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APPENDIX C

PROJECT RIO BLANCO

GEOLOGY OF THE PICEANCE BASIN

REVISION NO. 1

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CER GEONUCLEAR

TABLE OF CONTENTS

			Page
I.	INTRODUCTION		1
II.	SURFACE GEOLOGY		2
	A.	STRUCTURE OF THE GREEN RIVER FORMATION	2
	B.	STRATIGRAPHY OF THE GREEN RIVER FORMATION	6
III.	JOINTS, LINEARS, AND FAULTS		11
	A.	INTRODUCTION	11
	B.	JOINTS AND LINEARS	13
	C.	FAULTS	17
		1. Surface	17
		2. Subsurface	17
IV.	SUBSURFACE GEOLOGY		21
	A.	STRATIGRAPHY	21
		1. Wasatch Formation	21
		2. Fort Union Formation	28
		3. Mesaverde Formation	28
		4. Mancos Formation	33
	B.	SAND CONTINUITY IN THE FORT UNION AND MESAVERDE FORMATIONS	34
		1. Introduction	34
		2. Statistical Analysis	34
		3. Comparison of Statistical Results and Sandstone Body Geometrics	35

			Page
		4. Sandstone Continuity Summary	45
	C.	STRUCTURE	46
V.	ROCK PROPERTIES		50
	A.	GREEN RIVER FORMATION	50
	B.	WASATCH FORMATION	57
	C.	FORT UNION FORMATION	59
	D.	MESAVERDE FORMATION	68
	REFERENCES		77

ILLUSTRATIONS

Figure No.		Page
1	Regional map and structural interpretation contoured on top of lower Cretaceous	3
2	Bedrock geological map of Piceance Creek-Yellow Creek Basin, Rio Blanco County, Colorado	4
3	Stratigraphic section of surface rocks in the Piceance Creek-Yellow Creek Basin	7
4	Major linears within one mile of the EW area	14
5	Subsurface structure at the Wasatch "G" Marker level	19
6	Subsurface structure at a Mesaverde II phantom level	20
7	Stratigraphy of northern portion of Piceance Basin	22
8	Chart showing comparison of nomenclature for the tertiary in the Piceance Basin	24
9	Regional map and structural interpretation contoured on top of lower Cretaceous and showing thickness of Wasatch-Fort Union formations	25
10	East-west cross section, showing configuration of upper Cretaceous and tertiary strata in central Piceance Basin	26
11	North-south cross section showing configuration of upper Cretaceous and tertiary strata in central Piceance Basin	27
12	Diagrammatic restored section of Cretaceous rocks, Wasatch Plateau, Utah to Axial Basin, Colorado	30

ILLUSTRATIONS

Figure No.		Page
13	Regional map and structural interpretation contoured on top of lower Cretaceous, showing isopach of the Mesaverde Formation	31
14	Paleocene, Eocene, and late Cretaceous deposits of Book Cliffs and Grand Mesa	32
15	Schematic of typical cut-and-fill sequence	36
16	S. P. Log response to a complete channel-fill sequence	37
17	S. P. Log response to a series of partial channel-fill sections	38
18	D. P. Log response to a series of partial channel-fill sections	39
19	Channel width and mean radius of curvature versus meander length	41
20	Two typical Cretaceous point bar fields	43
21	Point bar type sandstone lenses exposed by erosion of the Grand Hogback, north of Rifle, Colorado	44
22	Schematic cross section Piceance Creek Basin, Rio Blanco County, Colorado	47
23	Structure map of the northern part of the Piceance Creek Basin, Colorado	48
24	Geophysical logs obtained in Colorado Core Hole No. 1, Yellow Creek, Rio Blanco County, Colorado, showing pertinent horizons	51

ILLUSTRATIONS

Figure No.		Page
25	Relationships between density, velocity, and oil assay established by various investigators	52
26	Log cross section, Fawn Creek Unit Government No. 3, Boies No. 1, and Fawn Creek Government No. 1	54
27	Calculated compressional-wave, V_p and shear-wave velocity $V_{SH,SV}$, as a function of confining pressure and direction of propagation for dry Green River shale	55
28	Comparison of brittle ductile failure behavior of lean and intermediate grade oil shale with granite and salt	56
29	Geophysical log cross section in Rio Blanco experiment area, Wasatch section	58
30	Geophysical log cross section or Rio Blanco experiment area, Fort Union section	60
31	Water saturation versus porosity, Fort Union sandstone, calculated from IES logs	62
32	Core permeability versus porosity, Fort Union sandstone	64
33	Core permeability versus water saturation, Fort Union sandstone	65
34	Geophysical log cross section, Rio Blanco experiment area, Mesaverde section	69
35	Water saturation versus porosity, Mesaverde I sandstone, calculated from IES logs	71

ILLUSTRATIONS

Figure No.		Page
36	Core permeability versus porosity, Mesaverde I sandstone, Boies No. 1, Scandard Draw No. 1, Sulphur Creek No. 1	72
37	Core permeability versus water saturation, Mesaverde I sandstone	73

TABLES

Table No.		Page
I	Results of Trace Element Analyses of Shale	67
II	Results of Trace Element Analyses of Mesaverde Sandstone	76

I. INTRODUCTION

The Piceance Basin is an interesting geological area. This, coupled with its economic importance (oil shale, coal, and gas resources), has produced voluminous literature. A guidebook to the geology of northwestern Colorado (Ref. 1) lists a bibliography containing 396 articles published prior to 1961, and, of course, the number of articles has been accelerating in the last ten years. Thus, the most difficult part in a discussion of the geology of this basin is to select the information most relevant to the project and to slight some factors that are geologically interesting but not related to the Rio Blanco Project.

II. SURFACE GEOLOGY

A. STRUCTURE OF THE GREEN RIVER FORMATION

The Piceance Creek-Yellow Creek drainage basin is part of the more extensive Piceance Structural Basin (Figure 1). The Piceance Creek-Yellow Creek drainage basin will be referred to as the Piceance Creek Basin in the remainder of this Appendix. The dips of surface rocks are rather gentle, usually less than 500 feet per mile. A structural contour map of the "B" or Black Marker is part of Figure 2. The center of the basin is a north-trending trough between Piceance and Yellow creeks. The Piceance Creek Dome is the broad generally east-west trending positive feature centered in T2S, R96W. The Black Sulphur Creek Nose is a east-trending positive feature centered in T2S, R98W, and the small dome centered on the border of T2S and T3S, R97W, is a small anticlinal feature on an extension of the Black Sulphur Creek Nose.

The structure displayed by the "B" Marker, which is located near the base of the Evacuation Creek Member, is a reflection of deeper structural features. However, the near surface indication of the structure at depth are distorted in the center portion of the basin by the solution by groundwater of at least 100 feet of saline beds and lenses. This leaching, which has occurred in the Parachute Creek Member in an interval of about 700 feet below the "B" Marker, has resulted in surface and "B" Marker subsidence of 100 feet or more. The maximum subsidence has occurred in the areas where appreciable quantities of soluble saline minerals have been leached and removed. This

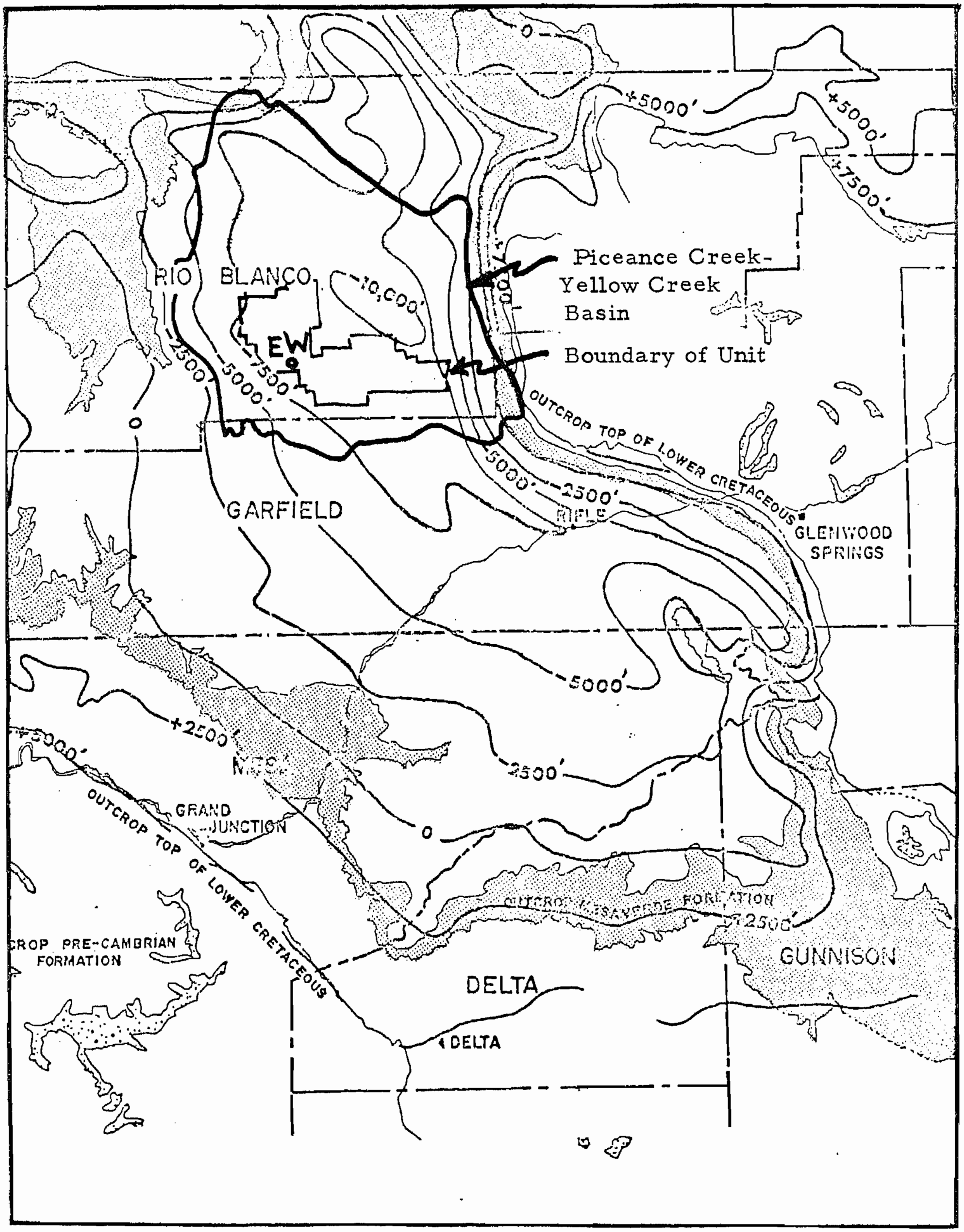

Figure 1. Regional map and structural interpretation contoured on top of lower Cretaceous.

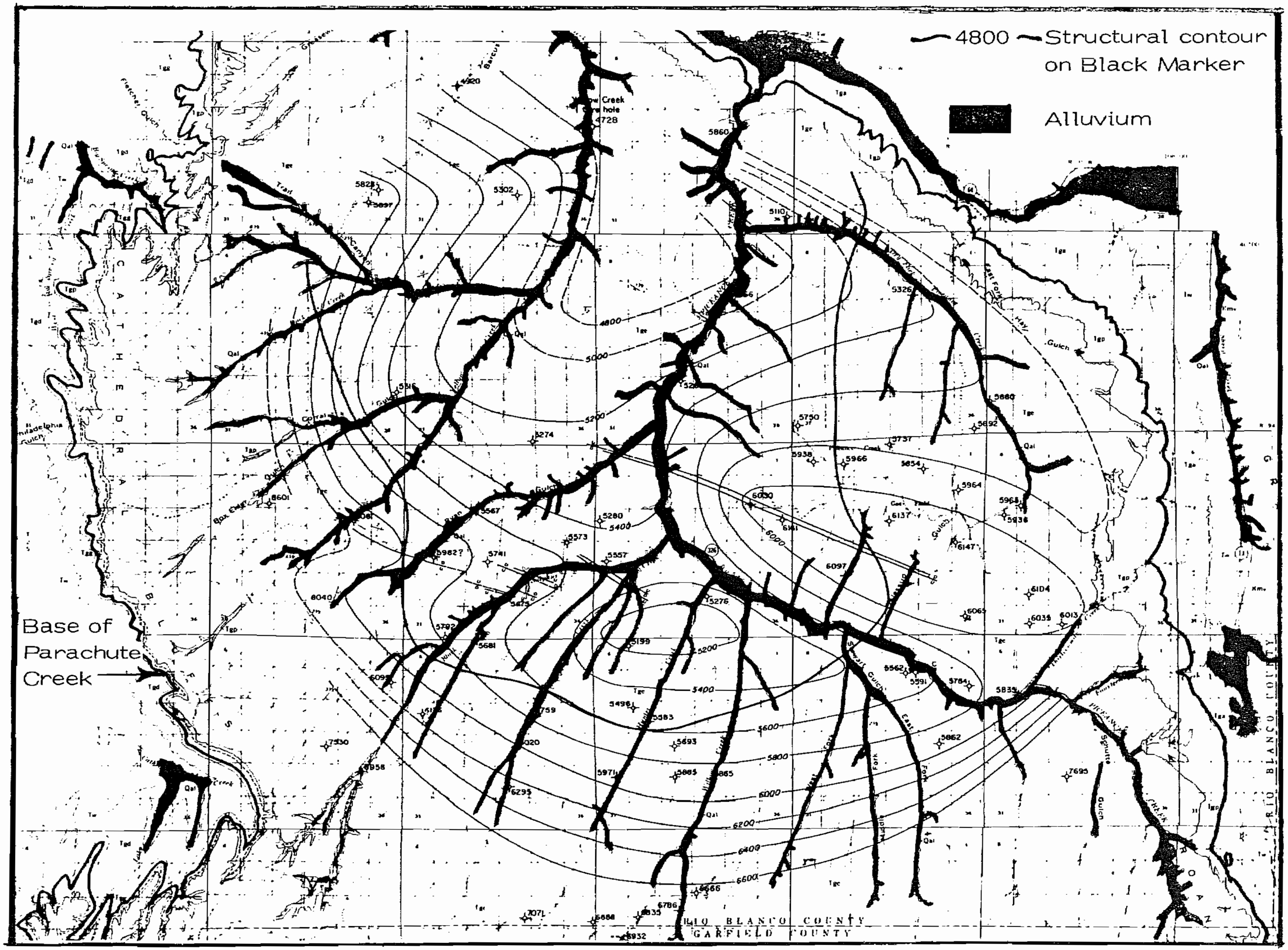

Figure 2. Bedrock geological map of Piceance Creek-Yellow Creek Basin, Rio Blanco County, Colorado

solution and sagging is a complex response to the original patterns of saline sedimentation, the Green River structure, and the groundwater movement.

B. STRATIGRAPHY OF THE GREEN RIVER FORMATION

The surface bedrock, in the portion of the Piceance Creek-Yellow Creek drainage basin shown in Figure 2 consists predominately of the Evacuation Creek Member of the Green River Formation. This unit is composed of light brown sandstone, gray marlstone, and siltstone. The dips are rather low over most of the basin, and the sandstone forms resistant horizontal ledges in the walls of the valleys. The narrow valleys are floored with Holocene alluvium, usually less than 100 feet thick, and some Pleistocene terrace and slide deposits are present on the basin margin cliffs (Ref. 2). The lower member of the Green River Formation and the Wasatch Formation crop out along the margins of the basin, on the east, facing the Grand Hogback, and on the west, in the Cathedral Bluffs. In general, however, the surface geology of the basin is the geology of the Evacuation Creek Member of the Green River Formation.

The relationships between the Green River and the underlying formations are displayed in the stratigraphic section shown by Figure 3 (Ref. 3). As indicated in this figure, the Evacuation Creek Member overlies all the other members of the Green River Formation. The original maximum thickness of the Evacuation Creek Member cannot be determined, since its upper margin is the current erosional surface. The greatest observed thickness is about 1,250 feet in Sec. 29, T2S, R95W (Ref. 4).

Age	Formation	Member	Description
	Piceance Creek-Yellow Creek Basin and Marginal Cliffs		
Holocene	"Alluvium" - 0-140 ft		Tan to brown boulder beds, sands and clays filling narrow valley bottoms
Pleistocene	"Landslide, Talus, and Terrace" 0-30 ft		Heterogeneous mixture of silt, sand, gravel, and blocks of sandstone and shale
Eocene	Green River 1,800-3,500 ft	Evacuation Creek	Light-brown and gray sandstone and siltstone, gray marlstone and siltstone
		*Parachute Creek	Black, brown, and gray marlstone (principal oil shale zone)
		Garden Gulch	Gray marlstone, oolitic limestone
		*Douglas Creek	Buff and brown sandstone, gray shale
		Anvil Points	Brown sandstone gray shale and marlstone
	Wasatch 200-5,000 ft	*	Variegated shale and claystone with lenticular sandstone and thin limestones
Paleocene	Fort Union 500-1,500 ft	*	Brown and tan lenticular sandstones, somber-colored shales, thin coal seams, and a basal conglomerate
		*Ohio Creek	
Upper Cretaceous	Mesaverde 5,500 ft ±	*	Resistant tan and white sandstone, brown to black shales and coal

* Indicates gas.

Figure 3. Stratigraphic section of surface rocks in the Piceance Creek-Yellow Creek Basin (after Ritzma, 1962).

The lithology of the Evacuation Creek Member is quite variable. The beds are very discontinuous and change character and thickness within short distances. Brown, medium-to-coarse-grained sandstone is the predominant rock type near the top. This grades into white-to-gray marlstone and siltstone, with some thin beds of oil shale near the base.

The Parachute Creek Member underlying the Evacuation Creek contains the bulk of the oil shale in the Green River Formation. The Parachute Creek is the whitish cliff-forming unit in the Cathedral Bluffs and in the cliffs on the western side of the Grand Hogback Valley. This member consists almost entirely of shale and marlstone in the outcrop, although it contains layers of saline minerals as much as 100 feet thick in the subsurface at the center of the basin. The thickness varies from 1,700 feet in Sec. 31, T1S, R96W to less than 500 feet in the northwest margin of the basin.

The richest zone of oil shale occurs approximately 500 feet below the top of the Parachute Creek and has been named the Mahogany Zone. This zone varies in thickness from a few feet at the northwestern margin of the basin to approximately 150 feet in the center of the basin. Individual shale layers in this zone have assayed as high as 79 GPT. Zone averages of from 40 to 50 GPT are reported from the center of the basin.

In the subsurface, the Mahogany Zone is extremely massive and tough (Ref. 4). Its base is marked by a barren bed of marlstone and analcitized tuff termed the "B" or Black Marker. This marker is a useful correlative point on the logs and is used frequently as the datum point for structural contour maps.

The Anvil Points Member is confined to the eastern portion of the basin, where it interfingers into the Parachute Creek at the top and into Wasatch Formation at the base. Towards the center of the basin, the Anvil Points fingers laterally into the Garden Gulch and Douglas Creek members.

The Anvil Points Member is also heterogeneous, containing approximately 30% gray shale, 25% interbedded gray shale and thin-bedded brown and gray sandstone, 20% massive brown sandstone, 10% marlstone (containing little or no oil) and minor amounts of siltstone, and algal and oolitic limestone. This member tapers from a maximum thickness of 1,870 feet along the upper reaches of the Piceance Creek to 0 feet a few tens of miles to the west in the Piceance Creek Gas Field (Ref. 4).

The Garden Gulch Member crops out in all but the eastern margin of the basin as steep, gray slopes between the whitish cliffs of the overlying Parachute Creek Member and the underlying brown and buff benches of the Douglas Creek Member. The usual composition in the outcrop area consists of barren marlstone, papery shale, thin beds of sandstone, oil shale breccia, and limestone. It is predominately gray shale in the subsurface in the center of the basin. The Garden Gulch varies from 900 feet in T8S, R100W, to 0 feet in the eastern part of the basin (Ref. 4).

The Douglas Creek Member is the basal unit of the Green River Formation over most of the basin. It consists of shale, cross-bedded sandstone, and minor amounts of algal, ostracodal and oolitic limestone. The Douglas Creek varies from 800 feet thick in T4S, R101W, to 0 feet in the eastern part of the basin (Ref. 4). The Douglas Creek Member conformably overlies the brightly colored Wasatch Formation.

III. JOINTS, LINEARS, AND FAULTS

A. INTRODUCTION

Faults and joints are terms given to fractures or breaks that occur in rocks. By definition, the faults are larger scale breaks in the earth that have experienced displacement, and joints are small scale breaks or fractures that show no displacement.

The Piceance Structural Basin is a marginal feature of the ubiquitously jointed Colorado Plateau. Hence, the jointing in the Rio Blanco area is an intrinsic surface feature that extends far beyond the boundaries of the area. The faulting, on the other hand, is confined to limited zones of major structural compensation.

Linears are "line-like" features that are discernible on topographic maps and aerial photos. They may be surface expressions of faults, joint systems, changes in lithology, or even such nongeological features as old road beds, fence lines, cultivated areas, etc. A technique commonly used to evaluate the surface jointing and/or faulting in an area, is to study the topographic maps and aerial photos to determine the "grain" of the area and to pinpoint the linears, then to study the linears in the field and evaluate their underlying cause.

The information presented in this section of Appendix C resulted from a study of linears as outlined above, from a study of ideas on jointing, and faulting presented in the literature, and from an analysis of detailed geological and geophysical studies made on the area. One such geophysical study was made specifically as a part of this project to evaluate subsurface faulting and structure within a few miles of the proposed Rio Blanco EW.

B. JOINTS AND LINEARS

The Colorado Plateau and its marginal elements are ubiquitously cut by regional joint systems (Ref. 5, 6). The primary regional joint system trends west-northwest and north-northeast with secondary systems trending slightly east and west of north and approximately east-west. Where the regional surface dip and drainage is roughly parallel to the primary joint set directions the streams tend to align with this jointing direction. This alignment can be seen in the southern part of the Piceance Creek Basin (NNE), the area north of the Roan Cliffs (NW), the East Douglas Creek area (NNE and NW).

The response of rocks to fracturing and jointing is a complex phenomenon. The occurrence of regional jointing has already been mentioned (Ref. 5, 6). Although the joint sets have relatively uniform orientations over broad areas, the areal distribution of the joint density is usually non-uniform (Ref. 7). (Density refers to the spacing of joints, i.e., number of joints per unit area.) In addition, local features can induce or modify joint set directions and density (Ref 8, 9).

