Chapter 16
Some Economic Issues in the Exploration for Oil and Gas

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Abstract In this chapter I present a simple economic model of exploration, and then discuss some predictions stemming from the model. I also describe some empirical phenomena relevant to exploration: trends in the probability of dry holes, the relation between oil prices and exploratory drilling, and developments in the deep water Gulf of Mexico.

16.1 Introduction

At the end of the twentieth century, two technological innovations were developed that greatly increased the volume of economically recoverable oil reserves in North America. The first of these, hydraulic fracturing, or fracking, was originally developed to enhance the production of natural gas. But over the next 5–10 years, this technique was adopted for production of crude oil, leading to substantial increases in production.[1] At about the same time, developments in the use of sophisticated imaging, such as 3-D imaging, increased the accuracy of exploratory ventures [20]. Together, these techniques made exploration and development of new deposits more efficient, and contributed to the rapid increase in US oil and gas production that has occurred in the past 10 years or so. These efforts led to the development of new hydrocarbon sources from formations that had previously been regarded as uneconomic, particularly shale oil formations in Texas and North Dakota, and offshore resources located in the deep waters of the Gulf of Mexico. Both new sources of oil turned out to be quite prolific.

In this chapter, I describe a simple economic model of exploration, and then discuss the predictions that come from that model. Two aspects are key here: the

[1] Gold [6] and Zuckerman [22] provide engaging and accessible accounts of the development of fracking in the USA since the turn of the century.

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probability that exploration will fail to find sufficient volumes of hydrocarbons (i.e., that the venture will result in a "dry hole"), and the anticipated price at which discovered resources can sold. I then discuss some empirical phenomenon relevant to exploration. First, I discuss the sharp decline in the probability of failure over the past 15 years (a phenomenon likely the result of the technological innovations described above). I then discuss the relation between oil prices and exploratory drilling. Finally, I discuss developments in the Gulf of Mexico, particularly in deep water.

16.2 Modeling Exploration

Early economic models of exploration typically involve a deterministic approach, the idea being that exploration translates into finds in a known way [13]. These models then gave way to analyses that paid explicit attention to uncertainty, particularly in terms of the results of exploration; examples include, but are by no means limited to Devarajan, & Fisher [4], Isaac [8], Lasserre [10], Mason [11], Pindyck [13, 14]. For the purposes of fixing ideas this approach has its merits, but it surely cuts important practical corners. To resolve this shortcoming, one could treat the result of exploratory efforts as a random variable [2] or the evolution of the stock of reserves as unknown [14]. This refinement of the original modeling variants has the attractive feature of analytic convenience and greater modeling realism, but again omits the key feature related to learning—that is, the notion that agents start off with a limited understanding of the underlying probabilistic process, which ignorance they might partially resolve by observing the outcomes from current efforts. Allowing for that sort of learning is a main theme of this monograph in general, and this chapter in particular.

A straightforward way to model exploration is by analogy to investment: the firm spends a certain amount up-front in anticipation of a reward in the event it is successful. To flesh out this idea, consider a firm extracting an oil deposit of size R. The firm values any finds at $V(R)$, which is an affine transformation of R.[2] To see this, suppose that the costs of extraction are $cq + F$, where q is the extraction rate, c is the average variable cost, and F is the fixed cost associated with actively extracting, then the present value of the stream of profits, discounted at rate r, is:

$$\int_0^\infty e^{-rt}\big[(p-c)q - F\big]\mathrm{d}t.$$

[2]That the value of the deposit is proportional to the amount of oil found is sometimes called the "Hotelling valuation principle," after Hotelling [7].

