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Hydrology of the uppermost Cretaceous and the lowermost Paleocene rocks in the Hilight oil field, Campbell County, Wyoming

by

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Prepared in cooperation with the

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Abstract

The lithologic equivalents of the Fox Hills Sandstone, Lance Formation, and the Tullock Member of the Fort Union Formation, as mapped on the east side of the Powder River Basin, can be recognized throughout the basin; however, the formations are in hydraulic connection and cannot be treated as separate aquifers.

Recharge to the Lance-Fox Hills aquifer in the Hilight oil field is largely by vertical movement; there is no recharge from the Lance and Fox Hills outcrops on the east side of the basin to the formations in the Hilight area.

At the end of the central Hilight water-flood project, the maximum possible drawdown resulting from the pumping of any one well at a distance of 10 miles from the pumped well, would be about 15 feet, if the projected pumping were evenly distributed among the project wells.

Within a few years after pumping has ceased, water in the project wells will approach the levels present before pumping began. The only irreversible effect of pumping will be the compaction of shale, with attendant subsidence, because the water derived from the shale probably will not be replaced.

Introduction

There was a comparatively large increase in the development of ground water from the Fox Hills Sandstone of Cretaceous age and some of the overlying aquifers in the Powder River Basin in 1970-71 for secondary recovery of oil, principally in Campbell County. The office of the Wyoming State Engineer, the State agency that controls ground-water appropriations, needed additional information on the extent of the aquifer and on the effect of pumping ground water in order to better manage the resource. The U.S. Geological Survey, in cooperation with the office of the Wyoming State Engineer, began a study of the geohydrology of the Fox Hills Sandstone in the Powder River Basin. The study of the Fox Hills Sandstone was expanded to include the overlying formations because secondary-recovery water is being developed from them.

This report is a detailed study of a small part of the basin--the Hilight oil field--in Campbell County, Wyoming. The detailed study was made (1) to determine the validity of extending quantitative data by use of geophysical logs, (2) to determine the control necessary to describe the spatial distribution of the aquifers, and (3), in general, to select methods of investigation and presentation of data for the basin as a whole.

The Hilight oil field was selected for the detailed study because there are nine water wells in that area, whereas other oil fields in the vicinity have only one or two water wells. An additional advantage in studying this oil field was that it is one of the largest in the basin in which all the oil wells penetrate the section of rocks being studied.

The location of the Hilight oil field and the area underlain by the Fox Hills Sandstone in the Powder River Basin in Wyoming are shown in figure 1.

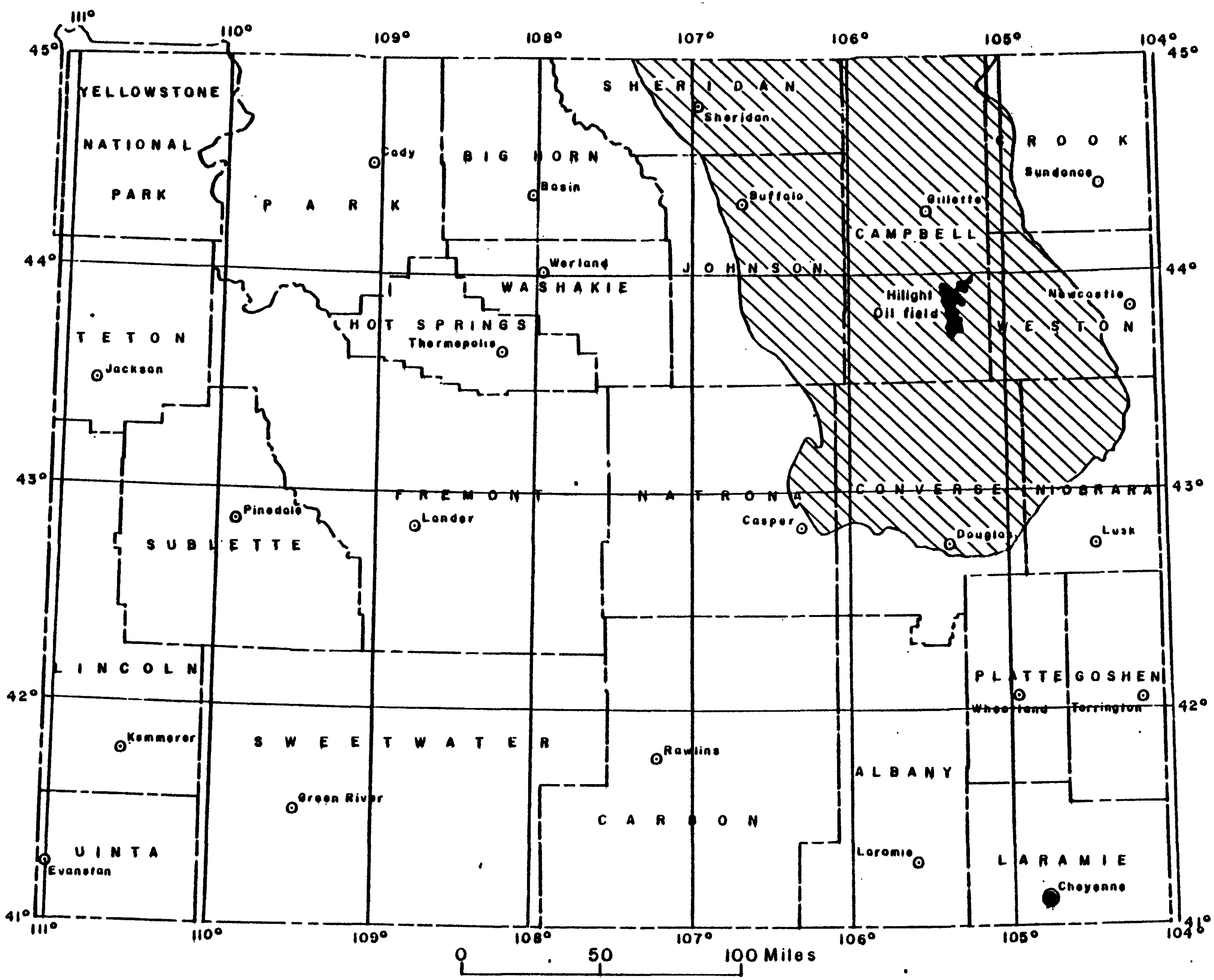

Figure 1.--Location of the Hilight oil field and the approximate extent of the Fox Hills Sandstone (hachured) in the Powder River Basin, Wyoming.

Acknowledgments

The cooperation of Tommy Sheets and Dean Burgess of the Inexco Oil Company in making data available for water wells in the Hilight oil field is gratefully acknowledged. This report would not have been possible without their assistance.

Geology

Water from wells in the Hilight oil field is obtained principally from the Lance Formation of Cretaceous age; a small percentage comes from the Fox Hills Sandstone of Cretaceous age and the Tullock Member of the Fort Union Formation of Paleocene age. The subsurface formations in the Hilight oil field are considered to be lithologic equivalents of the outcrops on the east side of the basin; the description of these outcrops is abstracted from the work of others.

Areal setting

Near the end of the Cretaceous Period, eastern Wyoming was covered by an oscillating inland sea, which caused several changes from marine to continental deposition in central Wyoming. The entire Powder River Basin was covered during the last transgression of the sea, and, during the final withdrawal of the sea from the area, the marine Pierre Shale and westward equivalent Lewis Shale were deposited. Overlying these shales, in ascending order, were deposited the marine Fox Hills Sandstone, the brackish and continental sediments of the Lance Formation, and the continental Fort Union Formation.

The Pierre Shale and the Lewis Shale and the Fox Hills Sandstone are rock-stratigraphic units that cross time lines and the formations are progressively older from east to west across the basin (Gill and Cobban, 1966, pl. 4). Deposition was continuous from the marine deposits through a transition zone into the continental deposits of the Lance; therefore, the basal part of the Lance is also a rock-stratigraphic unit that crosses time lines.

The position of the Paleocene-Cretaceous boundary, which is the Fort Union-Lance contact, has been controversial, especially in the early part of this century. The most important papers dealing with the problem have been discussed by Brown (1962, p. 3-11). The problem, which has not been completely resolved, is briefly described here as it affects the nomenclature in the Powder River Basin.

The Tullock was named by Rogers and Lee (1923, p. 19) for exposures along Tullock Creek in Big Horn and Treasure Counties, Montana. The Tullock was first described as a member of the Lance. Subsequently, it was raised to formation rank, and still later was reduced to a member of the Fort Union. The assignment of the Tullock to the Paleocene Fort Union rather than to the Cretaceous Lance is apparently based partly on fossil evidence found in the center of the basin.

Dorf (1942, p. 95) states, "In the Gillette coal field, as well as at its type locality and elsewhere, the Tullock is now known to contain plant remains of typical Paleocene Fort Union aspect." Brown (1962, p. 10) cited the original field notes of Rogers and Lee to point out that a dinosaur bone described by them as having been found in the Tullock (Rogers and Lee, 1923, p. 34) was actually found 50 feet below coal A. This coal is at the base of the Tullock.

In describing the limits of the Paleocene in the Tullock Creek coal field, the Glendive area, and other specific areas, in the same paper, Brown (1962) cited no paleontological evidence for assigning the Tullock in the type locality to the Paleocene but stated (p. 15), "Tullock Creek coal field.--G. S. Rogers and Wallace Lee in 1923 divided the enlarged but ambiguous Lance into a lower part (now the dinosaur-bearing Hell Creek Formation) and the Tullock Member. The latter, a light-colored, yellowish zone, with coal beds, was separated from the Hell Creek at the level of the lowest persistent coal seam--bed A. This, from what has just been said about the Glendive area, is the level of the Cretaceous-Paleocene boundary." Fossil evidence was cited for placing the Paleocene-Cretaceous boundary at the base of the coal-bearing beds in the Glendive area.

As previously stated, the Fox Hills Sandstone is a rock-stratigraphic unit that becomes progressively older westward. Apparently, then, the lithologic equivalents to the Lance and the Tullock, as they are mapped on the east side of the basin, can also be considered as rock-stratigraphic units that cross time lines because deposition occurred nearly uninterrupted through the interval, as the units are of fairly uniform thickness across the northern part of Wyoming.

Plate 1 shows the author's correlation of rock-stratigraphic units across northern Wyoming and their relation to the formally named units as they are mapped on the east and west sides of the basin (Robinson and others, 1964; Darton, 1906). (The locations of wells are shown in fig. 2.) The thickness of the Fox Hills Sandstone and the Tullock Member of the Fort Union Formation used for the east side of the basin is the thickness described by Robinson and others (1964, p. 97, 99) for exposures near the Wyoming-Montana State line. The 1,000 feet used for the thickness of the Lance Formation is double that in southern Montana (Robinson and others, 1964, p. 98), but the larger thickness is supported by examination of resistivity logs of wells drilled near the outcrop of the formation.

The thicknesses of the formations mapped on the west side of the basin were determined as follows: Darton (1906, p. 8) stated that the thickness of the Piney Formation, which included all strata from the top of the Parkman Sandstone of Cretaceous age to the base of the Lebo Shale Member of the Fort Union Formation, is 2,000 feet along Smith [Columbus?] Creek. Gill and Cobban (1966, pl. 3) assigned approximately the lower 200 feet of this sequence to the Lewis Shale and the Fox Hills Sandstone; therefore, about 1,800 feet of Darton's Piney Formation is what is now called Lance in the area.

