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GEOLOGICAL SURVEY

Estimates of the ultimate number of oil and gas fields expected to be found in the Minnelusa Play of the Power River Basin, Wyoming

by

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Introduction

The purpose of this study is to devise a methodology for, and forecast of the ultimate volume of oil and gas expected to be found in the Minnelusa play of the Powder River Basin, Wyoming.

The Minnelusa Sandstone Play

The Minnelusa sandstone play, on the broad east flank of the Powder River Basin, describes the occurrence of oil in a suite of primarily stratigraphic traps in the upper part of the Pennsylvanian and Permian Minnelusa formation. Reservoirs are principally quartzose aeolian dune sandstones of Wolfcampian age within a complex cyclic sequence of carbonates and sandstones of marine and non-marine origin.

Some Minnelusa traps are associated with a regional unconformity at the top of the formation. Others are formed by local variations in porosity and permeability related to depositional and diagenetic factors -- particularly of these (Van West, 1972; George, 1984; Fryberger, 1984) (Fig. 1). The play is limited to areas underlain by sandstone reservoirs in the upper part of the Minnesula formation, the "Upper Minnelusa" of industry usage. The oil is believed to derive from dark marine shales in the underlying Desmoinesian sequence (Clayton, 1984). To the south the play appears to be limited by the widespread occurrence of evaporites in the upper part of the Minnelusa in that area and their probable adverse effects on migration and reservoir porosity.

Lack of any large scale structural features within the play, beyond the bounding Black Hills monocline, emphasizes the importance of small scale stratigraphic and structural controls on hydrocarbon entrapment, which are readily documented in detailed studies. The significance of subtle larger paleotectonic features, such as the Belle Fourche Arch of Slack (1981) remains problematic.

The Study Area

For purpose of analysis, the Minnelusa is divided into two parts; one is the region which is moderately or extensively explored; the second is the remaining area which is very lightly explored. Statistical methodology will be applied to the former area while estimation by analogy is used in the latter. This report is concerned with estimates of undiscovered oil and ga fields in the moderately to extensively explored portion of the Minnelusa trend. Figure 2 shows the area of the Powder River Basin in which the Minnelusa Play has been moderately to extensively explored by drilling of wells. The symbols on the figure used to delineate the explored area of the play and a description of the data used to construct the figure are given in Appendix I. A brief description of the program logic used to construct the map is also given in Appendix I. The computer program used was written by David Root.

Description of the Data File

The study is based on 1,710 wildcat wells, beginning with one drilled in 1930 and continuing with those drilled through December, 1981. During this period, 151 oil fields but no gas fields were discovered. They contained 381.5 million barrels of oil (BO) and ranged in size from a few thousand BO to 51.7 million BO in the Raven Creek field, discovered in

March, 1960. Dissolved gas associated with these fields is very small and is not included. The number of wildcat wells and discoveries by year is presented in table 1.

From the results of the geologic analysis, the play was described, geographically delineated, and the boundary digitized to provide a framework for managing and editing stratigraphic, exploration, and geographic data for use in resource assessment studies. Exploratory drill holes were then mapped for the Minnelusa play, using data retrieved from the Well History Control System (WHCS) from a file of over 30,000 exploration and development wells in the basin. There were 1,710 exploratory tests for the Minnelusa play. The data were carefully analyzed to insure that all discovered pools in the Minnelusa play were represented by a single discovery well.

Finally, an example oil and gas field data file was created for the Minnelusa play, using several sources, which summarizes published data for each pool. This file contains information on 151 separate pools discovered through 1981. It characterizes the geologic properties of each reservoir, and it gives size data for pools, which were in part generated or verified by independent extrapolation of ultimate recoveries from production data. Principal sources of field data were PDS, WGA Powder River Basin Field symposium (1981), and state production statistical summaries.

