Strategic Responses to Advances in Seismic Technology in the Petroleum Industry*

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ABSTRACT
The world petroleum industry has been revolutionized by a change in exploration technology from two-dimensional (2D) to three-dimensional (3D) seismic mapping**.** One of the main effects of the newer technology has been to decrease the cost of finding oil, particularly in offshore fields. We examine the impact of the new technology on the exploration activities of the major international petroleum companies and find that they have aggressively increased petroleum exploration expenditures. As a result, we suggest that the companies have achieved a prisoner's dilemma outcome, where they are collectively worse off in terms of profits, providing a possible explanation for the recent wave of large-scale mergers in the industry.

Keywords: petroleum industry, exploration expenditures, oligopoly, strategic behaviour

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1. Introduction

This paper addresses the impact of cost-saving technological innovation on competitive behaviour. More particularly, the possibility that there may be an intensification of industry competition is examined. Examination of this issue is significant as it is usually assumed that firms will benefit from adopting cost-saving technology. This presumption holds for an individual firm adopting technology, but a beneficial outcome is far from assured when the oligopolistic interaction of firm adoption strategies is considered.

Competitive responses to actions of rivals are central in the analysis of firm behaviour under oligopoly. In non-cooperative oligopoly in the tradition of Cournot ([1838], 1897), responses to the output levels of rivals are depicted using reaction curves. We utilize the concept of a reaction curve in exploration activity to examine behaviour of petroleum companies in response to the introduction of a new technology, namely three-dimensional seismic mapping (3D), which has supplanted two-dimensional seismic mapping (2D) in many areas. The new technology facilitates exploration for oil reserves and reduces the cost of looking for reservoirs in new places, especially offshore at substantial depths.

There is a substantial theoretical literature on technological competition among firms in oligopoly, focussing largely on the speed and intensity of firm efforts to find new products and processes (see Reinganum, 1989 for a review and Doraszelski, 2003 for a recent contribution that focuses on reactions between a technological leader and followers). This modelling suggests the net payoff to firms varies in subtle ways with the costs of undertaking the competition. In applying the modelling approach to changes in the cost of research effort, Voola and Kilminster (2003) show that a reduction in the cost of undertaking research may in some circumstances leave firms worse off after the cost reduction. Likewise, a reduction in the cost of finding new oil deposits may lead individual petroleum companies to collectively spend so much more on exploration that they are left collectively worse off, with an aggregate change in net present value that is negative.

In a rare empirical study of reactions in technological competition, Grabowski and Baxter (1973) estimate competitive reactions in research and development (R&D) expenditures by large chemical firms in the US and find that chemical firms react positively to R&D expenditures by their rivals. We employ a similar approach in estimating competitive reactions in exploration expenditure by the world's largest petroleum companies. We also find evidence of positive reactions, with exploration expenditures by petroleum firms positively related to expenditures by their rivals. Further, our results show that the introduction of 3D seismic technology led to increased spending by the firms, which combined with the positive feedback in expenditure among firms, implies an aggressive expansion in exploration efforts after the introduction of 3D technology.

In the following section, we explain our approach to modelling competitive reactions in exploration expenditures. Section 3 discusses the data set used in estimation, while Section 4 present the results of estimating exploration expenditure equations for a panel of the major petroleum companies. We conclude with discussion of the implications of our findings for assessing competition in the petroleum industry and interpreting the recent wave of mergers among major companies.

2. Empirical Model

The standard approach to modelling exploration activities considers the cost of exploration and the expected return to an individual firm acting independently as a price taker (see Krautkraemer, 1998 for a general discussion of modelling exploration for non-renewable natural resources). When applied to petroleum firms operating in a specific exploration area, this approach emphasises the user cost (*in situ* value) of new discoveries and the 'discovery decline phenomenon' (cumulative exploration effort has a negative impact on expected further discoveries). Pesaran (1990), Favero (1992), Pickering (2002) and Kemp and Kasim (2003), among others, apply this approach to estimating regressions for exploration efforts of firms operating on the UK Continental Shelf and find that exploration effort, as measured by number of exploratory and appraisal wells drilled, rises with measures related to the price or user cost of oil and falls with the cumulative amount of previous exploration effort, at least after some critical threshold. Some of the studies also find evidence of an impact of the taxation regime applied by the British government.

