Real Option Exercise: Empirical Evidence *

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Abstract

We use detailed project-level investment data to examine the real option exercise decisions of firms. While aspects of exercise decisions are consistent with real option theory, firms' exercise behavior deviates from standard real option models in systematic and economically meaningful ways. Although project Net Present Value (NPV) is positive at the time of exercise, firms forego 52% of option value by not delaying investment. Using localized exogenous variation in peer investment activity we identify a channel linked with early exercise based on responses to competitors' exercise decisions. Our evidence is consistent with agency frictions and information externalities affecting investment timing and project value.

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Introduction

Every investment decision made by a firm is both a decision on which capital project to pursue as well as when to pursue it. The flexibility associated with the timing of investment decisions has value to the firm; this value is commonly referred to as real option value (Myers (1977)). Real options are a central component of models of the macro economy (Bernanke (1983)), and their exercise has received ample attention in the corporate finance theory literature (e.g., Dixit and Pindyck (1994)). However, despite the importance of real options, micro-level empirical evidence on exercise behavior remains limited.[1] In this study, we provide direct evidence on the real option exercise behavior of firms and contrast it with the patterns predicted by theory.

Characterizing firms' exercise behavior of real options is empirically challenging. First, detailed data on the timing flexibility associated with capital projects is typically unavailable. Second, in order to fully characterize a firm's exercise behavior, one needs to obtain data on all projects that the firm is contemplating; that is, not only those it decides to undertake but also those it decides *not* to pursue. This level of visibility is often not available. Third, being able to observe the key inputs that might drive option exercise decisions is necessary in order to contrast predicted behavior from actual behavior; these would include expected project cash flows, costs, and volatility of project cash flows. Lastly, identifying plausibly exogenous factors that may lead firms to modify their exercise behavior is challenging.

This study focuses on a setting which allows us to make significant progress on each of these challenges. We analyze $31.6 Billion in capital projects comprised of exercised and unexercised natural gas well investments in a major shale development in North America. The institutional structure of this setting allows us to have full visibility into the timing flexibility firms have in making drilling decisions. In particular, we can observe the exact date firms

[1] Kellogg (2014) studies oil drilling activity and finds that oil price volatility affects investment decisions in a manner consistent with real options models. However, the study does not assess or quantify how actual behavior may deviate from theoretical predictions or assess the importance of information externalities across firms. Moel and Tufano (2002) studies mine opening and closing decisions relative to what real options theories would imply, however, the setting does not have the inputs necessary to quantify deviations from predicted behavior.

decide to exercise their real options (drill wells), as well as how long they could have chosen to wait before initiating drilling. Second, due to the institutional structure of lease contract terms we are also able to observe the unexercised options at any given point in time. Third, because the key determinant of project cash flow is the price of natural gas, a commodity whose expected price and implied volatility is readily observable to the econometrician from financial derivatives, we have the inputs necessary to estimate the optimal stopping time (exercise time). Lastly, we are able to exploit institutional features of our setting to obtain plausibly exogenous variation in factors which may affect when these options are exercised in practice.

The option to drill on existing natural gas reserves can be viewed as an American option on the underlying asset (e.g., Paddock et al. (1988)). When considering the optimal exercise time of this option, similar to American options on dividend paying stocks, the firm should not wait until maturity to exercise. That is, because the production of natural gas from a reserve is similar to the dividend paid out on a stock, there is a tradeoff between the gains associated with potentially better pricing in the future and the opportunity cost of deferring revenues. The classic derivations of the optimal stopping time (see, e.g., Dixit and Pindyck (1994)) find a trigger rule for which a trigger value can be computed such that when the value of the underlying asset (natural gas reserves) exceeds the trigger value, it is optimal to exercise the option.

We find that while aspects of investment exercise decisions are consistent with real option theory, firms' exercise behavior deviates from standard real option models in systematic and economically meaningful ways. For example, we find that the propensity to exercise is dependent on the volatility of natural gas prices, as predicted by theory (e.g., Kellogg (2014)). However, we find systematic evidence that firms exercise their options too early, thereby foregoing substantial option value. The option value embedded in the ability to delay investments makes exercise costly because exercising means losing the option to wait, and hence foregoing the possibility of higher natural gas prices in the future. In particular, we find that firms tend to exercise at values well below this optimal "trigger point."

To quantify the importance of these deviations, we use the granular set of inputs in our data and solve for the trigger value firms would compute if they used a standard real options framework. We find that firms exercise on average when project NPV is 52% below the trigger value. Specifically, firms exercise when project NPV is $1.25 million, when the value of holding on to the option would have been worth $2.60 million. We run sensitivity analyses on our input parameters and find that, over a reasonable set of parameters, the option value foregone fluctuates from 32.5% to 76.2%. The substantial option value associated with these options is consistent with the long maturity time of the options in our setting and the highly volatile nature of natural gas, both factors which would increase the value of holding these options.[2] Firms tend to exercise projects once the internal rate of return of a project hits 18%, despite option theory suggesting that firms wait. On average, in the sample of projects that firms exercise, firms wait 22.3 months to exercise, despite having the flexibility to wait 240 months. To our knowledge this is the first micro-level empirical quantification of the difference in value between actual exercise behavior and the exercise behavior predicted by standard real option models with no market frictions or information externalities.

Why might firms be exercising early? Corporate finance real option theories provide a rich set of predictions as to why firms may deviate from a the predicted behavior of standard real option models with no frictions and information externalities. Some of these theories suggest firms may alter their own timing of investments due to the exercise behavior of competitors (e.g., Grenadier (1996), Grenadier (1999), Grenadier (2002), Novy-Marx (2007)). Firm decisions as a response to competition have a long history in the economics and finance literature (e.g., Cournot (1838), Bertrand (1883)). These theories typically rely on the role that information may play in affecting a firm's decision. Unlike financial options, real options have important information externalities. We focus our identification on assessing a particular channel linked with these information externalities and study how firms invest in response to adjacent competitor exercise decisions.[3] Our data is granular enough that we can observe

[2] The maturity of options in our study can exceed 20 years. Moreover, natural gas is highly volatile relative to other assets, with standard deviation of monthly returns of 11.4% compared to 2.9% for the S&P 500 and 8.5% for oil over the last 5 years.

[3] We acknowledge this is only one aspect of the many theories which attempt to explain early exercise; however, it is the only aspect our identification strategy allows us to directly identify. We leave additional explanations of early exercise for future research.

the specific drilling units a firm has, as well as the units adjacent to its asset. Every unit in our sample is adjacent to eight other units, so there is significant variation that we can exploit. For example, if a firm observes a competitor exercising an option adjacent to a drilling unit the firm owns, the firm now has potentially an important new signal about the quality of its own reserve, thereby potentially believing that its own option has hit the trigger value (e.g., Grenadier (1999)).[4] Alternatively, firms could feel pressure to signal to principals (shareholders and lenders) that the quality of their projects are as good as those of competitors in the adjacent vicinity. The underlying friction driving this behavior would be agency-based in this case (e.g., Grenadier and Wang (2005) and Grenadier and Malenko (2011)). Both these underlying frictions provide theoretical support for assessing the importance of how competitor activity may push firms to exercise early.

Our empirical design to assess why firms might exercise below the trigger value is based on a duration analysis using a hazard model. The objective of using a hazard empirical framework is that it allows us to compute how different factors affect the probability of exercising an option at time t, conditional on an option not being exercised up to time t. The data in our sample is conducive to this type of analysis because each option has a well defined starting point, we can clearly observe when an option is exercised (and drilled), and we have detailed data on how covariates vary during and up to the time of exercise. This modeling is consistent with others that have modeled drilling decisions (Kellogg (2014)).

Using duration analysis we find several features of exercise behavior directionally consistent with standard real options theory. Specifically, we find that a one standard deviation increase in natural gas price volatility decreases the likelihood of exercising an option by 28.5% relative to the baseline hazard rate. We find that an increase in natural gas prices of \$1 increases the likelihood of exercise by 11%, due to the relative increase in project NPV compared to the trigger value. However, while these effects are directionally consistent with

[4]Some of the literature has focused on information cascades and first-mover advantages (for instance in real estate (see Grenadier (1996)). Although in traditional oil pools, there could arguably also be a first-mover advantage for the firm that manages to extract from the shared resource before its competitors, shale drilling does not offer such an advantage as the hydrocarbons are trapped in the tight rock deep underground (see Section 1 for more description on shale drilling) and hence cannot be "stolen" by neighboring competitors.

what option theory would predict, they do not reconcile the gap in the level of NPV at which projects are exercised compared to the trigger value predicted by theory.

To directly test the role that competitor behavior may have on option exercise, we test whether unexercised options directly adjacent to options that are exercised by competitors are more likely to be exercised. We find that for each adjacent option that is exercised by a competitor, the likelihood that a firm exercises its own drilling option increases by 29.8%. However, a concern with a direct estimation of this effect using a hazard model is that a common geography specific or time specific factor may drive both competitor exercise and exercise by the firm. To mitigate this endogeneity concern we follow the approach of Leary and Roberts (2014) and use the residual of adjacent competitor activity after common time and geography specific effects have been controlled for. We find that using this residual, firms are still more likely to exercise when adjacent exogenous exercise occurs. While we cannot directly test for exogeneity of this measure, it controls for two of the most significant endogeneity concerns, that reserve quality (geography) and time effects (technology changes) may jointly be affecting option exercise. Consistent with this residual not being correlated with reserve quality, we show it has no correlation with the other signals of reserve quality a firm receives.

Our paper contributes to the literature on several dimensions. First, we provide new micro-level evidence of the option exercise behavior of firms relative to a standard real option benchmark and calculate the value difference between actual investment behavior and the behavior predicted by theory. This represents an important advancement to the work of Kellogg (2014) and Moel and Tufano (2002), both of whom calculate that firms adjust their exercise behavior when important factors that affect option value change (e.g., volatility), but neither study has an institutional settings which allows them to directly compute potential value effects between actual and predicted firm behavior.

Second, we provide the first empirical tests for the impact of hypothesized channels that may alter baseline exercise behavior (Grenadier (1996), Grenadier (1999), Grenadier (2002), Novy-Marx (2007), Grenadier and Wang (2005) and Grenadier and Malenko (2011)). Specifically, while existing literature documents that peer effects are important for a variety of firm decisions (e.g. capital structure (Leary and Roberts (2014))), we show that these effects also have an important impact on the timing of investment decisions.

The paper proceeds as follows. In Section 1, we provide the institutional background on the natural gas industry. In Section 2, we provide a detailed overview of standard real option theory and its predictions. In Section 3 we discuss our data, and in Section 4 we report our results and methodology. Section 5 concludes.

