THE FRONTIER FORMATION

IN THE SOUTHWEST POWDER RIVER BASIN, WYOMING

by

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Abstract

The Upper Cretaceous Frontier formation is a conspicuous sandy unit in the predominantly fine-grained rocks of the Colorado group in Wyoming. The Frontier formation is an important oil-producing formation in Wyoming. The formation was studied in detail in the southwest Powder River Basin, Wyoming, in order to determine the paleogeography and the structural and depositional history of the area during Frontier time.

Surface and subsurface exposures of the formation are correlated, and the formation is divided into four members. The results of laboratory investigation of the texture, mineralogy, and lithology of the rocks are combined with surface and subsurface data and are presented in charts, sections, and maps which aid in the interpretation of the sedimentation.

The Powder River Basin had essentially the same shape as it has at the present during Frontier time, and the Laramide structural pattern was apparent as early as Third Wall Creek time. The sediments were deposited in a shallow water marine environment on a sea bottom that had a varied topography. Sediments entered the area principally from the southwest, but there were minor amounts of sediment that came from the northwest and from the south. There probably was local uplift in the south during the deposition of the First Wall Creek member, and older Mesozoic rocks are the most probable immediate source of Frontier sediments.

The Frontier formation reveals a history of regular variation in water salinity and sediment supply. The basal bentonite of the Frontier formation is correlated with the Clay Spur bentonite of the Black Hills, and the concretions in the First Wall Creek member are correlated with the Greenhorn limestone of the eastern Powder River Basin.

ACKNOWLEDGMENTS

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Professor R. R. Shrock supervised the thesis and read the original manuscript.

William Leavitt provided equipment and helped with the radioactivity measurements.

Mrs. Towse aided in the editing of the manuscript and contributed in many intangible ways to the successful completion of the research.

Where data or conclusions of others are used, the author is cited in the text. For all other facts, conclusions, and theories the present writer assumes full responsibility.

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INTRODUCTION

The Frontier formation contains one of the great sandstone phases of the Cretaceous system of the Rocky Mountains and has been an important oil-bearing formation in Wyoming, producing oil or gas in all the major structural basins into which the state is divided. Recent deep drilling makes possible a detailed study of the formation over a wide area in the southwest Powder River Basin, a region interesting for its stratigraphy, its structural position, and its oil production.

In order to determine the paleogeography and the depositional and structural history of the Powder River Basin during Frontier time, the physical properties and areal variations of the rocks of the Frontier formation were extensively studied by the writer. His studies in the field let to the division of the formation into four members and to the establishment of correlation criteria and guide horizons that were successfully carried into the subsurface. Samples specially collected for the purpose were further studied in the laboratory by several techniques, including thin sections, mechanical analyses, and radioactivity measurements. The numerous data thus obtained are presented in maps, sections, and charts which are used to interpret the sedimentation.

Field work was done during the summer of 1949 and the summer and fall of 1950, and the winter and spring 1949-50 were spent in laboratory study at the Massachusetts Institute of Technology. Subsurface work was done in the Casper district office of the Amerada Petroleum Corporation during the winter of 1950-51.

Previous work.- Numerous reports of the Frontier formation in east-central Wyoming have been published since Darton (1908) discussed the formation in a paper on the stratigraphy of the Benton shale, of which the rocks now known as the Frontier formation are a part. Darton said that the Benton shale "inaugurated the vast later Cretaceous submergence in which marine conditions prevailed", that there were occasional deposits of sand and that one of them (the Frontier formation) in the latter part of the epoch was general over the greater part of the Rocky Mountain region. He believed that the widespread Greenhorn limestone in the middle of the Benton shale indicated a "uniform condition of sedimentation over an area of many thousands of square miles".

Many of the Geological Survey reports on the oil possibilities of the region mention the Frontier formation and discuss its stratigraphy. Wegemmann's reports on the Salt Creek area (1911, 1912, 1918) describe the formation in detail. He noted that the included fossils were marine but that they probably lived in no great depth of water. He correlated his sections with the type section of the Frontier formation in southwestern Wyoming, and his work led to the recognition of the upper thick sandstone of the formation as the Wall Creek member.

Hares (1916) noted the widespread occurrence of conglomerate in the lowest sandstone body of the Frontier formation in the southern part of the Powder River Basin and correlated the conglomerate horizon with the Peay sand, the lowest sandstone bed in the Frontier formation of the Bighorn Basin.

Hancock (1920) described the outcrops of the Frontier equivalents in the Lance Creek area and correlated the Turner sandy member of the Carlile shale with the Wall Creek member of the Frontier formation. Much of the previous work was reviewed by Thom and Spieker (1931) in their paper on the Salt Creek field.

Bartram (1932) stated that the "Wall Creek sandstones" were not sheets, but had the forms of low deltas, deposited by a river emptying near the southwest corner of Wyoming, with the actual shore line and coarse material present still farther west. He believed that the rocks of the Frontier formation in central Wyoming were finer sediments swept out onto the edge of the delta and deposited beneath the water, with shale layers representing probable seasonal changes in sediment supply. Bartram further noted that there were a few streaks of black chert and coarser material in the "Wall Creek sands", but that the sandstones were generally fine grained and had a tendency tc be shaley, with porosity largely determined by the amount of shale included with the sandstone.

Boyer (1932) discussed the Frontier formation which produced gas in the Billy Creek gas field in the northwestern part of the Powder River Basin. He believed that the Powder River Basin was a basin of deposition during Frontier time, that ocean currents entered the basin in the southwest and deposited the greatest load of coarse sediment in the Salt Creek-Tisdale area, and that the currents deposited less sandstone as they spread into the basin.

Thomas (1946) studied the paleontology of the Frontier formation in the Laramie Basin and found a fauna indicating Carlile age.

Much information on the Frontier formation in the Wind River Basin was presented by Thompson, et al, (1949). They found a fauna of Carlile and Niobrara aspect that indicated that the top of the Frontier formation was older in the western part of the area than in the eastern part. They reported that Paleozoic fossils are present in pebbles of conglomerates in the Frontier formation, but noted that exposures of Paleozoic rocks in the area during Frontier time are unknown.

Trask and Patnode (1942) presented results of sample study that showed a thinning of section and reduction in median diameter of sediment grains from east to west in the Frontier formation in Wyoming, with an increase in calcium carbonate content toward the southeast.

Previous reports of the Frontier formation in the southwest Powder River Basin have been part of regional works of a general nature or part of detailed descriptions of local oil fields. No intensive co-ordinated analysis of the Frontier formation in this area has heretofore been published.

Well PR of this report, the Stanolind No. 1 LaFleiche at Powder River, was included in order to provide a common point with the work of Thompson, et al (1949). The well is Section 11 on their charts.

TABLE I

STRATIGRAPHIC POSITION OF THE FRONTIER FORMATION

BLACK HILLS	SOUTHERN POWDER RIVER BASIN	BIGHORN BASIN
	---MONTANA GROUP---	
Pierre shale		Cody shale
	---COLORADO GROUP---	
Niobrara formation	Niobrara formation	Frontier formation
Carlile shale	Carlile shale	
Turner sandy member	Frontier formation	
Greenhorn limestone		
Graneros shale		
Belle Fourche shale member		
Mowry shale member	Mowry shale	Mowry shale
	Thermopolis shale	Thermopolis shale
Newcastle sandstone member	Muddy sandstone member	
Skull Creek shale member		
	---DAKOTA GROUP---	
Inyan Kara group	Cloverly group	Cloverly formation

(Adapted from Field Conference Guidebooks of the Kansas Geological Society 1940, and the Wyoming Geological Association 1946, with revisions by the author.)

Stratigraphic nomenclature.- The Frontier formation is a sequence of rocks containing a sandy phase of the marine predominantly shaley Colorado group of the Rocky Mountain Upper Cretaceous series. The Frontier formation, according to Wilmarth (1938), was originally defined as a coal-bearing sandstone sequence in southwestern Wyoming underlying the Hilliard formation and overlying rocks of Benton age. In the Rock Springs uplift the Frontier formation is overlain by Baxter shale and underlain by Aspen shale, while in the Hanna Basin and elsewhere, "it underlies Carlile shale and overlies Mowry shale". Table I shows the position of the Frontier formation in the southern Powder River Basin in relation to other formations there and in relation to rocks named Frontier in other areas. The Table is intended only to show the physical relations of the named lithologic units. The age relationships of the type Frontier formation and the formation in the eastern parts of the state have been discussed by Thomas (1936), Thompson, et al (1949), and Love (1950). The matter is still a subject of debate among geologists.

Wegemann (1911) named the "Wall Creek sandstone lentil of the Benton shale" with the type section west of Salt Creek. Wilmarth (1938) traces the development of nomenclature in the Powder River Basin since that time as follows:

"Later work resulted in tracing this sandstone over considerable area, and the name was later changed to Wall Creek sandstone member. Subsequently the deposits of Benton age in this part of

Wyoming were differentiated into (descending) Carlile shale, Frontier formation, Mowry shale, and Thermopolis shale, and the Wall Creek sandstone was found to form top member of Frontier formation. The drillers in this part of Wyoming began to identify sands in this part of the geologic column as (descending) 'First Wall Creek sand', 'Second Wall Creek sand', and 'Third Wall Creek sand'. Of these, the 'First Wall Creek sand' is Wall Creek sandstone member as defined. The 'Second Wall Creek sand' has also been called 'Lower Wall Creek sand'."

In this report the top of the Frontier formation is taken at the top of the highest sandstone in the section, usually the First Wall Creek member as defined. The top of the Mowry shale or base of the Frontier formation is as described by Wegemann (1912), and is placed at the top of the well cemented, platy, gray Mowry shale, with a thick bentonite present immediately above the Mowry shale. A shale with red-brown calcareous siltstone concretions lies directly above the basal bentonite of the Frontier formation and is here named the Lower shale member of the Frontier formation. Although the top of the Mowry shale described above is the top of the Mowry shale as defined in the earlier literature, Thompson, et al (1949) have placed the top of the Mowry shale considerably higher in the section, above the top of the Lower shale member of this report. (See Well PR, figured in Cross Section D, Plate 4.)

In order to study in detail the history of sedimentation over a wide area, four subdivisions of member rank in the Frontier formation are proposed: the First, Second, and Third Wall Creek members, and the Lower shale member. The First, Second, and Third Wall Creek members are shale and sandstone sequences that include at Salt Creek the Wall Creek sandstone member ("First Wall Creek sand"), the "Second", and "Third Wall Creek sands", respectively. The practice of naming the Frontier sandstone units numerically in the order in which they are penetrated by the drill is confusing, particularly with sandstone bodies that may pinch out or split into two or more units. "Wall Creek sands" called "first", "second", or "third" in one place may have no connection, either physically, positionally or chronologically with rocks of the same name at another place. Such a system defies the purpose of stratigraphic nomenclature. The addition to nomenclature introduced in this paper is made in order to correct the present confusion, with as little change in established practices as possible. No new names are introduced. Where "First", "Second", and "Third Wall Creek sand" names were reported previously and are used in this paper, they refer to sandstone bodies which are correlative positionally with the sandstones at Salt Creek, in accordance with the terminology used in this paper. Where the reported sands were named at variance with the usage of this report, the new "member" terminology is used.

Figure 2. Structure of the Southwest Powder River Basin

Identification of Major Structures shown on Map

a. Horn fault

b. Kaycee anticline

c. Tisdale anticline

d. Salt Creek anticline

e. Teapot dome

f. Sage Spring Creek structure

g. Castle Creek structure

h. Sulfur Springs anticline

i. Notches dome

j. North Casper Creek anticline

k. Powder River anticline

l. Cole Creek anticline

m. Midway dome

n. North Geary anticline

o. Geary anticline

p. Big Muddy anticline

q. Casper Mountain fault

r. Emigrant Gap anticline

s. Pine Mountain dome

t. Oil Mountain anticline

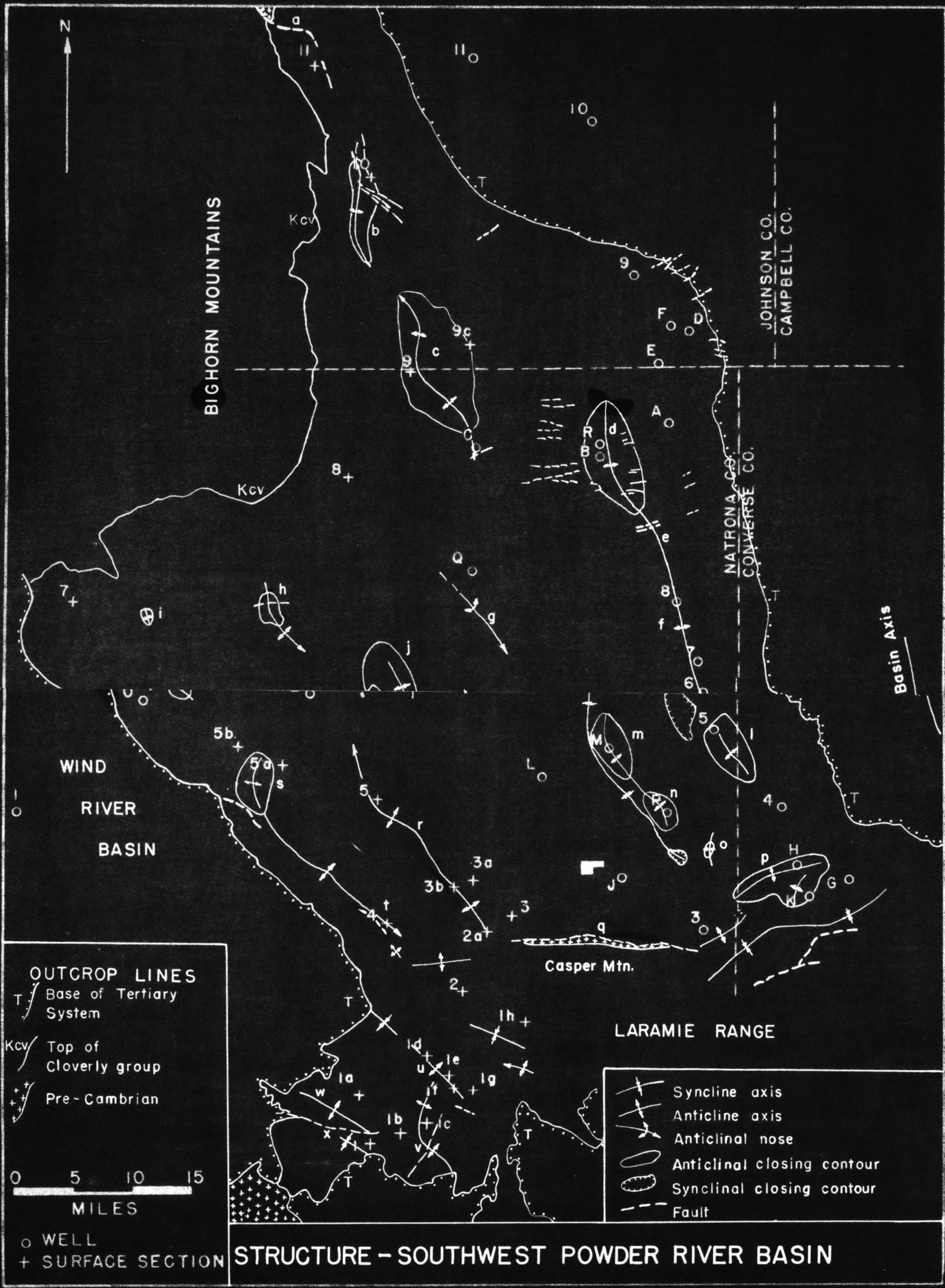
u. Bates Creek anticline

v. Bolton Creek-Spindletop anticline

W. Alcova anticline

x. Alcova fault

Compiled from several sources: 1. Pierce and Girard (1945). 2. Love and Weitz (1949). 3. Love (1935), (Tertiary outcrop southwest margin and outcrop south of Casper Mountain. Structure south of Casper Mountain is from interpretation of Love's map and from original field observations.) 4. Summerford (1948), Structures on the southwest margin.



STRUCTURE - SOUTHWEST POWDER RIVER BASIN

Figure 2

Location and Geologic setting.- The area covered in this report (see Figure 1) is in east-central Wyoming, in the southwest part of the Powder River Basin, and includes a small part of the southeast margin of the Wind River Basin.

The Powder River Basin is a structural and topographic depression with the central part covered by Eocene rocks. Rocks as old as Pre-Cambrian crop out on surrounding uplifts. A structural map by Pierce and Girard (1945) and a geologic map by Love and Weitz (1949) have recently been published. A geologic map of Natrona County by Love (1935) includes the southern and western borders of the basin which were not covered by the first two maps.

Several major uplifts border the basin--the Black Hills on the northeast; the Hartville uplift, Laramie Mountains, and Sweetwater uplift on the south; and the Bighorn Mountains on the northwest. The basin rises into the Montana plains in the north and is separated from the Wind River Basin in the southwest by steeply dipping folds and faults.

The area covered in this report includes the part of the Powder River Basin which has seen the most extensive deep drilling and includes and is bordered by several important structural features shown in Figure 2. The Horn fault, on the boundary between the southern and middle segments of the Bighorn Mountains, Chamberlin (1940), is in the extreme northwest corner of the area. The Bighorn Mountains strike northwest and curve slightly west of south, to join in the southwest with the essentially east-west trending Owl Creek uplift. The southwestern border is marked by a series of southeast-northwest folds, joining with the east-west Sweetwater uplift on the south, while the east-west folds and faults in the Casper Mountain area are the north and west extensions of the north-south trending Laramie Range. Pre-Cambrian rocks are exposed on Casper Mountain, and near Alcova on the northern edge of the Seminoe Plateau. Eocene Wind River rocks cover the eastern part of the Wind River Basin, and the greater part of the older rocks in the Sweetwater uplift-Seminoe Plateau area are covered by Tertiary Wind River and White River sediments.

The southwestern Powder River Basin, thus, is at the juncture of three diversely oriented structural systems, with the Laramie Range of the Rocky Mountain front range system striking to the south and the Bighorn Mountains striking to the northwest. Of less magnitude are the east-west Sweetwater and Owl Creek uplifts. The structures within the basin generally follow in trend those along the borders, with the majority of the folds striking nearly parallel with the northwest-southeast alignment of the Bighorn Mountains.

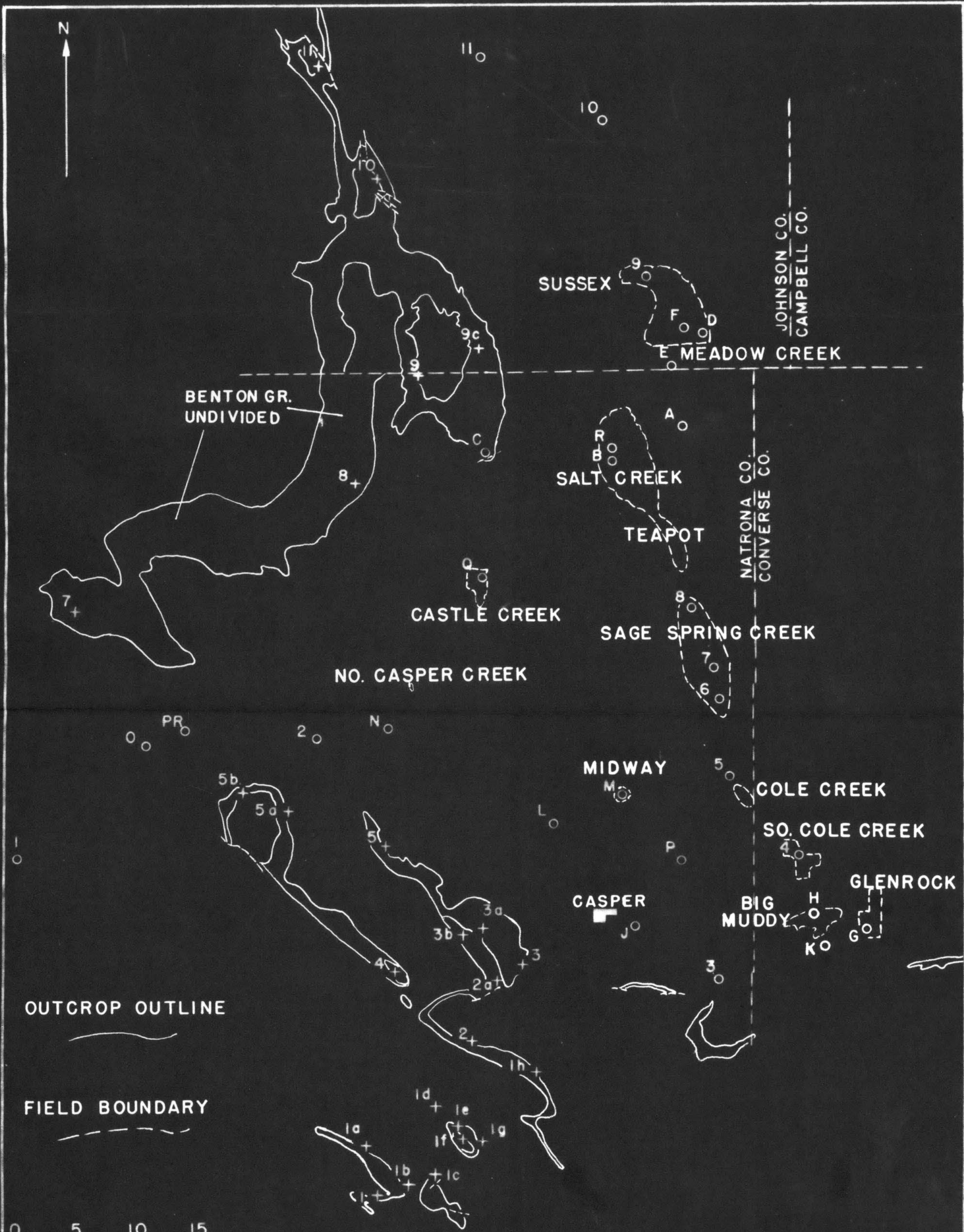
Figure 3. Frontier formation outcrop
and Oil fields penetrating the Frontier

Sources

Base: U. S. G. S. Geologic Base Map of Wyoming

Outcrops: Johnson County and northern Natrona County after Love and Weitz (1945); southern Natrona County after Love (1935)

Oil Fields: Salt Creek, Teapot, North Casper Creek, Midway, and Cole Creek after Pierce and Girard (1945). Other field producing areas are compiled from well data.



FRONTIER FORMATION OUTCROP
AND
OIL FIELDS PENETRATING THE FRONTIER

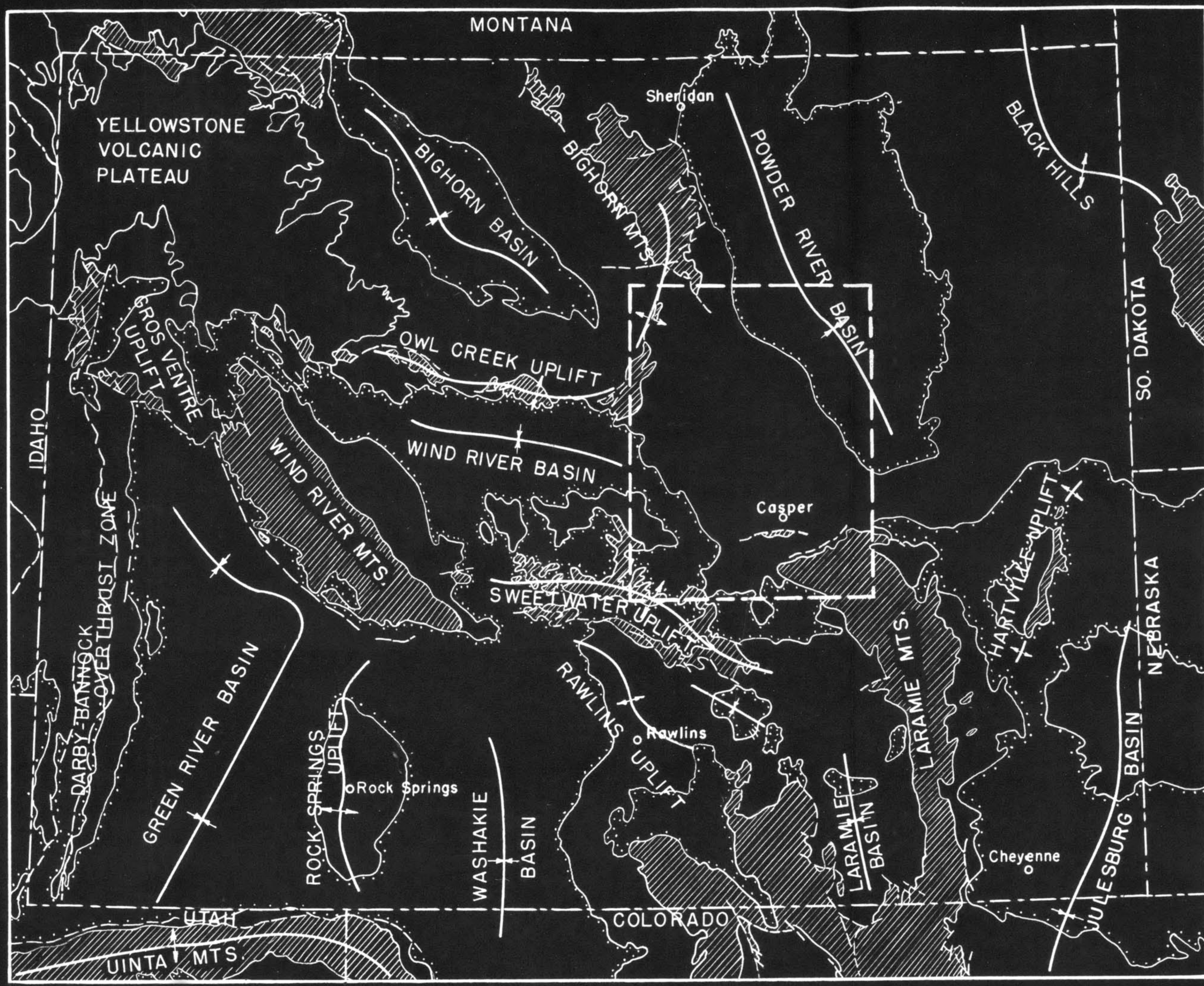
D. TOWSE

Figure 3

Outcrops.- The outcrops of the Frontier formation are shown in Figure 3. Cretaceous and older rocks are exposed on the flank of the Bighorn Mountains, in the structures on the southwest border, and along the north side of Casper Mountain and its eastward extensions. Exposures are good in the vicinity of Arminto in the southwest and along the Bighorn flank north to the north end of the Tisdale anticline, but faults, together with valley cover along the branches of the Powder River, make accurate stratigraphic work difficult in the Kaycee-Mayoworth area. North of the Horn fault the Upper Cretaceous rocks are partly covered by terraces of sand and gravel which lie on the flank of the Bighorn Mountains.

Mowry shale and younger rocks crop out on the structures in the south and southwest. Except where locally cut out by occasional faulting, outcrops are good and essentially continuous. Adequate measurement is difficult north of Casper Mountain because the outcrop is poor, is partly covered by alluvium, and is much complicated structurally.

The sandstone beds form prominent hogbacks, whereas the bottoms of the valleys are based on shale and are filled with alluvium. Bentonites are often exposed because of their swelling on slopes which are otherwise covered or partly covered. The Mowry shale outcrop forms rounded ridges, often tree covered, and the hard bed at its top and the overlying bentonite bed are generally exposed, except in valleys with considerable fill. Occasional gullies cut across the strike of the formations and provide the best exposures of the Frontier shales. Except in a few places, the upper sandstone ridge of the Frontier formation forms the youngest satisfactory outcrop; the shales above generally form flat country with a few rounded hills and considerable soil cover.



WYOMING

INDEX MAP, WITH OUTLINE OF AREA COVERED BY LARGE SCALE MAPS

Adapted from "Tectonic Map of the U.S." (A.A.P.G. 1944)

Tertiary outcrop   Pre-Cambrian   Fault

— D. TOWSE —

Methods of study.- Fifteen full sections and several partial sections of the Frontier formation were measured, sampled in the field, and later studied in the laboratory. Most of the sections were measured by Brunton leveling and pacing in places of moderate dip and topography, keeping to places of simple structure, with no faulting and only slight changes of strike. The accuracy of the method appears to be well within the limits of error of this report, the scale of the cross-sections, and the scale and contour interval of the maps. The total intervals measured agree well with data of other workers and with nearby wells. In places of steep dip and rough topography, sections were measured by plane-table triangulation, with dips by Brunton or plane-table three-point method where necessary. All values were corrected for variations in dip and strike.

