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Controls on Paradox Salt Deposition in the Area of Comb Monocline San Juan County, Utah

Jim S. Hinds

CONTROLS ON
PARADOX SALT
DEPOSITION

HINDS

CONTROLS ON PARADOX SALT DEPOSITION IN THE AREA OF COMB MONOCLINE SAN JUAN COUNTY, UTAH

By

Jim S. Hinds

A Thesis

Submitted in Partial Fulfillment of the

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This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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Chairman

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

CONTROLS ON PARADOX SALT DEPOSITION IN THE AREA OF COMB MONOCLINE
SAN JUAN COUNTY, UTAH

By
Jim S. Hinds

ABSTRACT

Comb monocline is situated on the southwest shelf of the Paradox salt basin in San Juan County, Utah. The present structure extends northward into the basin and forms the east boundary of the Monument upwarp, a principally late Cretaceous (Laramide) uplift. Study of post-Mississippian sediments in the area indicates that the Comb structure began forming at least as early as middle Pennsylvanian time. During the deposition of the middle Paradox salt facies, the Comb structure formed a stable north-trending salient into the southwest shelf area of the northwest-trending basin, and acted as a local peninsular sedimentational barrier. Evidence of subsidence on both sides of the structural axis indicates that the fold may have been a slightly inclined, east-tilted anticline during Pennsylvanian time. Later uplift of the Monument upwarp area during the Laramide deformation could have tilted the west limb of the fold in an easterly direction and given the structure its present monoclinal form. Middle Paradox sediments on the crest of the fold consist of less than 200 feet of black shale, dolomite, and gypsum. On the west side of the structure more than 500 feet of hypersaline and penesaline evaporite sediments and black shale were deposited, while in excess of 1000 feet of salt, anhydrite, gypsum, limestone, and black shale were deposited immediately east of the fold. The wedge-edge of the Paradox halite deposits encircles

the Comb fold at its northern extremities but does not cross the body of the structure within the thesis area. Structural relief of the monocline is approximately 3000 feet on top of the Triassic Chinle formation, 4000 feet on top of the Paradox formation and 4900 feet on top of the Mississippian Leadville limestone. Structural growth has been episodic, with rejuvenation in conjunction with regional tectonic activity during Pennsylvanian, Permian, and late Cretaceous times. The monoclinal fold appears to be the surface expression of a west-dipping, high-angle, reverse fault in the basement complex, and is probably the result of regional east-west compressional forces.

INTRODUCTION

Location and Extent of Area

The area of this study is located in San Juan County, southeastern Utah (Fig. 1). It encompasses about 1,170 square miles, extending southward from the middle of T. 33 S. to the southern boundary of T. 39 S., and in an easterly direction from the west side of R. 18 E. to the east side of R. 22 E.

Geography and Accessibility

Geographically the area lies on the east side of the Monument upwarp, which is in the Colorado Plateau physiographic province. This region is characterized by semi-arid climatic conditions, sparse vegetation, and great expanses of exposed sedimentary rocks which are locally disrupted by laccolithic mountains and incised by the deep canyons of entrenched streams.

Due to the construction of access roads coincident to drilling and uranium activities in the vicinity, many parts of the area may be reached by automobile from the town of Blanding. Transportation away from these roads, however, is mainly by jeep, horseback, or on foot.

Statement of Problem

This study was undertaken for the purpose of delineating the configuration of the Paradox salt wedge-edge in relation to the Comb monocline structure. It was designed to illustrate whether or not, and to what extent, the Comb structure was a submarine barrier controlling deposition of sediments on the western shelf of the Paradox seaway during middle Paradox time.

INTRODUCTION

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The area of this study is located in San Juan County, south-eastern Utah (Fig. 1). It encompasses about 1,170 square miles, extending southward from the middle of T. 33 S. to the south boundary of T. 39 S., and in an easterly direction from the west side of R. 18 E. to the east side of R. 22 E.

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This study was undertaken for the purpose of delineating the configuration of the Paradox salt wedge-edge in relation to the Comb monocline structure. It was designed to illustrate whether or not, and to what extent, the Comb structure was a tectonic feature controlling deposition of sediments on the western shelf of the Paradox basin during middle Pennsylvanian time.