1 Natural Gas Industry Institutional Background

1.1 Project Overview: Natural Gas Shale Drilling

Our setting exploits the institutional features of natural gas shale development and extraction to study firm behavior relative to what real option models may predict. To extract shale natural gas firms must first drill a well, then complete a well by hydraulically fracturing the well ("fracking"). The process of drilling a well may take a few days to a few weeks, while fracking is done as a separate process after drilling, and takes another few days. Both drilling and fracking entail substantial upfront capital costs of $4.8 million per well on average in our sample. Once a well is completed, it produces natural gas, and declines over time. The critical features determining the profitability of the cash flows are natural gas prices and the volume extracted. Costs include lease operating costs and royalty costs, and typically comprise less than 40% of a well's revenues after the well is drilled. Cash flows are at their highest level at the beginning of a well's life, then decline over time as pressure from the well declines, and once a well starts producing there is little that a firm can do to cause the production to go up or down outside of a wells natural decline without risking damage to a well. Figure 1 plots the cash flows and capital expenditures associated with drilling a well.

The features of a natural gas well investment map nicely into an option framework. Because the entire investment is essentially one sunk cost payment at the beginning of a project's life, this capital expenditure is analogous to a "strike" price in an American option framework. The net after tax cash flow that a well generates can be viewed as the underlying asset that a firm gets after exercising an option. Firms in our setting all produce the same commodity, natural gas, and the market provides indicators of expected futures prices and volatility, both of which can be used as inputs for an option pricing model.

One of the key features of our setting is the unique ability to observe the flexibility and maturity that firms have on their investment options. As in Kellogg (2014), we focus on "infill" drilling projects in order to have well defined maturity assumptions. An "infill" project corresponds to the decision to drill additional wells on a drilling unit that a firm already operates. The first (or existing well) on a unit contractually holds the operatorship of the acreage as long as the first well produces. A firm has the option to drill additional wells at any point in the future so long as the initial well is still producing. This provides firms with options with very long maturities as the life of the first well can range anywhere from 20 to 40 years. In the specific shale development that we study, a single drilling unit of 640 acres can support up to 8 shale wells (or roughly $38.6 million in Capex). The infill options firms have in this study entail large capital investments with a significant degree of flexibility on when to exercise these options. Figure 2 plots a timeline of the infill drilling decision.

Unlike most studies of investment decisions, we can observe options that are exercised as well as those that are not. Drilling units with an existing well, in which no additional wells have been drilled are effectively unexercised options. Our sample period begins with the first shale development in the Arkoma Woodford in 2005, and the number of outstanding available options gradually increases as the first wells are drilled to hold drilling units. By the end of our sample in 2015 there are 819 total infill drilling options, 306 of which have been exercised, and 513 which have not.

A key feature of our study is to look at firm investment responses relative to competitors. The regulatory and land environment of the Arkoma Woodford shale in Oklahoma, lends itself to being able to make these comparisons across firms and drilling units, as it relates to adjacent activity. This is a key distinction from Kellogg (2014) who focuses on single operated fields, where there is only one firm. We focus on the development of a major natural gas field across multiple operators, a setting where information and other externalities may be more relevant. Every drilling unit in our setting conforms to Jeffersonian survey, and is on a grid system with squares that are one mile by one mile. Every 6 by 6 group of squares rolls up to a township survey. This is attractive for several reasons. Every drilling unit, by construction, has 8 adjacent potential units, regardless of the operator or date of the project. Second, we will use the township survey information to control for potential geography or area specific effects. Figure 3 plots the shale drilling activity in a township. The lines represent the horizontal wellbores of wells. Sections in the grid are the drilling units, sections with one wellbore have not yet been infill drilled, while sections with multiple wellbores have been infill drilled.

2 Theory

2.1 Real Option Pricing

As noted in the introduction, the option to delay drilling when considering the investment decision of a well on proved reserves can be viewed as the owner having an American call option on the proved reserves. One of the key methods developed for option pricing models is through the use of replicating portfolios. The argument for this approach is straightforward: If one can construct a portfolio that replicates the payoff of the option at all times then, by arbitrage, the portfolio and the option should have the same value.[5]

The firm's option to infill drill corresponds to further developing their proven natural gas reserve in a given section. There are two ways to replicate such an asset. One is through a producing proved developed section and the other is through a non-producing proved developed section. The total return on any producing developed reserves can be decomposed into two components: (1) profits from production of γ unit (net of the corresponding depletion) and the (2) capital gain on holding the remaining reserves. It can easily be shown that, as long as the value of an extracted resource is worth more than the value of the resource left in the ground, the expected return on the producing reserves is greater than the expected

[5] In our case, the firm's output is a traded commodity. We can calibrate the parameters of the stochastic process from natural gas futures market data.

return on the non-producing reserves.[6]

If all assets are in equilibrium, then the expected return of the producing proved reserve $\mu_P$should be commensurate to its risk. From the argument in the previous paragraph, the expected return on the non-producing proved reserves μ should be lower than μ_P. However, McDonald and Siegel (1984) show that the replication strategy with an asset earning below equilibrium returns is inefficient and cannot be used to price the option. In equilibrium, the only efficient replicating strategy is to use the asset that earns the equilibrium return, in this case, the *producing* proved reserve. One can show that the correct pricing in this case corresponds to the value of a call option on the underlying asset with a dividend stream that corresponds to the oil production from the producing proved reserves, which does not accrue to the option-holder.

Following Paddock et al. (1988), let V_t be the value per unit (barrel) of *producing* developed reserves; B_t be the number of units (barrels) in the developed reserves; $\Pi_t$is the after-tax price per unit of resource sold., and $R_t d_t$ capture the instantaneous change in wealth (payoff) to the owner on the developed reserves. Further, let us assume that the production of the developed reserve lead to an exponential decline of the reserves at rate ω, i.e. $dB_t = -\omega B_t dt$, then:

$$
\begin{aligned}
R_t d_t &= \underbrace{\omega B_t \Pi_t dt}_{(1)} + \underbrace{d\left(B_t V_t\right)}_{(2)} \\
&= \omega B_t \Pi_t dt + B_t dV_t + dB_t V_t \\
&= \omega B_t \Pi_t dt + B_t dV_t - \omega B_t V_t dt
\end{aligned}
$$

The instantaneous payoff to the owner of the producing developed reserves can be decomposed in: (1) the profit earned on the barrels extracted overdt, and (2) the change in value of the reserves that remain in the ground.

Assuming further that the returns per unit on the producing proved reserves follow a Brownian motion $\left(\frac{R_t}{B_t V_t} dt = \mu_P dt + \sigma_P dz\right)$, whereby the drift μ_P corresponds to having the producing proved reserves earn a competitive market return, then, by combining the two equations above, one can show that the dynamics of V_t are given by:

[6]This assertion will hold true as long as the storage costs above ground are smaller than the time and money it takes to extract the natural resource from the ground.

$$dV_t = (\mu_P - \delta) V_t dt + \sigma_P V_t dz$$

where $\delta = \omega (\Pi_t - V_t) / V_t$. As long as the price per unit sold exceeds the value of the resource left in the ground, then δ is positive and the return on the non-producing asset is less than μ_P. δ represents the opportunity cost of not exercising the option.

From here, we can develop what should be the value for the *non-producing* proved reserves $F(V_t)$. The non-producing proved reserves can be viewed as an option to acquire producing proved reserves by expending the development (drilling and completion) costs (I). Hence the value of the non-producing proved reserves is given by the value of the option to develop the proved reserves. Following the well-established contingency claim approach, one can show that the dynamics of $F(V_t)$ need to satisfy:

$$\frac{1}{2}\sigma_P^2 V_t^2 \frac{d^2 F(V_t)}{dV^2} + (r - \delta) V \frac{dF(V_t)}{dV} - rF(V_t) = \frac{dF(V_t)}{dt}$$

where r is the return on the riskless asset.

Given the long time to maturity of the option to develop (infill drill) units with existing production, one can approximate the time to maturity to be infinite, in which case the partial differential equation (PDE) simplifies to:[7]

$$\frac{1}{2}\sigma_P^2 V_t^2 \frac{d^2 F(V_t)}{dV^2} + (r - \delta) V \frac{dF(V_t)}{dV} - rF(V_t) = 0$$

which corresponds to the well established PDE of an American call option on the underlying asset V_t paying a "dividend" equal to δ. This PDE has an analytical solution, given the following boundary conditions:

$$F(0) = 0$$

$$F(V^*) = V^* - I$$

[7] Smith (2016) provides a deeper discussion on the nature of the time-to-maturity conferred by the HBP provision.

$$\frac{dF\left(V^{*}\right)}{dV}=1$$

where $V^{*}$is the optimal trigger value (see next subsection). The second condition can be restated as $I=V^{*}-F\left(V^{*}\right)$, that is when you invest, you get the underlying but you lose the value of the option. Equivalently, we can rewrite the condition as $V^{*}=I+F\left(V^{*}\right)$, you only invest when the value of the project equals its direct cost plus its opportunity cost. The last condition is the so-called "smooth-pasting" condition.

The solution to this PDE is given by:

$$F\left(V\right)=AV^{\beta_1}$$

where

$$\beta_1=\frac{1}{2}-\frac{(r-\delta)}{\sigma_P^2}-\sqrt{\left[\frac{(r-\delta)}{\sigma_P^2}-\frac{1}{2}\right]^2+\frac{2r}{\sigma_P^2}}$$

and

$$A=\frac{(\beta_1-1)^{\beta_1-1}}{(\beta_1)^{\beta_1}\,I^{\beta_1-1}}$$

2.2 Optimal Stopping Time

When is it optimal to develop proved reserves? The optimal time to exercise a real option is similar to the optimal time to exercise a stock option and will depend on the underlying asset. If the natural resource left in the ground were more valuable than the extracted resource, the underlying asset of the replicating portfolio would be the non-producing proved reserves and the real option would simply correspond to an American call option on a non-dividend paying stock, where the stock would be the non-producing proved reserves. In this case, it is well established that it is never optimal to exercise early the option.

However, as we have shown in the previous section, because extracted natural resources are more valuable than those left in the ground, the underlying asset used in the replicating portfolio becomes the producing proved reserves. The production stemming from this asset (net of depletion) corresponds to a dividend that the option holder is foregoing as long as he does not exercise the option. In this case, the underlying corresponds to a *dividend-paying* stock and there is now a tradeoff between the cost of foregoing the current revenues related to the extracted natural resource (dividends) by delaying the exercise and the benefit of waiting for higher prices for the underlying asset. The tradeoff between no exercise (continuation) and exercise (stopping) can lead to an optimal stopping time prior to maturity. As with traditional financial options, the greater the volatility of the underlying asset, the greater value in the option to wait (delay exercise).

It can be shown that the optimal stopping time is given by a trigger rule under very general assumptions. Specifically, there exists V^*, a trigger value, such that for when the underlying asset crosses V^* from below for the first time, it is optimal to exercise.[8] The trigger value is given by:

$$V^* = \frac{\beta_1}{\beta_1 - 1} I$$

where $\beta_1$was defined in the previous section. When exercising at the optimal threshold, the firm gets $V^* - I$ where I is the infill drilling capital expenditure.

In the NPV framework, the NPV rule would state that one should drill as soon as $V = I$ or equivalently $\frac{V}{I} = 1$. Given that $\beta_1 > 1$, $V^* > I$, or equivalently $\frac{V}{I} > 1$, i.e. there is now a wedge between the NPV rule and the optimal exercise rule. Given the option value to delay, the value of the underlying asset needs to exceed the investment cost (and in some cases by a large margin) before it becomes optimal to exercise.