Sections were sampled as completely as possible. The ridge-forming sandstone beds of the formation are well exposed, but the shaley parts of the section are generally poorly exposed and difficult to sample. Three types of samples were collected. In very thin beds and in covered portions of the section spot samples were taken (a full sample bag from one spot), while chip samples were collected through thick sections with chunks every one, five, or ten feet, depending on the homogeneity of the outcrop. Channel samples, of shale especially, were taken in small or selected outcrops, or in places where there was a thin, intimate interbedding of different lithologies.

Samples were examined for lithology, grain size, rounding, mineralogy, and cementation, with lithology reported by macroscopic examination in order to obtain a description comparable to field description.

Grain size was measured on the longest dimension of the grain visible, by comparison with a millimeter scale divided into fourths, or with a net reticule with divisions corresponding to values of 1 mm., .34 mm., and .174 mm. on the stage, according to the power of the objective used. The largest and smallest grains on the stage and a representative of the most common size present were measured.

Rounding is reported as angular, subangular, subround or round, according to usual definitions of these characters. Grains are also described as "frosted" if they have a matte or very fine faceted surface. While some of the frosting is undoubtedly original, some may be due to finely crystalline cementing material adhering to the surface of the grains. Crystal forms or faces on the grain surface are reported as "facets" or "crystal faces".

Mineralogy was determined by examination under the binocular microscope, with occasional checks in immersion oils and a petrographic microscope. Hard white grains and hard clear grains are reported as quartz, although some of the grains identified as frosted quartz may be white chert or quartzite. Black hard grains and gray, dark brown, or grayish yellow grains are reported as gray or black chert. Feldspar content was estimated by count of grains showing kaolinization or feldspathic cleavage. Pink quartz is present as clear glassy or frosted varieties. All samples were tested with dilute hydrochloric acid, and calcite is reported as "abundant" with violent effervescence or "present" with good effervescence, while "small" and "trace" amounts are similarly estimated by effervescence. All samples were tested with a small, low powered hand magnet which was drawn below the base of the 1/32-inch copper tray used to hold samples during examination. Coal is typically present as grains and shreds of bright, black, splintery material lacking rust spots. In the sand and silt fractions, fine-grained rock fragments were indistinguishable, and are reported with the gray and black chert.

The rocks were gently disaggregated. Those easily broken between the fingers are reported as "medium cemented", those which broke down with no pressure are reported as "poorly cemented", those difficultly broken by hand are reported as "well cemented", and those which required splitting by mortar and pestle are described as "very well cemented". Some of the sandstones required treatment with dilute hydrochoric acid.

Amounts of minerals present were estimated by eye, and are reported by per cent, or as "much" or "abundant" (greater than 20 per cent), "present" (10 to 20 per cent), "small" (5 to 10 per cent), and "trace" (less than 5 per cent, with less than five grains observed in the sample).

Most of the outcrops studied were relatively unfossiliferous, and no attempt was made to make complete faunal collections. The paleontology as reported here is intended only as an aid in the interpretation of the sedimentation.

Thin sections were made of a representative sample of the different shales, sandstones, and conglomerate pebbles, but, owing to the nature and number of the samples, a complete petrographic study was impossible to complete in the time available.

Sample data were plotted graphically on stratigraphic cross-sections as an aid in the determination of correlation criteria. Surface correlations determined in the laboratory were later checked in the field, and rotary cuttings from eleven wells and all available electric logs of wells penetrating the Frontier formation were studied.

Several bentonites were disaggregated and their texture and mineralogy were studied. Samples of shale and bentonite from Section 2 at Coal Creek were tested for gamma ray activity in a Geiger Counter.

Mechanical analysis.- Measurement of the texture and sorting of representative samples of all the sandstone bodies studied on the surface was necessary in order to determine the source of the sediments and the details of their transportation. The large number of samples made necessary the development of a rapid method of measurement. A system based on the counting of 200 loose grains of a carefully quartered sample, using a binocular microscope with a calibrated net reticule in the ocular, was adopted.

One sandstone sample was tested using six different methods, with the following results:

Method	Median diameter (mm.)	Coefficient of Sorting
1. Sieving, fractions weighed, not corrected for sandstone fragments.	.173	1.35
2. Method 1, corrected for sandstone.	.170	1.35
3. Sieved, volume of fraction measured, uncorrected for sandstone fragments.	.17	1.3
4. Method 3, corrected for sandstone fragments.	.17	1.3
5. Thin section: grains measured on longest dimension.	.14	1.5
6. Loose grains measured on intermediate dimension.	.14	1.4

Two more samples were analyzed, using methods 2, 5, and 6, with the following results:

Sample:	a.	b.	c.
Method 2, median diam. (mm.)	.17	.16	.25
Method 5, " "	.14	.13	.18
Method 6, " "	.14	.11	.15

When calculated to two significant figures, the coefficients of sorting vary by one in the first decimal place, excluding the thin-section method, which may vary because of sampling. Of the three samples listed, the relative size of their median diameters remains unchanged in the three methods.

Relative values were desired, in order to find the areas of maxima and minima of the median diameters and sorting coefficients. Method 6 was chosen as the quickest satisfactory method.

The samples were disaggregated and spread on the microscope tray, and two hundred grains were measured, using a net reticule and the following class intervals (in millimeters): 0 - .09, .09 - .13, .13 - .175, .175 - .35, and .35 - .70. The ratios of these values are approximately as follows: 0 to 1, 1 to the square root of 2, square root of 2 to 2, 2 to 4, and 4 to 8. A cumulative curve was drawn on arithmetic probability paper and the median, 25 percentile, and 75 percentile values found graphically. Sorting is given by the sorting coefficient, i.e., the square root of the ratio of the 75- and 25-percentiles. The median and sorting values obtained by sieving methods are closely comparable to values obtained by other methods, and the relative size of the values obtained by any method are the same. Low sorting coefficients show better sorting, with 1.00 being perfect.

Measurements were made of sandstones, but not the shale streaks or pebbles of shaley or conglomeratic beds. Chip or channel samples were combined to obtain a composite sample of each important unit.

The data obtained were plotted on graphic charts (Figures 8, 10, and 12), with a line drawn connecting the maximum and minimum values of median diameter and sorting from each locality.

Five maps were prepared: The thickness of the Frontier formation (Figure 4); total sandstone thickness in the Frontier formation (Figure 5); and (Figures 7, 9, and 11) total sandstone thickness in each of the First, Second, and Third Wall Creek members.

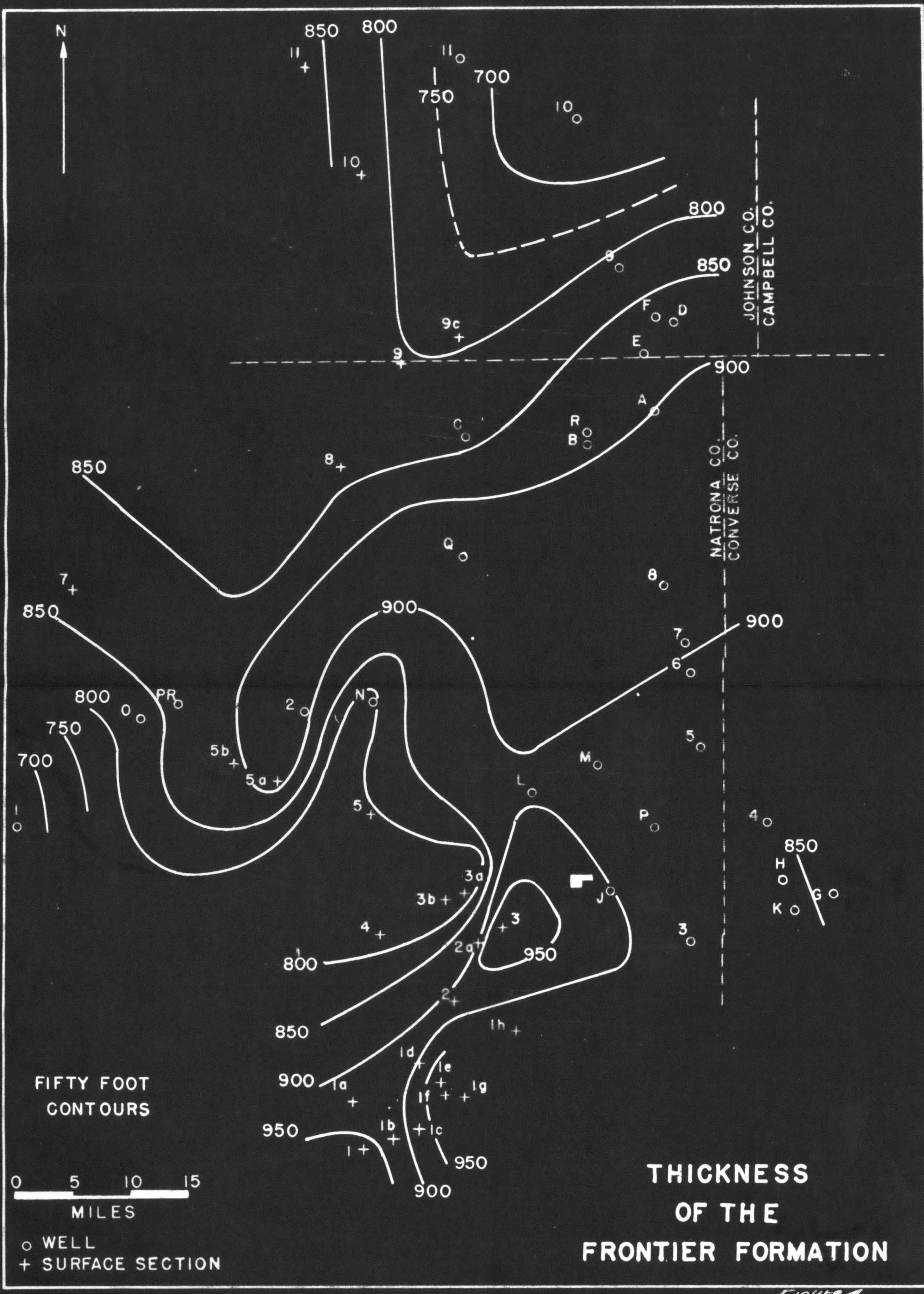
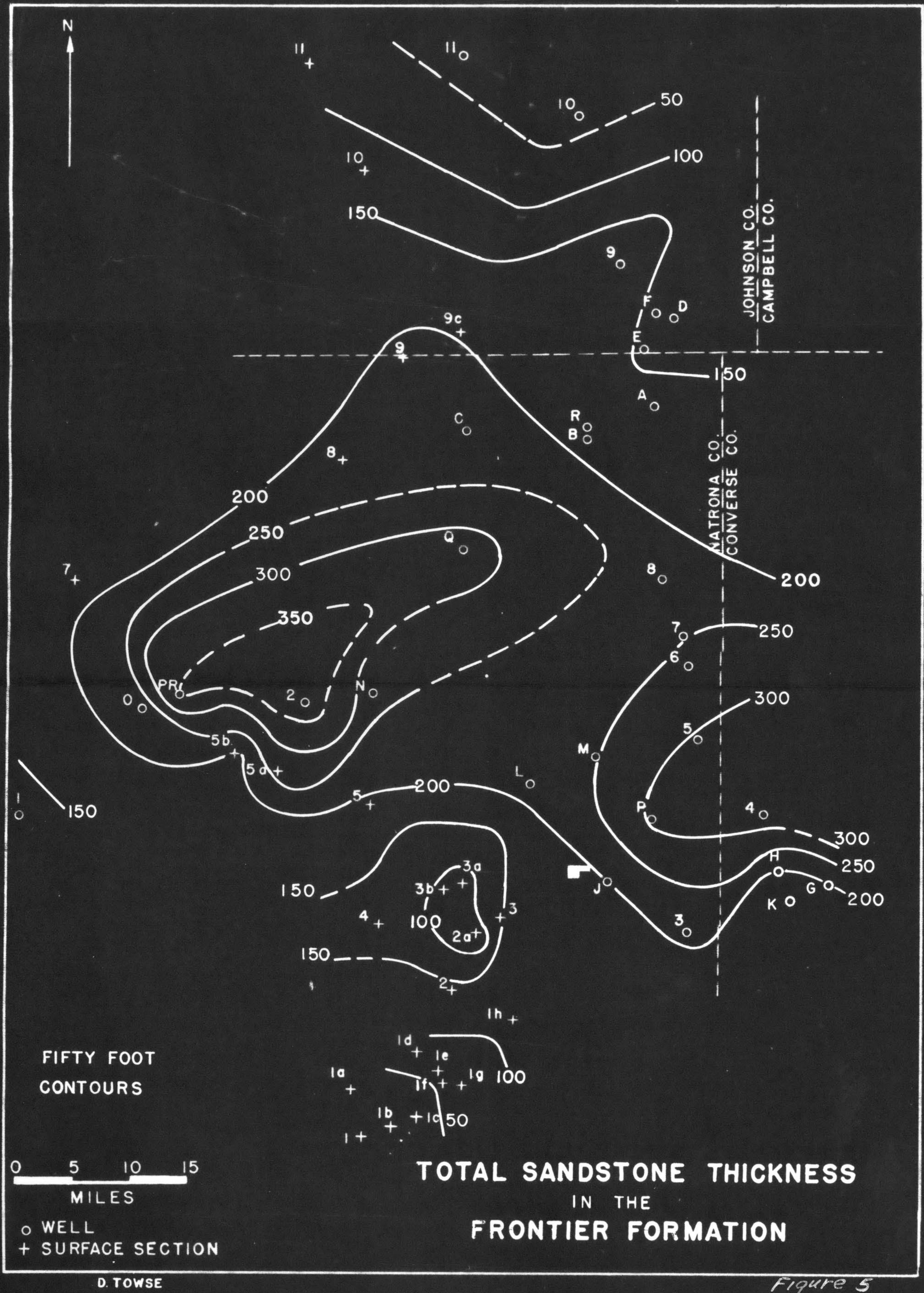

N
JOHNSON CO.
CAMPBELL CO.
NATRONA CO.
CONVERSE CO.
700
750
800
850
900
950
FIFTY FOOT
CONTOURS
0 5 10 15
MILES
○ WELL
+ SURFACE SECTION
THICKNESS
OF THE
FRONTIER FORMATION
D. TOWSE

Figure 4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+ SURFACE SECTION
JOHNSON CO.
CAMPBELL CO.
NATRONA CO.
CONVERSE CO.
50
100
150
200
250
300
350
TOTAL SANDSTONE THICKNESS
IN THE
FRONTIER FORMATION
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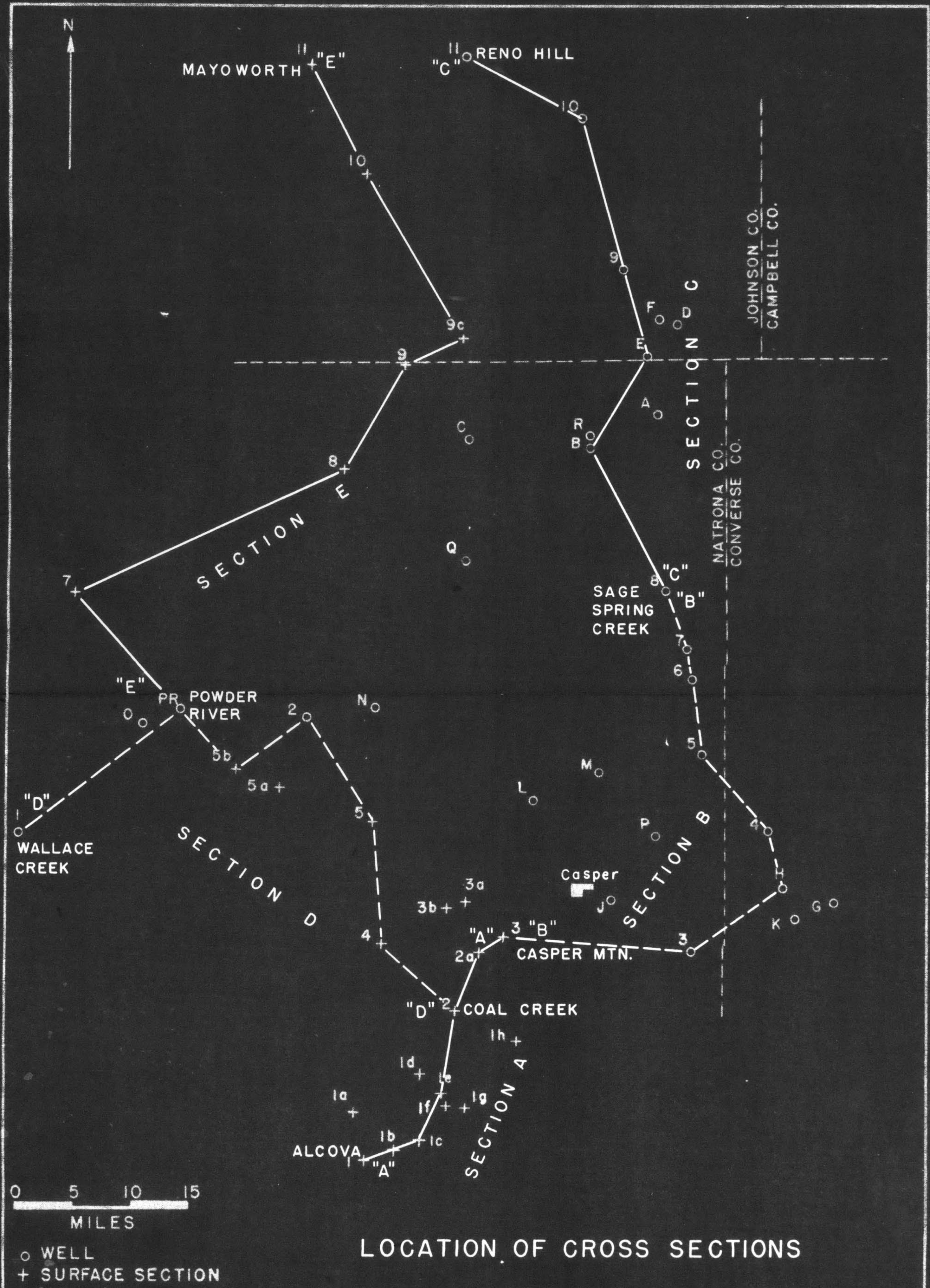
Figure 5



LOCATION OF CROSS SECTIONS

Figure 6

THE FRONTIER FORMATION

Introduction.- Table 2 (Appendix) lists the location of the stratigraphic sections used in this report. Names and locations of sections and wells are not listed in the report or on the maps, but they are referred to by number or letter. Data for the maps are compiled from measured sections and lithologic and electric well logs. Figure 6 shows the location of the stratigraphic sections and the locations of cross-sections A through E which are plotted in Plates 1 through 5. The lithologic well logs are interpretations of rotary cuttings made with the aid of electric logs, and the electric logs were interpreted with the aid of lithologic logs of nearby wells, with care taken to make the data from various sources comparable. Table 3 (Appendix) lists the data used in constructing the maps. The total sandstone reported for the formation is not in every case the sum of the totals for the members, because the total formation value and the three members were figured separately, in order to make each group of data consistent among themselves. Variations in interpretation account for the apparent inconsistencies. Those variations, however, are not critical in the interpretation of the maps, for it is the relative values that are considered significant.

General features.- The Frontier formation is a series of sandstones, shales, sandy shales, and several important bentonite beds, with minor amounts of limestone and limestone concretions.

The thickness of the formation in the area varies from 983 feet at the end of Casper Mountain (section 3) to 610 feet in the north at

Smith's Cut (Well 10) and 660 feet at Wallace Creek in the southeast Wind River Basin (Well 1). Total sandstone content is likewise variable, from a minimum of about 30 feet in the extreme south and north, to a maximum of 250 to 390 feet in the Powder River-Natrona area (Wells PR and 2).

Sandstones.- The sandstones of the Frontier formation are quartzose or cherty and have only minor amounts of other minerals. Black, gray, and white chert are present in all the sandstones, with some of the cherts partly recrystallized. Clear crystalline quartz and pink quartz are important in the First Wall Creek member, and there are large amounts of clear quartz in the Second Wall Creek member, but there are only traces of pink or clear quartz present in the Third Wall Creek member, where feldspars and feldspar weathering products are more common. Biotite and some muscovite are present throughout the formation, and they are often associated with scattered small amounts of glauconite. The sand grains range from angular to rounded, and the rounded and sub-rounded grains are frosted. Non-frosted and angular grains are often present with well-rounded and frosted grains in the same rock. Magnetite and eroded coal fragments are locally present. Clay material is the most common cementing material, with calcite next in importance, and, less often, the cement is siliceous, with grain and cement that have optical continuity in thin-section. Cementation and porosity vary between extremes, but moderately well clay-cemented medium porous sandstone is the most typical type. In texture, the sandstones vary from fine and shaley to coarse and conglomeratic. Medium grain is most common.

Thin conglomerates are widely distributed, with the pebbles well-rounded, and they contain pebbles of variously colored chert, rarely fossiliferous, white to gray quartzite, and occasional quartz and feldspar pebbles. Igneous rock pebbles are locally abundant in the north. Bedding in both sandstones and conglomerates is thin to massive, with cross-bedding and rippling common. The sandstones are locally very fossiliferous, but in general are barren, except for trails and fish teeth. Pelecypods of the genus Inoceramus are the most common of the invertebrate fossils, but ammonites are locally present.

The sandstones and conglomerates seem to be water-laid in a salt-water environment, but the conglomerate at Mayoworth may be a river deposit. Dark chert gives to the sandstones a "salt and pepper" color, or they are variously brown, tan, or reddish, because of the oxidation of iron-bearing minerals.

Shales.- The shales of the Frontier formation are generally soft, gray, and sandy, and those in the Lower shale member are soft, dark-gray to black, and bentonitic. The sandy shales of the upper parts of the formation are thin bedded and slightly better cemented than those of the Lower shale member. Some of the shales in the lower, less sandy part of the First Wall Creek member are slightly calcareous, and, in certain parts of the formation, the shales are bentonitic. The thin beds in some of the sandstone bodies are dark black, coaley, soft shale. No microfossils were found in the outcrop samples. Biotite, muscovite, and fine quartz or chert are the most common minerals in the silt and sand fraction of the shales, constituting a mineralogy related to the associated sandstones. Many of the shale sections have irregular thin beds of shaley sandstone as much as one inch thick.

Bentonite.- Several conspicuous beds of bentonite are present, including a thick, fairly pure bentonite with minor amounts of silt and gypsum that lies on top of the Mowry shale, and a shaley, dark colored, usually sandy bentonite that forms the top boundary of the Lower shale member of this report, and contains sandy siltstone concretions. A less conspicuous bed, often shaley and with gypsum crystals, forms the top boundary of the Third Wall Creek member and is often covered or obscured by shale material on the surface, but is more readily identified in subsurface samples and on the electric logs. A persistent and conspicuous bentonite forms the top boundary of the Second Wall Creek member. It is pure and has numerous chunks of fibrous and blocky crystalline milky calcite, is easily identified in most surface sections, and is a persistent feature on electric logs. Other thin bentonites occur near the top of the Second Wall Creek member, with shale and sandstone obscuring them in some places. The Lower shale member is the most bentonitic part of the formation.

Limestone.- Limestone is rare in the Frontier formation, but in many places a number of gray shaley limestones which form rounded concretions and contain septarian veins of calcite are present in the lower part of the First Wall Creek member. Tan clayey limestones with well-developed cone-in-cone structures are found in thin beds in the lower Wall Creek member and, rarely, elsewhere.

Formation boundaries.- The top of the Frontier formation in this report is placed at the top of the highest sandstone body. In the subsurface, a bentonite bed is present in the lower part of the Carlile shale 20 to 60 feet above the top of the first sandstone, and is persistent over a large area, indicating that the end of Frontier sand deposition occurred at nearly the same time in the entire area. No great changes in thickness, that would put the top of the Frontier formation at the general horizon occupied by the base of the Niobrara formation in other places, such as have been described by Thompson, et al (1949), were found. The electric log "chalk kick" described by Thompson in the Wind River Basin is placed at the base of the Niobrara formation in this report. On the surface the base of the Niobrara formation is placed at the base of a cream-weathering speckled calcareous shale, which has several oyster limestone beds near the base, and in the well samples it is placed at the base of a dark calcareous shale containing cream to white calcite specks. Sandy beds were found higher in the Niobrara formation at North Cole Creek (Well 5). The Frontier formation thickness measured near Arminto is close to that found in the well at Powder River (Section 7 and Well PR of Plate 5), although Thompson describes a great change in thickness between essentially the same locations.

The Carlile shale is gray, soft, slightly sandy, slightly bentonitic, and is slightly calcareous, with scattered limestone concretions similar to those in the lower part of the First Wall Creek member of the Frontier formation.

The top of the Mowry shale of this report is the horizon described by Wegemann (1911, 1912, 1918), who said that (at Tisdale Anticline) 250 feet of very dark shale, with numerous medial thin beds of ferruginous limey shale 1 to 2 inches thick, which weather to a deep reddish brown, lie above the bentonite at the top of the Mowry shale. The shale described above is, in it's lower part, the Lower shale member of this report. The Mowry shale is hard, fine, dark gray, laminated, siliceous shale, that weathers to silvery gray chips. The top part is slightly sandy, and the top surface of the formation is covered with a very thin coating of medium to coarse sand grains. The lowest bed of the Frontier formation is a thick, apple-green to white, pure bentonite, and the shale immediately above the bentonite is soft and black, with the concretions described by Wegemann. The top of the Mowry shale is difficult to determine in well samples because the typical Mowry fish scales usually begin 20 feet or more below the top of the formation, and the characteristic gray color of the Mowry shale outcrop is only developed by weathering. The Lower shale member of the Frontier formation, however, has a characteristic low resistivity on the electric logs, while the well cemented Mowry shale has a high resistivity, and the basal bentonite of the Frontier formation is conspicuous in the electric log and may be found in samples, although it is difficult to distinguish in samples from other bentonites both above and below it. Thompson, et al (1949) place the top of the Mowry shale much higher into the Frontier formation as defined in this paper. (See Well PR, Section D, Plate 4.)

Generalized section.- A generalized section of the Frontier formation in the southwest Powder River Basin is as follows:

	THICKNESS
First Wall Creek member	
Sandstone and sandy shale, with sandstone thickness totalling 10 to 230 feet. There are important amounts of pink and crystalline quartz in the sandstones. The Wall Creek sandstone member is a thick sandstone body in the upper part of the member.	100 to 370 feet
The lower shaley part is slightly calcareous and contains limestone concretions.	
Bentonite with crystalline calcite is the lower boundary of the member.	
Second Wall Creek member	
Sandstone and sandy shale, with sandstone thickness totalling 0 to 115 feet. The sandstones have less pink quartz and more clear quartz than the sandstones in the First Wall	50 to 210 feet

Creek member. The lower boundary of the member is a series of bentonitic shales and bentonite with gypsum.

Third Wall Creek member

Shaley sandstones and sandy shales, with sandstone thickness totalling 0 to 130 feet. The sandstones have very little pink and clear quartz, contain more feldspar and clay, and are generally shaley. — 200 to 340 feet

Lower shale member

Dark, soft, bentonitic shales with numerous dark brown calcareous siltstone concretions. A shaley bentonite with siltstone concretions forms the top boundary, and a thick pure bentonite overlying the Mowry shale forms the lower boundary. — 50 to 220 feet

Total thickness: 620 to 983 feet

Thickness and sandstone content.- Thickness and sandstone content of the Frontier formation are shown in Figures 4 and 5. The thickness of the formation is from 850 to 900 feet over most of the region, and the formation thins to less than 700 feet in the north and the southwest and becomes thicker in the south. The most abrupt change in thickness is southwest of Casper, where the thickness varies more than 150 feet in four and a half miles.

The total sandstone content ranges from 150 to 250 feet in most of the area. The greatest sandstone concentration is in the Powder River - Natrona area, where, although the shape and direction of the contour lines of the thickness map and the sandstone map are similar and the thickness is near normal, the sandstone content is 350 feet and more. Lack of subsurface control in the area between Sage Spring Creek and Castle Creek fields makes exact delimitation of the sandstone area impossible. Whereas the thickness change and the absolute change in sandstone content is similar in the north and the southwest, the well in the southwest (Well 1, Wallace Creek, Wind River Basin) has 100 feet more total sandstone thickness than the wells in the north. Another thick sandstone area in a region of normal thickness occurs in the east, and an area of low sandstone content lies in the region of most rapid thickness change southwest of Casper. In the south decrease in sandstone content is associated with thickening of the section.

The changes in sandstone content may be classified as follows:
1. Increase of sandstone with little change in section thickness.
2. Decrease of sandstone with decrease in section thickness. 3. Decrease of sandstone with increase in section thickness.