The jointing response of rocks is not only influenced by regional and local structural features, but also by the characteristics of the rocks. In general, it has been observed that the thinner and more brittle the rock unit, the denser the jointing (Ref. 8). This general concept can be expressed quantitatively by:

$$D \cong (D_n F)/h$$

where:

D = Joint density, number of joint traces/m^2

D_n = Normalized* joint density, number of joint traces/m^2/ft

h = Thickness of bed, ft

F = Formation lithology factor, >1/4 in. plastic, rich oil shales, to >2 in. brittle limestone layers

The specific picture of the near surface jointing in the Piceance Creek Basin, developed during field examinations in a number of areas (Figure 4), is that of series of roughly horizontal rock units that are jointed with a characteristic density. The individual joint sets may persist vertically for a few tens of feet but then terminate at the boundary of a unit that has responded to jointing as a separate structural entity. The horizontal persistence of individual joints in a rock unit is in the order of a few hundred feet, and the joint density varies laterally within the individual rock units. The lateral variation in joint density in rock units may vary by a factor of 2 to 3 whereas the variation in joint density between vertically adjacent rock units may vary by orders of magnitude.

A periodicity is noted in the lateral variation of joint density in an individual rock unit. The characteristic "wave length" in the thicker Green River oil shales is on the order of a few hundreds of feet. Hence, there may be several more densely jointed trends lined up under a stream valley and a large number encountered transversing a ridge adjacent to the valley.

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*Normalized joint density is density at the specific area of interest in a hard sandstone, one foot thick.

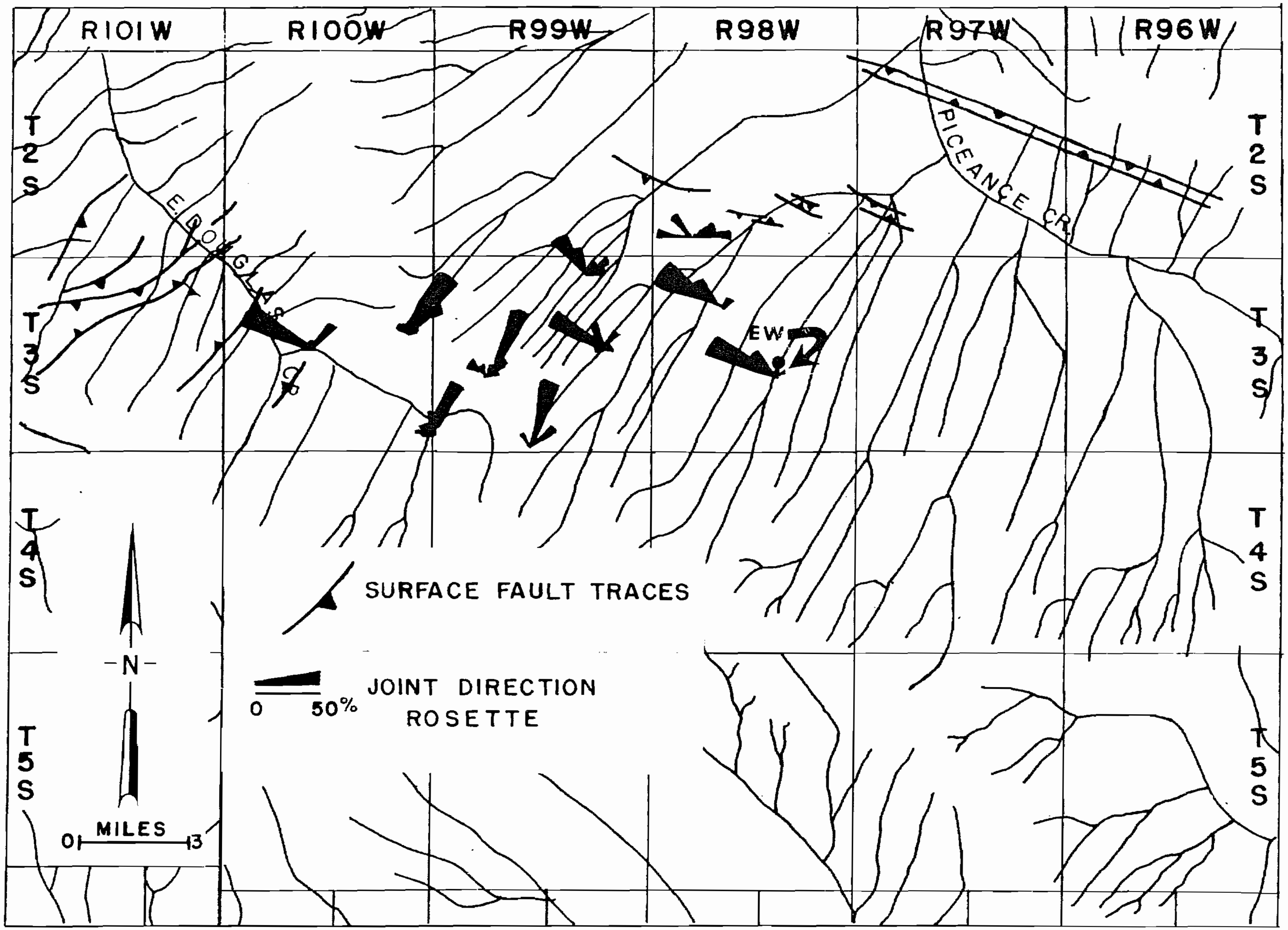


Figure 4. Joint density and orientation rosettes plotted on a stream pattern and surface fault trace base map.

The orientation of the most frequently occurring joint direction in the southern part of the Piceance Creek Basin is perpendicular to the orientation of Fawn Creek. This feature is illustrated by the joint density and orientation rosettes presented for several locations and displayed in Figure 4. This figure also shows the stream patterns in the southwestern part of the basin and adjacent areas, as well as illustrating the surface faulting.

The joints tend to close at some depth (between 1,500 to 2,500 feet in the Piceance Creek Basin), depending upon rock plasticity and overburden bulk density (Ref. 10). The occurrence of impermeable rocks by layers at these depths is demonstrated by the gas trapped in lower Green River sands in many parts of the basin. The "plastic" Mahogany zone in all but the basin edge, appears to have a low joint density, even at depths of burial less than 1,500 feet. Thus, the jointing should not pose a containment problem.

A professional paper on the jointing and fracturing in the Piceance Basin is being written for 1972 publication in the AAPG Bulletin.

C. FAULTS

1. Surface

The surface faulting seems to correlate with local positive structural features. The fault zones, usually grabens, are easily identifiable on the surface, since the offsets are apparent in the steep valley walls and the fault traces are expressed as linear surface features.

The major zones of faulting in the Piceance Creek Basin are associated with the Piceance Creek Dome, T2S, R96W, and the Black Sulphur Creek Nose, T2S, R98W. These surface faults are shown in Figure 2. The faults generally have displacements of less than 100 feet, and the displacements may be modified by the solution of saline layers and lenses in the Parachute Creek Member and by the sagging or takeup that results from this phenomenon.

"Faults" with maximum offsets of a few inches to a few feet have been noted in the upper Green River sandstones in the area west of the emplacement well. These features are oriented generally northwest-southeast with dip angles from 45 to 60° southwest, and the displacement appears to die out within a stratigraphic interval of 50 to 100 feet. These features appear to be associated paracontemporaneously with deposition. Hence, these offsets are near surface phenomena that will not compromise containment.

2. Subsurface

Interpretation of subsurface faulting in the basin is based heavily upon geophysical studies. The relatively wide well spacing, the small fault displacement, the local variations in stratigraphic thickness, and the lenticular and discontinuous nature of the sandstone elements make it difficult to pick fault cuts from the well logs.

The subsurface structure at the Wasatch "G" Marker level is presented in Figure 5, and at a Mesaverde II phantom level (several hundred feet below the base of the shot-affected region of the Rio Blanco experiment) in Figure 6. These structural maps were drawn using information from seismic surveys and log correlations.

The nearest subsurface fault zones to the Rio Blanco experiment area are associated with the Black Sulphur Creek Nose. The area near the projected EW is free from subsurface fault indications.

A detailed subsurface geophysical study in the Rio Blanco experiment area showed no faults within a distance of two miles of the proposed EW (Ref. 11).

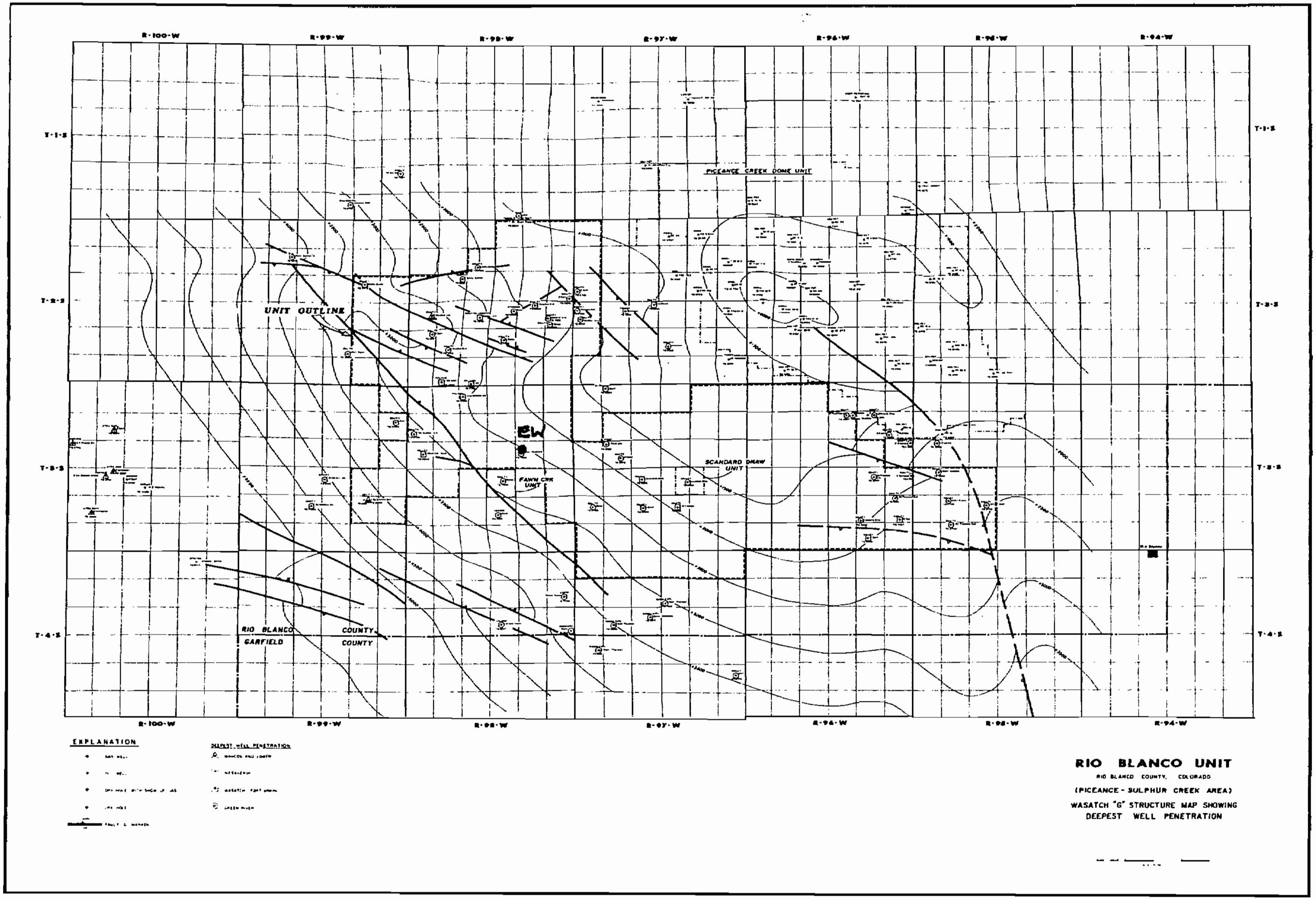


Figure 5. Subsurface structure at the Wasatch "G" Marker level.

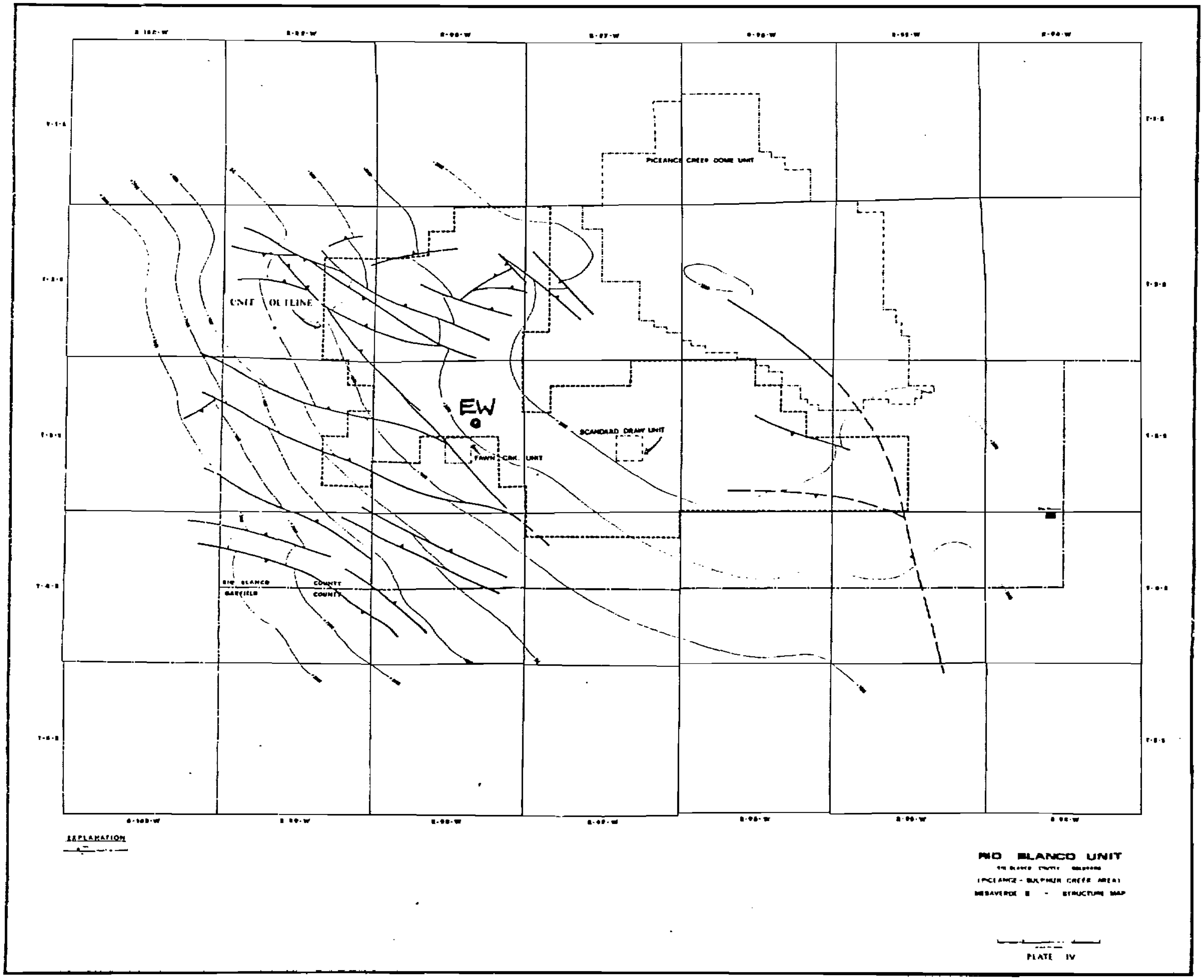


Figure 6. Subsurface structure at a Mesaverde II phantom level.

IV. SUBSURFACE GEOLOGY

A. STRATIGRAPHY

The Piceance Basin sedimentary rocks vary in age from recent to Cambrian and overlie the pre-Cambrian basement. A generalized stratigraphic chart for the northern part of the basin is presented in Figure 7 and shows the sequence of rock units in the basin, their general lithology, and an order of magnitude thickness. This stratigraphic discussion will be confined to the Wasatch-to-Mancos sequence, since the stratigraphy of the Green River Formation has already been discussed as part of Section II, Surface Geology. The units below the Mancos shale are adequately summarized for this discussion on Figure 7 since they are remote and are not of primary concern to this project.

1. Wasatch Formation

The Wasatch Formation, which underlies the Green River, is distinguished from the overlying, subdued grayish-green, gray, brown, and tan, beds of the Green River Formation by its red, maroon, and purple claystone and shale. The definition of the base of the Wasatch is obscure. In relatively current literature, the Wasatch Formation is sometimes defined as inclusively as from the base of the Green River to the top of the Mesaverde. Other authors define it more narrowly, from the base of the Green River to the top of the Fort Union, i.e., down to the basal Eocene or Paleocene.

SYSTEM AND PERIOD		"FORMATIONS"	GENERAL LITHOLOGY	APPROX. THICKNESS
Quaternary		"Recent"	Low terrace, floodplain, and alluvial deposits	100'
		"Pleistocene"	Terrace and fan sand and gravel, pediment gravel, colluvium, mudflow, and solifluction deposits	200'
Tertiary		Green River	Oil shales, marlstones, and sandstones (dark color)	2,100'
		Wasatch	Bright colored clays and shale with minor sandstone	3,000'
		Fort Union	Brown-gray shale, sandstone and conglomerate	1,000'
Cretaceous	Upper	Mesaverde	Shale - sandstone	2,500' +
	Lower	Mancos	Gray shale	2,700' ±
		Naturita	Shale - sandstone	600'
		Dakota Cedar Mt.	Sandstone	200'
Jurassic		Morrison	Variegated shale and sandstone with interbedded tuff and ash	800'
Triassic		State Bridge	Red arkosic sandstone	600'
		Schoolhouse	Sandstone	60'
Permian		Maroon	Buff-red sandstone	1,000'
Pennsylvania		Minturn	Continental red beds interbedded with white Weber type sandstone	
		Eagle Valley	Evaporites (chiefly anhydrite)	2,800'
		Belden	Gray to black shale with basal conglomerate	
Cambrian through Mississippian		Madison, etc.	Limestone, dolomite and quartzite	700'
Pre-Cambrian			"Basement" metamorphics and plutonics	

Figure 7. Stratigraphy of northern portion of Piceance Basin.

Figure 8 is a comparison of various authors' usage (Ref. 12-17). The definition used in this report follows that of Millison (Ref. 17) in which in the subsurface, an electric log marker is used as the division between the Wasatch and the Fort Union formations. This marker is the general stratigraphic equivalent of the Wasatch-Fort Union boundary recognized in surface mapping on the northeast edge of the Piceance Creek Basin.

The Wasatch Formation in the center of the basin is predominately a shaly sequence which contains very discontinuous sandstone lenses. The formation reaches its maximum thickness on the south and east margins of the Piceance Structural Basin. In this area, the lower Wasatch is relatively sandy. The Molina Member, exposed in the Colorado River drainage basin, is described as a thick, brown, ledge-forming, massive sandstone with thin interbeds of variegated claystone (Ref. 12). Along the Grand Hogback and extending in the subsurface as far as the Piceance Dome Gas Field, the lower Wasatch contains thick permeable sands which have good reservoir characteristics. These sands pinch out on the eastern flank of the dome (Ref. 15).

The overall thickness of the Wasatch varies from 5,000 feet along the southeastern margin of the Piceance Creek Basin to 200 feet in the northwest. Figure 9 is a generalized isopachous map of the combined Wasatch-Fort Union formations showing the maximum thickness and correspondence of depobasin and structural basin. Figures 10 and 11 are

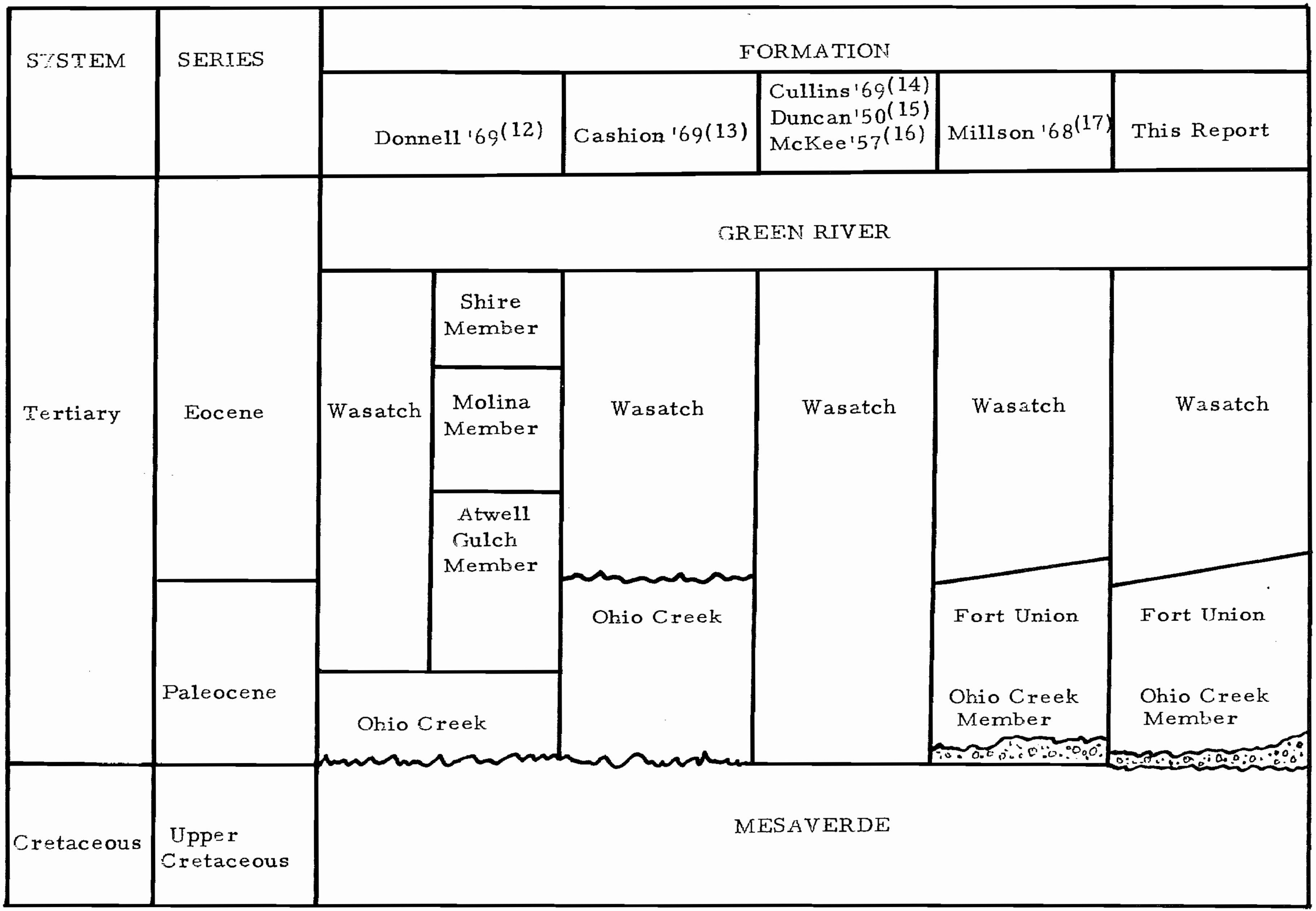


Figure 8. Chart showing comparison of nomenclature for the tertiary in the Piceance Basin.

