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THE SIGNIFICANCE OF GEOLOGIC CONDITIONS IN NAVAL PETROLEUM RESERVE No. 3, WYOMING

BY
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WITH A SECTION ON THE
WATERS OF THE SALT CREEK-TEAPOT DOME UPLIFT

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By W. T. Thom, Jr., and Edmund M. Spieker

INTRODUCTION

SCOPE AND PURPOSE OF REPORT

Certain geologic facts and factors naturally entered into the formulation of governmental policy after the restoration to the Government of Naval Petroleum Reserve No. 3 (popularly known as the Teapot Dome Reserve), and it was to supply such information that this report was prepared for the United States Geological Survey, for transmission to the Navy Department. In order that conclusions may be stated most intelligibly, the writers will give an outline of the general geologic features of the area; an analysis of the factors controlling fluid movements within or from the reserve; and an enumeration of the tests needed to clear up points on which available evidence at the time the study was made was not conclusive. The location of the reserve is shown on Figure 1.

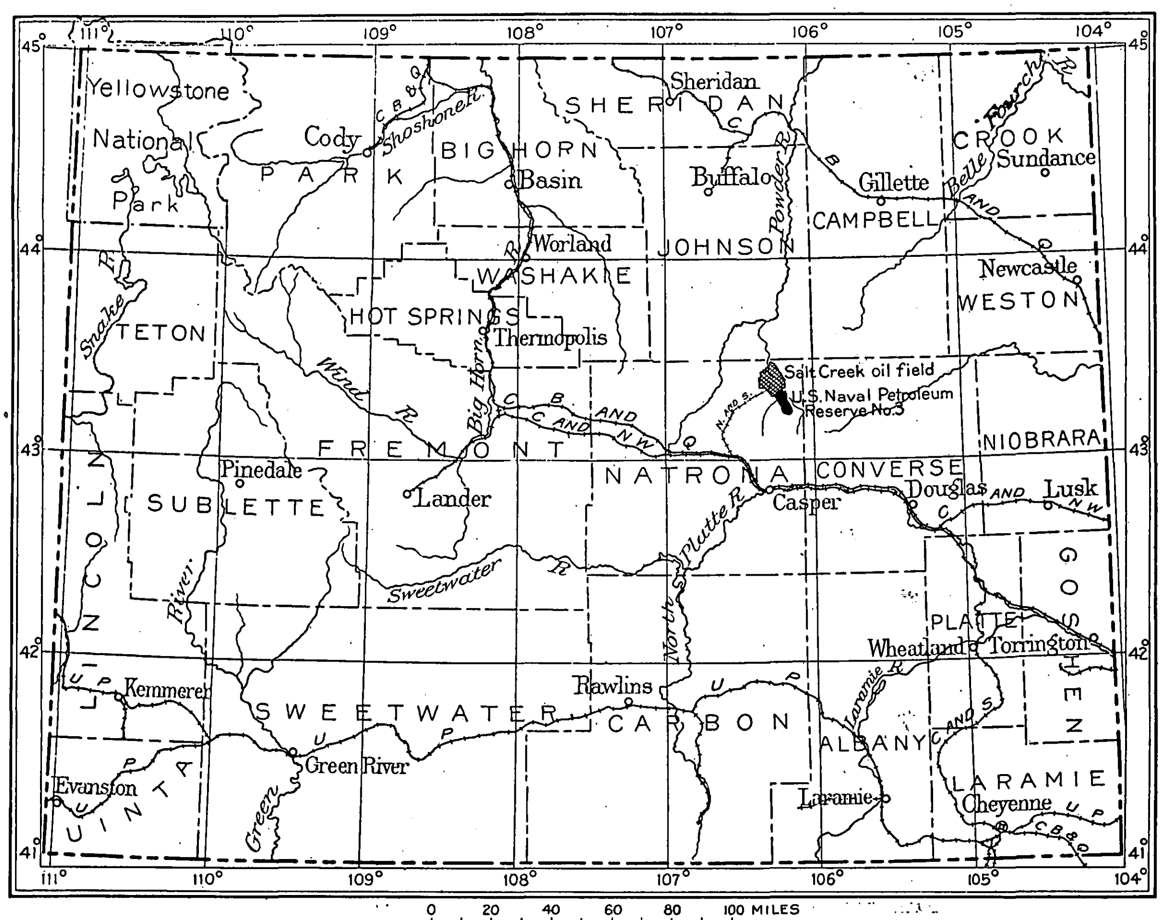


Figure 1.—Sketch map showing location of Naval Petroleum Reserve No. 3.

FIELD WORK AND ACKNOWLEDGMENTS

The work on which this report is based consisted of detailed field and office studies which occupied the greater part of the summer of 1927. During this period mapping was done with plane table and telescopic alidade on a scale of 1 inch to 1,000 feet, and wells, faults, and outcrops within the productive part of the Teapot field were located in detail; the inner Parkman "rim" encircling the field was mapped by stadia traverse; a detailed reconnaissance of the area between the rim and the productive field was made; and a detailed study was made of the portion of the Salt Creek field adjacent to the reserve. In addition, the records of the more than 1,600 "Second Wall Creek sand" wells in the Salt Creek field were reviewed and tabulated, and a graphic analysis was made of the dates of completion and relative yields of the wells drilled to this sand in the southern third of the Salt Creek field. (See pl. 13.) During the field work and subsequent compilation and interpretation of field results and of well and production records, the writers were assisted by Vladimir Pentegoff and were in frequent conference with J. W. Steele, of the Geological Survey, supervisor of oil and gas operations in the Rocky Mountain district; with Lieut. Commander W. H. Osgood, of the Navy Department, inspector of naval petroleum and oil-shale reserves; with J. S. Ross, petroleum engineer, Geological Survey, Midwest, Wyo.; and with other members of the Geological Survey's staff acquainted with development in the naval reserve or actively interested in the problems of oil production from the Salt Creek and Teapot fields. Great assistance and cordial cooperation were received from all of these gentlemen and are hereby acknowledged with sincere thanks. Acknowledgments are also due to Messrs. W. L. Connolly and J. W. Jordon, of the Mammoth Oil Co., for many courtesies and for practical aid; to officials of the Midwest Refining Co. and the New York Oil Co. for courteous and material assistance; to Capt. W. C. Stuart, of the Navy, and to Herman Stabler, chief of the conservation branch of the Geological Survey, who supervised the work of the writers in both field and office; and to Director George Otis Smith, of the Geological Survey, who took a personal interest in the work, authorizing it in the first place in his capacity as chairman of the President's Committee on Naval Oil Reserves.

PREVIOUS FIELD STUDIES

The geology of Naval Petroleum Reserve No. 3 has been studied in greater or less detail on numerous occasions, and many events in the development of the Salt Creek-Teapot area have been recorded by Wegemann,[1] by Estabrook and Rader,[2] and by Lewis.[3] Of the several early field studies of the Teapot area, those of particular importance were two made by Wegemann, described in the bulletins cited; a survey made in 1919–20 by Estabrook and Morley[4]; one made in 1921 by Case and Olds[5]; and studies of the Teapot field, more especially of the "saddle" area—made by Lewis[6] and Clapp[7] in 1923.

HISTORY OF DEVELOPMENT

According to the reports above cited, seepages or other indications of oil had been found in the Salt Creek region prior to 1880, and the existence of a former oil seepage in the NE. ¼ SW. ¼ sec. 22, T. 38 N., R. 78 W., just outside of the reserve boundary, was reported to Wegemann[8] by T. S. Harrison during or before 1911. Wegemann also noted occurrences of mineral wax or ozokerite within Naval Reserve No. 3 in 1915.

The history of oil discovery and development in the Salt Creek field, which adjoins reserve No. 3, has been summarized by Estabrook and Rader[9] as follows:

The presence of oil seeps at Salt Creek were reported before 1880, and the first drilling in the vicinity was done in 1889. The first development was in the Shannon pool, which is a small accumulation of oil in the Shannon sand on the north flank of the Salt Creek dome and about 1½ miles north of the point where that sand outcrops to form the escarpment around the dome. The Shannon pool was developed from 1889 to 1905. Shipments of oil began in 1893, and about 15,000 barrels were produced from 1893 to 1896; the oil was hauled by teams to Casper. Only minor amounts were shipped from 1897 to 1911, but during the latter part of 1912 a pipe-line connection was made and regular production was resumed. From January 1, 1913, to May, 1915, when the wells were finally shut down, 38,441 barrels of oil were produced and sold. The Shannon oil was green with a paraffin base but contained almost no gasoline. The Baumé gravity was only 24° and the initial boiling point 210°.

The discovery of shale oil in 1906 and of First sand oil in 1908 directed attention to the Salt Creek dome proper, and oil placer claims were soon staked out over most of the area now producing from the Second sand. Some of the early claimants seem to have failed to protect their titles fully, so that in some cases several claims were filed covering the same land. The situation was further complicated by the withdrawal from entry, on September 27, 1909, of all Government land in the Salt Creek field. The claimants under the old placer law took their cases to court, and the litigation continued until the passage of the leasing bill, in 1920, which made possible an equitable settlement of the disputes.

The early history of Salt Creek and Shannon and some of the intricacies of the land and title situation have been described by Wegemann. The first well that produced oil from the Frontier sands is now known as No. 15, on the SE. ¼ sec. 23, T. 40 N., R. 79 W. This well was completed on October 23, 1908, with an initial production of 200 barrels per day. The oil was found in the First Wall Creek sand at a depth of 1,000 feet. The existence of oil in commercial quantities in the Second Wall Creek sand was proved on August 26, 1917, by well No. 1 of the E. T. Williams Oil Co., in the SE. ¼ sec. 11, T. 39 N., R. 79 W. The Second sand was reached at a depth of 2,270 feet, after a heavy flow of water had been found in the First sand and cased off. * * *

[1] Wegemann, C. H., The Salt Creek oil field, Wyoming: U. S. Geol. Survey Bull. 452, pp. 38–40, 1911; Bull. 670, pp. 6–9, 1918.

[2] Estabrook, E. L., and Rader, C. M., History of production of Salt Creek oil field, Wyoming: Petroleum Development and Technology in 1925, pp. 200–204, Am. Inst. Min. and Met. Eng., 1925.

[3] Lewis, J. O., Report of the geological conditions of Teapot dome (Naval Reserve No. 3, Wyoming): Hearings before the Committee on Public Lands and Surveys, U. S. Senate, on S. Res. 282 and S. Res. 294, pp. 72–73, 1923.

[4] Estabrook, E. L., and Morley, H. T., Structure contour map, Salt Creek and Teapot domes, Natrona County, Wyo.; prepared for Midwest Refining Co., under supervision of Harrison & Eaton, consulting geologists, 1920.

[5] Case, W. B., and Olds, T. H., Structure contour map, Salt Creek and Teapot domes, Natrona County, Wyo., under supervision of Fisher & Lowrie, August, 1921.

[6] Lewis, J. O., op. cit., pp. 69–110.

[7] Clapp, F. G., Report on Teapot Dome Naval Reserve No. 3: Idem, pp. 111–154.

[8] Wegemann, C. H., op. cit. (Bull. 452), p. 67.

[9] Estabrook, E. L., and Rader, C. M., op. cit., pp. 200–203.

Oil is reported to have been found in the Third Wall Creek sand in E. T. Williams well No. 2, SE. ¼ sec. 11, T. 39 N., R. 79 W., in 1917 or 1918, but no record seems to have been made of the amount. In the fall of 1923 the same company obtained what is thought to be Third sand oil in well No. 25A, on the SW. ¼ sec. 11, T. 39 N., R. 79 W., but it was accompanied by water (probably First sand water leaking from above) and was finally plugged off. The first important production from the Third sand in another part of the field was from well No. By-12 of the Producers & Refiners Corporation near the center of the NW. ¼ sec. 20, T. 39 N., R. 78 W., brought in on March 11, 1924. Three other producers have been found in the same vicinity, but in general less than 25 per cent of the wells that have been drilled to the Third Wall Creek sand have obtained commercial production.

Several important seepages of oil from the shale were found by the early investigators, but the first occurrence of crevice oil in a well was in the Iba, now called No. 13, on the southwest corner of sec. 22, T. 40 N., R. 79 W., which was drilled in December, 1906.

Shale crevice oil above the First sand may be found anywhere in the field, as well as over a considerable area across the syncline to the west. Between the First and Second sands it seems to be found only near the top of the dome. Shale oil has also been found between the Second and Third sands, and to a depth of 500 feet below the Third sand.

Lewis[10] states that between 1909 and 1915

> A few wells of negligible value had been drilled to the Shannon sand in the Teapot dome, but that was all the development that had taken place there (within the reserve) and constituted the only tangible evidence that it was actually oil-bearing.

Prior to the leasing of the reserve to the Mammoth Oil Co., on April 7, 1922, some dozen or more wells of appreciable depth had been put down just outside the eastern or western borders of the reserve, but without yielding promise of oil or gas production.

On February 2, 1920, leases were issued by the Department of the Interior on the SE. ¼ sec. 17 and the E. ½ SW. ¼ sec. 20, T. 39 N., R. 78 W., both of which directly adjoin the reserve, and on June 15, 1921, rights to leases covering the remaining tracts adjoining the northwestern boundary of the reserve (see fig. 2) were sold at public auction. Leases covering these tracts were issued during 1921 or in February and March, 1922.

The map of the Teapot area made by Estabrook and Morley in 1920 indicated that the structural saddle between the Teapot and Salt Creek domes lay within the naval reserve, and the map made by Case and Olds in the August (1921) following the sale of leases along the reserve boundary confirmed this indication. Moreover, it has been reported[11] that an old well drilled about 1918 by the Wolverine Oil Co. in the NW. ¼ sec. 9, T. 39 N., R. 78 W., and at first regarded as a water well was later repaired and yielded a small oil production from the "Second Wall Creek sand," which was reached at an altitude of about 2,050 feet above sea level, or lower than the position of the same sand in the saddle between the Salt Creek and Teapot domes.

Largely on the basis of the facts above set forth Wegemann,[12] as chief geologist for the Midwest Refining Co., submitted a memorandum in the fall of 1921, pointing out to the Government the possibility of loss of oil from the naval reserve through wells drilled near the northwestern boundary and recommending the development of the reserve as a unit. After the submission of Wegemann's memorandum, K. C. Heald, of the Geological Survey, made a reconnaissance visit to the Teapot dome and checked the new determination of the position of the Salt Creek-Teapot saddle, reporting this finding in a memorandum[13] which also agreed with Wegemann's prediction that ultimately some oil would be lost from the reserve through nearby drilling, although holding that such loss was not imminent.

The naval reserve was leased to the Mammoth Oil Co. on April 7, 1922, a few days after the completion of a 2,000-barrel oil well[14] (now Prairie well No. 1) in the NW. ¼ sec. 20, T. 39 N., R. 78 W., about a quarter of a mile from the reserve boundary. At the time the lease was signed an overproduction of oil existed in Wyoming, and an agreement was in effect in the Salt Creek field limiting each operator's output to 35 per cent of the rated capacity of his wells. Notwithstanding this situation an active development campaign was undertaken in the northern part of the reserve, although the holders of leases adjoining the reserve attempted[15] "to get the Mammoth Oil Co. to subscribe to their conservation policy of equitably prorating production among the producers of Salt Creek, because they held the Mammoth Oil Co., drawing upon its wells to 100 per cent capacity, would drain oil from their wells across the line that were producing at the rate of only 35 per cent." Lewis also further stated:[16]

> It is likely that this part of the [Salt Creek] field would not have been developed so rapidly had drilling not been stimulated by drilling on the reserve.

The dates of commencement and completion of the wells offsetting the reserve boundary are given in Table 1, and the locations of these wells are shown by Plates 7 and 8.

[10] Lewis, J. O., op. cit., p. 73.

[11] Tough, F. B., Memorandum to the Secretary: 67th Cong., 2d sess., S. Doc. 210, p. 39, 1923.

[12] Wegemann, C. H., A report on the position of the dividing line between the Salt Creek and Teapot domes: 67th Cong., 2d sess., S. Doc. 210, pp. 36-37, 1923.

[13] Heald, K. C., Memorandum to Director through chief geologist: Idem, pp. 37-38.

[14] Tough, F. B., op. cit., p. 39.

[15] Lewis, J. O., op. cit., p. 87.

[16] Idem, p. 90.

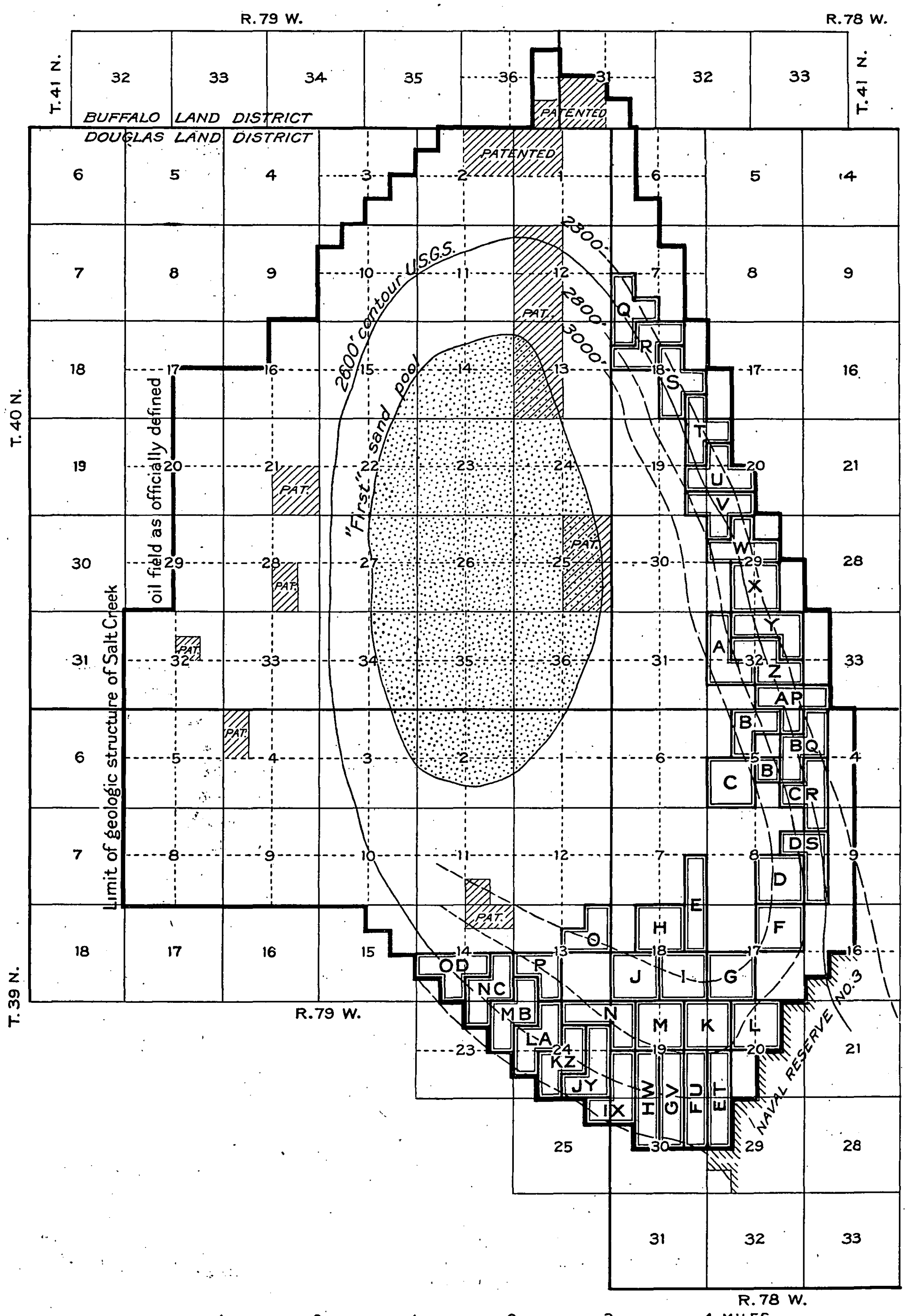


FIGURE 2.—Map showing location of leases sold at auction June 15, 1921. Tracts at 33⅓ per cent royalty, A to P, inclusive. Tracts at 25 per cent royalty, Q to Z and AP to OD, inclusive

TABLE 1.—*Dates of completion of Mammoth Oil Co.'s wells along northwestern boundary line of reserve, as compared with dates of completion of wells on adjacent leased lands in Salt Creek oil field*

Wells in Salt Creek field				Mammoth Oil Co.'s offset wells		
No.	Location (T. 39 N., R. 78 W.)	Begun	Completed	No.	Begun	Completed
Argo No. 4	SW. ¼ sec. 16	July 5, 1922	Nov. 26, 1922	201–21	July 11, 1922	Jan. 27, 1923
Argo No. 3	SE. ¼ sec. 17	Oct. 12, 1922	Dec. 29, 1922	102–20	Sept. 19, 1922	Dec. 10, 1922
Argo No. 4	do	June 15, 1923	Aug. 28, 1923			
Argo No. 5	do	May 19, 1923	July 13, 1923	103–20	Mar. 31, 1923	June 4, 1923
Producers & Refiners No. 8	NE. ¼ sec. 20	Apr. 7, 1923	May 29, 1923			
Producers & Refiners No. 2	do	June 26, 1922	Sept. 6, 1922	101–20	Aug. 10, 1922	Dec. 20, 1922
				105–20	Apr. 27, 1923	July 27, 1923
Producers & Refiners No. 9	do	May 20, 1923	July 7, 1923	407–20	May 27, 1923	July 11, 1923
				408–20	May 30, 1923	Aug. 24, 1923
Producers & Refiners No. 5	do	Nov. 19, 1922	Feb. 3, 1923			
Producers & Refiners No. 7	NW. ¼ sec. 20	Mar. 8, 1923	May 8, 1923	401–20	Sept. 26, 1922	May 1, 1923
Argo No. 3	SW. ¼ sec. 20	June 11, 1923	July 28, 1923			
Argo No. 5	do	Mar. 25, 1924	June 3, 1924	409–20	May 15, 1924	June 30, 1924
Argo No. 6	do	Apr. 23, 1924	June 18, 1924	410–20	May 26, 1924	July 17, 1924
				402–20	Feb. 20, 1923	May 12, 1923
Argo No. 2	do	Mar. 19, 1923	May 17, 1923	101–29	Apr. 1, 1923	June 5, 1923
				201–29	July 20, 1922	Nov. 29, 1922
Argo No. 4	do	Apr. 4, 1923	June 2, 1923			
Ohio No. 4	do	May 2, 1923	Aug. 4, 1923	203–29	Mar. 23, 1923	June 24, 1923
Ohio No. 3	NW. ¼ sec. 29	Mar. 10, 1923	June 20, 1923			
Ohio No. 5	do	Apr. 10, 1923	June 15, 1923	204–29	Apr. 5, 1923	May 24, 1923

Active drilling within the reserve continued through 1923, and three wells were completed during the first half of 1924. The salient facts regarding the wells drilled are given in Table 2, and the dates of completion of the wells and their relative yields of oil and gas are shown graphically in Plate 13.

TABLE 2.—*Well history of Naval Petroleum Reserve No. 3*

[Compiled from well logs by F. M. Cole, May, 1927]

Well No.	Date begun	Date completed	Altitude of well mouth (feet)	Shannon sand		"First Wall Creek sand"		"Second Wall Creek sand"		Shale production
				Depth to top (feet)	Thickness (feet)	Depth to top (feet)	Thickness (feet)	Depth to top (feet)	Thickness (feet)	
6A NE 20	June 23, 1922	Aug. 2, 1922 [a]	--------	35	120	2,268	102	--------	------	
301-2	Sept. 17, 1922	Oct. 5, 1922	5,154	500	115	--------	------	--------	------	Show at 1,435 feet, production at 1,515 feet.
401-33	Sept. 4, 1922	Nov. 17, 1922	5,145	415	105	2,624	116	2,989	51	Show at 1,685 feet.
201-29	July 20, 1922	Nov. 29, 1922	5,012	100	135	2,375	105	2,756	30	
102-20	Sept. 19, 1922	Dec. 10, 1922	4,991	95	115	2,265	95	2,680	28	
301-3	Aug. 30, 1922	Dec. 14, 1922	5,180	296	110	2,490	97	2,914	45	Show at 1,410 feet.
101B-20	Aug. 10, 1922	Dec. 20, 1922	5,025	--------	------	2,205	125	2,624	36	
201-21	July 11, 1922	Jan. 27, 1923	4,981	100	145	2,260	160	2,702	22	
201-3	Sept. 2, 1922	Feb. 18, 1923	5,215	415	105	2,595	105	3,048	60	Good show at 1,225 feet.
101-28	Sept. 21, 1922	Feb. 20, 1923 [b]	5,021	380	130	2,610	116	--------	------	Show at 1,225 feet.
301-14	Sept. 26, 1922	----do--------	5,239	630	105	2,775	95	3,260	15	Show of gas at 2,150 feet.
201-2	Sept. 15, 1922	Mar. 3, 1923	5,122	565	130	2,779	118	3,198	16	
201-34	Sept. 17, 1922	Mar. 4, 1923	5,106	505	55	2,620	95	2,953	22	
201-28	Sept. 3, 1922	Mar. 9, 1923	5,006	175	120	2,426	101	2,830	62	
401-28	Aug. 11, 1922	Mar. 21, 1923	5,067	248	47	2,570	70	2,868	55	
301-21	July 26, 1922	Mar. 22, 1923	4,991	212	103	2,470	105	2,862	16	Show at 890–905 feet.
301-27	Aug. 26, 1922	Apr. 26, 1923	5,058	405	35	2,605	155	3,033	60	Show at 3,270–3,285 feet.
301-28	Aug. 20, 1922	Apr. 29, 1923	5,082	275	70	2,560	110	2,929	50	Sandy at 1,900–1,910 feet.
401-20	Sept. 26, 1922	May 1, 1923 [c]	5,052	5	140	2,245	75	2,661	35	
401-10	Sept. 21, 1922	May 4, 1923	5,192	295	95	2,415	110	2,857	63	1,610–1,615 feet; 50 barrels daily at 2,195 feet.
101-15	Sept. 24, 1922	May 5, 1923	5,244	405	110	2,570	80	2,986	43	139 barrels at 1,300 feet.
402-20	Feb. 20, 1923	May 12, 1923	5,014	95	110	2,355	135	2,735	7	
106-29	Apr. 28, 1923	----do--------	4,980	140	150	--------	------	--------	------	657 feet.
101-10	Nov. 1, 1923	May 13, 1923 [d]	5,217	300	110	2,540	70	2,940	50	625, 1,020 and 2,052 feet.
203-3	Apr. 13, 1923	May 16, 1923	5,197	410	100	--------	------	--------	------	Show at 840 feet; production at 2,010 feet.
204-29	Apr. 5, 1923	May 24, 1923	5,016	161	89	2,440	80	2,826	27	
302-3	Apr. 1, 1923	June 1, 1923	5,199	317	93	2,535	120	2,933	57	Show at 700 feet and 1,635 feet.
103-20	Mar. 31, 1923	June 4, 1923	5,018	90	110	2,205	85	2,638	20	
101-29	Apr. 1, 1923	June 5, 1923	5,003	120	105	2,365	165	2,756	42	
204-3	May 14, 1923	June 6, 1923	5,170	405	110	--------	------	--------	------	1,405–1,410 feet.
301-11	Sept. 9, 1922	June 7, 1923	5,165	430	110	2,640	100	3,080	17	Show at 1,515 and 1,630 feet.
203-34	Apr. 20, 1923	June 15, 1923	5,088	475	105	2,450	120	2,826	72	
202-34	Apr. 7, 1923	June 20, 1923	5,093	489	76	2,485	140	2,890	26	
103-33	May 13, 1923	June 21, 1923	5,132	235	55	2,445	100	2,831	20	
203-29	Mar. 23, 1923	June 24, 1923	5,020	105	75	2,375	95	2,763	25	Show of gas at 365 feet, of oil at 2,060 feet.
202-3	Apr. 19, 1923	June 26, 1923	5,232	416	120	2,620	70	3,009	65	Show at 680–690 feet.
101-33	June 3, 1923	June 27, 1923	5,154	485	115	--------	------	--------	------	Sandy at 1,910–1,922 feet.
104-33	May 15, 1923	-----do-------	5,119	210	130	2,465	135	2,854	14	
107-29	Apr. 27, 1923	July 4, 1923	4,974	80	150	2,345	85	2,739	35	
407-20	May 27, 1923	July 11, 1923	5,056	15	85	2,210	105	2,673	31	
103-29	Apr. 18, 1923	July 12, 1923	4,988	150	140	2,475	[e] 85	2,832	18	
105-29	May 5, 1923	-----do-------	4,985	155	145	2,425	105	2,939	25	
204-34	May 21, 1923	-----do-------	5,093	425	90	2,420	180	2,804	76	
403-20	May 7, 1923	July 22, 1923	5,012	105	100	2,306	114	2,713	36	
404-20	May 10, 1923	-----do-------	5,004	110	62	2,280	150	2,730	35	Show of gas at 335 feet.

[a] Drilling suspended by United States marines.
[b] Drilling suspended.
[c] Diamond drilling completed Sept. 14, 1925.
[d] Diamond drilling suspended Feb. 22, 1924.
[e] Logged sandy shale at 2,325–2,475 feet.

TABLE 2.—*Well history of Naval Petroleum Reserve No. 3*—Continued

Well No.	Initial production of oil (barrels)	Gas (M cubic feet)	Rock pressure (pounds)		Total depth (feet)	Remarks
			Initial	Later		
6A NE 20					2, 388	Mutual well, plugged and abandoned July 5, 1924.
301–2	28, 000–30, 000				1, 520	Shale well.
401–33	45				3, 041	
201–29	383. 5				2, 788	Stray sand at 2,490–2,530 feet, dry.
102–20	84. 3				2, 710	Plugged back to 2,704 feet.
301–3		24, 000	960	Oct., 1924, 735	2, 959	
101B–20	155. 5				2, 661	
201–21	36. 9				2, 724	Plugged back to 2,717 feet.
201–3	121. 2				3, 110	Test Mar. 6, 1923, showed 30 barrels of oil, 1,700 M cubic feet of gas.
101–28					2, 815	
301–14					3, 275	15 feet in "Second Wall Creek sand," hole filled 2,500 feet with water.
201–2	100 per cent water.				3, 214	Do.
201–34	252. 9				2, 975	Plugged back to 2,972 feet. Bottom water at 2,973 feet.
201–28	10. 5				2, 895	
401–28	105. 0				2, 925	
301–21	Mostly water				2, 880	300 feet of oil, 2,200 feet of water in hole. Plugged and abandoned.
301–27					3, 340	
301–28	50				3, 108	5 bailers of oil an hour at 1,900 feet. Plugged back to 2,974 feet.
401–20	68. 5				2, 881	"Third Wall Creek sand," at 2,873–2,881 feet; oil and gas.
401–10		17, 500	1, 050	June, 1926, 690	2, 920	1 bailer of oil an hour at 1,750 feet.
101–15		60, 000	√1, 050	June, 1926, 680	3, 025	Shale oil also at 1,900, 2,215, and 2,305 feet.
402–20	8, 000				2, 742	
106–29					657	Shale well.
101–10	312				3, 050	Shale producer June 13 to Nov. 13, 1923.
203–3	124				1, 165	
204–29	266. 16				2, 853	Plugged back to 2,838 feet, bottom water.
302–3		13, 000	1, 050	Aug. 1925, 680	3, 000	
103–20	120				2, 658	
101–29					2, 798	Bottom water; plugged back to 2,787 feet.
204–3					1, 410	Shale well.
301–11	150				3, 097	
203–34		14, 000			2, 906	Shale break at 2,876–2,878 feet.
202–34	45				2, 916	
103–33		56, 990	√1, 050	Apr., 1924, 850 June, 1926, 460	2, 831	
203–29	√200				2, 788	
202–3		16, 096		Apr., 1924, 840 Aug., 1925, 670	3, 075	
101–33	120				1, 922	Shale well.
104–33		39, 126			2, 868	Dry gas.
107–29	40				2, 775	
407–20	125				2, 704	Stray sand at 2,330–2,347 feet.
103–29	40				2, 850	
105–29	50				2, 864	
204–34		7, 000	1, 060	Aug., 1925, 525	2, 885	Dry gas.
403–20					2, 749	600 feet of oil in hole.
404–20	205				2, 765	Reported good flow of oil and gas in first 4 feet of "Second Wall Creek sand." 700 barrels after being shot.

√ Estimated.

TABLE 2.—*Well history of Naval Petroleum Reserve No. 3*—Continued

Well No.	Date begun	Date completed	Altitude of well mouth (feet)	Shannon sand		"First Wall Creek sand"		"Second Wall Creek sand"		Shale production
				Depth to top (feet)	Thickness (feet)	Depth to top (feet)	Thickness (feet)	Depth to top (feet)	Thickness (feet)	
401–29	July 2, 1923	July 23, 1923	5, 036	220	95	--------	------	--------	------	1,740–1,745 feet.
105–20	Apr. 27, 1923	July 27, 1923 [g]	5, 006	10	120	2, 210	75	2, 673	27	
402–28	June 22, 1923	Aug. 2, 1923	5, 082	240	100	2, 450	180	2, 865	47	
104–29	Apr. 17, 1923	Aug. 3, 1923	4, 982	170	130	2, 485	90	2, 866	26	
102–33	June 13, 1923	Aug. 7, 1923	5, 149	300	90	2, 465	110	2, 844	58	
201–10	Sept. 25, 1922	Aug. 8, 1923	5, 238	405	145	2, 615	95	3, 001	60	840, 1,120, 1,820, and 2,000 feet.
404–28	June 19, 1923	Aug. 10, 1923	5, 080	190	130	2, 450	240	2, 828	48	
403–28	June 26, 1923	Aug. 18, 1923	5, 060	270	110	2, 480	125	2, 870	53	
408–20	May 30, 1923	Aug. 24, 1923 [h]	5, 029	15	110	2, 227	98	2, 666	28	
402–29	Aug. 8, 1923	Aug. 24, 1923	5, 032	235	110	--------	------	--------	------	1,438–1,453 feet.
301–34	Oct. 2, 1923	----do--------	5, 153	375	125	2, 600	120	2, 995	50	Show at 1,920–1,970 feet.
305–28	Aug. 6, 1923	Aug. 27, 1923	5, 055	221	94	--------	------	--------	------	Sandy at 1,597–1,630 feet.
404–33	Aug. 13, 1923	Aug. 28, 1923	5, 160	430	115	--------	------	--------	------	Sandy at 1,105–1,161 feet.
306–28	Aug. 12, 1923	Aug. 29, 1923	5, 040	195	115	--------	------	--------	------	1,532 feet.
405–20	June 20, 1923	Sept. 3, 1923	4, 997	117	143	2, 300	100	2, 750	36	Show at 1,400 and 1,580 feet.
403–33	Aug. 19, 1923	Sept. 9, 1923	5, 139	445	100	--------	------	--------	------	2,024–2,076 feet.
402–33	July 25, 1923	Sept. 11, 1923 [i]	5, 162	470	130	2, 570	210	2, 882	63	Show at 1,885–1,890 feet.
102–10	Sept. 24, 1923	Sept. 15, 1923	5, 218	310	100	--------	------	--------	------	2,097 feet.
303–21	July 12, 1923	Sept. 17, 1923	4, 991	140	100	2, 347	101	2, 755	35	Show at 1,391–1,410 feet.
406–20	July 7, 1923	Sept. 19, 1923	4, 999	110	100	2, 320	80	2, 723	35	Show of gas at 710 feet.
110–29	Aug. 14, 1923	Sept. 24, 1923	4, 967	115	135	2, 355	95	2, 775	39	Show at 870 feet.
302–21	July 30, 1923	Sept. 28, 1923	4, 999	140	95	2, 355	85	2, 769	38	Show at 1,080 feet.
101–3	Aug. 5, 1923	Oct. 7, 1923	5, 171	400	120	2, 615	105	3, 024	38	
111–29	Aug. 22, 1923	Oct. 7, 1923	5, 025	185	135	2, 450	100	2, 855	37	Show at 2,000 feet.
202–28	Aug. 16, 1923	Oct. 12, 1923	4, 964	150	100	2, 420	75	2, 764	30	
303–28	July 25, 1923	Oct. 13, 1923	5, 049	225	105	2, 440	165	2, 870	41	
109–29	July 19, 1923	Oct. 18, 1923	4, 965	95	155	2, 350	135	2, 753	42	
304–28	Aug. 2, 1923	Oct. 22, 1923	5, 072	225	130	2, 470	130	2, 884	51	
203–28	Aug. 20, 1923	Oct. 27, 1923	4, 974	175	95	2, 380	118	2, 776	39	
108–29	Aug. 4, 1923	Oct. 27, 1923 [j]	4, 969	90	85	2, 360	110	2, 750	61	
405–28	Sept. 9, 1923	Oct. 30, 1923	5, 049	275	110	2, 475	170	2, 887	52	
201–11	Aug. 1, 1923	Nov. 1, 1923	5, 177	410	100	2, 575	100	3, 000	60	
201–33	Sept. 4, 1923	Nov. 6, 1923	5, 150	350	125	2, 550	145	2, 963	63	
303–27	Sept. 12, 1923	Nov. 27, 1923	5, 069	310	130	2, 510	185	2, 895	75	
302–27	Sept. 21, 1923	Jan. 20, 1924	5, 070	250	110	2, 515	185	2, 889	54	
304–21	Sept. 20, 1923	Feb. 13, 1924 [k]	4, 983	75	105	2, 325	100	2, 742	27	
302–28	Aug. 22, 1923	Mar. 6, 1924 [k]	5, 094	225	90	2, 510	80	2, 854	46	
205–28	Dec. 7, 1923	Apr. 20, 1924 [k]	5, 018	160	150	2, 425	135	2, 832	40	Show at 580 and 890 feet.
409–20	May 15, 1924	June 30, 1924 [l]	5, 043	82	98	2, 280	96	2, 883	31	Show at 1,160 feet.
410–20	May 26, 1924	July 17, 1924	5, 022	75	130	2, 295	100	2, 704	37	Show at 450, 595, and 1,210 feet.

[g] Diamond drilling completed Dec. 25, 1925.
[h] Diamond drilling completed Nov. 2, 1925.
[i] Diamond drilling completed Jan. 29, 1924.
[j] Diamond drilling suspended Feb. 24, 1923.
[k] Drilling suspended.
[l] Diamond drilling completed Jan. 22, 1926.

TABLE 2.—*Well history of Naval Petroleum Reserve No. 3*—Continued

Well No.	Initial production of oil (barrels)	Gas (M cubic feet)	Rock pressure (pounds)		Total depth (feet)	Remarks
			Initial	Later		
401–29	165				1, 745	Show at 1,600 feet.
105–20	60				2, 945	"Third Wall Creek sand" at 2,912–2,916 feet. Plugged back to 2,702 feet.
402–28	140				2, 912	
104–29	20				2, 893	Sandy shale above "Second Wall Creek sand" at 2,684–2,866 feet.
102–33		10, 000			2, 905	
201–10		9, 375		Apr., 1924, 900 June 1926, 300	3, 063	Dry gas. Mudded off May, 1927.
404–28		9, 750		Apr., 1924, 800 June, 1926, 435	2, 884	Making 1,225,000 cubic feet of gas a day and 40 barrels of water an hour, Jan. 30, 1926.
403–28	250				2, 923	
408–20	390				2, 906	Oil from "Second Wall Creek sand"; "Third Wall Creek sand" at 2,902–2,906 feet, 50 barrels 80 per cent water.
402–29	135				1, 108	Shale well.
301–34	185				3, 045	
305–28	147				1, 630	Do.
404–33	100				1, 161	Do.
306–28	100				1, 532	Do.
405–20	30				2, 786	
403–33	65				2, 076	Shale well. Show also at 1,445 feet.
402–33	70	15, 000	1, 050?		3, 141	"Third Wall Creek sand" at 3,107–3,124 feet. Plugged back to 3,124 feet. Oil from "Third Wall Creek sand," gas from "Second Wall Creek sand."
102–10	240				2, 097	Shale well.
303–21	50				2, 791	Some water in sandy shale at 2,555–2,570 feet.
406–20	75				2, 759	Plugged and abandoned Sept. 14, 1926.
110–29	60				2, 814	Sandy shale at 2,500–2,614 feet.
302–21	35				2, 809	
101–3	550				3, 062	
111–29	75				2, 901	
202–28	75				2, 794	
303–28	150				2, 912	
109–29	75				2, 795	
304–28	400				2, 935	
203–28	75				2, 815	
108–29	Show of oil and water.				2, 870	Shale break at 2,787–2,789 feet.
405–28	300				2, 939	
201–11	200	10, 000			3, 061	
201–33	40	365			3, 029	
303–27	125				2, 987	
302–27	225				2, 954	
304–21	11				2, 980	Sandy shale at 2,917–2,980 feet, dry.
302–28		16, 000			3, 065	Mudded.
205–28					2, 873	1,200 feet of oil ("Second Wall Creek") in hole.
409–20	75				2, 926	"Third Wall Creek sand" at 2,918–2,925 feet.
410–20	25				2, 741	

TABLE 3.—*Monthly production from Naval Petroleum Reserve No. 3, October, 1922, to December, 1927*

[Furnished by U. S. Navy Department]

Month	Barrels	Number of wells producing
October, 1922 (2 days)	830. 16	1
November	19, 191. 97	2
December	17, 221. 16	4
January, 1923	30, 379. 64	6
February	27, 606. 05	6
March	37, 980. 34	8
April	41, 399. 81	8
May	119, 296. 42	13
June	122, 744. 83	23
July	115, 675. 83	27
August	124, 588. 38	34
September	127, 659. 61	44
October	138, 081. 51	51
November	131, 647. 06	59
December	119, 888. 80	61
January, 1924	123, 242. 29	62
February	108, 393. 27	60
March	106, 229. 09	60
April	94, 058. 08	60
May	87, 162. 97	59
June	82, 757. 41	59
July	74, 727. 95	61
August	68, 712. 88	61
September	74, 661. 42	62
October	65, 975. 49	61
November	57, 483. 02	62
December	60, 353. 32	62
January, 1925	62, 439. 58	61
February	57, 272. 98	62
March	63, 136. 07	62
April	56, 477. 67	62
May	54, 607. 44	62
June	51, 330. 55	62
July	48, 770. 15	62
August	48, 982. 96	62
September	47, 586. 31	63
October	48, 662. 97	62
November	47, 117. 09	62
December	46, 317. 89	62
January, 1926	39, 613. 97	63
February	39, 154. 00	62
March	41, 683. 16	62
April	38, 958. 97	62
May	38, 031. 44	62
June	35, 801. 09	62
July	35, 027. 50	64
August	34, 415. 74	64
September	32, 536. 63	61
October	28, 751. 63	62
November	30, 482. 90	63
December	31, 227. 76	61
January, 1927	28, 294. 62	61
February	24, 935. 60	61
March	31, 277. 04	61
April	25, 216. 87	61
May	29, 225. 61	61
June	25, 657. 42	61
July	27, 650. 29	62
August	27, 663. 66	62
September	23, 578. 06	62
October	26, 494. 48	62
November	20, 271. 81	62
December	22, 626. 96	53
	3, 549, 227. 63	

SUMMARY

	Barrels		Barrels
1922	37, 243. 29	1926	425, 684. 79
1923	1, 136, 948. 28	1927	312, 892. 42
1924	1, 003, 757. 19		
1925	632, 701. 66		3, 549, 227. 63

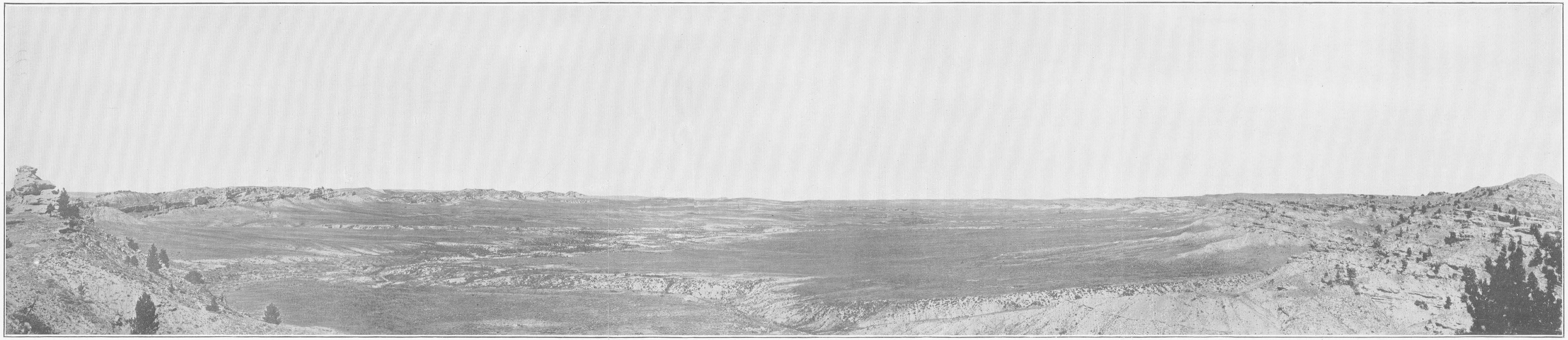
Subsequently special counsel for the Government filed suit to have the Mammoth Co.'s lease canceled, and on March 13, 1924, a receivership was created to maintain the status quo within the reserve pending decision of the suit. After hearings in the lower courts the case was brought before the Supreme Court of the United States, which on October 10, 1927, handed down a decision ordering the cancellation of the lease. Accordingly, on December 29, 1927, the receivers rendered an accounting and control of the reserve was returned to the Navy Department.

