currently classified as unproved are excluded and, second, reserve estimates for individual fields prepared prior to full development and an established production history normally experience significant appreciation (Drew and Lore, 1992).

A review of the empirical data on total exploration effort, the sizes of discovered fields, and industry success rates reveals some interesting trends. The annual number of gas fields discovered has been steadily increasing, while the number of oil fields discovered has varied, never exceeding 10 and averaging about 3.5 per year (figure 8). Through 1959, 38 percent of all fields discovered were oil. This percentage declined steadily until only 10 percent of the fields discovered during the 1980's were oil fields. The hydrocarbons discovered in each period also became progressively more gas-prone, swelling from 58 percent natural gas in the 1947-1959 time frame to 77 percent during the 1980's. This reflects an industry change in emphasis.

Until the latter part of the 1970's, exploration on the OCS focused primarily on discovering large oil fields. Significant gas reserves were also discovered and developed, but principally as a byproduct of the search for oil fields (Lore, 1994). Exploration activity directed toward the discovery of gas fields was stymied by price controls, the economic hurdles presented by deep drilling and deep water, and the generally high cost of marine operations. A surge in exploration activity targeting significant gas reserves was fueled by several factors including optimism concerning higher anticipated future prices, realization of the continued inevitable decline in the size of the oil fields being discovered and the introduction of new seismic technologies that dramatically lowered the risk in identifying gas reservoirs (Lore, 1992).

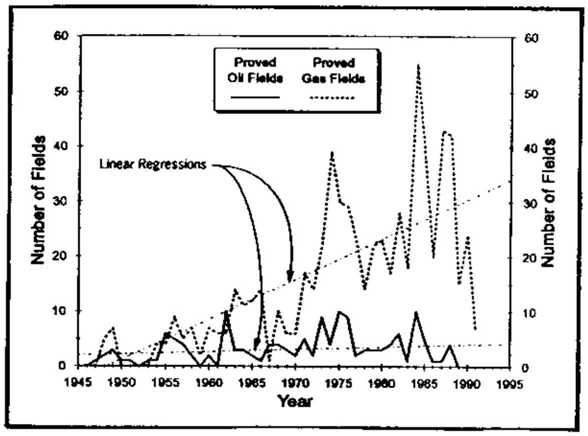


Fig. 8. Annual number of proved oil and gas field discoveries, Gulf of Mexico OCS.

Attributes typical of petroleum-producing basins are that the large fields are discovered early in the exploration process and subsequent discoveries are smaller and the product of increasingly greater effort. These characteristics are primarily an outgrowth of the highly skewed underlying field size distribution. The observed conformance of the patterns of exploration and the discovery history of the GOM OCS to these two features is clearly illustrated in figure 9. The cumulative probability of success, defined in terms of the number of proved fields discovered per exploratory well drilled, and mean field size are plotted versus the total number of exploratory wells drilled. This reflects exploratory effort expended, a measure of exploration maturity, without a consideration of time. There was a very short and rapid "learning curve" followed by a period of highly successful exploration in terms of exploration success and the discovery in rapid succession of very large fields. This has been followed by a long period distinguished by a consistent trend of rapidly decreasing success rates and mean field sizes. As dictated by the size distribution of undiscovered fields, prospects were becoming increasingly smaller, more difficult to identify, and more expensive on a unit recovery basis to exploit. Meisner and Demiren (1981) observed these phenomena in several basins, determined they were attributes characteristic of the exploration of a play or basin, and applied the term "creaming" to the process. Meisner and Demiren partially attributed their creaming effect to declining overall success rates as exploration proceeded. They argued that exploratory success rates reflect depletion of a potentially productive sediment volume. As additional wells are drilled within a particular area and volume of sediment, the chance of discovering a field of any given size is decreased. Thus, initially, the probability of finding large fields and then successively smaller-sized accumulations decreases as additional exploratory wells are drilled. In the GOM OCS, early cumulative success rates in excess of 80 percent steadily decreased to the present 7 percent. These success rates are derived using only the number of proved fields discovered. If the 70 fields classified as unproved are considered, the overall aggregate success rate increases to 8 percent. Consideration of the number of unproved fields in the analysis of rates of "economic" success constitutes an upper bound since some portion of these fields will ultimately not be developed. On the other hand, estimates of the quantities of reserves discovered in recent years are considered conservative due to both the large number of discovered fields currently classified as unproved and the significant growth in estimates of proved reserves made early in the life of a field. The GOM empirical data presented in figure 9 is a classic example of Meisner and Demiren's creaming effect.