Analysis of the Historical Rates of Discovery

For purposes of analyses the 151 fields discovered through the end of 1981 were partitioned into size classes. The endpoints of each of these class intervals age given in table 2. In figure 3, the graphs of the cumulative discovery curves for oil and gas fields in classes 11 through 15 (the letters 'k' through 'o') reveal that most of these largest fields were discovered very early in the exploration history of the region. (The letter k symbolized the data for field size class 11, l field size class 12,..., onto o for size class 15). For example, all the fields in the four largest class had been discovered by early 1967 when only 727 wildcat wells had been drilled in the region. No fields were discovered in size class 14. This pattern of discovery, in which the largest fields are discovered early, is widely observed in other plays.

The cumulative discovery curve of size class 10 (the letter 'j') at about 300 cumulative wildcat wells begins to show a rollover effect (Fig. 4). The curve remains flat till 600 wells approximately, but then between 600 and 700 wells and again between 1200 and 1300 discoveries occur frequently. The characteristics exhibited in this discovery curve are suggestive of a multiple play. Leasing or other restrictions on drilling can sometimes cause this periodic group of discoveries; however, the form of the discovery curve in class 10 may be due to statistical fluctuation.

By contrast, the cumulative discovery graph for class 9 (0.76×10^6 BO to 1.52×10^6 BO; the letter 'i' in fig. 4) shows that fields of this size are found at relatively even intervals throughout the discovery sequence. It can be deduced from this observation that many more fields of this size remain to be discovered in the study area. Class size 9 is the mode of the distribution of discoveries with 27 fields having been discovered through the end of 1981.

Estimating the Undiscovered Petroleum

Before an estimate of the number of oil and gas fields remaining to be found can be made, a brief digression is made to note that the sudden termination of the discoveries in class sizes 11 through 15 precluded the use of a 'smooth curve' discovery process such as the negative exponential, Arps-Roberts model. For example, in size class 11 (the letter 'k') in figure 3, fields were discovered at a more or less uniform rate through the

15th discovery which occurred in April, 1975, by the 1198th wildcat well. No other discoveries in this class were made during the drilling of 412 additional wildcat wells. Because of the failure to discovery fields in these size classes during this period, we infer that the probability of discoveries of additional fields is very small.

The lack of a well defined asymptotic behavior in the graph for the cumulative discoveries for field size class 10 suggests that a number of fields remain to be discovered in this size class. The nature of the size class 10 data series makes it difficult to obtain statistically meaningful results using an Arps-Roberts type of approach. As an alternative, a negative exponential model was fit to cumulative BO in size classes 10 and greater. The cumulative BO discovered for each 100 wells for classes 10 and greater versus cumulative wildcat wells is plotted in figure 5. The model used to estimate the ultimate volume of BO in these size classes is:

$$U_{10G} = U_w(1 - \exp(-kw))$$

where U_{10G} is ultimate volume of oil expected to be found in size classes greater than or equal to 10 and U_w is the oil found by w wildcat wells in these size classes. The ultimate U_{10G} and k were estimated by NLIN2 (Marquardt, 1963), a nonlinear least squares program and yielded U_{10G} = 361.1 x 10^6 BO. There were 332.8 x 10^6 BO found by 1,710 wildcat wells through the end of 1981. Thus, 28.3 x 10^6 BO is the estimated undiscovered volume of oil in size classes 10 and greater. This BO was assigned to class 10 and resulted in 12.5 additional fields expected to be discovered (12.5 = 28.3/2.26, where 2.26 x 10^6 BO is the average field size of discovered deposits in class 10). A similar type of estimation procedure was used in a study of the Permian basin (pages 22 to 28, USGS, 1980).

The oil and gas remaining to be discovered in the study area is expected to be found in small fields. An estimate of the number of remaining fields is obtained by assuming that the underlying field size distribution follows a Pareto, or that the number of fields in the different size classes has a geometric distribution and that the distribution of discovered fields which appears to be lognormal in shape results from economic truncation. For example, see Drew, Schuenemeyer, and Bawiec (1982), and Schuenemeyer and Drew (1983). For the Minnelusa data it appears that the economic truncation point is between classes 9 and 10 (at approximately 1.52×10^6 BO). As a consequence of economic truncation the numbers of fields in smaller size classes (size class 9 and smaller) have been under reported and thus it is not possible to obtain meaningful estimates in these size classes using standard discovery process estimation techniques.