GEOGRAPHY

Location and extent of field.—United States Naval Petroleum Reserve No. 3 embraces an area of about 9,300 acres in Tps. 38 and 39 N., R. 78 W., Natrona County, Wyo., 25 to 35 miles north-northeast of Casper (see fig. 1) and about an equal distance southeast of the Big Horn Mountains. The outlines and geography of the field are shown in greater detail by Plates 7 and 8.

Accessibility.—Geographically, as well as geologically, the Teapot field is closely related to the larger Salt Creek oil field, and avenues of communication for one field are essentially the same as those for the other. An excellent highway connecting Casper with towns in the Salt Creek field and with Sheridan passes just northwest of the reserve; the North & South Railway extends from Casper to Salt Creek and Midwest and to intervening stations 5 to 10 miles northwest of the Teapot field; and the reserve itself is crossed by several pipe lines leading to Casper and by the Sinclair pipe line, which connects with transcontinental trunk lines at Freeman, Mo.

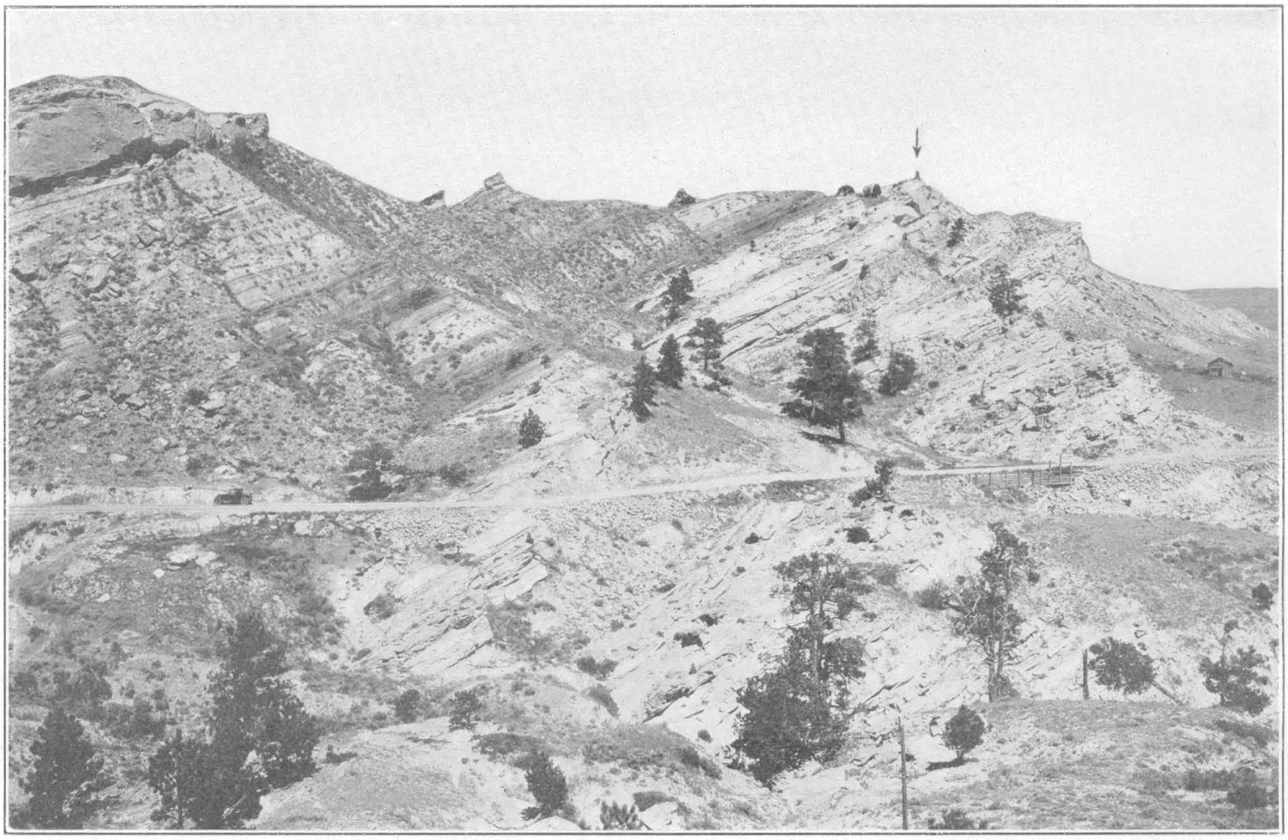
Topographic features.—Naval Petroleum Reserve No. 3 lies near the western margin of the High Plains, or western part of the Great Plains region, and is characterized by the topographic features, the assemblages of plant types, and the climatic conditions normally found in such a region. The surface of the central part of the reserve consists of a grassy plain, dotted with sagebrush and gashed by ravines, bordered by an encircling rim of sandstone which has, because of its superior hardness, resisted the forces of erosion that have scooped out the basin in the soft shales exposed above the apex of the Teapot uplift. The surface features of the field are well illustrated by Plate 1, *A*. The main camp of the Mammoth Oil Co. is visible on the left in the middle distance, and the tank farm, formerly belonging to the Sinclair Crude Oil Purchasing Co., is visible on the right. In the extreme background are to be seen Castle Rock and other parts of the Shannon escarpment, which borders the southeast end of the Salt Creek field. Plate 1, *B*, shows the Teapot field from the



A. PANORAMA OF TEAPOT DOME FROM POINT ON PARKMAN RIM AT SOUTH END OF DOME

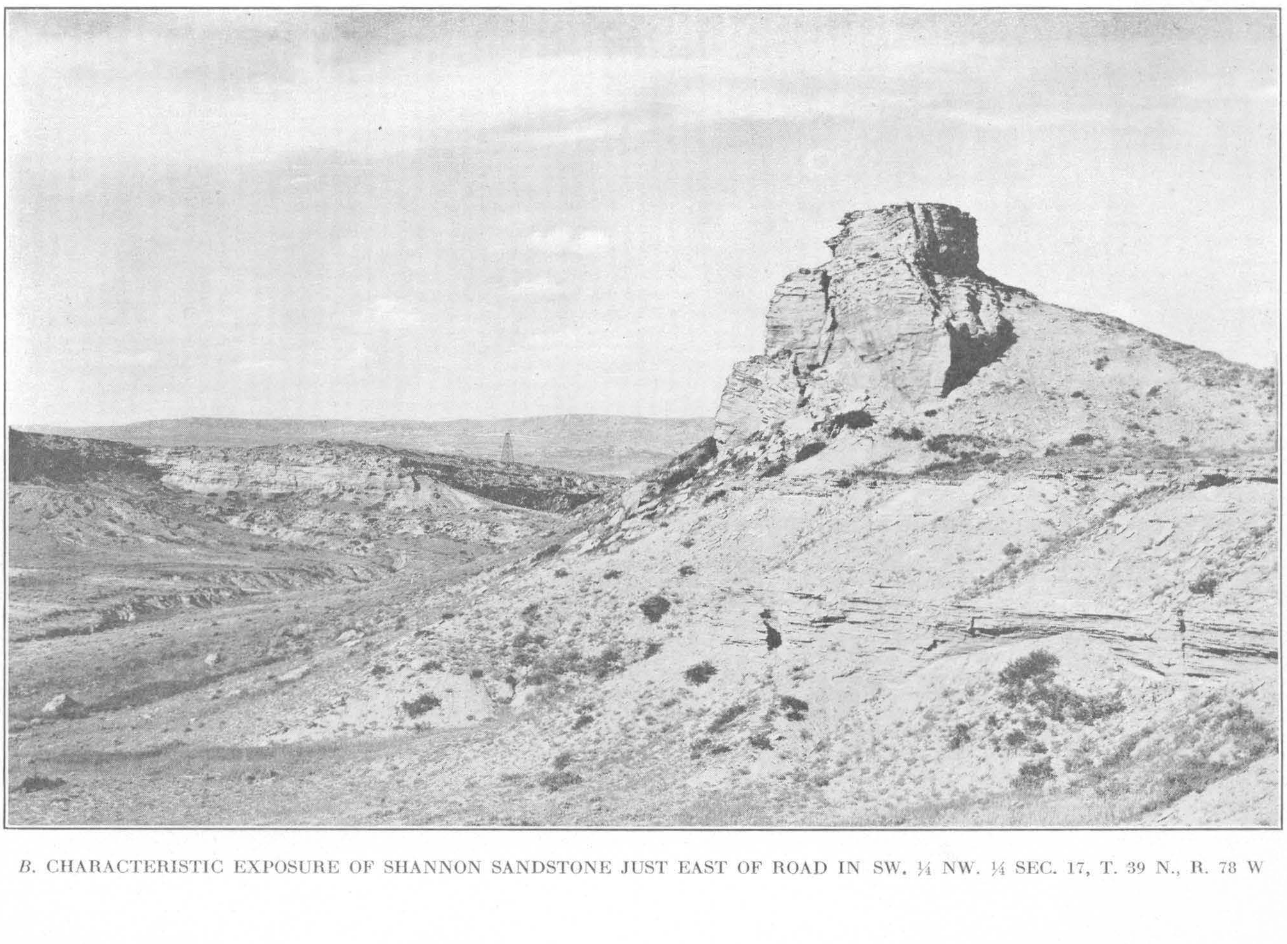
B. PANORAMA OF SOUTHERN PART OF TEAPOT DOME FROM POINT ON SHANNON RIM NORTHWEST OF MAMMOTH CAMP No. 1

PANORAMA OF TEAPOT DOME FROM SHANNON RIM AT SOUTHEAST END OF SALT CREEK FIELD



A. PARKMAN SANDSTONE JUST NORTH OF ROAD FROM CAMP No. 1 TO CASPER

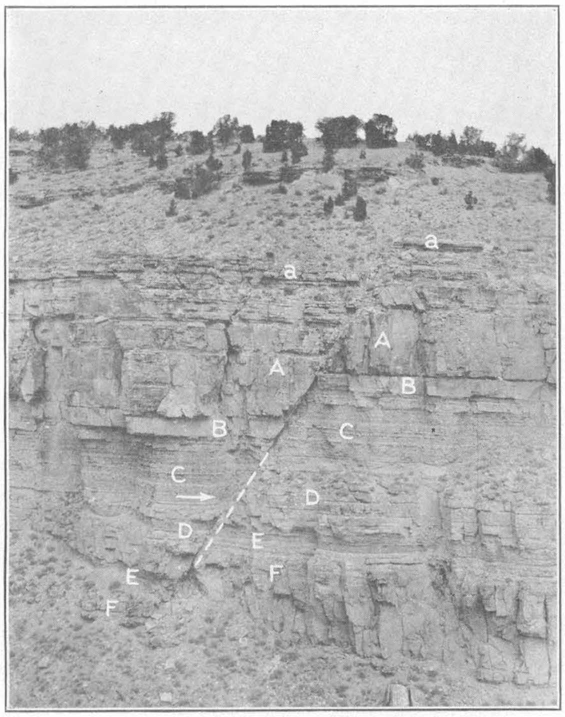
Arrow shows triangulation point on lower sandstone of Parkman member mapped by the writers in structural study



B. CHARACTERISTIC EXPOSURE OF SHANNON SANDSTONE JUST EAST OF ROAD IN SW. ¼ NW. ¼ SEC. 17, T. 39 N., R. 78 W

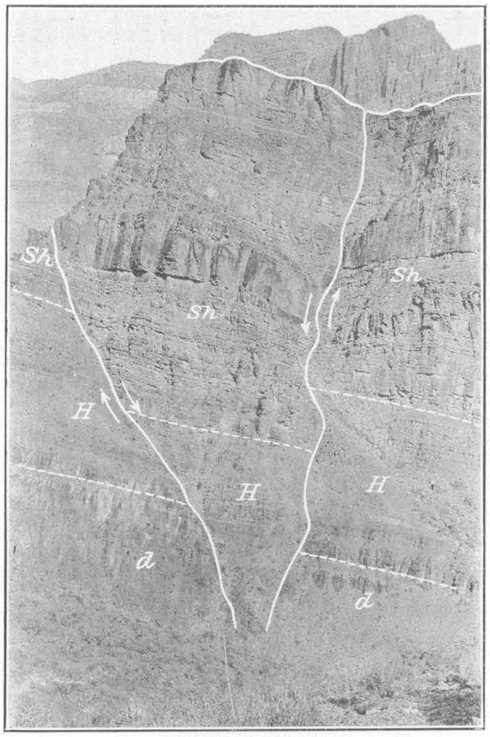
A. PARKMAN SANDSTONE FROM POINT NORTHWEST OF CAMP No. 1

B. PANORAMA SHOWING CHARACTER AND STRUCTURE OF FORMATIONS ABOVE PARKMAN SANDSTONE, EXPOSED JUST WEST OF NAVAL PETROLEUM RESERVE No. 3



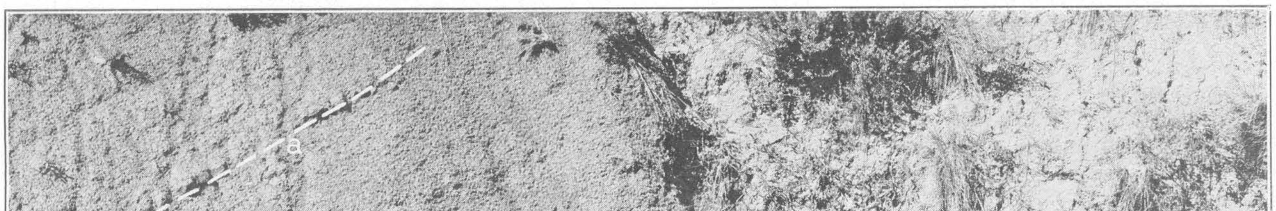
A. A FAULT

The letters indicate corresponding strata on the two sides of the fault and show the extent of the displacement.



B. 1,000-FOOT VERTICAL SECTION OF UNKAR WEDGE, OR "GRABEN" BLOCK, EXPOSED IN GRAND CANYON OF ARIZONA

H, Hakatai shale; *Sh*, Shinumo quartzite; *d*, diabase.



C. BIG FAULT EXPOSED IN RAVINE NEAR CENTER OF NW. ¼ SEC. 33, T. 39 N., R. 78 W.

a, Concretion beds in dropped block, showing tilting due to drag near fault; b, bentonite drawn out to featheredge by drag on fault; D, downthrow; U, upthrow.

opposite direction, and Plates 2, 3, *A*, and 4 give further details as to surface features in or near the field.

At a time fairly well back in the glacial epoch the surface features of the Teapot field had been eroded to essentially their present form. Then, probably owing to a renewed advance of the ice sheet into regions north of this field the streams were more or less ponded, and silt was deposited over their valley bottoms, locally to depths of 50 feet or more. The alluvial plains thus formed are now being attacked by a renewed down-cutting, and the alluvial lowlands are trenched by deep and narrow stream courses, bordered at intervals by bluffs 40 feet or more in height.

Drainage and water supply.—Although the North Platte River passes within 25 miles of the south end of the Teapot dome and flows thence almost due eastward to join the Missouri near Omaha, the streams that drain Naval Petroleum Reserve No. 3 are tributary to Salt Creek, a branch of the Powder River, which in turn joins the Yellowstone River near Miles City, Mont. The run-off from the reserve thus reaches Omaha by a route several hundred miles longer than if it followed the North Platte Valley. The reserve lies immediately within the drainage basins of Little Teapot and Teapot Creeks. Even these larger creeks are intermittent in their flow, owing to the semiaridity of the climate, and such water as they contain has a high content of dissolved salts. Water for drilling was obtained from reservoirs formed by damming ravines (see pl. 1, *B*), and water for general camp use was obtained from a group of wells near the Casper-Salt Creek highway, which drew their water from the Shannon sandstone. A large volume of water under artesian head exists in the "First Wall Creek sand" beneath the reserve, but, like the other waters of the area, it is too highly mineralized to be satisfactory for domestic use. In both the Salt Creek and the Teapot fields it is customary to distill water to be used for drinking or for such purposes as require noncorrosive or nonmineralized water. Owing to the abundant supply of natural gas such distillation can be done cheaply.

Culture.—In its cultural as well as in its geographic features the Teapot field is essentially a continuation of the Salt Creek field, and the systems of roads, camps, telephone lines, oil wells, pipe lines, oil tanks, etc., constructed within the reserve (see pls. 1, *B*, and 2) closely resemble similar systems developed in the Salt Creek field.

GEOLOGY

STRATIGRAPHY

GENERAL SECTION

The sedimentary formations that are exposed within or underlie the Teapot and Salt Creek oil fields are of wide extent in eastern Wyoming and were deposited along or near the shores of a sea or gulf which in early Cretaceous time extended over much of the Rocky Mountain region and later on occupied smaller areas, as, for example, the Powder River Basin—the great structural depression corresponding to the lowland area surrounded by the Big Horn Mountains on the west, the Black Hills on the east, and the Casper Mountains and Hartville uplift on the south and southeast.

The Teapot-Salt Creek area lies along the western margin of this major basin, and thus the formations penetrated by wells drilled in the two fields consist of marine shales interbedded with beach and near-shore sands that grow thinner toward the east and northeast, where progressively greater depths of water existed when the formations were being laid down. Some limy beds also underlie the Teapot dome, but thick limestones are present only in the part of the sedimentary column far below the sands so far penetrated within the reserve.

The sequence of the formations underlying part or all of the Teapot and Salt Creek fields, and their general character and thickness, are indicated by Table 4.

EXPOSED ROCKS

PARKMAN SANDSTONE MEMBER OF MESAVERDE FORMATION

The youngest rocks exposed within the reserve belong to the Parkman sandstone, which is the lowest member of the Mesaverde formation in this area. This member normally consists of three parts, the general nature and sequence of which are shown by Plates 3, *A*, and 4, *A*.

Upper sandstone.—The upper part consists locally of massive yellow sandstone, which is not persistent but merges laterally, within short distances, into yellow sandy shale and thinner beds of sandstone, as may be seen by comparing Plates 3, *A*, and 4, *A*, the massive sandstone at the upper left in Plate 3, *A*, being the same as that visible on the extreme right in Plate 4, *A*. Wegemann[17] gives the thickness of this sandstone as about 110 feet and reports that fossil dinosaur and crocodile remains were found in its top about 10 miles northwest of the Teapot field.

Both east and west of the reserve boundary the Parkman sandstone is conformably overlain by a marine shale unit, which is in turn overlain in order by the Teapot sandstone, forming the top member of the Mesaverde, and the Lewis shale, including the equivalent of the Fox Hills sandstone. Plate 4, *B*, shows characteristic exposures of these units visible in the southward-sloping trough that lies just west of the Teapot field. The V-shaped outcrop of pine-covered rocks in the middle foreground consists of the Teapot sandstone exposed on both flanks of the southward-pitching synclinal fold; and the high hill in the left background is capped by a tongue of sandstone in

[17] Wegemann, C. H., op. cit. (Bull. 670), pp. 21–22.

the upper part of the Lewis shale, which projects northward along the axis of the downfold.

Middle shale.—The middle part of the Parkman member consists chiefly of dark carbonaceous shale (see pl. 3, *A*) containing layers of iron ore and thin coal beds developed in brackish coastal-plain swamps. Local channel sandstones are also to be seen here and there along the outcrop, and one or two persistent white sandstones occur in the lower part. A massive gray sandstone is also found at the base near the south end of the dome, and channeling at the base of this sandstone is clearly evident in many places. The thickness of this unit is given by Wegemann[18] as about 190 feet.

Lower sandstones.—The lower part of the Parkman member was mapped by the writers in the course of their structural study and comprises the series of sandstone beds forming the inner face of the horseshoe-shaped escarpment that borders the Teapot field. As shown in Plate 3, *A*, and more especially in Plate 4, *A*, it does not consist of solid sandstone but is made up of several near-shore or beach sandstones separated by minor shale beds which yield more readily to erosion and leave notches in the cliff profile. Normally there are four main sandstone beds or groups of beds, which are exposed in characteristic fashion in the headland west of the Mammoth camp. (See pl. 4, *A*.) The lowest sandstone normally makes a bold cliff, the second sandstone commonly makes a minor cliff, and the third sandstone is the main rim rock of the inner escarpment and forms the second main promontory west of the camp. (See pl. 4, *A*.) The fourth sandstone, which is in places of a snowy whiteness, is much softer and in consequence usually crops out on the back slope of the third sandstone and just at the base of the carbonaceous clays of the middle part of the Parkman. (See pls. 1, *B*, 3, *A*, and 9.)

The basal sandstone of the Parkman, the lowest of the four just mentioned, grades downward into the shale below and attains a thickness of 40 feet or more. Its top is commonly marked by a zone of irregular reddish-weathering calcareous and ferruginous concretions about 5 feet thick. The second sandstone, which attains its principal observed development near the northeastern margin of the reserve, is likewise of marine origin and develops an irregular and pitted upper surface where exposed to weathering and solution. The third sandstone is relatively resistant to erosion and normally is capped by a hard red platy or ripple-marked layer, which the writers used as a key bed for determining structure. The fourth sandstone is a soft sandstone of beach origin, in which numerous impressions of *Halymenites*, a fossil seaweed, are visible. Around the southern part of the Teapot uplift this sandstone is cut out and replaced by the massive gray channel sandstone at the base of the middle division; and in its outcrop northeast of the field, near the valley of Salt Creek, it assumes a yellowish banded phase, being streaked with iron stain and associated with considerable quantities of hematite, apparently formed by the alteration of an old chemical precipitate of hydrated iron oxide. The thickness of this white sandstone above the key bed ranges from 38 to 54 feet, and the aggregate thickness of the whole of the lower division of the Parkman ranges from about 170 to 190 feet, the bottom of the member, because of its gradational character, being rather arbitrarily determined.

STEELE SHALE

The Steele shale includes the beds between the Parkman sandstone member of the Mesaverde formation and the Niobrara shale and consists of upper and lower shale members separated by the Shannon sandstone member. These three members are roughly equivalent, in descending order, to the Claggett shale, the Eagle sandstone, and the Telegraph Creek formation of southern Montana. Almost the entire thickness of the upper shale member is exposed within the reserve, and its remaining basal beds and the underlying Shannon sandstone are well exposed in the immediately adjacent parts of the Salt Creek field. The beds of the lower member are only partly exposed in the Salt Creek field and were not studied by the writers, information regarding them being obtained either from well records or from descriptions by Wegemann and others of the constitution of the member where exposed in the Tisdale (Powder River) anticline or along the flank of the Big Horn Mountains.

Upper member.—The upper member of the Steele shale is about 1,450 feet thick and apparently underlies the Parkman conformably, the persistent series of thin sandstones in the upper part of the Steele, which form minor ledges beneath the Parkman rim (see pl. 4, *A*), apparently belonging to the same gradational series as the sandstones of the basal Parkman. For about 800 feet below this zone of thin sandstones the Steele consists of soft bluish shale containing layers or zones of hard concretions, some of which can be seen projecting from the shale exposures on the sides of the ravine above the reservoir in the view given in Plate 4, *A*. The concretions of the lower 200 feet of this section are normally gray calcareous nodules; those of the upper part commonly weather red because of their iron content.

Numerous beds of bentonite, a white claylike substance, are conspicuously developed in a zone between 400 and 550 feet above the base of the upper member of the Steele shale and afford one of the important guides for determining the structural details within the Teapot field. The outcrops of these bentonites form the white patches on the landscape visible in the middle foreground in Plate 1, *B*, also the white streaks visible between the derricks and oil tanks at the left

[18] Wegemann, C. H., op. cit. (Bull. 670), p. 21.

TABLE 4.—*Principal rock formations in Teapot dome and Salt Creek oil fields*

System	Series	Formations and members: As recognized in Bulletin 670		Formations and members: As defined by present writers		Character	Thickness (feet)		Number of wells producing oil from formation in Salt Creek field, Mar. 1, 1927	Gravity of oil produced (° Baumé)
Cretaceous	Upper Cretaceous	Parkman sandstone member of Mesaverde formation		Parkman sandstone member of Mesaverde formation		Massive yellow sandstone or yellowish sandy shale. Forms rim at top of Parkman scarp		110±	-	-
						Black carbonaceous shale, thin coal beds, lenticular sandstones, and two or three persistent white sandstones near base		190±		
						Massive to flaggy marine sandstones. White sandstone at top. Makes inner Parkman rim		170–190		- ---
		Steele shale		Steele shale		Soft bluish gray shale containing concretionary layers. Also a group of bentonite beds and an underlying thin sandstone ("water sand") 400–550 feet above base		1,400–1,460		- ---
			Shannon sandstone member		Shannon sandstone member	Greenish gray marine sandstone (commonly in two benches), sandy shale, and ferruginous beds		135±	38 (idle)	29
						Gray shale with thin ferruginous layers, a few bentonite beds, and a thin conglomerate bed 400–500 feet above base				
		Niobrara shale		Niobrara shale		Light colored shale, with some harder calcareous beds, especially near top		1,650–2,140	65	38–42
		Benton shale		Carlile shale		Dark marine shale				
			Wall Creek sandstone member	Frontier formation	Wall Creek sandstone member	Cross bedded sandstone and sandy shale, commonly in two beds ("First Wall Creek sand")	90–160	390–400	267	38
						Gray shale, sandy shale, and thin sandstones			-	-
						Gray to bluish white sandstone with partings of bentonite, which are not numerous near south end of Salt Creek field ("Second Wall Creek sand")	40–90	220–250	1,612	37.7
						Gray shale and irregular lenses of sandstone				-
						Fine grained sandstone in irregular and discontinuous patches ("Third Wall Creek sand")		0–30	12	39
						Dark gray shale, sandy shale, and hard sandstone lenses		300±		-
			Mowry shale member	Mowry shale		Hard fissile shale weathering light gray and containing fish scales. Numerous bentonite layers		230		
				Thermopolis shale		Dark soft shale		20±		
						Soft fine grained sandstone with some coal and fossil wood fragments ("Muddy sand")		0–11	21	38
						Soft black shale containing plant remains and a few shark teeth		200±		
	Lower Cretaceous	Cloverly formation		Cloverly formation		Lenticular white or brown sandstone ("Dakota sand")	0–20	100±	1	
						Soft light colored or massive dark shale				-
						Conglomerate and gritty sandstone, with lenses of coal ("Lakota sand")	20–75		70	36
Cretaceous (?)		Morrison formation		Morrison formation		Soft massive variegated clay and thin hard sandstones, especially in middle of formation		285–360±		
Jurassic	Upper Jurassic	Sundance formation		Sundance formation		Green and gray shale, gray, white, and brown sandstone, and some sandy limestone		235–285	3	33.4
Triassic		Chugwater formation		Chugwater formation		Soft massive red shale, red sandstone, thin limestones, and massive beds of gypsum		700±		
Carboniferous	Permian			Embar formation		Alternating red shale and varicolored limestones and sandstones		220±		
	Pennsylvanian			Tensleep sandstone		Massive white cross bedded sandstone, with some brown calcareous layers		270±		

Many of the data as to formations below Second Wall Creek sand and all data as to number of wells producing oil and as to gravity of oil taken from U. S. Geological Survey drawing "Midwest 8355" compiled by F. M. Cole and approved by J. S. Ross. (See pl. 11.)

end of the picture. The outcrop of these beds around the south end of the dome is also shown, rather obscurely, in Plate 4, *A*, at the base of the cloud shadow just above the derrick near the left end of the picture. The lowest of the large bentonite beds of this group is underlain by a persistent zone of light yellowish-gray concretions which split along vertical planes into multitudes of thin hard plates. This concretion zone (called by the writers, for convenience, the "shell" bed) is in turn underlain by a bentonite layer about 1½ feet in thickness; and at the base of this bentonite is half an inch or so of brown to honey-colored "silky" calcite or satin spar, mentioned by Lewis [19] as a good marker bed. Layers of gray concretions associated with beds in the upper part of the bentonite series can also be used over considerable areas in mapping structure, but without continuous tracing they can not be correlated across wide concealed intervals with absolute certainty, because of the large number and similarity of such beds. About 20 feet below the "silky" calcite layer, or 25 feet below the base of the lowest large bentonite bed, there is a bed of soft sandstone or sandy shale about 10 feet in thickness, within which is an almost continuous layer of sandstone nodules that affords the best key bed for mapping the structural details of the productive part of the Teapot dome. This sandstone, which is commonly known as the water sand, lies about 395 feet above the top of the Shannon sandstone, and because of its hardness it occurs extensively as a protective capping on hills and ridges near the crest of the Teapot uplift.

Many nodule layers, some weathering yellow and others red, occur in the interval between the Shannon and water sands, and a number of these are sufficiently distinct and continuous to be usable in detailed work for mapping structure over considerable areas. One such bed, consisting of a double layer of yellow sandy concretions splitting into thin slices and otherwise closely resembling the "shell" bed previously mentioned, is exposed in the critical area south of wells 201 and 205, in sec. 28, T. 39 N., R. 78 W., and a gray nodular bed that contains many fossils of the genus *Inoceramus*, lies about 3 feet above a prominent yellow concretion layer, and crops out around the hill just southeast of well 304–28 was also used in the SW. ¼ sec. 28. The tops of these two beds lie, respectively, about 174 and 131 feet below the top of the water sand and a thick bentonite bed conspicuously exposed in or near the northwestern part of the reserve lies about 90 feet above the top of the Shannon. Thinner layers of bentonite also occur within this 90-foot interval.

Shannon sandstone member.— The top of the Shannon sandstone is exposed along or just outside of the northwestern edge of the reserve, and the whole member can be studied in detail along its escarpment a mile northwest of the reserve boundary.

Within and near the northwestern part of the Teapot field the Shannon is about 135 feet thick, and its general appearance and character are indicated by Plate 3, *B*, supplemented by the following partial section measured at the hill shown in the foreground in the photograph.

Partial section of Shannon sandstone member east of road in SW. ¼ NW. ¼ sec. 17, T. 39 N., R. 78 W.

1. Sandstone, hard, calcareous; caps persistent bench	2
2. Sandstone, thin bedded, grading downward into massive dark sandy clay	26½
3. Clay, dark, containing massive greenish sandstone concretions	3
4. Clay, bluish gray, massive, somewhat sandy	35
5. Ironstone layers weathering to red flakes, sandy shale, and some sandstone	3
6. Sandstone, hard; caps lower prominent bench	2
7. Sandstone, thin bedded, and thin shale beds	19½
8. Sandstone, ferruginous, carbonaceous, in thin irregular beds separated by shale partings; rests on eroded surface of lower member of Steele shale	19
	110

Thus normally the Shannon consists of two benches of sandstone capped by hard layers (1 and 6) separated by an interval of dark clay (4) containing large concretions of greenish sandstone. This erosional effect is illustrated in the foreground in Plate 3, *B*, and more especially in the far hillside beneath the derrick, where the double cliff formed by the two sandstone benches can be seen and where the rounded slope formed by the soft upper part of the Shannon is also characteristically displayed. The part of the Shannon above bed 1 of the measured section is about 25 feet thick and consists of greenish sandstone thickly sprinkled with ferruginous matter like that of bed 5 or more commonly of sandy shale and soft sandstone. Owing to the softness of this bed, the top of the Shannon is logged in many well records at the top of the hard ledge-cap layer. Some dark chert nodules having corroded surfaces occur at the top of the Shannon, and the base of the member rests upon a somewhat eroded surface of the shale beneath.

Water and minor amounts of oil have been found in the Shannon. (See p. 23.)

UNEXPOSED ROCKS

The sedimentary rocks below the Shannon sandstone are not exposed in the Teapot field, and their sequence and general character, indicated in Table 4, are known either from well records, from partial exposures in the Salt Creek and Tisdale uplifts, or from outcrops along the flank of the Big Horn Mountains.

STEELE SHALE

Lower member.—The lower member of the Steele shale corresponds closely to the Telegraph Creek

[19] Lewis, J. O., op. cit., p. 77.

formation[20] of southern Montana, and according to Wegemann[21] consists, in the Salt Creek field, of about 1,000 feet of gray shale interbedded with thin ferruginous layers and a few bentonite beds. A thin conglomerate, commonly spoken of as the "fish-tooth conglomerate," occurs about the middle of the member and, besides shark teeth, contains fossil saurian bones. Cone-in-cone structure is conspicuously developed in the concretionary layers near the base of the member.

NIOBRARA SHALE

The Niobrara shale underlies the Steele and consists of about 750 feet of buff or bluish-gray shale interbedded with thin limestone layers, especially in the upper part of the formation.

CARLILE SHALE

The Niobrara is underlain by about 220 feet of dark shale, commonly correlated with the Carlile shale of the Black Hills region, beneath which lie the "Wall Creek sands" of the drillers, which, with their intervening shales, are referred by most geologists to the Frontier formation. However, the presence of the characteristic Carlile fossil *Prionocyclus wyomingensis* at the base of the "First Wall Creek sand"[22] apparently indicates that rocks of Carlile age extend down through the "First Wall Creek sand," possibly to the base of the conglomerate[23] that locally marks the top of the "Second Wall Creek sand" and elsewhere seems to occur within the body of the sand.

FRONTIER FORMATION

The current classification, which makes the Wall Creek sandstone member ("First Wall Creek sand" of drillers) the top of the Frontier formation, is accepted in this report. The "Wall Creek sands" are at the present time of major importance as sources of oil in the Teapot and Salt Creek fields, and they will therefore be described in some detail.

"First Wall Creek sand."—The uppermost or "First Wall Creek sand," as stated by Estabrook and Rader,[24] is usually logged in well records

> as a continuous sand with an average thickness of 136 feet, but it is really composed of two distinct parts separated by either a shale bed or a layer of hard limy sand. The upper layer, or bench, is 80 to 100 feet, and the lower about 20 feet thick. As suggested by Nowels,[25] the conditions under which the oil and water are found in the two layers are quite different. The lower sand contains water under high pressures and is sometimes sufficiently porous to yield an artesian flow of several thousand barrels per day when first tapped. In some places this bed seems to pinch out entirely, and only the inconsequential water of the upper layer will be encountered in a well, but usually water will fill the hole 1,000 feet or more as soon as the lower bench is tapped. The water line in the First sand as usually reported is the water line in the lower bench.
>
> The upper part of the sand is more irregular in porosity than the lower, and the water and oil content are under much less pressure. The outer limit of the oil in the upper bench is irregular and much further down on the structure than in the lower; oil in appreciable amounts has been found 1 mile or more outside the water line in the lower part. Usually only a small amount of water is found in the upper bench, but occasionally the hole will fill with water as soon as the sand is tapped. Such water is probably coming up under pressure from below through wells in which the cement has not confined the high-pressure water within its natural channels.

At its outcrop this sand consists of medium-grained cross-bedded sandstone of a dirty buff color, which contains fragments of petrified wood, shark teeth, and the shells of marine invertebrates.[26]

In the Tisdale (Powder River) area the "First Wall Creek sand" is underlain in turn by 20 feet of shale, 15 feet of sandstone and shale, 65 feet of shale, 10 feet of sandstone, 20 feet of shale, 20 feet of shaly sandstone, and 110 feet of shale,[27] and the presence of local sandstone beds in this interval is recorded by the logs of a number of Salt Creek wells. A thin bentonite marks the base of the lowest shale bed, and the normal aggregate thickness of the "First Wall Creek" and underlying beds mentioned in the Salt Creek and Teapot fields is 390 to 400 feet.

"Second Wall Creek sand."—The "Second Wall Creek sand" is the one of present importance in the Teapot field and has yielded the greater part of the oil obtained at Salt Creek. It was studied at its outcrop by Wegemann before it was known to be oil bearing in the Salt Creek region and was described by him as follows:[28]

> This sandstone is usually referred to as the "Lower Wall Creek sandstone." It is not over 20 or 25 feet thick in its massive part, although sandy shale above and below it may carry oil. It is the highest bed that carries pine trees and is a massive medium-grained sandstone, with a calcareous cement, and would apparently form a good reservoir for oil. The sand grains composing the rock are colorless quartz, but the sandstone as a whole has a bluish-white cast, due to the presence among the quartz grains of innumerable black particles, which were apparently derived from the same rock that furnished the numerous well-rounded dark quartzitic pebbles that are distributed sparsely through the mass of sandstone. On top of the sandstone is a 6-inch bed of conglomerate formed of these same rounded black pebbles, which range in diameter from an eighth of an inch to an inch. Among them are found here and there a few pebbles of transparent quartz. It is interesting to note that thin beds of conglomerate composed of similar black pebbles have been reported at about this horizon from the Big Horn Basin.[29] Overlying this bed of conglomerate in the Powder River [Tisdale] field is a bed of bentonite about 12 inches thick.

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[20] Thom, W. T., jr., Oil and gas prospects in and near the Crow Indian Reservation, Mont.: U. S. Geol. Survey Bull. 736, p. 38, 1922.

[21] Wegemann, C. H., op. cit. (Bull. 670), p. 20.

[22] Idem, p. 18.

[23] Idem, p. 17.

[24] Estabrook, E. L., and Rader, C. M., op. cit., pp. 205-206.

[25] Nowels, K. B., Preliminary report on water conditions in the First Wall Creek sand, Salt Creek oil field, Wyo.: Am. Assoc. Petroleum Geologists Bull., 1924, p. 492.

[26] Wegemann, C. H., op. cit., p. 18.

[27] Idem, p. 17.

[28] Idem, pp. 17, 18.

[29] Hewett, D. F., The Shoshone River section, Wyoming: U. S. Geol. Survey Bull. 541, pp. 89-113 (especially p. 98), 1914.

Within the Salt Creek field the "Second Wall Creek sand" consists of a number of sandstone layers, rather than of a single sandstone bed; and it is quite probable—from the variations in gas flow found at different depths in the sand and from the water conditions reported—that the same situation exists in the Teapot field, though the well records available are so poor that they do not give satisfactory evidence on this point. The existence of shale "breaks" in the "Second Wall Creek" and its lateral variability in thickness and composition have been described by Estabrook and Rader,[30] who state that in the Salt Creek field

The Second Wall Creek sand varies in thickness from 20 to 100 feet. In the northern half of the field the thickness will average 75 feet and in the southern half about 60 feet. In secs. 8 and 9, T. 39 N., R. 78 W., the sand is thinnest; and in secs. 22, 23, 25, and 26, T. 40 N., R. 79 W., it is consistently the thickest. Thin partings of shale, often containing much bentonite, are common throughout the field, but they thicken toward the south and east and split the sand into several distinct layers. A number of wells in T. 39 N., R. 78 W., report three or more layers of sand separated by shale beds from 2 to 25 feet thick. The lower benches of the sand are usually the most productive, and even in those parts of the field where the sand is reported to be continuous the best production is found in the lower half.

These thin shale partings of bentonite material make the Second a "dirty" sand. "Cleaning out" for weeks is often necessary before a Second sand well is in shape for pumping.

The best production is obtained from the northern half of the [Salt Creek] field. In much of the southern half the production is so small that many of the wells are unprofitable, and in one area, around the quarter corner between secs. 7 and 18, T. 39 N., R. 78 W., several dry holes have been drilled.

The average production per acre from the Second sand was 4,967 barrels on January 1, 1925. The most productive 160-acre tract was the SE. ¼ sec. 25, T. 40 N., R. 79 W., with 75,037 barrels per acre.

Further facts bearing upon the composition and continuity of the "Second Wall Creek sand" within the Salt Creek field are given by R. F. Peake,[31] of the Midwest Refining Co., as follows:

In the first place, the First Wall Creek sand is 125 feet thick and the Second is only 60 feet thick. The First sand is probably more uniform than the Second. * * * More important still is the fact that there is a difference in hydrostatic heads. There are even two hydrostatic heads in the First sand itself. There is a hydrostatic head in the bottom of the Second sand that is much larger than the hydrostatic head in the top. How uniform it is we have not been able to determine and we are working on it. The hydrostatic head in the Second sand is not as great as the hydrostatic head in the bottom of the First sand.

At the outcrop the "Second Wall Creek sand" is separated from the "Third Wall Creek sand" by 150 feet of gray shale, and in the Salt Creek-Teapot area the interval is occupied by gray shale containing variable lenses of sandy shale and sandstone. The total interval between the tops of the two sands ranges from 215 to 275 feet.

"Third Wall Creek sand."—At its outcrop the "Third Wall Creek sand" comprises two benches,[32] the lower one, from 30 to 40 feet thick, consisting of "medium-grained dirty-white sandstone" supporting a growth of pine trees, and the upper one, separated from the lower by 35 feet of gray shale, consisting of "25 feet of shaly sandstone, also carrying a growth of pine." Regarding this sandstone, Estabrook and Rader [33] state:

The Third Wall Creek sand is found from 625 to 675 feet below the top of the First sand. At Powder River [Tisdale], where measured by Wegemann, it consisted of two benches, the upper 20 feet and the lower 30 feet thick with a 35-foot shale bed between them. At Salt Creek the lower bench of sand is seldom found and the upper bench is very lenticular.

Thirty wells have been drilled to the Third sand horizon [in the Salt Creek field]. Commercial production was obtained in seven wells, small shows of oil and gas in five, a dry sand was found in seven, no sand at all in nine, and water is reported in two wells; 23 per cent of the wells were productive, and 30 per cent encountered no sand. The average thickness of sand in the producing wells is 20 feet; in the 20 wells reporting some sand the average thickness is 15 feet. The sand generally appears to be thin and tight and not likely to be an important producer, although it is possible that thicker and more porous lenses that will yield valuable amounts of oil may be found. The possible productive area of the Third sand appears likely to be as large as in the Second sand. The total production from the Third sand up to January 1, 1925, has been about 75,000 barrels.

