MEMOIR 17

Geology of Pennsylvanian and Wolfcampian Rocks in Southeast New Mexico

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Abstract

The area of this study includes about 38,700 square miles in southeast New Mexico that lie within the Great Plains physiographic province on the east and the Basin and Range province on the west. Pennsylvanian and Wolfcampian rocks are discontinuously exposed in the mountain ranges on the west and in boreholes elsewhere.

Major positive elements of the area during Pennsylvanian and Wolfcampian time included the Pedernal uplift, which extended in a north-south direction through the center of the area, and the Central Basin platform, the northwest corner of which lay in the southeast part of the area. Minor positive features included the domical Roosevelt uplift in the northeast, the Oscura and Joyita uplifts in the northwest, and the Diablo platform in the southwest. Major negative elements were the Permian basin on the east and the Orogrande basin on the west. Subprovinces of the Permian basin were the Northwest shelf and the Delaware basin, which included the Salt Flat embayment. Subprovinces of the Orogrande basin were the Robledo and Sacramento shelves. The Orogrande basin merged northward with the extreme south end of the Estancia basin, and in like manner the Permian basin joined the Tucumcari basin.

Pennsylvanian and Wolfcampian rocks are subdivided into stages based upon biostratigraphic zones defined by occurrences of fusulinids. It is possible to trace the zones over the entire area, thus effecting correlation of subsurface occurrences with outcroppings of rocks of the same age. The Pennsylvanian System here includes, in ascending order, the Morrowan Stage of the Lower Pennsylvanian Series, the Derryan and Desmoinesian Stages of the Middle Pennsylvanian Series, and the Missourian and Virgilian Stages of the Upper Pennsylvanian Series. Permian rocks described are those of the Wolfcampian Stage (Lower Permian Series).

Prior to Pennsylvanian time, the area was the site of a shelf across which were deposited Cambrian, Ordovician, Silurian, Devonian, and Mississippian sediments in seas entering the area from the south. Post-Chesteran uplift on the north resulted in southward tilting, and erosion, of pre-Pennsylvanian rocks. Pennsylvanian strata were deposited across Mississippian rocks to the south and on progressively older rocks northward, where Precambrian is exposed. In pre-Morrowan time, the Pedernal uplift was formed, which divided the area into two parts throughout the balance of the Pennsylvanian.

Morrowan rocks are the most areally restricted of the various stages and contain the largest proportion of coarse elastic material. They attain thicknesses of 1250 feet in the Permian basin and 75o feet in the Orogrande basin. Topographic relief over the Pedernal uplift was probably at a maximum during this time, most pre-Pennsylvanian sediments being eroded from it. Erosion of the granite core provided quartzose sandstone to the basins.

Derryan seas of the Estancia and Orogrande basins were separated from those of the Tucumcari and Permian basins by the Pedernal uplift. Derryan rocks consist of dark-colored sandstones, shales, and limestones 75o to 1000 feet thick. Graded bedding is found locally in the south Estancia basin, suggesting crustal instability; in the area as a whole, relief was less than before, as evidenced by lower sandstone-shale ratios.

Rocks of the Desmoinesian Stage are predominantly carbonate, mostly limestone. However, elastic rocks occur over the Sacramento shelf and a delta has been identified there. These strata attain a maximum thickness of 1000 feet. Reefs are found on the Robledo and Sacramento shelves and at several places in the Permian basin, where they form petroleum reservoirs. Graded bedding is found locally in the south Estancia basin.

Missourian rocks, ranging in thickness up to moo feet, contain a large proportion of elastics, indicating increased instability of the Pedernal uplift. Graded beds occur in the south Estancia basin and red beds are common elsewhere.

Greatly increased thickness of Virgilian rocks indicates increased negativity of the Orogrande basin, where as much as zoo feet of elastics, carbonates, and evaporites accumulated, compared with 1000 feet of limestones and shales in the Permian basin. Reefs are found in the subsurface of the Permian basin, along the north margin of the Delaware basin and on three sides of the Orogrande basin, on the south and along the edges of the Robledo and Sacramento shelves. Deposits with graded laminations accumulated on the Robledo and Sacramento shelves, in the latter area in lagoons between the reefs on the west and the land area of the Pedernal uplift to the east.

Apparently sedimentation in the Permian basin was continuous from Pennsylvanian time throughout Wolfcampian. To the west, however, an unconformity is present between older rocks and Lower Wolfcampian marine and nonmarine sediments, which were deposited from the north toward the south as far as the north end of the Sacramento shelf. Following withdrawal for part of middle Wolfcampian time, the sea advanced across the south part of the Orogrande basin, and in it were deposited marine limestones; these interfinger with red shales formed from red tidal flat muds being carried into the area from the north. Wolfcampian strata range in thickness to 3500 feet; the rocks include reefs on the north part of the Sacramento shelf, on the Robledo shelf, and in many places in the Permian basin.

The Pedernal and Roosevelt uplifts were positive features during much or all of Pennsylvanian time and were finally buried by Wolfcampian sediments. The Central Basin and Diablo platforms and the southeast margin of the Pedernal uplift are the result of Wolfcampian deformation which, at least in the case of the Central Basin platform and Pedernal uplift, took the form of normal or high-angle reverse faulting. Compressional anticlinal folding took place in the Permian basin in Early and Early Middle Pennsylvanian time and was followed by supratenuous folding in Early Late Pennsylvanian and Wolfcampian time. Pre-Wolfcampian compressional folding, which involved strata as young as Virgilian, occurred on the Sacramento shelf. Pre-Desmoinesian vertical uplift of the Central Basin platform resulted in removal of

Morrowan and Derryan rocks and erosion of the northwest-trending anticlines of that structural element.

Thus, during Pennsylvanian and early Permian time, southeast New Mexico was characterized by crustal instability, greatest in Early, early Late, and latest Pennsylvanian and diminishing during other times. Coarse clastic rocks characterize periods of maximum instability. Apparently topographic relief was greatest during the Morrowan and generally decreased during later time. As relief lessened, the seas were able to cover more and more of the area. Renewed structural activity occurred at the end of Pennsylvanian time, most notably in the form of normal faulting.

During the Wolfcampian Age, the various structural elements were buried under marine and nonmarine sediments. The Wolfcampian Stage was succeeded by the Leonardian Stage, following deposition of which topographic relief of the old structural elements had been essentially eliminated.

By the end of 1962, a total of 126,819,261 barrels of crude oil, 1,781,151 barrels of natural gas liquids, and 79,867,286 thousand cubic feet of natural gas had been produced from Pennsylvanian and Wolfcampian rocks; this production began with the first discovery in 1944. Of the 93 crude-oil pools, 85 will produce 5,000,000 barrels or less each; 8 pools will thus account for 76 per cent of the petroleum production. Three pools will produce in excess of 25,000,000 barrels and 2, from Io,000,000 to 25,000,000 barrels each. Ninety-five per cent of the crude oil is produced from the Northwest shelf, with 78 per cent coming from Virgilian and Wolfcampian reservoirs.

Introduction

This study encompasses an area (fig. r) of 38,723 square miles, which is about z8 per cent of New Mexico. The area is bounded by longitude 107°W., by latitude 34°21' N., and by the New Mexico—Texas state line on the east and south.

Petroleum has been produced from rocks of Pennsylvanian and Wolfcampian ages in southeastern New Mexico since 1944. Most of the dry-gas production is from sandstones in Lower Pennsylvanian strata, while most of the crude oil comes from carbonate rocks of Middle and Late Pennsylvanian and Wolfcampian ages. Present production in the area is from the Permian basin.

Outside the area of petroleum production, Pennsylvanian and Wolfcampian rocks crop out and have been subdivided into rock-stratigraphic units. At other places in the area, the rocks neither crop out nor yet produce oil; of these, the Orogrande basin will most likely produce petroleum in the future.

The present investigation was undertaken in order to place the strata in the area, both subsurface and outcrop, into a framework of time-stratigraphic units (stages) based upon fusulinid zones. In this way, the geologic history of the area as a whole may be described.

ACKNOWLEDGMENTS

Geologists for many oil companies kindly furnished data not otherwise available for certain of the oil fields. The author did the sample work while employed by the Humble Oil & Refining Company. Mr. John W. Skinner and Mr. Garner L. Wilde of the Humble Company identified the fossils. Mr. Ward W. West, Permian Basin Sample Laboratory, Midland, Texas, lent sample description sheets and furnished sample logs. Mr. Raymond Molina, New Mexico Bureau of Mines and Mineral Resources, drafted the figures under the supervision of Mr. William E. Arnold, Scientific Illustrator. The manuscript was critically read by Professors John M. Jewett, William M. Merrill, Arthur B. Leonard, and Floyd W. Preston, University of Kansas; Mr. George 0. Bachman, U. S. Geological Survey; and Dr. Frank E. Kottlowski, New Mexico Bureau of Mines and Mineral Resources. Dr. Preston also programmed the correlation coefficient study, and Mr. Dean Lebestky of the University of Kansas programmed the oil field sort, sum, and average study. Mr. Alvin J. Thompson, Director of the New Mexico Bureau of Mines, provided some financial support. The writer gratefully acknowledges the assistance of these people.

The report was submitted to the Department of Geology and the Faculty of the Graduate School of the University of Kansas in part fulfillment of the requirements for the degree of Doctor of Philosophy.

GEOGRAPHY

Southeast New Mexico is characterized by the featureless plains of the Great Plains province east of a line extending north to south through Roswell and Carlsbad (fig. z) and by the mountains and valleys of the Basin and Range province west of that line. All the ranges trend north-south except the Capitan Mountains, which extend east-west. Sierra Blanca Peak, north of the Sacramento Mountains, attains an elevation of 12,003 feet above sea level, the highest in the area. The mountain ranges are marked by bold escarpments facing the Tularosa Valley, in which elevations are about 4000 feet above sea level, the lowest in the Basin and Range part of the area. The lowest elevation in the entire area, 300o feet above sea level, occurs in the extreme southeast corner.

The principal drainage is the Pecos River, which flows from north to south a few miles east of the boundary between the two physiographic provinces. The Tularosa Valley is characterized by interior drainage and by the occurrence, west of Alamogordo, of the White Sands, which consist of dunes of gypsum sands. The Rio Grande crosses the extreme southwest corner of the area, flowing southward.

The region is crossed by a number of paved highways and by many gravel and dirt roads that are generally accessible both in summer and winter. Two railroad lines cross the area from south to north, one through the Tularosa Valley and one through the Pecos River Valley.

GEOLOGIC SETTING

To acquaint the reader with the main geologic and physiographic features of the area, frequent reference is made to the four cross sections (pls. 1-4), to the map showing the lines of cross section (fig. 3), and to the map showing the location of the principal geologic and physiographic features (fig. z). Figure **2** also indicates the positions of the boreholes and stratigraphic sections utilized in the report and listed in Table r.

Pennsylvanian rocks are exposed (fig. **z** and succeeding maps) in isolated Basin-and-Range uplifts, where various formation names have been applied to them. The history of the nomenclature is reviewed by Kottlowski (1960a,b; 1962), who also includes a detailed correlation chart of rock-stratigraphic units (1960a, pl. 9). Details of stratigraphic nomenclature may be found in the lexicon of Jicha and Lochman Balk (1958). Southeast New Mexico is bisected in a north-south direction by the buried Pedernal uplift (fig. 2); therefore, Pennsylvanian sediments do not extend from west to east across it.

Rocks of Wolfcampian age are better exposed at the surface than those of the Pennsylvanian (fig. **2);** in addition, they cross the entire area (pls. 1 and 2).

Two major negative and five positive elements, whose general geographic locations appear in Figure 3, are found in the area. Most of these are included on at least one of the cross sections (pl. 1-4; fig. 3). However, all the positive elements are not delineated on every map since they vary in age and are not always relevant features. Where they are important, their location is apparent from the contour lines or map patterns employed.