Lower shale member

Detailed description.- Following is a measured section of the Lower shale member at Section 2, Coal Creek valley southwest of Casper, Section 36, Township 32 North, Range 81 West. Beds are listed in descending order.

Measured Section Lower shale member, Section 2

Bed	Description	Thickness
1.	Gray bentonitic shale, with concretions in the middle.	10 feet
2.	Persistent hard pink sandstone concretions which are rust red in color and seem to be a sandstone zone with cracks and weathering and rounding along the joints.	8 inches
3.	White bentonite.	6 inches
4.	Gray bentonitic shale.	8 feet, 10 inches
5.	Shale, soft, brownish black, with a few scattered, large, brown, hard siltstone concretions.	20 feet
6.	Limestone, hard, yellow, with cone-in-cone structure.	3 inches
7.	Shale, thin-bedded, dark gray, with concretion zone at the top	5 feet, 9 inches
8.	Shale, with very few concretions.	5 feet.
9.	Shale, with concretion zones at top and middle and with yellow limestone above the middle zone. The shale in the bottom half is sandy and light gray. The top half of	10 feet

the bed is black, flaky, and there is an eighteen inch yellowish bentonite two and a half feet from the top.

10.	Shale, thin-bedded, soft, dark gray, with persistent zones of concretions at 3 foot intervals. (Note: The concretions in this part of the section are hard, reddish brown, discoidal, 8 to 15 inches by 1 to 10 feet. They appear to be siltstone weathered by iron rusting.)	10 feet
11.	Shale as above, with concretions. Four inch yellow limestone with cone-in-cone structure lies above the concretions in the middle.	5 feet
12.	Shale as above, with concretions at top and middle.	10 feet
13.	Alternating gray shale, concretions, and yellow limestone. Beds are badly slumped.	2 feet
14.	Gray shale.	2 feet
15.	Yellow bentonite which weathers gray-white. Swelling makes accurate thickness measurement difficult.	8 feet
	Total	90 feet

Mowry shale

16.	Hard gray siltstone with a flat, persistent sandy top surface.	6 inches

17.	Hard gray shale.	6 inches
18.	Hard, flaky, gray shale with fine fish scale fragments.	5 feet.
19.	Similar shale with larger fish scales. (Shale below is similar, but the base was not measured.)	10 feet

Basal Bentonite.- The bentonite samples were carefully processed, dried, and analyzed in order to determine the amount of detrital sand-size material and the amount of non-detrital sand-size material in the sample. The maximum sizes of both detrital and non-detrital material of sand-size were measured, and in the sand fraction all obviously eroded and rounded grains were classed as detrital, whereas sharp, fresh, and shard-like material was called non-detrital. The non-detrital material should represent phenocrysts and fragments of the original volcanic material from which the bentonite was derived. (Rubey, 1929.) The sand was separated by washing the bentonite through a No. 200 sieve (.074 mm. opening).

Analyses of the basal bentonite of the Frontier formation, Bed 15 above, from 5 different localities are as follows:

Sections:	2	5	6	7	9
Per cent of detrital sand in the sample.	12.5	0.7	0	0	0.1
Non-detrital sand, per cent of non-detrital fraction.	1.6	2.3	1.3	2.7	2.3

Maximum size of non-detrital material. (millimeters)	0.50	0.35	0.60	0.45	0.40

Bed 15 was sampled with 1 foot channel samples. The samples were numbered from 1 to 12, beginning 4 feet above the top of the bentonite. Sample 5 is the top 1 foot of Bed 15. The following table gives the results of the analyses of the samples from Bed 15.

Sample Number	Per cent Sand	Per cent Shale	Per cent sand, non-detrital fraction	Max. size, non-detrital fraction	Max. size, detrital fraction
1	0.2	20	0.8	0.5 mm.	0.5 mm.
3	0	53	1.1	0.25	clay
5	0	0	0.1	0.4	clay
7	0	0	0.7	0.5	clay
9	0.2	0	1.5	0.35	0.15
11	0	0.2	2.3	0.35	clay
12	3	10	4.6	0.35	0.55

The per cent of sand material in the non-detrital fraction increases toward the bottom of the bentonite, and the intermixture of foreign sediments is clearly shown by the percentages of sand and shale. The larger particles evidently settled to the bottom before the finer particles did, and the fine particles were altered to bentonite.

The bentonite is white, with a few scattered specks and fine streaks of slightly rusted biotite, and the base of the stratum contains round frosted sand grains with diameters from .3 to .4 mm. There is no magnetite, and the unweathered bentonite is hard and has a conchoidal fracture.

A thin, hard, gray sandstone with grains as much as 0.3 mm. in diameter is present in the basal bentonite at Section 9. The thin section of that rock contains quartz, orthoclase, microcline, and a small amount of plagioclase feldspar ($Ab_{50}An_{50}$). There is a large amount of matrix material in the form of angular and shard-like fragments of a gray material that appears to be devitrified glass.

Top of the Mowry shale.- The top 6 inches of the Mowry shale at Section 2 is siltstone, gray in color, with rounded light colored inclusions. The top surface is one layer of sand grains .5-.9 mm. in diameter, including angular gray and white quartz, fresh biotite, and plagioclase feldspar. The siltstone is hard, well cemented, and massive, and the grains include quartz, muscovite, with grain diameters up to .1 mm.

A thin section (No. 193) of the siltstone contained quartz, orthoclase, biotite, microcline, and a small amount of acid plagioclase, with much fine micaceous material and some Radiolaria. Particles are angular shard-like fragments, opaque organic shreds, and some angular grains with indistinct aggregate extinction which are probably altered ash. The bed described above makes a prominent flat outcrop everywhere exposed, and was found at Sections 1, 2, 5, 5a, 5b, 7, 8, and 9.

Upper Bentonite.- The upper bentonite of the Lower shale member, Bed 1 of the detailed description, is one of the most persistent beds of the Frontier formation in this area. Samples from several sections were analyzed as described above, with the following result:

Sections:	2	5	6	7	8	9
Per cent of detrital sand in the sample.	0.6	0.4	0.2	30.5	2.9	0
Non-detrital sand, per cent of non-detrital fraction.	5.1	14.5	0.8	9.7	4.5	0.7
Maximum size of non-detrital material.	0.45	0.50	0.30	0.30	0.40	0.35 mm.

There is a maximum of both size and amount of non-detrital sand at Section 5, indicating it is closest to the source ofash.

The bentonite is white to gray, with a small amount of biotite, much calcite, and no magnetic minerals. Siltstone concretions similar to those in the shale below are in Bed 1 at Section 2. Those concretions are red-black with much black (organic?) material, much calcite, frosted quartz, biotite, pyrite, and no magnetic minerals; and they are hard and well cemented. Thin section No. 164 is mostly irregular opaque material with much iron oxide, calcite veining, subangular quartz, and partly devitrified glass.

A small amount of sandstone is present in the bentonite bed within the Lower shale member at Section 9. The sandstone has grains as much as .3 mm. in diameter, and these include light and dark chert, frosted quartz, and biotite, and the rock is well cemented. The thin-section (No. 909) shows quartz, orthoclase, microcline, glauconite, and a trace of gray material with aggregate extinction that is probably devitrified glass, all in angular fragments and shards. There is some silica cement, some iron oxide, and a patchwork of calcite cement.

Subsurface characteristics.- A characteristic sample description of the Lower shale member from South Cole Creek (Well No. 4) follows:

Depth	Description
7785 feet	Bentonite, gray very sandy.
7785-7865:	Shale, black, flaky.
90-7800:	Bentonitic streaks.
-10:	Biotite.
50-60:	Bentonite, gray, spongy, sandy.
-65:	Bentonite, white, waxy.
7865 feet	Top of Mowry shale. (7862 by electric log)

The top of the member is generally easy to pick, and is placed at the point where the gray sandy shale above is replaced first by bentonite and then by fine black shale. Both the top and basal bentonites are represented by "notches" of low resistance on the electric log. The black shale has a low resistance, whereas the sandy shale above and Mowry shale below have characteristically high resistances.

Summary.- That the Mowry shale immediately below the Frontier formation is marine is shown by the included abundant fish remains and Radiolaria. At the Frontier-Mowry boundary is a sharp break in the degree of cementation of the shales that needs explanation. Rubey (1929) ascribed the cementation of the Mowry shale to silica deposition controlled by microorganisms in the sea water. He further explained the abrupt cessation of silica cement deposition by the wholesale annihilation of the responsible organisms due to the heavy ash-falls which occurred during the time the upper part of the Mowry shale was being deposited. Whatever the ultimate cause of the abrupt change in silica content, the top of the Mowry shale over a wide area is marked by the cessation of the deposition of cementing silica. An abrupt change in the chemical properties of sea water is an event which, subject to some variations due to current action and other factors, would occur at nearly the same time in all parts of a connected body of water. For this reason the top of the Mowry shale is defined as the top of the siliceous shale, and it is a horizon which is as near the same age over a wide region as any geologic horizon may be. The top of the Mowry shale as thus defined is not a lithologic boundary, but a chemical boundary, for the mineralogy of the shale above and below the boundary is closely similar.

Of the Mowry shale in the Black Hills region, Rubey (1929, p. 154) wrote as follows: "The Mowry underlies, with sharp lithologic change, the Belle Fourche shale member of the Graneros, a partial equivalent of the Frontier formation of western Wyoming. The Belle Fourche member consists of 450 to 850 feet of soft dark shale that in its upper part contains bentonite beds and many calcareous concretions. The lower 25 to 200 feet contains abundant concretions of manganiferous siderite about a foot in diameter, and this zone forms a low scarp near the Mowry hogback. The contact between the soft dull-gray concretion-bearing shale of the Belle Fourche and the hard shale of the Mowry is further emphasized by a persistent bed of bentonite from 1 to 4 feet thick at the top of the Mowry shale. This bed was traced 175 miles along its outcrop in northeastern Wyoming, and it can be recognized with reasonable certainty in South Dakota beyond the limits of this mapping."

The above described bentonite bed was called the Clay Spur bentonite bed by Rubey (1930), and the basal bentonite of the Frontier formation corresponds to the Clay Spur bentonite. Bentonites derived from a single ashfall must have been deposited at essentially the same time over their area of distribution. The basal bentonite of the Lower shale member was traced on the surface and in wells over the area of this report, making a formation boundary that can vary but little in age, its variation being negligible considering the accuracy of other geologic time measurements. The other prominent bentonite beds used as boundaries of the divisions of the Frontier formation in this paper likewise vary little in age.

No fossils were found in the Lower shale member, so criteria of other kinds are necessary in defining its environment of deposition. The characteristic fine texture of the shale suggests little wave or current action, and the relatively high calcite content of the rocks suggest marine environment, as is probable because of the member's immediate position over the Mowry shale. Claudet (1950) has suggested that the resistance of shales as shown in electric logs may indicate the salinity of the original interstitial water and thus the salinity of the water in which they were deposited. The Lower shale member exhibits very low resistivity, leading to the conclusion that it was deposited in relatively saline water.

The many concretions which lie in bands in the shale contain volcanic material and are the result of the cementation and action of ground water on originally continuous beds and lenses of relatively coarse volcanic material, whereas the coarse sand surface on the top of the Mowry shale is similarly interpreted as the first coarse part of a large ashfall. The sand grains may have stuck on the surface of the soft Mowry mud or may have been gently spread by current action.

The Lower shale member was deposited in sea water little affected by waves or currents, with a large ashfall at the beginning and at the end of the time during which it was deposited and with other less important ashfalls during that time.

Third Wall Creek member

Detailed description.- The following is a measured section of the Third Wall Creek member at Section 2, Coal Creek valley, measured at the same location as the section of the lower shale member which was given before, and it is the most completely exposed outcrop of the Third Wall Creek member studied.

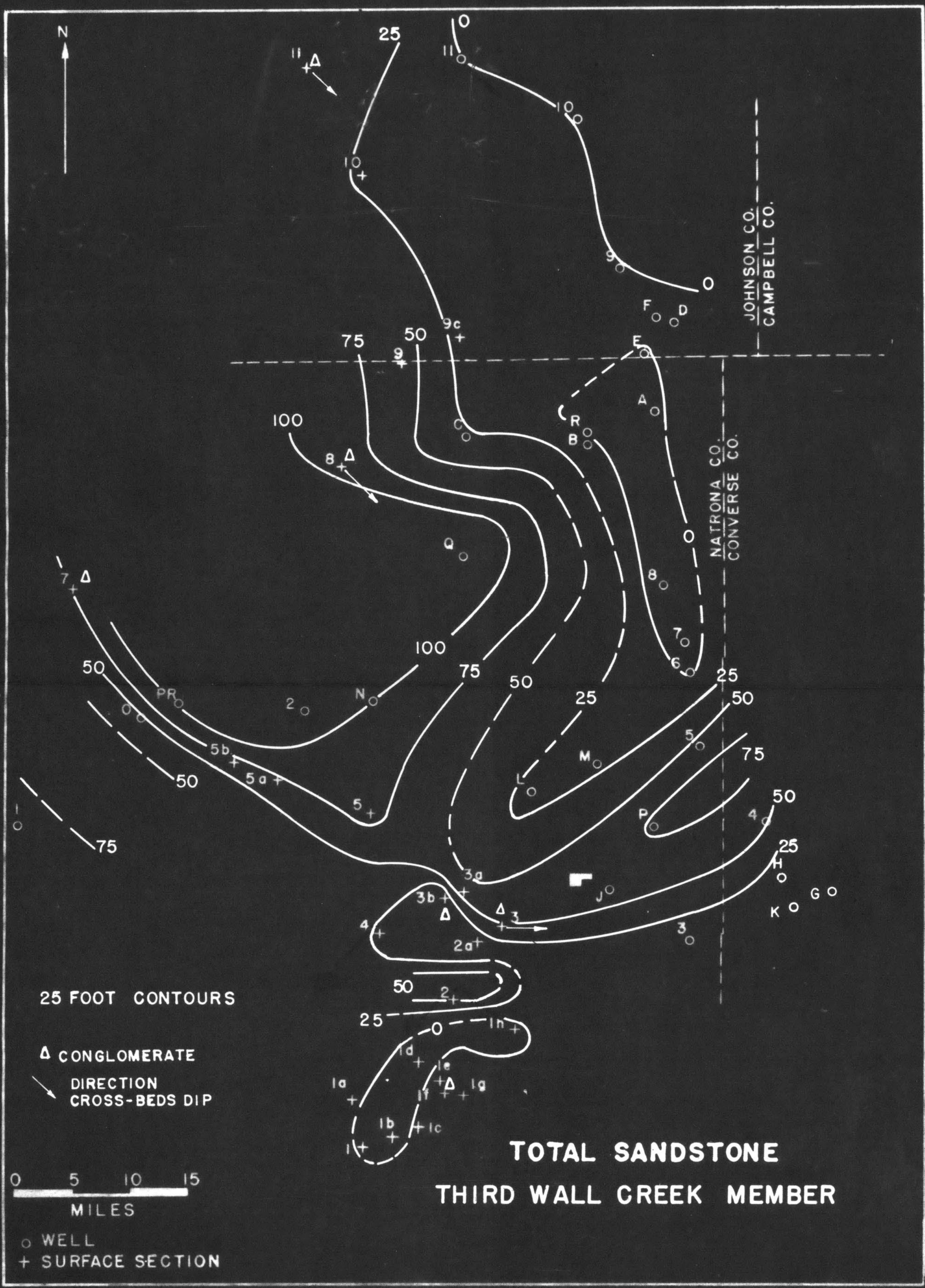
Measured section, Third Wall Creek member, Section 2

Bed	Description	Thickness
1.	Yellow-brown bentonite, with crystalline gypsum. Exact thickness is doubtful due to swelling.	5 feet

2.	Shaley sandstone, thin bedded and more sandy at top.	50 feet
3.	Thin sandstone and shale.	30 feet
4.	Sandy shale, more black shale.	5 feet
5.	Sandy shale, small ridge.	5 feet
6.	Sandy shale.	15 feet
7.	Black flaky shale, slightly sandy.	5 feet
8.	Shale and sandstone.	5 feet
9.	Shale, less sandstone.	15 feet
10.	Shale and sandstone.	5 feet
11.	Black flaky shale and sandy shale.	15 feet
12.	Hard sandstone.	1 foot
13.	Black flaky shale, slightly sandy, with thin sandstone and gypsum. Eighty per cent bentonite.	14 feet
14.	Black flaky shale, slightly sandy, with thin sandstone.	5 feet
15.	Black flaky shale, slightly sandy.	5 feet
16.	Thin shaley sandstone and brown-gray sandstone.	5 feet
17.	Shaley sandstone, with 8-inches hard sandstone at top.	5 feet
18.	Shaley sandstone, with thin shale partings.	10 feet
19.	Shale and sandstone. Ridge.	5 feet

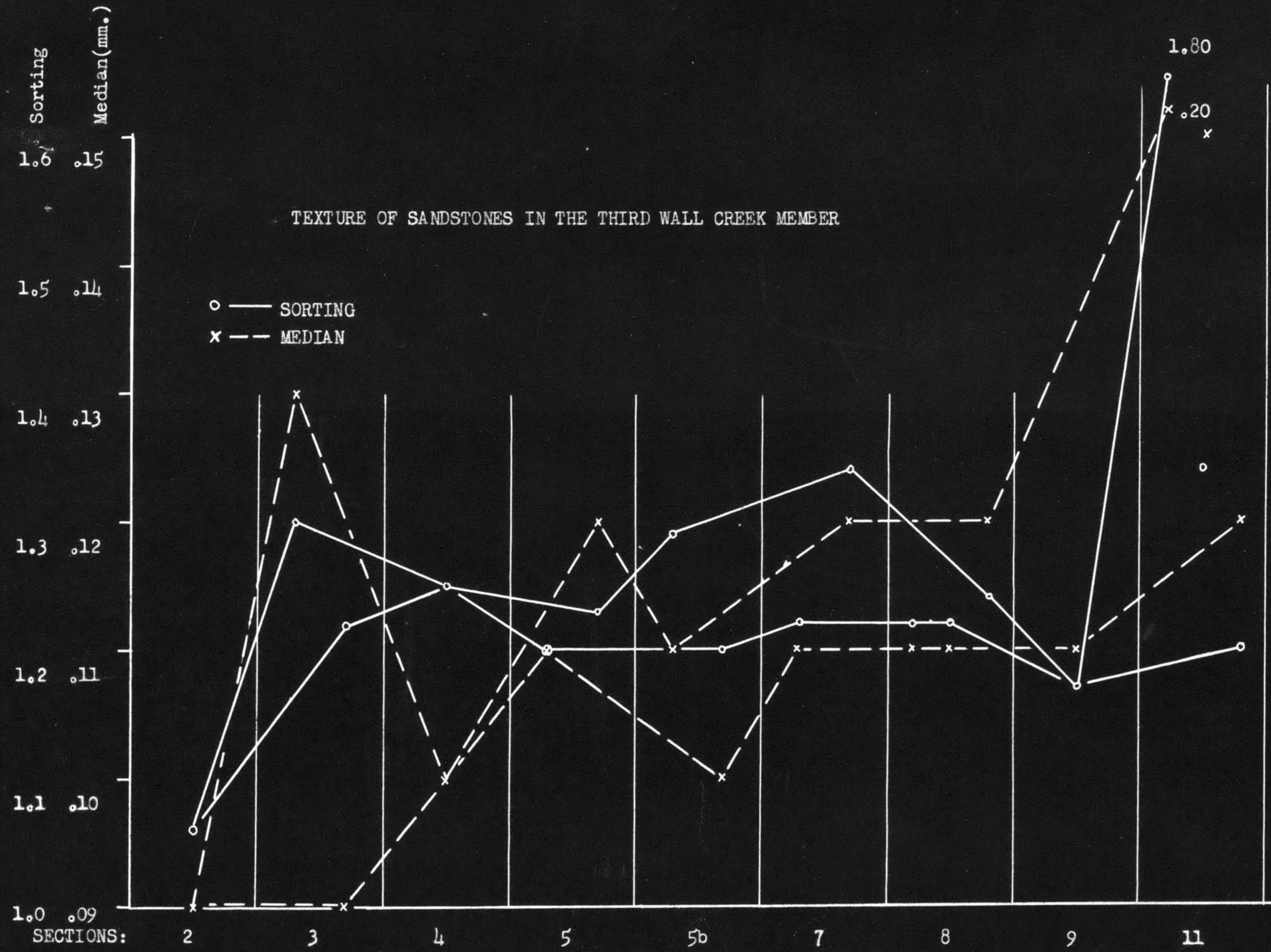
20.	Covered dip slope. Brown sandy clay soil.	25 feet
21.	Shale and thin sandstone, with 4 and 5 inch concretionary sandstones 2 feet from top and base. Ridge.	10 feet
22.	Shale and thin sandstone.	10 feet
23.	Shale and sandy shale.	5 feet
24.	Covered.	15 feet
25.	Shale and thin sandy shale.	35 feet
26.	Ditto. Less sandy.	5 feet
27.	Shale and thin sandy shale.	5 feet
28.	Black shale.	10 feet
29.	Grayish-brown shale.	5 feet
	Total thickness:	332 feet

- Bed 1, Lower shale member -



D. TOWSE

Figure 7


Sorting
Median(mm.)
TEXTURE OF SANDSTONES IN THE THIRD WALL CREEK MEMBER
SORTING
MEDIAN
1.6 .15
1.5 .14
1.4 .13
1.3 .12
1.2 .11
1.1 .10
1.0 .09
1.80
.20
SECTIONS: 2 3 4 5 5b 7 8 9 11
Figure 8

Thickness and sandstone content.- The Third Wall Creek member varies in thickness from 200 to 340 feet and varies in sandstone content from 0 to 130 feet. (See Figure 7.) In general, the thickness varies with the sandstone content, with the most sandstone in the west and with less sandstone northward and toward the center of the basin. There is no sandstone in the Alcova region to the south, and there are local concentrations southwest of Casper and in the east in the Cole Creek Area.

Textures.- The sand grains measured are mostly fine to medium grained, with an average median diameter of .11 to .12 millimeters. Sections 2 and 3, and Section 11 exhibit both maxima of sorting and median diameter and the greatest difference between maxima and minima. (See Figure 8.) The sorting is mostly good, with 1.2 to 1.3 being the normal range. The highest conglomeratic bed in Section 11 shows the poorest sorting, and the sorting is generally better in the finer grained beds. The upper conglomerate in Section 11 has a binodal frequency curve, but all other frequency curves are simple.

Lithology.- The member is a series of sandy shales and sandstones, with a few conglomerates. The sandstones are often shaley or have shale streaks, and thin streaks of sandstone are common in the shale sections. Coal, feldspar, and glauconite are variable in amount, and pink and clear crystalline quartz are present only in small or trace amounts.

Table - Variable Mineralogy of Sandstones of the Third Wall Creek member

Section:	3	4	5	5b	7	8	9	11
Average per cent Feldspar:	8	10	8	6	8	5	8	7
Coal:	xx	x	x	xxx	x	xx	x	
Glauconite:	xx	xx	x	x	xx	xxx	xx	x

xx (present) xxx (abundant) x (small)

Section 2a is incomplete, and the lower sandstone there has been correlated with the Third Wall Creek sandstones at section 2 and 3 by its mineralogy. When the mineralogy of the sandstones is plotted graphically, it is found that certain minerals are present everywhere, while others vary vertically and from place to place. Glauconite, coal, pyrite, calcite, and gypsum may be partially the product of environment, but the presence of chert, crystalline quartz, pink quartz, biotite, muscovite, or magnetite is thought to have been controlled by the source rock from which the sand was derived. Gray and black chert and biotite are universally present, but the other minerals vary. If the source rocks changed from time to time, the presence of different suites of minerals should indicate the relative ages of sandstones in different localities. Owing to the lenticularity of the sandstone bodies, the approximate correlation by the use of minerals can show nothing of the physical continuity of the rock bodies, and such correlations prove only probably derivation from a similar source. The minerals believed affected by environment are not used in correlation, and magnetite, due to its density, may be separated locally by the processes of sedimentation. The varieties of quartz and chert, however, are not subject to the limitations imposed by environment and sedimentation and are used in this study for correlation when other criteria are not available. Detailed tracing of outcrops between measured sections that had previously been correlated by mineralogy indicate that the method is reliable where short distances are involved.

Table - Variable Mineralogy of Sandstones in the Second and Third Wall Creek members

	Third Wall Creek			Second Wall Creek		
Section:	2	2a	3	2	2a	3
Feldspar:	X	X	XX	X	X	XX
Clear quartz:	X	X	X	XX	XX	XX
Pink quartz:	X	X	X	X	X	X
Biotite:	XX	X	XX	XX	X	X
Glauconite:		X	XX		X	XX

X: Small or trace amounts. XX: Normal or large amounts.

The preceding table shows the variation of minerals between the upper sandstone in the Third Wall Creek member and the lowest sandstone in the Second Wall Creek member in Sections 2, 2a, and 3. The Second Wall Creek sandstone is characterized by relatively large amounts of clear quartz. Bentonites exposed in Sections 2 and 3 confirm the correlation, but the mineralogy is sufficient to draw an approximate boundary between the two members in all three of the sections. Boundaries between members were determined in Sections 7 through 11 largely on the basis of mineralogy.

Boundaries.- The top boundary of the member is in many places poorly exposed in outcrops, requiring the separation of the Second and Third Wall Creek members on the basis of their sandstone mineralogies. Where exposures are good, the top boundary has been placed at a bentonite and gypsum bed. In the subsurface that bentonite bed is found in samples at the place where the electric log indicates a characteristic low resistance. The boundary between the Third and Second Wall Creek members is the least well defined of the stratigraphic boundaries used in this report, and the base of the Third Wall Creek member is the well-defined top of the Lower shale member.

Subsurface characteristics.- The top of the Third Wall Creek member is placed where a concentration of bentonite is present in the samples. A characteristic "kick" on the resistance curve is used in mapping because it comes in the bentonitic beds, and because in samples a definite top is often difficult to determine. With good samples and well developed sandstones it is possible to pick the top of the member by sand mineralogy.

Typical sample description of the Third Wall Creek member

Well 4, South Cole Creek

Depth (feet)	Description
7470-80	Bentonite, gray, very sandy.
7480-7580	Shale, gray, sandy, with small sandstone.
7480-85	Sandstone, fine, gray, slightly shaley, tight.
7500-10	Thin gray sandstone streaks.
12	Thin, very sandy bentonite with milky calcite.
25	Gray bentonite, porous and soft.
30-40	Small amount of fine, gray salt-and-pepper sandstone.
50-60	Gray bentonite, porous and soft.
-80	Sandstone streaks.
7580-90	Sandstone, gray salt-and-pepper, fine, soft, porous, slightly shaley.
7590-7610	Shale as above.
-7600	Small bentonite.
-10	Sandstone streaks.
7610-7630	Sandstone, fine to medium, gray salt-and-pepper, soft, porous, with shale partings, glauconite, feldspar, and no pink or clear quartz.
7630-7650	Shale.
-40	With sandstone streaks.
-50	Black, dull.

7650-7670	Sandstone, fine, shaley, salt-and-pepper, hard and tight.
7670-7700	Shale, dull black, with sandstone streaks.
7700	Bentonite, soft, gray, fluffy.
7700-7785	Shale, gray, slightly sandy.
10-20	Small mica.
30-40	Thin sandstone streaks.
	-Lower shale member-
7785	Bentonite, gray, very sandy.
7785-7865	Shale, black, flaky.

The base of the member is usually apparent in samples, because bentonite is present, and the shale changes from gray and sandy to black.

Summary.- None of the evidence presented points to fresh water deposition of the sandstones in the Third Wall Creek member. The cross-bedding and channelling is the type produced by moving water, whereas the few shark-like fish teeth and the occasional glauconite concentrations point toward a marine environment. The water in which the sandstones were deposited was not always so deep as to put the bottom on which the sand lay below the action of waves and currents, as evidenced by the cross-bedding. Occasional trails were made by some organism crawling over the bottom. The irregularity of the deposition indicates a great variation in competency of the transporting agents from place to place and from time to time. The currents or waves competent to move the pebbles which form conglomerates on the top of many of the sandstone bodies must also have been competent to move the sands from temporary resting places to other places where they could remain permanently.

The thickness of the sandstone bodies must depend on two things: The supply of sediment, and the relation of the place of deposition to the base-levels of deposition and erosion. The thick sandstones are thus attributable to proximity to sediment source or to protection from erosion by currents, waves, or streams. The area of high sandstone content on the west is interpreted as being near a supply of sand. Coal is also more common there, and the sandstones are relatively coarse and poorly sorted. The coal is finely ground and plant fragments are missing, but the unusual concentration of coal at Section 8 points to a relatively nearby source of plant material, either terrestrial or marine. The areas of low irregular sandstone content in the north and center of the area, the Sage Spring Creek, Salt Creek, Sussex, and Reno Hill area, and in the south are, conversely, attributed to distance from sediment supply. Possibly, deeper water conditions prevailed there. The sandstone concentrations in the Cole Creek area and at Section 2 are believed to be due to absence of erosion, probably due to greater depth of water in those places. The sandstones in both places are relatively fine grained. On the other hand, relatively low sandstone development is associated with coarser sediments southwest of Casper in the region of Section 3. The sand concentrated in other places may have travelled over that region, and currents may have been active there.