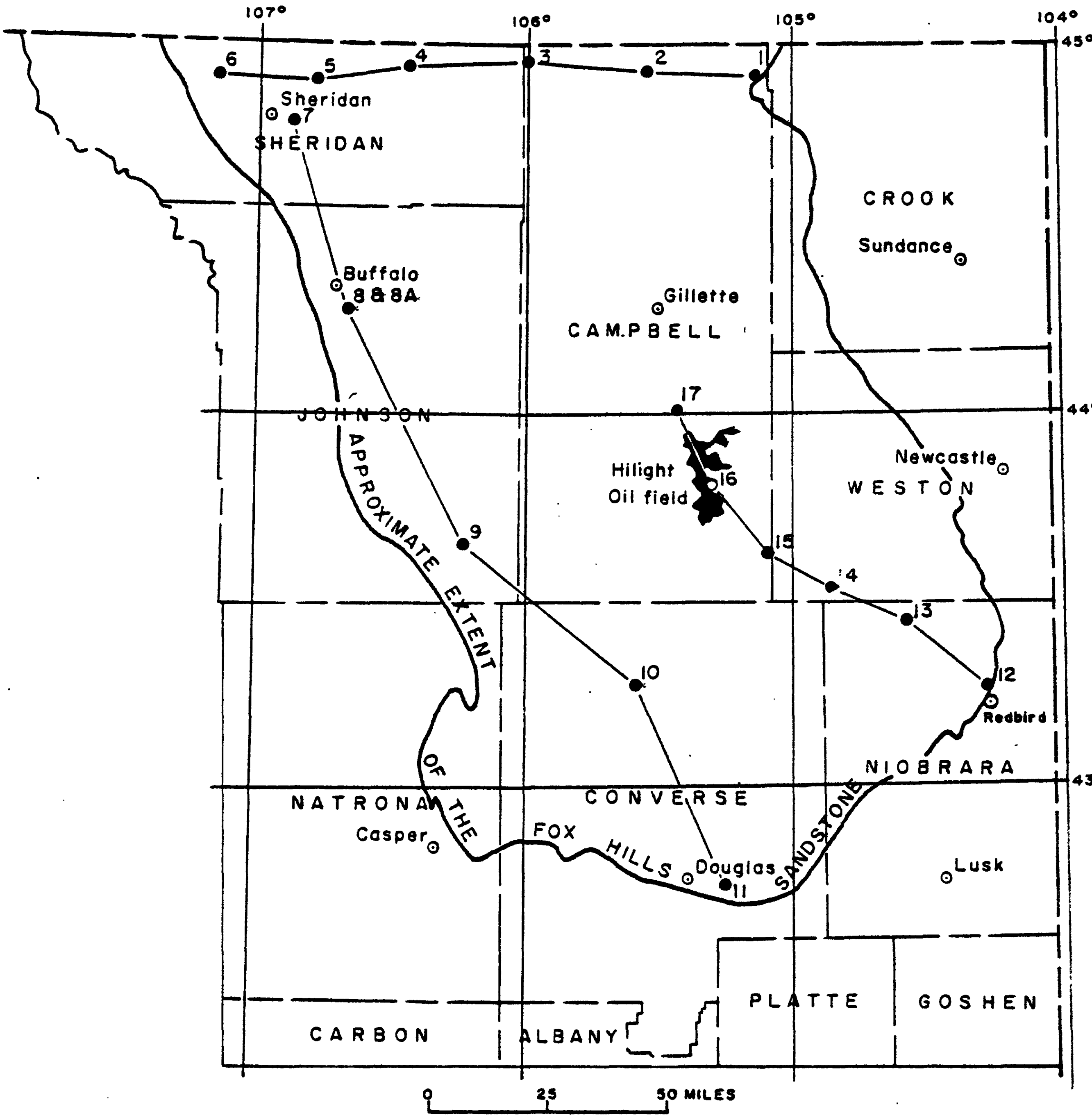

Figure 2.--Locations of wells shown on plates 1, 2, 3, and 4.

If the section shown in plate 1 is correct, Brown's correlation of the Paleocene-Cretaceous boundary westward across Montana on the basis of lithology is not justified. The type locality of the Tullock (Treasure County, Mont.) is about 60 miles north of the west end of the section shown on plate 1; Glendive (Dawson County, Mont.) is about 160 miles north of the east end of the section. The relation is further complicated by the fact that there is no fossil evidence for position of the Paleocene-Cretaceous boundary in Sheridan County, Wyo., or to the south in Johnson County, Wyo. Hose (1955) assigned 1,950 to 2,200 feet of strata to the Lance in the Crazy Woman Creek area in Johnson County, Wyo. He states (p. 65), "The lower 600 feet of the formation, which contains dinosaur bones, is of Late Cretaceous age. No fossils have been found in the upper part of the Lance Formation within the mapped area, and the assignment of the entire Lance Formation to the Upper Cretaceous is one of convenience."

Plate 2 shows the correlation of the lithologic equivalent of the Tullock along the west side and south end of the basin where it is mapped as part of the Lance Formation.

Stratigraphy

Contiguous formations

The Pierre Shale at the reference locality at Red Bird consists of about 3,100 feet of dark- to light-gray weathering noncalcareous shale of marine origin (Gill and Cobban, 1966, p. A1). Sandstones occur in the equivalent section farther west but in the Hilight oil field the uppermost sandstone is about 300 feet below the Fox Hills Sandstone.

The Lebo Shale Member of the Fort Union Formation is 200 to 250 feet thick in the northeastern part of Campbell County (Robinson and others, 1964, p. 99). Here the member consists mostly of light- to dark-gray claystone and shale, subordinate light-gray, fine-grained sandstone in discontinuous lenses, and beds of brown carbonaceous shale. The Lebo Shale and the Tongue River Members of the Fort Union are mapped as a unit along most of the eastern margin of the basin (Love and others, 1955). The lower 250 to 400 feet of this sequence as far south as Rozet, however, resembles the Lebo Shale Member (Robinson and others, 1964, p. 100), and similar lithology is described in the subsurface in the southwest and west-central part of Campbell County (Wyo. Geol. Assoc.). Geophysical logs in the Hilight oil field, in general, also show a marked increase in shale for the Lebo Shale Member over that in the underlying Tullock Member.

Description of units on the east side of the basin

Fox Hills Sandstone

The Fox Hills Sandstone was named for exposures along the Missouri River in South Dakota. Waage (1961, p. 239-240), described the Fox Hills Sandstone at the southern end of the outcrop belt in Niobrara County, Wyoming, as follows:

> "It is interesting that the gross stratigraphic features of the Fox Hills in the Niobrara County area are roughly similar to those of the Fox Hills in its type area. The upper 75 feet or more of the Pierre Shale in the Lance Creek area is sandy and resembles the Trail City beds in general lithology, although it lacks the abundantly fossiliferous concretions. Above this, the lower part of the Fox Hills is chiefly massive sandstone like that in the Timber Lake Member and contains similar concretions with *Sphenodiscus* and other fossils. The massive sand is succeeded by a distinctive unit of thin-bedded sandstone with minor sandy shale reminiscent of the "banded beds" of the Bullhead Member. These thin-bedded sands also grade in their upper part into massive white sands that have locally been called the Colgate Member."

The Fox Hills Sandstone is poorly exposed along much of the outcrop on the east side of the basin. It is characterized as a low, grass-covered ridge standing above the less-resistant Pierre Shale. Measured sections in Niobrara and Crook Counties, Wyoming, and in Carter County, Montana, are given below.

Section of the Fox Hills Sandstone east of Lance Creek in $SW\frac{1}{4}$ sec. 14,

T. 36 N., R. 64 W., Niobrara County, Wyo.

[After Stanton, T. W. (1910, p. 186)]

	Feet
Lance Formation: Sandy shale with thin beds of coal	25
Fox Hills Sandstone:	
Massive white sandstone with Halymenites major	60
Yellowish massive sandstone with brown concretions	20
More thinly bedded brown sandstone with Halymenites	25
Massive white sandstone	75
Soft, somewhat sandy shales with thin sandstone bands containing marine Fox Hills shells	30
Brown shaly sandstone	5
Massive white sandstone	60
Thin-bedded brown and gray sandstone	130
Yellowish massive sandstone with concretions containing Fox Hills fauna	100
Total Fox Hills	505
Pierre Shale.	

Part of Fox Hills Sandstone in sec. 17, T. 48 N., R. 66 W.,

Weston County, Wyo.

[After Robinsen and others (1964, p. 97)]

	Feet
Top of ridge.	
Fox Hills Sandstone (part):	
Sandstone, yellowish-gray, fine-grained, locally crossbedded; a few thin partings of gray sandy shale	40
Shale, gray	17
Sandstone, light-gray to yellowish-gray, fine-grained	1
Shale, gray	8
Sandstone, light-gray, fine-grained; gray sandy shale in middle part	8
Shale, gray; some yellowish-gray sandy shale	20
Sandstone, brownish-gray, fine-grained	1
Shale, gray, sandy	22
Sandstone, light-gray, fine-grained	½
Shale, gray	11
Shale, gray, sandy; a few thin light-gray fine-grained sandstone beds in upper part; a bed 1 ft thick of light-gray fine-grained friable sandstone at base	6
Shale, gray; thin partings of yellowish-gray sandy shale	17
Partial thickness (rounded) of Fox Hills Sandstone	152
Pierre Shale (part):	
Shale, dark-gray; a few gray limestone concretions near base	25

Fox Hills Sandstone in sec. 11, T. 9 S., R. 55 E.,

Carter County, Montana

[From Robinson and others (1964, p. 97)]

	Feet
Lance Formation (part):	
Partly covered; mostly light-gray to light-brown fine-grained sandstone	17
Fox Hills Sandstone:	
Colgate Sandstone Member:	
Sandstone, grayish-white, medium-grained, arkosic, micaceous, massive; contains numerous yellow limonite specks	15
Covered	20±
Sandstone, light-gray to light greenish-gray, weathers grayish white, medium-grained, arkosic, micaceous, friable; contains small clay pellets; beds 2 to 6 in. thick	28
Sandstone, gray to light greenish-gray, weathers light gray, medium-grained; a few small yellow ferruginous sandstone nodules in upper part; beds 4 to 15 ft thick separated by lenticular partings of gray shale; forms cliff	49
Thickness of Colgate Sandstone Member	112

Fox Hills Sandstone in sec. 11, T. 9 S., R. 55 E.,

Carter County, Montana--continued

	Feet
Fox Hills Sandstone:--continued	
Lower part:	
Claystone, very light greenish-gray, silty to sandy-----	2
Sandstone, light to dark greenish-gray medium-grained, micaceous; beds about 1 to 10 in. thick separated by partings of siltstone and silty claystone; a bed of brown-weathering calcareous sandstone concretions as much as 8 ft long at base; forms slope----------------	10
Sandstone, medium-gray, weathers light gray to light brownish gray, fine-grained, silty, crossbedded, friable; beds 1 to 6 ft thick; a few thin partings of gray shale; forms slope----------------------------	30
Sandstone and siltstone, medium- to dark-gray, weathers light gray to light yellowish gray, calcareous; beds 1 to 6 in. thick; thinner bedded at base; forms ledge----------------------------------	5½
Siltstone, medium-gray, weathers brownish gray, sandy---	3
Thickness of lower part (rounded)------------------	50
Thickness of Fox Hills Sandstone------------------	162

Lance Formation

Hatcher (1893, p. 137) described the Lance Formation at the type locality, the Lance Creek area in Niobrara County, Wyo., as consisting of alternating sandstones, shales, and lignites with local deposits of limestone and marl. The lower contact was chosen at the change from marine to fresh-water sediments. Hatcher noted the absence of vertebrate fossils in beds overlying the Lance.

