The Timing and Incidence of Exploratory Drilling on Offshore Wildcat Tracts

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This paper documents exploratory drilling activity on offshore wildcat oil and gas leases in the Gulf of Mexico sold between 1954 and 1980. We calculate the empirical drilling hazard function for cohorts in specific areas. For each year of the lease, we study the determinants of the decision whether to begin exploratory drilling and their relationship to the outcome of any drilling activity. Our results indicate that equilibrium predictions of plausible noncooperative models are reasonably accurate and more descriptive than those of cooperative models of drilling timing. We discuss why noncooperative behavior may occur and the potential gains from coordination. (*JEL* C73, D83, L71)

This paper is an empirical study of learning and strategic delay in exploratory drilling. The specific context is drilling on federal land off the coasts of Texas and Louisiana. Between 1954 and 1990, the U.S. federal government held a number of sales in which it sold the oil and gas rights to thousands of parcels of its offshore land. These parcels, known as tracts, each cover an area of five thousand acres on average. The typical sale involves more than a hundred tracts. Most sales are wildcat sales, which consist of tracts located in areas where there has not been prior exploratory drilling, and on-site drilling is not permitted prior to the sale. Firms have access only to seismic information and as a consequence face considerable uncertainty. The rights to the tracts are sold individually using a first-price sealed-bid auction, and ownership of tracts in an area is typically distributed among several firms. Tracts within an area often share common geological features, and a subset may be located over a common pool. In either case, the ex post value of nearby leases will be correlated and, as result, there is an information externality associated with exploratory drilling.

The presence of information externalities generates a free-rider problem. Most leases have a relatively small number of neighbors in an area of information spillover during the period when their owners must decide whether to initiate drilling. The lease term, which applies only to the exploration phase, is 5 years. If a firm has not engaged in any exploratory drilling by the end of the lease term, ownership of the lease reverts to the government. The exploration decision is a costly one, in that unsuccessful drilling can cost millions of dollars. Moreover, outcomes are uncertain. In our sample, only half of the tracts that were explored yielded positive revenues (that is, production was commercially viable), so many tracts were unprofitable ex post. Further, revenues on productive tracts were quite variable. For example, the sample standard deviation of the logarithm of discounted revenues on productive tracts is approximately 1.5. As a result, information concerning likely drilling outcomes can be quite valuable and so each firm has an incentive to delay its drilling decision.

To study the empirical implications of strategic delay, we develop a parametrized model of learning that captures the salient features of

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exploration on federal offshore leases. We then model the firm's decision of whether and when to drill its lease(s) as a game of timing known as war of attrition. (Hendricks and Charles A. Wilson [1995] provide a general analysis of the game in discrete time, and Hendricks and Dan Kovenock [1989] and R. Mark Isaac [1987] discuss applications to exploration.) Firms with marginal leases prefer to wait and learn more about the value of their leases by observing the drilling outcomes of other leases in the area. However, if everyone waits, each firm waits in vain, in which case it would have been better to drill earlier and avoid the time cost of delay. The equilibrium of the game generates a probability distribution over drilling times. A distinguishing property of this distribution is that the probability of both leases being drilled in the last period is relatively high.

We find that the incidence and timing patterns in area-cohorts are consistent with the predictions of the war of attrition model. An area-cohort is defined as a set of leases sold in the same year and located in one of the 51 areas specified by the government within the offshore region covered in our sample. The amount of time required to drill a well is about three months so we divided the 5-year lease term into 20 quarters. Both the number of tracts drilled and the hazard rate (the proportion of remaining, or not yet explored, tracts that are drilled) are declining functions of the number of quarters that the lease has been held, except in the last quarters, when both rates increase dramatically. That is, both the fraction of tracts drilled and the associated hazard rate follow a U-shaped pattern over the term of the lease. Furthermore, this pattern cannot easily be ascribed to aggregation over dissimilar area-cohorts. We classify area-cohorts into three categories: those with 10 or fewer tracts, those with 11 to 20 tracts and those with more than 20 tracts. The hazard function is essentially the same in each size category. This result strongly suggests that firms behaved noncooperatively. If firms had coordinated their drilling programs, drilling would have ended earlier in smaller area-cohorts.

The model also yields predictions on how date-of-sale and post-sale information affects the decision whether and when to drill. The date-of-sale information consists of bids submitted on each lease and the identity of the bidders, which are announced at a public meeting held shortly after the sale. The post-sale information consists of drilling outcomes on nearby leases.[1] (For most of our sample, real wellhead oil and gas prices are virtually constant.) We report the results of a probit regression of the determinants of the incidence of initial drilling activity, for each year of the lease. The main finding is that, initially, a tract is more likely to be explored the more the lease owner bid to acquire it, but as time progresses bid levels are decreasingly accurate predictors of whether drilling will be initiated. Instead, firms appear to be increasingly reliant on the information generated by post-sale drilling activity in the local geographic area. We also present some evidence that if lease holdings in an area are relatively asymmetric across firms, drilling is less likely to be delayed. These results are consistent with noncooperative behavior.

Hendricks et al. (1987), in their study of Outer Continental Shelf (OCS) tracts off the coasts of Texas and Louisiana sold between 1954 and 1969, document that 29 percent of wildcat leases expired without any wells being drilled. These tracts received bids averaging $800,000 in 1972 dollars. The probit results indicate that the decision to abandon tracts without exploratory drilling is a rational one and in part reflects the arrival of date-of-sale and post-sale information. We explore the issue of rationality further using a Tobit regression of drilling outcomes on the determinants of the drilling decision, for each year of the lease. The pattern of correlations is generally the same as in the probit regression, but there is some evidence of under response to some factors.

The theoretical literature on social learning in multiagent settings is extensive and growing

[1] In our study of drainage auctions (Hendricks and Porter, 1988), we argued that tract productivities are highly correlated within narrow geographic areas, and that drilling outcomes on neighboring tracts are more accurate predictors of tract productivity than seismic records.

(see Patrick Bolton and Christopher Harris [1993] for a review). Exploratory drilling is an example of what Bolton and Harris have called a game of pure strategic experimentation. They study a class of infinite-horizon games in which N gamblers, each owning identical pairs of slot machines, have to decide individually in each period whether to play the machine with the known certainty-equivalent payoff or the machine with the unknown payoff. The gamblers obtain information about the latter machine by observing the outcome of their own plays and those of the other gamblers. Exploratory drilling is essentially a finite version of this game. It is analogous to a situation in which each player has purchased the right to play the risky slot machine a fixed number of times in a given period of time. The number of plays corresponds to the number of leases and the period of play corresponds to the lease term.

Empirical work on the effect of the free-rider problem on equilibrium rates of experimentation is almost nonexistent. An exception is the recent work on the adoption of a new variety of high yielding cotton by Timothy Besley and Anne C. Case (1994). The exploration decision has been examined empirically by Dennis Epple (1985), Scott Farrow and Marshall Rose (1992), Franklin M. Fisher (1964), Hendricks and Alfonso Novales (1987), Frederick M. Peterson (1975), and Peter C. Reiss (1990), among others. Several of these authors have noted that information externalities may be an important factor in exploration. However, they were unable to measure its significance since they employed data that were more aggregated than ours. An advantage of our data set is that we observe both actions and outcomes on individual tracts. That is, our data set contains unusually detailed information.

The paper is organized as follows. In Section I we develop a parametrized model of learning and characterize the equilibria of the timing game. In Section II we examine drilling patterns for evidence of delay and duplication. In Section III we describe the detailed data set and report on the determinants of drilling times and outcomes. Section IV contains several concluding remarks.

I. The Theoretical Framework

Prior to a lease sale, firms can conduct seismic surveys but not engage in any on-site drilling. These surveys provide noisy signals about the likelihood of finding oil and gas on the tracts. Firms use this information to determine whether and how much to bid for individual leases that are available in the sale. All bids have to be submitted by a certain date, at which time the government announces the values of the bids that have been submitted on each tract (if any) and the identities of the bidders. Thus, each firm can use the bidding information to update its beliefs about individual leases prior to making any drilling decisions. As drilling outcomes on nearby leases become public information, firms with undrilled leases will revise their beliefs accordingly.