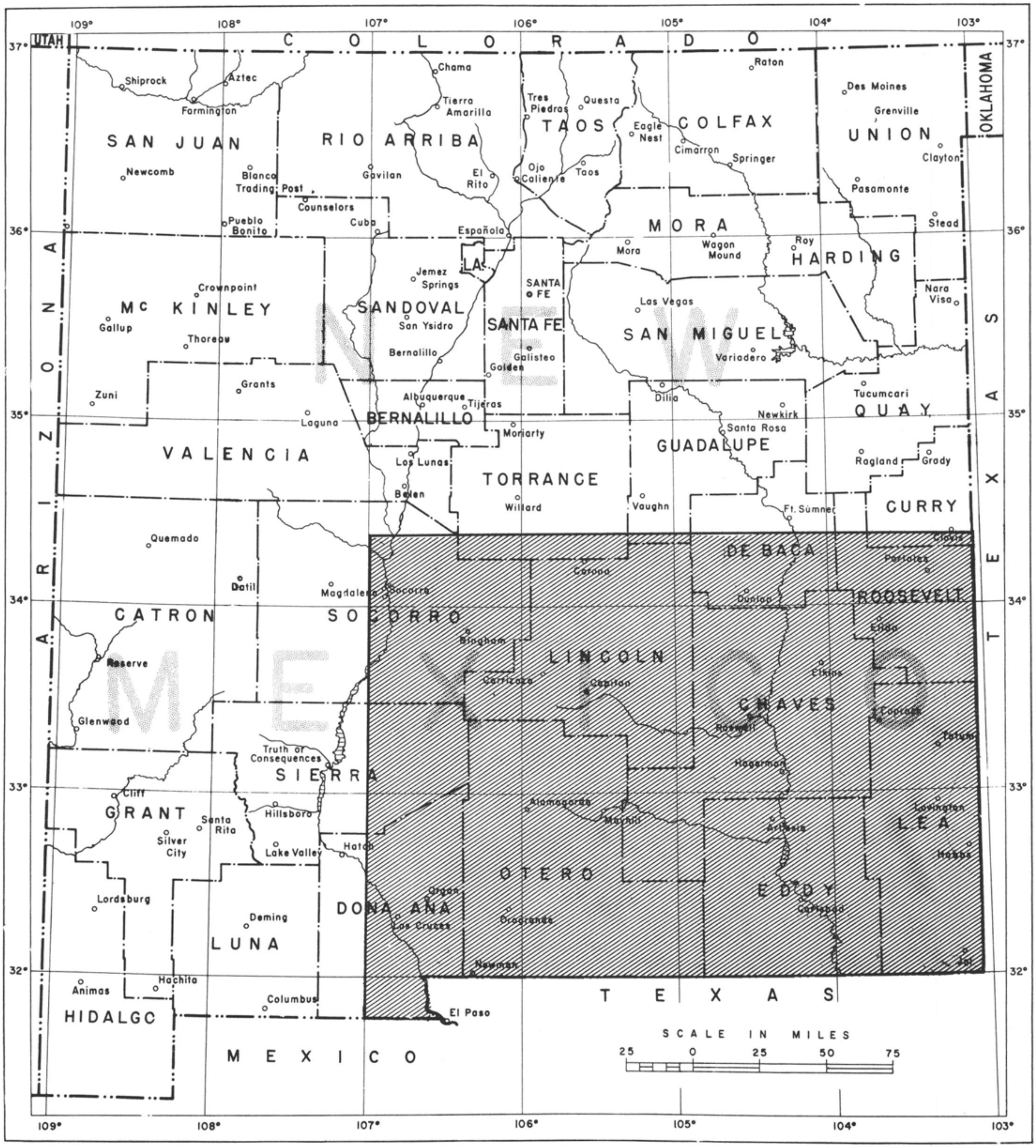


Figure 1
MAP OF NEW MEXICO SHOWING AREA OF THIS REPORT

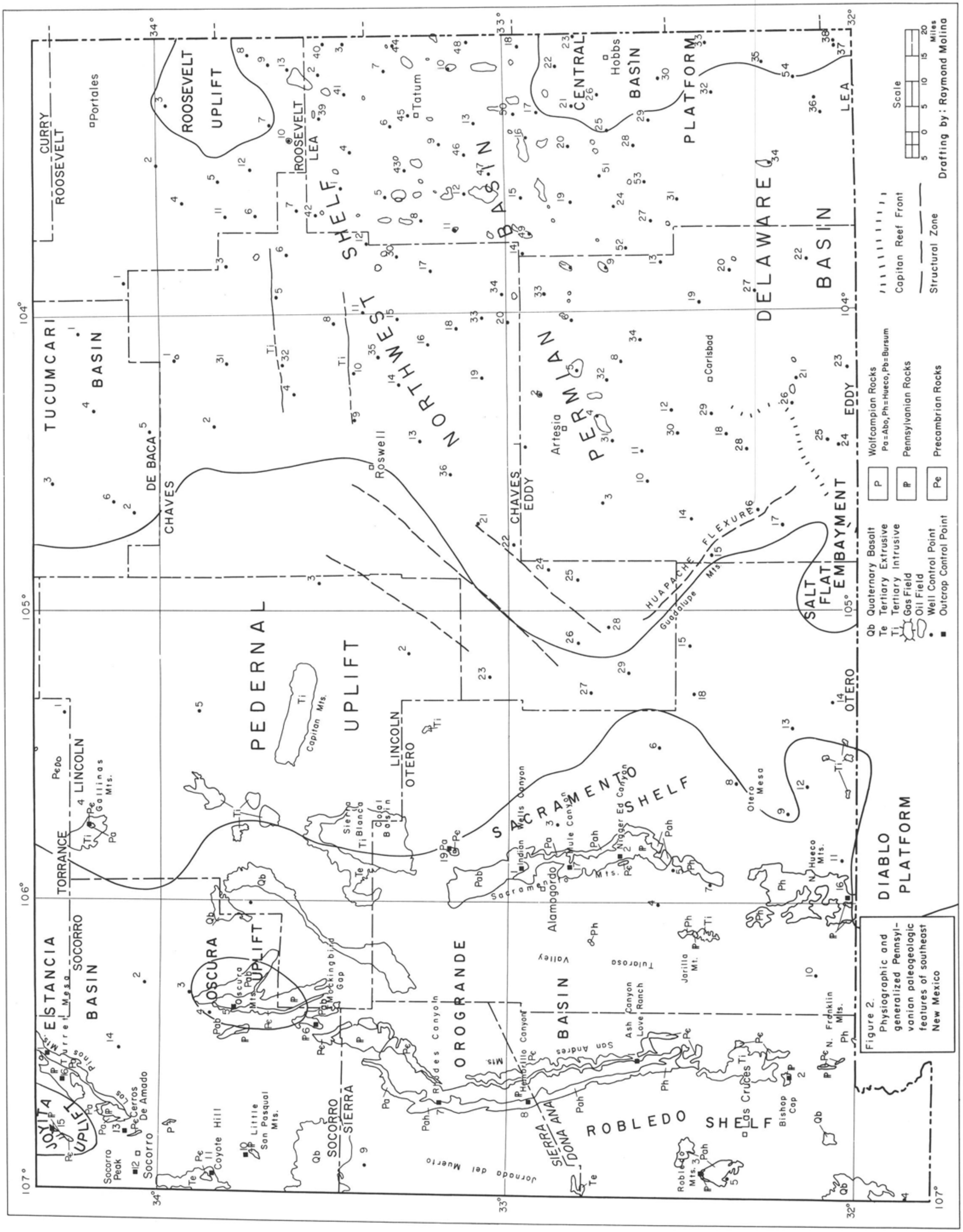


Figure 2. Physiographic and generalized Pennsylvanian paleogeologic features of southeast New Mexico

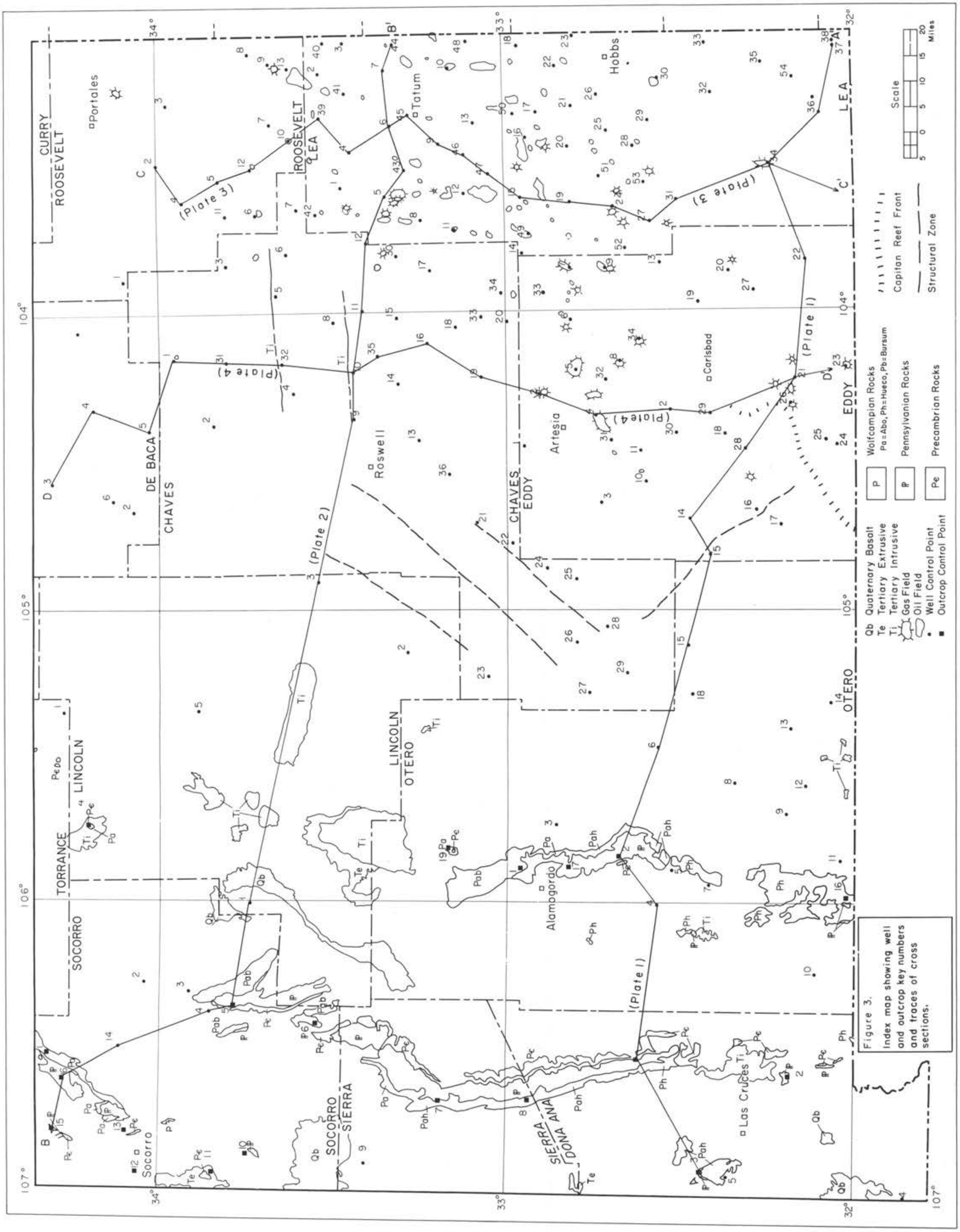


Figure 3. Index map showing well and outcrop key numbers and traces of cross sections.