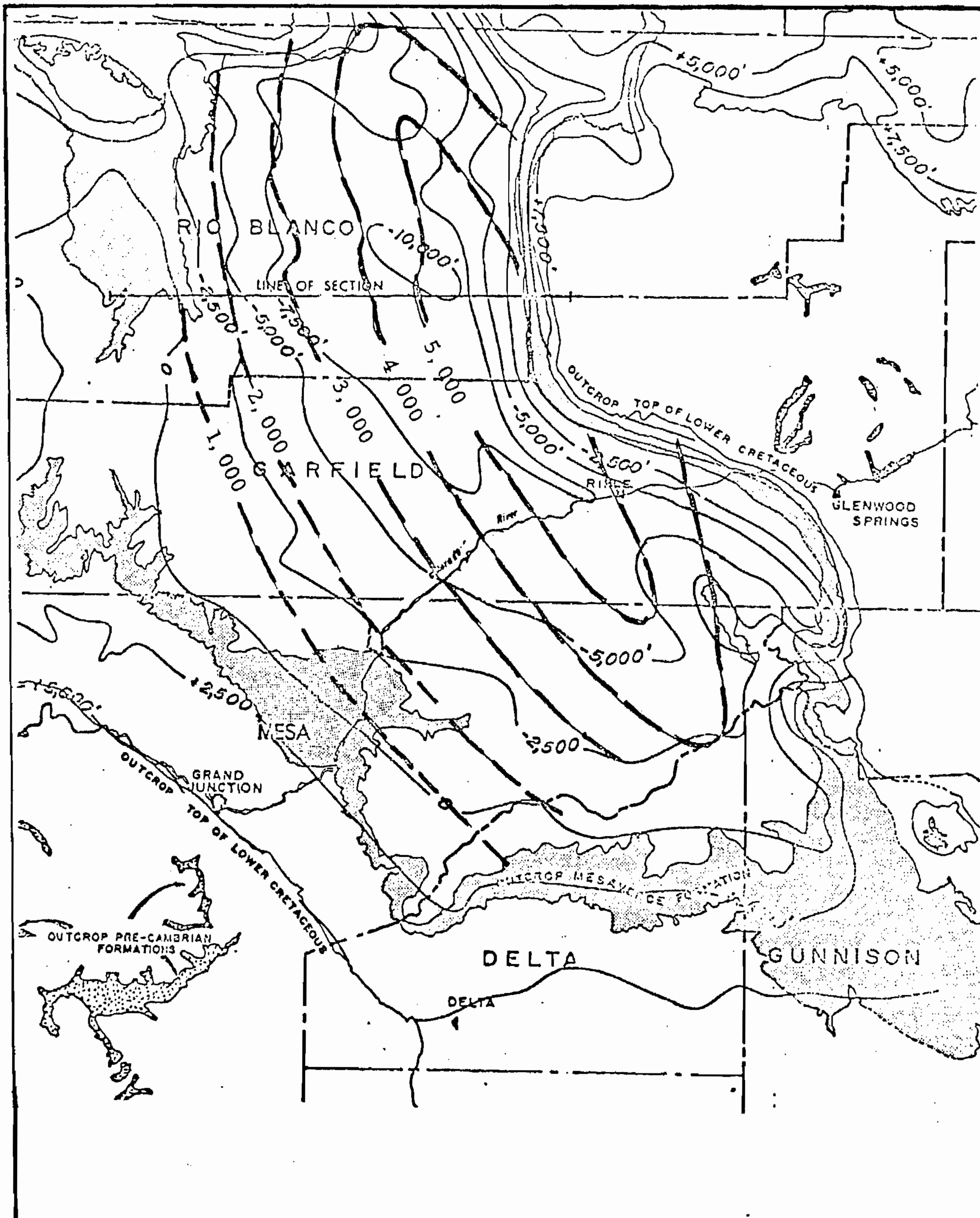


Figure 9. Regional map and structural interpretation contoured on top of lower Cretaceous and showing thickness of Wasatch-Fort Union formations (after Millison, 1968).

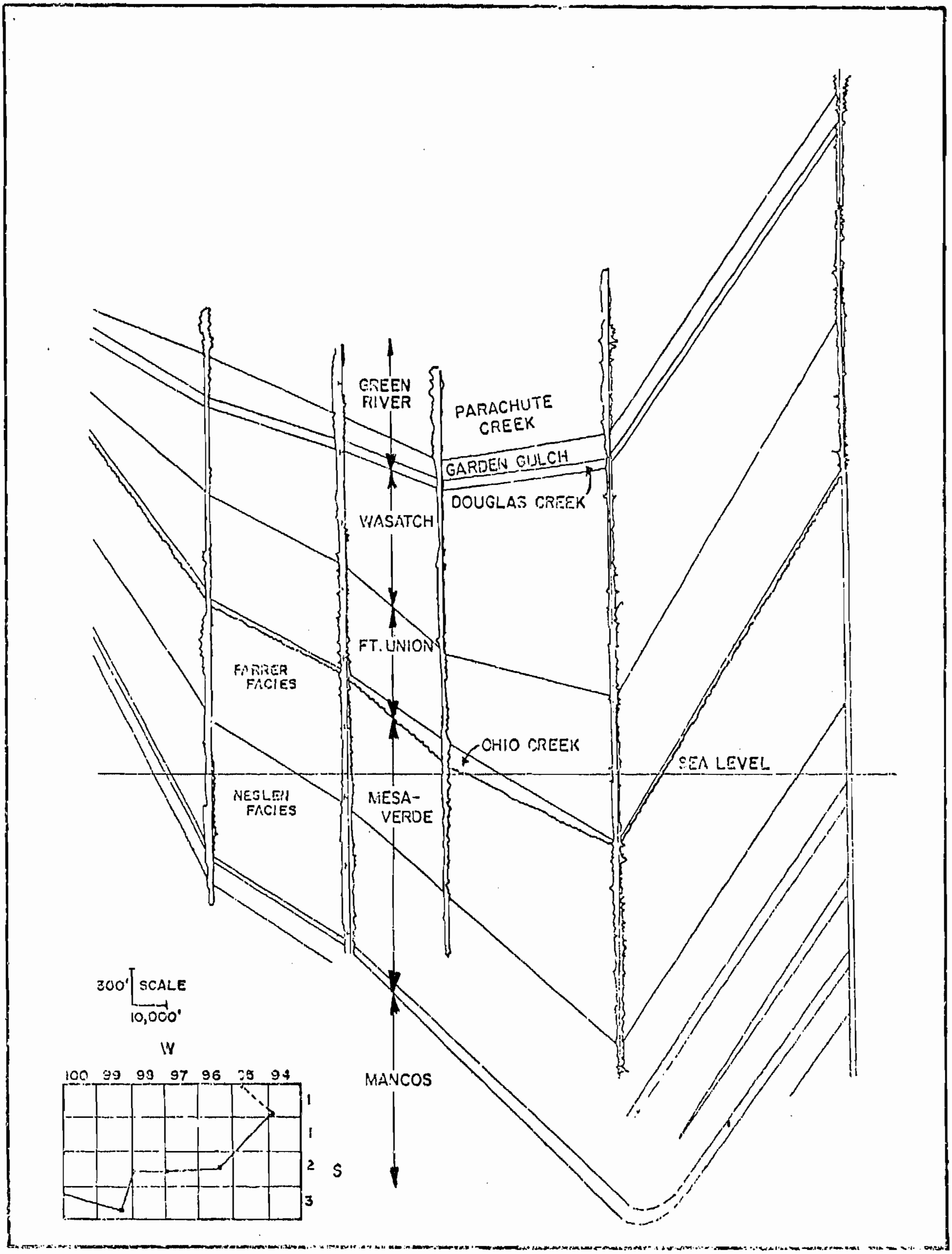


Figure 10. East-west cross section, showing configuration of upper Cretaceous and tertiary strata in central Piceance Basin. (after Millison, 1968.)

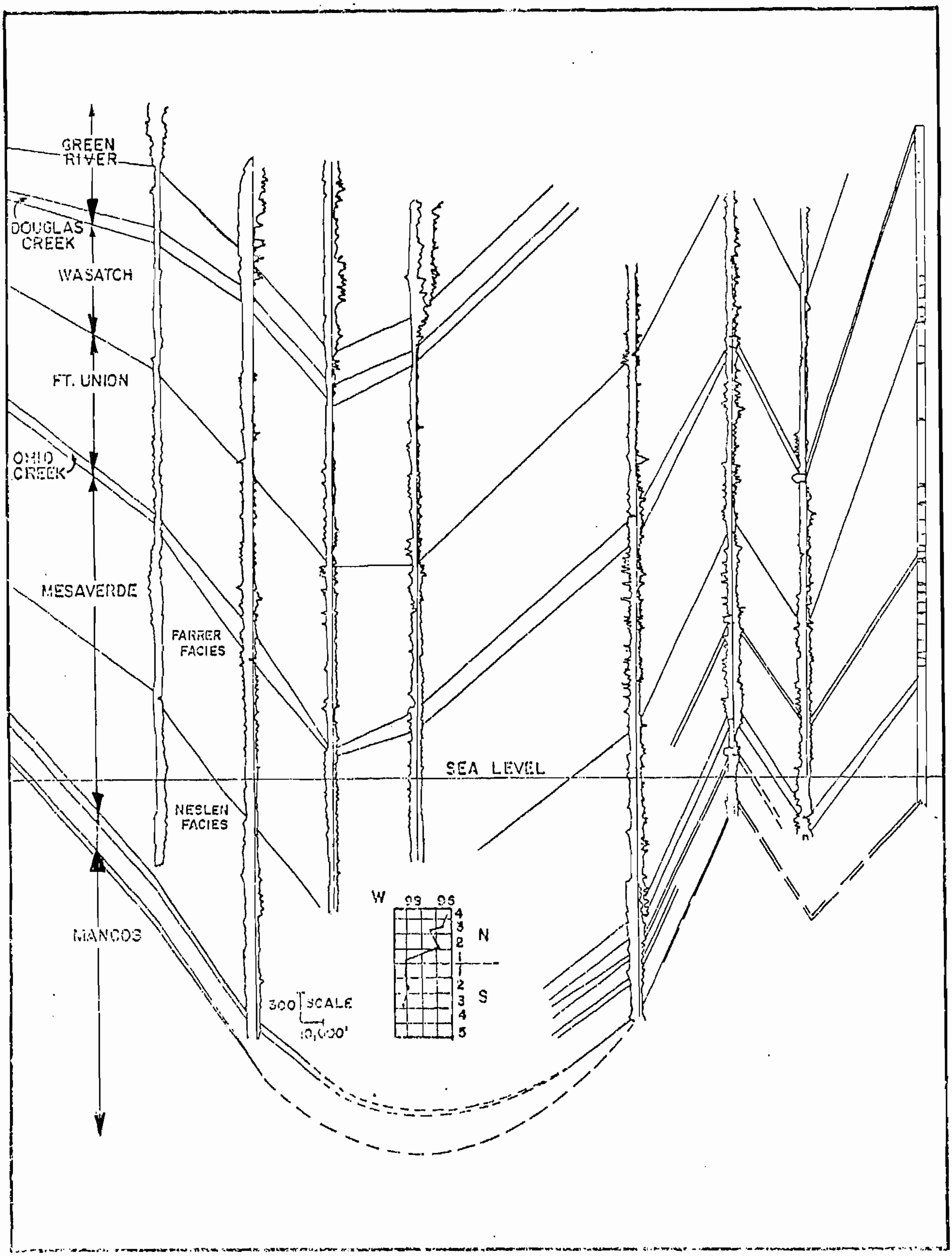


Figure 11. North-south cross section showing configuration of upper Cretaceous and tertiary strata in central Piceance Basin (after Millison, 1968).

east-west and north-south cross sections showing the configuration of the Wasatch, Fort Union, and upper-Cretaceous Mesaverde and Mancos formations.

2. Fort Union Formation

The Fort Union is a sequence of sandstones and conglomerates with interbedded claystones, shales, and coal beds of Paleocene age underlying the Wasatch and overlying the Mesaverde Formation. The basal portion is termed the Ohio Creek Member.

The basal Ohio Creek is a coarse or conglomeratic sandstone, 10 to 40 feet thick, that grades upward into an interbedded sandstone-shale sequence in the southern portion of the Piceance Basin (Ref. 18, 19). The interbedded shales are grayish-greens and grade into the main Fort Union sequence of brownish-yellow sandstones and shales, containing Paleocene plant and animal fossils.

The Fort Union displays a thickness variation of from 1,500 feet along the eastern basin margin to a pinchout in the southwest. The Fort Union rocks are of fluvial, swamp, and lacustrine origin.

3. Mesaverde Formation

The Mesaverde Formation of Cretaceous age is a complex assemblage. The basal marine sandstone section is overlain by a coal-bearing fluvial-coastal swamp sequence called the Neslen facies, which is in turn overlain by fluvial deposits termed the Farrer facies (Ref. 20, 21).

A marine transitional sand member called the Trout Creek sandstone is present in the Neslen facies on the north and eastern margin of the basin (Ref. 22) (Figure 12). This member cannot be traced in the subsurface into the center of the basin. The reddish weathering middle Mesaverde section occurs above the Trout Creek sand. The color is the result of the oxidation of the highly carbonaceous rock. This colored zone is present in the Grand Hogback and Douglas Creek areas, even when the Trout Creek is not present.

A second marine transition zone, termed the Fox Hills sandstone in the Axial Basin, is present in the Farrer facies in the northeastern portion of the basin (Ref. 22). The Fox Hills has a distribution that is more limited than the Trout Creek; hence, it is generally not encountered in the outcrops, except in the northeast corner of the basin.

The general configuration of the Mesaverde is displayed in the isopachous map, Figure 13. The correspondence between the depocenter and structural center of the basin is illustrated in this figure.

One additional cross section along the Book Cliffs (Ref. 19) (Figure 14) shows the intertonguing relationship of the more continuous marine transition, basal Mesaverde sandstones. Correlative layers in the Rio Blanco area are appreciably below ($>$ 1,000 feet) the zones proposed for stimulation in the Rio Blanco experiment.

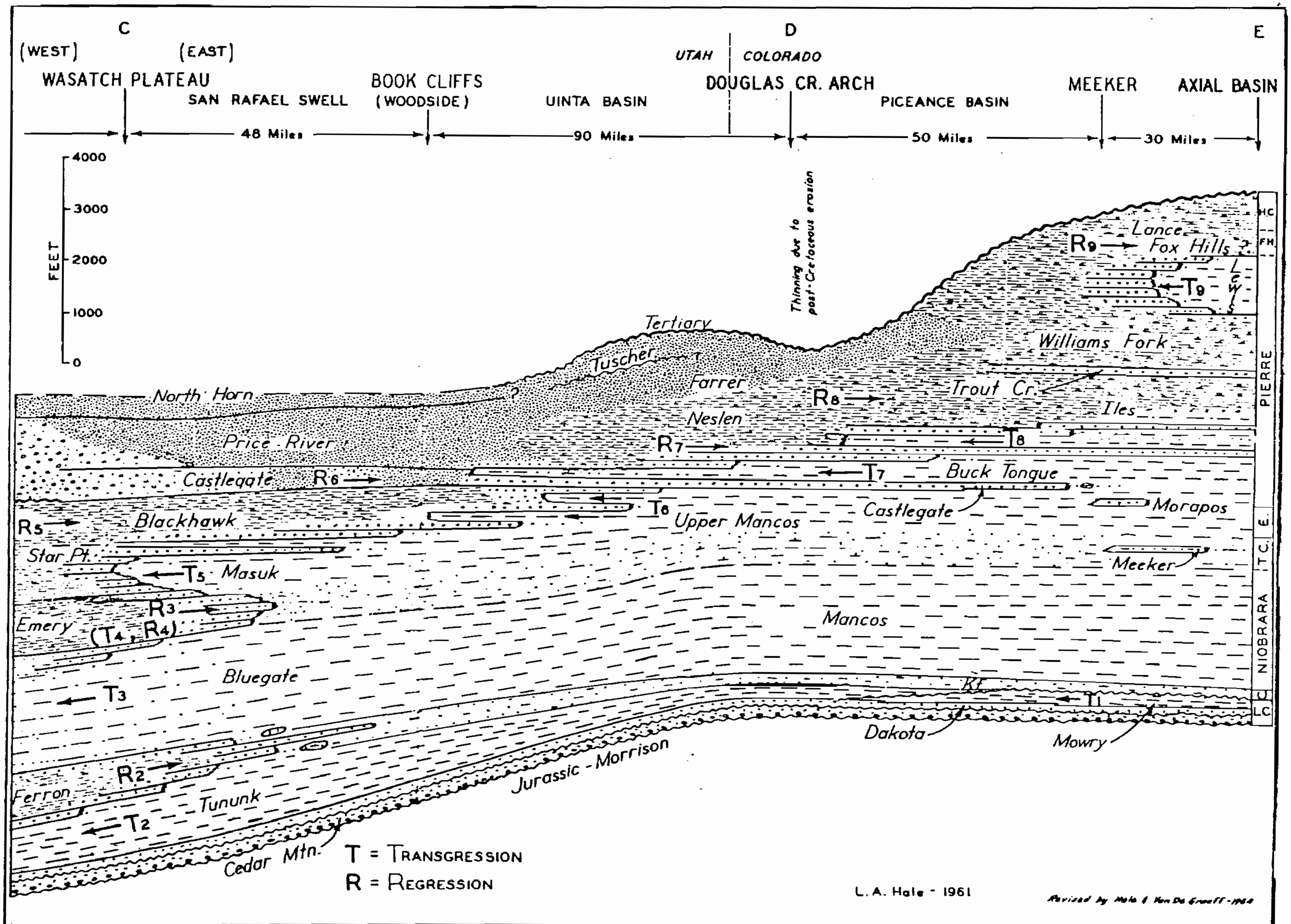


Figure 12. Diagrammatic restored section of Cretaceous rocks, Wasatch Plateau, Utah to Axial Basin, Colorado. Note Trout Creek and Fox Hills transgressions.

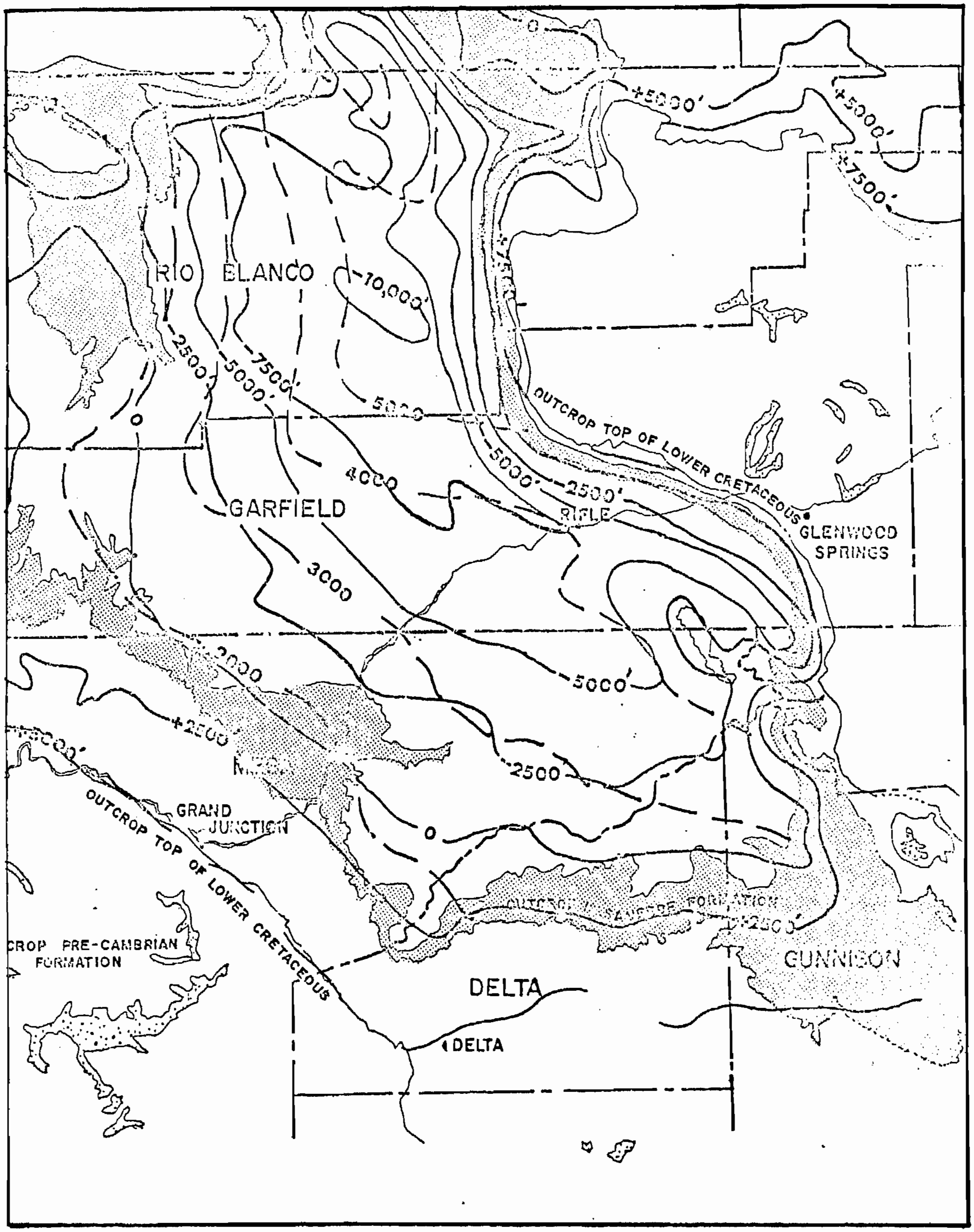


Figure 13. Regional map and structural interpretation contoured on top of lower Cretaceous, showing isopach of the Mesaverde Formation (after Millison, 1968).