We model this learning process as follows. The size of the deposit on each lease is assumed to be a random draw from a lognormal distribution with geometric mean $\exp(\theta)$ and precision h. These parameters are fixed within an area but can vary across areas. The firms' lack of information about the value of the leases is parametrized by assuming that they know h but not θ. They learn about θ through surveys and drilling. In describing this process, it will be convenient to work with the log of the size of the deposit, denoted by X, rather than the size. Thus, X is a normal random variable with unknown mean θ and precision h. Without loss of generality, h is normalized to 1.

A firm must pay fixed costs c to initiate a drilling program, where these costs are independent of whether the tract is productive. A firm always discovers a deposit when it drills an exploratory well but the size of the deposit has to exceed some minimum level to be worth developing. Otherwise, the drilling outcome is reported to be a dry hole.[2] The value of productive leases may be thought of as the present value of revenues net of royalty payments and the costs of developmental, as opposed to exploratory, wells. Let $\pi(x)$ represent the value

[2] After the increase in oil prices in 1973, many leases that had been abandoned were resold and developed.

of a lease with a deposit of size x. Finally, lease terms are of length T periods, and firms discount future profits according to a common discount factor β. Thus, the net present value of a lease that is drilled in period t and has a deposit of size x is $\beta^t(\pi(x) - c)$.

Bids from the sale provide information on the sizes of the deposits. Let N denote the number of tracts receiving bids in the area. The sale information relevant for lease i is described by a real-valued signal s_i, which is assumed to be distributed normally with mean x_i and precision τ_i. Precision can vary across leases since the amount of information available may differ on individual leases, as measured, for example, by the number of bids. Surveys are less informative than drilling outcomes, so the value of τ_i is less than 1. Firms use the signals to update their beliefs about θ and deposit sizes. Ignoring prior beliefs, it can be shown using Bayes rule that the density function that describes each firm's beliefs about θ after the bids are announced is normal with mean μ and precision ρ where

$$\mu = \sum_{i=1}^{N} s_i\tau_i(1 + \tau_i)^{-1}/\rho \quad \text{and}$$

$$\rho = \sum_{i=1}^{N} \tau_i/(1 + \tau_i).$$

The firms' beliefs about x_i conditional on $(s_1, \ldots, s_N)$ are described by a normal distribution with mean $(\mu + \tau_i s_i)/(\tau_i + 1)$ and precision $\rho(\tau_i + 1)^2/[\rho(\tau_i + 1) + 1]$.

As leases are drilled and outcomes publicly observed, the state of information about θ changes. Without loss of generality, suppose leases are ordered by their signals and the k highest signal leases are drilled with outcomes $(x_1, \ldots, x_k)$. Let $\bar{x}$ denote the average discovery size.

LEMMA 1: *Conditional on $(x_1, \ldots, x_k, s_1, \ldots, s_N)$, beliefs about θ are given by a normal distribution with precision $\rho_k = k + \sum_{i=k+1}^{N} \tau_i/(1 + \tau_i)$ and mean*

$$\mu_k = \left[k\bar{x} + \sum_{i=k+1}^{N} s_i\tau_i(1 + \tau_i)^{-1} \right] \Big/ \rho_k.$$

PROOF:

Apply Bayes rule (see Morris H. DeGroot, 1970).

Lemma 1 states that the posterior mean of θ is a weighted average of average discovery size and the sum of appropriately weighted signals on the tracts that have not been drilled. Signals are informative about θ only because they are informative about the sizes of the deposits. Once x_i is known, s_i is redundant information. Hence, the relevant information set in each period consists of the vector of drilling outcomes on leases that have been drilled and the signals on leases that have not yet been drilled.

Using Lemma 1, we can calculate beliefs about the sizes of the deposits on the remaining leases.

LEMMA 2: *Conditional on $(x_1, \ldots, x_k, s_1, \ldots, s_N)$, beliefs about X_i, $i = k + 1, \ldots, N$ are normal with precision $\rho_k(1 + \tau_i)^2/[1 + \rho_k(1 + \tau_i)]$ and mean $(\mu_k + \tau_i s_i)/(1 + \tau_i)$.*

PROOF:

Use Bayes rule to calculate the distribution of X_i conditional on s_i and θ and then integrate over θ using the density given in Lemma 1.

The learning model possesses several features that are important to the analysis. First, drilling outcomes across leases are not perfectly correlated. A positive outcome on the first lease drilled does not mean that every other lease in the area is worth drilling nor does a negative outcome imply that all of the leases in the area should be abandoned. Second, leases are heterogenous. They differ not only in expected deposit size but also in their informational value. Drilling outcomes on leases with low precision generate more information about θ than outcomes on leases with high precision. Third, expected lease values increase with average discovery size.

These features do not require normality. Indeed, if we were interested only in a theoretical analysis, we would have assumed that drilling outcomes and information are affiliated; this would have been sufficient to insure that the likelihood of drilling and the expected revenues from drilling are increasing functions of earlier outcomes. The normality is used in the empirical work. In particular, it implies that exploration histories possess sufficient statistics that are easily constructed from data: μ_k is a weighted average of discovery sizes and bids on leases in the area, ρ_k is the number of wells drilled in the area, and τ_i can be measured by the number of bids submitted on lease i. In the next section, we examine how the probability of drilling varies with respect to each of these variables.

A. *A War of Attrition*

Following the sale, each firm has to decide whether and when to drill its lease. For some firms, the decision is obvious. Those owning leases with very optimistic signals are likely to drill their leases immediately. They believe that the probability of obtaining information that would cause them to change their beliefs about the profitability of drilling is low relative to the costs of delay. Firms that own leases with very low signal values are also likely to have a dominant strategy. They wait with probability 1 since the expected net value of drilling is currently negative. Note that it is not irrational for firms to purchase such leases if they anticipate that drilling outcomes in the area may lead them to revise their beliefs about the unprofitability of drilling. The option to drill has positive value. Alternatively, the revelation of bidding information may cause them to revise their priors.

Most firms, however, are likely to own leases where the decision to drill is a strategic one. The expected value of these leases is positive but not so high that their owners are willing to drill immediately. They would prefer to wait and learn more about the value of their leases by observing drilling outcomes on other leases in the area. On the other hand, they cannot be sure that others will drill. Consequently, they may wait in vain, in which case it would have been better to drill right away and save the time costs of delay.

We focus initially on a situation where there are only 2 leases, each owned by a different firm. One reason for focusing on the 2-lease situation is that any analysis of the many firm case must begin with the subgame in which 2 firms remain. More importantly, the behavioral predictions of the many firm model are not substantially different from those obtained in the 2-firm model, where a complete characterization of the set of subgame perfect equilibria is possible.

A (behavioral) strategy for each firm specifies the probability of drilling each period as a function of the state of the world, conditional on not having drilled previously. Here, the state vector is easy to describe, as is a portion of the optimal strategy. There are two possibilities. One is that the rival firm has not drilled yet either, in which case beliefs are unchanged. The other possibility is that the rival firm has drilled and found a deposit of size x. In that case, the firm updates its beliefs about θ using Bayes rule and solves a 1-person decision problem. The solution is to drill immediately if the expected value of the lease is positive and to let the lease expire otherwise. Therefore, in order to compute a subgame-perfect equilibrium, it is only necessary to solve for the probability of drilling each period given that no one has drilled yet.

