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Estimating the Gas Drainage Patterns of Western Tight Sand Reservoirs

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ABSTRACT

This document describes a method of estimating the gas drainage patterns of tight sand gas reservoirs. The method allows the placement of gas wells within a reservoir so that the likelihood of wells competing for the available gas is minimized.

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PREFACE

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Introduction

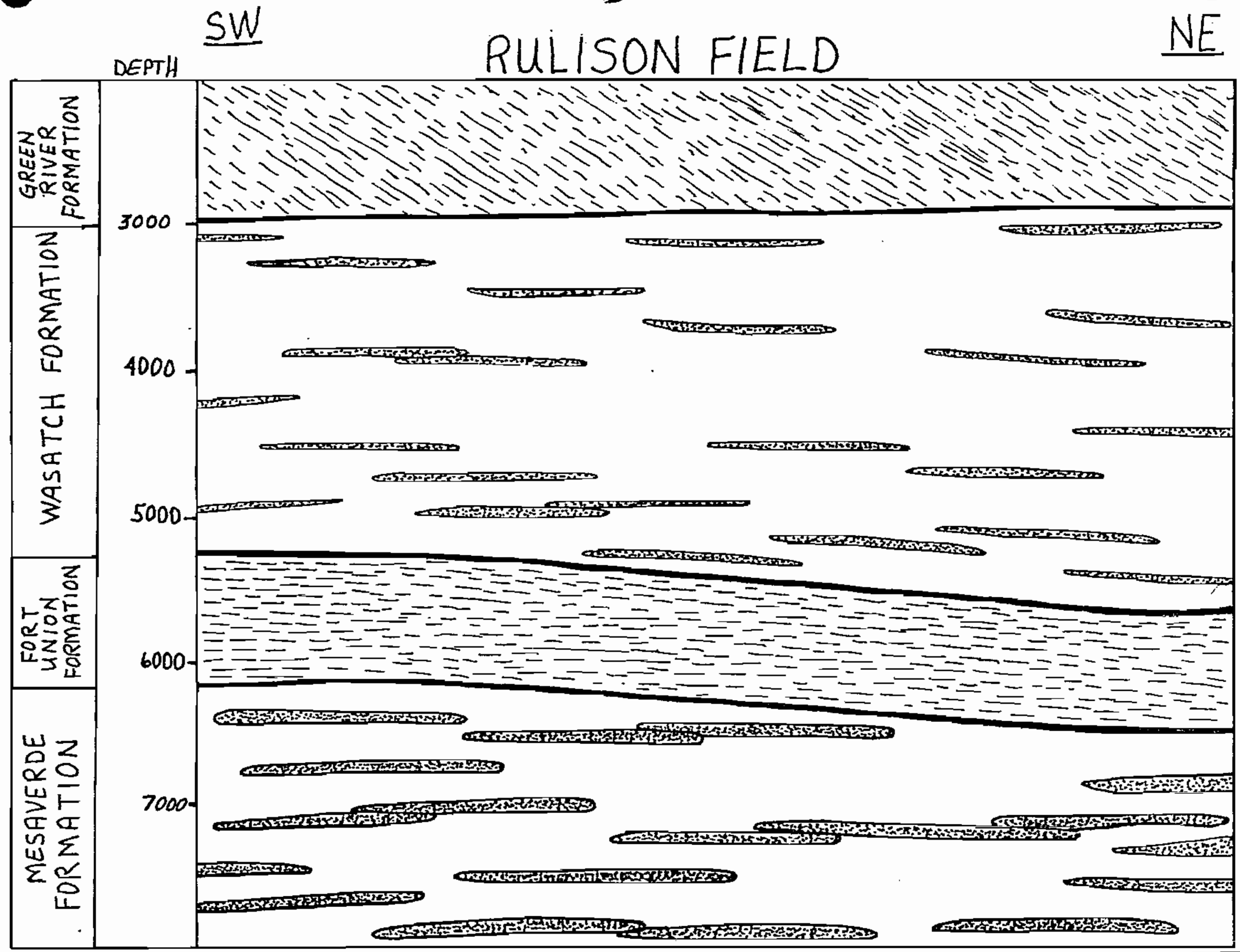
Because of the structure of western tight sand formations, the gas-drainage patterns of these basins are likely to differ from the patterns observed in more conventional gas reservoirs. Unlike the fairly homogeneous rock structure of the conventional gas reservoir, the tight sand formations consist of gas bearing sand lenses distributed throughout a shale matrix (1) (figure 1). The gas is trapped in the sand lenses by the surrounding shale. In this study I assume that the gas flows only through the sand lenses. It is possible that fractures in the shale will allow gas flow between the lenses; however, since the sandstone is denser than the surrounding shale, the fractures will tend to move through the medium of least resistance, the shale (2). Thus, only sand "lense clusters" through which the well bore passes can be drained. A lense cluster is a group of one or more intersecting sand lenses.

Given that no significant flow of gas occurs outside the sand lenses, the gas-drainage patterns of a well will be defined by the orientation, size, and shape of the tapped sand lense clusters. By obtaining reliable estimates of these sand lense dispositional properties, a minimum error estimate of the gas-drainage patterns of a western tight sand field can be calculated. By identifying the specific area a well is draining, a maximum production well spacing pattern can be developed. An effective well spacing pattern would reduce the number of lense clusters being tapped by more than one well, and increase the number of independent lense clusters tapped per well drilled. Thereby, gas production efficiency increases. The methods used in this study to calculate a minimum error estimate of the gas-drainage patterns for a western tight gas sand field can be used to estimate the drainage patterns of other tight sand gas fields.

Methods

In this study, we estimate gas-drainage patterns of two tight gas sand formations, the Wasatch and Mesaverde Formations in the Rulison Field of southwestern Colorado (figure 2). Since it is often difficult to measure the specific properties of a reservoir that lies 5,000 feet beneath the surface, the parameters of a reservoir must often be estimated. This study assumes that the size, shape, and orientation patterns are the same as the values measured in an outcrop study by Knutson (1 and 2). This study analyzed nearby outcroppings (figure 3) of the Wasatch, Mesaverde, and other tight sand formations. The data reported in these outcrop studies, as well as the reported mean net production interval and the estimated average size of the drainage area in the Rulison Field (3), are used to calculate a minimum error estimate of the extent and shape of the Wasatch and Mesaverde Formations well-drainage patterns.