Our study differs in its focus from studies mentioned above. First, we are especially interested in the world petroleum industry, so we measure exploration effort by the major petroleum companies across all geographic areas. Second, we are interested in the impact of the change in technology, namely the development of 3D seismic exploration methods to supplant 2D seismic in some prospective areas, particularly in the search for offshore reservoirs in deep water. Because we are examining exploration effort over disparate areas and disparate methods, we use exploration effort rather than the number of wells drilled as our dependent variable measuring exploration effort.

Our choice of explanatory variables is also influenced by our focus. We examine the role of oligopolistic interactions by using competitor exploration expenditures as an explanatory variable. Likewise, because of our interest in the impact of the change in seismic technology, we use a dummy variable to measure the time at which each company adopted the new 3D technology. In some models of oligopoly access to funds is an important influence on firm behaviour, so we include a operating profits as an explanatory variable. Finally, due to the substantial differences in sizes of companies in our sample, we use firm size measured in sales as a control in our set of explanatory variables.

The empirical relationship estimated in this paper is of the form:

$$E_{it} = \alpha_i + \beta X_{1it} + \eta X_{2it} + \pi X_{3it} + \lambda X_{4it} + \varepsilon_{it} \quad (1)$$

In (1), E_{it} is the amount of exploration expenditure by company i in period t, α_i is the fixed effect associated with company i (sometimes assumed to be uniform across companies), X_{1it} is the ith company's own profit in period t; X_{2it} is company i size in period t; X_{3it} is a dummy variable whether company i has introduced 3D technology in period t and X_{4it} is the aggregated value of competitor exploration expenditures for company i in period t. All variables, other than the dummy variable, are measured in natural logarithms so that the coefficients can be interpreted as elasticities of exploration expenditures with respect to the particular variable.

We expect each company's exploration expenditures to vary positively with company size (due to the wider range of activity) and with profits (as a measure of the ability to finance risky investments that might act as a barrier to entry, a so-called 'long purse'). The cost reduction for exploration effort associated with the introduction of 3D technology increases the optimal level of exploration effort. If this increase is large enough to offset the reduced cost of such effort, total expenditure rises and the coefficient of the 3D dummy variable is positive. Following Grabowski and Baxter (1973) we expect that there is rivalry in exploration expenditures, so that the coefficient on competitors' exploration expenditure is positive. [1]

3. Data Set

We use data for the seven major international petroleum companies, Amoco, British Petroleum (BP); Chevron, Exxon, Mobil, Shell and Texaco, for the years 1975 through to 2000. The data set includes companies that merged in the later years (BP and Amoco merged on 31st December 1998, Exxon and Mobil merged on 30th of November 1999). In order to accommodate for this, the data set is expanded to nine companies instead of seven, with the merged entities treated as separate companies. This means that we have an unbalanced panel of data, with BP and Amoco, leaving the sample in 1998 and the new entity, BPAmoco, entering the sample in replacement. Likewise, Exxon and Mobil leave the sample in 1999 and are replaced by the new entity, ExxonMobil. In the year 2000 these companies in the current merged entities accounted for approximately 55% of total world sales of crude petroleum, with ExxonMobil at 20%, Shell at 14%, BPAmocco at 12%, Texaco at 4.5% and Chevron also at 4.5% according to Standard and Poor (2000).

The data for each company includes annual exploration expenditures, E_{it}, where i indicates the identity of the company and t the year of the observation. Competitor's expenditures are taken to be the aggregate for the other players, $X_{4it} = \sum_{j \neq i} E_{jt}$, where j stands for each of the companies in the sample. Exploration expenditures (variables E and X_4) are both in US dollar values (in millions), as this is the original stated value for all companies except British Petroleum and Shell. Data for the latter companies are in pounds and are converted into US dollars at the average exchange rate for that year. The profits (X_1) and sales (X_2) of individual firms are similarly reported in millions of US dollars for United States based companies and converted from British pounds for British Petroleum and Shell, where the latter amounts are converted into US dollar equivalents at average exchange rates as above.

The change-over dates of 2D to 3D seismic (X_3) is captured by the use of a dummy variable, so that a value of 1 applies from the year of introduction of 3D seismology and the value of 0 applies previously. The years of introduction of the new technology, 3D is approximate, and based on information that has been gathered from various industry sources. The particular challenge in capturing the switching dates from 2D to 3D lies in the fact the introduction of 3D was gradual and considerable amount of experimentation with the technology was undertaken in patches.[2] Hence, identifying and associating particular times of introduction requires the use of judgement.[3] An appeal to anecdotal evidence, personal communication and reference to industry material is used in constructing the date of introduction of 3D.