When sufficient data are available, an estimate of the geometric ratio $r = F_{i-1}/F_i$, where F_i is the ultimate number of fields expected to be found in size class i, is obtained directly. For this study, r = 1.65 was chosen by analogy. In order that the number of fields expected to be found in size class 9 and smaller does not depend exclusively on the estimated ultimate number of fields in size class 10, a smoothed estimate of the F_i (F_i^*) in the larger (non-truncated) size classes is made. To preserve the expected ultimate oil in size classes 10 through 13 set:

$$(\hat{U}_{10G} - \hat{U}_{14G}) = F_{13}^* \sum_{i=10}^{13} \bar{y}_i r^{13-i}$$

where $\hat{U}_{10G} - \hat{U}_{14G} = (361.1 - 51.7) \times 10^6$ BO

$= 309.4 \times 10^6$ BO

the expected ultimate oil in size classes 10 through 13, F_{13}^* is the smoothed estimate for the ultimate number of fields to be found in size class 13, and $\bar{y}_i$ is the mean BO in size class i. (Size classes 14 and 15 were excluded from the smoothing process because they contained only one field.) Solving the preceding equation, yields $F^*_{13} = 6.217 \times 10^6$ BO. Since

$$F^*_{10} = r^{13-10}F^*_{13}$$
$$= 1.65^3 \times 6.217 \times 10^6 \text{ BO}$$
$$= 2.79 \times 10^6 \text{ BO}$$

The smoothed estimates of the ultimate number of deposits expected to be found are computed from the formula

$$F^*_i = r^{(10-i)}F^*_{10},\ i = 6,...9$$

and are given in column 3 of table 3.

A result of this analysis is that 141.5×10^6 BO is estimated to remain to be discovered in the study area in field size class 10 down to and including field size class 6 (95,000 to 3,040,000 BO). About 73 percent of the total amount of oil and gas occurring in the Minnelusa in fields larger than 95,000 BO has been discovered. The oil and gas that remains is forecast to occur in 363.6 expected fields. From table 3, it can be seen that the volume of oil and gas remaining to be found is uniformly distributed through size classes 6 through 10. Forty percent of the BO remaining to be found is expected to occur in the 306.1 smallest fields (those in classes 6 and 7).

References

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Schuenemeyer, J. H., and Drew, L. J., 1983, A procedure to estimate the parent population of the size of oil and gas fields as revealed by a study of economic truncation, Journal of the International Association for Mathematical Geology, v. 15, no. 1, p. 145-161.

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Appendix I

Map Specifications

Date run: 3/15/86 Date file current to: 12/31/83

Name of Province: Powder River Basin

Name of Play or Zone: Minnelusa Play

Name of Computer Data File: Well History Control System

Geographic Coverage: Powder River Basin

Penetrations included: All Permian Minnelusa Formation partial and complete penetrations

Production and shows mapped are from: Permian Minnelusa Formation

Radius used to determine prospective cells: 2.0 miles

Gas Infill Radius: 1.0 miles

Map Legend

<u>Drilled Cells</u>

Dry:

No show

x Oil show

÷ Oil and gas show

- Show: type unknown

Producing:

□ Oil producing

∇ Gas producing

Oil and gas producing

<u>Undrilled Cells</u>

Prospective cells

Cells surrounded on at least 3 sides by oil producing cells in the play or zone (□)

Cells surrounded on at least 3 sides by gas producing cells in the play or zone (∇) or cells added by a gas infill routine

Y Cells surrounded on at least 3 sides by oil and gas producing cells in the play or zone (x, □, ∇)

Explanation of the Program Used to Produce the Map

Grid Cells

The computer program divides the area being mapped into a regular system of cells. The well data is then accumulated into the cell system and the cell status is classified with respect to the several attributes shown in the Legend. The spacing between grid cells is given in the map title; generally it is 1/2 mile, and the area covered by a cell is approximately 1/4 of a square mile. Cell areas vary slightly across the map because the grid system is established as a fraction of a degree at a base latitude.