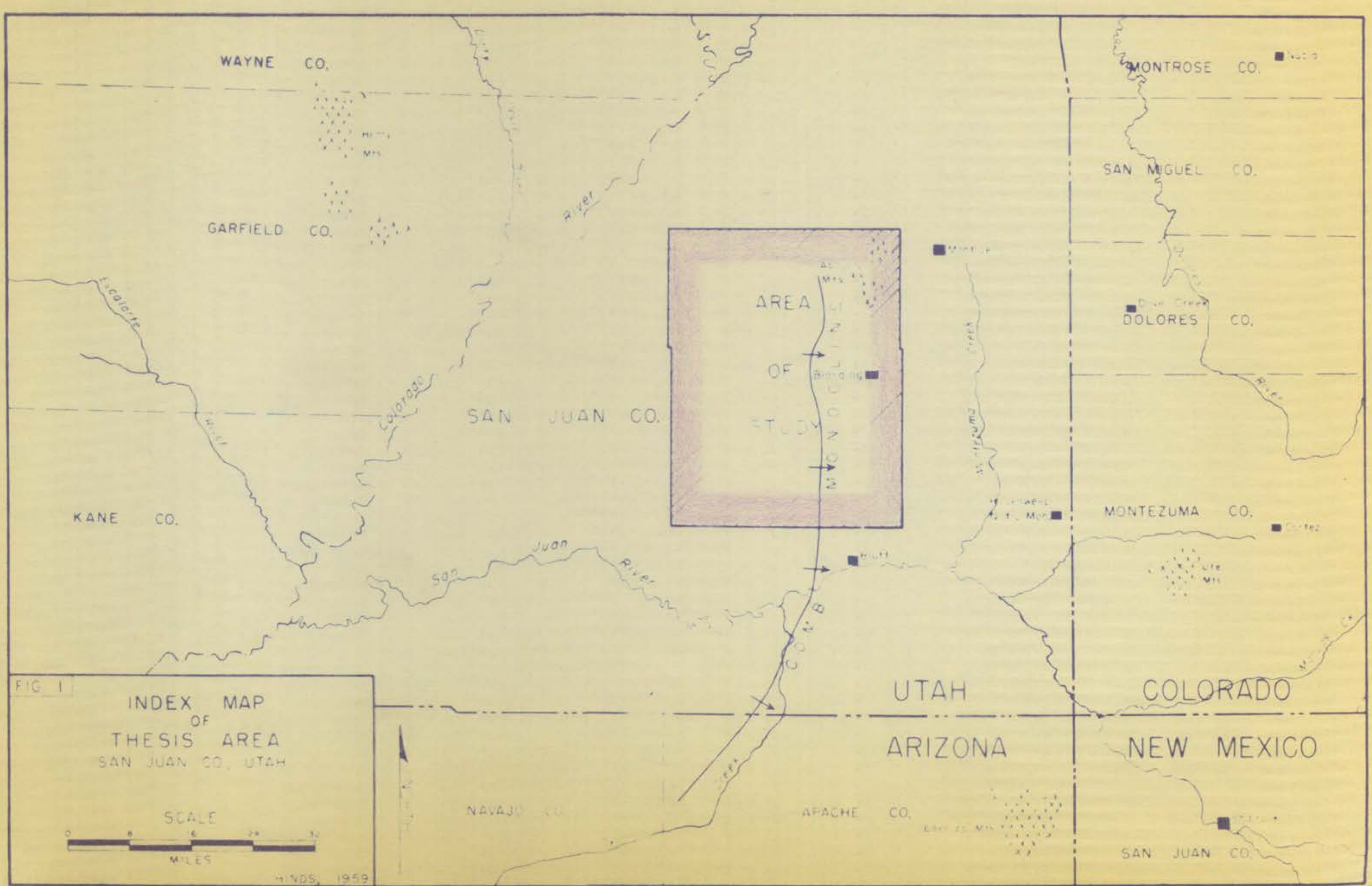


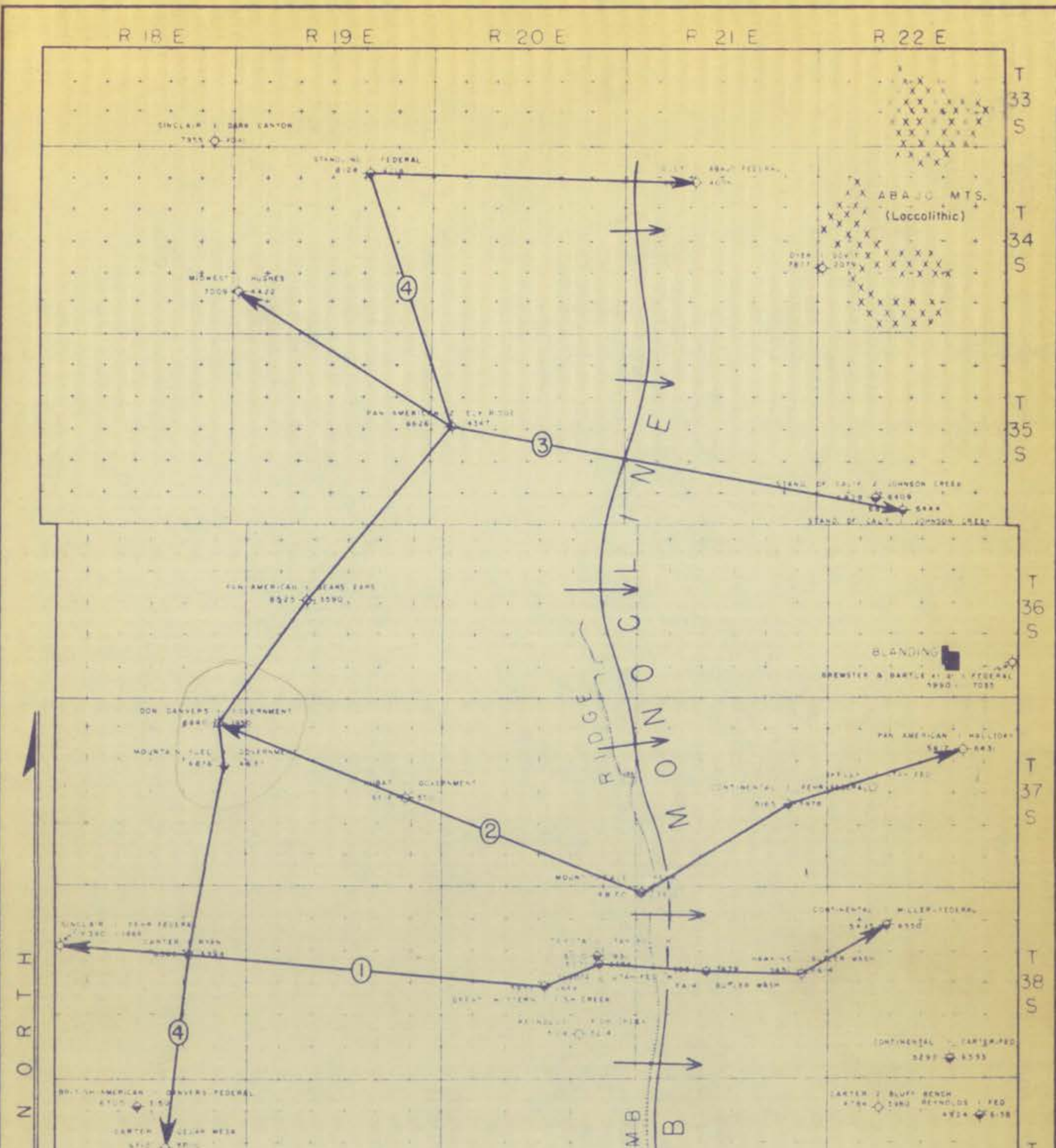
FIG. 1 INDEX MAP OF THESIS AREA SAN JUAN CO., UTAH

Method of Investigation

Thirty-three deep tests had been drilled in this area as of November 1, 1958 (Fig. 2). The pre-Rico Pennsylvanian strata penetrated by these tests were studied by means of lithologic, electric, and radioactivity logs, scout reports, and well-completion data. Four lithologic-stratigraphic cross-sections were constructed, using data from 20 of these tests (Figs. 2, 10-13). A structure contour map was made of the top of the Paradox formation (Fig. 5). Three isopachous maps were made showing the thickness of the middle Paradox member, the Honaker Trail formation, and the total Pennsylvanian section below the Rico transition (Figs. 6-8). The pertinent literature was reviewed and published surface maps were examined. Parts of two published surface maps, showing geologic structure and surface outcrop patterns, were incorporated into the report (Figs. 3, 4).

Acknowledgments

The writer is indebted to Dr. Sherman A. Wengerd for the use of his personal files, for discussions of the problem, for much helpful advice, and for serving as chairman of the thesis committee; to Drs. Abraham Rosenzweig and Roger Y. Anderson for reading and commenting on the manuscript and serving on the thesis committee; and to numerous others of the university staff and from industry for enlightening discussions and generous support of the investigation.



TITLE

LOCATION MAP

SCALE

0 2 4 6 8

MILES

FIGURE: 2 HINDS, 1959

LEGEND

② TRACES OF CROSS SECTIONS

DIP DIRECTION

POSITION OF COMB MONOCLINE

(BASED ON AERIAL PHOTOGRAPHS, SURFACE GEOLOGIC MAPS, TOPOGRAPHY, AND PUBLISHED SOURCES.)

WELL DATA

DRY HOLE

GAS SHOW

OIL SHOW

OPERATOR NO. LEASE

ELEVATION TOTAL DEPTH

NOVEMBER, 1958

GENERAL GEOLOGY

Structure

The dominant structure of the area of this report is the east-dipping, sinuous, Comb monocline, which trends in a southerly direction from a northern terminus on the west flank of the Abajo laccolithic mountains to a southern terminus near the town of Kayenta in northeast Arizona. This fold forms the eastern hingeline of the Monument upwarp, a massive north-trending uplift of late Cretaceous (Laramide) age, which dominates the west half of the area (Fig. 3). The monoclinal axis roughly parallels the northerly trend of the upwarp and its subsidiary folds, with the notable exception of the Fish Creek anticline, which has a northwest structural trend. The monocline also comprises the western boundary of the Blanding basin to the east and abruptly terminates that basin's westward development (Fig. 3). Structure contours on the top of the Triassic Chinle formation suggest a vertical component of folding or structural declivity of the monocline on the order of 3000 feet in the vicinity of Fish Creek anticline (Fig. 3). A comparison of the Chinle structure map with a similar map of the top of the Paradox formation (Fig. 5), based on subsurface data, discloses an interesting feature. At the site of the Reynolds, Fish Creek No. 1 test, west of Comb monocline, the top of the Paradox formation was encountered at an elevation of 3644 feet above sea level. Four miles to the northeast, in the Fair, Butler Wash No. 1 test, the top of the Paradox formation was encountered 386 feet below sea level, indicating a structural relief of 4030 feet between the two tests. These tests lie immediately adjacent to and on opposite sides of the Comb monocline.