Also, recall that at the optimum, $F(V^*) = V^* - I = NPV$, and thus we should find that the option value equals the NPV of the project at the time of exercise, as long as firms drill at the optimal time. Note that we have assumed that the only source of uncertainty in the proved reserves is related to commodity prices. If there is extraction risk in the shale play, then we would be underestimating the value of the option with the formulas developed above.

[8] Certain conditions need to be met for this trigger value to exist and be unique (see Kellogg (2014)).

3 Data

3.1 Construction of Real Option Input Variables

An attractive feature of our setting is that we are able to obtain all of the inputs needed to compute the real option decision model for firms within the standard real option framework. The critical components of this data include data on drilling costs, cash flows, natural gas prices, and natural gas implied volatility. The setting for our study is the Arkoma Woodford shale development, and is an institutional environment in which all of the key inputs needed are available during the time frame of our study from 2005 to 2015.

To obtain the cost of each well we collect data from the Oklahoma Corporation Commission pooling regulatory documents. This data is disclosed by all firms who initiate the drilling of the first well in a drilling unit, and is used by other firms with ownership stakes in the drilling unit who are deciding whether to participate in the well or not. Drilling costs fluctuate due to the supply and demand for drilling and completion services, and vary little across operators and geography within a shale basin at a given point in time (Gilje and Taillard (2016)), but they do vary substantially over time. We have detailed data on 996 wells to estimate the costs of the infill wells in our sample.

Cash flows from wells are based on production, prices, lease operating costs, and royalty costs. We obtain detailed production data at a monthly frequency on every well in our sample from IHS energy. In total, there are 1,776,811 well-month observations in this data. This data is based on reports that firms make to state regulatory bodies on production. We also use this detailed month level data to derive the depletion rate, ω, a key parameter in standard real option models. Natural gas prices and the implied volatility of natural gas are obtained from Bloomberg data on natural gas price futures contracts. In our main hazard model specifications, we use the 18 month futures price of natural gas and 18 month implied volatility of natural gas as estimates of the overall gas prices and implied volatility of natural gas over the life of a well (consistent with Kellogg (2014)). Lease operating costs are based on estimates obtained from 10-Ks. Royalty estimates are based on royalty percentages obtained from DrillingInfo on 71,120 oil and gas leases signed in the Arkoma Woodford shale basin, the sensitivities we report encompass a range that is covered by 89.6% of the royalty terms in the sample.

Taken together the institutional environment of the Arkoma Woodford shale allows us to calculate each of the key inputs that are needed to compute the “trigger value” and exercise decisions predicted by standard real option models such as those of Paddock et al. (1988).

3.2 Construction of Panel for Hazard Model

Our main hazard model analysis is based on a panel data construction of decision to exercise infill well drilling options. The unit of observation in this panel is at the option-month level, in total there are 54,208 option-months prior to exercise in our sample. For each option-month observation we include the 18-month natural gas futures price from Bloomberg and 18 month implied volatility of natural gas prices. Both of these variables have clear predictions as to how they might affect exercise based on a standard options framework, with volatility being negatively correlated with exercise and natural gas prices being positively correlated. We also include information on nominal interest rates in our panel construction. To proxy for the overall quality of the reserve that the option to drill is on, we include the log of the first well’s production in the first year as an explanatory variable (the first well is the well prior to the infill option being exercised). Table 1 reports the summary statistics for the panel we use in the hazard model.

The key event that we use to determine whether an option is exercised is the “spud date” of the infill well. This is the date when drilling capital expenditure is initiated and the drilling of a second well begins. Figure 4A plots the number of options exercised over time, while Figure 4B plots the amount of time firms wait to exercise an option for the subset of options that are exercised. Because an option only becomes available to exercise after the first well has been drilled on a drilling unit, the number of options during the sample period is not the same across time. Figure 4C plots the number of options over time, as well as the number of options exercised at any given point in time.

3.3 Calculation of Real Option Exercise Thresholds

For every section in the shale play, we need to determine first the expected value of the developed reserves that can be tapped by the new infill well (V), the optimal exercise threshold (V^*), and the value of the undeveloped reserves, i.e. the value of the option $F(V)$. We rely on the formulas derived from option theory in the previous sections.

To obtain the expected value of the well's developed reserves (V), we rely on a set of commonly used assumptions. First, we make the simplifying assumption that the 18 month future price of gas (P) can be used to compute the value of the stream of cash flow over the entire life of the well and that firms' discount their cash flows at the discount rate μ. Second, the net profit per barrel is obtained by taking into account the operational cost (ϕ), the royalty rate (ρ), the accounting depreciation rate (θ) and the corporate tax rate (τ). Then, we define the net per-barrel profit as: $\Pi = P[(1-\phi-\rho)-\tau(1-\phi-\rho-\theta)]$. Finally, we assume that the well's reserves are being depleted at the exponential rate, ω, which enable us to model the value for one barrel of developed reserves as $V_0 = E_0 \int_0^\infty \omega \Pi e^{-(\omega+\mu)t} d_t = \frac{\omega\Pi}{\mu+\omega}$.

3.3.1 Estimates of the Model Parameters

In the baseline scenario, we set the discount rate at 10%, in line with the industry discounting practice and recent empirical work estimates.[9] Then, we estimated the reserves' depletion rate, ω. From the exponential depletion rate formula of the reserves, we have that the monthly production at a given point in time t is equal to $Prod_t = \omega R_0 e^{-\omega t}$, where R_0 is the initial available reserves. Since we only observe the monthly production, but not the initial available reserves we compute the ratio of monthly production such that $\frac{Prod_t}{Prod_{t-1}} = e^{-\omega}$. As such, for each well we empirically estimated ω from the ratio of monthly productions. In our sample, the average well has an annual depletion rate of 27%. In a subsequent section, we run a set of sensitivity analysis varying the ω parameters from 25% to 29%, roughly representing the 90^{th} confidence interval of the depletion rate distribution. For the royalty rate, we obtain

[9]See Kellogg (2014). In the sensitivity section, we run the calculation using discounting rate ranging from 7.5% to 12.5% on an annual basis.

the lease data from all the wells in the play, and the median royalty rate is equal to 18,75%.[10] Finally, we set the depreciation rate to 40% and the effective tax rate at 0%.[11]

3.3.2 Developed Reserves Value Calculation

To obtain the expected value of the total reserves accessible by the infill well ($B_0 * V_0$), we need to compute the expected number of barrels produced by the infill well. We compute the expected total reserves of the infill well in three steps. First, using realized data from past infill wells drilled in the same play, we regress the first year of production of the second well on the first year of production of the first well for each section.[12] Second, we use the estimated regression coefficient to obtain a *prediction* of the infill well's first year of production ($Production_{t=1}$) for all the wells that we include in our experiment. Finally, we obtain the expected total reserves tapped by the infill well by computing $B = \frac{Production_{t=1}}{\omega}$. Lastly, the expected value of the initial reserves corresponds to $B_0 * V_0$.

3.3.3 Optimal Threshold Calculation

To obtain the optimal threshold value of each wells, we need an estimate of the well drilling cost. From an empirical perspective, drilling cost tend to be strongly correlated with oil prices which has been supported by recent empirical works (i.e. Kellogg 2014). To allow for time varying drilling costs, we obtained well level drilling cost and estimated the expected drilling cost for every month of our sample. We then compute the optimal threshold value (V^*) using the results derived in the previous sections.

[10] In our sample, the average royalty rate is 18.89%, but the industry standard is 18.75%, and 81% of the well's lease set a royalty rate of 18.75%.

[11] During the covered period, oil exploration firms benefited from multiple generous deduction and tax credit. It enabled them to virtually pay no cash taxes.

[12] The regression yield a strong R^2 of 74%.

4 Results

4.1 Exercise Behavior: Actual vs. Predicted

In this subsection we calculate the real option decision rules that firms would have if they rigorously followed the behavior predicted by real option theory and compare this predicted exercise behavior with their actual exercise behavior. Over the period of interest, there were a total of 807 potential infill well real options available. Of these infill well options, 271 are exercised. The objective of this section is to assess, using the granular parameters in section 3, whether at the time of exercise, the project values (V) were above their trigger value (V^*) implied by the standard real option model of Dixit and Pindyck (1994), as outlined in Section 2.

We find that in our base case firms forgo an average of $1.34 million or 52% of the option value. While the projects are positive NPV at the time of exercise, $1.24 million on average and with a long positive tail as shown in Figure 5, the value of not exercising the option is much higher, at $2.58 million on average. Figure 6 plots the distribution of foregone option value at exercise time. The histogram clearly shows that the majority of the wells are exercised when V minus $V*$is negative, reflecting the fact that most decisions result in foregone option value by exercising too early.

Although we have very granular inputs for our model parameters, and every parameter is derived directly from the real data that a firm would be using to compute its exercise behavior, it is prudent to assess how sensitive the project values and trigger values are to changes in model parameters. In Table 2 we report sensitivities across every major parameter in the model: depletion rate, operational costs, discount rate, taxes, and royalties. We find that in the case where the wedge between project value and option value is the smallest, 32.5% of the option value is still lost by early exercise. In each case, the average of the forgone option value in our sample is statistically different from zero.

4.2 Baseline Hazard Model

Our baseline tests of actual exercise behavior relative to the behavior predicted by the theory suggests that firms are exercising real options before hitting the trigger value predicted by theory. To assess factors that might affect firms exercise behavior we transition our analysis to a duration analysis based on hazard functions. The objective of using a hazard function is that it allows us to compute the probability of exercising an option, within an interval, conditional on having survived up to the time of the interval. The unit of observation we focus on to estimate which factors may affect a firm's decision to exercise an option, conditional on the option being unexercised at a given point in time, is at the option-month level.

$$h(t) = h_0(t)\exp(\beta_1 NGPrice_t + \beta_2 NGVol_t + \beta_3 IntRate_t + \beta_4 FirstWellProd_i)$$

A useful baseline when conducting hazard analysis is to plot the survival function, this allows us to observe the rate at which options are being exercised in the sample, we do this in Figure 5. The plot begins at 1 and then declines as time passes (in months) and options are exercised (and no longer survive). By the end of the time period available 37.4 % of all options are exercised.

Having established a baseline we can then assess which covariates may cause a shift up or down in the curve in Figure 5, that is, what are the factors that might explain firms exercising options sooner or later. Within the context of trigger values (V^*) and project value (V), standard option theory predicts that higher volatility will raise the trigger value (V^*), while not affecting (V), therefore, all else equal an increase in volatility would push firms to delay investment. By including volatility of natural gas as a covariate that can affect the hazard rate, we can assess whether this theoretical relationship holds in the data. In Table 3 we find that this relationship does hold, higher volatility reduces the hazard rate (the rate at which options are exercised) and results in an upward shift in the curve plotted in Figure 5. Alternatively, natural gas prices tend to have a positive effect on the hazard rate, as an increase in the natural gas price increases the value of the project (V) relative to (V^*). These results are consistent with those found by Kellogg (2014), and suggest that firms behavior is directionally consistent with these key predictors of activity, even though we find in Table 2 that there are economically important differences in threshold levels firms exercise at relative to those predicted by theory.