Let (μ, ρ) describe the state of information about θ. Using Lemma 2, the expected value of the deposit on lease i in state (μ, ρ) can be written as

$$V_i(\mu, \rho) = \int (\pi(x_i) - c)\phi(x_i; (\mu + \tau_i s_i)/(\tau_i + 1), \rho(\tau_i + 1)^2/(\rho(\tau_i + 1) + 1))\, dx_i$$

where $\phi(\cdot; \theta, h)$ denotes the density of a normal distribution with mean θ and precision h. Thus, in period t, if no one has drilled previously, the expected payoff to firm i from drilling its leases is $V_i(\mu, \rho)$. Alternatively, firm i can wait and hope firm j drills in period t. If firm j does so, it follows from Lemma 1 that the state of information on θ changes to $(y, \rho + (\tau_j + 1)^{-1})$ where

$$y = [\mu\rho + (x_j - s_j\tau_j(1 + \tau_j)^{-1})]/[\rho + (1 + \tau_j)^{-1}].$$

From firm i's perspective in period t, y is a random variable since it is a function of firm j's drilling outcome, which is not observed until the end of the period. Firm i's beliefs about X_j at the beginning of period t are described in Lemma 2. A transformation of variables yields the distribution of y, which is normal with mean μ and precision $\rho + \rho^2(\tau_j + 1)$. Hence, the expected payoff to firm i from waiting one period and responding optimally to firm j's drilling outcome in the following period is

$$W_i(\mu, \rho) = \int \max[0, V_i(y, \rho + (\tau_j + 1)^{-1})] \times \phi(y; \mu, \rho + \rho^2(\tau_j + 1))\, dy.$$

In the discussion that follows, we will suppress the dependence of V_i and W_i on (μ, ρ). Note that W_i is greater than V_i since there is always some chance that firm j's drilling outcome would cause firm i not to drill.

The game is solved recursively. In the last period, if there has not been any drilling, firm i will drill if and only if V_i is positive. In period $T - 1$, if there has been no prior drilling, drilling by firm i yields expected payoff V_i. If instead firm i waits, and its rival's probability of drilling is q_j^{T-1}, then the expected payoff is $\beta[q_j^{T-1}W_i + (1 - q_j^{T-1})\max(0, V_i)]$. The first term in the square brackets corresponds to the event that firm j drills and firm i updates its beliefs about θ and X_i and responds optimally. The second term corresponds to the event where firm j does not drill, in which case firm i drills in the final period if V_i is positive. Firm i is indifferent between drilling and waiting if and only if

$$q_j^{T-1} = (1 - \beta)\max(0, V_i)/\beta(W_i - \max(0, V_i)) = q_j^*.$$

Here q_j^* is positive if V_i is positive. It is less than 1 if V_i is less than βW_i, that is, if the discounted profits from waiting one period and responding optimally to firm j's drilling outcome exceed the expected profits from drilling immediately. In that case, the game is a war of attrition, since the payoffs from following (letting the other firm drill first) exceed the payoffs from leading, and the latter declines with time. Note that when the gains from waiting are insufficient, q_j^* exceeds 1, which means that the optimal strategy for firm i is to drill immediately. This will be the case when β is close to 1 and s_i or τ_j is sufficiently large. In either case, the expected payoff to firm i is V_i.

Suppose V_i is positive and less than βW_i for both leases. Then, in period $T - 2$, if no drilling has occurred, the payoff from drilling immediately is V_i. If firm i waits, its expected payoff is exactly the same as from waiting in period $T - 1$, since by construction the expected payoff in that period, in the event that firm j also does not drill in $T - 2$, is V_i. Hence, in equilibrium, $q_j^{T-2} = q_j^*$. Thus, despite the finite lease term, the game is stationary, in the sense that $q_j^t = q_j^*$ for $t = 1, 2, \ldots, T - 1$. As described above, q_j^T equals 1.

The distinguishing characteristics of the mixed strategy equilibrium described above are delay and duplication.[3] Leases may be drilled at any time during the lease tenure, with delay until the last period highly likely if T is not too large. The leases may also be drilled simultaneously instead of sequentially. For example, the latter event is certain to occur if firms wait until the last period to drill. The equilibrium differs from the optimal drilling program as implemented by a single owner (or a drilling consortium). In the latter program, at least one lease is always drilled if either $V_1 + \beta W_2$ or $V_2 + \beta W_1$ is positive whereas no leases are drilled in equilibrium if V_1 and V_2 are negative. Firms fail to internalize the value of the information externality, which leads to underinvestment. Noncooperative play can also result in leases being drilled in the wrong order. Finally, the optimal drilling plan never dictates delay beyond the second period, whereas the equilibrium plan can involve delay beyond the second period and, depending upon the parameters of the model, a significant probability of delay until the last period.

[3] There are also (two) pure strategy equilibrium outcomes in which firms coordinate drilling plans and drill sequentially without delay. For reasons that will become clear later, we largely ignore these equilibria.

How likely is this outcome for OCS leases? The amount of time required to initiate and complete a drilling program on a lease is reportedly about 3 months. Given this period length, the discount rate β is close to 1, say 0.99 (corresponding to a discount rate of 1 percent per quarter). The value of V_i can be approximated by the sample average of discounted revenues less royalty payments and drilling costs on the set of tracts drilled (including "dry" tracts), \$3.65 million (in 1972 dollars). The difference between W_i and V_i is roughly equal to drilling costs times the probability that the first well drilled in the area is a dry hole. The cost of an exploratory well offshore leases is about \$1.5 million and the hit rate is $^1/_2$. These parameter values yield an estimate of q^* that is roughly 0.05. The length of the typical lease is 5 years, which translates into a value of T equal to 20. Together, these values imply that the probability that neither lease is drilled until the last period is 0.15.

How does q^* vary with respect to the underlying parameters? Higher values of μ and s_i causes expectations about θ and x_i to increase, thereby increasing the value of V_i. The gain from waiting, $W_i - V_i$, decreases since the likelihood that firm j's drilling outcome can cause firm i to change its views about the profitability of drilling its lease is lower. Hence, higher expectations about θ and x_i will cause q^* to increase. Higher values of ρ means that firm i is more certain about the value of θ, which in turn reduces its uncertainty about x_i. The effect of this reduction on V_i and $W_i - V_i$ depends in part upon the properties of $\pi(x)$. However, as ρ gets large, the likelihood that x_j can move expectations about θ significantly goes to zero. A similar argument applies to τ_i. In each case, the informational value of x_j becomes small and implies that firm i should not wait to drill its lease (that is, q^* is equal to 1).

The above calculations ignore heterogeneity and assume that each area consists of only 2 tracts. Nevertheless, we think that a more realistic model would generate similar estimates. The reason is that the cost of foregone interest earnings from waiting are small given the short period length, whereas the expected gain is proportional to the cost of drilling, which is relatively large at \$1.5 million. Furthermore, if the probability of a dry hole is $^1/_2$, then the above model predicts that 25 percent of the tracts will not be drilled. This is comparable to the abandonment rate of 24 percent for the OCS sample described below and suggests that the proportionality factor used to determine the value of the information externality may be representative.

B. *Extensions*

The bidding process is likely to reveal a great deal of information, but firms may still possess private information following the sale. The analysis of a model with private information is more complicated since delay is an informative event, as it signals that a firm is not very optimistic. Wilson (1984) characterizes the equilibria of continuous time wars of attrition between two firms in a wide variety of informational environments and Hendricks and Kovenock (1989) analyze a 2-firm, 2-period model in a common value setting. The equilibrium outcomes are qualitatively similar to those of the mixed strategy equilibrium sketched above. That is, the probability of drilling conditional on no prior drilling is low for periods prior to T, so delay until the end of the lease tenure is quite likely if T is not too large. The main point to be drawn from these models is that the equilibrium is usually unique. Hence, private information can be used to justify the selection of the mixed strategy equilibrium as descriptive of firm behavior.

In a typical OCS area there are more than 2 tracts, with more than 2 lease holders. This raises a number of issues. When firms own several leases, they may engage in strategic experimentation, the major point modeled in Bolton and Harris. Firm i may wish to drill one of its leases in an early period in order to encourage subsequent drilling by other firms, from which firm i can then gain further information on the likelihood of success of drilling on its remaining leases. Bolton and Harris refer to this incentive as the *encouragement* effect and show that it partially offsets the free-rider effect in determining equilibrium rates of experimentation.

