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Brett - Int. 33787

UNITED STATES
DEPARTMENT OF THE INTERIOR
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Washington, D. C.

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2. Gross Theoretical Waterpower, Developed and Undeveloped, State of California, by R. N. Doolittle and K. W. Sax. 28 p. 8030 Federal Building, Sacramento, California; 232 Appraisers Building, San Francisco, California, and 1031 Bartlett Building, Los Angeles, California.

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# SUBSURFACE GEOLOGY OF THE UPPER CRETACEOUS KIRTLAND AND FRUITLAND FORMATIONS OF THE SAN JUAN BASIN, NEW MEXICO AND COLORADO



By

James E. Fassett

This report is preliminary and has not been edited or reviewed for conformity with U. S. Geological Survey standards

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# SUBSURFACE GEOLOGY OF THE UPPER CRETACEOUS KIRTLAND AND FRUITLAND FORMATIONS OF THE SAN JUAN BASIN, NEW MEXICO AND COLORADO

By

James E. Fassett

## ABSTRACT

The San Juan Basin is an asymmetrical structural basin in northwestern New Mexico and southwestern Colorado. The basin contains sedimentary rocks ranging from Cambrian through Recent in age and attaining a maximum thickness between 14,000 and 15,000 feet. The Upper Cretaceous sedimentary rocks exceed 8,000 feet in thickness and can be divided into two groups: the lower Upper Cretaceous which is composed of intertonguing marine and non-marine rocks and the upper Upper Cretaceous which is composed of the non-marine Kirtland and Fruitland Formations. The Kirtland Shale is subdivided into the lower shale, Farmington Sandstone, and upper shale members.

The rocks of the Kirtland and Fruitland Formations consist of fluviatile and flood plain deposits and range in thickness from 1750 feet in the northwest part of the basin to 0 feet on the east

side of the basin. The thinning of the Kirtland and Fruitland Formations from west to east is primarily the result of erosion following tilting of the San Juan Basin area toward the west after either part or all of the upper shale member had been deposited. The overlying Ojo Alamo Sandstone rests on progressively older rocks across the basin overstepping the under lying upper shale member, Farmington Sandstone Member, Fruitland Formation, and finally resting on the Lewis Shale on the east side of the basin. The source area for the rocks of the Kirtland and Fruitland Formations was probably to the north or northwest of the San Juan Basin area.

The Kirtland and Fruitland rocks have produced minor amounts of oil and gas. The Fruitland Formation contains large coal deposits some of which are currently being strip mined near Fruitland, New Mexico

# INTRODUCTION

## Purpose and Scope

The purpose of this report is to illustrate and describe the subsurface occurrence of the Upper Cretaceous Fruitland Formation and Kirtland Shale of the San Juan Basin, New Mexico and Colorado as determined from drill hole logs. The Fruitland

Formation has no members. The Kirtland Shale is composed of a lower shale member, the Farmington Sandstone Member, and an upper shale member.

In this study I will discuss some of the earlier work done on the Kirtland and Fruitland Formations and trace the evolution of geologic thought regarding these units to the present time. I will then attempt to relate these earlier, primarily surface studies, to my subsurface findings.

## Location and Extent of Area

The area herein discussed is shown on figure 1 and is essen-

FIGURE 1. - - Index map of the San Juan Basin, New Mexico and Colorado.

tially equivalent to the structural Central San Juan Basin of Kelley (1951). It is bounded structurally on the west, north, and east sides by the Hogback Monocline and on the south side by the Chaco Slope. Geologically, the area is bounded, except for the east side, by the outcrop of the top of the Pictured Cliffs Sandstone (plate I) which except on the southwestern and southern

PLATE I - -Geologic map of the San Juan Basin (in pocket).

rim of the basin is coincidental with the Hogback Monocline. On the east side the geologic boundary is the top of the Lewis Shale.

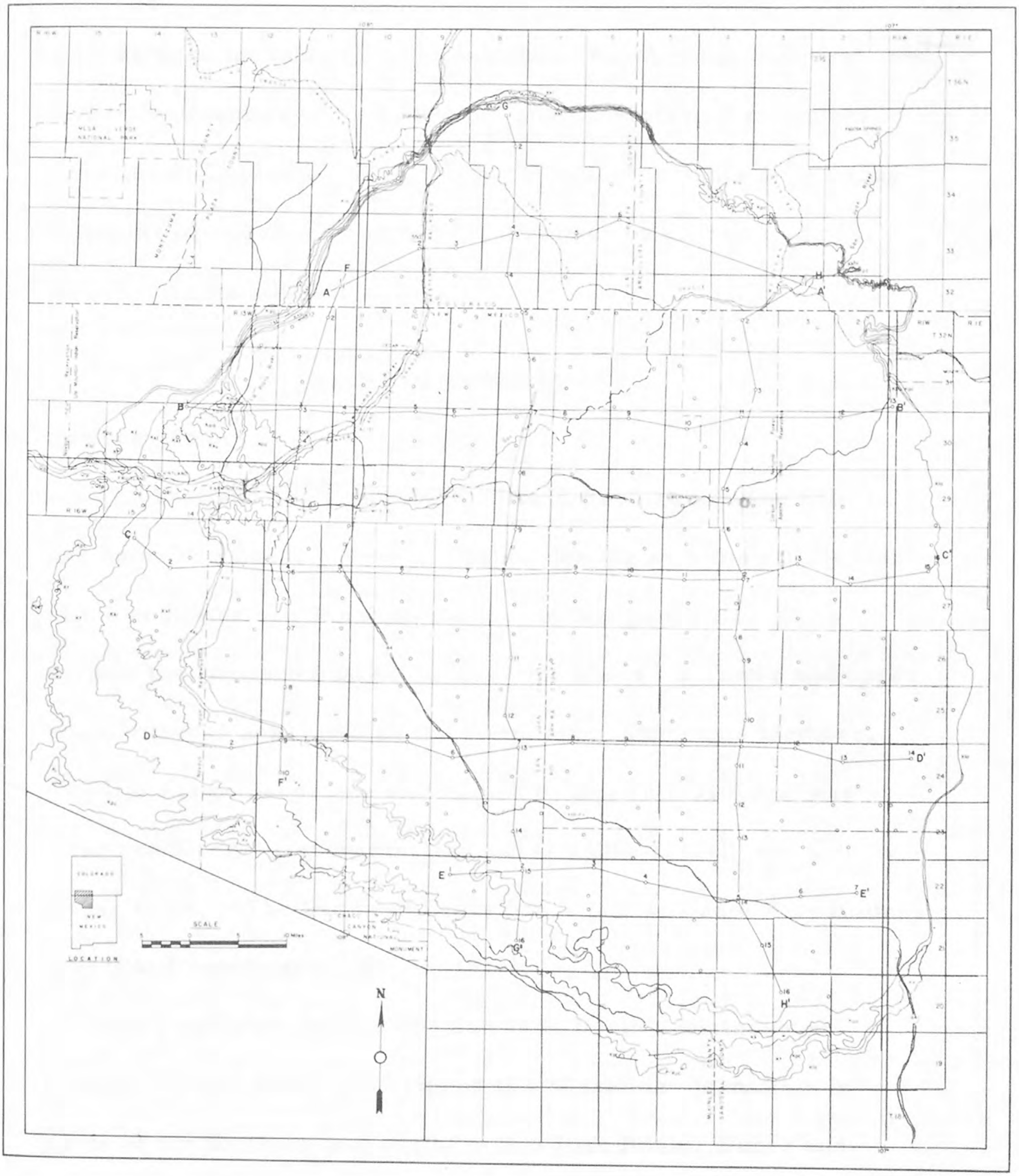


Figure 1 - - Index map showing the location of the San Juan Basin and the lines of cross sections in this report

The area includes parts of San Juan, Rio Arriba, Sandoval, and McKinley Counties of New Mexico, and La Plata and Archuleta Counties of Colorado. It is roughly elliptical in shape with a long diameter of 104 miles and a short diameter of 91 miles and has an area of about 30,000 square miles.

## Previous Work

### Surface geology

The Kirtland Shale and the Fruitland Formation were defined and named by Bauer (1916) in a paper dealing with the stratigraphy of the southwestern San Juan Basin. In this paper Bauer subdivided the Kirtland Shale into three members: a lower and upper shale member separated by the Farmington Sandstone Member. The Ojo Alamo Sandstone was named by Brown (1910) and was later redefined, first by Sinclair and Granger (1914), and then by Bauer (1916). The Pictured Cliffs Sandstone was named by Holmes (1877) and redefined by Bauer (1916).

Other early workers in the San Juan Basin area included Gardner (1906, 1908) who mapped the "Laramie" formation in parts of the northern and southern San Juan Basin, Bauer and Reeside (1921) who described the occurrence of coal in the Fruitland Formation in the west and southwest portion of the basin, Reeside (1924) whose paper on the western part of the San Juan Basin summarized earlier data and offered new conclusions as to the stratigraphic relationships of the rocks comprising the Kirtland and Fruitland Formations and Dane (1936), who mapped an area in the southeastern part of the basin and noted that the Pictured Cliffs and Fruitland Formations are not present in that area. Subsequent to these early works the entire outcrop of the basin has been mapped (plate I).

## Subsurface geology

The first significant subsurface studies of the Kirtland and Fruitland rocks were done by Silver (1950, 1951). In these reports Silver illustrated the subsurface attitude of the Kirtland and Fruitland rocks and speculated on their source and origin. In a later report Silver (1957) modified slightly some of his earlier opinions. Dilworth (1960) wrote a Master's thesis on the subsurface occurrence of the Farmington Sandstone Member of the Kirtland Shale in northeastern San Juan County, New Mexico. Baltz (1962) did a surface and subsurface study of part of the east side of the San Juan Basin in which he disagreed with some earlier findings by Dane regarding the Kirtland and Fruitland rocks there.

Present Work

This report grew out of a study of the coal in the Fruitland Formation of the San Juan Basin which was started by the U. S. Geological Survey in 1961. The Fruitland and Kirtland Shale were studied by the use of well logs, sample descriptions, cores, drilling time records, and at first hand by "sitting" on wells as they drilled through the Kirtland and Fruitland Formations.

This study is based mainly on information obtained from drill hole records. In the course of the study some 1,000 electric logs were examined. Of these 1,000 logs 99 were reproduced on eight geologic cross sections (fig. 1) and over 300 were used as control in constructing two structure contour maps and an isopach map.

Correlation of rock units on the geologic cross sections is based strictly on the interpretation of electric logs. Where practical the cross sections are tied to the surface outcrops. A composite geologic map of the San Juan Basin was compiled from published maps and reports (plateI). Another map showing the areal extent of the units comprising the Kirtland and Fruitland Formations (fig. 2) was constructed.

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FIGURE 2. - - Map showing limits of the Fruitland Formation; the lower shale, Farmington Sandstone, and upper shale members of the Kirtland Shale; and the Ojo Alamo Sandstone.

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The economic aspects of the Kirtland and Fruitland Formations are briefly summarized. A comprehensive study of the coal deposits of the Fruitland Formation was beyond the scope of this report.

## Geography

### Drainage.

The Continental Divide trends generally north on the east side of the San Juan Basin. The streams east of the Divide are in the San Juan River drainage area. The largest river of the San Juan Basin is the San Juan which flows southwest through the Colorado part of the basin and northern New Mexico to the town of Blanco from whence it flows in a westerly course across the rest of the basin (plate I). The Animas River flows south through Durango, Colorado into New Mexico and joins the San Juan River at Farmington, New Mexico. The La Plata River flows southward along the west rim of the basin and joins the San Juan River west of Farmington. In addition to these three perennial streams many intermittent streams drain the San Juan Basin.

### Land forms

The San Juan Basin lies in the Navajo physiographic section (Fenneman and Johnson, 1946) of the Colorado Plateau Province.

The total relief in the basin approaches 3, 000 feet. Elevations range from slightly more than 8, 000 feet in the northern portion of the basin to around 5, 100 feet on the west side where the San Juan River crosses the rim of the basin. The most prominent physiographic feature is Hogback Monocline which rims the basin on three sides and which rises as much as 700 feet above the adjacent country on the west side of the basin. The central part of the basin is essentially a dissected plateau, the surface of which slopes gently to the west. The major streams have cut deeply into the plateau forming deep steep-walled canyons. Between the canyons, on the upland plains, sand dunes are abundant.

Along the San Juan and Animas Rivers several stream terraces can be distinguished. These terraces represent either past episodes of uplift in this region or periods of increased stream flow, probably the latter.

Climate and vegetation

The climate throughout most of the San Juan Basin is arid to semiarid. The rainfall in the basin varies from as low as 3 or 4 inches at the lower altitudes to nearly 20 inches a year at the higher altitudes with an everage annual rainfall of less than 15 inches. Rain is generally rare in summer and more frequent in the fall and winter. The temperature ranges from below 0°F.

in the winter to above 100°F. in the summer. The mean annual temperature at Farmington, New Mexico is 52.6° and the annual range is about 115°. The daily variation in temperature often exceeds 40°.

The native vegetation is of types adapted to semiarid conditions. At the lower altitudes short grass, sagebrush, and many varieties of cactus are common. The mesas of the basin generally support a growth of pinon and juniper with scattered sagebrush and occasional scrub oak. On the higher areas, mostly around the north and east rims of the basin, yellow pine is found. Cottonwood trees grow in the valleys of many of the streams of the basin.

