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Stratigraphic Analysis of the Upper Cretaceous Pictured Cliffs Sandstone in Northeastern San Juan County, New Mexico

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STRATIGRAPHIC ANALYSIS OF THE UPPER CRETACEOUS PICTURED CLIFFS SANDSTONE IN NORTHEASTERN SAN JUAN COUNTY NEW MEXICO

CALDWELL

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By

John W. Caldwell

A Thesis
In partial fulfillment of the
Requirements for the Degree of
Master of Science in Geology

The University of New Mexico
1953

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MASTER OF SCIENCE

E. H. Castetter
DEAN

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DATE

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Sherman A. Wengerd.
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ABSTRACT

The San Juan Basin is located in northwestern New Mexico and southern Colorado and is physiographically a part of the Colorado Plateau province.

The Upper Cretaceous Pictured Cliffs sandstone is exposed around the perimeter of the San Juan Basin and is present throughout the greater part of the Basin in the subsurface. This economically important gas-bearing sandstone is situated in a structural basin in which the strata are upturned on the basinward flanks of the nearby Laramide uplifts.

The Cretaceous regional stratigraphy of the area indicates deposition of clastic material which originated from highlands to the west in an irregular sequence of transgressive and regressive seas and later continental deposits. The Pictured Cliffs sandstone represents the last marine regression of the late Cretaceous sea in the area, and the lithology of the sandstone shows the environment of deposition to have been gradational from the marine-littoral zone to the infraneritic zone. A study of the fossils suggests that the Pictured Cliffs sandstone is of Montana age.

The gas-producing section ranges in average thickness from 30 to 60 feet in the Pictured Cliffs sandstone. The total lateral extent of the productive section is not yet known, however, areas of present gas production appear to

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The gas-producing section ranges in average thickness from 30 to 60 feet in the Pictured Cliffs sandstone. The total lateral extent of the productive section is not yet known, however, areas of present gas production appear to

be limited by the extent of water incursion from the outcrops.

The present structure on the southwest flanks of the San Juan Basin is monoclinal and the present location of Pictured Cliffs gas is indirectly related to regional structural declivity by providing an intake area for meteoric water. The accumulation of Pictured Cliffs gas is thus in part a result of stratigraphic entrapment. The Pictured Cliffs gas occupies areas of less porosity and permeability in the sandstone, and the same stratigraphic traps which hold the gas exclude the greater part of the water.

Reservoir fluids comprise brackish and fresh water, condensate, and some oil, with no appreciable amount of oil being produced in commercial quantities from the Pictured Cliffs sandstone in the area studied. Reservoir pressure of the gas is considerably less than hydrostatic pressure. An increase of reservoir pressure and initial potential is noted in the southeastern parts of the present areas of gas production, indicating eventual extensions of the fields in that direction.

Five possible origins for the Pictured Cliffs gas are presented: from the underlying Lewis shale, from within the Pictured Cliffs sandstone, from the overlying Fruitland formation, from formations below the Lewis shale, and from formations above the Fruitland formation.

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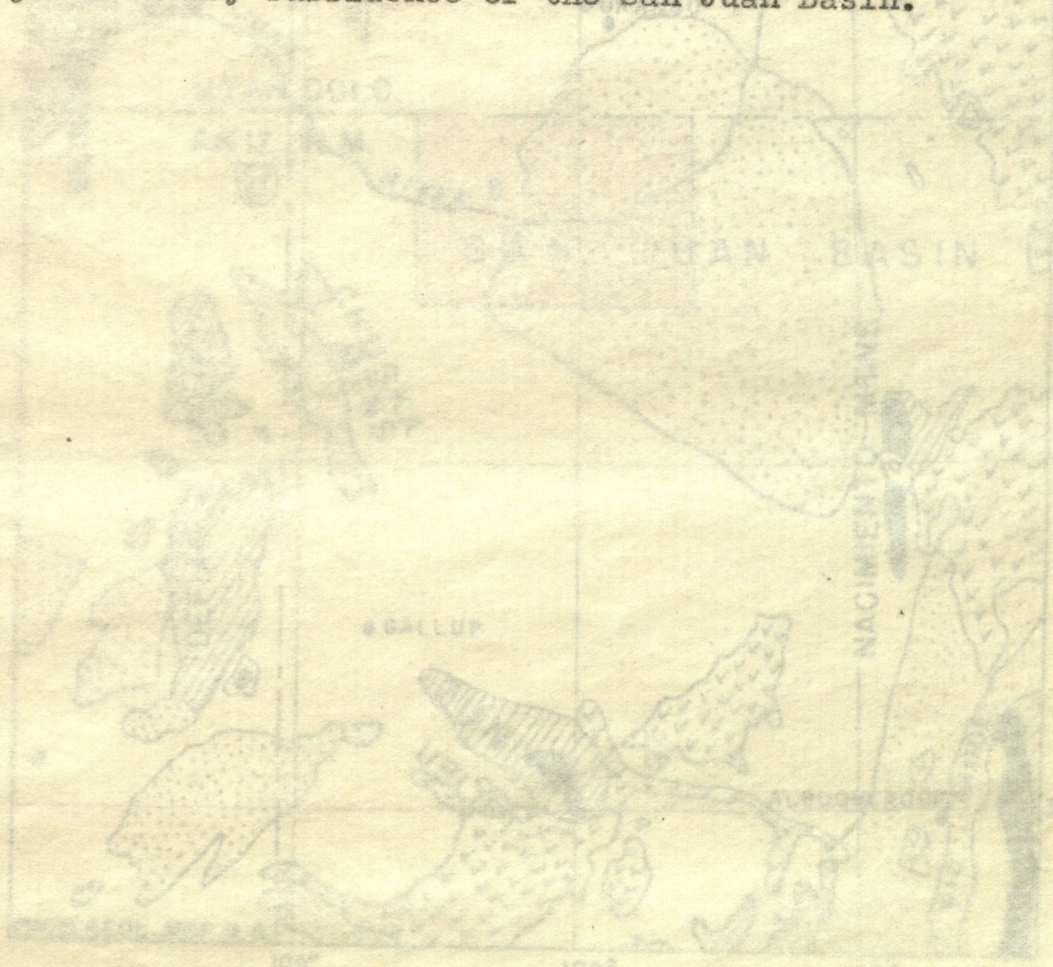
Two major migrations effected the accumulation of Pictured Cliffs gas, with a general regional accumulation toward the northeast when the area was inclined to the west, succeeded by local displacement to its present position with the advent of water from the outcrop subsequent to major Tertiary subsidence of the San Juan Basin.



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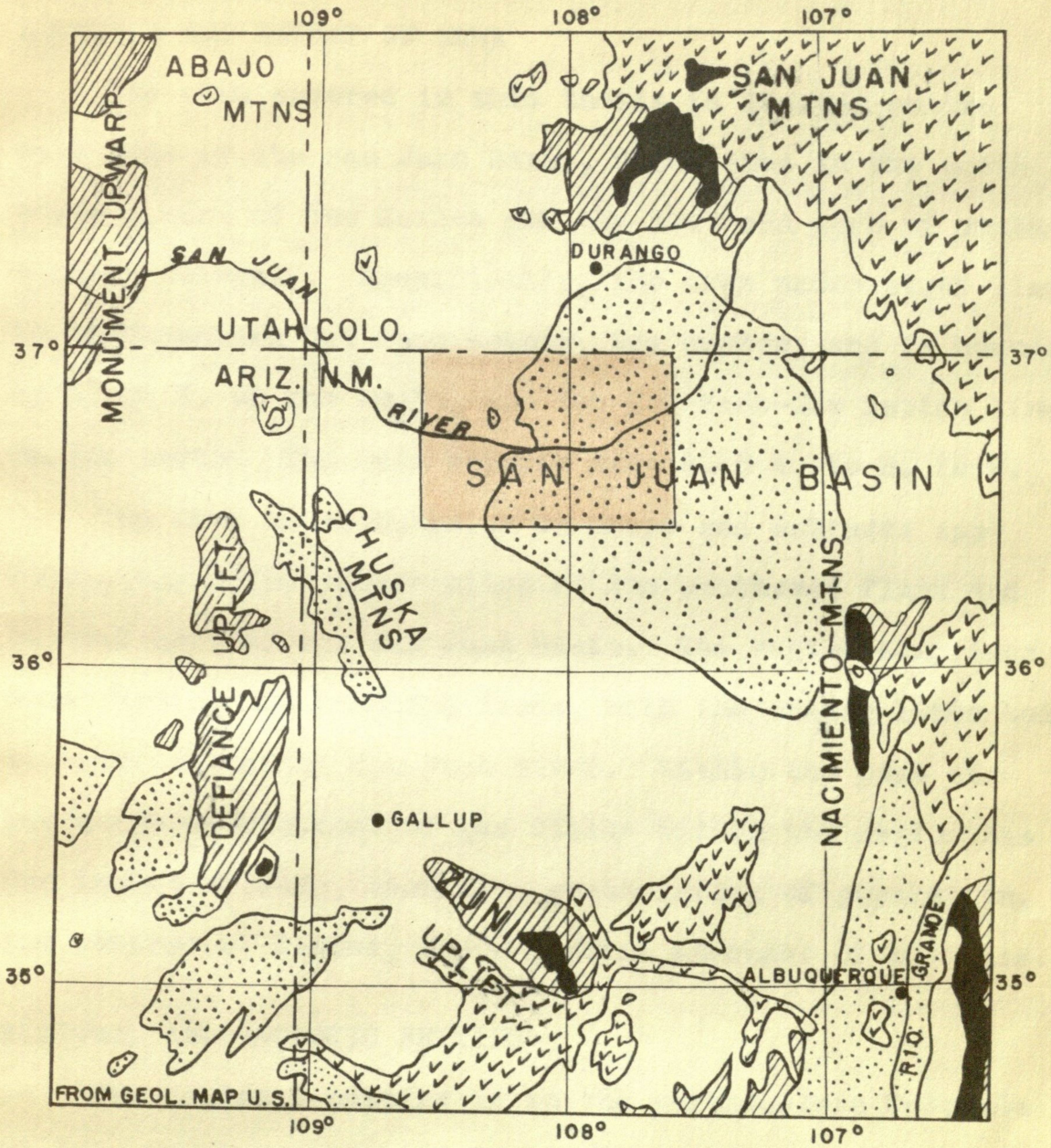

LEGEND

RE-CAMBRIAN | PALEOZOIC | MESOZOIC | CENOZOIC | TERTIARY VOLCANICS

FIGURE I.