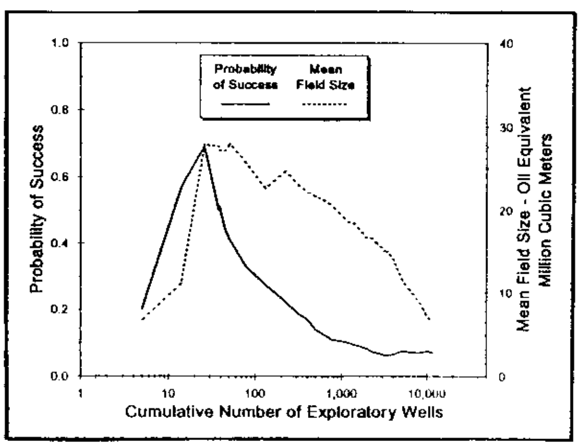


Fig. 9. Cumulative probability of success and mean field size, Gulf of Mexico OCS.

EXPLORATION EFFICIENCY AND PERFORMANCE

An often-used measure of the attractiveness of an area as an exploration target or investment opportunity is the quantity of reserves discovered per unit of effort, e.g., number of exploratory wells, cumulative basin volume explored, or exploratory footage drilled (White, 1990). Industry performance is frequently examined in terms of the sequence of field discoveries and the ability to replace production with new discoveries.

Figure 10 is a semi-log plot of oil-equivalent volume discovered per meter of exploration drilling versus year and dramatically demonstrates the creaming effect.

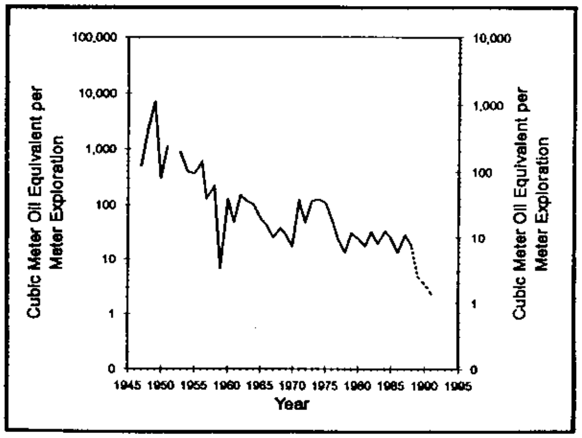


Fig. 10. Original proved reserves discovered per meter of exploratory drilling, Gulf of Mexico OCS.

From 1950 through the early 1980's there was more than a hundredfold decrease in the proved reserves discovered per meter of exploratory drilling. Both the magnitude and rapidity of the decrease in the discovery rate clearly demonstrate that the majority of proved reserves were discovered very early, with increasingly smaller amounts accrued with each subsequent increment of effort. The inescapable conclusion is one of profoundly less reward (reserves) per additional unit of effort. The field size distribution governs the discovery rate trend, since once the largest fields are discovered, even increased geologic knowledge and technological progress will be unable to maintain early discovery rates (Attanasi and Root, 1993).

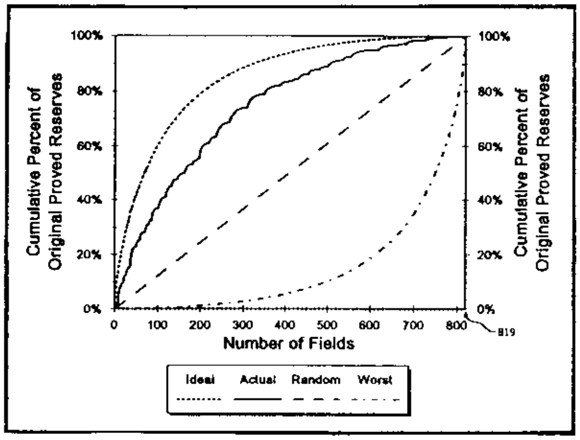


Fig. 11. Sequence of field discoveries.