Since Estabrook and Rader prepared their paper it has become more apparent that the "Third Wall Creek sand" exists only in strips or scattered patches beneath the Teapot and Salt Creek fields and probably has its principal local development in the southeastern part of the Salt Creek field. It is underlain by 250 to 300 feet of dark shale containing some lenses of sandy shale and sandstone and thin ferruginous layers that weather into flakes of a deep reddish-brown color.

MOWRY SHALE

The Mowry shale is conspicuous at its outcrop because of its light color, scarp-forming habit, and abundance of contained fossil fish scales, but commonly it is not recorded in the logs of wells which penetrate it. It consists of hard dark shale that splits into thin plates and weathers a silvery gray, interbedded with several layers of bentonite, one of which rests upon the top layer of the "fish-scale" shale. The local thickness of the Mowry probably ranges from 230 to 280 feet.

THERMOPOLIS SHALE

The Thermopolis shale, which underlies the Mowry, consists chiefly of very dark soft shale containing plant remains but commonly includes near its top a thin sandstone that is generally regarded as the equivalent of the "Muddy sand" of the Big Horn Basin. This bed, which is usually 6 feet or less in thickness, lies about 20 feet below the Mowry shale and consists of

[30] Estabrook, E. L., and Rader, C. M., op. cit., p. 206.

[31] Peake, R. F., Petroleum development and technology in 1926, p. 217, Am. Inst. Min. and Met. Eng., 1926.

[32] Wegemann, C. H., op. cit., p. 17.

[33] Estabrook, E. L., and Rader, C. M., op. cit., p. 207.

white sandstone or sandy shale containing fragments of petrified wood and local lenses of coaly material.

The lower part of the Thermopolis consists of 175 to 200 feet of dark shale containing plant fragments. Shark teeth are also found in the basal beds.

CLOVERLY FORMATION

The Cloverly formation underlies the Thermopolis shale and consists of two sands and an intermediate shale. The upper sand is called by the drillers the "Dakota sand" and the lower one the "Lakota sand," but the correlations implied by these names are not established. For convenience the driller's terms are here used.

"Dakota sand."—At its outcrop the "Dakota sand" consists of 14 feet of shaly sandstone which is strongly ripple-marked in its upper layers,[34] and in the Salt Creek field it ranges from an inch or less to 14 feet in thickness and contains small amounts of oil and gas.[35]

Middle shale member.—The shale that underlies the "Dakota sand" is a varicolored or dark massive shale 70 to 80 feet in thickness.

"Lakota sand."—According to Estabrook and Rader[35] the "Lakota sand" as developed in the Salt Creek field is about 70 feet thick and consists of sandstone beds separated by thin layers of shale. This multiple character is indicated by variations in the yield of oil and by the temperature of water encountered at different depths in the sand.

At its outcrop northwest of Salt Creek this sand consists of

> a conglomerate containing some layers of sandstone, the whole 56 feet thick, and including at the base a thin bed of coal, which in many localities suffered erosion before the conglomerate was laid down, as is shown by bits of coal that occur throughout the bed. There is much cross-bedding in the conglomerate. In the Powder River [Tisdale] field the sandstone is a lithologic unit, but 25 miles to the north, where it crops out along the Big Horn uplift, it consists of numerous thin layers of sandstone and conglomerate interbedded with shale, some of it pink and not very different in appearance from the underlying Morrison. In this region fossil plants were collected from layers of shale that lay between beds of conglomerate near the base. * * * According to Mr. Knowlton, these are undoubtedly Kootenai species. There appears to be little question, therefore, that the conglomerate is equivalent in age to at least a part of the Kootenai of Montana, probably being the same as the Pryor conglomerate of the Elk Basin oil field. The conglomerate, so far as known, is the principal oil-bearing formation of the Powder River [Tisdale] field.[34]

MORRISON FORMATION

In the Salt Creek field the Morrison appears to consist of about 300 feet of soft purple to green clay interbedded with hard fine-grained sandstone, especially between 110 and 225 feet above the base of the formation. At its outcrop the Morrison is about 250 feet thick [36] and consists of shale interbedded with four or five hard thin sandstones which form conspicuous ledges along the outcrop. Oil seeps from at least two of these sandstones in the Tisdale anticline [36] and fresh-water shells and the bones of dinosaurs have been found along the Morrison outcrops over wide areas.

SUNDANCE FORMATION

The Sundance formation, of Upper Jurassic age, underlies the Morrison conformably and as ordinarily identified in well records consists of a 100-foot upper bench of limestone and sandstone; a lower bench, 60 feet thick, of sandstone, limestone, and shale; and a middle member, 90 feet thick, of grayish shale, sandy shale, and soft sandstone. Part of the red rocks below the lower hard bench may belong either to the Sundance or to the Upper Triassic Jelm formation; but definite evidence on this point is lacking.

CHUGWATER FORMATION

The Chugwater formation ("Red Beds"), of Triassic age, as at present identified in Salt Creek well records, consists of about 700 feet of massive red shale and sandstone, interbedded with some limestone beds and beds of gypsum.

EMBAR FORMATION

Beds tentatively correlated with the Embar formation, of Permian age, underlie the Chugwater and consist of 220 feet of alternating limestone and red shale, interbedded with a few layers of varicolored sandstone.

TENSLEEP SANDSTONE

The Tensleep sandstone, of Pennsylvanian age, underlies the Embar and consists of about 270 feet of massive cross-bedded white sandstone, interbedded with a few thin layers of dark-brown limestone. This sandstone has been reached by a deep well just southwest of the town of Midwest, in the Salt Creek field, and there yields a flow of several thousand barrels a day of water having a temperature of about 170° F. A second well drilled in 1930 in the SW. ¼ NW. ¼ sec. 35, T. 40 N., R. 79 W., reached the Tensleep at a depth of about 3,780 feet and obtained an initial yield of about 1,900 barrels a day of heavy oil.

OLDER FORMATIONS

The nature and sequence of formations beneath the Tensleep sandstone in the Teapot area is as yet a matter of conjecture. However, in view of the results of the Salt Creek deep test well, above referred to, which penetrated about 1,500 feet of sedimentary beds beneath the Tensleep, it is probable that the Tensleep at Teapot is underlain by at least 1,500 feet of sedimentary rocks corresponding in a general way to the Amsden formation (Pennsylvanian and Mississippian), Madison limestone (Mississippian), Bighorn dolomite (Ordovician), and Deadwood formation (Cambrian). As some oil has been produced from both the Amsden and the Madison in Montana, and as petroleum resi-

[34] Wegemann, C. H., op. cit., p. 15.
[35] Estabrook, E. L., and Rader, C. M., op. cit., p. 207.
[36] Wegemann, C. H., op. cit., p. 14.

dues have been reported from outcrops of the Deadwood formation, these lower rocks can not be ignored as possible sources of oil within Naval Petroleum Reserve No. 3.

STRUCTURE

GENERAL FEATURES

The term "structure" as applied by the geologist to sedimentary strata means their present slope and attitude. Most sedimentary formations, especially the marine shales and sandstones that yield the greater part of our commercial oil and gas supplies, were laid down in almost horizontal layers of wide extent and of fairly uniform thickness within local areas. Since their deposition these beds have been uplifted and warped or folded by the great forces active in the earth's crust and thus have been deformed or tilted. Trough-shaped folds are spoken of as synclines, and archlike folds are called anticlines, or if the length and breadth of such folds are nearly equal, they are spoken of, respectively, as structural basins and domes. During folding or tilting the beds may have been broken and displaced, and the breaks on which displacement has occurred are spoken of as faults. (See pl. 5, *A*.)

The development of faults during folding, and the accompanying earthquakes, may be important causes of the concentration of oil and gas (probably originally present in tiny droplets and bubbles scattered through great thicknesses of rock) into the commercially valuable pools now found concentrated in our present oil and gas bearing sands.[37] The relative lightness of oil and gas in comparison with water means that in water-bearing sands any gas and oil that may be present will be found in upfolds—that is, beneath domes and anticlines—with water around the flanks of such folds and in the synclines or downfolds. Where free gas, oil, and water occur in the same fold, gas, being lightest, will be found in the top of the fold, then oil, then water. (See fig. 3 and sketch with pl. 8.)

METHODS OF REPRESENTING STRUCTURE

Several graphic methods are used for representing geologic structure upon a map. In one method dip symbols are used, each consisting of a bar showing the direction of a level line drawn on the bed mapped; an arrow drawn at right angles to the strike line, showing the direction of the bed's slope; and a figure beside the arrow showing, in degrees, the slope of the bed, measured from the horizontal downward. (See pl. 6.)

A second method, and the one chiefly used in this report, is that of contour lines drawn on the surface of certain key strata. The principle is the same as that employed in topographic mapping, except that the contour lines show the altitude of the underground or restored surface of some particular bed instead of the surface of the ground. (See fig. 3 and pls. 7 and 8.) Each contour line connects all points on the key bed at a specified altitude above sea level, and the difference in altitude between adjacent contours is usually a fixed interval, as, for example, 10, 20, 50, or 100 feet. Thus with a uniform contour interval the crowding of the contour lines together means a steep structural slope, and wide spacing of the contour lines means a gentle slope. As a fault is a break along which the beds on one side are displaced with reference to those on the other, the contours on opposite sides of the fault will be offset, and the amount of throw of the fault may be ascertained by comparing the altitudes of the same bed on opposiet sides of the fault at the same point. Thus if the 1,050-foot contour as determined on one side of a fault is exactly opposite the 1,100-foot contour on the other side, the downthrow at that point is just 50 feet, toward the side of the lower altitude. (See pl. 6.)

[37] Mills, R. V. A., Natural gas as a factor in oil migration and accumulation in the vicinity of faults: U. S. Bur. Mines Repts. Inv. 2421, December, 1922.

STRUCTURE OF REGION SURROUNDING NAVAL PETROLEUM RESERVE NO. 3

Naval Petroleum Reserve No. 3 lies near the southwestern margin of the great structural depression commonly spoken of as the Powder River Basin, which is bordered by the Big Horn Mountain uplift on the west, by the Casper Mountains and Hartville uplift on the south and southeast, and by the Black Hills uplift on the east. The position of this major basin is clearly indicated on the geologic map of North America and on the map of the coal fields of the United States by the oblong tongue of coal-bearing rocks which projects southward from Montana into the part of Wyoming between the Big Horn Mountains and Black Hills.

Near Kaycee an anticlinal spur projects southeastward from the Big Horn Mountains into the southwestern part of the Powder River Basin, on which the minor uplifts of the Kaycee, Tisdale (Powder River), and Salt Creek anticlines are superimposed. The Salt Creek anticline extends at least from the northern part of T. 40 N., R. 79 W., into the southwestern part of T. 37 N., R. 77 W., and upon this anticline the Salt Creek and Teapot domes are in turn superimposed.

The structural relationships in this region have been well described by Wegemann,[38] who states:

> The Big Horn Mountains are flanked on the southeast by several anticlines, arches of strata that rise like a series of waves, each higher than the last, toward the major arch that forms the mountains themselves. On the easternmost—the outermost—of these anticlines is the Salt Creek oil field [and also the related Teapot field]. * * *

[38] Wegemann, C. H., op. cit., p. 24.

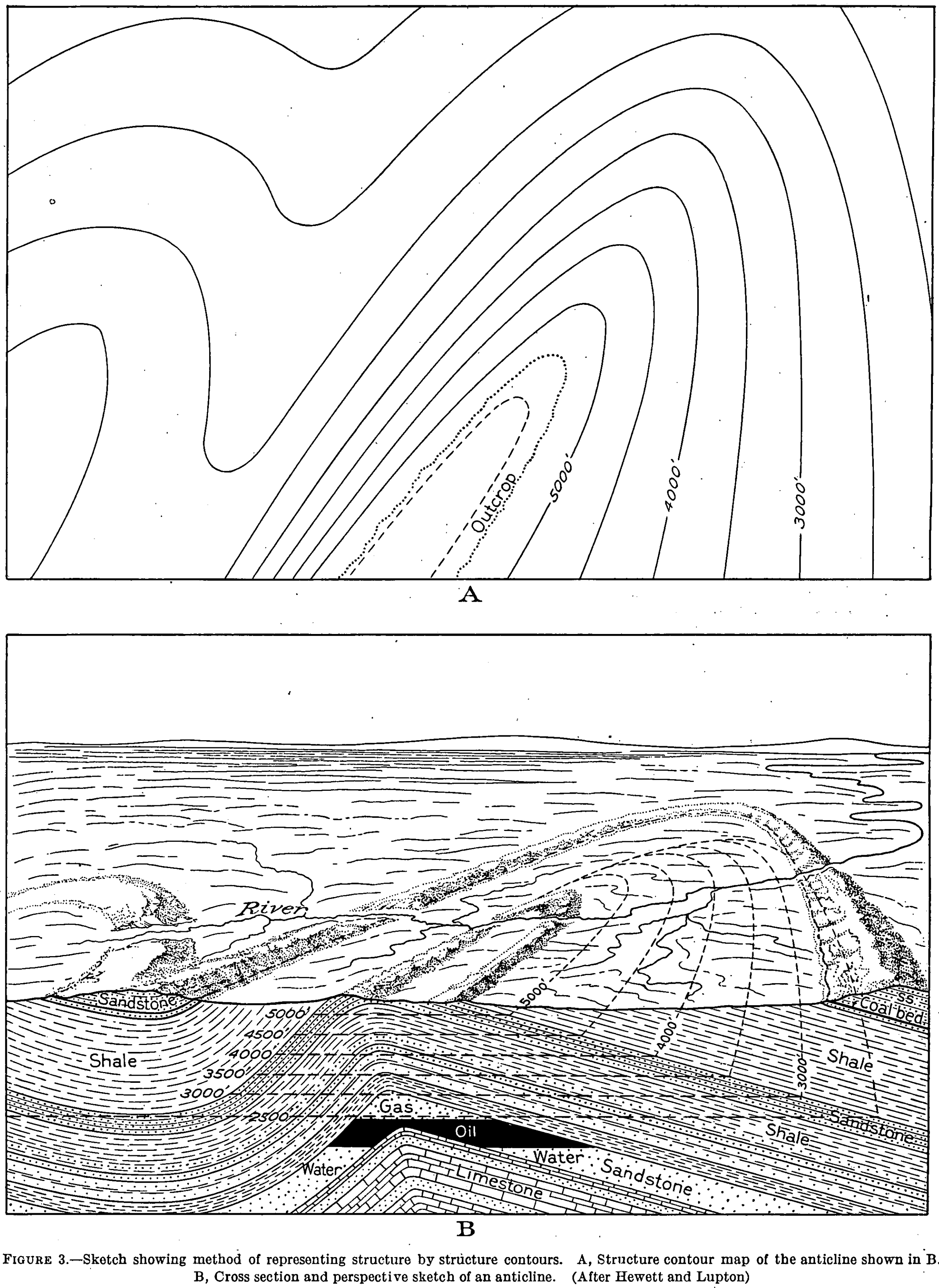


FIGURE 3.—Sketch showing method of representing structure by structure contours. A, Structure contour map of the anticline shown in B. B, Cross section and perspective sketch of an anticline. (After Hewett and Lupton)

The [Salt Creek] fold is not symmetrical, for its crest is much nearer its western than its eastern limit. The width of the eastern limb of the fold, measured from the crest to the bottom of the adjoining syncline, is about 20 miles, whereas the width of the western limb, measured from the crest to the bottom of the adjoining syncline, is only about a mile and a quarter. From northwest to southeast the Salt Creek anticline [including the Teapot field] is approximately 30 miles long.

Wegemann's map (pl. 6), though requiring modification as to details, gives a picture of the relative size and position of the Salt Creek and Teapot domes, although the Teapot uplift is shown as two complete domes instead of a single elongated uplift broken by faults into a number of segments.

The Salt Creek dome lies upon the north end of the Salt Creek anticline, and its apex rises structurally about 1,200 feet above that of the Teapot uplift. It is much larger and less elongated than the Teapot dome, but the two domes have similar steepening of the west flank and similar fault patterns.

As revealed by the writers' recent mapping (see pl. 8) a minor faulted uplift, the Castle Rock dome, intervenes between the Salt Creek and Teapot uplifts, lying southwest of Castle Rock and centering within the SE. ¼ sec. 18, T. 39 N., R. 78 W. Minor half domes, bounded on the north by faults, also occur between the Castle Rock and Salt Creek domes. The Teapot and Salt Creek domes thus lie, respectively, near the south and north ends of the Salt Creek anticline and are separated by the Castle Rock and other minor faulted uplifts—a fact which, though significant, has not been brought out in previous descriptions of the structure of the Salt Creek and Teapot fields.

STRUCTURE WITHIN NAVAL PETROLEUM RESERVE NO. 3

Structural conditions within Naval Petroleum Reserve No. 3 are shown in considerable detail by Plates 7 and 8, which serve to illustrate the multiplicity of faults or fractures that cut the upfolds into numerous segments and wedges. These maps and the structure section (pl. 8) drawn along a line approximately following the crest of the Teapot uplift show the irregular depression or saddle extending from the east-central part of sec. 29, T. 39 N., R. 78 W., across the NW. ¼ sec. 28 and the southern part of sec. 21. North of this saddle the beds rise irregularly to the apex of the Castle Rock dome, which lies three-quarters of a mile northwest of the naval reserve; and south of the saddle the beds rise irregularly to the major apex of the Teapot dome, in sec. 10, T. 38 N., R. 78 W., and slope thence southward to and beyond the southern boundary of the reserve.

Because of their direct bearing on questions of oil migration and production the faults in and near the naval reserve were studied in detail, both at the outcrop and as revealed by well records. As shown by this study, the displacement along the local faults ranges from a few inches to about 280 feet. The arrangement of the faults with respect to the anticline and with respect to each other clearly shows that they were breaks which developed during the elevation and flexing of the anticline. Compression was produced by forces applied, at once upward and northeastward, against the west flank of the Teapot dome, causing breaks to develop across the axis of the fold, approximately in the direction of the forces applied. In places this faulting was accompanied by lateral crowding of one fault wall past the other, with consequent differential upbowing along parts of the anticlinal axis, as is well illustrated by the series of half domes present on the plunging north and south ends of the Teapot uplift. Elsewhere rotational movement caused the opening of tensional fissures into which thin slices of rock were dropped, giving rise to the "graben" blocks or wedges which are so characteristic and conspicuous a feature of the Teapot-Salt Creek area.

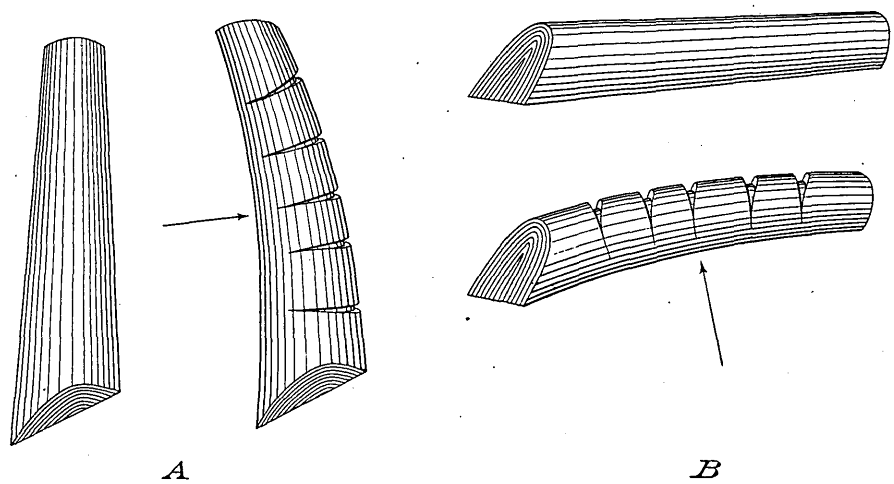


FIGURE 4.—Sketches showing fissure systems developed when horizontal (A) and vertical (B) forces are applied locally to anticlinal folds

Though only a partial representation of the conditions, the sketches in Figure 4 give an essentially correct idea of how tensional fissuring set the stage for down-dropped wedges, or grabens, to form. Plate 5, *B*, shows a cross section of such a graben exposed in the Grand Canyon in Arizona. The upper part of such a wedge, which crosses the northern parts of secs. 2 and 3, T. 38 N., R. 78 W., is exposed in the Parkman rim in the southeastern part of sec. 35, T. 39 N., R. 78 W. (see pl. 9), where the block is about 300 feet wide and has dropped vertically about 120 feet, bringing the white upper sandstone of the basal division of the Parkman member opposite the brown marine sandstones at the base of the Parkman. Drag on the left-hand fault is practically absent, showing that movement on that wall was almost vertically downward, which is also suggested by the horizontal and undisturbed condition of the principal mass of strata within the block. On the right-hand fault the down-faulted beds have been dragged or bent upward sharply near the fault, showing that strong friction occurred along this fault plane as the graben wedge sank.

Such drag at another fault is also shown by the slope of the hard layers visible at the left in Plate 5, *C*. The thin gray layer at the right of this picture has been bent downward and dragged out to a featheredge along the fault plane, which is marked by the hammer and the white calcite masses below it. Evidence of irregular displacement of down-faulted blocks is also clearly afforded by the thin hard layer capping ridges in the northeast corner of sec. 35, T. 39 N., R. 78 W., visible in the central foreground in Plate 10, *A*.

The approximate position and magnitude of the several faults mapped within or near the reserve can be understood by comparing Plates 7 and 8. Written description of such faults will therefore be limited to a few words regarding the particularly large group of fractures that cross secs. 33 and 34, T. 39 N., R. 78 W. These faults (U, V, V–1, and V–3, pl. 8) separate the northern and southern gas areas and apparently have planes on which the northern fault walls were thrust almost horizontally eastward with respect to the southern walls, the crest line of the fold being thus offset by the faults. The vertical displacement of the "Second Wall Creek sand" on fault U is approximately 200 feet near the center of sec. 33. This displacement decreases to 175 feet, more or less, near the center of sec. 34, where the main fracture of fault U probably merges with that of fault V, which has a throw of about 260 feet near the north line of sec. 26. The surface trace of fault U is clearly marked just southwest of the New York Oil Co.'s gas plant (see pl. 7) and in the ravines both east and west of the road near well 201, in sec. 33. East of its intersection with fault V fault U appears to have a displacement of only 20 to 50 feet.

Faults V–1 and V–3, which radiate from the intersection of faults U and V near the center of sec. 34, also step the "Second Wall Creek sand" down to the south. On fault V–1 the throw is approximately 50 feet at the center of sec. 34, increases to about 100 feet near well 401, in sec. 33, and decreases thence westward. On fault V–3 also the throw is about 50 feet to the south near the center of sec. 34 but decreases southwestward until it fades out in sec. 4.

OCCURRENCE OF OIL, GAS, AND UNDERGROUND WATER

Except beneath the higher parts of the Salt Creek and Teapot upfolds the sands that yield oil in these fields contain water under strong hydrostatic or artesian pressure. Consequently the oil and gas present, being lighter than the water, have accumulated beneath the uplifts—free gas, being lightest, tending to occupy the tops of the domes. (See diagrammatic sketch on pl. 8, also fig. 3.)

MIGRATION AND ACCUMULATION OF OIL AND GAS

According to commonly held views the oil-bearing sands and intervening shale beds were laid down in marine waters, and the voids between the sand grains and mud particles were originally filled with sea water with which at that time or subsequently were mingled gas bubbles and disseminated droplets of oil. Because of the high pressures existing underground considerable quantities of gas became dissolved in the interstitial water, and because of the greater solubility of gas in oil much larger quantities were dissolved in the oil. Then as folding of the beds of rock progressed, faults formed and afforded avenues for the escape of the compressed fluids, which rushed toward the openings just as oil or gas rushes to a well when it is drilled. Therefore, as oil that is rendered frothy by the expansion of the gas dissolved in it moves more readily than water,[39] the local reduction in rock pressure caused by the formation of faults near the anticlinal crests induced a migration of both gas and oil toward the folds. Much of the gas and a part of the oil escaped from the faults at surface seepages; but after a time the hydrostatic pressure exerted on the sand by the column of oil extending upward to the surface equaled the effective pressure in the sand, and the escape of oil and gas practically ceased. During this period of quiet channels for upward migration were sealed off, owing either to plastic settling of the shale beds, to the hydration and swelling of the bentonite layers, to the settling and collection of mud in the constricted parts of the fault fissures, to local cementation of the sand by calcite, or to cementation of the fault walls and the development of the calcite fissure fillings which are so commonly found marking the fault planes in the Salt Creek and Teapot fields. After the faults were sealed local pressures were rebuilt or redistributed through regional hydrostatic and hydraulic adjustments, and gravitational readjustments went on within the folds, producing a segregation of gas above oil and of oil above water, as in the Teapot field. With increasing pressure increased quantities of the free gas became redissolved in the oil, this process apparently going so far in the Salt Creek field as to cause the reabsorption of whatever free gas may have existed there after the initial accumulation had taken place.

The views set forth above are emphasized by Mills [40] as follows:

> The fact that nearly all the productive domes and anticlines in the Rocky Mountain fields are cut by fault fissures furnishes striking evidences that faulting and fissuring have played an important rôle in the migration and accumulation of oil into these entrapments. Probably the best example of this is the petroleum geologists' paradise at Salt Creek, Wyo., described by Wegemann. The huge Salt Creek structure and the some-

[39] Mills, R. V. A., op. cit.
[40] Idem, pp. 4–6.

what smaller Teapot dome are literally cut to pieces by fault fissures which are evidenced at the surface both by rock displacement and by calcite veins and stringers. At several places in the Salt Creek field the calcite veins and stringers contain ozokerite intermixed with calcite crystals.

The presence of open fissures below the surface is indicated by the occurrence of so-called shale oil in commercial quantities in the shales overlying the First Wall Creek sand, by the ejection of calcite crystals along with shale oil issuing from wells, and by the escape of oil and gas through these fissures incident to drilling operations. Shale oil and gas in crevices fairly permeate the Steele shale at various depths, sometimes within 4 or 5 feet of the surface. Wegemann [41] has described these features of the field in considerable detail. The so-called shale-oil wells in the Salt Creek and Teapot fields evidently tap fissures through which the oil has migrated upward from the Wall Creek sands.

Many of the fissures in the Salt Creek field are only partly filled with calcite, and much of the calcite filling is porous, with free surfaces of well-defined crystals lining vugs that are empty or filled with ozokerite. The writer has observed this same porous, vuglike structure in calcite that was deposited in oil and gas wells near Butler, Pa.

Evidence that the escape of small proportions of the gas and oil has continued practically to the present time is furnished by the occurrence of numerous seepages in the Salt Creek field. The spotted character of the production, together with the phenomenally high initial rates of production of some of the wells tapping fault zones in the Second Wall Creek sand, give further evidences of the relation that faulting bears to underground fluid movements in the Salt Creek field.

Again, the comparatively small productive area in the First Wall Creek sand is probably due, in part at least, to the loss of oil through fissures in the overlying strata. In this same connection there is the possibility that the First Wall Creek sand has received its oil by upward migration through fissures from the Second Wall Creek sand. An example of this type of oil migration and accumulation in Osage County, Okla., was recently described by Paul V. Roundy before the Geological Society of Washington.

These relations of faulting and fissuring to the migration and accumulation of oil and gas are further indicated by the large proportion of productive structures that are faulted in the Mid-Continent, Gulf Coast, and California fields. One of the most interesting examples of oil accumulation under the influence of faulting seems to be the El Dorado, Ark., field, which is severely faulted but is practically devoid of any anticlinal structure. The processes herein outlined have probably been largely responsible for the accumulation of oil in that field.

Primary and secondary gas accumulation.—For the purposes of this paper the retention and accumulation of a part of the gas that originally accompanied the oil is termed primary gas accumulation; whereas the subsequent migration and accumulation of gas into a faulted entrapment is termed secondary gas accumulation.

Where the gas originally accompanying the oil and water (primary gas) has escaped through the fissures, the accumulated oil may be practically devoid of gas, as at Soap Creek and Cat Creek, Mont.; at Mule Creek, Plunket, Maverick Springs, and other fields in Wyoming; and at Eldorado, Kans. But where considerable gas under high pressure accompanies oil in faulted and fissured structures it seems probable that this gas is either primary gas retained by the early sealing of the fissures, or that it is secondary gas which formed in or migrated to the entrapment after the fissures were sealed. It is possible that both phases of gas accumulation are represented in many structures. That there has been an enormous escape of gas incident to the migration and accumulation of oil in most fields is indicated by the high concentration of salts in the waters associated with the oil. This concentration has undoubtedly been brought about through the removal of water vapor in escaping gases.[42]

Retention of oil.—The question is sometimes asked, Why did not all the oil and gas escape from faulted areas before the fissures were sealed? The question might just as well be asked, Why does all the oil not flow from a productive sand through the wells that tap that sand? In both cases the flow ceases when the propulsive force becomes inadequate to propel the oil to the surface. Let it be remembered that under ordinary conditions of recovery about 80 per cent of the oil originally contained in a productive sand may, and probably does, remain underground when an oil field is abandoned.[43] As is the case with wells, the complete escape of oil through open fissures has probably failed largely because of dissipated gas pressures, whereas the final retention of the oil is due to the sealing of the fissures before the gas pressures in the vicinity of the faults have again built up through regional adjustments.

Summary.—In conclusion, the following points are emphasized:

1. Under favorable conditions, especially in firm consolidated strata, faulting that has yielded open fissures has been an important factor in the migration and accumulation of oil and gas.
2. Differential pressure, caused by the release of pressure through fault fissures, has been largely responsible for the migration of oil and gas to the places of accumulation, enriching the sands immediately around the fissures as well as the fissures themselves.
3. The migration of gas and oil through fissures has been upward either to the surface or from one bed to another. Fissuring has also facilitated the lateral migration of oil and gas through porous beds toward these points of escape. This corresponds with the lateral migration of oil and gas through sands toward producing wells.
4. The propulsive force of expanding gas, more especially the gas absorbed in oil and water under high pressure, has been one of the important factors in the migration of oil through porous strata toward fissures where the pressures were relieved.
5. Oil is propelled more effectively than water by the propulsive force of absorbed gas. Immediately upon the release of pressure, the absorbed gas expands and propels the oil from within. The comparatively high absorption capacity of oil and its tendency to remain entangled with the flowing and expanding gas appears to be largely responsible for this effective propulsion.
6. The migration and accumulation of oil and gas under the influence of differential pressures caused by faulting has been a comparatively rapid process, not the long drawn out process that is generally pictured.
7. The occurrence of faults in the Rocky Mountain and Mid-Continent fields is a valuable criterion in the search for petroleum. In these regions a closed structure that is faulted should generally be given preference to one that is not faulted. Further application of these facts may possibly be made in other fields.
8. Shallow sands have generally undergone more advanced drainage of oil and gas through fault fissures than have the deeper sands.

CHARACTER AND DISTRIBUTION OF UNDERGROUND WATERS IN THE TEAPOT AND SALT CREEK OIL FIELDS

The oil pools occurring within the sands beneath the Salt Creek and Teapot domes are surrounded by waters

[41] Wegemann, C. H., The Salt Creek oil field, Wyoming: U. S. Geol. Survey Bull. 670, pp. 36-39, 1918.

[42] See U. S. Geol. Survey Bull. 693.

[43] Lewis, J. O., Methods of increasing the recovery from oil sands: U. S. Bur. Mines Bull. 148, 1917; Our future supplies of petroleum products: U. S. Bur. Mines Repts. Inv. 2174, October, 1920.

that vary in character and are under unequal and to a certain extent irregular pressures. The difference in the character of the several waters found in the Salt Creek field is pointed out in detail by Mr. Stabler on pages 38–62 and has also been described by Young and Estabrook [44] and by Ross and Swedenborg.[45]

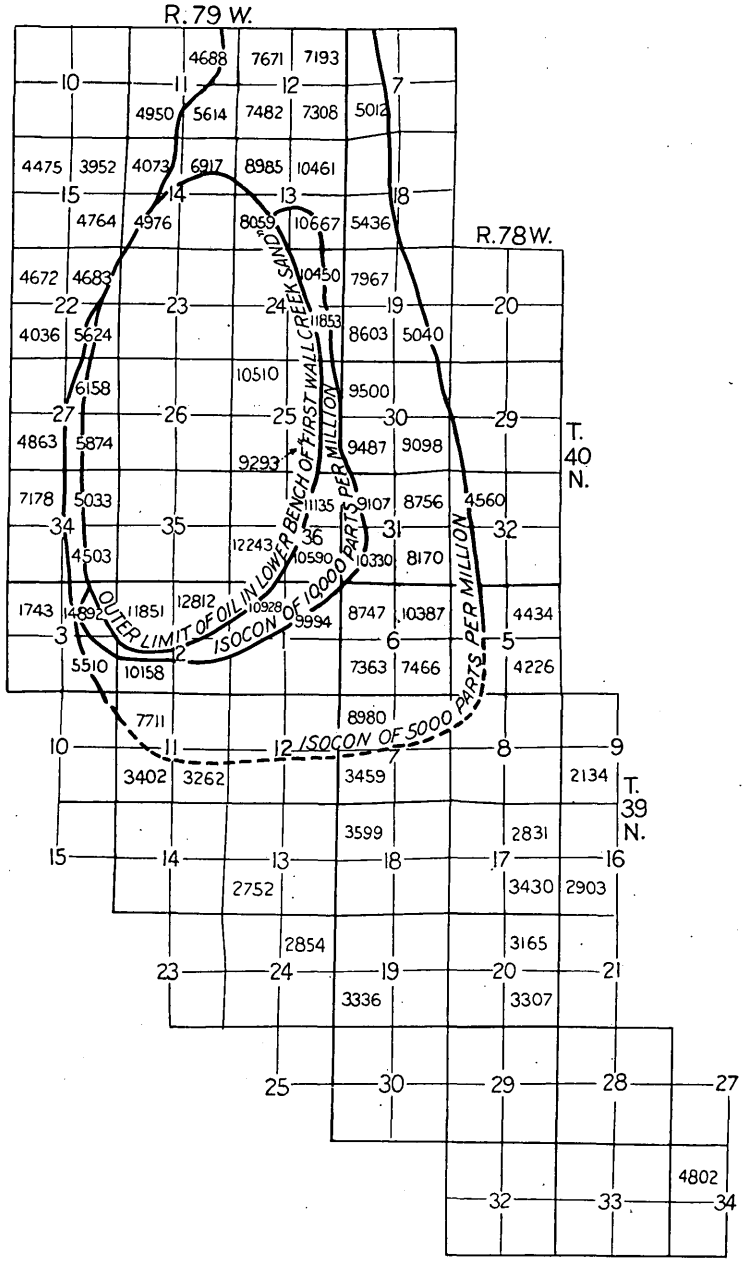


FIGURE 5.—Map showing concentration of dissolved solids in water of "First Wall Creek sand" in Salt Creek oil field. (By Young and Estabrook)

The history and present relations of these waters are largely revealed by what is known regarding their pressures and content of dissolved matter. Thus the Shannon sandstone, which crops out around the Salt Creek field, contains a sulphate and carbonate water essentially similar to the average surface water of the region. The water of the "First Wall Creek sand" is a brackish bicarbonate water which shows a marked geographic variation in its concentration and character, as shown by chloride-carbonate ratio (see fig. 5), the content of dissolved solids being much greater southeast and east of the oil pool in the "First Wall Creek sand," suggesting the existence of an eastward movement of artesian water from the high outcrop west of Salt Creek and perhaps a less active northward movement of water from the south and southwest across the saddle north of the Teapot field and up the east side of the Salt Creek dome. As was pointed out on page 14, water movement is apparently more active in the lower bench of the "First Wall Creek sand" than in the upper bench, and, probably as a result, the oil pool in the lower bench is proportionately smaller.

The water in the "Second Wall Creek sand" is a somewhat diluted and altered brine which occurs in much more concentrated form, with lower carbonate-chloride ratio and under less pressure, than the water in the "First Wall Creek sand"; and these facts, together with what is known regarding edge-water encroachment in the "Second" sand, suggest that owing to irregularities of bedding or cementation in the "Second" sand it is practically sealed off from active intake of water along its outcrop, and that essentially stagnant conditions prevail within the sand except as movement has been induced by drilling operations. Probably because of this retarded or nonexistent water movement in the "Second Wall Creek," its productive area in the Salt Creek field is far larger than that of the "First" sand. Also the "Second Wall Creek" is oil bearing over a considerable area in the Teapot field, whereas the "First" sand there is barren of oil.

The water in the "Dakota sand," which here is a thin, discontinuous sandstone, is of about the same concentration as the "Second Wall Creek" water but is more nearly a normal brine, strongly suggesting stagnant conditions. In contrast with this situation, the "Lakota sand," a few feet below the "Dakota sand," contains circulating artesian waters that resemble the more dilute samples of "First Wall Creek" water in composition; and coincidently the oil-bearing area of the "Lakota sand" at Salt Creek is somewhat smaller than that of the "First Wall Creek sand" and very much smaller than that of the "Second Wall Creek sand."

Little information regarding the waters of lower sands is yet available. It is, however, worthy of note that a well drilled to the Tensleep near the center of

[44] Young, H. W., and Estabrook, E. L., Waters of the Salt Creek field, Wyoming: Petroleum Development and Technology in 1925, pp. 256–261, Am. Inst. Min. and Met. Eng., 1926.

[45] Ross, J. S., and Swedenborg, E. A., Analyses of waters of the Salt Creek field applied to underground problems: Am. Inst. Min. and Met. Eng. Tech. Pub. 157, 1928.

sec. 25, T. 40 N., R. 79 W., yields large volumes of water that has a temperature of about 170° F. and contains relatively little dissolved matter.

SANDS WHICH ARE OR MAY BE RESERVOIRS FOR OIL AND GAS IN THE TEAPOT AND SALT CREEK FIELDS

Up to the present time commercially valuable amounts of oil and gas have been found within Naval Petroleum Reserve No. 3 only in the "Second Wall Creek" and "Third Wall Creek" sands and in fissures in the shales above the "First Wall Creek sand." In the Salt Creek field, however, commercial oil has been yielded by the Shannon, the "First Wall Creek," the "Second Wall Creek," the "Third Wall Creek," the "Muddy," the "Dakota," the "Lakota," the Sundance, and the Tensleep sands and by fissures in shale. Other sands—for example, those in the Morrison and pre-Sundance formations—may also be found locally productive in the Salt Creek field and perhaps in the Teapot field also. (See pl. 11.) According to all reports, the "First Wall Creek sand" is exclusively water bearing in the naval reserve, but a possibility remains that the "Lakota sand" and lower sands may contain oil and gas within the reserve.

Shannon sandstone.—The Shannon sandstone normally consists of two cliff-forming benches of sandstone overlain by a 25-foot bed of sandy shale or soft sandstone. An escarpment formed by the Shannon encircles the Salt Creek field, and the bed dips below the surface near the northern edge of the naval reserve (see pl. 2) and is within 400 feet of the surface over most of the productive part of the Teapot field. Some heavy oil has been produced from the Shannon sand just north of the main Salt Creek field, and noncommercial quantities of oil have been found in it at places in or near the Teapot reserve; but elsewhere water is found in the Shannon, or it is reported to be dry, indicating that faulting or irregularities of cementing or bedding prevent free fluid movement through the sand. Consequently, although some oil may yet be found in the Shannon within the reserve, it is probably unimportant commercially, except perhaps for ultimate exploitation by the sinking of shafts and actual mining of oil-soaked sand, as is now being done at Pechelbronn, in Alsace.

"First Wall Creek sand."—The "First Wall Creek sand" normally consists of about 125 feet of soft sandstone and sandy shale divided into two benches by a break 20 to 40 feet above the base of the sand. The lower bench, besides being thinner, contains water under stronger pressure and is the one which was principally exploited during the earlier development of the Salt Creek field. Porosities in the upper bench at Salt Creek are more irregular than in the lower, the recorded variations for the sand being between 7.6 and 25.8 per cent, and Estabrook and Rader[46] state that oil in appreciable amounts has been found (in the upper bench) a mile or more outside the water line in the lower part.

[46] Estabrook, E. L., and Rader, C. M., op. cit., p. 209.

Oil was found in this sand in the Salt Creek field in 1908, and until the opening of the "Second Wall Creek sand" in 1917 it was the principal productive formation of that field. The size of the productive area of the "First Wall Creek sand" at Salt Creek is difficult to estimate because of the twofold character of the sand and the incompleteness of early records, but it is probably between 4,500 and 5,000 acres. In the naval reserve the "First Wall Creek sand" is reported to be water bearing throughout.

"Second Wall Creek sand."—The "Second Wall Creek sand" which was opened by wells drilled at Salt Creek in 1917, has yielded the greater part of the oil produced in both the Teapot and Salt Creek fields and is the sand principally involved in present discussions. There is evidence indicating that in the Salt Creek area it normally consists of a number of layers of sandstone and sandy shale rather than of a single massive bed of sandstone. The presence of bentonitic shale "breaks" in the sand, especially toward the south end of the Salt Creek field, is stressed by Estabrook and Rader. Furthermore, the existence in that field of a much larger hydrostatic pressure in the base of this sand than in its top has been pointed out by Peake. The records of wells drilled in the naval reserve also indicate marked irregularities in thickness of this sand and the probability that it consists of at least two distinct layers. This view was set forth by H. B. Hill, of the Bureau of Mines, in an unpublished report on water conditions in the Teapot dome, dated February 28, 1924, in which he says:

> A study of the logs and history of the field leads one to believe that there is a shale break in the Second Wall Creek sand from 30 to 40 feet from the top, and that below the break, especially in wells low on the structure, the sand contains oil and water. For this reason it is deemed advisable to stop drilling in the upper part of the sand.
>
> Drilling has been stopped in a number of wells before reaching the break, and I believe that possibly all of these wells are making practically clean oil.

The lack of pressure communication (or of interference) between near-by wells in parts of the Salt Creek field also suggests that the "Second Wall Creek sand" is there to a considerable extent divided into separate reservoir units by cementation along joint planes parallel to the crest of the fold, on which the crest has settled slightly, as the keystone of an arch settles when the sides of the arch are spread apart somewhat, or the independent performance (noninterference) may be due to composite bedding or cross-bedding in the sand, which may consist of sand lenses overlapping shingle fashion. (See pl. 10, *B*.)

"Third Wall Creek sand."—The "Third Wall Creek sand" lies 215 to 275 feet below the top of the "Second Wall Creek sand" and has yielded some oil in both the Salt Creek and Teapot fields. In neither area has it

been completely tested, but because of its irregularity and relative thinness it does not appear to be of great prospective importance.

"Muddy sand" and "Dakota sand."—The "Muddy sand" and perhaps other sandy beds in the Thermopolis shale and the "Dakota sand" have yielded considerable quantities of oil in the Salt Creek field and elsewhere in Wyoming. They have not been completely tested at Salt Creek and are as yet wholly untested in the Teapot field, but in spite of their comparative thinness they appear to be of considerable potential importance within the naval reserve.

"Lakota sand."—The "Lakota sand" of the drillers is a coarse conglomeratic sandstone, normally containing artesian water under strong pressure and also containing a considerable oil pool beneath the higher part of the Salt Creek dome. It is as yet untested within the naval reserve and may be found to contain commercial quantities of oil and gas, although from the apparent strength of the water movement in the sand in the Salt Creek field it is believed that there is less than an even chance that it will yield oil in the reserve.