SHOWING

LOCATION OF AREA

SCALE

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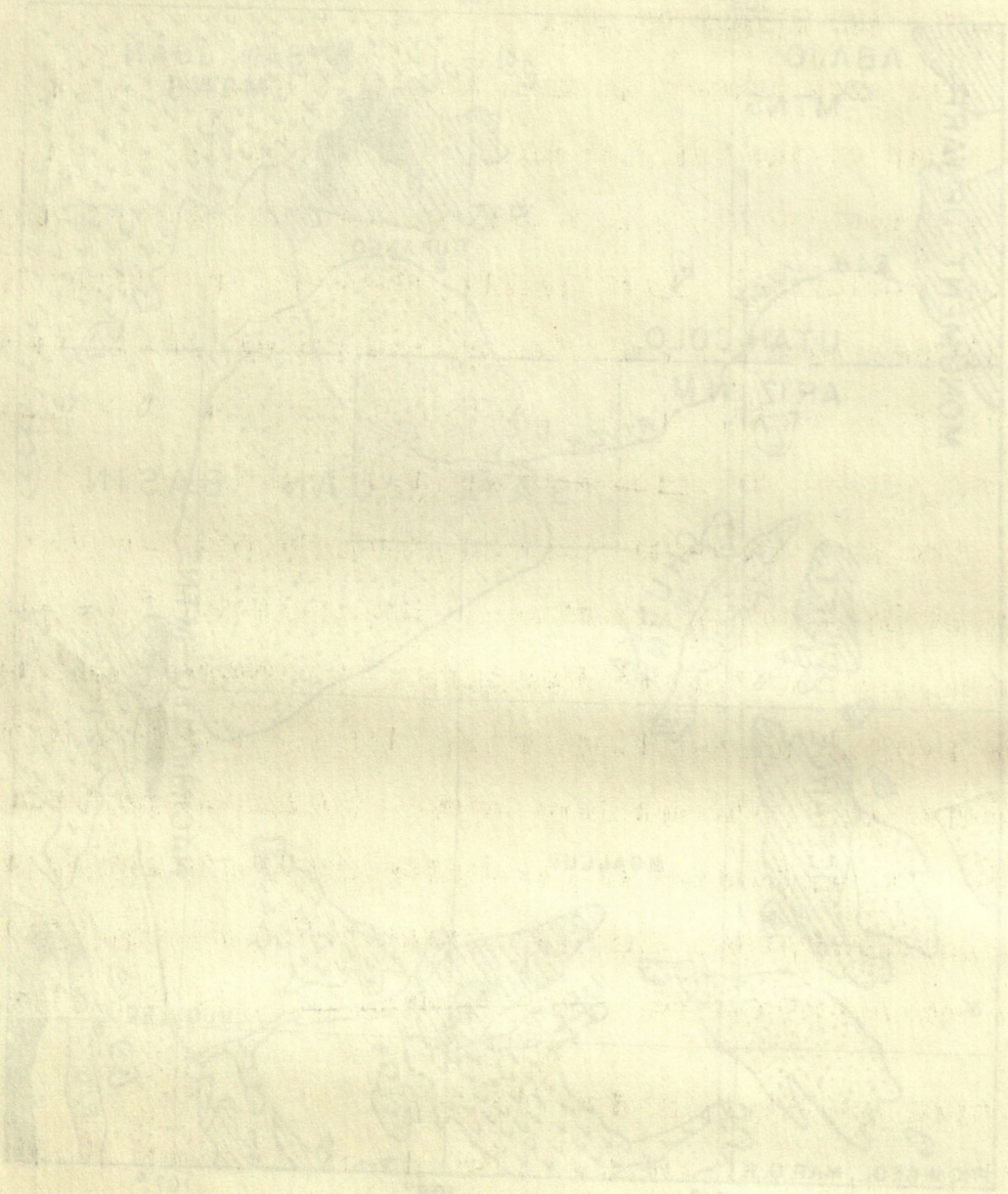

INTRODUCTION

LOCATION AND EXTENT OF AREA

The area covered in this thesis is located on the west side of the San Juan Basin, which lies in the northwestern part of New Mexico and the southern part of southwestern Colorado. Specifically, the area under study lies in northeastern San Juan County, New Mexico, and is bounded by T. 26 N. on the south, and the Colorado-New Mexico line on the north. The area extends from R. 8 W. to R. 16 W.

The area is rectangular in shape and embraces approximately 2,200 square miles of the southwest flank and central part of the San Juan Basin. The region comprises some farming and ranching lands, with the arable lands being situated along the San Juan River. Within the past six years the development of gas fields within the region has had marked effects, such as a great influx of population, new sources of income, and a general increase of business.

REGIONAL AND GEOLOGIC SETTING

The regional setting is in the northeastern Colorado Plateau physiographic province. The particular area under study lies within the San Juan Basin, which is characteristic of the broad downwarped basins of the Colorado Plateau.

Geologically, the area is a structural basin with the formations gradually rising from the structurally deepest

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part of the basin in the vicinity of the San Juan-Rio Arriba County line towards the uplifts surrounding it. The region is bounded on the north by the San Juan Mountains of southwestern Colorado, on the east by the Nacimiento Mountains of north-central New Mexico, on the south by Mt. Taylor and the Zuni Mountains, and on the west by the Defiance Uplift, which lies west and adjacent to the border of northwestern New Mexico and northeastern Arizona.

HISTORY OF EXPLORATION FOR, AND DEVELOPMENT OF, PICTURED CLIFFS GAS

Interest in the region was created by the discovery of small quantities of oil in the Seven Lakes area by Henry Brock and Jerry Farris in 1911. The oil produced did not prove to be commercial in quantity and the field was practically abandoned by 1913 (Gregory, 1917, p. 145). Non-commercial quantities of gas had been encountered in the Pictured Cliffs sandstone during the drilling of deeper wells seeking production in the Mesaverde formation in the Blanco field in 1927. The first commercial gas from the Pictured Cliffs sandstone was found in what was formerly known as the Kutz Canyon field. The discovery well was completed in 1927 by the Congress Oil Company in Sec. 34, T. 29 N., R. 11 W., at a depth of 1,910 feet, for 1,500,000 cubic feet of gas per day. (Bates, 1942, p. 112)

The Pictured Cliffs discovery well in the Fulcher Basin field was made in 1934. By 1941 approximately 50 wells had been drilled to the Pictured Cliffs sandstone in the two fields. The Kutz Canyon and Fulcher Basin fields were joined in 1947, when the area separating the two fields was found to be productive of commercial quantities of gas. The field then was designated the Fulcher-Kutz-Pictured Cliffs field by the New Mexico Oil Conservation Commission. Exploration and drilling were moderate until 1949. In July of 1950, with the approval of the El Paso Natural Gas Company's 24-inch pipe-line to California, which offered an assured outlet for gas produced in the area, drilling and exploration increased at a rapid rate. This period of extensive exploration led to the discovery of the West Kutz-Pictured Cliffs field in 1950. This field parallels the Fulcher-Kutz-Pictured Cliffs field and lies five to ten miles to the west. The boundaries of these two major Pictured Cliffs fields have been only partially determined, particularly on the southeastern edge of both fields. It is possible that these two fields may be joined eventually when the area to the southeast has been tested. There is also a possibility that one or perhaps both fields may be extended to the southeast far enough to connect with the South Blanco and the Dogie Canyon fields in southwestern Rio Arriba County, which

also produce gas from the Pictured Cliffs sandstone.

PREVIOUS WORK

The Pictured Cliffs sandstone was first described by W. H. Holmes in 1875 in his "Geologic Report of the San Juan District," which was published in the U. S. Geological and Geographical Survey of the Territories, Ninth Annual Report. Holmes named the sandstone the Pictured Cliffs after the Indian petroglyphs found where he described the section. (See Fig. 9) The type locality is located about one and one quarter miles west of the village of Fruitland and approximately one quarter of a mile north of U. S. Highway 550. The type locality is in Sec. 4, T. 29 N., R. 15 W., San Juan County, New Mexico.

Many papers have been published on the geology and fuel resources of the area, but little has been published on the Pictured Cliffs sandstone. The published papers deal mainly with the overlying Fruitland formation which contains coal. The best of these early papers is by J. B. Reeside, Jr. (1934). Very little subsurface information on the Pictured Cliffs sandstone is being released at present, owing to the commercial aspects of the stratigraphic problems involved. Two papers by Caswell Silver (1950; 1951), however, describe the sandstone, its extent, and its subsurface position throughout the San Juan Basin.

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PURPOSE OF THE REPORT

The purpose of this report is to present a stratigraphic analysis of the Pictured Cliffs sandstone of northeastern San Juan County, New Mexico. An effort has been made to show the regional aspects, the structure and its origin, source areas for the sediments, environment of deposition, lithology, and correlation. A part of this thesis is devoted to a discussion of the accumulation of gas, with a view to determination of the relations of structure and stratigraphy to accumulation as well as the extent the formation waters have controlled the migration of commercial gas. Several possible origins of the gas are considered.

METHOD OF STUDY

Seven days were spent in the field—measuring sections, collecting fossils, and studying the local and regional setting and surface exposures. The remainder of the work was done in the laboratory. Well locations, Pictured Cliffs tops, and pressures were assembled on base maps from scout tickets and electric logs. This information includes only those wells available for study before October 1, 1952. Samples available from 21 wells were examined with the binocular microscope and their lithology correlated with the electric logs. In those wells

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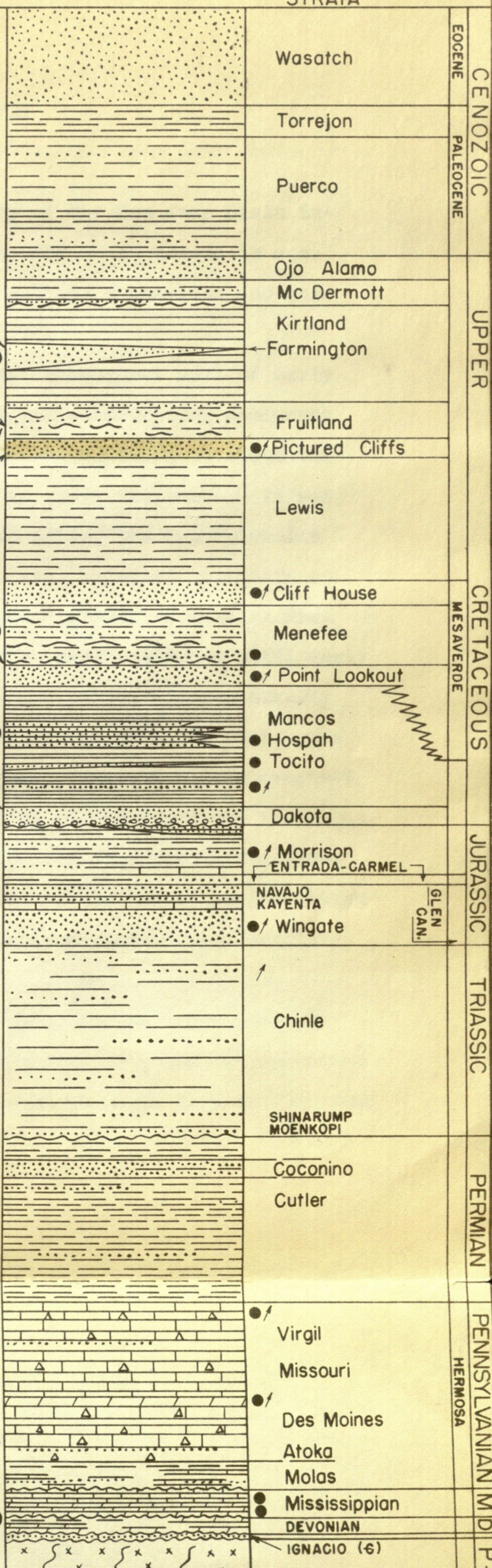
NORTHWESTERN NEW MEXICO

FIELDS AND AVERAGE DEPTHS

STRATA



AZTEC - 1000'
BLANCO-1800'
BLOOMFIELD-725'
FULCHER BASIN-950'-1000'
OSWELL-1800'

IGNACIO-2800'
BLANCO-2000'-2500'
FULCHER BASIN-1800'
KUTZ CANYON-1700'-1900'
AZTEC-BLOOMFIELD-1700'
WEST KUTZ CANYON-1700'-2000'
DOGIE CANYON-3000'

BLANCO-3150'-4150'
RED MTN.-475'-500'
SEVEN LAKES-400'-500'
STONEY BUTTES-775'-850'
TA-BLANCO-LARGO CANYON-5000'-6000'

HOSPAH-1575'
CHROMO-700'
CHIMNEY ROCK-600'
DOGIE CANYON-6500'
IGNACIO-7500'
BARKER-2400'-3100'
FULCHER BASIN-6600'
HOGBACK-650'-800'
RATTLESNAKE-800'
SOUTHERN UTE-2300'
TABLE MESA-1300'-1400'

FIGURE 2.