Dry Cells and Oil and Gas Shows

Dry cells are those cells within which one of the wells that penetrate the play or zone produce oil and/or gas from the play or zone. Because more than one show may be reported for a particular play or zone in a single well or for the same play or zone in different wells within the same grid cell, a show hierarchy is used to rate the show data. The highest rated show is retained in the grid cell data file. If the show type for that show is not reported then the show type for the highest rated show for which the commodity is identified in the cell is stored and mapped. If no show type is reported for any show within the cell for the play or zone being mapped, the show type is identified as unknown. The show rating system from highest to lowest is: Production test, drill stem test, wire line test, core test, and sample test.

Producing Cells

Producing cells are cells that contain at least one producing well that produces oil and/or gas from the play or zone. Producing cells may contain some dry holes.

Undrilled Grid Cells

Cells, identified by special calculation routines, that do not contain wells.

Prospective Cell Routine - The program identifies an undrilled grid cell as prospective when the center of the cell lies inside the convex set of wells that are within a circle of a radius (R).

Dry hole

R

Grid cell

Producing Well

All grid cells with centers inside the triangular area in the figure are identified as prospective.

For the case where the cell is surrounded by three wells the areal drilling density is at least $3/\pi R^2$ wells/square mile. For the rarely-occurring case where the cell center lies on the line connecting only 2 wells the drilling density is at least $2/\pi R^2$ wells/square mile. These maps have been constructed, unless otherwise noted, using a radius of two miles. For a prospective cell with 3 wells inside the 2 mile radius and surrounding the undrilled grid cell, the drilling density is at least 0.24 wells/square mile. For most productive plays the prospective cells, based on a radius of 2 miles, together with the drilled cells, help delineate "exploration fairways(s)" in the play.

Producing Cell Infill Routine - Oil and gas development wells are sometimes spaced more than 1/2 mile apart and, therefore, the distance between producing wells is greater than the grid cell spacing of 1/2 a mile. Two routines in the program identify additional producing cells that do not contain any producing wells. The first routine infills any undrilled cell that is surrounded on at least 3 sides by producing cells in the same play or zone. The commodity identified for these cells is determined by the commodity or commodities produced in the surrounding cells. The second routine, which follows the first routine, infills undrilled gas producing cells not identified by the first routine. The second routine operates in the same way as the prospective cell routine but in this case uses only the gas producing wells in the file. Normally a radius of 1 mile is used to calculate the undrilled gas producing cells.

Drilling Statistics

The drilling statistics are for all wells that penetrate the play zone. Care should be exercised in using these data because they may include data for plays or zones that underlie the play or zone being mapped.

Table 1.--Drilling and discovery data by year.

Year	Wells	Cumulative Wells	Number of Discoveries	Year	Wells	Cumulative Wells	Number of Discoveries
1941	1	1	0	1964	85	498	6
				65	107	605	11
48	2	3	1	66	104	709	16
49	2	5	0	67	90	799	10
50	2	7	0	68	69	868	2
51	2	9	0	69	60	928	4
52	5	14	0	70	34	962	2
53	3	17	1	71	25	987	2
54	3	20	0	72	44	1031	9
55	6	26	0	73	73	1104	5
56	4	30	0	74	69	1173	6
57	7	37	1	75	60	1233	7
58	9	46	2	76	39	1272	3
59	25	71	2	77	42	1314	2
60	48	119	5	78	95	1409	4
61	62	181	5	79	62	1471	7
62	108	289	8	80	95	1566	8
63	124	413	11	81	144	1710	11

Table 2.--Description of deposit-size class

Class	Size range[1]
1	0 to 0.006
2	.006 to .012
3	.012 to .024
4	.024 to .047
5	.047 to .095
6	.095 to .19
7	.19 to .38
8	.38 to .76
9	.76 to 1.52
10	1.52 to 3.04
11	3.04 to 6.07
12	6.07 to 12.14
13	12.14 to 24.3
14	24.3 to 48.6
15	48.6 to 97.2

Table 3.--Summary data and estimates of the ultimate number of oil and gas fields by class size and contained resources for the Minnelusa trend.