Mr. Knutson reports separately the typical sand lense dimensions observed in the Mesaverde Formation. The observed average length/width/height ratio for the Mesaverde sand lenses is 140:14:1 (1). The Wasatch Formations lense sizes were not reported separately, and consequently had to be estimated from limited data. He reported that the mean length to width to height ratios of the Wasatch were larger than the same mean Mesaverde ratios. However, the number of Wasatch samples measured were too few to conclude that the observed Wasatch



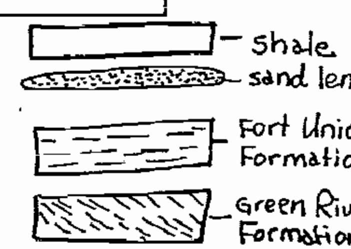


Figure 1. Schematic cross section of Western Tight Sand Formations

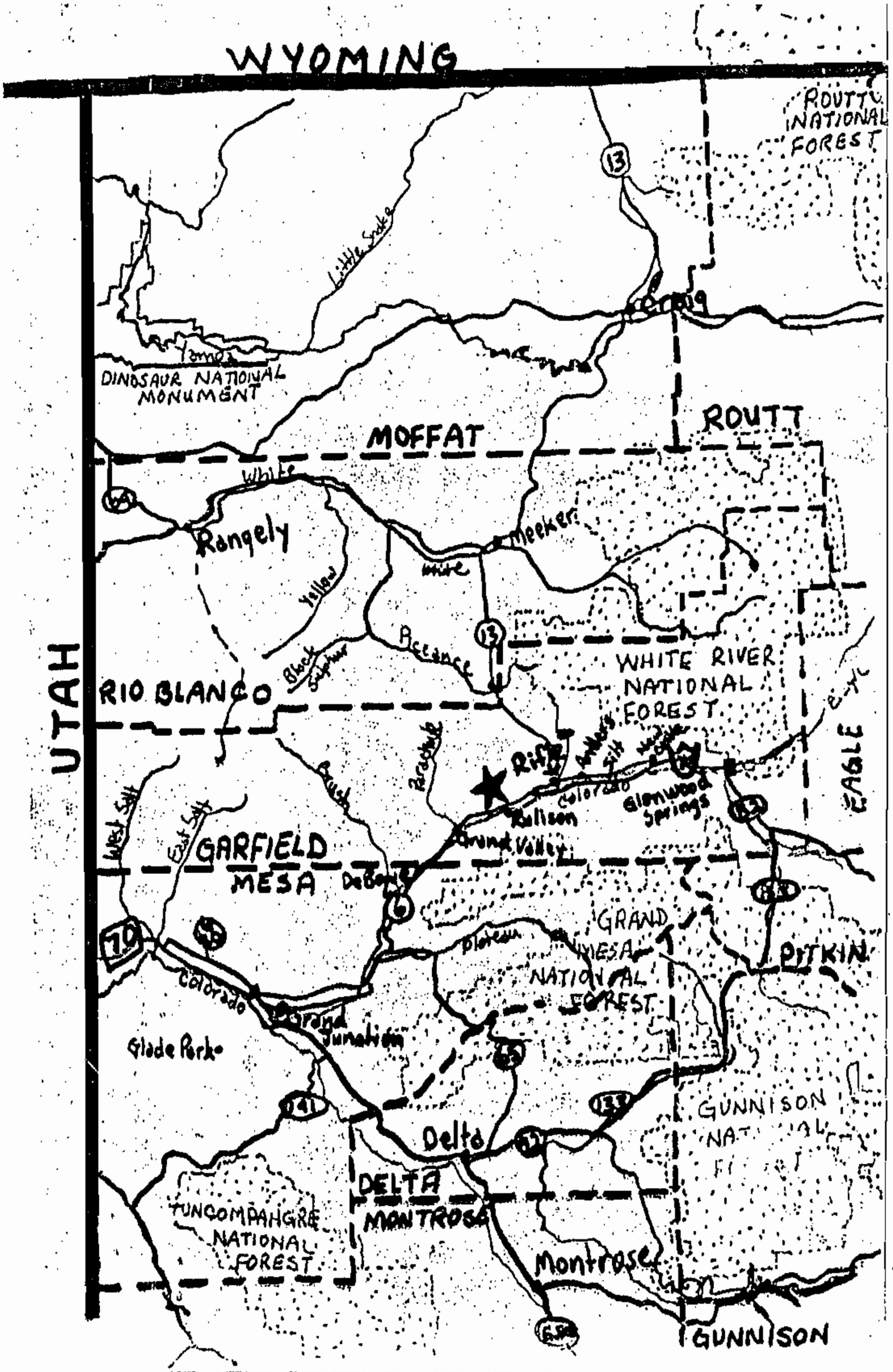


Figure 2. Location of Rulison Field (★), Colorado

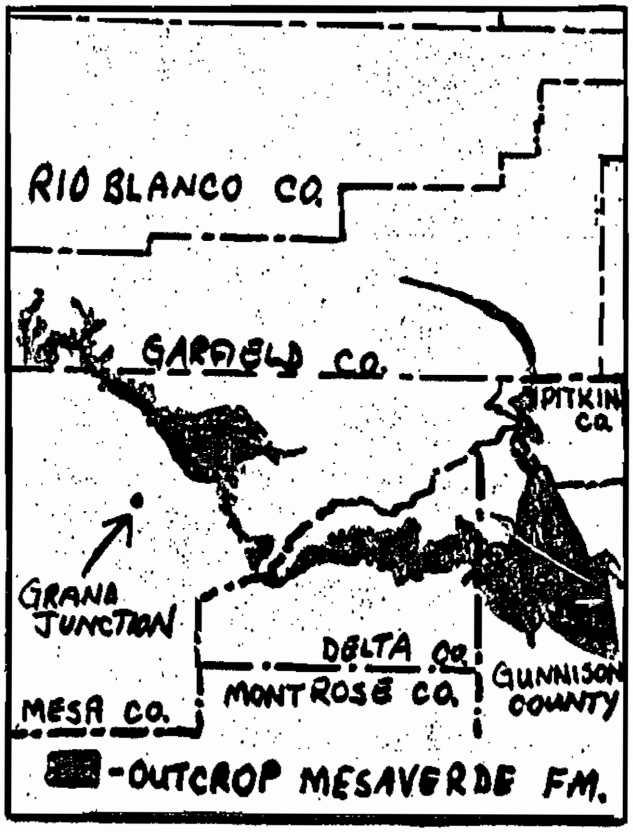


Figure 3. Colorado regional map showing outcrop area used in study of Mesaverde Formation by C.F. Knutson

lenses were larger than the Mesaverde lenses when tested at the 95 percent confidence level. Mean reservoir sand lense length/height ratios as large as 250 to 1 have been observed (2). A 190:19:1 dimension ratio (length/width/height) was selected for the Wasatch lenses in this study. (The sensitivity of this analytical method to these dimensions or any of the other parameters used to estimate the well-drainage patterns is not known at this time.) Knutson reports that the measured lenses in the outcrops had thickness values ranging from 10 to less than 30 feet (1). The average reported net production interval, the total producing sand that the well hole vertically intersects, is 65 feet for the Wasatch wells in the Rulison Field. Using these reported values, the range of lense thicknesses and the producing sand interval intersected by a well, gives us the most likely number of lenses per well as shown in table 1.

