UNITED STATES
DEPARTMENT OF THE INTERIOR
HAROLD L. ICKES, Secretary
GEOLOGICAL SURVEY
W. C. MENDENHALL, Director

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CIRCULAR 5

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GEOLOGY OF THE NORTH AND SOUTH McCALLUM ANTICLINES, JACKSON COUNTY, COLORADO WITH SPECIAL REFERENCE TO PETROLEUM AND CARBON DIOXIDE

By

J. C. MILLER

WASHINGTON

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GEOLOGY OF THE NORTH AND SOUTH McCALLUM ANTICLINES JACKSON COUNTY, COLORADO WITH SPECIAL REFERENCE TO PETROLEUM AND CARBON DIOXIDE

By J. C. Miller

Abstract

The McCallum anticlines, embracing an area about 2 miles wide and 12 miles long, are about 6 miles east of the town of Walden, Jackson County, Colo., on the east side of the Continental Divide. A cover of flat-lying Quaternary gravel obscures the outcrop of Pierre shale at many points on the two anticlines. Wells start in the upper part of the Pierre and penetrate all of the underlying Upper Cretaceous series to the top of the Dakota sandstone, where production of oil and carbon dioxide is obtained. The first prospecting for oil was reported in 1912, but it was not until December 1926 that oil was discovered in commercial quantities.

Two geologic sections across the anticlines, extending to the outcrop of the Dakota sandstone at the base of the Medicine Bow Range, to the east, disclosed a marked thickening between this formation and a fossiliferous sandstone in the Pierre shale which was used as a key bed. Immediately beneath the Dakota sandstone along one of these cross sections a sandy volcanic ash resembling that found at the horizon of the Mowry shale in Wyoming was discovered. However, it is considered here the top bed of the Morrison formation.

The impossibility of obtaining dips along the crests, owing to the cover of terrace gravel, made it necessary to construct ten structure sections across these anticlines, using the geometry of conic sections in their development. From the geometric figures developed structure contours were obtained graphically.

The occurrence of carbon dioxide in large volumes in association with petroleum on each of these anticlines provides an unusual problem in oil production. Experimental data relative to the physical properties of this gas offer an approach to the solution of the problem. The applicability of such data to actual operating conditions is yet to be tried, but the work of early investigators in the field of physical chemistry suggests the feasibility of mixing air with the carbon dioxide to assure continuity of production, which heretofore has not been attained in this area.

Introduction

Location and extent of the area.- The McCallum anticlines lie in the northeastern part of North Park, on the east side of the Continental Divide, in Jackson County, Colo., about 20 miles from the Wyoming line and about 173 miles by road from Denver. Their location with respect to the principal topographic features is shown on plate 1. The anticlines occupy an area about 12 miles long and 2 miles wide, lying 6 to 9 miles east of Walden, a town on the Laramie, North Park & Western Railroad, which extends to Laramie, Wyo., on the Union Pacific Railroad. The town of Coalmont, about 12 miles southwest of Walden, is also on this railroad and is the center of coal-mining activity of North Park. At present, only biweekly runs are made by the railroad between Coalmont and Laramie. The roads of this area are generally good gravel or dirt roads. The road to Laramie is used daily by bus and is well maintained throughout the year, and most of the travel goes that way, but an effort is made to keep open the southern passes to permit travel to Denver. North Park as a whole comprises an area of about 1,400 square miles.

Earlier work.-Previous geologic examination of North Park was reported by King[1] in 1876, by Hayden[2] in 1877, by Hague[3] in 1877, and by Beekly[4] in 1915. During the summer of 1911 Beekly examined this district with the object of obtaining all available facts concerning the coal resources and of making a study of the general geology in order to correlate, if possible, the formations of this area with those on the east and west slopes of the Rocky Mountains.

A detailed examination of the McCallum anticlines was made by C. I. Jennings, E. P. Philbrick, and C. C. Adams for the Mutual Oil Co., in 1924. This work was checked in 1927 by the Continental Oil Co., which acquired the holdings of the Mutual.

Present investigation.-Examination of available areal and structural maps of the anticlines disclosed an apparent error in correlation and suggested its probable cause, prior to actual field work. The present investigation was therefore undertaken with a view to (1) ascertaining the correctness of Beekly's and other available maps, (2) determining, if possible, the source of carbon dioxide, and (3) suggesting drilling and producing methods to combat the difficulties encountered in developing the field.

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1 King, Clarence, U. S. Geol. Expl. 40th Par. Atlas, 1876.

2 Hayden, F. V., Atlas of Colorado, U. S. Geol. and Geog. Survey Terr. 1877.

3 Hague, Arnold, and Emmons, S. F., U. S. Geol. Expl. 40th Par. Final Rept., vol. 2, pp. 112-129, 1877.

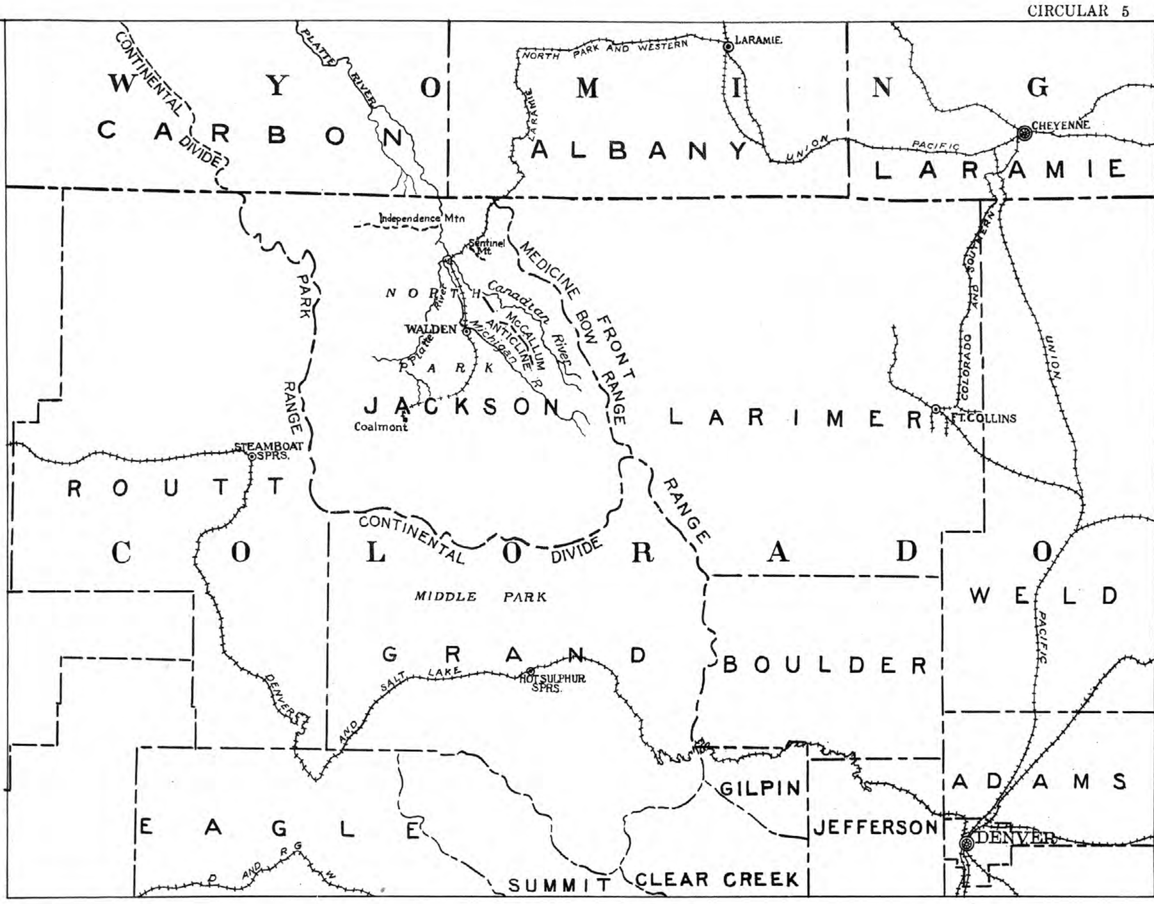
4 Beekly, A. L., Geology and coal resources of North Park, Colorado: U. S. Geol. Survey Bull. 596, 1915.