Table 3 also highlights another central feature of real options models and investment, and that is the relation between interest rates and investment. As Dixit and Pindyck (1994) point out, a puzzle in the literature is why aggregate investment does not increase more when interest rates are reduced. Specifically, a reduction in interest rates should result in a direct reduction in a firms cost of capital, potentially moving projects from being negative NPV to positive NPV, holding cash flows constant. However, as Dixit Pyndick point out, a reduction in interest rates also makes waiting more appealing, as cash flows in the future are valued more today. The results in Table 3 are consistent with these contravailing incentives, and provide micro-level evidence that interest rates do not necessarily have an effect on pulling forward investment.

Lastly, we also control for the quality of the first well that is drilled in specification (4) of Table 3. The intuition behind this control is that the first well is an indicator of the quality of the geology in an area, and that the more it produces, the higher the NPV of the additional infill projects will be, and the more likely the project will be above the trigger value. As can be seen in Table 3, the higher the quality of the first well, the more likely a firm is to exercise the option. Specifically, a one standard deviation increase in the quality of the first well results in an 111.4% increase in the likelihood of exercise.

4.3 Peer Effects and Option Exercise

The baseline hazard models we report provides results broadly directionally consistent with what real option theory would predict as to how the hazard function ought to shift in response to changes in key covariates. However, there remains an important level difference that was identified between the trigger value (V^*) and the project value (V). To assess why this difference may exist we test whether adjacent competitor investment decisions (peer-effects) may cause shifts in the hazard rate, and cause firms to exercise sooner, i.e. below the trigger value. The theory underpinning this channel is that a firm may have a noisy signal as to the quality of the project it has when it infill drills. While the first well on a drilling unit provides a signal as to the quality of the natural gas reserve, there is some noise associated with the signal. If firms that have adjacent drilling units begin exercising infill drilling options, this information will result in a firm updating positively on the project value it has (V), thereby the firm potentially believing that the project value is above the trigger ($V*$). Alternatively, firms may suffer from agency problems in which managers may need to mimic competitor exercise decisions to signal to shareholders that the firm is capable of extracting reserves at similar quantities and economics as peers. In either case the end result is that firms exercise options faster (at hazard rates that are higher).

We test the effect of competitor activity on the decision to exercise an infill decision on a drilling unit by calculating the number of adjacent drilling units (as many as 8) that have infill options exercised at each point in time for each option in the sample. We also control for the covariates in Table 4, and include controls for adjacent option exercise behavior of the firm itself. We find a strong positive relationship between exercising early and competitor behavior. Specifically, one additional option exercised by an adjacent competitor increases the likelihood that a firm will exercise its infill option by 29.8%.

If adjacent activity matters for option exercise, can it help explain why firms are exercising below the trigger value? To assess this conjecture, we calculate the project value (V) and trigger value ($V*$) for the options that are exercised that are adjacent to competitor activity, and find that the difference between these two figures is statistically different from zero. Therefore, at least for the subset of firms that have adjacent activity from competitors, our results are consistent with this activity driving a wedge between the actual versus the standard behavior predicted by real option models. That said, we are cautious to note that the effect we identify likely does not account for the entire value discrepancy and that there are likely other important explanations of exercise behavior below the trigger value for both drilling units adjacent as well as drilling units that are not adjacent to competitor activity.

4.4 Endogeneity: Peer Effects and Option Exercise

A potential concern with the interpretation of Table 4 is that adjacent competitor activity cannot be viewed as exogenous. For example, a common factor, such as local reserve quality or technology change, could affect both the adjacent competitor's decisions to exercise as well as a firm's own decision to exercise. To identify the exogenous component of adjacent exercise activity, we follow an approach similar to Leary and Roberts (2014), and first estimate a model to strip out both the common component and time component of competitor activity, and then estimate our hazard model with the residuals after these components have been removed. The intuition of this identification strategy is that if investment is a function of endogenous factors linked with location specific or time specific factors, using the residuals of activity allows us to use variation that is not driven by these factors. As Leary and Roberts (2014) point out, a downside of this approach is that we cannot take a stance on what the underlying actual data generating process is. However, this strategy does provide us with variation that is not correlated with the most plausible endogenous issues that one might be concerned about, that is firms with the same assets in the same area all behave the same due to reserve quality or overall (technology-related) time trends.

Table 5 presents the hazard model using residuals of adjacent activity as covariates, rather than the actual adjacent activity. The results using this exogenous adjacent competitor activity measure are consistent with the initial results. Specifically, an increase of one adjacent real option exercised by a competitor increases the likelihood that a firm will exercise its own real option by 24.6%, a figure that is neither statistically nor economically different than the 29.8% reported in Table 4. We also include a dummy variable specification in (2) and (4). The economic interpretation of having more than 1.5 adjacent competitor options exercised indicates the the baseline hazard rate increases by 129.5%. We plot the survival function based on the full sample in Figure 7 and we contrast it with Figure 8 based on the dummy variable classifications in the hazard models. Consistent with the coefficients reported, the survival function for drilling units with more than 1.5 adjacent competitor wells drilled indicates a likelihood of exercise that is more than double the baseline rate.

4.5 Internal Validity

To assess how plausible the assumption is that the residuals we use to estimate the model in Table 5 are exogenous, and appropriately control for potential common factors that could be driving exercise behavior, we estimate the correlation of these residuals with other variables. For example, if the adjacent residuals really proxy for the reserve quality a firm might have or production technology changes, one might expect that the adjacent residuals at the time of exercise would be correlated with the production on the first well in a drilling unit. Such a correlation would suggest that the procedure we employ to adjust for localized common effects, and time trends is not capturing the localized reserve quality a firm has. When we estimate a regression in Table 6, the log of the first well on a unit's production regressed on the residuals, we find that there is neither an economically nor statistically significant relationship between reserve quality and the first well's production. This suggests that the residuals are picking up other components of variation, such as private information competitors have on how economic it is to extract reserves, which they are then signaling by the exercise of their adjacent drilling unit. Overall, these results provide empirical support for the use of residuals as an exogenous measure of adjacent competitor activity.

5 Conclusion

In this paper we exploit detailed data on a set of real options that firms have, to empirically characterize the option exercise strategies they employ. We find that while aspects of exercise behavior is correlated with predictions of standard real option theories, firms also deviate significantly from these predictions. Specifically, we find that firms tend to exercise options at values below the trigger values that theory would predict, forgoing substantial option value.

Why might firms exercise early? We investigate factors related to competitor activity as potential explanations of early exercise. We find results consistent with information externalities and agency properties of real options being important channels in explaining exercise behavior. To date, the empirical real options literature has been limited, largely by data constraints. Our paper provides important micro-level evidence on both how real options are exercised, and how this observed behavior differs from some of the standard predictions from real option theory. Our results suggest that that there is important additional work needed to help bridge our understanding of actual exercise behavior of real options.

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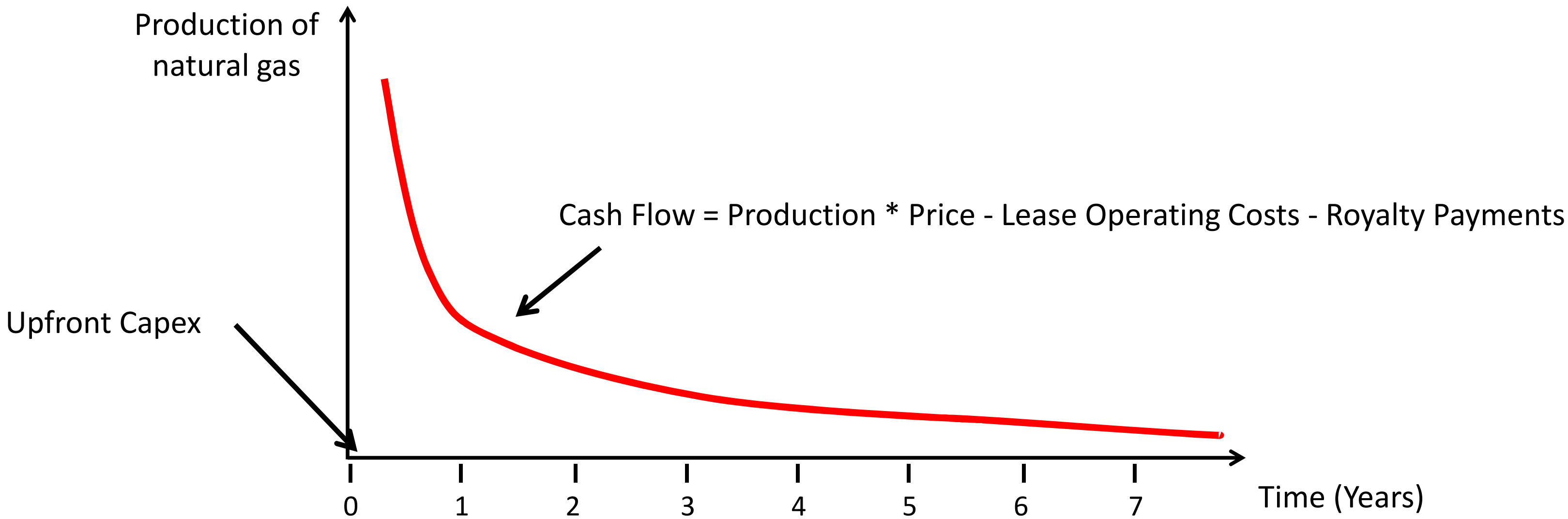

Figure 1: Project Timeline
This figure plots a typical production curve over time for a natural gas well, once production begins. It is based on similar figures found in Lake, Martin, Ramsey, and Titman (2012) as well as company investor presentations.

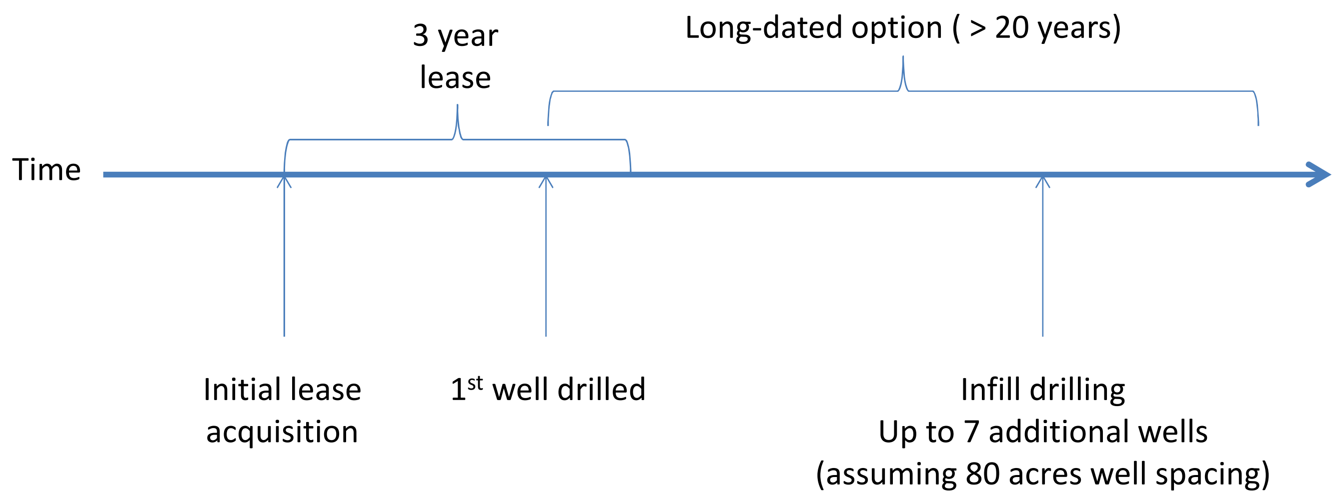

Figure 2: Infill Drilling Option Exercise Timeline
This figure plots the timeline associate with the option to infill drill.