Table 1. Probable Wasatch lense thickness/
Number of lense combinations

Lense thickness (feet)	Number of lenses** per well	Estimated lense surface area* (acres)
10	6	9
13	5	15
16	4	20
21	3	36
30	2	91

* Assuming a 190:19:1 ratio
** 65 feet/lense thickness

The Wasatch gas wells are draining approximately 28 acres, with a maximum of 40 acres (3). Because the well can drain only an intersected lense cluster, and because three and four lense intersections per well approximate the observed drainage area, either number would be reasonable. I choose three. The typical lenses are constructed, as reported in table 2, by the estimated length/width/height ratios, and height values.

Table 2. Typical lense dimension

Formation	Length (feet)	Height (feet)	Thickness (feet)
Mesaverde	3,500	350	25
Wasatch	4,000	400	21

In the Mesaverde with lense thicknesses of 25 feet (1) and an average net production interval of 180 feet, the number of separate lense clusters that a well intersects would be approximately seven. The estimation of the percent of the formations' sand lense volume may be simplified by conceptualizing either formation as a series of flattened boxes, each as deep as the lense thickness (figure 4). The estimated percent of lenses per a lense-thickness slab are shown in table 3.

Table 3. Percent of sand lense per formation

Formation	Mean lense clusters/well	Net pay (feet)	Formation thickness (feet)	Percent of sand lense/slab*
Wasatch	3	65	1,228	5.3
Mesaverde	7	180	1,286	14.0

* Net pay/formation thickness x 100

Mr. Knutson estimated the percent of lense surface per plane of the Mesaverde Formation as 30 percent. The discrepancies between the two estimates may be because some lenses are not gas productive, or may be because of differences between the outcrop area and the Rulison Field. The value used in this study, 22 percent, is the mean of the two estimates.

The percentage of sand lenses and an assumption of uniform dispersion of lenses throughout the basin provide an estimate of the probability of a sand lense occurring within a basin plane. Therefore, the estimated probabilities that a given surface point of a slab will contain a lense are: 1 in 20 (.05) for a 21-foot slab in the Wasatch, and 4 in 20 (.22) for a 25-foot slab in the Mesaverde. The estimates of the percentage of sand surface area of each lense thickness slab cannot be used to calculate directly the number of lenses within the Rulison Field Formations because of the lost sand lenses surface area when the sand lenses overlay. The number of lense overlays and the resultant loss of surface area must be estimated to ascertain their effect on the area values. Then the number of lenses in each formation can be calculated. To simplify the calculations, all lenses are treated as rectangles with average sand lense length, width, and height values. By dividing the plane into small grids with each grid equally likely to contain a lense midpoint (figure 5), a vast number of possible reservoir layouts can be created. The simulated reservoir models must use the relative reservoir and lense sizes, and the surface area must have the correct percentages of sand lenses and shale. The reservoir constraints and relative sizes of the lenses were computerized and the midpoint locations of the lenses were randomly generated with a uniform distribution. The number of lense overlays, or clusters, and the number of lenses per cluster were counted in each reservoir model created. This procedure, commonly called a monte carlo simulation, produced, on the average, the number of lenses per cluster in the Mesaverde and Wasatch Formations that are listed in table 4.