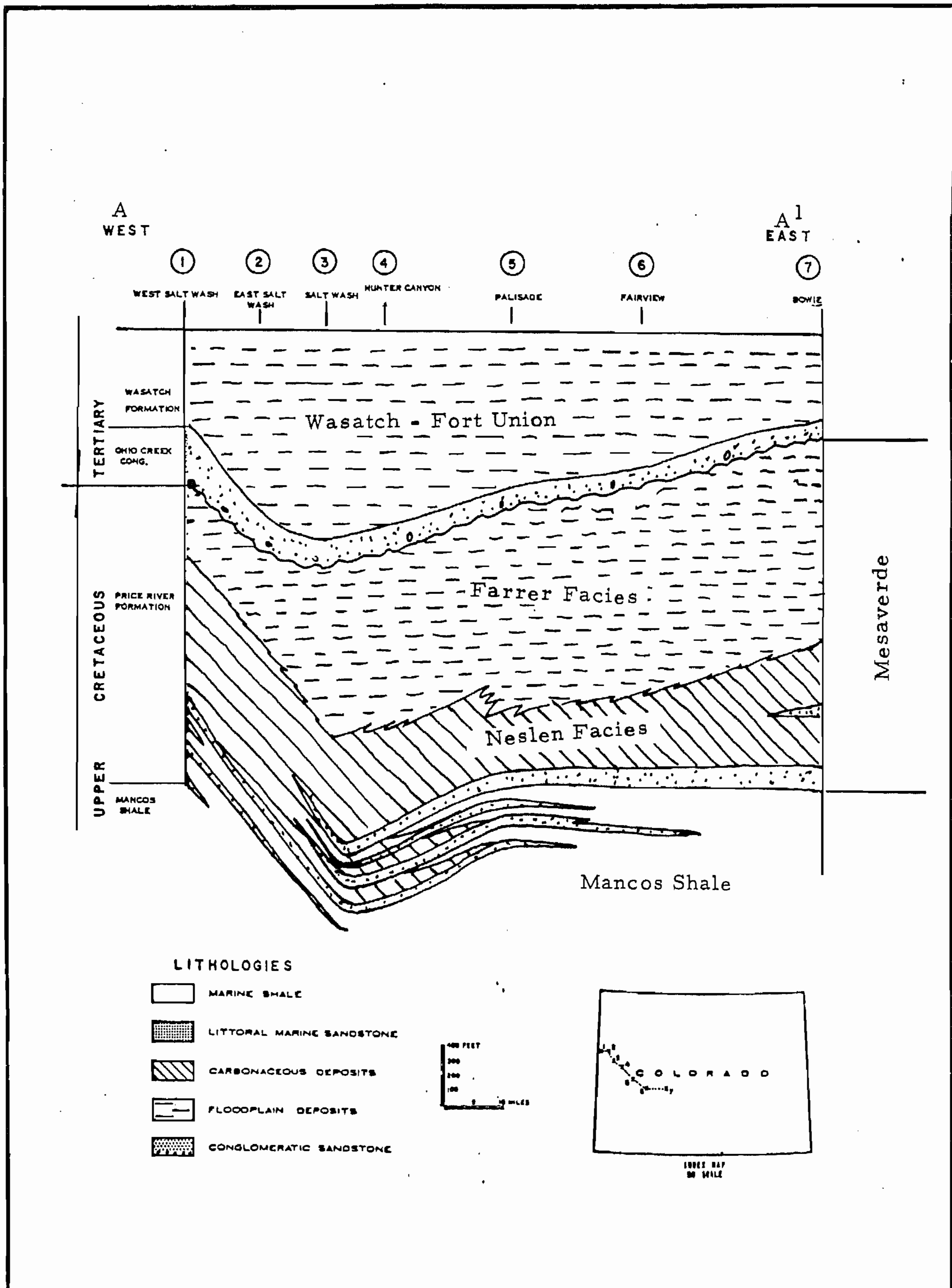


Figure 14. Paleocene, Eocene, and late Cretaceous deposits of Book Cliffs and Grand Mesa (after Quigley, 1968).

4. Mancos Formation

The Cretaceous, Mancos Formation is a dark colored, marine shale sequence that underlies the Mesaverde. The Mancos is approximately 3,000 feet thick in the central portion of the basin and contains no porous or permeable zones.

B. SAND CONTINUITY IN THE FORT UNION AND MESAVERDE FORMATIONS

1. Introduction

The problem of sandstone lens continuity in the Fort Union and Mesaverde formations is one of the critical factors in the reservoir performance in the Piceance Basin. Outcrop studies (Ref. 23-26) verify the fluvial origin of the Fort Union and upper Mesaverde sand bodies. These sandstones are complex channel fill and point bar deposits.

2. Statistical Analysis

The length/thickness ratios of sandstone lenses measured in the outcrops in the northern half of the Piceance Structural Basin showed low correlation with thickness. This means that the lenses can be considered to be part of one population, and thin or thick lenses will have roughly the same gross geometry. The correlation coefficient between length/thickness ratio and orientation was low, but significant; thus, there seems to be a preferential orientation of long axis of the elongated sandstone lenses.

The mean of the length/thickness ratios is 34 and the standard deviation is .74 logarithmic cycles (Ref. 26).

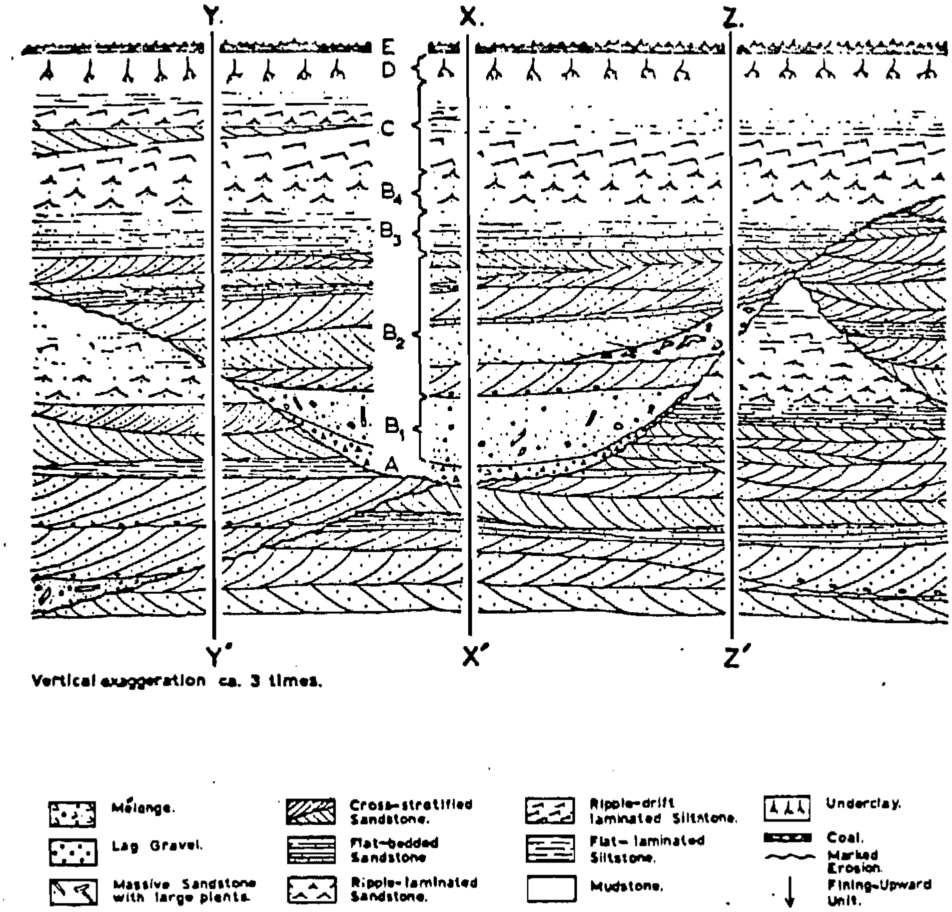
3. <u>Comparison of Statistical Results and Sandstone Body Geometries</u>

A comparison of the observed geometries of channel-fill and point bar depositional types with the Fort Union-Mesaverde outcrop data provides additional insight into the expected subsurface sand lens geometries.

Channel-fill sandstones vary widely in size. They are typified by cut-and-fill structures and frequently form composite sand bodies both in plan and cross section (Ref. 27).

Outcrops frequently will display a "typical" channel-fill structure. This cut-and-fill sequence, displayed schematically in Figure 15, is termed a "fining-upward sequence" and displays a characteristic pattern on an electric log (Figures 16, 17, 18). These figures display the SP log response to the composite channel-fill sequence displayed in Figure 15. Figure 16 shows a complete channel-fill sequence which has cut into a previously deposited channel. Figures 17 and 18 show a series of partially developed sequences resulting from profile locations that do not intersect the axial region of a single channel fill sequence.

The width of the channel is a function of the stream size and varies from a few feet in small streams to more than a mile in major streams such as the Mississippi. The width of a channel fill deposit is approximately that of the channel in which it originated. The length of the deposit depends upon the local conditions of burial and subsequent erosion. Hence, there is no simple intrinsic width-length ratio for this



Highly schematized diagram to illustrate illustrate importance of section viewed in controlling apparent type of fining-upward cyclic sequence formed by a complex of cross-cutting, discrete channel fills.

In upper channel fill, complete A-E sequences can be observed only in axial region, as in section X-X'; a marginal section, Y-Y', begins with B_2 sandstone facies, and similar profile at Z-Z' begins with a slide breccia, followed by B_2 sandstone. Lower sequences indicate effects of erosion in truncating upper parts of fining-upward cycles.

Figure 15. Schematic of typical cut-and-fill sequence.(after Kelling, 1968).

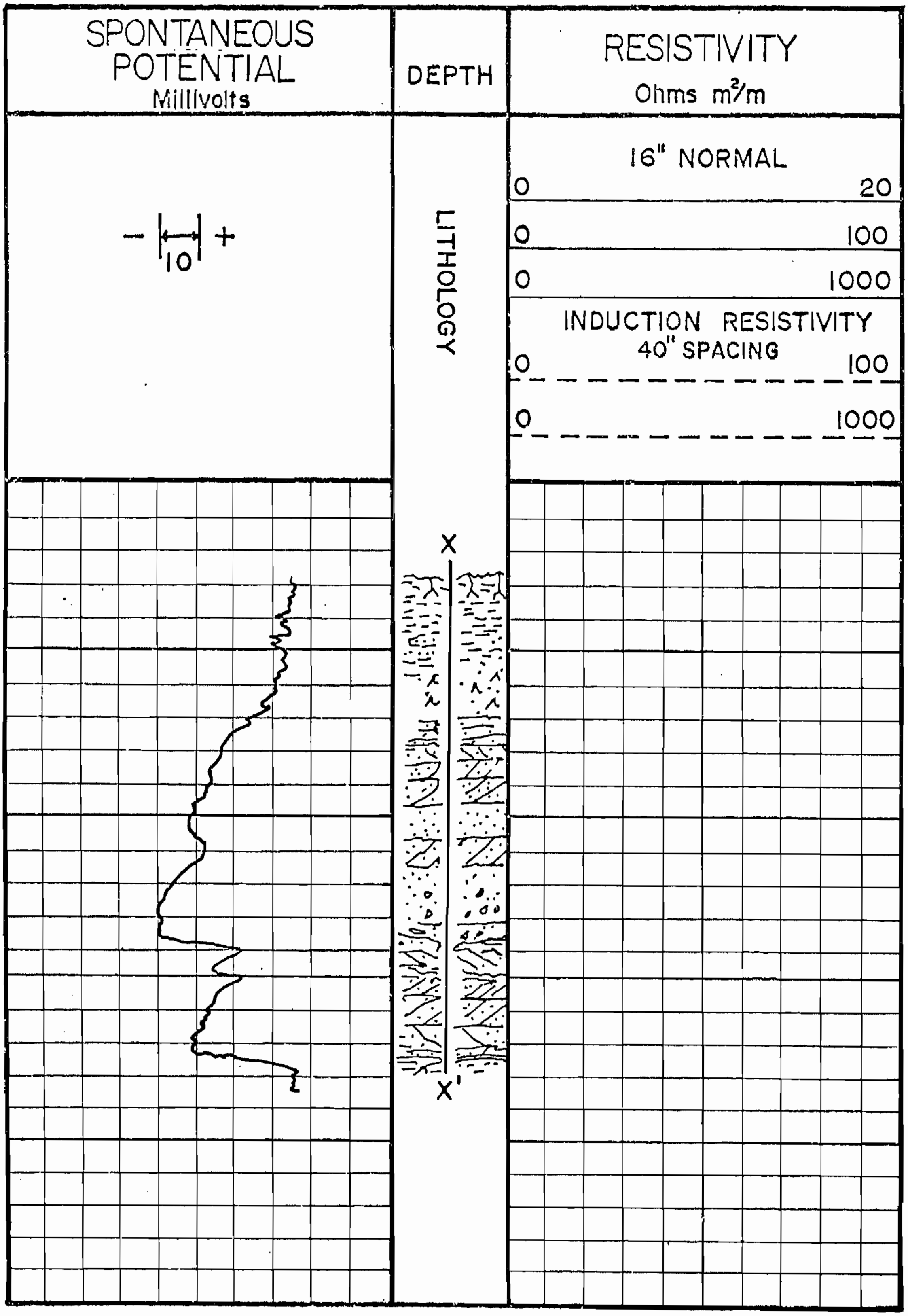


Figure 16. S. P. log response to a complete channel-fill sequence.

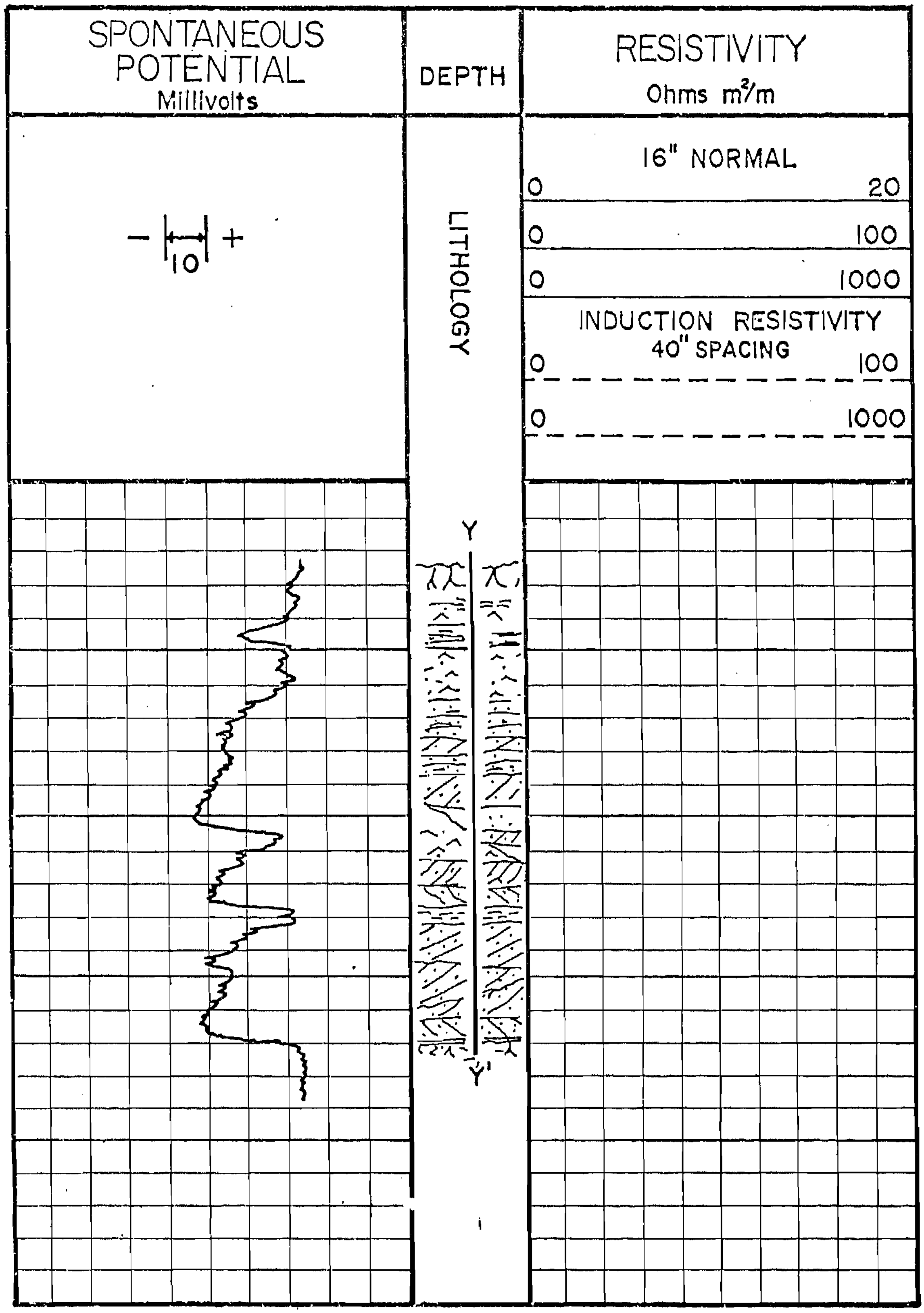


Figure 17. S.P. log response to a series of partial channel-fill sections.

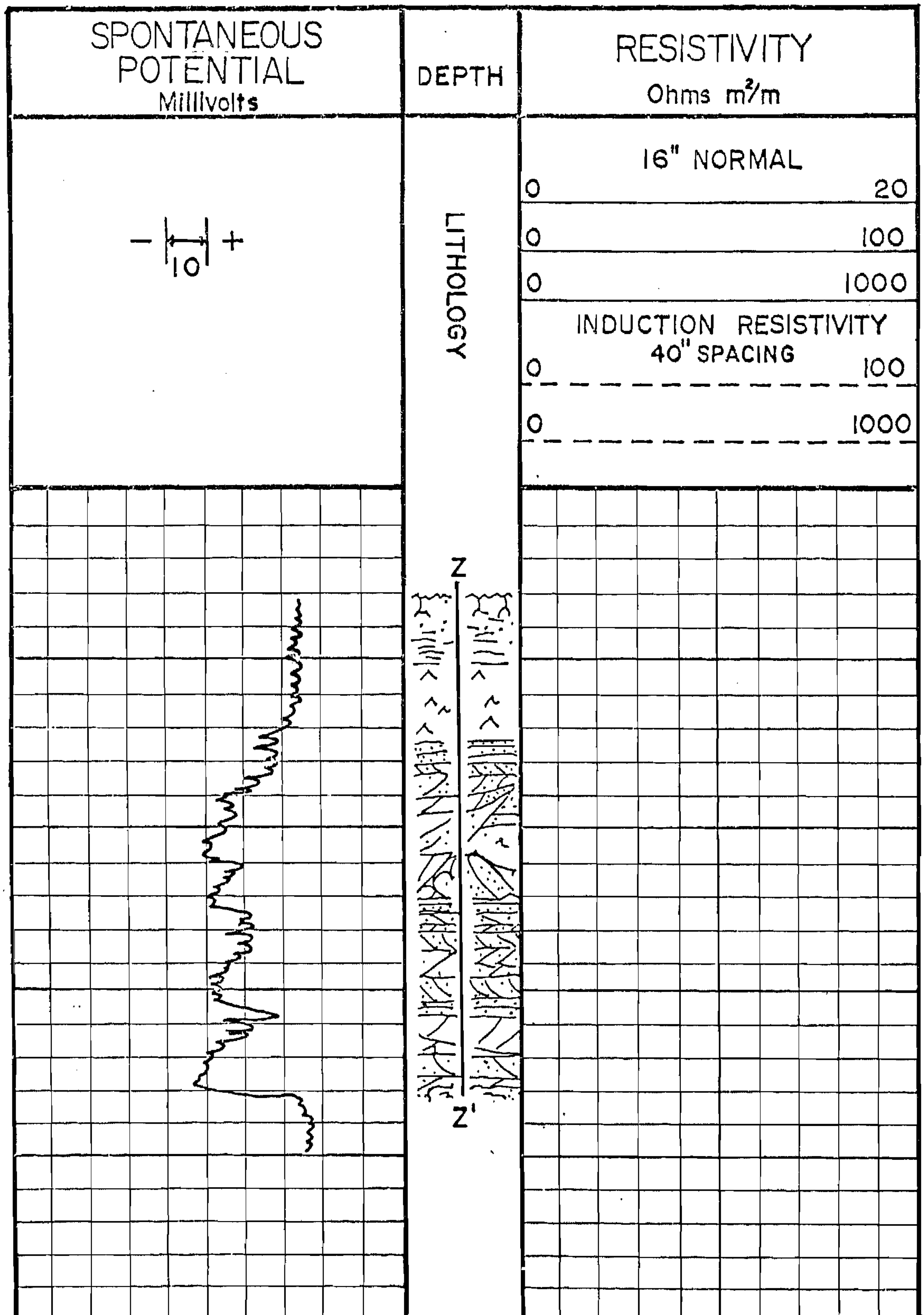


Figure 12. S. P. log response to a series of partial channel-fill sections.

type of "sandstone lens," although typical length/width ratios would be from 2.5 to $>$ 10. Typical channel width-height ratios are 10/1 to 14/1, but this also varies widely (Ref. 28).

Some of the Fort Union-Mesaverde sandstone layers in the outcrop study have the characteristics of channel-fill deposits. These lenses are frequently 20 to 30 feet thick but may form composite sandstone layers 50 or more feet thick.

Based upon the foregoing discussion, the expected "sizes" of individual channel-fill sandstone lenses would be thicknesses from 20 to 30 feet, widths from 200 to 420 feet, and lengths from 500 to $>$ 4,000 feet.

The fining-up, channel-fill deposit is typical of the deposits found along the majority of stream profiles. However, braided stream deposits can produce fining down sequences. The braided stream deposits also have smaller size sand bodies and more irregular sand to shale distributions than the more normal meandering stream deposits (Ref. 28, 29). Therefore, a more complex relationship is a possibility when a combination of braided and meandering stream deposits occur together.