The conglomerates at Section 11 contain pebbles of trachyte porphyry found nowhere else, and the cross-bedding and channelling are evidence of strong currents flowing toward the southeast. These features indicate a local source of sediments to the northwest, with the coarse grain of the sandstones further indicating high competency in the transporting water and/or proximity to the source of the sand and pebbles. The channel conglomerate at Section 11 shows no features pointing to a marine origin, and it may have been deposited by a local stream. Any large stream would presumably have left a larger deposit of sediment, the supply of sediment must either have been low, because there is no sandstone near on the east, or most of the sand and gravel travelled to the south.

A general picture of the region when the Third Wall Creek member was deposited would be that of a shallow sea, with sediment entering in quantity on the west and locally in the northwest, with a deeper area on the north and east and a local ridge in the south that was subjected to some erosion. That erosion possibly accounted for a large amount of sand becoming trapped in a deeppart of the ocean floor in the Cole Creek area. The Alcova area was far from the main supply of sediment, and a great thickness of shale was deposited there.

Second Wall Creek member

Detailed description.-

Measured section of the Second Wall Creek member

Tisdale anticline, Section 9.

Bed	Description	Thickness
1.	Bentonite, with much cream, fibrous calcite.	5 feet
2.	Sandstone, massive, with cross-bedding near the top which dips toward the southwest. There are many pebbles at the top, some oolitic chert, and black and gray chert to 2 inches in diameter.	45 feet
3.	Sandstone, very friable, thin-bedded, with shale partings. Gypsum near base.	35 feet
4.	Sandy shale with thin sandstone and bentonite streaks.	150 feet
	Total thickness	235 feet
	-Third Wall Creek member-	
1.	Bentonite, yellow, sandy, with thin black shale and a small amount of calcite.	10 feet

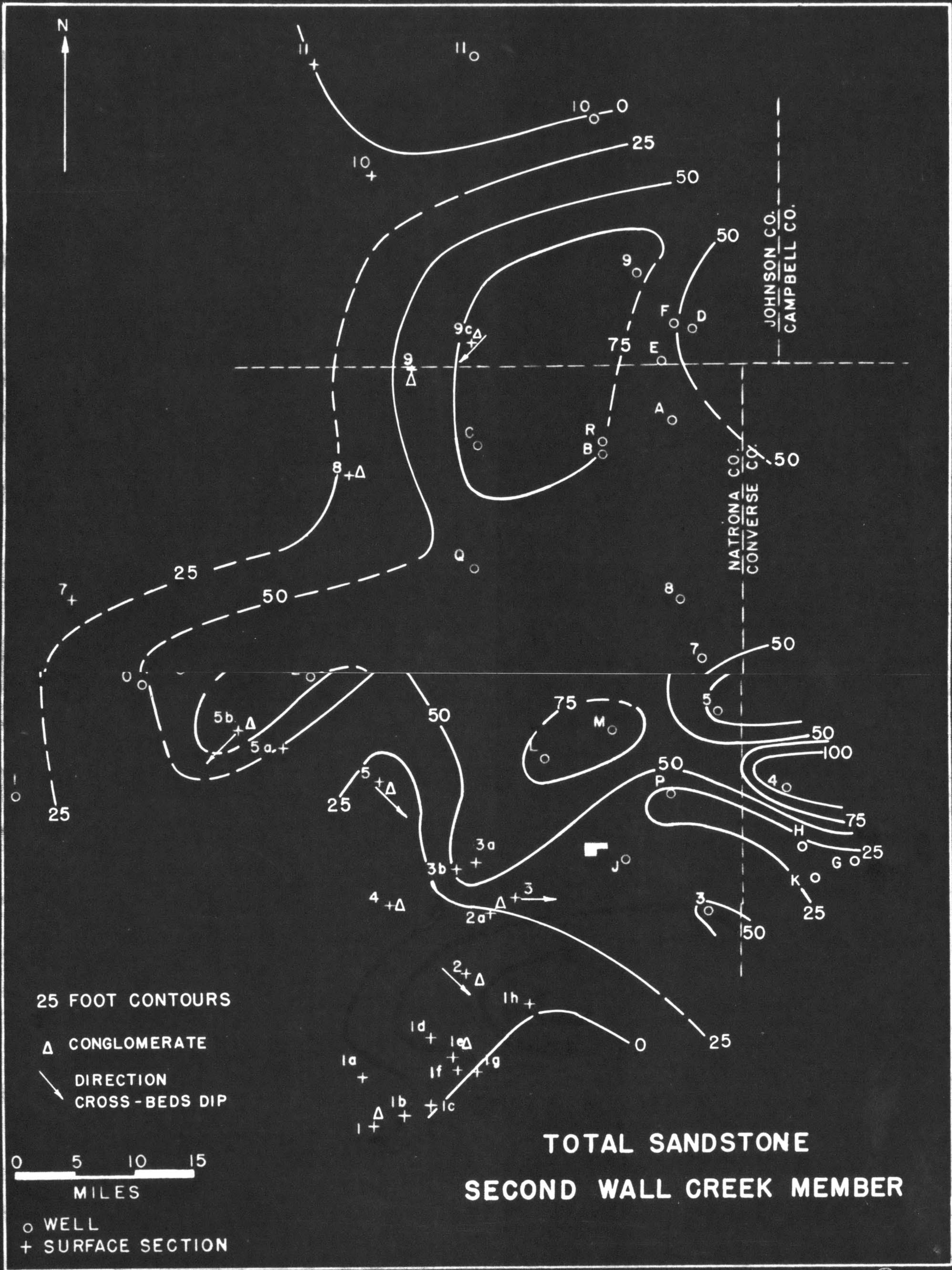


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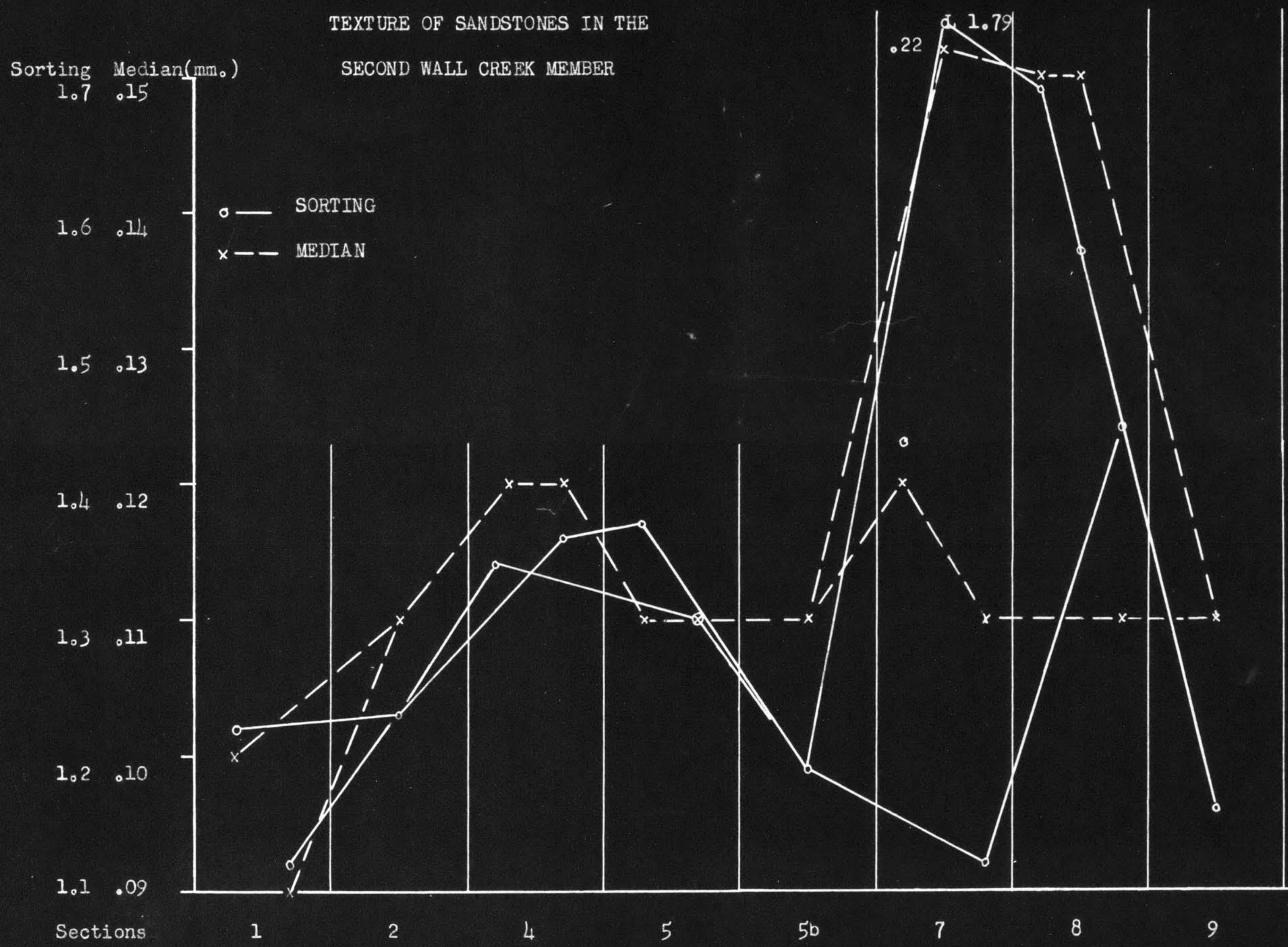
Figure 9



TEXTURE OF SANDSTONES IN THE
SECOND WALL CREEK MEMBER
Sorting
Median(mm.)
1.7 .15
1.6 .14
1.5 .13
1.4 .12
1.3 .11
1.2 .10
1.1 .09
SORTING
MEDIAN
.22
1.79
Sections
1
2
4
5
5b
7
8
9

Figure 10

Thickness and sandstone content.- The thickness of the member varies from 50 to 270 feet, with most of the area containing a thickness of 150 to 180 feet. The thinnest section is at Section 3, southwest of Casper, and the thickest is at Section 11, Mayoworth. Sandstone content as shown in Figure 9 varies between 0 and 115 feet. The member contains from 50 to 75 feet of sandstone over most of the region, with no sandstone in either the extreme north of the extreme south. There are moderate concentrations of sandstone in the Salt Creek-Sussex, Midway, and Powder River areas, and there is a localized large concentration in the South Cole Creek area. Thickness of the member varies with amount of shale.

Texture.- Texture is shown in Figure 10. The sandstones are medium grained, with the median diameters of sand grains varying from .09 to .22 mm., with most being from .11 to .12 mm. Sorting is generally poor, with the coefficient of sorting varying from 1.12 to 1.79, with most of the values between 1.20 and 1.40. Areally, the greatest spread in values and the maxima of sorting and diameter are on the flank of the Bighorn Mountains, in Sections 7 and 8, which is an area of thin sandstone development. The finest grained and best sorted sandstones are at Alcova, Section 1. Conglomerates are more widespread than in the Third Wall Creek member. Cross-beds dip toward the south-southwest along the mountain flank and dip toward the southeast in the south. The sandstones are generally less shaley than those in the Third Wall Creek member.

Upper Bentonite.- The bentonite at the upper boundary of the member is a persistent horizon both in wells and on the surface. Crystalline calcite is usually found included in the bentonite, both on the surface and in well cuttings. Over most of the region the electric log shows rounded resistivity maxima at the top of the member, with well-defined low-resistance bentonite development.

Samples of the bentonite from several localities were analyzed, and the results are given in the following table.

Analyses of bentonite, Top of the Second Wall Creek member

Sections:	1	2	3	4	5	9	11
Per cent of detrital sand in the sample.	4.7	10.8	0	7.2	0	1.5	0.4
Non-detrital sand, per cent of non-detrital fraction.	3.6	10.3	26.0	7.4	4.6	11.5	0.4
Maximum size of non-detrital material.	0.40	0.30	0.60	0.25	0.40	0.35	0.60 mm.

The average size of the material believed to be original crystals and volcanic fragments is similar to the average size of similar material in the top bentonite of the Lower shale member, but the maxima are higher. The maximum, both in size and amount of original material, is at Section 3, where the bentonite is also most adulterated by detrital material. The adulteration makes the significance of the data doubtful. The rest of the data show little well-defined variation, as the values are largely erratic.

Boundaries.- The upper bentonite of the member is the top boundary, and the base is the top boundary of the Third Wall Creek member, described in the preceding section. Delimitation of the member in partly covered sections is accomplished by correlation with well exposed sections, by means of the mineral content of the sandstones.

Subsurface characteristics.-

Sample log of Second Wall Creek member

Well No. 6, Sage Spring Creek No. 4 Unit

Depth (feet)	Description
6555	Bentonite, gray, slightly sandy.
6555-6600	Shale, gray, sandy.
6570	Bentonite, gray, slightly silty.
-80	Thin sandstone streaks.
90-6600	Trace of sandstone.
6600-6640	Sandstone. (Core No. 1, 6606 to 6636)
6600-6610	Medium grained, salt-and-pepper, porous, friable.
-30	Medium to fine grained, hard, with some clay matrix and shale streaks. Clear quartz, no pink quartz.
-40	As above, with a small amount of glauconite.
6640-6670	Shale, gray, sandy.
6670-6710	Shale, dark gray, biotitic.
6690-6700	Thin sandstone streaks.
-10	Bentonite, white, biotitic.
6710-6790	Shale, gray, sandy.

20-30	Small red silty sandstone.
38	Bentonite, white, slightly silty.
88-90	Bentonite, white, sandy. (Top of Third Wall Creek member.)
6790-6840	Shale, dark gray, micaceous.

The shales of the member are similar to those above and below, but the minerals in the sandstones can be used for delimitation of the member. The top bentonite often has crystalline calcite associated with it, as it has in surface exposures. Boundaries have electric log characteristics as described elsewhere, and the resistance of the shales is generally lower than the resistance of the shales in the Third Wall Creek member.

Table

Variable Sandstone Minerals, Second Wall Creek member.

Section:	1	3	4	5	7	8	9
Average per cent							
Feldspar:	10	5	5	7	15	7	7
Biotite:	X	X	XX	XX	X	X	XX
Glauconite:	XX	XX			XX	XX	X
Coal:	XX			X	X		
Pink quartz:		X			X	X	
Clear quartz:	X	XX	XX	X	XX	X	XX
Teeth:					X		X

XX: Present; X: Small or trace amounts; XXX: Abundant.

Summary.- The Second Wall Creek member is characterized by having relatively more clear quartz, more widely distributed glauconite, and less coal than the Third Wall Creek member. The amount of sandstone in the member is less variable than in the Third Wall Creek member, indicating less variation in the competency of the transporting media. The extremely poor sorting and high median diameters of the sandstones in Sections 7 and 8, together with the thin sandstone bodies and coarse grained conglomerates in that region, lead to the conclusion that, in the area along the southern Bighorn Mountain flank, the sands were eroded or the region was an area of non-deposition. The sandstones on the flank of the southern Bighorn Mountains differ from those in the Third Wall Creek member there, because well-defined local concentrations of coal are absent in the Second Wall Creek member, and because the glauconite content is low. The fresh fish teeth are evidence of a marine environment there, and the texture data point to that place as the direction from which sediments came. The concentrations of sandstone at Salt Creek, Midway, Powder River, and Cole Creek are interpreted as being deposited in areas protected from erosion and close to sediment supply. Some of the sandstones in the areas of thin sandstone development have pebbles scattered throughout the sandstone and have a pebble conglomerate at the top. The conglomerate at the top indicates an increase in competency such that the sand was carried away and only the pebbles left. The concentration of sandstone at Cole Creek is in the same place as the concentration of sandstone in the Third Wall Creek member. The shale that is interbedded with the sandstone there indicates that the processes of sorting did not go to completion, perhaps because of rapid deposition and burial. The section at Section 3 is the thinnest studied, with sandstone content nearly 100 per cent. The numerous cross-beds at Section 3 point to variable currents that flowed both northeast and southeast, and the environment there is interpreted as a channel, with much erosion and no chance for shale to be preserved. The thick sandstones at Cole Creek may well have been washed in from this exposed area. The regions of thicker shale and less sandstone are places far from the main supply of sand, and they probably had deeper water. The east flank of the Bighorn Mountains may have been a beach or may have been near shore.

The clean sandstones and widespread conglomerates point to slower sedimentary processes with attendant closer approach to more complete and widespread sorting, but these features could also be the result of the reworking of older Frontier sediments in another place. The lower resistance of the shales may indicate increased salinity of the water as compared to the Third Wall Creek member.

The high feldspar content in Section 7 and the igneous pebbles at Section 9 indicate a local source of igneous rock.

First Wall Creek member

Detailed description.-

Measured section of the First Wall Creek member

Tisdale anticline, Section 9

Bed	Description	Thickness
1.	Sandstone, thin bedded. The basal part has shale partings.	65 feet
2.	Dark shale and thin sandstone. Partly covered.	95 feet
3.	Sandstone with six inches of limestone concretions at top. Slightly conglomeratic, with pebbles at top.	15 feet
4.	Shale with thin sandstone beds.	85 feet
	Total thickness:	260 feet
	-Second Wall Creek member-	
1.	Bentonite, shaley, dark, with crystalline calcite chunks.	5 feet

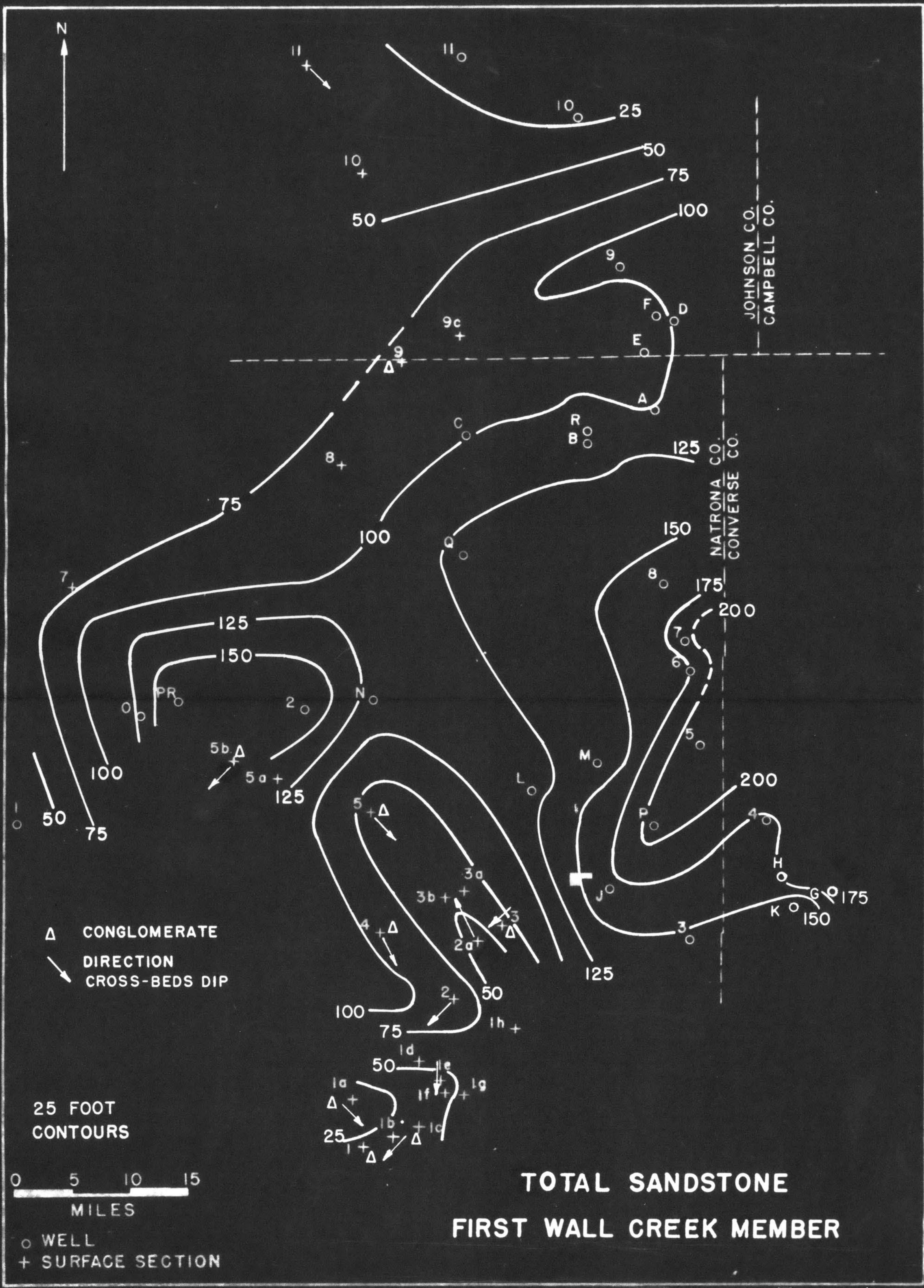


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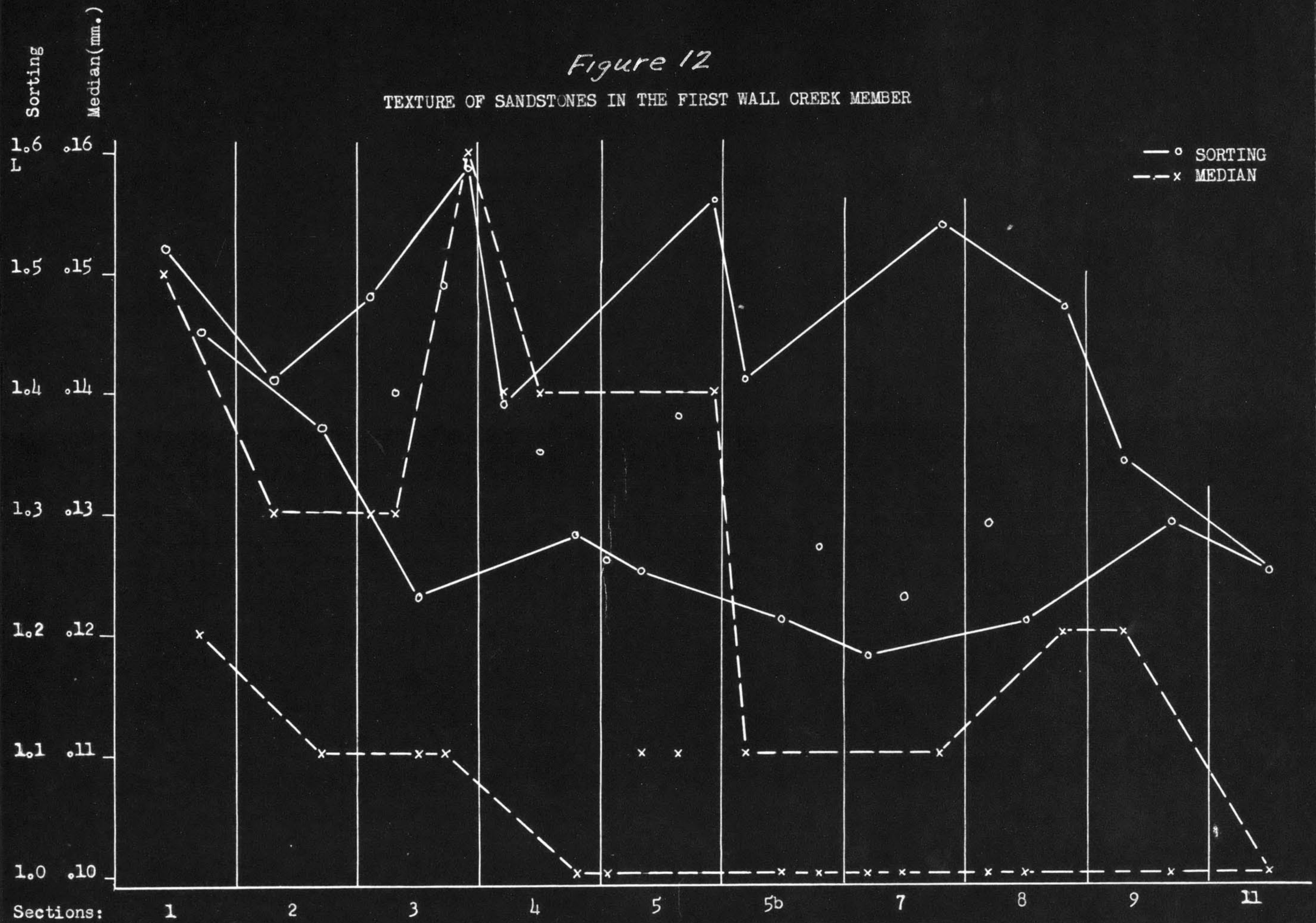
Figure 11

Figure 12

TEXTURE OF SANDSTONES IN THE FIRST WALL CREEK MEMBER



Thickness and sandstone content.- The thickness of the First Wall Creek member varies from 100 feet at Section 11 to 370 feet at Section 3, whereas normal thickness ranges from 260 to 340 feet. Sandstone content (see Figure 11) varies from 10 to 20 feet in the north and south to 230 feet at Well 5, North Cole Creek, and the thickness of the member generally increases with increased sandstone content.

Over most of the region the First Wall Creek member contains 75 to 125 feet of sandstone, with low sandstone areas present in the north and extreme south. There are local concentrations of sandstone in the Powder River-Natrona and Cole Creek areas, with a small region of low sandstone development near Section 2a at Goose Egg. Over a large part of the region the sandstone content increases slowly in a southeast direction.

Texture.- The sandstones in the member as shown in Figure 12 are generally fine grained with .10 to .13 mm. being a normal median diameter of the sand grains. Sorting is fair, and coefficients of sorting are generally in the 1.2 to 1.4 range. There is a well defined maximum of sorting coefficient, maximum in median diameter, and maximum spread between values at Section 3. Toward the north along the Bighorn Mountain flank the sandstones become generally finer grained and better sorted. Conglomerates are less widely distributed in the First Wall Creek member than in the Second Wall Creek member, and they are concentrated in the south. Directions of the dip of cross-bedding are generally southward, but are extremely variable.

Boundaries.- The top boundary of the First Wall Creek member, which is also the top boundary of the Frontier formation, is placed at the top of the highest sandstone. Both on the surface and in wells that horizon is the most readily mappable, and in well samples and in electric logs there is characteristically a bentonite bed a short distance above the top sandstone. With the exception of the sandstones at Sections 7 and 8, the top sandstone wherever studied contains pink quartz, and the thickness of the Carlile shale varies little. Those facts, together with the persistent bentonite in the basal part of the Carlile shale, indicate that the top of the formation and member as defined varies little with age in this region. The bentonite top of the Second Wall Creek member has been described before, and that bed is the base of the First Wall Creek member. In many places concretionary limestones are present in the lower part of the member.

Subsurface characteristics.-

Sample Log through the First Wall Creek member

Well 2, Natrona

(Begins in Carlile shale)

Depth (feet)	Description
2900-3070	Shale, slightly sandy, with occasional calcite and pyrite.
2900-2970	Poor samples.
3000-3010	Calcite, chunks.
25-35	No samples.
50-60	Trace of bentonite, calcite chunk.

3070	-Top of Frontier formation.
3070-3115	Sandstone, salt-and-pepper.
70-80	Coarse, friable, with clear and pink quartz.
-90	Biotite, much feldspar.
-3100	Tighter, harder, with rust spots.
-10	Medium grained, porous, friable, with rust spots.
-15	Finer, harder.
3115-3150	Shale, gray, sandy.
20-30	Small blue-gray bentonite.
40-50	Small yellow-white sandy bentonite.
3150-3275	Sandstone.
3150-60	Very shaley, gray.
-70	Coarse grained, salt-and-pepper, poorly sorted, friable. Pink quartz, no clear quartz.
75-80	Shale interbedded.
-85	Shale, very sandy, gray, slightly bentonitic.
-3200	Medium grained sandstone, salt-and-pepper, slightly shaley, soft.
-10	Poorly sorted, trace of clear quartz.
-20	Hard, with abundant clear quartz.
40-50	Glauconite.
-60	Small fibrous calcite.
65-70	No sample.
3275-3330	Shale, gray, sandy.

3275-80 Small bentonite.

-90 Small bentonite. Fine grained sandstone interbedded.

3300-10 Brown crystalline calcite veins.

20-30 Calcite as above. Thin sandstone interbedded.

3330-60 Sandstone with shale breaks.