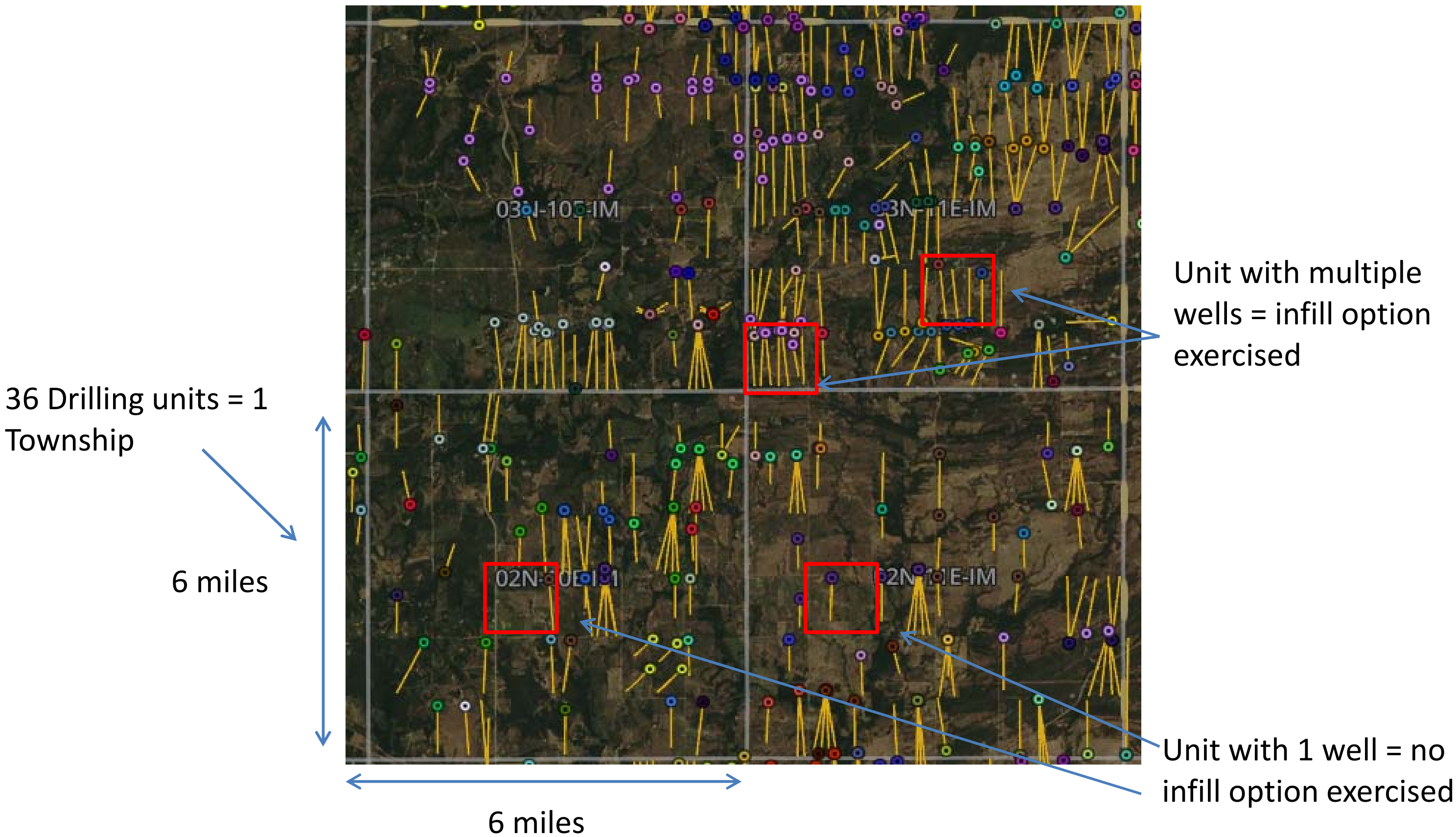

Figure 3: Map of Real Option Exercise Activity

This figure provides a map of drilling activity in the Arkoma Woodford shale. The area covers approximately 4 townships, and 144 individual drilling units. The yellow lines are the horizontal well-bores of the wells in the drilling units, and the multiple horizontal lines in a drilling unit correspond to the real option to "infill" drill being exercised.

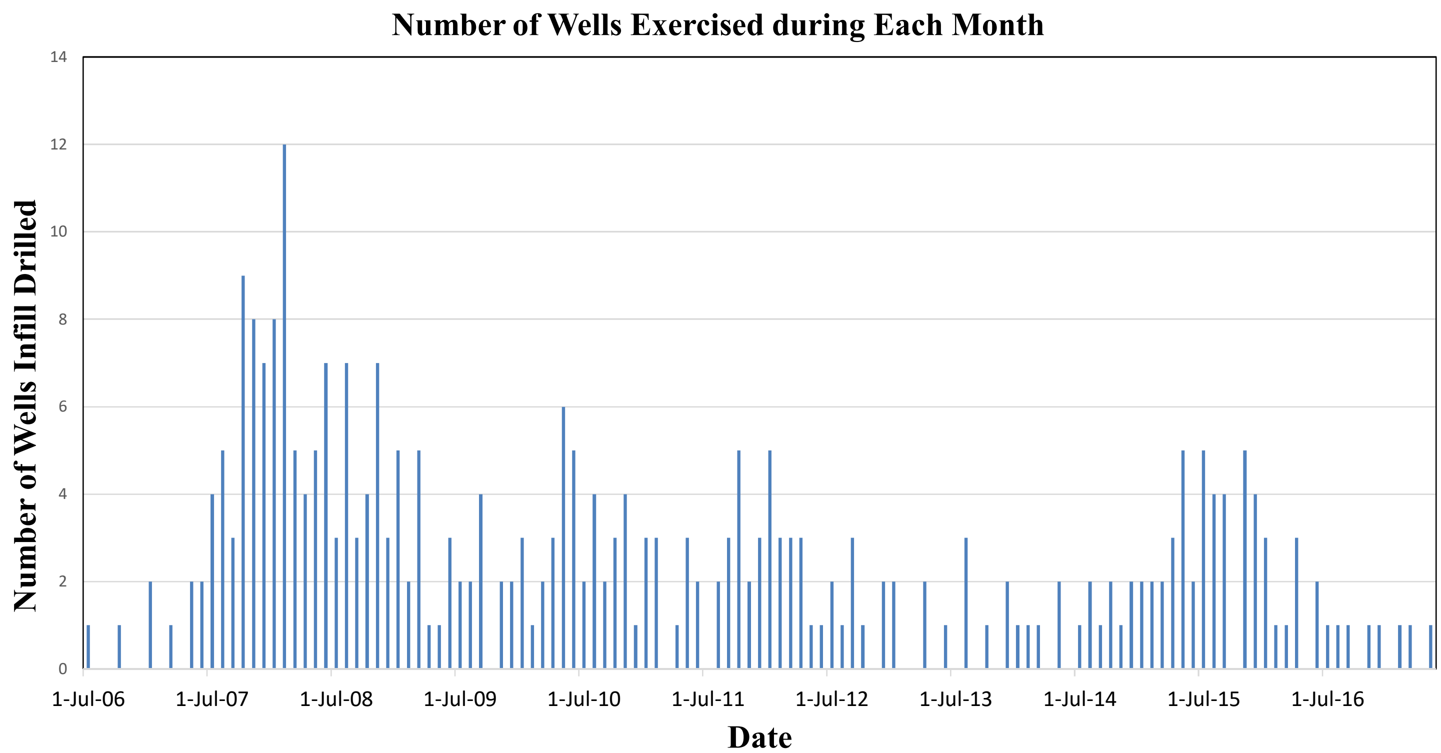

Figure 4A: Number of Infill Well Exercised Over Time
This figure plots the infill drilling activity, measured by the number of infill wells drilled in a given month, for the time period 2005 through 2016.

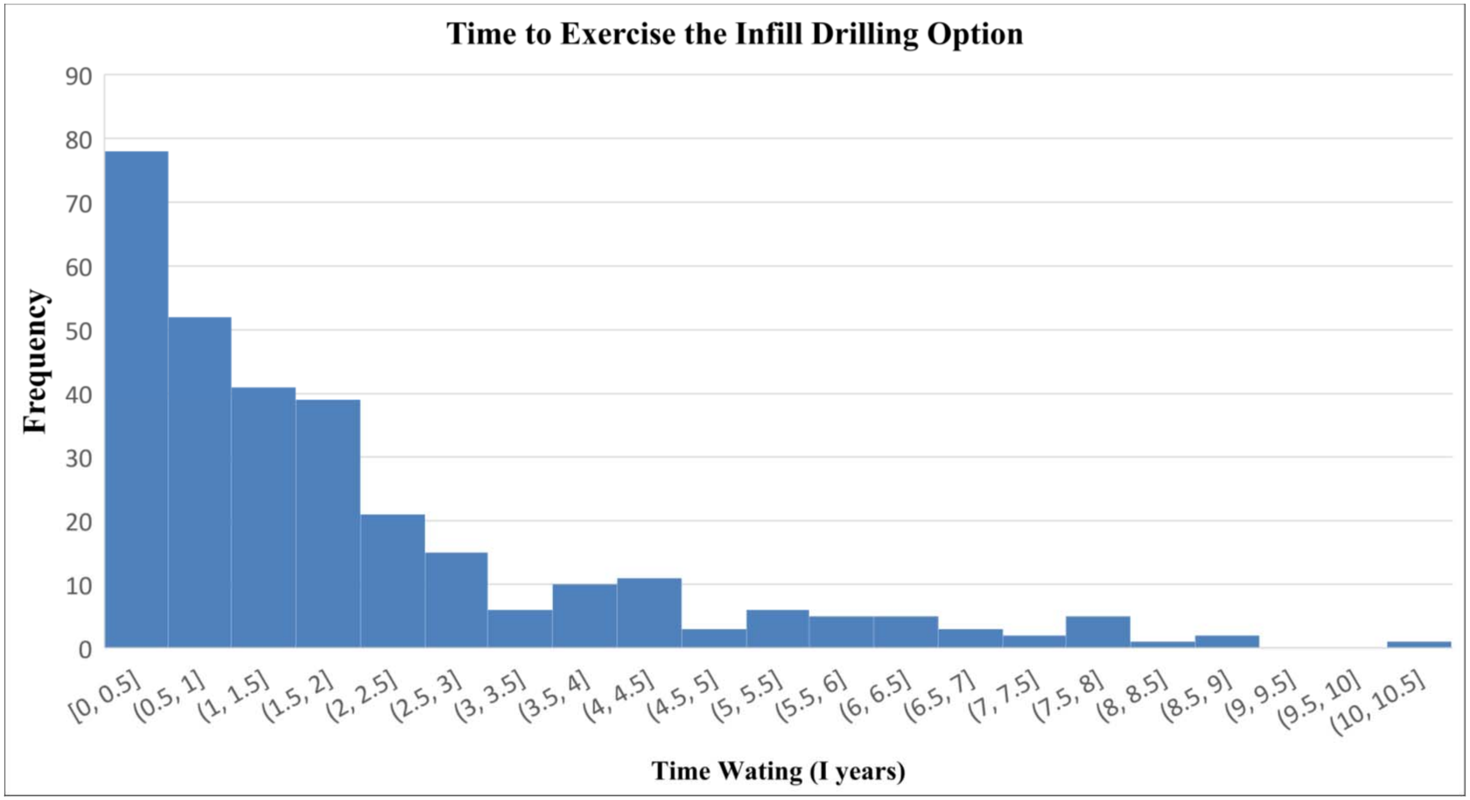

Figure 4B: Time to Exercise the infill Drilling Option
This figure plotes the frequency distribution of the time that firms wait before exercising the infill drilling option, for the time period 2005 through 2016.