Asymmetries in the distribution of lease holdings can also lead to more coordination and less delay. For example, suppose firm 1 acquires $N - 1$ leases and firm 2 has only 1 lease. Then, in any period t, firm 1 may not be able to threaten not to drill any of its leases until after firm 2 has drilled its lease. The reason is that, even if firm 2 drills its lease, firm 1 may want to drill at least one of its leases in order to obtain additional information for its drilling decisions in subsequent periods. This situation is certain to occur in period $T - 1$ if firm 1 has a sufficiently large number of leases remaining. As a result, firm 1 may be forced to drill some of its leases first, in which case it should do so earlier rather than later. (Hendricks and Porter [1993] analyze this situation in more detail.)

The third issue concerns the multiplicity of equilibria. When N increases, the number of equilibria gets very large. To see this, suppose N firms have not drilled by period $T - 1$, and the state of beliefs is such that each firm prefers to wait for at least one drilling outcome rather than drill its lease immediately. Then, for each $k = 2, \dots, N$, there exists equilibria in which k firms randomize and $N - k$ wait. Thus, the number of mixed strategy equilibria is $2^N - N - 1$. Furthermore, the multiplicity matters because firms that wait earn a higher payoff than those who randomize. The implication is that, in period $T - 2$, firms are not identical, since their incentive to drill depends upon which equilibrium is selected for every possible state of beliefs in period $T - 1$. This in turn makes it difficult to characterize the entire set of equilibria, although in all of these equilibria coordination failure is present and drilling is delayed.

C. *Empirical Implications*

The main (nonparametric) prediction of the strategic model of drilling is that, in the absence of perfect coordination, drilling patterns on most leases should exhibit delay and duplication. Tracts with very high signal values may be drilled immediately because their owners believe that the costs of waiting are high relative to the probability of receiving information that would cause them to change their beliefs about the profitability of drilling. But tracts with lower signal values are not likely to be drilled until the end of the lease tenure, if at all. There should also be a significant decrease in the quality of tracts drilled in the last period compared to preceding periods. The magnitude of the difference provides a measure of the expected benefit of waiting. Finally, the pace of drilling activity should be higher in area-cohorts that are perceived to be more valuable.

The multiplicity of equilibria makes it difficult to use structural methods of estimation such as the one developed by Besley and Case (1994). In our context, their approach implies estimating the parameters θ and h using data on size of discoveries, and then simulating equilibrium paths in an area-cohort for specific values of (μ, ρ) using bids and number of bids as proxies for s_i and τ_i, respectively, and plausible values for β and c. These paths can then be compared to the actual path and the optimal values of (μ, ρ) chosen by maximizing an appropriate likelihood function. However, the simulated path depends upon which equilibrium is selected at each stage. We are not sufficiently confident of any particular selection rule to believe the estimates obtained under that rule. For this reason, we have adopted a more modest approach which focuses mainly on predictions about the empirical hazard function.

II. Drilling Behavior

In this section we describe the data set and compute the aggregate empirical hazard function. We compare its properties to those predicted by the theoretical model. We then disaggregate the data based on area-cohorts and study how heterogeneity within an area-cohort and across area-cohorts affects the empirical hazard function.

Our focus is on wildcat sales of tracts off the coasts of Texas and Louisiana, in which firms submitted fixed bonus bids with royalty payments preset at one sixth of revenues and the high bid was accepted. The firm submitting the highest bonus bid wins the tract provided it is deemed acceptable by the government. (Some tracts were sold under alternative auction rules and have been deleted from our sample.) A sale usually involves hundreds of tracts scattered over several different areas. Many of the tracts (usually half) do not receive any bids. There are 6,178 wildcat tracts in the full sample, which includes tracts sold from 1954 until March 21, 1990.

We restrict our attention to a smaller data set that consists of wildcat tracts off the coasts of Texas and Louisiana that were auctioned between 1954 and 1979, inclusive. The reason for working with the smaller data set is that there is no censoring of either the exploration or production phase. In the sample period, 2,510 tracts received bids. The high bid was rejected by the government on 255 tracts, so 2,255 leases were sold. The mean winning bid on the 602 unexplored tracts is $2.86 million dollars (in 1972 dollars). (The mean winning bid for the entire sample of 2,255 wildcat tracts is $6.07 million.) It is worth repeating that abandonment of a tract, without conducting exploratory drilling, entails walking away from, on average, substantial sunken costs. As a matter of comparison, the average drilling costs on the 897 unproductive tracts in our sample are $1.52 million, based on American Petroleum Institute estimates.

Our data set includes the following information for each tract: the dates it was put up for sale (some were sold more than once); its location and acreage; which firms bid and the value of their bids; whether or not the high bid was accepted; if sold, the number and date of any wells that were drilled and monthly production of oil, gas, condensate, and miscellaneous through 1990 if any oil or gas was extracted. The drilling and production data were used, together with the annual survey of drilling costs conducted by the American Petroleum Institute, to calculate ex post discounted revenues and costs for each tract. Production flows were converted into revenues using the real wellhead prices at the date of sale, and discounted to the auction date at a 5-percent per annum rate.

A. *The Aggregate Hazard Rates*

Hazard rates in our sample are computed by identifying the period of the lease term in which each tract is first drilled, if at all. We aggregate the monthly drilling data to the quarterly level, because it takes about 3 months to set up and complete an exploratory drilling program. (The features of the quarterly data described below also appear in the monthly data.) In 75 cases, exploratory drilling began after the 5-year lease horizon, according to well drilling records, and we classify these tracts as being never drilled. (The following results do not change much if these tracts are classified as having been drilled in the fifth or sixth year after acquisition.) Tracts registered as first drilled after quarter 20 may have been misclassified, or else exploration began in time but drilling itself started after the 5-year clock expired. Alternatively, an extension may have been granted if the government delayed the sale of the tract while deciding whether to reject the winning bid as inadequate.

Table 1 describes the distribution of initial drilling by quarter for our sample of leases, as well as the number of leases that were never explored. The striking feature of the table is the U-shaped pattern in the number of tracts drilled in a given quarter, and especially in the (Kaplan-Meier) hazard rates. The quarterly aggregate hazard rate is plotted in Figure 1. There is an increase in both numbers at the beginning of the lease term, as there is an adjustment period in setting up an exploratory drilling program. Thereafter, the hazard rate declines monotonically until quarter 12, slowly increases after that, and then jumps up in the quarters 19, 20, and 21, with a peak in quarter 20. In this sample, 24.3 percent of the 2,255 tracts were never explored. A similar pattern is evident if the drilling data are plotted at monthly or annual frequencies.

The table reports standard errors for the hazard rates. If H_t is the hazard rate in quarter t, and R_t the size of the risk set, then the variance of the hazard is $H_t(1 - H_t)/R_t$. The standard error of the difference in hazard rates over time can then be approximated by the square root of the sum of the individual variances. (This is an approximation, because the hazard rates in different periods are not independent.) By this method, the increase in the hazard rate between quarters 19 and 20 is significant, with a t statistic of 2.34. Figure 1 plots plus or minus two standard deviation confidence bands for the empirical hazard.