Size class	Number of fields found by 1,710 wildcat wells	Expected ultimate number of fields to be found	Expected total ultimate resource (BO x 10^6)	Expected remaining resource (BO x 10^6)	Percent of total resource remaining
6	10	206.8*	30.0	28.5	20.1
7	16	125.3*	32.2	28.1	19.9
8	17	76.3*	43.8	34.0	24.0
9	27	46.0*	54.7	22.6	16.0
10	14	26.5	59.9	28.3	20.0
11	15	15	58.5	0.0	0
12	12	12	96.7	0.0	0
13	6	6	94.2	0.0	0
14	0	0	0	0.0	0
15	1	1	51.7	0.0	0
	151	514.6	521.7	141.5	100.0

*Smoothed estimate F_0^* using r = 1.65.

DIAGRAMMATIC SECTION ILLUSTRATING SEVERAL TRAPPING MECHANISMS IN THE MINNELUSA FORMATION

FIELD EXAMPLES NOT GEOGRAPHICALLY LOCATED

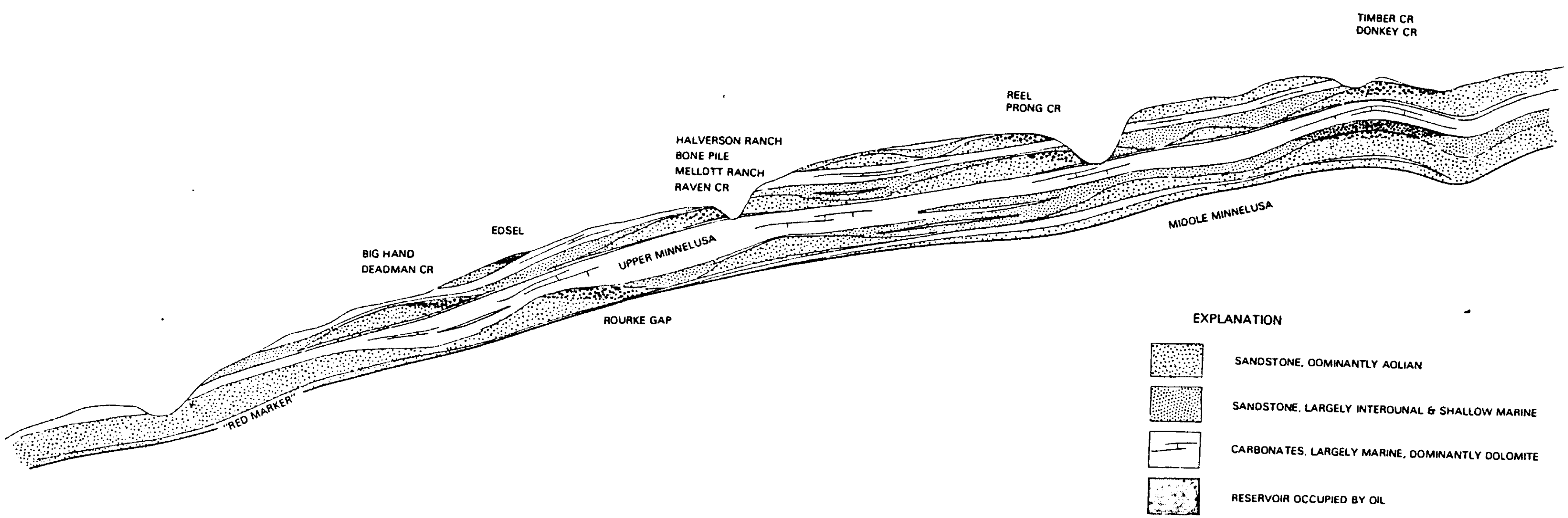

Figure 1

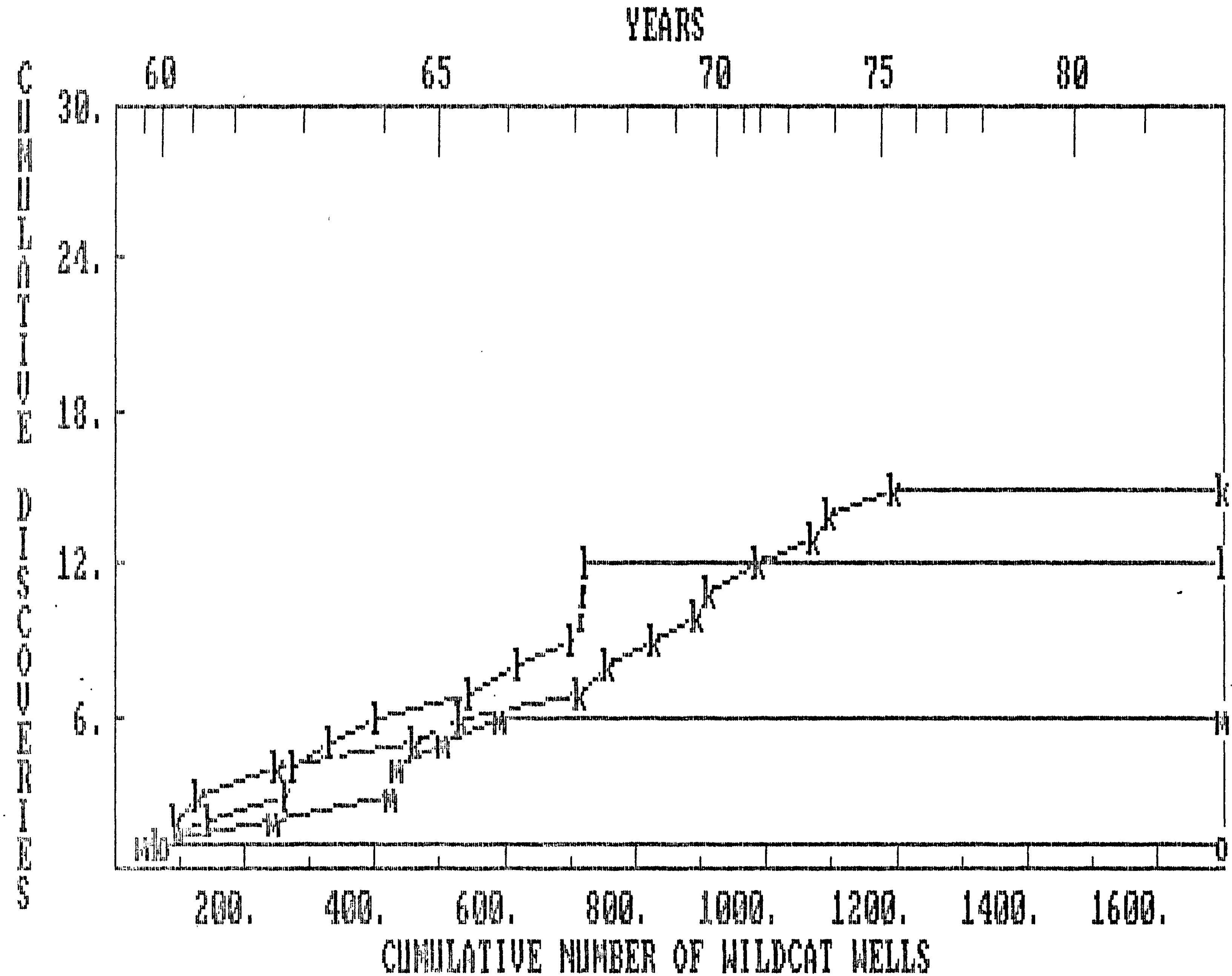

Figure 3. Cumulative number of oil fields discovered by December 31, 1981 in size classes 11 through 15 in the Minnelusa Play.