In an ideal situation with all costs being equal, industry's preference would be to discover with consecutive wells the largest field first, the second largest next, and so on. One measure of exploration efficiency, as measured by discovery sequence and not effort expended, compares industry's effectiveness with this ideal model and to the results expected from a random discovery process. The theoretical ideal chronological order of field discoveries (figure 11) would be the field size distribution of figure 3. The worst case scenario, representing zero percent efficiency, would be to discover fields in order of increasing size, smallest to largest. The diagonal line represents the expectation of the results of a discovery process in which different size fields are discovered in a random order - there is no size bias inherent in the discovery process. Industry's actual performance is depicted as a plot of the cumulative percent of total original recoverable proved reserves versus the actual observed sequence of field discoveries. Jones et. al. (1982) and Forman and Hinde (1985, 1986) have used similar curves to obtain measures of exploration efficiency for numerous basins worldwide. The relative efficiency of exploration is reflected by the difference in reserves discovered for a given level of effort over the random drilling expectation and the extent to which it approaches the ideal.

For the GOM OCS, 59 percent of the total original proved re-serves were discovered with the first 200 fields, compared to 79 percent in the theoretical ideal case and about 27 percent expected from a purely random discovery process. Considering the economics and historical technological challenges of offshore operations and the long history of constrained leasing on the GOM OCS prior to 1983, it's startling how efficient exploration has been in discovering the larger fields first.

Another measure of exploration performance is the ability to discover sufficient volumes of reserves to replace production, to maintain or increase the reserves-to-production ratio. Not since the mid-1970's has exploration on the GOM OCS consistently attained this objective. If gas reserves are credited to the field discovery year, there has been an annual shortage (production minus new reserves discovered) in gas discoveries every year since 1977 (figure 12). The cumulative deficit during this period was 1.15 x 10^{12} m^3 of gas. If the measure of choice for crediting gas discoveries is the reservoir disco-very date, then industry performance in replacing reserves is slightly improved. In this case reserves discovered exceeded production in every year through 1978. There was an annual shortfall during 1979-1981, but surpluses in 1982-1984. The deficit has remained intact every year since and has totalled about 464 x 10^9 m^3 . The oil experience is similar. Considering field discovery year there has been an annual shortfall since 1976 with a cumulative deficit of 505 x 10^6 m^3 (figure 13). Again, performance is better if reservoir discovery year is used as the basis for crediting reserve discoveries. In this instance a deficit has persisted only since 1985 and totalled 188 x 10^6 m^3 of oil. As a consequence of this performance, the

370 x 10^6 m^3 of oil and 906 x 10^9 m^3 of gas proved reserves estimated to remain at year end 1991 are the lowest since MMS began reporting reserves in 1975 (Melancon and others, 1992).