A central result from the Hotelling [7] analysis is that the discounted value of the difference between price and marginal extraction costs is equal for all points in time at which extraction occurs. As a result, the present discounted value of the profit stream is

$$(p-c)\int_0^\infty e^{-rt}q\mathrm{d}t - \int_0^T e^{-rt}F\mathrm{d}t = (p-c)R - \int_0^T e^{-rt}F\mathrm{d}t,$$

as the integral of extraction rate equals economically recoverable reserves, and where T is the date at which extraction ceases (i.e., the deposit is shut in). If T is large, $\int_0^T e^{-rt}F\mathrm{d}t$ is approximately F/r; this leads to the approximate characterization of the value associated with a deposit of size R:

$$V(R) = (p-c)R - Fr.$$

To procure deposits, the firm must first undertake exploratory activities, which cost an amount C_e. These efforts will lead to a discovery R, which is a random variable. Let the probability density function over R be denoted by $\phi(R)$, and the associated cumulative density function by $\Phi(R)$. It is conceivable the firm will drill a "dry hole," which really means the amount discovered is too small to be economically viable.[3] In other words, there is a critical value of discovery, call it $\underline{R}$, with the property that the firm will only develop the oil deposit if the recoverable amount found by exploration exceeds $\underline{R}$.[4] The probability of a dry hole can then be expressed as $\Phi(\underline{R})$. The expected net benefits from exploration are then

$$\int_{\underline{R}}^\infty \left[(p-c)s - \frac{F}{r}\right]\phi(s)\mathrm{d}s - C_e.$$

Putting this all together, then, we see that larger levels of exploration will result from lower chances of suffering a dry hole or higher spot prices. I consider each of these elements in the next section, where I discuss some relevant empirical issues.

[3]While it is conceivable that the efforts literally unearth zero oil, a more likely outcome is that the finds are relatively small. For example, Shell's recent failure in the Chukchi sea did not come up completely empty; rather, the find was much smaller than hoped—to the point it did not merit paying the large development costs that would be required to extract and deliver that oil to market.

[4]If one also takes uncertainty about prices into account, then this cutoff must also include an "option value," which can be interpreted as the potential increase in profit associated with waiting a small period of time in the hope that price will rise [5, 12].

16.3 Some Empirical Evidence

In this section, I discuss some empirical considerations that are relevant to exploration decisions. I start by reviewing the pattern of dry hole probabilities over the past 40 years.

16.3.1 Trends in the Probability of a Dry Hole

In the summer of 2015, Shell Oil made the difficult decision to abandon its efforts to find and develop hydrocarbon resources in the Chukchi Sea. Shell walked away from this venture despite having spent billions of dollars on leases and costs related to exploration in the Arctic. The key development that lead to their abrupt departure was the disappointing result from the sole exploratory well they managed to drill in these waters. That well indicated insufficient hydrocarbons were present to motivate further development. While this unfortunate "dry hole" was certainly unwelcome, it was far from unexpected: exploratory ventures come up empty with some regularity. But over the past 15 years or so, this rather gloomy result has become far less likely.

To shed light on the probability an exploratory venture yields a dry hole, I gathered data from the US Energy Information Administration [16]. The information at this website includes the number of exploratory wells drilled and the number of dry holes resulting from those efforts, from which the fraction of wells resulting in dry holes is readily calculated. Figure 16.1 plots this fraction, for every month from January 2007 to December 2011.[5] For a long period of time, from the earliest date at which data are available late into the twentieth century, the probability an exploratory well would come up dry was in the 70–80 % range. As late as the end of the century, the dry hole probability remained well over 50 %; it was about 63 % in January of 2000. But thereafter, this probability began to drop: the fraction of dry holes was smaller than 40 % for a lengthy period, from early 2005 to mid-2008.

It is conceivable that the drop in dry hole probability partly reflected the improving conditions in the global oil market—as price rises, more wells become economic, and so one would expect the fraction of dry holes to fall. But this effect alone cannot explain the pattern displayed in Fig. 16.1. Indeed, the probability of a dry hole was virtually identical in June 2006, when oil was selling for slightly less than $71/barrel, and June of 2008, when oil was selling for nearly $134/barrel. A second explanation for the pattern evidenced in the diagram is that technological

[5]The EIA stopped updating this information after 2011. The available data report the combined number of dry holes associated with exploration for oil dry holes associated with exploration for natural gas.