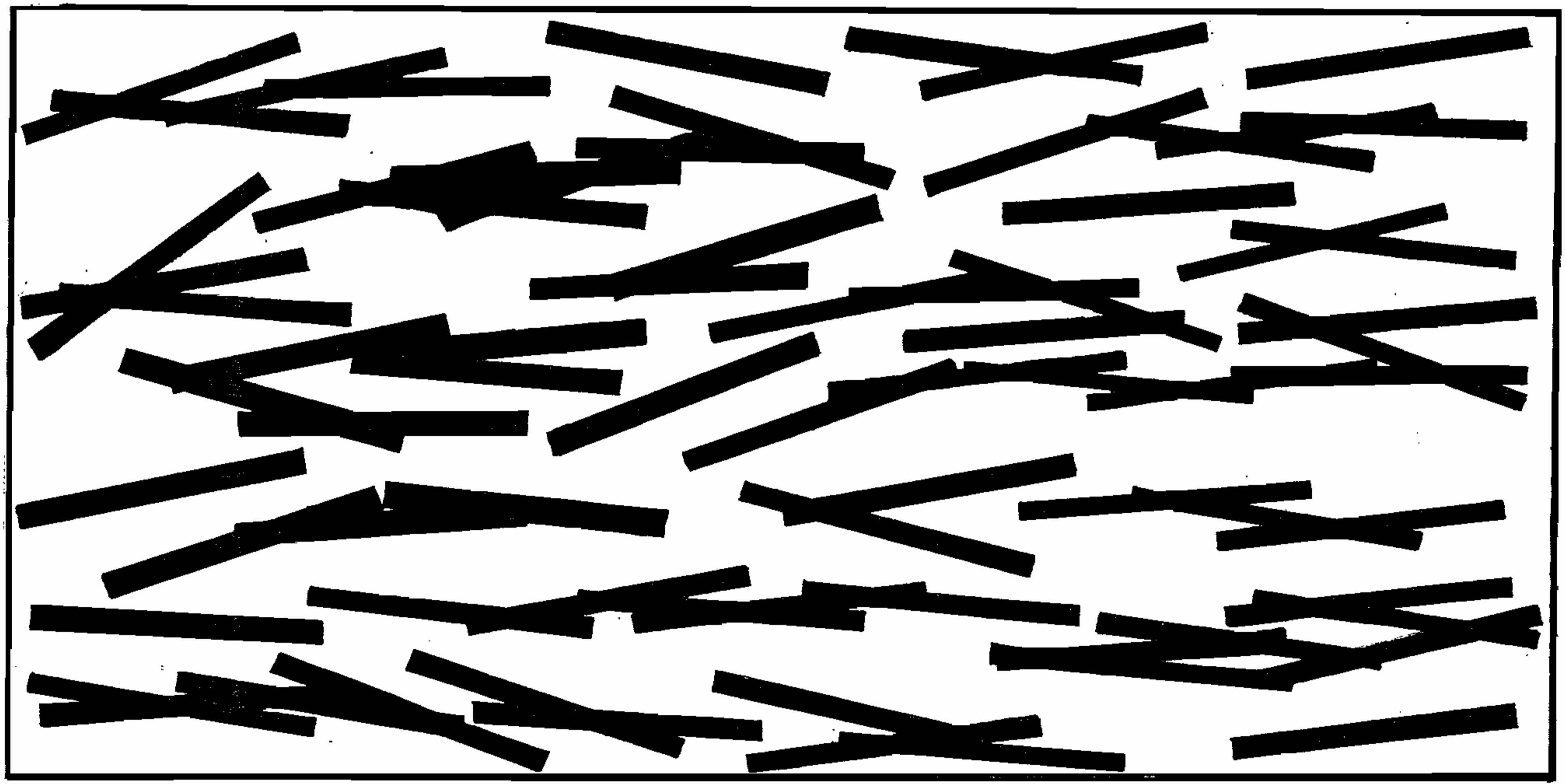


Figure 4. Aerial view of the flattened lense - thickness slab of the Mesaverde Formation

(Area is approximately 4 miles by 2 miles.)

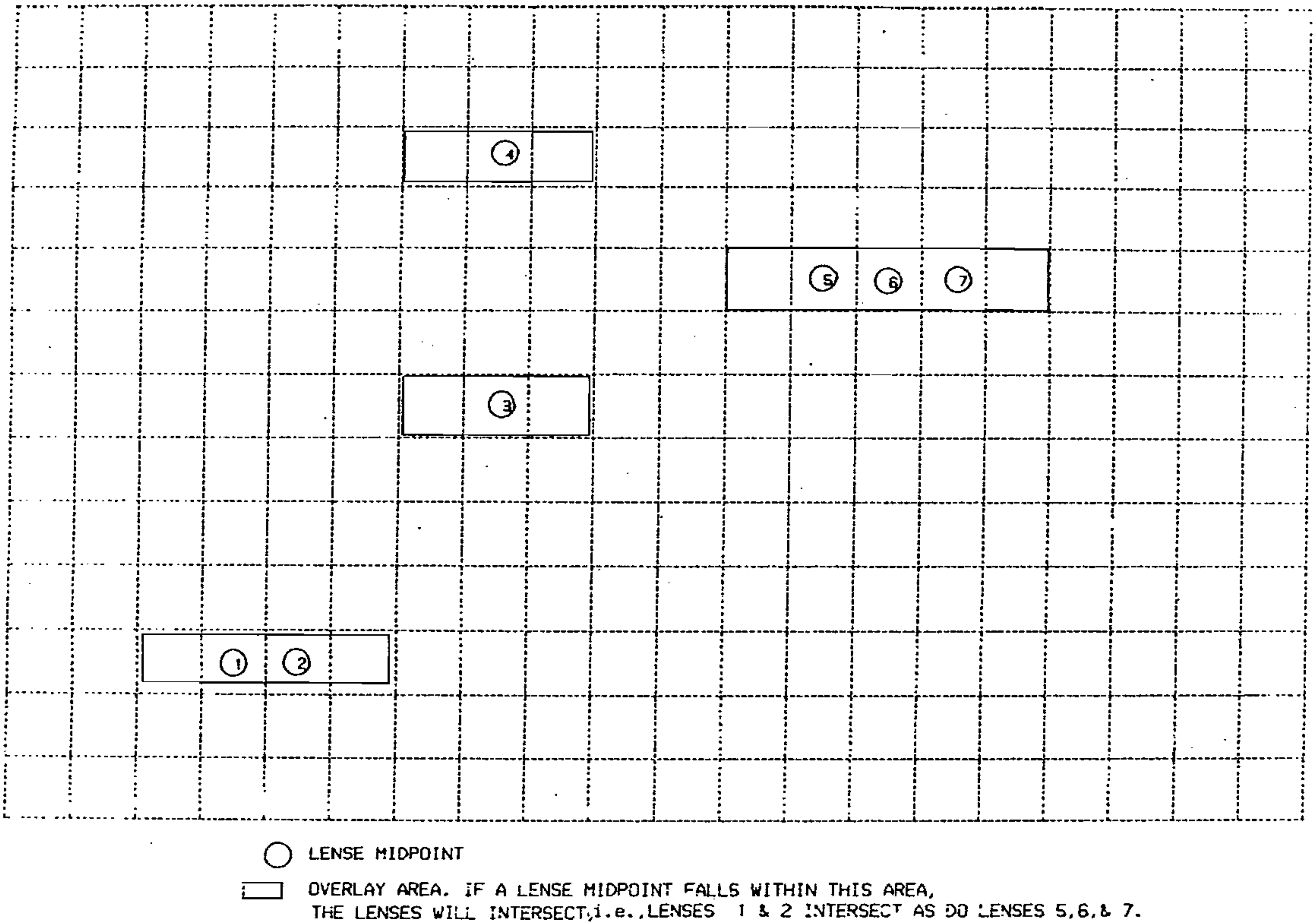


Figure 5. Grid of reservoir plan showing possible lense cluster overlay areas

Table 4. Probability distribution of lenses per cluster

Formation	Number of lenses per cluster	Probability (Mean)
Wasatch	1	.81
	2	.17
	3	.02
Mesaverde	1	.29
	2	.17
	3	.15
	4	.15
	5	.13
	6	.10
	7	.03

The monte carlo runs placed an average of 37 lenses per 5-square-mile plane in the Mesaverde shale while the Wasatch averaged six lenses per 5-square-mile plane.

Because of the typical rectangular shape of the lenses, the length orientation will dominate the direction of the well "drainage extensions." The drainage extension is the maximum distance the gas flows from the reservoir to the well bore in a given direction. The orientations of the sand lense lengths were also measured and reported in the Knutson outcrop study. The orientations are the measured compass directions of the length dimension in degrees clockwise from true north. As before, the Mesaverde values were reported separately, and the Wasatch values were not. Table 5 lists the lense orientations. Both the Mesaverde lense orientations and the "all other" lense orientations appear to have a dominant south-easterly direction. Fifty-one percent of the Mesaverde lenses are in the 130 to 140 degree category, and 82 percent of the other group are in the 130 to 160 degree category. The "all other"-group lenses were used for the Wasatch Formation values.

