CEEPR Center for Energy and Environmental Policy Research

North Sea Reserve Appreciation, Production and Depletion

by
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99-011 WP October 1999

A Joint Center of the Department of Economics, Laboratory for Energy and the Environment, and Sloan School of Management

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Abstract

Oil field "growth" has become a well-recognized phenomenon in mature, well-explored provinces such as the United States leading to the continual under-estimation in oil production forecasts. This working paper explores the role of field growth, what is here called reserve appreciation, in newer oil-producing provinces, such as the North Sea, which have also generally exceeded earlier forecasts of production levels. The analysis seeks to determine the regularities in North Sea reserve appreciation as a function of the years produced, the size of the field, the time period, and whether location in the Norwegian or UK sector matters, using standard panel regression techniques. The analysis finds that the reserves in North Sea oil producing fields have appreciated at rates varying between 2% and 3% pr annum, with the notable exception of mid-sized oil reserves. In the end, about one-quarter of 1996 production from the North Sea can be attributed to reserve appreciation. This result indicates that, although reserve appreciation is important in the North Sea, new discoveries are the primary source of the greater than expected production from this oil producing province.

Acknowledgements

This study was carried out in cooperation with the Norwegian Petroleum Directorate (NPD) and Statoil, but none of its conclusions should be interpreted to represent the views of either of these organizations. Both organizations were very helpful in providing additional data that is not readily available in the public record and in answering our many queries over the course of the research. We are particularly indebted to Eric Mathiesen of the NPD and Berit Saltnes of Statoil. Michael Lynch of MIT generously provided data he had assembled earlier concerning the early years of operation in the UK sector. We benefited greatly from comments and suggestions from Professor Morris Adelman and Michael Lynch. Finally, we wish to acknowledge and thank Statoil for the financial support extended to Tone Sem during her visit to MIT. As always, we alone are responsible for any errors in the data and interpretation.

[1] Respectively, visiting researcher (Nov, 1997 to June 1998) and executive director at the Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology.

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1 Introduction

The era of oil and gas is not very old in the North Sea countries compared to the many of the oil producing nations of OPEC and the United States. The North Sea production started with the Ekofisk field on the Norwegian Continental Shelf (NCS) in 1971. Production rose steadily from a mere 12 million barrels (annually) in the first years to around 100 million barrels in 1976. Other fields started producing in 1977, also from the Ekofisk area, and thereby contributing to the growth in production on the NCS. In the UK oil was first produced, in any significant quantity, in 1976. The first fields were Argyll and Forties which both started producing in the fall of 1975, and rose to plateau production the following year.

Production is today at 700 million barrels annually for the UK fields and around 1,100 million barrels for the Norwegian fields[2], a remarkable increase. This is of course mainly due to the finding and development of new fields, but one factor behind the production growth is the greater than expected production from some fields due to reserve appreciation. Among the known ‘over performers’ is for instance the large Statfjord field, which has produced more than foreseen just a few years ago. Such an unanticipated increase in reserves and production at such a large field, and it raises the more important question of whether such revisions are random corrections of earlier reserve estimates or part of a more general pattern. In this analysis, we apply rigorous statistical techniques to address this question.

[2] These production figures are for the fields included in this analysis, which account for nearly all of the total volume of crude oil produced in the North Sea. A number of very small fields in the UK sector were deemed inconsequential and therefore not included, and some “pre-production” oil was omitted as explained in footnote 4.

2 The Data and Analytical Model

2.1 Data sources

The UK data, for both reserve estimates and production, have been collected from various editions of the UK Brown Book, published annually by the Ministry of Industry and Trade. Part of the early data was a contribution from Mike Lynch at the Massachusetts Institute of Technology (MIT), who had some years ago started the task of collecting reserve data from the British Continental Shelf. This provided the starting point of the data collection, which has been expanded to cover all producing offshore oilfields – both British and Norwegian- up to the latest report of 1997 providing the data for 1996, which is the last year of our study.

As a source for the reserve data on the Norwegian Continental Shelf, the annual reports from the Norwegian Petroleum Directorates (NPD) were used. The first report available to us is for 1973 and then annually from 1976 onwards – with 1996 being the last one. The estimates for the years 1971-1975 are assumed to be unchanged from the 1973 estimate. However, this affects only the Ekofisk field, as it is the only one starting production that early (1971). The production data are mainly from Statoil's "portfolio analysis" that is a complete field by field data collection of both historical and future (estimated) production, investment and operating expenditures. Since the historical production figures are published in a number of places, no confidentiality issues are raised by the use of these data. The Norwegian Petroleum Directorate provided reserve and other data for individual fields in the Ekofisk area[3] since these fields are normally grouped together in the published production numbers.

2.2 What data are included?

The data set includes 96 fields from the UK and 30 fields from Norway for a total of the 126 oil fields listed in Table 1 in Appendix 1. The basic data elements are the annual reserve

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[3] Tor, Edda, Embla,Eldfisk, Ekofisk 1, Albuskjell, Cod, Ekofisk V

estimates and production for each field and derived variables such as age (years from initial production) and size (the reserve estimate when production started).

Only offshore oil fields are included for two reasons. First, the large number of natural gas fields on the British Continental Shelf made it advisable to reduce the data set to a more manageable level. Second, the connection between oil reserve additions and production is less complicated since oil reserves do not face the transportation and marketing obstacles that affect natural gas reserves and are thereby more immediately marketable.

Unlike other studies of field growth, we analyze reserve appreciation from the time production starts instead of from the time of initial discovery.[4] As a result, the reserve appreciation we measure is less what has been cited by others that start with the year of discovery. The start of production is a more clearly and more easily identifiable event in the life of any field than any other. Moreover, by this time, exploratory and development drilling subsequent to discovery will have removed much of the initial geological uncertainty, or enough of it to justify a significant investment in production facilities. Finally, reserve appreciation after production facilities are in place has a much more direct consequence on output than revisions of reserve estimates in fields that are not yet producing and may never produce.

2.3 Distribution of fields

Size will change with reserve appreciation, but for the purposes of this working paper, size is defined as the reserves reported in the first year of production. Three size categories seemed reasonable, and we decided to define small fields as those with less than 100 million barrels, which would have been considered too small to warrant production in the early years of North Sea development. The division between medium and large fields is arbitrary, but a break in the distribution of fields by size in the Norwegian sector occurs at 400 million barrels and this

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[4] A few of the Norwegian fields recorded some production during the exploratory phase, before development and production plans were approved [Oseberg (1986,1987), Mime (1990,1991) and Troll ph.2 (1990,1991)]. This early production is not included in the data set as we chose to be consistent to the term ‘production start’. Also, data was lacking in the early years for some fields (Argyll). In these cases, we used the data for the first recorded year.

number was used as the upper limit for medium sized fields. Large fields are therefore those estimated to have more than 400 million barrels of oil when production started.

Table 1 shows the population of fields by year, country, and size. By 1996, 117 fields were producing and only nine fields had ceased production.[5]

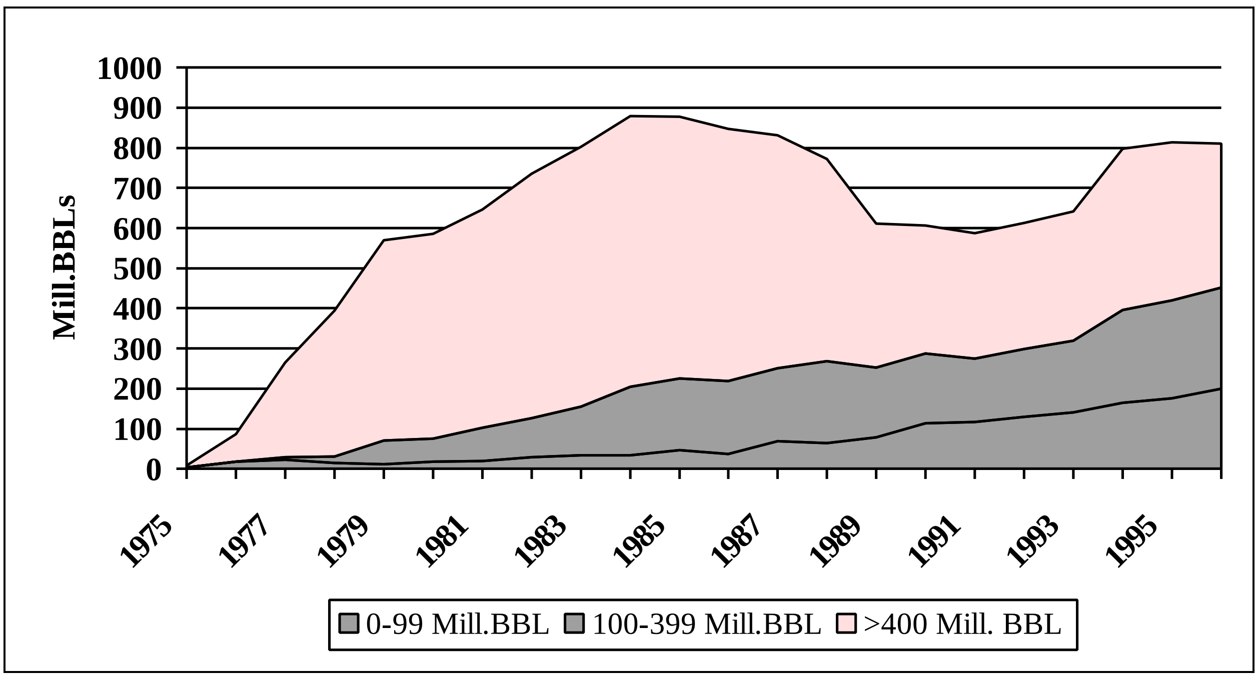
Table 1: Number of Producing Fields in the North Sea, 1971-96

	Norway				**U.K**			
	Small	Medium	Large	Total	Small	Medium	Large	Total
1971	0	0	1	1	0	0	0	0
1972	0	0	1	1	0	0	0	0
1973	0	0	1	1	0	0	0	0
1974	0	0	1	1	0	0	0	0
1975	0	0	1	1	1	0	1	2
1976	0	0	1	1	2	1	4	7
1977	1	1	1	3	2	1	5	8
1978	1	2	1	4	2	3	7	12
1979	2	3	3	8	3	3	7	13
1980	2	3	3	8	3	4	7	14
1981	2	3	3	8	4	6	7	17
1982	2	4	3	9	4	6	9	19
1983	2	4	3	9	5	9	10	24
1984	2	4	3	9	6	10	10	26
1985	2	4	3	9	9	10	10	29
1986	3	5	4	12	11	10	10	31
1987	3	5	4	12	12	12	10	34
1988	4	5	5	14	13	13	10	36
1989	4	5	5	14	20	14	10	44
1990	5	7	5	17	24	15	10	49
1991	5	7	5	17	23	15	10	48
1992	6	7	6	19	29	16	10	55
1993	7	8	7	22	31	20	11	62
1994	7	10	7	24	35	22	12	69
1995	8	11	9	28	38	22	12	72
1996	9	11	9	29	52	24	12	88

Overall, the number of fields has risen by about three-fold since 1985, but there has been a particularly great increase in the number of small fields in the UK sector. By 1996, well over half the fields in the UK sector were small fields, whereas the distribution of fields among small, medium and large was more or less equal in both the UK and the Norwegian sectors in 1985, and continued to be so in the Norwegian sector in 1996.