30-40 Sandstone, medium grained, salt-and-pepper, soft with pink quartz and small pyrite.

-45 Shale.

-50 Sandstone as above, with shale streaks.

-55 Shale.

-60 Sandstone, soft, with some brown crystalline calcite.

3360-3400 Shale, dark gray, less sandy.

3360-80 Small bentonite.

-90 Thin sandstone streaks. Small gray, slightly sandy bentonite.

-3400 Bentonite as above.

3400-3440 Shale, gray, sandy.

3400-10 Small bentonite, small brown-white crystalline calcite, pyrite.

-20 Thin sandstone streaks.

3425 -Top of Second Wall Creek member, by electric log.

3420-30 Small sandy bentonite.

-40 Ditto, with small fibrous calcite, pyrite.

3440 -Sample top of Second Wall Creek member.

Well cuttings become more bentonitic toward the bottom of the member, and sandstone content is smaller toward the bottom. The white and brown crystalline calcite is believed to be vein material from limestone concretions that are observed on the surface in both the Carlile shale and the First Wall Creek member.

Variable Sandstone Minerals, First Wall Creek member

Section:

Average per cent	1	1a	2	3	4	5	7	8	9	11
Feldspar:	5	10	5	10	8	10	12	10	7	10
Biotite:	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
Glauconite:	X	XX		XX	XX	XX	X	XX	X	XX
Coal:						X	X	X		
Pink Quartz:	X	X	XX	XX	XX	X	X	XX	X	X
Clear Quartz:	XX	XX	XX	XX	XX	XX	XX	XX	XX	XXX

XX: Present; X: Small or trace amounts; XXX: Abundant.

Summary.- The limestones and marine fossils found in the lower part of the member indicate a marine environment of deposition. The glauconite in the upper sandstone bodies indicates marine conditions also, although that evidence is not conclusive. There is no evidence of terrestrial origin of the thick upper sandstone of the member, so the presumption is that it also is marine, particularly with the marine Carlile shale directly overlying it. Cross-bedding again indicates relatively shallow water, whereas the conglomerates indicate at least temporarily highly competent transporting media which were active even into the middle of the area, where conglomerates are found in wells. Areas of high sandstone content persist in the Cole Creek and Powder River areas, but the lithologies on the southern and western boundaries of the map area are different from those in the Second and Third Wall Creek members. The coarsest sand is at Section 3, indicating an entry of sediment into the area from that direction. The lines on the map that enclose the area of high sandstone content at Powder River are open to the south, rather than to the west as in the older parts of the section. At Alcova one of the sandstone bodies that was present at Bates Creek (Section le) is missing. (See Plate 1.) Correlation by mineralogy indicates that the second sandstone at Bates Creek has disappeared, and that at Alcova the sandstone which rests directly on the limestone concretion horizon is correlative with the top sandstone at Bates Creek. The constant interval from the top of the upper sandstone to the base of the Niobrara formation further supports that correlation. The eroded limestone concretions and coarse conglomerate at the base of the upper sandstone at Section la, together with the loss of section between the limestone horizon and the base of the upper sandstone, indicate a local unconformity in the area, caused by erosion and/or non-deposition of the sandstone and the shale that lie between the limestone and the upper sandstone at Bates Creek.

That unconformity is the only one found in the Frontier formation in this study, and it indicates relative uplift in the south.

The change in texture pattern and the distribution of sand deposition are significant in connection with the unconformity just described. Local concentrations of coal and coarse conglomerates on the Bighorn Mountain flank indicate that the area continued to be relatively close to shore, although the region of the present Bighorn Mountain flank was no longer the main avenue through which sediments reached the southwestern Powder River Basin.

The pattern of sedimentation was more uniform over the region during First Wall Creek time, with sand deposition more regular than it had been earlier. After the last sandstones of the Frontier formation had been deposited, there were essentially uniform marine conditions during the time of Carlile deposition. The addition of a sandstone body which contains no pink quartz at the top of the Frontier formation in the region of Sections 7 and 8 perhaps indicates later sand deposition there than in the rest of the area. Shale resistivity increases gradually upward in the member, and that is indication of probably decreasing salinity of the water in which the sandstones were deposited.

Table

Relative Radioactivity of Surface Samples

Frontier formation

Section	Position	Radioactivity	Sample description
2	353-57	1.0	Bentonitic shale with calcite. Top of Second Wall Creek member.

- Third Wall Creek member -

2	493-98	0.4	Bentonite with gypsum.
	666	0.4	Dark gray, soft shale.
	756	0.7	Shale, gray, hard, silty.
	766	0.6	Shale, sandy, gray-brown.
	776	0.4	90% dark gray shale, 10% shaley sandstone.
	786	0.3	90% green-gray shale, 10% bentonite.
	796	1.0	90% black, thin shale, 10% bentonite.
	806	0.9	Black, thin-bedded shale.

- Lower shale member -

2	816-22	0.9	Bentonitic shale, top of member.
	822	0.5	Sandy bentonite with calcite and gypsum.
	826-31	0.7	Sandy siltstone, with gypsum, calcite, and bentonite.
	836-41	0.9	Dark gray sandy shale with gypsum.
	846-51	0.5	Gray, soft shale.
	858-63	0.9	Gray, soft shale.
	873-78	0.7	Dark gray silty shale.
	883-88	0.5	Gray sandy shale.
	883-88	-0.1	Yellow shaley limestone.
	888-98	0.3	Gray sandy shale.
	893	0.1	Hard, red, calcareous siltstone concretion.

	888-902	0.6	Basal Frontier bentonite, calcareous, shaley.
	902-05	1.0	Same bed, pure, with biotite.
	905-08	0.5	" "
	908-10	0.5	" "
	Mowry shale	0.4	Top siltstone bed.
	Mowry shale	0.7	Dark gray silty shale with fish scales, 10 to 15 feet below top of the formation.
3	Mowry shale	0.6	From road cut, about 75 feet below the top of the Mowry shale. Dark shale with abundant fish scales and spines.
1a	10-13	0.0	Gray gypsiferous shale at base of the upper sandstone of the Frontier formation.
	10	0.4	Septarian limestone concretion.
5		0.3	Basal Frontier bentonite, apple-green, silty, calcareous.
	Flint Shot	0.0	Calibration sample. Specimen S5-50, M.I.T. Sedimentology Coll. Commercial product of the Ottawa Silica Co., Ottawa, Ill.

Cherokee shale 1.1	Calibration sample. Sample of the shale above the Bartlesville sand, Sinclair Prairie Oil Co. No. 1 T. K. Newman, Sec. 25, T. 25N., R. 16 E., Oklahoma

Note.- Position given in feet below top of the Frontier formation. Radioactivity is given in Gamma counts/ 1000 seconds/ gram.

Radioactivity

Sample measurements.- A number of samples were measured in a Gamma counter in an effort to locate radioactive marker horizons or radioactive zoning which might be an aid in correlation. The preceeding table lists results on some of the samples. The bentonites are generally higher in radioactivity than the shales, and the sandy shales and limestones are low in radioactivity. A measurement of the Cherokee shale is given for comparison. Some selected black shales in the Frontier formation approach the value for the Cherokee shale, but none equals or surpasses it. In general the Frontier sediments are moderately radioactive, and there are no definite radioactive marker horizons. Bentonite concentration is the usual cause of higher radioactivities, but bentonites may be little active.

Gamma Ray logs.- Bentonites show very high gamma activity in gamma ray well logs, and are the only radioactive marker horizons in the Frontier formation. The general level of gamma activity slowly and regularly decreases upward from the top of the Muddy sand to the base of the sandstones in the Second Wall Creek member. In the upper part of the Second Wall Creek member the activity is slightly higher than that below, with a slow decrease upward to the base of the upper sandstone of the First Wall Creek member. The level of activity in the lower part of the Carlile shale is lower than that in the upper part of the Second Wall Creek member.

The radioactivity work done in connection with this research was an attempt to find radioactivity marker horizons. The bentonites are the only such markers, and they are usually well expressed in electric logs. Radioactivity criteria are valuable where the bentonite markers are masked by other sediments or where conditions in the well make satisfactory electric logging impossible.

CONCLUSION

Correlations.- If placed at the top of the siliceous Mowry shale, the base of the Frontier formation is an extensive horizon that lies at the top of strata that vary little in age. The basal bentonite of the Frontier formation is probably the lithologic extension of the Clay Spur bentonite of the Black Hills. The bentonite beds used as stratigraphic boundaries in this report are valid time-rock units, and they are therefore locally useful in separating the Frontier formation into units in order to study temporal and spatial variations in sedimentary processes and products.

It is suggested that the widespread horizons of limestone concretions in the lower part of the First Wall Creek member of the

Frontier formation may be the lithologic extension of the Greenhorn limestone of the eastern Powder River Basin.

The top of the upper sandstone is a satisfactory upper boundary of the Frontier formation in the southwest Powder River Basin.

Environment.- The Frontier formation in the southwest Powder River Basin was deposited in a shallow sea which had a varied bottom topography and was generally shallower in the west, with local shallow regions southwest of Casper. There were deeper areas in the Powder River-Natrona and Cole Creek regions which persisted throughout most of Frontier time.

Source of sediments.- A large part of the coarse sediments of the Frontier formation entered the southwest Powder River Basin across the site of the present eastern flank of the southern segment of the Bighorn Mountains. Smaller amounts of sediment entered from the northwest near Mayoworth, and, during the deposition of the First Wall Creek member, an important quantity of sand and gravel reached the basin across its present southern border.

The particles of much of the sand and gravel studied in this research are well rounded, polished, and sorted, indicating that they had a long history of sedimentation. Most of the sediment was probably derived from sedimentary rocks, and the rounding or crystalline character of the grains was inherited from the source sediment. The rounded quartz of the Frontier formation is quite similar to that found in the Dakota formation in the immediate area, and the chert and quartzite pebbles are macroscopically indistinguishable from those of the Lakota and Morrison formations. Pink quartz is also common in the Lakota formation, and Love, _et al_ (1948) described a "quartz crystal sandstone" that lies at or near the base of the Cloverly group. The chert pebbles found in Frontier conglomerates in the Bighorn Basin were reported by Hunter (1950) as identifiable Madison and Tensleep formation types. The pebbles were originally made from Paleozoic rocks, but they may have gone through several cycles of sedimentation before they were deposited in the Frontier formation, and Mesozoic rocks may have been the immediate source of the Frontier sediments. It is unfortunate that many of the older rocks in the regions to the south and west are either eroded or covered.

Love, _et al_ (1948) mapped a conspicuous area of thinning of the Lower Cretaceous Cloverly and Jurassic Morrison interval in the Sweetwater uplift area and in western Natrona and northeastern Fremont Counties. Those areas of thin early Mesozoic rocks are in the local source areas from which the Frontier sediments of the southwest Powder River Basin were probably derived. Love and his colleagues consider the thinning a suggestion "that during or at the close of Cloverly time gentle folds trending northwest developed in the Lost Soldier-Big Sand Draw area and in the Alcova-Lost Cabin area. This suggestion is based on the distribution of thin and thick sections, for there is no measurable angular unconformity between any of the formations".

The petrography of the igneous pebbles in the conglomerate at Mayoworth indicates that they may have been derived from a small intrusive.

The intrusive may now be covered or eroded, because, according to Thompson, et al (1949), no outcrop of such an igneous rock is known in that region.

Structural control.- The sedimentational features of the Frontier formation are similar in shape, trend, and position to the present structural features of the region. It is improbable that such a persistent relation should be fortuitous, and it is, therefore, a necessary conclusion that during the deposition of the Frontier formation a structural pattern similar to that of the present affected the sedimentation of the region. There is an important break in the content of the sediments across the present boundary of the Powder River and Wind River Basins, and in the west the sedimentation follows the present Bighorn Mountain trend. The postulated deep areas persistently lie near the intense folding on the southwestern border of the basin and north of the present Casper Mountain fault system. It is concluded that, during the time of Frontier deposition, the Powder River Basin was a structural depression with shape and boundaries similar to those of the present.

The local depressions at Powder River-Natrona and Cole Creek were the sites of later folding that produced a group of important structures, and the persistent Frontier trough north of Casper Mountain now lies in front of a fault of great stratigraphic displacement. Thus there is some correspondence between the early structure of the region and its subsequent deformation. The evolution of the Laramide structural pattern of the region began as early as the time when the Third Wall Creek member was being deposited, i.e., early in the middle part of the Late Cretaceous.

History.- The geologic history of the southwest Powder River Basin may be divided into the following four parts. 1. Widespread stable marine conditions prevailed during deposition of the Mowry shale and the Lower shale member of the Frontier formation. Conditions then gradually changed as the sands of the Third Wall Creek member were laid down. 2. Environmental conditions continued to favor sand deposition, with a gradual change to clear water marine conditions and some limestone deposition during deposition of the First Wall Creek member. 3. Sands of the upper part of the First Wall Creek member were widely spread over a shallow marine bottom. 4. After deposition of the last Frontier sandstone, uniform marine conditions prevailed during deposition of the Carlile shale and the lower part of the Niobrara formation.

Local positive areas were present during Third Wall Creek deposition and persisted throughout Frontier time. There apparently was uplift in the south during the deposition of the First Wall Creek member.

Suggestions for future research.- The lack of published detailed petrographic descriptions of the rocks of the region makes determination of sediment source difficult. More petrographic work would be helpful to future studies of this sort.

More mapping of the regional lithologic and thickness variations of the Mesozoic rocks is needed before comprehensive interpretations of the sedimentary and structural history are possible.

As more information becomes available, the detailed study of the Frontier formation should be extended toward the eastern Powder River Basin and across the Sweetwater uplift.

Some of the conclusions outlined in this paper point toward factors that may affect the oil accumulation in Frontier sediments. A correlation between sedimentary conditions and oil production, in conjunction with detailed investigations in oil fields that have been intensively developed, might determine the conditions necessary for oil production from the Frontier formation.

Research of the nature reported here is aided by several conditions enjoyed by the author during the progress of the research. These include the free exchange of well data, samples, and electric logs by many operators and the freedom and the generous time allowed for the work by supervisors, both academic and company.

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Plate 6

Photomicrographs of sandstones

(Magnification: 140 diameters. Polarized light.)

1. Second Wall Creek member sandstone. Section 2, Coal Creek

The rock has 40 per cent fine grained micaceous matrix. There are grains of quartz and chert, 15 per cent orthoclase, and 5 per cent plagioclase (Ab14 An 86). Some of the quartz has undulatory extinction, and there is no grain enlargement.

2. Second Wall Creek member sandstone, Section 2, Coal Creek

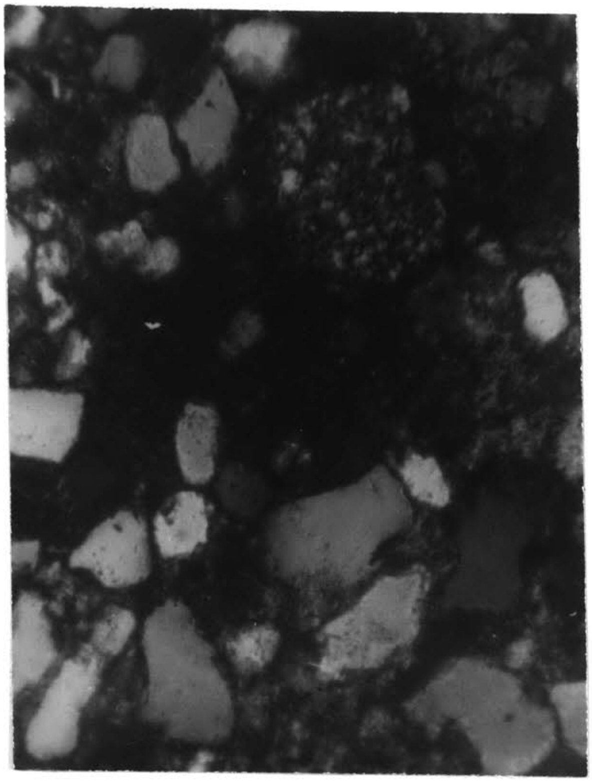
The sandstone contains 50 per cent quartz, 30 per cent chert, and 20 per cent feldspar. The feldspar is 50 per cent orthoclase, 30 per cent microcline, and 20 per cent plagioclase (Ab92). The grains are angular to rounded, but most are subrounded. There is some iron oxide and very little cement, but some of the grains are enlarged and cemented by optically continuous quartz.

3. Lower sandstone in the Second Wall Creek member, Section 2.

This rock has 40 per cent quartz, 20 per cent chert, 20 per cent orthoclase, and 20 per cent calcite. It is well cemented, and all the pores are filled with calcite.

4. Second sandstone in the First Wall Creek member, Section 3, west end of Casper Mountain

Quartz, chert, mica, orthoclase, and a small amount of plagioclase(Ab70) appear to float in the abundant calcite cement.



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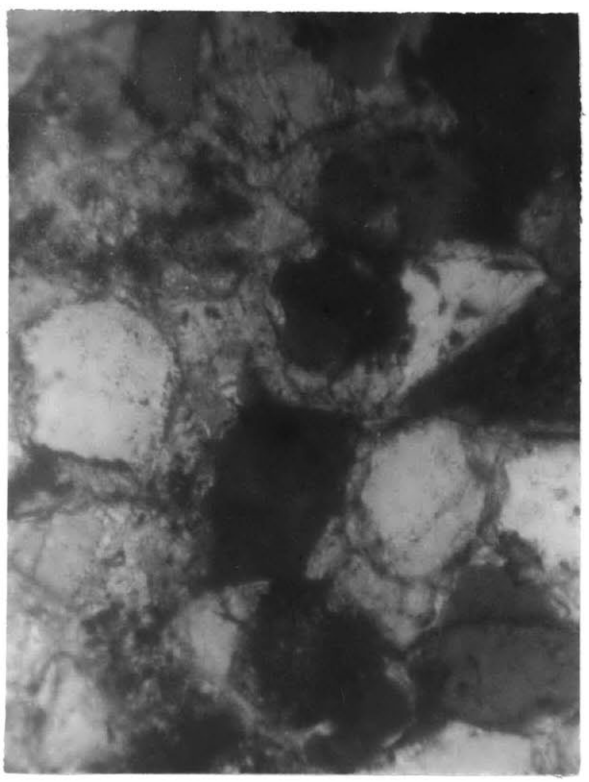

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Plate 6

Photomicrographs of conglomerate pebbles. Magnification:140 diameters.

Plate 7

1. From upper sandstone of the Third Wall Creek member, Section 11, Mayoworth. Polarized light.

This pebble of trachyte porphyry has phenocrysts of orthoclase, microcline, and a few of rounded hornblended in a fine grained groundmass. The feldspars are zoned and badly altered.

2. From upper sandstone of the Second Wall Creek member, Section 9, Tisdale. Plain light.

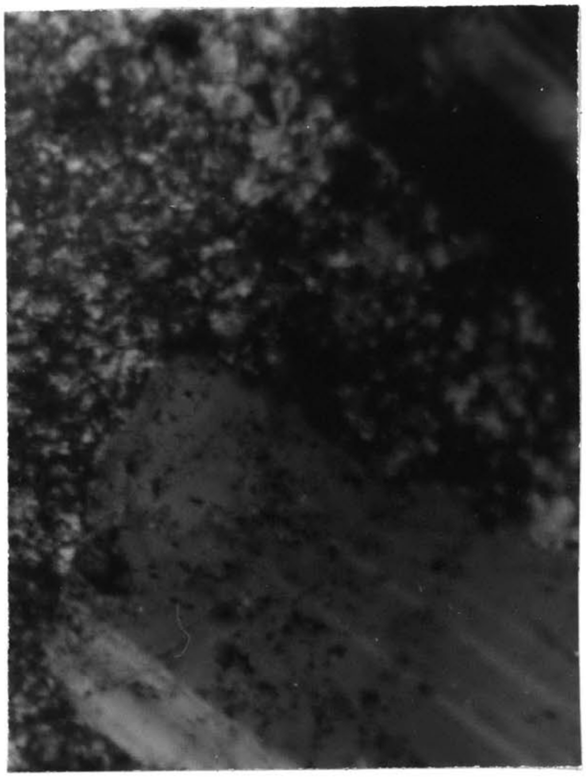
The pebble is partly recrystallized chert with Endothyra and fragments of mollusc shells.

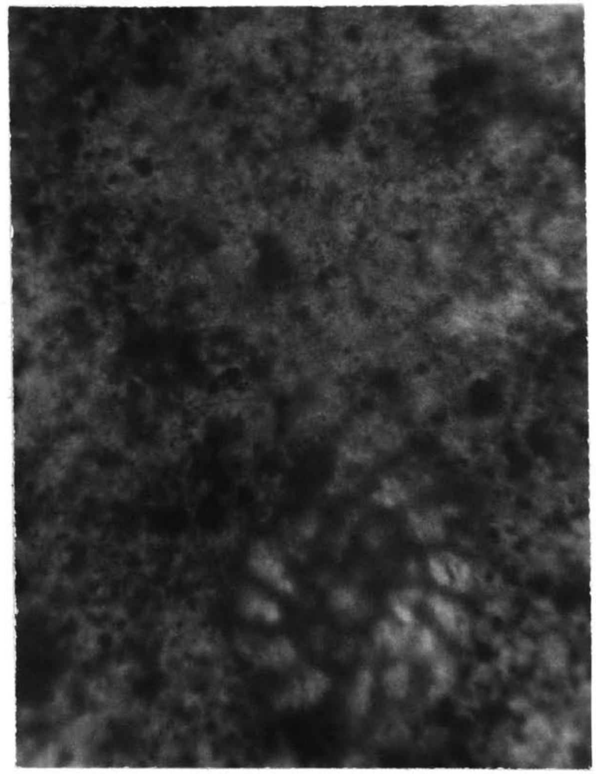
3. From lower sandstone of the Third Wall Creek member, Section 8, Wall Creek. Plain light.

The chert is recrystallized, and it contains round and egg-shaped oolites, some of which have needle-like centers. The pebbles are dark, and they were identified in the field as volcanic rock with flow structure.

4. From the First Wall Creek member, Section 1a, Alcova. Plain light.

The pebble is a hard sandstone, and the grains of quartz, chert, and quartzite float in brown calcite cement. Some of the quartz has undulatory extinction.





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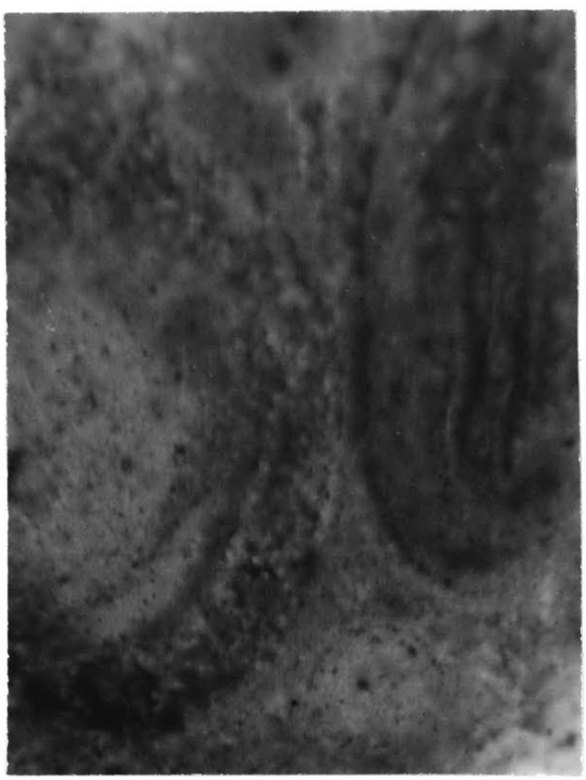

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Plate 7

Plate 8

Photomicrographs of rocks associated with bentonite beds.

Magnification: 140 diameters. Polarized light.

1. Sandstone in a bentonite of the Lower shale member, Section 9.

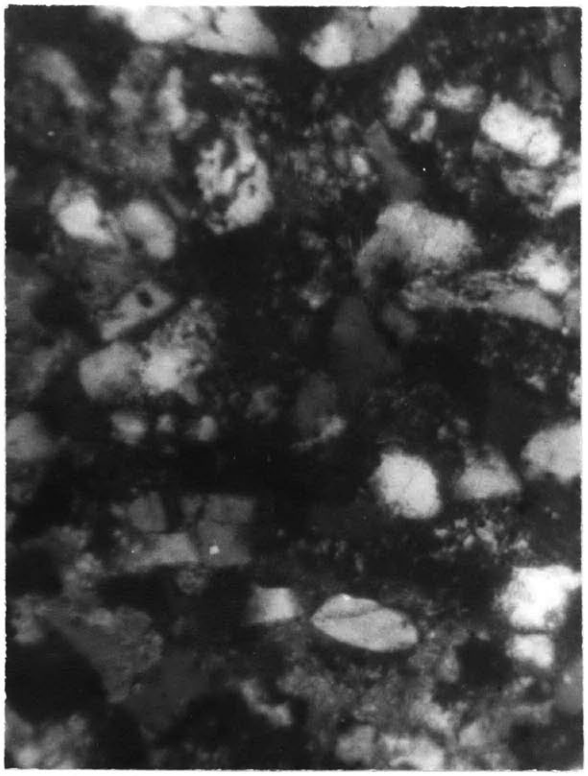
The rock contains shards of quartz, orthoclase, microcline, albite, and glauconite. Some of the fragments may be devitrified glass; they are gray and have aggregate extinction. Cementing materials include silica, calcite, and iron oxide.

2. Sandstone in a bentonite bed of the Lower shale member, Section 5.

Quartz, chert, orthoclase, microcline, plagioclase (Ab74, An26), mica, and glauconite are present as grains, and the matrix is clayey.

3. Siltstone at the top of the Mowry shale, Section 2, Coal Creek.

The rock contains quartz, orthoclase, microcline, and a small amount of plagioclase in a matrix of fine micaceous material. A radiolarian is visible in the lower right corner of the picture. The grains are angular, and some gray grains with aggregate extinction may be devitrified glass. Thery are many opaque brown shreds of organic material, and the rock is hard and well cemented.



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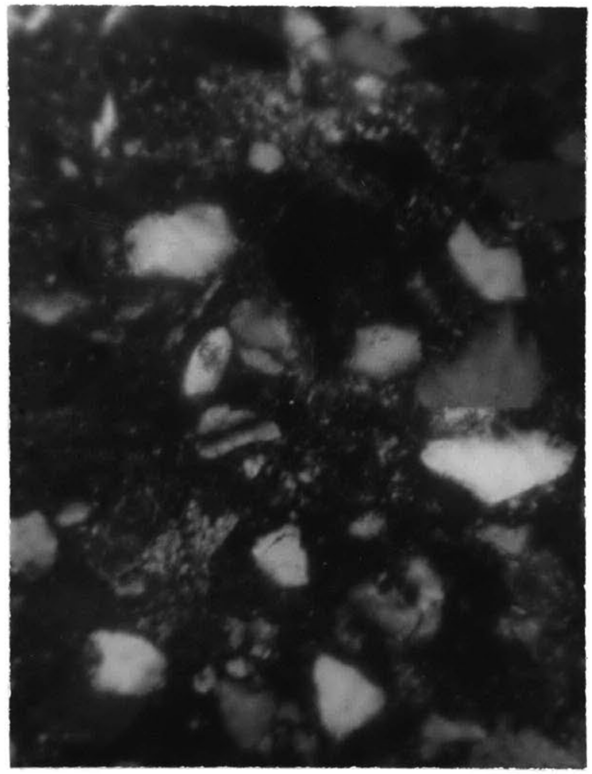

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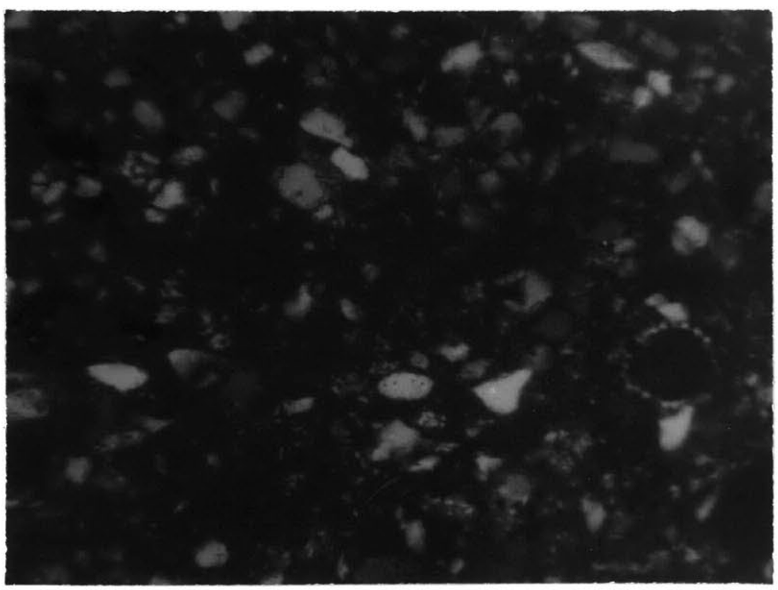

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Plate 8

Explanation of Plates

Plate 9

Limestone boulders and conglomerate at the base of the sandstone in the First Wall Creek member at Section 1a, Alcova.