Table 5-A. Mesaverde lense orientations

Length orientation (degrees)	Number	Applied* orientation	Applied probability
65	3		
90	1	100	.04
110	25	110	.28
120	1	120	.01
130	18	130	.27
140	5	140	.24
145	23		
150	1	150	.14
160	2	160	.02

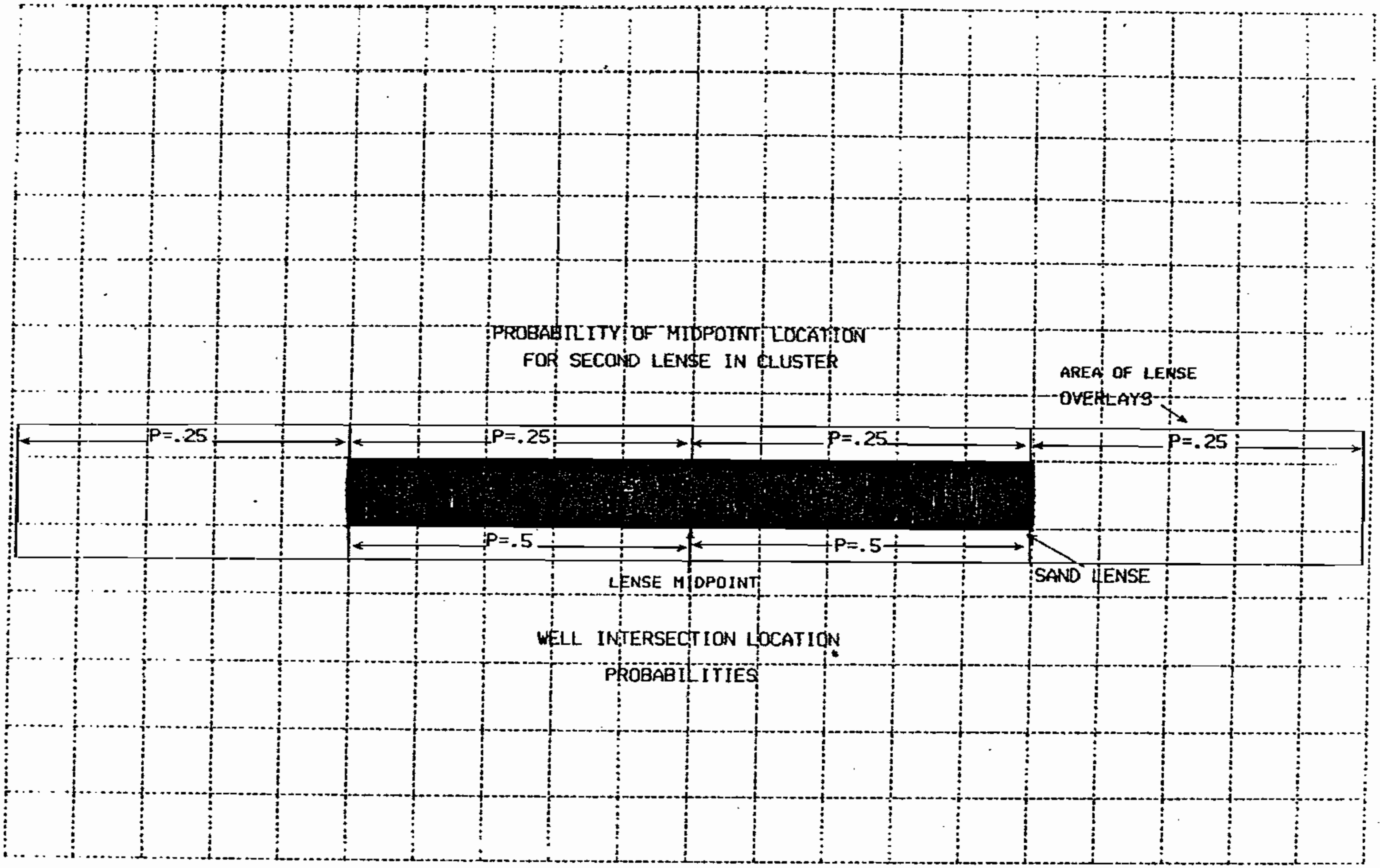
Table 5-B. All other lense orientations

Length orientation (degrees)	Number	Applied orientation	Applied probability
70	150	70	.14
100	14		
105	15		
125	55	120	.04
130	285	130	.31
135	45		
140	55	140	.12
145	95		
150	60	150	.14
155	75		
160	165	160	.24
165	60		

* "Applied" values are the values used in this study

The information necessary to define the extent and direction of a single-lense is now available: If a single-lense is intersected by the well bore, then the point of intersection is equally likely at all lense surface points. The minimum error estimate of the intersection point is the center of the lense. The probability of the well hole going through the exact center of the lense is quite small, but by choosing the center as the hypothetical intersection, the distance between the actual intersection and the hypothetical intersection is minimized. The average extension from the well bore will be equal on either side of a single lense. Thus, in the Mesaverde, the minimum error distance of gas flow to the well will be 1,750 feet; in the wasatch the distance will be 2,000 feet, half the lense lengths. Therefore, a single-lense would extend half the length of the lense in both the direction of the lense orientation, and in the orientation direction plus 180 degrees. If another lense intersected the lense touching the well bore, the second lense's midpoint would be as likely to reside at any point on either side of the first lense's midpoint, or in any point within the first lense (figure 6). If the second lense had the same orientation as the first, then half of the time the lense cluster would extend half the length of the second lense in the orientation direction, and half the time the extension would be in the opposite direction. The minimum error extension of the second lense is one fourth the typical lense length. Each extension length (with equal orientations) will add the following amount to the distance the well drainage extends from the well: the product of .5 raised to the Ith power and the original lense length, where I is the Ith lense in the cluster; i.e., $(.5)^I$ x lense length. However, the likelihood of a number of lenses all having the same "transport" direction is small. The effects of multiple transport angles must be included in the analysis because of the high probability of this occurrence. Two sides, both lense extensions, and an angle of an imaginary triangle are known (figure 7); by applying the Law of Cosines, the length of the third side can be calculated. This third side of the triangle would be the total length that the two lenses extend from the well.