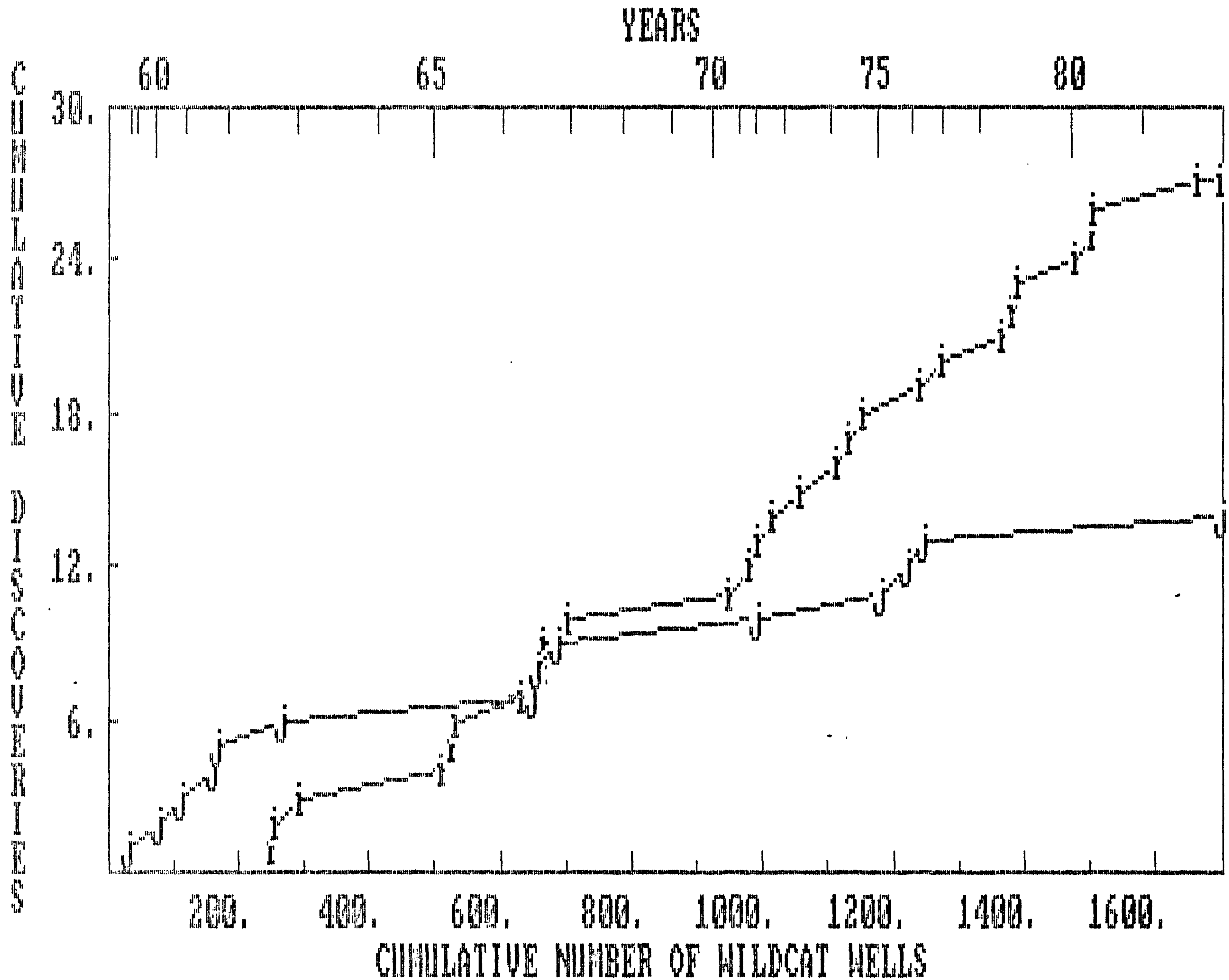

Figure 4. Cumulative number of oil fields discovered by December 31, 1981 in size classes 9 and 10 in the Minnelusa Play.