Production shares are another matter, as shown in **Figures 1** and **2**. The largest shares of production come from the big fields in both sectors, although the contribution of the small fields has risen significantly in the UK sector over the last 10 years.

Figure 1: UK Production by Field Size

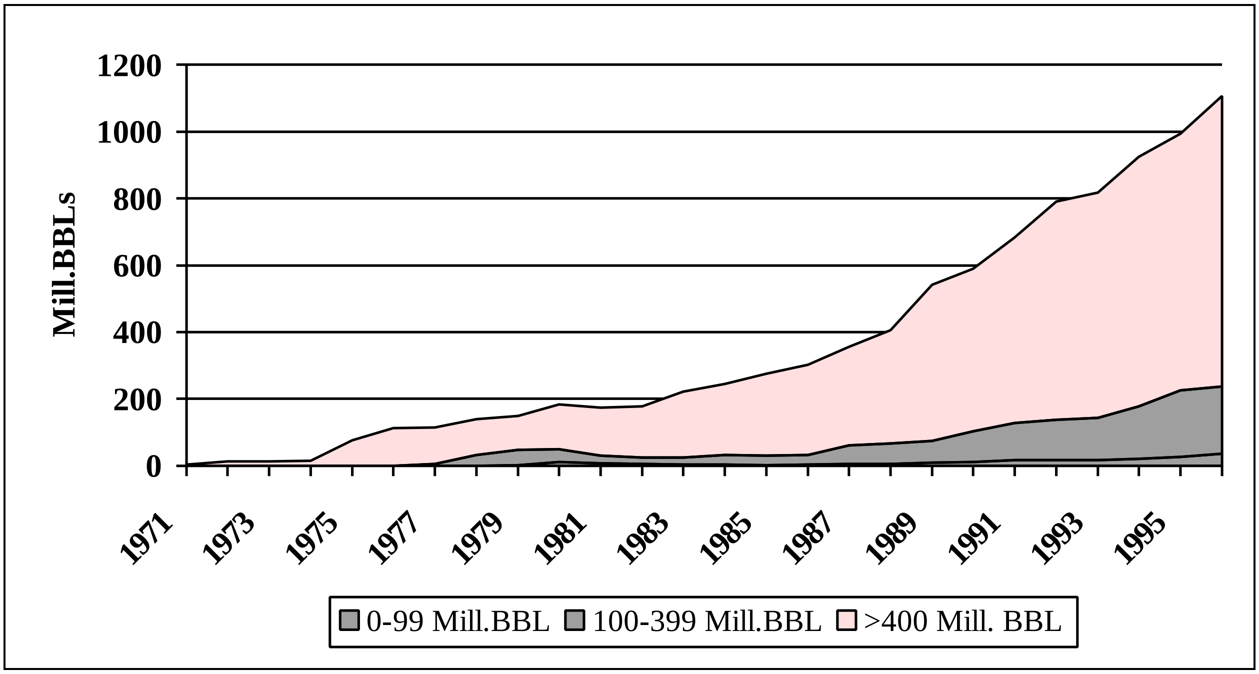


In the UK, the smaller fields are now 25% of the total volume while the medium category provides around 30% of produced oil and the large fields 45%. Earlier the smaller fields held a

[5] Angus, Argyll, Brae West, Captain, Crawford, Duncan, Innes, Linnhe, Staffa (UK) and Mime (Nwy)

much lower share of the volumes, and the big fields had the lion's share of production. After the late 80's, the smaller fields came into the picture, taking a larger share. The medium fields have had a steady growth from the early days through 1996.

Figure 2: Norwegian Production by Field Size



On the Norwegian Continental Shelf the present situation is quite different. Although the contribution from the medium fields has increased in the past ten years, the giant fields account for most of production. Ekofisk 1 was the only producing field on the NCS until 1977, at which time other fields from the same area also began production. The Statfjord field – another giant – started its production in 1979. Even though smaller fields started producing in the late 1970s,[6] the volumes have only made up around 2-5% of the total oil production. The medium fields have contributed somewhat more, 15-20% during the more recent years.

[6] Cod and Edda (both from the Ekofisk area) started production in 1979.

2.4 Method for analyzing data

The tools used for data analysis have been Excel and STATA (Statistical Software), the latter being used for conducting the regression analysis. A cross-sectional time-series dataset was formed where x_{it} is a vector of observations for field *i* and year *t*. Each field-year entry contains data for initial and current reserves, current production, and several categorical variables for size, age, and vintage, as well as for location in either the Norwegian or UK sector. Appendix 2 provides an example of the datasheets.

Fixed effects panel regression is used throughout since the data set includes the entire universe of oil-producing fields in the North Sea. This technique permits a more efficient estimate of the effect of the passage of time on reserve appreciation because field-specific, time-invariant characteristics are gathered in a "fixed effect" coefficient and thereby separated out from the time specific effect common to all fields. For instance, if small fields or chalk fields were to grow more or less than other fields by a fixed amount, this characteristic would be captured in the fixed effect coefficient. Dummy variables representing identifiable field characteristics, such as size, can be interacted with the time variable to separate these effects from the fixed effect coefficient and to capture differences in reserve appreciation according to these categories.

No theory of reserve appreciation is developed in this paper. Instead, our purpose is simply to identify the extent to which reserve appreciation is occurring in the North Sea and any obvious distinguishing characteristics. The model applied to the analysis of the data is a simple one. In all cases, a ratio or the log of the ratio for each field is regressed either on a time dependent variable, such as age, with various interaction terms or on a set of dummy variables representing specific ages. The particular specifications and results are presented in the following section.

3 Analysis

3.1 Reserve appreciation

3.1.1 Age and size

An initial estimate of the effect of age on reserve appreciation is obtained by equation 1.

1) $\ln(R_{it}/R_{i0}) = \alpha + \beta * Age + \gamma_i + \varepsilon_{it}$

in which the left-hand variable is the log of the ratio of current reserves to reserves in the first year of production for the *i*-th field. We use age as the principal right-hand-side variable to facilitate comparison with the later discussion of depletion and remaining reserves, which follow well-established patterns that are a function of age. The coefficient β will be the same, whether year or age is used as the time-related regressor, since the changes in this variable will be identical with each passing year.[7] To the extent that reserve appreciation is occurring over time, the coefficient β will be positive. The variable, γ_i, represents the field-specific, time-invariant fixed effects coefficient, and ε_{it} is the usual normally distributed error term. **Table 2** presents the results of this first regression.

Table 2: Results for Fixed Effects Regression with Age

	Coeff.	Std.Err	T-statistic	P>|t|	95% Conf. Int	
Age	0.02271	0.00150	15.18	0.000	0.01978	0.02565
Constant	-0.11745	0.01271	-9.24	0.000	-0.14205	-0.09250

R^2 within = 0,2014, R^2 between=0.0034, R^2 overall=0.0031

[7] The remaining time related variable, vintage, defined as the initial year of production, shows no correlation whatsoever with observed changes in reserves. Accordingly, there is no observable tendency for early fields to

These results provide a strong indication of reserve appreciation. The age coefficient implies that the fields grow at an annual rate of 2.27% with a 95% confidence interval between 2.0% and 2.6%. The R^2 within – which is the ordinary R^2 when doing the fixed effects analysis - does not indicate a very good fit, but reserve growth can be reasonably assumed to depend on many other variables besides age and the time-invariant, field specific factors captured by the fixed effects coefficient.[8] The constant is also significantly different from zero, which suggests a tendency to reserve shrinkage in the early years, but it may also reflect some compositional difference that is not captured in the assumed, uniformly constant rate of reserve appreciation across all fields.

To see whether the size categories are important, the dummy variables, small (D_S=1) and large (D_L=1), are introduced and the corresponding interaction terms, *smallx* and *largex*, are defined as D_S*age and D_L*age, respectively. The regression equation is now:

2) $\ln(R_{it}/R_{i0}) = \alpha+\beta*A_{it} + \beta_S*D_S*A_{it} + \beta_L*D_L*A_{it} + \gamma_i + \varepsilon_{it}$

Where: A_{it}=Age for the number of producing years for field i.

For D_S =1:

3) $\ln(R_{it}/R_{i0}) = \alpha + (\beta + \beta_S)*A_{it}$

and similarly for large fields when D_L=1. Medium fields constitute the default category when D_S=0 and D_L=0. **Table 3** gives the results for this less restrictive fixed effect specification follow.[9]

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grow more than later fields, or vice versa. Consequently, we ignore vintage for the remainder of the analysis.

[8] Taking fixed effects into account does raise the R^2 to .20 from .03 when OLS regression is used.

[9] Random effect panel regression could be used to include the effect of size-related intercepts, and the inclusion of such terms causes the intercept always to be insignificantly different from zero. Fixed effect regression is more appropriate because the complete universe is included in the data set and to control better for time invariant conditions. The age coefficients for the fixed and random effect estimators are very similar in all cases. For instance, the rates of growth yielded by the random effects estimation for the specification reported in Table 3 are +3.46%, +0.69%, and +2.69% for small, medium and large fields, respectively.

Table 3: Fixed Effects Regression of Age Interacted with Size

	Coeff.	Std.Err	T	P>|t|	95% Conf.Int	
Age	0.00816	0.00255	3.20	0.001	0.00315	0.01317
Smallx	0.02617	0.00390	6.71	0.000	0.01851	0.03382
Largex	0.01897	0.00338	5.61	0.000	0.01233	0.02562
Constant	-0.11880	0.01250	-9.51	0.000	-0.14333	0.09427

R^2 within = 0.2445, R^2 between = 0.0599, R^2 overall = 0.1467

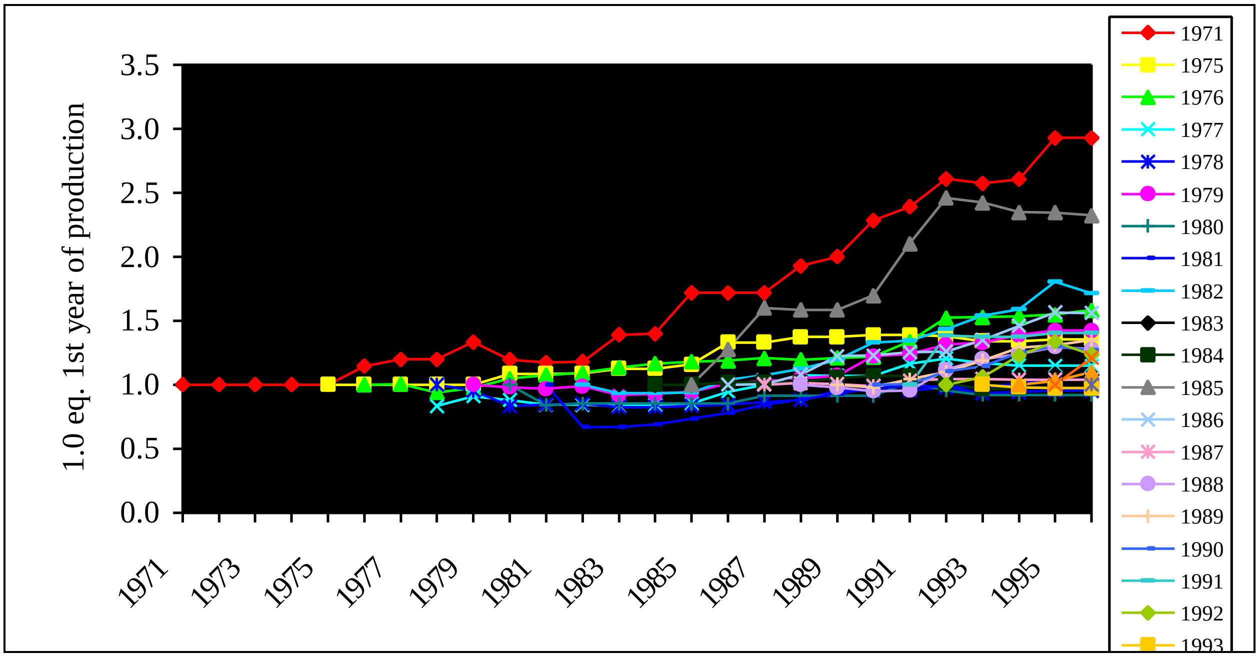
The constant is very little changed, but the rates of reserve appreciation differ significantly according to the size of reserves when production starts. The small fields grow at around 3.4% per annum, medium fields at 0.8%, and the larger fields 2.7%. Both large and small fields appreciate at significantly greater rates than medium fields. Although the estimated coefficients indicate a higher rate of growth for small fields, this difference just fails of being significantly different at the 95% level (P>F=0.052).