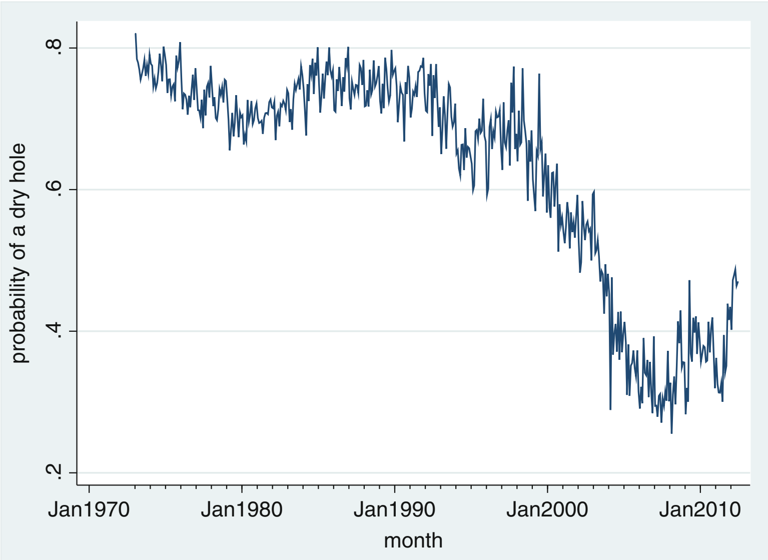

Fig. 16.1 Fraction of exploratory wells that were dry holes, 1973–2011

improvements, such as the development of sophisticated 3-D imaging techniques and the emergence of hydrological fracturing as a method for extracting oil from shale deposits, made successful exploration more likely. This explanation seems a more plausible explanation than the explanation associated with increasing prices.

16.3.2 Trends in Price and Drilling

The model I sketched out in Sect. 16.2 points to the importance of anticipated future revenues in motivating exploration. These expected future revenues are tied to anticipated prices. There is substantial evidence that oil prices evolve slowly over time, so that a good predictor of future price is current price [21]. Thus, one might expect to see the level of exploration moving in the same direction as the oil price.

Figure 16.2 provides some visual evidence corroborating this conjecture. Here, I plot the number of exploratory wells drilled, for each month from January 1986 to December 2011; these values are measured on the left-most *y*-axis.[6] On this graph, I superimpose the real price of crude oil for the same time period, measured against the right-most *y*-axis. This time series is constructed by dividing the monthly average West Texas Intermediate (WTI) spot price—widely regarded as the appropriate benchmark price for crude oil for most of this time frame—by the cost of

[6]As I noted in footnote 5, the EIA stopped reporting these data after 2011.

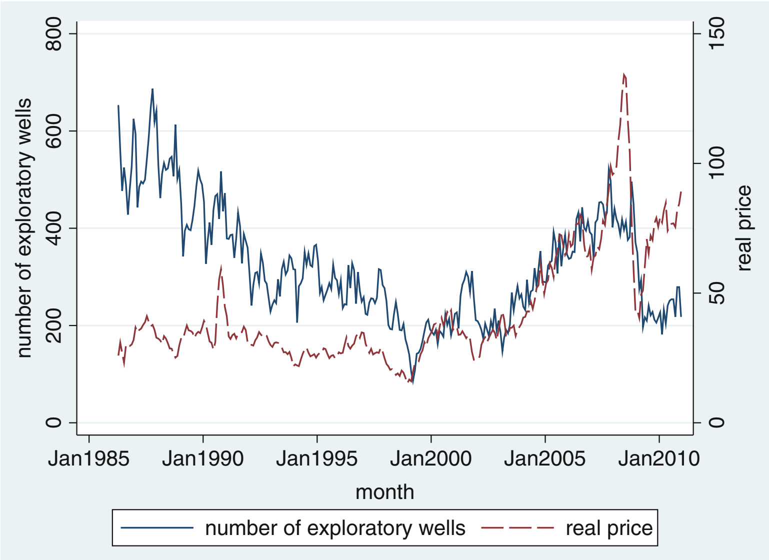

Fig. 16.2 Exploration and real oil prices, 1986–2010

living, as measured by the Consumer Price Index.[7] While the correlation between these two time series is relatively weak through much of the twentieth century, it strengthened considerably after 1999. From that point until 2009, during the depths of the oil price crash, the movements between the two series are strikingly similar. On balance, then, this data is supportive of the conjecture that the oil price is an important driver of exploratory efforts.