As a check on whether our more detailed 1954–1979 data set is representative of the 1954–1990 sample, we reproduced the calculations of Table 1 for the full sample accounting for censoring in later quarters. For

TABLE 1—QUARTERLY HAZARD RATES 1954–1979

Quarter	Risk set	Number drilled	Hazard rate	Standard error
1	2,255	155	0.0687	0.0053
2	2,100	223	0.1062	0.0067
3	1,877	191	0.1018	0.0070
4	1,686	164	0.0973	0.0072
5	1,522	134	0.0880	0.0073
6	1,388	106	0.0764	0.0071
7	1,282	62	0.0484	0.0060
8	1,220	61	0.0500	0.0062
9	1,159	63	0.0544	0.0067
10	1,096	49	0.0447	0.0062
11	1,047	41	0.0392	0.0060
12	1,006	35	0.0348	0.0058
13	971	36	0.0371	0.0061
14	935	43	0.0460	0.0069
15	892	30	0.0336	0.0060
16	862	46	0.0534	0.0077
17	816	48	0.0588	0.0082
18	768	52	0.0677	0.0091
19	716	52	0.0726	0.0097
20	664	62	0.0934	0.0113
21	602	44	0.0731	0.0106
22	558	5	0.0090	0.0040
23	553	5	0.0090	0.0040
Never	2,255	548	0.2430	

Note: The "Never" category refers to tracts that were never drilled. In this case, the "Hazard rate" equals the fraction of the 2,255 tracts that were never drilled. Otherwise, the hazard rate is the fraction of tracts in the risk set that were first drilled in that quarter.

example, if a tract sold in December 1989 had not been drilled on or before January 31, 1991, we do not know whether it was drilled after quarter 4 of its lease. The risk set includes the tracts remaining in a given quarter that had not yet been drilled. The risk set therefore falls over time as tracts are drilled, or if we can no longer observe whether they have been drilled. The results are quite similar. A larger fraction of tracts are never explored, 30 percent, but the hazard function has the same U-shape (Hendricks and Porter, 1993).

In interpreting the aggregate data, it is important to realize that the sequence of hazard rates implied by a mixed strategy equilibrium in a single war of attrition, described by the vector of conditional probabilities of drilling for each player, does not correspond to what we observe in the data. Tracts with negative expected values should not be part of the risk set. Moreover, such tracts are likely to represent an increasing fraction of the risk set as positive value tracts are drilled and eliminated from the set. This implies that the empirical hazard rate should decrease in periods 2 through $T - 1$, even ignoring heterogeneities across area-cohorts.

B. *Area-Cohort Hazard Rates and Heterogeneity*

Theory defines an area in terms of correlation of outcomes. In reality, the degree of spatial correlation is probably not uniform and fades with distance. Ideally, one would want the data to determine the pattern of correlation and classify tracts accordingly. (We are currently working on this problem by matching tract identification indicators with tract locations.) For the purposes of this paper, however, we use an exogenous classification provided by the government which divides the offshore region off the coasts of Texas and Louisiana into 51 separate geographical areas. We consider all tracts within a given area to be potential neighbors.

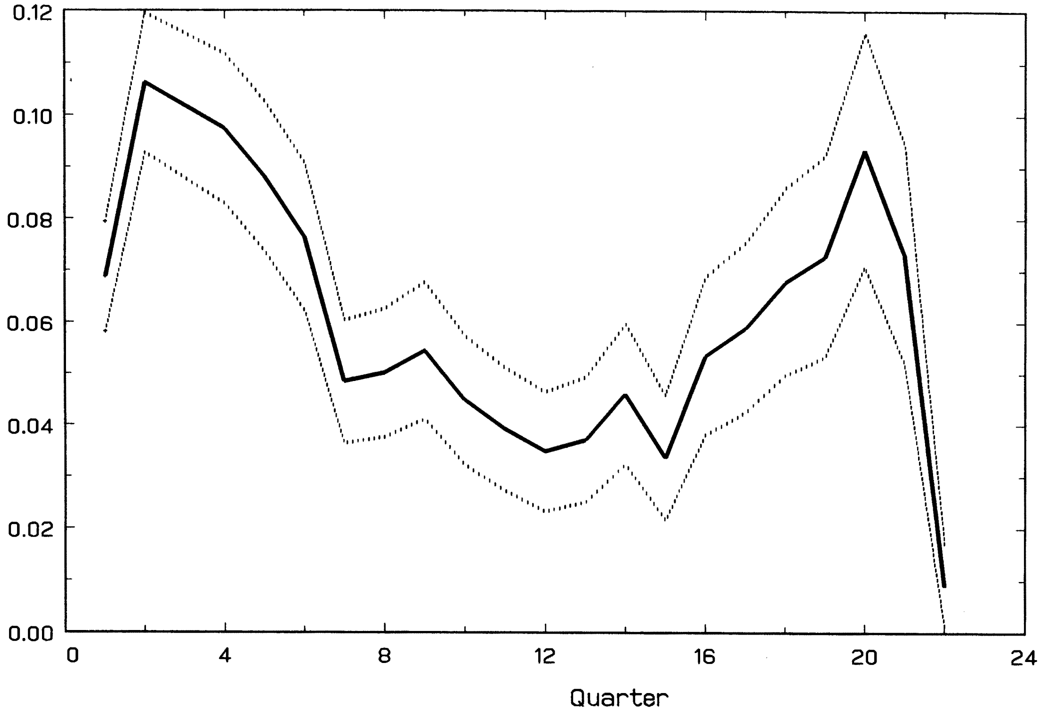

FIGURE 1. HAZARD RATE FOR EXPLORATORY DRILLING ON WILDCAT TRACTS, 1954–1979.

How good is this classification? On the one hand, it is too narrow since adjoining leases may lie in two different areas. On the other hand, it is almost surely too broad a classification since the typical area contains hundreds of tracts. A mitigating factor is that we focus on area-cohorts. Over time, the federal offshore land has been explored in a series of bands that extend along the coastline and move outward from the shoreline into the Gulf of Mexico. As a result, in any given sale, tracts in a particular area tend to be clustered.

There are 270 area-cohorts in our sample, with 8.35 tracts per area-cohort on average. The number of tracts per area-cohort ranges from 1 to 40, inclusive. There are 15 sale years in total, and tracts are spread across 18 different areas in a sale on average.

The panels in Table 2 provide information on area-cohort drilling patterns. The area-cohorts are classified by size into three categories: area-cohorts with 10 or fewer tracts, area-cohorts with 11 to 20 tracts, and those with more than 20 tracts. For each size category, we report a 6×6 matrix whose (i, j) element is the number of tracts first drilled in lease year j in area-cohorts abandoned in lease year i. "Never" corresponds to never being drilled, or first drilled after the fifth year. The number of area-cohorts abandoned in each lease year and the total number of tracts in these area-cohorts are reported in the last two columns of the table. These numbers, together with those given in the 6×6 matrix, are used to compute two empirical hazard rates that appear in the bottom two rows of each panel. The first row (Hazard rate A) assumes that the risk set consists of all tracts not yet drilled. The second assumes that the risk set consists of all tracts not yet drilled in area-cohorts that are still active. (That is, to compute Hazard rate B, the risk set in column i excludes area-cohorts with no drilling in year i or subsequently.)

TABLE 2—AREA-COHORT DRILLING PATTERNS

Panel A: Area-cohorts of size 1–10

Last year of drilling	Number of tracts drilled in lease year: Never	1	2	3	4	5	Total	Number of area-cohorts
Never	32						32	13
1	20	63					83	37
2	11	44	40				95	32
3	25	32	17	38			112	28
4	24	20	19	5	23		91	22
5	62	98	49	30	19	95	353	69
Total	174	257	125	73	42	95	766	201
Hazard rate A		0.33	0.25	0.19	0.14	0.35		
Hazard rate B		0.35	0.27	0.22	0.19	0.61		

Panel B: Area-cohorts of size 11–20

Last year of drilling	Number of tracts drilled in lease year: Never	1	2	3	4	5	Total	Number of area-cohorts
Never	14						14	1
1	0	0					0	0
2	2	19	3				24	2
3	5	18	5	5			33	2
4	17	11	7	4	4		43	3
5	81	142	84	36	43	94	480	31
Total	119	190	99	45	47	94	594	39
Hazard rate A		0.32	0.25	0.15	0.18	0.44		
Hazard rate B		0.33	0.25	0.16	0.20	0.54		

Panel C: Area-cohorts of size > 20

Last year of drilling	Number of tracts drilled in lease year: Never	1	2	3	4	5	Total	Number of area-cohorts
Never	22						22	1
1	0	0					0	0
2	29	23	17				69	3
3	9	19	15	3			46	2
4	6	21	2	1	2		32	1
5	168	223	105	66	64	100	726	23
Total	234	286	139	70	66	100	895	30
Hazard rate A		0.32	0.23	0.15	0.17	0.30		
Hazard rate B		0.33	0.24	0.17	0.19	0.37		