Purpose of the report.-The purpose of this report is to present a summary of the general geology of these anticlines and the adjacent area, also a detailed account of their structure. In addition, owing to the widespread interest in recent years in natural carbon dioxide, the writer has included information of general interest on that subject. Of prime importance, however, was the determination of structural features affecting the accumulation of oil and gas, inasmuch as it seems desirable and in the interest of conservation to operate the lands involved under a unit system. Authority for Government lessees to engage in a unit plan of development is granted under an amendment (Public no. 853, 71st Congress), approved March 4, 1931, to sections 17 and 27 of the general leasing act of February 25, 1920 (41 Stat., 437).

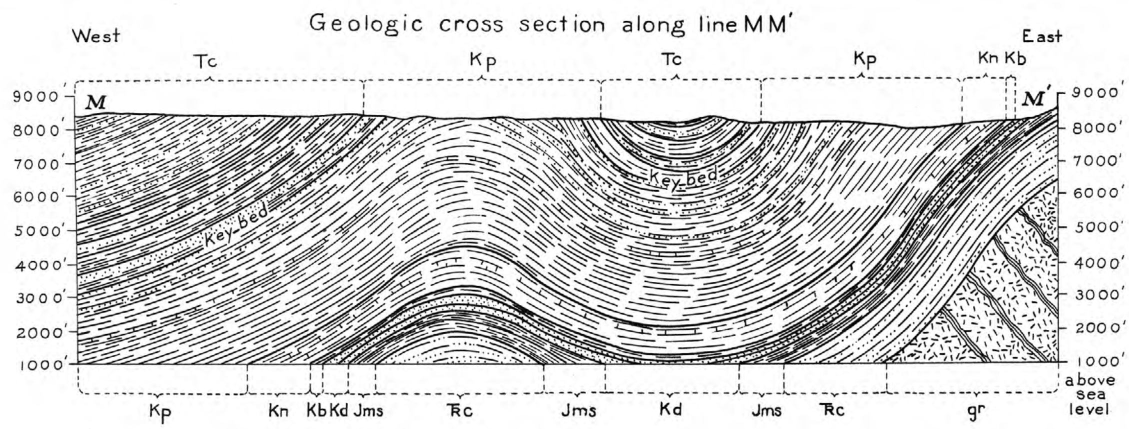
Acknowledgments.- The writer is indebted to Herman Stabler, chief, and to John D. Northrop, assistant chief, of the conservation branch of the United States Geological Survey, for their cooperation and able direction in the accomplishment of this work. Thanks are also due to H. D. Miser and John B. Reeside, Jr., for their helpful criticism of the manuscript. In addition the writer expresses his appreciation to J. R. Schwabrow for his assistance in the field work.

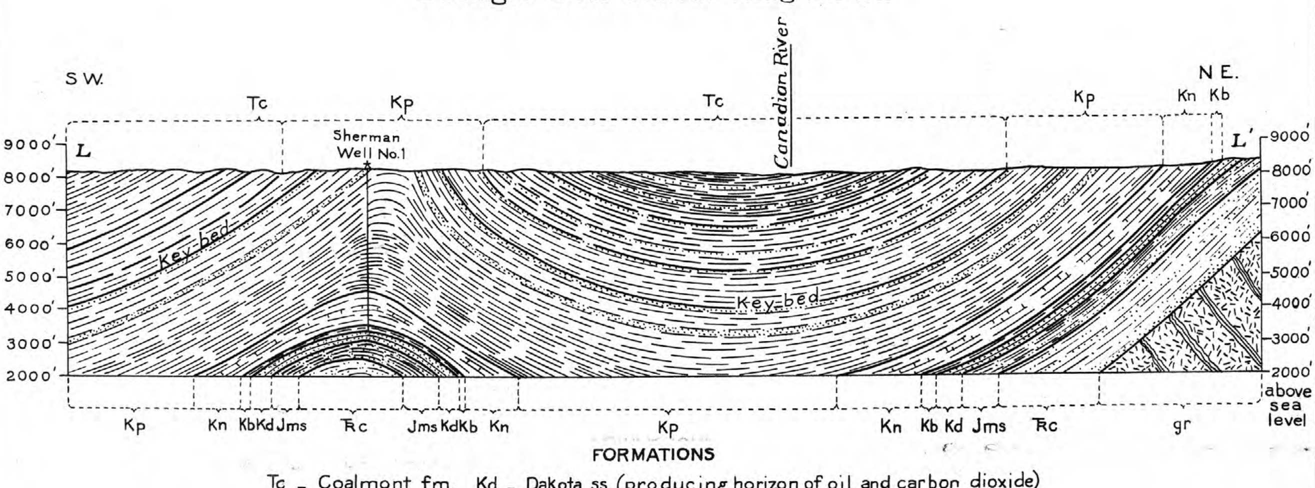
Preparation of the map

Base map.- The base for horizontal control in the construction of the accompanying map is a land net established by surveys made under contract for the United States Land Office from 1878 to 1883. Of the section corners established by the Land Office probably only four were found, one of which appeared to be the original stone--namely, that found loose at the northwest corner of sec. 17, T. 9 N., R. 78 W. Four-inch posts at the southwest and the southeast corners of this section were also found. The northwest corner of sec. 31, T. 9 N., R. 78 W., was established by the presence of fence intersections. This corner and that marking the northwest corner of sec. 17 of the same township were indicated as found by Beekly and were shown on his map. In general the sections of the townships involved showed no marked irregularities according to the Land Office plats. Owing to the irregular sections shown on later maps of the McCallum anticlines from other sources, the Geological Survey on November 14, 1932, requested the resurvey now in progress by the General Land Office involving parts of Tps. 8, 9, and 10 N., R. 78 W., and Tps. 9 and 10 N., R. 79 W., sixth principal meridian, Colorado.



INDEX MAP





FORMATIONS

Tc – Coalmont fm.
Kp – Pierre sh.
Kn – Niobrara fm.
Kb – Benton sh.
Kd – Dakota ss. (producing horizon of oil and carbon dioxide)
Jms – Morrison fm.
Ꞧc – Chugwater fm.
gr – Pre-Cambrian granites, gneisses, and schists

STRUCTURE SECTIONS, NORTH & SOUTH McCALLUM ANTICLINES

Datum for elevations is mean sea level

1 0 5 Miles

Geology by J. C. Miller, assisted by J. R. Schwabrow

Field Work.-The field work by the writer was done during September and October 1932. Coal outcrops, mines or prospects, wells, and nine or ten different beds of sandstone or sandy limestone were mapped by plane table on a scale of 4 inches to the mile. An effort was made, wherever convenient, to locate corners. Scattered over the area are numerous posts set by placer-mining claimants, but these were found to be of doubtful value. The plane-table survey was started from the Sherman no. 1 well, in the NW1/4 sec. 12, T. 9 N., R. 79 W., with an altitude of 8,232.89 feet above sea level. This altitude had been determined earlier by the Continental Oil Co.

Geography

The North and South McCallum anticlines (pl.1) are situated in the northeastern part of North Park, which is a comparatively level, roughly quadrangular basin. The park is a sharply defined topographic unit surrounded on all sides by mountains rising to altitudes of 11,000 to 13,000 feet. Along the east side of the park the sharp, rugged peaks of the Medicine Bow Range form a huge crescent-shaped ridge. On the north side of the basin Sentinel Mountain and Independence Mountain form a connecting link between the Medicine Bow Range on the east and the Park Range on the west. The Park Range presents, when viewed from the east, a fairly even and regular crest having the appearance of a much dissected high plateau on which a few more or less prominent peaks attain altitudes of 11,000 to 12,000 feet. Toward the southwest corner of the park the crest becomes narrower and more ridgelike, decreasing in altitude to less than 9,000 feet. The high Continental Divide forms the south side of the park. In the eastern half of the divide sharp peaks rise to altitudes of 11,500 to more than 12,400 feet, but the western half of the divide, in the direction of Muddy Pass and Rabbit Ears Pass, is much lower and more rounded.