Exxon is designated 1982 (Greenlee and Johnson 1994, p370) and Mobil 1981 (Bakerhouse, 2001) for the introduction of 3D seismic. British Petroleum is designated 1988, where this later year of introduction of 3D is due to a deliberate management decision to not involve themselves with the 3D (Lee, 2001). Amoco is assigned 1989, as the company is classified one of the herd, and generally followed the industry trend in absorption of the technology. Shell is assigned 1985 (Moody-Stuart 1993, p.271) and Chevron, given the absence of indicators of early adoption is assigned the late year of 1989. Texaco is assigned 1985 in accordance to the industry average, as well as according to Krail (2002).

The data are deflated by the price of a barrel of oil (in US dollars). This means exploration expenditure and other nominal magnitudes are expressed in terms of barrel of oil equivalents. This a convenient way to remove fluctuations in the sales variable that are due to changes in oil prices. The other nominal magnitudes, exploration expenditures and profits, do not necessarily move in proportion to oil prices. For these variables, deflation by the price oil may not precisely remove the impact of inflation.[4]

4. Estimation Results

The model specified in equation (1) study is estimated with the use of cross-section and time-series data. In this particular instance, the cross section of the sample is the nine firms: Amoco, BP, BPAmoco, Chevron, Exxon, ExxonMobil, Mobil, Shell and Texaco. The time series is for the observations for the 26 years 1975 through to 2000. For the companies that merge late in the sample period, there are no observations for the separate companies in the years after merger and no observations for the merged companies early in the sample period. Thus, the sample constitutes an unbalanced panel of observations, with 26 observations each for Chevron, Shell and Texaco, 23 observations for BP and Amoco, 24 observations for Exxon and Mobil; three observations for BPAmoco, and two observations for ExxonMobil.

The POOL command in Shazam (Version 9) is used to estimate the regressions. Shazam uses the Parks (1967) method as described in Kmenta (1986, section 12.2, pp. 616-625) and Greene (1993, section 16.3), which employs a set of assumptions that the disturbance covariance matrix is cross-sectionally heteroskedastic and time-wise autoregressive. We run several regressions, with and without company dummies as well as with and without allowing coefficients of the explanatory variables to vary across companies.[5] We also use instrumental variables estimation to allow for the possibility that the explanatory variables for operating profits and competitor's exploration expenditures are determined simultaneously with the company's own exploration expenditures.

Equation (1) is estimated using the ordinary least square (OLS) option with pooling of the data across the unbalanced sample. In the first regression, we assume that the disturbance term in equation (2) is identically distributed for each company and for each time period. A heteroskedastic-consistent covariance matrix for pooled regression models as discussed in Beck and Katz (1995) is used. All data are in natural logarithms except for dummy variables. The results from this estimation are given in the first column of Table 1.

The results in column 1 of Table 1 are disappointing. Only some 24 percent of the variance of expenditures from the mean is explained. Only firm size is a highly significant, with a positive impact on exploration expenditures. As firm size and exploration expenditures are both measured in logarithms, the coefficient of firm size provides an estimate of the elasticity of expenditures, so the fact that it is less than one indicates that the ratio of expenditures to sales is decreasing with firm size. The coefficient of operating profits is marginally significant, but is negative contrary to expectations. The 3D introduction dummy is not significantly different from zero, suggesting that the introduction of 3D technology has not impacted on exploration expenditures by the major petroleum firms. Finally, the coefficient of exploration by rivals is highly significant and negative, contrary to finding of aggressive rivalry in R&D spending by chemical firms found by Grabowski and Baxter (1973).[6]

Table 1: OLS Regressions for Company Exploration Expenditures (Standard errors in parentheses)