3.1.2 The effect of early and late periods

The significantly negative intercept suggests that the age coefficients may not be constant. In fact, visual inspection of the data indicates that such a change in appreciation occurred around the year 1985-86.

In **Figure 3**, the total reserves for all the fields in each North Sea vintage, including UK and Norwegian fields of all sizes, is indexed to 1 for the first year of production and subsequent reserves are shown as a ratio of current to initial reserves. With the exception of the 1971 vintage (only Ekofisk), reserve appreciation appears to be more or less constant until the mid-eighties and to grow thereafter.

Figure 3: North Sea Reserve Appreciation by Vintage



A test of whether reserve appreciation occurred only in these later years can be conducted by creating a dummy variable for the post-1985 years and interacting it with all the other terms. The results of this regression are given in **Table 4**.

Table 4: Results for Random Effect Regression for Age, Size and Period

	Coeff.	Std.Err	t-statistic	P>|t|	95% Conf.Int	
Age	-0.03042	0.00891	-3.41	0.001	-0.04791	-0.01293
Smallx	+0.06797	0.01275	+5.33	0.000	+0.04294	+0.09299
Largex	+0.04778	0.01090	+4.38	0.000	+0.02639	+0.06918
Pst85x	+0.03161	0.00700	+4.51	0.000	+0.01787	+0.04536
P85smlx	-0.03432	0.01009	-3.40	0.001	-0.05412	-0.01451
P85lrgx	-0.02384	0.00842	-2.83	0.005	-0.04037	-0.00732
Constant	-0.08432	0.01558	-5.41	0.000	-0.11491	-0.05374

R^2 within = 0.2634, R^2 between = 0.0969, R^2 overall = 0.1997

Each of the interaction terms is significant at the 99% confidence level, as is the constant, although the negative effect of the latter has been diminished somewhat. **Table 5** provides the coefficients and differences that result from the complex structure of interaction terms in this specification. The outlined box contains the six distinct age coefficients, while the differences are outside. The t-statistics are in parentheses and bold-faced entries denote statistical significance at the 95% confidence level.

Table 5: Coefficients with Size and Time Distinctions

	Pre 1986	Post 1985	Pre/Post Delta
Small	**+3.75%**	**+3.48%**	-0.27%
	(4.1)	**(10.8)**	(0.4)
Medium	**-3.04%**	+0.12%	**+3.16%**
	(3.4)	(0.4)	**(4.5)**
Large	**+1.74%**	**+2.51%**	+0.78%
	(2.8)	**(10.0)**	(1.7)
Small - Medium Delta	**+6.80%**	**+3.36%**	
	(5.3)	**(7.7)**	NA
Large - Medium Delta	**+4.78%**	**+2.39%**	
	(4.4)	**(6.2)**	NA
Large - Small Delta	-2.01%	**-0.97%**	
	(1.8)	**(2.4)**	NA

The first point to note is that the size difference remains significant regardless of period. Small and large fields appreciate significantly more than medium sized fields whether before or after 1985/86. In fact, the pre/post distinction is important only for the medium fields, which go from a significantly declining rate in the pre-1986 period to a later rate that, while not increasing, is also not declining. As was the case when the time distinction was not made, small fields appear to appreciate more rapidly than large fields, with an apparently larger difference in the early period. This difference is however erroneous. There are many fewer observations in the early period, and as indicated by the t-statistics, a significant difference between the small and large fields cannot be accepted at the 95% confidence level in the early period, although it can be for the smaller difference in the later period.

3.1.3 Country differences

The effect of location in either the UK or Norwegian sectors of the North Sea can be tested by a similar specification with UK interaction terms to designate those fields. These results are reported in **Table 6**.

Table 6: Results for Random Effect Regression for Age, Size and Sector

	Coeff.	Std.Err	T	P>|t|	95% Conf.Int	
Age	+0.01605	0.00431	+3.72	0.000	+0.00759	+0.02452
Smallx	+0.00798	0.00696	+1.15	0.252	-0.00568	+0.02164
Largex	+0.02433	0.00584	+4.17	0.000	+0.01287	+0.03578
UKx	-0.01198	0.00532	-2.25	0.024	-0.02242	-0.00155
Uksmall	+0.02636	0.00837	+3.15	0.002	+0.00995	+0.04278
Uklarge	-0.00724	0.00712	-1.02	0.310	-0.02121	+0.00674
Constant	-0.1196	0.01236	-9.68	0.000	-0.14385	-0.09533

R^2 within = 0.2659, R^2 between = 0.0695, R^2 overall = 0.1597

Fewer of the interaction terms are significant in this specification in which the reserve appreciation rate is constrained to be constant over the entire period but allowed to vary by size and sector. As before, **Table 7** provides the coefficients and differences that result from the complex structure of interaction terms in this specification.

The difference in reserve appreciation rates between fields located in the two sectors is significantly different, but not in uniform way.[10] Small fields appreciate more on the UK side, while medium and large fields appreciate less. Size continues to be the main distinction although with more nuance. In Norway, the difference in reserve appreciation between small and medium fields is not statistically significant, although the rates of appreciation for the two categories remain clearly positive.

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[10] When the UK interaction term is constrained to be constant over size categories, it takes a value of –0.90%, and it

Table 7: Coefficients with Size and Sector Distinctions

	Norway	UK	UK Delta
Small	**+2.40%**	**+3.84%**	**+1.44%**
	(4.1)	**(11.2)**	**(2.2)**
Medium	**+1.61%**	+0.41%	**-1.20%**
	(3.7)	(1.3)	**(2.3)**
Large	**+4.04%**	**+2.12%**	**-1.92%**
	(10.3)	**(8.0)**	**(4.1)**
Small - Medium Delta	+0.80%	**+3.43%**	
	(1.1)	**(7.4)**	NA
Large - Medium Delta	**+2.43%**	**+1.71%**	
	(4.2)	**(4.2)**	NA
Large - Small Delta	**+1.63%**	**-1.73%**	
	(2.4)	**(4.0)**	NA

3.1.4 Fully interacting country and time differences

The effects of sector and time period can be combined in one final regression with all possible interactions of size, sector and whether before or after 1985/86.

With more regressors, the R^2 improves over what it is with either of the simpler specifications. All size and the post85 interaction terms are statistically significant at the 95% confidence level. In this more finely discriminating specification, the UK distinction fails to be significant for all interaction terms except one, that distinguishing small UK fields. In **Table 9**, the same format is followed as before with each cell listing both the pre-1986 and post-1985 coefficients.

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is significant at the 95% confidence level. This is however nothing more than the average of the larger negative differences for medium and large fields and the positive difference for small fields.

Table 8: Results for Random Effect Regression for Age, Size and Sector

	Coeff.	Std.Err	T	P>|t|	95% Conf.Int	
Age	-0.03037	0.01100	-2.76	0.006	-0.05196	-0.00878
Smallx	+0.04715	0.01414	+3.34	0.001	+0.01940	+0.07489
Largex	+0.05270	0.01181	+4.46	0.000	+0.02953	+0.07588
Post85x	+0.03747	0.00819	+4.58	0.000	+0.02141	+0.05354
P85smlx	-0.03158	0.01000	-3.16	0.002	-0.05121	+0.01195
P85lrgx	-0.02294	0.00831	-2.76	0.006	-0.03925	-0.00662
P85UKx	-0.01034	0.00708	-1.46	0.144	-0.02423	+0.00355
UKx	+0.00159	0.01016	+0.16	0.876	-0.01835	+0.02153
UKsmallx	+0.02527	0.00828	+3.05	0.002	+0.00901	+0.04152
UKlargex	-0.00807	0.00704	-1.15	0.252	-0.02190	+0.00575
Constant	-0.08547	0.01540	-5.55	0.000	-0.11570	-0.05524

R^2 within = 0.2861, R^2 between = 0.1143, R^2 overall = 0.2286

Table 9: Coefficients with Size, Time and Sector Distinctions

	Norway		UK		UK Delta	
Small	+1.68%	**+2.27%**	**+4.36%**	**+3.92%**	**+2.69%**	**+1.65%**
	(1.4)	**(3.9)**	**(4.7)**	**(10.8)**	**(2.5)**	**(2.5)**
Medium	**-3.04%**	+0.71%	**-2.88%**	-0.17%	+0.16%	-0.88%
	(2.8)	(1.5)	**(3.0)**	(0.5)	(0.2)	(1.6)
Large	**+2.23%**	**+3.69%**	**+1.58%**	**+2.00%**	-0.65%	**-1.68%**
	(2.6)	**(8.8)**	**(2.2)**	**(6.7)**	(0.6)	**(3.4)**
Small - Medium Delta	**+4.71%**	**+1.56%**	**+7.24%**	**+4.08%**		
	(3.3)	**(2.1)**	**(5.7)**	**(8.2)**	NA	
Large - Medium Delta	**+5.27%**	**+2.98%**	**+4.46%**	**+2.17%**		
	(4.5)	**(4.9)**	**(4.1)**	**(4.9)**	NA	
Large - Small Delta	+0.56%	**+1.42%**	**-2.78%**	**-1.91%**		
	(0.4)	**(2.0)**	**(2.5)**	**(4.1)**	NA	
Post85 Delta, Small	+0.59%		-0.44%			
	(0.7)		(0.6)		NA	
Post85 Delta, Medium	**+3.75%**		**+2.71%**			
	(4.6)		**(3.7)**		NA	
Post85 Delta, Large	**+1.45%**		+0.42%			
	(2.3)		(0.8)		NA	

The pattern of reserve appreciation emerging in the previous specifications continues here. Small and large fields show positive reserve appreciation in sharp contrast to the medium sized fields. The indicated rate of appreciation for small Norwegian fields prior to 1986 is not statistically significant; however, the number of fields and observations is small (2 fields and 16 observations) so that little weight can be placed on this estimate. When the sample is not divided so finely, as in the two previous specifications, a clear tendency to reserve growth is evident for small Norwegian fields and for pre-1986 fields. When the pre-1986 small Norwegian fields are compared to large Norwegian fields during the same time and small Norwegian fields after 1985, this small subset cannot be distinguished from either of these other, more numerous groups, both of which experience significantly positive reserve appreciation.