Point bars are channel associated deposits. They have rather constant relationships between channel width, radius of curvature, and meander length (Ref. 30); i.e.:

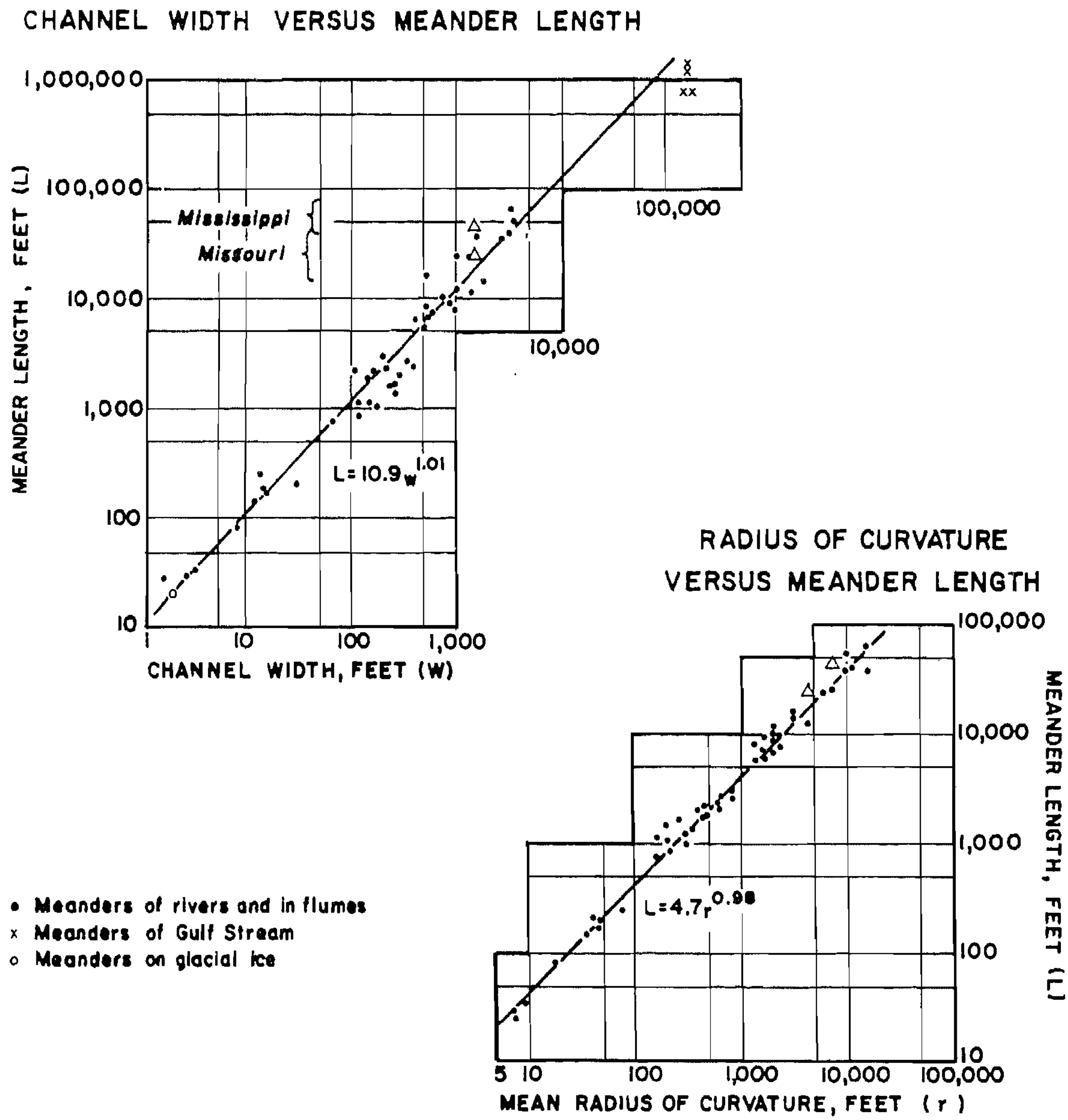


Figure 19. Channel width and mean radius of curvature versus meander length (Ref. 30).

L = 10.9W

L = 4.7r

where:

L = Meander, length, feet

W = Channel width, feet

r = Radius of curvature, feet

This relationship is plotted as Figure 19 for such diverse types of meandering as that exhibited by rivers, meltwater streams flowing on ice, meandering of the Gulf Stream, and meanders produced in flume boxes. The width of a meander-type sand body is approximately equal to the radius of curvature, and length is approximately equal to one-half the meander length. Thus, simple point bars have length/width ratios of approximately 2.4 (Ref. 30).

Two typical point bar type reservoirs are depicted in Figure 20 (Ref. 31). Average length/width/thickness ratios for these two fields are:

Coyote Creek, L/W/H = 20,000/7,000/75

Miller Creek, L/W/H = 13,000/4,000/50

Unfortunately, not many sandstone lenses of this size are known from the alluvial facies of the Fort Union-Mesaverde in the Piceance Basin. However, some point bar type sandstone bodies with lengths greater than 1,800 feet were observed in the basal Fort Union along the Grand Hogback (Figure 21). Hence, a few lenses with sizes of the order of length/width/thickness greater than 2,000/800/15 (feet) should be encountered in the subsurface.

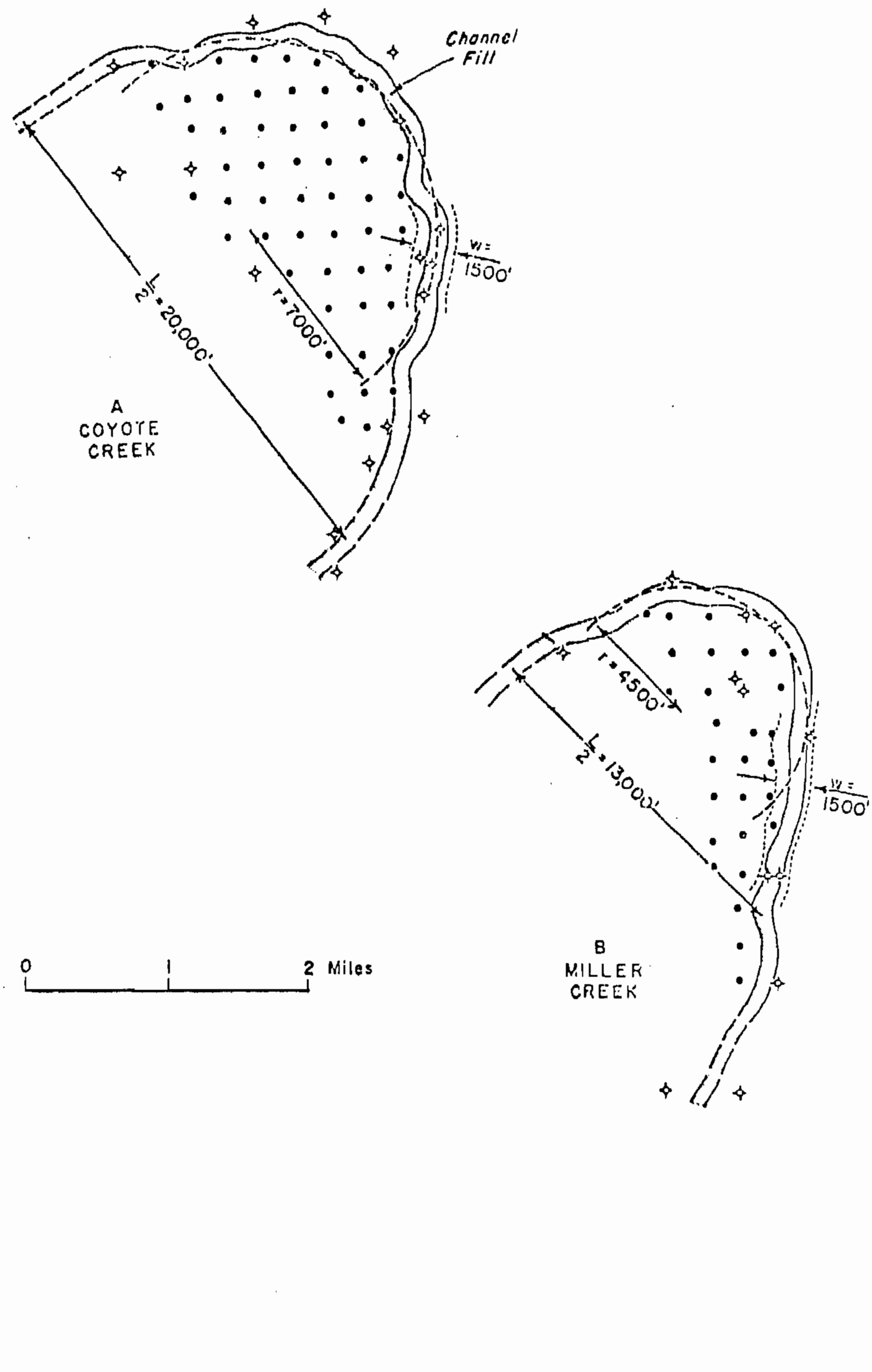


Figure 20. Two typical Cretaceous point bar fields (after Berg, 1968).

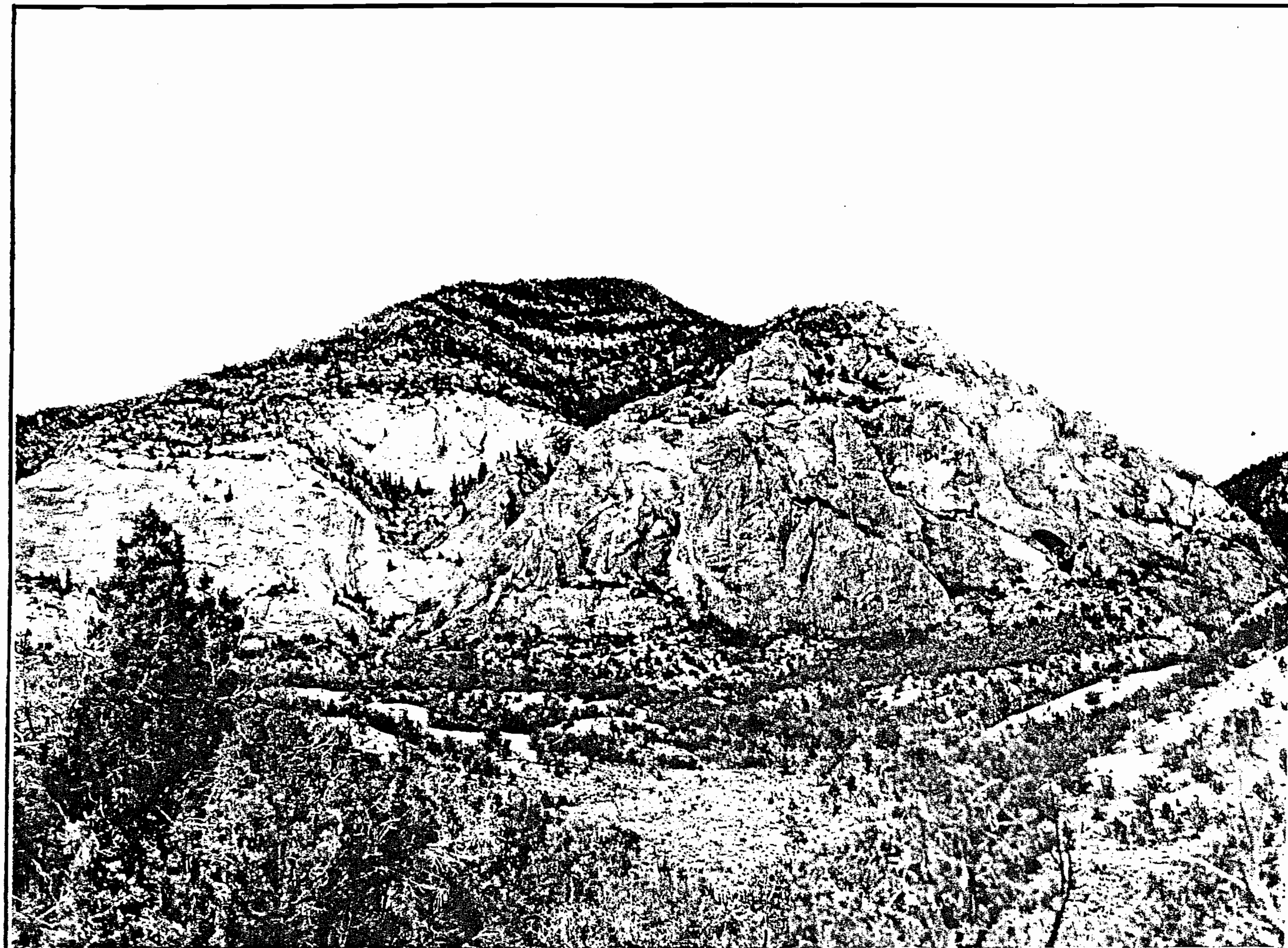


Figure 21. Point bar type sandstone lenses exposed by erosion of the Grand Hogback, north of Rifle, Colorado.

4. Sandstone Continuity Summary

The Fort Union-Mesaverde sandstone bodies in the central Piceance Creek Basin appear to be predominately fluvial, channel-fill deposits with some point bar sands. The most commonly observed thickness was between 20 and 30 feet, and the mean length/thickness ratio (L/H) was 34 for all of the observed sand body lens cross sections.

Length/width ratios (shape of body in plan view) are expected to be 2.4/1 or larger, based upon an evaluation of the types of sandstone depositional environments that produced the Fort Union-Mesaverde reservoir rocks. The channel-fill sandstones probably have widths in the order of 350 feet and lengths that generally would be more than 1,000 feet. The point bar type sandstones would be expected to have lengths in the order of 3,000 plus feet and widths in the order of 1,200 feet.

It is significant that more than 25% of the sand lenses observed in the outcrop study with a thickness of 20 feet or more had lengths greater than 1,000 feet. This augurs some optimism on average drainage radius for nuclear stimulation in this area (Ref. 22). However, the maximum expected length of any of the sand bodies would be in the order of a few miles and even considering the interconnection of sand bodies that has been observed the maximum continuity of drainage will be less than about five miles. Thus, no extensive aquifers would be expected in sandstones with this type of depositional environment.

C. STRUCTURE

The general subsurface structural configuration of the Piceance Basin is displayed by the lower Cretaceous contour map of Figure 1. The asymmetric nature of the basin is apparent, with gentle dips on the west and steep dips on the east. Some of the marginal folds extend into the basin, and terracing is common on the western flank. The east-west cross section, Figure 22, shows the general relationship of the dips and the basin center faulting.

The structural configurations of the various formations are relatively conformable, as indicated by Figure 22. However, disconformities do occur that change the section thickness in local areas.

Figure 3 shows the structure of the base of the Mahogany Zone ("B" or Black Marker), which is near the top of the Parachute Creek Member. Figure 23 shows the structure of the Orange Marker near the base of the Douglas Creek Member. The structure displayed in this latter figure shows an enhanced definition of structural features compared to the contours of the "B" Marker. Some structural control and variations in sedimentation characteristics during deposition is indicated by local unconformities and erosion. In addition, the solution of saline layers and lenses in the leached zone of middle Parachute Creek section has produced sagging of the "B" Marker and overlying rocks and part of the observed structural variation between the "B" and Orange Markers.

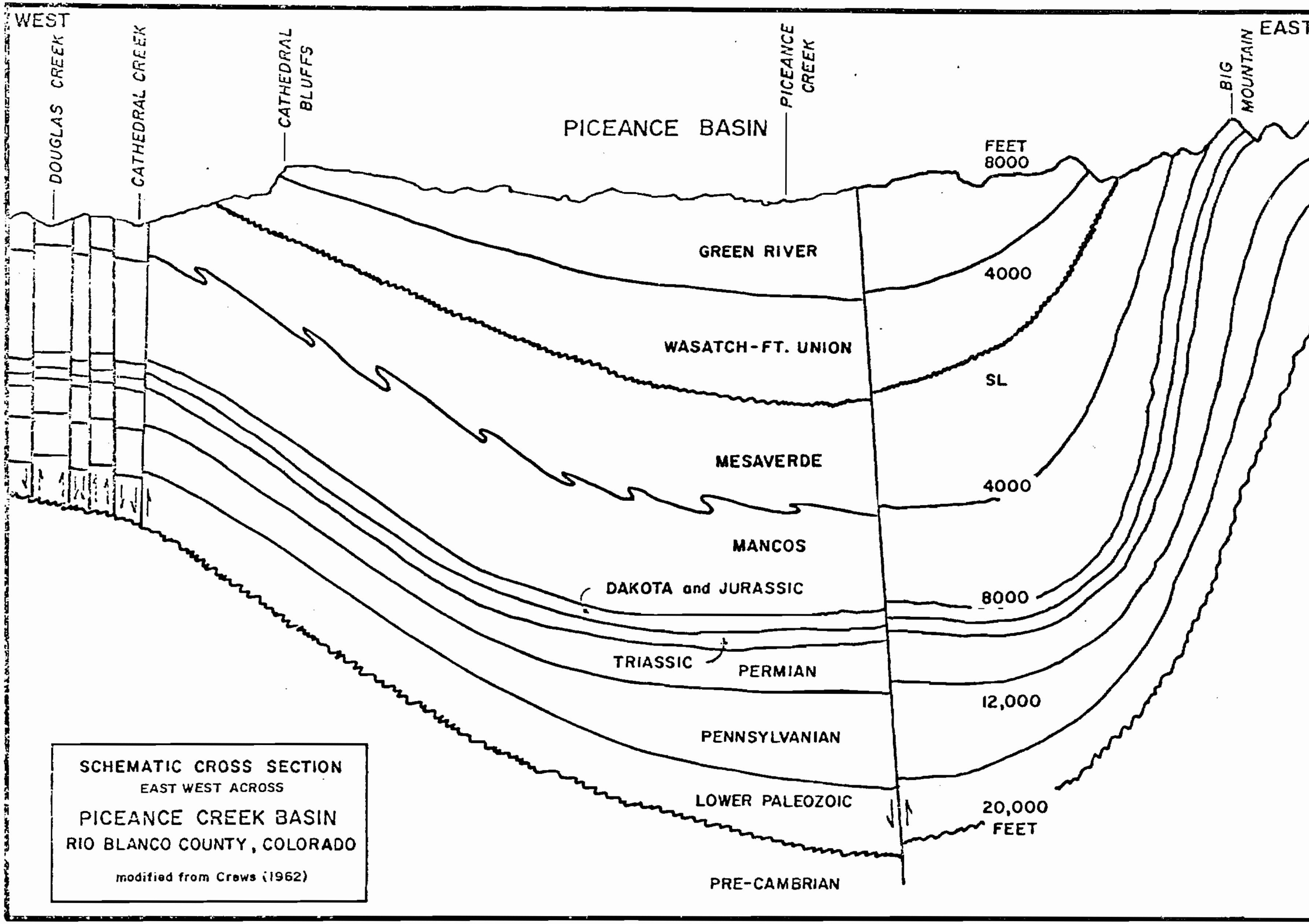


Figure 22. Schematic cross section Piceance Creek Basin, Rio Blanco County, Colorado.

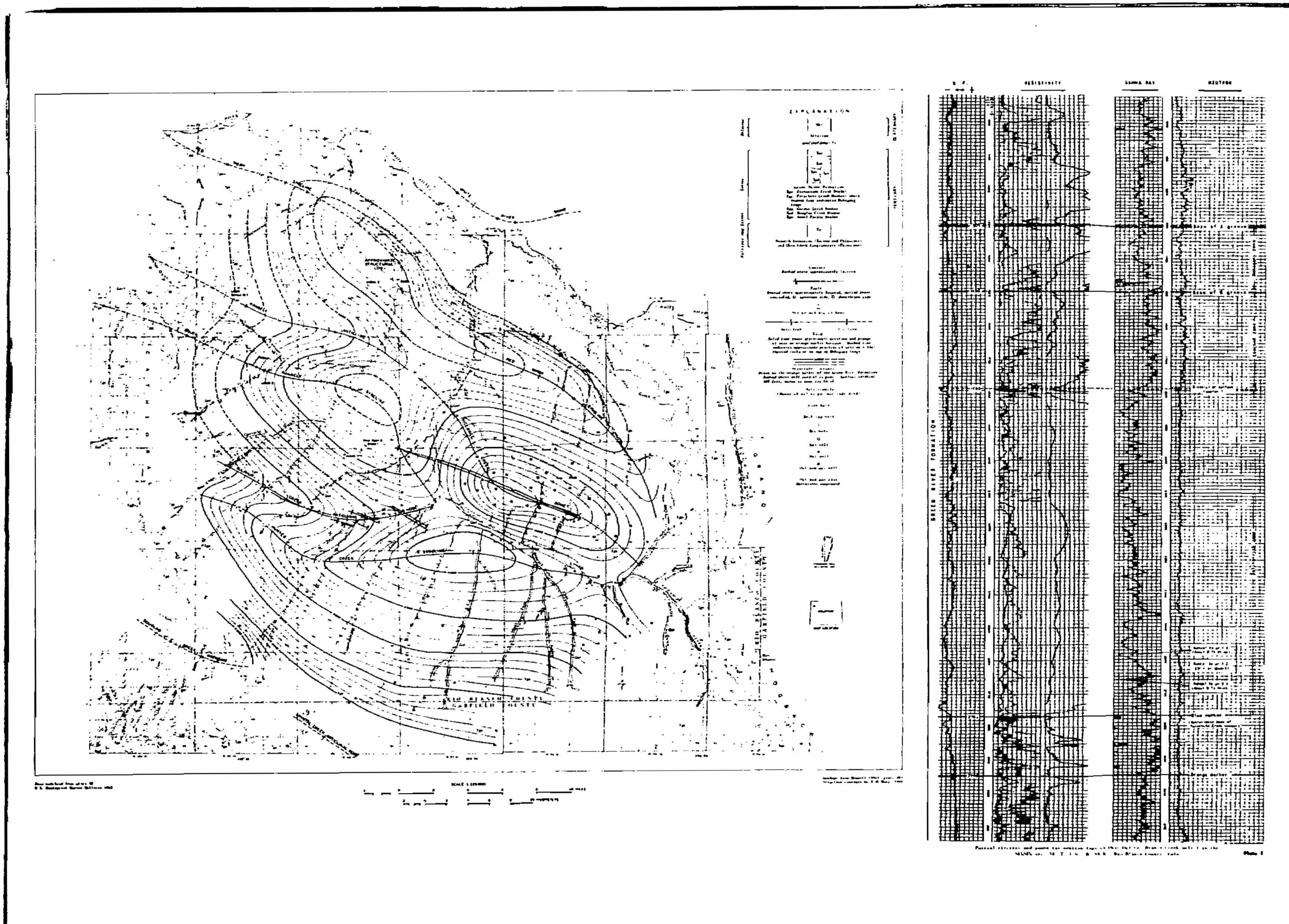


Figure 23. Structure map of the northern part of the Piceance Creek Basin, Colorado (Dyni, 1969).