Sands in Morrison and Sundance formations.—The Morrison and Sundance formations contain a number of sands which may serve as reservoirs for oil and gas accumulation. (See pl. 11.) The existence of oil seepages from some of these beds where they crop out on the Tisdale anticline has been reported by Wegemann,[47] and the few wells drilled to these sands in the Salt Creek field indicate their potential value as oil reservoirs. The results of recent drilling in northwestern Colorado also suggest that important oil and gas pools may be found in Morrison and Sundance sands underlying the Teapot uplift.

Sands of the Chugwater and Embar formations.—The Chugwater formation consists of 700 feet of red shales and sandstones and is probably though not certainly barren of oil and gas in the Salt Creek and Teapot fields. The underlying Embar formation contains "black" oil in many parts of central Wyoming and is as yet inadequately tested in the Salt Creek field and wholly untested within the naval reserve. There is believed to be less than an even chance that it contains oil within the Teapot field.

Tensleep sandstone.—The Tensleep sandstone yields large flows of artesian water in the Tisdale and Salt Creek fields, and because of the indicated strength of the water movement it is probably barren of oil beneath the Teapot dome, although the presence of an oil pool in this sand beneath the crest of the Salt Creek dome (revealed by drilling in 1930) indicates the possible existence of a similar pool in the Tensleep at Teapot. Because of its considerable thickness and high porosity, however, there is a bare possibility that it contains very large quantities of oil beneath the naval reserve—a possibility which it would be unwise to ignore.

Older formations.—The formations that underlie the Tensleep sandstone at depths of 6,000 to 7,000 feet or more below the surface of the Teapot dome include beds that yield some oil in other areas in Wyoming and Montana. However, because of the minor importance of such known occurrences, the barrenness of these beds at Salt Creek, and the great depth of the formations in the reserve, it is believed that the drilling of wells to test beds below the Tensleep would not be warranted under any conditions that are likely to exist during the next decade.

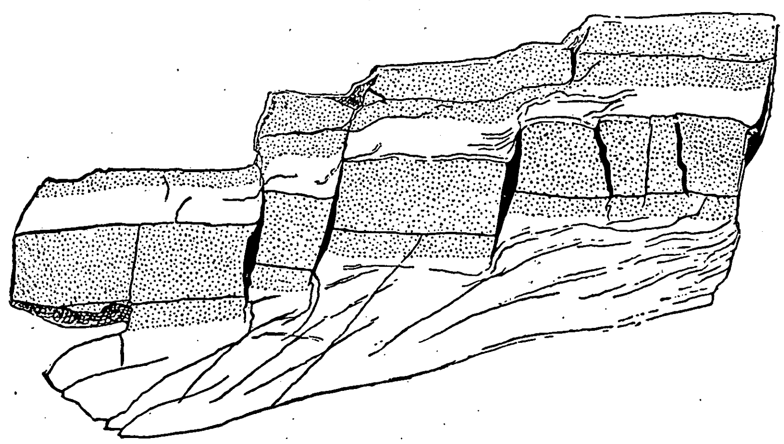


FIGURE 6.—Diagram showing how open fault fissures in brittle beds change degree of slope and become closed in plastic beds. (After Willis)

FISSURES IN SHALE

Many of the faults that cut the Teapot and Salt Creek uplifts have induced a shattering of brittle beds along the fault planes or have formed gaping fissures due to change of dip of the fault planes where they pass from soft into hard beds. (See fig. 6.) Much oil has been produced from such "crevices" within both the Teapot (pl. 12) and the Salt Creek fields and even outside the area of anticlinal uplift. The abundance of such open fissures, many of them entirely empty, and their practical bearing have been described by Wegemann,[48] who says:

> In practically all the wells drilled in the Salt Creek field more or less oil is encountered in the shale at different depths. These depths do not correspond in adjoining wells, and a comparison of logs shows that the oil is not obtained in porous beds within the shale but from some other source. The shale is so fine grained that it would not in itself constitute a reservoir for oil, as the openings between the particles are too small to permit oil to flow rapidly through them. Some wells in the Salt Creek field have obtained oil from the shale in large quantities, a few obtaining 1,500 barrels or more a day, indicating that the openings from which the oil is supplied to the wells are large enough to allow rapid flow. A comparison of analyses of the oil from the shale with analyses of the oil from the [First] Wall Creek sand shows that the two are practically identical, the only difference being that the oil from the sand contains a little more dissolved gas.

[47] Wegemann, C. H., op. cit., p. 14.

[48] Idem, pp. 36, 37.

In "drilling in" the shale wells, which start flowing under considerable pressure, it is often noticed that fragments of calcite are ejected from the wells. The calcite is like that which fills or partly fills the fissures produced by faulting in the shale. All the phenomena of the known shale wells indicate that the oil in them is derived from fissures in the shale, and that this oil is derived from the [First] Wall Creek sand below. Certain of the faults in the shale extend down to the sand and afford passages through which the oil in the sand, under great pressure, has been forced upward into the shale. As the fissures in the shale are not confined to the dome itself but extend into the adjoining syncline on the west, oil has been forced laterally through the fissures into the shale of the syncline, in which it is encountered in commercial quantities in wells drilled in the shale. The Wall Creek sand, wherever it has been reached in this area, has produced water. * * *

The shale above the [First] Wall Creek sand is fractured by many faults and probably contains many fissures unfilled by either oil, water, or calcite. There can be little question that faults which break the oil sand and throw its broken edges against impervious shale beds partly or wholly seal the sand along the fault planes so as to prevent the migration of oil across them. If the broken edges of the beds are left even slightly separated oil will find an easy passage through the fissure, but if the edges are compressed against each other or if the fissure is filled with calcite or other deposits, the fault forms an impervious barrier to the migration of oil in certain directions. Were these fissures all connected with one another or with the Wall Creek sand below, they would probably long ago have been filled with the oil which is now held under great pressure in the Wall Creek sand, and in filling the fissures a large part of the oil in the sand would doubtless have been dissipated. Several wells in the Salt Creek field were drilled to the sand and afterward capped and allowed to remain idle. When first drilled these wells may have shown considerable gas pressure and consequent large production of oil, but on being opened several weeks or several months later it was found that the pressure had decreased in some of them and that these wells were comparatively small producers. The explanation is obvious. A well drilled through the shale to the sand passes through one or more fault fissures, and as the casing is not firmly set in the hole the oil, under pressure in the sand, finds its way around the outside of the casing up to these fissures, gradually filling them. By this process the oil in the area drained by the well is in large part dissipated through these openings in the shale, the pressure is diminished, and the production of the well is greatly reduced. On entering the fissures the oil is in part doubtless absorbed by the shale on the sides of the fissures and so held in the rock, from which it can never be recovered. It is reported that during one cold winter the 2-inch line from well No. 6, in the NW. ¼ sec. 36, T. 40 N., R. 79 W., became choked with paraffin, virtually shutting the oil in, so that within a few hours oil seeps appeared at the surface 200 feet west of the well. A pit was then dug at the seeps and oil was pumped from it at the rate of several hundred barrels a day. When the clogged line from the well was opened the oil ceased to rise in the pit.

There can be no doubt that the life of the field and its production will be greatly increased by care in the proper setting of casing upon the sand. The additional expense involved by this care will probably be many times repaid by the resulting prolongation of production.

At the time that Wegemann wrote the statements quoted above the view had not been developed that oil had migrated into the fault fissures during anticlinal uplift and that the upper parts of the fissures had subsequently been sealed off from the sands below, although his observations and interpretations are in harmony with such a view. A very illuminating statement regarding the presence of fissures in the beds overlying anticlinal uplifts in the Rocky Mountain region is also given by Estabrook and Rader,[49] who say:

Oil in commercial quantities is found in crevices in the shale above the First Wall Creek sand in about 5 per cent of the wells started. Few wells fail to find some shows of oil in the crevices, and occasionally the production is very large and valuable. Crevice oil must be taken when found, for a well drilled only a few feet away may miss it entirely. It is the practice, in the Salt Creek field, to suspend drilling whenever crevice oil is found in amounts of 25 barrels or more per day; the production may last only a few weeks or may continue for years. Drilling is suspended until an adequate production test has been made and is then resumed or a new hole started, as determined by the staying qualities of the shale production.

Shale oil has been found all over the Salt Creek dome and also in 20 or more wells located across the syncline, west and entirely outside of the dome. At Teapot dome, where the First sand contains only water, there are numerous occurrences of shale oil (above the First Wall Creek). The most spectacular shale well opened in the district was the Mammoth Oil Co.'s well No. 301, in the southwest corner of sec. 2, T. 38 N., R. 78 W., Teapot dome, which came in October 5, 1922, flowing a solid 12-inch stream of oil over the crown block. The production during the first few hours is thought to have been at the rate of 15,000 barrels per day, but after the initial flow the production declined rapidly, and a year later the well was a small pumper.

In Salt Creek the best shale well of which there is a complete production record is No. 16, in the NW. ¼ sec. 11, T. 39 N., R. 79 W., which came in at about 1,500 barrels and, after producing 92,000 barrels in the 25 months ending December 31, 1924, was still pumping 42 barrels per day. The oil from the big shale well on the NW. ¼ sec. 27, T. 40 N., R. 79 W., which came in at 2,250 barrels per day and after two years was still making 90 barrels per day, has been run with the other wells on the lease, and no record has been kept of this production. Most shale wells are short lived—when the fissure is drained the production ceases. Some of the best sustained shale production lies across the syncline west of the field. Well No. 2, in the SW. ¼ sec. 33, T. 40 N., R. 79 W., came in at 150 barrels, and in 10 years has produced over 100,000 barrels of oil.

These crevices in shale are of common occurrence on the anticlines of the Rocky Mountain region. Oil in commercial quantities has been found in them at Florence [50] and Rangely,[51] Colo., and in the Salt Creek, Big Muddy, and Pilot Butte fields, Wyo. During 1924 discoveries of crevice oil in what appears to be commercial quantities have been made at the Fort Collins, Iles, and Tow Creek domes, Colo. Empty crevices are more common than those containing oil and are found on almost every dome where any of the Colorado shale is present. Rotary holes lose their circulating mud in the crevices, and cable-tool holes lose their fluid or get crooked in the fractured ground. Wagonloads of rock, dumped in to aid in straightening a hole, may disappear. When mudding behind the casing above the First Wall Creek sand in Salt Creek, often a large amount of mud is lost in the crevices.

Shale crevices frequently contain oil, rarely free gas, but almost never any water. The absence of water is especially

[49] Estabrook, E. L., and Rader, C. M., op. cit., pp. 209-211.

[50] Washburne, C. W., The Florence oil field, Colo.: U. S. Geol. Survey Bull. 381, p. 517, 1910.

[51] Gale, H. S., Geology of the Rangely oil district, Rio Blanco County, Colo.: U. S. Geol. Survey Bull. 350, 1908.

noteworthy, as the shale bodies contain sands carrying water under artesian pressure. At Salt Creek the First sand contains water under pressure everywhere except in the oil-producing area of about 4,500 acres on the crest of the dome, yet except in one or two cases no water has been reported in the shale crevices until recently. This lack of water has been the more surprising in Salt Creek because, in some of the early wells, water from the First sand rose nearly to the surface of the ground and for years was free to enter any crevices that might have been exposed. Water from this source and from drilling and mudding operations is constantly entering the shale crevices, and reports of its presence may be expected more frequently in the future. The ability of the shale to absorb some of the water that entered the crevices may have been a factor in the problem, but no investigation on that point has been made.

The absence of water in the shale crevices makes it difficult to believe that there has been any direct connection through them to the sands below, or that oil entered the crevices from the oil sands.

The writers are not in agreement with the suggestion that the absence of water in the fault fissures conclusively negatives the idea that these fissures ever communicated directly with the sands below. It is evident, as Mills has suggested (see p. 20), that for some reason—whether it be cementation by calcite, the plastic flowage of soft beds abutting against the fault, the hydration and swelling of bentonites, or the natural mudding off of the sands by the settling and compacting of fine mud in constricted parts of the fissures—the fluid in the sands, especially the water in the "First Wall Creek sand," no longer has access to the open parts of the fissures that cut the shale beds. It is believed to be probable that the empty fissures were once filled by water and that the shale of the fissure walls has absorbed the water by capillary processes, in part stimulated by the unloading incident to the erosion of some hundreds of feet of strata from the surface of the oil field.

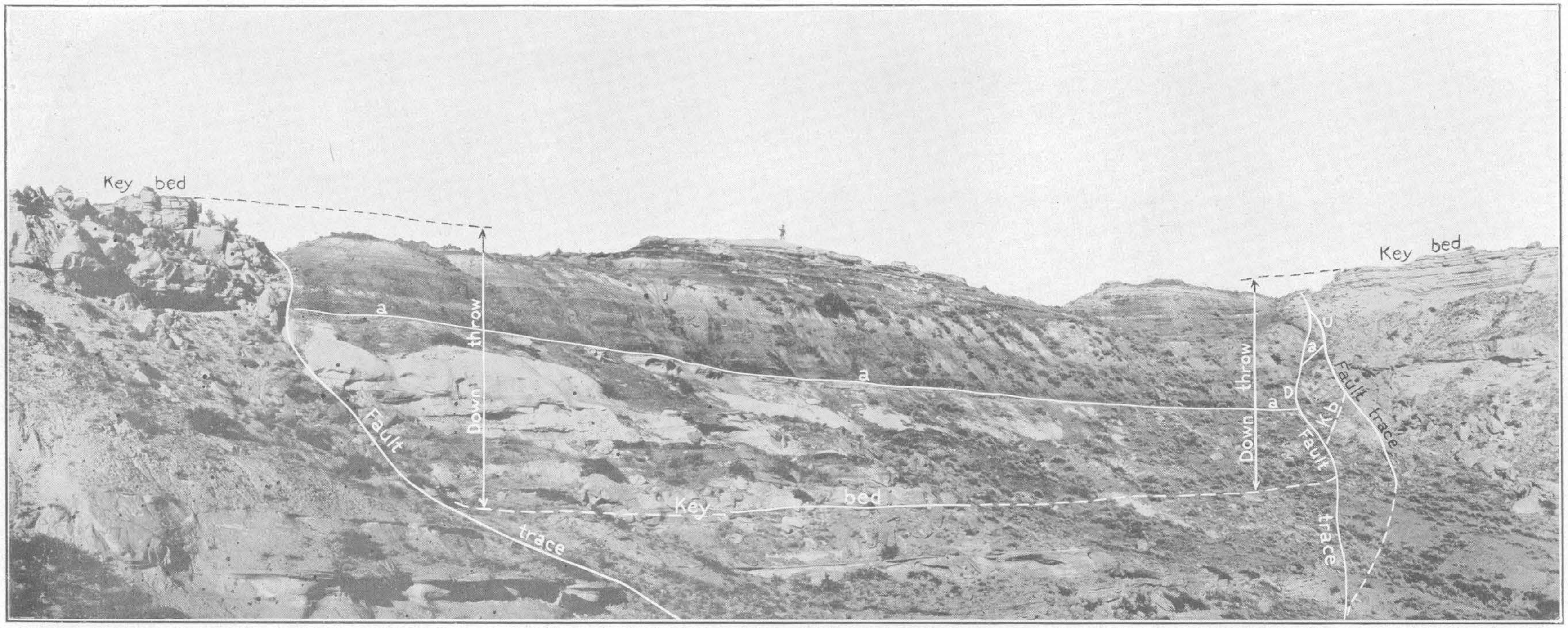
The foregoing rather lengthy statement as to the nature and distribution of fissures in the shales in the Salt Creek and Teapot areas has been given partly as indicative of the underground losses of oil and gas which may occur if wells are not properly drilled and cased, but more especially because a very appreciable part of the oil remaining in Naval Petroleum Reserve No. 3 may occur in such fissures. Not only are these oil-bearing fissures numerous, as is attested by the facts set forth by Plate 12 and Table 5, but they may be found anywhere within the reserve, whereas the buried sands, if oil-bearing at all, will be found to be productive beneath only a fraction of the reserve area.

TABLE 5.—*Wells in Naval Petroleum Reserve No. 3 which obtained oil or gas from fissures in shale, depth of occurrence, and yield*

[Compiled by Mammoth Oil Co.]

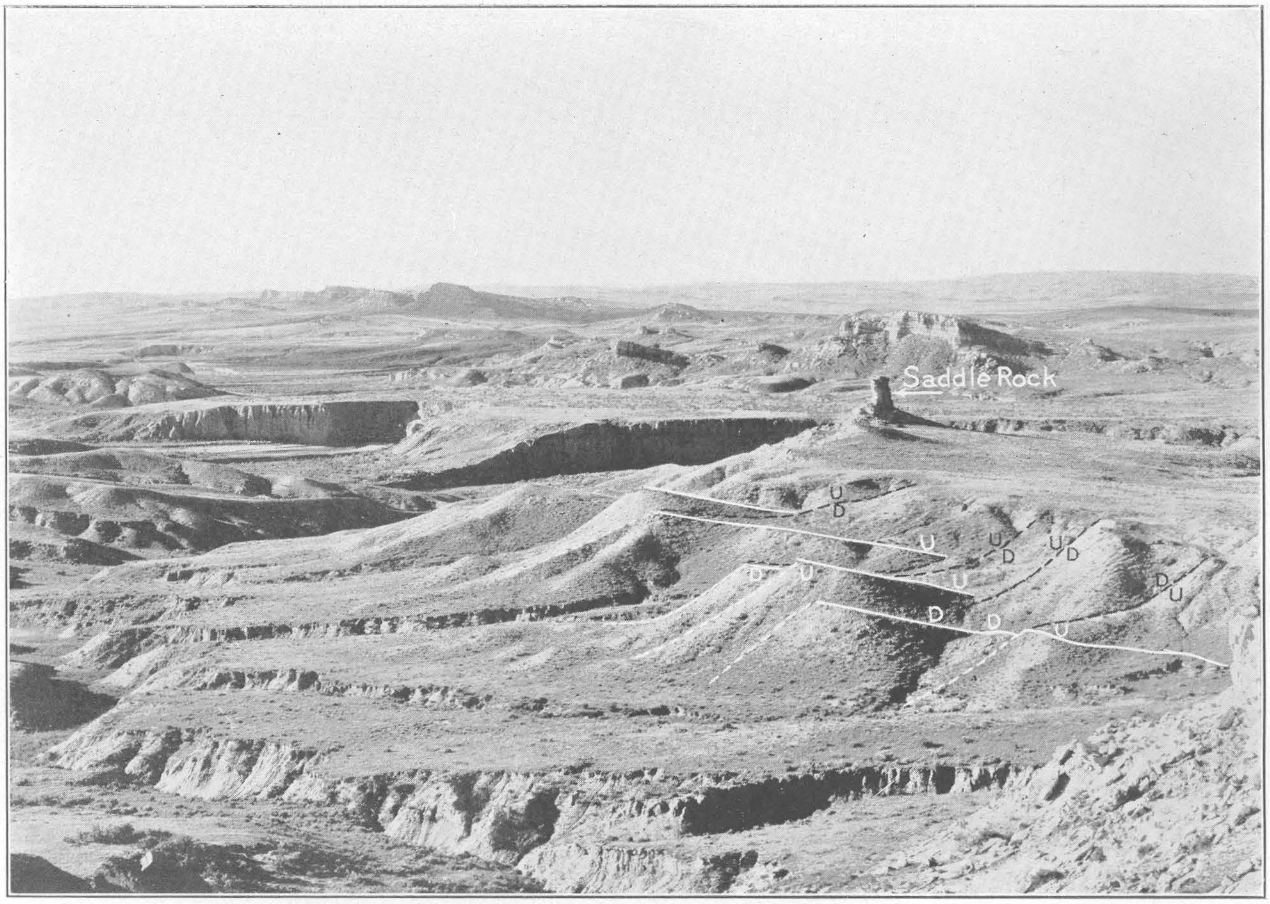
Well No.	Surface altitude (feet)	Depth of shale oil (feet)	Production (barrels)			Remarks
			First 24 hours	Second 24 hours	From shale, July 1, 1927	
301–2	5,153.7	1,435	Small showing			Producing from shale.
		1,515	8,000	200	5	This well flowed over derrick through 12½-inch casing on afternoon of strike.
201–3	5,215.0	1,225	Small showing		Drilled deeper	Produced approximately 12 barrels a day for six weeks from 1,260 feet.
		1,260	12	12		
202–3	5,237.52	680–690	Small showing			Drilled deeper; no test.
203–3	5,196.90	850	do	142	36	Producing from shale.
		2,010	124			
204–3	5,172.71	1,405–1,410	106		32	Do.
301–3	5,180.4	1,945	Small showing			Drilled deeper; no test.
302–3	5,198.96	700	Show of oil and gas			Do.
		1,635	do			
101–10	5,217.1	625	do			Flowed through 15½-inch casing from 1,020 feet; was producing from May 13 to Nov. 13, 1923, when drilled deeper for deep test.
		1,020	312	135		
102–10	5,218.11	760–900	Show of oil and gas			Producing from shale.
		2,097–2,070	240	15		
201–10	5,238.17	840				1 barrel an hour. Not produced.
		1,120				5 barrels an hour. Not produced.
		1,820				3 barrels an hour. Not produced.
		2,000				3 barrels an hour. Not produced.
401–10	5,192.19	660				Small amount of oil, gas, and water.
		800				100 feet of oil in hole.
		1,615	[a] 82			900 feet of oil in hole at 1,615 feet; produced well till Jan. 1, 1923.
		1,750	1 bailer per hour			
		2,290	do			
301–11	5,164.9	1,515				Showing of shale oil.
		1,630				Do.
101–15	5,244.1	1,290	137			Hole full of oil at 1,290 feet; production fell off to 40 barrels in 20 days; drilled deeper.
		1,900				Showing of oil.
		2,215				5 bailers of oil.
		2,305				Oil and gas.
405–20	4,996.75	1,400				Show of oil.
		1,580				Do.

[a] Oct. 26, 1928.



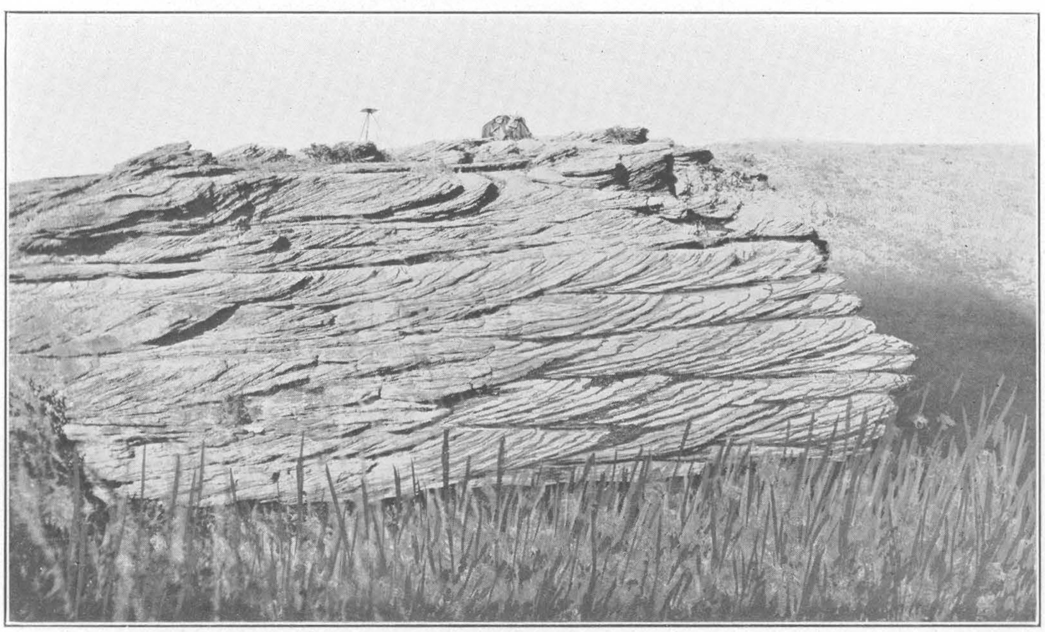
WHITE PARKMAN SANDSTONE IN GRABEN IN PARKMAN RIM EAST OF TEAPOT DOME, SEC. 35, T. 39 N., R. 78 W.

a, Top of white sandstone; Kb, key bed; D, downthrow; U, upthrow.



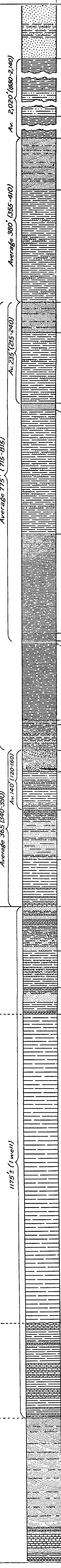
A. VIEW NORTHEASTWARD FROM POINT NEAR CENTER OF NE. ¼ SEC. 35, T. 39 N., R. 78 W., SHOWING OFFSETTING OF THIN HARD LEDGE CAP CAUSED BY SMALL FAULTS

D, Downthrow; U, upthrow; dashed lines, fault traces.



B. CROSS-BEDDING AND LAMINATION IN A LITTORAL SANDSTONE

Eagle sandstone as exposed on Broadview dome, Lake Basin field, Montana.



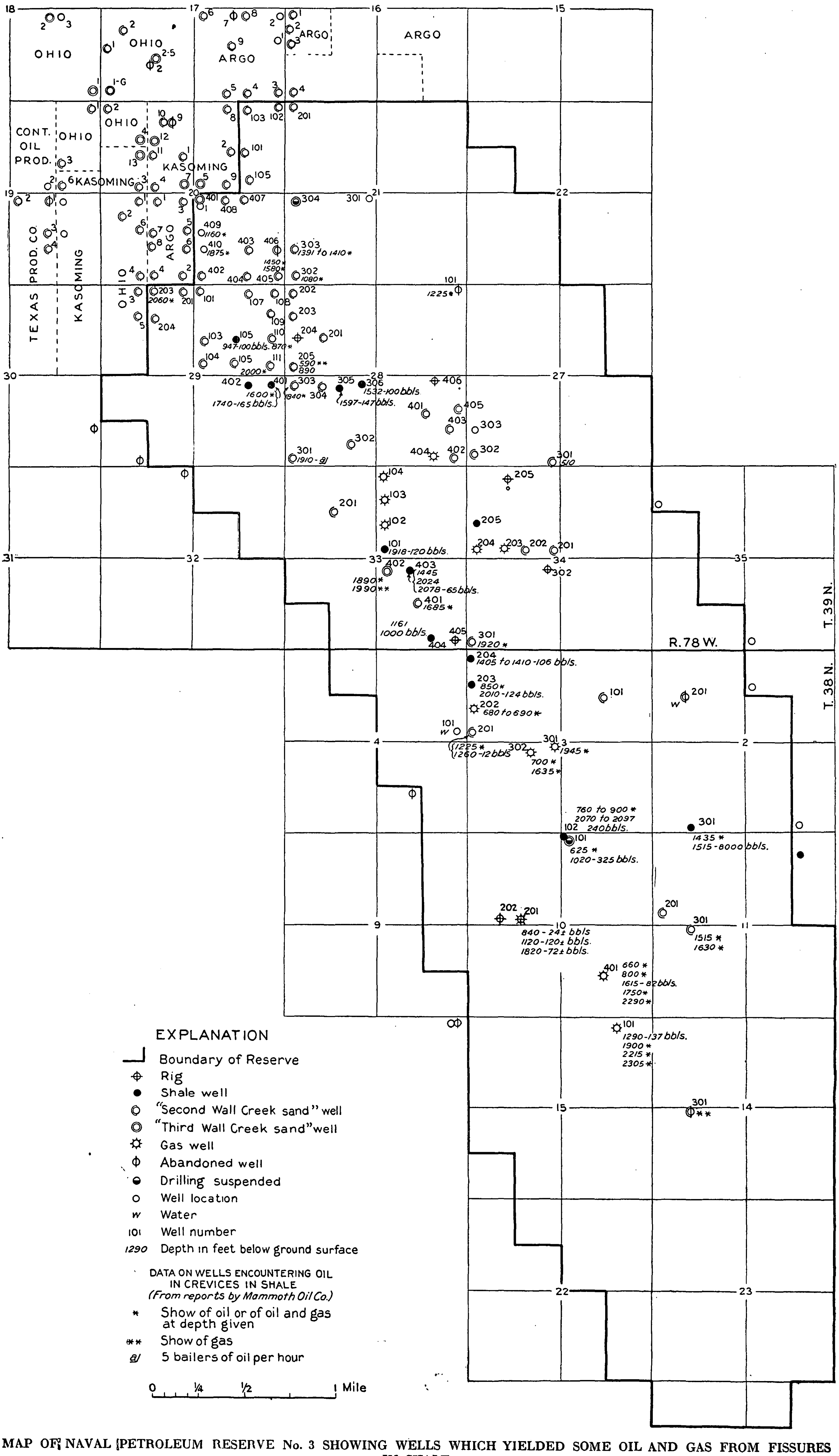
System	Series	Average thickness (feet)	Formation name	Description[a]	Gravity of oil (°Baumé)	Number of producing wells March 1, 1927
CRETACEOUS	Upper Cretaceous	125	Steele shale. Shannon sandstone member.	Buff resistant sandstone with intermediate zone of softer sandstone and shale. Oil produced from lower bench. Thickness 90–170 feet.	29	38 (idle)
		1,090	Steele shale.	Gray shale with thin calcareous layers and abundant cone-in-cone structure near base. "Shark-tooth conglomerate" 2± feet thick, 400 to 500 feet above base.		
		730	Niobrara shale.	Light-colored shale, somewhat sandy, with thin lime beds at top. *Ostrea congesta* clustered on fragments of *Inoceramus* are characteristic.	38–42	65
		200	Carlile shale.	Dark shale; thin ferruginous lime beds at 50 to 60 foot intervals.		
		?				
		120	Frontier formation (1,035± feet). Wall Creek sandstone member ("First Wall Creek sand").	Hard, gritty, gray, medium to fine grained cross-bedded sandstone with shale parting 20 to 40 feet above base. Contains small black chert pebbles and a few shark teeth. Thickness 90–160 feet.	38	267
		260		Gray shale, slightly sandy. Interval 230–310 feet.		
		70	"Second Wall Creek sand."	Gray medium to fine grained sandstone with thin partings of shaly bentonite. Partings more prominent to south and east. Thickness 50–90 feet.	37.7	1,612
		165		Gray shale, with variable sandy zones and sandstone lenses. Interval 145–170 feet.		
		15	"Third Wall Creek sand."	Tight gray sandstone, lenticular or absent in central and northern portions of field. Thickness 0–30 feet.	39	12
				Dark-gray shale and sandy shale with variable sandstone lenses.		
		230±	Mowry shale	Firm fissile dark shale, weathering silver-gray. Prominent slabby bed of bentonite at top, thinner beds near base. Abundant fish scales.		
				Soft black shale.		
		7	Thermopolis shale (200 ± feet). "Muddy sand."	Inconsistent, soft, fine shaly white sandstone, with coal and fragments of petrified wood. Thickness 0–11 feet.	38	21
				Soft black shale bearing plant remains and rarely shark teeth.		
	? Lower Cretaceous	8	Cloverly formation (100± feet). "Dakota sand."	White and brown sandstone, local distribution erratic. Iron pyrites common. Thickness 0–15 feet.		1
				Beds of variable character. Soft light-colored shale and thin shells or else massive dark shale.		
		50	"Lakota sand."	Interbedded conglomerate and coarse gritty white sandstone; few thin coal lenses. Iron pyrites common. Thickness 20–75 feet.	36	70
CRETACEOUS (?)	Lower Cretaceous (?)	90	Alternative interpretation of top of Sundance formation.	Soft variegated purple to green shale with thin hard fine sandstone beds predominant in middle zone. Fresh-water origin. Iron pyrites common. Thickness 285–360 feet. (May include part of Sundance formation.)		
		115	Morrison formation (315 feet).			
		110				
		?				
JURASSIC	Upper Jurassic	100	Sundance formation (250 feet). Upper bench.	Alternating gray, white, or brown limestone and sandstone, with intermediate zone predominantly gray shale. Thickness 235–285 feet.	33.4	3
		60	Lower bench.			
		(b)				
TRIASSIC		705±	Chugwater formation ("Red Beds").	Soft massive red shale, with beds of sandstone, gypsum, and lime.		
CARBONIFEROUS	Permian	220±	Embar formation.	Alternate lime and red shale with few sandstone members. Cream-colored to brown, and pink to purple.		
	Pennsylvanian	270±	Tensleep sandstone.	Massive fine to medium white cross-bedded sandstone. Few bands of dark-brown lime.		

Vertical scale

0 100 300 500 FEET

[a] Description of formations above "First Wall Creek sand" based on U. S. Geological Survey Bulletins.
[b] Below this point the data were obtained from one well only, 12 Tp, SW. ¼ sec. 25, T. 40 N., R. 79 W.

COMPOSITE WELL LOG OF SALT CREEK OIL FIELD SHOWING SEQUENCE OF FORMATIONS AND POSITION OF BEDS YIELDING OIL



MAP OF NAVAL PETROLEUM RESERVE No. 3 SHOWING WELLS WHICH YIELDED SOME OIL AND GAS FROM FISSURES IN SHALE

TABLE 5.—*Wells in Naval Petroleum Reserve No. 3 which obtained oil or gas from fissures in shale, depth of occurrence, and yield*—Continued

Well No.	Surface altitude (feet)	Depth of shale oil (feet)	Production (barrels)			Remarks
			First 24 hours	Second 24 hours	From shale, July 1, 1927	
409–20	5, 043. 08	1, 160				Show of oil.
410–20	5, 022. 05	1, 875				Do.
302–21	4, 998. 5	1, 080				Do.
303–21	4, 991. 46	1, 391–1, 410				Tested but not commercial.
301–27	5, 057. 54	510				Show of oil and gas.
101–28	5, 021. 38	1, 225				Show of oil.
205–28	5, 018. 32	590				Show of gas.
		890				Show of oil.
301–28	5, 081. 73	1, 910				5 bailers of oil an hour; not produced.
303–28	5, 049. 31	1, 840				Show of oil.
305–28	5, 055. 42	1, 597	147		7	Producing from shale.
306–28	5, 039. 86	1, 532	100		10	Do.
106–29	4, 980. 33	947	100		5	Do.
110–29	4, 967. 24	870				Show of oil and gas.
111–29	5, 024. 59	2, 000				Show of shale oil.
203–29	5, 020. 26	2, 060				Do.
401–29	5, 038. 32	1, 600				Do.
		1, 740–1, 745	165		6	Producing from shale.
402–29	5, 035–23	1, 438–1, 453	135		5	Do.
101–33	5, 153. 51	1, 918–1, 922	120		10	Do.
401–33	5, 145. 16	1, 685				Show of oil and gas.
402–33	5, 162. 44	1, 890				Show of oil.
		1, 990				Show of gas.
403–33	5, 142. 92	1, 445				Show of oil.
		2, 024				Do.
		2, 076	65		6	Producing from shale.
404–33	5, 159. 62	1, 161	100		4	Do.
301–34	5, 150. 39	1, 920–1, 970				Show of oil.

Shale wells producing July 1, 1927, 12; wells showing shale oil while drilling, 25; total 37.

ORIGINAL DISTRIBUTION OF OIL, GAS, AND WATER IN THE "SECOND WALL CREEK SAND"

In describing or depicting the distribution of oil, free gas, and water in a sand it is necessary to bear in mind that the so-called edge-water line or marginal contact between an oil pool and the surrounding water is not a line but a zone in which oil is floating on water, their plane of contact cutting obliquely across the sand (see diagrammatic sketch forming part of pl. 8); also that edge water commonly rises to a higher altitude on the steep flank of a dome than on the gentle flank and that it may be found at different altitudes in different sands, and even in different layers of the same sand.

The original position of the "Second Wall Creek sand" edge-water line in the Salt Creek dome or the Teapot field is not known with precision, but it is safe to say that the original oil-water contact in this sand in the Salt Creek field corresponded roughly with the closing contour, or lowest structure contour, that completely encircles the domelike uplift. The contact rose above this contour on the steep west flank of the Salt Creek dome and followed a plane inclined southeastward toward the saddle between the Teapot and Salt Creek domes. Owing to this southeastward slope of the water line in the Salt Creek field, it was found that in the "Second Wall Creek sand" the oil-bearing area of the Salt Creek and Castle Rock domes was continuous with that of the Teapot dome, although the connection was rather tenuous, water being found in the lower part of the sand almost up to the axis of the fold in sec. 29, T. 39 N., R. 78 W., and also being found between 20 and 30 feet below the top of the sand in wells 102–20 and 201–21, a mile northeast. (See pl. 13.)

The map of the reserve given on Plate 8 presents an interpretation as to the original limits of the area that contained oil, or oil and water, in the "Second Wall Creek sand." It also presents an interpretation as to the area from which gas alone was produced or from which gas was produced in such volume with respect to the accompanying oil as to make the productive wells normally classifiable as gas wells rather than oil wells. The unruled area surrounding the gas caps therefore includes a fringe marginal to the gas caps which would yield some oil, but only with wastefully large gas-oil ratios. The unruled area beyond the limits of this fringe includes a wide or narrow zone whose yields would range from 100 per cent oil to 100 per cent water. The apparent oil area as shown by the map is not therefore to be regarded as an area all of which would give commercial oil yields. The area of prospective commercial oil yield is from half to three-quarters of the total unruled area. It is worthy of note that the Salt Creek field contained no free-gas area comparable to those found beneath the Teapot dome.

ESTIMATES OF OIL CONTENT OF NAVAL PETROLEUM RESERVE NO. 3

Until more data of a fundamental nature have been obtained there appears to be no particular point in attempting to supplement the estimates of oil content made by Clapp and Lewis. Clapp calculated that about 26,000,000 barrels was recoverable by natural methods from the "Second Wall Creek sand" of the reserve, out of a total sand content of about 119,000,000 barrels. Lewis estimated the recoverable oil as between 12,000,000 and 24,000,000 barrels from the "Second Wall Creek sand" and from shale fissures above the "First Wall Creek sand." Such statements as to "recoverable" oil of course do not indicate the actual magnitude of the oil deposits underlying the field discussed but refer to a fraction—it may be but a small fraction—of the total amount of oil present.

As Beal and Lewis [52] state,

The difference between oil content and the amount of oil that may be recovered, or the ultimate production, is important. The recoverable oil of a sand underlying an area is the quantity that may actually be taken from the sand rather than the amount present in it. This recoverable oil is a percentage of the total oil content, and it varies with the conditions under which the oil occurs in the sand and under which it is produced. The proportion recovered, using only the natural forces, from a certain area depends mainly upon the porosity and size of the pores, upon the available energy within the sand for expelling the oil from the pores of the sand, and upon the efficiency of this energy. The last, in turn, is controlled largely by the external artificial conditions affecting the well or property.

The main force that expels oil from a formation is the gas compressed and dissolved in or associated with the oil. Gravitation and direct water pressure occasionally play an important part in expulsion but by no means as important a part as gas. Artificial forces are now being employed more and more to increase oil recovery, such as vacuum pumps, by the use of which suction is placed on the productive sands; water flooding, by which the oil is driven to oil wells by water flowing through the sand from strategically located wells; and compressed air or gas forced into the sand to simulate the original conditions of absorbed and compressed gas in the oil and oil sand.

The efficiency with which these forces can be employed governs the ultimate amount of recoverable oil. The friction of the oil passing through the porous formation retards the expulsion forces to a degree depending on the viscosity of the oil but principally on the character of the porous medium containing the oil. Other factors governing the efficiency of expulsion are the distance the oil must flow through the sand to the well outlet, and the mechanical conditions obtaining at the well. In some cases the expulsive forces are wasted and the recovery is reduced. These wastes may be due to improper casing, which allows the gas to escape through a barren or partly depleted oil sand above; to inefficient operating; and sometimes the expulsive force is wasted because of the nature of the sand or because of the infiltration of water.

The term "exhaustion of a well," therefore, pertains more to the forces available for expelling the oil than to the actual depletion of the oil contained in the sand. These points have been discussed in general by Lewis and Beal [53] and in some detail by Lewis.[54]

Lewis also pointed out [55] that much of the "irrecoverable" oil could be made "recoverable" by use of the newer production methods:

That much of the oil in a field is never recovered is well known, but how large a proportion is left underground and the possibility of increasing the recovery can not be fully realized until one clearly understands that the exhaustion of an oil well is due more to the exhaustion of the natural gas, which is the principal agent in driving the oil into the well, than to the exhaustion of the oil itself.

Facts presented in this bulletin go to show that the capacities of the oil sands in the various fields of the United States are five to ten times greater than the quantities of oil commonly extracted from them. If it could be fully established, as seems most probable, that the pores of the oil-bearing sands were completely filled with oil at the time the fields were first developed, then 80 to 90 per cent of the oil is left underground when the wells are abandoned. Although the evidence at hand does not permit positive statements that this proportion is being left underground, there is abundant evidence that much oil capable of being recovered remains in the sands. Complete extraction is not to be hoped for, yet there is no reason to conclude that the maximum possible recovery has been reached when the natural forces have been exhausted, and, furthermore, it has been demonstrated that it is practicable to get more oil from the sands by the processes described in this report.

It is too soon to know just how much to expect from these methods of increasing recovery, but the results have been so encouraging that they give possibilities of new values to the properties of every producer and to the country as a whole as a new source of supply to ward off the threatened shortage. It would thus seem the part of wisdom for the individual producer and for the general public to see that the oil fields are left in condition to use these or any new or improved processes that may be discovered in the future. It should be insisted, as far as practicable, that oil wells not now profitable be abandoned in such manner that they may be reclaimed at some later date, when, as seems probable, new discoveries and improved economic conditions will make their operation profitable once more.

In 1926 the same author said: [56]

At first thought it would seem absurd that 80 to 90 per cent of the oil was being left underground, and the industry has justifiably demanded ample proof of such claim. When I made my first estimates for the Bureau of Mines in 1916 I had more reasons to support the conclusions of myself and others as to this low recovery than I then published, for I thought it wise to be conservative on so radical a proposition. The evidence since has been confirmatory, especially that from France and Germany, of 14 per cent recovery, which closely coincides with my estimate of 10 to 20 per cent, but exact estimates are still impossible. However, the evidence is, I think, sufficient for present purposes. I do not think this oil left underground can fairly be considered a waste, for it is still recoverable and its value as a reserve for future needs is greater than would have been its value if it had been possible to throw it on the market during these past years of overabundant supply.

Broadly speaking, I estimate that one-seventh of the oil has been recovered by old processes, another seventh seems possible by present commercial practices for rejuvenating depleted oil fields, another two-sevenths seems possible by improvements in present rejuvenating processes, and three-sevenths can be recovered only by radical improvements over methods now in use. * * *

The knowledge that a huge oil reserve of unrecovered oil is being left under ground introduces a new element into the

[52] Beal, C. H., and Lewis, J. O., Some principles governing the production of oil wells: U. S. Bur. Mines Bull. 194, pp. 12–13, 1921.

[53] Lewis, J. O., and Beal, C. H., Some new methods for estimating the future production of oil wells: Am. Inst. Min. Eng. Bull. 134, pp. 478–480, 1918.

[54] Lewis, J. O., Methods for increasing the recovery from oil sands: U. S. Bur. Mines Bull. 148, p. 20, 1917.

[55] Idem, pp. 8, 9.

[56] Lewis, J. O., The rejuvenation of depleted fields: Federal Oil Conservation Board Hearings, Feb. 10–11, 1926, pp. 53, 61.

economics of the oil industry. Production, as a whole, declines naturally about 25 to 35 per cent from one year to the next, and to make up this loss, as well as to provide for growth in demand, it has been necessary to find new pools each year. The existence of new pools can only be inferred by geological evidence and not certainly known until drilled; consequently, there is always uncertainty as to the future oil supply, for no one can foretell whether new pools will provide a feast or a famine.