APHY & PRODUCTIVE ZONES

EXPLANATION

SANDSTONE
SHALE
LIMESTONE
DOLOMITE
COAL
UNCONFORMITY
OIL PRODUCTION
OIL SHOW
GAS PRODUCTION
GAS SHOW
FOOTAGE-OIL AND GAS

ATE VERTICAL SCALE

CH=1200 FEET

RATTLESNAKE-6585'-6770'
BARKER-8400'-8700'

RATTLESNAKE-9000'
TOCITO-8500'
TABLE MESA
HOGBACK

STRATIGRAPHY

REGIONAL STRATIGRAPHY

The regional stratigraphy of the San Juan Basin includes rocks ranging from Precambrian to Eocene in age. However, the region does not contain a complete and uninterrupted sequence of deposition.

The area of the basin was, throughout most of early Paleozoic time, a positive region contributing sediments to surrounding seas or oscillatory downward to allow the deposition of pre-Pennsylvanian shelf sediments. It was not until late Paleozoic time, during the Pennsylvanian and Permian periods, that the area received sediments of major proportions. Continental deposition, grading from marine deposits of Pennsylvanian age, continued until early Cretaceous time when the area was tilted epeirogenically and became the southwest shelf of the Rocky Mountain geosyncline. During late Cretaceous time the region received thick marine clastics ranging up to 5,000 feet in thickness. Subsequent to the deposition of the Pictured Cliffs sandstone, the region rose epeirogenically out of marine waters and became the site of the latest Cretaceous and Tertiary continental deposition.

Numerous unconformities occur in the lower part of the stratigraphic section (See Fig. 2), and determination of the stratigraphy below Cretaceous rocks is doubtful owing

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14. Pressure-contour map.....in pocket

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1. Floral and faunal chart.....18

to a paucity of deep tests.

Lower Cretaceous rocks, however, have been tentatively identified by Reeside (1944, map) in the northern part of the Basin. Silver (1951, p. 105) states

> "....similar rocks of like thickness appear to be locally present in northern New Mexico..... Subsurface information from the few wells presently drilled to that horizon indicates that these rocks are generally present in the subsurface through the northern half of the basin."

Regional disconformities occur between what are believed to be Devonian and Mississippian strata, between Mississippian and Pennsylvanian strata, at the top of Permian strata, and between Jurassic and Upper Cretaceous strata.

Mesozoic rocks comprise the greater part of the section. The Hermosa formation of Pennsylvanian age comprises the only complete record of deposition during Paleozoic time. The remainder of the Paleozoic systems are either not represented or their strata have been partially eroded.

From late Cretaceous time to the Eocene epoch, there is a thick sequence of beds showing a virtually continuous deposition of sediments. There is some doubt, however, concerning the exact age of the Ojo Alamo and McDermott formations. The Ojo Alamo and McDermott formations are of continental origin and the scarcity of fossils makes their relative age determination difficult.

Most of the Upper Cretaceous section is comprised of sandstone and shale, with some coal occurring in the

to a paucity of deep tests.

Lower Cretaceous rocks, however, have been tentatively identified by Needle (1944, map) in the northern part of the basin. Silver (1951, p. 105) states

> "....similar rocks of like thickness appear to be locally-present in northern New Mexico..... Subsurface information from the few wells presently drilled to that horizon indicates that these rocks are generally present in the subsurface through the northern half of the basin."

Regional disconformities occur between what are believed to be Devonian and Mississippian strata, between Mississippian and Pennsylvanian strata, at the top of Pennsylvanian strata, and between Jurassic and Upper Cretaceous strata.

Mesozoic rocks comprise the greater part of the section. The Permosa formation of Pennsylvanian age comprises the only complete record of deposition during Paleozoic time. The remainder of the Paleozoic systems are either not represented or their strata have been partially eroded.

From late Cretaceous time to the Eocene epoch, there is a thick sequence of beds showing a virtually continuous deposition of sediments. There is some doubt, however, concerning the exact age of the Ojo Alamo and McDermott formations. The Ojo Alamo and McDermott formations are of continental origin and the scarcity of fossils makes their relative age determination difficult.

Most of the Upper Cretaceous section is comprised of sandstone and shale, with some coal occurring in the

Menefee, Fruitland, and Kirtland formations. The Jurassic Todilto and Upper Cretaceous Greenhorn strata represent the only limestone present in the section above the Pennsylvanian Hermosa formation.

The Upper Cretaceous stratigraphic section represents repeated transgressions and regressions of the sea in the Rocky Mountain geosyncline. During certain stages, the area was covered by the seas, and was succeeded by swamps and alluvial deposits. From Dakota time to the final regression of the sea which deposited the Pictured Cliffs sandstone, the sea was relatively shallow but fluctuating in depth and position of strandline. It possessed during this time a combination of environments resulting in the intertonguing of sandstone, shale, and coal. The remaining sediments above the Pictured Cliffs sandstone are of continental origin and comprise sandstone, shale, and coal.

In general it can be said that the stratigraphic sequence of beds represents a varied and complex history of sedimentation represented by sandstone, shale, coal, and conglomerate in almost every possible gradation and combination.

DISTRIBUTION

It should be pointed out that this thesis deals primarily with the southwest lobe of the Pictured Cliffs

sandstone as defined by Silver (1950, p. 112), unless otherwise stated. All data such as well information, pressures, structural contours, and figures are based on wells drilled into the southwest lobe of the Pictured Cliffs sandstone.

The Pictured Cliffs sandstone, as such, is known only in the San Juan Basin. It appears to be present in an area of approximately 7,500 square miles. It undoubtedly has correlatives in other areas; however, due to the structural nature of the San Juan Basin, the beds are exposed on the perimeter of the Basin and erosion has removed them from the surrounding adjacent areas. It is impossible, thus, to trace the bed directly, other than around the rim of the Basin, and throughout the Basin by use of subsurface information. The Pictured Cliffs sandstone has been encountered throughout a large part of the basin in well samples. Silver (1951, p. 115) states that the Pictured Cliffs sandstone

> "crops out on the north, west and south sides of the basin. It is notably absent on the east side."

According to Dane (1946, map), the Pictured Cliffs sandstone is found as far south on the eastern side of the Basin as T. 31 N., R. 1 W. and is not found again on the east side until T. 20 N., R. 2 W., a distance of approximately 70 miles or one-fifth of the linear outcrop along the perimeter of San Juan Basin.

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The eastern limit of distribution in the subsurface has not been determined definitely because of the lack of wells drilled in the locale where the sandstone grades into a shale sequence.

THICKNESS

The thickness of the Pictured Cliffs sandstone varies greatly throughout its surface and subsurface extent in the San Juan Basin. The presence of the northeast lobe is responsible for the increased thickness of the Pictured Cliffs section in the northern part of the Basin. A 400-foot thickness of Pictured Cliffs sandstone has been measured near Durango, Colorado, and this thickness represents both the northeast and southwest lobes; however, on the eastern side of the San Juan Basin, in the vicinity of Cuba, New Mexico, the Pictured Cliffs sandstone is absent from the stratigraphic section.

The respective thicknesses of the main sandstone lentil and total thicknesses of the Pictured Cliffs sections measured for this thesis can be noted in the descriptive stratigraphic sections in the appendix. The average thickness of the Pictured Cliffs sandstone in the area studied for this thesis is 70 feet.

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LITHOLOGY

The Pictured Cliffs formation is predominantly

sandstone with interbedded gray shale, carbonaceous shale, siltstone, some coal, and thin-bedded calcareous sandstone.

The Pictured Cliffs sand is angular to subangular and medium to fine grained. The sandy facies shows a remarkable lithologic consistency throughout the immediate area studied. The only variation in grain size seems to be from the top to the bottom of the section. There appears to be a greater quantity of fine-grained sand grading into siltstone near the bottom of the section, as the formation grades into the Lewis shale below. There are numerous exceptions to this as can be clearly noted in Figure 12, A and B. Local variations within the section occur where interbedded shales and siltstones are generally associated with fine-grained sand lentils.

The composition of the sand is largely detrital quartz, with varying amounts of interstitial clays and rounded claylike detrital material which is carbonaceous in part. Traces of muscovite, biotite, and possibly chlorite were observed. The varying amounts of interstitial clays and detrital material increase towards the north and east. This can be observed in Figure 12, A and B, which show the electric log characteristics and the lithology of cross sections in the area. In Krynine's classification of sedimentary rocks (1948, table 3), the Pictured Cliffs sandstone appears to be a quartzose semi-graywacke.

Representative samples of the interstitial clays were collected from numerous wells throughout the area for examination. The clay mineral content of the Pictured Cliffs sandstone, from differential thermal and X-ray spectrometer analysis, showed the sample to contain 20-30 percent clay minerals, almost exclusively kaolinite, with suggestions of small amounts of illite and montmorillonite; the latter two together do not exceed one percent. Seventy to eighty percent of very fine quartz and potash feldspar, about equally divided, make up the bulk of the clay size components. Traces of calcite and mica were also observed. The clay samples were analyzed by Carl W. Beck and Clarence S. Ross.

The cross sections in Figure 12, A and B show the stratigraphic section from the top of the Pictured Cliffs sandstone down into the Lewis shale and are structurally related to sea level datum. The lithology was determined by examination of samples from the respective wells, and correlation of sample logs with electric logs.

Cross-bedding is prevalent and prominent near the top of the section, as one might expect in gradations into terrestrial beds above. Where the sandstone crops out it usually forms a cliff, varying in height with the thickness of the massive sandstone lentils. The uppermost prominent bed of sandstone shows little trace of bedding planes. A

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part of the massive sand body is conchoidally fractured on a large scale and displays some vertical jointing. The weathered surface ranges in color from buff to dark reddish-brown. The exposed surface shows differential weathering of the clayey layers, and displays an irregularly weathered surface formed by a more rapid disintegration or decay in some parts of the rock than others. (Note Figure 10.)

PALEONTOLOGY

Although different fossil genera are numerous and occur in many parts of the Pictured Cliffs sandstone in the San Juan Basin, they are poorly preserved and comparatively sparse in any one locality.

Halymenites major Lesquereux is common throughout the Pictured Cliffs section and is present in most parts of the San Juan Basin. Near the base of the Pictured Cliffs sandstone in the Highway section, Sec. 5, T. 29 N., R. 15 W., San Juan County, New Mexico, small unidentifiable plant fragments were found within the sandstone beds interbedded with shale. The plants are usually preserved as carbonaceous remains or poorly preserved impressions, and are present in the shale as well as in the thin-bedded sandstone beds.