The position of the Paleocene-Cretaceous boundary is based on fossil evidence. Brown (1958, p. 112) states that the Lance-Fort Union contact can be mapped throughout the basin by using the following formula: "Search the given area for remains of dinosaurs as high as they can be found. Then look for the first good coal zone no matter how thin. The base of this zone is the Cretaceous-Paleocene contact."

Hatcher (1893, p. 139) estimated the thickness of the Lance to be 3,000 feet at the type locality. The formation thins northward to 1,600 feet in Weston County and to 500 feet in southern Powder River County, Mont., (Robinson and others, 1964, p. 98). No complete sections of the Lance were measured, but a partial section of the upper part is given on pages 27-29 and the lithology in the middle part is described in the following section:

Part of the Lance Formation in the $SW\frac{1}{4}$ sec. 7, T. 54 N., R. 67 W.,

Crook County, Wyo.

[After Robinson and others, 1964, p. 99]

	Feet
Top of hill.	
Lance Formation (part):	
Sandstone, light-yellowish-gray to light-gray, medium- to fine-grained, friable; a few partings and laminae of gray and brown carbonaceous shale; scattered gray- to brown-weathering calcareous sandstone concretions in middle and upper parts; a few layers 1 to 2 in. thick of yellowish-gray cone-in-cone sandstone concretions; 3 beds about 1 ft thick of brown carbonaceous shale about equally spaced in the unit----------------------------------	60+
Shale, medium-gray, silty, slightly carbonaceous; grades in upper 2 to 3 ft into brown carbonaceous shale--------------	8
Sandstone, light-gray, weathers, olive-gray, fine-grained, crossbedded, very friable; a few laminae of gray and brown shale; 8 ft of brown carbonaceous shale near top-----------	30
Claystone, medium-gray, sandy, carbonaceous-----------------	16
Sandstone, light-gray, weathers light-brownish gray, fine- to medium-grained, friable; a few thin partings of medium-gray sandy shale--	15
Shale, medium-gray to olive-gray, slightly sandy; selenite and bone fragments weather out on slope-------------------	3

Part of the Lance Formation in the SW$\frac{1}{4}$ sec. 7, T. 54 N., R. 67 W., Crook County, Wyo.--continued

	Feet
Lance Formation (part):--continued	
Sandstone, light-gray, weathers light-yellowish-brown, fine- to medium-grained, friable, crossbedded; abundant dark-colored minerals; scattered dark-brown-weathering calcareous sandstone concretions as much as 10 ft long-----	95
Shale, medium-gray, slightly carbonaceous; lower half brown locally; a few seams of coal about 1/8 in. thick-----	12+
Partial thickness of Lance Formation-------------------	239

Base of exposures.

Tullock Member of the Fort Union Formation

The Tullock Member of the Fort Union was named for exposures on the west side of the Powder River Basin in Montana; however, in Wyoming it is mapped only on the east side of the basin. The following brief summary of the lithology is adapted from Robinson and others (1964, p. 99).

The Tullock Member consists of fine-grained sandstone, gray sandy or silty shale, and numerous brown beds of carbonaceous shale and coal. The coal beds are lenticular and generally are less than 2 feet thick. The sandstone is mostly soft and friable. Details of lithology are given in the following measured section:

Parts of the Tullock Member of the Fort Union Formation and the Lance Formation in sec. 35, T. 56 N., R. 69 W., Campbell County, Wyo.

[After Robinson and others, 1964, p. 100-101]

	Feet
Top of hill.	
Fort Union Formation (part):	
Tullock Member (part):	
Sandstone, very light-gray, medium- to fine-grained, friable; contains calcareous sandstone concretions as much as 5 ft thick, 25 ft wide, and 50 ft long-----	10
Shale, dark-brown to black coaly-----------------------	2
Sandstone, light-gray, weathers yellowish-gray, very fine grained, friable----------------------------------	9
Claystone, medium-gray; a bed of brown carbonaceous shale 2 ft thick near top---------------------------	11
Siltstone, light-yellowish-gray, shaly-----------------	3
Claystone, medium-gray to brown; a few brown-weathering ferruginous siltstone concretions--------------------	7
Sandstone, very light-gray, very fine grained; locally shaly; a few brown-weathering siltstone concretions as much as 6 in. long; forms local slabby ledges------	21
Shale, gray to brown, carbonaceous---------------------	5
Sandstone and siltstone, light-gray, very fine grained--	8
Claystone, light- to medium-gray; sandy at top----------	2
Shale, dark-brown to black; a few thin stringers of coal--	1

Parts of the Tullock Member of the Fort Union Formation and the Lance Formation in sec. 35, T. 56 N., R. 69 W., Campbell County, Wyo.--continued

	Feet
Fort Union Formation (part):--continued	
Tullock Member (part):--continued	
Claystone, gray, sandy------------------------------------	3
Shale, brown and gray, silty, carbonaceous; seam of coal 1 in. thick near top--------------------	3
Shale, gray, carbonaceous-------------------------------	3
Sandstone, light-gray, weathers yellowish-gray, fine-grained, friable---------------------------------------	6
Shale, gray to brownish-gray, silty--------------------	2
Sandstone, light-gray, weathers light-yellowish-gray, fine-grained, micaceous, friable---------------------	3
Shale, medium-gray; carbonaceous near middle------------	3½
Sandstone, light-gray, weathers yellowish-gray to brownish-gray, fine-grained; contains nodules of orange-brown-weathering siltstone as much as 3 in. in diameter; slabby to friable--------------------------	8

Parts of the Tullock Member of the Fort Union Formation and the Lance Formation in sec. 35, T. 56 N., R. 69 W., Campbell County, Wyo.--continued

		Feet
Fort Union Formation (part):--continued		
Tullock Member (part):--continued		
Shale and coal, as follows:	Feet	
Shale, gray, slightly carbonaceous------	1.8	
Shale, brown, carbonaceous--------------	1.6	
Coal------------------------------------	.7	
Shale, brown, carbonaceous--------------	.9	
Coal------------------------------------	.7	
Shale, dark-brown, carbonaceous---------	.9	
Coal------------------------------------	1.4	
Shale, dark-brown to black, carbonaceous-------------------------	5.0	
Total--		13
Partial thickness (rounded) of the Tullock Member of Fort Union Formation--------------		124
Lance Formation (part):		
Sandstone, medium- to light-gray, medium- to fine-grained, slightly carbonaceous------------------------		5
Claystone, light- to dark-gray, sandy, slightly carbonaceous--		6
Sandstone, gray, weathers brownish-gray, medium- to fine-grained, friable; slightly carbonaceous at base--		5

Parts of the Tullock Member of the Fort Union Formation and the Lance Formation in sec. 35, T. 56 N., R. 69 W., Campbell County, Wyo.--continued

	Feet
Lance Formation (part):--continued	
Shale, brown, carbonaceous------------------------------	1
Claystone, gray, slightly carbonaceous; sandy at base---	10
Sandstone, gray, medium- to fine-grained, friable; slightly carbonaceous at base------------------------	8
Shale, brown to gray, carbonaceous---------------------	1½
Claystone, gray, silty----------------------------------	4
Sandstone, light-gray, weathers yellowish-brown, medium-grained, friable-------------------------------	1
Claystone, medium-gray, sandy--------------------------	4½
Sandstone, light-brownish-gray, fine-grained, friable---	5
Claystone, dark-gray, silty; carbonaceous in lower part-	7
Shale, dark-brown, carbonaceous------------------------	2
Claystone, gray; sandy at base; slightly carbonaceous at top--	9
Sandstone, light-gray, fine-grained, very friable-------	2
Claystone, light- to dark-gray; sandy near base; carbonaceous at top----------------------------------	11
Sandstone, light-gray, weathers brownish-gray, medium- to fine-grained; partings of gray sandy shale and brown-weathering siltstone concretions as much as 1½ ft thick and 3 ft long----------------------------	46

Parts of the Tullock Member of the Fort Union Formation and the Lance Formation in sec. 35, T. 56 N., R. 69 W., Campbell County, Wyo.--continued

	Feet
Lance Formation (part):--continued	
Sandstone, light-gray, weathers yellowish-gray, medium-grained, friable; elongate sandstone concretions several feet long------------------------	40
Covered--	6
Siltstone, gray, sandy----------------------------------	2
Shale, gray---	1
Shale, brown, carbonaceous------------------------------	1½
Claystone, gray---	10
Partial thickness (rounded) of Lance Formation-----	188

Base of exposures.

Geophysical-log limits of units

The vertical extent of the three units are defined, for the purpose of this thesis, by their geophysical-log characteristics. The resistivity logs are the most important logs because they are the only ones usually run in the Tullock-Fox Hills part of the section. A complete suite of logs is generally run only in deeper zones where oil may be present. The log limits described are neither precise nor exactly the same interval as would be mapped on the surface, but the log response is equated to depositional differences in the units. The hydrology is dependent upon the lithology of the three environments.

Gill and Cobban (1966, pl. 2) correlated the reference section of the Pierre Shale at Red Bird to a nearby oil well in the SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 15, T. 38 N., R. 62 W. Although the change in the position of the sandstone because of change in age makes the use of any datum for the Fox Hills-Pierre contact inappropriate for use throughout the basin, their determination for the contact is used for this report and the correlation from Red Bird to the Hilight oil field is shown on plate 3. (Locations of wells are shown in fig. 2.) The Fox Hills Sandstone at the Red Bird section includes transition beds mapped with the Pierre by some investigators (Gill and Cobban, 1966, A5).

The top of the Fox Hills Sandstone, ideally, is chosen by use of multiple logs. On resistivity logs, the top was chosen at the uppermost bed that could be correlated in nearby wells. This criteria divides the more extensive marine sediments from the lenticular continental deposits. The best results, then, would be by inspection of several logs at one time to pick the top of the Fox Hills. This procedure would be too time consuming to meet the broader project objectives in the given time and, therefore, correlation, where logs were physically laid out, generally was with only two logs. More often contacts chosen by inspection of a single log without rechecking where errors were suspected.

The change to a more thin-bedded sequence also aids in choosing the top of the Fox Hills Sandstone on resistivity logs. The change is best expressed on acoustic-velocity logs, but it is also expressed to varying degree by other so-called porosity logs and by caliper logs. Comparison of resistivity and density logs shown in figure 3 illustrates that the change in character of the porosity log at the top of the Fox Hills is not necessarily caused only by the change in the size of the bore; however, the size does greatly affect the porosity log of most wells. The error most likely to be incurred in using logs to choose the contact is to include part of the Fox Hills with the Lance for localities where they intertongue. Sonic logs for four wells shown on plates 1, 2, and 3 are shown on plate 4.