The dormant oil reserves in the old pools are of different nature. Their existence is known definitely, and it remains but to apply improved methods, and the rate at which it can be brought to the surface is largely within the control of the industry.

The cost of recovering this dormant oil will not be as much as many have thought. This will be especially true if the pressure method can be applied in unit operations. The cost of producing each barrel of oil is considerably reduced, and this production will not be charged with the large cost of finding, acquiring, and developing oil in new pools, which is increasing year by year.

The rate at which oil from these reserves will be brought to market will be largely in response to our needs.

As Lewis estimated that the average recovery of oil by flowing and pumping amounts to one-seventh of the total oil in the ground, his estimate of 12,000,000 to 24,000,000 barrels of recoverable oil in Naval Petroleum Reserve No. 3 suggests that he regarded the gross oil content of the reserve as between 84,000,000 and 168,000,000 barrels. These estimates however, are regarded by the writers as of doubtful value, because of the fact that in spite of the drilling which has been done in the reserve the extent, porosity, and degree of saturation of the oil-bearing portions of the "Second and Third Wall Creek sands" are as yet incompletely known; the magnitude of the oil in fissures above the "First Wall Creek sand" is uncertain; and the possible productivity of the Shannon sand and of sands below the "Third Wall Creek sand" has not been determined. Core drilling of the Shannon sand and further drilling to test the oil-bearing extent of productivity of the "Second Wall Creek" and lower sands are therefore highly desirable.

SUSCEPTIBILITY OF NAVAL PETROLEUM RESERVE NO. 3 TO LOSS BY DRAINAGE

A number of those who favored the leasing of the reserve appear to have done so because they regarded the "Second Wall Creek sand" as a continuously permeable reservoir bed which would permit loss of gas pressure to extend throughout the field from wells drilled near the boundary, or because they felt that the Navy's best interests would be served by recovering as much oil as possible (at the least cost) by current methods of production, discounting improved processes of recovery, or future methods of secondary oil recovery as being too uncertain or too costly to merit consideration. Those who opposed leasing the naval reserve did so because they held that these reserves had been created to insure a supply of oil for the Navy when it would no longer be able to obtain adequate quantities by purchase or requisition—cost consequently becoming subordinate to adequacy of supply—also because they believed that any losses from the reserve due to line drilling would consist chiefly of loss of gas and of gas pressure and only to a minor degree of oil, and that with the perfection of methods for repressuring fields and for other forms of secondary oil recovery, such loss of gas pressure, while regrettable, would not prevent the naval reserve from serving its intended purpose.[57] (See pp. 37–38.) Some also believed that because of the geologic conditions prevailing there was doubt as to whether the loss of pressure caused by drilling outside the reserve would extend for more than an insignificant distance within the Teapot field.

The absence of dangerous or extensive loss of gas and oil from Reserve No. 3 by drainage to wells just outside the reserve boundary has now been demonstrated beyond reasonable doubt, partly as a result of pressure observations taken on key wells within the reserve and partly by an analysis of the production records of leases adjoining the reserve boundary. The operators of the several leases adjoining the reserve boundary have all been granted reductions in royalty payments to the Government because of the scant yield of their properties. The absence of any large-scale migration of oil from the reserve to these wells was therefore evident at the time these reductions were granted.

However, because of the publicity which the "drainage" issue has received, it is probably desirable to review the grounds for past differences of opinion on the subject and also for the belief, even at the time the reserve was leased, that drainage was not a serious menace to the reserve.

Opinions as to the desirability of leasing the reserve differed largely because of differences in conception of the policy and intent underlying the establishment of the naval petroleum reserves. To this basic disagreement were added others arising from incomplete knowledge and incomplete analysis of the geologic factors entering into the problem. In order to arrive at a judgment as to whether drainage was or was not greatly to be feared at the time the reserve was leased it is necessary to review (1) the nature of the factors controlling oil, gas, and water movements through uniform sands; (2) the pressure conditions in the Salt Creek-Teapot area; (3) the evidence indicating that oil migration could not take place over long distances through the "Second Wall Creek sand" because of lack of water movement in the sand, because of local cementation of the sand, because of the bedding of the sand, or because of discontinuity of the sand due to faulting.

[57] Lewis, J. O., Methods for increasing recovery from oil fields: U. S. Bur. Mines Bull. 148, 1917.

FACTORS CONTROLLING FLUID MOVEMENTS WITHIN OR FROM RESERVE

The rate at which oil, gas, and water move through a uniform and continuous sand, under the same pressure differentials, is inversely proportional to the frictional resistance to movement offered by the sand to each fluid. Gas and water, because of their lack or relative lack of viscosity, will move through an ordinary continuous sand under pressure differentials as low as 1 pound to the mile.

Oil from which gas is escaping rapidly (being thereby in a state of active expansion or having been converted to a froth) may flow through a sand even more rapidly than water. On the other hand, oil from which the dissolved gas has escaped or from which it is escaping slowly will move through a sand only under pressure differentials measurable in hundreds of pounds to the mile. The difference in behavior of oil under the two conditions may be illustrated by imagining what will happen if a bottle is filled with sand and then with ginger ale or some other carbonated liquid. If the cap is removed from such a bottle and it is shaken vigorously a miniature gas eruption will ensue, spattering a part of the liquid over a large area and leaving a residue of liquid in the bottle practically free of gas. On the other hand, if the bottle is opened carefully and then allowed to stand, bubbles of gas will gradually form and escape from the liquid until eventually all the excess gas has escaped from solution—or, as it would be put by oil men, the liquid has become "gas drained." The fluid, however, will never cease to be a liquid and will maintain its general properties without major change throughout the transition from the gas-charged to the gas-free condition.

When an oil well is completed the oil near the hole ordinarily effervesces violently, the hole becomes filled with an oily froth or frothy oil, and gas and oil flow from the well. This behavior is due to the great difference in pressure between the well opening and the gas-charged oil in the sand and also to the agitation caused by drilling or by the explosion of a charge of nitroglycerine. The effervescence spreads radially from the well. It decreases in intensity as the increasing distance from the hole causes increased resistance to flow. This decrease continues to a distance of several hundred feet, where the retarded movement is practically limited to that of gas bubbles passing or "slipping" through the oil without pushing it forward appreciably. At length, even near the well the escaping gas passes through the upper part of the sand, which has become drained of oil, and hence no longer pushes oil toward the well, the weak force of gravity alone remaining to bring oil within reach of the pump. Because ordinary sands resist the flow of gas-drained oil, drainage by gravity extends but a short distance from a well. It is believed by experienced engineers that in fields where oil is recovered through flowing and pumping—that is, through utilization of the forces of dissolved gas and of gravity—but one-fifth to one-tenth of the oil in the sand is normally extracted.[58] In such fields wells normally show large initial oil yields and quickly decline to a small output, which may continue with gradual diminution over a period of many years.

The radius to which oil drainage extends from a well is largely dependent upon the grain size of the sand and the viscosity of the oil, oils of high Baumé gravity characteristically moving through the sand with far greater ease than "low gravity" asphaltic oils.

Regarding the influence of grain size on drainage Brewster [59] states that the flow of oil to a well "varies inversely as the logarithm of the distance through the sand. The finer grained the sand the less is the distance from the well where frictional resistance becomes equal to the differential flowing pressure and flow toward the well practically ceases." For petroleums having gravities similar to those of Teapot crude the slight areal extent of oil drainage has been indicated by the work of Cutler.[60]

In other fields the first flush yield of oil under gas impulse may give place to a comparatively large and long-sustained yield of oil that is being borne forward by advancing water, but the yield will die out rapidly as the water reaches the well, first through the lower or more porous parts of the sand and then progressively through its entire thickness. In such fields the water surrounding the oil pool moves in, as the escape of gas and oil lessens pressures within the field. The yield by water flooding may be from 40 to nearly 100 per cent of the oil in the sand, compared with 10 to perhaps 25 per cent under the impulse of dissolved gas. The yield depends upon the character of the sand and of the oil, upon the slope of the reservoir bed, and upon the temperature and salt content of the water.

In the Salt Creek field the oil pools beneath the domelike uplifts are surrounded by water under pressures of 1,000 pounds or more to the square inch, and production from such pools would therefore be expected to show the twofold phase of yield—by gas impulse and by the "drive" of encroaching water. The encroachment of edge water and its effect have gradually become apparent in the "First Wall Creek sand" at Salt Creek and are clearly marked in the "Lakota sand." Water encroachment in the "Second Wall Creek sand," however, except perhaps along certain fault planes, appears to be slight or almost nonexistent. This fact is referred to on page 33 in the discussion of factors that have suggested the

[58] Lewis, J. O., Methods for increasing recovery from oil fields: U. S. Bur. Mines Bull. 148, pp. 8-9, 1917; The rejuvenation of depleted fields: Federal Oil Conservation Board Hearings, Feb. 10-11, 1926, p. 53. Swigart, T. E., and Bopp, E. C., Experiments in the use of back pressures on oil wells: U. S. Bur. Mines Tech. Paper 322, pp. 36-37, 1924. Ambrose, A. W., Underground conditions in oil fields: U. S. Bur. Mines Bull. 195, p. 121, 1921.

[59] Brewster, F. M., Petroleum development and technology in 1925, p. 39, Am. Inst. Min. and Met. Eng., 1926.

[60] Cutler, W. W., jr., Estimation of underground oil reserves by oil-well production curves: U. S. Bur. Mines Bull. 228, pp. 86-87, 101, 1924.

discontinuity of the "Second Wall Creek sand" as a porous bed.

In contrast with the energy of dissolved or associated gas, which is of definite amount and is speedily expendable, the hydrostatic pressure of artesian edge water usually does not diminish greatly as an oil field is developed unless water waste is permitted, for water taken in along the outcrop of the sand tends to satisfy the deficit caused by oil or water withdrawn in the oil field. For this reason water may drive oil for much greater distances than gas does, particularly up a structural slope.

Because of its sustained pressure and relatively low viscosity water normally moves more rapidly than oil except in the first stages of flow. Consequently, on the assumption that the "Second Wall Creek sand" was a continuous and uniformly porous bed, it was natural to expect that, as oil was withdrawn from wells near the northern boundary of the reserve, water would encroach across the "saddle" or structural low point north of the Teapot dome and would then "drive" northward to these wells the recoverable oil between the saddle and the reserve boundary.

Under the assumption of uniformity of sand conditions Wegemann [62] described what would happen when wells were drilled along the northern reserve boundary, as follows:

> It is obvious that as wells are drilled along the northwest line of the naval reserve, part of the oil produced by those wells will be drawn from the naval reserve itself. As the amount of oil in the sand is reduced and the gas pressure also relieved, the water which is present in the sand on the flanks of the structure below the oil will gradually invade the oil sand. It will advance into the lowest part of the structure first. In other words, it will creep into the saddle between the two structures on the NW. ¼ sec. 28 and the E. ½ sec. 29. This invading body of water will gradually work its way entirely across the saddle separating the oil in the S. ½ sec. 28 from the oil in the NE. ¼ sec. 29.

H. B. Hill, of the Bureau of Mines,[64] also expressed the view that

> The water will at a time not far distant be gradually drawn in from each side toward the axis until the northern part of Teapot or the southern end of the Salt Creek field is entirely separated by water from the southern or main part of the Teapot dome.

PRESSURE CONDITIONS IN SALT CREEK-TEAPOT AREA

Because of their bearing upon the problems of fluid movement just discussed pressure conditions must be thoroughly understood before the importance of their evidence as to possible drainage, even in 1921, can be fully comprehended. A summary of pressure conditions in the several sands of the Salt Creek-Teapot area is therefore given below.

The "First Wall Creek sand" in the Salt Creek field consists of two benches separated by a break of shale or of nonporous sand. Both benches contain oil pools surrounded by water under artesian pressure, and the pressure in the lower bench is greater than that in the upper.

The hydrostatic head or pressure in the "Second Wall Creek sand" is roughly 100 pounds to the square inch lower than that in the "First" and, according to Peake (see p. 15), is smaller in the upper part of the "Second" sand than in the lower part. Hydrostatic pressures in the "Lakota sand" and the Tensleep sandstone are higher than in the "Second Wall Creek sand," an artesian well near Midwest yielding a large flow of hot water (about 170° F.) from the Tensleep.

In contrast with the high artesian pressure existing in the "First Wall Creek sand" the pressure in the empty fissures found in the shale a short distance above the sand is practically zero, necessarily indicating a sealing of the fissures at points between the openings and the water-bearing sand.

It is reasonably certain that fluid pressures within the "Second Wall Creek sand" were essentially in equilibrium when the accumulation of oil and gas in the sand (within the Teapot-Salt Creek area) was about completed. The drillers' field reports as to initial gas and water pressures in several wells in the naval reserve indicate that a pressure equilibrium existed throughout the reserve at the time it was opened. (See fig. 7.) These pressures had also, beyond serious question, been in equilibrium with the original rock pressures in the Salt Creek field, which had been revealed by the height to which water rose in wells drilled at the margins of that field. It is true that these drillers' reports regarding pressure measurements made on Teapot gas wells and regarding the height to which water rose in the edge wells are given in round figures; but when the weights of water and of Salt Creek crude oil are borne in mind it appears that the original fluid pressures in the "Second Wall Creek sand" in the Teapot-Salt Creek area were approximately 1,100 pounds to the square inch at the 2,000-foot structure contour. The top of this sand lies between 2,150 and 2,200 feet above sea level in the saddle and rises to somewhat above 2,300 feet in the higher parts of the Teapot dome and to more than 3,500 feet near the crest of the Salt Creek dome. Consequently, because of these differences of sand altitude, a zero fluid pressure in the sand at the crest of the Salt Creek uplift would be in equilibrium with a fluid pressure of about 500 pounds in the sand at the saddle and with a pressure of about 450 pounds at the crest of the Teapot dome. It was therefore evident that in so far as gas pressures and gravity were concerned, on the assumption that water did not encroach, the tendency was for oil to move from Salt Creek toward Teapot instead of the reverse.

These facts are illustrated graphically by Figure 7, which also indicates the relative decrease in fluid heads

[62] Wegemann, C. H., A report on the position of the dividing line between the Salt Creek and Teapot domes: Hearing before the Committee on Public Lands and Surveys, U. S. Senate, Oct. 22, 1923, Exhibit G, p. 62.

[64] Letter to F. B. Tough, Aug. 28, 1923.

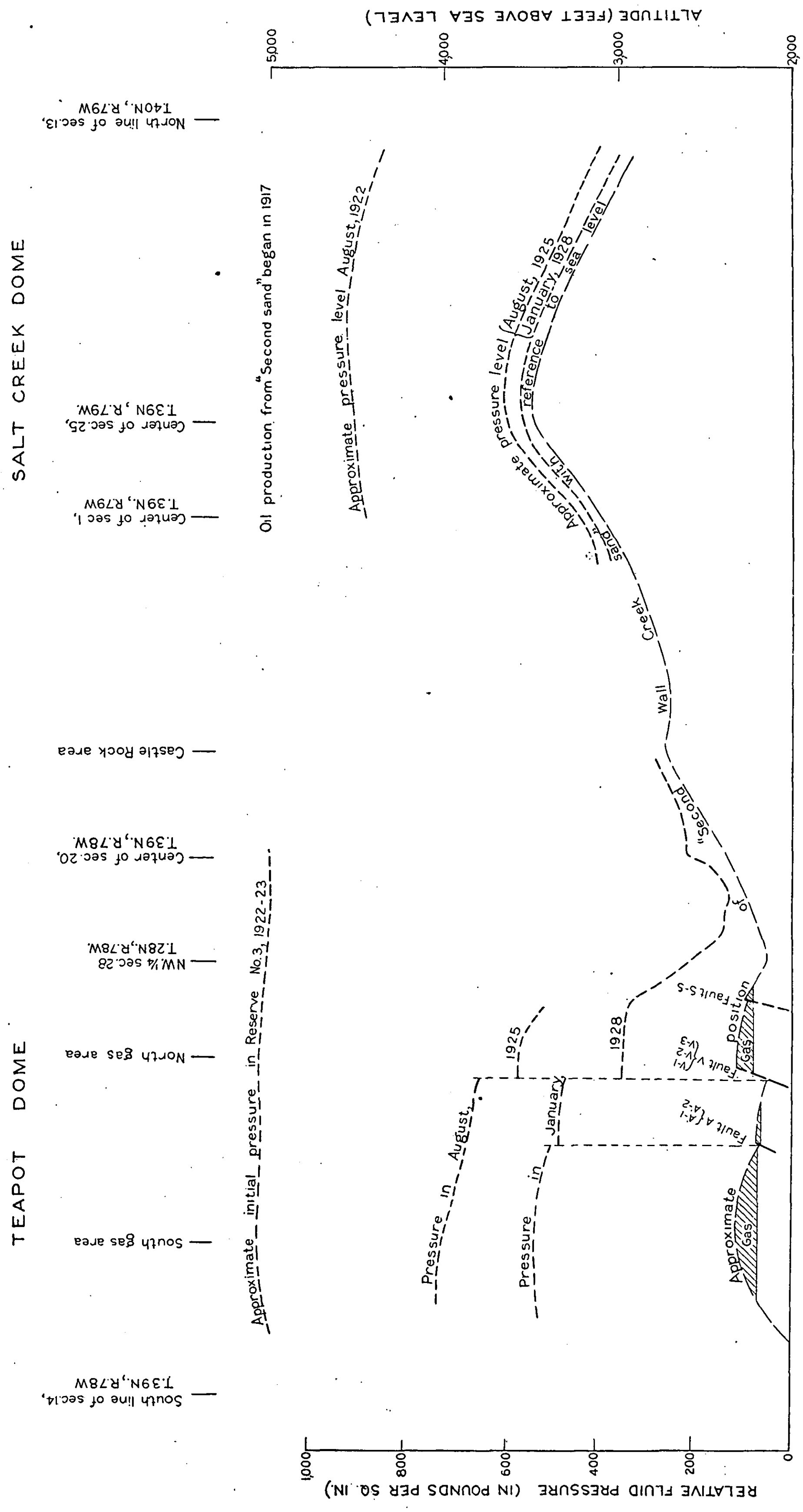


FIGURE 7.—Relation between geologic structure and reported rock pressure in wells in Naval Petroleum Reserve No. 3 and the Salt Creek oil field

in the Salt Creek and Teapot fields as determined at various times.

PROBABLE DISCONTINUITY OF "SECOND WALL CREEK SAND" AS A POROUS BED

Although dogmatic statements were not warranted prior to the closing in of the reserve, a number of lines of geologic and engineering evidence available from the Salt Creek-Teapot area strongly suggested that the "Second Wall Creek sand" was not sufficiently continuous as a porous and pervious bed to permit fluids to flow through it for more than relatively short distances—in other words, that the sand probably did not afford an avenue for widespread drainage.

The factors that appeared to indicate the localization of fluid movement within and through this sand were (1) the lack of water encroachment in the sand around the margins of the Salt Creek field; (2) the known existence of a "tight-sand" area extending across the Salt Creek field just north of the reserve; (3) the cementation of the sand in certain places near faults and joints; (4) the displacement of the sand by faults; and (5) the probably cross-bedded character of the sand.

LACK OF WATER ENCROACHMENT IN SALT CREEK-TEAPOT AREA

In considering the evidence as to sand conditions yielded by water encroachment (or rather by the lack of encroachment), a knowledge of both past and present water conditions is necessary.

At the end of Cretaceous time water pressures in the "Second Wall Creek sand" were slightly greater than those in the "First Wall Creek sand," because of greater depth of burial. Moreover, as the "Second Wall Creek sand" now crops out along the mountain side a few miles west of Salt Creek at altitudes at least equal to those of the "First Wall Creek" outcrop, wells drilled to the "Second Wall Creek sand" in the Salt Creek and Teapot fields should have found initial hydrostatic heads to be larger than those in the "First Wall Creek," provided there were equal sand continuity. Such higher pressures were not found, however, for although the "First Wall Creek sand" and the Tensleep sandstone gave flowing water wells, the water in the "Second Wall Creek sand" failed to reach the surface by some hundreds of feet.

The contents of dissolved solids in the "First Wall Creek" and Tensleep waters likewise show that artesian circulation has been very active in the Tensleep, moderately so in the "First Wall Creek," and much less so in the "Second Wall Creek." The lack of free fluid movement in the "Second Wall Creek sand" was also indicated by the fact that the decrease in pressure incident to production from this sand at Salt Creek took place first around the margin of the oil field and spread thence inward toward the crest, indicating that dissolved gas and not water pressure was the important force inducing oil flow. In this connection Estabrook and Rader[65] say:

> Pumping from the Second sand started in the southern half of the [Salt Creek] field and spread northward along the edges. The gas pressure is rapidly declining, even in the best parts of the field, and by the end of 1926 probably there will be few flowing wells from the Wall Creek sands. The decline in gas pressure is concentric and moves gradually inward toward the apex of the dome.

At the present time, even though pressures in the "Second Wall Creek sand" at Salt Creek average less than 25 pounds to the square inch, water encroachment in the sand is hardly detectable, although production from this sand began in 1917 and original water pressures in wells at the margins of the field were and are about 1,000 pounds to the square inch. It therefore seems reasonably evident that the water pressures found when the field was drilled were due to cubic compression of water in one or more sealed systems—such pressures, because of the slight compressibility of water, being dissipated by a slight expansion of the water. An alternative suggestion is that barriers in the sand prevented water migration over any considerable distance; otherwise under normal artesian pressure in a continuous sand water would have moved in as oil was withdrawn and would have caused not only a marked water encroachment but also a maintenance of pressures around the edges of the field.

"TIGHT SAND" AREA NORTH OF RESERVE

Moreover, in the southern part of the Salt Creek field there is an area of small oil production (the "tight sand" area, so called), which occupies a strip more than a mile wide extending across the whole width of the field in the vicinity of Castle Rock. It includes all that part of the Salt Creek field adjacent to the naval reserve except for a belt a few hundred yards wide next to the reserve boundary. (See pl. 13.)

Regarding this "tight sand" area Estabrook and Rader[66] say:

> In much of the southern half [of the Salt Creek field] the production is so small that many of the wells are unprofitable, and in one area around the quarter corner between secs. 7 and 18, T. 39 N., R. 78 W., several dry holes have been drilled. [See pl. 13 for dates of completion of wells.] * * *
>
> In the southern part of the [Salt Creek] field there are several thousand acres where the production is so small that the wells are not profitable and but little further development is to be expected.

Obviously, therefore, in this area at least, which separates the Teapot field from the main part of the Salt Creek field, the "Second Wall Creek sand" is so impervious or so irregular in porosity that fluid movement through it for considerable distances is practically prohibited.

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65 Estabrook, E. L., and Rader, C. M., op. cit., p. 219.
66 Idem, pp. 203, 206.

MULTIPLE BEDDING AND CROSS-BEDDING OF THE SAND

Because of its mode of origin the "Second Wall Creek sand" probably consists of overlapping layers and lenses of sand and sandy shale rather than of a single uniform or persistent sand bed. (See pl. 10, *B*.) Sands of this type are produced by rhythmic earth movements causing oscillations of the sea level and coincident migrations of the strand line; and it is common to find such sands—as, for instance, the Eagle sandstone of Montana or the Parkman sandstone member of the Teapot field—consisting of a relatively uniform and persistent basal sandstone, a clayey carbonaceous middle bed, and an upper bed of thin lenticular sands and sandy shales. The "First Wall Creek sand" clearly shows this general composition and character. On the other hand, the "Third Wall Creek sand" consists, in the Salt Creek area, of a number of discontinuous sand lenses or porous areas rather than of a single bed, as is shown by the results of deep drilling. Out of 30 wells drilled to the "Third Wall Creek sand" horizon commercial production was obtained in 7 wells, small shows of oil and gas in 5, a dry sand was found in 7, no sand at all was found in 9, and water is reported in 2 wells. The sand generally appears to be thin and tight. (See p. 15.) The "Second sand," which is intermediate between the "First" and "Third" in stratigraphic position, is also of intermediate character and composition, as is suggested by the quotations from Estabrook and Rader and from Peake given on page 15.

It consists of more than one bed or lens in the naval reserve, as is indicated by its recorded irregularities of thickness and composition (pl. 13) and by the occurrence of water in the base of the sand in some wells (and not in others) north of the saddle. The record of well 101–15 also supports this view, its log of the "Second Wall Creek sand" being as follows:

	Depth (feet)
Show of gas	2, 982
Sandy shale, with 2 million feet of gas	2, 982–2, 990
Sand, with 3 million feet of gas	2, 990–3, 002
Shell (hard, tight sand)	3, 002–3, 004
Sand, with 5 million feet of gas	3, 004–3, 020
Shell (as above)	3, 020–3, 025
Sand, with 60 million feet of gas	3, 025

Evidently three and probably four distinct gas-bearing beds were encountered in this well, of which the lowest obviously afforded the most open avenue for gas discharge.

A review by the writers of the logs of some 1,600 wells drilled to the "Second Wall Creek sand" in the Salt Creek-Teapot area further emphasizes the multiple bedding of this sand. A comparison of the records of near-by wells suggests that the planes separating the sand layers may be inclined, causing the composite sand to consist of numerous lenses that overlap more or less, in shingle fashion, successively higher lenses coming in toward the west.

FAULTS AND KEYSTONE JOINTS

Such initial complexity as may have been caused by irregularity of sand deposition has been tremendously increased by the subsequent development of the myriad faults which extend from west to east across the crest of the Salt Creek, Castle Rock, and Teapot domes and intervening parts of the Salt Creek anticline. As Mills [67] says:

> The huge Salt Creek structure and the somewhat smaller Teapot dome are literally cut to pieces by fault fissures, which are evidenced at the surface both by rock displacement and by calcite veins and stringers. * * * The spotted character of the production, together with the phenomenally high initial rates of production of some of the wells tapping fault zones in the Second Wall Creek sand, give further evidences of the relation that faulting bears to underground fluid movements in the Salt Creek field.

Minor irregular cross fractures connect some of the faults, but the larger ones clearly have a general systematic east-west arrangement and were products of the forces that caused the folding and domal uplift. Such faults, which trend across the axes of uplifts, are characteristic features of Rocky Mountain domes and anticlines and are familiar to all geologists who have worked in the Rocky Mountain region. Their distribution and probable mode of origin have been discussed by Irwin [68] and by Link,[69] and the writers' conception of the way in which the faults have been formed is outlined on pages 19–20. It is certain that the faults cause maximum displacement of the several sands at or near the crests of the uplifts, their "throw" dying out toward the flanks.

As was pointed out by Mills in the passages quoted on pages 20–21, many of these faults when first formed afforded open channels extending to the surface, through which oil and gas, and probably water, escaped until equilibria were developed between fluid pressures in the sand and the hydrostatic pressures exerted by the fluid columns extending from the sand to the surface.

A set of subsidiary faults or joints extend approximately at right angles to the major set and have been caused by the in-dropping of the crest of the arch, just as the keystone of a span would settle if the arch became somewhat spread. These joints or faults, parallel to the axis of the anticline, are referred to as keystone joints, and vertical movement along them rarely exceeds a foot or so. They are therefore important as interruptions to fluid movement only if they have induced the cementation of the sand along their planes—a possibility suggested by the following note by Estabrook: [70]

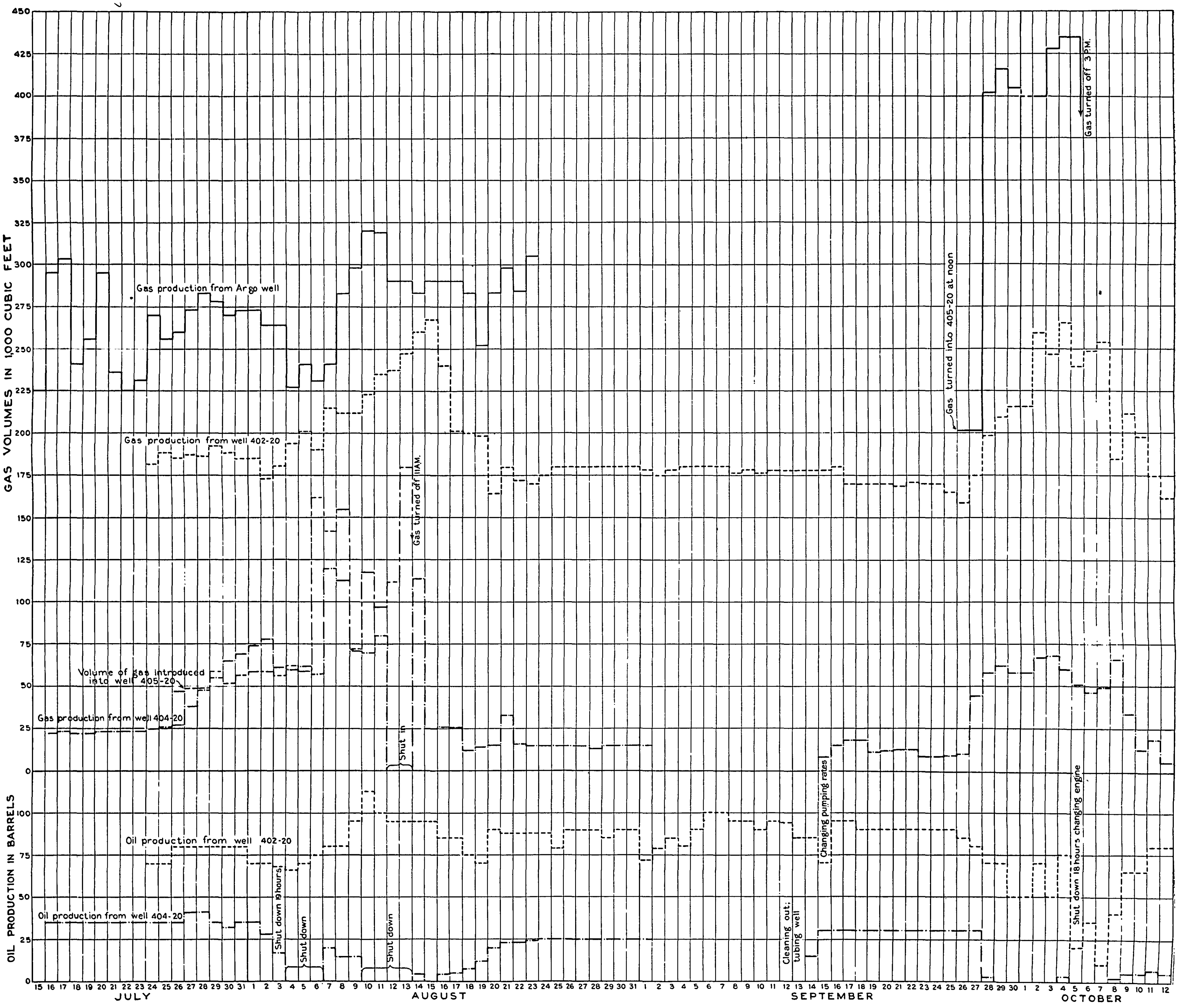
> Well No. 21, on the SE. ¼ sec. 34–40–79, Salt Creek field, Wyo., was commenced on November 3, 1924. It was just an

[67] Mills, R. V. A., op. cit., p. 4.

[68] Irwin, J. S., Faulting in the Rocky Mountain region: Am. Assoc. Petroleum Geologists Bull., vol. 10, pp. 105–129, 1926.

[69] Link, T. A., The origin and significance of "epi-anticlinal" faults as revealed by experiments: Idem, vol. 11, pp. 853–866, 1927.

[70] Estabrook, E. L., Am. Assoc. Petroleum Geologists Bull., vol. 9, p. 1295, 1925.



GRAPH SHOWING EFFECT OF INTRODUCTION OF COMPRESSED GAS INTO WELL 405-20 ON OIL AND GAS PRODUCTION OF NEAR-BY WELLS inside location, drilled in the normal course of development, and no one's reputation was at stake. At 1,313 feet it reached the top of the First Wall Creek sand; at 1,375 found a small show of oil; and at 1,422 looked good for about 10 barrels per day. When casing was run it stopped at 1,361, showing a crook in the hole at that point. After attempting unsuccessfully to straighten the hole in the sand the well was filled with rock back to 50 feet from the surface and a new hole started. The new hole reached the top of the sand at 1,310, showed oil at 1,340, and began to flow at 1,400. It was called a completion on May 5, and on May 8 pumped 320 barrels. An almost dry hole and a 320-barrel well under the same derrick floor! * * *

P. S.—The writer believes this is one of the comparatively rare cases where a "fault" has something to do with the results. The dry hole "slid off" into an inclined fault plane with more or less indurated walls.

Owing to cementation and to other causes there is a question as to whether oil and gas are migrating or can migrate across the fault system of the Teapot field. It seems probable that where faults of minute displacement cut a sand the more or less open fractures thus formed in the sand (see fig. 6) may facilitate the flow of oil to wells tapping such fracture zones—as, for example, well 402–20. Presumably the ease of flow in such zones would stimulate production in the same way that fractures produced by a shot of nitroglycerine stimulate production. On the other hand, pressure differentials, such as were found to exist between the upper and lower benches of the "First Wall Creek sand," between the "First Wall Creek sand" and the "Second Wall Creek sand," and between the "First Wall Creek sand" and the open fissures in the overlying shale, could have existed over long geologic periods only if these different sands, and the different benches of the same sand, were completely shut off from one another—in other words, only if the fault fissures were sufficiently sealed to prevent important fluid migration across them or between the several sand beds, and in spite of the fact that the sand "benches" of the "First Wall Creek" are only a few feet apart and the larger faults bring the "First Wall Creek" and the "Second Wall Creek" almost into contact. When it was found that pressures were different in the different sands and that the water in the "First Wall Creek sand" did not invade the oil-bearing "Second Wall Creek sand," in which pressures were about 100 pounds to the square inch lower, the conclusion therefore seemed fairly obvious that the faults were effectively sealed in the vicinity of the sands. The validity of the conclusion that there is little or no oil and gas movement across faults of appreciable displacement was further suggested by a graphic comparison of the dates of well completion with the initial yields of the wells. (See pl. 13.) The spotted character of the production revealed by this comparison and the anomalies of yield of many offset wells, completed at considerably different dates, apparently were explainable only on the assumption of lack of ready communication through the sand between such wells. In places anomalies of sand deposition, rather than faulting and cementation, may have caused the discrepancies of yield noted, but in many and probably in most places lateral oil movement and reductions in pressure apparently have extended less than 200 yards from productive wells (presumably because of local cementation by calcite, which has taken place along fault planes).

It therefore seemed probable that several of the faults extending east and west across the Castle Rock and Teapot domes interposed effective barriers to the movement of oil and gas from the Teapot dome northward toward Salt Creek—such calcite-cemented faults, as it were, cutting the field into separate parts just as the bulkheads in a ship's hold subdivide its space into a number of water-tight compartments. That this was a valid inference is to a certain extent evident now that disturbances due to oil and gas production have been eliminated from the Teapot field. Pressure and production records now available indicate that the reserve is cut by faults into at least three disconnected areas, only the smallest and most northerly of which (the area north of fault M, pl. 7) is subject to possibility of loss by drainage.

That there is slight danger of loss of considerable quantities of oil northward or westward across the reserve boundary is furthermore indicated by Plates 14 to 24. These diagrams show that the wells within the reserve near the northwest boundary were almost depleted when the reserve was closed down, except in so far as they might be rejuvenated by artificial restoration of pressures within the reserve. Statistics of oil and water yielded by certain wells during August, 1927, likewise confirm the suggestion of the approaching depletion of the part of the reserve adjoining Salt Creek, Figure 8 and Plate 25 indicating that such drainage from the reserve as may occur will probably be limited to movement along the fault passing through well 402, in sec. 20, T. 39 N., R. 78 W., and will be apparent as an increase in the yield of the Argo well, immediately west of well 402.

SUMMARY AND CONCLUSIONS

OIL CONTENT OF NAVAL PETROLEUM RESERVE NO. 3

Oil and gas occur in the Salt Creek field in the Shannon sandstone member of the Steele shale; "First Wall Creek sand" (Wall Creek sandstone member of Frontier formation); "Second Wall Creek sand" (in Frontier formation); "Third Wall Creek sand" (in Frontier formation); "Muddy sand" (in Thermopolis shale); "Dakota sand" (in Cloverly formation); "Lakota sand" (in Cloverly formation); Morrison and Sundance formations; and Tensleep sandstone; also in fissures in the shales overlying and underlying the "First Wall Creek sand" and to some extent in the shales beneath the "Second Wall Creek sand."

In the Teapot field some oil saturation has been found in the Shannon sandstone, which lies a few hundred feet below the surface, and commercial quantities

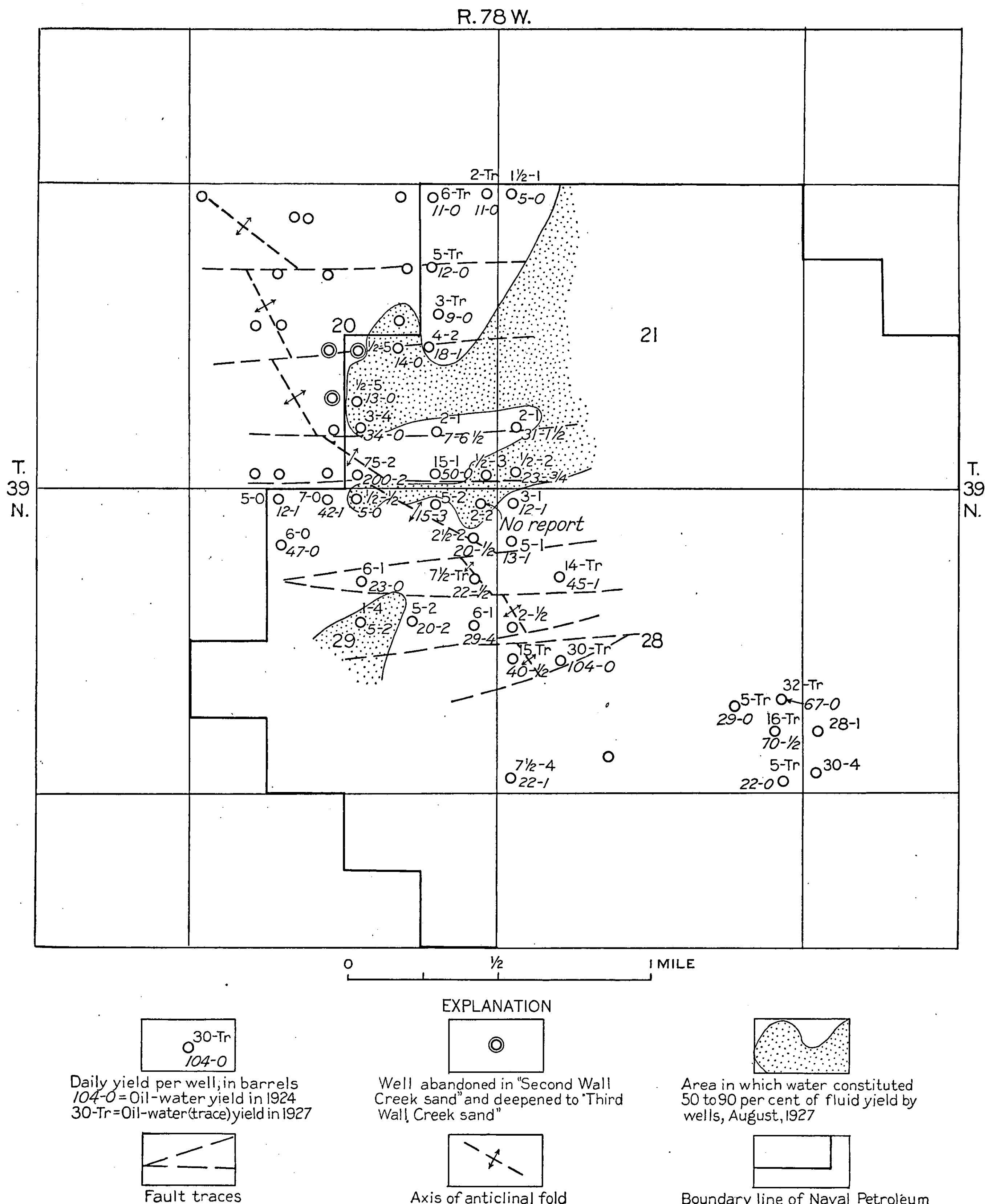


FIGURE 8.—Sketch map showing reported yields of oil and water from certain wells near north line of Naval Petroleum Reserve No. 3, August, 1924, and August, 1927

of oil have been obtained from fissures in shales above the "First Wall Creek sand" and from the "Second and Third Wall Creek sands."

Fissures in shale.—The reserve of oil in the shale fissures present within Naval Petroleum Reserve No. 3 can be determined only by complete drilling of the reserve, and it is therefore now impossible to say more than that this reserve is of considerable magnitude.

Shannon sandstone.—The degree of saturation of the Shannon sandstone is not known but may be sufficiently great to make the sand a prospective source of a large quantity of oil, recoverable by mining or by water-flooding operations. Test drilling to determine its potential value is therefore recommended.

"Second Wall Creek sand."—The "Second Wall Creek sand" has yielded most of the oil and gas so far produced from the Teapot Reserve and undoubtedly contains a fairly large volume of oil, much of which is certainly not recoverable by flowing and pumping or by other current production practices. The precise limits and porosity of the oil and gas bearing part of the sand are as yet indeterminate, and therefore the content of the sand can not be estimated with accuracy. For present purposes we can hardly do better than accept the estimates made by Lewis and Clapp in their report to the Senate investigating committee, remembering that Clapp's calculation indicated gross content of oil in the sand, whereas Lewis based his calculations upon the amounts recoverable by ordinary production practices, which may be regarded as yielding about one-fifth of the oil present in the ground. Clapp's estimates give an original total content in the sand in the naval reserve of 119,000,000 barrels, and multiplying Lewis's figures of recoverable oil by 5 would give the original gross oil content of the sand within the field as between 60,000,000 and 120,000,000 barrels. These figures are estimates and not verified calculations, and it is desirable that some half dozen wells be drilled to the "Second Wall Creek sand" in order to ascertain with approximate precision the magnitude and the location of the oil reserves remaining in that sand.

"Third Wall Creek sand."—Some oil has been produced from the "Third Wall Creek sand" in the reserve, but it has been the general experience that this sand is fairly thin, is notably irregular in thickness, and probably is not of sufficient importance as a prospective source of oil to merit testing, except as tests of it may be made in connection with wells drilled to deeper formations.

"Muddy," "Dakota," and "Lakota" sands.—The "Muddy" and "Dakota" sands and associated shales have yielded a considerable volume of oil in the Salt Creek field and may be important sources of oil in the reserve, and the underlying "Lakota" sand is an important source of oil in the Salt Creek field. The productivity of these sands within the reserve is as yet a matter of speculation. There is probably less than an even chance that they contain oil beneath the reserve, but because of their possible importance it is felt that at least two wells should be drilled to test them.

Sands of the Morrison and Sundance formations.—Oil seeps issue from the Morrison sands where exposed on the Tisdale uplift, and some oil has been found in the Morrison beds beneath the Salt Creek field. Several commercial oil wells have been drilled to the underlying Sundance formation at Salt Creek, and a considerable amount of oil is also being produced from the Sundance sands in northwestern Colorado. It is therefore suggested that the possibility of production from sands in these formations may be sufficiently great to warrant the drilling of test wells.