As the number of lenses in a cluster increases, the number of extension angles will increase and the "residence arc" of the lense tip will change. The position of each end of each lense is calculated to the nearest five degrees; this area is referred to as the residence arc and encompasses a ten degree cone moving out from the well bore (figure 8). The residence arc of all possible extension angles (to the nearest five degrees) is calculated by tracking the movement of the lense tip on the circumference of a circle with a radius equal to the current extension length. (To reduce the number of calculations, equal-angle transport arc extension lengths were used as estimates of the radius length.) This distance is equal to the length of a line perpendicular to the third side (the extension length) of the triangle which passes through the end point of the extension length and through the extended previous residence angle (figure 9). Two angles and a side are known; therefore, the distance that the end of the lense moves can be calculated by applying the Law of Sines. The overall effect on the residence arc of increasing the number of sand lenses in a cluster is to increase the probability of a lense group residing in the center residence arcs, and to decrease the likelihood of the lense residing in the extreme arcs.



Note: the lense overlay area is the area in which a lense overlay would occur if the area contained a lense midpoint.

Figure 6. Graphic conceptualization of lense overlay probabilities and well intersection location probabilities.

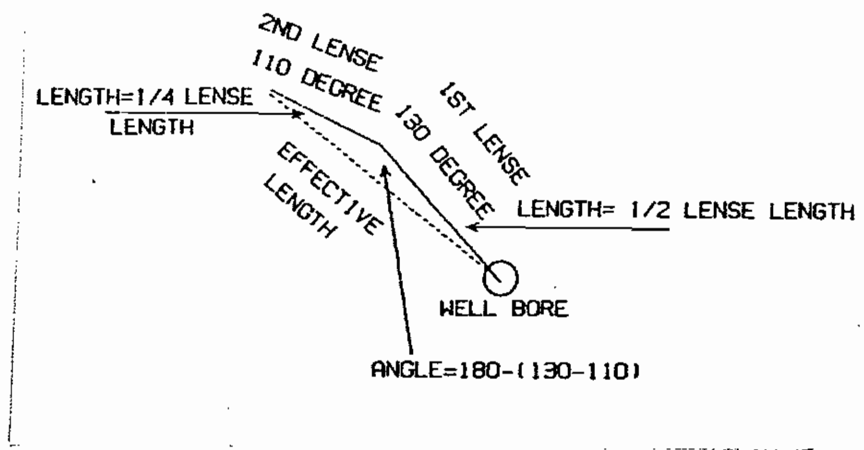


Figure 7. Calculation for length of lense cluster extension

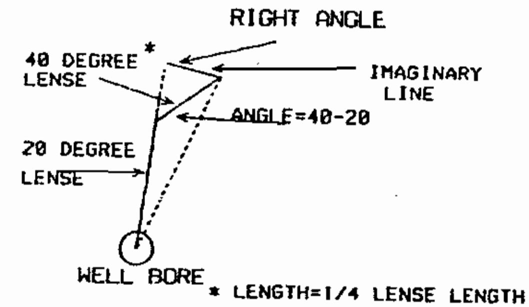


Figure 9. Calculation for residence placement of lense cluster

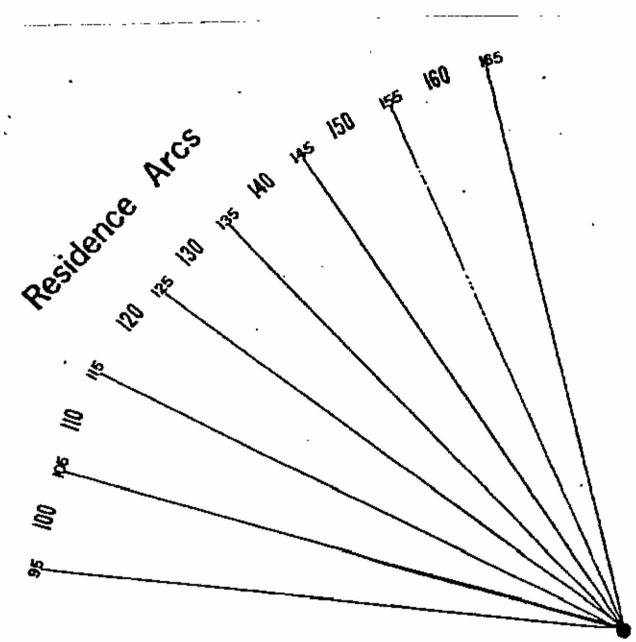


Figure 8. Example of residence arcs

Table 6. Probability distribution of lense cluster location

Residence arc	Probability of lense in arc	
	One lense	Two lenses
100	.08	.03
110	.32	.17
120	.01	.31
130	.23	.20
140	.19	.24
150	.14	.05
160	.03	.01

With the information we have gathered or derived, we can now calculate directly the estimates of the lense cluster lengths, the number of lenses per lense cluster, and the direction and resultant final placement of any lense extension. An estimate of a well's drainage pattern can now be calculated by using the expected extent of the lense in each residence arc. Even when using only mean lense extension values, and ten degree transport arc categories, there are numerous cluster configurations (258 in the Wasatch, and 960,799 in the Mesaverde). Each of these possible configurations has a calculable probability of occurrence, the sum of which must equal one. That is, if a well intersects a lense cluster, then the lense cluster must be one of the possible combinations. The "sum=1" lets us check the accuracy of the probability estimates, and allows us to estimate the expected value of the length extension into a given residence arc by calculating the weighted average of the lense configuration. The probability of a specified lense cluster occurring is equal to the product of the probability of the cluster containing n lenses and the probability of each lense orientation. (The probability of both X and Y occurring is equal to the probability of X times the probability of Y (4)). For example, the likelihood of a lense cluster in the Mesaverde Formation containing three lenses, with two of them having an orientation of 130 degrees and one having an orientation of 140 degrees is calculated as follows:

.15 (the probability of three lenses)
x.24 x.24 (the probability of 130 degrees)
x.19 (the probability of a 140 degree orientation)

This product equals .0109. The probability of an orientation combination of three 160 degrees lenses would be .15 x.04 x.04 x.04 or .0000096, or approximately 1 per 100 thousand lense clusters. Since the mean equals the sum of all observations divided by the number of observations, the mean also equals the sum of each observation divided by n (the weighted average); i.e., mean = ((n1+n2+n3+...+n999)/999) = n1/999+n2/999+...+n999/999. In this study the weighted average is calculated within each residence arc. It is the sum of the products of the expected lense length for each number of lenses per cluster, times the probability of the lense cluster containing a particular number of lenses, given that the cluster resides in the residence arc. The probability of the number of lenses in a cluster is equal to:

1. The sum of the probabilities of all lense configurations that reside in a residence arc with a particular number of lenses, times the likelihood of that number of lenses occurring (table 5).