### Access

The three main roads in the San Juan Basin are New Mexico State Highways 44 and 17 and U. S. Highway 550 (plate I). The Denver and Rio Grande Western Railroad has several spurs in the northern part of the basin. In addition, a myriad of oil and gas development roads furnish access to practically every part of the basin.

## GENERAL GEOLOGY

### Geologic Setting

The San Juan Basin is an asymmetrical structural depression containing Cambrian, Devonian, Mississippian, Pennsylvanian, Permian, Triassic, Jurassic, Upper Cretaceous, Tertiary, and Quaternary sedimentary rocks. The maximum total thickness of these rocks exceeds 14,000 feet in the deepest or northern part of the basin.

The Upper Cretaceous rocks of the San Juan Basin can be divided into two major groups: a lower group which includes marine units, and an upper group which does not contain marine units. The dividing line between these two groups is the top of the Pictured Cliffs Sandstone.

## Lower Upper Cretaceous Rocks

The lower group of the Upper Cretaceous rocks in the San Juan Basin consists of regularly interspersed marine and non-marine rocks. The interfingering of these units has been discussed in detail by Pike (1947) and Sears, Hunt, and Hendricks (1941). In general, the history of the lower group consists of two complete episodes of transgression-regression.

The first transgression of the sea from the northeast to the southwest resulted in deposition of the marine Dakota Sandstone which represents beach deposits. Behind the Dakota, the Mancos Shale representing deeper water deposition, was laid down. Next the sea withdrew to the northeast depositing as it did the Point Lookout Sandstone on top of the Mancos concluding the first transgression-regression cycle.

Behind the Point Lookout, the coal-bearing Menefee Formation, representing terrestrial deposits, was laid down. Then the sea again began to transgress depositing as it did the Cliff House Sandstone on top of the Menefee. Behind the Cliff House the Lewis Shale was laid down in deeper waters. Finally, the sea withdrew for the last time depositing the regressive Pictured Cliffs Sandstone on top of the Lewis Shale. The Pictured Cliffs is the last or youngest marine unit found in the San Juan Basin.

The total thickness of rocks comprising the lower group of sedimentary rocks is remarkably consistent, averaging around 4600 feet. This consistency is quite surprising in light of the complex sedimentational history of these rocks.

## Upper Upper Cretaceous Rocks

The upper group of Upper Cretaceous rocks consists of the two terrestrial units discussed in detail in this paper: the Fruitland Formation and the Kirtland Shale. In general, these units are composed of interbedded sandstone, siltstone, shale, and coal and range from 0 to more than 1750 feet in thickness (plate II).

PLATE II - - Isopach map of the Kirtland and Fruitland Formations (in pocket).

## Tertiary and Quaternary Rocks

The Tertiary rocks of the basin consist of the Paleocene(?) Ojo Alamo Sandstone, the Paleocene Animas and Nacimiento Formations, the Eocene San Jose Formation, and Miocene(?) lamprophyre dikes. The Quaternary sediments consist of Pleistocene and Recent terrace gravels and alluvium. These rocks are composed of interbedded sandstone and shale and attain a maximum thickness of more than 3900 feet.

# STRATIGRAPHY

## Pictured Cliffs Sandstone

### Definition

The lower boundary of the Kirtland and Fruitland Formations is the top of the Pictured Cliffs Sandstone. The Pictured Cliffs is a marine sandstone which was deposited as beach and near-shore sands as the Late Cretaceous sea retreated for the last time from the San Juan Basin area.

The Pictured Cliffs Sandstone was named by Holmes (1877, p. 248) for exposures along the north side of the San Juan River west of Fruitland, New Mexico where Indian petroglyphs are abundant. Holmes originally described the Pictured Cliffs as follows:

> Pictured Cliffs, 140 feet - 40 feet of white sandstone; 60 to 80 feet yellowish-gray sandstone; beneath these 30 to 40 feet of brown laminated sandstone.

Reeside (1924, p. 18) revised the original definition of the Pictured Cliffs to include the interbedded sandstones and shales beneath the massive sandstones.

Silver (1950; 1951) published papers on the subsurface occurence of the Pictured Cliffs Sandstone and at that time concluded that the Pictured Cliffs consisted of two separate sandstone lenses: "* * * an older southwestern and a somewhat younger northeatern unit, and that the southwestern unit or lobe is the important gas horizon in the basin". The two lobe theory which Silver proposed was based on rather limited well control and later, after many more wells had been drilled in the San Juan Basin, he stated (1957, p. 136):

> Drilling has revealed that its [Pictured Cliffs Sandstone] stratigraphic rise is more broken than any other regressive unit in the basin; and instead of being divisible into two major units (northeastern and southwestern lobes previously suggested - Silver, 1950) on a basis largely related to outcrop data, the major northeastern and southwestern lobes are in turn composed of a multiple number of stratigraphically-rising lenses separated but

merging into an overall sand horizon.

During the course of this study the writer has found that the description of the occurrence of the Pictured Cliffs Sandstone by Silver in 1957 was quite accurate.

Lithology

The Pictured Cliffs consists of two zones: a lower zone composed of interbedded sandstone and shale, and an upper zone of massive sandstone. The boundary between these two zones is placed at the top of the highest shale in the formation. The sandstone in both the upper and lower zones is fine to medium grained, slightly micaceous, and in places contains flakes of coaly material which gives it a "salt and pepper" appearance.

Contacts

The Pictured Cliffs is conformable with both the underlying Lewis Shale and with the overlying Fruitland Formation. The lower contact is gradational, with shales of the Lewis intertonguing with sandstones in the Pictured Cliffs. The upper contact with the Fruitland is sharper with either coal or shale beds lying directly on the massive sandstone of the Pictured Cliffs Sandstone. Locally, however, the Pictured Cliffs intertongues with the overlying Fruitland.

Extent and thickness

The Pictured Cliffs crops out above the Lewis Shale around the north, west, and south sides of the San Juan Basin and according to Dane (1936; 1946), the Pictured Cliffs is not present on the east side of thebasin (plate I). Baltz (1962, p. 46, 47), however, traced "* * * a zone of thin sandstone, siltstone, and interbedded shale believed to be equivalent to the Pictured Cliffs . . . . along the eastern side of the area as far north as sec. 4, T. 25 N., R. 1 E." (Dane (1936) had shown the Pictured Cliffs to be gone in T. 19 N., R. 2 E., N.M.P.M.) On plate III a zone of interbedded sandstone and shale is indicated on wells 15 and 16 below the Ojo Alamo Sandstone. Whether or not this zone is equivalent to the Pictured Cliffs Sandstone as Baltz indicates or represents a samdy zone near the top of the Lewis Shale as Dane suggested is a moot question as far as the writer is concerned.

PLATE III - - Geologic cross section C - C' (in pocket).

The Pictured Cliffs ranges in thickness from 0 feet on the east side of the basin to over 400 feet west of Fruitland, New Mexico and is not found outside of the San Juan Basin.

## Fruitland Formation

Definition

The Fruitland Formation is the youngest unit in the upper, non-marine series of rocks of the Upper Cretaceous of the San Juan Basin. The Fruitland was deposited in fresh and brackish water on the Pictured Cliffs Sandstone as the Late Cretaceous sea retreated to the north-east.

The Fruitland was first recognized as a formation by Bauer (1916). Bauer stated:

> Conformably above the Pictured Cliffs sandstone lie the brackish and fresh water beds of the coalbearing Fruitland formation, and the contact presents the usual characteristics of interfingering beds. The name Fruitland is derived from that of a settlement on San Juan River which lies on the outcrop of this formation. The formation consists of sandstone, shale, and coal. It is very irregularly bedded and the several beds range from sandy shale and shaly or clayey sandstone in all conceivable proportions to rocks that can be definitely called sandstone or shale. The variation in some places is so rapid both laterally and vertically that weathering of the unequally indurated rocks produces pillars, knobs, capped prisms, pyramids, and fantastic shapes of all sorts. This irregularity is most marked in the gray-white sandstone and gray sandy shale, but to some degree it affects also the coal beds. Nevertheless the coal beds, although they are lenticular, are more persistent than the sandstone and shale with which they are interbedded. Large concretions of iron carbonate which weather dark brown or black occur at several horizons. These concretions commonly contain barite, which has veen introduced into them subsequent to the deposition of the strata, and many of them have in this manner been converted by veins of crystallized barite into large septaria. The Fruitland formation is more sandy than the overlying Kirtland shale, into which it merges by a gradational zone containing in many places sandstone lenses that are apparently of fluviatile origin. The thickness of the Fruitland formation

> is fairly constant in this field, ranging from 194 to 292 feet. The fossils of this and the succeeding formations up to the Puerco are listed and discussed in the papers by Messrs. Gilmore, Stanton, and Knowlton already mentioned.

Before Bauer defined the Fruitland it had been included in the Laramie Formation of Holmes (1877). The old Laramie Formation is equivalent to the interval from the base of the Pictured Cliffs to the top of the Ojo Alamo Sandstone (Bauer, 1916, p. 273). This interval is not equivalent to the typical Laramie of the Denver Basin in Colorado. According to Wilmarth (1938, p. 1151):

> The Laramie as mapped by King, Hayden, and other early workers covered large areas in Rocky Mtn. region, and as more detailed geologic work in that region progressed it was found that the name Laramie fm. had been applied to rocks of different origin and of definitely both Upper Cret. and Eo. age, and also to rocks whose age is still questioned. Thus "What is the Laramie fm?" became a burning question among American geologists. In order to retain the name in the literature the U.S. Geol. Survey in 1910 decided to, for the present, restrict Laramie to Denver Basin region, and, after 20 years of disconnected study, it is still thus restricted, while the age of the probably equiv. Lance fm. of Wyo. and other areas to N. and E. long remained undecided, being classified as Tert. (?). The rocks in Carbon Co., Wyo., that were called Laramie by the early workersare now divided into (descending) Ferris fm. (Eo. and Upper Cret.) and Medicine Bow fm. (Upper Cret.). The so-called Laramie of other parts of Wyo.,

of Mont., of the Dakotas, and of NW. Colo. is now divided into Fort Union fm. (Eo.) and Lance fm. (Upper Cret.). The so-called Laramie of SW. Colo. is now divided into (descending) McDermott fm., Kirtland sh., Fruitland fm., and the Pictured Cliffs ss., all Upper Cret.

(The McDermott referred to above is roughly equivalent to the Ojo Alamo Sandstone throughout most of the New Mexico portion of the San Juan Basin.)

Lithology

The Fruitland Formation is composed of interbedded sandstone, siltstone, shale, carbonaceous shale, carbonaceous sandstone and siltstone, very thin limestone stringers, and coal. The thicker coal beds are confined to the lower one-third of the Fruitland throughout most of the basin; however, thick coal beds do occur in the upper half of the Fruitland in various scattered areas.

The three north-south cross sections F-F', G-G', and H-H' (plates IV, V, and VI) show that the Fruitland contains

PLATE IV - - Geologic cross section F-F' (in pocket).
PLATE V - - Geologic cross section G-G' (in pocket).
PLATE VI - - Geologic cross section H-H' (in pocket).

a much higher percentage of sand in the northern part of the basin than in the southern part. The dividing line between high and low sand content is between wells 3 and 4 on sections F-F', between wells 10 and 11 on section G-G', and between wells 7 and 8 on section H-H'.

Contacts

Bauer (1916) stated that the Fruitland Formation was conformable with the underlying Pictured Cliffs Sandstone and with the overlying Kirtland Shale but he was rather vague about exactly where the contacts were.

Reeside (1924, p. 20, 21) studied the Upper Cretaceous and Tertiary formations of the western San Juan Basin and was much more specific about the upper and lower contacts of the Fruitland Formation. Reeside wrote about the lower contact of the Fruitland: "The most convenient plane of division is at the top of the purely marine beds, which also at many locations is practically the base of the lowest coal bed." In regard to the upper contact of the Fruitland, Reeside wrote " Usually the highest of the sandstones has been taken as the top of the Fruitland formation and the overlying softer rocks have been assigned to the Kirtland Shale."

Dane (1936, p. 113) mapped the Fruitland in the Southern San Juan Basin and stated that the upper boundary was arbitrarily drawn "at the top of the stratigraphically highest brown sandstone". In 1953, Barnes suggested that the top of the Fruitland be drawn so as to "* * *include within the Fruitland Formation all thick persistent coal beds and all prominent sandstone beds.

In a subsurface study of the Farmington Sandstone, Dilworth (1960) picked the top of the Fruitland at the highest carbonaceous bed reflected on the electric log. This top is the one used by most of the petroleum geologists of the San Juan Basin.

In this paper I have picked the top of the first thick sandstone below the lowermost coal as the base of the Fruitland or the top of the Pictured Cliffs. The top of the Fruitland is picked at the uppermost carbonaceous response on the electric log (fig. 3). Where the unconformity at the base of the

FIGURE 3. - - Typical well log and generalized geologic section of the Kirtland and Fruitland Formations of the San Juan Basin.

Ojo Alamo Sandstone cuts the Fruitland, the top of the Fruitland is coincidental with the base of the Ojo Alamo.

Dane (1936; 1946) did not recognize a hiatus at the base of the Ojo Alamo on the east side of the San Juan Basin whereas Baltz (1962, p. 85) found "The contact of the undivided Fruitland formation and Kirtland shale with the overlying Ojo Alamo sandstone is unconformable. At all localities where the contact was observed it is erosional". The present study indicates that Baltz is correct and that the Ojo Alamo is not conformable with the underlying Fruitland on the east side of the San Juan Basin (plates III, VI, VII, VIII, IX).