Tensleep sandstone.—The Tensleep sandstone has not been completely tested in the Salt Creek field. One well drilled in the NE. ¼ SW. ¼ sec. 25, T. 40 N., R. 79 W., yielded water, and a deep test hole drilled in 1930 in the SW. ¼ NW. ¼ sec. 35, T. 40 N., R. 79 W., encountered an initial flow of nearly 1,900 barrels of oil a day in the Tensleep and reached granite at 5,420 feet. The maximum area in the Salt Creek field which will yield oil from the Tensleep probably will not exceed 2,000 acres, and the sand may contain only water in the naval reserve. However, because of the great thickness and porosity of the sand and because of the fact that it yields oil in other parts of Wyoming, at least two deep test wells should be drilled to the Tensleep near the higher parts of the Teapot uplift before it can be condemned as barren of oil within the reserve. These wells would at the same time test the possible oil content of the sands between the Tensleep sandstone and the "Second Wall Creek sand," thus completing the evaluation of formations which may be regarded as having present potential importance, in view of the results obtained by the Salt Creek deep test well. According to carefully made estimates the drilling of such Tensleep tests is feasible and would require the completion of wells about 5,800 feet deep.

SAFETY OF OIL DEPOSITS IN NAVAL PETROLEUM RESERVE NO. 3 FROM LOSS BY DRAINAGE TO NEAR-BY WELLS

Geologic evidence in hand or obtainable at the time the naval reserve was leased indicated that the reserve was probably not susceptible to serious loss of oil by drainage to near-by wells, and this probability has now been made a certainty as a result of evidence obtained since wells in the reserve were closed in. Pressure readings taken on key wells in the reserve show that at least two groups of faults (M–P and U–V, pls. 7 and 8) interpose effective barriers to northward oil and gas migration, and production records of leases adjoining the reserve on the northwest also show that there has been but little increase in the yields of oil and gas from these leases since the reserve was shut in. The oil in the "Second Wall Creek sand" in the Teapot field is therefore safe from drainage, and such possible oil pools as may be present in other sands underlying the reserve are, for geologic reasons previously given, likewise safe from loss induced by operations outside of the reserve.

WATERS OF THE SALT CREEK-TEAPOT DOME UPLIFT

By Herman Stabler

INTRODUCTION

The study whose results are set forth in the following pages is based chiefly on information supplied to the writer by Jack W. Steele, supervisor of oil and gas operations in the Rocky Mountain district. The analyses were made at the laboratories of the United States Geological Survey (operated prior to July 1, 1925, by the United States Bureau of Mines) and of the Midwest Refining Co. at Midwest, Wyo. In general they are believed to be reliable, but in a recent personal communication E. A. Swedenborg stated: "Upon investigating the condition of the wells, as shown by their logs, and the methods of sampling the waters, the sources of some of the waters were found to be doubtful, and the analyses were accordingly thrown out." Except as specifically noted, however, the use herein of some of these analyses subsequently found to be doubtful does not affect the matters discussed or the conclusions drawn. The writer is indebted to W. D. Collins, chemist in charge of the quality of water division, United States Geological Survey, Washington, D. C., to E. A. Swedenborg, chemist, United States Geological Survey, Midwest, Wyo., and to W. T. Thom, jr., and A. C. Spencer, geologists, United States Geological Survey, Washington, D. C., for friendly criticism and suggestions.

The water analyses on which the study is based are shown in Tables 6 to 14, being reported in parts per million and in reacting values both in parts per million and in per cent. The statements of analyses in parts per million were used to calculate reacting values and concentration values—that is, sum of reacting values in parts per million. All observations and conclusions are based on reacting values and concentration values, and all quantitative and qualitative statements have reference to these simplified and strictly chemical values.

The number of analyses of waters from other than the "First Wall Creek sand" is small, and it is probable that the variations in character and concentration are by no means fully disclosed by available data. The greater number of analyses of water from the "First Wall Creek sand" makes possible an instructive study of variations in character and concentration.

SURFACE WATERS

The Salt Creek-Teapot uplift is a region in which surface waters are not abundant. Rainfall is meager, and stream channels are for the most part dry or covered by a shallow trickle of water, though after summer storms they carry great flood flows including a heavy burden of surface wash and silt. As would be expected under such conditions, the analyses in Table 6, shown graphically in Figure 9, representative of surface waters of the region, show marked differences in concentration and appreciable differences in character but on the whole are fairly typical of surface waters of an arid or semiarid area whose surface soil is derived from marine sediments. These local waters differ from the water of the North Platte River at Fort Laramie, a large stream draining a great area, chiefly in containing smaller percentages of the calcium and bicarbonate radicles, but, like the North Platte water, they are characterized by secondary salinity—that is, the alkali radicles are insufficient to react with the strong-acid radicles—and in this respect, as well as in generally lower concentra-

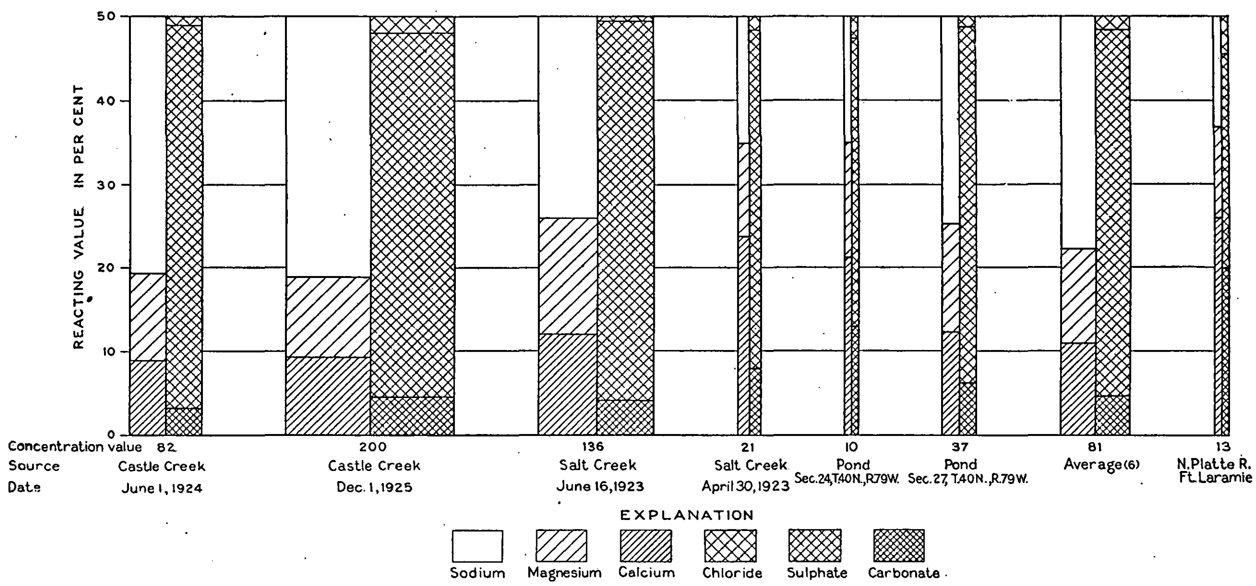


FIGURE 9.—Analyses of surface waters

tion, they are to be distinguished from subsurface waters above the Tensleep sandstone, which are all of primary alkaline type. The chloride radicle is low, but the sulphate radicle is most prominent and constitutes 35 per cent or more of the concentration value. Contamination of well waters from any sand by surface waters may well be suspected if they show, relative to other waters of the sand, a tendency toward secondary salinity, high sulphate content, or low concentration.

UNDERGROUND WATERS

WATERS OF THE SHANNON SANDSTONE MEMBER

The Shannon sandstone crops out as an escarpment around the greater portion of the Salt Creek-Teapot uplift, and its waters may therefore be expected to partake of the nature of surface waters in some places and to bear the character of a regional Shannon water, if such there is, in other places. The analyses in Table 7, presented graphically in Figure 10, show considerable variation in character. The water from well 106A, in sec. 29, T. 39 N., R. 78 W., is characteristically that of the "First Wall Creek sand" near the oil and may represent the general nature of waters of the Shannon sand when uncontaminated by surface drainage.[71] The water from well 2, in sec. 3, T. 39 N., R. 79 W., most closely approaches a surface water in character, primary alkalinity being negligible and the sulphate radicle prominent. It is closely paralleled in character and concentration by a mixture of 1 part of water from well 106A with 9 or 10 parts of water from the pond in sec. 27, T. 40 N., R. 79 W. The other Shannon waters may also be recognized as possible mixtures of waters typical of the lower sands with typical surface waters. Because Shannon waters partake to a considerable degree of the nature of surface waters, they, as well as surface waters, come under suspicion as the possible cause of relatively high sulphate found in the waters of some wells producing from the lower sands.

The Shannon sand is oil bearing in parts of the uplift, but production from it is small as compared with that from several of the lower sands.

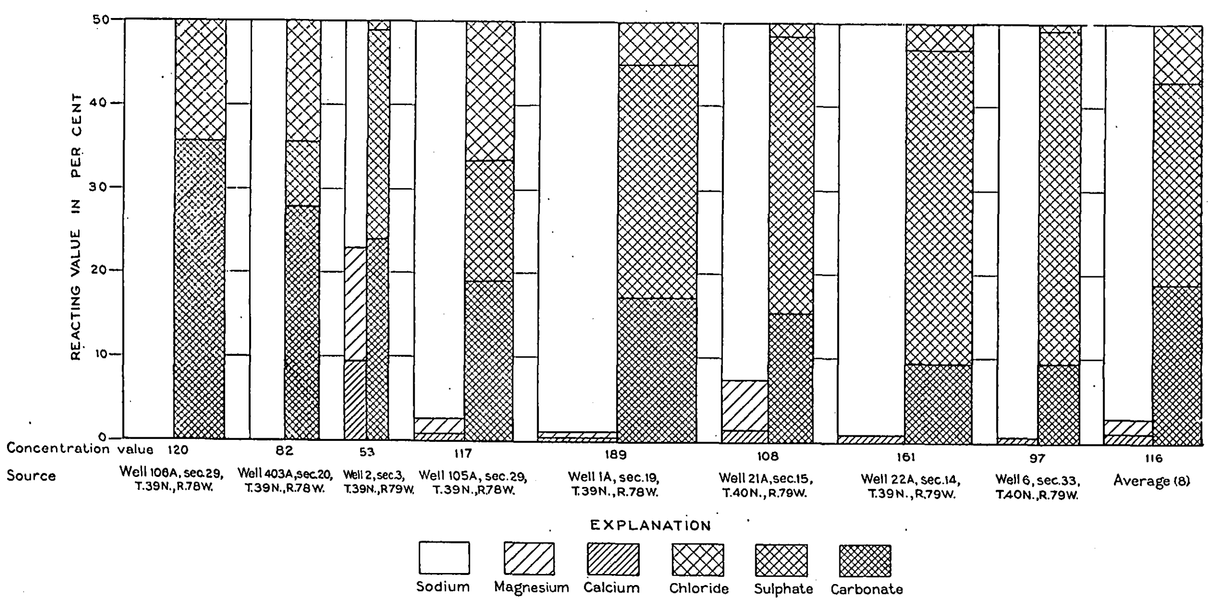


FIGURE 10.—Analyses of waters from the Shannon sand

INTERMEDIATE WATERS

Water is found at places in crevices or lenticular sands in the shale above the "First Wall Creek sand." A few analyses of such waters are shown graphically in Figure 11. They resemble average "Second Wall Creek" waters in character and concentration. Presumably derived from the "First Wall Creek sand," they differ from the waters of that sand as by solution of common salt. The available analyses are too few to warrant conclusions as to persistency of character over any considerable area.

WATERS OF THE "FIRST WALL CREEK SAND"

Apparently reliable analyses of waters reported to be derived from the "First Wall Creek sand" are available for study to the number of 155 and are presented in Table 8. Some few of these suggest a measure of contamination with surface or drilling water, but the contamination, if it exists, is too slight to warrant exclusion of these analyses from consideration as representing "First Wall Creek" water.

A great quantity of oil has been produced from the "First Wall Creek sand" in the Salt Creek field, but

[71] A subsequent review by E. A. Swedenborg indicates a doubt as to the source of water from well 106A and of some of the other waters here reported from the Shannon. It seems likely, therefore, that the water of well 106A is in fact a water from the "First Wall Creek sand," as its character indicates.

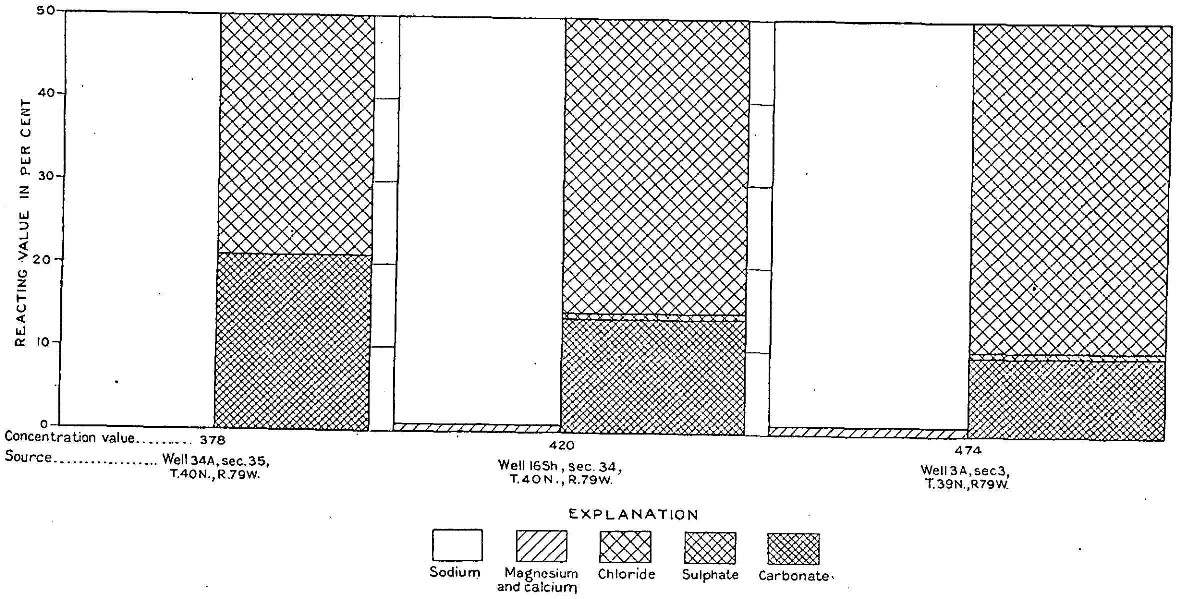


FIGURE 11.—Analyses of waters from shale and stray sands

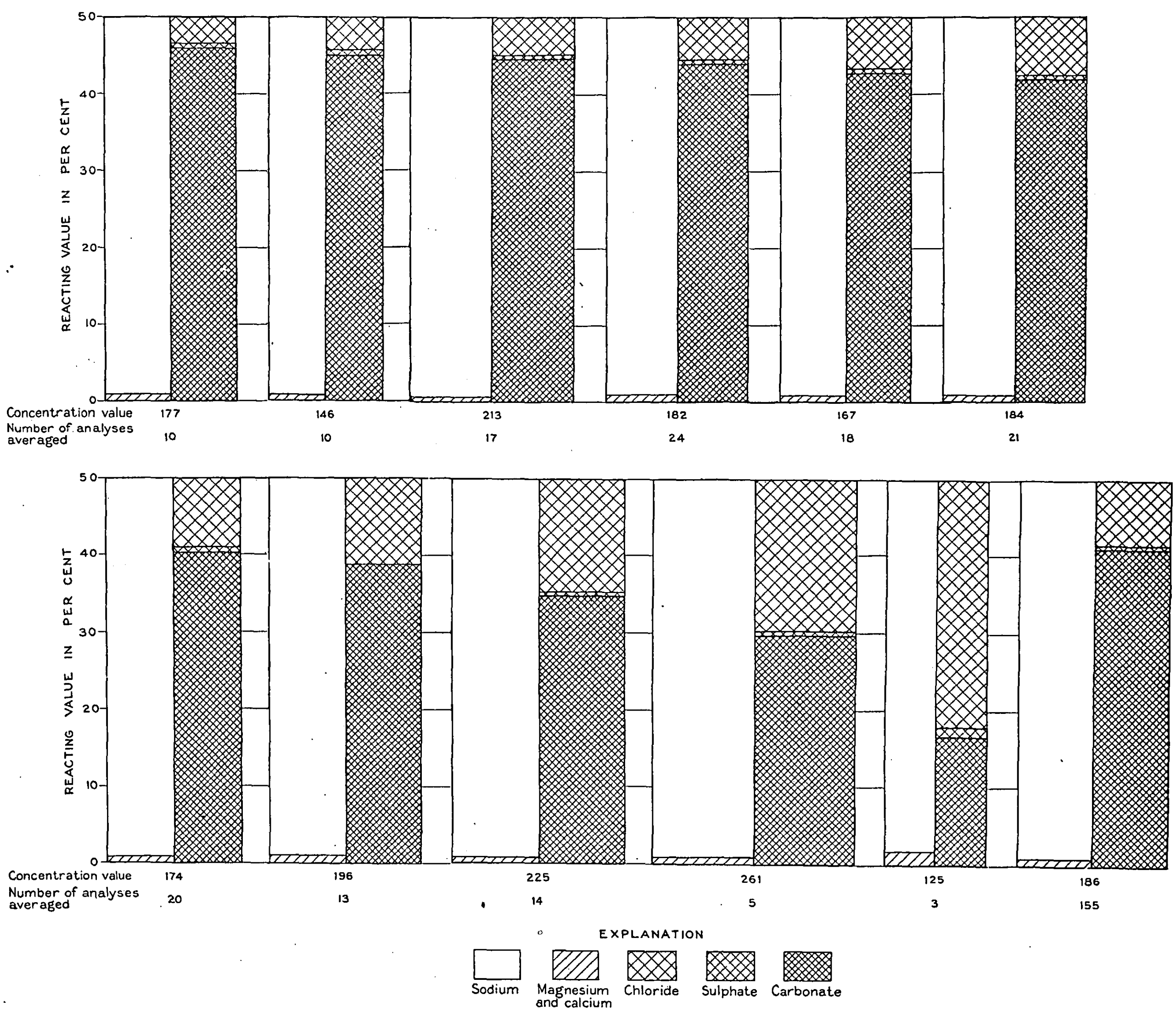


FIGURE 12.—Analyses of waters from the "First Wall Creek sand"

this sand is reported to be saturated with water throughout the Teapot dome, an area from which water analyses are not available.

The "First Wall Creek" waters differ widely in concentration values, ranging between extremes of 37 and 360 parts per million, a range of 1 to 10. Calcium, magnesium, and sulphate are present in amounts so small as to affect the character of the waters inappreciably. The waters may, indeed, be regarded as solutions of sodium chloride and sodium carbonate and bicarbonate. Their differences in character may readily be expressed in terms of the ratio of carbonate plus bicarbonate to chloride, herein referred to as the carbonate-chloride ratio, or in terms of per cent of carbonate or chloride in the concentration value. The carbonate-chloride ratio ranges from 0.24 to 18, or from 1 to 75. The range in character difference therefore is more than seven times the range in concentration. For graphic representation in Figure 12, the waters of approximately the same character have been grouped together and averaged, the number of analyses in each group being indicated on the chart. Each group contains dilute and concentrated waters, the range in concentration within the group being of about the same order of magnitude as the range in concentration for the area as a whole. It should be understood that the entire group of 155 analyses is indicative of continuously progressive change in character and that the division into 11 groups has been necessarily arbitrary and was made solely to facilitate graphical study. The figure portrays clearly the negligibility of calcium and magnesium among the bases and of sulphate among the acid radicles and the progressive increase of chloride over carbonates. The relative concentration values of the 11 groups do not appear to be significant but would seem to be accidental, depending chiefly on the number of analyses averaged and the number of relatively dilute samples included in each group. There is a measure of suggestion that, in general, higher concentration values and lower carbonate-chloride ratios go together. This is by no means clear in the figure, however. Detailed examination of the analyses, as well as of the range of concentration values in each group, shows that with increasing concentration both carbonates and chlorides increase but that the range of average carbonates in the 11 groups is from 72 to 96, or 1 to 1⅓, whereas for chloride the range between groups is from 6.3 to 51.7, or from 1 to 8.2. There is an apparent tendency for carbonates to remain relatively constant while chlorides progressively increase—the effect that would be obtained if a body of salt were to be leached with a solution of sodium bicarbonate.

By plotting on a map of the Salt Creek field the principal significant features of the analyses, some idea is obtained of the areal significance of differences in concentration and in character. On Plate 26 the concentration values have been plotted and lines of equal concentration, or isocons, have been drawn. These isocons are more or less symmetrical with respect to the oil pool of the "First Wall Creek sand." Concentration values less than 100 are found only south and west of the oil pool, but values less than 150 surround it, and there is a progressive increase of concentration from the outside toward the edge of the pool. Greatest concentrations are found near the edge of the oil pool on the south and east. There are, surprisingly enough, less than half a dozen wells whose waters do not conform closely to the general pattern of the isocons. Explanation of these anomalies is not obvious but may perhaps be found in doubtful analyses, trapped pools of water, or the influence of faults.

Plate 27 is a map showing lines of equal carbonate-chloride ratios. In any "Wall Creek" water the sum of the reacting values of the chloride and carbonate radicles determines its concentration value, but the ratio of carbonate to chloride determines its character. On Plate 27 the character changes produce a rather regular pattern. The highest ratios are found west of the oil pool, where concentrations are low. South of the oil pool and more than 2 miles south of the line between Tps. 39 and 40 N., where concentrations are low, carbonate-chloride ratios are approximately half the ratios for the region of equal concentration west of the pool. Beginning in sec. 11, T. 39 N., R. 79 W., and extending east and north around the south and east borders of the oil pool is a zone of relatively high carbonate-chloride ratios in which the ratios progressively decrease toward the north. South and east of this zone is a region of relatively low ratios, and north and west of it ratios rapidly decrease as the oil pool is approached. On this map, as on Plate 26, the number of anomalies is very small, the ratios conforming remarkably well to a regular pattern. Wells 25A3, in T. 39 N., R. 79 W., and 20A27, in T. 40 N., R. 79 W., show the only irreconcilable ratios, and the waters from these wells are very dilute for the area and conform poorly in other respects to "First Wall Creek" characteristics. They might well be rejected as nonrepresentative if indeed the analyses were made from samples actually taken from the "First Wall Creek sand." As shown on Plates 28 and 29, the chloride values are approximately symmetrical with respect to the oil pool but the carbonate values are asymmetrical, and this difference accounts for most of the lack of symmetry of the lines on Plates 26 and 27. The general tendency toward lower carbonate-chloride ratios as the center of the oil pool is approached is far more pronounced, as shown on Plate 27, than the tendency toward increased concentration, as shown on Plate 26.

Plate 28 is a map showing lines of equal chloride values, or isochlors. General symmetry of pattern with respect to the oil pool is evident, with greater values to the east than to the west. The lowest chloride values, less than 5.0, are found northwest of the pool and in a single analysis far to the south. Chloride values of 6.0 and 8.0 are found along the entire west and south borders of the pool, but no values less than 9.0 are shown on the east. An isochlor of 10, however, borders the entire east side and nearly encircles the oil pool. Of interest are the lobe-shaped area of relatively high chloride at the southeast and the narrow zone of relatively low values at the north following one edge of an upthrown fault block and separating the main oval pattern from a smaller oval of high values wholly beyond the limits of the main oil pool of the "First Wall Creek sand." The presence of a minor northern area containing some oil is suggested by the pattern. Chloride is perhaps the most stable element of the water solution reflected in an ordinary analysis. Once in the chemical system, the chloride radicle is removed only by precipitation from a saturated solution or by the application of intense heat. The areas of high chloride must therefore be regarded as areas in which saline deposits have been incompletely leached or as areas in which the water solution has been subjected to concentration, as by evaporation with escaping gas.

Plate 29 is a map showing lines of equal carbonate values, or isocarbs. In terms of reacting values, with only five exceptions in 155 analyses, carbonate (that is, carbonate plus bicarbonate) constitutes 30 per cent or more of the chemical system in the water solution, averaging 41.3 per cent. Next to sodium, it is the chief constituent in all but three of the water analyses. It is carbonate, therefore, that chiefly determines the concentration values shown on Plate 26. If chloride and an equivalent value of sodium were removed the analyses would show markedly greater uniformity in concentration and character, indicating that a normal "First sand" water acquires sodium chloride from the aquifer in the region of the oil pool. The pattern of isocarbs shows that there is low concentration of carbonate values (less than 40 parts per million of reacting value) over a large area at the south end of the Salt Creek field. Areas of less than 50 in carbonate value are found to the east and west of the field. In passing toward the oil pool from isocarb 50 greater carbonate values are encountered until the approximate position of the original oil line is reached. There a maximum is encountered, and values decrease thence toward the center of the pool. The area of maximum carbonate extends northward along the east side of the pool, but with decreasing intensity, to the extreme limits of the field. An area of maximum carbonate lies to the west of the pool, but it is small and, roughly, of only half the intensity of the eastern area. An area of low carbonates lies northwest of the pool and extends northeastward with slightly increased concentration to the limits of the field.

WATER MOVEMENT IN THE "FIRST WALL CREEK SAND"

In a surface lake there is water movement, more or less irregular, from inlet streams, possibly of different concentration and character, toward a single outlet, if there is one, or from one part of the lake to another in induced currents, if there is no outlet. Other things being equal, the larger the lake relative to volume of outflow the greater will be the concentration of the water and the greater will be the differences in character of the water in different parts of the lake. The ground-water body of a pervious sand, such as the "First Wall Creek sand," may be likened to a lake, the major differences being that for the same volume of flow movement will be much less free than in an open lake, being somewhat restricted to channels, as in a lake studded with islands; concentration should be greater because of intimate contact with rather finely divided mineral matter; and differences in concentration should be more widely varied and differences in character more notable because of differences in nature of material encountered. Even though very slow, long-continued water movement through a sand will leach it of readily soluble material, and the character and concentration of the water will tend to become more uniform and the mineral solution more dilute. On the assumption that the sands were once filled with water approaching present-day sea water in concentration, it is evident from the relative dilution of the waters now found in the sands that much leaching has taken place and that total water movement through geologic time has been great.

Plate 27, in terms of carbonate-chloride ratio, and Figure 63, in terms of percentage of carbonate, show the character of waters in the "First" sand in the vicinity of the oil pool and tell the same story. Chloride value, in per cent, is practically the difference between 50 and the percentage of carbonate and would provide a similar pattern. As shown on Plate 30, water with a carbonate content of 43 to 46 per cent and therefore of practically uniform character is found on the west side of the pool and in a zone south of it and extending northward along the east side. The 40 per cent carbonate line encircles the oil pool very close to the oil-water contact except at the north and where it swings a mile north and half a mile east of the line of contact. The pattern formed, generally concentric with the oil pool but shading out toward the northeast, and the character change indicated, from an alkaline carbonate to an alkaline chloride water as the oil-water contact is approached from the outside, are precisely what would be expected in a lake of alkaline carbonate water in which there was an island of common salt washed by a current moving gently toward the north and east. Plate 26, however, shows that in the zone of 43 to 46 per cent carbonate the concentrations are approximately twice as great on the east side of the oil pool, as on the west side, indicating that any water movement close to the oil pool is more rapid and leaching of the sand has progressed further on the west side than on the east. The zone of 43 to 46 per cent of carbonate on the south and east also shows progressive increase of concentration from the outside toward the oil pool. This suggests concentration as by evaporation, without change of character, carbonate and chloride radicles increasing in like proportion. Beyond this zone, to the west, concentration increases slowly as the proportion of chloride increases rapidly, as if chloride were replacing carbonate in the solution. East of the zone of 43 to 46 per cent carbonate the concentration decreases eastward as the proportion of chloride shows a tendency to increase slightly, suggesting the presence of an easterly bank to the channel of northward flow.

On the whole, the available data suggest rather strongly an eastward movement of water south of the oil pool, a northward movement west of the pool, and a northeastward movement northwest of the pool. There is probably also a less definite northward movement of water east of the pool, though this is by no means so evident within the limits of the available data. A former concentric movement of water toward the oil pool is also suggested, with concentration as by evaporation with escaping gas and as by solution of chlorides from less thoroughly leached sand. The concentric movement was evidently more vigorous on the west side than on the east, and the total water movement was greater at some distance from the pool than immediately adjacent to it, as if there had been a major escape of water and gas on the flanks of the uplift. In general faults appear not to affect the general water movement, unless the many cross faults cause or assist in causing the islandlike barrier to water movement that coincides in a general way with the oil pool. It is not unreasonable to assume that such faults provide an obstruction to northward movement in the anticline but die out on the flanks so as to permit fairly regular flow. An exception to the general effect of faults is found just north of the field, where a northeastward channel of flow apparently follows a fault or fault block. With production of oil there has also been a very definite tendency for water to encroach most rapidly along the fault lines.

WATERS OF THE "SECOND WALL CREEK SAND"

Thirty-eight analyses of waters reported from the "Second Wall Creek sand" are presented in Table 9 and shown in averaged groups in Figure 13. The first two groups in this figure are indistinguishable from groups of "First Wall Creek" waters shown in Figure 12. In fact, concentration alone distinguishes the third, fourth, and fifth groups in Figure 13 from some of the groups in Figure 12. The waters of both sands are essentially solutions of sodium carbonate and sodium chloride in varying proportions. The two figures show, indeed, a continuous overlapping series of character changes, from an almost pure sodium carbonate solution at the beginning of the "First Wall Creek" groups to an almost pure sodium chloride solution at the end of the "Second Wall Creek" groups. If chloride and an equivalent value of sodium were removed from both, the "First" and "Second" sand waters would be very doubtfully distinguishable from each other by concentration or character, though there seems to be a tendency toward slightly higher calcium, magnesium, and sulphate percentages in the "Second" sand. However, it is not difficult to distinguish between them as found at any locality, for the "Second Wall Creek" water from any well is more concentrated and carries a higher percentage of chloride than the "First Wall Creek" water from the same well. The analyses forming the extreme of the "Second Wall Creek" series on Figure 13 may represent a pocket of water not truly representative of the sand, and too much reliance can not be placed on them. The highly concentrated brine [72] from well 34A, in sec. 29, T. 40 N., R. 78 W., is the only water from the east side of the Salt Creek field represented in this group of analyses and suggests the absence of water circulation on that side. This brine has the characteristics of a fossil sea water from which the alkaline earths and sulphate have been removed. The other "Second" sand waters analyzed from the Salt Creek field came from wells along its west edge, and, though the analyses are too few to warrant the drawing of lines, they indicate a tendency toward increase of concentration and of proportion of chloride with approach to the oil pool, just as in the "First Wall Creek sand." A group of analyses from wells in secs. 28 and 29, T. 39 N., R. 78 W., approximately in the saddle between the Salt Creek and Teapot domes, shows an apparent tendency toward highest concentration along the axis of the anticline, with greater dilution on both east and west, thus conforming to the general rule for "First Wall Creek" waters of the Salt Creek field. The character of these waters, as portrayed by carbonate-chloride ratios, however, is very irregular, though showing a tendency toward a greater proportion of chloride toward the west. Other scattered analyses from the Teapot dome show considerable variation in concentration and character but without definite arrangement.

The available analyses of waters from the "Second Wall Creek sand" show that on the average samples from the Teapot dome have about 90 per cent and samples from the saddle about 75 per cent of the concentration of samples from Salt Creek.

The irregular variation in character of waters of the "Second Wall Creek sand" and their relatively

[72] This analysis was reported doubtful by E. A. Swedenborg on subsequent study of the well and sampling history, and any discussion of it should therefore be taken not too seriously.

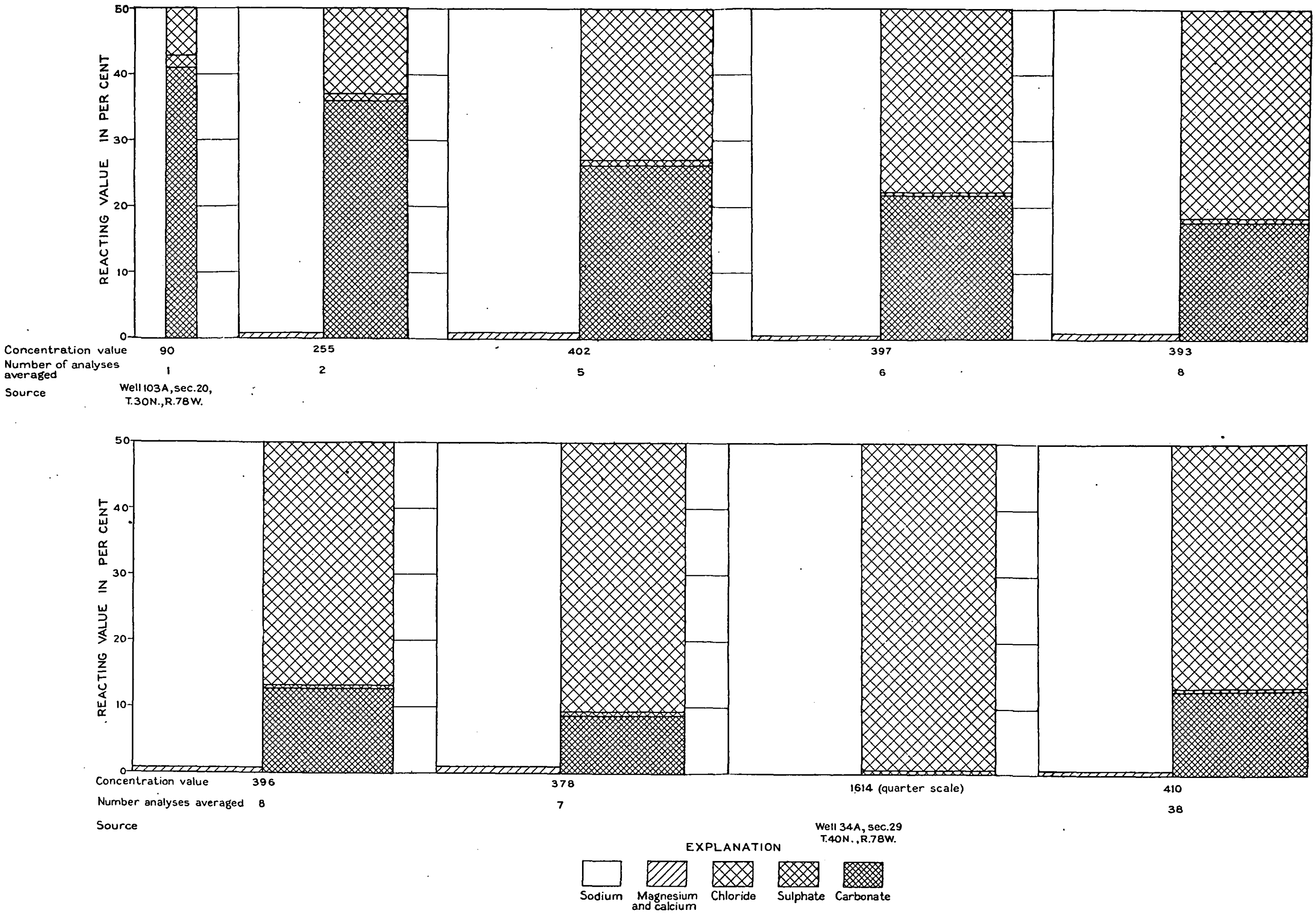


FIGURE 13.—Analyses of waters from the "Second Wall Creek sand"

higher concentration argue for much less water movement than in the "First Wall Creek sand" and perhaps for a general condition of present stagnation, though the analyses are too few and too widely spaced to warrant definite conclusions.

WATERS OF THE "THIRD WALL CREEK SAND".

A few analyses from the "Third Wall Creek sand" or from a stray sand stratigraphically above it in the vicinity of the saddle between the Salt Creek and Teapot domes are given in Table 10 and shown graphically in Figure 14. These samples were produced with oil from the "Third Wall Creek sand," but there is a suggestion that the water is derived not from the "Third Wall Creek sand" itself but from a stray sand above. They show greater concentration and higher percentage of chloride than the "Second" sand waters, the greater concentration being more than accounted for by the greater chloride content. These waters indicate a further step in the progressive change from alkaline carbonate to alkaline chloride character noted for "First" and "Second" sand waters. A less thorough leaching and even less water movement than for the "Second Wall Creek sand" is also indicated.

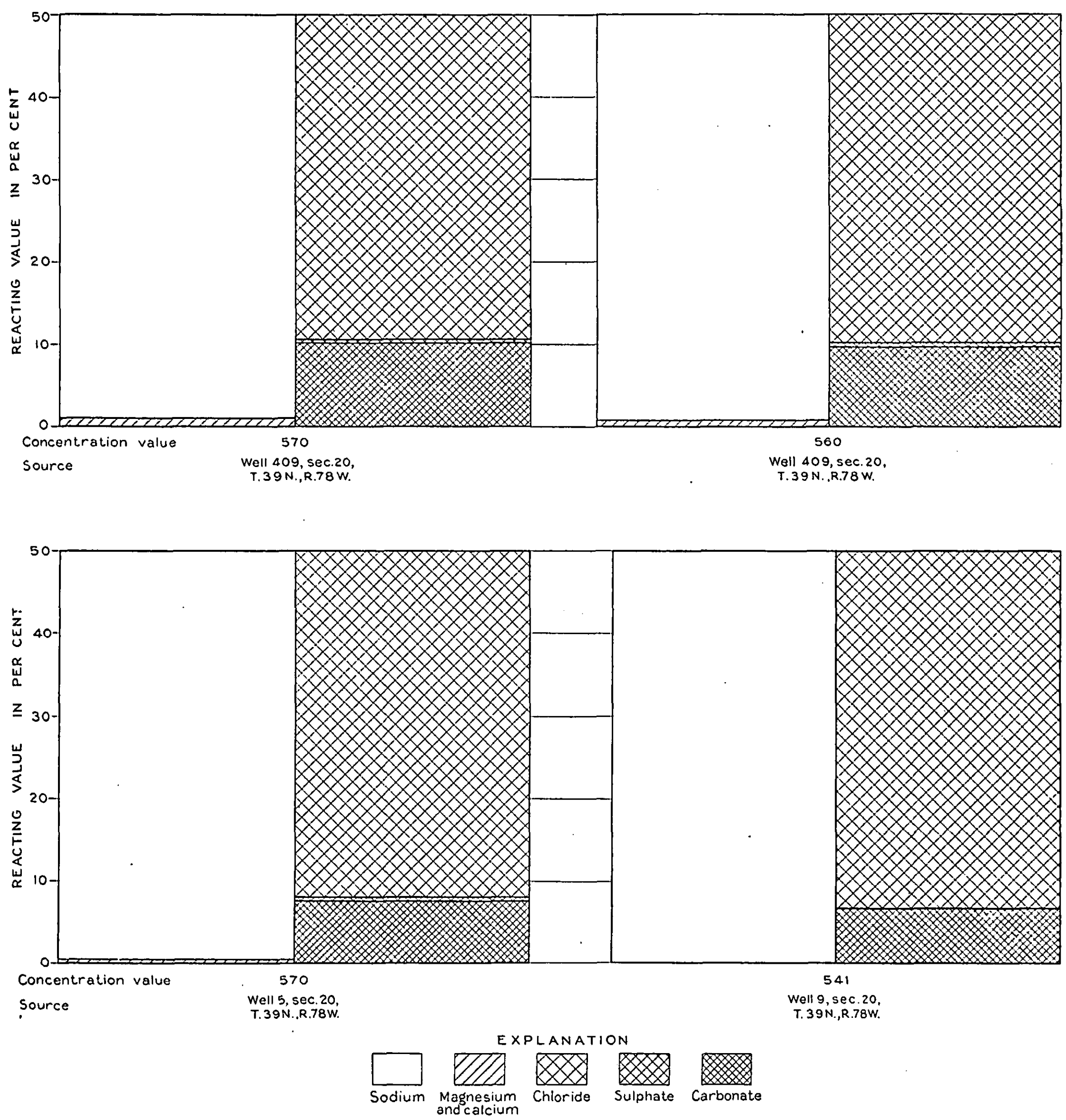


FIGURE 14.—Analyses of waters from the "Third Wall Creek sand"

WATER OF THE "MUDDY SAND"

A single analysis of water from the "Muddy sand" is available. (See Table 11 and fig. 15.) It shows a water indistinguishable in character from the average of "Second Wall Creek" waters shown in Figure 13. The concentration value is 281, or only about 70 per cent of that of the average "Second" sand water. A water movement somewhat more free than for the "Second" sand is indicated.

WATER OF THE "DAKOTA SAND"

A single analysis of water from the "Dakota sand" (Table 11), which, however, is substantially the same as the reported average of four analyses of water from this sand, is shown graphically in Figure 15. This water is essentially a sodium chloride solution with small percentages of sulphate and carbonate and is thus easily distinguishable from the waters hereinbefore considered. Its nearest counterpart is in the "Second" concentration nearer the oil pool is fairly well shown, and greater concentration from south to north and from west to east is suggested, but the analyses are too few to be considered conclusive. The percentage of carbonate ranges from 45.7 to 22.5, but whether this variation bears any relation to position with

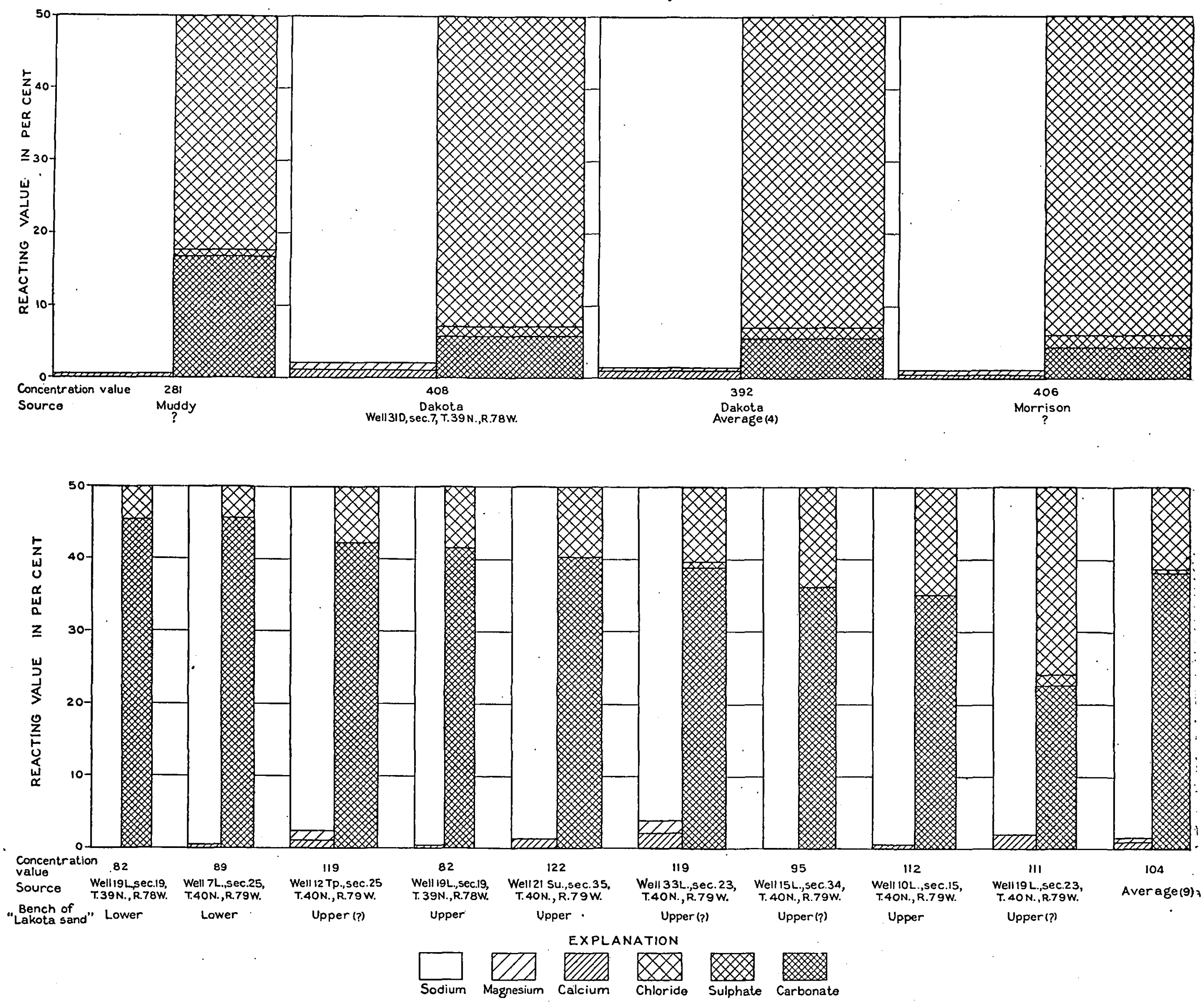


FIGURE 15.—Analyses of waters from the "Muddy," "Dakota," Morrison, and "Lakota" sands

sand waters of lowest carbonate-chloride ratio, which resemble it closely in concentration value.