TABLE 1. STRATIGRAPHIC SECTIONS AND TEST WELLS USED AS SOURCES OF MAP DATA

MAP NO.	NAME OF WELL OR STRATIGRAPHIC SECTION	LOCATION SEC.	T.	R.	REFERENCE
		CHAVES COUNTY			
C- 1	Olson 1 Noble Trust	18	4 S.	27 E.	
C- 2	Sanders 1 Sanders–Federal	25	5 S.	24 E.	
C- 3	Lion 1 Haire	12	6 S.	30 E.	
C- 4	De Kalb 1 Duke	14	8 S.	26 E.	
C- 5	Magnolia 1 State Z	36	7 S.	29 E.	
C- 6	Humble 1 Railroad Mountain Unit	8	8 S.	31 E.	
C- 7	Barnsdall 1 State A	23	8 S.	32 E.	
C- 8	De Kalb and others 1 White Y	30	9 S.	29 E.	
C- 9	De Kalb 1 Lewis	13	10 S.	25 E.	
C-10	Honolulu 1 Levick State	16	10 S.	27 E.	
C-11	De Kalb and others 1X White	28	10 S.	29 E.	
C-12	Stanolind 1 Polecat Canyon Unit	34	10 S.	31 E.	
C-13	Franklin and others 1 Orchard Park	22	12 S.	25 E.	
C-14	Humble 1 State Y	33	11 S.	27 E.	
C-15	Republic and others 1 White Ranch	34	11 S.	29 E.	
C-16	Malco 1 Waller	35	12 S.	28 E.	
C-17	Magnolia 1 Shaw–Federal	6	13 S.	31 E.	
C-18	Kerr–McGee 1 State A	32	13 S.	29 E.	
C-19	Vincent–Welch 1 Cassidy Federal	27	14 S.	27 E.	
C-20	Richfield 1 Mullis	21	15 S.	29 E.	
C-21	Magnolia 1 Turney–Federal	23	14 S.	22 E.	
C-22	Humble 1 Federal Gorman	30	15 S.	22 E.	
C-23	Humble 1 State N	35	14 S.	17 E.	
C-24	Black 1 Shildneck	24	16 S.	24 E.	
C-25	Westcoast Hydrocarbon 1 Black Hills Unit	28	17 S.	20 E.	
C-26	Texas Producers 1 State	29	17 S.	18 E.	
C-27	Gulf 1 Chaves U	10	18 S.	16 E.	
C-28	Kewanee 1 Four Mile Unit	26	18 S.	18 E.	
C-29	Sun 1 Pinon Unit	19	19 S.	17 E.	
C-30	Phillips 1 James A	34	11 S.	31 E.	
C-31	Samedan 1 Chatten Ranch	11	6 S.	27 E.	
C-32	Sinclair 1 State Chaves 129	2	8 S.	27 E.	
C-33	British American 1 Honolulu	27	14 S.	29 E.	
C-34	Texaco 1 Key–Federal	17	15 S.	30 E.	
C-35	Republic and others 1 White	9	11 S.	28 E.	
C-36	Continental 1 Lankford	2	14 S.	26 E.	
		DE BACA COUNTY			
D- 1	Cities Production 1 Hobson	12	1 S.	27 E.	
D- 2	Transcontinental 1 McWhorter	6	3 S.	22 E.	
D- 3	Katz 1 Field	13	1 S.	22 E.	
D- 4	Nearburg–Ingram 1 Milton	28	1 S.	25 E.	
D- 5	Nearburg–Ingram 1 Murray	23	3 S.	24 E.	
D- 6	Talbert 1 Andree	20	2 S.	22 E.	
		DONA ANA COUNTY			
Y- 1	Ash Canyon–Love Ranch, San Andres Mountains	28	19 S.	4 E.	Kottlowski et al., 1956
Y- 2	Bishops Cap, Organ Mountains	26	24 S.	3 E.	Kottlowski, 1960a
Y- 3	Robledo Mountains	35	21 S.	1 W.	Kottlowski, 1958a
Y- 4	Pure 1 Federal H	24	28 S.	2 W.	
Y- 5	Sinclair 1 Federal	27	22 S.	1 W.	
		EDDY COUNTY			
E- 1	Humble 1 Pearson	2	16 S.	25 E.	
E- 2	Continental 1 Duffield–Federal	21	16 S.	27 E.	
E- 3	Southern Union Production 1 Elliott	24	18 S.	23 E.	
E- 4	Standard of Texas 1 Everest	14	18 S.	26 E.	
E- 5	Stanolind 1 State AB	29	17 S.	28 E.	
E- 6	Gulf 1 Federal General American	24	17 S.	29 E.	
E- 7	Skelly 6 Lynch A	22	17 S.	31 E.	
E- 8	Stanolind 1 State AD	10	19 S.	28 E.	
E- 9	Pan American 1 Greenwood Unit	27	18 S.	31 E.	
E-10	Standard of Texas 1 Cass Ranch	3	20 S.	24 E.	
E-11	Stanolind 1 Lakewood Unit	34	19 S.	25 E.	
E-12	Kelly 1 Lake McMillan Unit	36	20 S.	26 E.	
E-13	Richardson–Bass 1 Cobb–Federal	23	20 S.	31 E.	
E-14	Standard of Texas 1 State E6584	16	21 S.	22 E.	
E-15	Continental 1 Bass–Federal	5	22 S.	21 E.	
E-16	Humble 2 Huapache Unit	23	23 S.	22 E.	
E-17	Union of California 1 Federal White	17	24 S.	22 E.	

TABLE 1. STRATIGRAPHIC SECTIONS AND TEST WELLS USED AS SOURCES OF MAP DATA (cont)

MAP NO.	NAME OF WELL OR STRATIGRAPHIC SECTION	LOCATION SEC.	T.	R.	REFERENCE
	Eddy County (cont)				
E-18	Stanolind 1 Guadalupe Foothills Unit	20	22 S.	25 E.	
E-19	Richardson–Bass 1 Fidel–Federal	27	21 S.	29 E.	
E-20	Richardson–Bass 1 Legg–Federal	27	22 S.	30 E.	
E-21	Union of California 1 Federal–Wiggs	31	24 S.	27 E.	
E-22	Richardson–Bass–Federal–Harrison	12	25 S.	30 E.	
E-23	El Paso 1X Welch Unit	21	26 S.	27 E.	
E-24	Superior 134 Government	12	26 S.	24 E.	
E-25	Gulf 1A Federal–Kelley	30	25 S.	25 E.	
E-26	Gulf 1 Estill AD	29	24 S.	26 E.	
E-27	Texaco 1 Remuda Basin	24	23 S.	29 E.	
E-28	Gulf 1 North Caverns Unit	11	23 S.	24 E.	
E-29	Gulf 1 Hackberry Hills Unit	1	22 S.	25 E.	
E-30	Phillips 1 Seven Rivers Unit	5	21 S.	25 E.	
E-31	Gulf 1 State AC	36	18 S.	25 E.	
E-32	Gulf 1 State CI	25	18 S.	27 E.	
E-33	Shell 1 Henshaw Deep Unit	24	16 S.	30 E.	
E-34	Sunray Mid-Continent 1 State Q	32	19 S.	29 E.	
	Lea County				
L- 1	Haskins and others 1 Lane Ranch Unit	4	10 S.	33 E.	
L- 2	Lone Star 1 Warren–Davis	19	9 S.	37 E.	
L- 3	Rowan 1 Simmons–Federal	8	10 S.	38 E.	
L- 4	Magnolia 1 Four Lakes Unit	15	10 S.	34 E.	
L- 5	Sinclair 1 State 262	22	11 S.	33 E.	
L- 6	Sunray Mid-Continent 1 State L	25	11 S.	35 E.	
L- 7	Markham 1 Webb Heirs	23	11 S.	37 E.	
L- 8	De Vegvar 1 State	26	12 S.	32 E.	
L- 9	Sharples 1 Alston Unit	17	13 S.	35 E.	
L-10	Forest–Houston 1 State	26	13 S.	37 E.	
L-11	Texas Pacific Coal and Oil 1 Dry Lake Unit	33	13 S.	32 E.	
L-12	Texas 2 State AT	10	14 S.	33 E.	
L-13	Blackwood–Nichols 1 Woodward	24	14 S.	35 E.	
L-14	Continental 1 West Anderson Ranch Unit	6	16 S.	32 E.	
L-15	Humle 1 South Saunders Unit	1	16 S.	33 E.	
L-16	American Liberty 1 State	12	16 S.	35 E.	
L-17	Shell 1 State CA	23	16 S.	36 E.	
L-18	Amerada 1 North Knowles Unit	1	16 S.	38 E.	
L-19	Phillips 6 Leamex	23	17 S.	33 E.	
L-20	Humble 1 State AC	22	17 S.	35 E.	
L-21	Shell 1 Spencer Unit	25	17 S.	36 E.	
L-22	McAlester Fuel 1 Toklan Royalty Co.	8	17 S.	38 E.	
L-23	Shell 1 Carter	32	17 S.	39 E.	
L-24	Pan American 1 Buffalo Unit	3	19 S.	33 E.	
L-25	Shell 1 State RA	31	18 S.	36 E.	
L-26	Phillips 1 Shipp	20	18 S.	37 E.	
L-27	Texaco 1 Muse–Federal	7	20 S.	33 E.	
L-28	Shell 1 Hooper	27	19 S.	35 E.	
L-29	Continental 1 Sanderson B-9	9	20 S.	36 E.	
L-30	Continental 4 Semu–Penn	23	20 S.	37 E.	
L-31	Phillips 1 Etz–Federal	1	21 S.	32 E.	
L-32	Texas Pacific Coal and Oil 39 State A Acct. 2	9	22 S.	36 E.	
L-33	Penrod 2 Jones	6	22 S.	38 E.	
L-34	Continental 4 Bell Lake Unit	6	24 S.	34 E.	
L-35	Restler–Sheldon 1 Fanning A	33	23 S.	37 E.	
L-36	Sun 1 Harper–Federal	26	25 S.	35 E.	
L-37	Stanolind 2 Federal–Leonard	12	26 S.	37 E.	
L-38	Plymouth 1 Lowe	7	26 S.	38 E.	
L-39	Magnolia 2 Betenbough B	14	9 S.	35 E.	
L-40	Warren 1 Border Unit	20	9 S.	38 E.	
L-41	Texaco Pacific Coal and Oil 1 South Crossroads Unit	10	10 S.	36 E.	
L-42	Amerada 1 State SRA	14	9 S.	32 E.	
L-43	Sunray Mid-Continent 1 East Bagley Unit	9	12 S.	34 E.	
L-44	Continental 1 East Gladiola Unit	34	11 S.	38 E.	
L-45	Sinclair 1 Anderson	17	12 S.	36 E.	
L-46	Pan American 1 East Saunders Unit	12	14 S.	34 E.	
L-47	Felmont 1 Etcheverry Unit	5	15 S.	34 E.	
L-48	Warren 1 Cox	21	14 S.	38 E.	
L-49	Continental 1 Anderson Ranch Unit	11	16 S.	32 E.	
L-50	Humble 1 Daughtry	32	15 S.	36 E.	
L-51	Continental 1 Tonto Deep Unit	22	18 S.	34 E.	

TABLE 1. STRATIGRAPHIC SECTIONS AND TEST WELLS USED AS SOURCES OF MAP DATA (cont)

MAP NO.	NAME OF WELL OR STRATIGRAPHIC SECTION	LOCATION			REFERENCE
		SEC.	T.	R.	
	LEA COUNTY (cont)				
L-52	El Paso 1 Lusk Deep Unit	19	19 S.	32 E.	
L-53	Pure 1 Federal C	3	20 S.	34 E.	
L-54	Shell 36-1 State B	36	24 S.	36 E.	
	LINCOLN COUNTY				
X- 1	Standard of Texas 1 Federal–Heard	33	6 S.	9 E.	
X- 2	Stanolind 1 Picacho Unit	10	12 S.	18 E.	
X- 3	Texas 1 Boyle	11	9 S.	20 E.	
X- 4	Gallinas Mountains	28	1 N.	3 E.	Kelley, 1947
X- 5	Elliott 1-10 Federal	10	5 S.	16 E.	
	OTERO COUNTY				
O- 1	Indian Wells Canyon Sacramento Mountains	33	15 S.	11 E.	Pray, 1961; Otte, 1959a; Kottlowski, 1960
O- 2	Nigger Ed Canyon–Sacramento Mountains	17	19 S.	11 E.	Pray, 1961; Otte, 1959a; Kottlowski, 1960
O- 3	Southern Production 1 Cloudcroft Unit	5	17 S.	12 E.	
O- 4	Plymouth 1 Federal	15	20 S.	9 E.	
O- 5	Sun 1 Pearson	35	20 S.	10 E.	
O- 6	Zapata 1 Federal	14	20 S.	14 E.	
O- 7	Otero 1 McGregor	5	22 S.	10 E.	
O- 8	Turner 1 Everett	34	22 S.	13 E.	
O- 9	Turner 1 Evans	22	24 S.	12 E.	
O-10	Ernest 1 Located Land Co.	20	25 S.	7 E.	
O-11	Seaboard 1 Trigg–Federal	18	26 S.	11 E.	
O-12	Union of California 1 McMillan	9	25 S.	13 E.	
O-13	Flynn and others 1 Donahue Permit	28	24 S.	13 E.	
O-14	Hunt 1 McMillan–Turner	5	26 S.	16 E.	
O-15	Standard of Texas 1 Scarp Unit	18	21 S.	18 E.	
O-16	Northern Hueco Mountains	23	26 S.	9 E.	Hardie, 1958
O-17	Mule Canyon–Sacramento Mountains	14	17 S.	10 E.	Pray, 1952
O-18	LeFors 1 Federal	22	21 S.	16 E.	
	ROOSEVELT COUNTY				
R- 1	Tidewater 1 Best	27	2 S.	29 E.	
R- 2	Signal–Makin 1 Bell–Federal	33	3 S.	33 E.	
R- 3	Mid-Continent 1 Strickland	9	4 S.	35 E.	
R- 4	Austral 1 Sadler	29	4 S.	32 E.	
R- 5	Goldston 1 Lambirth State	36	5 S.	32 E.	
R- 6	Amerada 1 Federal C	10	7 S.	32 E.	
R- 7	Shell 1 Harwood	27	7 S.	35 E.	
R- 8	Great Western 1 Bilberry	1	7 S.	37 E.	
R- 9	Felmont 5 Bluitt Unit	27	7 S.	37 E.	
R-10	Magnolia 1 Jacobs–Federal	18	8 S.	35 E.	
R-11	Gulf 1 Elida Unit	10	6 S.	32 E.	
R-12	Magnolia 1 Brown	6	7 S.	34 E.	
R-13	Shell 2 Bluitt Unit	16	8 S.	37 E.	
	SIERRA AND SOCORRO COUNTIES				
S- 1	Northern Los Pinos Mountains	8	1 N.	4 E.	Stark and Dapples, 1946; Needham and Bates, 1943; Wilpolt et al., 1946
S- 2	Lockhart 1 Stackhouse	14	3 S.	6 E.	
S- 3	Lockhart 2 Federal	33	4 S.	6 E.	
S- 4	Sun 1 Bingham State	23	5 S.	5 E.	
S- 5	Oscura Mountains	18	6 S.	6 E.	Thompson, 1942; Wilpolt and Wanek, 1952
S- 6	Mockingbird Gap, San Andres Mountains	9	9 S.	5 E.	Kottlowski et al., 1956
S- 7	Rhodes Canyon, San Andres Mountains	12	13 S.	2 E.	Kottlowski et al., 1956
S- 8	Hembrillo Canyon, San Andres Mountains	7	16 S.	3 E.	Kottlowski et al., 1956
S- 9	Sun 1 Victorio Land and Cattle Co.	25	10 S.	1 W.	
S-10	Little San Pasqual Mountains	5	7 S.	1 E.	Kottlowski, 1960a
S-11	Coyote Hills	28	5 S.	1 W.	Kottlowski, 1960a
S-12	Socorro Peak	9	3 S.	1 W.	Kottlowski, 1960a
S-13	Cerros de Amado	35	2 S.	1 W.	Wilpolt and Wanek, 1952
S-14	Skelly 1 Goddard	22	2 S.	4 E.	
S-15	Joyita Hills	23	1 N.	1 E.	Wilpolt and Wanek, 1952
S-16	Turret Mesa, Los Pinos Mountains	28	1 N.	3 E.	Wilpolt and Wanek, 1952
	TORRANCE COUNTY				
T- 1	Resler 1 Nalda	27	1 N.	15 E.	