The floor of the park appears remarkably flat when viewed from one of the surrounding mountain ranges. In reality the surface is more or less rolling and cut by stream valleys and by minor elevations, such as Sheep Mountain and Delanos Butte in the western part and Moore Mountain in the eastern part. The altitude of the stream valleys in places is about 7,900 feet, but in general the valley floor is 8,100 to 8,300 feet above sea level, the average altitude on the anticlines being about 8,200 feet.

The North Platte River, flowing northward across North Park into Wyoming, drains the entire area. The streams draining the anticlines are tributary to the Michigan River, flowing several miles west of the McCallum field, and to the Canadian River, within a few miles of the east side of the field, both of which are tributaries of the North Platte River. The main streams in the area are fed by the melting of snow collected on the surrounding mountains. They furnish abundant water supply during the season for irrigating the hay fields on the flood plains of the rivers. The streams are of importance in serving the cattle industry, which is the chief occupation of the district. In the western part of North Park a number of lakes have been formed where surface drainage has no outlet.

The climate of the region is arid. Snow storms are frequent in early spring and late fall. The winters are rigorous, owing to the high altitude and frequent snows, and after the first of December the snow usually remains on the ground in the park until the early part of May. Except for the flood plains of the rivers, the valley floor is covered with sagebrush. The higher slopes of the mountains are timber-covered, principally by conifers and some aspen. The snows on the mountain ridges accumulate to a depth of 5 or 6 feet. The temperature during the cold months is frequently subzero and may go as low as 40° below zero. Strong westerly winds are frequent. The severity of the winter renders oil and gas well drilling operations extremely difficult.

A plentiful supply of good water is available in either the Canadian or the Michigan River for drilling on the McCallum anticlines, although it is necessary to pipe the water a distance of 2 to 5 miles, depending on the location of the well. Either coal from local mines or oil from existing wells may be used for boiler fuel.

Stratigraphy

The McCallum anticlines are situated in the eastern part of the broad structural basin whose margins coincide in part with the boundaries of North Park. Except where obscured by the relatively thin deposit of Quaternary terrace gravel, only the upper half of the Pierre shale is exposed on these anticlines. Wells now completed have penetrated all the Upper Cretaceous rocks to the top of the Dakota sandstone.

On the east and west sides of the basin the tilted sedimentary rocks, ranging in age from late Carboniferous to Tertiary, rest upon pre-Cambrian granites, gneisses, and schists. On the north side of the park the sediments are brought abruptly into contact with the crystalline rocks by the Independence Mountain fault, which extends from the base of the tilted sedimentary rocks on the west side of the basin to their outcrop along the east side. Detailed examination of the south side of the park has not been made, and Beekly[5] shows at least three fourths of this southern boundary probably covered with Tertiary basalt or other formations which are obscured by timber. Morainal deposits of Quaternary age from valley glaciers are prominent features of the east slopes of the Park Range but are less evident on the east and south borders of the park. Sand dunes have developed in the foot-hills of the Medicine Bow Range opposite the large gaps in the crest of the ridge. The accompanying generalized geologic section was taken largely from Beekly's publication but was modified to accord with the writer's observations. Generalized graphic sections obtained by the writer accompany the structure-contour map. No specific evidence of unconformities between sedimentary rocks in the park has been observed, though the regional history shows that gaps in the sequence unquestionably exist. The unconformities recognized occur above the Pierre shale.

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5 Beekly, A. L., op. cit., pl. 17.

General geologic section in North Park, Colorado.

System	Series	Group	Formation	Character	Thickness (feet)
Quaternary				Alluvium Dune sand	0-30 0-50
				Terrace gravel	0-6
				Glacial material (silt, sand, and boulders).	0-hundreds
Tertiary	Mio-cene(?)		North Park formation	Shale, sandstone, volcanic ash, tuff, and conglomerate	600
		Unconformity			
	Eocene		Coalmont formation	Sandstone, conglomerate, shale, and coal beds	4,000-6,000
		Unconformity			
Cretaceous	Upper Cretaceous	Montana	Pierre shale	Dark shale and thin beds of sandstone	4,500-5,500
		Colorado	Niobrara formation	Calcareous gray and dark shale; thin beds of limestone	500-1,000
			Benton shale	Shale and sandstone	100-165
			Dakota sandstone	Sandstone, shale, and conglomerate (oil and gas)	310-352
Jurassic	Upper Jurassic		Morrison formation	Gray sandy shale, including at top 5 feet of red to gray sandy volcanic ash	335
				Gray, maroon, greenish, and dove-colored marl and shale, with some interbedded limestone and sandstone beds.	
				Coarse conglomerate	
Triassic			Chugwater formation	Brick-red sandstone and shale, with some interbedded clay and limestone beds.	1,350
Carboniferous				Limestone	0-30
Pre-Cambrian rocks				Granite, gneiss, and schist.	

Carboniferous system

The full extent of the traverse indicated by section L-L' is not shown on plates 1 and 2, but it was run to the granite on the Medicine Bow Range. At this point the Chugwater rests upon the granite, and there is no evidence of the limestone of Carboniferous age which occurs farther north along the slopes of the mountains. This limestone, with a maximum thickness of 30 feet, is thin-bedded and light bluish gray but weathers with a brownish tinge. It is considered to be of Permian or Pennsylvanian age because it underlies Chugwater red beds (which in this area are probably all of Triassic age) under conditions similar to those in the adjoining Laramie region in Wyoming. Like occurrences have been reported in the Carbon and Hanna Basins in Wyoming.

Triassic system

Chugwater formation

The Chugwater formation is poorly exposed along section L-L', extended, and its outcrop near the foot of the mountain slopes is obscured by a cover of debris of granitic rocks. It is made up of 1,350 feet of brick-red sandstone and shale and beds of limestone. The red sandstones are ripple-marked and cross-bedded in nearly all the exposures observed.

Jurassic system

Morrison formation

The Morrison formation in this region is usually composed of about 400 feet of gray, maroon, greenish, and dove-colored shale and marl interbedded with a few lenticular layers of limestone and sandstone. At the point of measurement in section L-L', extended, the basal 15 feet is a hard conglomerate consisting of cross-bedded grit containing pebbles as much as 4 inches in diameter and in places firmly cemented by limonite. The upper part of the Morrison is not well exposed, but it is believed to consist of 145 feet of gray shale capped by 5 feet of red to gray sandy volcanic ash. The middle part contains 170 feet of the variegated shales and other rock types that normally make up the formation.

A fair exposure of the Morrison and the overlying Dakota sandstone in sec. 21, T. 10 N., R. 78 W., yielded the following section:

Dakota sandstone:	Feet
Fine-grained soft buff sandstone; exposed	20
Unexposed, probably soft shale and sandstone	180
Fine-grained white to reddish sandstone	40
Conglomeratic sandstone	70
	310

Morrison formation:	
Red to gray sandy volcanic ash	5
Poorly exposed, probably gray shale	145
Chocolate, maroon, greenish, and dove-colored shale; base not exposed	170
Hard coarse conglomerate	15
	335

W. W. Rubey, of the United States Geological Survey, who examined microscopically samples of the sandy ash at the top of the Morrison, stated that it resembles that in the Mowry shale (Upper Cretaceous) of northeastern Wyoming.