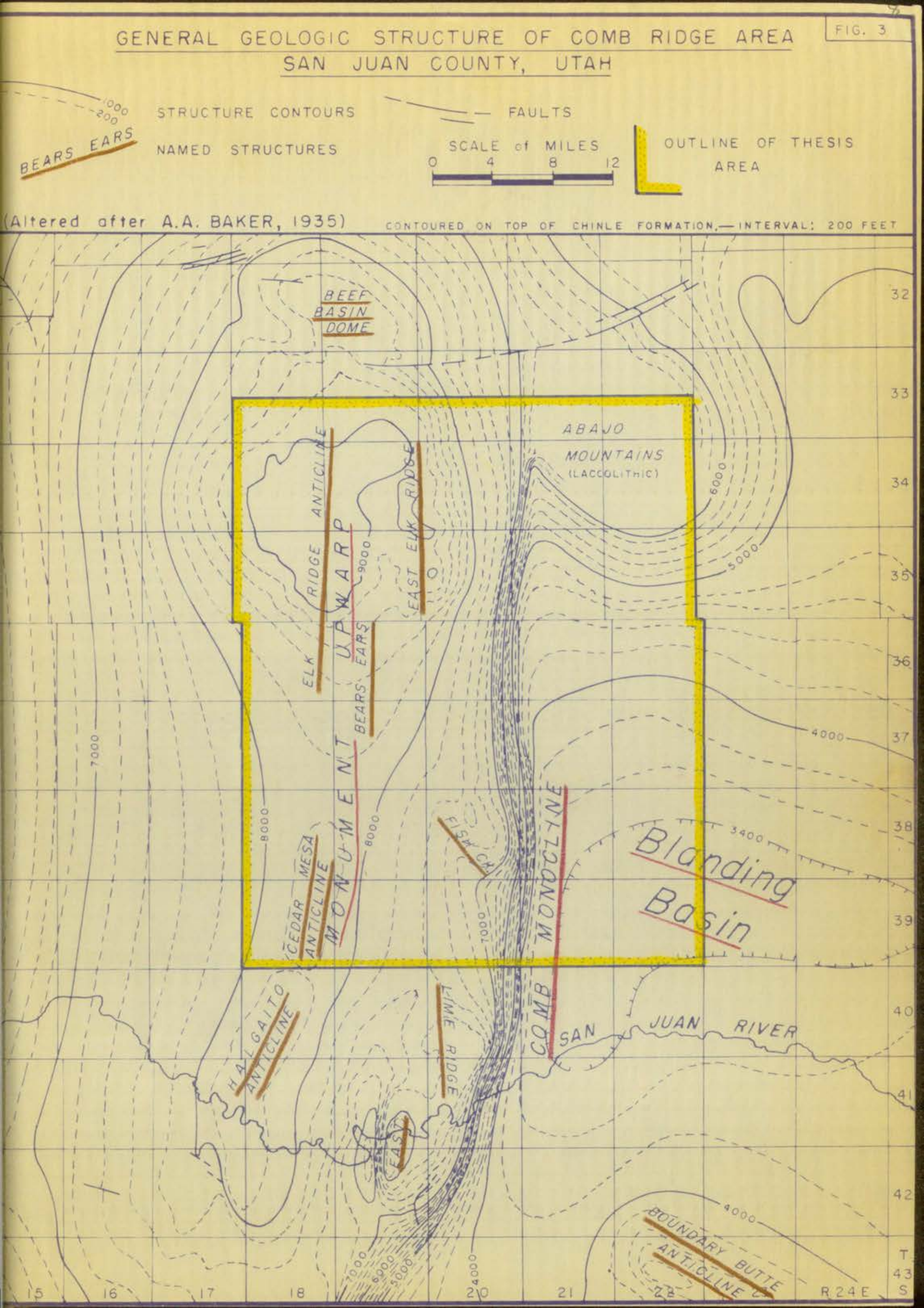
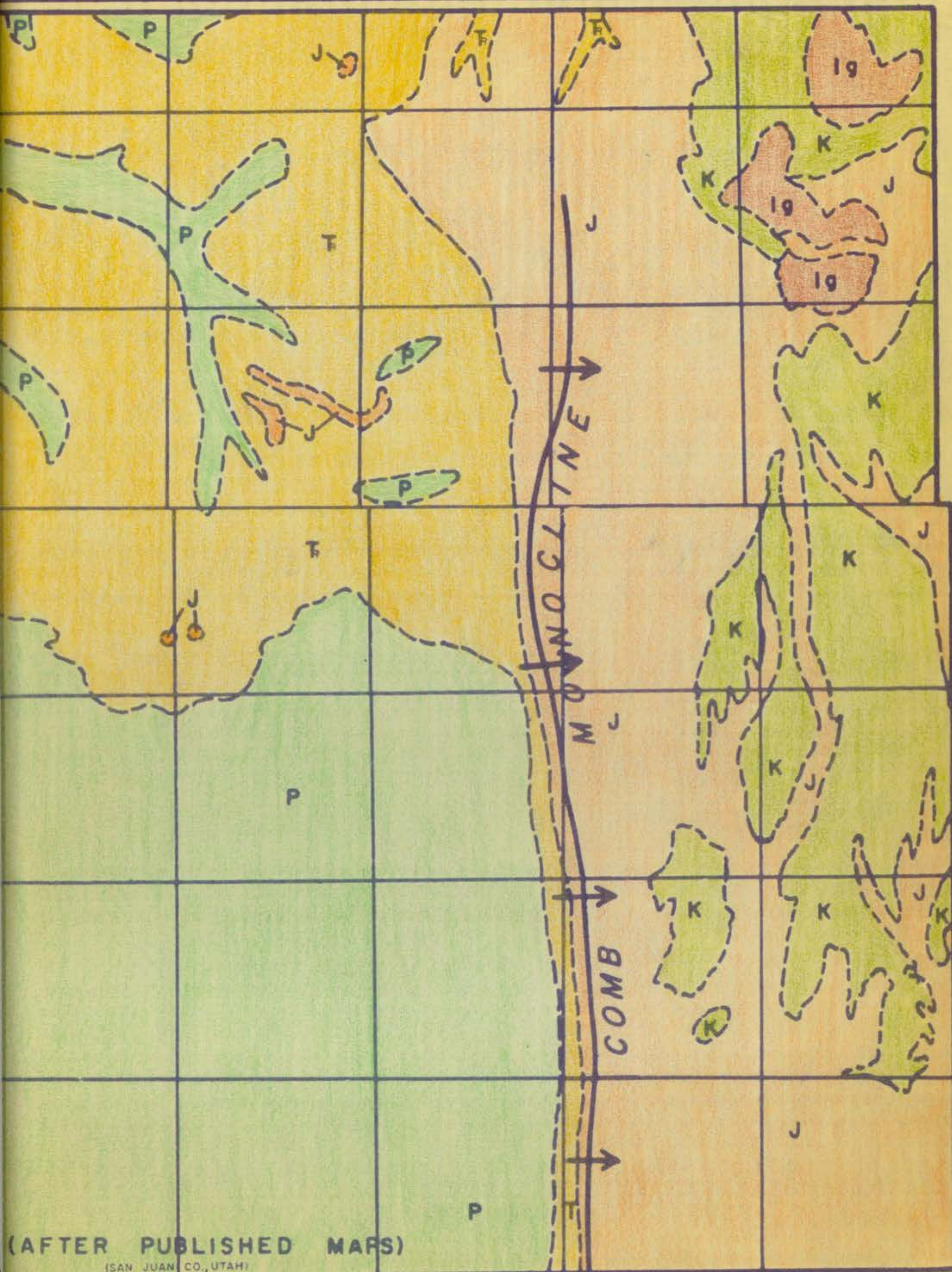


FIG. 3
GENERAL GEOLOGIC STRUCTURE OF COMB RIDGE AREA
SAN JUAN COUNTY, UTAH
STRUCTURE CONTOURS
FAULTS
BEARS EARS
NAMED STRUCTURES
SCALE of MILES
0 4 8 12
OUTLINE OF THESIS AREA
(Altered after A.A. BAKER, 1935)
CONTOURED ON TOP OF CHINLE FORMATION,— INTERVAL: 200 FEET
BEEF BASIN DOME
ABAJO MOUNTAINS (LACCOLITHIC)
ELK RIDGE ANTICLINE
EAST ELK RIDGE
BEARS EARS
MONUMENT UPWARP
CEDAR MESA ANTICLINE
FISH CR.
COMB MONOCLINE
Blanding Basin
HALGAITO ANTICLINE
LIME RIDGE
SAN JUAN RIVER
BOUNDARY BUTTE ANTICLINE
7000
8000
9000
6000
5000
4000
3400
15
16
17
18
20
21
R 24 E
32
33
34
35
36
37
38
39
40
41
42
T 43 S

SURFACE OUTCROP MAP

RETACEOUS P= PERMIAN
URASSIC Ig= IGNEOUS INTRUSIVE
RIASSIC

SCALE
0 5 10 Miles



The difference between the structural relief on the Chinle datum (3000 feet) and that on the Paradox datum (4030 feet) suggests that about 1000 feet of vertical structural relief was attained by the structure during the time interval between the deposition of the Pennsylvanian Paradox and Triassic Chinle formations, with some 3000 feet of structural relief added by folding after the deposition of the Chinle formation. Other observations concerning the times and scales of deformation along the monoclinal axis are discussed in a later section of this report.

Other outstanding structural features in the area are the Abajo laccolith and the Elk Ridge anticline. The laccolith is located in the northeast corner of the area and is expressed at the surface in the form of the deeply dissected Abajo mountains. The intrusion of the laccolith during the Tertiary period disrupted the previous structural configuration of the northeast corner of the thesis area and masks the earlier structural form of the northern terminus of Comb monocline. The Elk Ridge anticline, a large structure associated with the Monument Upwarp folding, covers most of the west half of the area and merges southward on trend into the Cedar Mesa anticline in the southwest corner of the thesis area (Fig. 3).

Surface Exposures

Strata of Permian to Cretaceous age are exposed within the area of this study. Figure 4 shows the general distribution of their outcrops. It may be noted that the position of Comb monocline roughly separates the exposures by age; outcrops of Triassic and Permian rocks are largely limited to the Monument upwarp area west of the monoclinal axis, whereas outcrops of Jurassic and younger rocks are mostly confined to the Blanding

the difference bet[illegible]
(5000 feet) and [illegible]
that about 1000 feet [illegible]
by the structure [illegible]
of the [illegible]
some 5000 feet of [illegible]
deposition of the [illegible]
ing the [illegible]
are discussed [illegible]

Other [illegible]
[illegible]
located in the [illegible]
the surface is the [illegible]
the intrusion of [illegible]
[illegible] the [illegible]
corner of the [illegible]
of the northern [illegible]
cline, a large [illegible]
folding, [illegible]
eastward [illegible]
west corner of [illegible]

[illegible]

Group of [illegible]
area of this [illegible]
[illegible]
cline results [illegible]
[illegible]
[illegible]
[illegible]

basin area east of the monocline. This distribution results from the geomorphic expression of the monocline as a topographic feature known as Comb Ridge.

Subsurface Stratigraphy

Rocks of every pre-Tertiary geologic period except Silurian and Ordovician have been penetrated by the drill in southeastern Utah. Descriptions of the various formations appear in the symposium (1952) and guidebook (1955) of the Four Corners Geological Society as well as elsewhere in the professional literature. To those interested in detailed lithologic descriptions, the writer recommends, as a more recent source, the ninth annual field conference guidebook of the Intermountain Association of Petroleum Geologists (1958). The present paper is concerned primarily with the Pennsylvanian strata which underlie the area at depths of 250 to 5000+ feet. The following chart summarizes the nomenclature proposed for these rocks by Wengerd in the I.A.P.G. guidebook referred to above (p. 109-34).

<table>
<tr><td>PERMIAN</td><td colspan="3">Cutler group</td></tr>
<tr><td></td><td colspan="3">Rico Transition</td></tr>
<tr><td rowspan="6">PENNSYLVANIAN</td><td rowspan="5">HERMOSA GROUP</td><td colspan="2">Honaker Trail formation</td></tr>
<tr><td rowspan="3">Paradox formation</td><td>upper member</td></tr>
<tr><td>middle member</td></tr>
<tr><td>lower member</td></tr>
<tr><td colspan="2">Pinkerton Trail formation</td></tr>
<tr><td colspan="3">Molas formation</td></tr>
<tr><td>MISSISSIPPIAN</td><td colspan="3">Leadville limestone</td></tr>
</table>

basin area east of the monocline. This classification results from the geomorphic expression of the monocline as a topographic feature known as Comb Ridge.