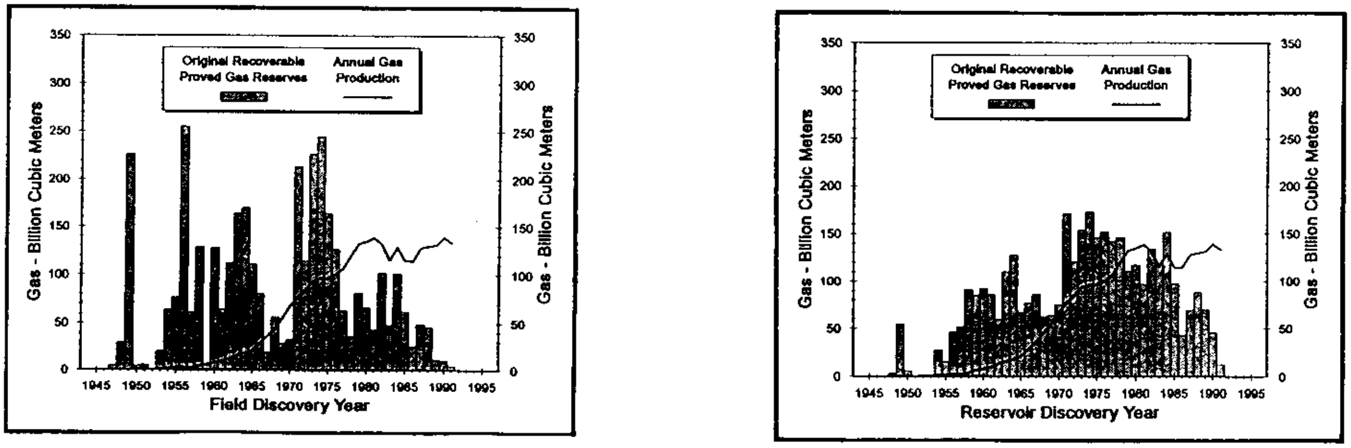


Fig. 12. Annual gas production and original proved gas reserves by discovery year, Gulf of Mexico OCS.

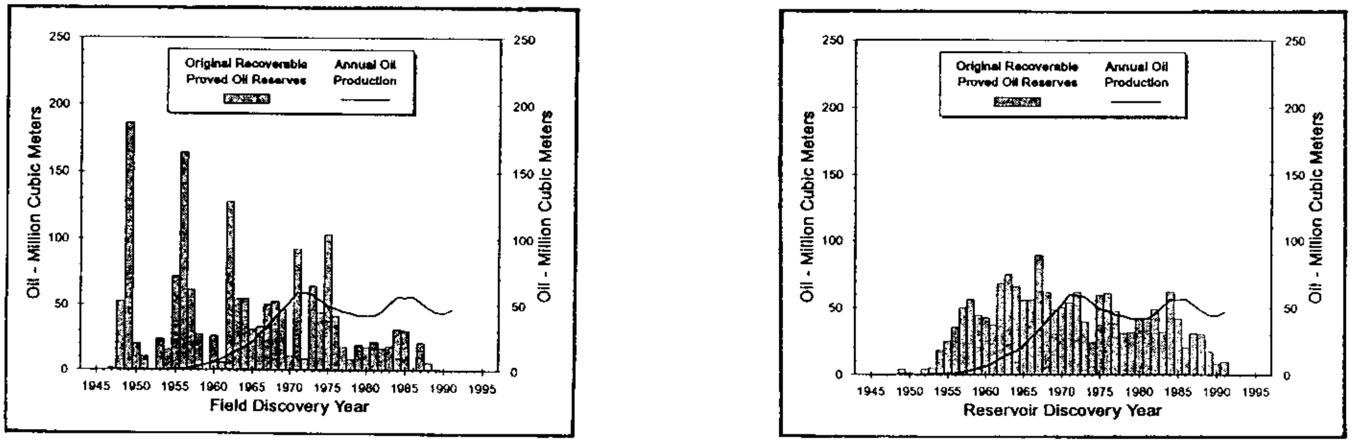


Fig. 13. Annual oil production and original proved oil reserves by discovery year, Gulf of Mexico OCS.

CONCLUSIONS

A prerequisite to long-term planning for future exploration and subsequent development of an area is the existence of an appropriate model. Clearly, long-range planning and forecasting are fraught with uncertainties and, ultimately, a good forecast involves a healthy dose of vision and serendipity as much as a sound model. A suitable paradigm can greatly improve the chances for reliable long-term planning. At the highest level, such a model describes overall patterns and trends that may occur as exploration proceeds and discoveries are made. It can be further refined through the determination of proper analogs and scaling factors to attempt to quantify such entities as resource potential, field size distributions, exploratory success rates, and even the actual sequence of discoveries. As a benefit of quantifying the relationships among these and other factors, the forecaster has developed the ability to perform sophisticated economic modeling. The GOM OCS experience, appropriately used, can serve as an acceptable paradigm at all levels of detail for many frontier and immaturely explored basins.