A small collection of invertebrate fossils was made and is listed in Table 1, a floral and faunal chart, following page 18. A single specimen of Brachidontes

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A small collection of invertebrate fossils was made and is listed in Table 1, a floral and faunal chart, following page 18. A single specimen of Brachiopodes

cf. B. laticostatus White was found, which is represented by a fragment of an external mold. Brachidontes laticostatus was originally described from the Mesaverde formation of Colorado, and Stanton (1916, p. 310) notes that it occurs in the Fruitland formation as well. Apparently, this species is of fresh- or brackish-water origin, although other species of the genus are marine. Two species of pelecypods, of the genus Mactra, were found. The genus Mactra is believed to be exclusively marine. (Northrop, oral communication, February, 1953) This small collection of fossils from the Pictured Cliffs sandstone is neither diagnostic of age nor environment. Fossils that have been identified from the Pictured Cliffs sandstone are listed in Table 1. The numbers heading the lists of fossil localities are U. S. G. S. locality numbers. Sources for the preparation of the floral and faunal chart are: Bauer (1916, p. 274), collection 2 (9278) identified by T. W. Stanton; Reeside and Knowlton (1924, p. 18), collections 6067 and 9278 identified by T. W. Stanton and collections 10139 and 10502; Lee and Knowlton (1917, p. 187), collections 6067, 6069, 6070, 6066, 5446 and 5448; Dane (1936, pp. 112-113), collections A and B, identified by J. B. Reeside, Jr.

Table 1 shows geographically and stratigraphically where certain flora and fauna have been found in the Pictured Cliffs sandstone. It may be noted from this table

TABLE 1.

FLORAL AND FAUNAL CHART

Fossil Localities

Fossils	Near Durango, Colorado			Near Fruitland, New Mexico				Near Cuba, N.M.	
	5446, 5448 T. 35 N. R. 8 W. near top of fm.	6066 T. 35 N. R. 8 W. 119-194 ft. below top of fm.	6067 Sec. 17, T. 35 N. R. 8 W. near top of fm.	6069, 6070 T. 35 N. R. 8 W. near top of fm.	10502 Sec. 27, T. 35 N. R. 9 W. near middle of fm.	9278 Sec. 7, T. 29 N. R. 15 W. 40 ft. above base of fm.	10139 Sec. 19, T. 30 N. R. 15 W. near base of fm.	Caldwell Sec. 10, T. 29 N. R. 15 W. near base of fm.	Dane's A Sec. 18, T. 19 N. R. 2 W.	Dane's B Sec. 17, T. 19 N. R. 3 W.
FLORA										
Conifers										
Abietites dubius Lesquereux	X									
Geinitzia formosa Heer?	X									
FAUNA										
Pelecypods										
Anomia sp.				X			X			
Baroda sp. undetermined							X			
Brachidontes cf. B. laticostatus White								X		
Cardium (Ethmocardium) whitei Dall ("C. speciosum" Meek and Hayden)			X			X	X		X	
Corbula subtrigonalis Meek and Hayden?				X						
Corbula sp. undetermined		X		X		X			X	
Inoceramus barabini Morton			X		X	X				
Inoceramus sagensis Owen					X					
Inoceramus sp. undetermined		X					X			
Leptosolen n. sp.						?	X			
Leptosolen sp.						X				
Mactra gracilis Meek and Hayden						X		X		
Mactra warrenana Meek and Hayden?							X	X		
Modiola cf. M. meeki Evans and Shumard							X			
Ostrea sp. undetermined		X	X				X			
Tellina scitula Meek and Hayden			?			?	?			X
Gastropods										
Acteon sp. undetermined						X	?			
Anchura sp. undetermined							X			
Buccinum? sp.									X	
Chemnitzia cerithiformis Meek and Hayden							X			
Cinulia n. sp.							X			
Haminea subcylindrica Meek and Hayden							X			
Haminea sp. undetermined						X				
Lunatia occidentalis Meek and Hayden							X			
Odontobasis? sp. undetermined		X				X				
Turris? sp. undetermined						X				
Turritella sp. undetermined							X			
Cephalopod										
Ammonite fragment					X					
Annelid										
Serpula sp. undetermined						X	X			
Problematica										
Halymenites major Lesquereux (probably a burrow, not an alga)	X	X	X	X	X	X	X	X	X	X

Numbers are U. S. G. S. fossil localities

that the greatest concentration of different fossil genera is to be found near the village of Fruitland, New Mexico, and that Halymenities major Lesquereux has been found at all fossil localities listed.

GEOLOGIC HISTORY

Age of the Pictured Cliffs Sandstone

The Pictured Cliffs sandstone was deposited in the last marine regression of the late Cretaceous sea and is considered to be Montana in age.

Reeside (1924, p. 19) states that the fossils listed by him are a littoral marine fauna of late Cretaceous age. He further writes that the Pictured Cliffs sandstone varies little in age throughout its entire extent.

Early workers believed the Pictured Cliffs to be of Laramie age and included it with the overlying Kirtland and Fruitland formations. (Reeside, 1924, p. 19) Further paleontological work by Stanton (Bauer, 1916, p. 274; Reeside and Knowlton, 1924, p. 18); Lee and Knowlton, (1917, p. 183); and Reeside (Dane, 1936, pp. 112-113) found the fossils in the Pictured Cliffs sandstone to be of Montana age.

Origin of the Pictured Cliffs Sandstone

In order to determine the origin of the southwest lobe of the Pictured Cliffs sandstone, it must be considered

in its entirety throughout the San Juan Basin. The Pictured Cliffs sandstone is presently represented as an isolated remnant of deposition. It is presumed that the source area for the majority of the underlying Upper Cretaceous sediments does not differ greatly from that of the southwest lobe of the Pictured Cliffs sandstone. The underlying Upper Cretaceous sediments are represented by a continuous sequence of deposition and their situation and position display a similarity, not only as to their deposition and lithology, but as to source area as well. More accurate and logical conclusions concerning the source of the Pictured Cliffs sediments may be reached if it is considered on a broader scope than the area specifically under study.

The Pictured Cliffs sandstone is thickest where it crops out southeast of Durango, Colorado, near the Florida River. Thickness of as much as 400 feet has been measured there. Various Pictured Cliffs sandstone lentils are separated by coal, coaly shale, and shale which divide the northeast lobe from the southwest lobe. The northeast lobe lies above the basal Fruitland coal and is younger in age than the southwest lobe. The coal represents a period of paludal environment and an hiatus in marine deposition between the northeast and southwest lobes of the Pictured Cliffs sandstone. The northeast lobe represents a later incursion and regression of the sea. The

STRATIGRAPHY

REGIONAL STRATIGRAPHY

The regional stratigraphy of the San Juan Basin includes rocks ranging from Precambrian to Eocene in age. However, the region does not contain a complete and uninterrupted sequence of deposition.

The area of the basin was, throughout most of early Paleozoic time, a positive region contributing sediments to surrounding seas or oscillatory downward to allow the deposition of pre-Pennsylvanian shelf sediments. It was not until late Paleozoic time, during the Pennsylvanian and Permian periods, that the area received sediments of major proportions. Continental deposition, grading from marine deposits of Pennsylvanian age, continued until early Cretaceous time when the area was tilted epirogenically and became the southwest shelf of the Rocky Mountain geosyncline. During late Cretaceous time the region received thick marine clastics ranging up to 5,000 feet in thickness. Subsequent to the deposition of the Pictured Cliffs sandstone, the region rose epirogenically out of marine waters and became the site of the latest Cretaceous and Tertiary continental deposition.

Numerous unconformities occur in the lower part of the stratigraphic section (See Fig. 2), and deformation of the stratigraphy below Cretaceous rocks is doubtful owing

presence of the two lobes separated by coal and shale, then, is indicative of two marine stages and one terrestrial stage of deposition. The situation and thickness of the two lobes furnish evidence that the sea withdrew in a northeast direction toward the axis of the Rocky Mountain geosyncline.

Clay analyses of the Pictured Cliffs sandstone indicate that the cementing material is high in potash feldspar and kaolin, and from the angularity of the quartz grains, a nearby source is suggested. Longer distances of transportation of sediments would have altered more of the feldspar to kaolin and neither would be present in such large amounts. Further transportation of the sediments would also have produced a greater degree of rounding than the quartz grains show. From the lithology of the sandstone and character of the quartz sand, it may be concluded that the probable source was primarily from acid igneous rocks, their metamorphic equivalents, or possibly an arkosic sand. The composition of the Pictured Cliffs sand bears close resemblance to the composition of granite or arkosic sand rich in potash feldspar.

During the middle and early part of late Cretaceous time, the Rocky Mountain geosyncline occupied a broad area and extended north and south forming a seaway, dividing the continent into two distinct land masses.

Marine waters came into the seaway from two directions, from the Arctic Sea southward and from the Gulf of Mexico northward. The waters were bounded on the west by the Mesocordilleran geanticline, which was distributing vast amounts of detrital sediments both east and west (Dunbar, 1949, p. 363) and extending over the Great Plains area to the east.

During the lengthy inundation by marine waters, the shore line to the west underwent many fluctuations, producing the intertonguing sandstone and shale of the Upper Cretaceous in the region. This situation generally resulted in thick deposits of clastic material near the Mesocordilleran geanticline, grading from sand through shale to limestone eastward.

In late Cretaceous time the area rose above the level of the waters and the northern arm of the sea began its retreat northward. During the retreat of the waters northeastward towards the axis of the Rocky Mountain geosyncline, the Pictured Cliffs sandstone was deposited on the northeast continental shelf of the Mesocordilleran geanticline. The Mesocordilleran geanticline existed as such for the greater part of the Mesozoic Era. This would provide a close source area and would produce sediments characteristic of the Pictured Cliffs sandstone. Sediments were probably derived from numerous sources along the

Mesocordilleran geanticline to the west.

Environment of Deposition of the Pictured Cliffs Sandstone

From the lithology and character of the sandstone, it may be concluded that the deposition took place in the marine-littoral to infraneritic zones. Characteristics of this type of deposition are well-sorted, relatively clean, fine sand, which usually consists of kaolin and fine quartz grains together with organic material; bedding is fairly regular with some cross-bedding evident.

Reeside (1924, p. 50) describes the Pictured Cliffs sandstone as being deposited in a shallow sea, the waters apparently withdrawing quickly from the whole area, and leaving as they went a relatively thin but widespread mantle of sand containing the remains of marine animals.

The Lewis shale immediately below the Pictured Cliffs sandstone represents the last marine transgression in Montana time. This was followed by an upward movement of the land succeeded by regression of the sea. The Pictured Cliffs sandstone was thus deposited in the environment of a continental shelf region as the sea withdrew northeastward. Following the regression of the sea, the Fruitland formation was deposited immediately on top of the Pictured Cliffs sandstone while the strandline of the sea was nearby. The Fruitland formation was laid down under

conditions similar to the Menefee formation, with small incursions of sea water into the Fruitland formation allowing several brackish marine organisms to live (Reeside, 1924, p. 50). A swamp and floodplain environment is suggested for the Fruitland formation. During a particularly strong and somewhat lengthy incursion of marine waters, the northeast lobe of the Pictured Cliffs sandstone was deposited and represents both transgressive and regressive deposition. In the northern part of the San Juan Basin, in southwestern Colorado, the southwest lobe is separated locally from the northeast lobe by shale and coal of the Fruitland formation.

Climate During Pictured Cliffs Time

The climate during the period of deposition of the Pictured Cliffs sandstone may be considered as being tropical to temperate. The abundance of potash feldspar in the clay content of the Pictured Cliffs sediment, suggests a semidesert area or one of high altitude over which plants cannot maintain an effective cover for the source. The fact that the sea covered a large area suggests that it would tend to somewhat stabilize the climate and lessen the seasonal fluctuations. The Fruitland formation overlying the Pictured Cliffs sandstone is composed of a sand-shale-coal sequence. Coal, which in most cases immediately overlies the southwest

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lobe of the Pictured Cliffs sandstone, was undoubtedly being deposited in part, at the same time as portions of the Pictured Cliffs sandstone were being deposited. The presence of the coal, then, suggests a temperate humid coastal climate with seasonal climatic conditions rarely severe, and sufficient moisture to support the rapid and abundant growth of plants necessary to produce coal.