16.4 Developments in the Gulf of Mexico

In this section, I look more deeply at factors influencing exploration in a key geographic sector in the oil and gas industry—the Gulf of Mexico. Oil and gas operations have been active in the Gulf of Mexico since the 1940s [15]. In the intervening years, exploration steadily increased; as indicated in Fig. 16.3, crude oil production in the Gulf had reached 300 million barrels by the early 1980s. This pattern accelerated over the next few decades, with output levels exceeding 500 million barrels by the turn of the century. This rise in production was echoed by the increasing role played by Gulf oil production, as a share of total US output, with shares exceeding 20 % by the late 1990s.

[7]Data on the WTI spot price are available at U.S. Energy Information Administration [17].

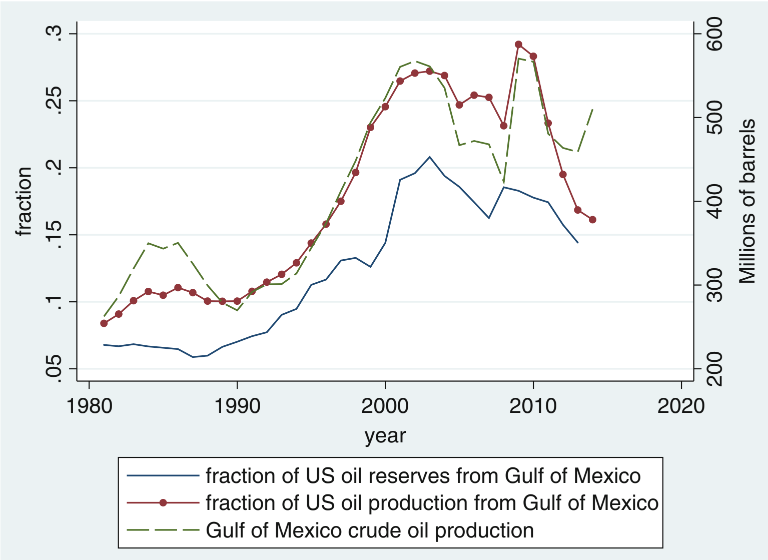

Fig. 16.3 Gulf of Mexico as a fraction of total US: crude oil

During this period, there was a clear migration towards deeper waters. As illustrated by Fig. 16.4, crude oil production from waters less than 600 ft in depth has fallen by about half over the past 20 years or so, with production from deeper waters rising steadily. This increase in production from deeper waters has been sufficient to outweigh the falloff in shallower water production, with the net effect that total production has remained roughly constant at about 40 million barrels per month—with the notable exceptions in August 2005, in the aftermath of Hurricane Rita, and in September 2008, following Hurricanes Gustav and Ike [3, 9].

The initial preference for shallower deposits can be readily explained by differences in exploration costs: while drilling in shallower waters can be readily accomplished at relatively low cost, operations in deeper waters were initially far more expensive [18, p. 12]. However, technological gains lowered drilling costs in deeper waters to the point that these deposits became economic to exploit over the past 15 years [19]. These observations point to deep water resources as increasingly important.

Drilling operations in the Gulf of Mexico are undertaken by six types of rigs: drillship, inland barges, jackups, platform rigs, semisubmersible, and submersibles. These rigs work in different parts of the Gulf. Inland barges, jackups, and submersibles are limited to shallower waters, while drillship, platform rigs, and semisubmersible ply deeper waters. Descriptive statistics concerning these various rigs are listed in Table 16.1. Here, I tabulate average number of days contracted,