POSITIVE ELEMENTS

Pedernal Uplift

The dominant positive feature is the Pedernal uplift (fig. 2), so-called by Ver Wiebe (1930) although shown earlier on a map by Willis (1929) as the *Pedernal positive element.* It has also been referred to as the *Pedernal land mass* (Thompson, 1942) and the *Pedernal massif* (Galley, 1958). *Pedernal uplift* is adopted herein for this feature, which has been elevated relative to adjacent areas at various times in the geologic past. It is intersected by cross section A-A' (pl. 1) at almost its narrowest configuration, where it may be bounded by faults or systems of faults on either side. The uplift is also shown on cross section B-B' (pl. 2), but here outcrops and boreholes are sparse and the feature is not closely controlled. The western border, in fact, probably rises abruptly in the vicinity of the Tertiary intrusives and then flattens at an elevation approximating that at which Precambrian rocks were encountered in the Texas Boyle 1 well (X-3).

A large area where Precambrian rocks crop out lies in Torrance County a few miles north of the limits of this report. At this outcrop, called *Pedernal Mountain* or the *Pedernal Hills,* Kottlowski and Foster (1960) report upper Leonardian Yeso Formation overlying granite and metamorphic rocks. Precambrian rocks also crop out along the trend of the Pedernal uplift in southeastern Torrance County (near), in Lincoln County in the Gallinas Mountains (X-4), and in Otero County near the village of Bent (0-19) (fig. 3). At the Gallinas Mountains and Bent localities, Precambrian rocks are encountered at shallow depths by the boreholes in these areas shown in Figure **2.**

Roosevelt Uplift

The Roosevelt uplift (fig. 2; pl. 3) is a dome-shaped feature in southern Roosevelt County named the *Roosevelt Positive* by Krisle (1959) and the *Milnesand Dome* (presumably for for an obscure nearby settlement of that name) by Adams et al. (1962). Because the Roosevelt uplift is aligned with, although widely separated from, the Matador arch (also called the *Matador Archipelago,* as well as other names), the term *Matador arch* is frequently applied to it (for example, Foster and Stipp, 1961). The Matador arch is comprised of a series of anticlines occurring in a narrow belt across the north end of the Midland basin in west Texas (Galley). The Matador arch and the Roosevelt uplift are genetically unrelated, so the names should be restricted to the features for which they were originally intended.

Central Basin Platform

The part of the Central Basin platform in southeastern Lea County (fig. **2;** pl. 1) is only the northeast corner of a rectangular, northwest-southeast-trending buried fault-block mountain about 150 miles in length and 50 miles in width. This feature was described by Willis as a double line of "highs" separating the main West Texas basin on the east from the Delaware Mountain basin on the west; Cartwright (1930) first applied the name *Central Basin platform.* The Central Basin platform acquired its present form during Virgilian or Early Wolfcampian time; however, it influenced later Permian sedimentation and was named, together with associated negative elements, on the basis of facies displayed by Upper Permian rocks in adjacent mountains and in shallow wells.

Oscura Uplift

The Oscura uplift is here named for the positive element centered on the northern Oscura Mountains. It causes a bifurcation of the north end of the Orogrande basin where the latter joins the southern extremity of the Estancia basin.

Joyita Uplift

The Joyita uplift is located in the extreme northwest corner of the report area. It was named by Wilpolt et al. (1946), who noted the anomalously thin Pennsylvanian section in the Joyita Hills. They suggested the presence of a monadnock of Precambrian rocks a short distance to the north during Pennsylvanian time.

Diablo Platform

The Diablo platform of Trans—Pecos Texas trends southeastward from the northern Hueco Mountains, which are in southwestern Otero County. This uplift was originally called the *Western platform* (Cannon and Cannon, 1932) and later the *Diablo platform* (King, 1942). The platform is important to this report only as it influences the data from outcrops in and adjacent to the Hueco Mountains.

NEGATIVE ELEMENTS

Two negative elements dominate the area, the Permian basin on the east side of the Pedernal uplift and the Orogrande basin on the west side. The southernmost extremities of two other basins appear along the north margin of the area, the Tucumcari basin on the east and the Estancia basin on the west. Each principal negative element includes subdivisions that may be given names for convenience of reference.

Permian Basin

The part of the Permian basin here mapped represents only a small part of the basin proper, which extends northward at least to southern Oklahoma and eastward to central Texas. Originally Willis called the area to the east of the Central Basin platform the main *West Texas basin* and the area west of the platform the *Delaware Mountain basin.* At the same time, Blanchard and Davis (1929) referred to the area west of the Central Basin platform as the *Delaware Basin* and show it on their map (fig. 8, p. 991) as the *Delaware Sand Basin.* The name *Delaware Basin* has been retained in the literature. In 1930, Cartwright renamed the main West Texas basin of Willis the main *Permian basin* and showed it to underlie the entire west Texas-southeast New Mexico region, exclusive of the Central Basin platform and the Delaware basin. The Upper Permian sediments of the Delaware basin are predominantly dark-colored and clastic, especially the siltstones and fine-grained sandstones. North of the Delaware basin, the equivalent sediments consist of reef limestones, shelf limestones, evaporites, and red beds. The shelf section of the Permian basin was named by King (1942) the *Northwest shelf* area. This nomenclature is useful and will be retained for describing areas of sedimentation.

The Salt Flat embayment is an arm of the Delaware basin extending northward from west Texas into the map area. The embayment may represent a depositional feature, or the sediments may simply represent a segment of more extensive deposits that have been preserved in a graben. Because its presence is inferred from contouring but is not yet proved, the embayment is not formally named.

Cross section A-A' extends across the Delaware basin part of the main Permian basin from the Pedernal uplift to the Central Basin platform. Cross section B-B' is drawn parallel to cross section A-A' but sufficiently far to the north so that it crosses the Northwest shelf. Cross section C-C' begins on the Roosevelt uplift and extends southward across the Northwest shelf and into the Delaware basin. Cross section D-D' commences at the south end of the Tucumcari basin, proceeds across a part of the Northwest shelf, crosses an eastward-bulging lobe of the Pedernal uplift, again traverses the Northwest shelf, and terminates in the Delaware basin.

Tucumcari Basin

The Tucumcari basin (Krisle, p. I) is contiguous on the east with the Palo Duro basin (Gould and Lewis, 1926) of north Texas. Only the southernmost extremity of the Tucumcari basin lies in southeast New Mexico, and its precise boundary with the Northwest shelf is indeterminate (note north end of cross section D-D').

Orogrande Basin

The Orogrande basin (Pray, 1959) is the principal negative element west of the Pedernal uplift. This basin occupies most of the area of the present Tularosa Valley as well as adjacent mountain areas. For convenience, the southeast margin of the Orogrande basin may be called the Sacramento shelf, as shown on cross section A-A'. The southwest margin of the basin may be referred to as the Robledo shelf, the sediments of which extend westward to the Florida uplift (islands) (Kottlowski, 1960a). The Robledo shelf is indicated on cross section A-A'.

Estancia Basin

The north end of the Orogrande basin is bifurcated by the Oscura uplift (fig. 2); in this area, beneath present-day Chupadera Mesa and bordered by the Pedernal uplift on the east and the Joyita uplift on the west, the Orogrande basin joins the south end of the Estancia basin (pl. 2). Precise location of the juncture is indeterminate. The name *Estancia basin* has apparently not been formally designated but is in common usage for the structural basin and basin of deposition, which approximately conforms to the topographic Estancia Valley. This valley is bounded on the south by Chupadera Mesa and on the east by the Pedernal Hills.

PREVIOUS WORK

The earliest regional study of the Pennsylvanian System in southern New Mexico is that of Thompson (1942), supplemented by his later reports (1948, 1954). On the basis of fusulinids found in numerous measured sections, he discarded all previous rock-stratigraphic nomenclature and proposed 24 new group, formation, and member names. These were placed in four series, three of which were standard Mid-Continent time terminology, Virgil, Missouri, and Des Moines, and one of which was new, the Derry Series. The latter was designated as the pre-Desmoinesian part of the stratigraphic section. When Morrowan rocks later proved to be present, the Derryan was redefined as post-Morrowan, pre-Desmoinesian and is so used in this report. Because Thompson's rock units were actually biostratigraphic, they were of little use to the field geologist. Unfortunately, only a few of his measured sections were published.

Reports have been published covering most of the mountain ranges in southern New Mexico. From these reports, as well as from regional studies, stratigraphic control was obtained for the rocks that crop out. Regional studies of the Pennsylvanian System include those of Needham (1940), Thompson (1942), Thompson and Kottlowski (1955), and Kottlowski (1959, 1960a,b, and 1962) for the western part of the area and those of Lloyd (1949), Jones (1953), Galley, Adams et al., and Wright (1963) for the eastern part. Regional Permian studies have been made by Darton (1928), Hardison (1955), Needham and Bates (1943) King (1942), Lloyd, Jones, and Galley.

Investigations by the U.S. Geological Survey include those of Read et al. (1944), Wilpolt et al., and Wilpolt and Wanek (1951) in the region of the Los Pinos Mountains and Chupadera Mesa; Kelley (1946) and Griswold (1959) in the Gallinas Mountains; King and Knight (1944) in the Sierra Diablo region; King, King, and Knight (1945) in the Hueco Mountains; King (1949) in the area east of the Hueco Mountains; and King (1949) and Hayes (1964) in the Guadalupe Mountains.

Publications for other local areas include the Los Pinos Mountains, described by Wilpolt (1942) and Stark and Dapples (1946), who divided the Pennsylvanian rocks into standard time-stratigraphic units; the San Andres Mountains, an area not generally open to the public by reason of its inclusion in the White Sands Missile Range, described by Kottlowski et al. (1956); the Hansonburg mining district at the north end of the Oscura Mountains (Kottlowski, 1953); the Chupadera Mesa region (Bates et al., 1947); the Organ (Dunham, 1935), Franklin (Nelson, 1940; Harbour, 1958), and northern Hueco (Hardie, 1958; Williams, 1963, 1964) mountains; the Sacramento Mountains (Pray, 1952, 1959, 1961) and northern Sacramento Mountains (Otte, 1959a,b); the Jarilla Mountains (Reynolds and Craddock, 1959); and a few small localities described by Kottlowski (1960a), notably those in the Little San Pascual Mountains, the Coyote Hills, and Socorro Mountain.