Stratigraphic Descriptions

Rocks of every pre-Jurassic system except Silurian and Devonian have been penetrated by the drill in southeastern Utah. Descriptions of the surface formations appear in the symposium (1952) and guidebook (1973) of the Four Corners Geological Society as well as elsewhere in the geological literature. To those interested in detailed lithologic descriptions, the writer recommends, as a more recent source, the ninth annual field conference guidebook of the Intermountain Association of Petroleum Geologists (1958). The present paper is concerned primarily with the Pennsylvanian strata which underlie the area at depths of 250 to 2000 feet. The following chart summarizes the nomenclature employed, the three rocks as described in the I.A.P.G. guidebook referred to above (p. 123-24).

System		Group	Formation	Member
PERMIAN		Cutler group		
PENNSYLVANIAN			Rico Formation	
		HERMOSA GROUP	Honaker Trail Formation	
			Paradox Formation	upper member
				middle member
				lower member
			Pinkerton Trail Formation	
			Molas Formation	
MISSISSIPPIAN			Leadville Limestone	

Brief descriptions of these formations are given in the next section of this report. Fuller accounts may be found in papers by Clair (1952), Wengerd and Strickland (1954), Herman and Sharps (1956), Herman and Barkell (1957), and Wengerd (1958).

PENNSYLVANIAN STRATIGRAPHY

Molas Formation

The clastic red-beds of the Molas formation overlie Mississippian strata throughout the area of this study. They comprise chiefly red, green, and variegated siltstones, silty shales and calcareous shales and siltstones, with a few lentils of gray to buff limestone. The basal part of the formation is composed of reworked fragments of Mississippian (Leadville) limestone imbedded in a clay-silt matrix.

The Molas deposits represent the development of a soil profile upon the karst surface of the Leadville limestone between late Mississippian and Atokan time. Subsequent marine transgression caused reworking and stratification of the soil zone and culminated in the deposition of the overlying Pinkerton Trail formation. Within the boundaries of this study the Molas formation ranges from less than 30 feet to more than 200 feet in thickness.

Hermosa Group

Pinkerton Trail formation

The Pinkerton Trail formation is composed of cherty gray limestone and dolomite with interbedded gray and green shale and, in the area of this study, some reddish brown siltstone lentils and traces of dark gray shale. The formation was named by Wengerd and Strickland in 1954 (p. 2168) from exposures in the Animas canyon north of Durango, Colorado. Previously, the rocks concerned were considered a part of the lower Hermosa member of the Hermosa formation (now Hermosa group).

According to Wengerd (1958, p. 118), the Pinkerton Trail formation is wholly of pre-Paradox origin and was deposited on

PENNSYLVANIAN-PERMIAN

Molas Formation

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Hermosa Group

Pinkerton Trail Formation

The Pinkerton Trail Formation is composed of mainly gray limestone and dolomite with interbedded gray and green shale and, in the area of this study, some reddish brown siltstone lentils and traces of dark gray shale. The formation was named by Wengerd and Strickland in 1954 (p. 2160) from exposures in the Animas canyon north of Durango, Colorado. Previously, the rocks concerned were considered a part of the lower Hermosa member of the Hermosa formation (now Hermosa group).

According to Wengerd (1958, p. 271), the Pinkerton Trail Formation is mainly of pre-[illegible] and was deposited in

an eastern shelf of the Cordilleran geosyncline. The formation ranges from Atokan to Desmoinesian (early Cherokee) in age. Thus, the Pinkerton Trail formation contains the important Atokan-Desmoinesian series time-surface in places where it is not within the Molas clastic section. Thickness of this formation ranges from 62 feet to 254 feet within the area of this report.

Paradox formation

The strata comprising the Paradox formation were deposited from the brine that filled the barred tectonic basin created by the subsidence of the Paradox geosyncline in middle Pennsylvanian time. Possible origins of the facies were discussed by Wengerd and Strickland in 1954 (p. 2176-2188). The formation is considered by them to be entirely of early Desmoinesian (Cherokee) age.

Clearly divisible into three members in the areas of thick salt deposition, the formation presents a problem of sub-division near and outside the salt wedge-edges. Contacts which are relatively clear and sharp basinward become gradational and obscure in the shelf facies, where the hypersaline deposits of the middle member grade into penesaline beds similar to those of the upper and lower members or wedge out westward into time-equivalent disconformities. However, with dependable and complete lithologic logs and good quality radioactivity logs the member boundaries may be defined with a fair degree of accuracy near the basin margins.

Lower member.- The lower member of the Paradox formation is composed chiefly of gray, silty, gypsiferous limestone and dolomite, with thin beds of gypsum, siltstone, and gray and black

up western shelf of the [illegible] geosyncline. The formation ranges from Atokan to Desmoinesian (early Cherokee) in age. Thus, the Pinkerton Trail formation contains the important Atokan-Desmoinesian series time-surface in places where it is not within the Molas clastic section. Thickness of this formation ranges from 50 feet to 250 feet within the area of this report.

Paradox Formation

The strata comprising the Paradox formation were deposited from the saline seas that filled the Paradox evaporite basin created by the subsidence of the Paradox geosyncline in middle Pennsylvanian time. Possible origins of the basin were discussed by Wengerd and Strickland in 1954 (p. [illegible]). The formation is considered by them to be entirely of early Desmoinesian (Cherokee) age.

Clearly divisible into three members in the areas of thick salt deposition, the formation presents a problem of sub-division near and outside the salt basin-edges. Contacts which are relatively clear and sharp in the salt become gradational and obscure in the shelf facies, where the hypersaline deposits of the middle member grade into penesaline beds similar to those of the upper and lower members or change westward into lime-equivalent [illegible]. However, with correlatable and complete lithologic logs and good quality radioactivity logs the member boundaries may be defined with a fair degree of accuracy near the basin margins.

Lower member. - The lower member of the Paradox formation is composed chiefly of gray, silty, argillaceous limestone and dolomite, with thin beds of gypsum, siltstone, and gray and black

shale. It was deposited in a penesaline environment during the first stages of subsidence of the Paradox geosyncline when marine circulation was partially restricted. In places it is gradational with the Pinkerton Trail formation below and the middle Paradox member above. The lower Paradox member ranges from 50 feet to about 80 feet in thickness in the Comb monocline area.

Middle member.- The middle Paradox member, informally called the "salt member", is the prime concern of this report. It consists essentially of great thicknesses of halite interbedded with gypsum, anhydrite, limestone and dolomite beds, and extensive euxinic black shale lentils which persist beyond the edges of salt deposition. In the central part of the Paradox basin, where rapid subsidence permitted deposition of the evaporites on a grand scale, thicknesses of more than 5000 feet have been attributed to the middle Paradox member, although salt flowage may account in part for the expanded section. Shelfward the member grades into penesaline deposits of evaporitic dolomite, limestone, and gypsum similar to the strata of the upper and lower members. Some thin lentils of fine clastics occur in the thinner high shelf sections. Figure 7 shows the thickness variations of this member within the thesis area and the probable position of the Paradox salt wedge-edge.

Upper member.- The upper member of the Paradox formation consists of penesaline deposits of massive gypsum and anhydrite; finely crystalline, argillaceous dolomite and limestone; bioclastic limestone lentils; black, calcareous, (in places silty or gypsiferous) evaporitic shales; and some lentils of calcareous or gypsiferous siltstone. A few fine-grained sandstone lentils are present in the Comb monocline area.

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Middle member.- The middle Paradox member, informally called the "salt member", is the prime concern of this report. It consists essentially of great thicknesses of halite interbedded with gypsum, anhydrite, limestone and dolomite beds, and extensive euxinic black shale wedges which persist beyond the edges of salt deposition. In the central part of the Paradox basin, where rapid subsidence permitted deposition of the evaporites on a grand scale, thicknesses of more than 5000 feet have been attributed to the middle Paradox member, although salt flowage may account in part for the expanded section. Shelfward the member grades into penesaline deposits of evaporitic dolomite, limestone, and gypsum similar to the strata of the upper and lower members. Some thin lentils of fine clastics occur in the [illegible] shelf sections. Figure 7 shows the thickness variations of this member within the thesis area and the probable position of the leached salt wedge-edge.

Upper member.- The upper member of the Paradox formation consists of penesaline deposits of massive gypsum and anhydrite; finely crystalline, argillaceous dolomite and limestone; bioclastic limestone (oolitic, algal, calcarenite, (in places silty or argillaceous) evaporitic shales; and some lentils of calcareous or argillaceous siltstone. A few fine-grained sandstone lentils are present in the [illegible] anticline area.

Within the limits of the present study, the upper Paradox member ranges from about 135 to 370 feet in thickness. It represents a transition from the highly saline conditions responsible for the deposition of the underlying salt member to a less saline environment as the basin was partially invaded by normal marine waters. This restoration of marine circulation ended the Paradox megacycle and permitted deposition of the normal shelf-type carbonates and clastics of the overlying Honaker Trail formation.