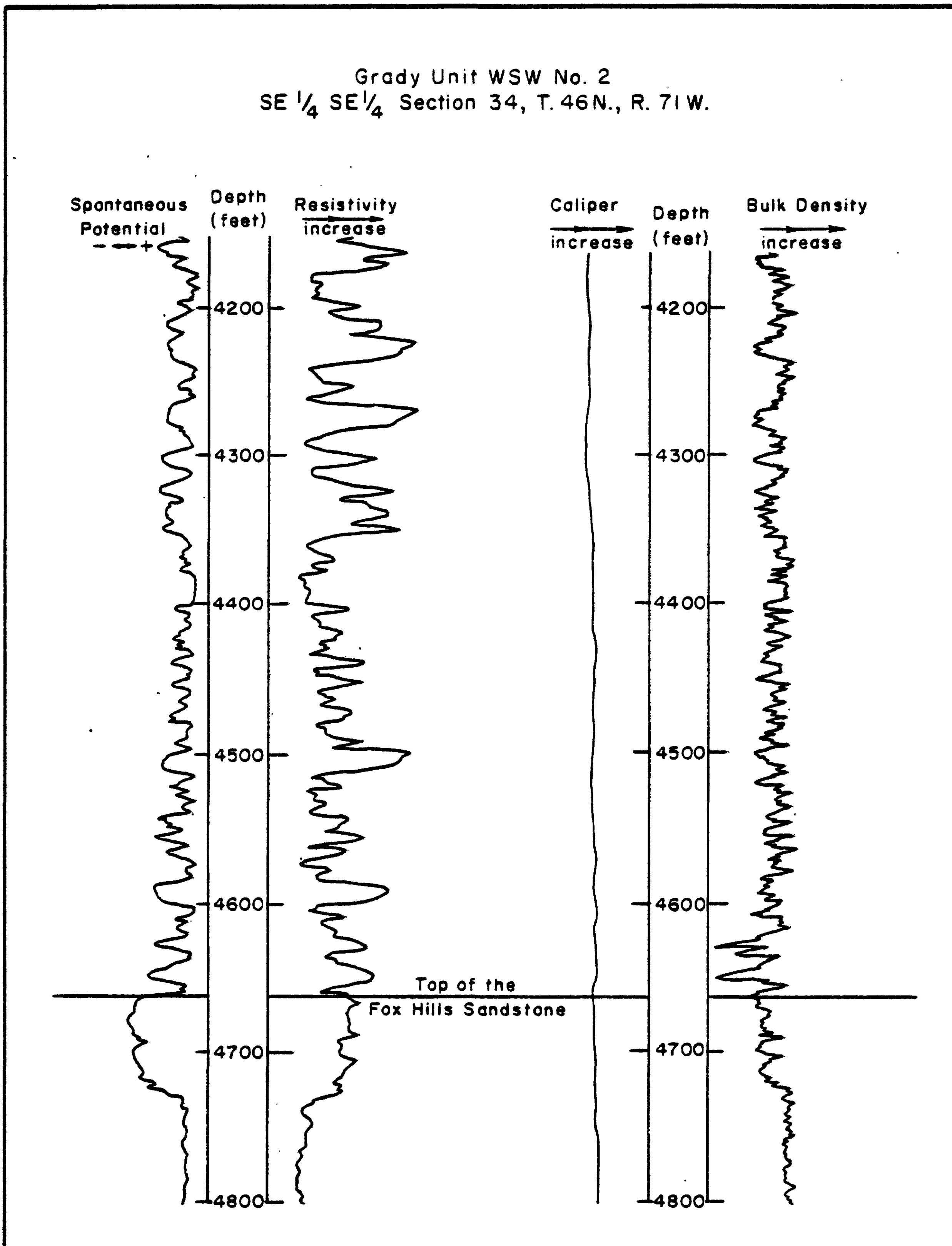

Figure 3.--Comparison of resistivity and density logs of part of the Fox Hills and Lance Formations. Depth in feet.

The log characteristics of the Lance Formation and the Tullock Member of the Fort Union Formation are essentially those described for the key Tertiary logs of the Powder River Basin (Wyo. Geol. Assoc.). Log characteristics of the lower part of the Lance Formation are similar to those of the Tullock but, in general, the Lance Formation is characterized by a zone of low resistivity with rather thick beds whereas the overlying Tullock is, as a whole, a zone of higher resistivity and composed of thinner beds. The change in log characteristics of some wells is sharp but it is usually transitional. (See plates 1 and 2.)

The top of the Tullock is marked by a change back to beds of lower resistivity containing thick shale. The log characteristics of the overlying beds resemble those of the Lance. Again, there is usually a transition zone. The spontaneous-potential curve can be used for choosing the Tullock in many wells because there is a change in the shale base to more negative values through the member.

Description of stratigraphy in the Hilight oil field

All the geophysical logs of wells in the Hilight oil field that are held in the office of the U.S. Geological Survey in Casper, Wyo., were examined. The data are summarized here principally by the use of illustrations. Structure contours drawn on the top of the Pierre Shale are shown in figure 4. This map can be used in conjunction with data in succeeding pages to estimate the depths to the top of other units.

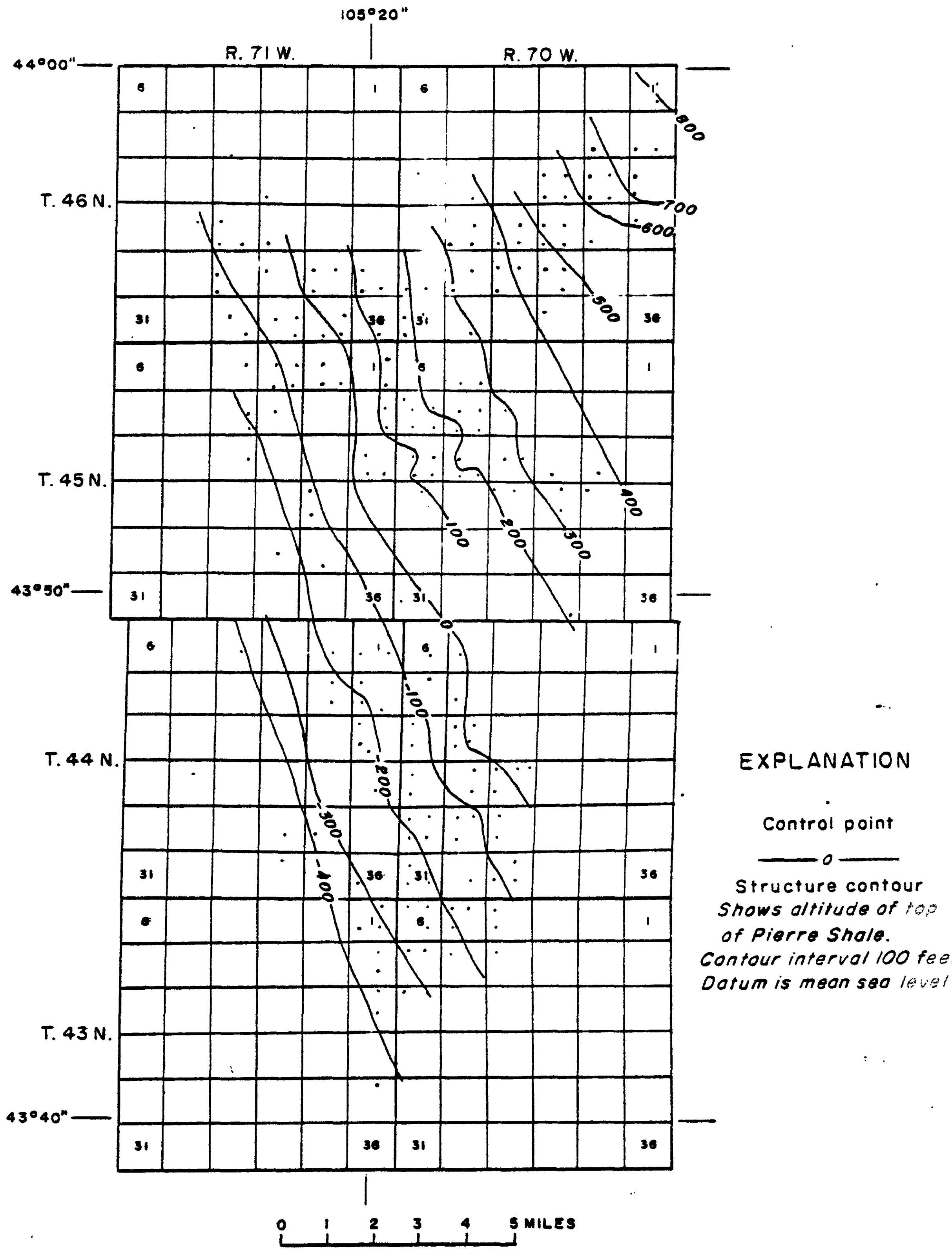

Figure 4 --Structure contours on top of the Pierre Shale in the Hilight oil field.

Fox Hills Sandstone

The Fox Hills and Lance intertongue and, therefore, no unique top could be used to prepare an isopach map of the thickness of the Fox Hills. (This intertonguing did not significantly affect contouring the thickness of the Lance because a large contour interval could be used.) Plate 5 shows: (1) The top of the Fox Hills as chosen from the resistivity logs by the method described previously, (2) the top of the Fox Hills as chosen from density logs for two wells, and (3) an interpretation of intertonguing of the Fox Hills and Lance based only on the logs in the line of sections. The intertonguing most nearly represents the change from the marine to continental deposition; however, there is not enough improvement in the data by this type of correlation to justify the additional time required to use it for the basin study, even if sufficient data were available.

The thickness of the Fox Hills chosen from resistivity logs in the Hilight field shows a general thickening of the formation from northwest to southeast. The thickest section is in the southern part of township 45, but the formation southward thins only slightly. The thickness of well-developed sands varies considerably, especially in the lower part of the formation. An average of about 25 percent of the interval assigned to the Fox Hills in the Hilight oil field consists of sandstone.

Lance Formation and Tullock Member of the Fort Union Formation

The thicknesses of the Lance and of the Tullock are shown in figures 5 and 6, respectively. Both units thicken to the southeast, thus indicating that subsidence, which formed the present basin configuration as illustrated by figure 4, had not begun until after deposition of the Tullock. Circled control points do not fit the mapped lines because the change is transitional and no single marker could be used for the contact between the two units. A map of the combined thickness (fig. 7) shows a similar line pattern and only one point that did not fit the lines marked.

In order to obtain at least a qualitative estimate of the sandstone percentage, the percentage of beds in the Lance and Tullock having high resistivity was determined by measuring the thickness of beds with a resistivity greater than an arbitrary value between 15 and 20 ohms. Only logs where the resistivity curve showed good character (variation) were used. Sandstone makes up most of the beds having high resistivity and the values are equated to sand percentage, although coal and limestone are also resistant and are included. A reasonable configuration was obtained contouring 10 percent change; however, a 10 percent difference was obtained by measuring the thickness of beds having a resistivity greater than each 15 and 20 ohms on the same log. The contour interval, then, is nearly the same as the accuracy.