PLATE VII - - Geologic cross section B-B' (in pocket).
PLATE VIII - - Geologic cross section D-D' (in pocket).
PLATE IX - - Geologic cross section E-E' (in pocket).

Extent and thickness

Previous work

The Fruitland Formation crops out on the north, west, and south sides of the San Juan Basin and is absent in the eastern part of the basin, as mapped by Dane (1936). Dane (1936, p.115) wrote that "* * * the Fruitland in the southeastern part of the basin is arbitrarily dropped from the section at Mesa Piedra Lumbre because of the absence of coal beds" (plate I of this report). In a later report Dane (1946) shows the Fruitland pinching out in the northeast part of the basin and states:

> The beds assigned to the Fruitland Formation are believed to grade laterally southward, in the southern part of T. 31 N., R. 1 W., into beds indistinguishable from the Lewis Shale. Carbonaceous clays and sandstones, and shales containing carbonaceous plant fragments and charcoal, however, are present locally in the uppermost part of beds assigned to the Lewis shale and in the lower part of the overlying Animas formation.

Baltz (1962, p. 54-60) in a study of the southeast part of the San Juan Basin disagreed with Dane and stated that:

> * * * detailed examination and mapping of outcrops in the San Pedro Foothills and Northern Hogback belt by the present writer indicate that, throughout this area, the undivided Fruitland formation and Kirtland shale are a persistent lithologic unit which is differentiated easily from the underlying Lewis sections measured in T. 23-24 N., R. 1 W., and T. 24-25 N., R. 1 E., beds which he included at different places in the upper part of the Lewis shale and the Ojo Alamo sandstone, and in the lowest parts of the Nacimiento formation of Tertiary age and the Animas formation of the Cretaceous and Tertiary age are equivalent to the unit mapped by the present writer as the undivided Fruitland formation and Kirtland shale.

The current study substantiates Dane in that the Fruitland is not present on the east side of the San Juan Basin, but it does not substantiate the statement by Dane that the Fruitland disappears due to interfingering with the Lewis Shale.

This study

Geologic cross section C-C' crosses the San Juan Basin in an east-west direction (fig. 1) and illustrates the structural and stratigraphic attitude of the Fruitland Formation and the Kirtland Shale. It shows that the Fruitland maintains a relatively uniform thickness across the western part of the basin to a point between wells 12 and 13. To this point, the thickness of the Fruitland ranges from 230 feet in well 7 to 380 feet in well 3 over a distance of about 75 miles This cross section shows that the variation in thickness is not due to a regular progressive thickening or thinning of the Fruitland, but rather is due to the irregular stratigraphic rise and fall of the top of the Fruitland.

East of a point between wells 12 and 13 the Fruitland thins, over a distance of 14 miles, from a thickness of 264 feet to 0 feet. This rapid thinning is the result, as is shown on plate III, of an unconformity at the base of the Ojo Alamo Sandstone which has cut out the Fruitland Formation some 4 miles short of the Lewis outcrop.

Geologic cross section B-B' (plate VII) crosses the basin in an east-west direction 18 miles north of cross section C-C' (plate III). Cross section B-B' shows a situation similar to that shown on section C-C'; that is, the Fruitland maintains a relatively constant thickness up to a point slightly west of well 11 where the unconformity at the base of the Ojo Alamo starts to cut out the upper part of the Fruitland Formation.

The thickness of the Fruitland in the interval between wells 1 and 11 ranges from 340 feet in well 5 to 520 feet in well 1 over a distance of about 60 miles. Again, as on C-C' this thickening and thinning is the result of an irregular variation of the stratigraphic position of the top of the Fruitland Formation. East from well 11 on cross section B-B' the Fruitland thins from 430 feet at well 11 to 140 feet at well 13 over a distance of about 17 miles due to the unconformity at the base of the Ojo Alamo. Dane (1948), on measured section 20, less than 2 miles from well 13 on B-B', shows the Fruitland to be 125 feet thick.

Geologic cross section D-D' (plate VIII), which crosses the basin in an east-west direction also shows a relative uniformity in the thickness of the Fruitland up to a point between wells 12 and 13. Up to that point the Fruitland varies in thickness from 170 feet in wells 1 and 2 to 320 feet in well 3. Beyond that point eastward to well 14 the Fruitland thins from 200 feet to about 55 feet due to the unconformity at the base of the Ojo Alamo. Geologic cross section E-E' (plate IX) shows only a slight thinning of the Fruitland Formation due to the unconformity.

The Fruitland Formation ranges in thickness from 560 feet in the northwestern part of the San Juan Basin to 0 feet on the east side of the basin. The range in thickness of the Fruitland, exclusive of the areas where its top is unconformable, is from 560 feet in the northwest to 170 feet in the southern part of the basin.

In general, the Fruitland thins stratigraphically from north to south (plates X, XI, XII). Its eastern edge, however, has been beveled off by the unconformity at the base of the Ojo Alamo. Figure 2 and plate II show the limit of the Fruitland Formation. The Pictured Cliffs structure map (plate X) shows

PLATE X - - Pictured Cliffs structure contour map (in pocket).

the present structural position of the base of the Fruitland Formation.

## Age

The fossils of the Fruitland Formation were tabulated by Reeside (1924, p. 21) as follows:

Vertebrates

Dinosauria:
- *Pentaceratops sternbergii* Osborn.
- *Monoclonius*?
- *Carnivorous dinosaur*

Chelonia:
- *Adocus* sp.
- *Aspideretes* sp.
- *Baena nodosa*? Gilmore.

Pisces:
- *Lepisisteus* sp.

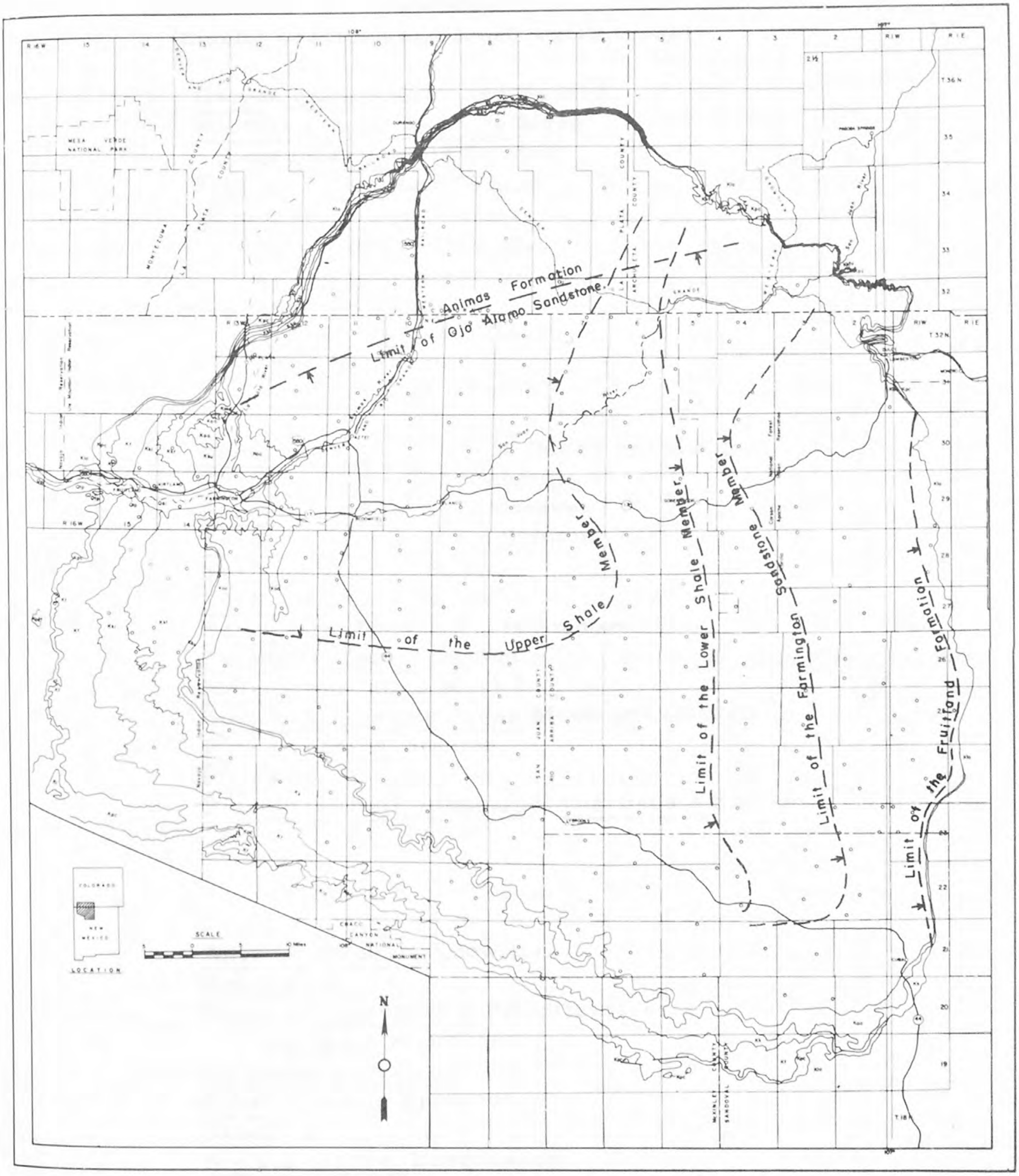



Figure 2 - - Map showing limits of the Fruitland Formation; the lower shale member, Farmington Sandstone Member, and upper shale member of the Kirtland Shale; and the Ojo Alamo Sandstone

Invertebrates
(mostly brackish and fresh water types)

Ostrea glabra Meek and Hayden.
Anomia gryphorhynchus Meek
gryphaeiformis Stanton.
Modiola laticostata (White)
Unio holmesianus White.
amarillensis Stanton.
gardneri Stanton.
reesidei Stanton.
brachyopisthus White.
baueri Stanton.
brimhallensis Stanton.
sp. cf. U. primaevus White.
Corbicula cytheriformis (Meek and Hayden).
Corbula chacoensis Stanton.
Panopea simulatrix Whiteaves?
Teredina neomexicana Stanton.
Neritina baueri Stanton
Neritina (Velatella) sp.
Campeloma amarillensis Stanton.
Tulotoma thompsoni White.
Melania insculpta Meek?
Goniobasis? subtortuosa Meek and Hayden.
Physa reesidei Stanton.
Physa sp.
Planorbis (Bathyomphalus) chacoensis Stanton.

Flora

Anemia hesperis Knowlton.
Anemia sp.
Sequoia reichenbachi (Geinitz) Heer.
obovata? Knowlton.
Geinitzia formosa Heer.
Sabal montana Knowlton.
Sabal? sp.
Myrica torreyi Lesqueseux.
Salix baueri Knowlton.
sp., a Knowlton.
Quercus baueri Knowlton.
Ficus baueri Knowlton.

curta? Knowlton.
praetrinervis Knowlton.
leei Knowlton.
prailatifolia Knowlton.
sp.
rhamoides Knowlton.
squarrosa Knowlton.
sp.
eucalyptifolia? Knowlton.
Laurus baueri Knowlton.
coloradoensis Knowlton.
Nelumbo sp.
Heteranthera cretacea Knowlton.
Pterospermites undulatus Knowlton.
neomexicana Knowlton.
Ribes neomexicana Knowlton.
Carpites baueri Knowlton.
Phyllites petiolatus Knowlton.
neomezicanus Knowlton.
Unassigned plant.

The above fossils indicate that the Fruitland Formation is of late Montana Age.

## Kirtland Shale

The Kirtland Shale is bounded by the Fruitland Formation below and by the Ojo Alamo Sandstone and the Animas Formations above. It is comprised of three members: the lower shale member, the Farmington Sandstone Member, and the upper shale member, in ascending order.

The Kirtland Shale was named and described by Bauer (1916, p. 274) as follows:

> The Kirtland shale lies conformably upon the Fruitland and is predominantly clayey. The

> name is taken from that of a post office on San Juan River. The strata are composed mostly of gray shale, with some brown, bluish, greenish, and yellowish shales, easily weathering gray-white sandstone, and the brown resistant sandstone of the Farmington member described below. Barite occurs in concretions and veins in these strata. The eroded surface of the Kirtland shale presents a billowy appearance, with well-rounded surfaces. It is readily affected by erosion, giving rise to extensive badlands. The shale, so far as known, is of fresh-water origin, although possibly it was formed in deltas and lagoons. It is divided, as shown in the San Juan River section, into three parts - a lower shale 271 feet thick, a sandy part, here named the Farmington sandstone member, and an upper shale 110 feet thick.

Each of the three members of the Kirtland Shale is described in detail below.

Lower shale member

Definition

The lower shale member was named by Bauer in 1916 (see above) but was not clearly described and defined by him at that time. Prior to the naming of the lower shale by Bauer it had been an undifferentiated part of the old Laramie Formation.

Reeside (1924, p. 22) in a later work described the lower shale member in more detail as follows:

> The lower member consists of gray shale with some brown and black carbonaceous lay-

ers and a minor amount of bluish, greenish, and yellow sandy shale and soft easily weathered gray white sandstones, all irregularly bedded.