WATERS OF THE "LAKOTA SAND"

Nine analyses of water from the "Lakota sand" (Table 11) are available and are shown graphically in Figure 15. Six of these waters came from wells adjacent to the Lakota oil pool of the Salt Creek field. Two came from a single well about 3 miles southeast of the pool, near the southern limits of the field, and one from a well about a mile northwest of the pool. The range in concentration value is from 82 to 122. Greater

respect to the oil pool seems doubtful with the meager data at hand. Well 19L23, showing the lowest percentage of carbonate, is the only well that shows chloride in excess of carbonate and the only one that shows an appreciable sulphate content. Contamination with water from the "Dakota sand" would affect these results. Two analyses are designated as representing water from the lower bench of the "Lakota sand." If these and the analyses from well 19L23 are left out of account, the percentage of carbonate ranges from 42.1 to 35.1, indicating very uniform character for what are presumably waters of the upper bench,

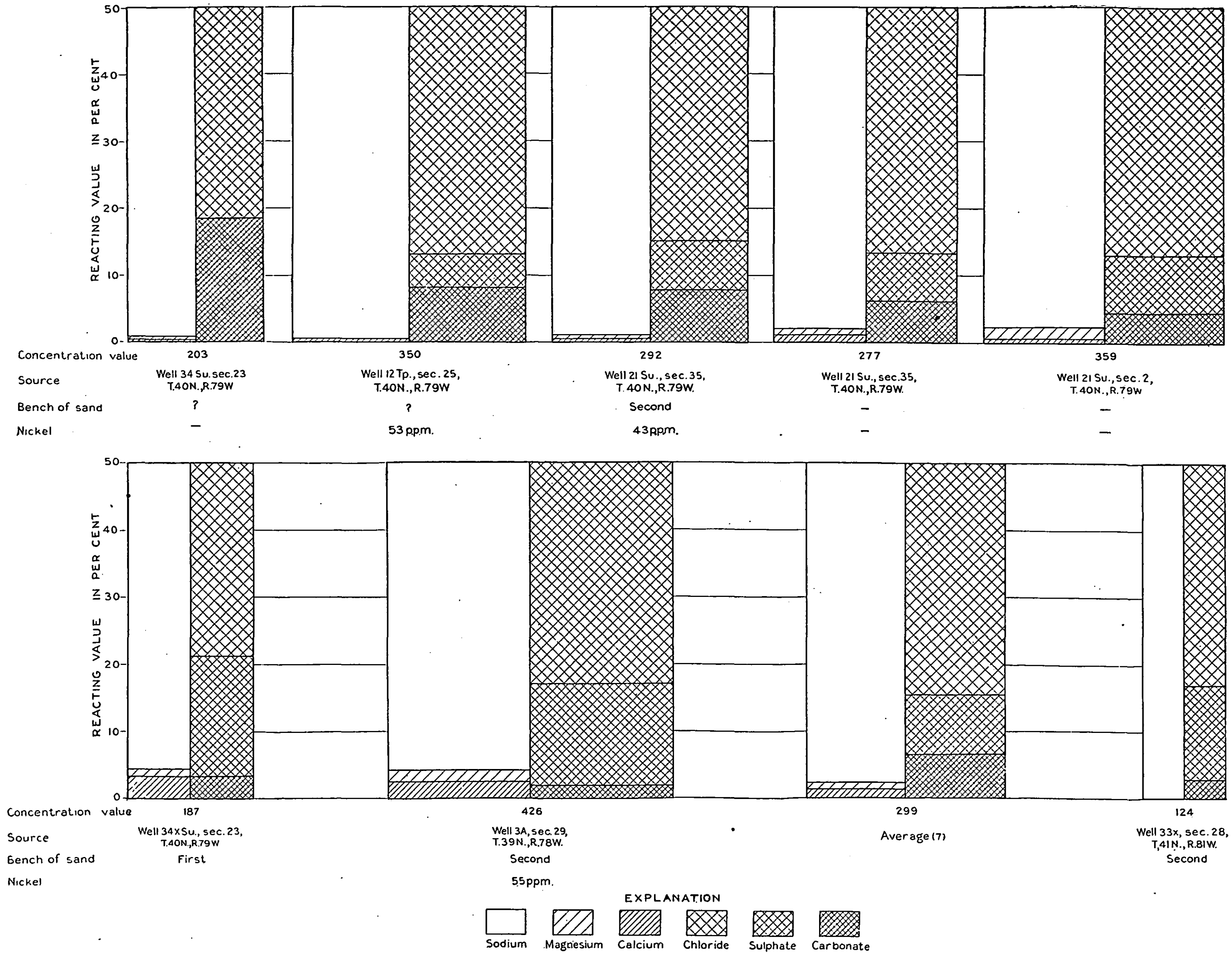


FIGURE 16.—Analyses of waters from the Sundance sand

though only two of the six are so designated. Analyses from well 19L19, T. 39 N., R. 78 W., show a percentage of chloride approximately twice as great in the upper bench as in the lower, and a similar difference is shown by the analyses from wells 7L and 12Tp, only a few hundred feet apart in sec. 25, T. 40 N., R. 79 W., suggesting that analysis 12Tp represents water from the upper bench.

"Lakota" waters have less than 60 per cent of the concentration of "First Wall Creek" waters and are apparently much more uniform in character, though

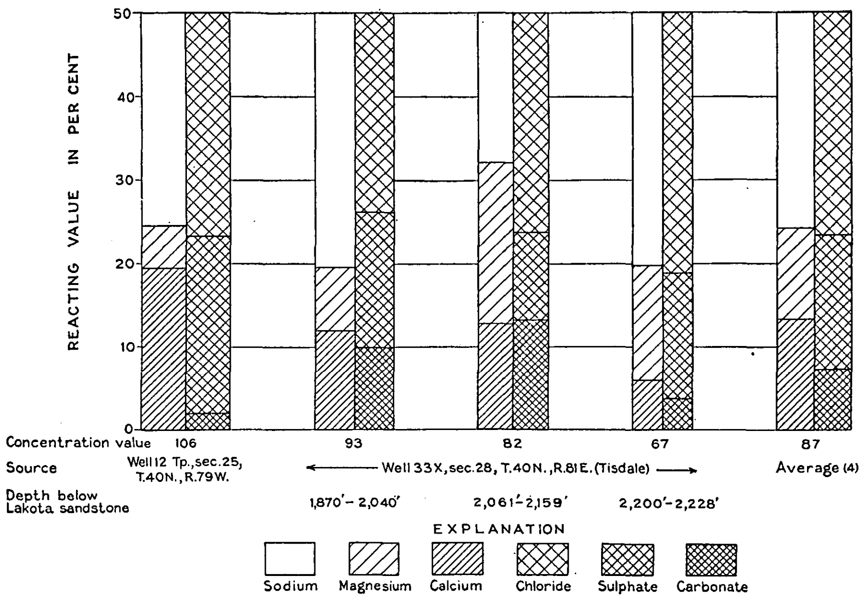


FIGURE 17.—Analyses of waters from the Tensleep sand

like the waters of the "First Wall Creek sand" they are essentially solutions of sodium carbonate and chloride. Water movement in the "Lakota sand" is therefore probably much more free than in the "First Wall Creek sand."

WATER OF THE SAND IN THE MORRISON FORMATION

A single analysis of water from the Morrison sand shown in Table 11 and Figure 15 indicates that it is of essentially the same character and concentration as water from the "Dakota sand."

WATERS OF THE SAND IN THE SUNDANCE FORMATION

Analyses of eight Sundance waters from four townships, including one from a well on the Tisdale dome, are shown in Table 12 and Figure 16. Calcium and magnesium are present in small amounts, the waters being essentially solutions of sodium salts. The chloride radicle is fairly constant at about 30 to 35 per cent of the chemical system. Sulphate and carbonate range from a trace to about 18 per cent, greater sulphate being accompanied by lesser carbonate and the sum of the two being nearly a constant. This relation of sulphate and carbonate, together with the presence of hydrogen sulphide, suggests reduction of sulphate and its replacement by carbonate. A noticeable amount of nickel is found in a number of the Sundance waters but is not indicated for waters from other horizons.

WATERS OF THE TENSLEEP SANDSTONE

A single analysis of water from the Tensleep sandstone is available for the Salt Creek field. This, together with analyses of waters from three separate benches of this sand from a well on the Tisdale dome, some 15 miles to the west, is given in Table 13 and Figure 17. All contain notable proportions of calcium and magnesium, a feature that distinguishes Tensleep waters from other subsurface waters of the region. Chloride is fairly constant at about 24 to 30 per cent of the chemical system. As in the Sundance waters, sulphate is present in noteworthy degree and varies inversely with carbonate. This feature, together with the presence of hydrogen sulphide, suggests the possibility of partial reduction of sulphate and replacement with carbonate. Tensleep waters are the most dilute of the subsurface waters, and, with the exception of the first bench water at Tisdale, they show an excess of chloride over sodium, a characteristic not found in other subsurface waters. Water movement in this sandstone is evidently free.

COMPARISON OF WATERS

The averages of analyses of waters from the various sands of the Salt Creek-Teapot region are shown graphically in Figure 18. All subsurface waters above the Tensleep are of the primary alkaline type, being solutions of sodium salts with very minor proportions of calcium and magnesium. Tensleep waters are distinguished from the others by secondary salinity and a very considerable proportional content of calcium and magnesium. Sulphate, perhaps introduced by surface-water contamination, is notable in Shannon waters but is inappreciable in waters from the "Wall Creek" or "Lakota" sands. Beginning with the "Muddy," sulphate becomes increasingly prominent with depth ("Lakota" sand excepted) and is noteworthy in the Sundance and prominent in the Tensleep waters. Chloride becomes more prominent and carbonate less prominent with depth through the "Wall Creek" series. The carbonate-chloride ratio of the "Muddy" is similar to that of the "Second Wall Creek," and that of the "Lakota" is like though less than that of the "First Wall Creek." The carbonate-chloride ratio

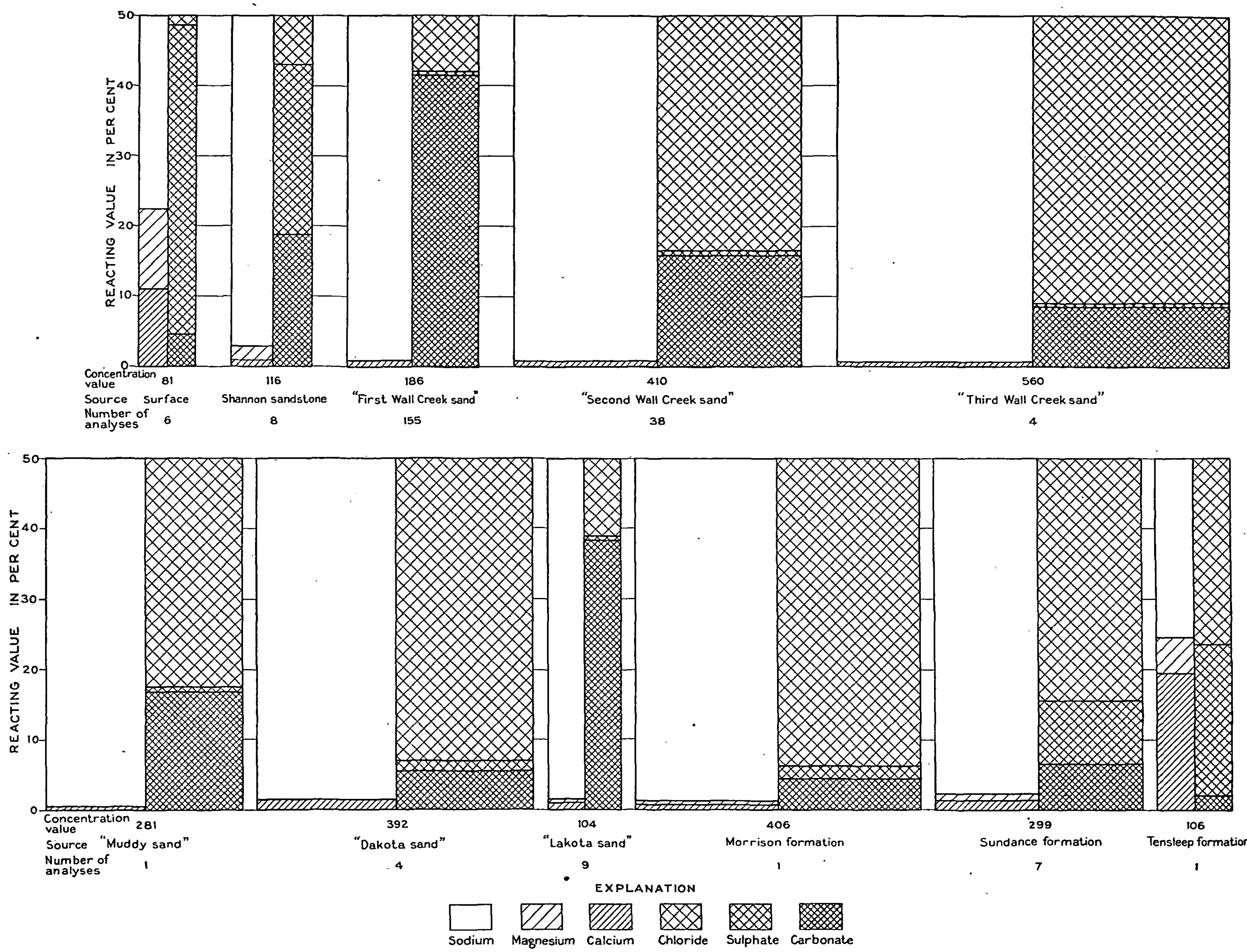


FIGURE 18.—Analyses of waters from various sands

of the "Dakota" and Morrison waters is smaller than for any other sands. Below the Morrison the carbonate-chloride ratio increases with depth through the Sundance and Tensleep. With the exception of the Tensleep, the carbonate-chloride ratio is greater than 1 for waters whose concentration values are less than 200 and less than 1 for the more concentrated waters, though the ratios and concentration values by no means run parallel. Greater concentration is in some waters due to greater chloride and in others to greater carbonate and chloride. Nickel is found only in Sundance waters but apparently not in all waters from this sand.

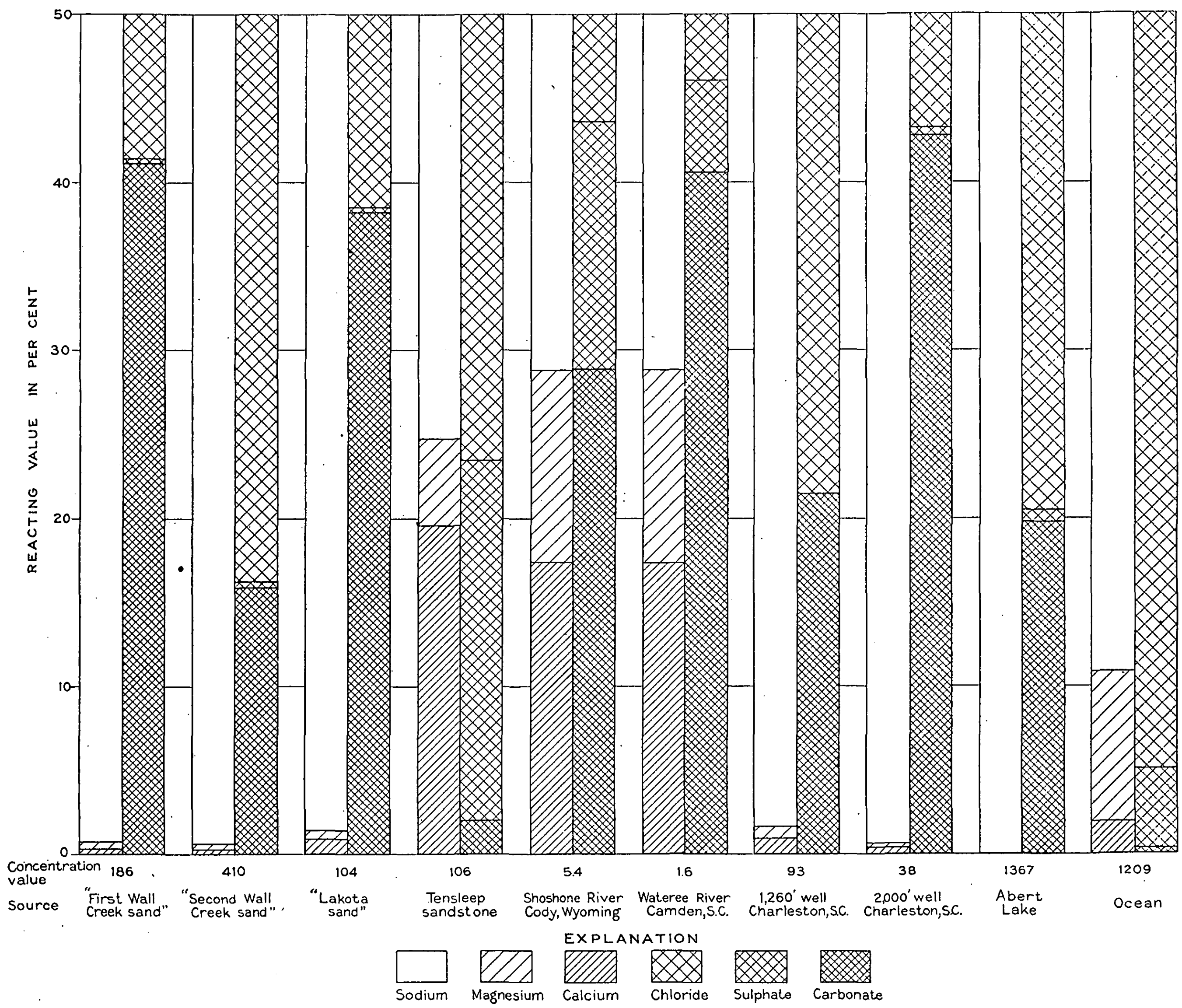


FIGURE 19.—Comparative analyses of waters from different sources

ORIGIN OF THE WATERS

Igneous rocks contain about 0.1 per cent of sulphur, and soluble sulphur compounds on the exposed igneous surface are notably rare. Silicates of the alkalies are among the most soluble constituents of igneous rocks, and these, with carbonic acid from the air, give character to waters flowing from an igneous terrain or from sand and gravel derived by the weathering of igneous rocks. With rare exceptions, therefore, waters in contact with primary rocks are of the primary alkaline or alkaline carbonate type, containing in general large proportions of sodium and bicarbonate radicles, appreciable amounts of calcium and magnesium, a little chloride, but little or no sulphate.

The subsurface waters of the Salt Creek-Teapot uplift, though showing variations, are of the primary alkaline type, and their origin in an area of igneous rocks is strongly suggested. It is thought that these waters in the main have migrated through the relatively porous sandstones from the igneous mountain masses to the west. No analyses from the streams of these mountain masses are available, but in Figure 19 is presented the average character of daily samples taken from the Shoshone River at Cody, Wyo., for a period of a year. This stream drains an area of mixed igneous and sedimentary rocks, but except for a relatively high proportion of sulphate, presumably derived from marine sediments, it is thought to represent fairly well the type of water in which the oil-field waters here considered had their origin.

Tensleep water may be conceived as having about 10 per cent of its solids derived from a water like that of the Shoshone River at Cody, 55 to 60 per cent derived from normal ocean water, and 30 to 35 per cent from gypsum beds. Shoshone River water seeping for some miles through marine sediments would be expected to exhibit such changes. Whether the ocean-water character exhibited by the Tensleep is the result of mixing with fossil water or the result of leaching saline deposits associated with gypsum is uncertain. Doubtless both influences have contributed, but the rather dilute character of the water suggests that ocean water originally in the sand has been largely flushed out and that the present mineralization is due principally to leaching of saline and gypsum deposits.

In contrast to the very simple explanation given for the origin and character of water from the Tensleep assumptions of chemical changes must be made to account for the character of waters from the "Wall Creek" and "Lakota" sands. These waters doubtless have originated in dilute primary alkaline solutions such as the water of the Shoshone River at Cody. The absence in the oil-sand waters of calcium and magnesium and of sulphate, all present in the water of the Shoshone River, requires explanation. Mere concentration, if carried far enough, would account for the loss of calcium and magnesium. Lake waters of the Lahontan Basin and the other alkaline lakes of California, Oregon, and Nevada, according to Clarke,[73] are primary concentrations of leached material from areas of igneous rocks in which rhyolites and andesites are especially abundant, and all, when fairly concentrated, have lost their calcium and magnesium by precipitation as carbonates, leaving solutions of sodium sulphate, chloride, and carbonate in different proportions. Such, of course, is the natural result of concentration of any primary alkaline water, just as it is the natural result of removal of excess of carbon dioxide from it. The water of Abert Lake, Oregon (see Table 14 and fig. 19), is such a water which has lost its calcium and magnesium by natural processes of evaporation and contains a relatively small proportion of sulphate. Though three times as concentrated it can scarcely be distinguished in character from many well waters of the "Second Wall Creek sand." Origin of the oil-field waters by mere concentration of nearly sulphate-free primary alkaline waters is therefore suggested as a possibility. However, the oil-field waters are not sufficiently concentrated to warrant taking the suggestion very seriously, and the absence, so far as known, of sulphate-free waters of origin further controverts the suggestion. Certainly, concentration alone of Shoshone River water would not produce waters of the type found in the oil sands. In the calcite deposits, particularly in fault traces, of the Salt Creek and Teapot fields, there is evidence of precipitation of calcium (and probably magnesium), but this is doubtless the result of loss of carbon dioxide on release of pressure and exposure to the air, perhaps facilitated by escaping natural gas, rather than an indication of deep-seated precipitation. Calcite has, however, been found in cores of both "First and Second Wall Creek sands." Another reasonable explanation of the absence of calcium and magnesium in the oil-field waters lies in base exchange, calcium and magnesium for sodium, through the medium of base-exchange silicates. The principle of base exchange in contact with certain silicates is used in certain types of modern water-softening plants in which waters practically free from magnesium and calcium are produced artificially. Bentonite, one of the most efficient of the base-exchange silicates, is found at the surface in the vicinity of the Salt Creek field and is encountered in drilling both in the oil sands themselves and in the intervening shales. The materials for a natural water-softening process are therefore ready at hand, and the softened character of the oil-field waters may be regarded as adequate evidence that nature has used the process effectively.

There remains the matter of sulphate. The available evidence indicates that the waters of origin (that is, the surface waters from which the oil-field waters are thought to have originated), though primary alkaline in character, contain an appreciable proportion of sulphates, but the primary alkaline waters of the "Wall Creek" and "Lakota" sands are practically sulphate-free, many samples analyzed showing not even a trace of sulphate. Something more than contact with the usual minerals of marine sediments is required to explain this change. Reduction of sulphates to sulphides and at least partial substitution of carbonates was proposed by Hoefer [74] as an explanation of the presence of sulphate-free alkaline carbonate waters in oil measures, and his hypothesis has been widely adopted in oil-field literature. Several references to the early literature on the subject are given by Riffenburg.[75] Palmer [76] strongly controverts the idea, stating that

> No experimental evidence worth mentioning is on record that it is possible for a sulphate to be reduced to a sulphide under conditions prevailing in oil fields. * * * Reduction of sulphate to sulphide is not spontaneous; the reaction is endothermic, so that it must be forced by continual application of external energy. * * * Reduction of sulphate to sulphide

[73] Clarke, F. W., The data of geochemistry, 5th ed.: U. S. Geol. Survey Bull. 770, p. 161, 1924.

[74] Engler, C., and Hoefer, H., Das Erdoel, Band 2, p. 28, 1909.

[75] Riffenburg, H. B., Chemical character of ground water of the northern Great Plains: U. S. Geol. Survey Water-Supply Paper 560, p. 38, 1925.

[76] Palmer, Chase, California oil-field waters: Econ. Geology, vol. 19, pp. 623-635, 1924.

is a fire process, and in the absence of proof to the contrary it may be accepted that sulphates are not reducible to sulphides in oil-field waters.

Palmer concludes that the alkaline waters of the California oil fields belong naturally to the formations in which they are found, having acquired their properties from the minerals of the local rocks, and that alkaline sulphide waters of the oil fields are alkaline carbonate waters more or less altered by absorption of a volatile sulphur compound emanating from the oil and are not formed by the reducing action of hydrocarbons on sulphates. Palmer's contention that alkaline waters of oil fields have acquired their properties from the minerals of the local rocks is most assuredly the logical explanation of the character of many oil-field waters. Applied to oil-field waters of the alkaline carbonate type that are sulphate-free, it presupposes a sulphate-free water of origin or contact with a sulphate-eliminating substance in the local rocks. For the Salt Creek-Teapot waters, a sulphate-free water of origin is improbable, though not beyond the bounds of possibility. Precipitation of sulphates by contact with barium salts would fulfil Palmer's specification, but barium is one of the rare earths, and its wholesale distribution over a wide area in sufficient quantity to effect the change appears unlikely. Furthermore, precipitation of sulphates by barium in an alkaline bicarbonate solution is by no means complete. The lack of other explanation drives us back upon the hypothesis of substitution of carbonate for sulphate by interaction with hydrocarbons. Although such a hypothesis is unsupported by experimental evidence or chemical theory, there is nevertheless considerable circumstantial evidence to support it. The occurrence of sulphate-free waters in the oil measures where no sulphate-free waters of origin are known to exist is perhaps the strongest and best known bit of evidence. Renick [77] has recorded an instance of apparent reduction of sulphate to sulphide and substitution of carbonate in the water system in shallow water wells of a nonoil area in Montana that carry methane, the methane-bearing, sulphate-free waters of some wells being in marked contrast to the methane-free, sulphate-bearing waters of other wells. Lindtrop [78] reports that in a region where the ground waters have a temperature of 170 to 190° F., in a well that had produced sulphate water with oil for four years, the sulphate was wholly replaced by carbonate while the well was shut in for three and a half months. The original sulphate character of the well water gradually returned on pumping and was completely reestablished after pumping for two days. He says:

> Not only in this well, but in some others also, it could be observed that the waters from the different sands are sometimes sulphate, sometimes reduced, but always the amount of reacting value of acids and the ratio are practically the same.

In discussing six aquifers from which analyses are shown, he says:

> In each horizon, practically, there are two kinds of water—sulphate and reduced waters.

Bastin [79] reports the finding of sulphate-reducing bacteria in oil-field waters and attributes the reduction of sulphates to the action of these bacteria. His results are suggestive but inconclusive and at best afford only circumstantial evidence of the activity at depth of these organisms, whose ability to reduce sulphates (usually with precipitation of sulphur or sulphides) is well known and is particularly noticeable in the cooling waters of springs whose high temperatures effectually negative the suggestion of subsurface bacterial activity. Except, perhaps, in the cooler waters of idle wells, the sulphate reduction in waters cited from Lindtrop is likewise apparently accomplished at temperatures that strongly suggest bacterial sterility. Whether the exchange of sulphate for carbonate is purely chemical, with or without one or more catalysts, or is aided or initiated by bacteria, there can be little doubt that it takes place under ground, and considerable reliance can be placed upon it for an explanation of the sulphate-free character of most waters of the Salt Creek-Teapot uplift.

In the Salt Creek field hydrogen sulphide is practically absent in the Frontier sands, though pyrites is reported in the formation. Does this mineral sulphide represent one end product of acid exchange? In some of the lower oil-bearing strata pyrites is reported, and in the Sundance and Tensleep sands hydrogen sulphide in considerable quantity is also reported. In these sands (see Tables 12 and 13) a fairly uniform proportional chloride content in the waters, with carbonate and sulphate supplementing each other in inverse degree to make up the balance, adds a further bit of circumstantial evidence supporting the hypothesis of some mechanism for acid exchange and suggests that it is even now in operation in these sands.

There is some little evidence that the ocean water that originally saturated them, or salts deposited from ocean water, have affected the waters of oil-bearing sands at Salt Creek. The common occurrence of traces of iodine and the increasing proportion of chloride on approach to the oil pools are both strongly suggestive of marine influence. The sulphate and magnesium content of sea water are not in evidence, however, these substances apparently having been removed from the water solution by some of the methods herein discussed. Ocean water, so modified, would be

[77] Renick, B. C., Some geochemical relations of ground water and associated natural gas in the Lance formation, Montana: Jour. Geology, vol. 32, pp. 668-684, 1924.

[78] Lindtrop, N. T., Outline of water problems in New Grosny oil field, Russia: Am. Assoc. Petroleum Geologists Bull., vol. 11, No. 10, 1927.

[79] Bastin, E. S., The problem of the natural reduction of sulphates: Am. Assoc. Petroleum Geologists Bull., vol. 10, No. 12, 1926.

essentially a solution of sodium chloride and would have precisely the same effect on circulating waters of the oil measures with approach to a zone of stagnation as has hereinbefore been noted with particular reference to waters of the "First Wall Creek sand."

Stephenson and Palmer [80] have provided an interesting comparison that suggests a water history similar to that of some of the Wyoming oil fields, and in Table 14 and Figure 19 are shown analyses of water from the Wateree River and from two deep wells at Charleston taken from Palmer's paper. The Wateree River at Camden, S. C., has flowed over the predominantly feldspathic rocks of the Piedmont Plateau, and its water is in consequence primary alkaline. It contains, however, appreciable amounts of calcium, magnesium, and sulphate. It is, on the whole, similar to the water of the Shoshone River at Cody, Wyo. Water of the Piedmont Plateau, of which the Wateree River is representative, is regarded by Stephenson and Palmer as the water of origin of the Charleston wells, just as waters of the igneous core of westward-lying mountain masses, of which the Shoshone River is representative, are regarded by the writer as the waters of origin of the greater part of the oil-field waters at the Salt Creek and Teapot domes. The water of the 1,260-foot Charleston well, though more dilute, is in character substantially like the average water of the "Second Wall Creek sand." The water of the 2,007-foot Charleston well, though more dilute, is substantially the same in character as water from the "Lakota" or "First Wall Creek sand." Waters from the Piedmont Plateau flow into the Cretaceous formations of the Atlantic Coastal Plain, as waters from the mountain masses of Wyoming flow into the Cretaceous formations that are oil bearing at Salt Creek and the Teapot dome. Both groups of waters undergo similar changes, doubtless mix to a minor degree with originally included sea water, and emerge at the wells substantially free from calcium, magnesium, and sulphate. In the Charleston wells green sand and other silicates capable of softening water by base exchange were encountered. The explanations presented for the practical absence of calcium and magnesium in Salt Creek oil-field waters may apparently serve for the similar condition in the Charleston well waters. The cause of loss of sulphate, whether derived from the fresh water of origin or from sea water, can not be explained on the basis of known facts. It is by no means unlikely that the same explanation will serve for Wyoming and South Carolina, though Charleston is not in an oil country and there is no suggestion that the Charleston well waters have encountered oil. They may have encountered methane and doubtless have been in contact with organic matter of various kinds within the Cretaceous sediments.

To summarize, the subsurface waters of the Salt Creek-Teapot uplift appear to have been derived from rainfall and the normal leaching of igneous rocks; to have been concentrated by passage through sand derived from igneous rocks, probably to some extent by evaporation incident to escaping gas, and by leaching of salt deposits or mixing with brines more or less coincident with the oil pools; to have had sodium substituted for at least a part of their content of calcium and magnesium by the action of base-exchange silicates; to have suffered some deposition of calcium by reason of deficiency of carbon dioxide resulting from escaping gas or possibly from the changes incident to sulphate reduction; and to have had their sulphate removed in whole or in part by reduction and carbonate substitution through contact with hydrocarbons.

RELATION OF WATERS TO AREA OF OIL OCCURRENCE

The fact that the areas of the three main oil pools ("First Wall Creek," "Second Wall Creek," and "Lakota") vary with the concentration of the waters found in the oil-bearing sands is of more than casual interest. It is natural to surmise that the differences in concentration follow differences in freedom of water movement and that where water movement is most free migrating oil has been swept past the trapping dome or, after being trapped, has been partly removed by water movement. In the "First Wall Creek sand" oil occurs 150 feet lower in the northeastern portion of the pool than in the southwestern portion, suggesting that with less vigorous water movement the oil pool would have been greater in area by the ring corresponding to about 150 feet of structural depth. These considerations encourage speculation. The relation between pool area and concentration value of water in the three main producing sands of the Salt Creek field may be expressed approximately by the equation $A=0.11r^2+1,000$, in which A is the pool area in acres and r is the average concentration value in parts per million. The values of A from this equation for given values of r for the several sands in the Salt Creek field are as follows:

	r	A
"First Wall Creek"	186	4, 800
"Second Wall Creek"	430	21, 000
"Third Wall Creek"	560	35, 000
"Muddy"	281	9, 700
"Dakota"	392	18, 000
"Lakota"	104	2, 200
Morrison	406	19, 000
Sundance	299	11, 000
Tensleep	106	2, 200

These figures should not, of course, be taken too seriously. If the values of A have any significance whatever it is merely that, if the soluble materials of

[80] Stephenson, L. W., A deep well at Charleston, S. C.: U. S. Geol. Survey Prof. Paper 90, pp. 69–90, 1915. Palmer, Chase, Mineralogy of waters from artesian wells at Charleston, S. C.; Idem, pp. 90–94.

the sands are essentially alike, water movement is such in the Salt Creek field that any oil accumulated within the areas indicated would probably not be removed by water circulation.

Moreover, the concentration values assumed for most of the sands are based on meager data and even if otherwise acceptable as indices of pool area would nevertheless be only suggestive, because of the great chance for error in the values used.

The "Third Wall Creek sand" has been found to be thin and notably irregular and, regardless of area, is not likely to be a major producer. The "Muddy" and "Dakota" sands and associated shales have yielded a considerable volume of oil in the field but are also thin and lenticular and not likely to be great producers.

A few wells have reached the Sundance, and although oil has been found in this formation, there is little indication that it will be highly productive over the area of 11,000 acres mentioned above.

Perhaps the most interesting feature of the foregoing speculation is the suggestion that the Tensleep sand may have an oil pool about the size of the "Lakota" pool. The Tensleep has been reached by only one well in the field, and in this well a strong flow of hot water but no oil was encountered. In this well, which lies outside the line of clean oil for the "Lakota" pool, the "Lakota" water encountered had a concentration value of 119, and the Tensleep water had a concentration value of 106. From these values the formula would suggest a smaller area for the Tensleep than for the "Lakota," or perhaps 2,000 acres. The character of Tensleep water, however, is rather suggestive of the absence of oil.[81]

In view of the water-bearing character of the "First Wall Creek sand" in the Teapot dome, the table suggests strongly that the "Lakota," Tensleep, and probably some other sands would also be free from oil in that field.

[81] In 1930, about three years after the above statement was written, a second well was drilled to the Tensleep sandstone in the Salt Creek field and encountered commercial quantities of oil in it. The structural relations of the two wells give strong confirmation of the suggestion that the oil pool now known to exist in the Tensleep may be of about the size of the "Lakota" pool.

TABLES

In the following tables, for constituents unreported the analyses showed no more than a trace.

TABLE 6.—*Analyses of water from surface sources* [a]

Source	Constituents (parts per million)						Reacting values: Parts per million							Reacting values: Per cent					
	Na	Mg	Ca	Cl	SO_4	HCO_3	Na	Mg	Ca	Cl	SO_4	HCO_3	Concentration value	Na	Mg	Ca	Cl	SO_4	HCO_3
Castle Creek, June 1, 1924	577	103	148	20	1,811	152	25.1	8.5	7.4	0.6	37.7	2.5	81.8	30.6	10.4	9.0	0.7	46.2	3.1
Castle Creek, Dec. 1, 1925	1,436	231	368	136	4,187	535	62.5	19.0	18.4	3.8	87.3	8.8	199.8	31.3	9.5	9.2	1.9	43.7	4.4
Salt Creek, June 16, 1923	720	223	312	24	3,100	338	31.3	18.3	15.6	.7	64.5	5.5	135.9	24.0	14.0	12.0	.5	45.6	3.9
Salt Creek, Apr. 30, 1923	71	28	98	12	400	98	3.1	2.3	4.9	.3	8.3	1.6	20.5	15.0	11.2	23.8	1.6	40.6	7.8
Pond in NE. ¼ sec. 24, T. 40 N., R. 79 W.	35	17	43	8	165	78	1.5	1.4	2.1	.2	3.4	1.3	9.9	15.0	13.8	21.2	2.3	34.8	12.9
Pond in NE. ¼ sec. 27, T. 40 N., R. 79 W.	213	59	92	13	770	142	9.3	4.8	4.6	.4	16.0	2.3	37.4	24.7	13.0	12.3	1.0	42.8	6.2
North Platte River at Fort Laramie, Wyo.	40	18	69	19	150	150	1.7	1.5	3.4	.5	3.1	2.5	12.7	13.1	11.1	25.8	4.4	25.5	20.1
Average							22.1	9.0	8.8	1.0	36.2	3.7	80.8	27.7	11.3	11.0	1.2	44.3	4.5

[a] North Platte River from U. S. Geol. Survey Water-Supply Paper 274, 1911; all others from Young, H. W., and Estabrook, E. L., Waters of the Salt Creek field, Wyo.: Petroleum development and technology in 1925, Am. Inst. Min. and Met. Eng., 1926.

TABLE 7.—*Analyses of water from wells of the Shannon sand* [a]

Well	Location			Constituents (parts per million)							Reacting values: Parts per million							Reacting values: Per cent					
	Sec.	T. N.	R. W.	Na	Mg	Ca	Cl	SO_4	HCO_3	CO_3	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3	Concentration value	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3
6	33	40	79	1,107		6	20	1,868	462	43	48.1		0.3	0.6	38.9	9.0	96.9	49.7		0.3	0.6	40.1	9.3
22A	24	39	79	1,825		18	177	2,896		451	79.4		.9	5.0	60.3	15.0	160.6	49.4		.6	3.1	37.6	9.3
21A	15	40	79	1,057	80	30	52	1,730	880	66	46.0	6.6	1.5	1.5	36.0	16.6	108.2	42.5	6.1	1.4	1.4	33.3	15.3
1A	19	39	78	2,133	20	6	324	2,552	1,452	260	92.7	1.6	.3	9.1	53.1	32.5	189.3	49.0	.8	.2	4.8	28.1	17.1
2	3	39	79	326	88	101	20	630	774		14.2	7.2	5.0	.6	13.1	12.7	52.8	26.8	13.7	9.5	1.1	24.8	24.1
105A	29	39	78	1,282	26	16	691	815		669	55.7	2.1	.8	19.5	17.0	22.3	117.4	47.5	1.8	.7	16.6	14.4	19.0
403A	20	39	78	939			425	307		689	40.8			12.0	6.4	23.0	82.2	50.0			14.5	7.7	27.8
106A [b]	29	39	78	1,376			603		2,294	156	59.8			17.0		42.8	119.6	50.0			14.2		35.8
Average											54.6	2.2	1.1	8.2	28.1	21.8	116.0	47.1	1.9	1.0	7.0	24.2	18.8

[a] Analyses made by Midwest Refining Co. and U. S. Geol. Survey and furnished by J. W. Steele, U. S. Geol. Survey, Casper, Wyo.
[b] Source from Shannon as reported doubtful as a result of subsequent study of well history by E. A. Swedenborg.