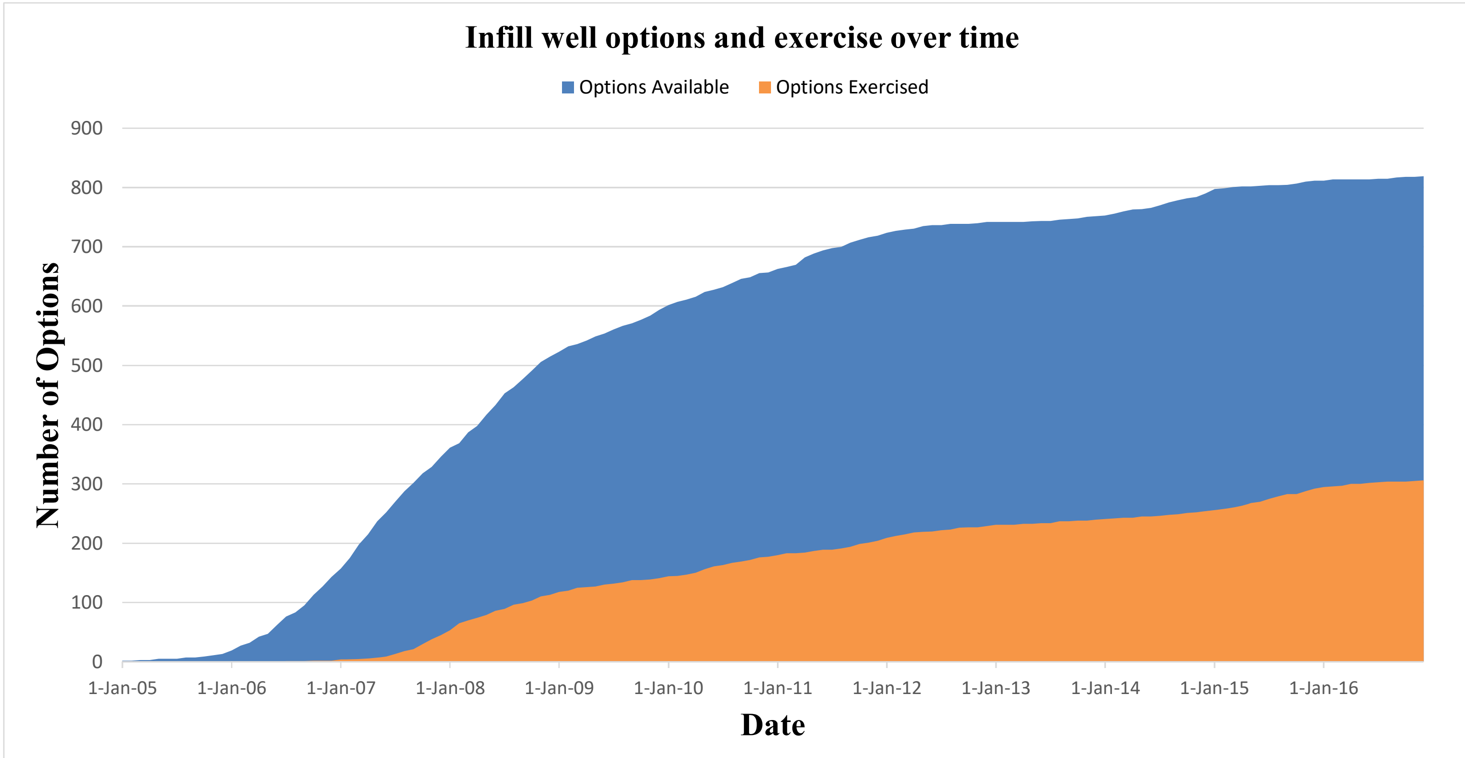

Figure 4C: Infill well options and exercise over time.
This figure plots the number of infill drilling option available and the number of option that have been exercised, measured by the number of infill wells drilled, for the time period 2005 through 2016.

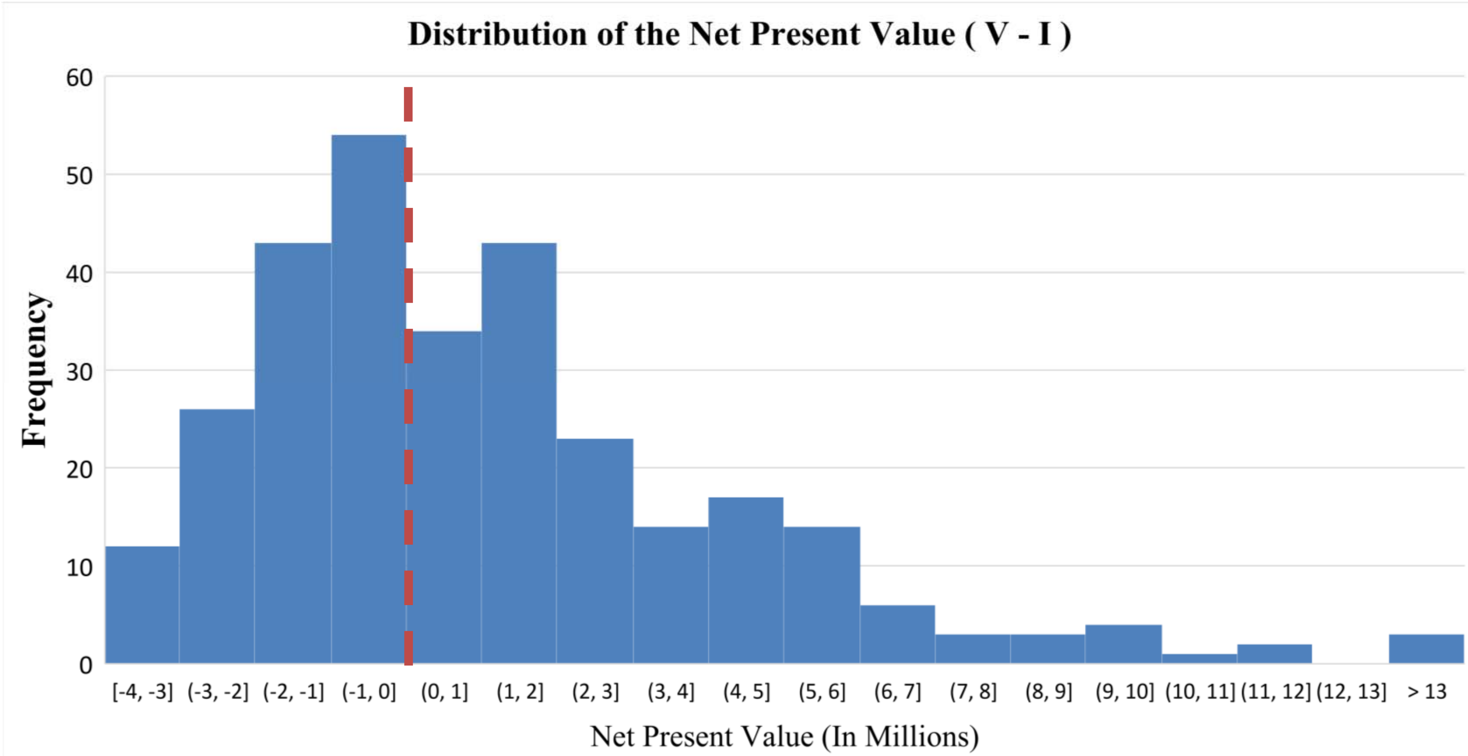

Figure 5: Distribution of the Net Present value (V-I)
This figure plots the distribution of the net present value (V-I) under the base case scenario, such that we set the depletion rate (ω) at 27%, the accounting depreciation rate (Θ) at 40%, the operational cost (φ) at 20%, the royalty rate (ρ) at 18.75%, the tax rate (τ) at 0% and the discount rate (μ) at 10%.