Cretaceous system

Dakota sandstone

The Dakota sandstone consists of three or more beds of light-colored sandstone separated by gray shale. In sec. 22, T. 10 N., R. 78 W., along section L-L', the exposure of these beds is not as complete as elsewhere along the foothills of the Medicine Bow Range. However, the total thickness of over 300 feet between the uppermost sandstone exposed here and the top of the beds assigned to the Morrison formation agrees favorably with the following section measured in sec. 36, T. 10 N., R. 78 W., by geologists for the Mutual Oil Co.:

	Feet
Fine-grained buff porous sandstone	58
Sandy shale	83
Soft fine-grained sandstone	26
Shale	19
Fine-grained reddish sandstone	48
Shale	27
Conglomerate	91
	352

In sec. 22 the lowest bed is cross-bedded and coarse, consisting of white sand and well-rounded quartz and chert pebbles an inch or more in diameter.

The enormous quantities of carbon dioxide gas with fairly large amounts of petroleum present in the two wells completed on the North and South anticlines are believed to be contained in the top of the Dakota sandstone.

Benton shale

The Colorado group is not well exposed east of the McCallum anticlines, and the descriptions of the Benton shale and Niobrara formation are based chiefly on observations elsewhere.

The Benton shale ranges in thickness from 100 to 165 feet. It consists of dark-gray shale in the lower part, light-gray to yellow shale and thin-bedded dark limestone in the middle part, and gray sandy shale and sandstone in the upper part. These divisions are strongly suggestive of the Graneros shale, Greenhorn limestone, and Carlile shale, respectively, which constitute the same interval east of the Front Range. Fossils reported by Beekly from the upper part of the Benton in North Park show that it is essentially equivalent to the Carlile shale. Dark-gray shale with a few thin limestone beds, probably Benton, overlying the Dakota sandstone, were reported in the logs of the Sherman no. 1 well and Hoye no. 1 well.

Niobrara formation

Overlying the Benton shale in North Park, the Niobrara formation attains a thickness ranging between 500 and 1,000 feet. It consists mainly of dark-colored shale, calcareous shale, and thin-bedded limestone, the limestone predominating in the basal portion and the upper part grading upward imperceptibly into the Pierre shale. A 4-foot hard calcareous sandstone is believed to mark the top of the formation along the Canadian River near the southeast corner of T. 9 N., R. 78 W.

Pierre shale

The Montana group is represented in this area by about 4,500 feet of drab shale, sandy shale, and sandstone overlain unconformably by coal-bearing rocks. Although the Fox Hills sandstone may be represented at the top, it was not identified, and the entire thickness is therefore assigned to the Pierre shale.

This formation in North Park is largely thin-bedded sandy shale, with several relatively thin, more or less lenticular sandstone beds, particularly near the top. The shale is usually olive-green or brown and in a few places dark gray, but the weathered outcrop of the shale is usually drab. Fossils are most common in the upper sandstone beds, which range in thickness within short distances from 1 to 10 feet or more. These sandstones vary in hardness, which depends on their iron content, and here and there two of the beds form ferruginous sandstone boulders ranging in size from 6 inches to 2 feet. Locally thin strata of white crystalline calcite or aragonite, 1 to 3 inches thick are associated with these fossiliferous upper sandstones. The sandstone selected as a key bed lies about 520 feet below the top of the Pierre and is a medium-grained light-brown to gray sandstone which is locally very calcareous. In places two or three similar sandstones separated by shale or sandy shale are present within a zone of 90 feet. The key bed, however, exhibits greater continuity and content of Inoceramus and Baculites, which are the most common fossils in the Pierre. The retreating Colorado sea and fluctuations in altitude are revealed in North Park by the presence of lenses of impure coal or lignite below the key bed. The writer observed lignite beds in at least two places on the McCallum anticlines - namely, in the SW1/4 sec. 7, T. 9 N., R. 78 W., and the SW1/4 sec. 26, T. 9 N., R. 78 W. A cover of gravel and sand obscures the marine outcrops at many critical points, and this adds to the difficulty of accurate areal and structural mapping. Fossils collected on or near the McCallum anticlines were compared with Beekly's collection of Pierre fossils, which were identified by T. W. Stanton. Among the additional forms identified with the aid of John B. Reeside, Jr., are the following:

Micrabacia americana.
Volutoderma sp.
Fasciolaria sp.
Perissonota protexta.
Anisomyon sexsulcata.
Pachydiscus sp.

Stratigraphic relations

The series of shales overlying the Dakota sandstone in North Park and belonging to the Colorado and Montana groups show some evidence of variation in thickness, presumably owing to the inclination of the pre-Colorado beds in consequence of gradual uplift to the east and a deepening syncline to the west.

In regard to the Colorado group in northeastern Colorado, Mather, Gilluly, and Lusk[6] report that both the Benton and the Niobrara are fairly constant in thickness, the former being about 400 to 600 feet thick along the Front Range south of the Wyoming line, and the latter ranging in thickness from 325 to 700 feet. They also show[7] that the major amount of variation takes place in the Pierre rather than in the beds of Benton age or in the Niobrara, and state[8] that the Pierre evidently thins to the north, east, and south from the Fort Collins region.

In North Park the thickness of beds between the key bed in the Pierre and the Dakota sand, according to the writer's correlation, is 4,000 feet in the vicinity of section L-L' and about 5,000 feet near section M-M', about 7 miles to the south.

Logs of the wells drilled to the Dakota sand on the North and South McCallum anticlines, considered in connection with structure sections through these wells, disclose a southward thickening of the same magnitude between the key bed and the Dakota. Although the writer's field work did not show whether the thickening takes place in the Pierre or in the underlying Cretaceous beds, it seems more probable that in a region which was emerging the greatest variation in thickness would occur near the top of the Cretaceous rather than near the base. The writer therefore attributes these variations to the Pierre.

The Montana group, according to Lavington,[9] who has made an extensive study of these strata in eastern Colorado, may be divided into six zones, at least four of which were previously recognized by members of the United States Geological Survey. Using this earlier work as a basis, he believes that the Montana group can be divided as follows:

Fox Hills sandstone
Transition zone
Cone-in-cone zone
"Tepee zone"
Rusty zone
Barren zone

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6 Mather, K. F., Gilluly, James, and Lusk, R. G., Geology and oil and gas prospects of northeastern Colorado; U.S. Geol. Survey Bull. 796, p.111, 1928.

7 Idem, pp. 114-115.

8 Idem, p. 112.

9 Lavington, C.S., Montana group in eastern Colorado; Am. Assoc. Petroleum Geologists Bull., vol. 17, no. 4, pp.397-410, April 1933.

Time did not permit investigation of possible divisions of the Montana sediments in North Park, but the writer is of the opinion that the lower three zones are recognizable in this area. The key bed used in the structural mapping lies in the most fossiliferous portion of the Pierre, and its fauna and lithology are almost identical with those described as characteristic of the "tepee zone." The highest marine fauna observed by the writer occurs about 500 feet above the key bed and about 20 feet below a coal bed which locally attains a thickness of more than 10 feet. Lavington states that this zone lies uniformly 2,600 to 2,800 feet above the Dakota sandstone in southeastern Montana, also south of the Black Hills and in eastern Colorado, although the underlying zones of the Pierre, the Niobrara, and the Benton shale all change considerably between widely separated areas. However, the interval between the key bed 520 feet below the top of the Pierre and the Dakota sandstone in North Park varies between 4,000 and 5,000 feet and does not exhibit the same degree of constancy. If the divisions suggested by Lavington are recognizable over widely separated areas, the explanation of this lack of agreement in northeastern Colorado and in North Park probably lies in their geographic position with reference to the Colorado geosyncline. No marked unconformity was observed within the group discussed, but the beds reflect a gradual transition from marine to nonmarine conditions of sedimentation.

Tertiary system

Coalmont formation

Lying above the marine Cretaceous, are 4,000 to 6,000 feet of fresh-water beds which Beekly considered either late Cretaceous or Tertiary. These beds are now regarded by the United States Geological Survey as of Eocene age. They include some light-colored shale and sands but are composed mainly of dark-colored shales and cross-bedded sandstones with numerous coal beds from 1 to 50 feet in thickness. Some geologists believe that this formation, named the "Coalmont," overlies the marine beds with angular unconformity. However, on the McCallum anticlines the unconformity appears to be erosional rather than angular.