The medium fields are clearly different for the small and large fields with negative appreciation rates in the pre-1986 period and improved but still not positive rates in the later period. These appreciation patterns obtain equally in the UK and Norwegian sectors in both time periods and both sectors experience a marked improvement between the early and later periods.

With the finer distinctions of this fully interacting specification, what had seemed to be clear distinctions between time periods and sectors lose much of their significance. As just noted, the improvement in appreciation rates indicated by the pre/post distinction applies almost exclusively to the medium sized fields. Moreover, the post-1985 distinction shows no discernible difference either for the small fields in either sector or for large fields in the UK sector. The large fields in the Norwegian sector do seem to appreciate more rapidly after 1985.

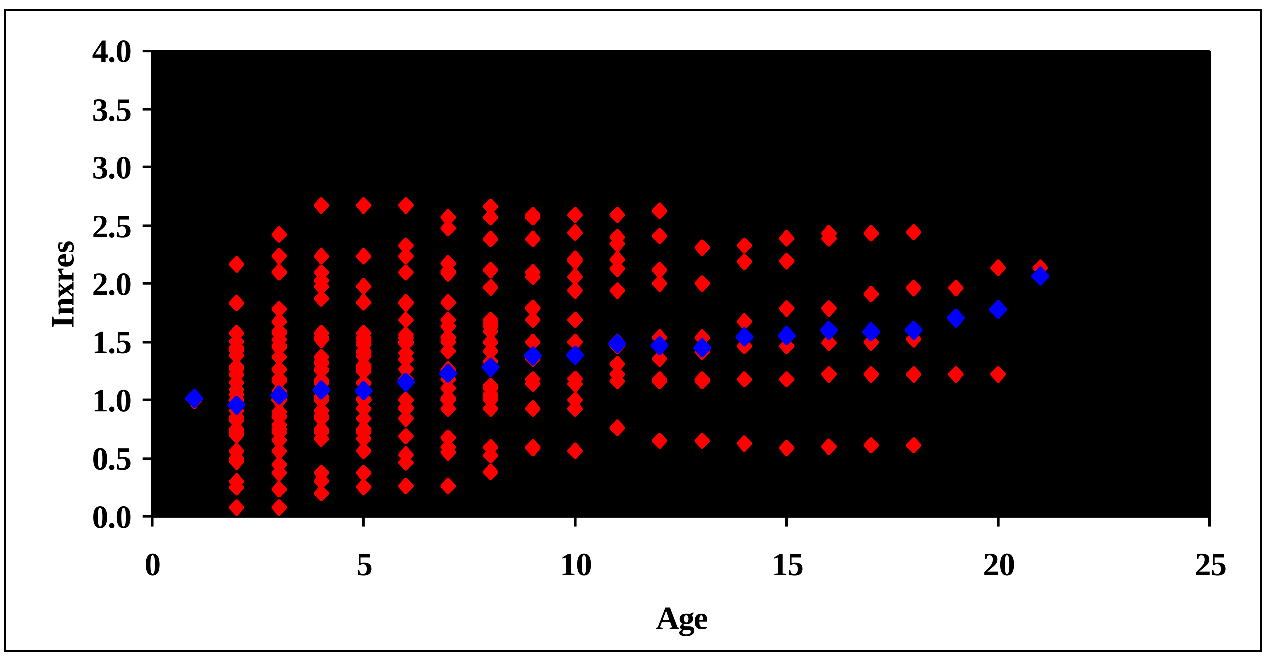
The UK distinction is strongest for the small fields; for both periods, UK small fields grow at a statistically significant higher rate than Norwegian small fields. Although the difference appears to be less in the later period, this inter-period difference is not significant as indicated by the standard error for the *p85UKx* variable. There also appears to be a difference between UK and Norwegian large fields in the post-1985 period, as a result of the discernible increase in the rate of appreciation of Norwegian large fields in the later period.

3.1.5 Non-constant age coefficients

All of the preceding estimates of reserve growth impose a constant rate of appreciation as the field matures with the exception of allowing for a different rate before and after the end of 1985. The restriction of a constant rate of appreciation can be relaxed by defining dummies for each age (*age1* =1st year, *age2* = 2nd year, etc.) to determine if there is any pattern to reserve appreciation as a field matures. Since the initial size of the reserve is already indicated as an important factor and there are plenty of observations, separate regressions where done for each size category and the prediction lines were estimated.

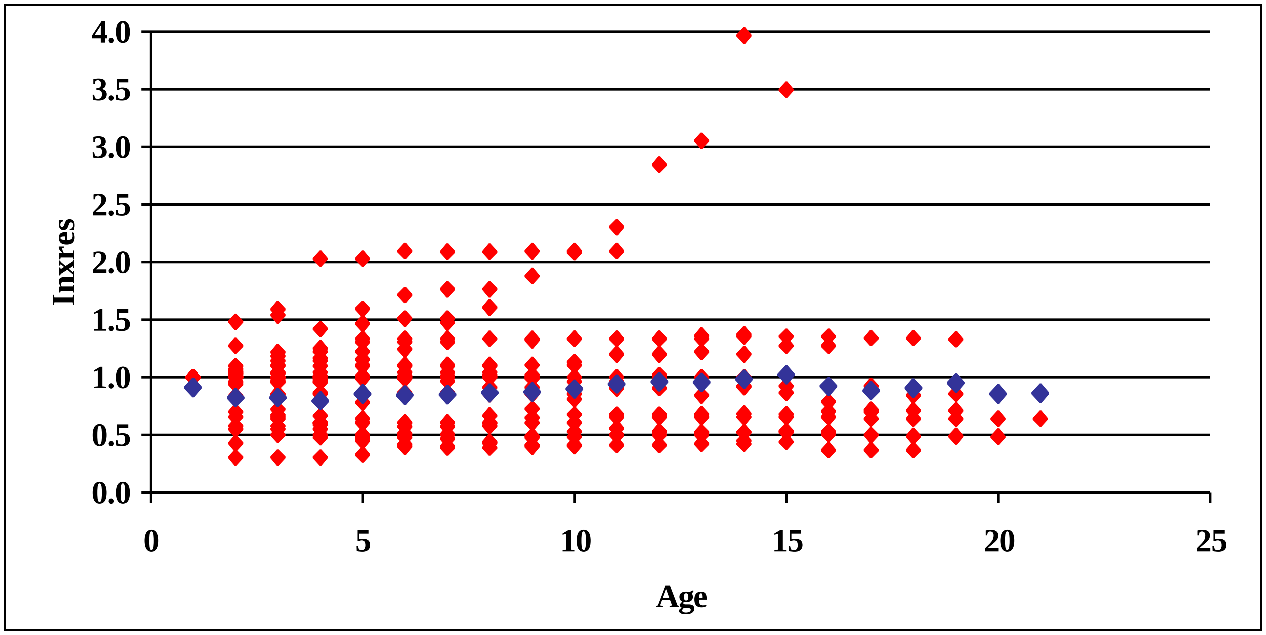
The statistical results of the regressions are shown in Appendix 4. The observed and predicted values are illustrated in **Figures 4** through **6**. For each size category, the observed ratios of current reserves to initial reserves (the *inxres* variable) are plotted against age to illustrate the spread of data in the different categories. The predicted value is also shown, and it can be interpreted as the average ratio of reserve appreciation for the corresponding age.

Figure 4: Reserves/Initial Reserves, Small Fields



For the smaller fields, the observed ratios vary from 0.5 to as much as 2.5 for all but the earliest ages, and a definite upward tilt can be observed. The regression statistics indicate that by the sixth year of production, positive reserve appreciation is statistically discernible.

Figure 5: Reserves/Initial Reserves, Medium Fields



The medium sized fields offer a marked contrast. With one notable exception (Valhall), few medium-sized fields attain ratios in excess of 1.5 and a number of observations of less than 0.50 can be found. A tendency to reserve appreciation can be observed between the fourth and fifteenth years of production; however, with the exception of the fourth year, none of the coefficients are significantly different from zero. The only significant coefficient is the constant, which is weakly negative indicating that when all the medium fields and ages are thrown together the average is slightly below the initial reserve size. The data is illustrated here:

The large fields show a much tighter distribution for most years, with most observations between 0.70 and 1.50, and a clear upward trend can be discerned even without reference to the two fields with significant reserve appreciation after the fifteenth year of production (Ekofisk and Beryl A&B). For the large fields, the predicted ratio does not grow as strongly as for small fields, but by the eighth year, reserve appreciation is statistically discernible. Little confidence can be placed in the results for ages beyond twenty, since there is only one field with more than 22 years of production –Ekofisk.

Figure 6: Reserves/Initial Reserves, Large Fields

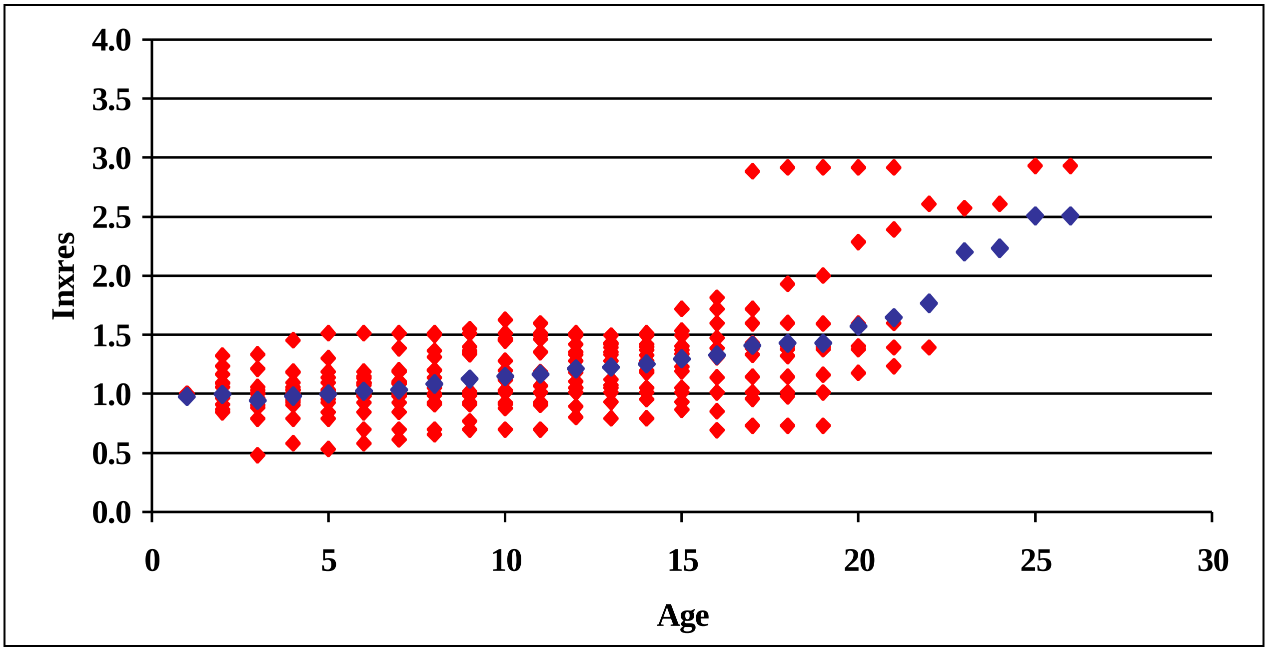


Figure 7 compares the prediction lines for the three size categories.