TABLE 8.—*Analyses of water from wells of the "First Wall Creek sand"* [a]

No.	Well	Location			Constituents (parts per million)							Reacting values												
												Parts per million							Per cent					
		Sec.	T. N.	R. W.	Na	Mg	Ca	Cl	SO_4	HCO_3	CO_3	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3	Concentration value	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3
1	33 A	6	39	78	1,612	----	----	139	----	4,036	----	70.1	----	----	3.9	----	66.2	140	50.0	----	----	2.8	----	47.2
2	4 A	6	39	78	2,491	5	8	240	42	6,194	----	108	0.41	0.40	6.8	0.87	102	218	49.6	0.19	0.18	3.1	0.40	46.5
3	36 A	11	40	79	2,058	11	3	204	----	5,096	40	89.5	.90	.15	5.8	----	84.8	181	49.4	.50	.08	3.2	----	46.8
4	13 A	11	39	79	2,304	----	----	229	----	5,260	216	100	----	----	6.5	----	93.4	200	50.0	----	----	3.2	----	46.8
5	3 A	11	40	79	1,791	----	----	185	----	4,115	134	77.9	----	----	5.2	----	71.9	155	50.0	----	----	3.4	----	46.6
6	26 A	15	40	79	1,268	6	4	140	----	3,163	----	55.1	.49	.20	4.0	----	51.8	112	49.4	.44	.18	3.5	----	46.5
7	13 A	11	40	79	1,547	19	37	180	----	4,000	----	67.3	1.56	1.85	5.1	----	65.6	141	47.6	1.11	1.31	3.6	----	46.4
8	25 A	27	40	79	2,936	----	----	344	----	7,200	----	128	----	----	9.7	----	118	256	50.0	----	----	3.8	----	46.2
9	12 A	1	39	79	3,044	----	----	390	----	7,460	----	132	----	----	11.0	----	122	265	50.0	----	----	4.1	----	45.9
10	29 A	14	40	79	1,122	15	6	149	----	2,736	45	48.8	1.23	.30	4.2	----	46.3	101	48.5	1.22	.30	4.1	----	45.9
11	19 A	14	40	79	1,045	4	5	134	78	2,181	147	45.4	.33	.25	3.8	1.62	40.6	92	49.4	.36	.27	4.1	1.76	44.1
12	13 A	15	40	79	1,184	10	10	153	----	2,866	----	51.5	.82	.50	4.3	----	47.0	104	48.7	.78	.47	4.2	----	45.8
13	33 A	NE.¼ 11	40	79	1,286	7	3	170	58	2,867	110	55.9	.58	.15	4.8	1.21	50.7	113	49.4	.51	.13	4.2	1.07	44.7
14	19 A	34	40	79	1,295	12	4	174	----	2,832	186	56.3	.99	.20	4.9	----	52.6	115	49.0	.86	.17	4.3	----	45.7
15	19 A	11	40	79	1,528	3	8	204	45	3,684	----	66.4	.25	.40	5.8	.94	60.4	134	49.5	.18	.30	4.3	.70	45.0
16	31 A	11	40	79	1,330	2	3	181	----	3,186	24	57.8	.16	.15	5.1	----	53.0	116	49.7	.14	.13	4.4	----	45.6
17	4 A	SE.¼ 31	40	78	2,348	14	5	323	----	5,760	----	102	1.15	.25	9.1	----	94.4	207	49.3	.56	.12	4.4	----	45.6
18	22 A	31	40	78	2,510	----	----	348	----	6,065	----	109	----	----	9.8	----	99.4	218	50.0	----	----	4.5	----	45.5
19	27 A	6	39	78	2,835	5	7	400	----	6,878	----	123	.41	.35	11.3	----	113	248	49.7	.16	.14	4.5	----	45.5
20	6 A	11	40	79	1,272	6	8	181	----	2,645	232	55.3	.49	.40	5.1	----	51.1	112	49.2	.44	.36	4.6	----	45.4
21	26 A	3	39	79	1,889	4	----	266	20	4,150	195	82.1	.33	----	7.5	.42	74.5	165	49.8	.20	----	4.6	.25	45.2
22	16 A	30	40	78	2,537	3	6	364	----	6,100	18	110	.25	.30	10.3	----	101	221	49.8	.11	.14	4.6	----	45.4
23	7 A	30	40	78	2,695	----	----	386	----	6,215	135	117	----	----	10.9	----	106	234	50.0	----	----	4.6	----	45.4
24	30 A	3	39	79	1,288	5	16	186	99	3,045	----	56.0	.41	.80	5.2	2.06	49.9	114	48.9	.36	.70	4.6	1.80	43.6
25	15 A	30	40	78	2,780	13	----	403	----	6,350	188	121	1.07	----	11.4	----	110	244	49.6	.44	----	4.7	----	45.3
26	31 A	1	39	79	2,036	7	8	298	----	4,950	----	88.5	.58	.40	8.4	----	81.1	179	49.5	.32	.22	4.7	----	45.3
27	35 A	30	40	78	2,978	----	----	432	----	7,152	----	129	----	----	12.2	----	117	258	50.0	----	----	4.7	----	45.3
28	13 A	SE.¼ 31	40	78	2,293	----	----	337	----	5,350	85	99.7	----	----	9.5	----	90.5	200	50.0	----	----	4.8	----	45.2
29	13 A	NW.¼ 31	40	78	2,290	10	12	343	----	5,540	----	99.6	.82	.60	9.7	----	90.8	201	49.3	.40	.30	4.8	----	45.2
30	15 A	31	40	78	2,382	5	----	356	----	5,720	----	104	.41	----	10.0	----	93.8	208	49.8	.30	----	4.8	----	45.2
31	6 A	31	40	78	2,590	----	----	386	----	6,210	----	113	----	----	10.9	----	102	226	50.0	----	----	4.8	----	45.2
32	33 A	31	40	78	2,317	----	----	346	----	5,552	----	101	----	----	9.8	----	91.0	202	50.0	----	----	4.8	----	45.2
33	3 A	SW.¼ 6	39	78	2,521	----	----	376	----	6,042	----	110	----	----	10.6	----	99.0	220	50.0	----	----	4.8	----	45.2
34	24 A	31	40	78	2,540	----	4	380	----	6,086	----	110	----	.20	10.7	----	99.7	221	49.9	----	.09	4.8	----	45.2
35	18 A	31	40	78	2,540	38	14	398	----	6,270	----	110	3.13	.70	11.2	----	103	228	48.3	1.37	.31	4.9	----	45.1
36	31 A	30	40	78	2,595	19	10	406	----	6,110	98	113	1.56	.50	11.4	----	103	230	49.1	.68	.22	5.0	----	45.0
37	3 A	NE.¼ 6	39	78	3,008	----	----	466	----	7,174	----	131	----	----	13.1	----	118	262	50.0	----	----	5.0	----	45.0
38	22 A	1	39	79	3,098	20	8	493	----	7,488	----	135	1.64	.40	13.9	----	123	274	49.2	.60	.15	5.1	----	44.9
39	18 A	6	39	78	2,420	11	----	388	----	5,810	----	105	.90	----	10.9	----	95.2	212	49.6	.43	----	5.1	----	44.9
40	34 A	18	40	78	1,957	8	5	312	134	4,543	----	85.1	.66	.25	8.8	2.79	74.5	172	49.5	.38	.14	5.1	1.62	43.3
41	24 A	1	39	79	2,814	----	3	452	----	6,277	208	122	----	.15	12.7	----	110	245	49.9	----	.06	5.2	----	44.8
42	21 A	31	40	78	3,043	21	----	489	57	6,960	169	132	1.73	----	13.8	1.19	120	268	49.4	.65	----	5.2	.44	44.4
43	19 A	1	39	79	3,125	----	----	496	----	7,015	195	136	----	----	14.0	----	122	272	50.0	----	----	5.2	----	44.8
44	3 A	30	40	78	2,290	17	30	384	20	5,585	----	99.6	1.40	1.50	10.8	.42	91.5	205	48.6	.68	.73	5.3	.20	44.5
45	36 A	30	40	78	2,452	----	----	402	----	5,592	121	107	----	----	11.3	----	95.7	214	50.0	----	----	5.3	----	44.7
46	24 A	27	40	79	1,684	4	3	280	----	4,036	----	73.2	.33	.15	7.9	----	66.2	148	49.7	.22	.10	5.3	----	44.7
47	12 A	22	40	79	1,119	6	----	188	----	2,410	130	48.7	.49	----	5.3	----	43.8	98	49.5	.50	----	5.4	----	44.6
48	34 A	3	39	79	1,296	6	5	218	----	2,832	139	56.4	.49	.25	6.2	----	51.0	114	49.4	.43	.22	5.4	----	44.6
49	1 A	34	40	79	2,123	----	----	354	----	4,382	319	92.3	----	----	10.0	----	82.4	185	50.0	----	----	5.4	----	44.6
50	19 A	6	39	78	1,773	15	30	305	56	4,284	----	77.1	1.23	1.50	8.6	1.17	70.2	160	48.3	.77	.94	5.4	.73	43.9
51	26 A	11	40	79	1,253	10	40	220	45	2,962	60	54.5	.82	2.00	6.2	.94	50.5	115	47.5	.76	1.74	5.4	.81	43.8
52	1 A	30	40	78	2,286	44	40	410	----	5,690	----	99.4	3.62	2.00	11.6	----	93.3	210	47.3	1.72	.95	5.5	----	44.5

53	5 A		6	39	78	2,040			357		4,800		88.7			10.1		78.7	178	50.0			5.7		44.3
54	16 A		31	40	78	2,591	17		466		6,150	22	113	1.40		13.1		102	229	49.4	.61		5.7		44.3
55	4 T		20	39	78	832	8	10	154	50	1,994		36.2	.66	.50	4.3	1.04	32.7	75	48.4	.88	.67	5.7	1.36	42.9
56	31 A		6	39	78	1,779	42	14	332		4,404		77.4	3.45	.70	9.4		72.2	163	47.5	2.11	.43	5.8		44.2
57	7 A		22	40	79	1,277	5	6	237		2,786	116	55.5	.41	.30	6.7		49.6	112	49.4	.37	.27	5.9		44.1
58	1 A		19	40	78	1,785	11	10	345		4,128	54	77.6	.90	.50	9.7		69.5	158	49.1	.57	.32	6.1		43.9
59	7 A		6	39	78	2,568			481		5,416	282	112			13.6		98.2	224	50.0			6.1		43.9
60	6 A		7	39	78	1,911	10	9	363	74	4,030	185	83.1	.82	.45	10.2	1.54	72.3	168	49.2	.49	.27	6.1	.92	43.0
61	13 A		19	40	78	2,022		3	384		4,462	122	87.9		.15	10.8		77.2	176	49.9		.08	6.1		43.9
62	12 A		13	40	79	2,191	7		424	15	4,105	487	95.3	.58		12.0	.31	83.5	192	49.7	.30		6.2	.16	43.6
63	11A		6	39	78	2,183	55	124	465	73	3,673	928	94.9	4.52	6.19	13.1	1.52	91.1	211	44.9	2.14	2.93	6.2	.72	43.1
64	4 A	SW. ¼	31	40	78	3,122	10	5	605	30	7,270		136	.82	.25	17.1	.62	119	274	49.6	.30	.09	6.3	.23	43.5
65	F 6 A		19	40	78	1,762		20	352		4,130		76.6		1.00	9.9		67.7	155	49.4		.64	6.4		43.6
66	6 A		30	40	78	2,577	7	11	516		5,660	170	112	.58	.55	14.6		98.5	226	49.5	.26	.24	6.5		43.5
67	30 A		31	40	78	3,007			602		6,078	430	131			17.0		114	262	50.0			6.5		43.5
68	2 W		11	39	79	1,022	8	3	209		2,148	125	44.4	.66	.15	5.9		39.4	90	49.1	.73	.17	6.5		43.5
69	22 A		18	40	78	1,664			335		3,457	172	72.4			9.4		62.4	144	50.0			6.5		43.5
70	2 A		13	39	79	873	6	10	181	35	1,274	371	38.0	.49	.50	5.1	.73	33.3	78	48.7	.63	.64	6.5	.93	42.6
71	21 A		24	39	79	873			177		1,604	200	38.0			5.0		33.0	76	50.0			6.6		43.4
72	14 A		22	40	79	1,329	3		272		3,068		57.8	.25		7.7		50.3	116	49.8	.20		6.6		43.4
73	14 A		30	40	78	2,897	7	10	602		6,310	188	126	.58	.50	17.0		109	253	49.6	.23	.20	6.7		43.3
74	1 A	NE. ¼	25	40	79	2,958	25		626		6,900		129	2.06		17.7		113	262	49.2	.79		6.8		43.2
75	6 A		17	39	78	977	2		209		2,242		42.5	.16		5.9		36.7	85	49.8	.19		6.9		43.1
76	34 A		12	40	79	1,984			433		4,296	110	86.3			12.2		74.1	173	50.0			7.0		43.0
77	8 A		17	39	78	846	6	10	188	40	1,557	184	36.8	.49	.50	5.3	.83	31.6	76	48.7	.65	.66	7.0	1.10	41.9
78	3 A		19	39	78	952	10		213		2,116	45	41.4	.82		6.0		36.2	84	49.0	.97		7.1		42.9
79	21 A		19	40	78	2,895	6		633	25	6,090	232	126	.49		17.9	.52	108	252	49.8	.19		7.1	.21	42.7
80	401 T		20	39	78	933	19	4	215		2,040	84	40.6	1.56	.20	6.1		36.2	85	47.9	1.84	.24	7.2		42.8
81	6 A		22	40	79	1,051	8		241		2,053	209	45.7	.66		6.8		40.6	94	49.3	.71		7.2		42.8
82	30 A		27	40	79	1,674	12	16	391		3,620	138	72.8	.99	.80	11.0		63.9	149	48.8	.66	.54	7.3		42.7
83	103 A		20	39	78	1,047			231	82	1,977	115	45.5			6.5	1.71	36.2	90	50.0			7.3	1.92	40.8
84	25 A		18	40	78	1,520	5	4	350	20	3,209	116	66.1	.41	.20	9.9	.42	56.5	133	49.5	.31	.15	7.4	.31	42.3
85	31 A	NW. ¼	19	40	78	2,722	15	4	639		6,220		118	1.23	.20	18.0		102	239	49.4	.52	.08	7.5		42.5
86	36 A		19	40	78	1,960	6		458		2,730	840	85.2	.49		12.9		72.7	171	49.7	.29		7.6		42.4
87	32 A		36	40	79	3,696	7		875	28	8,300		161	.58		24.7	.58	136	323	49.8	.17		7.6	.18	42.2
88	32 A		22	40	79	2,131			510		4,790		92.7			14.4		78.5	186	50.0			7.7		42.3
89	3 A		36	40	79	3,459	13	8	830		7,840		150	1.07	.40	23.4		128	303	49.5	.35	.13	7.7		42.3
90	21 A		5	39	78	1,225	6	6	300		2,596	93	53.3	.49	.30	8.5		45.6	108	49.3	.46	.28	7.8		42.2
91	27 A		12	40	79	2,147	6	16	519		4,590	130	93.4	.49	.80	14.6		79.5	189	49.3	.26	.42	7.8		42.2
92	5 A		19	40	78	1,440			348		3,221		62.6			9.8		52.8	125	50.0			7.9		42.1
93	13 A	SE. ¼	13	40	79	2,711	14		665		5,528	292	118	1.15		18.8		100	238	49.5	.48		7.9		42.1
94	25 A		13	40	79	2,942	11		728		6,555		128	.90		20.5		107	256	49.6	.35		8.0		42.0
95	4 A		12	40	79	1,594		15	423	82	2,718	482	69.3		.75	11.9	1.71	60.6	144	49.5		.54	8.0	1.16	40.8
96	25 T		11	39	79	1,018	6		257		2,290		44.3	.49		7.2		37.5	90	49.4	.55		8.1		41.9
97	13 A		24	40	79	2,918	24		752		6,600	22	127	1.97		21.2		109	259	49.2	.76		8.1		41.9
98	36 A		2	40	79	1,970			502		3,620	365	85.7			14.2		71.5	171	50.0			8.3		41.7
99	4 A		1	39	79	2,382	15	3	620		4,980	188	104	1.23	.15	17.5		87.9	211	49.4	.58	.07	8.3		41.7
100	31 A	SW. ¼	19	40	78	3,325	7		845	60	7,320		145	.58		23.8	1.25	120	291	49.8	.20		8.3	.43	41.3
101	4 A		19	40	78	1,467	3		379	25	3,198		63.8	.25		10.7	.52	52.4	128	49.8	.19		8.4	.41	41.2
102	19 A		29	40	78	1,148	4	40	320	158	1,950	278	49.9	.33	2.00	9.0	3.29	41.3	106	47.8	.32	1.92	8.4	3.08	38.5
103	24 A		15	40	79	1,362			358		2,478	255	59.2			10.1		49.1	118	50.0			8.6		41.4
104	1 A		13	39	79	871	4	17	237	25	1,654	141	37.9	.33	.85	6.7	.52	31.8	78	48.5	.42	1.08	8.6	.67	40.7
105	11 T		7	39	78	1,059	8	6	287		1,995	192	46.0	.66	.30	8.1		39.1	94	49.0	.70	.32	8.6		41.4
106	24 A	SW¼	12	40	79	2,348			620		5,170		102			17.5		84.7	204	50.0			8.6		41.4
107	19 A		12	40	79	2,094			561		4,490	48	91.0			15.8		75.2	182	50.0			8.7		41.3
108	8 A		36	40	79	3,340		123	952		7,660		145		6.14	26.8		126	304	48.0		2.03	8.8		41.2
109	9 A		18	39	78	1,051			285		2,231	32	45.7			8.0		37.7	91	50.0			8.9		41.1
110	30 A		12	40	79	1,717	15		479		3,379	212	74.7	1.23		13.5		62.5	152	49.2	.81		8.9		41.1
111	21 A		24	40	79	3,410			943		7,425		148			26.6		122	297	50.0			8.9		41.1
112	15 A		22	40	79	1,554			441		3,170	121	67.6			12.4		56.0	136	50.0			9.0		41.0
113	5 A		27	40	79	1,995	8	4	585		3,305	510	86.7	.66	.20	15.7		71.2	174	49.5	.38	.11	9.0		41.0
114	13 A		36	40	79	2,950			826		4,984	696	128			23.3		105	256	50.0			9.1		40.9
115	23 A		24	40	79	1,856	16	25	544	42	3,710	198	80.7	1.32	1.25	15.3	.87	67.4	167	48.5	.79	.75	9.2	.52	40.3

[a] Analyses made by Midwest Refining Co. and U. S. Geol. Survey and furnished by J. W. Steele, U. S. Geol. Survey, Casper, Wyo.

TABLE 8.—*Analyses of water from wells of the "First Wall Creek sand"*—Continued

No.	Well	Location			Constituents (parts per million)							Reacting values												
												Parts per million							Per cent					
		Sec.	T. N.	R. W.	Na	Mg	Ca	Cl	SO_4	HCO_3	CO_3	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3	Concentration value	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3
116	24 A	14	40	79	1,792		15	525	72	3,115	339	77.9		0.75	14.8	1.50	62.4	157	49.5		0.48	9.4	0.96	39.6
117	35 A	12	40	79	2,216	17	20	663		4,645	112	96.4	1.40	1.00	18.7		79.8	197	48.8	0.71	.50	9.5		40.5
118	24 A	NW¼ 12	40	79	2,220	11	2	654		4,780		96.5	.90	.10	18.4		78.3	194	49.5	.46	.05	9.5		40.5
119	5 A	12	40	79	1,916			576		3,500	294	83.3			16.2		67.2	167	50.0			9.7		40.3
120	16 A	13	40	79	2,996	15	8	912		6,135	169	130	1.23	.40	25.7		107	264	49.4	.45	.15	9.7		40.3
121	3 A	SW. ¼ 14	40	79	1,384	7	6	442		2,852	56	60.2	.58	.30	12.5		48.6	122	49.3	.47	.24	10.2		39.8
122	34 A	36	40	79	2,470	27	0	786		5,040	136	107	2.22		22.2		86.9	218	49.0	1.02		10.2		39.8
123	24 A	24	40	79	3,025	19		960		6,500		132	1.56		27.1		107	268	49.3	.70		10.1		39.9
124	18 A	22	40	79	877	17	6	292		1,720	102	38.1	1.40	.30	8.2		31.6	80	47.9	1.76	.38	10.3		39.7
125	4 A	27	40	79	1,841			600	32	3,480	150	80.0			16.9	.67	62.0	160	50.0			10.6	.42	39.0
126	3 A	22	40	79	1,552	10		524		2,600	328	67.5	.82		14.8		53.5	137	49.4	.60		10.8		39.2
127	1 A	14	40	79	2,104	6	5	710		4,417		91.5	.49	.25	20.0		72.4	185	49.6	.27	.14	10.8		39.2
128	15 A	25	40	79	3,518			1,218		6,850	218	153			34.3		119	307	50.0			11.2		38.8
129	2 A	12	40	79	2,134	115	20	824		4,645	112	92.8	9.46	1.00	23.2		79.8	206	45.0	4.56	.48	11.3		38.7
130	17 A	14	40	79	1,949			712		3,930		84.7			20.1		64.4	169	50.0			11.9		38.1
131	24 A	2	39	79	3,760	26	15	1,410		7,675		163	2.14	.75	39.8		126	332	49.1	.65	.23	12.0		38.0
132	7 A	12	40	79	1,881			705		3,778		81.8			19.9		61.9	164	50.0			12.1		37.9
133	33 A	SE. ¼ 11	40	79	2,220		40	866	54	4,130	162	96.5		2.00	24.4	1.12	73.1	197	49.0		1.0	12.4	.57	37.0
134	25 A	3	39	79	504			218		872	104	21.9			6.2		17.8	46	50.0			12.8		37.2
135	18 A	13	40	79	2,943	17	12	1,232		5,770		128	1.40	.60	34.7		94.6	259	49.2	.54	.23	13.4		36.6
136	29 A	2	39	79	3,797			1,571		7,380		165			44.3		121	331	50.0			13.4		36.6
137	1 A	SE. ¼ 25	40	79	2,071	15	7	884		3,540	265	90.0	1.23	.35	24.9		66.8	183	49.1	.67	.19	13.6		36.4
138	34 A	13	40	79	3,518			1,502		6,745		153			42.4		111	307	50.0			13.7		36.3
139	29 A	36	40	79	2,873	6	24	1,293		5,820	11	125	.49	1.20	36.5		95.8	259	49.3	.20	.47	13.8		36.2
140	15 A	27	40	79	1,854			828		2,960	268	80.6			23.3		57.4	161	50.0			14.5		35.5
141	15 A	24	40	79	4,018	19	18	1,910		7,925		175	1.56	.90	53.9		130	361	49.3	.44	.25	14.7		35.3
142	33 A	14	40	79	1,656	5	4	760	72	3,035		72.0	.41	.20	21.4	1.50	49.7	145	49.6	.28	.14	14.7	1.03	34.3
143	3 A	NE. ¼ 14	40	79	1,977	25	15	944	93	3,395	139	86.0	2.06	.75	26.6	1.94	60.2	178	48.4	1.16	.42	14.9	1.09	34.0
144	4 A	24	40	79	3,827			1,839		6,990		166			51.9		115	333	50.0			15.5		34.5
145	21	26	40	79	1,847	5	20	937		2,890	225	80.3	.41	1.00	26.4		54.9	163	49.1	.25	.61	16.2		33.8
146	13 A	NW. ¼ 13	40	79	2,951	28	4	1,502		5,396		128	2.30	.20	42.4		88.4	261	49.0	.88	.08	16.2		33.8
147	4 A	14	40	79	1,886	7	3	941	85	3,320		82.0	.58	.15	26.5	1.77	54.4	165	49.6	.34	.09	16.0	1.07	32.9
148	26 A	22	40	79	1,581	13	6	881		2,647	74	68.7	1.07	.30	24.8		45.9	141	49.0	.76	.21	17.6		32.4
149	33 A	13	40	79	2,558	5		1,435	87	3,805	197	111	.41		40.5	1.62	69.0	222	49.8	.18		18.3	.73	31.0
150	23 A	36	40	79	3,854	13	34	2,373		5,960	172	168	1.07	1.70	66.9		103	341	49.2	.30	.50	19.6		30.4
151	32	24	40	79	4,125	16		2,670		5,120	646	179	1.32		75.3		105	361	49.6	.37		20.8		29.2
152	4 A	13	40	79	2,691	15	11	1,810		4,060	56	117	1.23	.55	51.0		68.4	238	49.3	.52	.23	21.4		28.3
153	7	13	40	79	2,120	35	12	1,875		2,440	85	92.2	2.88	.60	52.9		42.8	191	49.2	1.51	.31	27.7		22.3
154	20 A	27	40	79	407	5	7	427		392		17.7	.41	.35	12.0		6.4	37	48.0	1.11	.94	32.6		17.3
155	18 A	36	40	79	1,658		34	1,982	205	778	28	72.1		1.70	55.9	4.27	13.7	148	48.8		1.15	37.8	2.89	9.3
	Averages:																							
	1–10											87.7	.46	.29	6.2	.09	82.2	177	49.6	.26	.16	3.5	.05	46.5
	11–20											72.2	.50	.26	6.4	.38	66.2	146	49.5	.34	.18	4.4	.26	45.3
	21–37											105.6	.49	.21	10.2	.15	95.9	213	49.7	.23	.10	4.8	.07	45.2
	38–61											89.8	.87	.45	9.8	.38	80.8	182	49.3	.48	.25	5.4	.21	44.4
	62–79											82.5	.70	.54	11.0	.25	72.2	167	49.3	.42	.32	6.6	.15	43.2
	80–100											90.9	.68	.18	14.4	.27	77.2	184	49.5	.37	.10	7.8	.15	42.1
	101–120											85.5	.42	.65	15.7	.34	70.8	174	49.4	.24	.37	9.0	.20	40.8
	121–133											96.0	1.44	.35	21.8	.14	75.9	196	49.1	.74	.18	11.1	.07	38.8
	134–147											110.9	.75	.38	33.0	.37	79.8	225	49.5	.33	.17	14.6	.16	35.3
	148–152											128.7	1.02	.51	51.7	.32	78.4	261	49.4	.39	.19	19.8	.12	30.1
	153–155											60.7	1.10	.88	40.3	1.42	21.0	125	48.4	.88	.70	32.1	1.13	16.7
	1–155											92.1	.72	.40	16.0	.30	77.1	186	49.4	.38	.21	8.6	.16	41.3

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TABLE 9.—*Analyses of water from wells of the "Second Wall Creek sand"*

No.	Well	Location			Constituents (parts per million)							Reacting values												
												Parts per million							Per cent					
		Sec.	T. N.	R. W.	Na	Mg	Ca	Cl	SO_4	HCO_3	CO_3	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3	Concentration value	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3
1	103 A	20	39	78	1,047	----	----	230	82	1,977	115	45.5	----	----	6.5	1.71	36.2	90	50.0	----	----	7.3	1.9	40.8
2	33 A	15	40	79	3,840	17	12	1,286	27	7,085	485	167	1.40	0.60	36.3	.56	132	338	49.4	0.4	0.2	10.7	.2	39.1
3	1 A	34	40	79	1,967	16	----	1,080	204	3,160	----	85.5	1.32	----	30.5	4.25	51.8	173	49.2	.8	----	17.6	2.5	29.9
4	36 A	27	40	79	3,316	79	60	2,302	68	5,333	----	144	6.50	2.99	64.9	1.42	87.4	307	46.9	2.1	1.0	21.1	.5	28.4
5	6 A	27	40	79	2,932	----	7	2,064	----	4,652	----	127	----	.35	58.2	----	76.2	262	49.9	----	.1	21.6	----	28.4
6	5 A	3	39	79	5,575	----	----	3,906	----	8,075	----	242	----	----	110	----	132	484	50.0	----	----	22.7	----	27.3
7	12 A	27	40	79	4,703	40	----	3,545	520	5,902	----	204	3.29	----	100	10.8	96.7	415	49.2	.8	----	24.1	2.6	23.3
8	16 A	11	40	79	6,100	48	78	4,775	----	8,350	----	265	3.95	3.89	135	----	137	545	48.6	.7	.7	24.8	----	25.2
9	401 A	33	39	78	4,472	----	9	3,598	93	5,584	----	194	----	.45	102	1.94	91.5	390	49.9	----	.1	26.0	.5	23.5
10	9 A	27	40	79	5,121	5	6	4,202	134	5,910	159	223	.41	.30	118	2.79	102	447	49.8	.1	.1	26.5	.6	22.9
11	24 A	24	39	79	3,513	7	20	3,040	----	4,000	85	153	.58	1.00	85.7	----	68.4	309	49.5	.2	.3	27.8	----	22.2
12	36 A	2	40	79	6,380	33	29	5,801	----	7,216	----	277	2.71	1.45	164	----	118	563	49.2	.5	.3	29.1	----	20.9
13	403 A	20	39	78	4,085	----	----	3,840	----	3,900	359	178	----	----	108	----	75.9	362	50.0	----	----	29.4	----	20.6
14	302 A	21	39	78	3,626	----	3	3,290	----	3,422	265	158	----	.15	92.8	----	64.9	316	49.9	----	.1	29.4	----	20.6
15	21 A	24	39	79	4,069	5	15	3,872	----	4,100	57	177	.41	.75	109	----	69.1	356	49.7	.1	.2	30.6	----	19.4
16	18 A	12	40	79	5,980	30	30	5,760	----	6,200	----	260	2.47	1.50	162	----	102	528	49.2	.5	.3	30.7	----	19.3
17	101 A	29	39	78	4,606	----	16	4,325	173	4,475	----	200	----	.80	122	3.60	73.3	400	49.8	----	.2	30.7	.9	18.4
18	403 A	28	39	78	3,565	59	----	3,545	33	3,634	----	155	4.85	----	100	.69	59.6	320	48.5	1.5	----	31.2	.2	18.6
19	201 A	28	39	78	4,650	----	----	4,608	204	----	2,232	202	----	----	130	4.25	74.4	411	50.0	----	----	31.2	1.0	17.8
20	Colossal	32	39	78	4,751	----	11	4,910	43	4,136	----	207	----	.55	138	.90	67.8	414	49.9	----	.1	33.4	.2	16.4
21	25 A	3	39	79	4,155	12	9	4,350	80	3,325	85	181	.99	.45	123	1.67	57.3	364	49.6	.3	.1	33.7	.5	15.8
22	31 A	34	40	79	3,906	20	43	4,170	39	3,360	----	170	1.64	2.15	118	.81	55.1	348	48.9	.5	.6	33.9	.2	15.9
23	108 A	29	39	78	4,842	----	7	5,250	----	3,810	----	210	----	.35	148	----	62.4	421	49.9	----	.1	35.2	----	14.8
24	8 A	14	40	79	4,602	9	12	5,125	----	3,480	----	200	.74	.60	145	----	57.0	403	49.6	.2	.2	35.9	----	14.1
25	34 A	3	39	79	3,806	----	32	4,260	----	2,550	150	165	----	1.60	120	----	46.8	333	49.5	----	.5	36.0	----	14.0
26	409 T A	20	39	78	3,864	----	----	4,300	----	2,850	----	168	----	----	121	----	46.7	336	50.0	----	----	36.1	----	13.9
27	111 A	29	39	78	4,940	27	13	5,728	----	2,018	697	215	2.22	.65	162	----	56.3	436	49.4	.5	.1	37.1	----	12.9
28	26 A	2	39	79	6,025	21	22	7,350	----	3,430	50	262	1.73	1.10	207	----	57.9	530	49.5	.3	.2	39.0	----	11.0
29	1 A	10	39	79	3,024	24	6	3,710	167	1,254	161	131	1.97	.30	105	3.48	26.0	268	49.2	.7	.1	39.0	1.3	9.7
30	302 A	27	39	78	5,003	----	12	6,100	----	2,810	----	218	----	.60	172	----	46.1	436	49.9	----	.1	39.4	----	10.6
31	4 A	13	39	79	2,547	30	60	3,290	----	1,414	----	111	2.47	2.99	92.8	----	23.2	232	47.6	1.1	1.3	40.0	----	10.0
32	201 A	10	39	78	4,974	8	46	6,345	62	2,440	15	216	.66	2.30	179	1.29	40.5	440	49.3	.2	.5	40.5	.3	9.2
33	104 A	29	39	78	3,813	----	----	4,800	----	1,855	----	166	----	----	135	----	30.4	332	50.0	----	----	40.8	----	9.2
34	204 A	29	39	78	4,472	53	24	5,484	59	2,062	----	194	4.36	1.20	158	1.23	33.8	393	48.6	1.1	.3	40.9	.3	8.8
35	301 A	14	38	78	4,200	----	----	5,317	----	2,008	----	183	----	----	150	----	32.9	365	50.0	----	----	41.0	----	9.0
36	301 A	27	39	78	4,415	----	----	5,601	----	----	1,023	192	----	----	158	----	34.1	384	50.0	----	----	41.1	----	8.9
37	29 A	2	39	79	5,680	2	68	7,475	313	1,970	34	247	.16	3.39	211	6.52	33.4	502	49.0	.3	.7	42.0	1.3	6.7
[a] 38	34 A	29	40	78	18,550	----	----	28,360	295	----	52	807	----	----	800	6.14	1.7	1,615	50.0	----	----	49.5	.4	0.1
	Averages:																							
	2–3	----	----	----	----	----	----	----	----	----	----	126	1.36	.30	33.4	2.40	91.9	255	49.4	.5	.1	13.1	.9	36.0
	4–8	----	----	----	----	----	----	----	----	----	----	196	2.75	1.44	93.6	2.44	106	402	49.0	.7	.3	23.2	.6	26.2
	9–14	----	----	----	----	----	----	----	----	----	----	197	.62	.56	112	.79	86.8	397	49.8	.1	.1	28.0	.2	21.8
	15–22	----	----	----	----	----	----	----	----	----	----	194	1.30	.78	125	1.49	69.8	392	49.5	.3	.2	31.9	.4	17.7
	23–30	----	----	----	----	----	----	----	----	----	----	196	.83	.65	148	.43	49.9	396	49.6	.2	.2	37.3	.1	12.6
	31–37	----	----	----	----	----	----	----	----	----	----	187	1.09	1.41	155	1.29	32.6	378	49.3	.3	.4	41.0	.4	8.6
	1–38	----	----	----	----	----	----	----	----	----	----	203	1.18	.85	139	1.42	64.7	410	49.5	.3	.2	33.9	.3	15.8

[a] Reported doubtful by E. A. Swedenborg on subsequent study of well history.

TABLE 10.—*Analyses of water from wells of the "Third Wall Creek sand"* [a]

Well	Location			Constituents (parts per million)							Reacting values: Parts per million							Reacting values: Per cent					
	Sec.	T. N.	R. W.	Na	Mg	Ca	Cl	SO_4	HCO_3	CO_3	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3	Concentration value	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3
409	20	39	78	6, 430	31	44	8, 024	51	2, 754	372	280	2. 5	2. 2	227	1. 1	57. 5	570	49. 2	0. 44	0. 39	39. 7	0. 19	10. 1
408	20	39	78	6, 375	18	31	7, 969	43	2, 902	199	277	1. 5	1. 5	225	. 9	54. 2	560	49. 4	. 29	. 29	40. 2	. 16	9. 7
5	20	39	78	6, 506	6	18	8, 500	60	2, 650	------	284	. 7	. 9	240	1. 2	43. 4	570	49. 7	. 12	. 16	42. 2	. 21	7. 6
9	20	39	78	6, 218	----	----	8, 300	----	2, 210	------	271	------	------	234	------	36. 2	541	50. 0	------	------	43. 3	------	6. 7
Average	----	----	----	--------	----	----	-------	----	-------	------	278	1. 2	1. 1	232	. 8	47. 8	560	49. 6	. 2	. 2	41. 4	. 1	8. 5

[a] Analyses made by U. S. Geol. Survey and furnished by J. W. Steele, U. S. Geol. Survey, Casper, Wyo. Samples from wells producing from "Third Wall Creek sand," but the water may be from a stray sand above.

TABLE 11.—*Analyses of water from wells of the "Muddy," "Dakota," Morrison, and "Lakota" sands* [a]

Sand and well	Location			Constituents (parts per million)							Reacting values: Parts per million							Reacting values: Per cent					
	Sec.	T.N.	R. W.	Na	Mg	Ca	Cl	SO_4	HCO_3	CO_3	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3	Concentration value	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3
"Muddy"	----	----	----	3, 232	0	10	3, 250	82	2, 920	4	140	-----	0. 5	91. 7	1. 7	47. 0	281	49. 8	-----	0. 2	32. 7	0. 6	16. 7
"Dakota": 31 D	7	39	78	4, 519	47	78	6, 208	267	1, 434	-----	196	3. 9	3. 9	175	5. 6	23. 5	408	48. 1	0. 95	. 95	42. 9	1. 3	5. 8
Average (4)	----	----	----	4, 420	20	65	6, 008	240	1, 257	14	192	1. 7	3. 2	170	5. 0	21. 1	393	48. 8	. 4	. 8	43. 3	1. 3	5. 4
Morrison	----	----	----	4, 580	24	36	6, 361	334	1, 049	-----	199	2. 0	1. 8	180	7. 0	17. 2	407	49. 1	. 5	. 4	44. 1	1. 7	4. 2
"Lakota":																							
19 L (LB)	19	39	78	943	----	----	124	-----	1, 824	229	41. 0	-----	-----	3. 5	-----	37. 5	82	50. 0	-----	-----	4. 3	-----	45. 7
7 L (LB)	25	40	79	1, 017	----	6	139	-----	2, 092	195	44. 2	-----	. 3	3. 9	-----	40. 8	89	49. 7	-----	. 3	4. 4	-----	45. 6
12 Tp	25	40	79	1, 302	18	25	332	-----	3, 050	-----	56. 6	1. 5	1. 2	9. 4	-----	50. 0	119	47. 7	1. 3	1. 0	7. 9	-----	42. 1
19 L (UB)	19	39	78	925	----	2	247	-----	1, 790	160	40. 2	-----	. 1	7. 0	-----	34. 6	82	49. 9	-----	. 1	8. 4	-----	41. 6
21 Su	35	40	79	1, 362	----	30	426	-----	2, 980	-----	59. 2	-----	1. 5	12. 0	-----	48. 8	122	48. 8	-----	1. 2	9. 8	-----	40. 2
33 L	23	40	79	1, 270	24	46	452	20	2, 928	-----	55. 2	2. 0	2. 3	12. 7	. 4	46. 4	119	46. 4	1. 7	1. 9	10. 6	. 4	39. 0
15 L	34	40	79	1, 091	----	----	465	-----	2, 090	-----	47. 4	-----	-----	13. 1	-----	34. 3	95	50. 0	-----	-----	13. 8	-----	36. 2
10 L (UB)	15	40	79	1, 281	----	7	586	-----	2, 390	-----	55. 7	-----	. 4	16. 5	-----	39. 2	112	49. 7	-----	. 3	14. 9	-----	35. 1
19 L	23	40	79	1, 232	----	39	1, 027	76	1, 440	42	53. 6	-----	2. 0	29. 0	1. 6	25. 0	111	48. 2	-----	1. 8	26. 1	1. 4	22. 5
Average (9)	----	----	----	--------	----	----	-------	-----	-------	-----	50. 3	. 4	. 9	11. 9	. 2	39. 6	104	48. 8	. 4	. 8	11. 5	. 2	38. 3

[a] Analyses made by Midwest Refining Co. and U. S. Geol. Survey and furnished by J. W. Steele, U. S. Geol. Survey, Casper, Wyo.

TABLE 12.—*Analyses of water from wells of the Sundance sand* [a]

Well	Location			Constituents (parts per million)								Reacting values												
												Parts per million							Per cent					
	Sec.	T. N.	R. W.	Na	Mg	Ca	Cl	SO_4	HCO_3	CO_3	Ni	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3	Concentration value	Na	Mg	Ca	Cl	SO_4	HCO_3+CO_3
3 A (2B)	29	39	78	4, 502	81	218	5, 012	3, 100	472	----	55	195	6. 9	10. 9	141	64. 5	7. 7	426	45. 9	1. 6	2. 5	33. 1	15. 1	1. 8
33 X (2B) [b]	28	41	81	1, 423	----	----	1, 452	845	118	43	----	61. 8	----	----	41. 0	17. 6	3. 3	124	50. 0	----	----	33. 1	14. 2	2. 7
34 X (1B) Su	23	40	79	1, 976	22	116	1, 920	1, 620	353	----	----	86. 1	1. 8	5. 8	54. 2	33. 7	5. 8	187	45. 9	1. 0	3. 1	28. 9	18. 0	3. 1
21 Su	2	39	79	3, 950	66	43	4, 720	1, 465	975	----	115	172	5. 4	2. 2	133	30. 5	16. 0	359	47. 9	1. 5	6. 6	37. 1	8. 5	4. 4
21 Su [c]	35	40	79	3, 064	33	51	3, 620	927	1, 035	----	----	133	2. 7	2. 6	102	19. 3	17. 0	277	48. 1	1. 0	. 9	36. 9	7. 0	6. 1
21 (2B) Su	35	40	79	3, 299	19	26	3, 610	1, 030	1, 405	----	43	143	1. 6	1. 3	102	20. 9	23. 0	292	49. 0	. 5	. 5	34. 9	7. 2	7. 9
12 Tp [d]	25	40	79	4, 010	----	20	4, 580	850	1, 725	----	53	174	----	1. 0	129	17. 7	28. 3	350	49. 7	----	. 3	36. 8	5. 1	8. 1
34 (1B) Su	23	40	79	2, 308	8	15	2, 272	0	2, 290	----	40	100	. 7	. 7	64. 1	----	37. 5	203	49. 3	. 3	. 4	31. 6	----	18. 4
Average (7)	----	----	----	----	----	----	----	----	----	----	----	143	2. 7	3. 5	104	26. 5	19. 3	299	47. 9	. 9	1. 2	34. 6	8. 9	6. 5

[a] Analyses made by Midwest Refining Co. and U. S. Geol. Survey and furnished by J. W. Steele, U. S. Geol. Survey, Casper, Wyo.
[b] From Tisdale dome. Excluded from averages.
[c] H_2S, 341 parts per million.
[d] H_2S, 185 parts per million.

TABLE 13.—*Analyses of water from wells of the Tensleep sand* [a]

Well	Location			Constituents (parts per million)							Reacting values												
											Parts per million							Per cent					
	Sec.	T. N.	R. W.	Na	Mg	Ca	Cl	SO_4	HCO_3	H_2S	Na	Mg	Ca	Cl	SO_4	HCO_3	Concentration value	Na	Mg	Ca	Cl	SO_4	HCO_3
12 Tp	25	40	79	615	65	416	998	1, 090	127	----	26. 7	5. 4	20. 8	28. 1	22. 7	2. 1	106	25. 3	5. 1	19. 6	26. 6	21. 4	2. 0
33X	28	41	81	650	86	224	790	721	566	173	28. 3	7. 1	11. 2	22. 3	15. 0	9. 3	93	30. 4	7. 6	12. 0	23. 9	16. 1	10. 0
				337	194	210	753	417	650	232	14. 7	15. 9	10. 5	21. 2	8. 7	10. 7	82	17. 9	19. 3	12. 8	26. 1	10. 7	13. 2
				468	114	80	742	484	154	----	20. 4	9. 4	4. 0	20. 9	10. 1	2. 5	67	30. 2	13. 9	5. 9	31. 2	15. 1	3. 7
Average	----	----	----	----	----	----	----	----	----	----	22. 5	9. 5	11. 6	23. 1	14. 1	6. 2	87	25. 8	10. 9	13. 3	26. 6	16. 3	7. 1

[a] Analyses made by Midwest Refining Co. and furnished by J. W. Steele, U. S. Geol. Survey, Casper, Wyo.
Well 12 Tp is in the Salt Creek field; well 33X is in the Tisdale dome, and the samples came from depths of 1,870–2,040, 2,061–2,159, and 2,200–2,228 feet respectively below the top of the "Lakota."

TABLE 14.—*Analyses of water from miscellaneous sources*

	Constituents (parts per million)								Reacting values												
									Parts per million							Per cent					
	Na	K	Mg	Ca	Cl	SO_4	HCO_3	CO_3	Na+K	Mg	Ca	Cl	SO_4	HCO_3+CO_3	Concentration value	Na+K	Mg	Ca	Cl	SO_4	HCO_3+CO_3
1	29	------	6. 7	23	11	35	87	------	1. 26	0. 55	1. 15	0. 31	0. 73	1. 43	5. 4	21. 3	9. 3	19. 4	6. 3	14. 8	28. 9
2	7. 2	1. 6	2. 3	5. 7	2. 2	4. 2	39	------	. 35	. 19	. 28	. 06	. 09	. 65	1. 6	21. 2	11. 5	17. 3	3. 8	5. 6	40. 6
3	1, 014	41. 0	8. 3	14. 0	944	------	1, 115	41	45. 0	. 68	. 70	26. 6	------	19. 9	93	48. 5	. 7	. 8	28. 6	------	21. 4
4	421	4. 4	. 4	3. 0	92	7. 2	872	54	18. 4	. 03	. 15	2. 6	. 15	16. 3	38	49. 5	. 1	. 4	6. 8	. 4	42. 8
5	15, 400	560	------	------	14, 100	740	------	8, 100	684	------	------	398	15	270	1, 367	50. 0	------	------	29. 1	1. 1	19. 8
6	10, 710	390	1, 300	420	19, 350	2, 700	------	70	476	107. 3	21. 2	545. 6	56. 1	2. 1	1, 209	39. 3	8. 9	1. 8	45. 1	4. 7	0. 2

1. Shoshone River, Cody, Wyo. U. S. Geol. Survey Water-Supply Paper 274.
2. Wateree River, Camden, S. C. U. S. Geol. Survey Prof. Paper 90.
3. Artesian well 1,260 feet deep, Charleston, S. C. U. S. Geol. Survey Prof. Paper 90.
4. Artesian well 2,007 feet deep, Charleston, S. C. U. S. Geol. Survey Prof. Paper 90.
5. Abert Lake, Oreg. Recomputed from U. S. Geol. Survey Bull. 330.
6. Ocean. U. S. Geol. Survey Bull. 479.

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