Pre-Pennsylvanian stratigraphy and structure of the area west of the Pedernal uplift are discussed by Bachman (1961), Foster (1959), Kelley (1955), Kottlowski (1960a), Pray (1961), Wilpolt et al., and Wilpolt and Wanek. Galley, Harrington (1963), Hayes, Hills (1963), and Lloyd have described the pre-Pennsylvanian geology of the area east of the Pedernal uplift.

The present report area falls in part in each of the four quarters of the new geologic map of New Mexico (Dane and Bachman, 1957, 1958, 1961; Bachman and Dane, 1962). These data are summarized on one sheet by the highway geologic map (Kottlowski et al., 1961).

Techniques of paleogeologic mapping have been summarized by Levorsen (1933, 1960). Structure, isopach, and facies mapping methods are described in Bishop (196o), Forgotson (1960), Krumbein and Sloss (1963), and Sloss, Dapples, and Krumbein (196o, p. vii-xii).

PRESENT INVESTIGATION

This report is primarily a subsurface study for which sample work was done intermittently between 1953 and 1960. The correlations, computations, cross sections, maps, and petroleum studies were done during the summers of 1962 and 1963.

In the course of the study, samples from more than z00 boreholes were examined; from the samples were recovered more than 5500 fusulinids. Subsequent to identification, the fossil names were plotted on mechanical logs (mainly gamma ray-resistivity) in the same fashion as they are plotted on columnar sections. A net work of intersecting cross sections was then constructed from the logs (pls. 1-4), and the stage boundaries were chosen on the basis of the fusulinid zones.

The data necessary for the various maps were compiled from the well logs and measured sections (fig. 3; table I). References to these locations are made in the text by key numbers. The key numbers are also shown above the headings on the cross sections. Isopach maps of the stages, together with maps showing combined elastic ratio and sandstone-shale ratio patterns (table z), indicate the geometry of the units and their lithologic distributions. Such maps are especially helpful in showing times of uplift as well as the nature of zero isopach lines. Shale isolith maps, together with shale color distribution maps, emphasize depositional environments. On other maps are included percentage contour lines to indicate the presence and distribution of specific, minor constituents.

TABLE 2. LITHOFACIES DEFINED BY CLASTIC RATIOS COMBINED WITH SANDSTONE-SHALE RATIOS

LITHOFACIES	CLASTIC RATIO	SANDSTONE-SHALE RATIO
Limestone	less than ¼	any
Limestone-sandstone	¼ - 1	greater than 1
Limestone-shale	¼ - 1	less than 1
Sandstone-limestone	1 - 8	greater than 1
Shale-limestone	1 - 8	less than 1
Sandstone	greater than 8	greater than 8
Sandstone-shale	greater than 8	1 - 8
Shale-sandstone	greater than 8	⅛ - 1
Shale	greater than 8	less than ⅛

Unit isopach maps were prepared first and the zero lines so determined were used as the zero lines for the succeeding maps of each stage sequence. In all instances, maps were drawn interpretatively; the anomalies that occur where data are scant, especially toward the margins of units, are based upon the most logical contouring of the individual maps. Many times, such anomalies could be eliminated or modified, thus making successive maps conform absolutely, but this would arbitrarily remove possibly meaningful information.

Because a large number of units is similarly treated, a certain monotony in presentation is inevitable; therefore, descriptions are as brief as possible. The maps themselves, together with the cross sections, contain the essential information for each period of time being described, so interpretations at variance with those given in the text may be possible.

All available data were utilized except in those parts of Lea and Eddy counties where information is so abundant, due to the density of borehole distribution, that it is necessary to be selective. In such areas, one or two wells a township were chosen. This results in a fairly even distribution of data points over most of the area, although unavoidable gaps occur where there are neither outcrops nor boreholes.

Over the Central Basin platform (fig. 2), data are exceedingly abundant and consequently the maps are generalized. Areal extent of the Pennsylvanian units is shown accurately, but distribution of the Wolfcampian Stage in the subsurface is very erratic, so that at most places Leonardian rocks unconformably overly pre-Wolfcampian beds.

Cross sections are stratigraphic in nature; datum plane for each is the top of the Wolfcampian Stage. In general, they demonstrate correlation of subsurface with surface rocks; relations of rock units with the time-rock units under study; nature of the stratigraphic column at each location; and major structural features. Locations of lines of cross sections are shown in Figure 3. All are highly exaggerated vertically (about 80:1) to emphasize stratigraphic details. Unfortunately structural features are correspondingly distorted.

All maps are drawn on a standard base designed to be as free of clutter as possible and yet show significant geological and geographical detail for purposes of orientation. Areal extent of Pennsylvanian and Wolfcampian rocks that crop out is shown, together with Tertiary and Quaternary igneous rocks. Data control points are included to indicate control density of different areas. Structural zones are prominent alignments of disturbed bed rock resulting from either anticlinal folding or faulting. The Capitan reef front is the surface exposure of the Guadalupian Capitan reef.

Paleontology

Although this investigation does not include systematic paleontology, the correlations are based upon fusulinid zonation. These foraminifers have been carefully studied in the United States for more than thirty years; utilizing them, zonation of Pennsylvanian and Permian strata has been accomplished comparable to that achieved with graptolites in the Lower Paleozoic and with ammonoids in the Mesozoic. Data on stratigraphic and geographic occurrences of individual species identified from southeast New Mexico and elsewhere in the United States indicate that the fossils are accurate guides for the various stages involved. Given closer stratigraphic control, through study of well cores rather than cuttings, each stage could be subdivided into substages, as has been demonstrated in the American cordillera by Bissell (1962). Many of the specimens from southeast New Mexico are conspecific with those in Bissell's lists, indicating the feasibility of such subdivision.

Below are listed, according to age, the fossils upon which correlations in this memoir were based. The specimens from the subsurface were identified by J. W. Skinner and G. L. Wilde, while those from areas of outcrop were obtained from published reports. In addition to those listed, specimens of the genera *Oketaella* Thompson and *Rugosofusulina* Rauser-Cernoussova were identified from the Wolfcampian, *Bartramella* Verville, Thompson, and Lokke from the Desmoinesian, and *Staffella* Ozawa from several stages.

FUSULINIDS BY STAGES

MORROWAN STAGE

Eostaffella advena (Thompson)
E. *circuli* (Thompson)
E. *inflecta* (Thompson)
Fusiella primaeva Skinner
Millerella marblensis Thompson

DERRYAN STAGE

Eoschubertella mexicana Thompson
Fusulina? insolita Thompson
Fusulinella acuminate Thompson
F. *devexa* Thompson
F. famula Thompson
F. fugax Thompson
F. juncea Thompson
F. texana Skinner and Wilde
Ozawainella plummeri (Thompson)
Profusulinella copiosa Thompson
Pseudostaffella needhami Thompson

DEMOINESIAN STAGE

Fusulina acme Dunbar and Henbest
F. distenta Roth and Skinner
F. euryteines Thompson
F. girtyi (Dunbar and Condra)
F. haworthi (Beede)
F. illinoisensis Dunbar and Henbest
F.? inconspicua Girty
F. knighti Dunbar and Henbest
F. leei Thompson
F. megista Thompson
F. mysticensis Thompson
F. novamexicana Needham
F. pattoni Needham
F.? rickerensis Thompson
F. *rockymontana* Roth and Skinner
F. similis (Galloway and White)
F. *socorroensis* Needham
F. taosensis Needham
Wedekindellina coloradoensis Roth and Skinner
W. dunbari Thompson
W. el fine Thompson
W. ellipsoides Dunbar and Henbest
W. euthysepta (Henbest)
W. excentrica (Roth and Skinner)
W. excentrica var. *magna* Roth and Skinner
W. henbesti (Skinner)
W. matura Thompson
W. minuta (Henbest)
W. uniformis Thompson

MISSOURIAN STAGE

Triticites burgessae Burma
T. *fresnalensis* Needham
T. *irregularis* (Staff)
T. *nebraskensis* Thompson
T. *neglectus* Newell
T. *newelli* Burma
T. *ohioensis* Thompson
T. *planus* Thompson and Thomas
T. *pygmaeus* Dunbar and Condra
T. *submucronatus* Thompson
T. *venustus* Dunbar and Henbest
T. *wellsi* Needham
T. *wyomingensis* Thompson and Thomas
Wedekindellina ultimata Newell and Keroher

VIRGILIAN STAGE

Dunbarinella ervinensis Thompson
Triticites acutus Dunbar and Condra
T. callosus Dunbar and Henbest
T. *cuchilloensis* Needham
T. *cullomensis* Dunbar and Condra
T. *gallowayi* Needham
T. *jemezensis* Needham
T. *kellyensis* Needham
T. *mediocris* Dunbar and Henbest
T. *moorei* Dunbar and Condra
T. plummeri Dunbar and Condra
T. *sacramentoensis* Needham
Waeringella spiveyi Thompson

WOLFCAMPIAN—VIRGILIAN STAGES

Schubertella kingi Dunbar and Skinner

WOLFCAMPIAN STAGE

Dunbarinella extenta Thompson
D. *eoextenta* Thompson
D. *fivensis* Thompson
D. *koschmanni* (Skinner)
D. *obesa* (Beede)
D. *tumida* (Skinner)
Monodiexodina linearis (Dunbar and Skinner)
Ozawainella huecoensis Dunbar and Skinner
Paraschwagerina acuminata Dunbar and Skinner
P. kansasensis Beede and Kniker
Pseudoschwagerina beedei Dunbar and Skinner
P. *rhodesi* Thompson
P. texana Dunbar and Skinner
P. texana var. *ultima* Dunbar and Skinner
P. uddeni (Beede and Kniker)
Schwagerina andresensis Thompson
S. *bellula* Dunbar and Skinner
S. compacta (White)
S. *diversiformis* Dunbar and Skinner

S. emaciate (Beede)
S. *emaciate* var. *jarillaensis* Needham
S. *forakerensis* Skinner
S. *franklinensis* Dunbar and Skinner
S. *gracilitatus* Dunbar and Skinner
S. *huecoensis* (Dunbar and Skinner)
S. *jewetti* Thompson
S. *laxissima* Dunbar and Skinner
S. *longissimoidea* (Beede)
S. nelsoni Dunbar and Skinner
S. *nelsoni* var. *opima* Thompson
S. *pinosensis* Thompson
S. *thompsoni* Needham
Triticites cellamagnus Thompson and Bissell
T. *confertus* Thompson
T. *creekensis* Thompson
T. *directus* Thompson
T. *inflatus* Galloway and Ryniker
T. *meeki* (Moller)
T. notus Thompson and Thomas
T. *onustus* Thompson and Thomas
T. *pinguis* Dunbar and Skinner
T. *pointensis* Thompson
T. *powwowensis* Dunbar and Skinner
T. *rhodesi* Needham
T. *rockensis* Needham
T. *subventricosus* Dunbar and Skinner T.
uddeni Dunbar and Skinner T.
ventricosus (Meek and Hayden) T.
victorioensis Dunbar and Skinner

LEONARDIAN STAGE

Boultonia guadalupensis Skinner and Wilde
Parafusulina bakeri Dunbar and Skinner
Schubertella melonica Dunbar and Skinner
Schwagerina crassitectoria Dunbar and Skinner S.
guembeli Dunbar and Skinner
S. *hawkinsi* Dunbar and Skinner
S. *hessensis* Dunbar and Skinner
S. *setum* Dunbar and Skinner

Results of the present investigation add little to knowledge of fusulinid paleoecology. Dunbar (1957) summarized the literature on this topic, and to his review may be added the studies of Newell (1957) on the Permian reefs of the Guadalupe Mountains of southeast New Mexico and west Texas and of Ross (1963) on the Pennsylvanian and Permian sediments of the Glass Mountains area, west Texas. In sample studies undertaken for this memoir, is was found that the fusulinids show a strong preference for the clean, light-colored, skeletal-micritic limestones and the variegated shales of the shelf areas. Such rocks imply low-energy environments and presumably well-oxygenated waters. Since most fusulinids were benthonic, as suggested by their generally heavy, calcareous tests, they are probably autochthonous in the sediments in which they are preserved. Associated with these fossils in the rocks are other foraminifers, mainly textularians, ostracodes, bryozoans, algae, and occasional small pelecypods and gastropods. Ground-up shell material of macrofossils is also common in the well cuttings.