In the lower 1,000 feet of Coalmont beds (all that is exposed on the flanks of the McCallum anticlines), three to five or more lenticular beds of coal are found. The first well-developed coal bed occurs about 500 feet above the fossiliferous Pierre sandstone used as a key bed, although marine fossils were found less than 25 feet below the bottom of this coal. The occurrence of several coal or lignite beds within this 1,000 feet of strata, as well as one or two occurrences of lignite below the key bed, the general lithology, and the apparent lack of marine fossils suggest that if Lavington's cone-in-cone and transition zones and Fox Hills time equivalents are present, they are represented by this 1,000 feet of strata. The thickness and lithology of this zone agree fairly well with those of Lavington's cone-in-cone zone. As he points out, however, cone-in-cone structure is not confined to this zone. The cone-in-cone bed that probably marks the top of this zone occurs a few feet below a coal of minable thickness.

Beekly considered the possibility that the 2,000 feet of lighter-colored sediments overlying the dark-colored coal-bearing beds, which in turn overlie the Pierre, may belong to a younger formation. The sandstone beds above the coal-bearing strata immediately adjacent to the McCallum anticlines contain an abundance of white quartz pebbles. Fossil leaves were obtained from a sandstone above the uppermost coal bed outcropping on the west flank of the South anticline. This coal bed is mined at the Conrad mine, in sec. 29, T. 9 N., R. 78 W., and is a younger bed than that from which coal is taken at the Marr mine, in sec. 35, on the east flank. These leaves were identified by R. W. Brown, of the United States Geological Survey, and are common to flora of Laramie age. The writer has not made any attempt, however, to determine the dividing line between the main coal-bearing beds and the overlying lighter-colored sediments included in the Coalmont formation. Evidence of angular unconformity between the lower portion of the Coalmont and the Pierre or within these nonmarine beds was not observed in the eastern part of the park.

Quaternary system

The dune sands found adjacent to the mountains on the east, the moraines, and the terrace gravel and alluvium within the park belong to the Quaternary system. The alluvium-covered areas are utilized as hay fields along the Canadian, Michigan, and North Platte Rivers. The gravel forming the top of the mesa in sec. 17, T. 9 N., R. 78 W., is firmly cemented by calcareous material. Large pebbles or boulders of igneous or metamorphic rock as much as 8 inches in diameter comprise the conglomerate capping the mesa on the east side of the anticline in sec. 17. The conglomerate here is 3 to 6 feet thick and consists of granite, chert, gneiss, and quartz pebbles. Capping the benches in secs. 20 and 28, however, is a gravel composed mainly of smaller angular fragments of red granite, less than 1 inch in their greater dimension. These benches on the west side of the anticline are about 200 feet higher than that in sec. 17.

The fluviatile deposits that cap the flat-topped hills in or adjacent to this area appear to have received sediments from two different sources. For example, the arkosic gravel crowning the benches in secs. 19, 20, and 28, T. 9 N., R. 78 W., is not present on the bench on which the Sherman well was drilled, in sec. 12, T. 9 N., R. 79 W., nor on the bench extending from the SE1/4 sec. 8 through sec. 16, T. 9N., R. 78 W., on the east flank of the South anticline. The latter bench appears to be a dissected continuation of the bench on which the Sherman well was drilled. These benches all appear to have been tilted eastward from 3° to 5°. The eastward tilt of these benches on opposite sides of the anticline suggests deposition and uplift subsequent to the folding of the Pierre and the coal series immediately overlying it. Remnants of what appeared to be old terraces were observed but not studied along the foothills of the Medicine Bow Range. Reconstruction of the ancient topography is not possible without more complete data, and tilting or warping of these old land surfaces during late Tertiary or Quaternary time is a subject for further study. In the writer's opinion the drainage on the McCallum anticlines is superimposed. Cursory inspection of the terraces adjacent to the Medicine Bow Range considered in connection with their present altitude, whether caused by the action of lake or river, seems to indicate their formation prior to glaciation in this region. It should be borne in mind that the Continental Divide lies along the west and south boundaries of the park.

Structure

General features.- North Park, near whose eastern border the McCallum anticlines are situated, occupies a huge synclinal basin bounded by uplifted granitic rocks that form the cores of the encircling mountain ranges. On the north the syncline is ended abruptly by the Independence Mountain fault; on the south it rises toward the Continental Divide, which separates North Park from Middle Park. On the east and the west the sedimentary rocks are steeply tilted against the mountain ranges. Minor folds and faults in these marginal outcrops interrupt the regular sequence of beds.

The North and South McCallum anticlines, from 3 to 9 miles east of the town of Walden, cover an area about 2 miles wide and 12 miles long in a northwest-southeast direction and reach a point on the south end about 2 miles from the foothills of the Medicine Bow Range. Between the North anticline and the steeply upturned sediments along the foothills to the east the available evidence strongly indicates a minor structural basin. East of the South anticline there is a sharp syncline, which is slightly warped in the vicinity of the abandoned Sudduth mine, in sec. 15, T. 9 N., R. 78 W. The north end of the North anticline is obscured in part by the cover of bench gravel, and the south end of the South anticline terminates near Moore Mountain, in the center of T. 8 N., R. 78 W. Further structural investigations should be made north, east, and south of these anticlines to determine in more detail their relation to other folds and flexures in this vicinity. The presence of the flat-lying gravel covering, which obscures for distances of a mile or more the marine outcrops on alternate flanks of the anticlines, hinders the determination of structure. The variations in the Pierre sandstones, particularly in hardness or degree of cementation, in abundance of fossils, and in thickness of individual members, tend to add to the difficulty of interpreting structure. At many critical points no structural information is obtainable, owing to the cover of bench or terrace gravel and surficial deposits. Undoubtedly minor faults and fractures in addition to those which appear on the south end of the South anticline are present, but lack of continuity of exposures precludes their determination.

Faults.-Beekly in 1915 and other geologists subsequently mapped a major fault separating the North and South anticlines and striking about N. 10°W. immediately east of the McCallum mine. The present investigation revealed no fault of importance between these two anticlines. Beds in the vicinity of the abandoned McCallum mine, in sec. 18, T. 9 N., R. 78 W., disclose some crumpling and perhaps squeezing, but the almost continuous outcrop of a soft fossil-bearing sandstone on both limbs of this plunging syncline about 25 feet below the coal outcrop indicates that no major vertical movement has taken place. In addition to a fair degree of continuity of this fossil bed in the immediate vicinity of the mine, the upper part of the coal bed on the east side of this syncline can be traced northward for a short distance to a point beyond which it is obscured by terrace gravel and a cover of alluvium. Moreover, the belief that a fault of such mangitude is not present is supported by the fact that the key bed of the upper Pierre can be traced around the east side and the south end of this syncline near the west quarter corner of sec. 17, T. 9 N., R. 78 W., to points within 900 feet of each other. Between these points terrace gravel prevents further mapping of beds.