## Lithology

The lower shale member of the Kirtland Shale is composed predominantly of shale with some interbedded sandstone, siltstone, and carbonaceous material. Geologic cross sections F-F' and G-G' (plates IV and V) show that the lower shale member contains more interbedded sandstone in the northern part of the basin than in the southern part. The type section of the lower shale member as measured for Bauer by Reeside (1924, p. 63) is as follows:

| Lower shale member: | Feet |
|---|---|
| Shale, clayey; light gray on weathered surface, drab on fresh exposure; contains a few thin sandstone layers | 14 |
| Shale, sandy, chocolate-brown, filled with carbonized plant fragments; much gypsum in small crystals present | 4 |
| Sandstone, buff, friable; stained with limonite | 2 |
| Shale, drab, very sandy; a few dark sandstone concretions present | 10 |
| Shale, dark bluish-gray, stained along seams with limonite and containing gypsum on joint planes; plant fragments abundant | 4 |
| Shale, light gray | 11 |

| | |
|---|---|
| Shale, somewhat sandy, black to dark brown, filled with cumminuted plant fragments | 2 |
| Shale, sandy, micaceous, light gray on weathered surface, mottled drab and brown on fresh surfaces | 13 |
| Sandstone, shaly, yellowish, soft; contains large crystals of gypsum and scattered lignitic material; large concretions of platy dark-brown sandstone | 10 |
| Shale, light gray | 20 |
| Shale, black, carbonaceous | 1/2 |
| Shale, dark gray | 18 |
| Shale, dark brown, carbonaceous | 1/2 |
| Shale, light gray on weathered surface, drab on fresh surface | 23 |
| Shale, yellowish, sandy; perhaps really a soft sandstone; contains much disseminated gypsum and a few thin lenses of dark-green indurated shale | 17 |
| Sandstone, buff, soft, with a line of dark-brown platy concretions at top | 5 |
| Shale, yellowish, very sandy, grading upward into the unit above | 16 |
| Shale, black, carbonaceous, with much gypsum | 1 |
| Shale, gray to yellow, very sandy | 6 |
| Shale, chocolate-colored, with carbonized plant remains | 2 |
| Shale, gray to yellow, sandy | 13 |
| Shale, black, carbonaceous | 1 1/2 |

| | |
|---|---|
| Shale, gray | 5 |
| Shale, brown, carbonaceous, with carbonized vegetable debris | 2 |
| Shale, drab, sandy in part | 35 |
| Shale, black, carbonaceous | 1 |
| Shale, drab, sandy | 34 |
| Total lower shale member | 271 |

Contacts

The lower contact of the lower shale member with the underlying Fruitland Formation has been discussed in detail under theFruitland Formation. The upper contact of the lower shale member with the overlying Farmington Sandstone Member was not clearly defined by Bauer in his definition of the lower shale. However, Bauer implied that the upper contact of the lower shale occurred at some point where the sandstones of the overlying Farmington Sandstone became the dominant lithology and that the contact was conformable.

Dilworth (1960, p. 18) was a little more explicit than any of the earlier workers had been regarding the upper contact of the lower shale member with the Farmington Sandstone and stated that "* * * the top and bottom of the [Farmington] sandstone member are arbitrary due to the lensing nature of the sandstone units."

In the present subsurface study, the top of the lower shale member has been picked at the base of the lowest good sandstone lens of the overlying Farmington Sandstone Member. By the "lowest good sandstone lens" is meant the lowest sandstone lens which appears to be a part of the Farmington Sandstone. (see figure 3).

Extent and thickness

Previous work - - The lower shale member of the Kirtland Shale crops out around the north, west, and south sides of the San Juan Basin but is not present on the east side of the basin (plate 1). Reeside (1924, p. 21) stated that the Kirtland Shale "* * * has been traced around the west side of the San Juan Basin but is overlapped on the north side by the Animas Formation and on the south side by the Ojo Alamo Sandstone. Whether it can be recognized on the east side of the basin the writer cannot say."

Dane (1936) noted that the Kirtland Shale decreased in thickness toward the east side of the San Juan Basin and later (1946, p. 115) stated:

> For these reasons [lack of coal] the Fruitland was not recognized east of T. 19 N., R. 2 W., and the combined unit was map-

> ped as Kirtland Shale. It is this unit that continues northward along the valley of Rio Puerco into T. 21 N., R. 1 W. From there northward, however, the laterally equivalent beds are included in the upper part of the Lewis shale as far north as the southern part of T. 25 N., R. 1 E.

In the northeast part of the basin Dane (1946) did not show the Kirtland Shale to be present on his map or measured sections and stated that the Animas Formation "* * * conformably overlies the Fruitland formation in the northern part of the region."

To date, the lower shale member of the Kirtland Shale has not been studied basin wide. Most past workers have either completely ignored the lower shale or included it undivided with the other two members of the Kirtland.

This study - - This paper is the first comprehensive study of the lower shale member of the Kirtland throughout the San Juan Basin. The extent of the lower shale is shown on figure 2 and on the eight geologic cross sections - plates III through IX and plate XI.

PLATE XI - - Geologic cross section A-A' (in pocket).

The five east-west cross sections, A-A' through E-E' (plates XI, VII, III, VIII, X) show that the lower shale lenses out one-third of the way from the east side of the basin (fig. 2).

On each of these five cross sections the lower shale maintains a rather uniform thickness for some distance across the basin and then suddenly, the lower sandstone beds of the Farmington Sandstone appear so low in the section as to completely take the place of the lower shale. On cross section D-D' (plate VIII) the Fruitland top has moved up in conjunction with the above mentioned lowering of the base of the Farmington Sandstone to replace the lower shale member.

The two north-south cross sections F-F' (plate IV) and G-G' (plate V) show that the lower shale member maintains a fairly uniform thickness with no progressive thickening or thinning across the basin in a north-south direction, varying in thickness from 200 feet in well 5 to 344 feet in well 8 of section F-F', and from 64 feet thick in well 9 to 300 feet thick in well 2 of section G-G'. Cross section F-F' shows the lower shale to be present in well 13 only since the line of section of F-F' is outside the limit of the lower shale (figs. 1 and 2) except at this well.

The maximum thickness of the lower shale is 445 feet in well 2 of section C-C' and well 2 of section D-D'. The minimum thickness of the lower shale is 0 feet along the line shown as the limit of the lower shale on figure 2. Generally speaking, the lower shale thins toward the east side of the basin.

## Age

Reeside (1924) compiled the following list of fossils known to occur in the Kirtland Shale:

Vertebrates

Dinosauria:
- Kritosaurus sp.
- Crested trachodonts
- Carnivorous dinosaurs
- Ceratops sp.
- Armored dinosaur (Scelidosauridae)

Chelonia:
- Baena nodosa Gilmore
  - sp. undetermined
- Neurankylus baueri Gilmore
- Adocus bossi Gilmore
  - kirtlandius Gilmore
- Plastomenus robustus Gilmore
  - sp. undetermined.
- Aspidereted sp.

Crocldilia:
- Crocodylus sp.
- Brachychampsa sp.

Pisces:
- Lepisosteus sp.
- Myledaphus sp.

Invertebrates

Unio Pyramidatoides Whitfield?
- baueri Stanton.
- sp. undetermined.

Viviparus sp.

Flora

Geinitzia formosa Heer

Salix sp.
Ficus praetrinervis? Knowlton.
leei Knowlton.

According to Reeside the above fossils indicate a late Montana Age for the Kirtland Shale. They also indicate a fluviatile origin for the Kirtland.

Farmington Sandstone Member

Definition

The Farmington Sandstone Member of the Kirtland Shale was defined by Bauer (1916, p. 275) and was described as follows:

> The sandstone member forms a prominent bluff on San Juan River, where it is 455 feet thick, but toward the south it is gradually replaced by lenses of shale. On the head of Coal Creek the member disappears as a mappable unit, and farther south it is represented only by isolated sandstone lenses in the Kirtland shale. A study of the sandstone lenses making up the Farmington shows that they are irregular in thickness, cross-bedded, and composed almost invariably of two parts--at the base an easily eroded yellowish sandstone carrying clay pellets of various sizes and in some lenses sandstone pebbles similar to the matrix, as large as 4 inches in diameter, and at the top a markedly resistant brownish sandstone whose upper portion is commonly of a dark chocolate-brown color on the exposed surface and dark gray on the fresh surface. All the lenses in the Farmington sandstone member lie on more or less irregular surfaces of interbedded shale and exhibit the characteristics of channel and flood-plain deposits. An individual lens will usually have a maximum thickness of 20 feet , a lateral extent of 15 or 20 yards, and a length of several hundred yards.

Before Bauer defined the Farmington Sandstone Member it had been an undifferentiated part of the old Laramie formation.

In 1924, Reeside in a study of the Upper Cretaceous and Tertiary rocks of the western San Juan Basin mapped the Farmington Sandstone Member of the Kirtland and wrote:

> The sandstones of the Farmington sandstone member are irregular, cross-bedded, and composed almost invariably of two parts--a lower, soft, easily eroded yellow to white sandstone containing clay pellets and locally sandstone balls of material like the matrix and reaching 4 inches in diameter, and an upper hard sandstone which is fine grained, dark gray on a fresh surface and dark feruginous brown on weathered surfaces. These lenses are of small lateral extent, not reaching more than several hundred yards as a rule, and few of them exceed 20 feet in thickness. The writer has not anywhere found pebbles in the Farmington sandstone. The sandstones of the Farmington member make marked benches where the dip of the beds is low and a ridge where the dip is high.

Since Reeside studied the Farmington Sandstone Member it has been mapped where present around the rim of the San Juan Basin by many different workers.

Dilworth 1960) wrote a Master's thesis, primarily subsurface on the Farmington Sandstone in San Juan County, New Mexico, and therein discussed the characteristics of the Farmington as as displayed on electric logs.

Baltz (1962, p. 62) divided his "undivided Kirtland-Fruitland" formation into three units on the east side of the basin which he has labeled A, B, and C in ascending order. He states that unit A is probably equivalent to part of the Fruitland Formation, unit B is possibly equivalent to "the lower member of the Kirtland Shale and part of the Farmington Sandstone", that "unit C is very similar to beds of the Farmington Sandstone member of the Kirtland shale." Baltz did not map these units separately on the surface on the east side of the basin but mapped them together as "undivided Kirtland-Fruitland."

Lithology

The Farmington Sandstone is composed of a series of sandstone lenses interbedded with shale. The individual lenses of sandstone which make up the Farmington are discontinuous, extending over a distance of a few hundred yards or so. The Farmington contains more sandstone and less shale in the northern part of the basin than in the southern part as is shown on the two north-south geologic cross sections F-F' and G-G'.

The type section of the Farmington was measured by Reeside for Bauer (1924, p. 62) and is reproduced below:

| Farmington sandstone member: | Feet |
|---|---|
| Sandstone, brown, massive, fine grained; contains lenses of grit with fine black chert and clay galls but consists mostly of quartz | 15 |
| Sandstone, friable, buff stained locally by limonite | 16 |
| Shale, drab, sandy, locally carbonaceous | 33 |
| Shale, sandy, salmon-colored | 5 |
| Sandstone, brown, rather coarse, cross-bedded; contains crusts of limonite | 12 |
| Shale, drab, clayey, and light-brown sandy shale, alternating irregularly; contains lenses of friable sandstone and dark-brown sandstone concretions | 98 |
| Sandstone, light brown, coarse, hard; fresh surface gray with fine white specks; much cross-bedded; locally pisolitic | 4 |
| Shale, drab, sandy | 5 |
| Sandstone, light gray, fine grained, friable, with a number of platy brown concretions; small limonitic crusts abundant | 10 |
| Shale, gray, sandy | 8 |
| Sandstone, fine grained, reddish brown on weathered surface, light gray on fresh surface, micaceous, massive resistant; locally contains clay galls and ferruginous concretions; impressions of stems of plants and parallelveined leaves abundant | 4 |
| Shale, light brown, sandy, with some drab streaks | 19 |

| | |
|---|---|
| Sandstone, reddish brown, fine grained, hard with platy concretions of dark-brown sandstone; clay galls numerous; lower part lighter and softer | 5 |
| Shale, olive, sandy | 22 |
| Sandstone, reddish brown, fine grained, massive; fresh surface light gray | 12 |
| Shale, gray and buff, sandy alternating irregularly and inclosing a few thin sandstones; gypsum present locally | 84 |
| Sandstone, reddish brown on weathered surface; mottled brown and white on fresh surface; massive, resistant unit | 35 |
| Shale, gray and buff, sandy, alternating at about 5-foot intervals with thin brown sandstones | 28 |
| Sandstone, yellowish, coarse, friable | 19 |
| Shale, gray, sandy | 16 |
| Sandstone, buff, friable, cross-bedded; dinosaur bone observed | 9 |
| Total Farmington sandstone member | 459 |

## Contacts

The lower contact of the Farmington Sandstone Member with the underlying lower shale member has been discussed at some length under the lower shale member. The upper contact of the Farmington Sandstone is similar to the lower contact in that in the past it has never been clearly defined in the literature. It would seem, however, that the upper contact has usually been picked at the top of the highest good sandstone of the Farmington. In all probability, every worker who has mapped the Farmington in the past has made his own interpretation of which sandstone should be picked as the top of the Farmington.

In this study, the top of the Farmington has been picked as the highest sandstone response on the electric log which can be logically (and often subjectively, admittedly) taken to be associated with the main body of the Farmington Sandstone Member. Figure 3 shows typical Farmington Sandstone on an electric log.

On geologic cross section B-B' (plate VII) the Farmington Sandstone, as interpreted from electric well logs, correlates well with the mapped surface outcrop of the Farmington at the west end ofthe section between wells 1 and 2. However, on cross sections C-C' (plate III) and D-D' (plate VIII) the subsurface interpretation of the Farmington contacts seems to be quite different from the contacts mapped at the surface.