Pennsylvanian and Wolfcampian fusulinids are uncommon in the dark-gray and black micrites and shales of the strata that are the basin equivalents of the shelf rocks. The basin micrites are frequently matted with siliceous sponge (?) spicules and not unfrequently the fossils have been replaced by chert. However, in the basin sediments, fusulinids sometimes occur, which show no evidence of transport or of alteration and therefore must have lived in waters sufficiently stagnant to have permitted the accumulation and preservation of organic debris. The size and weight of the shells precludes the possibility of the animals having been nekton, living in the well-aerated surface waters.

Where bottom conditions were favorable, foraminifers proliferated and individual species achieved wide geographic distribution through generally narrow vertical limits. For this reason, they make excellent guide fossils for time-stratigraphic units such as those employed in this report. Statistically, however, they must be considered facies fossils in the sense that they occur in shelf sediments at least I oo times more frequently than in basin sediments. This preference for the offshore, open-water habitat is also described by Thompson (1964).

One is thus faced, in a study of this type, with a widespread sequence of strata not readily divisible into rock-stratigraphic units and not characterized by any fossils known to be free of environmental controls on occurrence, yet present in sufficient numbers to be useful. It is therefore necessary to work with the materials at hand, realizing that, while vertical precision of subdivision is demonstrably good, horizontal control is weak as both nearshore and restricted-circulation offshore environments are reached. Where fossils are scant, correlations are correspondingly less certain, and the possibility that a given map is in error in a given area is increased accordingly.

Definitive statistical paleoecologic studies of fusulinids, as well as other fossils, will be greatly improved when systematic paleontologists record, as a matter of course, not merely the names of formations in which fossils occur but also lithology of the rocks from which the fossils are extracted.

Paleogeology

The paleogeology of the various units is depicted by means of subcrop (bird's eye view) and supercrop (worm's eye view; lap-out) maps. These are intended to show the areal geology of the surface on which each stage was deposited and of the surface by which each stage was succeeded. They thus give an idea of times of regional deformation that involve rocks of the Pennsylvanian System and the Wolfcampian Stage.

Considered as a unit, Pennsylvanian sediments were deposited over a surface of progressively older beds from south to north (fig. 4). Where Pennsylvanian rocks are absent, the pre-Pennsylvanian geology may be filled in from the Wolfcampian subcrop map (fig. 16). Pre-Pennsylvanian Paleozoic formations were deposited across the entire area and extended an indeterminate distance to the north. Post-Mississippian deformation and erosion resulted in the surface upon which Pennsylvanian sedimentation began. The Pennsylvanian supercrop map (fig. 5) indicates rocks of that age to be overlain everywhere by Wolfcampian strata except, in places, on the Central Basin platform, where the overlying beds are of Leonardian age.

Where they are present, Morrowan beds are shown by the subcrop map (fig. 6) to overlie the Mississippian System, except in southeast Roosevelt County, where the underlying rocks are of Siluro—Devonian age. During Morrowan time, therefore, older Paleozoic strata were exposed to subaerial erosion over much of the map area. Since the Mississippian beds below the Morrowan are almost everywhere of Chesteran age, a hiatus the length of the Springeran Age is represented by the record; Springeran rocks are not known in southeastern New Mexico. Morrowan strata were deposited in the negative areas, which are the sites of the Orogrande and Delaware basins. Prior to Early Morrowan time, the Orogrande basin was part of an older Paleozoic shelf; however, the Delaware basin was reflected in its present form in Chesteran time, as indicated by a facies change in rocks of that age from massive light-colored oolitic-micritic limestone on the Northwest shelf to black shale in the Delaware basin. The Morrowan supercrop map (fig. 7) shows the unit to be overlain generally by deposits of the succeeding Derryan Stage. The subsidence which began in Morrowan time became much more pronounced with the advent of Derryan sedimentation.

Although generally in conformable relations with the underlying Morrowan Stage, an unconformity is present at the base of the Derryan (fig. 8) northward beyond the limits of the Morrowan. The subcrop map (fig. 8) shows that the entire area west of the Pedernal uplift had become negative, as had the Tucumcari basin. The Roosevelt and Pedernal uplifts remained positive elements. Derryan rocks cover much of the Central Basin platform. The supercrop map (fig. 9) shows that the stage overlying the Derryan is commonly Desmoinesian. Derryan deposits are the first expression of extensive Pennsylvanian basin development in southeast New Mexico.

Desmoinesian rocks (fig. 10) were deposited mainly upon a surface of Derryan strata, with minor exceptions along the margins of uplifts and with a pronounced exception on the west side of the Roosevelt uplift. Desmoinesian rocks are the oldest of the Pennsylvanian System to extend continuously south to north across that part of the area east of the Pedernal uplift; they are also more extensively preserved on the Central Basin platform than are other Pennsylvanian units. The Desmoinesian supercrop map (fig. 11) clearly indicates that these rocks either were deposited more extensively than beds of Late Pennsylvanian age or else post-Pennsylvanian erosion removed the latter. Since the preceding maps show a progressive on-lap from earlier to later Pennsylvanian time, it may be inferred that post-Virgilian erosion permitted the Wolfcampian in places to rest unconformably upon the Desmoinesian.

As seen by the subcrop map (fig. 12), rocks of Missourian age nearly everywhere overlie Desmoinesian beds. Unconformable relations are revealed by numerous boreholes along the east-central margin of the Pedernal uplift and in the vicinity of the Roosevelt uplift, which is sharply reduced in areal extent. The supercrop map (fig. 13) shows that the Virgilian closely matches the Missourian areally; unconformable relations are apparent only marginally where Wolfcampian beds replace those of Virgilian age as the overlying formation. Minor structural movement involved each of the uplifts during or immediately following Missourian deposition.

The Virgilian is unconformable with older strata only along the south edge of the Roosevelt uplift, along the east-central margin of the Pedernal uplift, and perhaps in scattered localities elsewhere (fig. 14). It is absent from the Joyita uplift, in the northwestern corner of the map area, although Middle Pennsylvanian strata are present there. The Virgilian supercrop map (fig. 15) gives evidence of the widespread development of unconformities marginal to uplifts existing at the end of Virgilian time. The uplifts were buried by subsequent Wolfcampian sediments.

In the basins, the Wolfcampian Stage is conformable with the underlying Virgilian but the Wolfcampian subcrop map (fig. 16) shows that there are unconformities in marginal areas. Underlying rocks range in age from Precambrian through Virgilian. It may be seen that the Wolfcampian Stage extends over the entire area, with the exception of parts of the Central Basin platform. The supercrop map of the Wolfcampian (fig. I7) shows it to be overlain by Leonardian strata; structural events in the area terminated just prior to the close of Wolfcampian time, but the effects of Pennsylvanian and Wolfcampian deformation largely controlled the complex sedimentation that characterized later Permian time.

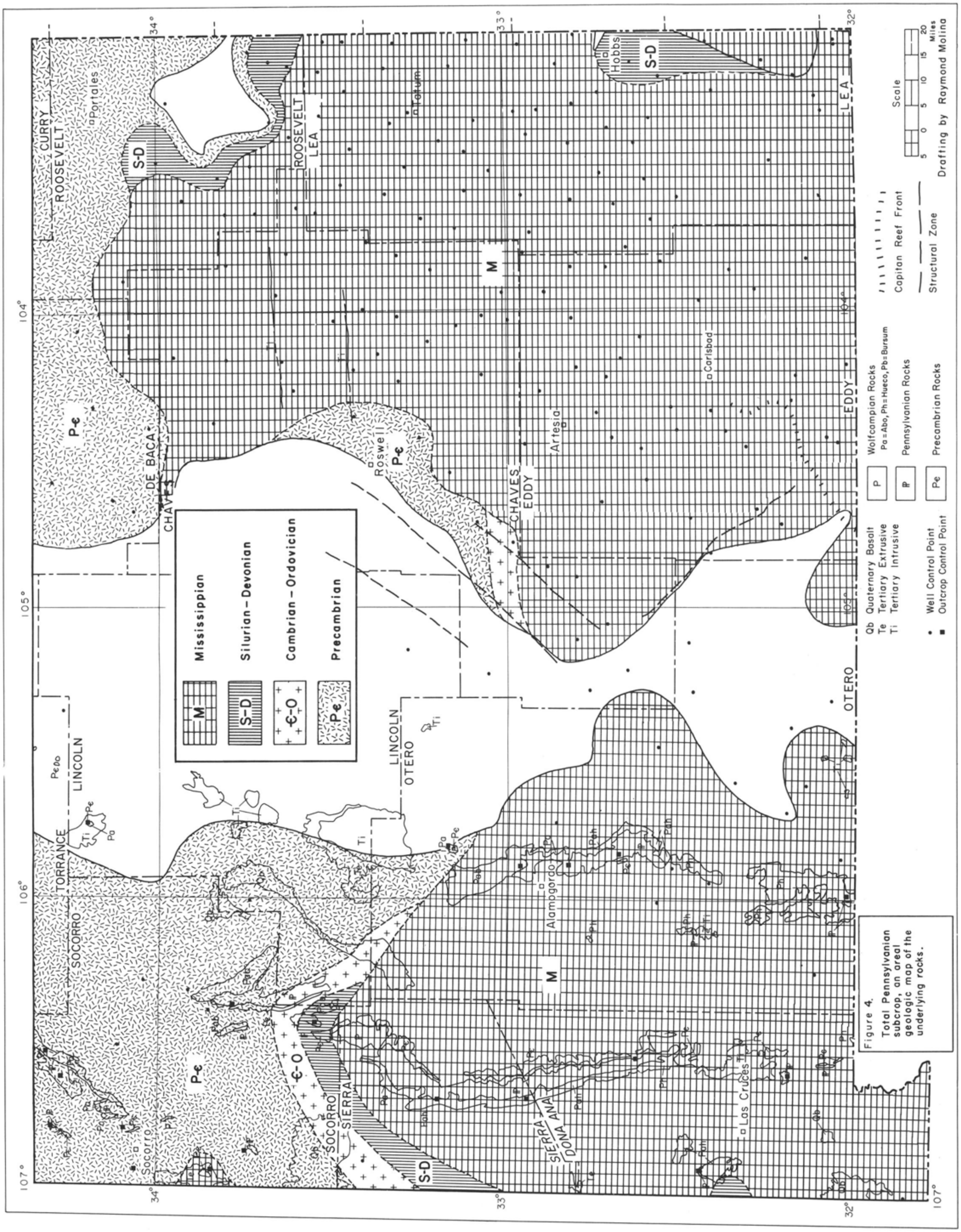


Figure 4. Total Pennsylvanian subcrop, an areal geologic map of the underlying rocks.

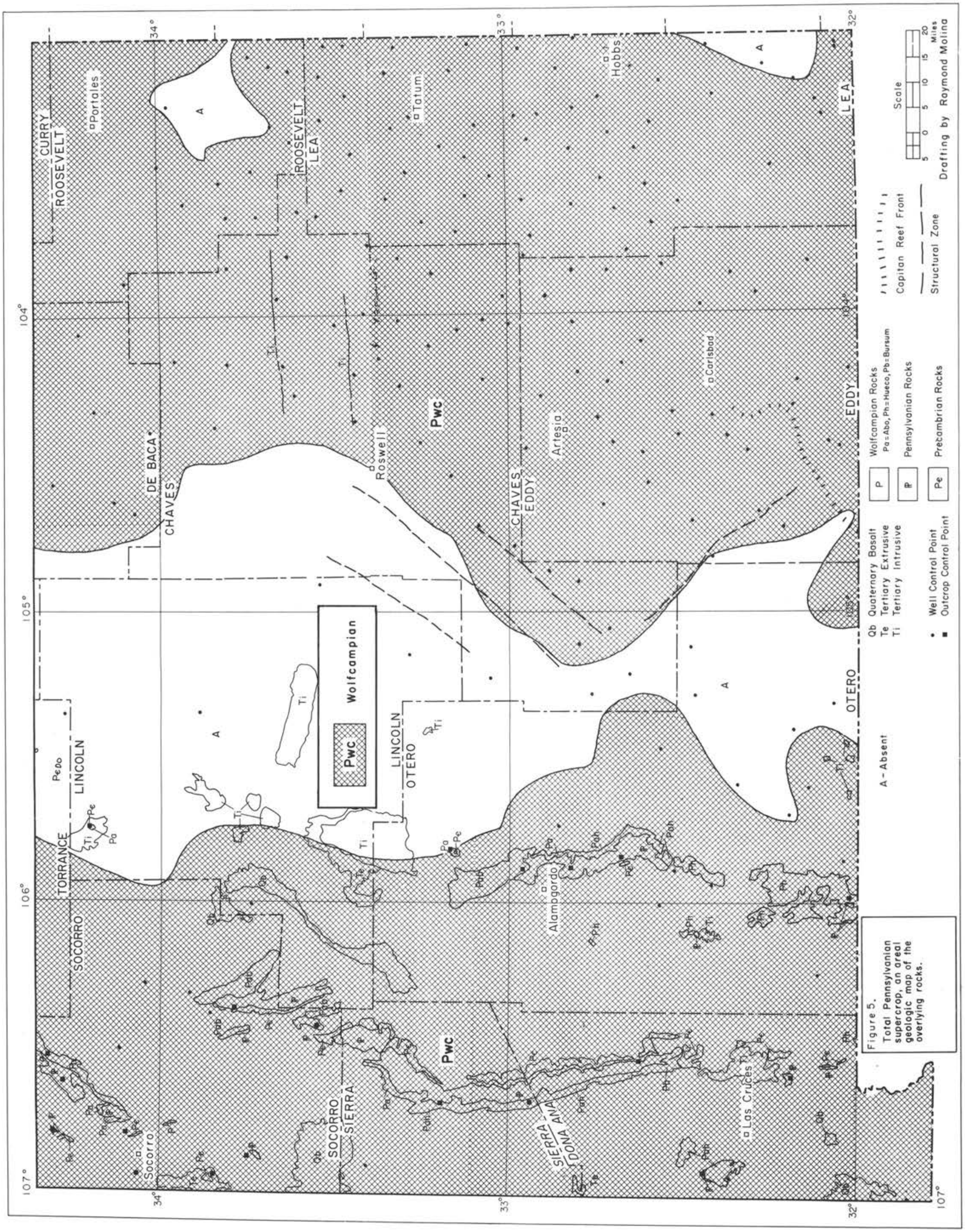


Figure 5. Total Pennsylvanian supercrop, an areal geologic map of the overlying rocks.