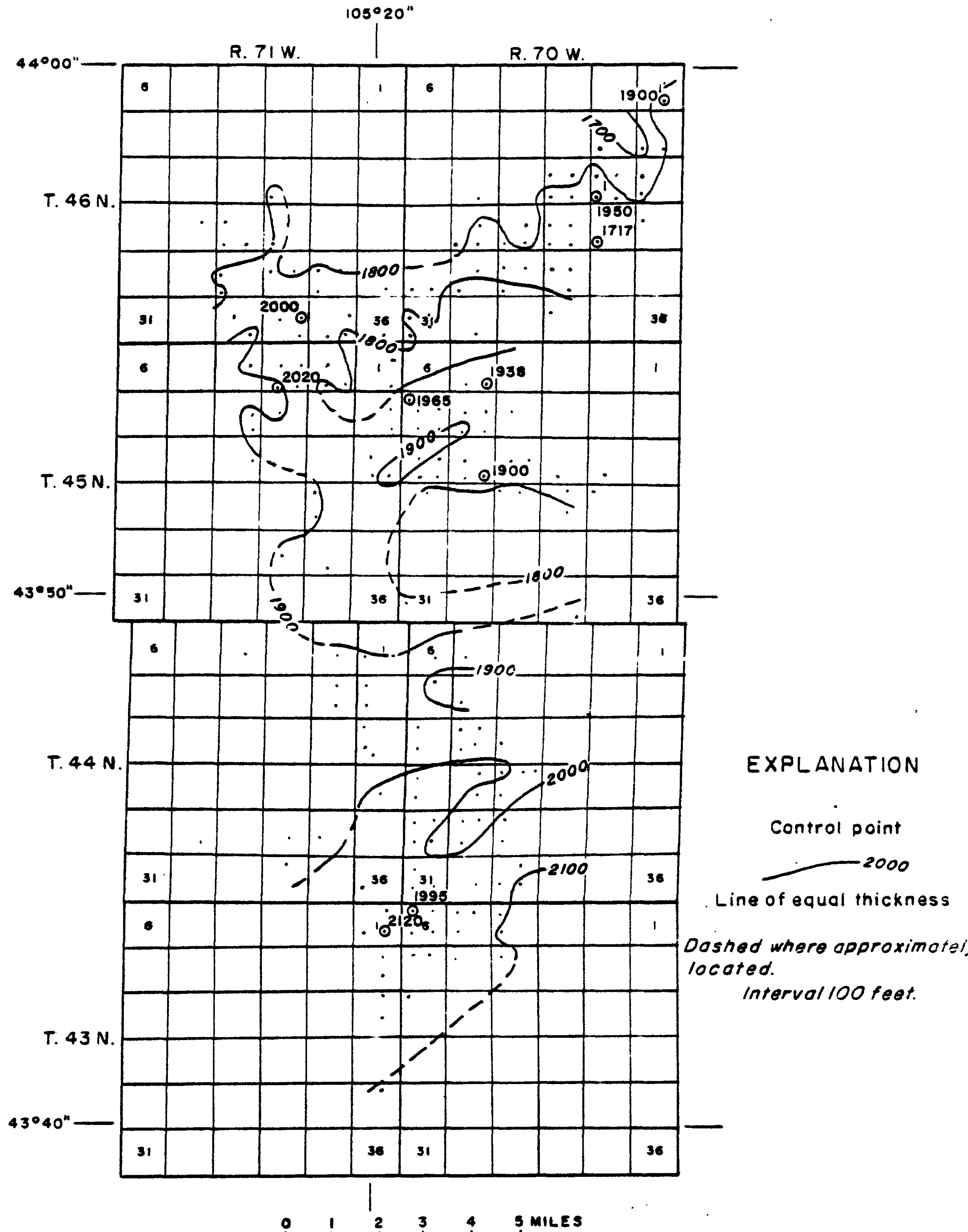

Figure 5.--Thickness of the Lance Formation, in the Hilight oil field. Circled points with values are those that do not fit indicated line.

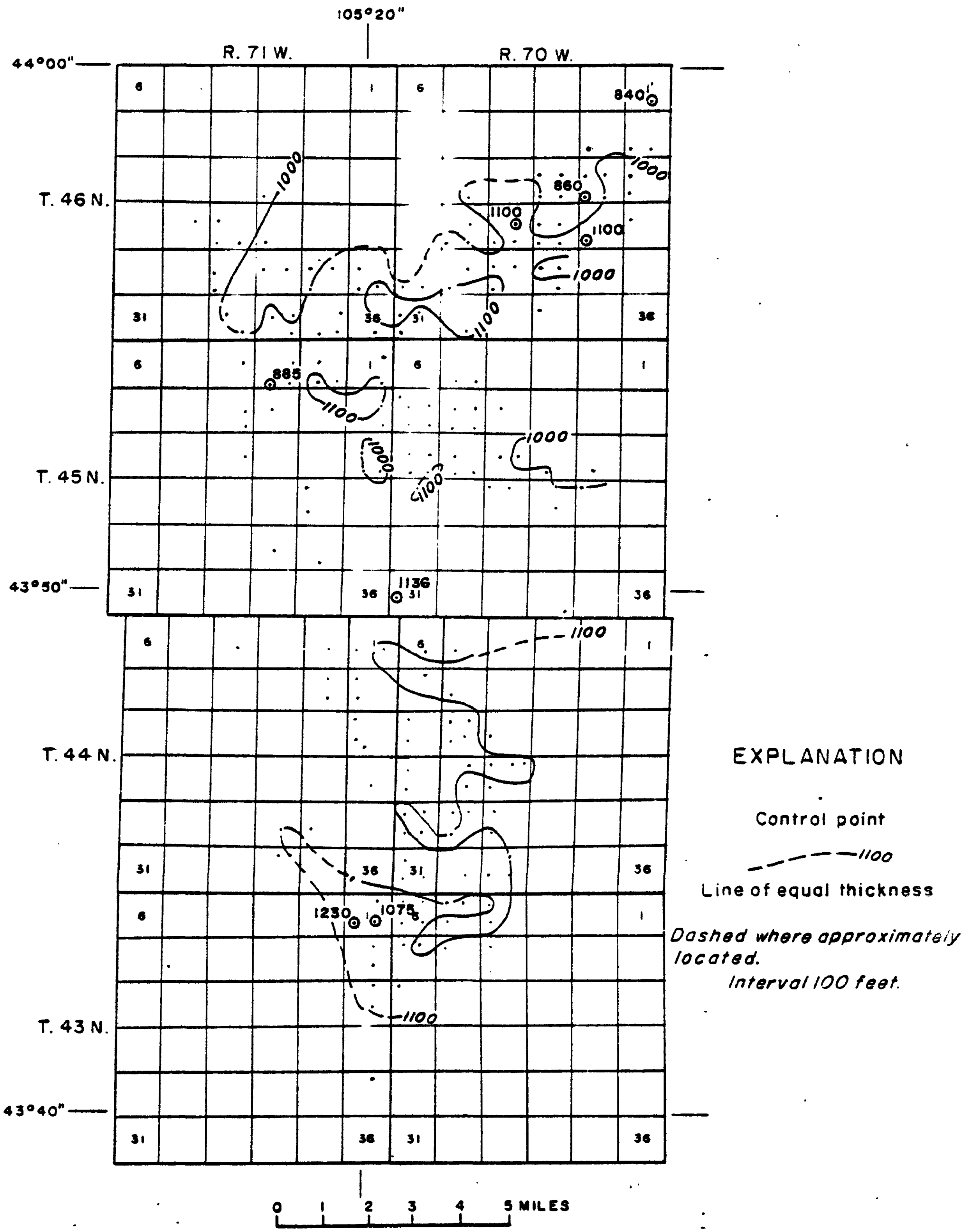

Figure 6.-- Thickness of the Tullock Member of the Fort Union Formation, in the Hilight oil field. Circled points with values are those that do not fit indicated line.

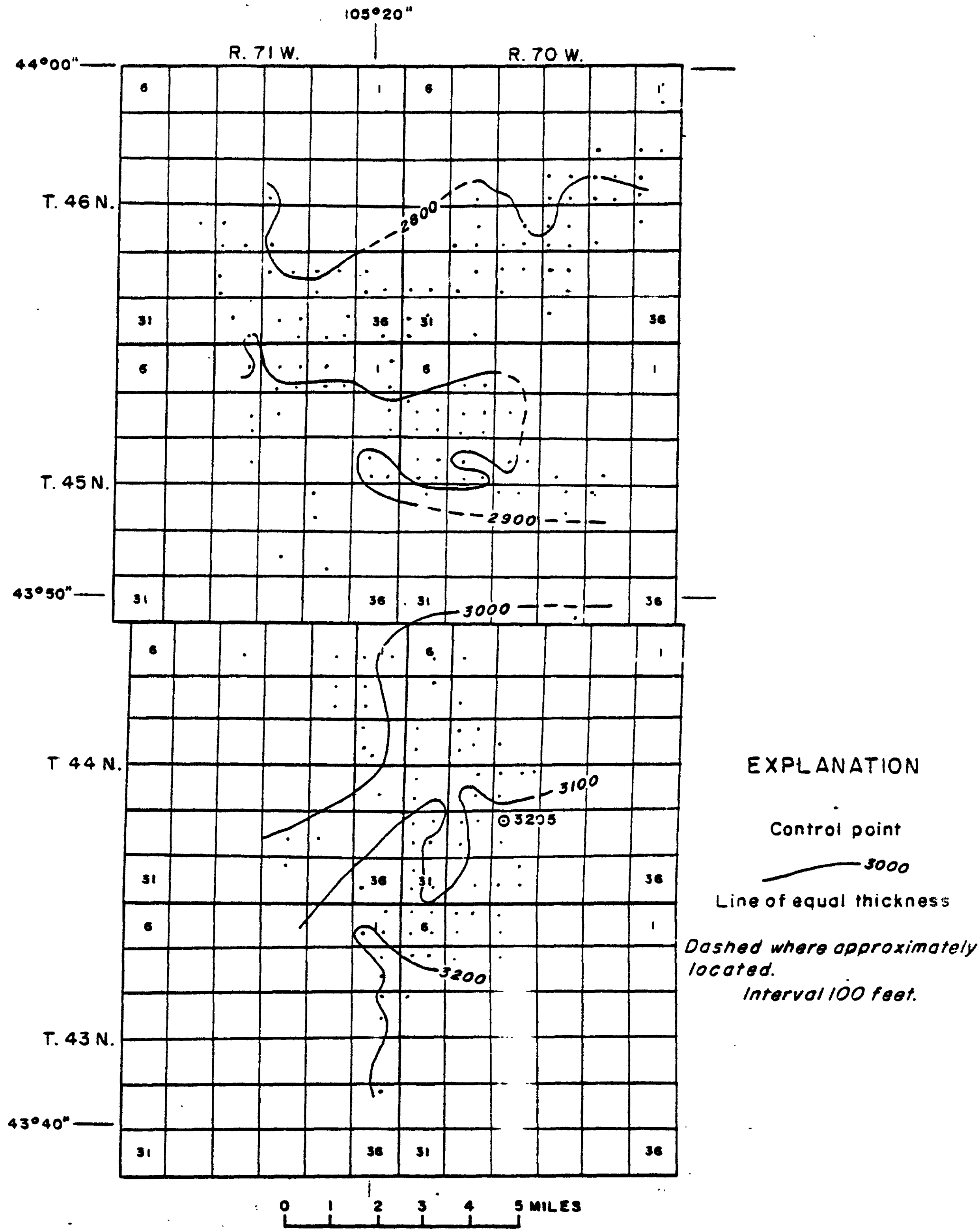

Figure 7.--Combined thickness of the Lance Formation and the Tullock Member of the Fort Union Formation, in the Hilight oil field. Circled points with values are those that do not fit indicated line.

The "sand percentage" maps (figs. 8 and 9) show an increase in sand percentage to the south similar to the direction of thickening of the units. Because the pattern of increase in sand percentage was the same for the Lance and Tullock, a regression analysis was made, using percentage of beds with high resistivity in the Lance and Tullock in the same well as the two parameters, to see if possibly nongeologic factors, such as tool characteristics and mud resistivity, were involved. Correlation coefficient for 190 data points was 0.02, or no correlation, and it is concluded that the maps give the true qualitative picture of sandstone percentage.