On the west flank of the anticlines in the SW1/4SW1/4 sec. 17, T. 9 N., R. 78 W., the strata above the key bed are more difficult to trace owing to a cover of gravel and alluvium. Here the key bed on both anticlines can be traced both northward and southward from points within 350 feet of each other on opposite sides of the supposed fault without showing any vertical movement to the south. A fault or a fault wedge or block might be postulated in this vicinity if coals that crop out were used for correlation; however, three to five coals are exposed on the east flank of the South anticline in sec. 8, T. 9 N., R. 78 W., and to base an interpretation of structure solely on coal beds that are known to be lenticular seems unwarranted. A strike fault of undetermined length and displacement was found in the SE1/4 sec. 16, T. 9 N., R. 78 W., and a step fault in the SE1/4 sec. 27. In both these localities definite determination of the length and displacement of the faults was impossible, owing to a cover of gravel and alluvium. These faults affect beds about 1,600 feet below the key bed. It is the writer's opinion that none of these faults in the Pierre continue to the producing sand and that they are not of sufficient throw to affect the accumulation of oil or gas. Owing to the uncertainty as to their extent, no cognizance has been taken of them in drawing the contours on the key bed. The faults on the south end of the South anticline extend under the alluvial cover to the south and under the terrace gravel to the north, but on the map the contour lines are broken to indicate the probable amount of throw. The dip of the coal beds is usually in close agreement with the dip of the underlying marine sandstones. Where dips are lacking along the line of a cross section, it is assumed that the nearest dip or a dip on the key bed nearby continues along the outcrop of the bed, or to the point where such an outcrop was inferred. In the construction of the cross sections parallel folding was assumed, although the writer recognizes the probability of squeezing or flowage toward the crest suggested by the steep dips on the east flanks. It is believed that enough sandstone and limestone is present in the 4,000 feet or more of strata overlying the producing sand (Dakota) to minimize the effect of flowage in the shales. If flowage to any marked degree has taken place in these anticlines it has probably introduced factors at depth which are not determinable at the surface by examination of outcrops and are impossible of accurate representation in cross section.

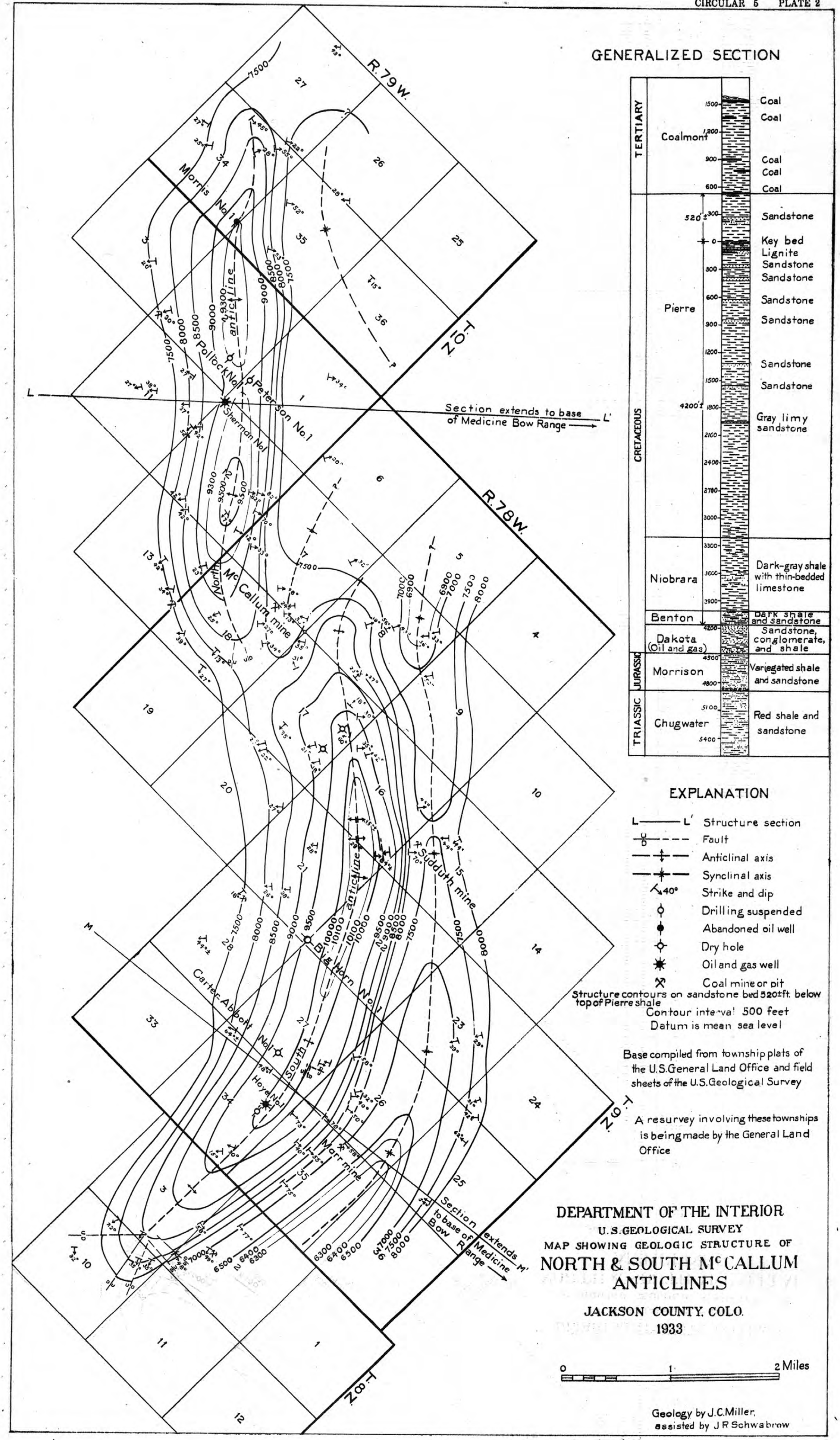
Subsurface structure.-The probable amount of shift in the crests of the folds that would have affected the productive sand could be determined only by a reasonably accurate representation of the axial plane. Without a certain amount of deduction as to the approximate position of the axial plane in asymmetric folds of this nature, an outline of acreage to be included in a unit plan of development for wells 5,000 feet or more in depth would serve only to increase the hazards of drilling and add to the risk of failing to include in the unit lands that might have an important bearing on the future course of development.

The significance of this feature has been appreciated for some time, particularly as drilling depths increase and as some of the steeper folds are drilled. Busk[10] has assembled a series of propositions developed from the geometry of conic sections, the principles of which were used in the construction of fourteen sections across the McCallum anticlines, only two of which are shown on plate 1. The writer recognizes the facts that the productive sand was reached at only two localities on these anticlines--in the Sherman well and the offset wells on the North anticline and in the Hoye well on the South anticline--and that any delineation of subsurface structure based on information supplied by these few wells may be extremely hypothetical. Nevertheless, in view of the thickening of the formations indicated by the well depths and a divergence of the same magnitude and in the same direction along the base of the Medicine Bow Range, the writer believes that a representation of subsurface structure taking into account the progressive thickening toward the south is worthy of consideration. An attempt was made to represent the configuration of the producing sand as developed by these cross sections, but owing to conjectures made necessary because of insufficient data, it was deemed inadvisable to reproduce a structure-contour map of the Dakota sand at this time.

Preparation of structure-contour map.- On the McCallum anticlines the beds dip from 20° to 80° or more, and scarcely any exposures exist along the crests except at the extreme ends. Reliable dip determinations are confined within a relatively narrow zone of not over 1,500 feet of strata. In the preparation of the accompanying structure-countour map parallel folding is postulated, but the principal reason for describing arcs based solely on dips on the flanks of the anticlines was the impossibility of obtaining any dips near the crest, owing to a cover of 6 feet, more or less, of loosely consolidated gravel. It is recognized that in sharp folds squeezing or flowage of shale is likely to take place, but information concerning the exact amount of such flowage or deformation in these anticlines is not obtainable, and any representation of similar folds where such data are lacking may be as much in error as the graphic method devised by the writer and described in the following paragraphs.

Ten sections across the anticlines, in addition to the two shown on plate 1, were constructed to the same vertical and horizontal scale--4 inches to the mile. From these cross sections the amount of shift of the crest of the fold in the Dakota sandstone can be obtained. The details of construction of structure sections are well described by Busk, but stated briefly the method consists of constructing normals

10 Busk, H. G., Earth flexures, their geometry and their representation and analysis in geological section, Cambridge University Press, 1929.