Variable	No Company Dummies	With Company Dummies	With Dummies and Interaction
Constant	2.118 (1.99)**	1.76 (2.10)**	8.303 ((0.68)
Firm Size	0.618 (5.36)*	0.223 (1.98)**	
Operating Profit	-0.081 (1.69)***	-0.076 (2.56)**	-0.078 (2.74)*
3D Dummy (introduction)	0.079 (0.68)	0.148 (2.08)**	0.226 (3.18)*
Exploration Expenditure by Competitors	-0.522 (3.79)*	0.452 (4.93)*	0.516 (5.58)*
Amoco		-1.996 (8.69)*	-5.437 (0.44)
BP		-0.825 (4.78)*	-7.341 (0.59)
Chevron		-2.44 (11.82)*	-6.488 (0.53)
Exxon		-2.061 (13.82)*	-9.875 (0.80)
Mobil		-2.571 (14.06)*	-9.807 (0.80)
Shell		-1.789 (12.11)*	-8.786 (0.71)
Texaco		-2.737 (12.45)*	-0.919 (0.07)
ExxonMobil		-1.95 (6.27)*	-38.432 (3.15)*
Amoco * Firm Size			-0.278 (1.39)
BP * Firm Size			0.162 (0.62)
Chevron * Firm Size			-0.175 (0.81)
Exxon* Firm Size			0.316 (2.01)**
Mobil * Firm Size			0.248 (1.44)
Shell * Firm Size			0.220 (1.75)***
Texaco * Firm Size			-0.947 (1.63)
ExxonMobil * Firm Size			3.442 (47.7)*
BPAmoco * Firm Size			-0.578 (0.41)
F statistic from the mean	*13.725**	*59.939**	*34.80**
R Square	*0.237*	*0.798*	*0.817*
Variance of the estimate σ^2	*0.366*	*0.105*	*0.100*
Wald test for joint significance of dummies with 8 df		*490.2**	*1047**
Wald test for joint significance of interactions with 8 df			*936.6**

* indicates significant at 1% level, ** indicates significant at the 5% level and *** indicates significant at the 10% level.

The above method of pooled analysis assumes that there are no non-random differences in the determinants of exploration expenditures across the companies in the sample. If company differences are non-random in their effect on the dependent variable, misspecification error occurs. We therefore estimate a pooled analysis with company dummy variables, with the results shown in the second column of Table 1. The constant term is retained in the regression in the second column, so only eight company dummies are included. The constant term gives the 'fixed effect' for the company without a dummy, namely BPAmocco. The 'fixed effect' for each of the other companies is given by the sum of the constant and the coefficient of the dummy for that company.

Allowing for fixed effects associated with companies, leads to a substantial increase in explanatory power moving from Column 1 to Column 2 in Table 1. The R^2 increases from 0.237 to 0.798, while the F statistic value increases from 13.725 to 59.939. Further, the Wald test statistic for the joint significance of the company dummy variables is 490.2, which is significant at the 0.001 level. Thus, there is clear evidence of 'fixed effects' associated with the individual companies. The company-specific fixed effect is positive for the omitted company, BPAmoco, as indicated by the positive and statistically significant constant term. However, all other company fixed effects are smaller, as indicated by the negative and highly significant coefficients for each of the separate company dummy variables.

Comparison of corresponding coefficient estimates between Column 1 and Column 2 in Table 1 indicates the impact of the misspecification due to the failure to allow for company differences. In particular, the coefficient of the 3D introduction dummy doubles in magnitude and becomes statistically significant at the five percent level, providing evidence that the new technology has increased exploration expenditures (as well as increasing effort). Even more dramatic is switch is sign of the coefficient on the exploration expenditures by rivals, which becomes positive rather than negative and is statistically significant at the one percent level. Thus, allowing for company effects reveals an aggressive response of firms to competitor exploration expenditures, which supports the expectation based on the work of Grabowski and Baxter (1973). The magnitude of the other estimated coefficients is affected but there are no dramatic changes in sign or statistical significance.

Given the importance of company-specific effects, we also check for the possibility of differences across companies in the slope coefficients that relate the dependent variable to each of the explanatory variables. The only variable for which we find evidence of differing slopes across companies is firm size. The results that are obtained when the impact of firm size on exploration expenditures is allowed to vary across the companies are shown in Column 3 of Table 1.[7]

While only a few of the company-specific coefficients for firm size are clearly different from zero using a t test, the Wald test statistic for all the coefficients being identical has a value of 936.6, which is statistically significant at the 0.001 level. Thus, there is clear evidence that the impact of firm size on exploration expenditures differs across the firms in the sample.

Inclusion of the company-specific firm-size variables clearly affects the magnitude and significance of the company-specific fixed effects. The low statistical significance of the company-specific effects in Column 3 can be attributed to the fact that by construction these company dummies are highly co-linear with the company-specific firm-size variables. Importantly, none of the other estimated coefficients is substantially affected in terms of sign, magnitude or statistical significance by inclusion of company-specific effects of firm size.

The coefficient of each interaction variable in Column 3 shows the elasticity of exploration expenditures with respect to the size of that company. It is interesting to note that the only statistically significant coefficients are for the two largest companies prior to the mergers, Exxon and Shell, and, especially, for the largest company after the mergers, namely ExxonMobil. These large companies apparently have a clear strategy of further enhancing their size through expanding exploration efforts to keep up with their growth. Not surprisingly Exxon (even prior to the merger) and Shell are the two companies that dramatically increased their shares of world oil production during the sample period of the last quarter of the 20^{th} century.