Honaker Trail Formation

The Honaker Trail formation comprises the predominantly carbonate sequence between the Paradox formation and the Rico transition. The lower parts of the formation consist of a series of massive limestone lentils interbedded with gray to greenish calcareous shale and siltstone, and white to gray sandstone. The upper part of the formation contains thick calcareous sandstone and thin to massive beds of gray sandy limestone. The formation is generally cherty and in many places fossiliferous. The name "Honaker Trail" was introduced by Wengerd in 1958 (p.115) to replace the previously used "Upper Hermosa".

Rico Transition

This zone marks the transition from marine to terrestrial sedimentation in late Pennsylvanian and early Permian time. It consists of thin lentils of interbedded gray marine carbonates and shales which grade upward into reddish brown terrestrial clastics of the Halgaito member, Cutler formation.

TECTONIC HISTORY OF COMB MONOCLINE

Pre-Paradox History

From this investigation it cannot be conclusively stated whether or not any structural deformation occurred along the axis of Comb monocline prior to Paradox time. A study of the Mississippian, Devonian, and Cambrian strata of the area might reveal an earlier development, but examination of pre-Pennsylvanian rocks was not included in the scope of this paper. Study of the lower Pennsylvanian Molas and Pinkerton Trail formations in the area disclosed nothing definite enough to base a conclusion on concerning whether or not the monocline was being expressed topographically during early Pennsylvanian time. There is a considerable thinning of the Molas and Pinkerton Trail rocks in the northwest part of the area, but this thinning has no obvious relation to the Comb structure. Lithologic-stratigraphic cross-sections nos. 3 and 4 (Figs. 2, 12-13) illustrate the northwesterly thinning of these two formations. The Molas formation thins from an average thickness of about 200 feet in the southern part of the area to slightly over 100 feet in the Midwest, Hughes No. 1 test (Sec. 30, T. 34 S., R. 19 E.) (Figs. 2, 12); to less than 70 feet in the Pan American, Elk Ridge No. 2 test (Sec. 18, T. 35 S., R. 20 E.)(Figs. 2, 12-13); and to less than 30 feet in the Stanolind, Federal No. 1 test (Sec. 2, T. 34 S., R. 19 E.)(Figs. 2, 13). The Pinkerton Trail formation thins from a normal thickness of more than 200 feet in the southern part of the area to 140 feet near the Midwest, Hughes No. 1 test; to about 100 feet in the vicinity of the Pan American, Elk Ridge No. 2 test; and to less than 80 feet at the site of the Stanolind, Federal No. 1 test (Figs.

2, 12-13). Whether or not these reduced thicknesses reflect a regional thinning of the two formations or are the result of local conditions of sedimentation and/or erosion caused by early Pennsylvanian structure is indeterminate from this areally restricted study. However, structure would seem at least partially responsible as the thicknesses are greater in the Midwest, Hughes No. 1 test than in the Pan American, Elk Ridge No. 1 test. If regional thinning were the only factor concerned, the Pan American test should have penetrated the thicker section, due to the more southeasterly location of the test-site (Fig. 2). Assuming, then, that early Pennsylvanian structure is reflected in the thickness variations of the Molas and Pinkerton Trail formations in the northwest part of the area, the question remains whether the influencing structure was genetically related to folding along the axis of the Comb monocline. This apparently was not the case, for there is no noticeable thinning of the Molas and Pinkerton Trail formations near the monoclinal axis in the southern part of the area. Lithologic-stratigraphic cross-section no. 1 (Figs. 2, 10) shows a consistent thickness of the Molas and Pinkerton Trail rocks as they approach and cross the axis of Comb monocline in T. 38 S. It should be noted, however, that the Pinkerton Trail strata become siltier and shalier, with fewer and thinner limestone beds, in the vicinity of the Great Western, Fish Creek No. 1 and Fair, Butler Wash No. 1 tests, which lie adjacent to and on opposite sides of the Comb structure (Figs. 2, 10). This increase of clastic content and decrease in carbonate deposits might be taken to indicate nearness to structure, but is considered by the writer to be insufficient evidence in itself of early

8, 15-19). Whether or not these regional thicknesses reflect a regional thinning of the two formations or are the result of local conditions of sedimentation and/or erosion caused by early Pennsylvanian movements is indeterminate from this greatly restricted study. However, structure would seem to at least partially responsible as the thicknesses are greater in the Mitchell, Hughes No. 1 test than in the Pan American, Elk Ridge No. 1 test. If regional thinning were the only factor concerned, the Pan American test should have penetrated the thicker section, due to its more southeasterly location of the test-site (Fig. 2). Assuming, then, that early Pennsylvanian structure is reflected in the thickness variations of the Molas and Pinkerton Trail formations in the northwest part of the area, the question remains whether the Pennsylvanian structure was genetically related to folding along the axis of the Bench anticline. This apparently was not the case, for there is no noticeable thinning of the Molas and Pinkerton Trail formations near the anticlinal axis in the northern part of the area. Lithologic-stratigraphic cross-section No. 2 (Figs. 8, 10) shows a consistent thickness of the Molas and Pinkerton Trail rocks as they approach and cross the axis of Bench anticline in T. 38 S. It should be noted, however, that the Pinkerton Trail strata became siltier and sandier, with fewer and thinner limestone beds, in the vicinity of the Bench anticline, Pitch Creek No. 1 and Pehr, Hamilton Unit No. 1 tests, which lie adjacent to and on opposite sides of the Bench anticline (Figs. 2, 10). This increase of clastic content and decrease in carbonate deposition might be taken to indicate nearness to shoreline, but is insuffi- cient in the absence of additional evidence in itself of early

Pennsylvanian structural growth along the axis of Comb monocline. The Molas depositional lithology is consistent throughout the thesis area, as is that of the Pinkerton Trail strata except for the anomalous occurrence noted above. Thus, there is some evidence both for and against structural development in the Comb monocline area during early Pennsylvanian time.

Paradox History

Lower Paradox time

The strata of the lower member of the Paradox formation exhibit a relatively consistent thickness and lithology throughout the area of this study. Lithologic-stratigraphic cross-sections nos. 1 and 4 (Figs. 2, 10, 13) disclose only a slight westerly thinning of this member from about 80 feet in the vicinity of the Fair, Butler Wash No. 1 test (Sec. 16, T. 38 S., R. 21 E.) to about 65 feet near the location of the Sinclair, Fehr-Federal No. 1 test (Sec. 7, T. 38 S., R. 18 E.). This thinning represents a regional variation of the lower member as it approaches the western and southern shelf areas of the Paradox basin, and was not caused by the presence of a structural anomaly in the vicinity of Comb monocline. The lower Paradox member is also somewhat siltier on the west side of the area as illustrated by lithologic-stratigraphic cross-sections nos. 1 to 4 (Figs. 2, 10-13). Such a facies gradation is also normal in the member as the shelf areas are approached and does not reflect early Paradox topographic relief of the Comb structure. Evidence at the present time is not indicative of deformation along the monoclinal axis during the deposition of the lower Paradox member of the Paradox formation.

Pennsylvanian structural growth along the axis of Cobb monocline. The Nolan depositional lithology is consistent throughout the thesis area, as is that of the [illegible] shale strata except for the anomalous occurrences noted above. Thus, there is some evidence both for and against structural development in the Cobb Monocline area during early Pennsylvanian time.

Paradox History

Lower Paradox time.

The strata of the lower member of the Paradox Formation exhibit a relatively consistent thickness and lithology throughout the area of this study. Lithologic-stratigraphic cross-sections nos. 1 and 2 (Figs. 2, 10, 11) disclose only a slight westerly thinning of this member from about 80 feet in the vicinity of the Aneth, Texas Pan-American No. 1 well (sec. 16, T. 38 S., R. 21 E.) to about 65 feet near the location of the Sinclair, Pan-Federal No. 1 well (sec. 7, T. 38 S., R. 18 E.). This thinning represents a regional gradation of the lower member as it approaches the western and southern shelf areas of the Paradox basin, and was not caused by the presence of a structural anomaly in the vicinity of Cobb monocline. The lower Paradox member is also somewhat thinner on the west side of the area as illustrated by lithologic-stratigraphic cross-sections nos. 1 to 4 (Figs. 2, 10-13). Such a facies gradation is also normal in the member as the shelf areas are approached and does not reflect early Paradox topographic relief of the Cobb structure. Evidence at the present time is not indicative of deformation along the monocline axis during the deposition of the lower Paradox member of the Hermosa Formation.

Middle Paradox time

The first concrete evidence of Pennsylvanian tectonic activity along the axis of Comb monocline is found in the lithologic and thickness variations of the middle member of the Paradox formation (Figs. 7, 10-13). This member, which consists of less than 200 feet of penesaline deposits of gypsum, dolomite, and black shale in the vicinity of the monoclinal axis, thickens westerly to more than 460 feet near the Carter, Ryan No. 1 test, and to more than 600 feet near the Don Danvers, Government No. 1 and Mountain Fuel, Government No. 1 tests (Figs. 7, 10, 11). The thicker westerly part of the member includes from 200 to 400 feet of hypersaline halite and anhydrite deposits which are absent over the crest of the Comb fold (Figs. 10-13). In an easterly direction the middle Paradox member thickens from less than 200 feet over the structure to 1100 feet at the site of the Fair, Butler Wash No. 1 test immediately east of the structural crest (Figs. 7, 10). The Fair test penetrated a total of about 900 feet of hypersaline strata which wedge out between the test and the fold (a distance of one mile)(Figs. 2, 10). The penesaline deposits which blanket the structure are represented by equivalent shale and limestone breaks in the thick salt section penetrated by the Fair test, and by gypsum, shale, and dolomite breaks in the salt section west of the fold (Figs. 10-13).