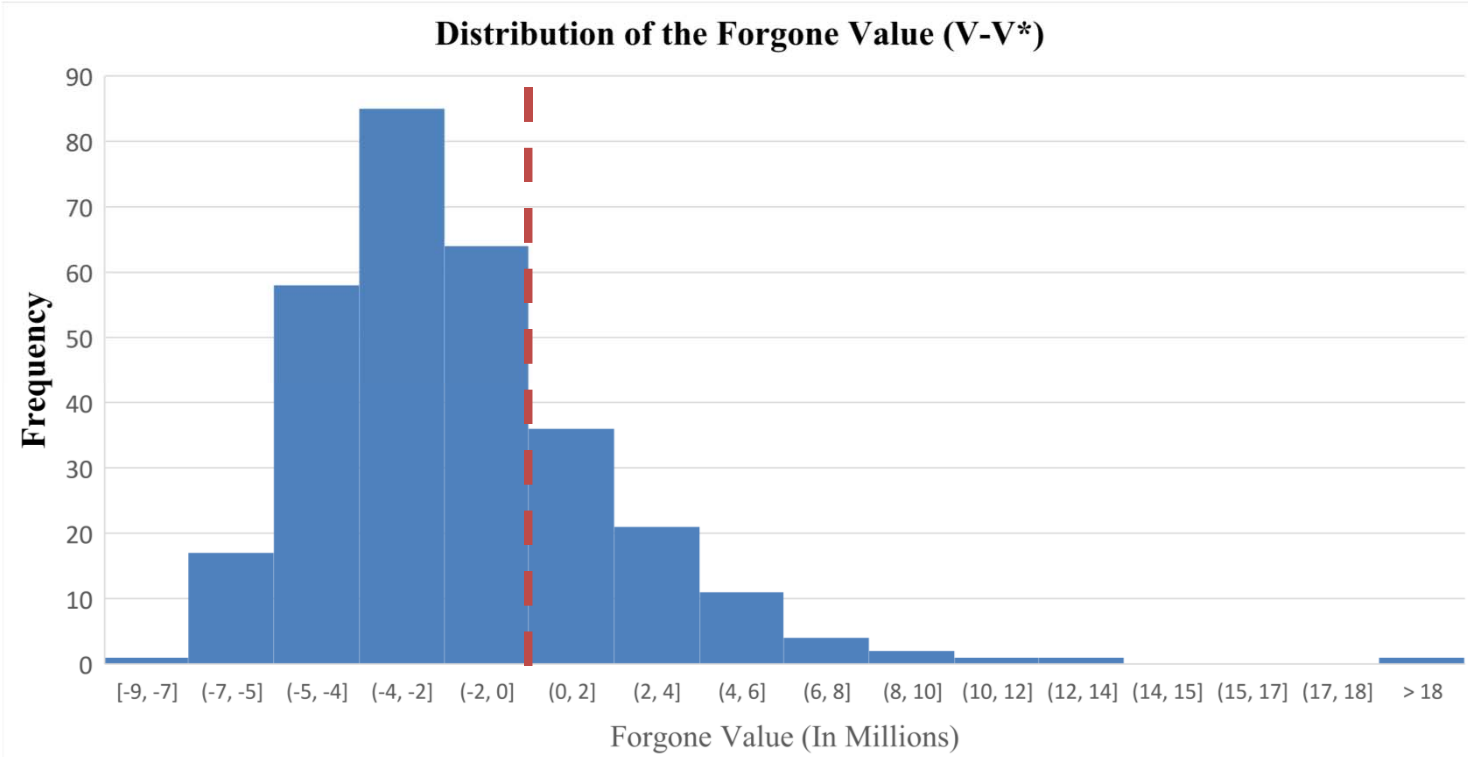

Figure 6: Distribution of the Forgone Value (V-V*)
This figure plots the distribution of the forgone value (V-V*) under the base case scenario, such that we set the depletion rate (ω) at 27%, the accounting depreciation rate (ϴ) at 40%, the operational cost (ϕ) at 20%, the royalty rate (ρ) at 18.75%, the tax rate (τ) at 0% and the discount rate (μ) at 10%.

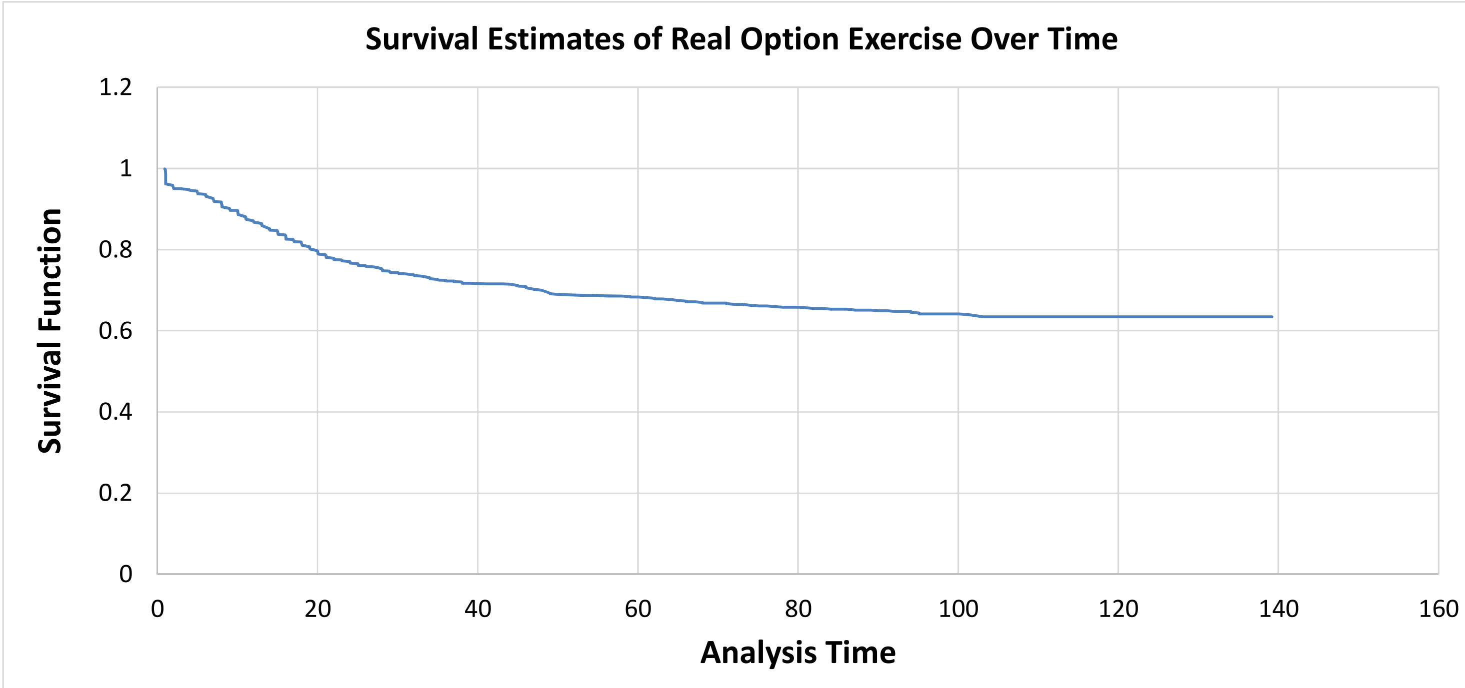

Figure 7: Survival Estimates for the full sample
This figure plots the survival function, measured by the amount of time it takes for the infill drilling option to be exercised, for the option available over the time period 2005 through 2016.

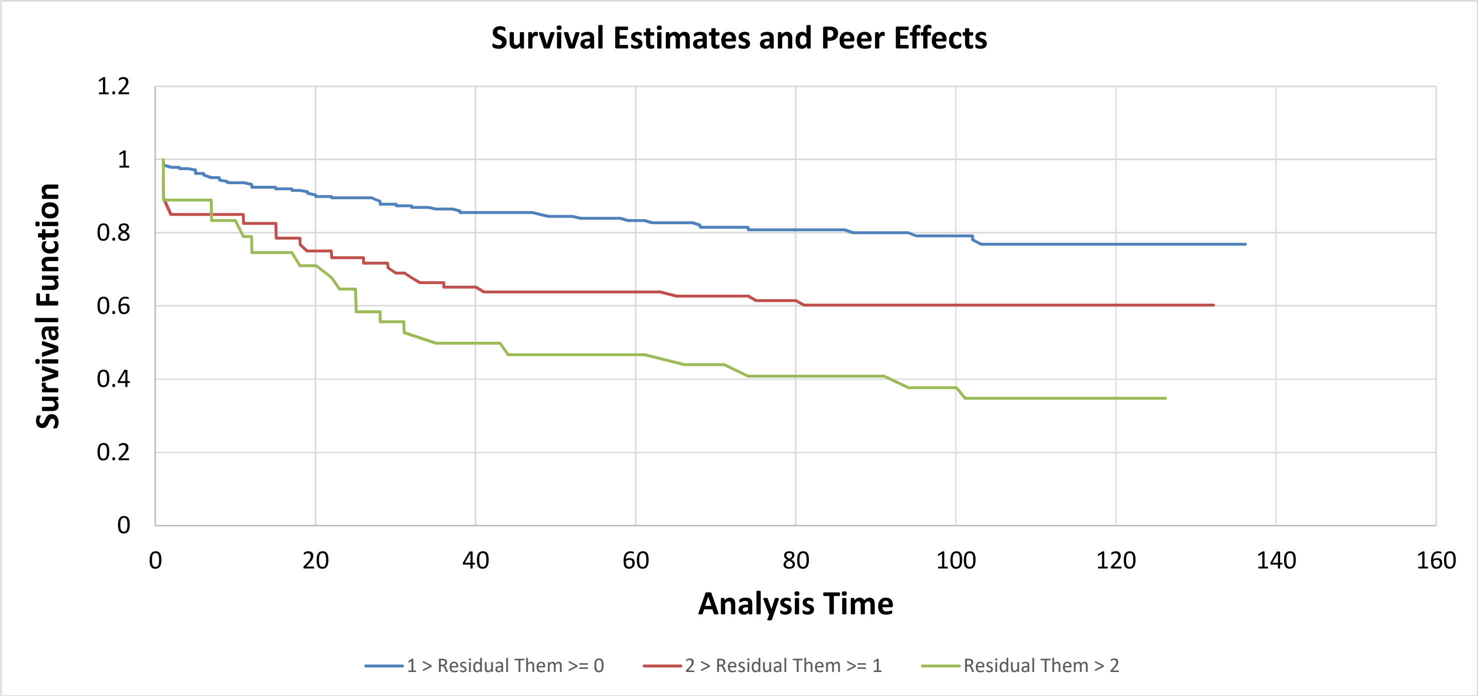

Figure 8: Survival Estimates and Peer Effects
This figure plots the survival function, measured by the amount of time it takes for the infill drilling option to be exercised, for the option available over the time period 2005 through 2016.

Table 1: Summary Statistics

This table contains summary statistics for the data in our study. Panel A presents an overview of the sample of options on infill drilling opportunities that firms have, including summary statistics on well costs and cash flows at the time of exercise. Panel B presents summary statistics on the panel data we estimate our hazard models on. The unit of observation in this panel is at the infill option-month level, that is, there is an observation for every available option to be exercised every month by all firms. The baseline variables are all variables used in the hazard model to assess whether exercise is directionally correlated with factors standard real option theories suggest are important. The peer effect variables are all variables used to assess whether competitor peer affects in adjacent drilling units alter option exercise decisions.

Panel A: Well Data Summary Statsitcs

Time Period	2005-2016			
Number of Total Options	819			
Number of Exercised Options at End of Sample	307			
Number of Firms	23			
Well Statistics at Exercise	N	Mean	Median	Std Dev
Well Costs	307	$ 4,823,213.9	$ 4,841,916.0	$ 560,165.8
Present Value of Well Cash Flow	307	$ 6,060,574.1	$ 5,349,278.6	$ 3,746,005.1

Panel B: Panel Data Summary Statistcs

Baseline Variables	N	Mean	Median	Std Dev
Natural Gas Price	146	5.80	5.03	2.44
Implied Volatility of Natural Gas	138	28.79	27.92	5.35
Interest Rates	146	2.33	1.78	1.33
Log(First Well Production)	819	12.83	12.96	0.97
Peer Effect Variables	*N*	Mean	Median	Std Dev
Adjacent Competitor Options Exercised	113472	0.59	0.00	1.19
Adjacent Own Firm Options Exercised	113472	0.67	0.00	1.24
Exogenous Adjacent Competitor Options Exercised	113472	0.00	0.00	0.82
Exogenous Adjacent Own Firm Options Exercised	113472	0.00	0.00	0.95

Table 2: Sensitivity of Option Value to Parameters

This table reports sensitivity of the values generated by a standard real options model (Paddock et al. (1988)) to different assumptions on model parameters. Depletion rate is the rate at which a well depletes its reserves, a rate of 27 can be interpreted as a wells production declining at a rate of 27% a year. Operational Cost is the percentage of cash flows going towards lease operating expenses, a rate of 20 can be interpreted as 20% of cash flows going to pay for ongoing costs. The discount rate is the firm's cost of capital, and the tax rate is the rate used to compute after tax cash flow.