CORRELATION

Dane (1936, p. 112) states that:

> "...the Pictured Cliffs sandstone has not been recognized outside of the San Juan Basin."

Reeside (1924, p. 10) writes:

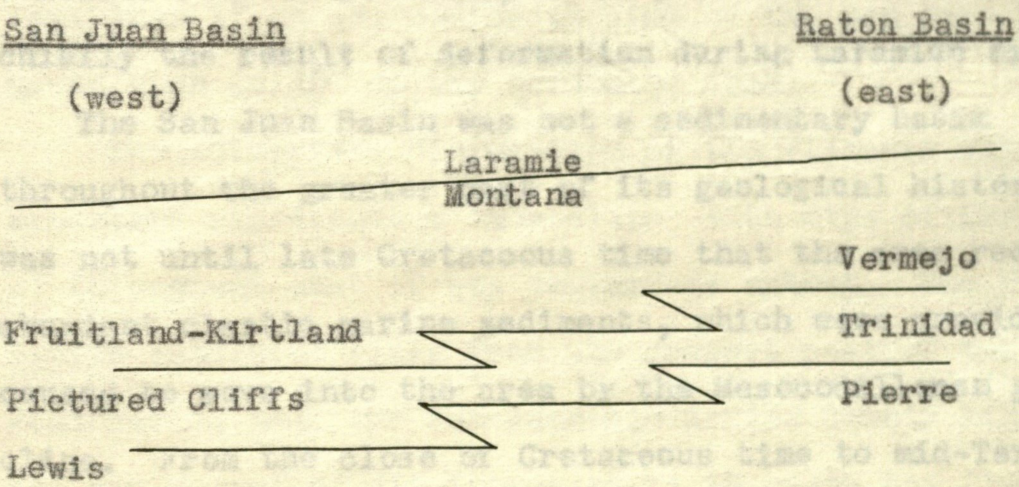
> "...there is no definite equivalent of the Pictured Cliffs sandstone known outside of the basin."

These statements are valid only if it is assumed that the correlation must be coincident in lithology and age alike.

According to G. H. Wood, of the U. S. Geological Survey (oral communication, February, 1953), the Pictured Cliffs sandstone may be correlated with the Trinidad sandstone of the Raton Basin in southeastern Colorado. Although the Trinidad sandstone is slightly younger than the Pictured Cliffs sandstone, both are of Montana age (ibid). The Trinidad sandstone possesses the same lithologic characteristics as the Pictured Cliffs sandstone

and may be considered to be a lithologic equivalent. The sediments underlying and overlying the Pictured Cliffs sandstone in the San Juan Basin and the sediments underlying and overlying the Trinidad sandstone of the Raton Basin may be correlated, as can be seen in the following diagram.

Correlation Diagram



The preceding diagram shows the correlatives of the Pictured Cliffs sandstone, the underlying Lewis shale, and the overlying Fruitland formations of the San Juan Basin in the Raton Basin.

Undoubtedly there are many age correlatives since the Upper Cretaceous sea in Montana time covered a large area. Areas such as the Uinta Basin of Utah probably possess Pictured Cliffs correlatives inasmuch as that Basin is believed to contain an uninterrupted sequence of Upper Cretaceous strata.

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Correlation Diagram

San Juan Basin (west)	Raton Basin (east)
Lewis shale	
Pictured Cliffs sandstone	Trinidad sandstone
Fruitland-Kirtland formations	Vermejo formation

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STRUCTURE

REGIONAL SETTING

The San Juan Basin must be considered as a whole to determine the regional geologic setting of the Pictured Cliffs sandstone. The San Juan Basin is a structural basin surrounded by uplifts. It is situated in the Colorado Plateau province, whose present structures are chiefly the result of deformation during Laramide orogeny.

The San Juan Basin was not a sedimentary basin throughout the greater part of its geological history. It was not until late Cretaceous time that the area received abundant clastic marine sediments, which were provided or caused to move into the area by the Mesocodilleran geanticline. From the close of Cretaceous time to mid-Tertiary time the Laramide orogeny and succeeding orogenies produced uplifts surrounding the Basin, turning strata up on the flanks of those nearby uplifts and forming the present structural basin. Later orogeny recurred during middle Tertiary time along virtually the same lines of deformation as those of the initial Laramide orogeny and served to accentuate the present structures (Kelley, 1951, p. 130).

H. F. Davies (1934, p. 685) writes:

> "the gradual subsidence and uplift mark the initiation of Laramide deformation which culminated near the close of the Cretaceous in sharp folding, erosion and thrust faulting, resulting in the formation of major basins of the Rocky Mountain district."

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REGIONAL SETTING

The San Juan Basin must be considered as a whole to determine the regional geologic setting of the Pictured Cliffs sandstone. The San Juan Basin is a structural basin surrounded by uplifts. It is situated in the Colorado Plateau province, whose present structures are chiefly the result of deformation during Laramide orogeny.

The San Juan Basin was not a sedimentary basin throughout the greater part of its geological history. It was not until late Cretaceous time that the area received abundant clastic marine sediments, which were provided or caused to move into the area by the Mesocontinental geanticline. From the close of Cretaceous time to mid-Tertiary time the Laramide orogeny and succeeding orogenies produced uplifts surrounding the Basin, turning strata up on the flanks of those nearby uplifts and forming the present structural basin. Later orogeny recurred during middle Tertiary time along virtually the same lines of deformation as those of the initial Laramide orogeny and served to accentuate the present structures (Kelley, 1955, p. 130).

H. P. Davies (1934, p. 689) writes:

> "the gradual subsidence and uplift mark the initiation of Laramide deformation which culminated near the close of the Cretaceous in sharp folding, erosion and thrust faulting, resulting in the formation of major basins of the Rocky Mountain district."

LOCAL SETTING

The Pictured Cliffs sandstone is well exposed where it crops out around the San Juan Basin, and is present on all sides of the Basin except the east, where the sandy facies is absent from the section. The outcrop band, in the area under study, is shown on Figure 13 (in pocket).

The dip on the Pictured Cliffs sandstone ranges from less than 1° on the southwest limb of the San Juan Basin to as much as 30° on the northwest limb.

The subsurface disposition of the Pictured Cliffs sandstone represents a "monocline" with dips of less than 1° throughout most of its subsurface extent. The Pictured Cliffs sandstone rises from the deepest part of the San Juan Basin, near the San Juan-Rio Arriba County line, and the degree of dip increases as it nears the flanks of the surrounding uplifts. In the structural center of the Basin the sandstone is covered by approximately 4,000 feet of post-Pictured Cliffs sediments.

Figure 13 is a subsurface structure-contour map on top of the Pictured Cliffs sandstone. It can be noted from this map that the dip of the Pictured Cliffs sandstone increases as it approaches the outcrop on the west, as a result of the strata being turned up on the flank of the uplifts in that direction. The structure-contour map shows the area to be a gently dipping "monocline" with indications

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of anticlinal noses and synclinal re-entrants. As more well data are obtained, anticlines and synclines of small closure may be defined. The surface area under study showed no evidence of faulting. Faults may be present in the subsurface but are certainly not of great magnitude.

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R16W R15W R14W R13W R12W R11W R10W R9W R8W

COLORADO

NEW MEXICO

T32N T31N T30N T29N T28N T27N T26N

UTE INDIAN RESERVATION

NAVAJO INDIAN RESERVATION

SAN JUAN COUNTY

LA PLATA SECTION

KPC HIGHWAY SECTION

COTTONWOOD SECTION

KPC

FARMINGTON

SAN JUAN RIVER

BLANCO MESAVERDE GAS FIELD

SOUTH AZTEC

FULCHER-KUTZ

WEST KUTZ

SOUTH BLANCO

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27

FIGURE 3.

INDEX MAP SHOWING LINES OF CROSS SECTIONS, AND FIELD OUTLINES.

LEGEND

KPC – PICTURED CLIFFS SS. OUTCROP

DRY HOLE

GAS WELL

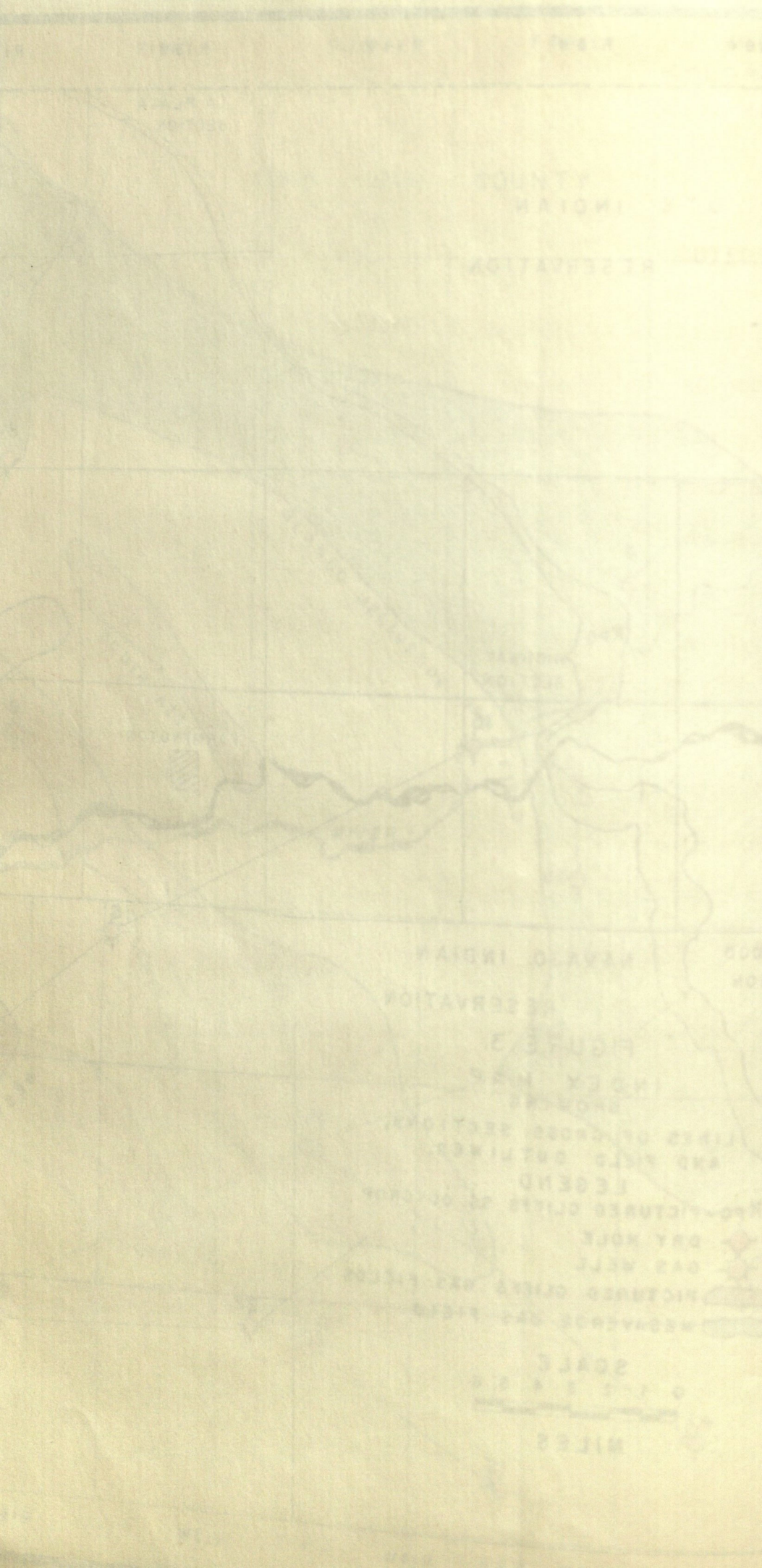
PICTURED CLIFFS GAS FIELDS

MESAVERDE GAS FIELD

SCALE

0 1 2 3 4 5 6

MILES



ACCUMULATION OF GAS

PRODUCTIVE SECTION

Thickness of Productive Section

The productive section of the Pictured Cliffs sandstone varies greatly in thickness throughout the area studied. The average pay zone is 30 feet to 60 feet thick. The difference is due to a decrease in thickness of the main sandstone lentil eastward and shale limiting the effective thickness of the pay zone also in that direction. The thickness of the Pictured Cliffs sandstone decreases to the north and east in the area studied and continues to decrease in thickness until it is absent from the stratigraphic section on the east side of the San Juan Basin. The time equivalent of the Pictured Cliffs sandstone on the east side of the basin, is represented by the Lewis shale. The increased argillaceous content of the Pictured Cliffs sand to the northeast can be noted in Figure 12A, and it is clearly shown in wells 1 through 7 and in Figure 12B, as well.