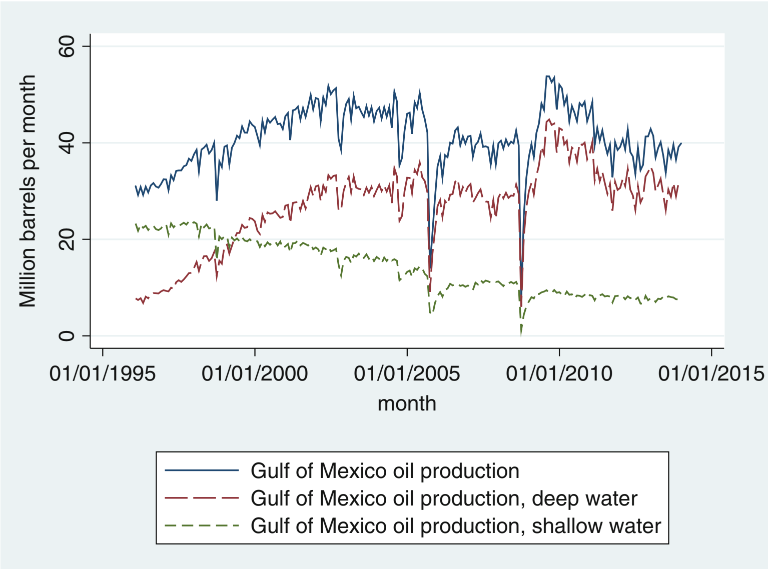

Fig. 16.4 Gulf of Mexico crude oil production

Table 16.1 Characteristics of different drill rigs in the Gulf of Mexico

Rig type (no. of obs'ns)	Number of days contracted	Depth (feet)	Day rate
Drillship (177)	411.3	6432.5	$519,462
	(682.7)	(2133.5)	(85638)
Inland barge (225)	274.2	15.80	$36,539
	(291.2)	(3.0)	(10956)
Jackup (1098)	156.1	122.4	$79,704
	(226.1)	(84.1)	(36638)
Platform rig (72)	144.6	1689.3	$37,847
	(247.2)	(1382.5)	(10417)
Semisubmersible (420)	234.6	4559.0	$409,729
	(332.2)	(3334.6)	(110225)
Submersible (25)	373.68	39.2	$69,620
	257.1829	(19.5)	(20480)

depth, and day rate for each of the six types of drill rigs.[8] Immobile rigs (jackups, platform rigs) tended to be contracted for relatively shorter periods of time, while more mobile rigs (drillship, semisubmersibles, submersibles) were contracted for

[8]These data are available from RigLogix (http://www.riglogix.com/). That information shows the starting and ending dates for each contract, the depth at which the rig operates, and the day rate (price per day), for 2547 drilling contracts under which drilling was undertaken between March 2002 and December 2014.

longer periods of time. This difference may reflect a desire on the part of operators to move contracted rigs between potential drilling sites. I note also that mobile rigs plying deep waters exhibit significantly higher day rates, presumably reflecting the greater difficulty associated with getting the rigs to the desired drilling location, along with the enhanced technical capabilities of those rigs. In light of the trend towards deeper waters that I noted above, the number of contracted drilling days per month in the deep water segment of the Gulf of Mexico merits closer investigation. I next turn to such an examination, in which I analyze the number of contracted drilling days per month associated with the three rig types that are used in deeper waters.[9]

In this analysis, I restrict attention to contracts undertaken between January 2010 and July 2014. The first month in this sample is near the bottom of the great recession; by that time oil markets had shaken off the doldrums associated with the financial collapse. At the end of the sample period, July 2014, oil markets were just about to collapse. Between these two dates, markets were relatively stable—making this a natural time frame in which to analyze drilling efforts.

The number of contracted drilling days can be thought of as a marker for the demand for exploration, and so one expects it to be positively impacted by elements that contribute to the benefits associated with exploration. As I noted above, the key element here is the oil price; one expects firms to contract for a larger number of days when prices are high than when prices are low. The price in question could be the current spot price or it could be an estimated future price. The relevant spot price for the Gulf of Mexico is Louisiana Light Sweet crude (LLS), as the trading hub for LLS is located on the gulf; the alternative spot price, West Texas Intermediate, is located several hundred miles inland.[10] To measure expected future prices, I look to the New York Mercantile Exchange (NYMEX) price; the US Energy Information Administration tabulates these futures prices for four time frames, reflecting 1, 2, 3, or 4 months ahead of the trading date U.S. Energy Information Administration [17]. Finally, one expects that water depth impacts the number of contracted drilling days, for two reasons. On the one hand, deeper waters are likely to be more costly to explore, which would serve to reduce drilling days. On the other hand, to the extent that deeper deposits are more remote there is likely a larger upfront cost associated with contracting for a drill rig, which might induce firms to write longer contracts. *Ex ante*, it is not obvious which of these two opposing effects dominate.