GENERALIZED SECTION
TERTIARY
Coalmont
Coal
Coal
Coal
Coal
Coal
CRETACEOUS
Pierre
520'±
4200'±
Sandstone
Key bed
Lignite
Sandstone
Sandstone
Sandstone
Sandstone
Sandstone
Sandstone
Gray limy sandstone
Niobrara
Dark-gray shale with thin-bedded limestone
Benton
Dark shale and sandstone
Dakota (Oil and gas)
Sandstone, conglomerate, and shale
JURASSIC
Morrison
Variegated shale and sandstone
TRIASSIC
Chugwater
Red shale and sandstone
EXPLANATION
Structure section
Fault
Anticlinal axis
Synclinal axis
Strike and dip
Drilling suspended
Abandoned oil well
Dry hole
Oil and gas well
Coal mine or pit
Structure contours on sandstone bed 520±ft. below top of Pierre shale
Contour interval 500 feet
Datum is mean sea level
Base compiled from township plats of the U.S. General Land Office and field sheets of the U.S. Geological Survey
A resurvey involving these townships is being made by the General Land Office
DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY
MAP SHOWING GEOLOGIC STRUCTURE OF
NORTH & SOUTH McCALLUM ANTICLINES
JACKSON COUNTY, COLO.
1933
0
1
2 Miles
Geology by J.C. Miller, assisted by J.R. Schwabrow
R.79W.
R.78W.
T.10N.
T.9N.
T.8N.
Morris No.1
Pollock No.1
Peterson No.1
Sherman No.1
North
McCallum mine
anticline
Sudduth mine
Big Horn No.1
Carter-Abbott No.1
Hoye No.1
South
Marr mine
Section extends to base of Medicine Bow Range
L
L'
M
M'

to the dips and of using their points of intersection as the centers of arcs representing the folded strata. Unit thicknesses are marked off along the radii, and successive arcs are described. The axial plane or surface is drawn in by joining with a smooth curve the apices of the units of thickness represented.

In order to obtain structure contours from these cross sections, the writer drew a perpendicular to a base line or horizontal plane equivalent to an altitude of 8,000 feet, intersecting the arcs representing the key bed and the Dakota sandstone. First, successive equal intervals of 100 feet were marked off on the perpendicular above and below the base line. Then, lines normal to this perpendicular were drawn through these points to intersect the curves formed by the top of the key bed and the top of the Dakota sandstone. The points of intersection of these equally spaced level lines with the outline of the key bed were projected to the base line or horizontal plane, and the points thus obtained were transferred to the tracing to give the spacing of contours. Only every fifth point on the key bed, however, was used in the preparation of the accompanying contour map (pl. 2).

Petroleum

History of the field.- On December 16, 1926, the Continental Oil Co. brought in its Sherman No. 1 well on Government land in the NW1/4NW1/4 sec. 12, T. 9 N., R. 79 W., at a total depth of 5,113 feet, with an estimated daily production of 30,000,000 cubic feet of carbon dioxide gas and about 500 barrels of oil of 49° A.P.I. gravity. This was the discovery well on the North McCallum anticline, but owing to the presence of this large amount of carbon dioxide with a casing-head pressure of 900 pounds to the square inch and the freezing action of expanding carbon dioxide the production of oil has probably been difficult and costly. During the following year two offset wells were started, but neither has been completed for production to date. The Morris well, in the SE1/4 sec. 34, T. 10 N., R. 79 W., was drilled in 1927, to a depth of 1,020 feet in the Pierre shale. In October 1932 some oil was seeping around a wooden plug placed in the top of the casing of this well. Large storage tanks were constructed to receive the oil near the railroad several miles north of the Sherman well. No shipments of oil have been reported since September 1931.

Prior to July 1924 two wells had been drilled on the South anticline. The Big Horn well of Boetcher & Campion, near the southeast corner of sec. 21, T. 9 N., R. 78 W., was abandoned at a reported depth of 3,200 feet in 1912, and the Carter Oil Co.'s well in the SE1/4 sec. 27, T. 9 N., R. 78 W., was abandoned at a depth of 3,928 feet in 1922. Both wells failed to obtain commercial production of oil or gas. The discovery well on this anticline, known as Hoye no. 1, was started by the Continental Oil Co. July 10, 19[illegible], on Government land, and the producing sand was encountered at a depth of 4,875 feet. The initial daily production of this well was reported as 50,000,000 cubic feet of carbon dioxide gas accompanied by a few barrels of oil with a gravity of 45.8° A.P.I. An offset well south of the discovery well was started in June 1929 and drilled to a depth of 1,025 feet. It proved to be a crooked hole and was plugged back to 295 feet, but at that depth drilling operations have been suspended since August 1929. No further prospecting operations have been attempted.

During the summer of 1930 an experimental plant was constructed near the Sherman well, on the North anticline, for the manufacture of solid carbon dioxide. It was dismantled in the summer of 1932. About 28,000 pounds of marketable solid carbon dioxide had been produced, but the difficulty of separating the oil from the gas and the high freight rates to markets are said to have led the company to abandon plans for the construction of a large plant.

Occurrence.-Petroleum occurs in small quantities in the Pierre shale, as shown by the logs of the Sherman well, in the NW1/4 sec. 12, T. 9 N., R. 79 W., and the Morris well, in the SE1/4 sec. 34, T. 10 N., R. 79 W. A good showing of oil was reported in the Hoye well, in the NW1/4 sec. 34, T. 9 N., R. 79 W., about 700 feet above the Dakota sand. These showings were not considered sufficient for commercial exploitation. Drilling was continued in the Sherman and Hoye wells until petroleum was found in the Dakota sand accompanied by large volumes of carbon dioxide gas. The occurence of petroleum fairly low on these anticlines, according to the structure-contour maps, provokes some speculation as to the concentration of oil and gas in the higher parts of both anticlines, particularly above the northernmost closing contour. Whether oil and gas in the Dakota sand are distributed as in an ordinary anticlinal fold or whether they have been flushed out in the more porous parts by fresh water entering the producing zone at the outcrop is problematical. The propinquity of the exposure of the producing zone certainly makes the possibility of the flushing action of circulating water an item to be considered when a drilling campaign is being planned.

No success has attended efforts to drill through the zone containing carbon dioxide, and consequently the exploitation of possible productive beds at greater depth has been left for future engineering skill.

<u>Engineering problems</u>.- Reports of operations in the McCallum field up to the present time show that trouble is experienced with crooked holes. This may be due in part to the steep dips and in part to the lithologic character of the Pierre shale. Drilling operations have been conducted by means of rotary and cable tools with varied success. Observation of exposures in the field points to the feasibility of using the rotary method to the top of the producing sand, with the aid of suitable rock bits.

A column of mud fluid at suitable temperature in the hole when the producing sand is reached seems imperative, because of the high pressure of the gas. During the early life of the Hoye well, on the South anticline, a weighted mud fluid was used in an attempt to hold the well under control while repairs to the casing were being made in order to produce the oil and gas. The well has been shut in since this attempt. In wells that have been drilled to the producing sand the gas has been found to have sufficient pressure to blow the tools out of the hole or to tear away surface fittings. This hazard to life and property adds to the ordinary expense of drilling and production. In order to reach a satisfactory solution of the engineering problems involved, it is essential that consideration be given to the physical properties of carbon dioxide in planning drilling and producing programs.

Carbon dioxide

The percentage of carbon dioxide in the gas produced with the oil in the Dakota sand in the McCallum anticlines is almost equal to that found elsewhere in the Rocky Mountain region, to which wells containing the highest proportion of carbon dioxide of all gas wells in the United States, according to present developments, appear largely to be confined.

Definite determination of the origin of carbon dioxide in the McCallum field was not within the scope of the present investigation. A general paper by the writer dealing with the origin of carbon dioxide in this and other Rocky Mountain fields was recently published elsewhere.[11] Either an organic or inorganic source may be postulated, and the geologic history of the region yields evidence favoring both sources of carbon dioxide. In the light of that history, it seems probable that oil and carbon dioxide may have originated from the same organic source,

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11 Miller, J. C., Discussion of origin, occurrence, and use of carbon dioxide; Oil and Gas Jour., vol. 32, no. 25, pp. 19-20, November 9, 1933.

but they were not contemporaneous. The writer regards the formation of carbon dioxide as a local phenomenon that preceded the generation of oil, which he attributes to dynamo-chemical changes in the organic matter incident to the Rocky Mountain orogeny. However, it is recognized that the volcanism which attended the formation of the Rocky Mountains may have provided an adequate inorganic source of carbon dioxide also.