On section C-C' the upper, surface contact of the Farmington near well 3 is considerably higher than the Farmington top as picked in the subsurface. On section D-D' the lower contact of the Farmington mapped on the surface is much higher than the lower contact as interpreted in the sub-surface. These variations in the position of the upper and lower contacts of the Farmington Sandstone are the result of the difficulty in determining which of the Kirtland sandstone lenses should be included in the Farmington Sandstone and which should not.

The upper contact of the Farmington Sandstone coincides with the base of the Ojo Alamo Sandstone on the east side of the basin where the unconformity at the base of the Ojo has cut out the intervening upper shale member.

Extent and Thickness

Previous work - - Bauer (1916, p. 275) stated that the Farmington Sandstone was 455 feet thick on the San Juan River (on the west side of the basin) and that it disappeared as a mappable unit at the head of Coal Creek. Bauer and Reeside (1921, p. 172) further added that south of where the Farmington disappeared it was "* * * represented only by isolated sandstone lenses in the Kirtland Shale".

Bauer and Reeside mapped the Fruitland outcrop in the west and southwest part of the basin in 1921 but they did not map the Farmington as a separate unit. Dane (1936) mapped the southern part of the basin but did not map the Farmington separate from the rest of the Kirtland Shale.

Later workers mapped the Farmington Sandstone around the northwest and northern parts of the basin; however, the Farmington was not mapped as a separate unit in the north-east part of the basin.

Dilworth (1960.p. 57) wrote "The Farmington Sand-stone Member of the Kirtland Shale thins northward, south-ward, and southeastward from Townships 30-31 North, Ranges 9-13 West, San Juan County, New Mexico." He also stated that in the area of his report the Farmington ranged from 27 to 818 feet thick.

Baltz (1962) mapped the "undivided Kirtland-Fruitland" in the southeast part of the San Juan Basin and stated that his "unit C" of this interval was probably equivalent to the Farm-ington Sandstone Member of the Kirtland Shale. He stated that "unit C" ranged from 0 to 120 feet thick and that it had been truncated by the erosion surface at the base of the Ojo Alamo and thus did not crop out on the east side of the basin.

<u>This study</u> - - The Farmington Sandstone Member crops out on the north, west, and south sides of the San Juan Basin and probably crops out in the southeastern and northeastern

parts even though it has not been mapped in these areas. The Farmington does not crop out on the east side of the basin (plate I).

Figure 3, shows the limit of the Farmington Sandstone Member along the eastern side of the basin. The Farmington is not present to the east due to truncation by the unconformity at the base of the Ojo Alamo Sandstone. Geologic cross section A-A' (plate XI) shows the Farmington decreases in thickness from 820 feet in well 6 to 90 feet in well 7 due to the unconformity at the base of the Ojo Alamo.

Geologic cross section B-B' (plate VII) shows the entire Farmington Member cut out by the unconformity between wells 8 and 11. The top of the Farmington has been eroded on the east side of the basin as shown on geologic cross section C-C' (plate III) and is completely gone at a point between wells 12 and 13. Cross section D-D' (plate VIII) also shows the unconformity truncating the Farmington at all points with the Farmington disappearing between wells 12 and 13. Cross section E-E' (plate IX) shows an erosional contact at the top of the Farmington with the last of the Farmington disappearing between wells 6 and 7.

The two north-south cross sections F-F' (plate IV) and G-G' (plate V) show the Farmington Sandstone Member thinning toward the south; from 480 feet in well 1 to 290 feet in well 9 of section F-F' and from 575 feet in well 1 to 210 feet in well 10 of section G-G'. Geologic cross section H-H' (plate VI) the line of which is very close to the limit line for the Farmington (fig. 3), shows only remnants of the Farmington Sandstone still remaining.

The Farmington Sandstone Member of the Kirtland Shale ranges in thickness from a maximum of 815 feet in well 6 of cross section A-A' (plate XI) to 0 feet along the Farmington limit line shown on figure 3. The minimum thickness of the Farmington, excluding the areas where the Farmington top has been truncated by erosion, is 190 feet in well 7 of cross section C-C' (plate III). As is clearly shown on cross section G-G' (plate V) the Farmington progressively thins toward the south due to lack of deposition. The Farmington thins toward the east due to the unconformity at the base of the Ojo Alamo Sandstone.

Age

The Farmington Sandstone has given up few fossils; however, Reeside (1924, p. 23) lists the following plant species from the Farmington:

> Ficus curta Knowlton.
> Phyllites petiolatus Knowlton.
> Several undescribed leaves.

Dilworth (1960, p. 25) collected the following fossils from the Farmington Sandstone southwest of the town of Farmington:

> Bathysiphon sp.
> Haplophragmoides sp.
> Ostracoda (fragments)

According to Dilworth these fossils indicate a marine origin for the Farmington Sandstone and he states:

> These fossils were found in a grayish- buff, micaceous, silty, shale unit somewhat near the center of the Farmington Sandstone Member. All of these fossils have been replaced by iron compounds and are of too poor quality to photograph. It cannot be said with certainty that these foraminifera do not represent a reworked fauna; however, it will be assumed in this paper that these microfossils were in place.

Dilworth further wrote:

> Several collections of fossils have veen made in the Kirtland shale, and at least six of these collections were from the Farmington sandstone (Bauer, 1916, pl. LXV). The majority of these collections were made in New Mexico and described by Gilmore, Stanton, Knowlton. According to Reeside (1924, p. 23) all of these fossils indicate a fluviatile origin for the Kirtland shale.

The present writer feels that the evidence for a fluviatile origin for the Farmington Sandstone far outweighs the evidence which might indicate that the Farmington is marine in origin. The three poorly preserved micro-fossils, which Dilworth conceeds might be reworked, are not, in the present writer's opinion conclusive evidence that the Farmington is marine in origin as Dilworth suggests.

According to Reeside (1924) the fossils of the Farmington indicate a late Montana age for the Farmington Sandstone.

Upper shale member

Definition

The upper shale member of the Kirtland Shale was named by Bauer (1916, p. 275) who stated:

> The upper part of the Kirtland Shale is remarkably uniform in thickness from San Juan River to the southern limit of the area ranging from 40 to 110 feet. It is composed of shale and lenses of easily weathered gray-white sandstone, and is thus very similar to the lower part. It is banded in many places with various colors, such as appear in the lower part of the Kirtland, but yellow blue-gray, and purplish beds are more common.

Before Bauer defined the upper shale member, it had been an undifferentiated part of the old Laramie formation.

Lithology

The upper shale member of the Kirtland Shale is lithologically very similar to the lower shale member and like it is composed predominantly of shale with minor interbeds of sandstone, siltstone, and carbonaceous material. Geologic cross sections F-F' and G-G' (plates IV and V) show that the upper shale member is sandier in the northern part of the San Juan Basin than it is in the southern part. The type section of the upper shale member as measured for Bauer by Reeside (1924, p. 63) is reproduced below:

| Upper shale member | Feet |
|---|---|
| Shale, yellowish sandy, stained with limonite in irregular patches, and gray to drab shale, with platy dark brown concretions 1 foot or less in diameter, alternating irregularly; dinosaur bone from horizon near top of unit | 80 |

Contacts

The lower contact of the upper shale member of the Kirtland Shale with the underlying Farmington Sandstone Member has been discussed at length under the Farmington Sandstone Member. The upper shale member makes contact with two overlying formations in the San Juan Basin : the Ojo Alamo Sandstone and the Animas Formation.

The upper contact of the upper shale with these two units is discussed in detail under the respective formation headings below.

Extent and thickness

Previous work - - According to earlier workers, the upper shale member crops out around the north and west sides of the San Juan Basin (plate I), and was not mapped separately around the northeast and southern parts of the basin.

Bauer (1916, p. 275) stated that the upper shale "* * * is remarkably uniform in thickness from San Juan River to the southern limit of the area ranging from 40 to 110 feet." Reeside (1924, plate II) shows the occurence of the upper shale member on columnar sections around the north, west and south sides of the basin. These sections show the upper shale being truncated by an unconformity at thebase of the Ojo Alamo at Escavada Wash in the southern San Juan Basin and by an unconformity at the base of the Animas Formation at the Los Pinos Piedra River divide in the northern part of the basin. Reeside also shows that the upper shale ranges from 0 feet to a maximum of 475 feet in thickness around the north, west, and south sides of the basin.

Beaumont and O'Sullivan (1955) mapped the upper shale member on the west side of the San Juan Basin as far south as T. 25 N., R. 13 W., N.M.P.M. The upper shale member has been mapped around the northwest and northern parts of the basin by various other workers.

This study - - This study shows the upper shale member of the Kirtland Shale to be much more limited than had earlier been supposed. Figure 3 shows the limit of the upper shale member. As can be seen, the upper shale is present over only about one-third of the San Juan Basin. The limit of the upper shale shown on figure 3 in the northern part of the basin agrees well with the limit shown by Reeside (1924, plate II). The limit of the upper shale in the southern part of the basin, however, as shown by Reeside and other earlier workers does not coincide with the limit shown on figure 3.

Figure 3 shows the limit of the upper shale to be at about the line between T. 26 N. and T. 27 N. on the west side of the basin. Reeside (1916), Beaumont and O'Sullivan (1955), and others have carried the upper shale member some distance south of there. In the writer's opinion, the geologists who thought that they were mapping the upper shale member in the southern part of the basin were, in reality, mapping one or several of the shales in the upper part of the Farmington Sandstone in areas where the uppermost sandstone of the Farmington had been removed by erosion.

For example, cross section G-G' (plate V) shows the upper shale to be truncated between wells 10 and 11. If these rocks were exposed at the surface and the contacts were not clearly visible (the contacts are poorly exposed on the west side of the basin) a geologist mapping the area might easily, erroneously correlate the upper shale member as shown in well 10 with upper shales of the Farmington Sandstone member found below the Ojo Alamo in wells 11 or 12.

In all probability the full thickness of the upper shale member is not represented anywhere in the San Juan Basin since the upper contact of the upper shale member appears to be unconformable everywhere. The upper shale reaches a maximum thickness of 450 feet on cross section B-B' (plate VII) in well 3 (this well is number 3 on cross section F-F' (plate IV). The minimum thickness of the upper shale member is 0 feet along the upper shale limit line shown on figure 3. The upper shale thins toward the east and south in the San Juan Basin.

Age

The upper shale member along with the other members of the Kirtland Shale and the Fruitland Formation is fluviatile in origin and is of late Montana Age. The fossils listed previously under the lower shale member are also found in the upper shale member.

Animas Formation

Definition

The Animas Formation overlies the Kirtland Shale in the northern part of the San Juan Basin (see fig. 2). Reeside defined the Animas Formation in his paper on the Upper Cretaceous and Tertiary formations in the San Juan Basin as follows:

> The writer here applies the name Animas to the greenish-gray and tan beds with much andesitic debris that on Animas River in the Ignacio quadrangle, Colo., lie unconformably upon the purple beds assigned to the McDermott formation and unconformably below the Torrejon formation. Andesitic beds on Animas River near Durango, Colo., were described without a specific name in 1892 by Cross, quoting field observations by T.W. Stanton. He described the deposits at greater length in 1896, naming them the "Animas River beds" and including the McDermott formation and part of the Animas formation as here distinguished. A complete section through both the McDermott and Animas formations was measured on Florida

River by Gardner in his work in the Ignacio quadrangle, though both were included under the designation Animas formation.

Lithology

The Animas Formation is composed of interbedded conglomerates, sandstones, and shales and locally contains thin, lenticular, coal beds. Reeside stated that "* * * all these beds are greenish gray to tan and contain much weathered andesitic material." A typical section of the Animas measured by Reeside (1924, p. 55) along Cat Creek north of Pagosa Junction, Colorado follows:

Unconformity

| Animas formation: | Feet |
|---|---|
| Sandstone, greenish gray and green, fine grained, tuffaceous | 30 |
| Shale, greenish gray to tan, tuffaceous | 70 |
| Sandstone, green to tan, fine grained, tuffaceous | 20 |
| Shale, greenish gray to tan, tuffaceous | 70 |
| Sandstone, green to tan, fine grained, tuffaceous; contains plant remains | 10 |
| Shale, greenish gray to tan, with some soft sandstone; tuffaceous | 120 |
| Sandstone, greenish gray, fine grained, tuffaceous; contains plant remains | 10 |

| | |
|---|---|
| Shale, greenish to tan, with some soft sandstone; contains plant fragments | 200 |
| Sandstone, greenish gray, massive, some lenses of fine conglomerate present | 40 |
| Shale, greenish, with some sandstone lenses | 20 |
| Sandstone, fine, greenish, tuffaceous | 15 |
| Shale, greenish gray to tan, tuffaceous | 85 |
| Sandstone, fine grained, greenish gray, tuffaceous, contains plant remains | 10 |
| Shale, greenish gray to tan | 30 |
| Sandstone, fine grained, greenish gray to brown; contains plant remains | 5 |
| Shale, greenish gray | 65 |
| Sandstone, greenish gray, platy, tuffaceous; contains plant remains | 5 |
| Shale, greenish gray to tan, tuffaceous and soft sandstone | 285 |
| Sandstone, greenish gray, tuffaceous | 5 |
| Shale and soft sandstone, tuffaceous, greenish gray | 190 |
| Conglomerate, pebbles, nearly all of greenish weathered andesite; matrix greenish andesitic debris; a few quartz and quartzite pebbles present; prominent ridge-forming unit; plant remains abundant | 75 |

| | |
|---|---|
| Shale and indurated sandstone, interbedded; all tuffaceous, greenish gray; some layers conglomeratic; plant remains abundant | 260 |
| Conglomerate, massive, greenish gray; pebbles of andesite with many of quartz, quartzite, and other rocks | 25 |
| Shale and thin sandstone , greenish gray, not well exposed | 195 |
| Total Animas formation | 1, 840 |

Contacts

Reeside (1924, p. 33) stated that the Animas was unconformable upon the McDermott and that it "* * * overlaps successively the McDermott formation, the Kirtland shale, and part of the Fruitland formation in the region between the Florida River-Pine River divide and Cat Creek, north of Pagosa Junction."