The rapid increase in the thickness of the middle Paradox member and the inclusion of a thick hypersaline facies in the member off either flank of the Comb structure clearly indicates that the crest of the fold remained relatively stable during middle Paradox time while the easterly and westerly flanking

Middle Paradox time

The first concrete evidence of Pennsylvanian tectonic activity along the axis of Lisbon anticline is found in the lithologic and thickness variations of the middle member of the Paradox formation (Figs. 7, 10-13). This member, which consists of less than 200 feet of [illegible] deposits of gypsum, dolomite, and black shale in the vicinity of the anticlinal axis, thickens westerly to more than 900 feet near the Carter, Ryan No. 1 test, and to more than [illegible] feet near the Pan [illegible] Government No. 1 and [illegible] Government No. 1 tests (Figs. 7, 10, 11). The thicker westerly part of the member includes from 200 to 400 feet of [illegible] halite and [illegible] deposits which are absent over the crest of the same fold (Figs. 10-13). In an easterly direction the middle Paradox member thickens from less than 200 feet over the structure to 1100 feet at the side of the fold, [illegible] No. 1 test immediately east of the structural crest (Figs. 7, 10). The Shell test penetrated a total of about 900 feet of [illegible] which wedge out between the test and the fold (a distance of one mile)(Figs. 8, 10). The [illegible] deposits which blanket the structure are represented by equivalent shale and limestone breaks in the thick salt section penetrated by the Shell test, and by gypsum, shale, and dolomite breaks in the salt section west of the fold (Figs. 10-13).

The rapid increase in the thickness of the middle Paradox member and the inclusion of a thick [illegible] section in the member off either flank of the Lisbon structure clearly indicates that the crest of the fold remained relatively stable during middle Paradox time while the westerly and easterly flanking [illegible]

areas were subsiding to allow accumulation of hypersaline evaporite sediments. Although this long peninsula was emergent, or nearly so, during the times of salt deposition in the barred basin, it remained generally in low topographic (but high structural) relief and received penesaline sediments during the periodic intervals when the stagnant sea into which it protruded from the south was flooded and freshened by normal marine waters from the northwest. Thus, although the hypersaline deposits are absent from the immediate area of the monocline, the euxinic black shales and penesaline gypsum and dolomite deposits of the middle member blanket the structure, just as they extend beyond the salt wedge-edge along other parts of the basin shelf. The observation may be made that the ancestral Comb structure endured as a stable salient extending northerly into the sagging northwest-trending basin of middle Paradox time, and during that time gained a structural relief of about 900 feet on its eastern limb, as shown by the rapid increase of section thickness from less than 200 feet on the crest of the fold to 1100 feet at the site of the Fair, Butler Wash No. 1 test (Figs. 7, 10). At that time the ancestral Comb structure was apparently an east-tilted, slightly inclined anticlinal fold, as is evident from the fact that subsidence permitted thick salt deposition on the west flank as well as the east flank of the axis (see preceding paragraph and Figs. 7, 10-13). Had the structure exibited a monoclinal dip during that period there should be a thinning, rather than thickening, of middle Paradox strata from the crest of the fold westward. Also, it would have been unusual for salt deposits to accumulate on the westerly up-dip slope of such a structure and not

on the structural crest, which would necessarily have been topographically lower on a monoclinal structure in a depositional basin.

Upper Paradox time

The upper Paradox deposits show some evidence of having been influenced in their deposition by the presence of a barrier in the vicinity of Comb monocline. This evidence consists of the distribution of several thin siltstone and fine sandstone lentils which occur in the upper Paradox member in the western part of the area, and in the percentage difference in type of carbonate deposition on the east and west sides of the structure. The clastic lentils, which are characteristic of the high southwest shelf upper Paradox facies, appear from the cross-sections (Figs. 2, 10-13) to be limited in extent in this area to the west side of the Comb structure. It is plausible that some type of local barrier in the vicinity of Comb monocline may have been influencial in restricting the local easterly distribution of these clastic lentils. The carbonate deposits on the west side of the area consist primarily of dolomite and dolomitic shale, limestone, and gypsum lentils, whereas on the east side of the area there is a preponderance of limestone carbonates and fewer dolomitic deposits. A low submarine barrier along the monoclinal axis could also have resulted in this carbonate facies change, by restricting local circulation and causing differences in the temperature, salinity, and chemical character of the water west of the structure.

The proposed upper Paradox barrier in the Comb monocline area need not have been due to structural deformation during this time. An upper Paradox biohermal development near the crest of

on the structural front, which would necessarily have been topographically lower on a monoclinal structure in a depositional basin.

Upper Paradox time

The upper Paradox deposits show some evidence of having been influenced in their deposition by the presence of a barrier in the vicinity of Cash monocline. This evidence consists of the distribution of several thin siltstone and fine sandstone lentils which occur in the upper Paradox member in the western part of the area, and in the percentage differences in type of carbonate deposition on the east and west sides of the structure. The clastic lentils, which are characteristic of the high southwest shelf upper Paradox facies, appear from the cross-sections (Figs. 2, 10-13) to be limited in extent in this area to the west side of the Cash monocline. It is plausible that some type of local barrier in the vicinity of Cash monocline may have been influential in restricting the local easterly distribution of these clastic lentils. The carbonate deposits on the west side of the area consist primarily of dolomite and dolomitic shale, limestone, and gypsum lentils, whereas on the east side of the area there is a preponderance of limestone carbonates and fewer dolomitic deposits. A low submarine barrier along the monoclinal axis could also have resulted in this carbonate facies change, by restricting local circulation and causing differences in the temperature, salinity, and chemical character of the waters east of the structure.

The proposed upper Paradox barrier in the Cash monocline area need not have been due to structural deformation during this time. It [illegible] original development of the crest of

the earlier fold could have well served as such a barrier. The structurally elevated, low-lying peninsula formed by the ancestral Comb structure during middle Paradox time could have presented ideal conditions for upper Paradox biohermal buildup in the Comb monocline area. However, irrefutable evidence of upper Paradox biohermal growth in the area has not yet been recognized by the writer. Until more tests are drilled in the immediate vicinity of the structure and additional data become available the question of upper Paradox biohermal growth in the area must remain somewhat conjectural. The writer presently believes that the area of the Comb fold was tectonically quiescent, or nearly so, during upper Paradox time, but that during this interval possible biohermal growth may have occurred along the trend of the earlier structural elevation in some localities.

Post-Paradox History

An isopachous map of the Honaker Trail formation was constructed in an attempt to determine if structural growth in the area of Comb monocline exerted any depositional controls in late Pennsylvanian time (Fig. 8). It was found that some thinning of the formation does occur over the northern extremities of the structure, suggesting that parts of the earlier fold may have had submarine topographic expression during Honaker Trail deposition. The evidence, however, is inconclusive, as the contour configuration illustrates. Wengerd and Matheny (1958, p. 2062) postulate the beginning of a slow rise of the Monument upwarp and other intra-basin areas during Honaker Trail (late Desmoinesian) time "to become broad low islands in the latest Pennsylvanian and Permian Wolfcampian seas." This

observation is not entirely verified by their isopachous map of the Honaker Trail formation (ibid., Fig. 17, p. 2092-93), which shows an apparent late Pennsylvanian sag over the north half of the Monument upwarp area. This sag closely reflects the middle Paradox sag west of Comb monocline described earlier in the present paper. It seems doubtful that any appreciable amount of uplift of the northern Monument upwarp area, other than immediately adjacent to Comb monocline, occurred prior to the Permian period.