As a final check on the specification of the results reported in Table 1, we re-estimate each of the regressions using instrumental variables (IV) estimation in place of OLS. We are particularly concerned with the possibility that exploration expenditures have an impact both on operating profits (through an accounting relationship to the degree that exploration expenditures are expensed) and on exploration expenditures by competitors (as a firm's expenditures are part of the expenditures of competitors for each of the other firms). Following standard practice, we use the lagged values of operating profits and exploration expenditures by competitors as our instrumental variables when treating the current values of these two variables as endogenous.

Comparing the IV results to those in the corresponding column in Table 1 indicates that the use of IV estimation generally produces less precise results than OLS estimation. This is indicated by lower t-ratios of individual regression coefficients and lower overall value of the R^2. However, the pattern of results is quite similar, particularly concerning the coefficients on our key variables of interest, the 3D introduction dummy and the exploration expenditures by competitors.[8] Thus, simultaneous equation bias does not seem to affect conclusions on the determinants of exploration expenditures drawn from the regression results in Table 1.[9]

One of the important issues that we examine is the response of individual companies to the change in the new technology, (3D). The new technology effectively reduces the cost of finding oil. Firms in the industry could respond by reducing their exploration expenditures, which effectively means, “saving the cost reduction”. The empirical analysis shows, however, that there is a positive relationship between the introduction of 3D seismic and exploration expenditures. This indicates that companies in the sample set have responded to the new technology’s cost-reducing effect, not by staying indifferent to the amounts of expenditures and exploration effort that they spend, but by increasing both effort and expenditure. This response is further augmented by aggressive behaviour between players in the industry with respect to exploration expenditures, as indicated by the positive and highly significant coefficient on the competitor’s expenditure variable.

5. Interpretation and Discussion of Results

The empirical results permit the following two conclusions. First, the use of the new seismic mapping technology is associated with increased exploration expenditures by the major petroleum companies. Companies did not pocket the ‘savings’ that the new technology permitted in terms of increased efficiency in exploration, but increased their exploration activity in response to the new technology. Second, the empirics show that the firms in the industry respond positively to each other in terms of exploration expenditures.

Both of these results set the condition for a prisoner’s dilemma outcome to occur, where individually rational strategies conflict with group success. Expansion of exploration expenditures by individual companies following the introduction of 3D technology has led to increase in reserves and output of oil, putting downward pressure on prices. Under such a situation, cooperative behaviour can emerge as a solution to resolving the worsening outcomes for individual players. In the context of our findings, it is interesting to note that there has been a wave of mega mergers in the petroleum industry in the ten to twenty years subsequent to the introduction of 3D seismic technology. Perhaps, the companies have decided that mergers are required to avoid the type of ruinous competition that followed their adoption of 3D technology.

References

Barkhouse, W., *Message from Bill French*, Email to French, W., french3d@geophy.curtin.edu.au, 15 January 2002.

Beck, N. & Katz, J. N., 'What to Do (and not to Do) with Time-Series Cross-Section Data', *American Political Science Review,* 1995, 89: pp. 634-647.

Bohi, D. R., *Changing Productivity in U.S Petroleum Exploration and Development*, Cambridge MA: Charles River Associates, 1998.

Buse, A., 'Goodness of Fit in Generalized Least Squares Estimation', *American Statistician,* 1973, 27, pp. 106-108.

Cournot, A., *Researches into the Mathematical Principles of the Theory of Wealth*, Paris: Hachette 1838, English translation by N. Barron, New York: Macmillan, 1897.

Doraszelski, U., 'An R&D Race with Knowledge Accumulation', *Rand Journal of Economics*, Spring 2003, 34(1), pp. 20-42.

Exxon, 'Exxon Corporation Net Annual 3D Seismic Expenditures', *Leading Edge,* July 1994, 13.

Favero, C. A., 'Taxation and the Optimization of Oil Exploration and Production: The UK Continental Shelf', *Oxford Economic Papers*, April 1992, 44(2), pp. 187-208.

Grabowski H. G. and Baxter, N. D., 'Rivalry in Industrial Research and Development: An Empirical Study', *Journal of Industrial Economics*, 1973, 21, pp. 209-225.

Greene, W. H., *Econometric Analysis,* 2nd edn, London: Macmillan, 1993.

Greenlee, S. M. and Johnson, M. G., '3-D Seismic Benefits from Exploration through Development: An Exxon Perspective', *The Leading Edge,* 1994, 13.