The present study substantiates the above statement by Reeside that successively older formations are overlapped to the east; however, it looks as if the unconformity is at the base of the Ojo Alamo rather than at the base of the Animas (see plates XI and VII). There appears to be little indication of an angular unconformity between the Animas and the underlying Kirtland Shale in the northern San Juan Basin.

Geologic cross section A-A' (plate XI) shows the lower contacts of the underlying formations up to well 6. Between well 6 and well 7 the upper shale member and most of the Farmington Sandstone Member have been overlapped by what looks like typical Ojo Alamo in well 7. It is possible that between wells 6 and 7, the lower Animas contact is unconformable, but there is no well control in the intervening area to substantiate this.

Cross section G-G' (plate V) shows a consistent thickness of the Kirtland and Fruitland rocks from well 1 to well 4; however, south of well 4 a progressive thinning of the Kirtland and Fruitland Formations takes place and angular discordance is indicated. Note that the combined Kirtland and Fruitland on this cross section maintains a uniform thickness where overlain by the Animas Formation but thins where overlain by the Ojo Alamo. It should be kept in mind here that an unconformity can exist without angular discordance.

## Extent

According to Reeside (1924) the Animas is confined to the northern rim of the San Juan Basin. He shows (figure 3, p. 48) the Animas and the Ojo Alamo to be similar in stratigraphic position but not connected or overlapping.

Dane (1948) mapped the Animas as far south as T. 25 N., R. 1 E. and stated that south of that area the Animas graded into the Nacimiento Formation.

In this report the writer has illustrated the extent and attitude of the Animas Formation in the northern part of the San Juan Basin. A determination of the extent of the Animas and its relationship to other units beyond the area in which it overlies the Kirtland Shale is beyond the scope of this report.

Age

Reeside (1924, p. 34) quotes Knowlton as saying of the Animas flora:

> On combining the Animas species found in the Denver, Raton, and Wilcox it appears that 33 species, or over 90 percent of those having an outside distrubution, are held in common and the conclusion is reached that the Animas formation is of the same age namely, Eocene Tertiary.

Reeside (1924) assigned an age of Tertiary(?) to the Animas Formation. Dane (1948) showed the Animas to be of Late Cretaceous and Paleocene Age. Barnes, Baltz, and Hayes (1954) said that the McDermott Member of the Animas Formation was of Late Cretaceous Age while the upper member of the Animas was Late Cretaceous and Paleocene in age.

Hayes and Zapp (1955) said that most Kirtland rocks in their area were Late Cretaceous in age, but they added that due to the lack of fossil evidence "the highest beds mapped as undifferentiated Upper Cretaceous are possibly of early Tertiary (Paleocene) age." O'Sullivan and Beikman (1963) show the Animas Formation (and the Ojo Alamo Sandstone) to be Late Cretaceous in age.

Obviously, the age of the Animas is still controversial. The writer feels that the key to this controversy lies in the area northwest of Farmington, New Mexico where the Animas, Ojo Alamo, and McDermott come together at the surface.

<u>McDermott Member</u>

<u>Definition</u>-- The McDermott Member of the Animas Formation was defined by Reeside (1924, p. 24) as follows:

> The name McDermott formation is here introduced for a series of lenticular sandstones, shales, and conglomerates containing much andesitic debris and usually in part of purple color. The name is derived from McDermott Arroyo, in the Red Mesa quadrangle, southwestern La Plata County, Colo., and the exposures in secs. 18 and 19, T. 32 N., R. 11 W., adjacent to McDermott Arroyo, may be considered typical of the formation. * * *
>
> The formation defined above is the lower part of the unit described by Cross in 1892 from observations made by T. W. Stanton as the "andesitic beds on Animas River" and in 1896 from his own observations as the "Animas River Beds."

> It is the same unit as the Animas formation of Shaler (1907) and Gardner (1909). It forms the basal part of the Animas formation as later conceived by Gardner. It is included in the upper part of the Ojo Alamo beds of Brown (1910), in the uppermost part of the Kirtland shale of Bauer (1916), and in the Ojo Alamo sandstone in part (north of Pinyon Mesa, N. Mex.) and the Kirtland shale in part (south of Pinyon Mesa) of Bauer and Reeside (1921).

Barnes, Baltz, and Hayes (1954) redefined the McDermott as follows:

> Reeside's typical section of the McDermott in the SW/4 NW/4 sec. 19, T. 32 N., R. 11 W. (Reeside, 1924, p. 57) is subdivided in this report as follows: the lowest 95 feet of pebble-bearing sandstone and sandy shale is part of the Kirtland shale, the overlying 127 feet of purplish beds is the McDermott member of the Animas formation, and the top 106 feet is included in the upper member of the Animas formation. It is thus proposed to reduce the McDermott from the status of a formation to that of a locally present member of the Animas formation. The two units are gradational, and aside from a contrast in color they show no consistent lithologic distinction.

Lithology - - According to Reeside (1924, p. 25):

> At the type locality the McDermott formation consists of an irregular assemblage of brown to yellow soft sandstone; gray-white coarse tuffaceous shale; green to drab coarse conglomerate with matrix almost entirely of andesitic debris and pebbles and cobbles nearly all of weathered andesite; in the upper part of the formation conglomerate with rusty brown matrix and pebbles nearly all of siliceous, resistant rocks, such as quartz, quartzite, and chert. These pebbles are much like those in the Ojo Alamo sandstone described on page 29. Nearly all the finer-

grained parts of the formation contain some volcanic debris, the purple shale particularly. Northward from the type locality the proportion of andesitic material in the formation increases. On Animas River it is composed of fairly pure and little weathered andesitic debris, predominantly purple. Some beds of it are very coarse indeed, masses several feet in diameter being common. East of Animas River notable beds of siliceous pebbles are present in the lower part of the formation, associated with yellow sandstone. Southward from the type locality the proportion of volcanic matter decreases. Beds of purely andesitic debris do not occur west of La Plata River in New Mexico, though sandstone, shale, and conglomerate with a notable amount of andesitic material in them mark the McDermott formation clearly in the region north of San Juan River. At San Juan River the McDermott formation is represented by thin irregular lenses of fine purple and green tuffaceous sandstone, coarse white with clay pellets, and purple and gray shale forming 30 feet of beds just beneath the Ojo Alamo sandstone. South of San Juan River the McDermott formation is a thin assemblage of brown sandstone and grit, gray-white sandstone, and purple and gray shale just beneath the Ojo Alamo sandstone. Except for the purple color of some of the beds this assemblage does not look greatly like the McDermott formation in Colorado. These beds, however, contain detritus from andesites.

The type section of the McDermott "formation" as measured by Reeside (1924, p. 57) at the south side of SW/4 NW/4 sec. 19, T. 32 N., R. 11 W., La Plata Co., Colorado is as follows:

Unconformity

| McDermott formation: | Feet |
|---|---|
| Conglomerate of pebbles of bright-red jasper, red and white quartzite, chert, and rarely andesite; pebbles all chatter-marked and as large as 6 inches in diameter; matrix andestic tuff | 4 |

| | |
|---|---|
| Shale, yellow-brown, sandy | 60 |
| Conglomerate like that above | 2 |
| Shale, purple and yellow, containing volcanic debris | 32 |
| Conglomerate, drab to green, composed of andesite pebbles, cobbles, and boulders as much as 1 foot in diameter and a sprinkling of small jasper, quartzite, and quartz pebbles; matrix andesitic tuff. Unit irregular along strike. Dinosaur and turtle bones in place | 8 |
| Shale, drab to purple, containing volcanic debris | 40 |
| Sandstone, light gray to white, containing pebbles of andesite and andesite debris | 20 |
| Sandstone, fine, soft, yellow-brown, capped by hard, thin platy greenish sandstone; loose fragments of dinosaur bone scattered on surface | 15 |
| Shale, purple, containing volcanic debris | 10 |
| Sandstone, gray-white, coarse | 2 |
| Shale, variegated, purple and blue-gray, containing volcanic debris | 40 |
| Concealed mostly but apparently occupied by sandy yellow-brown shale | 85 |
| Sandstone, gray-white, coarse, poorly exposed. Contains lenses of coarse grit and some small quartz and chert pebbles and also fossil logs | 10 |
| | 328 |

Contacts - - Reeside (1924) stated that the lower contact of the McDermott was conformable with the underlying Kirtland Shale but that is was unconformable with the overlying Animas Formation to the north and with the overlying Ojo Alamo to the South. Later workers have stated that they could find little evidence, of an unconformity between the McDermott and the overlying Animas Formation.

The writer has not attempted to show the subsurface attitude and extent of the McDermott since it cannot be reliably interpreted on electric logs.

Extent and thickness - - Reeside (1924, p. 24) stated, in speaking of the extent of the McDermott:

> The McDermott formation may be traced from the type locality northeastward to the divide between Florida and Pine Rivers, except in Bridge Timber Mountain, where it is covered by overlap of later beds. Farther east it was removed by erosion before the deposition of the Animas formation. Southward from the type locality the formation may be traced to a locality some miles beyond Ojo Alamo, N. Mexico. Beyond this place it seems to have been eroded away during the interval preceding the deposition of the Ojo Alamo sandstone. The outcrop, therefore, extends virtually around the western half of the San Juan Basin.

Beaumont and O'Sullivan (1955) mapped the west side of the San Juan Basin south of the San Juan River, but did not show the McDermott to be present there. Barnes, Baltz, and Hayes (1954) mapped the McDermott in the northwest part of the San Juan Basin as the lowermost member of the Animas Formation. Zapp (1949) mapped the McDermott as a formation around the northern rim of the San Juan Basin to a point about 9 miles east of Durango, Colorado.

Age--Reeside (1924, p. 27) said that "* * * indeterminable bones of dinosaurs, fragments of turtle bone, and fossil wood" have been collected near the type locality of the McDermott Formation. He further states:

> The paleontologic evidence as to age is therefore somewhat conflicting, though more favorable to an association of the McDermott formation with the underlying beds than with later deposits. The McDermott formation is continuous between the Colorado area and the New Mexico area and is everywhere terminated by an erosion surface. The base, on the contrary is a much less definite plane of separation. It seems to the writer, therefore, that the McDermott formation has much closer relations to the underlying than the overlying beds and that it should be placed in the Cretaceous. However, in view of the doubt that exists regarding its age this assignment is made with question in this paper.

Barnes, Baltz, and Hayes (1954) have assigned a Late Cretaceous Age to the entire Animas Formation including the McDermott Member.

Ojo Alamo Sandstone

Definition

The Ojo Alamo Sandstone overlies the Kirtland Shale and Fruitland Formations unconformably throughout most of the New Mexico part and a portion of the Colorado part of the San Juan Basin. It was named by Brown (1910) and described by him as follows:

> Less than a mile south of the store at Ojo Alamo the Puerco formation rests unconformably on a conglomerate that is composed of red, gray, yellow, and white pebbles. * * * Below the conglomerate there is a series of shales and sandstones, evenly stratified and usually horizontal * * * The shales below the conglomerate that contain numerous dinosaur and turtle remains I shall designate the Ojo Alamo beds. They were estimated to be about 200 feet thick, but owing to lack of time I was unable to determine their relation to the underlying formation.

Sinclair and Granger (1914) examined the Ojo Alamo at a later date and according to Reeside (1924, p. 28):

> Later Sinclair and Granger found that the same locality as referred to by Brown above there were two conglomerates enclosing between them a shale with reptilian remains resembling those in the shale beneath the conglomerate. They considered the lower conglomerate to split the original shale of Brown into two parts, the upper enclosed between the lower conglomerate and a higher conglomeratic sandstone and the lower extending downward for an unknown but considerable thickness. They applied the name Ojo Alamo to the whole mass of sandstones, conglomerates, and shales. Bauer showed that the lower conglomeratic sandstone of Sinclair and Granger when traced laterally became continuous with the upper by the pinching out of the included shale member and proposed to restrict the name Ojo Alamo to these

conglomeratic beds and the shale between them insamuch as the trading post Ojo Alamo is situated on them and to use the name Kirtland for the lower shale

Reeside further stated:

> The Ojo Alamo sandstone may be defined as a conglomeratic sandstone containing one or more lenses of variegated shale and soft sandstone bounded below by an unconformable contact with the McDermott formation and above at the type locality by an unconformable contact with the Puerco formation.