The objectives of this investigation did not require a detailed study of the effects of the Comb structure on post-Pennsylvanian sedimentation. It was noted, however, that there is an apparent difference between the structural relief of the fold on the top of the Paradox formation and the Triassic Chinle formation (See page 7 and figs. 3 and 5). According to Baker's map of 1935 (Fig. 3), the structural relief on the top of the Chinle formation along the axis of Comb monocline is about 3000 feet in the vicinity of Fish Creek anticline. The structural relief on the top of the Paradox formation in the same locality, between the sites of the Reynolds, Fish Creek No. 1 and Fair, Butler Wash No. 1 tests, is slightly over 4000 feet (Fig. 5). This indicates that the Comb structure gained about 1000 feet of vertical relief after the deposition of the Paradox strata and prior to the deposition and later folding of the Chinle formation. This relief was probably attained during times of regional tectonic activity in the intervening Permian period. The 3000 feet of structural relief evident on the top of the Chinle deposits was gained later, during the Cretaceous-Tertiary Laramide period of folding. In the writer's

opinion it was also probably during the Laramide folding that the Comb structure became a true monocline, due to the structural growth of the Monument upwarp and eastward tilting of the Comb structure's west flank from an earlier west dip to an east dip, with concurrent steepening of dip on the east limb of the structure. The east limb of the fold apparently had a considerable dip, as is shown by the sudden thickening of middle Paradox strata in an easterly direction from the crestal area. Reversal of dip on the west flank of the structure caused steepening of the original dip on the east limb and could have occurred in several ways. If the stresses which caused the uplift of the Monument upwarp to the west and the sag of the Blanding basin to the east were the result of vertical adjustments in the basement complex, then the area of Comb monocline was the hinge-line between these two structural developments. In this event the growth of the monocline probably would have been controlled by the presence of a deep-seated vertical shear zone. Folding over such a shear zone would probably consist of an easterly draping of strata from the uplifted side of the zone to the downthrown side, with the attitude of the beds on either flank of the crestal part of the fold dependent upon the direction of tilting of the respective underlying basement unit. The basement units, although separated at the zone of shearing, could not conceivably act independently of each other, such as tilting in opposite directions, at varying degrees, or at different times. Assuming that the Comb structure does in fact represent such a vertical shear development, an appreciable dip on the east limb of the fold could have been

opinion it was also probably during the Laramide folding that the Cody structure became a true monocline, due to the structural growth of the basement uplift and westward tilting of the Cody structure went from an earlier west dip to an east dip, with consequent steepening of dip on the east limb of the structure. The west limb of the fold apparently had a considerable dip, as is shown by the sudden thickening of middle Paleozoic strata in an easterly direction from the crestal area. Reversal of dip on the west flank of the structure caused steepening of the original dip on the east limb and could have occurred in several ways. If the stresses which caused the uplift of the Beartooth uplift on the west and the sag of the Bighorn basin to the east were the result of vertical adjustments in the basement complex, then the area of Cody monocline and the hinge-line between these two structural developments. In this event the growth of the monocline probably would have been controlled by the presence of a deep-seated vertical shear zone. Folding over such a shear zone would probably consist of an easterly draping of strata from the uplifted side of the zone to the downthrown side, with the attitude of the beds on either flank of the crestal part of the fold dependent upon the direction of tilting of the respective basement units. The basement units, although separated by the zone of shearing, could not conceivably act independently of each other, such as tilting in opposite directions, at varying degrees, or at different times. Assuming that the fault stresses are such in that basement took a vertical shear orientation, an appreciable dip on the east limb of the fold would have been

increased while an adjustment in the attitude of the basement unit underlying the west flank of the structure caused a reversal of the previous west dip of that flank. Now consider as a second possibility what might have occurred if the stresses causing the development of the Monument upwarp and associated structures were derived from east-west compressional forces (Baker, 1935, and Kelley, 1955). In such a case the Comb monocline might have been the surface expression of a west-dipping reverse fault in the basement complex. Such a fault would necessarily impart an early easterly dip to the beds on the east limb of an overlying fold. The west limb of the covering fold might assume either an east or west dip direction depending on the tilt direction of the westerly fault block, and whether or not the vertical stress component were localized along the fault plane or bending occurred in the block. Later uplift and tilt of the westerly fault block could impart an easterly dip to horizontally deposited strata while subsidence of the easterly fault block increased the earlier dip of the east limb of the fold. Thus, it may be shown that conversion of the middle Pennsylvanian east-tilted anticlinal structure to the post-Laramide, steeply east-dipping monoclinal fold evident from the structural attitude of the Chinle strata probably occurred.

Adding the structural relief gained on the east limb of the Comb fold during middle Paradox time (about 900 feet; see pages 20-21) to that of later times (4000 +/- feet during Permian

and Laramide deformations; see pages 7, 23-24), which appears on the top of the Paradox formation, it is demonstrated that the structural relief of Comb monocline today should total approximately 4900 feet on the top of the Mississippian Leadville limestone. A comparison of the elevation of the Leadville top at the sites of the Great Western, Fish Creek No. 1 and Fair, Butler Wash No. 1 tests verifies the accuracy of these figures. The Great Western test (Sec. 22, T. 38 S., R. 20 E.) was spudded at an elevation of 5933 feet (Fig. 2) and encountered the Leadville top at a depth of 3250 feet (Fig. 10), or, by computation, at an elevation of 2683 feet above sea level. The Fair, Butler Wash No. 1 test (Sec. 16, T. 38 S., R. 21 E.) was spudded at an elevation of 5237 feet (Fig. 2) and encountered the Leadville top at a depth of 7430 feet, or 2193 feet below mean sea level. If the Leadville limestone top lies at an elevation of 2683 feet at the site of the Great Western test and 2193 feet below sea level at the site of the Fair test, then the vertical component of structural relief on this top is 4876 feet between the two tests. This figure represents the total vertical component of all post-Mississippian deformation along the Comb monocline axis in the vicinity of Fish Creek anticline.

Summary of Tectonic History

Structural deformation along the axis of the Comb monocline began at least as early as middle Pennsylvanian (Paradox) time and possibly earlier. Structural growth of the fold has been episodic, with periodic rejuvenation in conjunction with regional tectonic activity during Pennsylvanian, Permian, and

late Cretaceous-Tertiary (Laramide) time. During late Paleozoic time the Comb structure was probably an east-tilted anticlinal fold. Laramide uplift and tilting of the west flank of the structure from an earlier west dip to an east dip, with concurrent steepening of the east limb, gave the fold its present monoclinal form. Vertical structural relief of the monocline in the vicinity of Fish Creek anticline ranges from about 3000 feet on top of the Triassic Chinle formation to about 4000 feet on top of the Pennsylvanian Paradox formation, and about 4900 feet on top of the Mississippian Leadville limestone. The development of the Comb fold may have been controlled by the presence of a deep-seated, reverse fault in the basement complex. This west-dipping reverse fault would have resulted from regional east-west compressional forces.

late Cretaceous-Tertiary (Laramide) time. During late Paleozoic time the Uncompahgre was probably an east-tilted anticlinal fold. Laramide uplift and tilting of the west flank of the structure from an earlier west dip to an east dip, with concurrent steepening of the east limb, gave the fold its present monoclinal form. Vertical structural relief of the monocline in the vicinity of Fish Creek anticline ranges from about 5000 feet on top of the Triassic Chinle formation to about 4000 feet on top of the Pennsylvanian Paradox formation, and about 4500 feet on top of the Mississippian Leadville limestone. The development of the Uncompahgre fold may have been controlled by the presence of a deep-seated, reverse fault in the basement complex. This east-dipping reverse fault would have resulted from regional east-west compressional forces.

DEPOSITIONAL AND ENVIRONMENTAL HISTORY OF THE MIDDLE PARADOX SALT MEMBER

General Statement

The strata of the Paradox formation were deposited in a giant evaporative sedimentational megacycle of penesaline (lower Paradox), to hypersaline (middle Paradox), to penesaline (upper Paradox). During the hypersaline (middle Paradox) phase of the megacycle, there was periodic freshening of the stagnant sea by normal marine waters, causing cyclic deposition of thin deposits of penesaline gypsum, dolomite, limestone, dolomitic biostromal limestone, and euxinic black shale. In the areas of salt deposition these middle Paradox penesaline strata occur as interbeds, breaking the continuity of the thick salt section. However, a higher water level during the flood periods resulted in the depositional extension of the penesaline beds beyond the wedge-edge of the Paradox salt, where they lie in contact with each other and with the lower Paradox penesaline strata below and the upper Paradox penesaline strata above. Outside the salt wedge-edge the hypersaline phases of middle Paradox deposition are represented by diastems in the penesaline strata. The Comb monocline area, lying high on the southwest shelf of the Paradox basin, exibits lithofacies gradations of this type, resulting from cyclic, eustatic changes of water level and salinity, combined with structural deformation along the axis of the monocline. Structural growth caused the vicinity of Comb monocline to remain above or near the surface of the shallow Paradox sea throughout middle Paradox time, with the exception of the periodic intervals

of flooding. During the flood intervals the low-lying area near the monocline was submerged, and the shoal area it formed was blanketed with deposits of penesaline evaporites and black shale.

Specific Statement

Figure 7 (isopachous map of the middle Paradox member), and figures 10 through 13 (lithologic-stratigraphic cross-sections) illustrate the thickness, lithology, and distribution of the middle Paradox member within the area of this report. The more notable features of the member in this area are:

1. The abrupt thinning of the member as it abutts the east limb of Comb monocline, and the wedgeout of the salt deposits immediately adjacent to this limb of the fold.
2. The thinness of the member over the fold and in the southwest corner of the area, and the absence of hypersaline deposits in the member in these vicinities.
3. The thickening of the member and the presence in the member of hypersaline anhydrite and salt deposits in the area of the middle Paradox sag west of the fold.
4. The continuation over the fold of the penesaline gypsum, dolomite, and euxinic black shale strata which occur at cyclic intervals in the salt facies off the flanks of the structure.
5. The indicated probable position of the middle Paradox salt wedge-edge (Fig. 7), paralleling the Comb structure immediately east of the axis, encircling the northerly terminus of the fold, and defining the configuration

of a "re-entrant" embayment over the area of middle Paradox sagging west of the ancestral Comb structure.