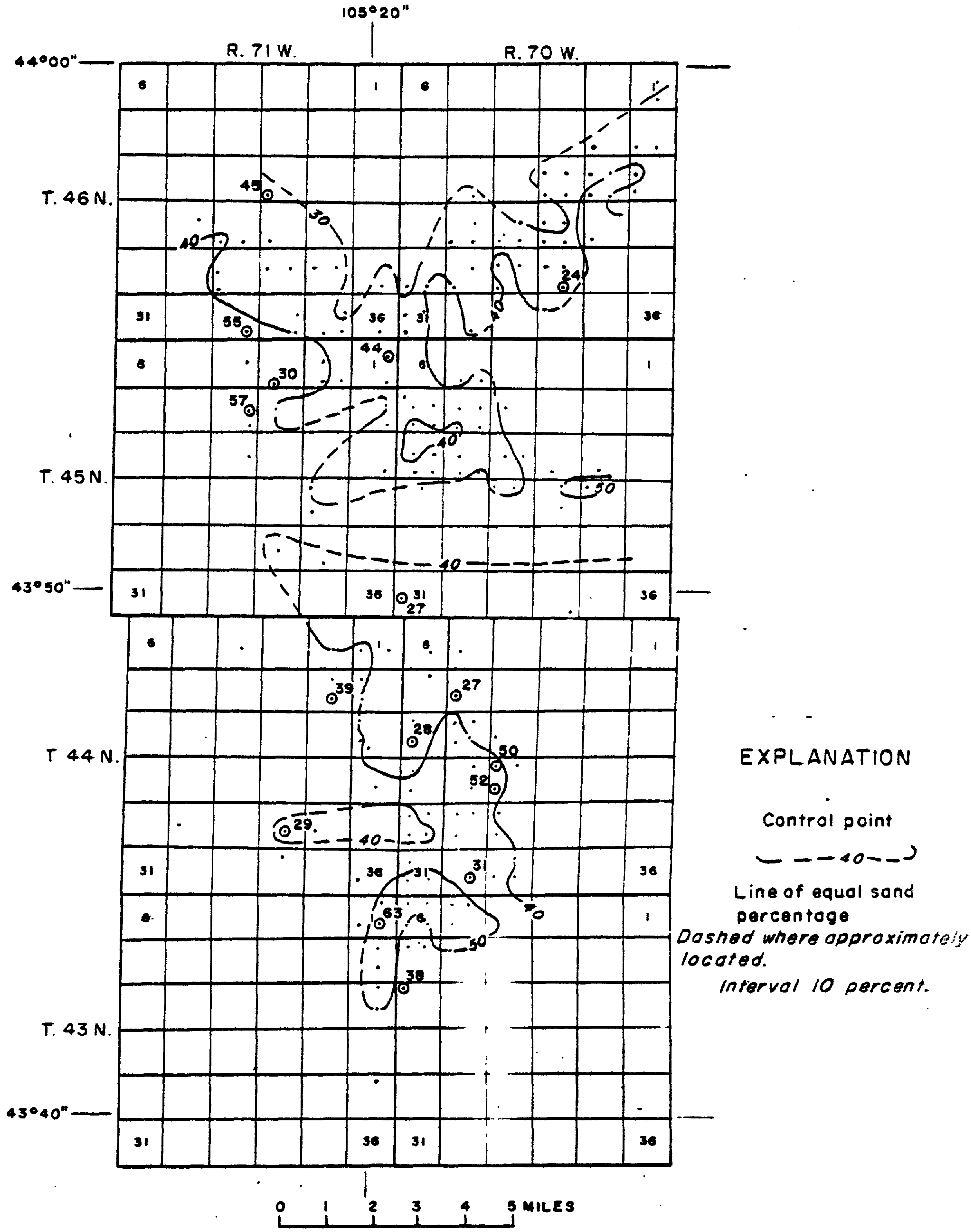

Figure 8.--Resistant beds in the Lance Formation, in percent of total thickness, in the Hilight oil field. Circled points with values are those that do not fit indicated line.

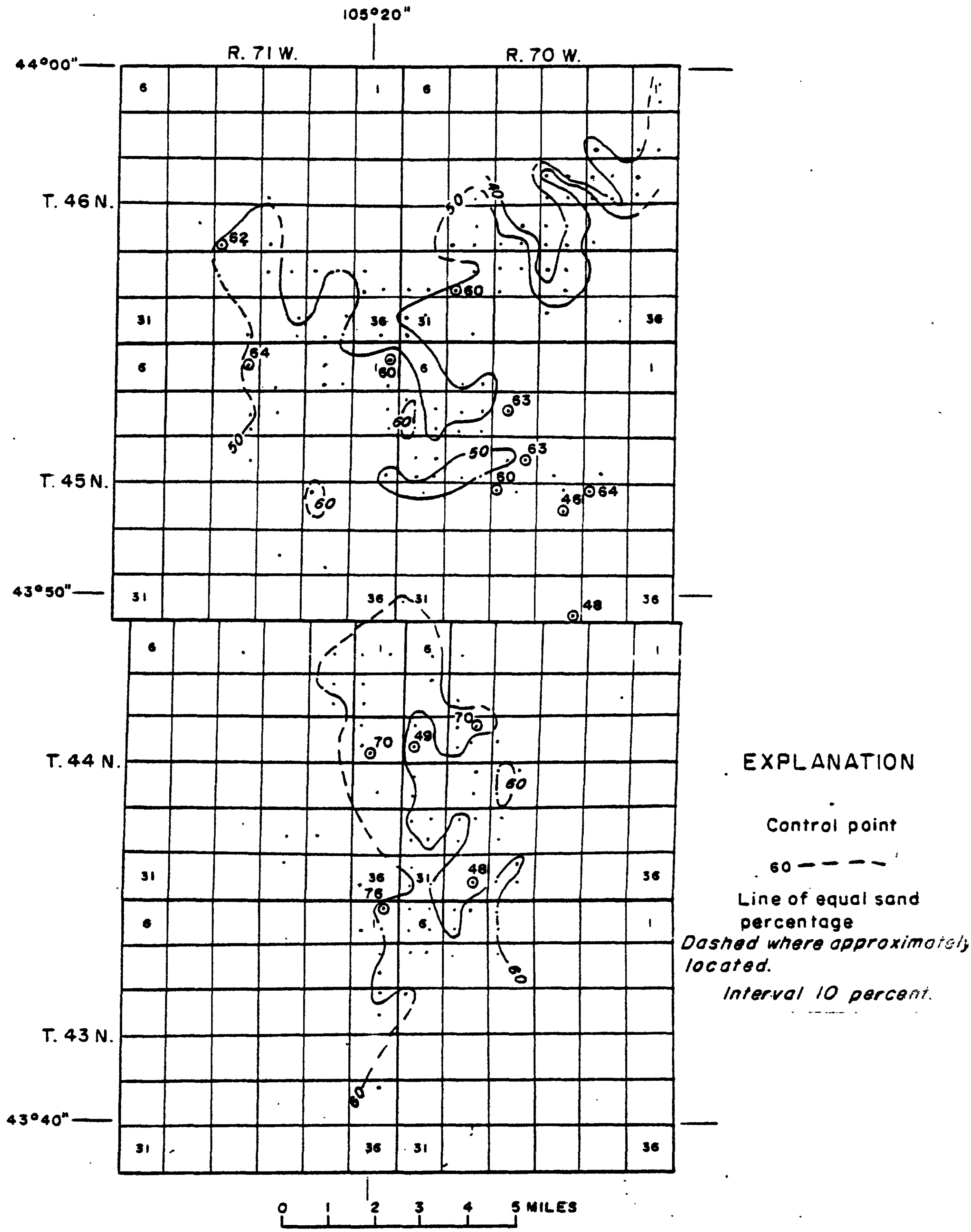

Figure 9.--Resistant beds in the Tullock Memeber of the Fort Union Formation, in percent of total thickness, in the Hilight oil field. Circled points with values are those that do not fit indicated line.

Hydrology

Movement of water

The direction of water movement is indicated by the direction of the slope of the potentiometric surface. Contours of the potentiometric surface are questionable in formations consisting of numerous lenticular aquifers, such as those in the Lance Formation, because most wells only partially penetrate the formations; therefore, the altitude of the water surface in the wells does not represent the same potentiometric surface throughout the area. Water wells in the Hilight oil field are perforated in the lower part of the Tullock, throughout the Lance, and in the upper part of the Fox Hills; therefore, the water level in each well is a composite of the levels in the separate aquifers in the formations. For simplification, the combination of the three aquifers is referred to as the Lance-Fox Hills aquifer.

Figure 10 shows the potentiometric surface based on water-level measurements in five of the nine wells. Preliminary data, provided by Inexco Oil Company, show the Grady Unit water-supply wells had produced about 7,000,000 ft^3 of water through February 1972. However, the cone of depression caused by pumping the Grady wells had not spread to the areas for which the contours are drawn. Well CHU WSW 1-1 had produced about 1,200,000 ft^3 of water through February 23, 1972; the other wells for which data were used in drawing the contours has been tested, but not used for water flooding. The water levels were measured March 1-2, 1972.

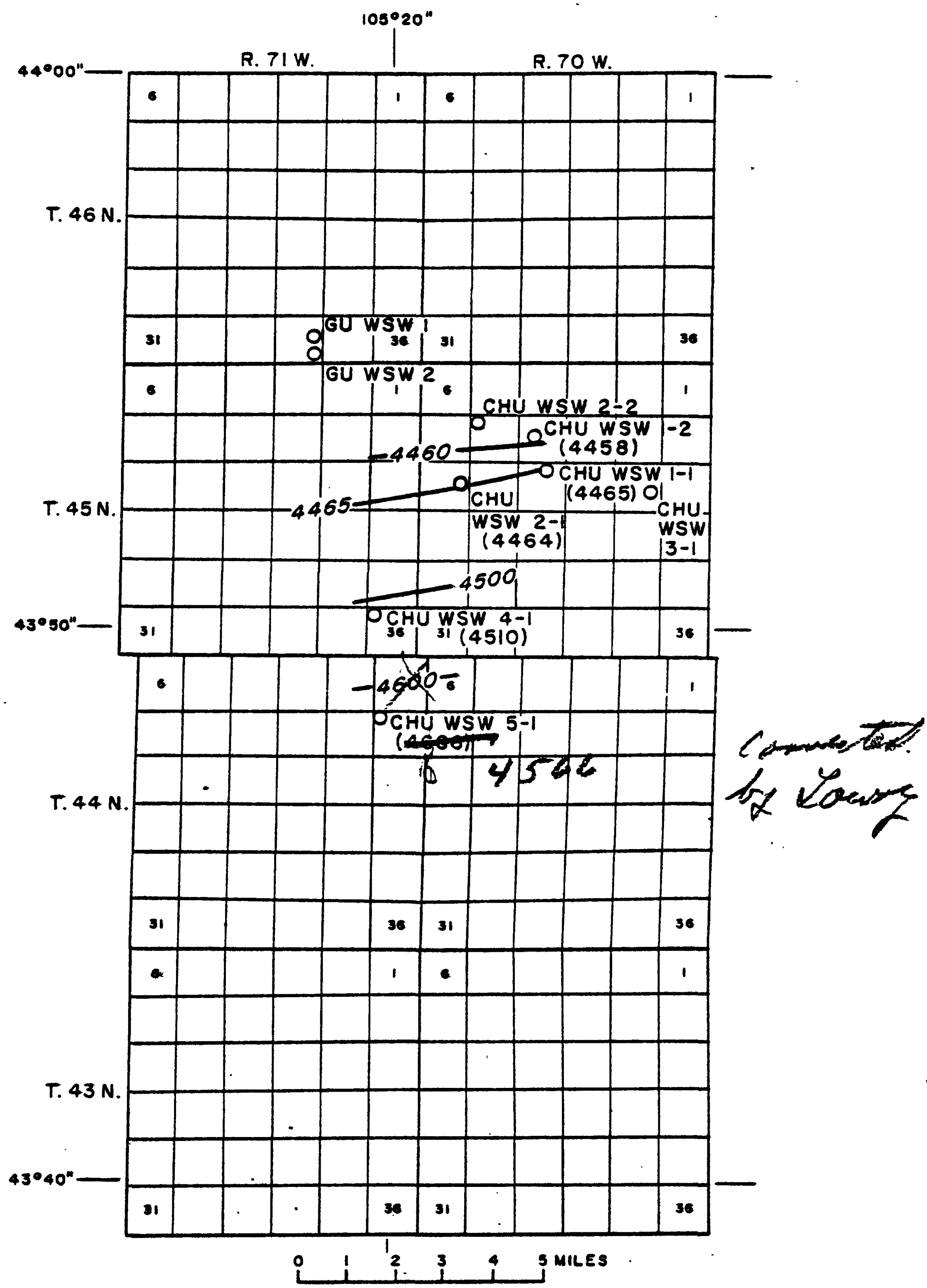

Figure 10.--Contours of the potentiometric surface in the Hilight oil field and location of all water wells tapping the Lance-Fox Hills aquifer. Contour interval, in feet above mean sea level, is irregular and is based on the five measurements in parentheses.