Plate 10

Trails and burrows in the top sandstone bed of the First Wall Creek member at Section 3 at the west end of Casper Mountain.

1. Casts of trails on the lower surface of the bed seen in cross section in picture 2.

2. Burrow. The shale and sandstone at the top of the bed are rippled. The trails and burrows are about 3/16 inch in diameter, and the thick sandstone bed is 20 inches thick.

Plate 11

1. Top bed of the Lower shale member at Section 2, Coal Creek. Bentonite is on the flat top surface, and the dark areas on the top of the slope are brown, weathered, siltstone concretions.

2. Cross-beds in the top sandstone of the First Wall Creek member at Section 3 at the west end of Casper Mountain.

1

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Plate 9

1

2

Plate 10

1

2

Plate 11

Plate 12

Gradational contact at the base of the lowest sandstone in the Third Wall Creek member at Section 3 at the west end of Casper Mountain

Plate 13

Top bed of the Mowry shale

The boy is standing on the hard, sandy top surface of the Mowry shale. The bottom of the basal bentonite bed of the Frontier formation is visible on the right.

Plate 14

Frontier formation hogbacks at Oil Mountain (Section 4) The gray bentonite visible on the valley floor marks the base of the First Wall Creek member.

Plate 15

Lower shale member at Emigrant Gap (Section 5)

The bentonite bed at the top of the member is at the top of the cliff in the left foreground. Beds of siltstone concretions lie in bands below, and a sandstone bed in the Third Wall Creek member forms the skyline on the left.

Plate 16

Frontier-Mowry contact at Coal Creek (Section 2)
The basal bentonite of the Frontier formation forms a gray band on the hillside, and the hard top bed of the Mowry shale protrudes from beneath the bentonite. The hillside to the left is Mowry shale, and the Lower shale member of the Frontier formation lies on the right.

Biography of the Author

Donald F. Towse was born Dec. 5, 1924 in Somerville, Mass. and was graduated from Stoneham High School, Stoneham, Massachusetts in June, 1942. He received a Hayden Memorial Scholarship and entered the Massachusetts Institute of Technology in September, 1942. He enlisted in the Navy in December, 1942, served in the Pacific area, and re-entered the Institute in November, 1945. He was graduated with the degree of Bachelor of Science in Geology in June, 1948 and entered the Graduate School of the Massachusetts Institute of Technology in September, 1948.

He was employed as a geologist by the Amerada Petroleum Corporation during the summers of 1948 and 1949, and was a Teaching Fellow in Geology at M.I.T. in the academic years 1948-1949 and 1949-1950.

He accepted permanent employment as a geologist for the Amerada Petroleum Corporation at Casper, Wyoming in August, 1950.

He is a member of the following scientific and honorary societies: Society of the Sigma Xi (Member), The American Association of Petroleum Geologists (Junior Member), and the American Institute of Mining and Metallurgical Engineers (Junior Member).

APPENDIX

Table 2

Location of Stratigraphic Sections

Surface Sections

Natrona County

1. East of Alcova. Sections 31 and 32, T. 30N., R. 82W. and Sections 4 through 7, T. 29N., R. 82W.

1a. Northeast of Alcova, on Highway 220. Section 8, T. 30N., R. 82W.

1b. Ledge Creek, east of Alcova. Sections 35 and 36, T. 30N., R. 82W.

1c. Spindletop. Northeast quarter of Section 30, T. 30N., R. 81W.

1d. Bates Creek anticline. Southeast quarter of Section 30, T. 31N., R. 81W.

1e. Bates Creek anticline. Section 4, T. 30N., R. 81W.

1f. " " " Sections 9 and 10, T. 30N., R. 81W.

1g. " " " Section 11, T. 30N., R. 81W.

1h. On Bates Hole road, Sections 9 and 16, T. 31N., R. 80W.

2. Coal Creek valley, southwest of Casper. Sections 28 and 36, T. 32N., R. 81W.

2a. Goose Egg. Section 1, T. 32N., R. 81W.

3. West end of Casper Mountain, Sections 31 and 32, T. 33N., R. 80W.

3a. Northwest flank of Emigrant Gap anticline. Sections 13 and 14, T. 33N., R. 81W.

3b. Southwest flank of Emigrant Gap anticline, south of the Poison Spider road. Section 15, T. 33N., R. 81W.

4. Oil Mountain. Section 35, T. 33N., R. 82W.

5. West end of Emigrant Gap anticline. Sections 9 and 10. T. 34N., R. 82W.

5a. Pine Mountain, east side. Section 29, T. 35N., R. 83W.

5b. Pine Mountain, north side. North half of Section 22 and south half of Section 15, T. 35N., R. 84W.

7. Northeast of Arminto. Section 33, T. 38N., R. 86W.

8. Wall Creek valley, south of Tisdale anticline. Sections 7 and 8, T. 39N., R. 82W.

9. Tisdale anticline, southwest flank. Sections 29 through 31, T. 41N., R. 81W.

Johnson County

9c. Tisdale anticline, northeast side. Sections 13 and 18, T. 41N., R. 81W.

10. Kaycee anticline. (Measured by J. D. Gorder and D. F. Towse), Section 4, T. 43N., R. 82W.

11. Near Mayoworth. Sections 13 and 14, 23 through 35, T. 45N., R. 83W.

Lithologic Well Logs

Natrona County

1. Wallace Creek, Bay and Superior No. 1 Unit, SE SW NE Section 15, T. 34N., R. 87W.

2. Natrona area, British-American No. 1 Unit, NE NE SW Section 27, T. 36N., R. 83W.

3. Hat Six, Yellowstone Drilling State-A No. 1, SW NE SE Section 1, T. 32N., R. 78W.

Converse County

4. South Cole Creek, Phillips No. 1 Unit, SW SW NW Section 17, T. 34N., R. 76W.

Natrona County

5. North Cole Creek, General Petroleum Government No. 7-8, NW SW SW Section 8, T. 35N., R. 77W.

6. Sage Spring Creek, Amerada No. 4 Unit, Center of the south half of NW NE Section 7, T. 36N., R. 77W.

7. Sage Spring Creek, Amerada No. 1 Unit, Center of the SW SE Section 30, T. 37N., R. 77W.

8. Sage Spring Creek, Amerada No. 6 Unit, Center of the SW SE Section 35, T. 38N., R. 78W.

Johnson County

9. Sussex, Continental No. 1 Unit, NW NW SE Section 17, T. 42N., R. 78W.

10. Smith's Cut, Amerada No. 1 Unit, Center of the SE SE Section 10, T. 44N., R. 79W.

11. Reno Hill, Amerada No. 1 Pheasant, Center of the SE NW Section 18, T. 45N., R. 80W.

Electric Well Logs

Natrona County

A. East Salt Creek, Keniland Oil and Gas, Government No. 1, SE SE SE Section 15, T. 40N., R. 78W.

B. Salt Creek, Stanolind No. 21 T.P.X., SW Section 35, T. 40N., R. 79W.

C. Tisdale, Norris Oil Government-Hill No. 88-25, SE SE SE Section 25, T. 40N., R. 81W.

Johnson County

D. East Meadow Creek, American Liberty No. 1 Irwin, NW NW NW Section 7, T. 41N., R. 77W.

E. South Meadow Creek, Macauley and Dorough No. 1 Government, SW SW SE Section 22, T. 41N., R. 78W.

F. Meadow Creek, Continental No. 2 Unit, NE SW SE Section 2, T. 41N., R. 78W.

Converse County

G. Glenrock, Ralph Lowe No. 1 Barber, SW NW NE Section 17, T. 33N., R. 75W.

H. Big Muddy, Continental No. 30 Kinney, SE NE SW Section 4, T. 33N., R. 76W.

K. South Big Muddy, Western Oil Fields No. 1 Barber-State, Center of the SE NW Section 22, T. 33N., R. 76W.

Natrona County

J. Evansville, Yellowstone Drilling No. 1 Pratt, NW NW NE Section 13, T. 33N., R. 79W.

L. Airport, Commercial Oil and Gas No. 1 Rubush, NE NE SE Section 35, T. 35N., R. 80W.

M. Midway, Kerlyn Oil No. 1 Midway, NW SE NW Section 23, T. 35N., R. 79W.

N. Gothberg, Cities Service No. 1 Government NW NE SW Section 22, T. 36N., R. 82W.

O. Hell's Half Acre, Ohio No. 1 Government-Boston, NW NE NE Section 32, T. 36N., R. 85W.

P. North Geary, Continental No. 1 McGarth, Center of the NW SW Section 15, T. 34N., R. 78W.

PR. Powder River, Stanolind No. 1 LaFleiche, NE SE SE Section 23, T. 36N., R. 85W.

Q. Castle Creek, Oil, Inc. No. 1 Government-Davis, NW NW NE Section 24, T. 38N., R. 81W.

R. Salt Creek, Stanolind No. 8-T, Center of the NW SW Section 26, T. 40N., R. 79W.

Table 3

Thickness and Sandstone Content of Stratigraphic Sections

Outcrop Data

Section	Column 1 Thickness of Frontier formation	Column 2 Total sandstone in Frontier formation	Column 3 Total sandstone, First Wall Creek memb.	Column 4 Total sandstone, Second Wall Creek memb.	Column 5 Total sandstone, Third Wall Creek memb.
1	977 feet	45 feet	30 feet	10 feet	0 feet
1a	---	10 plus	10	---	---
1b	---	30	30	0	0
1c	---	38	34	0	3
1d	---	74	56	14	0
1e	834	58	42	10	10
1f	---	58	40	15	5
1g	---	69	64	0	5
1h	---	118?	103?	15	0
2	915	160	93	17	50
2a	less than 935	80	41	24	15
3	983	151	68	39	46

Table 3 (continued)

Section	Column 1	Column 2	Column 3	Column 4	Column 5
3a	---	85	15	15	55
3b	713	84	54	26	4
4	780	134	98	13	21
5	798	179	63	18	81
5a	911	259	140	49	70
5b	Approx. 887	192	70 plus	88	59 plus
7	865	168	73	21	75
8	Approx. 840	220	83	28	88
9	805	223	80	58	70
9c	---	193	90	80	21
10	835	55 plus	35	0	20
11	Approx. 875	76	30	0	60

Lithologic Well Log Data

Well	Column 1	Column 2	Column 3	Column 4	Column 5
1	660	130	30	20	80
2	910	390	180	80	130
3	865	205	145	50	10
4	865	335	170	115	50
5	870	315	230	15	70
6	896	215	175	40	0
7	905	250	185	65	0
8	900	215	160	55	0

Table 3 (continued)

Well	Column 1	Column 2	Column 3	Column 4	Column 5
9	818	195	115	80	0
10	620	20	20	0	0
11	---	35	20	15	0
Electric Log Data					
A	900	170	100	70	0
B	875	190	105	75	10
C	---	165 plus	50	90	25
D	870	125	100	20	5
E	862	135	75	60	0
F	865	135	80	50	5
G	840	200-300	180	10-110	10
H	935	200	175	15	10
K	875	150	120	20	10
J	---	170 plus	170	---	---
L	890	215	120	80	15
M	885	255	135	95	25
N	795	270	120	50	100
O	---	217	125	46	46
P	855	305	210	20	75
Q	955	320	130	60	130
R	855	195	120	75	0
PR	855	351	184	67	100

Table 4

Texture of Sandstones in the Third Wall Creek member

Section	Position	Median Diameter (mm.)	Sorting	Remarks
2	490-540	.09	1.06	Shaley.
3	495-543	.13	1.30	Conglomerate upper part, shaley base.
3	640-45	.09	1.22	
4	510-35	.10	1.25	
5	465-78	.11	1.20	Slightly shaley.
5	-545	.12	1.23	
* 5b	535-655	.11	1.29	
* 5b		.10	1.20	
7	520-80	.11	1.22	Conglomerate in upper part.
7	620-42	.12	1.34	Conglomerate upper part, shaley base.
8	440-500	.11	1.22	
8	-530	.11	1.22	Shaley.
8	680-710	.12	1.24	Shaley, conglomerate in upper part.
9	480-575	.11	1.17	
11	409-11	.20	1.80	Conglomerate, binodal frequency curve.
11	418-37	.15	1.34	Conglomerate at top.
11	530-62	.12	1.20	Shaley.

Note: In Tables 4 through 6, position is given in feet below the top of the First Wall Creek member, with values taken from the graphic cross-sections (Plates 1-5).

Sorting is the sorting coefficient, the square root of the ratio of the 25-percentiles and 75-percentiles.

* Actual samples are from Section 6, a section measured in a faulted area close to Section 5b. Actual position of samples converted to position in Section 5b by correlation.

Table 5

Texture of Sandstones in the Second Wall Creek member

Section	Position	Median Diameter (mm.)	Sorting	Remarks
1	441-46	.10	1.22	
1	480-84	.09	1.12	
2	455-80	.11	1.23	Shaley, conglomerate at top.
4	355-60	.12	1.34	Conglomerate.
4	389-92	.12	1.36	
5	360-80	.11	1.37	Conglomerate.
5	-85	.11	1.30	Shaley base.
*5b	320-405	.11	1.19	Conglomerate at top.
7	258-62	.12	1.43	
7	288-90	.22	1.79	
7	412-30	.11	1.12	
8	250-52	.15	1.69	Conglomerate.
8	260-68	.15	1.57	Conglomerate.
8	290-305	.11	1.44	
9	480-575	.11	1.16	Bottom two-thirds shaley.

Table 6

Texture of Sandstones in the First Wall Creek member

Section	Position	Median Diameter (mm.)	Sorting	Remarks
1	0-15	.15	1.52	
1	260-65	.12	1.45	Conglomerate at top.
2	0-50	.13	1.41	
2	260-65	.11	1.37	
3	0-10	.13	1.48	
	-25	.13	1.40	
3	148-188	.11	1.23	Shaley.
3	208-10	.11	1.49	
3	298-308	.16	1.59	Conglomerate at top.
4	0-30	.14	1.39	
	-75	.14	1.35	
4	188-212	.10	1.28	Conglomerate at base.
5	0-10	.10	1.26	
5	105-40	.11	1.25	
5	165-72	.11	1.38	Slightly conglomeratic upper part.
	-98	.14	1.56	
*5b	0-60	.11	1.41	Shaley base.
*5b	240-50	.10	1.21	Conglomerate at top.
		.10	1.27	
7	0-25	.10	1.18	Shaley.

Table 6 (continued)

Section	Position	Median Diameter (mm.)	Sorting	Remarks
7	54-95	.10	1.23	Shaley
7	115-26	.11	1.54	
8	0-10 25-35	.10	1.29	
8	55-60	.10	1.21	
8	88-100	---	---	Not measured.
8	114-60	.12	1.47	Shaley.
9	0-65	.12	1.34	
9	160-77	.10	1.29	Conglomerate at top.
11	0-28	.10	1.25	Shaley base.

OIL FIELDS

There have been oil fields in the Powder River Basin for many years, and they produce oil from several Cretaceous, Jurassic, and Pennsylvanian formations, but this report will deal in detail only with those fields which produce from the Frontier formation. Figure 3 shows those producing fields which penetrate the Frontier, but not all of them produce from the Frontier formation.

Espach and Nichols (1941) have summarized the history of the oil and gas fields of Wyoming, and the data on the older fields presented here are taken largely from their work.

Salt Creek.- Salt Creek field was discovered in 1906, and since then the "First", "Second", and "Third Wall Creek sands" have proven productive. In 1908 a well drilled to the "First Wall Creek" produced initially 200 barrels per day. Initial production of 105 wells drilled to the "First Wall Creek" from 1908 to 1919 averaged 335 barrels per day, with one producing initially 4,000 barrels a day. Approximately 2,500 acres are oil bearing in the "First Wall Creek sand", with a recovery to 1938 of 17,272 barrels per acre. The oil ranged from 37 to 41 degrees A.P.I. gravity, with some gas in solution. Total production (to 1938) from the "First Wall Creek sand" was 43,180,787 barrels.

Production was discovered in the "Second Wall Creek sand" in 1917 with an initial production of 60 barrels per day. The initial production averaged 669 barrels per day for 339 wells drilled from 1917 to 1921, and the largest well produced over 10,000 barrels per day. The oil ranged from 33 to 38 degrees A.P.I. gravity, with an "appreciable" amount of dissolved gas. Total production was 207,251,372 barrels, over 80 per cent of the field's production to 1938. With 20,500 productive acres, recovery was 10,110 barrels per acre.

The "Third Wall Creek sand" was proven productive in 1923, but production is not consistent, due to the lenticular character of the sand. Twenty-three wells in the south and southwest part of the field produced from the "Third Wall Creek sand", averaging 37 degrees A.P.I. oil, with a total to 1938 of 530,085 barrels.

Naval Reserve No. 3 Teapot Dome, had similar production. It is now shut in.

<u>Big Muddy</u>.- Frontier production in Big Muddy field is from the "First Wall Creek sand". The field was discovered in 1916, and in 1917 a well in the "First Wall Creek sand" produced 128 barrels per day. In 1938, 114 wells produced 900 barrels of 35 degree A.P.I. green oil per day from the Frontier. The largest production was 30 barrels per day, with other wells producing between 2 and 25 barrels per day.

<u>Midway</u>.- The Midway field has a small production from the "Second Wall Creek sand", and was discovered in 1931 with 400 barrels of 31 degree A.P.I. oil initial daily production. In 1938, two wells were producing about 50 barrels of oil a day, and in 1932 the field produced a peak of 27,489 barrels. A recent well, Midway Oil Corp. Gov't. No. 5, completed in January 1951, had an initial daily produc-

tion from the "Second Wall Creek sand" of 75 barrels of 33 degree A.P.I. oil and 50 barrels of water, pumping.

Sussex and Meadow Creek.- Four wells produce oil from the Frontier formation in the large Sussex-Meadow Creek area in southern Johnson County. Shows of oil and gas have been reported and tested in both the First and Second Wall Creek members. Petroleum Information (Dec. 22, 1950) reported that one well in Sussex had a potential of 35 barrels of oil per day and that the Continental No. 16 Unit, Section 11, Township 41N., Range 78W. had an average flow potential of 150 barrels of oil per day. Initially it pumped 200 barrels of 41.7 degree A.P.I. oil per day from the "Second Wall Creek sand". No. 9 Unit pumped 240 barrels of 38.4 degree A.P.I. oil per day, and No. 15 Unit flowed 234 barrels of 42.6 degree A.P.I. oil per day.

Continental No. 10 Unit, Section 23, Township 42N., Range 78W., at Sussex, had an initial production of 144 barrels of 40.5 degree A.P.I. green oil per day, with .4 per cent basic sediment and water. Production is from the "First Wall Creek sand" at 6372 feet.

Continental's No. 1 Unit at Sussex, Well 9 of this report, proved dry in the Frontier sands. A drill stem test of the First Wall Creek member recovered mud with a gas odor. A core in the interval 6717-6750 feet found saturated sand, but a drill stem test recovered salt water.

Powder River.- The Powder River field, near the town of Powder River, has produced small quantities of gas and oil from the sandstones in the First and Third Wall Creek members of the Frontier formations. A small volume of gas was discovered in the First Wall Creek member in 1917, and in the next 14 years 11 wells were drilled. Two wells reported initial productions of 75 and 100 barrels of oil per day from a sandstone in the Third Wall Creek member, but the field was never produced commercially and was virtually abandoned in 1938. The Stanolind Oil and Gas Company drilled the No. 1 LaFleiche well there late in 1944. Petroleum Information (September 1944 to February 1945) reported no tests of the Frontier formation and reported that the well was completed in the Sundance formation as a gas producer. Thompson, et al (1949, Section 11) show no staining in the Frontier formation. The No. 1 LaFleiche is Well PR of this report, and the electric log figured in Cross Section D, Plate 4.

Arminto and Lox.- These small gas fields produce gas from the Second Wall Creek sand. The Arminto anticline is in Sections 17 through 20, Township 37N., Range 86W., Natrona County, about 3 miles south of Surface Section 7 of this report. A well at Arminto in 1917 produced 200,000 cubic feet of gas daily, and one in 1923 produced 5 million cubic feet daily. Beginning in 1932 the gas was produced for domestic production at Arminto. Lox is in Sections 34 and 35. A well there in 1921 produced 3 million feet of gas daily and was abandoned, and in 1920 a dry hole was drilled.

Castle Creek.- This small oil field produces oil from sandstone in the Second Wall Creek member. The Oil, Inc. Gov't.-Davis No. 1, in Section 24, Township 38N., Range 81W., was completed and abandoned in November 1947, plugged back to 2269 feet, perforated from 2260 to 2269 feet, and swabbed 40 barrels of oil and 760 barrels of water in 24 hours. That well is Well Q of this report, and four additional wells have been drilled. The best well pumped 40 barrels of oil per day initially; another pumped 20 barrels per day; one swabbed 1 barrel of fluid (60% 27 degree A.P.I. oil) per hour and was abandoned; and one was dry and abandoned.

A recent completion at Southeast Castle Creek, Atlantic Refining Gov't. No. 1, in Section 32, Township 38N., Range 80W., tested the interval 2413 to 2443 feet, probably in the same Second Wall Creek member sand, and recovered mud and fresh water.

Correlation of the wells at Castle Creek with other wells and outcrops is difficult. The thick sandstone in the Third Wall Creek member is near the top boundary of that member, whereas the thick sandstone in the Second Wall Creek member is close to the base of that member, with the boundary between members probably within a 10 to 15 foot shale break between the two sandstones. Others have called a poor sandstone in the lower part of the First Wall Creek member the "Second Wall Creek sand" and have called the thick basal section, which produces in its upper part, the "Third Wall Creek sand".

Billy Creek.- Billy Creek field, though north of the area of this report, is of interest because it has produced gas from a Frontier sandstone. The field is in the west half of Township 48N., Range 82W., Johnson County, close to the Bighorn Mountains. In 1923 the discovery well tested 58 million cubic feet of gas per day. Eleven wells were drilled to the Frontier; of these, one produced 20 degree A.P.I. oil, and eight produced gas. The producing sand, according to Boyer (1935), is correlative with part of the Wall Creek sandstone member at Salt Creek. The field is now used as a gas storage reservoir.

LITHOLOGIC DESCRIPTIONS

In the following detailed discussions, the outcrops and wells studied will be described in the order in which they are figured in cross-sections A through E (Plates 1 through 5). Light and dark colored chert and frosted quartz are present in all the sandstones, and they are, therefore, not listed in the descriptions. Textural analyses are given in Tables 4 through 6.

Third Wall Creek member.- The upper boundary of the member is partly covered in section 1, and it lies somewhere in a partly covered section of dark sandy shale which contains some bentonite. The lower part of the member is dark sandy shale with thin sandstone streaks, and there is no distinct sandstone bed. Section 1c is contorted and faulted at the bottom, but a 3 foot bed of coarse sandstone there may be in the Third Wall Creek member. Most of the member at 1e is covered, but one outcrop contains 10 feet of coarse sandstone with some black pebbles as much as 1/2 inch in diameter.

The top part of the member at section 2 contains 50 feet of shaley, thin-bedded sandstone which is more shaley at the bottom. Minerals include rounded, frosted quartz, black chert, biotite, occasional magnetite, fresh muscovite, small amounts of coal, and bentonite. The rock is hard and gray, weathers brown, and the cementation is variable.

There are two sandstone bodies, and upper, thick, conglomeratic unit and a thin lower bed, in the member at section 3.

The top 7 feet of the upper sandstone are conglomeratic, with erratic small pebbles on the bedding planes, and the rest of the unit is light-colored salt-and-pepper sandstone with shaley streaks. The top is coarse; the middle is thick-bedded; and the base is shaley and contains numerous walnut-size concentrations of sandstone and individual sandstone and shale stringers that pinch and swell. The sandstone is channelled into the shale below, and stringers of sandstone pinch out to the south. There is a 12 foot cross-bedded unit in the middle of the sandstone, and it has steep cross-beds which dip northeast and shallow cross-beds which dip southeast. Shallow cross-beds which lie 5 feet above the base dip 2 degrees southeast. The cross-beds in the middle of the unit are the type figured and described by Shrock (1948, p. 251) and explained as the result of rapidly shifting currents that scour channels,then backfill them.

The member in well 3 has very little sandstone, with the exception of tight shaley streaks interbedded in the shale and a 10 foot bed of fine-grained, tight, gray sandstone. The electric log at Big Muddy (Well H) indicates similar lithology. Both wells 4 and 5 have several beds of fine to medium grained, tight to medium porous, gray, shaley sandstone. The sandstones of well 4 contain feldspar and glauconite, and those in well 5 have clear quartz and a small amount of coal in the top bed. Wells 6, 7, and 8 have similar sandstones in poorly defined streaks. The upper sandstones contain clear quartz, but it is absent in the lower parts.

The Salt Creek well (B) has a high resistivity and some self-potential on the electric log. The "Third Wall Creek sand" at Salt Creek, according to Thom and Spieker (1931) has two benches of medium grained, dirty white sandstone, an upper bench of 25 feet and a lower one 30 to 40 feet thick. The lower bench is seldom found at Salt Creek and the upper bench is very lenticular. In producing wells the sand averages 20 feet thick, is thin and tight, and occurs only in strips or scattered patches. It probably has its principal development in the southeast part of the field.

Electric logs north of Salt Creek show little indication of porous sand development. Third Wall Creek samples in wells 9 and 10 have only streaks of fine, tight, shaley, gray sandstone, and there is some brown sandstone and siltstone in well 10 and a small amount of coal in the top of the member.

Outcrops and wells between Coal Creek and Powder River generally have good sandstone development, but have no conglomerates. There is some oil staining in well 2. There are 21 feet of sandstone in the member at section 4. The sandstone there is thin-bedded, carbonaceous, and the top 3 feet are massive. The quartz is frosted, and the other minerals include 10 per cent feldspar, glauconite, calcite, and a small amount of coal.

There is more sandstone at section 5. There are 81 feet of thin-bedded, salt-and-pepper colored sandstone with very thin shale partings. The top 10 feet are less carbonaceous, and the outcrop has a hard, brown top surface which is produced by weathering. Cementation is good except in the middle part, and grain shape varies from angular to subround. Frosted quartz and gray and black chert are abundant, and there is a trace of clear quartz and some glauconite in the upper part of the sandstone. Coal is first present in the middle of the sandstone, and its amount increases downward. Other minerals include muscovite, biotite, 5 to 10 per cent feldspar, and calcite. Black shales with thin sandstone streaks lie above and below the sandstone.

Well 2 contains a thick sandstone which has gray shaley sandstone and shale streaks at the top and the bottom. The main body of the sandstone is fine to medium grained, salt-and-pepper color, porous, and glauconite is abundant in the top 10 to 15 feet.

Rocks of similar lithology are exposed at section 5b. The sandstone there is soft and thin-bedded, and the basal part is shaley. The top of the sandstone is poorly exposed, and the outcrop is a series of resistant sandstone ledges separated by partly covered shaley intervals.

Well 1, in the Wind River Basin, penetrated a Third Wall Creek section that contains only thin sandstone streaks. The sandstones are coarse to medium grained, and there is some brown sandstone and siltstone. The samples from 10,030 to 10,040 feet had a light oil stain with slight fluorescence.

The outcrops along the flank of the Bighorn Mountains have thick sandstone beds and numeroud conglomerates in the Third Wall Creek member. Section 7 has two thick sandstone beds. The top bed is medium grained, and the lower one is thin-bedded and coarse grained. Thin conglomerates are present at the top of both sandstone bodies. The upper sandstone is rust-colored, and the grains are angular to subround. The quartz at the top is frosted, that near the base clear. Minerals include calcite and small amounts of biotite, muscovite, glauconite, and coal. There is less calcite and glauconite in the basal part of the bed. The lower sandstone bed is well cemented, and the grains are angular to subangular. Minerals include clear quartz grains which have a few crystal faces, 10 per cent feldspar, biotite, and coal.

The conglomerate pebbles are subangular to subround and 2 to 40 mm. in diameter. The pebbles are quartzite, light and dark chert, mottled pink quartzite, and dark, fine-grained igneous rock. All the pebbles are smooth, and the smaller ones are polished.