The empirical hazard functions are all U-shaped and do not vary much across the three size categories. Panels B and C reveal that drilling in most area-chorts of size greater than 10 did not end until year 5. If firms had coordinated their actions, drilling in many of these area-cohorts would have ended well before the expiration date, given the length of the

TABLE 3—TRACT CHARACTERISTICS, BY YEAR OF INITIAL DRILLING, 1954–1979

	Year after acquisition				
Variable	1	2	3	4	5
Risk set:					
Number	2,255	1,522	1,159	971	816
BID	14.46	13.91	13.64	13.52	13.46
	(1.62)	(1.48)	(1.43)	(1.44)	(1.46)
Number of bids	3.76	2.87	2.51	2.41	2.30
	(3.26)	(2.47)	(2.15)	(2.13)	(2.06)
Tracts drilled:					
Number	733	363	188	155	214
(fraction)	(0.325)	(0.239)	(0.162)	(0.160)	(0.262)
BID	15.62	14.77	14.26	13.82	13.50
	(1.26)	(1.31)	(1.18)	(1.31)	(1.18)
BIDDIF1	0.757	0.687	0.553	0.464	0.148
	(0.041)	(0.059)	(0.079)	(0.096)	(0.075)
BIDDIF2	0.616	0.502	0.389	0.381	0.058
	(0.037)	(0.054)	(0.066)	(0.082)	(0.060)
Number of bids	5.62	4.00	3.06	2.99	2.33
	(3.86)	(3.03)	(2.22)	(2.37)	(1.75)
HIT	403	163	87	70	82
(fraction)	(0.550)	(0.449)	(0.463)	(0.452)	(0.383)
REV	16.29	15.52	15.55	15.52	15.22
	(1.54)	(1.64)	(1.71)	(1.96)	(1.55)

Notes: Standard deviations are displayed in parentheses, except when listed as "fraction": for number of tracts drilled it is the fraction of the risk set; for HIT it is the fraction of tracts drilled. BIDDIF1 is the difference between the BID (the logarithm of the winning bid in 1972 dollars) and the average value of BID on tracts in the risk set that were sold in the same year. BIDDIF2 is the difference between BID and the average value of BID on tracts in the risk set that are in the same area-cohort. For BIDDIF1 and BIDDIF2, standard errors of the sample means are displayed in parentheses.

lease tenure relative to the amount of time required to drill a well. The evidence presented in Panel A is more mixed. The last year of drilling occurred before year 5 in approximately 65 percent of the area-cohorts of size 1–10. Note, however, that the average number of tracts in these area-cohorts is 3.12. By contrast, the average size of the 69 area-cohorts in which drilling did not end prior to year 5 is 5.12 tracts. The conclusion which we draw from Table 2 is that firms may have been able to coordinate drilling plans in area-cohorts where the number of tracts is quite small but, for larger area-cohorts, the pattern of drilling is more consistent with noncooperative behavior.

It is also worth noting that there were 15 area-cohorts, mostly containing a small number of tracts, that were abandoned without any drilling. One explanation is that firms purchased these leases for their option value, thinking that other firms might purchase tracts in the area and drill them. Alternatively, they may have concluded from the relatively few bids that their tracts were not worth drilling.

Table 3 reports, for each year of the lease, the number of tracts not yet explored (the risk set) and how many were drilled, as well as characteristics of the two sets. The average number of bidders is reported, together with the mean of the logarithm of the high bid in 1972 dollars (BID). HIT describes the number of explored tracts where there was subsequent production, and REV the mean of the logarithm of discounted revenues on productive tracts. (Again, production is valued at wellhead prices in 1972 dollars in the sale year, and discounted at a five-percent rate. To the extent that firms anticipated any post-sale changes in real prices, this is a flawed measure of revenues. However, REV captures big strikes. It may be preferable to view REV as an output measure, where relative prices at the sale date indicate how to aggregate oil, gas, condensate and miscellaneous production.) BIDDIF1 measures the difference between

BID on tracts that were drilled, and the average level of BID on tracts in the risk set that were sold in the same year. (This is akin to accounting for cohort effects.) BIDDIF2 measures the difference between BID on tracts that were drilled, and the average level of BID on tracts in the risk set that belong to the same area-cohort. (This is akin to accounting for area-cohort effects.)

The results indicate that, in each lease year, tracts that were a priori judged to be more productive, as indicated by BID, were more likely to be drilled. The means of BIDDIF1 and BIDDIF2 are significantly positive throughout. However, the magnitude and significance level of both means wane further into the lease term. Hit rates, and deposit sizes conditional on a hit, fall over the lease term, and the decreases are largest after the first year and in the final year of the lease. Note also that average bids on drilled tracts fall more than hit rates or average revenues from the second year of the lease term through the fourth year, so that ex post tract profits are increasing over these three years of the lease term for the set of tracts that are drilled. This pattern is consistent with the acquisition of payoff relevant information. Finally, as expected, the quality of tracts drilled in the last year of the lease is significantly lower, as reflected by the hit rate and REV.

The evidence presented in this section strongly supports the hypothesis of noncooperative rather than cooperative behavior. As predicted by the strategic model, there is substantial delay and duplication in an area-cohort, with many firms waiting until the last period to drill. Heterogeneity across and within area-cohorts can explain the decreasing portion of the empirical hazard function, but not the increasing portion of the hazard rate near the end of the lease term. There is a set of tracts where the prior expectation of profits is sufficiently high that they are drilled immediately. The remainder are held in reserve, and are drilled later in the lease term if at all. Area-cohorts with higher average bid levels are drilled more rapidly, and within an area-cohort, tracts with high bids tend to be drilled earlier than those with low bids. There is a sharp drop in the quality of tracts drilled in the last period, measured either ex ante by bids or ex post by hit rates and revenues. Finally, the relative magnitudes of the empirical hazard rates are roughly in accord with equilibria in which firms fail to coordinate.

III. Determinants of Drilling Decisions and Outcomes

In this section, we study how date-of-sale and post-sale information determine whether and when firms drilled their leases. The theoretical model suggests two sets of variables for the regression analysis. One set describes the firm's beliefs about the value of the lease immediately after the sale. A second set describes exploration experience following the sale in the area where the lease is located. The learning model predicts that the relative importance of the sale information should decline as drilling experience in the area accumulates.

A. *The Variables*

For each area-cohort, we create three variables to capture local drilling experience. They include the total number of tracts explored to date (the number drilled), the number of drilled tracts that were productive (the number of hits), and total discoveries on productive tracts (the sum of the logarithm of discounted real revenues on productive tracts—where a 5-percent discount rate is employed and wellhead prices in 1972 dollars as of the date of sale of individual tracts are used to evaluate oil, gas, condensate, and miscellaneous production). In our regressions, we employ the changes in each of these three historical variables since the sale date for individual tracts for each year after they were acquired (that is, the post-sale experience for the relevant area-cohort). These post-sale variables are denoted DRPOST, HITPOST, and REVPOST. DRPOST is the logarithm of (1 plus) the total number of tracts explored since the sale date (it equals zero if there were no tracts drilled); HITPOST is the logarithm of (1 plus) the number of drilled tracts that were productive (again, zero if there are no hits), and REVPOST is the mean of the logarithm of discounted revenues on productive tracts (it equals zero if there are no hits). For example, HITPOST in the fourth year after acquisition is the logarithm of the number of productive tracts drilled in that area in the preceding three years. The post-sale variables all equal zero in the first year after the sale date, and so do not appear in the year 1 regressions.

Information revealed at the sale date includes the logarithm of the winning bid (BID), which represents our best measure of presale beliefs of the winning firm. A firm's bid is some fraction of its expectation of tract value, where the fraction depends on the perceived degree of competition as well as the precision of ex ante information. A significant component of the difference across tracts in prior expectations of value is likely to be accounted for by the bid level.