The different rates of appreciation for the three size categories can be clearly seen. The small fields have experienced the greatest reserve appreciation, but the large fields are not far behind, and both stand in marked contrast to the medium sized fields. The data in Figure 7 can be summarized by five year intervals as is done in **Table 10** below, which shows the within interval and cumulative compounded annual rate of appreciation for each size category.

Figure 7: Prediction lines, Reserves/Initial Reserves

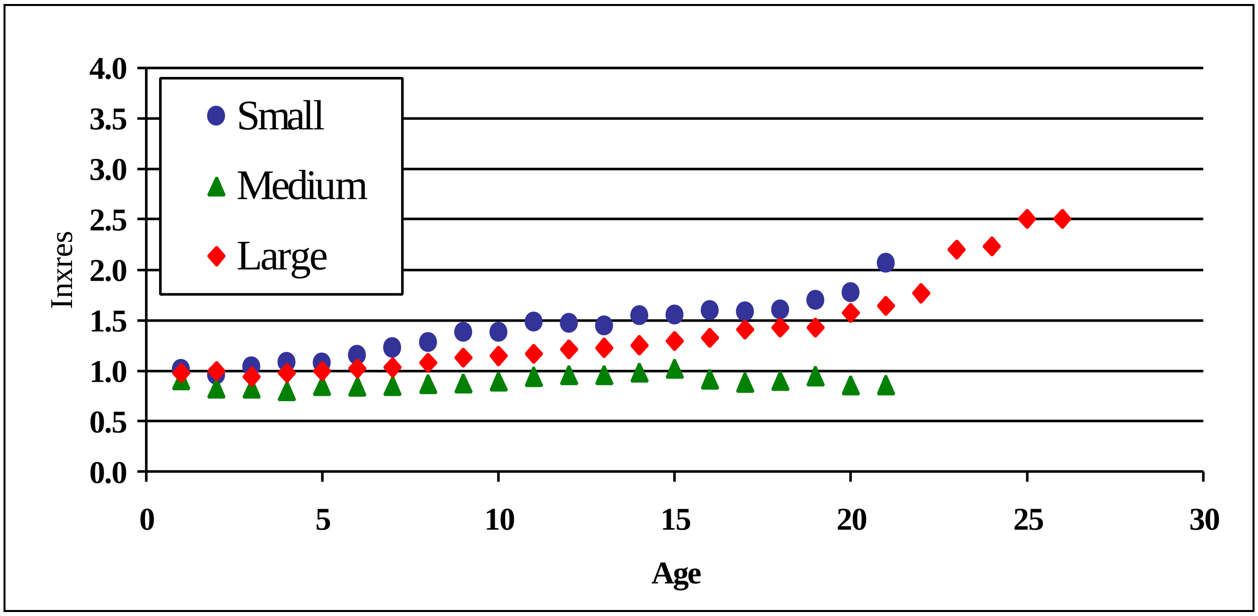


Table 10: Reserve Appreciation Rates by 5-year Intervals

	Small	Medium	Large
0 to 5 years	+2.55%, +2.55%	-1. 45%, -1.45%	+0.87%, +0.87%
5 to 10 years	+5.05%, +3.80%	+2.17%, +0.36%	+2.67%, 1.77%
10 to 15 years	+1.49%, +3.03%	-0.51%, +0.07%	+2.57%, 2.04%
15 to 20 years	+5.11%, +3.54%	-1.30%, -0.27%	+4.29%, 2.60%
20 to 25 years	N/A	N/A	+8.44%, 3.77%

There appears to be some tendency to acceleration after the first five years, which will be years after peak production for most fields; however, tests for the significance of either post-age-5 or post-peak reserve appreciation failed to show any statistical significance, even at the 90% confidence level. In the main, this specification reveals the same structure as the earlier regressions with constant age coefficients. Small and large fields appreciate noticeably more than medium sized fields, which do not appreciate at all.

3.1.6 Chalk fields

One particular geological circumstance has been suggested to us as an explanation for reserve appreciation, especially in the more recent years. Most of the fields in the most southern part of the Norwegian sector, generally the Ekofisk area, reside in chalk formations. These formations have the peculiar characteristic that the chalk residue often degrades production in the early years of production, while later subsidence of the formation enhances production. As oil is extracted in the later years, the formation subsides increasing the pressure and natural drive for the extraction of the remaining oil.

Tests of the influence of these fields failed to reveal any statistical significance on patterns of reserve appreciation. The reason is not hard to discover from inspection of the reserve data for chalk fields. Although a few chalk fields have increased their reserves spectacularly, most have not, as shown in **Table 11**. In fact, in each size category, there is one outstanding example of reserve appreciation but an equal or greater number of non-appreciating chalk fields. Moreover, differences in vintage do not explain the differences among the chalk fields, as evidenced by the medium and small fields.

Table 11: Data on Chalk Fields

	Initial Year of Production	Initial Reserve (million bbls)	1996 Reserve (million bbls.)	Reserve Index (1996/Initial)
Large Fields				
Ekofisk	1971	868	2541	2.93
Eldfisk	1979	522	511	.98
Medium Fields				
Ekofisk Vest	1977	157	76	.48
Tor	1978	187	160	.86
Albuskjell	1979	126	47	.37
Valhall	1982	207	726	3.51
Small Fields				
Edda	1979	50	31	.62
Tommaliten Gamma	1988	40	24	.60
Hod	1990	25	55	2.20

3.2 Depletion

We define depletion as the annual rate at which a field's reserves are produced, expressed as a percentage of current reserves in order to take into account the appreciation experienced up to that time. The left-hand-side of the regression is

$$4)\ Pctprod_t \equiv P_{it} / R_{it}$$

which is then regressed on separate dummy variables for each age.

The rate of depletion will vary over a field's lifetime for numerous reasons. First and foremost, the natural pressure drive of fields will cause output to be greatest in the early years and then to decline exponentially. Second, this "natural" rate can be modified by new technologies to increase production, i.e. by applying additional pressure (from gas or water injection), or increased recovery (IOR) methods such as 'washing the reservoir.'[11] As stated before, no attempt has been made in this analysis to consider enhanced recovery or other time-varying factors that might influence reserve appreciation.

The appropriate time-related variable for regressing *pctprod* is age, or the number of years since production began at the field. A constant age term would be inappropriate for this regression since the depletion rate has a well-established pattern of first rising and then declining exponentially. Accordingly, specific age terms ranging from 1 to 26 are used as the regressors to provide complete flexibility in specifying the age profile of depletion. The regressions and the corresponding output tables are listed in Appendix 4 by size category. **Figures 8** through **10** present the observations for each size category and the prediction line from the corresponding regression.

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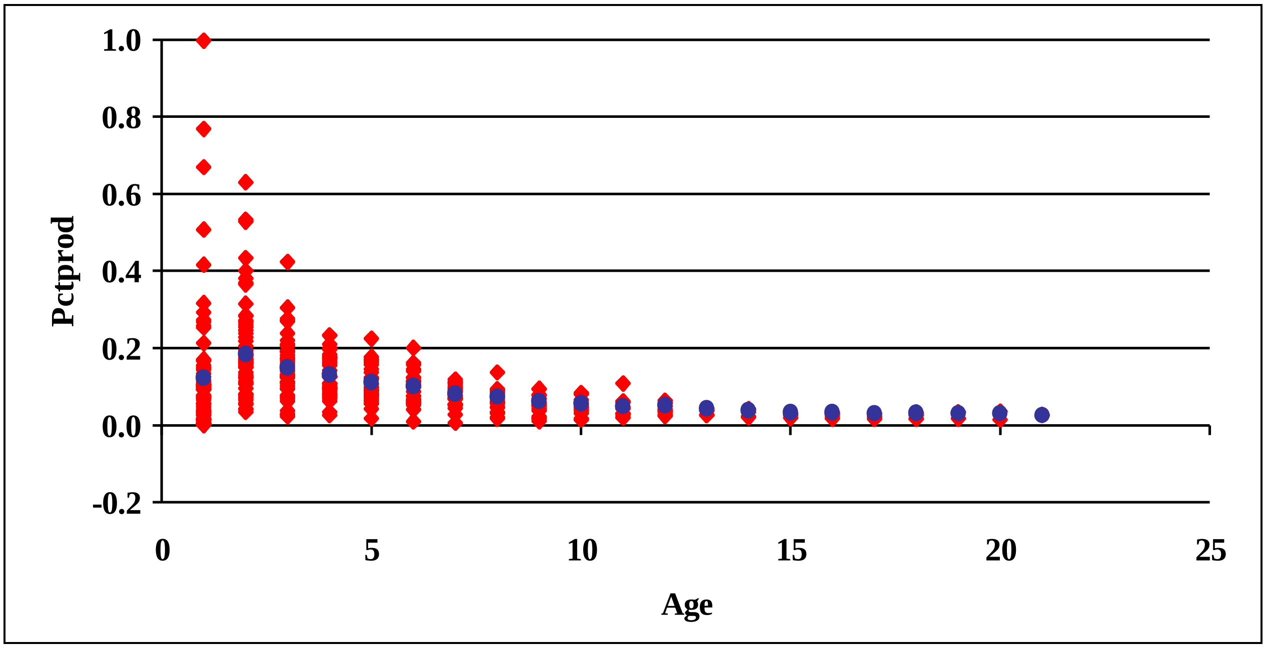
[11] IORs can be a 'detergent' type of solution, foam etc. (Very "layman's" terminology).

Figure 8: Annual Production as Percent of Reserves, Small Fields



The depletion curve for the small fields starts around 15% of reserves, increasing to 20% of total reserves – and after the second year follows the typical decline rate. The observations vary quite a lot for the first years, indicating the large difference in the time it will take to empty a small reservoir. Some fields will have an extremely short production period of only 2-3 years, while other will follow a more 'normal' curve of several years of production.

The medium fields start out more slowly and reach a lower peak of around 12-14 % in the 2nd and 3rd years, before declining. The observations for the medium size fields are also clustered more around the prediction line – indicating much less variation in depletion rates.

The larger fields, above 400 million barrels of oil, have yet another depletion pattern with an even longer build-up to the peak and a lower peak as a percent of reserves. For these fields it takes about four years to reach the plateau production, and the peak, at about 9%, is reached on average in the 6th year.