The GOM OCS throughout its history as a hydrocarbon exploration target and a major producing region has been at the forefront of technological advances, particularly in offshore operations. As each new technology evolved and was applied in the GOM to overcome a barrier, the technological frontier advanced to keep pace with the next exploration and development challenge. Nevertheless, many of the patterns and trends observed in the GOM OCS should serve as excellent models for other offshore areas. Clearly, initial exploration and development operations are no longer limited to nearshore, shallow-water regions (except in arctic environments where the ability to deal with sea ice is the limiting technological factor) and, generally, an overwhelming bias toward achieving and developing oil discoveries no longer exists (although there is still a distinct preference toward oil). Yet, the economics of offshore development with large minimum infrastructure and substantial capital requirements demands large threshold resource size and will ensure the emergence of similar patterns and trends.

The GOM OCS can serve as a useful working prototype for many frontier or immature offshore basins. It exhibits discovery process characteristics that adhere to basic tenets of the hydrocarbon discovery process model. As such, with its wealth of available data and information it should be considered as a paradigm for the discovery process in other basins.

ACKNOWLEDGEMENTS

The reserves estimates and associated analyses that form the basis for this report represent the combined efforts of numerous geoscientists, petroleum engineers, and technicians associated with the Reserves Inventory Program over a period of more than 17 years. The contributions of Katherine Ross in extracting specific information from the extensive database, for her efforts in resolving data discrepancies, and in the preparation of the visuals and tables contained in this paper are greatly appreciated.

REFERENCES

Attanasi, E.D., and Root, D.H., 1993. Statistics of Petroleum Exploration in the Caribbean, Latin America, Western Europe, the Middle East, Africa, Non-Communist Asia and the Southwest Pacific. - U.S. Geol. Survey Circular 1096.

Drew, L.J. and Lore, G.L., 1992. Field Growth in the Gulf of Mexico - A Progress Report. - In: Carter, L.M.H. (Ed.) USGS Research on Energy Resources, 1992. - U.S. Geol. Survey Circular 1074: 22-23.

Forman, D.J., and Hinde, A.L., 1985. Improved statistical method for assessment of undiscovered petroleum resources. - Am. Ass. Petrol. Geol. Bull. 69: 106-118.

Forman, D.J., and Hinde, A.L., 1986. Examination of the creaming methods of assessment applied to the Gippsland basin, offshore Australia, *in*: D.D. Rice, ed., Oil and Gas Assessment - Methods and Applications. - Am. Ass. Petrol. Geol. Studies in Geology 21: 101-110.

Jones, D.A., Buck, N.A., and Kelsey, J.H., 1982. Model to evaluate exploration strategies. - Am. Ass. Petrol. Geol. Bull. 66: 317-331.

Lore, G.L., 1992. Exploration and Discoveries, 1947-1989: An Historical Perspective. - Minerals Management Service OCS Report 91-0078. 87 p.

Lore, G.L., 1994. Conventional Gas Resources of the Gulf of Mexico Outer Continental Shelf-- Past Experience, Current Activities, Future Potential. - In: Howell, D.G., (Ed.) The Future of Energy Gases. U.S. Geol. Survey Professional Paper 1570: 157-170.

Meisner, J., and Demiren, F., 1981. The creaming method, a Bayesian procedure to forecast future oil and gas discoveries in mature exploration provinces. - J. Roy. Statistical Soc. 144: 1-31.

Melancon, J.M., Kinler, C.J., Marin, D.A., and Prendergast, M.T., 1992. Estimated Proved Oil and Gas Reserves, Gulf of Mexico, December 31, 1991. - Minerals Management Service OCS Report 92-0037. 61 p.

White, D.A., 1990. Short Course Notes: Prospect and Play Assessment. - Minerals Management Service, New Orleans, Louisiana, March 5-9, 1990. Oil and Gas Consultants, International, Tulsa.