To account for the level of competition, we also include a dummy variable that equals one if the winning bid was the only bid submitted (ONEBID). We also include a "money left on the table" variable, MLT, defined as the logarithm of the ratio of the highest to the second highest bid. In cases where there is one bid, the announced reserve price is employed instead of the second highest bid. Because money left on the table has a different connotation in this event, we also include a ONEBID $\times$ MLT interaction term. All of these variables might affect subsequent drilling decisions if firms' expectations of tract profitability change when they see whether, and how much, other firms bid. For example, they may learn to their surprise that other firms did not share their optimistic expectations, and so be less likely to begin exploration. Alternatively, if they knew beforehand that they alone were optimistic, then they will have bid less relative to their expectations, and thus, for a given bid level, they will be more likely to initiate exploration.

As suggested by the learning model in Section I, we consider two variables to capture area-cohort pre-drilling information revealed in the auction. They are NRISKSET, the logarithm of the number of tracts in the area-cohort not yet drilled in each year of the lease, and AREABID, the average value of BID for the tracts in the area-cohort risk set. Over the lease term of a tract in an area-cohort, tracts that are drilled are no longer counted in NRISKSET or in the mean AREABID, as suggested by Lemmas 1 and 2.

We construct HERF, a Herfindahl index of the dispersion of lease holdings among solo bidders in an area-cohort. For this measure, bids are classified as solo if there was one bidder, or only one experienced partner in a joint bid (and that firm had at least a fifty-percent share). For each area-cohort, we compute each bidder's share of the leases acquired by solo bidders. HERF is the sum of these shares squared. It equals 1 if 1 firm acquired all the solo bid leases, and $1/N$ if N firms split the leases equally. Thus, higher values of HERF correspond to more concentrated lease holdings. According to the strategic model, area-cohorts with higher values of HERF should experience less delay.

We also include the logarithm of tract acreage (ACRE). Some blocks that are ex ante believed to be more valuable are split into two tracts for the wildcat auction. Such divisions may exacerbate war of attrition problems, unless the tracts are known to be productive, in which case tracts with smaller acreage are more likely to be drilled right away.

We employ a set of yearly dummy variables, to account for variations in oil and gas prices and expectations of these prices, as well as year-to-year variations in the perceived productivity of tracts offered for sale. There is substantial variability over time in the productivity of leased tracts. The annual dummy variables also control for variations in interest rates.

Finally, we consider the dummy variable REOFFER, which equals 1 if the tract is being reoffered. Tracts may be sold a second (or third) time if the government previously rejected the high bid, or if a previous leaseholder relinquished the lease without drilling. There are 158 reoffered tracts in our sample, 107 of which were reoffered after a high bid was rejected.

We experimented with a number of other variables to control for observable heterogeneities across tracts and area-cohorts. These include the number of submitted bids on a tract, whether the winning bid is submitted by a consortium of firms, and the fraction of leases in an area-cohort that were acquired by joint bids. These variables have little explanatory power, and so are excluded here. Hendricks and Porter (1993)

TABLE 4—PROBIT ESTIMATES OF THE PROBABILITY OF INITIAL DRILLING, BY YEAR AFTER ACQUISITION

	Year after acquisition				
Variable	1	2	3	4	5
NRISKSET	−0.062	−0.212	−0.290	−0.201	−0.316
	(0.050)	(0.064)	(0.077)	(0.081)	(0.078)
AREABID	−0.148	−0.025	0.022	−0.134	0.087
	(0.061)	(0.076)	(0.095)	(0.100)	(0.097)
BID	0.564	0.437	0.155	0.236	−0.026
	(0.037)	(0.047)	(0.060)	(0.066)	(0.068)
MLT	−0.035	−0.103	−0.064	0.057	−0.113
	(0.039)	(0.060)	(0.077)	(0.092)	(0.106)
ONEBID	−0.142	0.230	−0.798	0.141	−0.576
	(0.211)	(0.209)	(0.241)	(0.248)	(0.241)
ONEBID × MLT	0.064	−0.049	0.264	−0.157	0.248
	(0.073)	(0.089)	(0.109)	(0.126)	(0.132)
HERF	0.067	−0.075	−0.286	−0.234	−0.224
	(0.206)	(0.231)	(0.290)	(0.296)	(0.294)
ACRE	−0.095	0.041	0.597	0.649	0.267
	(0.107)	(0.125)	(0.208)	(0.210)	(0.161)
REOFFER	0.126	0.046	0.466	−0.379	0.505
	(0.146)	(0.177)	(0.203)	(0.308)	(0.251)
DRPOST		0.236	−0.077	0.108	0.139
		(0.121)	(0.134)	(0.130)	(0.131)
HITPOST		0.188	0.292	−0.069	−0.023
		(0.102)	(0.121)	(0.125)	(0.128)
REVPOST		−0.017	0.007	0.029	0.042
		(0.009)	(0.012)	(0.013)	(0.014)
Sample size	2,255	1,522	1,159	971	816
Log-likelihood	−1,032.5	−692.0	−446.1	−377.3	−404.6

Notes: Standard errors are displayed in parentheses. Each regression includes a set of 14 year-specific dummy variables. The sample is the set of tracts not yet drilled by that year. The dependent variable equals 1 if the tract was first drilled in that year.

report some regressions that include these variables.

B. *Determinants of Drilling Activity*

Table 4 reports on the determinants of the incidence of initial drilling activity by lease year. For each year of the lease term, the sample is the risk set, the set of tracts not yet explored. The dependent variable is a dummy variable equaling 1 if exploratory drilling began in that year. The explanatory variables are those described above and include a set of dummy variables for each sale year. (Because only 15 tracts were sold in 1976, there is one dummy variable for 1976 and 1977.) The post-sale changes in the area-specific drilling history variables are relevant, and reported, only for the last four years of the lease. All non-qualitative variables are expressed in logarithms. The estimates are from a probit regression.

The BID coefficient is initially large and significant, but it falls over the lease term, and is negative and insignificant by the final year. The coefficients of the other bidding variables indicate that leaseholders do not respond much to the information revealed by their rivals' bids. In particular, the coefficient of the variable measuring money left on the table, MLT, is more than an order of magnitude smaller than that of BID in year 1, and also insignificant. Alternatively, this information may have been anticipated by the winning firm when it submitted its bid, and hence included in BID.

The bidding on other tracts in the area-cohort does play a role. Initially, firms are less likely to drill if AREABID is high. This might occur because other leaseholders are more likely to drill early in the lease term. In the final year of the lease, firms are more likely to drill if AREABID is high, albeit insignificantly so. When there are no further gains to delay, the valuation of a tract is higher the better the signals on tracts not yet drilled, as suggested by Lemma 2.

In the first year of the lease term, the coefficient of HERF is positive, but not significant. This is consistent with asymmetries of lease holdings mitigating any information externalities and enhancing coordination, and therefore reducing any incentive to delay.

The effects of post-sale drilling activity on drilling decisions support the hypothesis of information spillovers, but not as strongly as one might expect. The coefficient of DRPOST is positive and significant in the first year of the lease. That is, there is initially more drilling in areas with substantial post-sale activity, all else equal. If one views DRPOST as a measure of sample size, and HITPOST the number of positive outcomes, then the signs and relative magnitudes of their coefficients are somewhat surprising. One might expect the number of positive outcomes to have a larger coefficient, and perhaps also that the DRPOST coefficient would be negative. The sum of the two coefficients is positive, as expected, indicating that proportional increases in DRPOST and HITPOST increase the likelihood of drilling. The findings suggest that there may be significant unobservable heterogeneity across areas, specific to particular sale dates, that the area-cohort specific variables do not capture and that are correlated with DRPOST. For example, firms may observe HITPOST with a longer lag than DRPOST, in which case a large value of DRPOST may be a signal of relatively optimistic assessments of area-wide productivity by rival firms. That is, firms might have private information that is revealed by their drilling decisions.