These patterns clearly indicate that during middle Paradox time the ancestral Comb monocline structure stood in low relief and acted as an effective, low-lying, peninsular barrier, disrupting the continuity of the southwest Paradox shelf. The main body of the Paradox seaway lay to the north and east of the salient ridge. A shallow embayment of the sea flanked the west side of the low peninsula, extending from the northerly terminus of the Comb fold, southward to the marine limits of the basin shelf. During times of salt deposition, the intertidal zone of the Paradox beach in this area probably followed closely the position of the salt wedge-edge indicated in figure 7. During times of flooding and freshening of the Paradox sea, the peninsular salient formed by the Comb structure appeared as a low submarine shoal area between the local westerly sag and the main part of the Paradox seaway. As a shoal area, the vicinity of the fold recieved thin deposits of penesaline strata and black shale. The presence of this shoal area apparently exerted some control on the types, as well as distribution, of sedimentation during the penesaline stages of deposition. Figures 10 through 13 (lithologic-stratigraphic cross-sections) show that the character of the carbonate lentils in the middle and upper Paradox members differs on the east and west sides of Comb monocline. In the tests drilled on the west side of the structure the carbonate strata penetrated consist of evaporitic dolomite and dolomitic gypsum, with only a few minor lentils of limestone and dolomitic limestone. On the east side of the fold the carbonate rocks of the upper and middle Paradox members

of a "re-entrant" embayment over the area of middle Paradox occupying most of the ancestral Dome structure.

These patterns clearly indicate that during middle Paradox time the ancestral Dome anticline structure stood in low relief and acted as an extensive, low-lying, peninsular barrier, disrupting the continuity of the northeast Paradox shelf. The main body of the Paradox seaway lay to the north and east of this salient ridge. A shallow extension of the sea flanked the west side of the low peninsula, extending from the northerly terminus of the Dome fold, southward to the marine limits of the basin shelf. During times of salt deposition, the inter-tidal zone of the flanks or beach in this area probably followed closely the position of the salt wedge-edge indicated in figure 7. During times of flooding and freshening of the Paradox sea, the peninsular salient formed by the Dome structure appeared as a low submarine shoal area between the local westerly sag and the main part of the Paradox seaway. As a shoal area, the vicinity of the fold received thin deposits of penesaline strata and black shale. The presence of this shoal area apparently exerted some control on the types, as well as distribution, of sedimentation during the penesaline stages of deposition. Figures 10 through 13 (lithologic-correlation cross-sections) show that the character of the carbonate lenses in the middle and upper Paradox members differs on the east and west sides of Dome anticline. In the wells drilled on the west side of the structure the carbonate cycles penetrated consist of evaporitic dolomite and dolomitic gypsum, with only a few minor lenses of limestone and dolomitic limestone. On the east side of the fold the carbonate rocks of the upper and middle Paradox members

consist chiefly of thin limestone and dolomitic biostromal limestone lentils. Thus, it appears that the middle Paradox barrier in the vicinity of Comb monocline was actively effecting conditions of carbonate deposition in this area, probably because of restricted local circulation in the evaporating sea causing variations in temperature, salinity, pH concentration, and chemical composition in the surrounding waters. It is probable that the submarine to subaerial barrier caused other, less obvious, differences in deposition between the western embayment and the eastern seaway. Such differences may have been in the times of deposition of various lithologic types on the two sides of the fold, or in undisclosed "micro-" lithofacies variations within single lithologic lentils.

It was noted during this study that there are a few thin siltstone lentils present in the middle Paradox strata on the west side of the area. These clastics illustrate the proximity of the subaerial shelf area to the south and west, and are not indicative of facies gradation caused by the Comb monocline barrier except insofar as it may have limited their local easterly distribution.

CONCLUSIONS

One of the many classic geomorphic expressions of tectonic deformation in southeastern Utah is the impressive east-dipping hogback of Comb ridge. The ridge is the surface expression of a monoclinal fold which began forming at least as early as middle Pennsylvanian time, and possible earlier. Development of this fold was probably controlled by displacement along a west-dipping reverse fault in the basement complex caused by regional compressional forces. Structural growth along the monoclinal axis has been episodic, with periodic rejuvenation in conjunction with regional tectonic activity during Pennsylvanian, Permian and late Cretaceous (Laramide) times. Structural relief of the fold in the vicinity of Fish Creek anticline ranges from about 3000 feet on top of the Triassic Chinle formation, to about 4000 feet on top of the Pennsylvanian Paradox formation, and about 4900 feet on top of the Mississippian Leadville limestone. Evidence from thickness variations, distribution of sediments, and lithofacies gradations indicates that during Pennsylvanian time the ancestral Comb structure was an east-tilted anticlinal fold that formed a sedimentational barrier on the southwest shelf of the Paradox seaway. Later uplift of the Monument upwarp area west of the fold during the late Cretaceous Laramide deformation reversed the original dip of the west limb of the structure and gave the fold its present monoclinal character.

During middle Paradox time the earlier Comb fold formed a stable salient extending northward from the southwest shelf of the basin, and acted as a low peninsular barrier in the

[illegible]

Use of the [illegible]
deformation in [illegible]
aspects of [illegible]
dimensional [illegible]
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also, a [illegible]
caused by [illegible]
since the [illegible]
rejuvenation in [illegible]
during [illegible]
since. [illegible]
Greek [illegible]
Triassic [illegible]
Pennsylvanian [illegible]
of the [illegible]
thickness [illegible]
facies [illegible]
the [illegible]
fold [illegible]
shelf of [illegible]
upward [illegible]
tectonic [illegible]
line of [illegible]
clinal [illegible]

[illegible]
a [illegible]
of the [illegible]

Paradox seaway. The crest of the fold was emergent, or nearly so, during times of advanced evaporation, and no salt was deposited on its crest, although hundreds of feet of salt and anhydrite accumulated off its east and west flanks. During the periodic intervals when the basin was flooded and freshened the low-lying structure was submerged, and received deposits of penesaline evaporites and black shale totaling about 200 feet. Thus, the middle Paradox penesaline strata blanket the structure, but the wedge-edge of the Paradox salt encircles the fold near its northern extremities and does not cross the main body of the monocline.

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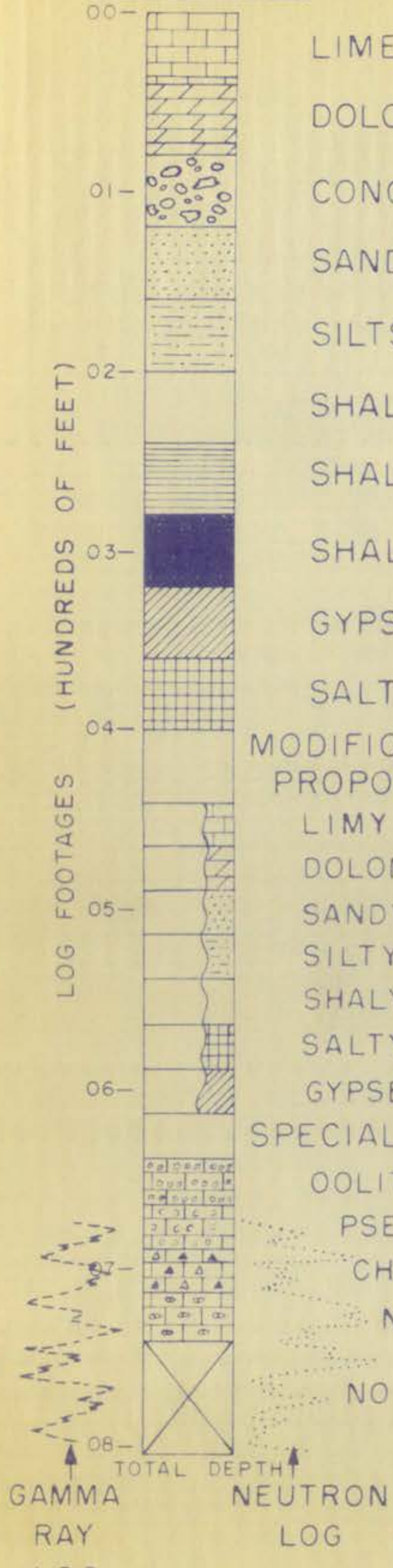
KEY TO GRAPHIC SYMBOLS
OF
LITHOLOGIC-STRATIGRAPHIC CROSS SECTIONS



SYMBOLS — **ROCK TYPES**

LIMESTONE

DOLOMITE

CONGLOMERATE OR BRECCIA

SANDSTONE

SILTSTONE

SHALE (LIGHT)

SHALE (DARK GRAY)

SHALE (BLACK)

GYPSUM OR ANHYDRITE

SALT

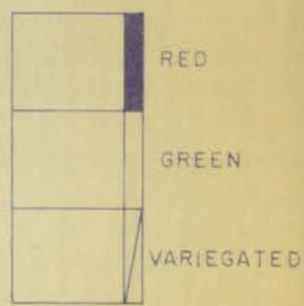
MODIFICATIONS ARE SHOWN IN RELATIVE PROPORTIONS AT RIGHT OF BASIC SYMBOL

- LIMY
- DOLOMITIC
- SANDY
- SILTY
- SHALY
- SALTY
- GYPSEOUS OR ANHYDRITIC

SPECIAL TYPES

- OOLITIC LIMESTONE
- PSEUDO-OOLITIC
- CHERTY (LIGHT & DARK)
- NODULAR
- NO SAMPLE INTERVAL

COLORS



(RADIOACTIVITY LOG TO RIGHT & LEFT OF COLUMN)