Depletion Rate Sensitivity	Mean	Pr(Mean = 0)	Median	Pr(Median = 0)
Net Present Value (NPV at Exercise)				
Depletion Rate (ω = 25)	$1,571,664	0.00	$864,563	0.00
Depletion Rate (ω = 27)	$1,246,636	0.00	$592,958	0.04
Depletion Rate (ω = 29)	$935,837	0.00	$294,551	0.42
Forgone Value (Option Value at Exercise - NPV at Exercise)				
Depletion Rate (ω = 25)	$986,699	0.00	$1,706,985	0.00
Depletion Rate (ω = 27)	$1,335,764	0.00	$2,012,502	0.00
Depletion Rate (ω = 29)	$1,649,026	0.00	$2,246,117	0.00
Operational Cost Sensitivity	Mean	Pr(Mean = 0)	Median	Pr(Median = 0)
Net Present Value (NPV at Exercise)				
Operational Cost (ϕ = 15)	$1,741,377	0.00	$994,503	0.00
Operational Cost (ϕ = 20)	$1,246,636	0.00	$592,958	0.04
Operational Cost (ϕ = 25)	$751,895	0.00	$115,620	0.64
Forgone Value (Option Value at Exercise - NPV at Exercise)				
Operational Cost (ϕ = 15)	$837,100	0.00	$1,568,662	0.00
Operational Cost (ϕ = 20)	$1,335,764	0.00	$2,012,502	0.00
Operational Cost (ϕ = 25)	$1,834,427	0.00	$2,386,784	0.00
Discount Rate Sensitivity	Mean	Pr(Mean = 0)	Median	Pr(Median = 0)
Net Present Value (NPV at Exercise)				
Discount Rate (μ = 7.5%)	$1,685,808	0.00	$951,620	0.00
Discount Rate (μ = 10%)	$1,246,636	0.00	$592,958	0.04
Discount Rate (μ = 12.5%)	$863,055	0.00	$223,752	0.49
Forgone Value (Option Value at Exercise - NPV at Exercise)				
Discount Rate (μ = 7.5%)	$1,891,249	0.00	$2,561,597	0.00
Discount Rate (μ = 10%)	$1,335,764	0.00	$2,012,502	0.00
Discount Rate (μ = 12.5%)	$1,131,576	0.00	$1,707,499	0.00
Tax Rate Sensitivity	Mean	Pr(Mean = 0)	Median	Pr(Median = 0)
Net Present Value (NPV at Exercise)				
Tax Rate (τ = 0 %)	$1,246,636	0.00	$592,958	0.04
Tax Rate (τ = 15 %)	$931,239	0.00	$290,078	0.42
Tax Rate (τ = 30 %)	$615,841	0.00	-$11,748	1.00
Forgone Value (Option Value at Exercise - NPV at Exercise)				
Tax Rate (τ = 0 %)	$1,335,764	0.00	$2,012,502	0.00
Tax Rate (τ = 15 %)	$1,653,662	0.00	$2,248,707	0.00
Tax Rate (τ = 30 %)	$1,971,559	0.00	$2,499,681	0.00
Royalty Rate Sensitivity	Mean	Pr(Mean = 0)	Median	Pr(Median = 0)
Net Present Value (NPV at Exercise)				
Royalty Rate (ρ = 13.75%)	$1,741,377	0.00	$994,503	0.00
Royalty Rate (ρ = 18.75%)	$1,246,636	0.00	$592,958	0.04
Royalty Rate (ρ = 23.75%)	$751,895	0.00	$115,620	0.64
Forgone Value (Option Value at Exercise - NPV at Exercise)				
Royalty Rate (ρ = 13.75%)	$837,100	0.00	$1,568,662	0.00
Royalty Rate (ρ = 18.75%)	$1,335,764	0.00	$2,012,502	0.00
Royalty Rate (ρ = 23.75%)	$1,834,427	0.00	$2,386,784	0.00

Table 3: Baseline Determinants of Real Option Exercise

This table reports coefficient estimates from a Cox hazard model of real option exercise. The time period of the sample is from 2005 to 2016. The unit of observation in the underlying panel is at the infill drill option *i* month *t* level. The spell in the hazard model is defind as the time period from which an infill option becomes available (first well drilled) to when the infill option (two or more wells) are drilled. The implied volatility of natural gas is the implied volatility based on option prices 18 months in the future, and the natural gas price is the price of the natural gas futures contract 18 months out into the future. The five year risk free rate is the 5 year nominal risk free rate on U.S. Treasury bonds. The log first well production variable is fixed for a given option, and is the logarithm of the first year year of production of the first well on the drilling unit, which corresponds to production prior to the exercise of the infill option. The hazard impact percentage (HI), which is the percentage change in the hazard rate per unit change of the covariate is reported next to the coefficient. *t* statistics are reported in brackets below the coefficients. * indicates significance at the 10% level, ** at the 5% level, and *** at the 1% level.

	Basic Exponential Hazard		Includes Interest Rate	
	(1)		(2)	
	Estimates	HI (%)	Estimates	HI (%)
(β_1) Implied volatility of natural gas (percent)	-0.0547***	-5.32	-0.0473***	-4.62
	[-3.02]		[-2.58]	
(β_2) Natural gas price ($/mcf)	0.1042***	10.98	0.1374***	14.73
	[2.76]		[2.79]	
(β_3) 5 years risk free interest rate			0.1425	15.32
			[1.55]	
(β_4) Log first well production			0.7645***	114.79
			[8.50]	
Log Likelihood	-1732.5818		-1690.8287	
N	54,208		54,208	

Table 4: Peer Effects and Real Option Exercise

This table reports coefficient estimates from a Cox hazard model of real option exercise. The time period of the sample is from 2005 to 2016. The unit of observation in the underlying panel is at the "infill drill option" *i*, month *t* level. The number of adjacent exercised option (competitor) for an unexercised option *i* at time *t* is the number of the adjacent 8 drilling units owned by competitors in which the "infill drill option" has been exercised by time *t*. The number of "own" adjacent options exercised for an unexercised option *i* at time *t* is the number of the adjacent 8 drilling units owned by the firm itself in which the "infill drill option" has been exercised. The hazard impact percentage (HI), which is the percentage change in the hazard rate per unit change of the covariate is reported next to the coefficient. *t*-statistics are reported in brackets below the coefficients. * indicates significance at the 10% level, ** at the 5% level, and *** at the 1% level.

	Basic Exponential Hazard		Exponential Hazard With Controls	
	(1)		(2)	
	Estimates	HI (%)	Estimates	HI (%)
(β_1) Implied volatility of natural gas (percent)	-0.0576***	-5.60	-0.0548***	-5.33
	[-3.13]		[-2.96]	
(β_2) Natural Gas price ($/mcf)	0.1187***	12.60	0.1031**	10.86
	[3.30]		[2.15]	
(β_3) Number of adjacent exercised options (Own)	0.6227***	86.40	0.5925***	80.85
	[15.57]		[14.55]	
(β_4) Number of adjacent exercised options (Competitor)	0.3098***	36.32	0.2605***	29.76
	[6.90]		[5.47]	
(β_5) Log first well production			0.6539***	
			[6.83]	
(β_6) 5 years risk free interest rate			0.2437**	27.60
			[2.57]	
Log Likelihood	-1635.8360		-1607.8077	
N	54,208		54,208	

Table 5: Real Option Exercise and Exogenous Peer Effects

This table reports coefficient estimates from a Cox hazard model of real option exercise. The time period of the sample is from 2005 to 2016. The unit of observation in the underlying panel is at the "infill drill option" i, month t level. The number of adjacent exercised option (competitor) for an unexercised option i at time t is the number of the adjacent 8 drilling units owned by competitors in which the "infill drill option" has been exercised by time t. The number of "own" adjacent options exercised for an unexercised option i at time t is the number of the adjacent 8 drilling units owned by the firm itself in which the "infill drill option" has been exercised. The hazard impact percentage (HI), which is the percentage change in the hazard rate per unit change of the covariate is reported next to the coefficient. *t*-statistics are reported in brackets below the coefficients. * indicates significance at the 10% level, ** at the 5% level, and *** at the 1% level.

	Basic Exponential Hazard Model				Exponential Hazard Model with Controls			
	(1)		(2)		(3)		(4)	
	Estimate	HI (%)	Estimate	HI (%)	Estimate	HI (%)	Estimate	HI (%)
(β_1) Implied volatility of natural gas (percent)	-0.0531***	-5.17	-0.0547***	-5.32	-0.0465**	-4.54	-0.0497***	-4.85
	[-2.92]		[-3.01]		[-2.53]		[-2.72]	
(β_2) Natural Gas price ($/mcf)	0.0766**	7.96	0.0724*	7.51	0.1047**	11.04	0.0804	8.37
	[2.03]		[1.93]		[2.10]		[1.60]	
(β_3) Num exog adjacent exercised options (Own)	0.6011***	82.41			0.5629***	75.58		
	[9.86]				[9.36]			
(β_4) Num exog adjacent exercised options (Competitor)	0.2402***	27.15			0.2178***	24.33		
	[3.04]				[2.73]			
(β_5) Log first well production					0.7629***	114.45	0.7548***	112.72
					[8.20]		[7.96]	
(β_6) 5 years risk free interest rate					0.1346	14.41	0.1908**	21.02
					[1.46]		[2.04]	
(β_7) [0.5,1.5] Dummy exog adjacent exercised (Competitor)			0.3416*	40.72			0.2912	33.80
			[1.79]				[1.52]	
(β_8) >1.5 Dummy exog adjacent exercised (Competitor)			0.8310***	129.56			0.7230***	106.06
			[3.76]				[3.27]	
(β_9) [0.5,1.5] Dummy exog adjacent exercised (Own)			1.0981***	199.85			0.9994***	171.67
			[6.86]				[6.22]	
(β_{10}) >1.5 Dummy exog adjacent exercised (Own)			1.9895***	631.19			1.9734***	619.51
			[11.96]				[11.74]	
Log Likelihood	-1692.1098		-1666.8090		-1653.5811		-1630.0280	
N	54,208		54,208		54,208		54,208	

Table 6: Internal Validity

This table reports the coefficient estimates of an ordinary least squares (OLS) regression of first well's production on exogenous measures of adjacent exercise activity. The unit of observation is at the option level at the date of option exercise. The exogenous measures of adjacent activity are based on the number of exercised adjacent options in the 8 drilling units surrounding an infrill drill option at the time the option is exercised. *t*-statistics are reported in brackets below the coefficients. * indicates significance at the 10% level, ** at the 5% level, and *** at the 1% level.

	Dependent Variable = Log (First Well Production)
	(1)
(β_1) Number of adjacent infilled well exercised (Owned)	-0.0087
	[-0.21]
(β_2) Number of adjacent infilled well exercised (Competitor)	0.0204
	[0.65]
R square	0.0023
N	261