The Wasatch structural map contoured on the "G" Marker (Figure 5) indicates faulting as a more important deeper structural element. The faulting seems to be associated with the positive structural elements of the basin such as the Piceance Creek Dome, and the Sulphur Creek Nose.

The Mesaverde structural map, Figure 6, is contoured on a phantom horizon near the base of the upper Mesaverde. Except for an accentuation of relief and an increase in fault density, the Mesaverde and Wasatch structural maps are quite similar. The throw of the faults is greater at greater depth, and the Fort Union faults seem to continue downward through the Mesaverde (Ref. 32).

V. ROCK PROPERTIES

A. GREEN RIVER FORMATION

The Green River Formation has been cored and logged more extensively than the other rock units in the basin. Figure 24 shows the typical log response for the section from the northern part of the basin. The logs allow a general lithologic evaluation, as well as yielding semi-quantitative results of oil yield from oil shale (Ref. 33, 34, 35). Figure 25 displays the shale oil yields versus density log and sonic log response (Ref. 36). The correlations from two sources are indicated above the density log heading and from one source above the sonic log in Figure 24. These correlations are also graphically displayed in Figure 25.

The variation in response through the Green River is tabulated below:

Log	Readings Maximum	Readings Minimum	Units
Natural gamma	240	24	API
Neutron	1,450	550	API
Sonic	145	67	microsec/ft
Density	2.57	2.0	g/cc
16" Normal	400	4	ohm m
Induction	Saturation (600)	2	ohm m
Lateralog	∞	4	ohm m

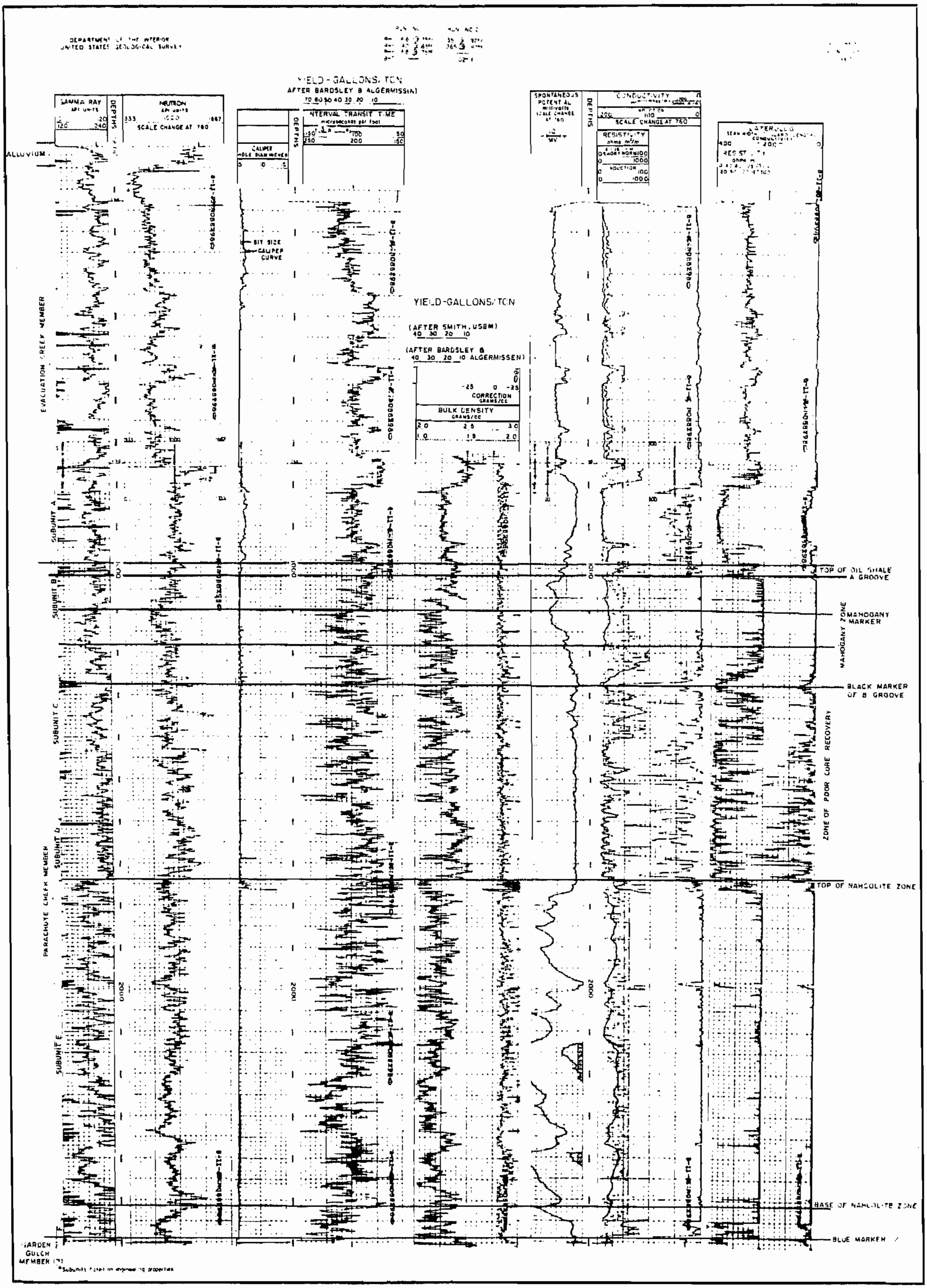


Figure 24. Geophysical logs obtained in Colorado Core Hole No. 1, Yellow Creek, Rio Blanco County, Colorado, showing pertinent horizons. (Subunits based on engineering properties.)

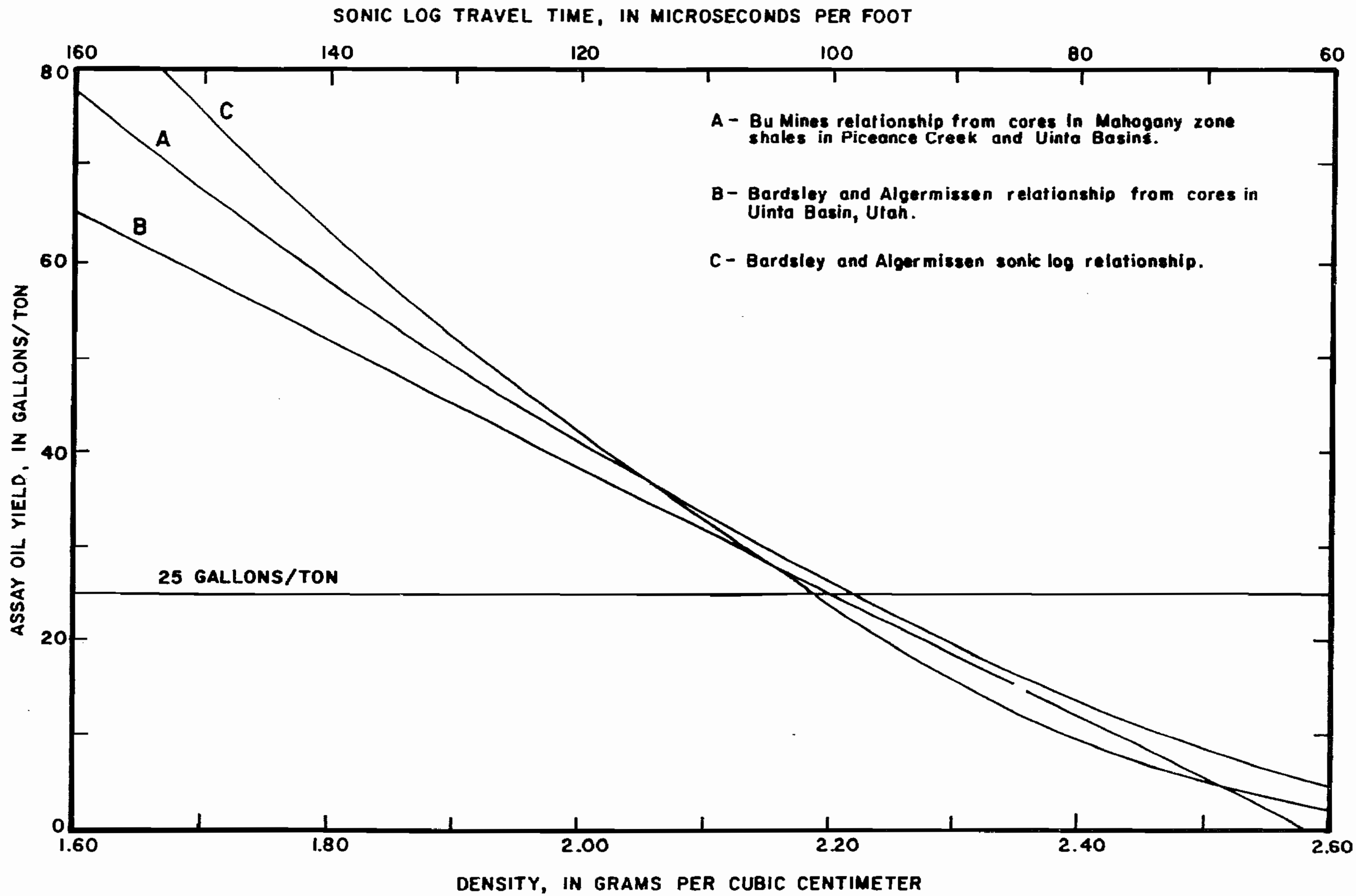


Figure 25. Relationships between density, velocity, and oil assay established by various investigators.

Three wells with logs and oil shale data are available in the general Rio Blanco experimental area (Ref. 37, 38). They are the Fawn Creek Government Number 1, Fawn Creek Unit Government Number 3, and Boies Number 1. These logs are displayed as Figure 26. The logging suite is not as comprehensive in this area as that of Figure 24, but a comparison of equivalent logs shows that the response of the geophysical logs to the oil shale is relatively constant on a basin-wide basis.

The properties of the Green River oil shale have been extensively studied because of their economic importance. Physically, the oil shale is quite anisotropic. This is illustrated in Figure 27. The compressional and shear wave velocities are variables that depend upon the direction of the propagation and orientation of the wave (as well as the confining pressures). The strength and the brittle-plastic limits of the oil shale are a function of the shale oil yield (Ref. 40-43). Figure 28 indicates the variation in the brittle-ductile transition point in samples of 26 and 18 GPT oil shale. The 26 GPT oil shale behaves in a plastic or salt-like manner, while the 18 GPT oil shale behaves more like granite.

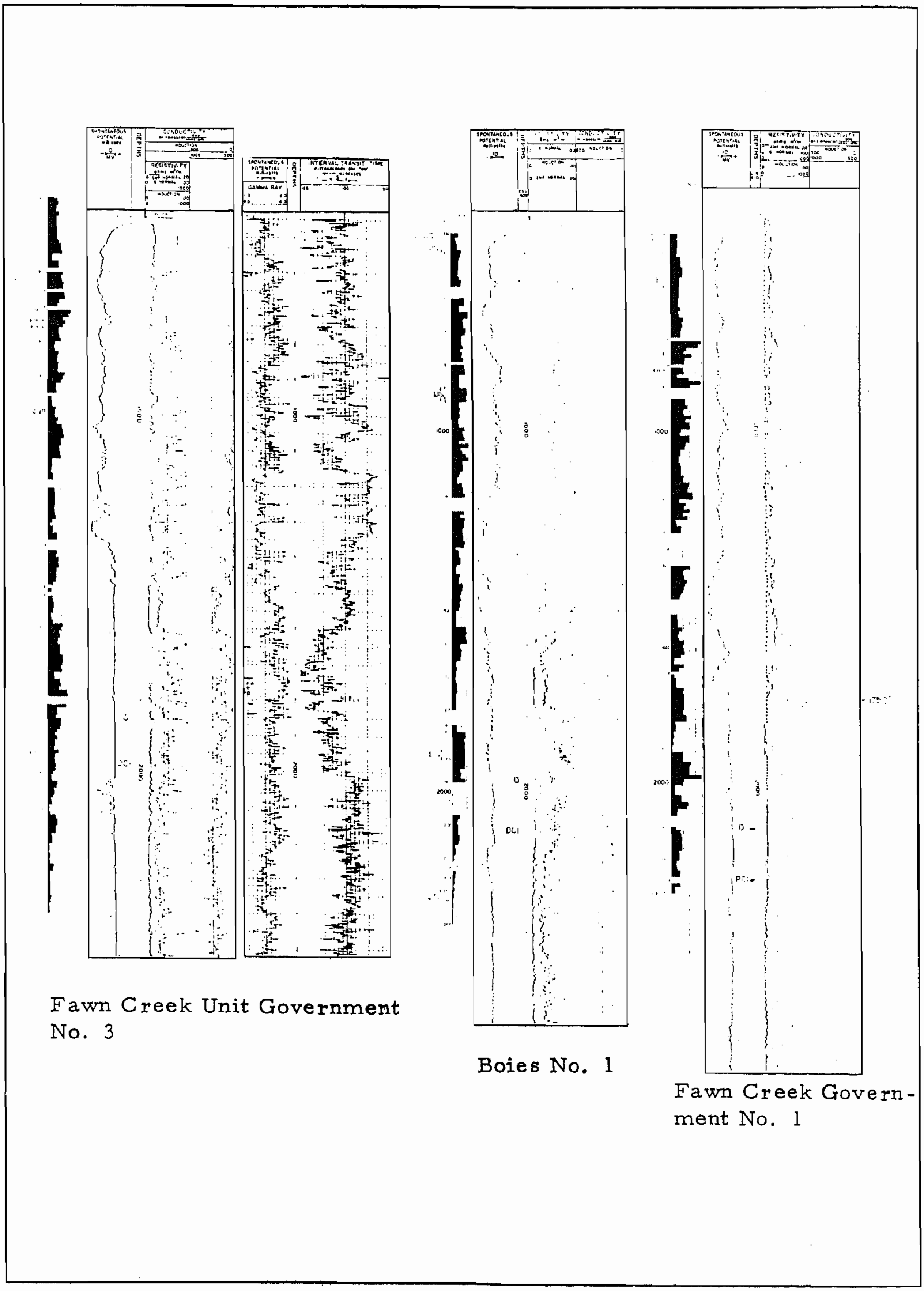


Figure 26. Log cross section, Fawn Creek Unit Government No. 3, Boies No. 1, and Fawn Creek Government No. 1.

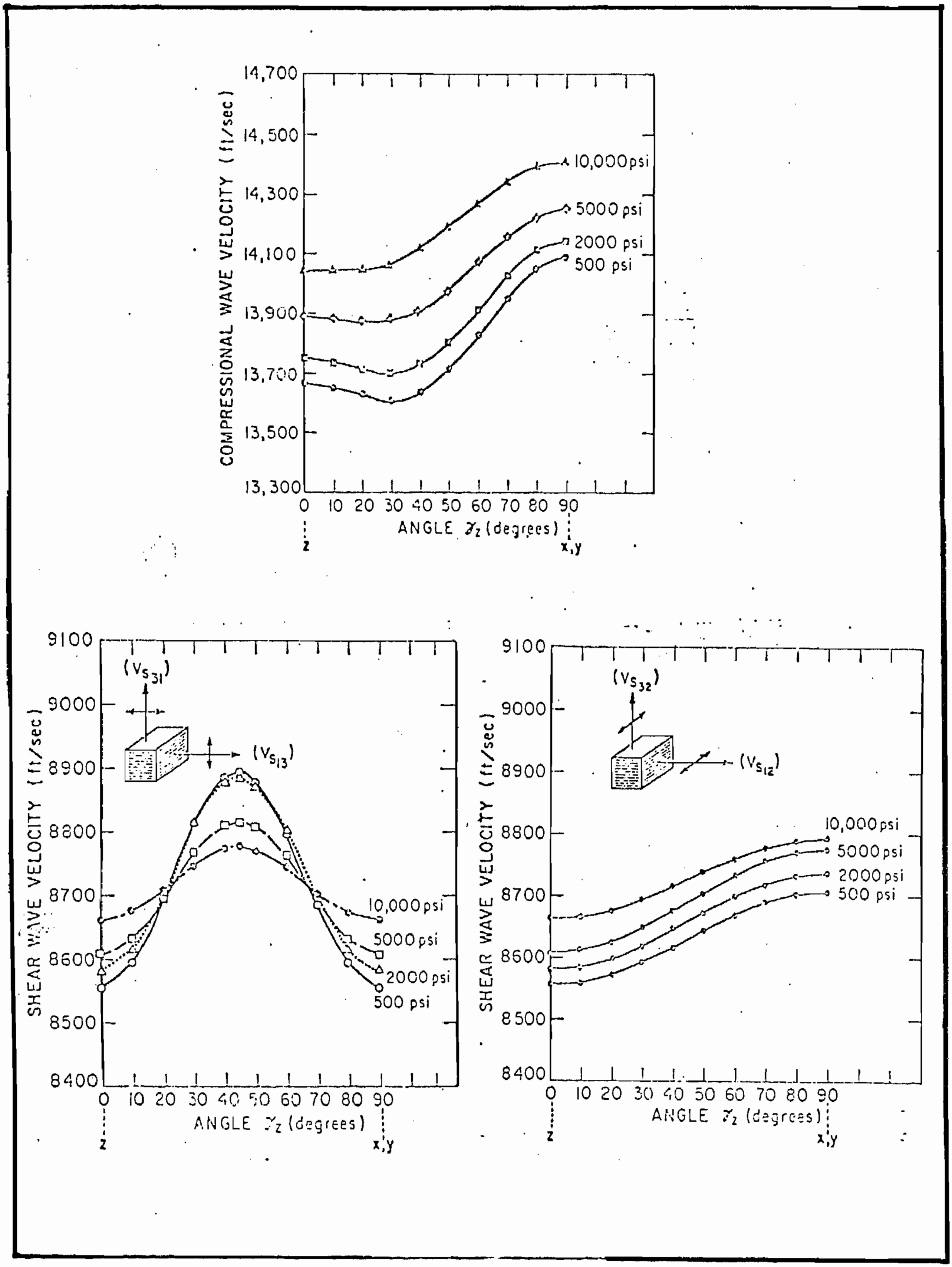


Figure 27. Calculated compressional-wave, V_P and shear-wave velocity $V_{SH,SV}$, as a function of confining pressure and direction of propagation for dry Green River shale (after Podio, 1968).

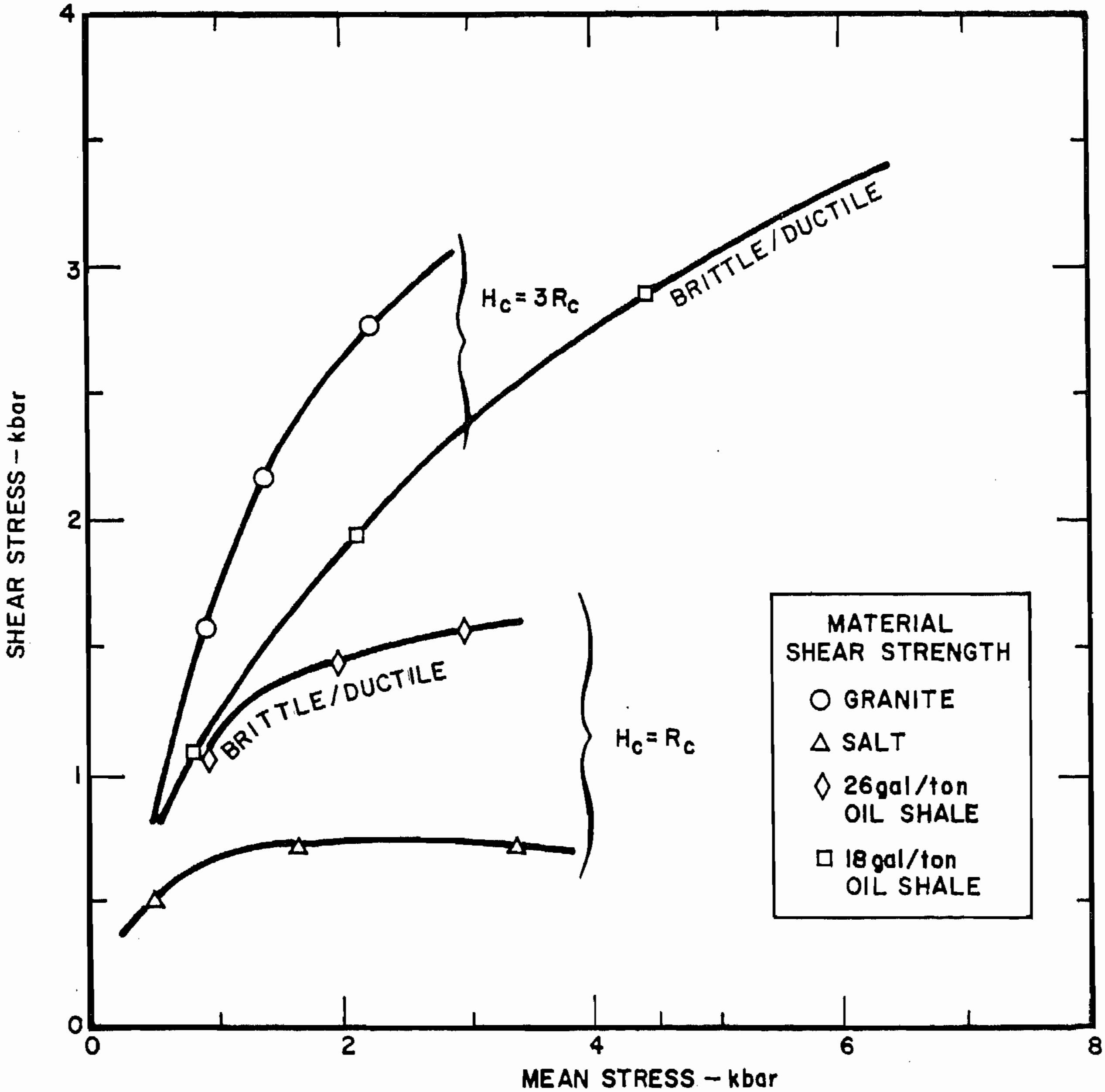


Figure 28. Comparison of brittle ductile failure behavior of lean and intermediate grade oil shale with granite and salt.