Figure 9: Annual Production as Percent of Reserves, Medium Fields

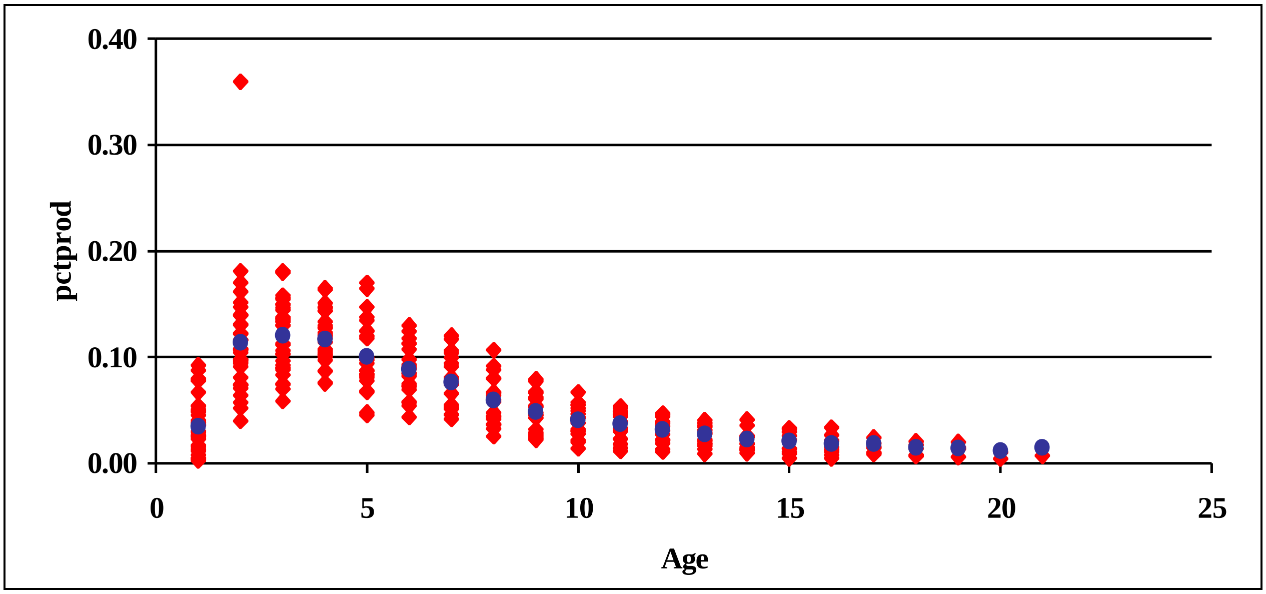
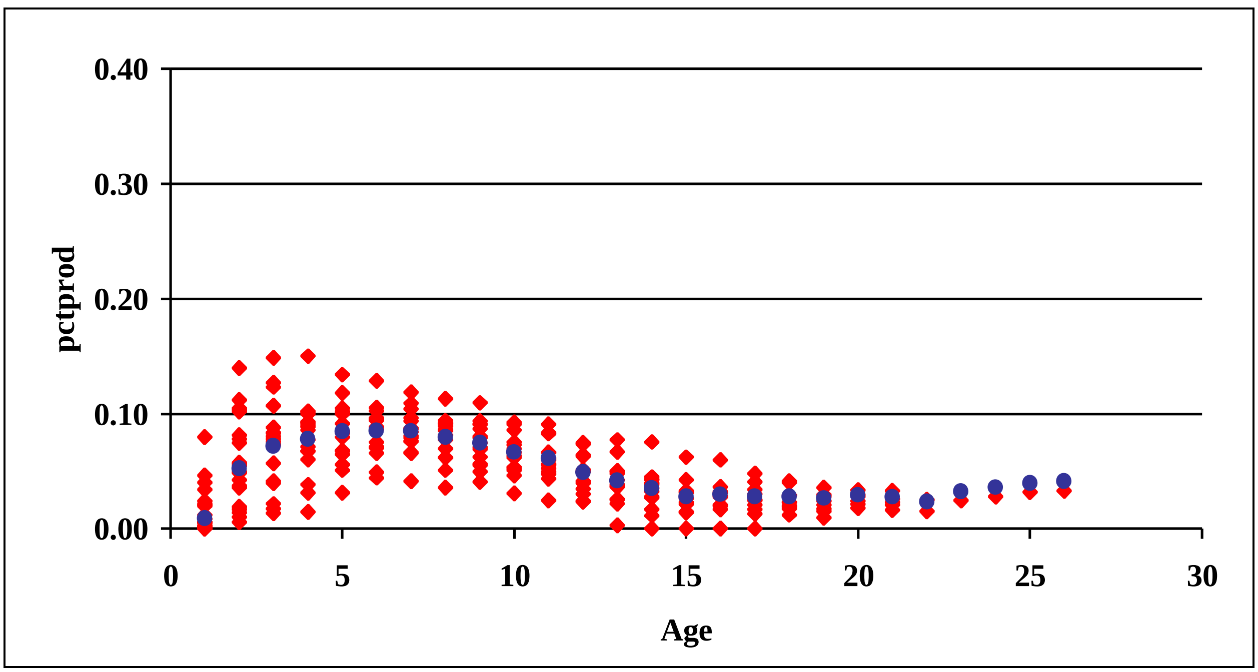
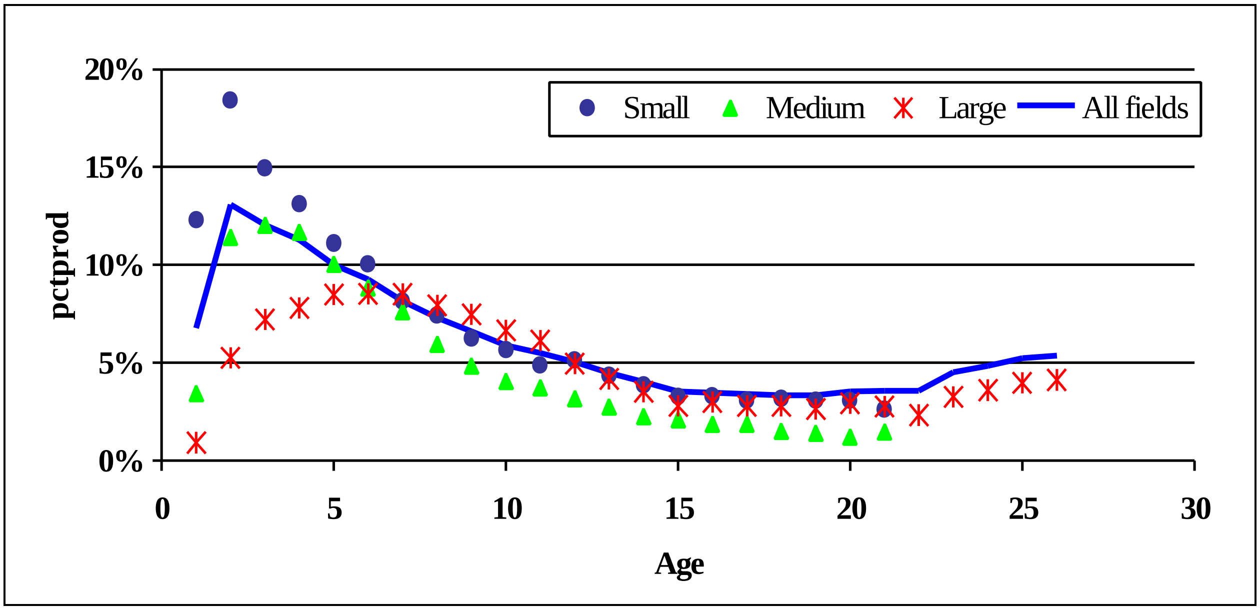


Figure 10: Annual Production as Percent of Reserves, Large Fields



When the prediction lines for the three size categories are plotted, as in **Figure 11**, some clear differences emerge.

Figure 11: Annual Production as Percent of Reserves, by Size Category



A clear tendency to a slower build-up and lower peak exists when moving from the small to the large size categories. For the first four years, the similarity of the depletion rates can be rejected at the 95% confidence level; thereafter the differences in depletion rates among size categories are generally not statistically significant.

3.3 Remaining reserves

The index of remaining reserves, expressed as its ratio to initial reserves, provides a summary statistic that includes the effects of both reserve appreciation and depletion. **Figures 12** through **14** show the observations and prediction lines for the different size categories, and **Figure 15** compares the three prediction lines. The regression results are given in Appendix 3.