2. This quantity is divided by the sum of these quantities when calculated for all likely numbers of lenses per cluster.

Table 7. Values for calculating the expected lense cluster extension for a given residence arc

Table 7-A. Wasatch formation

Residence Arc		Number lenses in cluster	Weighted average length[1] (feet) (WAL)	Probability of cluster number in residence[2] (P(Res))	Weighted contribution (feet) (WAL x P(Res))
160		1	2000	.92	1840
		2	2996	.08	239
		3	3471	.01	35
	Expected Extension				2114
150		1	2000	.73	1460
		2	2945	.24	707
		3	3421	.03	103
	Expected Extension				2270
140		1	2000	.68	1360
		2	2954	.29	856
		3	3436	.03	103
	Expected Extension				2319
130		1	2000	.89	1780
		2	2997	.10	298
		3	3437	.01	34
	Expected Extension				2112
120		1	2000	.93	1860
		2	2985	.07	208
		3	3482	.003	10
	Expected Extension				2078
70		1	2000	.97	1941
		2	3000	.03	90
		3	3500	.000	0
					2031

[1] The weighted average of the lengths that fall within a residence arc, given that the number of clusters occurs.

[2] Probability of the number of lenses in a cluster (table 5) times the probability that that number of lenses per cluster resides in the residence arc.

For example, in the Wasatch Formation (table 7-a.), in the 160 arc calculation, 8 percent of one-lense clusters will reside in residence arc 160, and occur 81 percent (table 4) of the time. Two-lense clusters reside in arc 160 3.2 percent of the time and occur 17 percent of the time. Three-lense clusters reside in arc 160 1.4 percent of the time and occur 2 percent of the time.

The one-lense product (.81 x .08) is .06, the two-lense product is .005, and the three-lense product is .00028. The likelihood of a cluster containing one lense, given that it resides in the 160 residence arc, is then .06/(.06+.005+.00028), which is equal to .92. The expected or average length is simply the sum of the probabilities of a configuration occurring, times the extension length (pages 11 and 12), divided by the sum of the extension length probabilities. This value is equivalent to the weighted average length for each number of lenses per cluster. Thus, the one-lense clusters are all equal to the weighted average of one lense extension (2000 feet), the expected extension length of a single lense.

Table 7-B. Mesaverde formation*

Residence arc	Expected length (feet)
160	1871
150	2317
140	2638
130	2650
120	2918
110	2447
100	2183

* The contribution of the fourth through the seventh lense was estimated as 116 feet for all arcs. The probabilities of a residence arc were assumed to remain constant.

By calculating the weighted average of each residence arc, a minimum-area drainage area can be constructed (figure 10). The tear-shape pattern extending in each direction is the result of the middling tendency as the number of lenses in a cluster increases.