Jack, I., *Industry Finding Costs*, Email to French, W., french3D@geophy.curtin.edu.au, 11 July 2001.

Kemp, A. and Kasim S., ‘An Econometric Model of Oil and Gas Exploration Development and Production in the UK Continental Shelf: A Systems Approach’, *Energy Journal*, 2003, 24(2), pp. 113-141.

Kmenta, J., *Elements of Econometrics,* 2nd edn, London: Macmillan, 1986.

Krail, P. M., *Resend of Texaco Response*, Email to: French, W., french3d@cbs.curtin.edu.au, 21 January 2002.

Krautkraemer, J. A., ‘Nonrenewable Resource Scarcity’, *Journal of Economic Literature*, Decmeber 1998, 36, pp.2065-2107.

Lee, L., *re: Query*, Email to: Voola, J., voolaj@cbs.curtin.edu.au, 13 December 2001.

Moody-Stuart, M., 'Opportunities From Partnership', *The Leading Edge*, April 1993, 12, pp. 269-273

Parks, R. W., 'Efficient Estimation of a System of Regression Equations when Disturbances are Both Serially and Contemporaneously Correlated', *Journal of the American Statistical Association,* 1967, 62, pp. 500-509.

Pesaran, H. M., ‘An Econometric Analysis of Exploration and Extraction of Oil in the U.K. Continental Shelf’, *Economic Journal*, June 1990, 100, pp.367-390.

Pickering, A., ‘The Discovery Decline Phenomenon: Microeconometric Evidence from the UK Continental Shelf’, *Energy Journal*, 2002, 23(1), pp. 57-71.

Reinganum, J. F., ‘The Timing of Innovation: Research, Development and Diffusion’, in R. Schmalensee and R. Willig, eds., *Handbook of Industrial Organization, Volume 1*, Amsterdam: North-Holland, 1989, pp. 849-908.

Standard and Poor, *Oil (Integrated International) Industry Constituents*, [Online], Available: http://mi.compustat.com/cgi-mi-docs/docs (accessed 21 September 2000).

Voola, J., '*Strategic Interactions in the Petroleum Industry*', PhD thesis, Perth, WA: Curtin University of Technology, 2002.

Voola, J. and Kilminster, D., 'Cost-reducing Technology and Cournot Competition', paper presented at the *2003 Econometric Society Australian Meetings*, University of New South Wales, Sydney, NSW, July 2003.

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[1] Cumulative exploration expenditure is not included as a variable because the exploration expenditures are not limited to a single prospective area. The introduction of 3D technology has expanded the range of geography over which oil exploration is potentially profitable to include offshore deepwater prospects. Also, the price of oil is excluded as an explanatory variable because all our nominal magnitudes, including exploration expenditures, are deflated by the price of oil, so there is a potential for a spurious relationship between the price of oil and the dependent variable.

[2] The timing of the introduction of the new technology is assigned a point in time, when in reality the switch over dates of 3D seismic have not been discrete.

[3] Incorrect assignment of the date of introduction of 3D technology introduces error into the dummy variable measure. The estimated coefficient of the variable in regression analysis is then biased towards zero and its significance understated. Nonetheless, we are able to establish a positive and significant coefficient in the regression results reported below.

[4] No specific deflator is available for either exploration expenditures or profits and general price deflators are for individual countries, whereas we are concerned with teh

worldwide activities of petroleum companies. The price of oil provides a relevant, albeit imperfect, general deflator.

[5] We also experiment with regressions that allow for variation across time in regression results not reported here. The influence of time is not generally statistically significant. Pickering (2002) in a study of exploration effort on the UK continental shelf using a different conceptual model and set of explanatory variables also finds significant company effects but no significant time effects.

[6] In a Cournot model with firms making output decision, each firm has a downward sloping reaction function, showing that its profit-maximizing output declines as the output of rivals increase. Applying this concept to exploration expenditures would suggest a negative relationship of own expenditures and expenditures by rivals as found in Column 1 of Table 1.

[7] The original firm size variable is excluded and replaced with a separate variable obtained by multiplying firm size by each company dummy variable.

[8] Full results for the IV estimates are available from the authors. Further results estimate OLS regressions with lagged values of operating profits and exploration expenditures by competitors. The results are similar to those reported in Table 1. These results may also be obtained from the authors on request.

[9] These conclusions are also supported by further results in Voola (2002) using a balanced panel of firms with the merged firms combined retrospectively.