Analysis of gas.-A sample of gas from the Sherman well, obtained in 1927 by George G. Law, of the Geological Survey, was analyzed by the Bureau of Mines with the following results:

Carbon dioxide - - - - - - - - - - -	91.82
Oxygen - - - - - - - - - - - - - -	.63
Methane - - - - - - - - - - - - - -	2.76
Ethane - - - - - - - - - - - - - -	1.89
Nitrogen - - - - - - - - - - - -	2.90

Difficulties of production.- Under past operating conditions on the McCallum anticlines the oil was produced with the gas in the form of a slush. If production was too rapid the well froze, and production ceased. Early experiments with pure gas and with nitrogen mixtures, though confined to small volumes in a state of rest, are of value in formulating methods of production and suggest the efficacy of a mixture of the gas produced in the McCallum field with air. Experimental data on the properties of such mixtures in large volumes of flowing gas under conditions similar to the usual methods of production of gas wells are not available. Nevertheless Andrews and others have presented notable results from their investigation of mixtures with air or nitrous oxide. Among the early contributions to the physical chemistry of carbon dioxide, the work of Andrews[12] is outstanding. As an outgrowth of his first experiments he published a paper presenting isothermal curves of carbon dioxide, which have a direct bearing on problems encountered in wells producing large quantities of carbon dioxide. The isothermal curves given in figure 1, based on Andrews' work, show among other things that liquid and vapor phases occur at temperatures below the critical temperature - that is, 31°C. or 88°F. - and below the critical pressure of 73 atmospheres.

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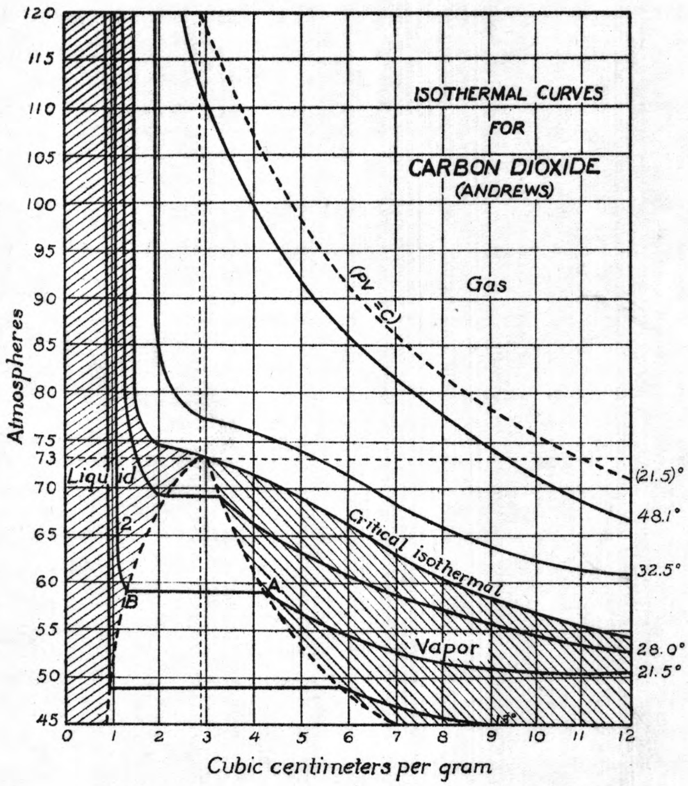
12 Andrews, Thomas, On continuity of the gaseous and liquid states of matter: Royal Soc. London Philos. Trans., vol. 159, pp. 575-591, 1869.



ISOTHERMAL CURVES
FOR
CARBON DIOXIDE
(ANDREWS)
Gas
(PV = C)
Liquid
Critical isothermal
Vapor
A
B
2
(21.5)°
48.1°
32.5°
28.0°
21.5°
13°
Atmospheres
120
115
110
105
100
95
90
85
80
75
73
70
65
60
55
50
45
0
1
2
3
4
5
6
7
8
9
10
11
12
Cubic centimeters per gram

In his last work, reported in 1887, Andrews[13] completed his experiments on carbon dioxide and nitrogen gases, in which he obtained further proof of the failure of Dalton's law at high pressures and low temperatures--that is, temperatures below the critical points. In this paper he states that "With a mixture of 6.2 volumes carbonic acid and 1 volume nitrogen, and which therefore contained 13.9 percent of nitrogen, liquid first appeared at the temperature of 3.5° when the pressure was raised to 48.3 atmospheres. As the pressure was increased the volume of the liquid augmented. * * * For a mixture composed of 1 volume of nitrogen and 3.43 volumes carbonic acid, or containing 22.5 percent nitrogen, the critical point of temperature was found to be 14.0°, and the corresponding pressure 98 atmospheres."

The French investigators Caillete and Caubet obtained results similar to those of Andrews in their work with gaseous mixtures.

According to Chwolson,[14] Strauss in 1880 derived a formula for a mixture of two fluid substances, which later was found to apply to gaseous mixtures. This formula is repeated here in modified form and is considered as giving only approximate results for carbon dioxide mixtures:

$$\frac{T_c = a_1 t_1 + a_2 t_2}{a_1 + a_2}$$

where T_c = critical temperature of the mixture
t_1 = critical temperature of one constituent
t_2 = critical temperature of the other constituent
a_1 and a_2 = percentage of each substance in mixture.

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13 Andrews, Thomas, Gaseous and liquid states under various conditions: Royal Soc. London Philos. Trans., vol. 178, ser. A, pp. 45-56, 1887.

14 Chwolson, O. D., Lehrbuch der physik, vol. 3, p. 838, 1905.

In this connection Chwolson states that it appeared that the critical temperature was always somewhat lowered but the critical pressure was markedly raised by a mixture of two gases. The critical temperature of a mixture consisting of 25 percent air and 75 percent carbon dioxide is computed from the formula as follows:

$$T_c = \frac{75 \times 30.98 + 25\ (-140.7)}{100} = -11.94^\circ C.$$

This result is equivalent to 10.5° Fahrenheit. For a mixture of 10 percent air and 90 percent carbon dioxide, the critical temperature was computed to be about 57°F. according to this formula.

Van Orstrand[15] has estimated that the well temperature in the McCallum anticlines at a depth of 5,000 feet would be not less than 90°F. nor more than 140°F. These estimates are based on measurements of well temperature in the Fort Collins field, Colorado. The average annual temperature is assumed to be about 40°F. in North Park, which is 48°below the critical temperature of carbon dioxide. There is a slight loss of heat between the bottom and the top of the hole, owing to absorption of heat by the strata in the upper part of the hole, but it is believed that the effect of this loss on the flowing gas is negligible. The dissipation of heat is apparently due principally to expansion and to cooling at the surface, extending from the point of discharge back to and below the well head. At an average annual temperature of 40°F. either adiabatic or isothermal expansion of the nearly pure gas in the operation of individual wells presents complications difficult of practicable solution.

The mixture of a relatively noncondensable gas, such as air, either by injection into the well or perhaps better into the flow lines after the oil and gas pass through the separators, in proportions suggested by the experiments of Andrews, Strauss, and others, seems to offer a means of obtaining continuity of production, provided the operating well pressures prove to be such that the cost of compressing air does not preclude its use. In fields where the carbon dioxide content of the gas is low it has been demonstrated that production can be maintained by proper control of pressures and temperatures alone. It is questionable, however, in the light of the experimental data here discussed, whether under similar conditions production could not be maintained at lower pressures and at a faster rate by mixture with compressed air.

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15. Van Orstrand, C. E., personal communication, December 1932.