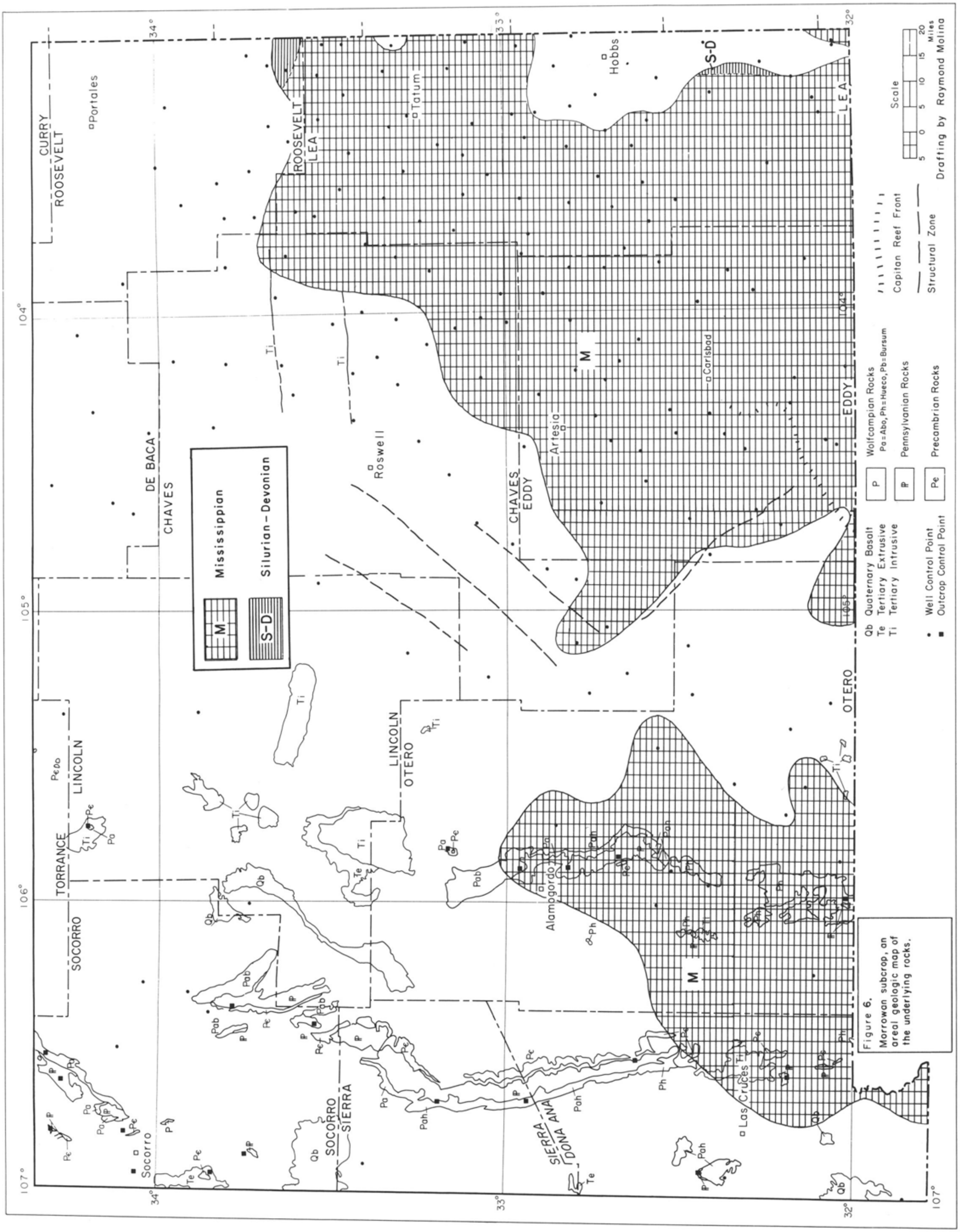


Figure 6.
Morrowan subcrop, an areal geologic map of the underlying rocks.

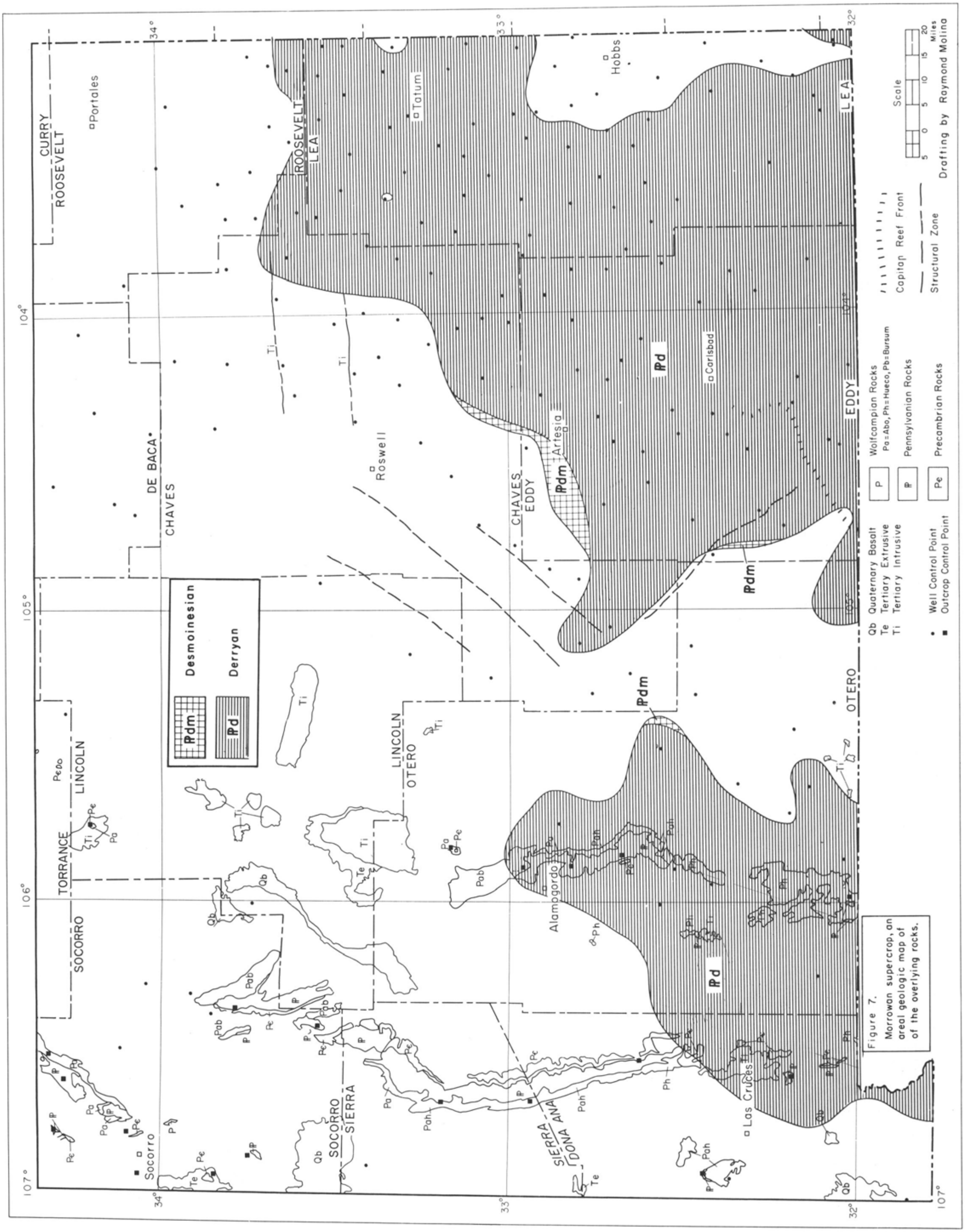


Figure 7. Morrowan supercrop, an areal geologic map of the overlying rocks.

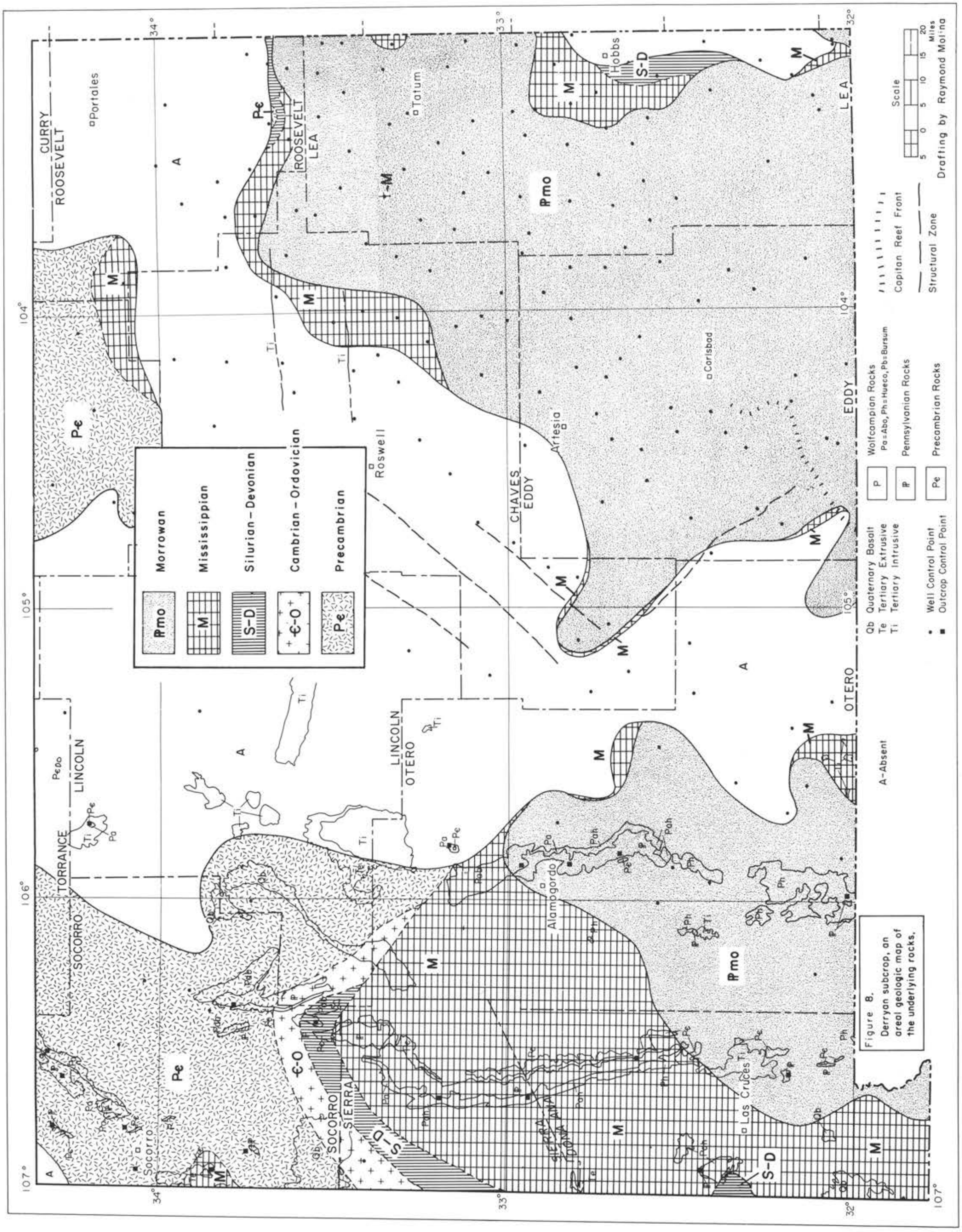


Figure 8. Derryan subcrop, an areal geologic map of the underlying rocks.