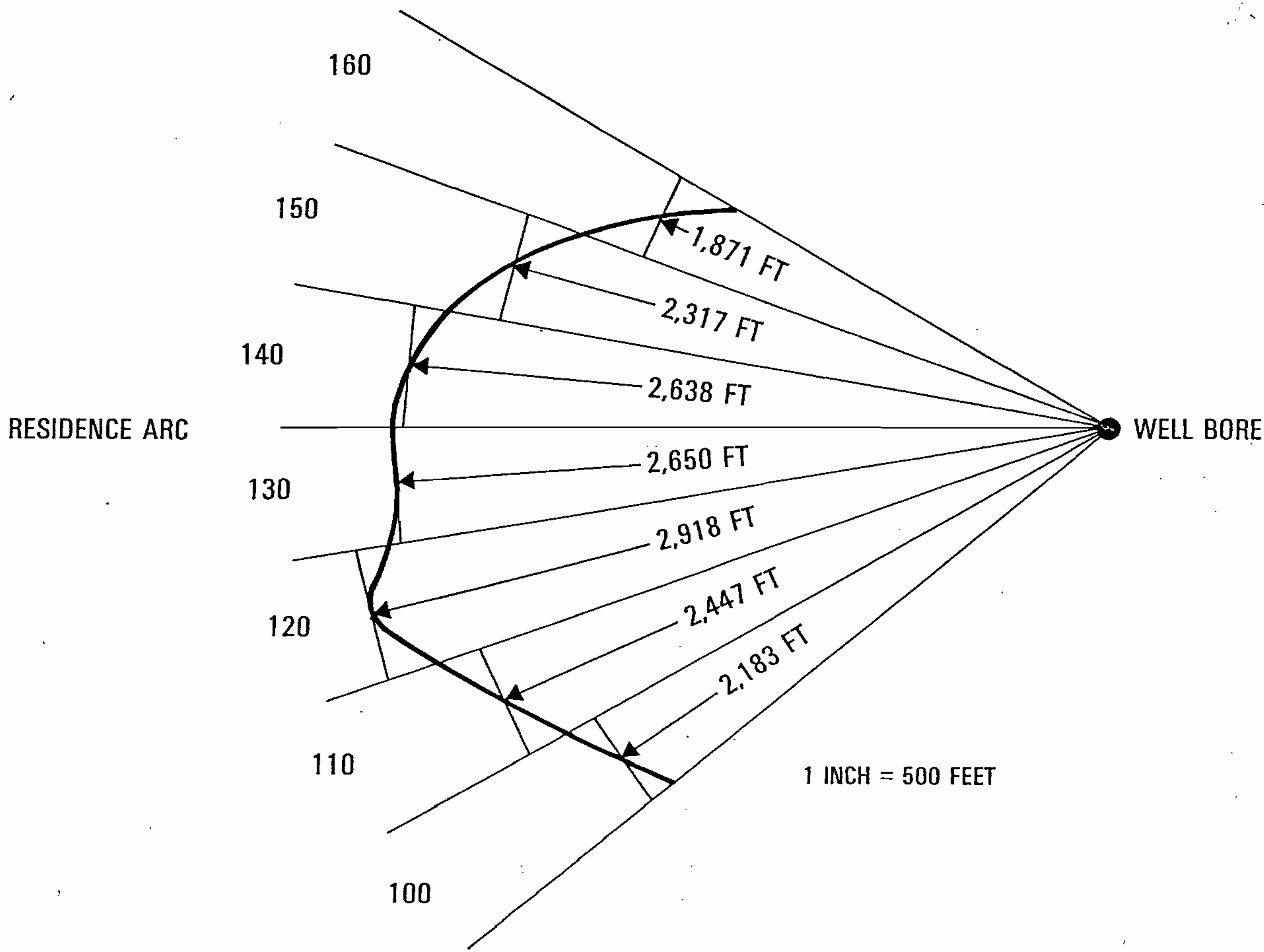


Figure 10. Half of expected well-drainage pattern, constructed from table 7

Discussion

By placing the wells within a reservoir so that the drainage patterns do not overlap (figure 11), the efficiency of gas recovery will be increased. The wells will generally not compete with each other by draining the same lense clusters. The procedure uses the orientation patterns of the lense lengths and the size estimates of the sand lenses to estimate the probable well-drainage patterns. The lense sizes, as well as the well bore intersection points, are treated as constants, and the minimum error value was selected as the best constant value. The actual lense cluster extensions will nearly always be larger or smaller than the estimate, but the difference between the actual value and the estimate is minimized.

Although the exact probability of wells tapping the same cluster is not calculated, it appears that the likelihood of multiple wells per lense cluster is quite small. By not allowing drainage estimates to overlap, a lense cluster in the Mesaverde Formation would have to extend 5836 feet from the well in a N.W./S.E. direction before well overlapping would occur. An example of the chances of this occurring is calculated for the most likely number of lenses in a cluster. The probability of a single-lense cluster intersecting two well bores would be equal to the probability of a lense being 5800 feet long times the probability that the bore was 5800 feet from an end of the lense. Given that the lense is 5801 feet long, the chances of a six-inch diameter well bore intersecting an end would be 2 (one for each end) times .5 feet divided by 5801 feet or .0001. A reliable estimate of the chances of a lense being 5801 feet long or longer requires an estimate of the standard deviation, lense length values, and of the distributional properties of the lense length. Assuming a normal distribution, a rough estimate of the lense lengths standard deviation of 884 was calculated. (The estimated length of each lense is not available in the outcrop study report. The observed lense lengths used by Mr. Knutson to calculate length/height ratio values were used to estimate the standard deviation.) The lense length will be less than 3786 feet 95 percent of the time. The likelihood of a lense being 5800 feet is less than (1 - .95) or .05. Thus, .0001 x .05 or 1-in-a-million would be a conservative estimate of the likelihood of a single lense cluster extending 5800 feet. It may be that a risk analysis indicating a tighter well spacing may be more effective economically.

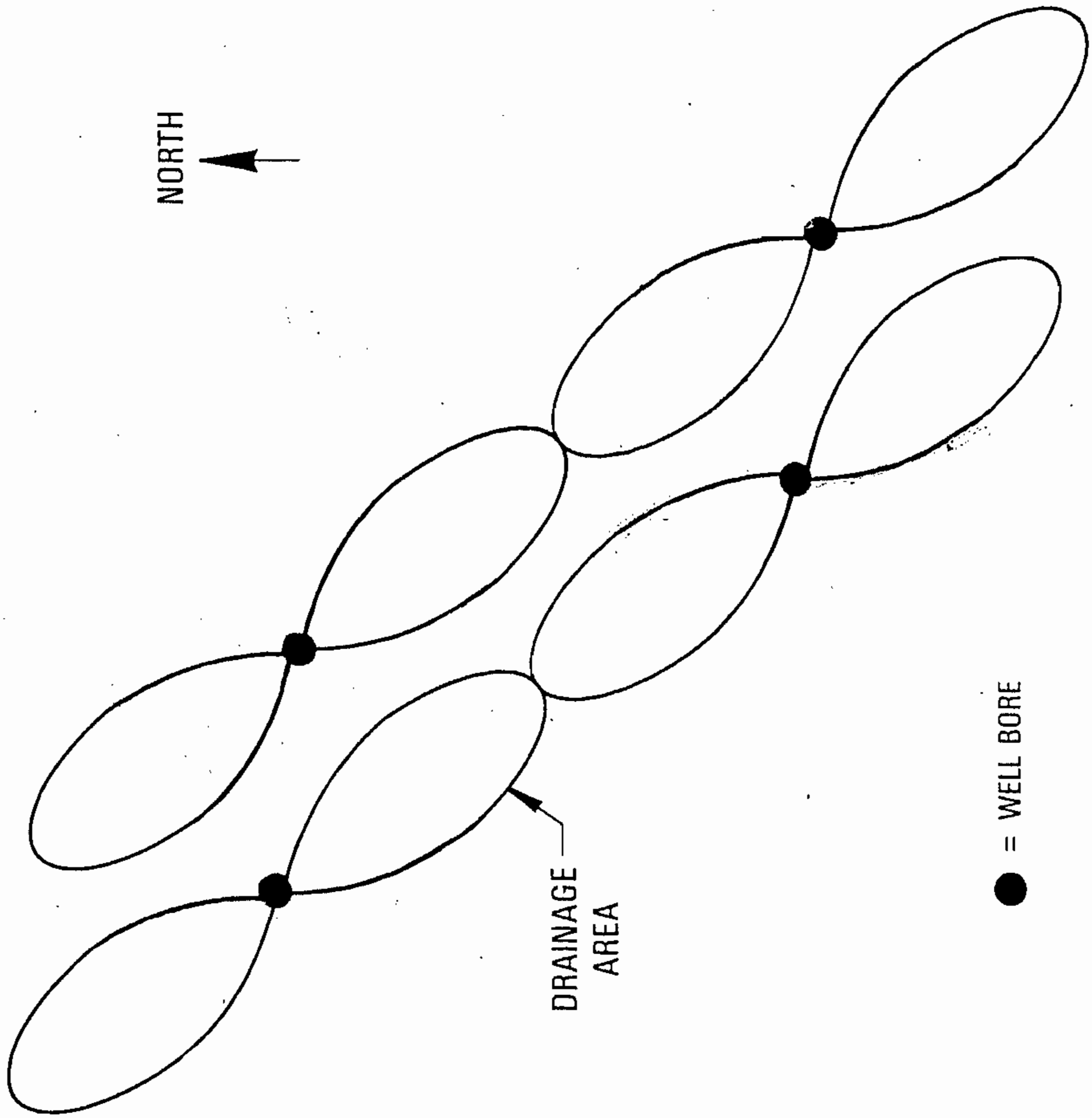


Figure 11. Reservoir well drainage map