The potentiometric surface shown in figure 10 is based on scanty data; however, some tentative conclusions can be reached regarding the movement of water.

The head at any point is the net result of two components--that due to the aquifer boundaries and that due to vertical movement of water from, or into, adjacent formations. The maximum head observed in the Hilight oil field was 4,666 feet in well CHU WSW 5-1. If the observed head were due solely to two-dimensional flow, in this case parallel to the bedding, the only possible recharge areas would be where the altitude of the outcrop is greater than 4,666 feet, and discharge would occur in outcrop areas that are less than 4,666 feet in altitude.

A two-dimensional model was constructed to determine the head distribution that would result if flow were horizontal. The model was constructed by applying highly conductive silver paint to represent recharge and discharge areas on a map of the area cut from conductive paper. A thin line was painted along the edge of the outcrop where it is at an altitude of about 5,000 feet to represent recharge areas and at an altitude of about 4,500 feet to represent discharge areas. In addition, discharge that would occur from outcrops in Montana was modeled by making the State line a discharge boundary. A voltage was then applied and lines of equal potential across the model were drawn. (See fig. 11.)

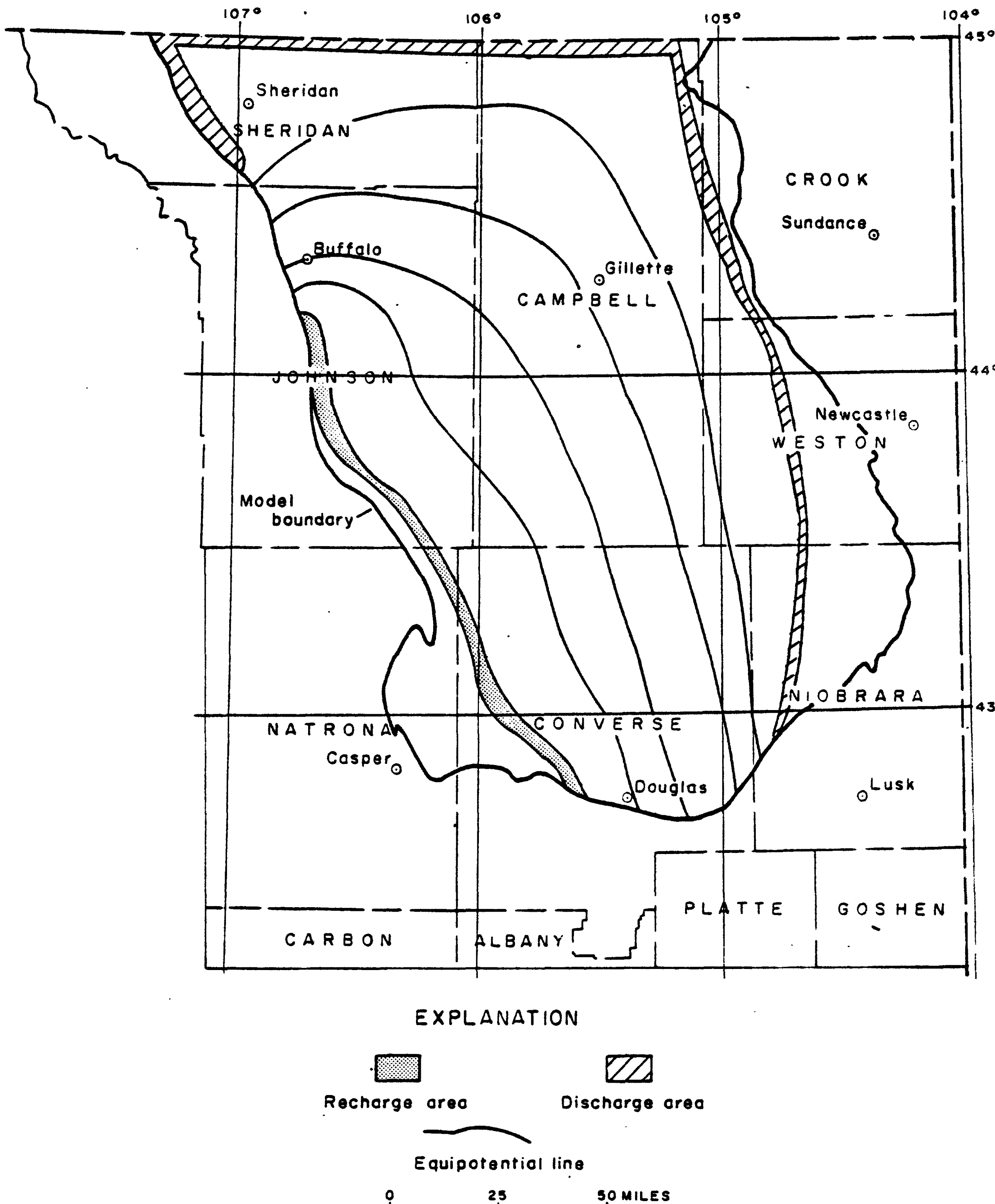

Figure 11.--Diagram of two-dimensional analog model.

In constructing this type of model, uniform transmissivity is assumed; however, transmissivity in the southern part of the basin may be greater because of the thickening of the Lance Formation. If this increase in transmissivity does occur, it could result in a southward shift of the potential lines of the model, thereby more nearly matching those shown for the Hilight oil field in figure 10. However, in either case of two-dimensional flow, flowing wells should occur where the formations are tapped in both the northeastern and southeastern parts of the basin, and the variation of the slope of the potentiometric surface in the Hilight oil field would have to be explained by changes in transmissivity. Flowing wells occur in the northeastern but not in the southeastern part of the basin, and the available geologic evidence does not indicate that the difference in transmissivity would be as great as the change in slope indicates. The two-dimensional model, therefore, does not adequately describe the potentiometric surface in the Hilight oil field.

Water levels in wells completed at shallower depth in the Wasatch Formation and the upper part of the Fort Union Formation are in the order of 100 feet higher than the water levels in the Lance-Fox Hills aquifer in the Hilight area; therefore, a positive head difference is present and vertical flow into the Lance-Fox Hills aquifer therefore is possible.

The northward slope of the potentiometric surface in the center of the basin is supported by contours drawn on the potentiometric surface for wells tapping the lower part of the Lance Formation and the Fox Hills Formation just north of Wyoming (written communication, 1972, Miller and Hopkins). It is tentatively concluded that recharge to the Lance-Fox Hills aquifer in the center part of the basin is largely from vertical movement of water from overlying formations. The simplified concept that recharge occurs in the outcrop and then moves down dip is probably valid only in the outcrop area.

Maximum possible drawdown due to pumping of wells in the central Hilight unit

The central Hilight water-flood operation, which started during the spring of 1972, is projected to last 10 years. The volume of water that will be required from the Lance-Fox Hills aquifer will decrease with time because of an increase in water produced with the oil. This water will be reinjected, thus reducing the requirement for water from the Lance-Fox Hills aquifer. The proposed pumping schedule from the Lance-Fox Hills aquifer is as follows:

Year of operation	Pumpage ($ft^3 day^{-1}$)
1	485,580
2	254,200
3	152,670
4	108,270
5	86,970
6	76,760
7	56,570
8	50,450
9	45,940
10	35,540

The average discharge for the 10 years will be about 135,295 $ft^3 day^{-1}$.

The drawdown of water levels in the vicinity of the Hilight oil field that would result from the central Hilight water-flood operation cannot be accurately predicted because the three-dimensional distribution of hydraulic conductivity in the region affected by the wells and the storage characteristics of the aquifer are not known. The construction of observation wells near the pumped wells would be necessary to obtain this information.

An assessment of the possible effect of the central Hilight water-flood operation on water levels can be made by determining limiting values of transmissivity and storage coefficient and using these values to determine the maximum possible drawdown that could occur. A judgement can then be made as to whether the cone of depression could be great enough to cause concern and warrant additional study, or whether the cone of depression would be of little consequence considering the large size of the aquifer.

Limiting values of transmissivity and storage coefficient can be obtained from data collected for wells CHU WSW 4-1 and CHU WSW 5-1. The wells are 2 miles apart. CHU WSW 4-1 began pumping at an average rate of 42,776 $ft^3 day^{-1}$ on May 28, 1972. The water level in CHU WSW 5-1 on July 10, 1972, 44 days after CHU WSW 4-1 started pumping, was 0.6 foot lower than the water level on June 12, 1972 but it was about 4 feet higher than the water level measured March 2, 1972. Therefore, the cone of influence caused by the pumping of CHU WSW 4-1 either had not spread the 2-mile distance between the two wells, or it had caused little effect on the water level at this distance. By arbitrarily assigning a small value for drawdown at the 2-mile distance, a limiting curve of transmissivities, with corresponding storage coefficients, can be determined by use of the Theis (1935) equation:

$$s = \frac{Q}{4\pi T} W(u) \qquad (1)$$

where

$$u = \frac{Sr^2}{4Tt} \qquad (2)$$

By substituting in equation (1) 1 foot for drawdown, s, 42,776 $ft^3 day^{-1}$ for discharge, Q, and then solving for W(u) for various values of transmissivity, T, a corresponding storage coefficient, S, can be determined from equation (2) by finding the value of u from the table of W(u) and u (Ferris and others, 1962, p. 96-97). The transmissivity and corresponding u from the table are substituted along with 10,560 feet for the radius, r, and 44 days for the time, t. Points below the resulting curve (fig. 12) will have drawdowns greater than 1 foot under the stated conditions and are excluded as possible combinations.

The range of transmissivity values can be further limited by estimating a minimum value from the specific capacities that are given in table 1 (p. 60) by multiplying the specific capacity by 1.4. The factor 1.4 is somewhat larger than that used by other investigators; however, the lower values are for water-table conditions, and Theis (1963, p. 333) states that in going from water table to artesian conditions there will be an increase in the constant. The smallest value of transmissivity for the nine wells estimated by this method is 36 $ft^2 day^{-1}$. The specific capacities in table 1 were computed from initial production data, and they are minimum values as the wells are reportedly becoming better developed with use. A transmissivity of 35 $ft^2 day^{-1}$ apparently would be a conservative estimate of the minimum and, therefore, all smaller values are excluded.