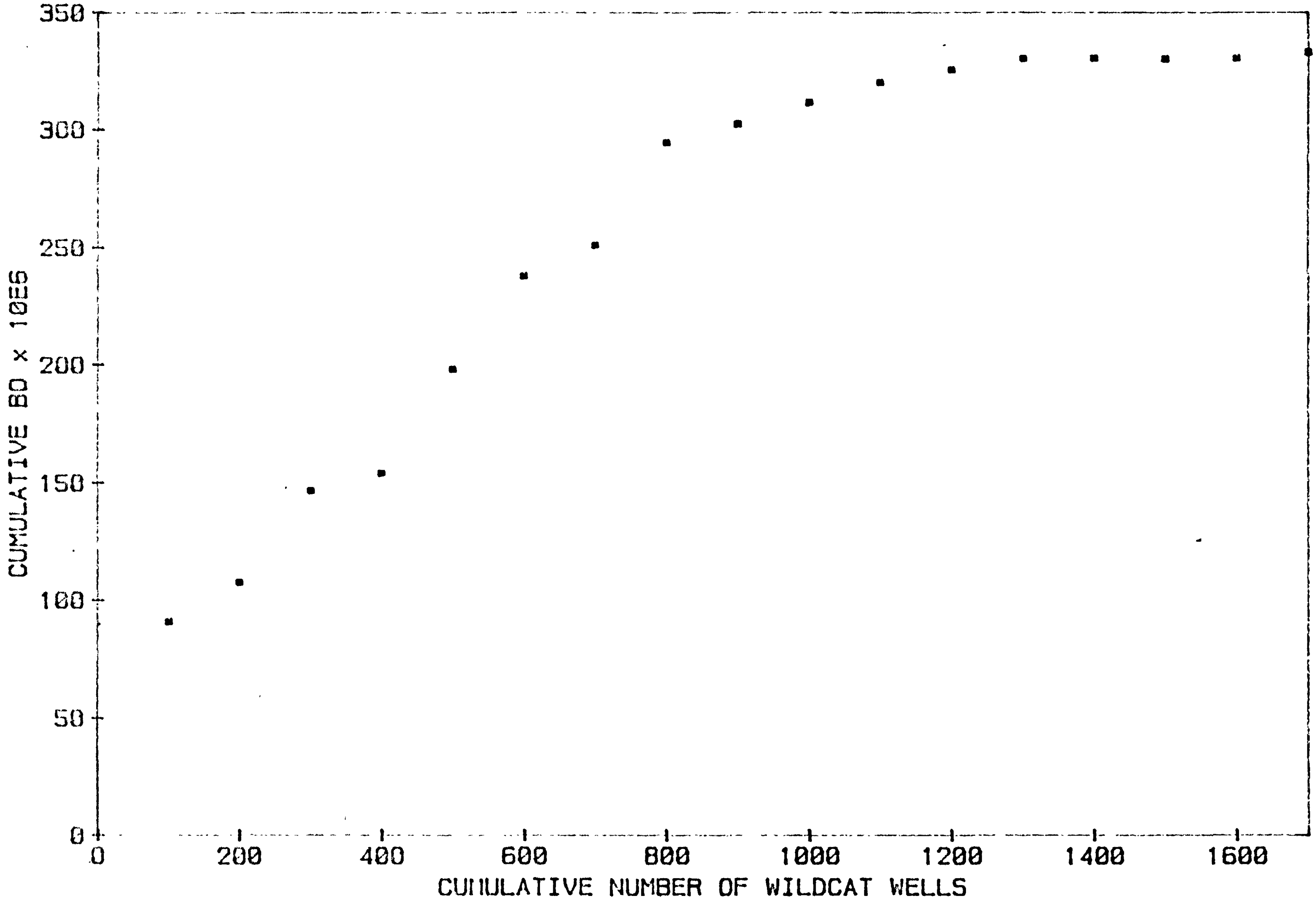

Figure 5. Cumulative volume of oil discovered by December 31, 1981 in size classes 10 through 14 in the Minnelusa Play.