Section 8 has two widely separated thick sandstone bodies. The top two-thirds of the upper sandstone is massive, and there are trails on the bedding surfaces. Shallow cross-beds dip in two directions, south west and northeast. The drift on top of the upper sandstone contains red sandstone and pebbles which indicate a now covered or eroded conglomerate on the top of the sandstone. The lower part of the bed is thin-bedded, with shaley carbonaceous streaks and thin coal seams, and the top is channelled and filled with cross-laminated sandstone whose cross-beds dip south and southeast. A 1/4 inch coal seam lies 20 feet from the base, and the beds at the base are thinner and more shaley than those at the top. The sandstone is finer grained at the bottom than at the top. Angular clear quartz is present in trace or small amounts, and feldspar content varies between 5 and 10 per cent. Glauconite is present throughout and is abundant in the lower part of the unit. Other minerals include biotite, small amounts of pink quartz and coal, and calcite. The loose pebbles at the top range in diameter from 17 to 70 mm. and include much yellow chert and some dark chert.

The lower sandstone has at its top an 18 inch conglomerate bed with a rippled top. The sandstone grains are angular to subangular, with most grains about .3 mm. in diameter. There is about 5 per cent feldspar and a small amount of pink quartz in the middle of the unit, and other minerals include coal, biotite, and a small amount of calcite. There is a trace of glauconite at the top, more in the middle, and none at the base. Conglomerate pebbles are from 2 to 40 mm. in diameter and are mostly fine black chert. One of the chert pebbles in thin section contained round- and egg-shaped oolites with needle-like centers.

There is one thick sandstone body in the member at section 9. The top 25 feet are thin-bedded and clean, and the lower part has shaley partings and thicker shale beds near the base.

Minerals include small amounts of angular clear quartz and pink quartz, 10 per cent feldspar, glauconite, biotite, a small amount of magnetite, and much calcite. The shaley sandstone has grains that are angular to subangular and are mostly about .15 mm. in diameter. Minerals include a small amount of angular clear quartz, 5 per cent feldspar, a trace of frosted pink quartz, biotite, glauconite, a trace of coal, and no magnetite or calcite.

Section 9c, a short distance away, has much less sandstone, with a top bed of sandstone, shale, and conglomerate 15 feet thick. An 18-inch conglomerate near the top of the unit has shallow cross-beds, fish teeth, and pebbles as much as 1 inch in diameter. The thicker sandstone bed has thin shale partings and included fragments of shale.

Section 10 has 20 feet of sandstone exposed in the member. The sandstone is salt-and-pepper in color and has trails and rust spots the size and shape of buckshot.

Section 11 has sandstone in two places. One conglomeratic sandstone is at the top of the member, and a shaley unit is close to the base.

Measured section of the Third Wall Creek member, Section 11

Bed (descending order)	Description	Thickness
L.	Bentonite with a small amount of gypsum. The bottom is white and platy, and the top is green and flaky.	13 feet

M. Covered. Shale with thin sandstone is probable. 25 feet

N. Coarse sandstone. Conglomerate scour fillings are at the top, and they have cross-beds that dip southeast. There is thin sandstone and shale above. 3

O. Thin sandstone and shale. 8

P. Sandstone, thin-bedded at the top. Cross-beds dip southeast, and there is a conglomerate bed with an irregular base at the top. Pebbles are dark chert and trachyte porphyry, and there are a few pebbles scattered throughout the lower part of the bed. 18

Q. Shale with thin sandstone. Partly covered 95

R. Sandstone, 1/2 to 2 inch beds with 1/2 to 1 inch shale partings. 5

S. Sandstone, soft, friable, with 1 to 2 inch shale partings. The base is covered. 25

Bed N has a salt-and-pepper matrix, and the grains are angular to subround. Minerals include frosted quartz, gray and black chert, 10 per cent feldspar, a small amount of frosted pink quartz, dark chert, round grains and shreds of magnetite, and no calcite. Pebbles are from 2 to 35 mm. in diameter and angular to subround, and most are 5 to 10 mm. in diameter. They are dark chert, feldspar, trachyte porphyry and quartzite. There are no teeth in the conglomerate.

The trachyte porphyry has large white phenocrysts in a fine grained green groundmass, with large phenocrysts of orthoclase and microcline and a few rusted hornblende crystals contained in a very fine grained groundmass of similar mineralogy. The feldspars were badly altered and zoned.

Bed P is a salt-and-pepper sandstone with angular to subround grains. Minerals include frosted quartz, angular clear quartz, gray and black chert, a small amount of frosted pink quartz, 5 per cent feldspar, s small amount of biotite and glauconite, platy angular magnetite, and calcite. The conglomerate pebbles are similar to those in Bed N.

Bed R has 40 per cent salt-and-pepper colored sandstone, and the grains are subangular to round. Minerals include a small amount of angular clear quartz and biotite, glauconite, less than 5 per cent feldspar, and a trace of calcite.

Bed S is 90 per cent sandstone, and the grains are angular tO subangular. Minerals include a small amount of glauconite and biotite.

Second Wall Creek member.- Section 1 contains three sandstone bodies in the member, and all are 5 feet or less in thickness. They are medium to fine grained, and the middle sandstone may be conglomeratic. Pebbles were found on the slope above the middle sandstone, but none were found in the exposed outcrop. The upper sandstone is quite shaley, dark brown, and has much clay material.

Grains are angular to subround and include clear quartz, 15% feldspar, 20% coal, a trace of glauconite, and much calcite. The middle sandstone is salt-and-pepper in color, and grains are angular to subangular. Minerals include a few clear quartz grains with some crystal faces, 10% feldspar, abundant glauconite, biotite, magnetite, and much calcite. Beds are about 1/8 inch thick. The lower sandstone is fine grained and has subangular to round grains. Included is a small amount of coal, 5% feldspar, and calcite. Section 1c has very little sandstone. There is a 1 foot thick bed near the top of the member and thin streaks of sandstone interbedded with the sandy shale in the lower part.

Near the top of the member at section 1e are two 5 foot beds of sandstone. The upper bed is fine conglomerate with black and white pebbles as much as 1/4 inch in diameter, and the lower one is a salt-and-pepper sandstone with come cross lamination. Section 2 has a relatively thick sandstone in a unit totalling 21 feet. The upper part of the unit is a salt-and-pepper conglomerate that has scattered pebbles throughout and that has trails and cross-beds that dip southeast. Most of the lower part of the unit has shale beds and is thin bedded. The sandstone is fine grained and contains frosted, mostly subangular, quartz and a few angular and round grains. Also included are black chert, biotite, and much fine interstitial clay material. Conglomerate pebbles are mostly discoidal and ovoidal gray chert 1/2 to 1 1/4 inches in diameter, and there are a few white soapy-feeling quartzite pebbles, one of irregular hard ironstone, and one 1/4 inch disc of quartzite pebbles cemented with iron oxide. At section 2a a short distance away, only 12 feet of massive sandstone with cross-beds and burrows and trails is exposed. Its top and bottom are covered.

Section 3 has a thick section of sandstone, and there is very little shale in the member. The sandstone is fine to medium grained, hard, and white to rust colored. Cross-beds in the top dip southeast and northeast in separate 6 inch to 1 foot thick beds. The base of the sandstone has sandy shale in 1/2 to 1 1/2 inch beds. The sandstone is salt-and-pepper, shaley in part, with grains angular to subround, and a few grains are round. Minerals include clear quartz with crystal faces, glauconite, 5 to 10 per cent feldspar, a small amount of biotite, variable amounts of magnetite and calcite, and a trace of pink quartz.

Well 3 has 20 feet of sandstone with slight oil stain and fluorescence in the Second Wall Creek member. The sandstone is medium grained, salt-and-pepper in color, and hard and tight. The remainder of the member is shale with sandstone streaks and some bentonite. The member at well 3 has begun to thicken from the minimum at section 3. Well H at Big Muddy shows in electric log very little permeable sandstone development.

Well 4 has a thick unit of sandstone, but most of it is shaley, with shale interbedded, and there is more shale toward the base and a few chert pebbles in the middle of the unit. The sandstones are medium to fine grained, gray, and salt-and-pepper in color. Most of the member in well 5 is very sandy shale with sandstone streaks. There is a thin, medium to coarse grained, porous sandstone containing clear quartz in the middle of the unit.

The sandstones in the member in wells 6, 7, and 8 are coarse to medium grained, salt-and-pepper in color, and contain shale streaks. Porosity decreases to the north, and there is less sandstone and more shale. Minerals include clear and pink quartz in small amounts and some glauconite and shell fragments in well 7. A drill stem test of the sandstone in well 8 recovered very slightly oil and gas cut mud. That sandstone is abundantly glauconitic in the basal part, and it has a few white chert pebbles as much as 2 1/4 mm. in diameter at the top.

Thom and Spieker (1931) described the "Second Wall Creek sand" at Salt Creek as a number of layers with sandstone and shale streaks. The sandstone beds vary from 20 to 100 feet thick and average 75 feet thick in the north and 60 feet thick in the south. There are three or more sand layers separated by thin bentonitic shales which are 2 to 25 feet thick. The electric log of well B illustrates that lithology, and it shows more resistance and potential than either of the wells to the north or south that are figured in Plate 3.

Well 9 at Sussex has a thick sandstone section with some shaley parts. The sandstone is medium to coarse grained, salt-and-pepper color, and porous, and it is more shaley and has shale streaks in the base. Minerals include clear quartz, a trace of pink quartz, a small amount of weathered feldspar, biotite, and abundant glauconite. The shale is sandy with sandstone streaks. The upper part of the member is more bentonitic. Well 10 has several coarse sandstone streaks which contain some crystalline calcite chunks. Most of the member is bentonitic or sandy shale and thin sandstone streaks.

Well 11 has about 20 feet of tight salt-and-pepper sandstone with a small amount of calcite and clear quartz.

Section 4 has two dark salt-and-pepper sandstone bodies. The upper body has conglomerate at the top, and the lower body is thin-bedded and has a possible conglomerate at the top. The upper sandstone has angular to round grains, and the minerals include angular clear quartz, biotite, 5 per cent feldspar, magnetite, and much calcite. Pebbles are very abundant and constitute approximately 75 per cent of the conglomerate. The pebbles are round, smmoth, dark chert, and a few are polished. Most are from 3 to 5 mm. in diameter. The lower sandstone has a similar mineralogy, and the grains are subangular to round.

There is one well-developed sandstone in section 5. The top part is medium grained, and the bottom is thin-bedded and carbonaceous with shale partings. There is a 3 foot lense of conglomerate near the top which has small pebbles in a dark sandstone matrix, and cross-beds in the conglomerate dip southeast. The sandstone is salt-and-pepper sandstone, and its grains are subangular to round and are finer toward the base. Minerals include 5 to 10 per cent feldspar, glauconite, biotite, muscovite, a small amount of coal at the top, and a small amount of clear quartz.

Well 2 has a thick section of salt-and-pepper sandstone which is coarse and porous at the top and fine and shaley with shale streaks toward the base. There are grains of clear quartz at the top and no pink quartz. Section 5b has a thick section of sandstone which has a shaley interval in the lower part. The bottom part of the upper bench is fine grained and friable, whereas there are 6 inches of very pebbly conglomerate at the top. The conglomerate lies on a slightly irregular but mostly flat surface. The lower sandstone bench of the unit is shaley and has carbonaceous shale partings.

The sandstone in well 1 is thick and has a shale break in the middle. The top of the sandstone is medium to coarse grained, and there is a trace of bentonite, small oil stain, and fluorescence. Most of the sandstone is fine grained and shaley and has small amounts of coal, light brown calcite, and bentonite near the base.

The sandstone in section 7 is in three units, two thin beds near the top and a thicker bed near the bottom of the member. The top thin sandstone is medium grained, salt-and-pepper colored, slightly shaley, and thin-bedded, whereas the sandstone below it is coarse grained and slightly glauconitic. The sandstone at the bottom if fine grained and thin-bedded. The upper thin sandstone weathers brown and has many dark shaley streaks and burrows. Grains are angular to subangular, and the minerals present include a small amount of angular clear quartz, 10 per cent feldspar, biotite, glauconite,a small amount of coal, and much iron rust. There were in the sample one .08 mm. long fish scale impression and two .08 mm. long broken teeth. The lower, thin sandstone is coarser grained, and the grains are angular to subangular. The feldspar content is high, 30 per cent. Other minerals include clear quartz with crystal faces, a small amount of glauconite, and much calcite. The sandstone near the base of the member has angular to subround grains, and minerals include glauconite, 5 per cent feldspar, a small amount of coal, small amounts of clear and pink quartz, and no calcite.

The sandstones at section 8 include two thin upper conglomerate beds with coarse matrices and black, white, and pink pebbles and a thick lower sandstone that is shaley in its basal 2 feet. The conglomerates are similar; they have coarse salt-and-pepper matrices; and the grains are subangular to round. Minerals include 10 per cent feldspar, a small amount of clear quartz, glauconite, and much calcite. Pebbles are subangular to subround, and most of their diameters are about 9 mm. They include quartzite, a small amount of feldspar, light and dark chert, and fossilifersous oolitic chert with crinoid stem fragments. The basal sandstone is salt-and-pepper in color, and the grains are angular to subangular. Minerals include a trace of clear quartz, 5 percent feldspar, a small amount of frosted pink quartz, biotite, glauconite, and small amounts of magnetite and calcite.

Section 9 has two sandstones with conglomeratic tops. The upper sandstone is friable and fine grained with a conglomerate at the top . Most of the pebbles are greater than 1/2 inch in diameter. The sandstone is silty, with angular to subangular grains. Minerals include clear quartz, biotite, a small amount of glauconite, 5 per cent feldspar, and much calcite. The rock is cream-gray, friable, and poorly cemented. Pebbles are subrounded, and most are about 25 mm. in diameter. They are mostly dark chert and a few fine grained porphyry pebbles. A thin section of one dark chert pebble revealed partly recrystallized chert and Foraminifera of the genus Endothyra (an upper Paleozoic form), other unidentifiable individuals, and mollusc fragments. The lower sandstone is coarse and has conglomerate at the top. Most of the pebbles are less than 1/2 inch in diameter, but a few are as large as 1 1/2 inches. The sandstone has angular to subround grains, and minerals include clear quartz, 10 per cent feldspar, biotite, glauconite, a few shiny crystals of magnetite, and much calcite. Pebbles are subangular to subround; diameters range to as much as 40 mm., but most are about 5 mm. in diameter. They include dark chert, a few fine grained, dark, slightly porphyritic igneous rock pebbles and a few pink feldspar pebbles. There are a few gray and amber colored teeth which show little wear and are 2 to 10 mm. long.

Section 9c was described in detail at the beginning of the main text discussion of the Second Wall Creek member, and there are no sandstones exposed in sections 9 and 11. It is presumed that there are no important sandstone bodies in those sections, because thick sandstones where present are usually exposed even in partly covered outcrops.

First Wall Creek member.- At section 1 there are two sandstone beds in the member. The upper sandstone is 25 feet thick, salt-and-pepper color, and the beds are 1 to 6 inches thick. Cross-beds dip southeast. The lower sandstone is dark salt-and-pepper color, medium grained, and slightly conglomeratic with scattered pebbles throughout. The upper sandstone has angular to subround grains, and the minerals include clear quartz, a trace of pink quartz, glauconite, biotite, less than 5 per cent feldspar, and calcite. The lower conglomerate has angular to round grains, and the minerals include clear quartz with a few crystal faces, a trace of pink quartz, 10 per cent feldspar, biotite, a trace of glauconite, much calcite, and fibrous magnetite. It is well cemented, with scattered pebbles throughout, and with greater concentrations of pebbles in some beds. Pebbles range to 8 mm. in diameter, but most are about 2.5 mm. in diameter and are rounded or pea- to bean-shaped. They are milky quartz, dark and black chert, and sandstone.

Ten feet of sandstone are exposed at section 1a, 4 miles north of section 1. The sandstone is separated from the cream-colored calcareous, thin-bedded Niobrara shale by 280 feet of soft, gray shale which contains scattered zones of limestone concretions. The sandstone is thin-bedded, with 1 to 6 inch beds, and it is coarse-grained, with occasional small pebbles as much as 1/2 inch in longest dimension. Trails, burrows, and fish teeth are abundant. In a 6 inch cross-laminated layer the cross-beds dip southeast. There are many discoidal limestone boulders at the base of the sandstone that are as large as 18 by 8 inches. The limestone is gray, shaley, with a septarian network of brown to white calcite veins which contain a few galena crystals. The shaley limestone has been eroded, and the box-like network of calcite veins stands above the surface of the boulders. Hollows between the boulders are filled with conglomerate, with pebbles as much as 2 inches in longest dimension. The limestone boulders disappear within 20 feet along strike to the east, and the conglomerate becomes thinner. The base of the outcrop is covered on the west. The sandstone has angular to round grains which include clear angular quartz with a few crystal faces, 10 per cent feldspar, biotite, glauconite, and much calcite. The conglomerate grains are angular to subround, whereas the pebbles are egg-shaped and are mostly about 35 mm. in length. Minerals include biotite, small amounts of clear quartz, pink quartz, and glauconite, and much calcite. The pebbles are mostly dark colored, hard gritstone, and there are a few teeth and dark chert pebbles. Some of the pebbles are weathered, and the dark chert is well polished. The limestone boulders weather readily, leaving a 1 to 2 mm. thick network of raised polygonal calcite walls on the outer rounded surface. There is much yellow clay on the surface, and there are many rusty spots in the main part of the calcite. A thin section of the gritstone pebble from the conglomerate has rounded to angular grains "floating" in brown calcite. The grains are quartz, chert, and quartzite. Some of the quartz grains have undulatory extinction.

At section 1c there are 34 feet of coarse, salt-and-pepper sandstone in thin beds, and they contain irregular cross-beds and shaley streaks. The base is very calcareous and contains pebbles as much as 3/4 inch in diameter and fragments of Inoceramus. Limestone concretions which are similar to those at section 1a, except that they show no signs of erosion, are first encountered 24 feet below the base of the sandstone. They lie in widely separated bands within the black shale and thin sandstone streaks in the middle of the member.

Section 1e has two sandstone beds. The upper one is thin bedded, with trails and south dipping cross-beds near the top. The lower sandstone is massive and has cross-lamination and trails near the top. The lower part is thin bedded and shaley. The top limestone concretion bed here lies directly below the lower sandstone, and the base of the Niobrara formation is 273 feet above the top of the upper sandstone.

Two sandstones are exposed at section 2, and the rest of the member is covered. The soil cover indicates that the covered portions are sandy shale. The upper sandstone is 50 feet thick and is salt-and-pepper in color. The top and bottom are hard and massive, and the middle is friable and thin bedded. The lower sandstone forms a cliff, and it is salt-and -pepper color, is 43 feet thick, and is coarsest at the top. The beds are 2 inches to 1 foot thick and have shaley partings. The sandstone contains cross-beds which dip southwest, trails, and a 7 1/2 foot sandy shale bed and 6 inches of sandstone at the top. The upper sandstone has mostly angular to subangular grains and a few rounded grains. Minerals include clear quartz with crystal faces, biotite, some pink quartz, feldspar, a small amount of magnetite, and calcite. The lower sandstone has subangular to subround grains, and the minerals are like those in the upper sandstone body.

Section 2a has two units of sandstone. The upper unit is massive, cross-laminated, and thin-bedded in its lower part. The lower unit has four coarse beds: (in descending order) 10 feet of sandstone which has black shale 3 feet from the top and has septarian limestone concretions at the base; 2 to 5 feet of sandstone; 5 feet of sandstone with conglomerate; and at the base 4 feet of sandstone with scattered black pebbles. The covered areas presumably mark the presence of sandy shale. A few pelecypods of the genus Inoceramus and a few cephalopods of the genera Prionocyclus and Scaphites were found in some of the limestone concretions. Weathering and recrystallization made exact identification difficult, but the fossils appear to be the same kinds as those described by Wegemann (1918) from the Wall

Creek member at Tisdale. The fossils were not broken or abraded.

The member at section 3 has three thick sandstone bodies and a thin sandstone bed near the middle. The middle sandstone is dark brown, very calcareous, and it has irregular bedding. The grains are subangular to round, and the minerals include frosted quartz, clear angular quartz, gray and black chert, 10 per cent feldspar, green quartz, and much calcite. That bed is in a similar position to that of the concretions in section 2a, and it is considered to be equivalent to the concretion zone, but it is in a place where the supply of sand was sufficiently large that limestone deposition was prevented. (See line A, Plate 1.)

The top sandstone bed is cream to brown, salt-and-pepper, and trails and burrows 1/8 to 1/4 inch in diameter are present 1 foot from the top and 7 feet from the base. Cross-beds dip northwest in a 1 foot bed near the top,and 3 feet below that bed is a brown sandstone with cross-beds which dip southwest and southeast. Most of the beds are from 1 to 2 inches thick. The basal 10 feet are thin-bedded and shaley and contain some soft, sandy shale. The grains are subangular to round, and those at the base are more angular. Minerals include small amounts of clear quartz, pink quartz near the top, biotite, glauconite, 10 per cent feldspar, and variable calcite.

The second sandstone is shaley, has shale partings, and has beds 1 to 2 inches thick. Grains are angular to round, and the grains at the top are more angular. Minerals include clear quartz, biotite, 10 per cent feldspar, glauconite near the base, and calcite.

The lower sandstone is 6 to 10 feet thick, with a 1 foot bed of conglomerate 3 feet from the base. The coarsest pebbles are at the base of the conglomerate, which grades upward into sandstone, and the top of the outcrop is partly covered. The grains are mostly angular to subangular, but a few grains are round. Minerals include clear quartz with prism and pyramid faces, gray and black chert, glauconite, pink quartz, and much calcite. Pebbles are pea-shaped and range in size from 2 to 50 mm., although most are about 5 mm. in length. They are present in layers and are scattered throughout the bed. The pebbles include black chert, pink feldspar, and brown to pink quartz. The chert is weathered, and there are a few 1/2 by 1 mm. translucent, brown fish teeth.

Well 3 has a small bench of sandstone at the top and a thick lower sandstone near the base of the member. The top bench is salt-and-pepper color, glauconitic, and tight. The thick lower sandstone is fine grained to shaley, and the top and base are coarse grained. Minerals include pyrite, biotite, glauconite, and pink and clear quartz, and the porosity and cementation vary between extremes. Coal and bentonite are common near the base, and there are some iridescent shell fragments in the basal part of the sandstone body. The top part has slight oil stain and fluorescence.

The lower sandstone is medium grained, salt-and-pepper color, hard, and tight, and it has a slight stain and no fluorescence.

A small amount of shale is interbedded.

Well 4 has a thick sandstone bed with many shale breaks, and a conglomerate is present near the bottom of the bed. The sandstone is medium to coarse grained, salt-and-pepper color, and it is mostly tight and shaley. Minerals include pink and clear quartz, biotite, feldspar, pyrite, and wood in the middle. Bentonite and fibrous calcite are near the base. There is slight oil staining near the top. The conglomerate near the base of the member is very coarse grained and tight, and it contains large black and white chert pebbles.

There is a thick upper sandstone and a thinner basal one in well 5. The sandstone is medium to coarse grained, porous, and medium cemented, and there is a small amount of shale in the upper sandstone beds. Minerals include pink and clear quartz, much weathered feldspar, glauconite, biotite, and small amounts of bentonite. A tooth was found near the middle of the upper bed.

There is one thick, medium to coarse grained, salt-and-pepper sandstone in well 6. Shale streaks are scattered throughout the sandstone and are most common in the base. Minerals include pink and clear quartz, biotite, glauconite, and muscovite in the base. Porosity is generally good, and cementation is poor. The sandstone has slight oil stain throughout, but none of the samples examined had fluorescence.

Well 7 has two sandstone bodies. The upper body is medium grained, porous to slightly shaley, and has a conglomerate bed near the top and thin shale streaks at the base. The lower sandstone is medium grained, coarse at the top, medium porous to tight, and it has shale streaks through most of its thickness and gypsum at the base. Well 8 has one sandstone bed, which is fine to medium grained and porous in the upper part, but which is mostly shaley with shale stringers in the bottom part. There is a conglomeratic streak near the top. Minerals include clear quartz, biotite, and small amounts of bentonite. A pelecypod fragment was found in the middle of the unit.

According to Thom and Spieker (1931), the "First Wall Creek sand" at Salt Creek is continuous and averages 136 feet in thickness. There are two parts, an upper 80 to 100 foot sand and a lower 20 foot sand, which are separated by shale or hard limey sandstone. The lower sand seems to "pinch out entirely in some places." Wegemann (1918) described the sandstone as a medium grained, cross-bedded, dirty buff sandstone which contains petrified wood, shark teeth, and marine invertebrate shells at the outcrop on Tisdale anticline.

North of Salt Creek there is less sandstone in the First Wall Creek member. In well 9 the sandstone is fine to medium grained, with shale streaks, and the porosity is medium to poor. The sandstone is salt-and-pepper colored, and it contains clear quartz, feldspar, biotite, abundant glauconite near the base, and a trace of pink quartz. Weathered feldspar is abundant in the middle, and there is a local concentration of coal and coarse sand there. The shale below is sandy, and there are sandstone streaks and brown to white.

calcite chunks in the samples.

Well 10 has three ill-defined sandstone beds in the member. The top one is gray salt-and-pepper colored, fine grained, hard and tight. The middle sandstone is fine-grained and medium porous, and it contains biotite and clear quartz. The lower sandstone is coarse, salt-and-pepper colored, and tight, and it has a small amount of calcite cement and clear quartz. There is a small amount of shaley sandstone and some crystalline calcite in the 12,260 to 12,270 feet interval, and that is taken as the probable top of the Frontier formation. The thick sandstone at Reno Hill (Well 11) and the lower sandstone at Smith's Cut (Well 10) are correlated by electric log with a section called Greenhorn limestone at Sussex, and those sandstones are considered to be Greenhorn equivalents.*/

Section 4 has two thick sandstone bodies. The upper bed is 76 feet thick and is composed of four units. The upper 13 1/2 feet are thin-bedded, and the beds at the top are 6 inches thick. Shallow cross-beds dip southwest and south-southwest. The second unit of 17 1/2 feet contains similar sandstone, but it is less well cemented and has cross-beds in 2 to 3 foot units which also sip southwest and south-southwest. The third unit contains 22 1/2 feet of similar

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*/ C. S. Agey, Amerada Petroleum Corp., Tulsa, Okla. Personal letter, March 24, 1950.

sandstone with beds 1 to 2 inches thick. The fourth unit is thin-bedded, clayey, carbonaceous sandstone which is 22 1/2 feet thick.

The lower sandstone is 23 feet of medium grained salt-and-pepper sandstone. There is a conglomerate of small pebbles at the base, and the bottom is covered. There is a 10 inch cross-laminated layer above the conglomerate, and the cross-beds originally dipped toward the northeast. The upper sandstone is salt-and-pepper colored, and the grains are angular to subround, are coarsest at the top, and are more angular in the lower part. Minerals include traces of calcite, 5 to 10 per cent feldspar, clear quartz with crystal faces, pink quartz, biotite, and glauconite. The lower sandstone has angular to round grains, and minerals include clear quartz with crystal faces, 5 per cent feldspar, biotite, glauconite, and much calcite. The conglomerate at the base has rounded, smooth, egg-shaped pebbles of dark and light colored chert which are as long as 3/4 inch.

Section 5, to the northwest, has three sandstones, a thin upper bed and two thick sandstones in the middle of the member. The upper bed is 10 feet of medium grained salt-and-pepper sandstone which has cross-beds dipping southeast. The middle sandstone is 34 feet thick, and it is salt-and-pepper colored, thin bedded, and has shaley partings. The outcrop is a series of resistant ledges separated by covered intervals. The lower sandstone unit is 32 feet thick, medium grained, conglomeratic, and has a 2 foot yellow cone-in-cone limestone bed in the middle. The upper sandstone has angular to subround grains, and minerals include clear quartz, 10 per cent feldspar, biotite, glauconite, pink quartz, and much calcite. The middle sandstone has a few dark, shaley streaks; the sand grains are subangular to subround; and there is some finer material. Minerals are clear quartz with some crystal faces, a small amount of coal, biotite, glauconite, 10 per cent feldspar, and much calcite. The lower sandstone is divided into two units. Above the limestone the grains are angular to subround, and the minerals are clear quartz, glauconite, biotite, 10 per cent feldspar, and much calcite. The conglomerate pebbles are concentrated on one plane, and they are subround, smooth, unpolished, black chert. They are as long as 20 mm., but most are about 4 mm. long. Below the limestone the sandstone is finely conglomeratic, and the grains are angular to subround. Minerals include clear quartz, 10 per cent unweathered feldspar with good cleavage, abundant glauconite, and much calcite. The larger grains are black chert and feldspar. The conglomerate grades upward to fine grained cone-in-cone, slightly shaley, yellow-brown limestone.