Figure 12: Remaining Reserves/Initial Reserves, Small Fields

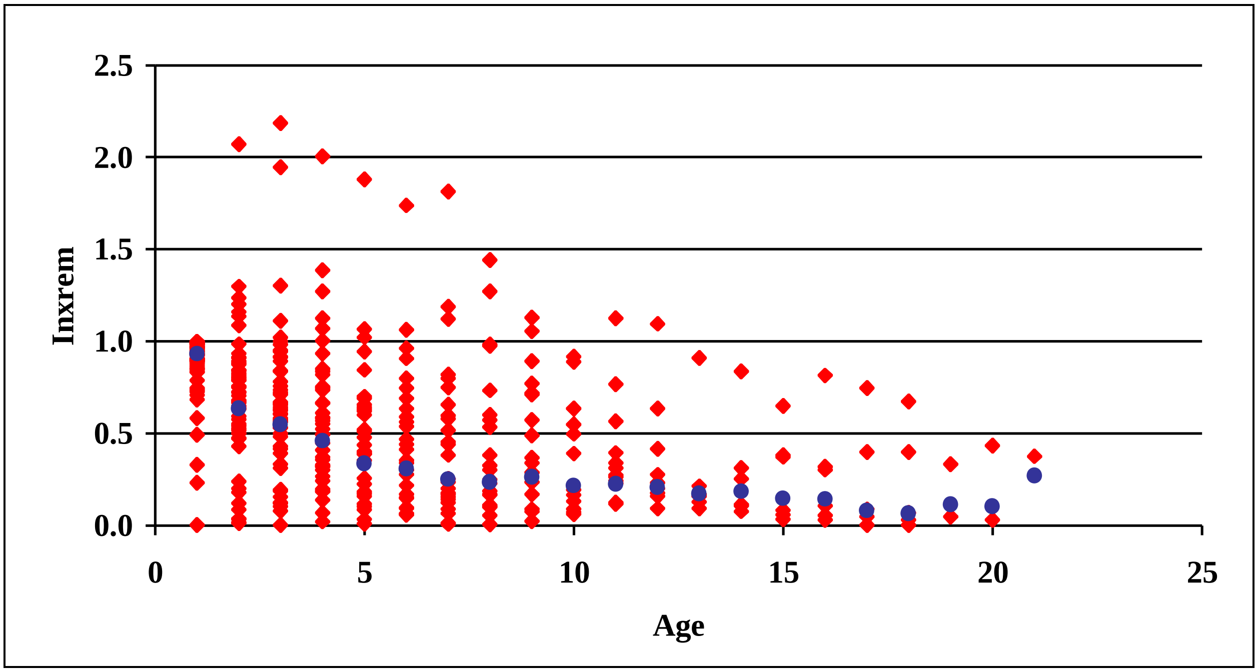


Figure 13: Remaining Reserves/Initial Reserves, Medium Fields

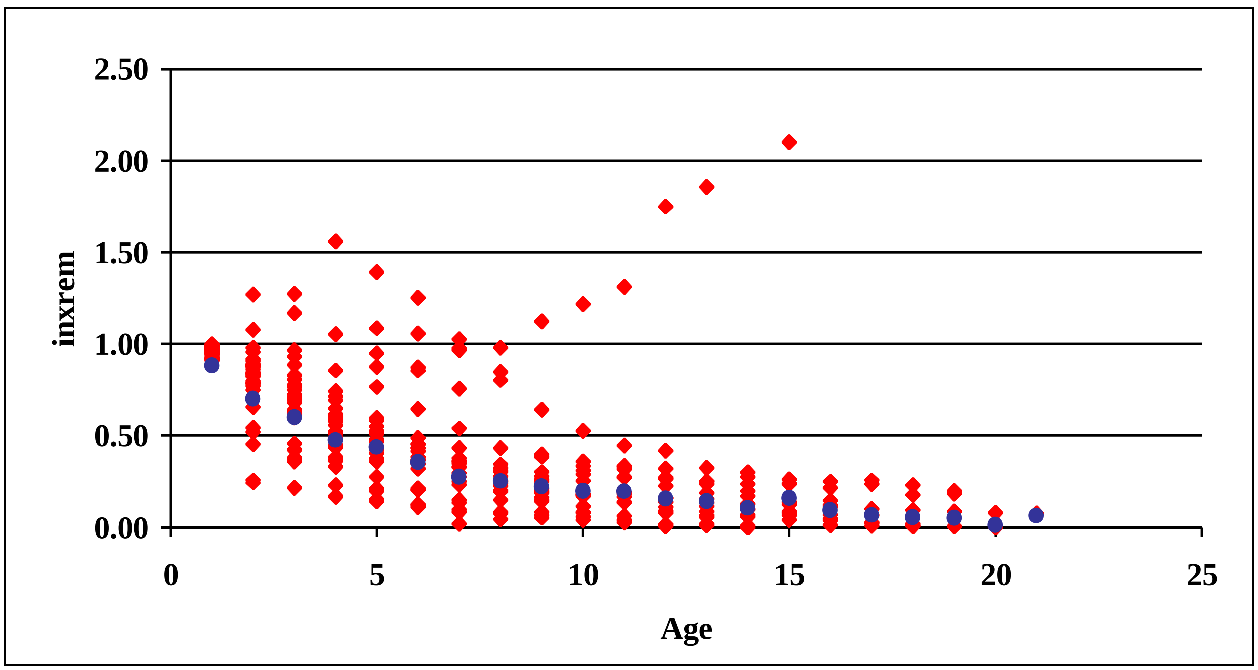
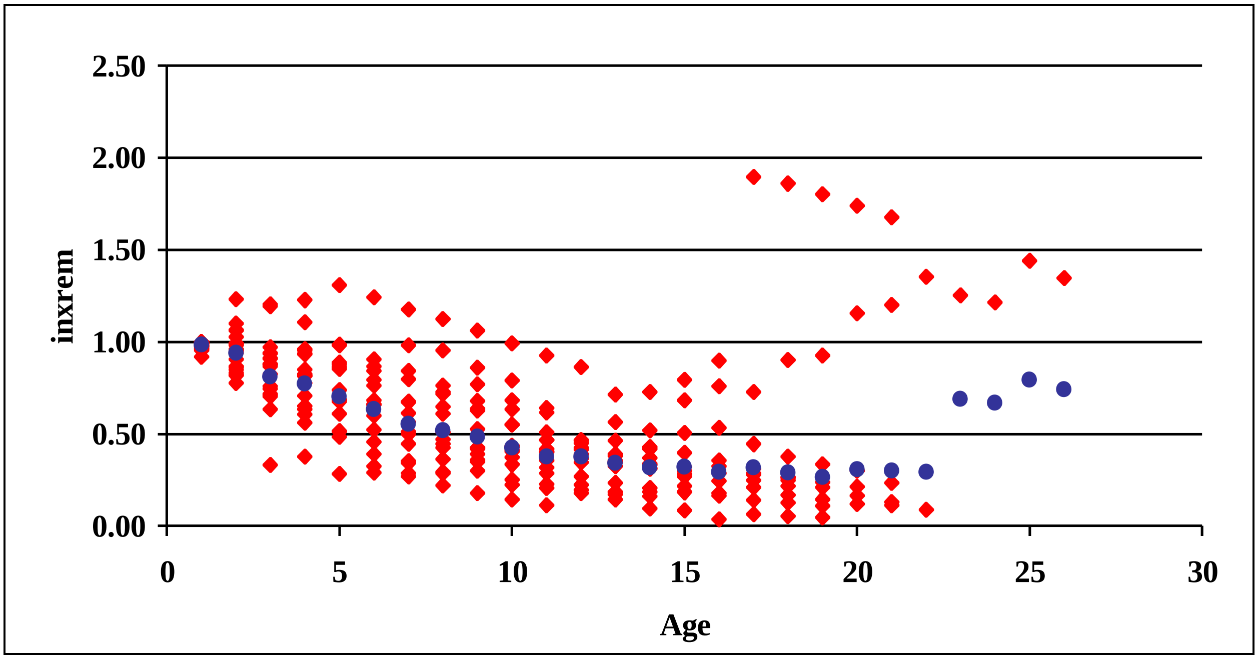


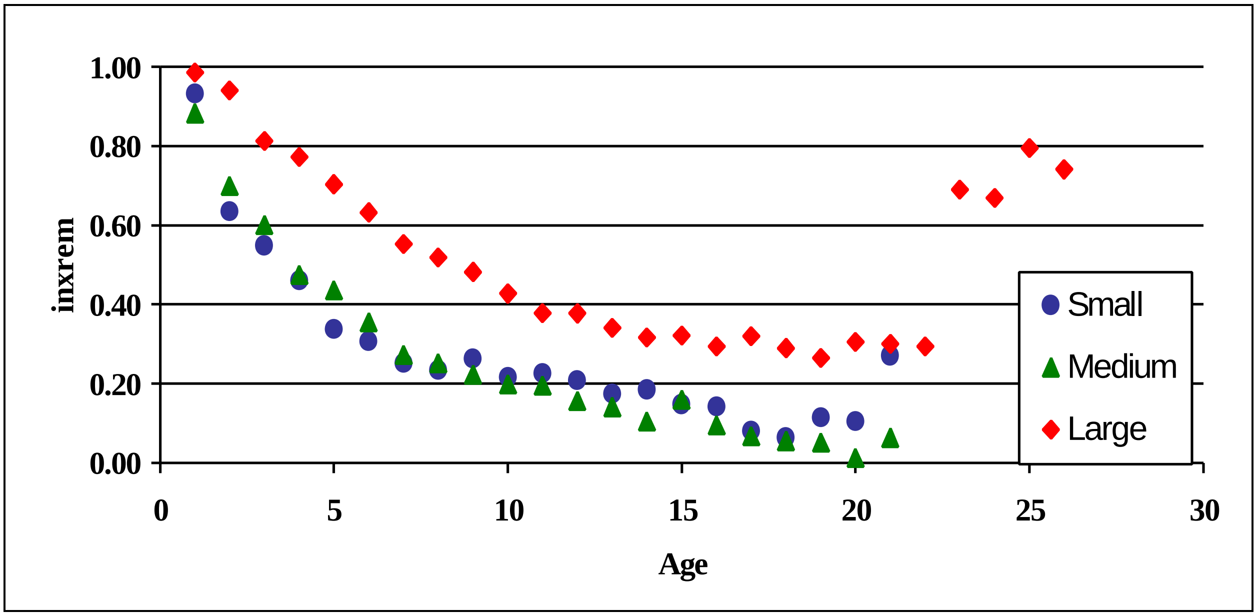
Figure 14: Remaining Reserves/Initial Reserves, Large Fields



In each size category, there are a few fields in which remaining reserves are higher than initial reserves for a number of years, but these are clearly exceptions. The general trend is exponential decline as indicated by the prediction lines for each size category.

The remaining reserve profile is very similar for the small and medium fields. In the case of the small fields, depletion is faster than for medium fields, but reserve appreciation is greater in compensation. For both, remaining reserves reach a level of about 20% by the tenth year, after which a slower decline sets in and the small fields appear to stabilize at about ten percent of initial reserves.

Figure 15: Remaining Reserves/Initial Reserves, North Sea



Large fields exhibit a discernibly different profile. Depletion is slower and reserve appreciation also occurs, such that by the tenth year, remaining reserves are on average forty percent of initial reserves, twice the level of the small and medium fields. Thereafter, they too experience a slower decline; however, but at least in the North Sea, they seem to stabilize at somewhere between 25-30% of initial reserves after the fifteenth year. Although increases in remaining reserves are indicated for large and small fields of more than twenty years age, the observations are too few for any reliable conclusions to be drawn.

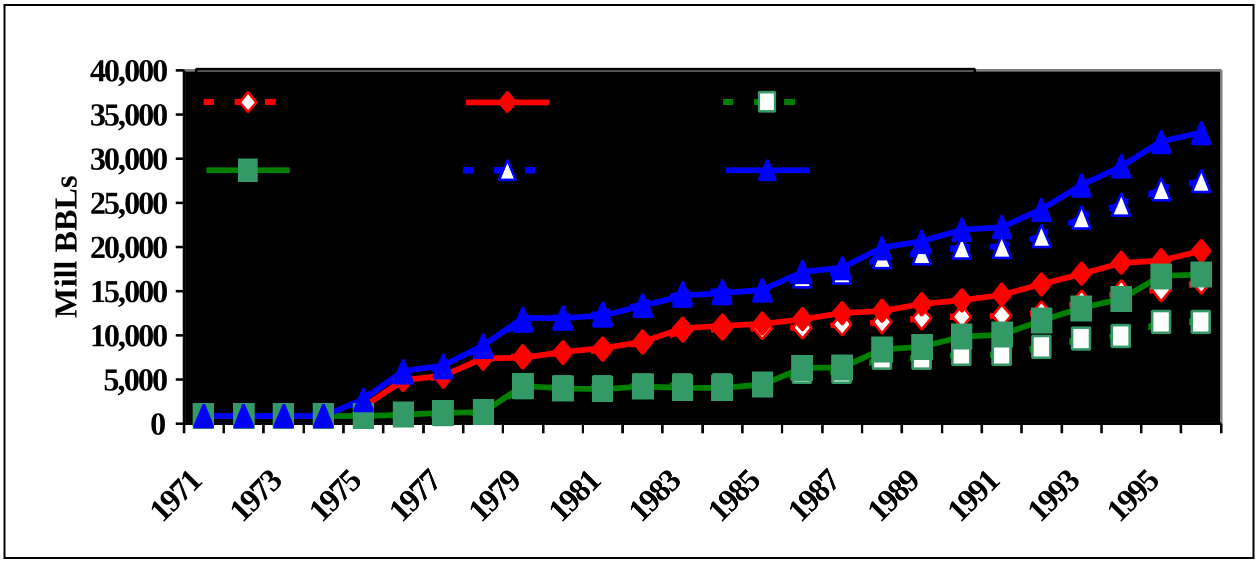
The tendency to stabilization of remaining reserves in the small and large categories has an obvious explanation from the preceding analysis. When reserves are appreciating at 2-3% of total reserves and depletion is occurring at similar rates, production is being replaced. The result is a more or less constant level of inventory at a reserve to production ratio of approximately ten.

3.4 Effect on production and reserves

As a result of the analysis above, an interesting exercise is to take a look at the "What ifs?" What if the appreciation of reserves did not take place, how much difference would this make for the resource base? What effect would this have on production?

To illustrate the first question, **Figure 16** compares the aggregate updated reserves – including annual revisions both up and down – for UK, Norway and the total North Sea with the corresponding initial reserves, plotted as if there had been no revisions in reserve estimates. Reserve appreciation accounts for an important, but not overwhelming part of current reserves.

Figure 16: Initial and Current Reserves, Total and by Country



For the UK continental shelf, current reserves are 19.5 billion barrels instead of around 16 billion barrels of oil as they would have been without reserve appreciation, about 22% higher. For Norway this difference is even larger, with slightly less than 17 billion barrels of current reserves compared to an unappreciated 11.5 billion barrels, about 48% higher.[12]

Figures 17 and **18** compare cumulative production for each sector with cumulative appreciated reserves and with cumulative initial reserves.