The results from Table 4 should be viewed as suggestive. We have concentrated on relatively simple functional forms, because of uncertainty on our part about the information set facing lease holders. The issue is whether and when information becomes available publicly. We have experimented with different decision frequencies, such as quarterly, and a variety of lag structures for the information variables. The reported specification is representative, and (to our minds) plausible a priori. Firms can certainly observe when their neighbors are drilling, and hits would be difficult to disguise for long periods. (For example, developmental wells must be drilled.) More problematic is the implicit assumption that actual production levels are observable. Annual royalty payments are observable, and initial production is correlated with eventual production, so that our discounted production measure is probably a noisy proxy of what firms observe. This may explain why REVPOST does not appear to have much of an effect on drilling decisions, except in the last two years of the lease when it has a significantly positive effect.

C. *Determinants of Drilling Outcomes*

Table 5 reports on the determinants of the productivity of a drilled tract. The set of regressors is the same as in Table 4. The estimates are from a Tobit regression, where the dependent variable is REV, the logarithm of discounted revenues if the tract had positive revenues, or zero if it was unproductive.[4] As mentioned previously, the idea behind this regression is to see whether the determinants of drilling activity are correlated with drilling outcomes. There is an obvious sample selection problem in that we observe outcomes only on tracts that are viewed most favorably and hence drilled. Nevertheless, within the set of drilled tracts, one can still ask how accurate ex ante information is.

The pattern for BID coefficients mirrors those in Table 4. Also, the AREABID coefficient is not significant initially, as one might expect if AREABID reflects the selection of a particular timing pattern, rather than being correlated with actual initial productivity assessments. In contrast, AREABID is positive and significant in the last year, indicating that the firms rationally incorporated this information in their end-of-lease drilling decisions.

[4] The Tobit specification accounts for the fact that tracts are not developed if deposits are too small, by specifying the censoring threshold to be slightly lower than the lowest observed positive value of REV for each area considered rather than 0.

TABLE 5—TOBIT ESTIMATES OF THE LOGARITHM OF DISCOUNTED REVENUES ON DRILLED TRACTS, BY YEAR OF INITIAL DRILLING

	Year after acquisition				
Variable	1	2	3	4	5
NRISKSET	−0.282	−1.181	−0.355	0.338	−0.420
	(0.410)	(0.794)	(0.890)	(0.997)	(0.855)
AREABID	0.481	−0.132	1.187	−0.245	1.914
	(0.502)	(0.898)	(1.111)	(1.056)	(0.943)
BID	2.337	0.832	0.815	0.374	−0.848
	(0.320)	(0.540)	(0.668)	(0.720)	(0.698)
MLT	−0.897	0.395	−0.126	1.561	2.960
	(0.314)	(0.635)	(0.792)	(0.897)	(1.021)
ONEBID	−3.434	−2.746	0.575	0.190	−0.345
	(2.693)	(2.967)	(2.715)	(2.963)	(2.245)
ONEBID × MLT	1.497	−0.205	−0.489	−0.483	−2.298
	(0.758)	(1.139)	(1.095)	(1.366)	(1.176)
HERF	−2.023	−4.359	−2.004	−0.638	2.141
	(1.919)	(2.728)	(3.482)	(3.154)	(2.693)
ACRE	−2.188	−2.861	−4.016	3.256	−1.201
	(0.981)	(1.215)	(2.779)	(3.209)	(1.659)
REOFFER	3.170	−0.482	−0.020	6.400	0.741
	(1.320)	(1.886)	(1.758)	(3.395)	(2.133)
DRPOST		6.892	1.368	2.136	2.367
		(1.500)	(1.476)	(1.397)	(1.339)
HITPOST		−4.766	−2.072	−4.816	−1.839
		(1.366)	(1.483)	(1.478)	(1.571)
REVPOST		0.006	0.201	0.125	0.076
		(0.104)	(0.129)	(0.138)	(0.146)
Sample size	733	363	188	155	214
Log-likelihood	−1,575	−669	−330	−266	−321

Notes: Standard errors are displayed in parentheses. Each regression includes a set of 14 year-specific dummy variables. The sample is the set of tracts drilled in that year. The dependent variable equals the logarithm of discounted revenues on productive tracts, and 0 on unproductive tracts. The Tobit procedure employs a lower threshold, slightly less than the lowest observed positive value of the dependent variable for each year considered.

There are two other notable differences between the sets of estimates in Tables 4 and 5. MLT has essentially no effect on the probability of drilling but its coefficient is negative and significant in the first year, and much larger in absolute value relative to BID, in the revenue equation reported in Table 5. This suggests that firms may not correctly update their beliefs about the value of their leases after the sale.

The other difference concerns the post-sale drilling variables. As in Table 4, the DRPOST coefficient is positive and often significant in Table 5. The HITPOST coefficient is negative and often significant, contrary to what one might expect, more so than in Table 4. The negative HITPOST coefficients in the productivity equations indicate that firms may not be processing information optimally. Alternatively, they may observe HITPOST with a longer lag than DRPOST, as noted above. Finally, the REVPOST coefficient is positive in Table 5, consistent with the supposition that revenues are only observed with a lag.

The results reported in the preceding tables are relatively robust. Hendricks and Porter (1993) describe a number of alternative specifications with similar results. Hanno Ritter (1995) reports similar results with different post-sale experience variables.

In general, the variables we consider do not explain drilling outcomes very well. This is a further reflection of the uncertainty that firms encounter in their drilling decisions.

IV. Conclusion

Our hypothesis is that drilling programs on the OCS are the outcome of a noncooperative Nash equilibrium. The main nonparametric implication of the equilibrium is that a U-shaped hazard function with a disproportionate number of leases should be drilled near the end of the lease term. We find that the hazard function in the data is indeed U-shaped (except possibily for very small area-cohorts) and of the order of magnitude predicted by the theory. Furthermore, it cannot be attributed to aggregation of area-cohorts of different sizes.

There are several ways firms can coordinate their actions on the OCS. First, joint bidding consortia are legal, except those involving two or more of eight designated firms after 1975. Second, once a common pool has been discovered, revenues from developmental wells are usually unitized. Unitization agreements, which are encouraged by the federal government, allocate revenues from a common pool according to a prespecified rule, such as acreage owned above the pool, in order to prevent overdrilling of developmental wells (Gary D. Libecap and Steven N. Wiggins, 1985; and Wiggins and Libecap, 1985).

So why does apparently noncooperative behavior occur in the exploratory drilling phase? Part of the answer may concern asymmetries of information. In the bidding game, informational heterogeneities are present, because firms interpret imperfect seismic information differently. As a consequence, joint ventures between firms actively engaged in exploratory drilling are relatively uncommon. Instead, it is as common for firms to turn to outside partners to raise capital or to bid alone. An obstacle to the formation of joint bidding agreements is the incentive to free ride on the information gathering expenditures of prospective partners (Hendricks and Porter, 1992). Therefore, firms do not usually emerge from the bidding process in strong multilateral arrangements.

Unitization agreements are common on federal lands, unlike state lands, in part because negotiations occur relatively early in the process, when information is not too asymmetric. In terms of the model above, the uncertainty regarding the presence of deposits is not resolved, and uncertainty remains about the distribution of rents between the leaseholders. Unitization on federal lands typically occurs after the leases are acquired, and prior to exploratory drilling. However, it is notable that unitization agreements pertain to common pools, and not to fields that share common geological structures. In our sample, only 383 of the 2,255 tracts were unitized.

An agreement with respect to exploratory drilling of necessity must be consummated prior to the resolution of uncertainty concerning whether a pool, or a broader area, is productive. While unitization agreements probably encourage coordination of drilling on common pools, this bargaining mechanism is not available for broader areas. In those cases, firms' expectations of their shares may be difficult to reconcile, due to different interpretations of seismic data, and yet some sources of uncertainty are common. Then one would expect noncooperative behavior to ensue.

Finally, an obstacle to coordination in the exploration phase is that firms may fear sacrificing information or expertise advantages in future auctions. For example, if in the process of coordinating drilling decisions firms must reveal how they interpret seismic data, then they may lose a competitive advantage. This is another example of potential free-rider problems.

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