Lithology

The Ojo Alamo Sandstone consists of conglomeratic sandstone beds separated by shale interbeds. A measured section from the type locality of the Ojo Alamo from Reeside (1924, p. 68) follows:

| Ojo Alamo sandstone: | Feet |
|---|---|
| Sandstone, brown to yellow, cross-bedded, irregularly indurated; contains silicified logs and scattered pebbles | 33 1/2 |
| Shale, sandy light bluish green | 7 1/2 |
| Shale, blue-gray | 1 |
| Sandstone, white, soft, cross-bedded, contains concretions of brown sandstone 8 to 10 inches in diameter | 16 1/2 |
| Shale, wine-red, with irregular blotches of light-yellow sandy shale | 3 1/2 |

| | |
|---|---|
| Sandstone, white, soft, with concretions of brown sandstone | 6 |
| Shale, blue-gray | 3 |
| Sandstone, white, soft | 5 1/2 |
| Shale, gray, sandy | 2 |
| Conglomerate of siliceous pebbles several inches in diameter; matrix coarse white sand with rust-colored blotches | 8 |
| Total Ojo Alamo | 86 1/2 |

Contacts

Reeside (1924) stated that the base of the Ojo Alamo is unconformable with the underlying McDermott and Kirtland Shale. Dane (1936) in a paper dealing with the southern San Juan Basin stated that he could find no evidence of extensive erosion at the base of the Ojo Alamo. Baltz (1960, p. 100) stated that the Ojo Alamo was unconformable throughout the area he studied. He states "* * *The combined thickness of the Fruitland formation and Kirtland shale on the western side of the Central Basin near Farmington is more than 1,600 feet; thus it is possible that asmuch as 1,400 feet of Fruitland and Kirtland rocks was eroded from the eastern part of the basin prior to deposition of the Ojo Alamo."

The present study indicates that Reeside and Baltz are correct about the lower contact of the Ojo Alamo; indeed, it would seem that the estimate by Baltz that "as much as 1,400 feet of Fruitland and Kirtland rocks was eroded" prior to deposition of the Ojo Alamo is conservative and that in all probability more than 1,750 feet of "Fruitland and Kirtland" is missing on the east side of the San Juan Basin.

All of the Geologic Cross Sections included with this report strongly indicate that an unconformity is present at the base of the Ojo Alamo Sandstone at every point within the San Juan Basin where the Ojo Alamo occurs.

Extent

Previous work - -Previous studies of the Ojo Alamo Sandstone in the San Juan Basin show that it is present on only the south and west sides of the Basin. Dane (1946) stated:

> The Ojo Alamo thins northward with a probable decrease in size and abundance of pebbles, and similarly thins westward from T. 21 N., R. 1 W., with an accompanying decrease in pebble size. Although much diminished in thickness, the Ojo Alamo has been traced northward with some assurance to T. 24 N., R. 1 W., but it is only doubtfully identified in Tps. 24 and 25 N., R. 1 E.

Baltz (1960) was able to trace the outcrop of the Ojo Alamo almost continuously throughout the area of his report (as far north as sec. 6, T. 26 N., R. 1 E.). The Ojo Alamo has not been mapped on the surface north of the area mapped by Baltz.

This study--In this study, the writer has traced the Ojo Alamo Sandstone in the subsurface throughout the San Juan Basin up to a line which lies just slightly north of the New Mexico-Colorado line in the eastern part of the basin and just slightly south of the state line in the western part of the basin (fig. 2). South of this line the Ojo Alamo overlies the Kirtland Shale, while north of this line the Animas Formation overlies the Kirtland.

The northermost occurrence in the subsurface of a good recognizable Ojo Alamo Sandstone is shown in well 7 of cross section A-A' (plate XI) (well 1 of cross section H-H plate VI). Earlier workers have included the Ojo Alamo Sandstone of the northern part of the San Juan Basin in the overlying Animas Formation. The writer feels that the Ojo Alamo is a distinct recognizable unit in the subsurface throughout much of the northern part of the basin. Cross section H-H', the trace of which runs north-south along the east side of the San Juan Basin (fig. 1, plate VI), shows the continuity of the Ojo Alamo Sandstone into the northern part of the basin.

In the subsurface, the transition from the Ojo Alamo to the Animas appears to take place over a narrow band along the line shown of figure 2. In the transition zone the good, massive, distinct Ojo Alamo is replaced laterally by a zone of interbedded sandstones and shales which represent the basal Animas Formation (see cross sections F-F', G-G', and A-A' plates IV, V, and XI).

Age

Reeside (1924, p. 32) discussed the age of the Ojo Alamo and stated that "The known flora suggests Tertiary rather than Montana age. . ." and concludes that the Ojo Alamo should be classified as Tertiary (?) Dane (1936, p. 121) stated that:

> The paleontologic evidence tends very strongly to support the view that there is no hiatus between the Ojo Alamo sandstone and the underlying Kirtland shale and that the Ojo Alamo sandstone should be classified as Cretaceous.

Baltz (1960, p. 108) discussed the Ojo Alamo at great length in his report on the southeast part of the San Juan Basin and concluded:

> To summarize, the rocks mapped as Ojo Alamo sandstone in the present area rest with slight angular and erosional unconformity on older rocks, and probably correlate with the upper sandstone of the Ojo Alamo at the type locality. This sandstone rests with erosional disconformity on dinosaur-bearing beds, and only plant fossils suggesting Tertiary (?). It should be stated here that the

> contact of the Ojo Alamo and underlying rocks is a physical feature and is not considered to be a time-stratigraphic surface.

The present writer feels that Reeside and Baltz were correct in assigning a Tertiary (?) age to the Ojo Alamo Sandstone; however, more detailed work needs to be done in the northwest part of the basin, north of Farmington, New Mexico, where the Ojo Alamo, the McDermott Member of the Animas Formation, and the Nacimiento Formation come together at the surface to conclusively resolve this problem.

## ELECTRIC LOG INTERPRETATION

### General Remarks

Several kinds of devices are used to determine conditions in and around a borehole. Each kind of device measures some characteristic of the formations penetrated. For example: the electric log measures the resistivity, conductivity, or spontaneous potential of the formation; the radioactivity log measures the natural radioactivity and the induced radioactivity of the formation. Other devices measure the size of the borehole, temperature in the hole, inclination of the hole, etc.

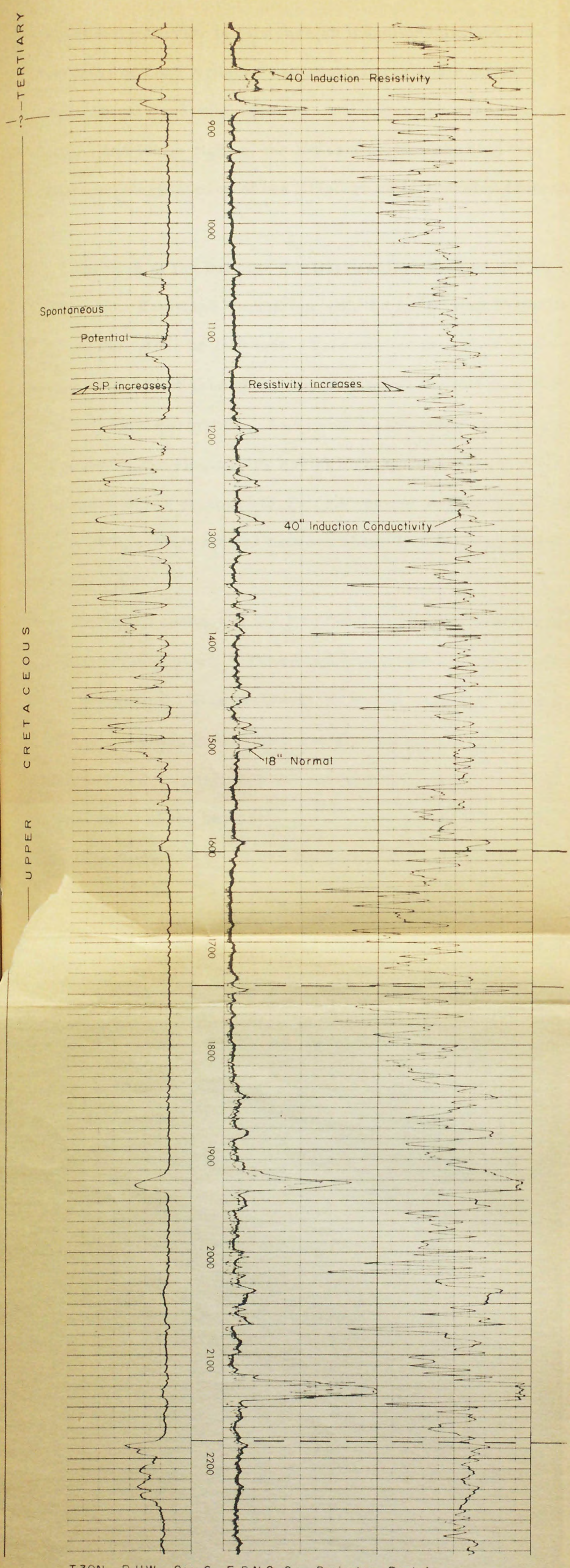
The geologist, in attempting to interpret the subsurface occurrence of rocks with subsurface records must make use of all the logs available to cross check his interpretations. In some areas one kind of log may clearly show the subsurface geologic conditions. In other areas several kinds of logs will not furnish enough information to make reliable interpretation of geologic conditions possible.

The primary limitation in the use of electric logs and other borehole devices in interpreting the subsurface geology of an area is that the log is only a record of a few of the characteristics of the formation. Characteristics such as color, grain size, exact lithology, cross-bedding, nature of contacts in specific areas, and many others cannot be determined from the log. If possible, the geologist should attempt to look at the rocks he is interpreting on the electric logs. In most cases the outcrop of a unit can be studied. In other instances cores and drill cuttings are the only form in which the actual rocks can be studied.

Another limitation inherent in the use of electric logs is that a given rock unit cannot be continuously traced. No matter how close together the wells are (in many areas a minimum distance between wells is set by law) there still remains an area between any two logs where the geologic

## TYPICAL WELL LOG

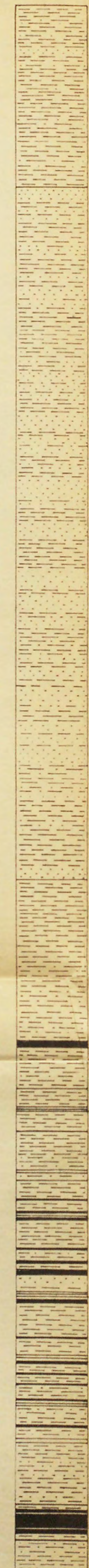
(INDUCTION-ELECTRIC LOG)




T. 30N., R. 11 W., Sec. 6, E. P. N. G. Co., Bruington Pool 4

## GENERALIZED GEOLOGIC SECTION

Column



| Formation | Member | Thickness Range | Lithologic Description (Modified from Reeside, 1924, p. 4-5) |
|---|---|---|---|
| Kirtland Shale | Upper Shale Member | 0'-450' | Light-gray to blue-gray shale with some black carbonaceous and brown shale and soft white sandstone. |
| | Farmington Sandstone Member | 0'-815' | Gray to brown indurated sandstone lenses separated by gray shale. |
| | Lower Shale Member | 0'-450' | Shale and soft sandstone similar to upper member. |
| Fruitland Formation | | 0'-560' | Gray sandy shale, gray-white cross-bedded soft sandstone, brown indurated sandstone, siltstone, carbonaceous shale and sandstone, and coal. |

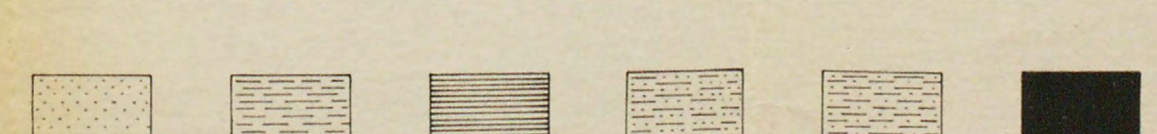



Figure 3 -- Typical well log and generalized geologic section of the Kirtland and Fruitland Formations of the San Juan Basin.

Fruitland interval, in this case an induction-electric log. The contacts of the Fruitland Formation, lower shale member, Farmington Sandstone Member, and upper shale member are shown and to the right of the log is a column showing the writers interpretation of the lithology as interpreted from the log.

Starting at the bottom, the first contact seen on the log is that of the Fruitland Formation with the underlying Pictured Cliffs Sandstone at 2183 feet. This contact is picked at the top of the first good sandstone response below the last coal bed of theFruitland Formation. As is shown, the coals are quite distinctive on the electric log having high resistivity with little or no spontancous potential (S.P.). A zone or series of coal beds with thin partings occurs between about 2120 feet and 2144 feet on the log.

The upper contact of the Fruitland Formation with the lower shale member of the Kirtland Shale is shown at 1742 feet on the log on figure 2. It is picked at the top of the highest carbonaceous response in the Fruitland Formation. This contact is quite erratic in position from log to log and is quite tenuous in some parts of the basin.

The contact of the lower shale member with the overlying

Farmington Sandstone Member is shown at 1611 feet. This contact is placed at the base of the first good sandstone above the lower shale member which can logically be included with the sandstones of the Farmington. The upper contact of the Farmington Sandstone Member with the overlying upper shale member is at 1094 feet on the log. This contact is picked at the top of the last sandstone which is clearly a part of the Farmington Sandstone.

The upper contact of the upper shale member is picked at the base of the overlying Ojo Alamo Sandstone at 893 feet. The lower contact of the Ojo Alamo is almost always quite distinct because of the highly resistive electric log response which occurs at its base. This response probably represents the basal conglomerate of the Ojo Alamo.

The eight geologic cross sections on which electric logs have been reproduced clearly show that every well log has a slightly different character and that a continuous tracing of lithologic units can only be accomplished with a series of relatively closely spaced logs.