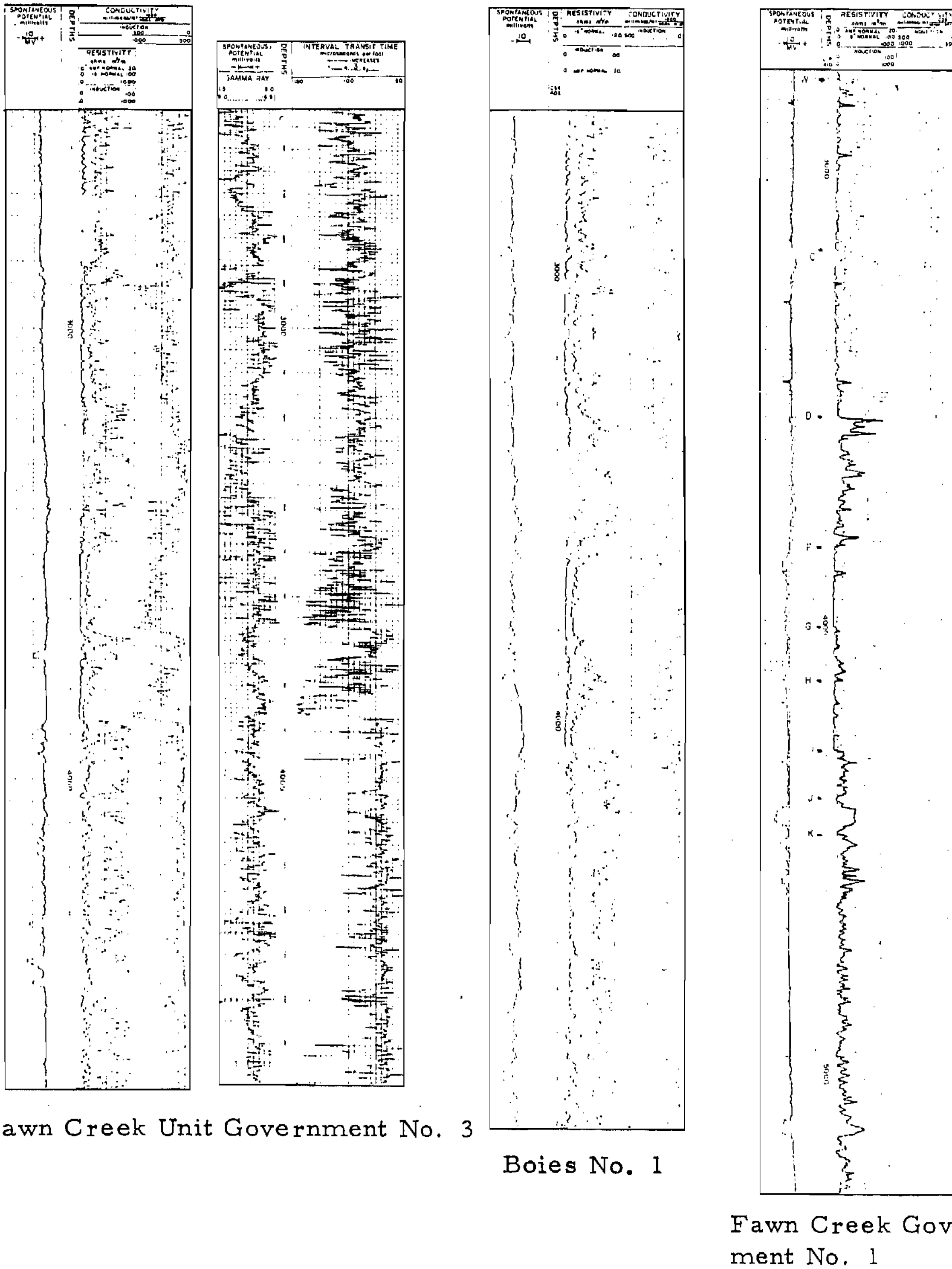
B. WASATCH FORMATION

Geophysical logs from the wells in the Rio Blanco experiment area are displayed in Figure 29. The response of the logs is summarized in the following table.

Log	Readings Maximum	Readings Minimum	Units
SP	+10	-32	Millivolts
16" Normal	17	1	ohm m
Induction	19	1	ohm m
Gamma	16	1	GR
Sonic	145	62	microsec/ft

Limited data on Wasatch Formation core analysis are available from the Rio Blanco area and the Piceance Creek Field. The averages from the core analyses are tabulated below.

Sand	Porosity, %	Permeability, MD	Density Bulk gm/cc	Density Grain gm/cc
A	16.7	79.3	2.26	2.68
D	8.5	0.8	-	-
G	11.5	0.2	2.41	2.70



Fawn Creek Unit Government No. 3

Boies No. 1

Fawn Creek Government No. 1

Figure 29. Geophysical log cross section in Rio Blanco experiment area, Wasatch section.

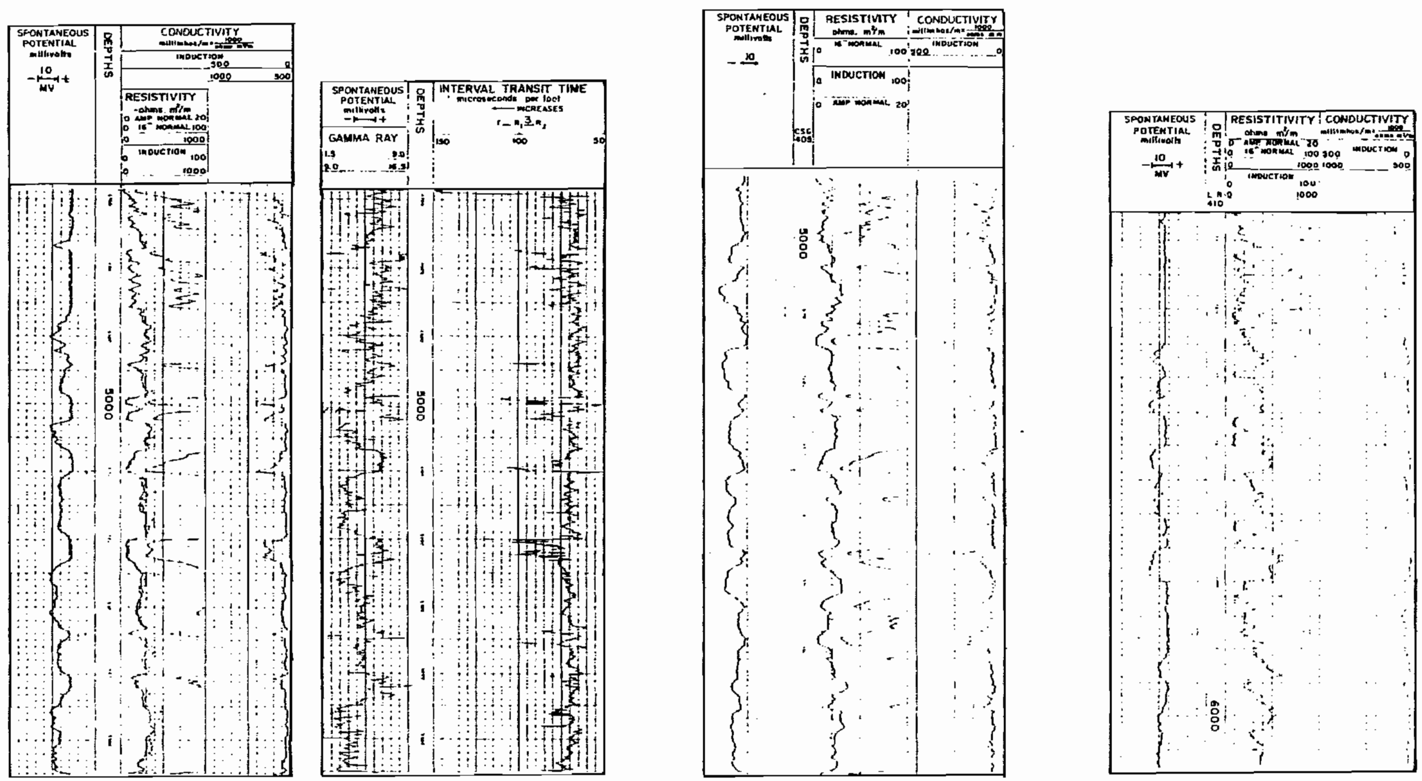
C. FORT UNION FORMATION

The logs from the Fort Union Formation in the Rio Blanco experiment area are displayed in Figure 30. The maximum and minimum responses are presented in the following table.

Log	Readings Maximum	Readings Minimum	Units
SP	0	30	millivolts
16" Normal	60	5	ohm m
Induction	80	5	ohm m
Gamma	13	2	GR
Sonic	110	60	microsec/ft

The logs and core analysis data were used in an attempt to calculate permeabilities, porosities and water saturations for the Fort Union reservoir rock.

Fort Union porosities (ϕ) and water saturations (S_w) were determined from a limited number of cores analyzed by a number of commercial laboratories, A statistical analysis of the data occurs in Reference 44, with the ranges and median values of Fort Union core measurements given in the following tabulation. S_w values greater than 70% and ϕ values less than 5% were excluded.



Fawn Creek Unit Government No. 3

Boies No. 1

Fawn Creek Government No. 1

Figure 30. Geophysical log cross section of Rio Blanco experiment area, Fort Union section.

PORØSITY (Ref. 44)

	Number of Samples	Range (%)	Median (%)
Gabbs-Thurman Government Number 4	64	7.2 - 17.7	10.1
Shannon Government Number 1	30	5.3 - 12.6	8.0
Sulphur Creek Number 3	7	9.0 - 11.9	10.4
Scandard Draw Number 1	7	8.8 - 16.9	14.5
Aggregate	108	5.3 - 17.7	9.8

WATER SATURATION (Ref. 44)

	Number of Samples	Range (%)	Median (%)
Gabbs-Thurman Government Number 4	12	45.6 - 65.5	59
Scandard Draw Number 1	6	56.0 - 69.5	61
Shannon Government Number 1	30	27.4 - 69.0	41
Aggregate	48	47.4 - 69.5	47

The results of 72 Fort Union porosity and water saturation calculations from IES logs of Sulphur Creek numbers 4, 5, 6, 7, Fawn Creek Government Number 1, Scandard Draw Number 1, and Stuarco-Sulphur Creek Number 1 are presented in Figure 31. No clear-cut relationship between ϕ and S_w is evident from this figure, as indicated by the high degree of scatter. The median ϕ and S_w values, as indicated in the plot, are 13.5% and 60%, respectively. Ranges are 8 to 22% and 33 to 70%, respectively. These values are somewhat greater than those indicated by core analysis. However, they are believed to be more representative of the entire Fort Union section than the core values,

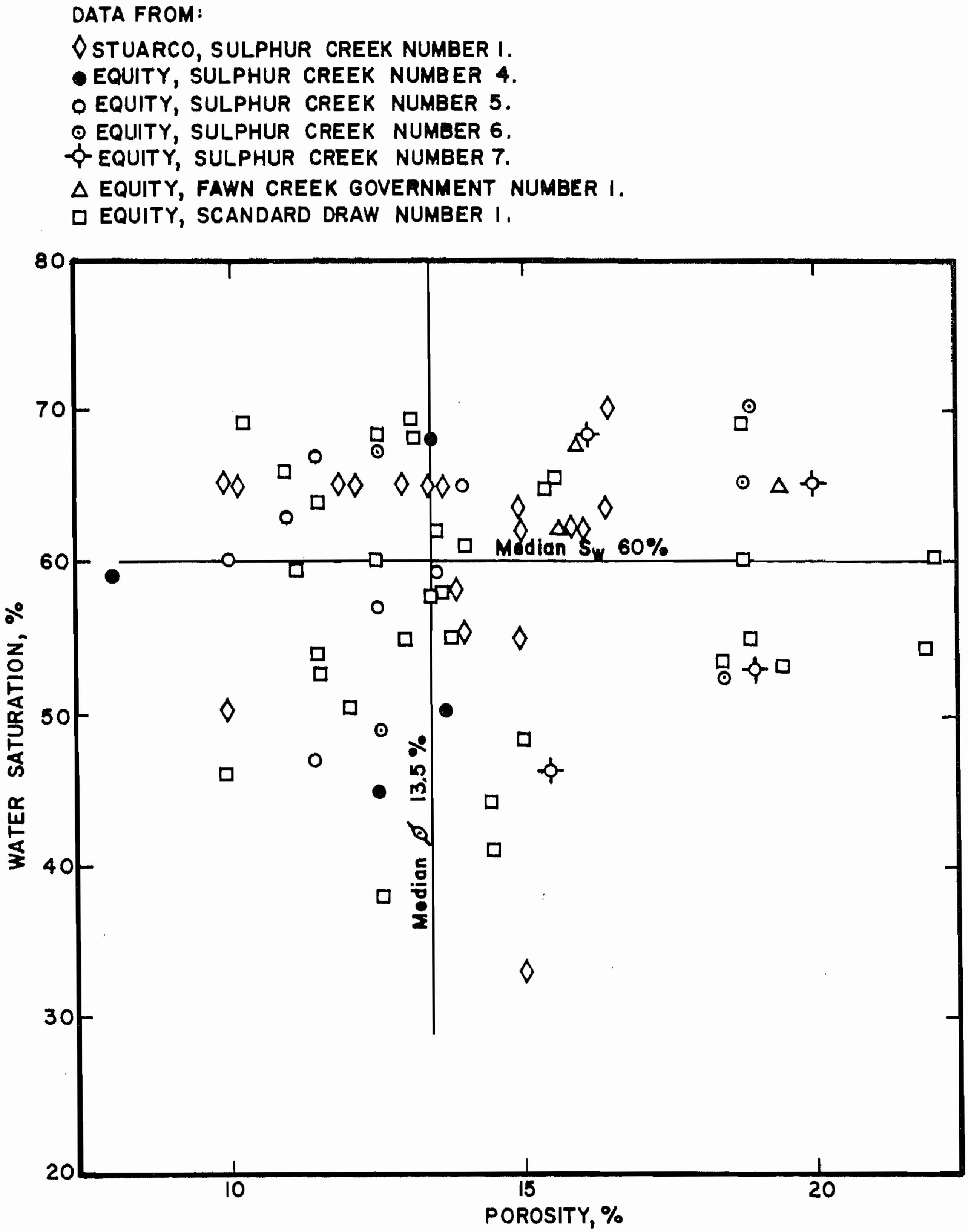


Figure 31. Water saturation versus porosity, Fort Union sandstone, calculated from IES logs.

which are limited to select zones; therefore, these log median values seem most appropriate to characterize the Fort Union. The effect of this selection upon the resource calculations is inconsequential, since the median gas-filled porosities calculated from both the core and log data are very close--5.2% for core and 5.4% for log data.

Core permeabilities are plotted as a function of porosity and water saturation in Figures 32 and 33, respectively. Figure 32 shows the range of permeabilities to be 0.01 to 5.5 md, with a median of 0.09 md. Figure 33 shows the irreducible water saturation at 0.09 md to be approximately 50%. Based on the log analysis, it would appear that a 60% S_w is more typical of the reservoir (Ref. 44).

By assuming the median log S_w value of 60% to be the irreducible water saturation at the median log porosity of 13.5%, the median permeability can be estimated using the empirical equation from Schlumberger (Ref. 45).

$$k = \left[79\,\phi^3 / (S_w)irr\right]^2 = 0.106 \text{ md}$$

where:

k = Permeability in md

ϕ = Porosity, expressed as a fraction

$(S_w)irr$ = Irreducible water saturation, expressed as a fraction

The log calculated value of 0.106 md is in close agreement with the core value of 0.09 md.

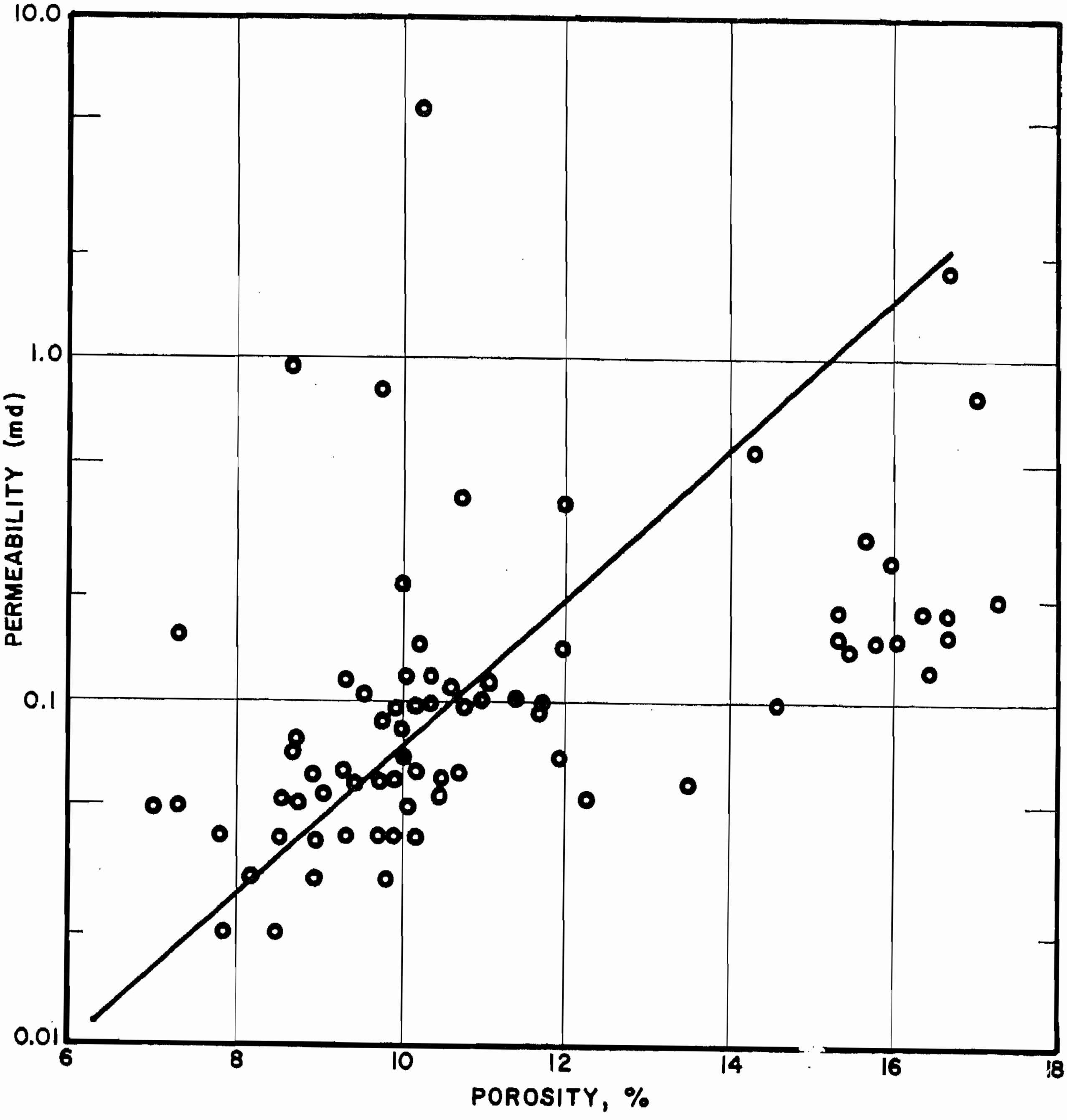


Figure 32. Core permeability versus porosity, Fort Union sandstone.

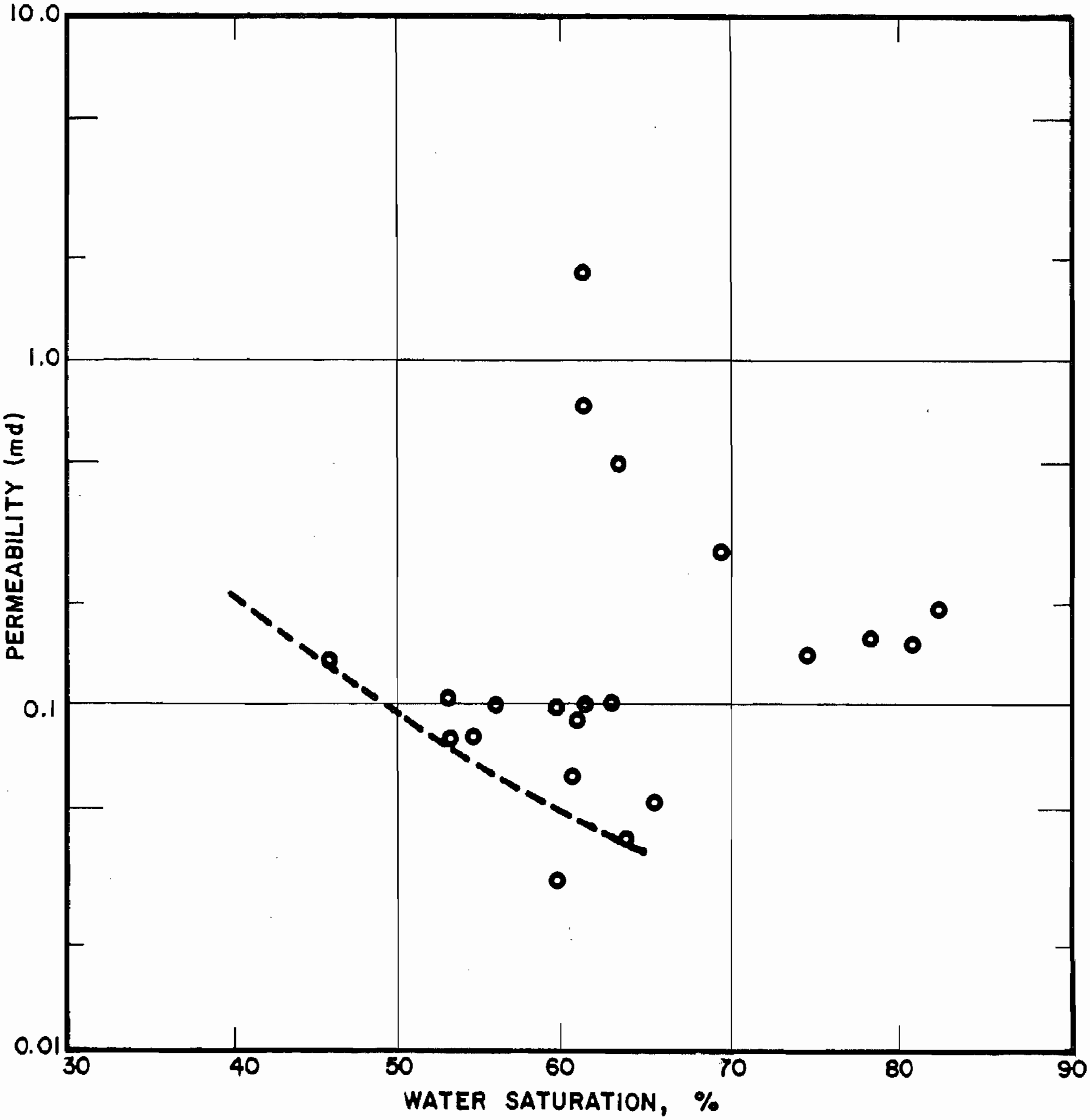


Figure 33. Core permeability versus water saturation, Fort Union sandstone.