The thickness of the section and the amount of shale present in the section is an important factor in the accumulation of the gas in commercial quantities; however, electric logs and samples indicate adequate sand thickness in tested areas which are dry or have only shows of gas.

This is evident in wells 21 and 15 (Fig. 12A), which have adequate sand thickness but are dry, and well number 8 (Fig. 12A), which records a show of gas. These facts indicate that there are additional factors which play a major role in the accumulation of commercial gas from the Pictured Cliffs sandstone; these additional factors will be pointed out in succeeding pages.

Lateral Extent of Productive Section

The lateral extent of the commercial production of gas from the Pictured Cliffs sandstone in the area studied is confined at the present time to four nearly parallel fields of production, represented by the Fulcher-Kutz, West Kutz, South Aztec, and South Blanco fields. These fields, their present extent, location, and relationship to one another may be noted on Figure 3.

Electric logs and samples show the Pictured Cliffs sand to be present throughout the subsurface of the area studied. The lateral extent of commercial production is limited at present to the fields indicated; however, the productive limits of these fields have not been definitely established. A northeastern limit of porosity has been established by examining electric logs and samples. This limit of effective porosity is represented by a line on Figure 14 (in pocket). This line parallels the Fulcher-Kutz field on the northeast at a distance of 12 to 14

miles and limits the lateral extent of the possible production of commercial gas from the Pictured Cliffs sandstone in that direction. Examination of the electric log and lithologic characteristics of the Pictured Cliffs sandstone beyond this line suggests that the effective porosity of the productive section was limited by finite shale lentils and an increased amount of argillaceous material within the sandstone lentils themselves. Examples of wells drilled northeast of this line showing the electric log characteristics and lithology of the Pictured Cliffs sandstone are wells 5, 6, and 7 (Fig. 12A) and wells 6 and 27 (Fig. 12B).

RELATION OF STRUCTURE TO ACCUMULATION OF GAS

Figure 13 is a structure-contour map on top of the Pictured Cliffs sandstone. The structure represented is a northeasterly dipping "monocline". Minor variations in the form of anticlinal noses and synclinal re-entrants are evident but appear to have had no effect on the migration of accumulation of gas. The present field outlines thus show no apparent causal relationship to the present structure. Silver (1950, p. 119) writes:

> "The location of gas is not related to any known structure and is not related to the present structure of the San Juan Basin."

The evidence presented indicates that accumulation is controlled by other factors. Structure, however, has

indirectly affected the position of the gas. The Laramide and later orogenies turned the strata up on the flanks of nearby uplifts, where subsequent erosion exposed the Pictured Cliffs sandstone. The incursion of water from the outcrop has altered the position of gas accumulation. The importance of this will be discussed in a subsequent section.

RELATION OF STRATIGRAPHY TO ACCUMULATION OF GAS

All available data point to the existence of stratigraphic traps, rather than structural entrapment of gas in the Pictured Cliffs sandstone. Several possible methods of stratigraphic entrapment of Pictured Cliffs gas are indicated, and accumulation may be due to one or a combination of several.

Silver (1951, p. 115) states:

> "Water is apparently encroaching from the outcrop in some areas at the present time and the area of gas will apparently be limited only by the extent of water invasion."

On Figure 14 is a dashed line which represents the limit of water incursion from the outcrop. This line was determined by noting the wells in which water was found to be present in the Pictured Cliffs sandstone. Several of these wells flowed fresh water indicating hydrostatic pressure in the more porous areas of the Pictured Cliffs sandstone.

The Laramide and later orogenies during Tertiary

time exposed the Pictured Cliffs sandstone, enabling fresh water to move into the formation readily. The dip of the beds to the northwest ranges from 15° to 30°, enhancing the incursion of water from that direction.

Umbach (1949, p. 1145) states that:

> "Reservoir accumulation is caused by the change in porosity and permeability of the sandstone."

From the structure contour map (Fig. 13) it may be noted that the accumulation of Pictured Cliffs gas is not related to the present structure. It may be noted from Figure 14 that the limit of water, represented by the water incursion line, separates the West Kutz and Fulcher-Kutz Pictured Cliffs fields. From these figures the relationship between the present areas of gas production and the limit of water incursion may be seen. This, then, indicates that there are changes in the porosity and permeability of the Pictured Cliffs sandstone which permit the concentration of gas and water into separate zones.

The interstitial porosity in the Pictured Cliffs sandstone is 0 - 12 percent and permeability is as much as 5 millidarcys (Wengerd, oral communication, March, 1953).

From these facts it is possible to postulate an important factor in the stratigraphic accumulation of gas in the Pictured Cliffs sandstone.

From the position of the water incursion line which appears on Figure 14 it will be noted that there are three major embayments of the water incursion line. These embayments of the line closely follow the boundaries of the South Aztec, Fulcher-Kutz, and West Kutz fields. Inasmuch as water is a more viscous fluid than natural gas, it has incurred along strandlines of greater porosity and permeability, forcing the gas into areas of lesser permeability. The water-gas contact is thus a permeability boundary which affords an effective seal of the gas reservoir. This seal is made effective by three agencies, namely, relative viscosity, capillarity, and immiscibility. Relative viscosity affords the segregation of the gas and water and permits the gas to invade areas of less permeable material from which the more viscous water is withheld. From the fact that the porosity and permeability are exceedingly low, the capillarity of the water, under hydrostatic pressure, affords a firm grip on the small pores in the rock and the capillary action of the water produces a high degree of surface tension through which the gas, at a lower pressure in smaller pores, is unable to penetrate. The immiscibility prevents the intermingling of the gas and water, although it is entirely likely that the heterogeneous porosity of the Pictured Cliffs sandstone has allowed some gas to move into smaller pores interspersed with the larger water-

filled pores along the gas-water contact zone.

Microfracturing may be responsible for trends of higher permeability and the resulting higher initial potential of wells located within the gas fields. The orogenies that occurred in the area after the deposition and lithification of the Pictured Cliffs sandstone may have produced trends of microfracturing by compressional and tensional stresses involved in the orogenies. Microfracturing would account for the accumulation of gas in commercial quantities where the low porosity and permeability of the Pictured Cliffs sandstone seemingly suggests that a much lower rate of production of gas would be expected than is normally found. A detailed study of cores, however, would be necessary to establish microfracturing as being responsible for the accumulation of gas.

The presence of Pictured Cliffs lentils containing higher concentrations of montmorillonite may be the limiting factor in the accumulation of gas in the Pictured Cliffs sandstone. From information now obtainable in cores and cuttings layers of such nature have not been found. In the clay analysis of the sand, traces of montmorillonite were found. The samples submitted for analysis came from wells studied for the cross sections which appear in Figure 12 A and B. The samples were taken without regard to production or stratigraphic position within the Pictured Cliffs section.

-36-

The results of the clay analysis are thus not indicative of any particular area, but are of a general nature. Extensive sampling of productive and nonproductive wells, as well as stratigraphic position within the section, would be necessary to determine what effect, if any, montmorillonite has in the accumulation of gas in the Pictured Cliffs sandstone.

In certain localized areas, gas entrapment may be the result of large sand lenses sealed by shale, however, the data obtained in this study are not sufficient to prove or disprove this hypothesis.

RESERVOIR FLUIDS

Formation Waters

Wells in which water has been encountered in the Pictured Cliffs sandstone are indicated on Figure 14. Fresh water has incurred in the main sandstone lentils of the Pictured Cliffs sandstone and the extent of this incursion is represented by the water incursion line on Figure 14. It is believed that the same stratigraphic trap responsible for the accumulation of gas, excludes this water (p. 35).

According to Bates (1942, p. 104):

> "The basal Fruitland formation carries water immediately below the lowest coal bed and just above the gas pay, as it does at Kutz Canyon. This water correlates with the water from the Kutz Canyon field, but shows about 50 percent dilution."

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This indicates that fresh water is incurring from the outcrop causing the dilution at the Fulcher Basin field.

Water has been encountered below the pay zone of the Pictured Cliffs sandstone in the present areas of gas production. This water is brackish and apparently has no connection or association with the fresh water encroaching from the outcrop in the main sandstone lentil of the Pictured Cliffs sandstone. There is little information in regard to this water as few wells drilled for Pictured Cliffs production penetrate this zone.

Condensate

The gas carries considerable amounts of condensate in the Kutz Canyon field whereas little or none is evident at the Fulcher Basin field. According to a fractional distillation analysis (Bates, 1942, p. 114) of wet gas from the Kutz Canyon field, 0.619 gallons of gasoline are produced per thousand cubic feet of gas.

Oil

Silver (1951, p. 115) states:

> "No free oil has as yet been found in the Pictured Cliffs sandstone and none is indicated for the southwestern lobe."

However, since the publication by Silver, and from information available, a show of oil from the Pictured Cliffs sandstone has been reported. This show of oil

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was reported in the Lackey No. 1 Hauck in Sec. 1, T. 29 N., R. 10 W. This indicates that oil in commercial quantities may possibly be present in the southwest lobe of the Pictured Cliffs sandstone.

RESERVOIR PRESSURES

Figure 14 is a contour map of casing-head pressures recorded from the Pictured Cliffs sandstone. The shut-in pressures range from 225 pounds (Sec. 26, T. 26 N., R. 11 W.) to 872 pounds (Sec. 26, T. 27 N., R. 8 W.). The hydrostatic pressure for the West Kutz field, using an average depth of 1,700 feet and a water density of 0.446, is 758 pounds. It will be noted from Figure 14 that a majority of the shut-in pressures in the West Kutz field range from 400 to 500 pounds, with an average shut-in pressure of about 450 pounds, The hydrostatic pressure for the Kutz Canyon field, using an average depth of 1,920 feet and a water density of 0.446, is 856 pounds, whereas the average shut-in pressure is 550 pounds. The shut-in pressures are considerably less than hydrostatic pressure, being 59.4 percent of hydrostatic at the West Kutz field and 64.5 percent of hydrostatic at the Kutz Canyon field.

It may be noted from the contours on Figure 14 that areas of high pressures have a tendency to conform with areas of water incursion, with the exception of the southwest side of the West Kutz field, where insufficient evidence is available. These pressures near the water

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incursion line closely approach hydrostatic pressure, which would be expected if the wells contained water incurring through more porous sections from the outcrop. The shut-in pressures in the respective fields of production are areas of low pressure which would indicate that the gas has accumulated in less permeable rock, and that the water presently occupies the areas of greatest permeability (Wengerd, oral communication, March, 1953).