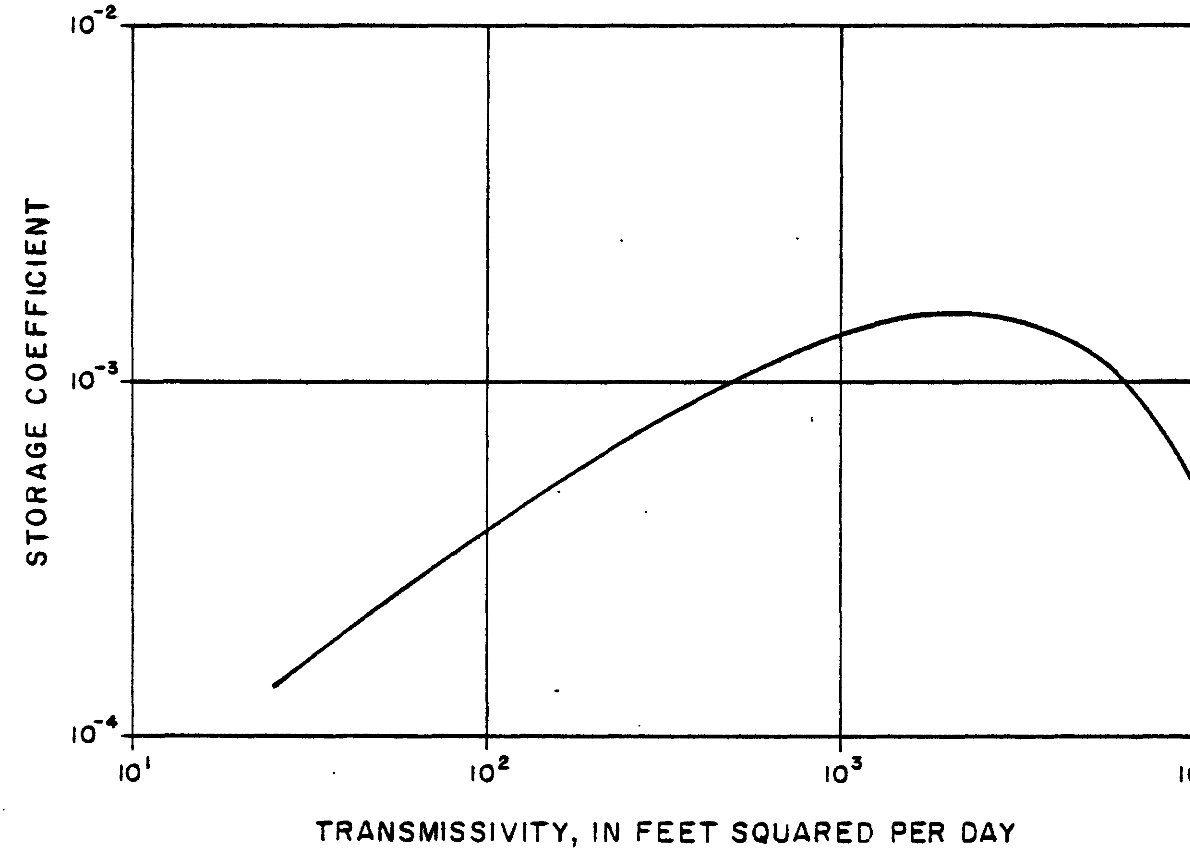

Figure 12.--Transmissivity and storage coefficient combinations that would result in 1—foot drawdown under conditions described in text.

Table 1.--Records of water wells tapping predominantly the Lance-Fox Hills aquifer in the Hilight oilfield, Campbell County, Wyo.

Number 1/	Location	Depth (feet)	Top of perforated interval (feet)	Number of perforations	Yield ($ft^3 day^{-1}$)	Drawdown (feet)	Specific capacity ($ft^3 day^{-1} foot^{-1}$) 2/
GU WSW 1	SE¼NE¼ sec. 34, T. 46 N., R. 71 W.	4,830	2,110	2,970	73,152	1,600	45.7
GU WSW 2	SE¼SE¼ sec. 34, T. 46 N., R. 71 W.	4,830	2,086	2,564	68,731	2,200	31.2
CHU WSW 1-1	NW¼NE¼ sec. 16, T. 45 N., R. 70 W.	4,453	2,030	2,781	68,503	1,050	65.2
CHU WSW 1-2	SE¼NW¼ sec. 9, T. 45 N., R. 70 W.	4,358	2,016	3,017	72,770	610	119.3
CHU WSW 2-1	SE¼NE¼ sec. 18, T. 45 N., R. 70 W.	4,510	2,042	2,843	72,995	584	124.3
CHU WSW 2-2	NW¼NW¼ sec. 8, T. 45 N., R. 70 W.	4,425	2,000	2,898	51,096	1,021	50.0
CHU WSW 3-1	NE¼SE¼ sec. 14, T. 45 N., R. 71 W.	4,750	2,000	2,598	44,385	1,707	26.0
CHU WSW 4-1	NW¼NW¼ sec. 36, T. 45 N., R. 71 W.	5,000	2,010	3,020	48,289	1,428	33.8
CHU WSW 5-1	NW¼NW¼ sec. 12, T. 44 N., R. 71 W.	5,110	2,000	3,050	59,519	1,728	34.0

1/ GU, Grady unit well; CHU, central Hilight unit well.

2/ Initial data. The specific capacity has reportedly improved for some wells.

Considering the 10-year life of the project, the maximum possible drawdown at 10 miles from pumping would occur for the smaller values of transmissivity because of the inverse relation of transmissivity and drawdown in equation (1), and the inverse relation between the rate of spread of the cone of depression and storage coefficient. From the preceding consideration, a transmissivity of 35 $ft^2 day^{-1}$ and storage coefficient of 1.8×10^{-4} are the values, within the limitations imposed by data of figure 12 and the minimum transmissivity estimated from specific capacity, that would result in the maximum possible drawdown being observed at a radius of 10 miles at the end of the water-flood project. These values were used to construct the distance-drawdown curve (fig. 13) by use of a modification of the Theis (1935) formula by Stallman (1962, p. 120) from the proposed pumping schedule.

The water wells are as much as 6 miles apart; therefore, the shape of the cone of depression in the area will depend upon the distribution of pumping among the seven wells. Figure 13 shows the drawdown that would result from one well pumping one-seventh of the proposed total volume of water for each year.

The Theis (1935) formula used to calculate the distance-drawdown curve is based on the assumption that the aquifer is homogeneous and isotropic, and that the cone of depression has not intercepted the recharge or discharge boundaries. If, in gross aspect, these assumptions are approximated, the drawdown should be less than that shown in figure 13 for the following reasons:

1. The initial assumption of 1-foot drawdown is in excess by an unknown amount.
2. The transmissivity is a minimum value.
3. Recharge from the overlying Fort Union Formation will occur.
4. Much of the water pumped during the 10-year period will be derived from the shale interbedded with the sandstone aquifers.

Discussion

The drawdown at any point within the cone of depression will be the summation of the effects of pumping each well. The drawdown at a given point, depending on the distance to each well and the discharge from each well, could be several times that indicated by figure 13.

Perhaps the most important of the four factors that will tend to result in less than the predicted drawdown is the effect of dewatering some of the shale. It is possible that a large percentage of the water pumped could come from the shale as the result of compaction in response to reduced pressure in the aquifer. Some subsidence will result from the compaction of the shale. Water levels will recover to nearly their original levels within a few years after pumping stops but the water lost from the shale probably will not be recharged.

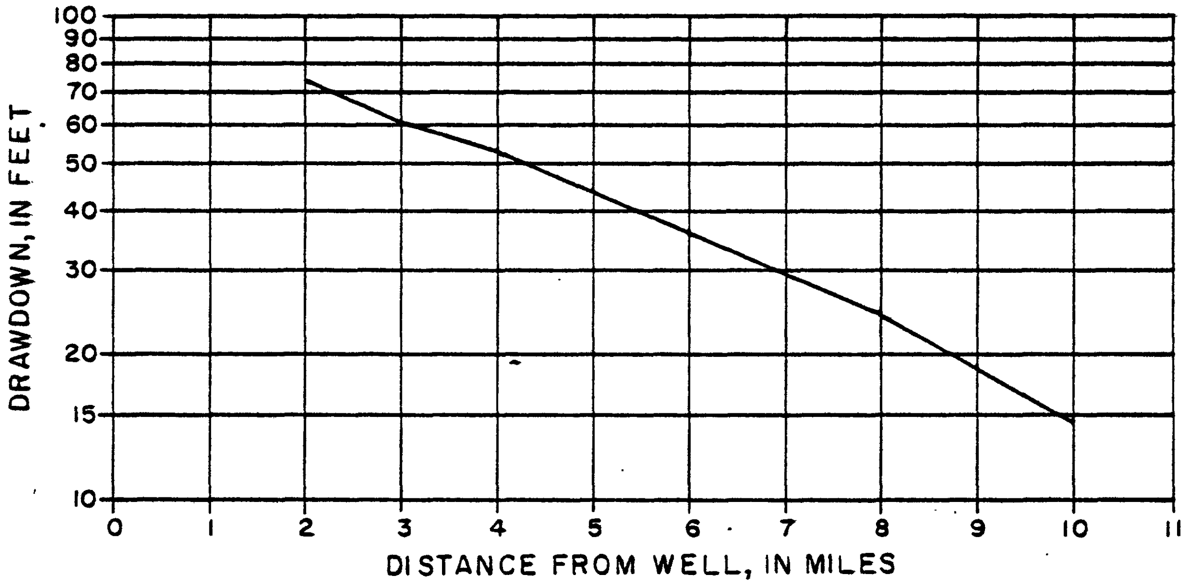

Figure 13.--Drawdown at the end of 10-year project resulting from one well pumping one-seventh of projected volume of water under conditions described in text.

Summary

The lithologic equivalents of the Fox Hills Sandstone, Lance Formation, and the Tullock Member of the Fort Union Formation, as they are mapped on the east side of the Powder River Basin, can be identified throughout the basin by use of geophysical logs. The thickening of the Lance and the Tullock to the south is apparent on both a regional basis and locally in an area as small as the Hilight oil field; however, no conclusions could be made concerning the spatial distribution of the aquifers within the formations.

Recharge to the Lance-Fox Hills aquifer in the Hilight oil field is largely by vertical movement, and there is no recharge to the Lance-Fox Hills in the Hilight area from the east side of the basin. Because there is vertical movement of water, the aquifers cannot be treated as separate aquifers.

Tests that would describe the aquifer properties could not be made; therefore, the original objective of extending quantitative data by use of geophysical logs was not achieved. The possible combinations of transmissivity and storage coefficient that would give the maximum possible drawdown at the end of the 10-year project are 35 $ft^2 day^{-1}$ and 1.8×10^{-4}, respectively. If, in gross aspect, the aquifer responds as a homogeneous, isotropic aquifer, then the maximum possible drawdown, resulting from the pumping of any one well, 10 miles from the well would be about 15 feet if the projected pumping were evenly distributed among the seven water wells in the central Hilight unit. The maximum possible drawdown at 10 miles could be several times larger depending on the actual distribution of pumping among the wells and the cumulative effect of the pumping of each well. The drawdown at any point computed by use of the distance-drawdown curve will be in excess of that which will occur because the transmissivity used in the calculations was a minimum; movement from overlying formations will occur; and water will be obtained by compaction of the shales. However, without data to describe the three-dimensional distribution of hydraulic conductivity and the storage coefficient, no better estimate of possible effects of pumping can be made.

Within a few years after pumping has ceased, the water levels will approach those present before pumping began. The only irreversable effect of pumping will be the compaction of the shale, with attendant subsidence, because the water derived from the shale will not be replaced.

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