Limited production testing in the Fawn Creek Government Number 1 Well yielded relative gas permeability that ranged from 0.02 to 0.06 md (Ref. 26); therefore, the permeabilities from the various sources are in general agreement.

Two Fort Union shale samples were qualitatively analyzed using x-ray diffraction techniques (Ref. 46). The results are:

	Depth (ft)	
Mineral	5,200 - 5,230	5,600 - 5,640
Quartz	M	M
Feldspar	W	W
Illite	M	M
Koolinite	M	M
Dolomite*	2	1
Calcite*	4	2

M = 10 - 50 wt %

W - $<$ 10 wt %

Trace element analyses results from these shale samples are presented in Table I (Ref. 47).

*Acid evaluation results.

Table I. (after Hill, 1971) Results of Trace Element Analyses of Shale

	Element	Fawn Creek Government No. 3 5,200 - 5,230	Fawn Creek Government No. 3 5,600 - 5,640	*Accuracy
Wt. %	Ca	2.18	1.48	±2%
	Mg	1.06	1.03	±2%
	ACID CO_2	2.99	1.30	±5%
	Total C	1.56	1.10	±5%
	C as CH_x	0.74	0.75	±5%
Wt. ppm	Li	46	46	±10%
	B	70	70	±50%
	Sc	12	12	±50%
	Y	25	20	±50%
	La	50	50	±50%
	Ce	50	50	±50%
	Nd	50	50	±50%
	Eu	< 2	< 2	±50%
	Dy	< 5	< 5	±50%
	Yb	2	2	±50%

*Probable accuracy expressed as a percent of the concentration.

D. MESAVERDE FORMATION

The Mesaverde geophysical log section from the Rio Blanco experiment area is presented as Figure 34. The maximum and minimum responses are presented in the following table.

Log	Reading Maximum	Reading Minimum	Units
SP	0	-30	millivolts
16" Normal	65	6	ohm m
Induction	90	1	ohm m
Gamma	10	2	GR
Sonic	130	55	μsec/ft

The porosities, permeabilities, and water saturation characteristics of the Mesaverde section were evaluated using a combination of log and core analysis data.

Upper Mesaverde porosities and water saturations were obtained from core analysis and analyzed in a similar statistical manner to those from the Fort Union Formation with the following results (excluding ϕ less than 5% and S_w greater than 70%).

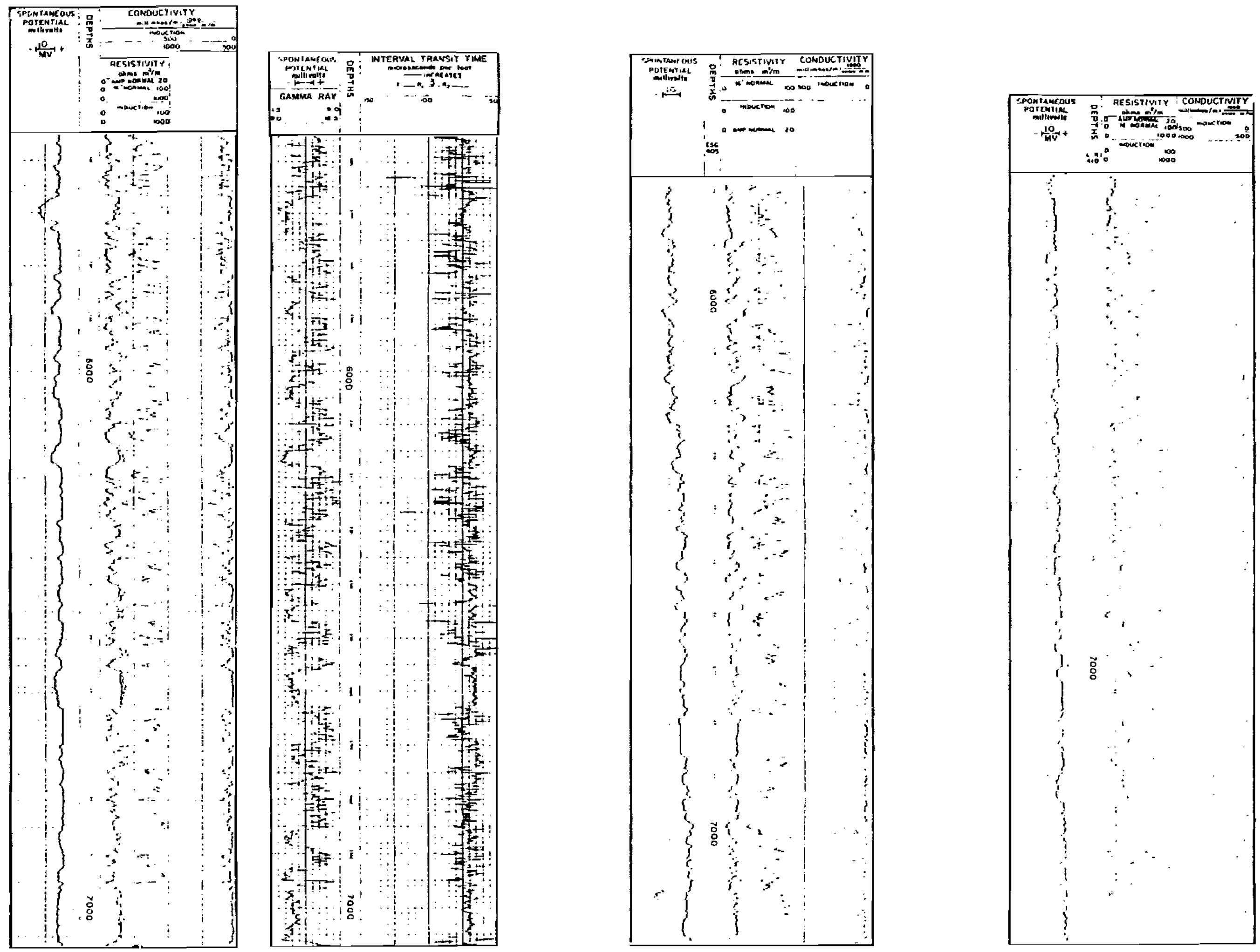


Figure 34. Geophysical log cross section, Rio Blanco experiment area, Mesaverde section.

POROSITY (Ref. 44)

Well	No. of Samples	Range (%)	Median (%)
Boies Number 1	285	5.0 - 18.0	12.6
Scandard Draw Number 1	13	5.0 - 9.4	8.0
Sulphur Creek Number 1	67	5.0 - 12.7	10.0
Aggregate	365	5.0 - 18.0	12.0

WATER SATURATION (Ref. 44)

Well	No. of Samples	Range (%)	Median (%)
Boies Number 1	28	30.5 - 69.8	56
Scandard Draw Number 1	7	51.0 - 68.0	57
Sulphur Creek Number 1	13	48.0 - 66.5	55
Aggregate	48	30.5 - 69.8	56

The results of 64 upper Mesaverde porosity and water saturation calculations from the IES logs of Sulphur Creek numbers 4, 5, 6, 7, Fawn Creek Government Number 1, and Scandard Draw Number 1 are presented in Figure 35. The median ϕ and S_w indicated in this plot are 10.5% and 60%, respectively. Porosities range between 5.5% and 16.5%; water saturations between 34% and 70%. These values are quite close to the values obtained through core analysis (Ref. 44).

Core permeabilities are plotted as a function of porosity and water saturation in Figures 36 and 37, respectively. Figure 36 indicates a fairly good straight line relationship between the porosity and the log of the permeability. Permeabilities range between 0.01 and 47 millidarcies with a median of 0.35.

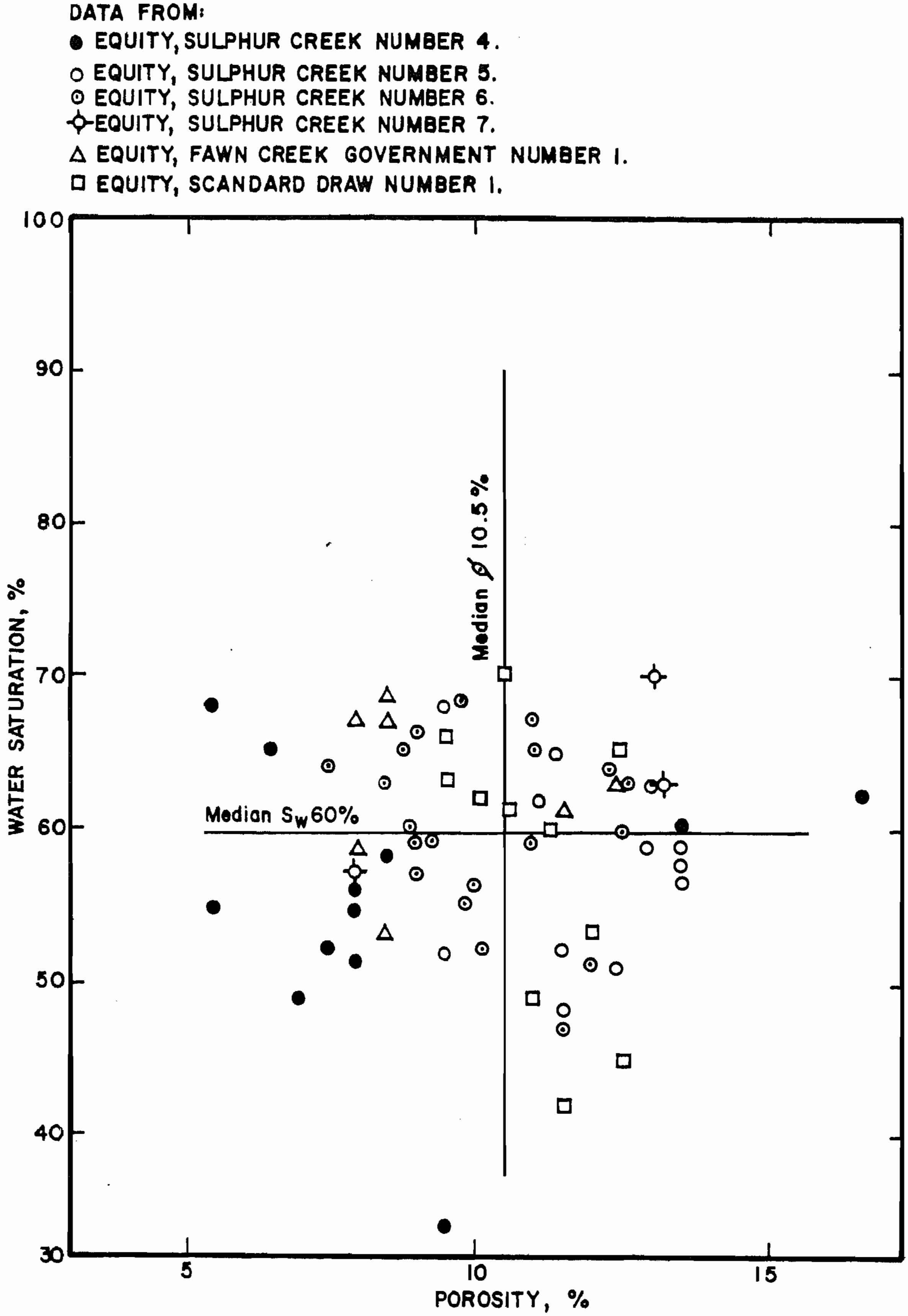


Figure 35. Water saturation versus porosity, Mesaverde I sandstone, calculated from IES logs.

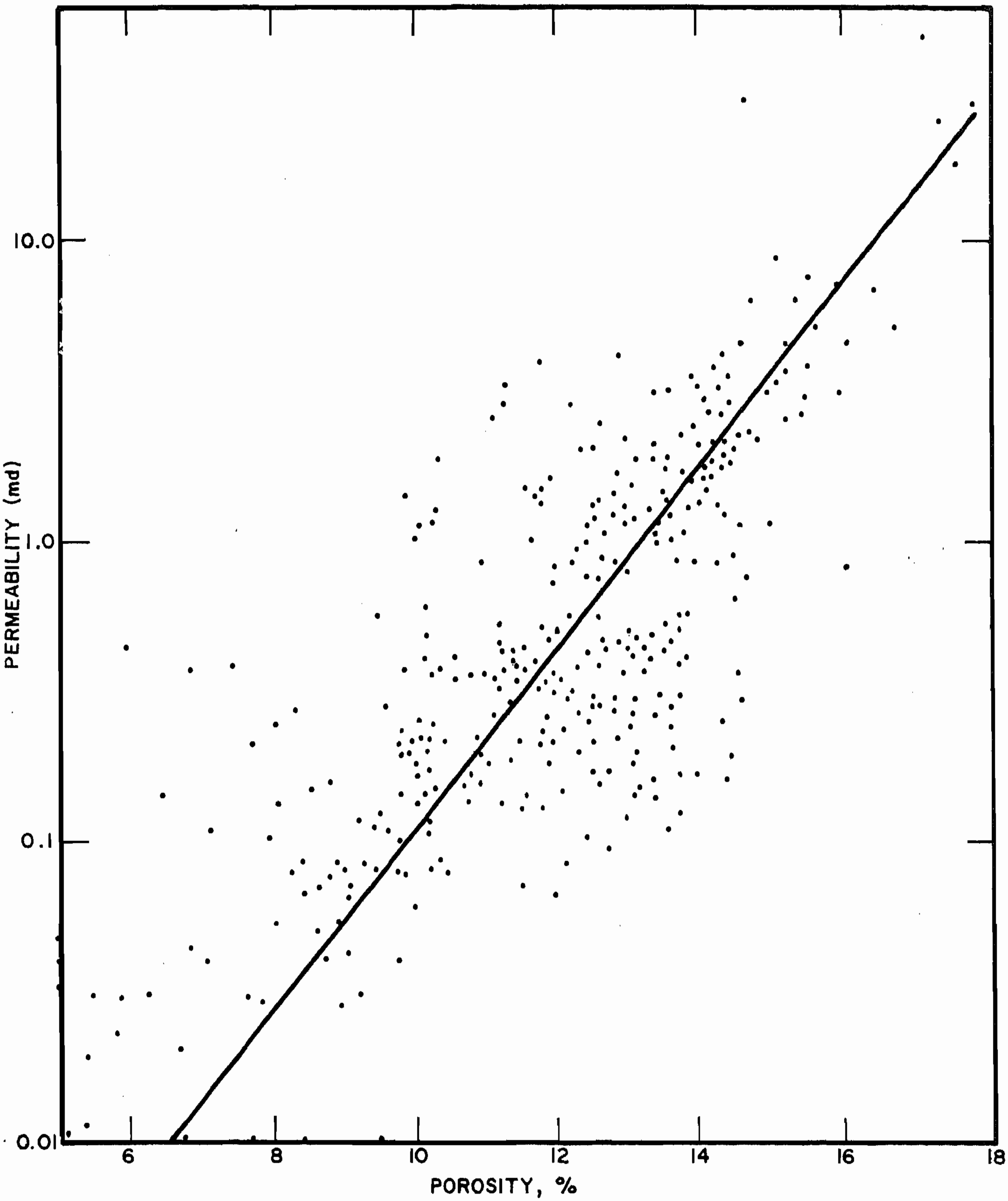


Figure 36. Core permeability versus porosity, Mesaverde I sandstone, Foies No. 1, Scandard Draw No. 1, Sulphur Creek No. 1.

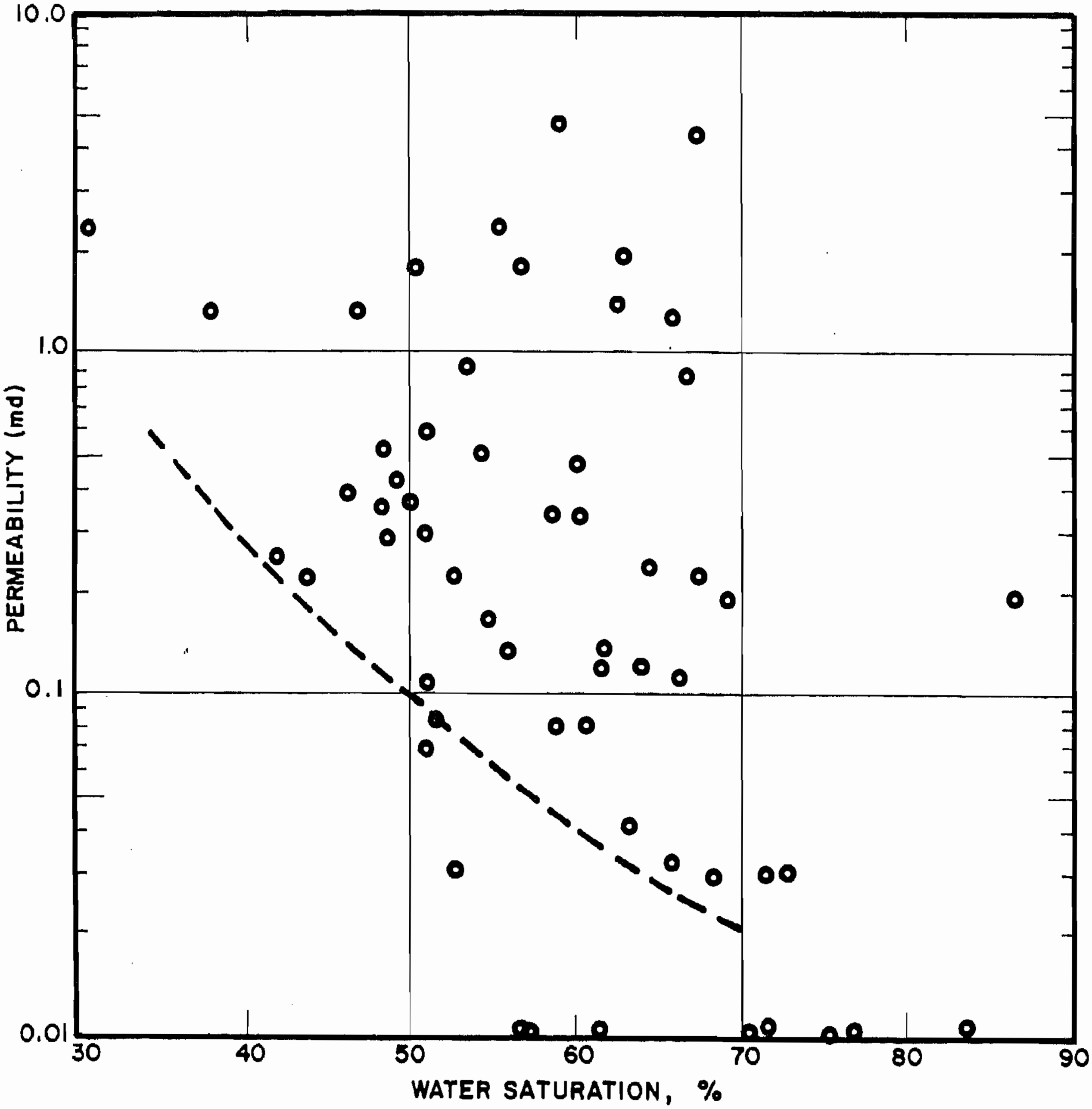


Figure 37. Core permeability versus water saturation, Mesaverde I sandstone.

The irreducible water saturation at this median value is estimated from Figure 37 to be approximately 35%. Since the S_w value of 60% appears to be more typical of the reservoir (as indicated by log analysis) this value is suggested for use in resource calculations. The median permeability, calculated from log data (Ref. 45) in a manner similar to that used for the Fort Union, is approximately 0.01 md.

A limited number of thin sections of upper Mesaverde sandstone from the South Sulphur Creek Number 4 Well were examined utilizing a petrographic microscope. The sandstone is composed predominately of fine to very fine grains of quartz. However, there is an appreciable fraction of weathered feldspar grains (10 to 40%) and carbonate grains (3 to 10%). It is interesting to note that the carbonate grains occurs in this manner instead of cement. Carbonaceous and clayey streaks and wisks and oxidized opaque grains are common. Based upon grain counts, the relative amounts of the rock forming oxides are:

$$SiO_2 > Al_2O_3 > CaO \cong Na_2O \cong K_2O > FeO \cong MgO$$

The qualitative x-ray defraction results from two Mesaverde samples are consistant with the above estimates (Ref. 46).

Mineral	Mesaverde Depth (ft) 6,399 - 6,400	6,411 - 6,412
Quartz	S	S
Feldspar	M	M
Illite	M	M
Dolomite (wt. %)*	7	5
Calcite (wt. %)*	1	0

S = >50 wt %

M = 10 - 50 wt %

W = < 10 wt %

Trace element analyses are also available from the two Mesaverde sandstone samples (Ref. 47), see Table II.

*From acid evaluation measurements.

Table II. (after Hill, 1971) Results of Trace Element Analyses of Mesaverde Sandstone

Element		South Sulphur Creek Number 4 6,411 - 6,412	6,399 - 6,400	*Accuracy
Wt. %	Ca	1.48	1.0	±2%
	Mg	0.66	0.87	±2%
	ACID CO_2	2.39	3.76	±5%
	Total C	0.94	1.41	±5%
	C as CH_x	0.29	0.37	±5%
Wt. ppm	Li	6.7	6.7	±10%
	B	25	25	±50%
	Sc	3	3	±50%
	Y	15	15	±50%
	Ce	25	25	±50%
	Nd	15	15	±50%
	Eu	< 2	< 2	±50%
	Dy	< 5	< 5	±50%
	Yb	1	1	±50%

*Probable accuracy expressed as a percent of the concentration.

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