Table 16.2 presents results for two regressions. Both regressions include water depth (measured in feet) as an explanatory variable. In regression 1, I use the NYMEX 4-month ahead futures price to capture expected future prices, while in

[9]Focusing on these three rig types limits observation to operations in waters exceeding 500 m of depth. This cohort lies comfortably within the range the Bureau of Ocean Management interprets as deep water (drilling depths in excess of 1000 ft).

[10]Moreover, during the period I analyze, 2010 to mid-2014, there was a glut of oil in storage near Cushing, OK—the location of the WTI trading hub—which depressed the WTI spot price [1]. This unusual effect did not manifest at the LLS trading hub.

Table 16.2 Number of contracted drilling days in the Gulf of Mexico

Right-side variable	(1)	(2)
Depth	0.044**	0.042*
	(0.021)	(0.022)
NYMEX 4 month-	6.32**	–
ahead futures price	(2.60)	
LLS spot price	–	4.72***
		(1.54)
Constant	−614.7**	−488.2***
	(250.2)	(174.3)
R^2	0.15	0.17

Number of observations: 55 Standard errors in parentheses
$*p < 0.10$; $**p < 0.05$; $***p < 0.01$

regression 2 I use the LLS spot price (also measured in US Dollars per barrel) to reflect firms anticipated rewards from a successful venture. In both regressions, the coefficient on water depth is positive, though small. The magnitude, roughly 0.04, suggests an increase of 4 contracted days for each 100 ft increase in water depth. This coefficient is statistically important at the 5 % level for regression 1; it is only statistically important at the 10 % level in regression 2. Regarding price, both regressions indicate that anticipated financial rewards exert a substantial influence on contracted drilling. Every three dollar rise in the 4-month ahead was associated with a roughly 20 day increase in the number of contracted drilling days. Similarly, a four dollar rise in the LLS spot price was associated with about a 17-day increase in the number of contracted drilling days. Relatedly, here was considerable variation in prices during the sample period, with spot prices ranging from about \$75 (May 2010) to about \$120 (April 2012) and futures prices ranging from about \$78 (July 2010) to about \$111 (April 2011). The range in contracted drilling days was also quite variable, ranging from a low of 7 (November 2012) to a high of 773 (July 2014).

16.5 Discussion

This chapter presented a simple model of exploration, and considered some intriguing related empirical phenomenon in oil and gas markets—the sharp decline in the probability of failure over the past 15 years and the relation between oil prices and exploratory drilling, along with a discussion of developments in the deep water Gulf of Mexico. I close the chapter by discussing the relation between this material and events since July 2014.

When crude oil markets started to collapse in the Summer of 2014, many pundits expected US oil producers to start cutting back on drilling. When drill rig counts did not respond as anticipated, a host of explanations were offered: perhaps firms were desperate to obtain revenues so as to service their debt, or perhaps they had locked in (now) higher prices by undertaking hedges prior to the collapse. No doubt these explanations have some merit, but there are competing explanations. For example, there was talk in late 2014 of oil prices rebounding in 2015, suggesting that key players in the industry anticipated price increases going forward into 2015.[11] When those optimistic conjectures were proved wrong in middle and late 2015, drilling operations persisted, albeit in focused "hot spots," locations where firms anticipated lower drilling costs of hitting oil, combined with significant extraction levels at low production costs.

These two alternative explanations are consistent with the model and empirical results in this paper. Firms explore when they expect the future stream of payoffs to adequately cover the up-front costs. Those anticipated payoffs are larger when firms are optimistic about future prices, or when they are optimistic about the success of the drilling venture. The former conjecture is consistent with the casual evidence in early 2015, as well as the conjecture that some firms had fortuitously locked in higher prices by hedging their bets prior to the oil price collapse. And the results in Sect. 16.3.1 suggest the latter conjecture is also reasonable: in the past 15 years or so, exploration has become more accurate, with the probability of a dry hole falling, thereby making exploration a more profitable gamble. To the extent that firms can focus on better prospects, in hot spots, this effect would be enhanced.

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[11]That such predictions turned out to be wrong does not undercut their potential impact on drilling decisions made in the context of those predictions.

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