## STRUCTURE

The structural elements of the San Juan Basin and surrounding areas are shown on figure 4. The structure of the basin is

FIGURE 4. -- Structural elements of the San Juan Basin. After Kelley (1951, p. 125)

illustrated on plates X and XII which are structure contour maps

PLATE XII - - Kirtland Shale structure contour map (in pocket)

contoured on the top of the Pictured Cliffs Sandstone and on the top of the Kirtland Shale respectively. Both plates show that the San Juan Basin is asymmetrical, trends northwest-southeast, and has a steeply dipping northeast flank and a more gently dipping southwest flank. The eight geologic cross sections herein contained, particularly plates III and V also illustrate the structure of the basin.

The subsurface relief of the basin, based on the top of the Pictured Cliffs Sandstone, is 4,900 feet ranging from 8,000 feet in the northern part of the basin to less than 3,100 feet in the deepest or north central part of the basin (plate X).

## GEOLOGIC HISTORY

The last retreat of the Late Cretaceous sea from the San Juan Basin area was accompanied by deposition of the near shore and beach deposits comprising the Pictured Cliffs Sandstone. According to Pike (1947, figure 7 and p. 97) the shoreline of the sea trended northwest-southeast and the sea retreated

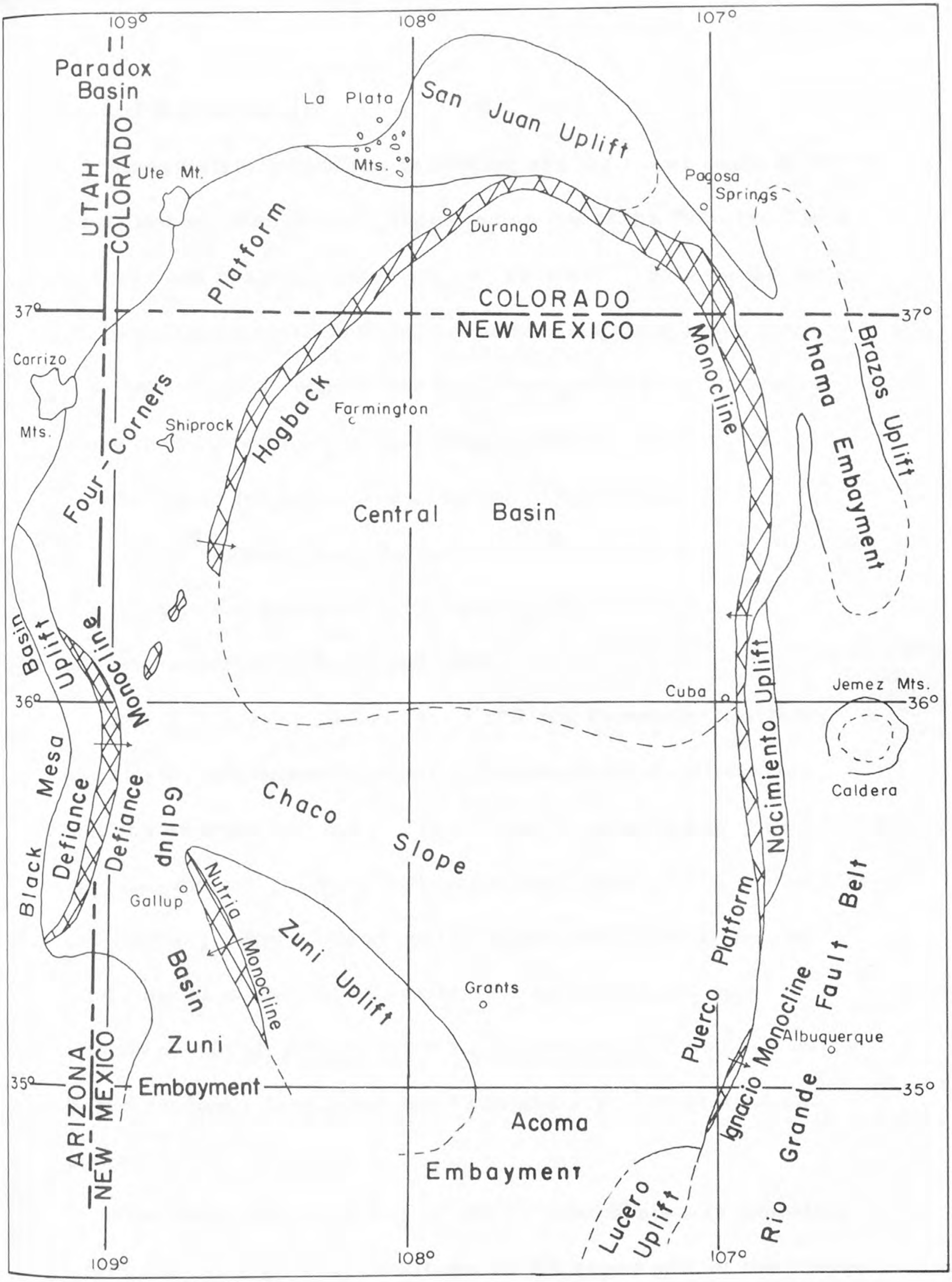



Figure 4 -- Structural elements of the San Juan Basin. After Kelley (1951, p. 125)

toward the northeast.

Immediately behind the retreating sea the lower coals of the Fruitland Formation were deposited on top of the Pictured Cliffs in fresh and brackish water coastal swamps. The swamps were probably fairly small and not interconnected since individual coal beds of the Fruitland are quite lensy and cannot be traced more than a few miles in most areas. Only rarely can a coal bed be traced for a few tens of miles. Occasional brief reversals of the regression of the Late Cretaceous sea took place resulting in the deposition of tongues of the Pictured Cliffs Sandstone above the Fruitland coals.

Above the lower coals of the Fruitland Formation fluviatile and flood-plain deposits consisting of sandstones, siltstones, and shales were laid down. The rivers were probably quite sluggish most of the time with occasional episodes of overflowing and flooding. Some inland coal swamps existed in later Fruitland time as evidenced by scattered coal beds in the upper Fruitland. In all probability the thick massive sandstones which occur randomly throughout the Fruitland are channel sand deposits.

The lower shale member of the Kirtland Shale was deposited under the same general conditions as the upper part of the Fruitland except that little or no coal was deposited. Next, the sands and interbedded shales of the Farmington Sandstone were laid down on top of the lower shale. These sands are indicative of higher energy and were probably the result of uplift in the source area. Dilworth (1960) made cross-bedding studies of the Farmington in five locations along the west side of the San Juan Basin. These studies indicated a south to southwestern source for the Farmington Sandstone Member.

The present study indicates a thinning of the Farmington toward the south and southwest and a higher percentage of sandstone in the Farmington to the north and northwest. This would indicate a north or northwest source area for the Farmington.

The sequence of events resulting in the deposition of the Farmington Sandstone was probably as follows. Toward the end of the time when the lower shale was being deposited uplift took place to the north and northwest and possibly to the west of the area of deposition of the lower shale. This uplift resulted in increased streamflow which caused deposition of the sandstone lenses of the Farmington Sandstone on top of the lower shale member. Somewhat later the entire San Juan Basin area began to be uplifted very slowly and tilted toward the north and northwest resulting in a lessening of deposition of sandstone in the east and southeast portion of the basin. The east side, however, did not become elevated above base level and continued to receive sediments. At this time the sands being brought in from the northwest were being concentrated in a deeper part of the area which Silver (1950, p. 119) called the "Kirtland Basin".

Silver stated that the Kirtland Basin was a "lesser basin of deposition in the southwestern half of the area of the present San Juan Basin". The present writer agrees that there was a lesser basin of deposition at the time the Farmington Sandstone was being deposited; however, this basin was probably located in the northwest rather than in the southwest part of the area of the present San Juan Basin.

Continued uplift and northwestward tilting of the San Juan Basin area took place throughout the time of deposition of the Farmington Sandstone causing a gradual decrease in the gradient of the streams bringing in sands from the north and northwest, consequently bringing to an end the deposition of the Farmington Sandstone.

Next the sands and silts of the upper shale member were deposited on top of the Farmington Sandstone. The original extent and thickness of the upper shale cannot be determined because the top of the upper shale has been eroded at all points throughout the San Juan Basin.

Sometime during deposition of the upper shale (or conceivably at a later time) the rate of the westward tilting and uplift of the basin area was increased resulting in the erosion and beveling of the rocks already deposited in the area. This erosion removed as much as 1750 feet of rock from the east side of the San Juan Basin and truncated all of the rocks above ( and possibly including) the Pictured Cliffs Sandstone (fig. 2). Most of the material eroded from the east side of the basin was carried completely out of the area toward the west. Some of the eroded material, however, may have been redeposited in the northern part of the basin and be represented by the lower Animas rocks.

As the tilting and uplift of the basin area diminished, the Hogback Monocline (fig. 4) on the east side of the basin began to form, as evidenced by greater angular discordance at the base of the Ojo Alamo on the east side of the basin (plate C-C'). At this time the sediments now composing the Ojo Alamo Sandstone were brought into the basin with great energy, as evidenced by the basal conglomerate and large logs found in the Ojo Alamo. Concurrently, the sediments now forming the Animas Formation were, apparently conformably, being deposited in the extreme northern part of the basin. Sometime after deposition of the Ojo Alamo and the Animas Formations the central part of the basin was downwarped and the remainder of the Hogback Monocline was formed. Subsequently, the basin was filled by the sediments of the San Jose Formation.

## ECONOMICS

### Oil and Gas

The oil and gas production from rocks of the Kirtland and Fruitland is rather minor, the majority coming from the Farmington Sandstone Member of the Kirtland Shale. According to Dilworth (1960 p. 52) the Farmington has produced a cumulative total of 82,587 barrels of oil and 338,885 thousand cubic feet of gas. Dilworth states the following concerning fluids of the Farmington Sandstone:

(1) oils range from $50^{o}$ - $59^{o}$ A.P.I. gravity,
(2) waters are brackish to saline
(3) gasses are flammable and consist of 63 to 70 percent methane and 20 to 28 percent ethane

According to the New Mexico State Conservation Commission (written communication Jan. 1964) the Fruitland Formation has produced a cumulative total of 131,449 thousand cubic feet of gas.

### Coal

The coal beds of the Fruitland Formation have been studied extensively and in great detail by the U. S. Geological Survey during the past four years. The coal study, which included subsurface sampling of coal beds from rotary well cuttings and subsequent analyses of the coals, has shown that the Fruitland coals are much thicker and more widespread than had previously been supposed. The study by the Survey also revealed that the heating value of the coals in the subsurface of the basin is on a par with the heating values of coals at the surface and range from 9170 Btu to 13,350 Btu (written communication from J. S. Hinds, April, 1964).

## PRINCIPAL CONCLUSIONS

This report is the first comprehensive study of the subsurface geology of the rocks of the Kirtland and Fruitland Formations of the San Juan Basin. To illustrate this report five east-west and three north-south geologic cross sections were constructed. These cross sections contain a total of 99 reproductions of electric and induction-electric well logs through the Kirtland and Fruitland. In addition, two structure contour maps, contoured on the top of the Pictured Cliffs Sandstone and on the top of the Kirtland Shale, and an isopachous map of the total combined thickness of the Kirtland and Fruitland Formations were constructed and a geologic map of the San Juan Basin was compiled.

This report offers additional evidence bearing on some of the earlier controversies about the Kirtland and Fruitland Formations as follows:

1. Kirtland and Fruitland rocks on the east side of the San Juan Basin.

   Some earlier reports have suggested that the Kirtland and Fruitland rocks are not present on the east side of the San Juan Basin, while others have suggested that these rocks are present on the east side.

   This study has shown that the Kirtland and Fruitland Formations are missing along the central part of the east side of the San Juan Basin.

2. Reason for absence of Kirtland and Fruitland rocks on the east side of the San Juan Basin.

   Earlier workers have suggested that Kirtland and Fruitland rocks are not found on the east side of the San Juan Basin because of non-deposition. Others have suggested that these rocks are absent because of erosion.

   This report shows that the Kirtland and Fruitland Formations are not present on the east side of the basin because they have been removed by erosion prior to deposition of the overlying Ojo Alamo Sandstone.

3. Unconformity at the base of the Ojo Alamo Sandstone.

Earlier workers have disagreed as to whether or not an unconformity is present at the base of the Ojo Alamo Sandstone.

This study shows that wherever the Ojo Alamo Sandstone is present in the basin there is an angular unconformity at its base. Erosion prior to deposition of the Ojo Alamo has removed all of the Kirtland and Fruitland rocks in the east-central part of the San Juan Basin with as much as 1750 feet of these rocks being missing there.

4. Source area for the Farmington Sandstone Member of the Kirtland Shale.

Most of the earlier workers have suggested a south to southwestern source area for the Farmington Sandstone.

Results of this study indicate a north or northwestern, source area for the Farmington Sandstone.

5. Extent and termination of the Farmington Sandstone.

It has been suggested that the Farmington Sandstone is not present in the southern and eastern thirds of the San Juan Basin and that the Farmington pinches out due to lack of deposition.

This study shows that the Farmington does not pinch out anywhere in the San Juan Basin due to lack of deposition but that its absence is the result of truncation by erosion prior to deposition of the Ojo Alamo Sandstone. This study also shows the

Farmington to be more extensive than was previously supposed.

In addition, this study shows a higher percentage of sandstone in all of the units comprising the Kirtland and Fruitland interval of the San Juan Basin in the north to northwestern part of the basin. This might indicate a northerly source area for all of the Kirtland and Fruitland rocks.

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