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[12] This is not taking into account the depletion that has taken place from these fields.

Figure 17: Cumulative Production vs. Reserves, Norway

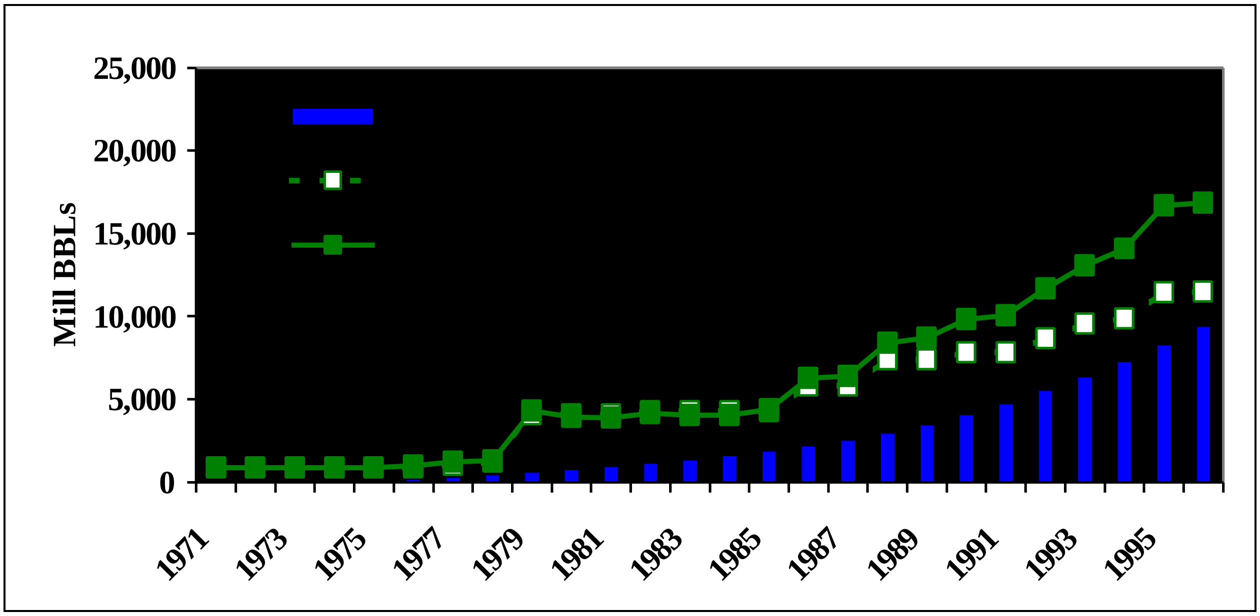
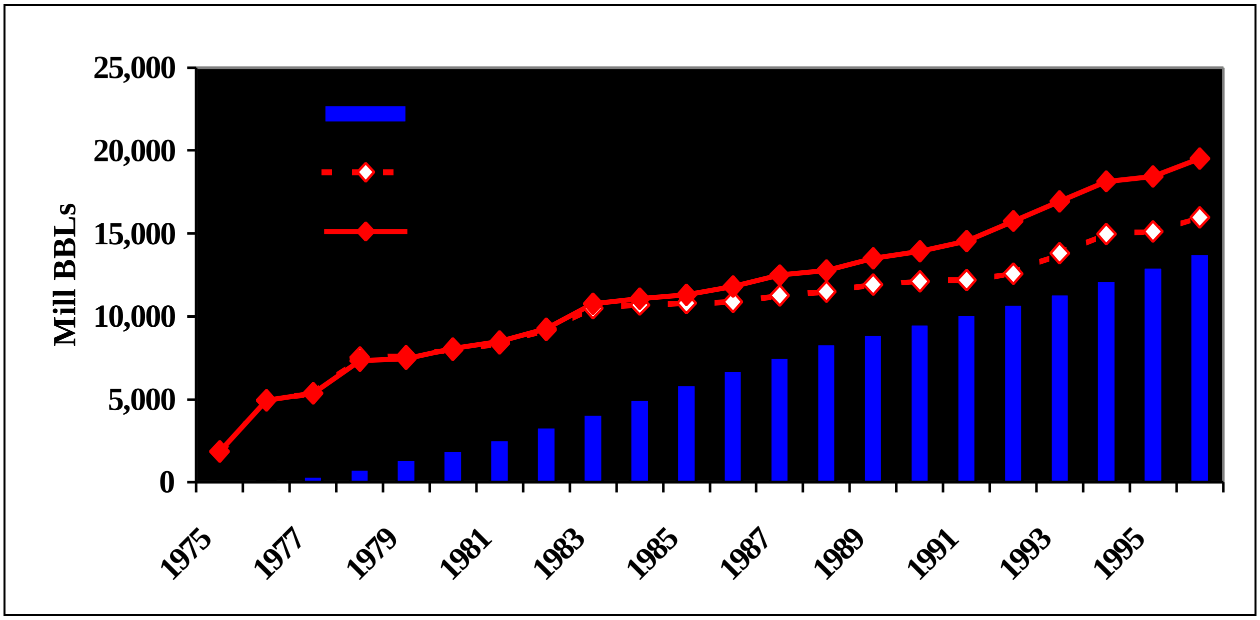


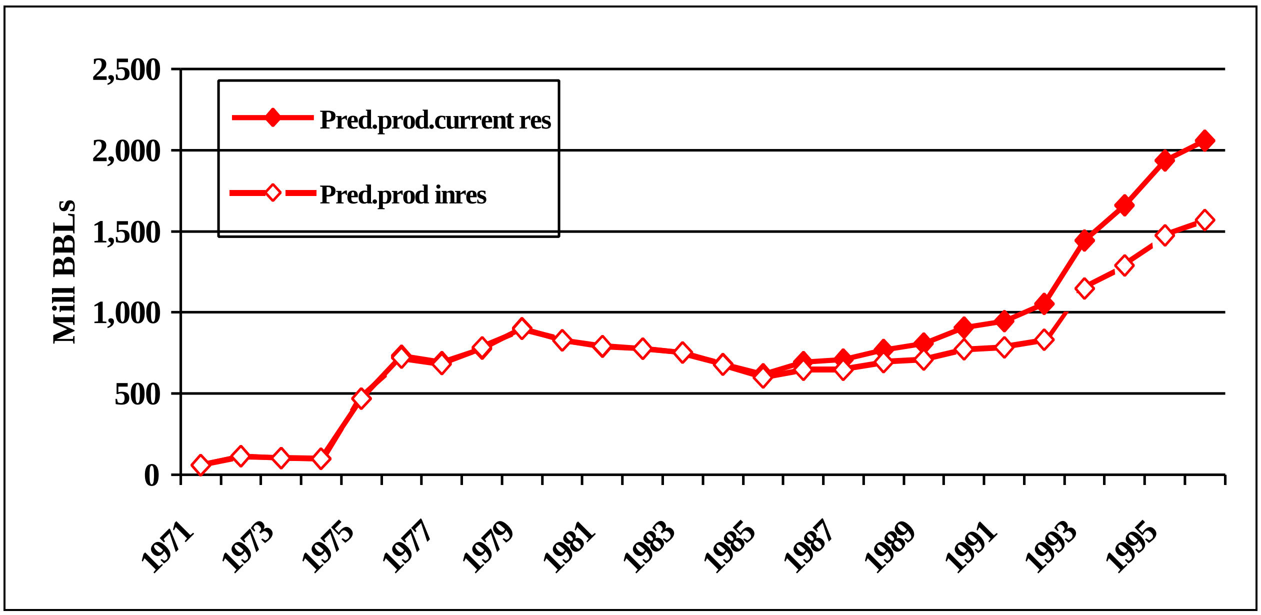
Figure 18: Cumulative Production vs. Reserves, UK



For Norway, total cumulative production is close to 9.5 billion barrels – 2 billion barrels less than the unappreciated reserves. Thanks to the substantial reserve growth that has taken place, 7.5 billion barrels remain. For the UK, cumulative production was 14 billion barrels at the end of 1996, also about 2 billion less than unappreciated reserves, but with appreciation about 5.5 billion barrels remain.

The effect of reserve appreciation on production can be illustrated by assuming that the observed percent of reserves produced at each field would have been maintained but as a fraction of initial reserves instead of the actual appreciated reserves. Figure 19 compares actual production with what may be assumed to have been production without appreciation based on the depletion rates calculated above.

Figure 19: Annual Production - Current and Initial Reserves, North Sea



The difference is around 500 million barrels per year, that is, ¼ of the total production in the North Sea. This difference is not broken down into country specific production in figure 19, but reserve appreciation in the Norwegian sector accounts for 300 million barrels.

The increase in production due to reserve appreciation does not account for the much-predicted, but continually receding peak for North Sea production. Although there are a few fields in which reserve additions subsequent to the start of production cause remaining reserves to be greater than initial reserves, these fields are the exception. As indicated by the depletion and remaining reserve profiles, the average experience of a North Sea field is decline, albeit with a somewhat different profiles, particularly for the large fields. Rather the implication of this analysis is that when new discoveries have been largely exhausted, production will not drop off to zero but stabilize at some level. Of course, the greater the rate of appreciation and the longer the time, the less important are the new discoveries and the less the expected decline in production.

4 Conclusion and Discussion of Future Work

As is observed elsewhere particularly in North America, oil reserves in the North Sea also show positive appreciation over the years. The surprising feature in the North Sea is not the existence of positive reserve appreciation, but the absence of discernible appreciation for medium sized fields, defined here as those with reserves between 100 and 400 million barrels in the first year of production. The explanation for this anomaly eludes us, as well as those to whom we have posed the question. It may of course be nothing more than an anomaly, a low probability sample of the possible medium sized fields that contains a large number of non-appreciating fields.

Other distinctions that are suggested by the data, such as those between the UK and Norwegian sectors, before and after the end of 1985, and before and after peak production, do not stand out with the same salience as the passage of time and initial size. When the data are kept to a high degree of aggregation, the UK and post85 distinctions appear to be significant, but as the universe is more finely divided these distinctions disappear or apply only to certain sub-sets of the data. For instance, only small fields appreciate more rapidly in the UK sector than the Norwegian sector. When size is not distinguished, the large number of small UK fields makes it appear that reserve appreciation is greater in the UK sector, but it is so only for the small fields. Also, the medium fields in both sectors exhibit clearly different behavior before and after 1985, as do the large fields in the Norwegian sector. Greater rates of reserve appreciation are observed in the later period in these instances; however, given the large number of fields in other categories that do not exhibit statistically discernible higher rates in the later period, a firm conclusion on this point cannot be made. What is more firmly established by this analysis is that the norm, excepting the medium sized fields, is for oil reserves to appreciate at a statistically significant 2-3% per annum regardless of sector, year, or age.

The explanation of the anomaly of the medium sized fields remains a puzzle, but a more important research topic is determining the importance of other factors in explaining reserve appreciation. This analysis has been restricted to time related variables, interacted with some other readily observable largely time-invariant factors. Other time-invariant variables may add explanatory power; however, these factors should be captured in the fixed effect coefficients. Moreover, for the one factor we have explored, chalk fields, the distinction does not help. Rather, time varying factors such as the amount of development drilling, injection, prices or perhaps changing tax treatment may contribute to a greater understanding of reserve appreciation in the North Sea.