Umbach (1949, p. 1145) indicates that the average initial potential of the Kutz Canyon field is one million cubic feet of gas per day, and that the better wells are in the southeast extension of that field. The low initial potentials and pressures indicate low permeability with the exceptions provided by wells drilled very near the water incursion line which produce quantities of fresh water with lesser quantities of gas. The increase of initial potentials and pressures which can be noted on Figure 14 to the southeast, point to possible extensions of the field in that direction.

ORIGIN OF THE GAS

The possibility of five different origins for the Pictured Cliffs gas is presented: (1) from the underlying Lewis shale, (2) from within the Pictured Cliffs sandstone, (3) from the overlying Fruitland formation, (4) from

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formations below the Lewis shale, and (5) from formations above the Fruitland formation.

Lewis Shale

The Lewis shale, which underlies the Pictured Cliffs sandstone, is of marine origin and fossil evidence shows that it possessed an environment favorable for the formation of oil and gas. The gas would be formed in the marine shales of the Lewis from the decay of plant and animal remains. The gas would be retained in the marine muds, which later formed the Lewis shale, until compaction and lithification had begun. These forces would drive the gas ahead of them and upward in the section. This process of formation of gas and compaction would continue until the gas had migrated into the recently deposited Pictured Cliffs sandstone, before compaction and induration of the Lewis shale was completed. The gas would be trapped in the Pictured Cliffs sandstone by changes of lithology within the sand as well as in the partially indurated overlying Fruitland formation.

Pictured Cliffs

The origin of gas from within the Pictured Cliffs sandstone is highly possible and deserves careful consideration. The gas would originate in the infraneritic zone between the clean sands shoreward, and sands which were exceptionally dirty or shaly seaward. The gas

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would be trapped where it was formed, or migrate to the cleaner sands in a southwesterly direction toward the ancient shorelines. The present gas fields may represent strandlines, since they are nearly perpendicular to the direction in which the sea retreated, which may account for the present northwest-southeast arrangement of the gas fields.

Entrapment would be due to interstitial clays and cementing material trapping the gas landward, in a southwest direction, and increased amounts of lithified shale and detrital material trapping the gas seaward, in a northeast direction. The gas would be distributed over a much larger area than is represented at the present time. The gas would be driven and accumulated into its present position with the advent of water encroaching from the outcrop when the Pictured Cliffs sandstone had been exposed.

Fruitland Formation

Gas, in the form of swamp gas, may have been associated with the formation of coal in the Fruitland formation. The gas could have been produced from the same decaying plant material which formed the coal. If this theory were tenable, large amounts of the gas may have been lost by escape into the air; however, some gas would be retained in the muds as in the paludal environment of today. Later deposition and compactional forces may have forced the gas

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downward, where it could have entered the more permeable Pictured Cliffs sandstone below. The migration of the gas downward into the Pictured Cliffs sandstone would have had to occur prior to the induration and lithification of the Fruitland formation, otherwise the possibility of gas having been retained and moved through the lithified and indurated sediments is unlikely.

Formations Below the Lewis Shale

The possibility that gas originated in any formations below the Lewis shale and migrated into the Pictured Cliffs sandstone is unlikely. The gas would have had to migrate through the Lewis shale, averaging 1,700 feet in thickness, to reach the Pictured Cliffs sandstone. Before the complete deposition of the Lewis shale, lithification certainly must have already commenced in the lower part of the shale body, thereby preventing any further migration of gas through the main body of the shale. Fracturing, however, could possibly have furnished passages through the Lewis shale and gas that had formed earlier may have migrated through these fractures into the Pictured Cliffs sandstone from beds below.

Formations above the Fruitland Formation

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of the sea. The possibilities of an adequate environment existing, for the formation of gas, above the Fruitland formation with a subsequent migration downward into the Pictured Cliffs sandstone are doubtful. Fresh-water swamps may have been present in the upper strata inasmuch as coal is present in some lentils of the Kirtland formation; however, the migration of swamp gas through the lithified and indurated Fruitland sediments below to reach the Pictured Cliffs sandstone is improbable.

MIGRATION OF GAS

Silver (1951, p. 115) states that:

> "Gas is widely distributed in the Pictured Cliffs sandstone over more than 1,500,000 acres and appears to have accumulated in the northeast end of the southwestern lobe at a time when this unit was inclined to the west."

The inclination of the southwest lobe to the west marks the initial accumulation of Pictured Cliffs gas.

Further migration of gas may have taken place within the Pictured Cliffs sandstone with the advent of water incurring from the outcrop during Tertiary time. It is likely that the gas formerly occupied the areas of greater permeability and porosity and with the advent of water the gas was displaced or migrated to its present position in the San Juan Basin. This hypothesis is seemingly substantiated by the presence of fresh water incurring from the outcrops and separating the present areas of gas

production. The decrease of initial potential and increase of pressure in wells approaching the gas-water contact also suggest that the gas is presently accumulated in less permeable areas and that before the advent of water, it is likely that the gas occupied the more permeable zones.

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CONCLUSIONS

From evidence presented in this thesis, several logical conclusions may be reached. Throughout the thesis all possibilities have been presented where information is not sufficient to arrive at a definite conclusion. Facts and ideas have been presented in each case which tend to substantiate or disprove the various possibilities.

The Pictured Cliffs sandstone was deposited in a regressive sea. The present site of the Pictured Cliffs sandstone is in the San Juan Basin which is a structural basin and was not a differentially subsiding sedimentary basin during Pictured Cliffs time.

The Pictured Cliffs sandstone has lithologic and age correlatives. Under similar conditions of deposition and timing certain of these correlatives may prove economically valuable both inside and outside the confines of the San Juan Basin.

Entrapment of the Pictured Cliffs gas is due to sedimentary features, and not structural controls. Accumulation, however, is related to regional structure and is a result of the water incurring from the outcrop, providing an effective seal regulating the accumulation of the gas.

Origin of the Pictured Cliffs gas is seemingly limited to three possibilities: origin from the Fruitland coaly strata, within the Pictured Cliffs sandstone itself,

CONCLUSIONS

From evidence presented in this thesis, several logical conclusions may be reached. Throughout the thesis all possibilities have been presented where information is not sufficient to arrive at a definite conclusion. Facts and ideas have been presented in each case which tend to substantiate or disprove the various possibilities.

The Pictured Cliffs sandstone was deposited in a regressive sea. The present site of the Pictured Cliffs sandstone is in the San Juan Basin which is a structural basin and was not a differentially subsiding sedimentary basin during Pictured Cliffs time.

The Pictured Cliffs sandstone has lithologic and age correlatives. Under similar conditions of deposition and timing certain of these correlatives may prove economically valuable both inside and outside the confines of the San Juan Basin.

Entrapment of the Pictured Cliffs gas is due to sedimentary features, and not structural controls. Accumulation, however, is related to regional structure and is a result of the water incoming from the outcrop, providing an effective seal regulating the accumulation of the gas.

Origin of the Pictured Cliffs gas is seemingly limited to three possibilities: origin from the Fruitland coaly shale, within the Pictured Cliffs sandstone itself,

from the underlying Lewis shale, or some combination of one or more of all these sources.

from the underlying Lewis sheets, or some combination of
two or more of all these sources.

APPENDIX

Descriptive Stratigraphic Sections

San Juan County, New Mexico

La Plata Section

Sec. 15, T. 32 N., R. 13 W.

No.	Description	Thickness (in feet) Unit	Cumulative
	(Fruitland formation above) Top of Pictured Cliffs sandstone:		
3	Sandstone: cross-bedded; buff to reddish-brown; fine to medium-grained; flaggy and ironstained	11	11
	Covered	6	17
2	Sandstone: massive, cliff-former; buff to light-gray on fresh surface; medium-grained; spheroidal weathering; Halymenites abundant; gradationally finer grained and silty near bottom	109	126
1	Sandstone: thin-bedded; interbedded with thin shale; light gray; fine-grained; silty; poorly consolidated	11	137
	(Lewis shale below)		

Highway Section

Sec. 5, T. 29 N., R. 15 W.

(Fruitland formation above)
Top of Pictured Cliffs sandstone:

APPENDIX

Descriptive Stratigraphic Sections

San Juan County, New Mexico

La Plata Section

Sec. 15, T. 32 N., R. 13 W.

No.	Description	Thickness (in feet) Unit	Cumulative
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1	Sandstone: cross-bedded; buff to reddish-brown; fine to medium-grained; flaggy and ironstained	11	11
	Covered	6	17
2	Sandstone: massive, cliff-former; buff to light-gray on fresh surface; medium-grained; spheroidal weathering; <u>Halymenites</u> <u>roundant</u>; gradationally finer grained and salty near bottom	109	126
1	Sandstone: thin-bedded; interbedded with thin shale; light gray; fine-grained; silty; poorly consolidated	11	137
	(Basin shale below)		

Highway Section

Sec. 5, T. 29 N., R. 15 W.

(Fruitland formation above)
Top of Pictured Cliffs sandstone:

No.	Description	Thickness (in feet) Unit	Cumulative
16	Sandstone: cross-bedded; buff to reddish-brown on weathered surface, buff on fresh surface; fine to medium-grained; poorly consolidated	20	20
15	Sandstone: thin-bedded, flaggy; reddish-brown; fine to medium-grained	3	23
14	Sandstone: cross-bedded; buff to reddish-brown on weathered surface; fine to medium-grained; poorly consolidated	9	32
13	Sandstone: massive cliff-former; buff to reddish-brown on weathered surface, buff to white on fresh surface; fine to medium-grained; Halymenites common	58	90
12	Shale: gray; sandy	1/2	90 1/2
11	Sandstone: massive; buff on weathered surface; fine to medium-grained	3	93 1/2
10	Sandstone: thin-bedded, with thin stringers of siltstone and shale; gray on weathered surface; very fine grained	6	99 1/2
9	Shale and sandstone rapidly alternating: thin-bedded; sandstone light-gray, shale dark-gray; traces of plant remains	2	101 1/2
8	Cover	14	115 1/2
7	Sandstone: thin-bedded; buff to gray on weathered surface; very fine to fine-grained; poorly consolidated	3	118 1/2
6	Shale and sandstone: alternating, 5 to 15 inch beds; poorly consolidated	3	121 1/2

Thickness (in feet)

No.	Description	Unit	Cumulative
16	Sandstone: cross-bedded; buff to reddish-brown on weathered surface, buff on fresh surface; fine to medium-grained; poorly consolidated	20	20
15	Sandstone: thin-bedded, flaggy; reddish-brown; fine to medium-grained	3	23
14	Sandstone: cross-bedded; buff to reddish-brown on weathered surface; fine to medium-grained; poorly consolidated	9	32
13	Sandstone: massive cliff-former; buff to reddish-brown on weathered surface, buff to white on fresh surface; fine to medium-grained; Heiyuenpites common	58	90
12	Shale: grey; sandy	1/2	90 1/2
11	Sandstone: massive; buff on weathered surface; fine to medium-grained	3	93 1/2
10	Sandstone: thin-bedded, with thin stringers of siltstone and shale; gray on weathered surface; very fine grained	6	99 1/2
9	Shale and sandstone rapidly alternating; thin-bedded; sandstone light-gray, shale dark-gray; traces of plant remains	2	101 1/2
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No.	Description	Thickness (in feet) Unit	Cumulative
5	Sandstone: thin-bedded; gray on weathered surface; very fine to fine-grained; silty with a few thin shale stringers	8	129 1/2
4	Shale: gray to brown; traces of plant remains	1/2	130
3	Sandstone: thin-bedded; buff to gray on weathered surface; very fine to fine-grained; silty; poorly consolidated	6	136
2	Covered	6	142
1	Sandstone: thin-bedded; buff to gray on weathered surface; very fine to fine-grained; poorly consolidated	6	148
	(Lewis shale below)		