Well 2 has two thick sandstone beds and one thin one. The upper sandstone is salt-and-pepper colored, friable, porous, and coarse grained. It is finer grained at the base. Minerals include clear and pink quartz, biotite, and much feldspar. The middle sandstone is thick, and it is medium to coarse grained, poorly sorted, friable, and slightly shaley. It is quite shaley in the top part and has a gray, sandy, slightly bentonitic shale break near the top. Minerals include glauconite and pink quartz, but there is no clear quartz. A small amount of fibrous calcite was found near the base. The lowest sandstone unit in the member is medium grained, soft, salt-and-pepper sandstone and has two important shale breaks. There is a small amount of brown crystalline limestone in the samples from the lower part.

The shale between the middle and lower sandstone units is gray and sandy, with a small amount of bentonite and sandstone streaks, and it has brown crystalline limestone in the lower part.

The top sandstone at section 5b is 60 feet thick, is thin-bedded and shaley at the base and top, and has streaks of massive sandstone in the middle. The lower sandstone is coarse and has a few pebbles on top. Limestone concretions lie in the shale below.

Well 1 has two sandstone units; neither one is very well developed. The upper sandstone is fine to medium grained, gray, tight, shaley, and salt-and-pepper in color. There is some fibrous calcite in the base. The lower unit contains two 10 foot beds of fine-grained tight sandstone separated by about 10 feet of sandy shale and bentonite.

Section 7 has three sandstone units. The top one is 28 feet thick and is thin-bedded and shaley. The middle unit is 40 feet of thin-bedded sandstone, with shaley partings and a carbonaceous shaley 5 foot layer in the bottom half. The lower sandstone is 9 feet thick and is thin-bedded, medium grained, and salt-and-pepper in color. The upper sandstone has angular to subangular sand grains and much finer material. Minerals include angular clear quartz, biotite, glauconite, 10 per cent feldspar, and a small amount of muscovite. The middle unit has angular to subround grains, and they are most angular in the top part. Minerals include 15 per cent feldspar, much coal, small amounts of biotite and glauconite, clear and pink quartz, and calcite. The lower sandstone has angular to subround grains, and the minerals include clear quartz, pink quartz, 10 per cent feldspar, biotite, glauconite, a small amount of carbonized wood, and calcite. The lower sandstone has burrows .5 mm. in diameter and contains the mold of a small bivalve, 10 by 10 by 1 mm.

Section 8 has three sandstone units. As in section 7, the top unit has no pink quartz. The top unit has two 10 foot sandstone beds separated by 15 feet of sandy shale and thin sandstone. The middle sandstone is medium grained and calcareous, and it contains numerous Inoceramus shells, many of which are jammed together, and some are broken and piled in an irregular manner. The lower unit contains an upper bed of medium grained, thin bedded sandstone 15 feet thick which is separated by a covered, probably shaley, interval from a lower bed of thin bedded sandstone which is 45 feet thick and whose top is hard and coarse grained.

The upper sandstones of the top unit are salt-and-pepper colored, and the grains are angular to subround. Minerals include angular clear quartz, much biotite, 5 to 10 per cent feldspar, muscovite, coal, a small amount of glauconite in the top, and calcite.

The middle sandstone has angular to subround grains, and the minerals include clear quartz, a small amount of pink quartz, much biotite, glauconite, and much calcite. Most of the *Inoceramus* shells are 40 mm. long.

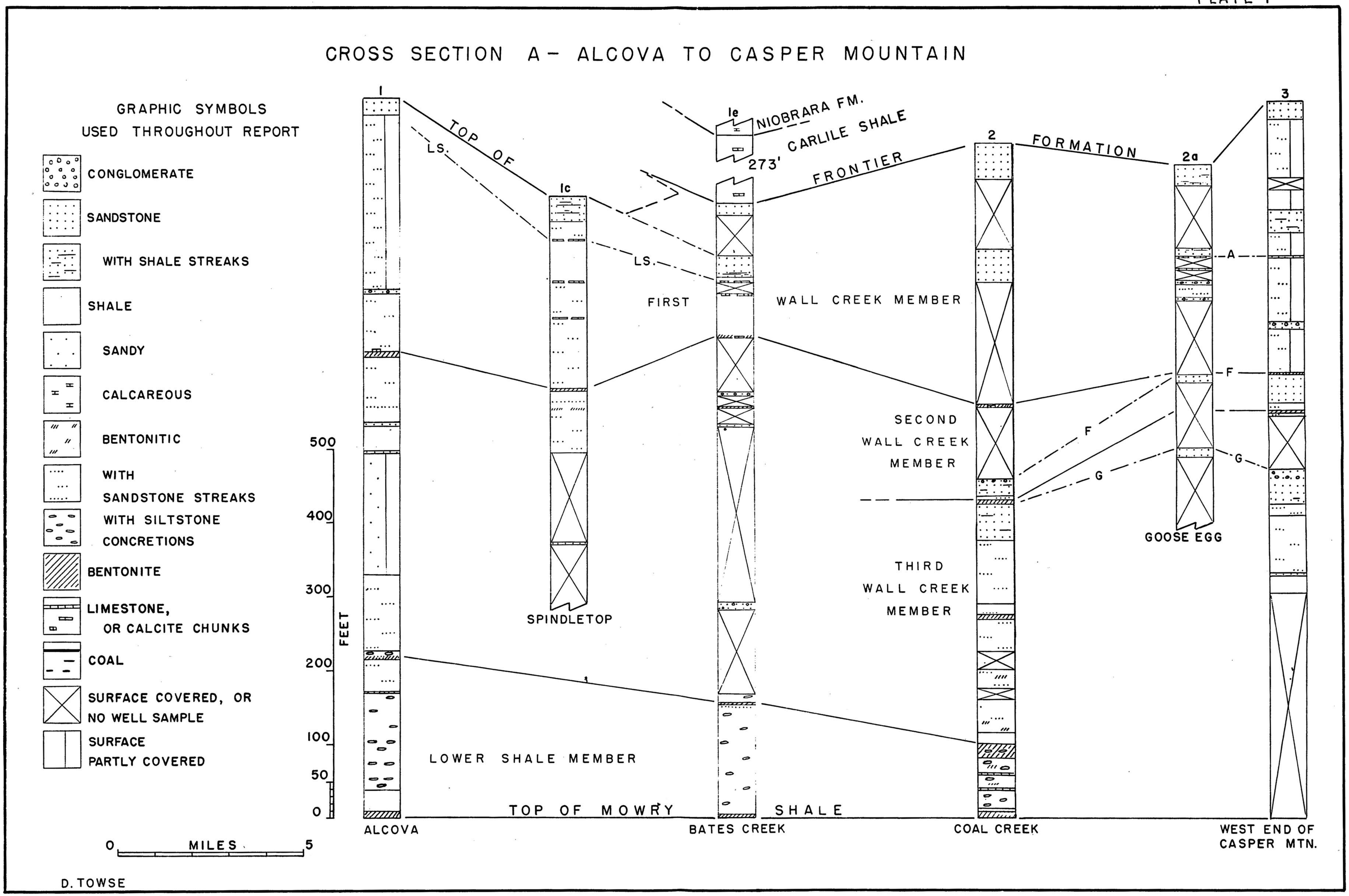
The sandstones of the lower unit are finer at the top, and the grains are angular to round and more angular in the lower bed. Minerals include clear quartz, frosted pink quartz, 5 to 10 per cent feldspar, biotite, glauconite, calcite, and a small amount of coal in the base.

A detailed description of section 9 was given in the discussion of the First Wall Creek member. The upper sandstone has angular to subround grains, and minerals include a small amount of angular clear quartz, a small amount of pink quartz, biotite, muscovite, 15 per cent feldspar, a small amount of glauconite, and much calcite. The lower sandstone is slightly conglomeratic and contains some silt and clay material. Minerals include frosted quartz, angular clear quartz, a small amount of biotite and glauconite, a small amount of coal, less than 5 per cent feldspar, and much calcite. A few pebbles of subangular gray chert are concentrated in the top layer of the sandstone. Most of the pebbles are 2 to 5 mm. in diameter, but some are as large as 15 mm.

The limestone concretions in the shale below the sandstone are gray, shaley, hard, and they have 3 to 10 mm. thick cream and brown calcite veinlets in laminated layers.

The upper sandstone at section 9c is 65 feet or more thick, and the top is obscure. The sandstone is massive; the top half is more thin bedded and has black shale partings. There are cross-laminated units throughout. The lower sandstone is thin bedded, has shale partings, and has pea sized pebbles on the top surface. The sandstone is calcareous and contains fragments of ammonites which are probably the *Prionocyclus* described by Wegemann (1918).

The sandstone at section 10 is salt-and-pepper colored and 35 feet thick, whereas that at section 11 is thin bedded and 25 feet thick and has cross-beds that dip southeast. The sandstone at section 11 is coarse grained, and its grains are angular to subangular. Minerals include much angular clear quartz, 10 per cent feldspar, biotite, glauconite, a trace of phlogopite and calcite, and a small amount of frosted pink quartz.


CROSS SECTION A- ALCOVA TO CASPER MOUNTAIN
GRAPHIC SYMBOLS
USED THROUGHOUT REPORT
CONGLOMERATE
SANDSTONE
WITH SHALE STREAKS
SHALE
SANDY
CALCAREOUS
BENTONITIC
WITH SANDSTONE STREAKS
WITH SILTSTONE CONCRETIONS
BENTONITE
LIMESTONE, OR CALCITE CHUNKS
COAL
SURFACE COVERED, OR NO WELL SAMPLE
SURFACE PARTLY COVERED
1
1c
1e
2
2a
3
NIOBRARA FM.
273' CARLILE SHALE
TOP OF FRONTIER FORMATION
LS.
LS.
FIRST WALL CREEK MEMBER
SECOND WALL CREEK MEMBER
THIRD WALL CREEK MEMBER
LOWER SHALE MEMBER
TOP OF MOWRY SHALE
A
F
F
G
G
SPINDLETOP
GOOSE EGG
FEET
500
400
300
200
100
50
0
ALCOVA
BATES CREEK
COAL CREEK
WEST END OF CASPER MTN.
0 MILES 5
D. TOWSE

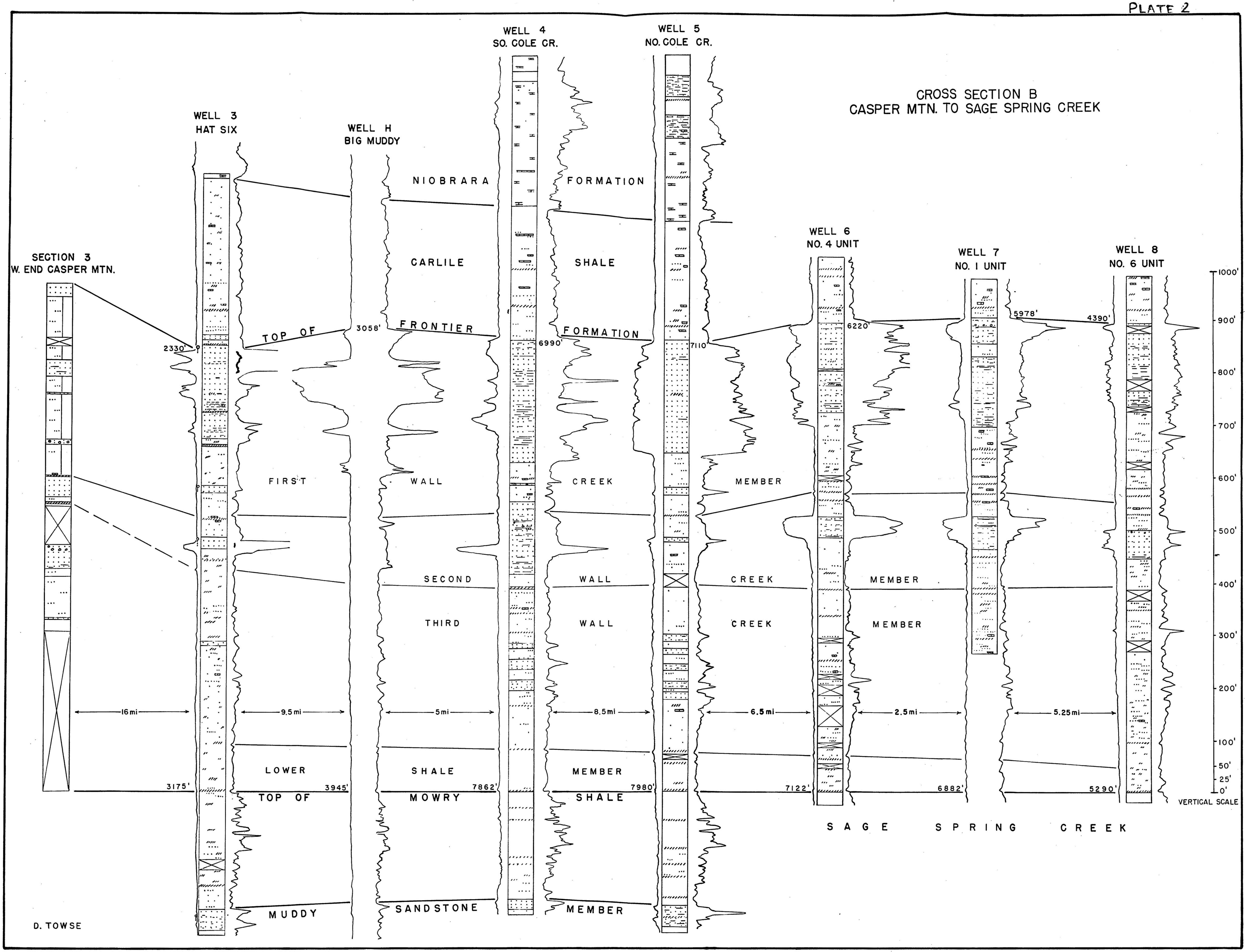
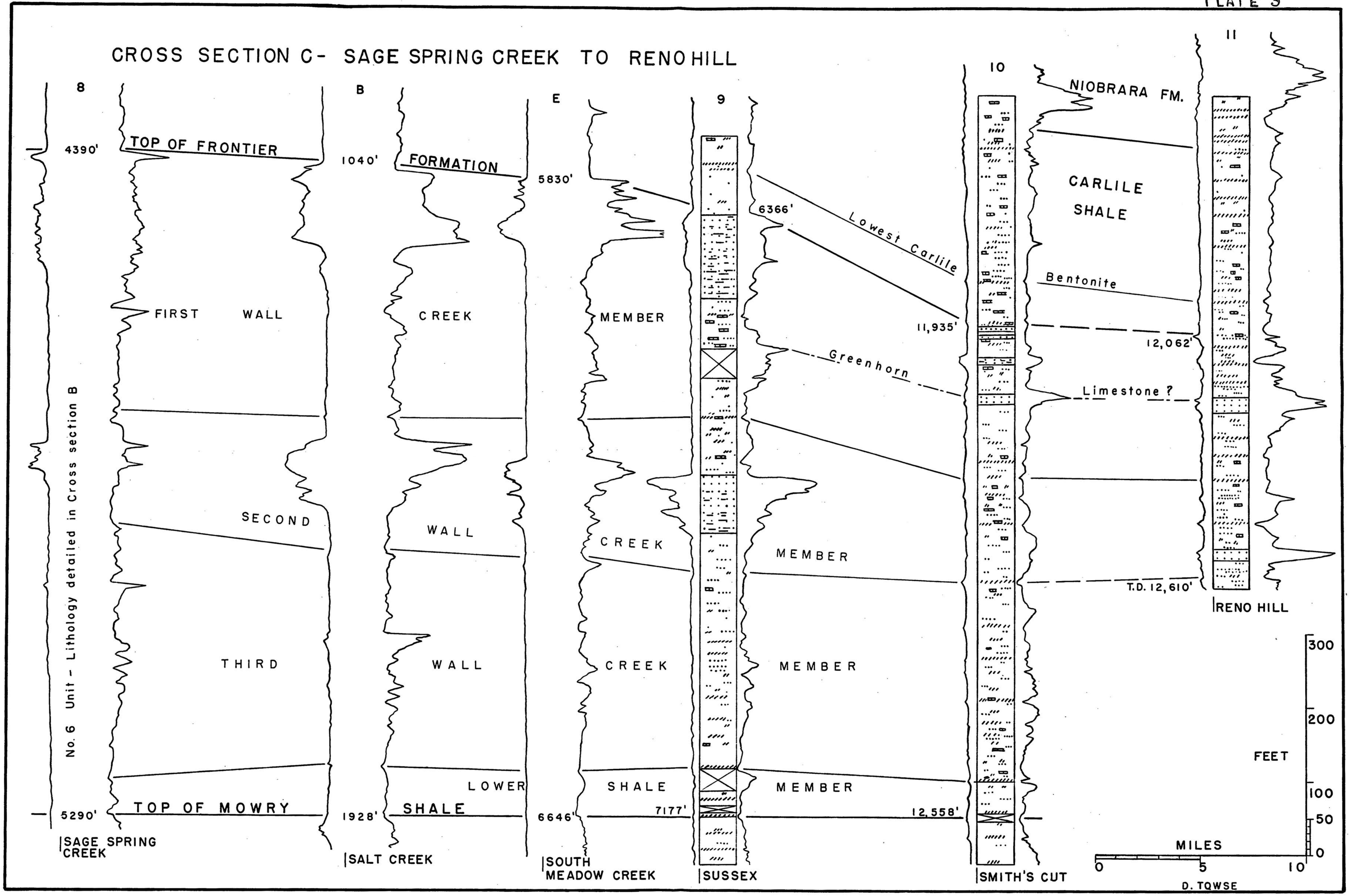
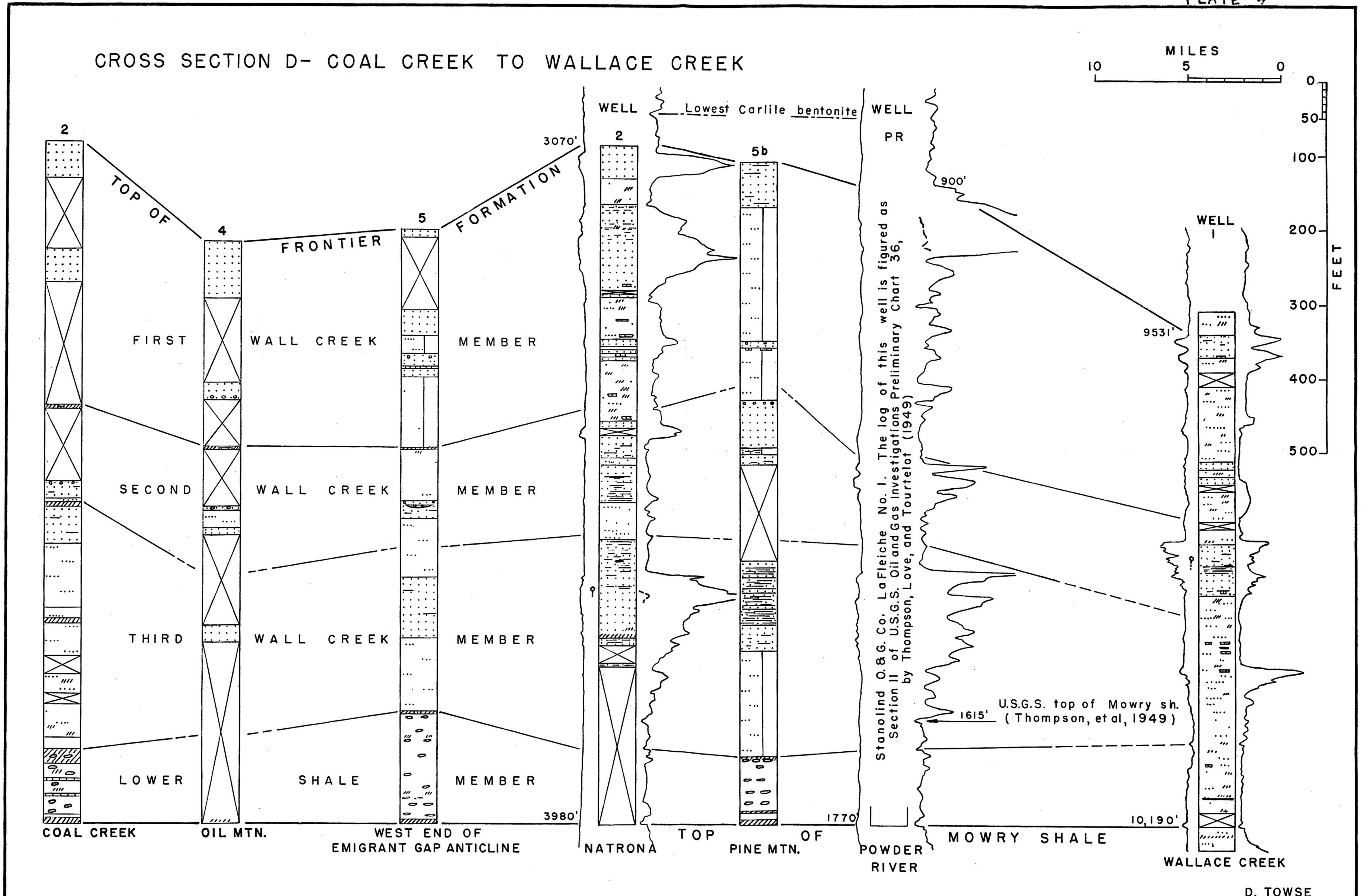
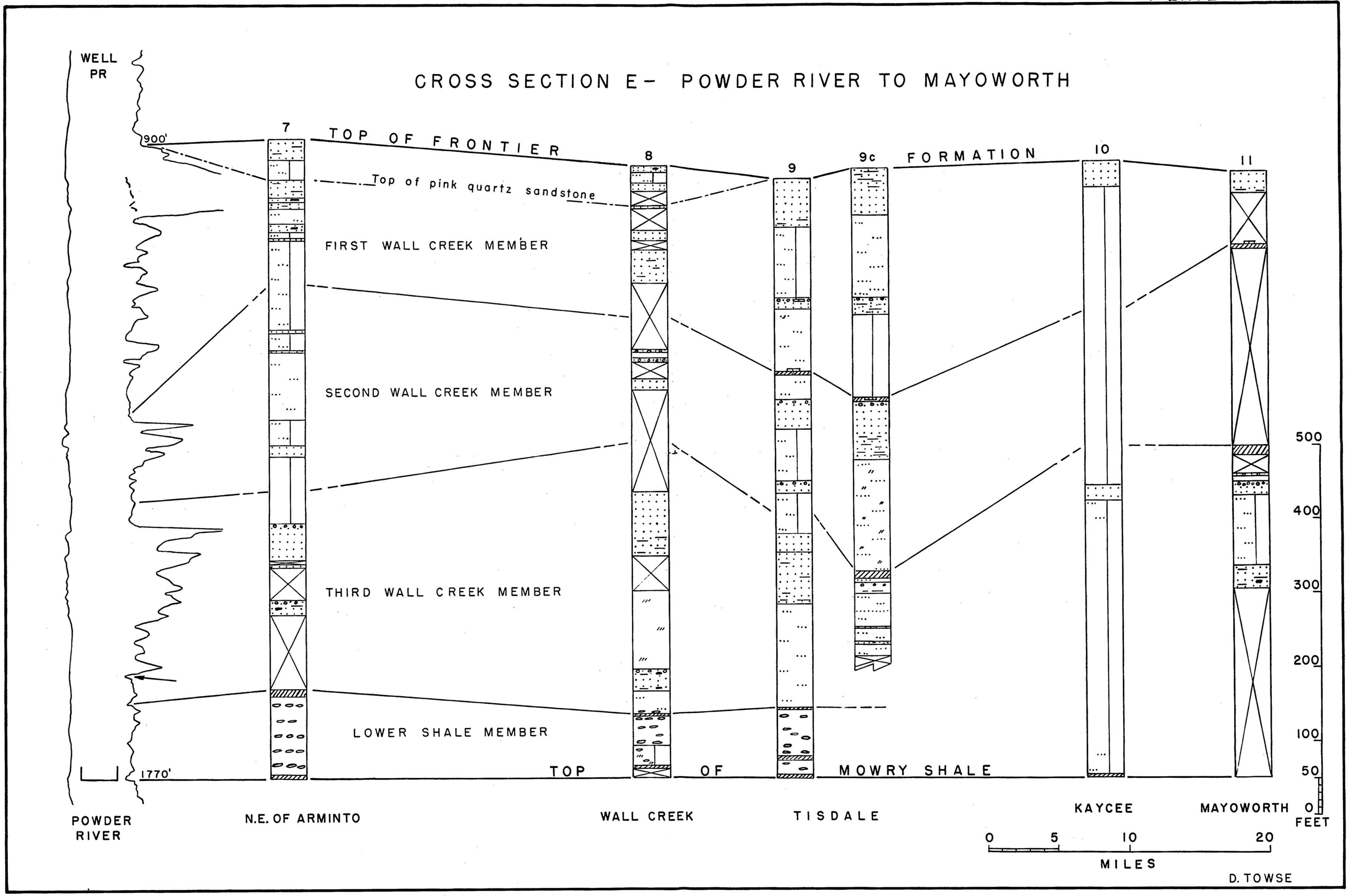

CROSS SECTION B
CASPER MTN. TO SAGE SPRING CREEK
SECTION 3
W. END CASPER MTN.
WELL 3
HAT SIX
WELL H
BIG MUDDY
WELL 4
SO. COLE CR.
WELL 5
NO. COLE CR.
WELL 6
NO. 4 UNIT
WELL 7
NO. 1 UNIT
WELL 8
NO. 6 UNIT
NIOBRARA FORMATION
CARLILE SHALE
TOP OF FRONTIER FORMATION
2330'
3058'
6990'
7110'
6220'
5978'
4390'
FIRST WALL CREEK MEMBER
SECOND WALL CREEK MEMBER
THIRD WALL CREEK MEMBER
16 mi
9.5 mi
5 mi
8.5 mi
6.5 mi
2.5 mi
5.25 mi
LOWER SHALE MEMBER
3175'
3945'
7862'
7980'
7122'
6882'
5290'
TOP OF MOWRY SHALE
MUDDY SANDSTONE MEMBER
SAGE SPRING CREEK
1000'
900'
800'
700'
600'
500'
400'
300'
200'
100'
50'
25'
0'
VERTICAL SCALE
D. TOWSE

PLATE 3


CROSS SECTION C- SAGE SPRING CREEK TO RENO HILL
8
B
E
9
10
11
4390'
TOP OF FRONTIER
1040'
FORMATION
5830'
6366'
Lowest Carlile
11,935'
NIOBRARA FM.
CARLILE SHALE
Bentonite
12,062'
Greenhorn
Limestone ?
FIRST WALL CREEK MEMBER
SECOND WALL CREEK MEMBER
THIRD WALL CREEK MEMBER
LOWER SHALE MEMBER
No. 6 Unit - Lithology detailed in Cross section B
T.D. 12,610'
5290'
TOP OF MOWRY SHALE
1928'
6646'
7177'
12,558'
SAGE SPRING CREEK
SALT CREEK
SOUTH MEADOW CREEK
SUSSEX
SMITH'S CUT
RENO HILL
FEET
300
200
100
50
0
MILES
0
5
10
D. TOWSE


CROSS SECTION D- COAL CREEK TO WALLACE CREEK
MILES
10 5 0
0
50
100
200
300
400
500
FEET
2
TOP OF FRONTIER FORMATION
4
5
3070'
WELL 2
Lowest Carlile bentonite
5b
WELL PR
900'
WELL 1
9531'
FIRST WALL CREEK MEMBER
SECOND WALL CREEK MEMBER
THIRD WALL CREEK MEMBER
LOWER SHALE MEMBER
Stanolind O.&G. Co. LaFleiche No. 1. The log of this well is figured as Section II of U.S.G.S. Oil and Gas Investigations Preliminary Chart 36, by Thompson, Love, and Tourtelot (1949)
U.S.G.S. top of Mowry sh. (Thompson, et al, 1949)
1615'
3980'
1770'
10,190'
TOP OF MOWRY SHALE
COAL CREEK
OIL MTN.
WEST END OF EMIGRANT GAP ANTICLINE
NATRONA
PINE MTN.
POWDER RIVER
WALLACE CREEK
D. TOWSE


CROSS SECTION E- POWDER RIVER TO MAYOWORTH
WELL PR
900'
1770'
POWDER RIVER
7
8
9
9c
10
11
TOP OF FRONTIER FORMATION
Top of pink quartz sandstone
FIRST WALL CREEK MEMBER
SECOND WALL CREEK MEMBER
THIRD WALL CREEK MEMBER
LOWER SHALE MEMBER
TOP OF MOWRY SHALE
N.E. OF ARMINTO
WALL CREEK
TISDALE
KAYCEE
MAYOWORTH
500
400
300
200
100
50
0
FEET
0 5 10 20
MILES
D. TOWSE