Cottonwood Section

T. 28 N., R. 16 W.

	(Fruitland formation above)		
	Top of Pictured Cliffs sandstone:		
11	Sandstone: cross-bedded; buff on weathered surface; fine to medium-grained; poorly consolidated	15	15
10	Sandstone: massive; buff to reddish-brown; fine to medium-grained; well consolidated; contains concretions from 2 mm. to 2 1/2 feet in diameter	8	23
9	Sandstone: massive, cliff-former; buff to reddish-brown on weathered surface; fine to medium-grained; Halymenites common	48	71

No.	Description	Thickness (in feet) Unit	Cumulative
8	Sandstone: medium-bedded; light-gray to yellow; fine to medium-grained; silty; poorly consolidated	4	75
7	Sandstone: medium-bedded; light-gray to yellow; fine to medium-grained; silty; well consolidated	5	80
6	Sandstone: medium-bedded; light-gray; fine to medium-grained; ironstone concretion and ironstained	5	85
5	Covered	5	90
4	Sandstone: cross-bedded; thin-bedded and flaggy; brown to gray; fine-grained; contains carbonaceous material	8	98
3	Sandstone: massive; buff to light-brown; fine to medium-grained; spheroidal weathering; ironstone concretions	27	125
2	Shale: gray; with thin siltstone stringers	2	127
1	Sandstone: thin-bedded; light-brown, weathers to gray; fine-grained; silty; poorly consolidated	2	129
	(Lewis shale below)		

Description	Thickness (in feet)	
	Unit	Cumulative
Sandstone: medium-bedded; light-gray to yellow; fine to medium-grained; silty; poorly consolidated	4	75
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Sandstone: medium-bedded; light-gray; fine to medium-grained; ironstone concretion and ironstained	5	85
Covered	5	90
Sandstone: cross-bedded; thin-bedded and flaggy; brown to gray; fine-grained; contains carbonaceous material	8	98
Sandstone: massive; buff to light-brown; fine to medium-grained; spheroidal weathering; ironstone concretions	27	125
Shale: gray; with thin siltstone partings	2	127
Sandstone: thin-bedded; light-brown, weathers to gray; fine-grained; silty; poorly consolidated.	2	129

(Cycle shale below)

Figure 4. Aerial view of type locality. The Pictured Cliffs sandstone forms the cliff in mid-foreground. Northeastward view in Sec. 4, T. 29 N., R. 15 W.

Figure 5. Aerial view south across the San Juan River from type locality. The Pictured Cliffs sandstone forms the cliff in mid-foreground. Southward view in Sec. 7, T. 29 N., R. 15 W.

Figure 4

Figure 5

Figure 4

Figure 5

Figure 6. View north of type locality. The Pictured Cliffs sandstone forms the ridge in near-background.

Figure 7. Near view of type locality. Note conchoidal fracturing and vertical jointing.

Figure 6. View north of type locality. The
pictured Cliffs sandstone forms the ridge
in near-background.

Figure 7. Near view of type locality. Note
conchoidal fracturing and vertical jointing.

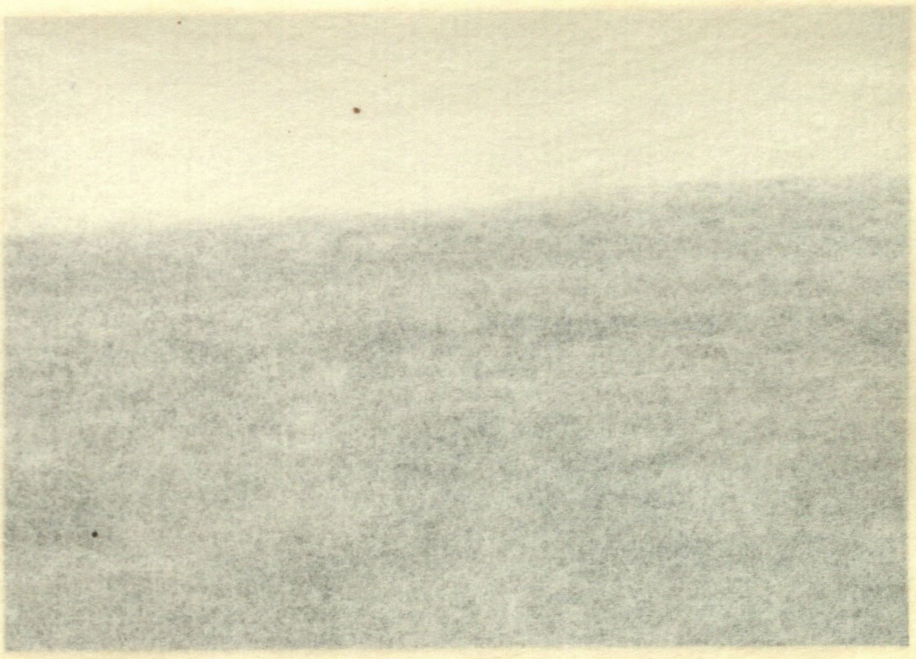

Figure 6

Figure 7

Figure 6

Figure 7

Figure 8. Prominent cliff of Pictured Cliffs sandstone at Highway section. This is the 58-foot main sandstone lentil as described in the descriptive sections.

Figure 9. Indian petroglyphs at Highway section. From writings such as these, W. H. Holmes named the sandstone the Pictured Cliffs.

Figure 8. Prominent cliff of Pictured Cliffs sandstone at Highway section. This is the 58-foot main sandstone lentil as described in the descriptive sections.

Figure 9. Indian petroglyphs at Highway section. From writings such as these, W. H. Holmes named the sandstone the Pictured Cliffs.

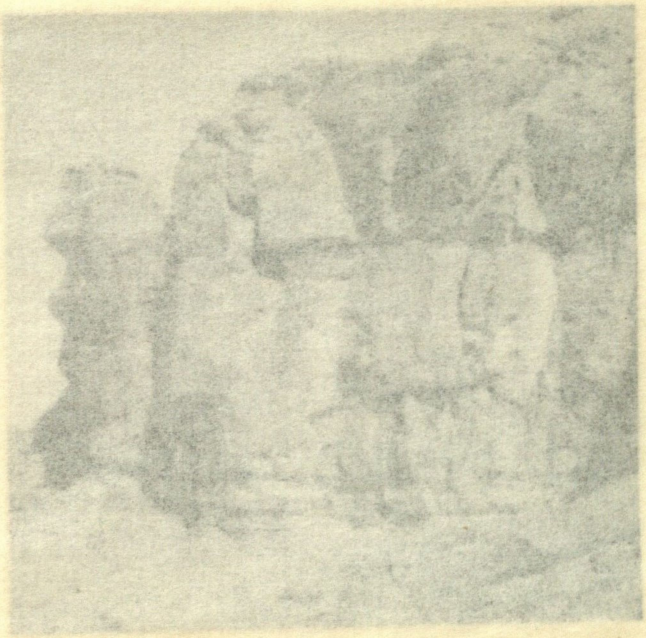

Figure 8

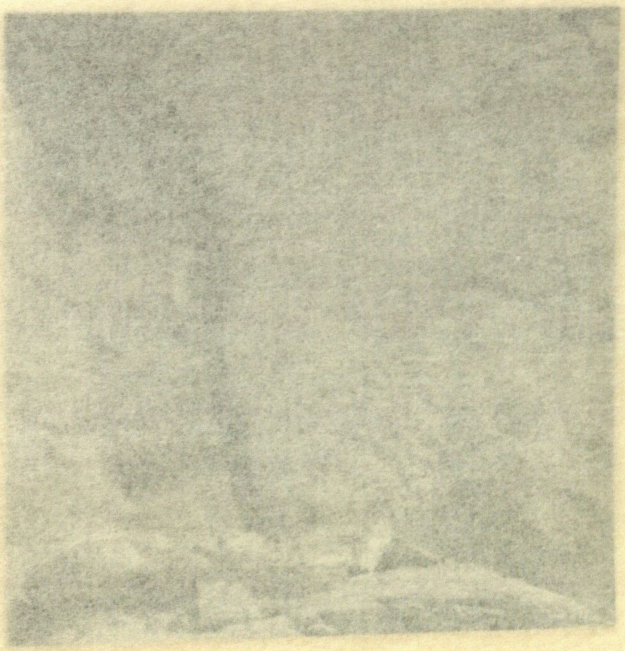

Figure 9

Figure 8

Figure 9

Figure 10. Prominent cliff of Pictured Cliffs sandstone at La Plata section. Note fretwork appearance on cliff face.

Figure 11. Fossil locality near Highway section.

Figure 10

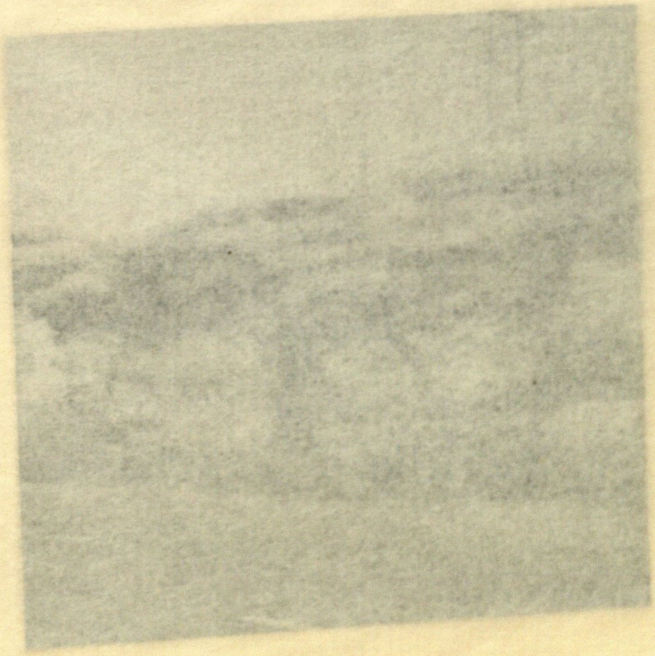

Figure 11

Figure 10

Figure 11

Description	Thickness (in feet) Unit	Cumulative
Sandstone: thin-bedded; gray on weathered surface; very fine to fine-grained; silty with a few thin shale stringers	8	129 1/2
Shale: gray to brown; traces of plant remains	1/2	130
Sandstone: thin-bedded; buff to gray on weathered surface; very fine to fine-grained; silty; poorly consolidated;	6	136
Covered	6	142
Sandstone: thin-bedded; buff to gray on weathered surface; very fine to fine-grained; poorly consolidated	6	148

(Lewis shale below)

Cottonwood Section

T. 28 N., R. 16 W.

(Fruitland formation above)
Top of pictured Cliffs sandstone:

Sandstone: cross-bedded; buff on weathered surface; fine to medium-grained; poorly consolidated	15	15
Sandstone: massive; buff to reddish-brown; fine to medium-grained; well consolidated; contains concretions from 2 mm. to 2 1/2 feet in diameter	8	23
Sandstone: massive; clay-former; buff to reddish-brown on weathered surface; fine to medium-grained; calcareous cement	48	71

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