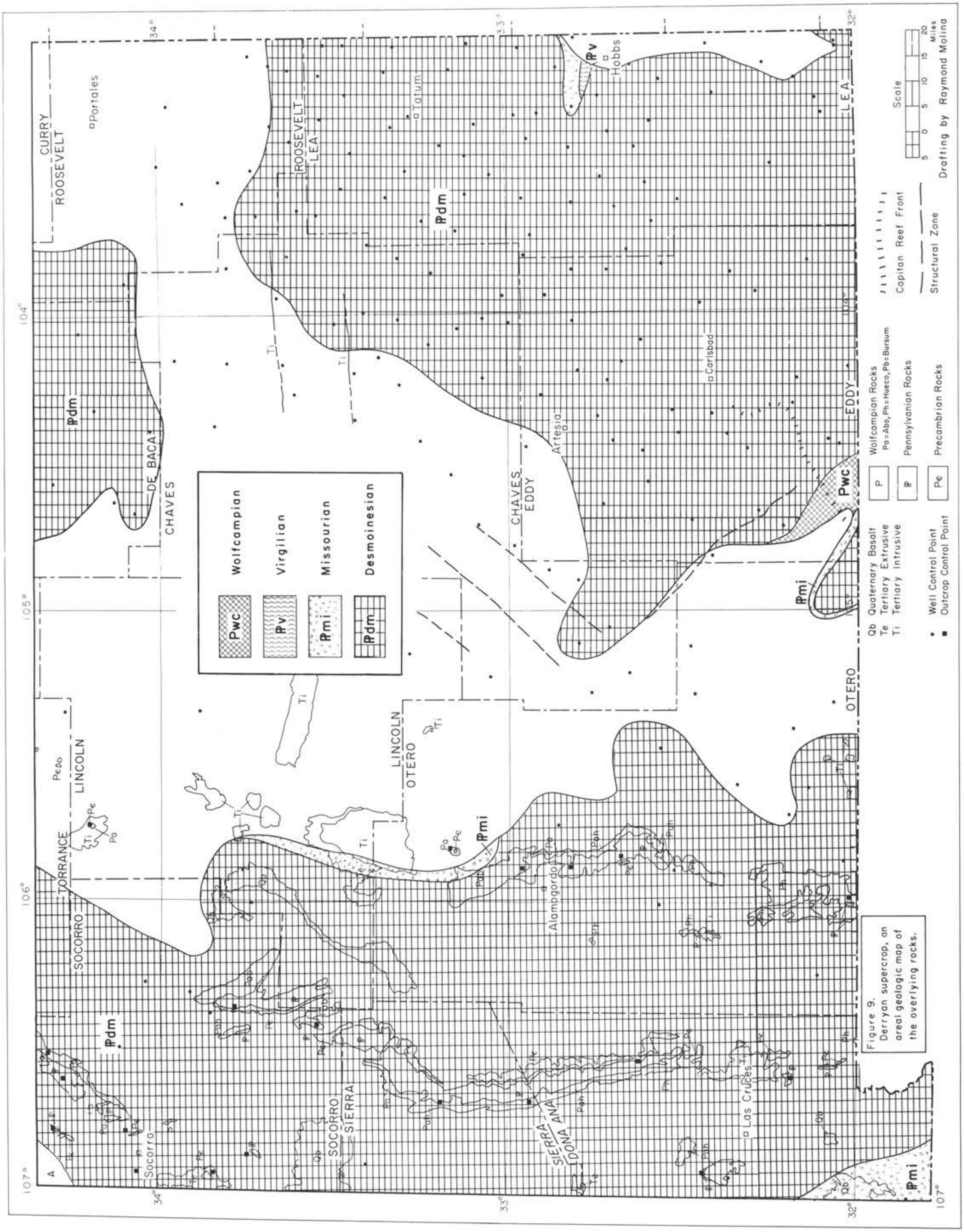


Figure 9. Derryan supercrop, an areal geologic map of the overlying rocks.

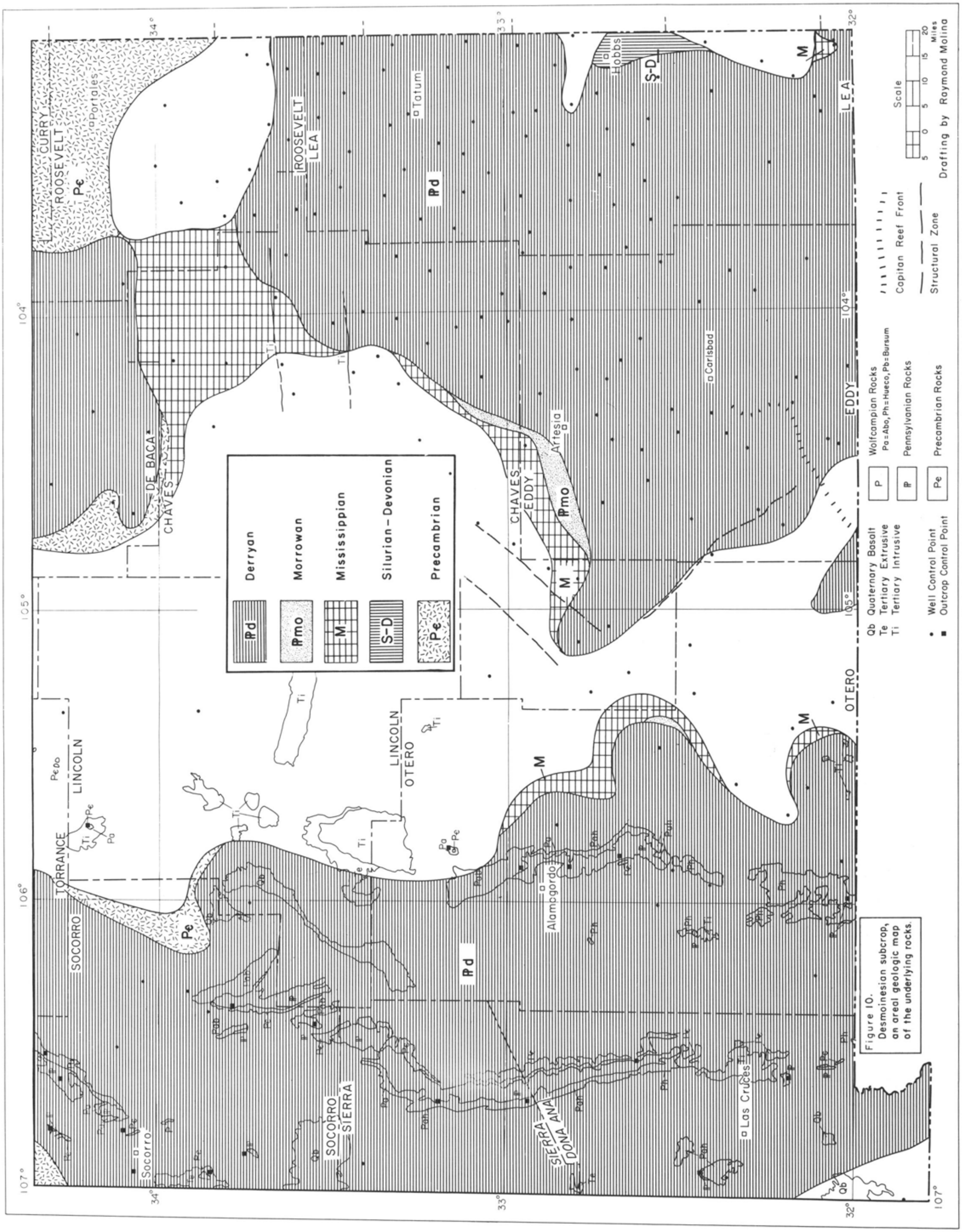


Figure 10. Desmoinesian subcrop, an areal geologic map of the underlying rocks.

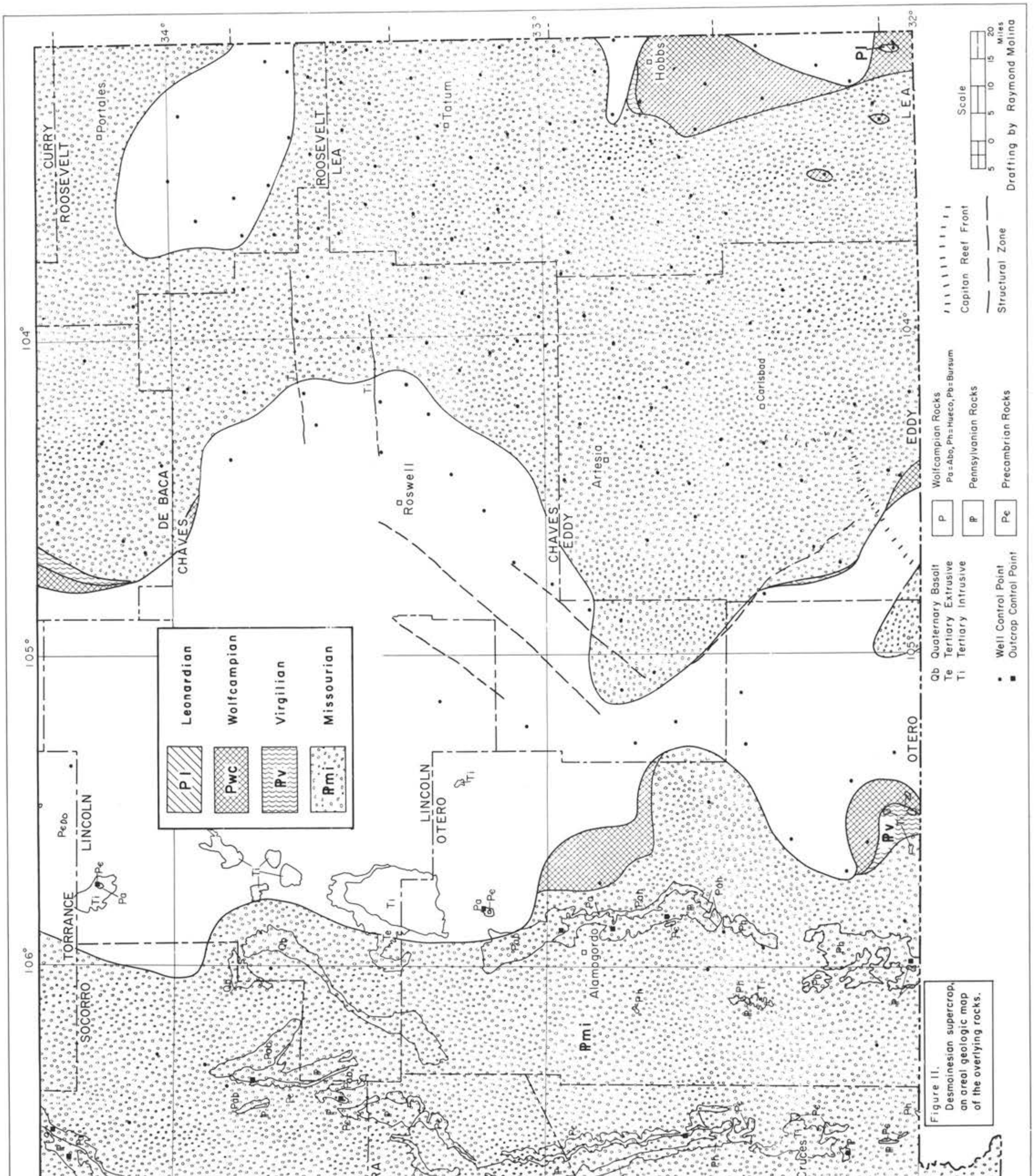


Figure 11. Desmoinesian supercrop, an areal geologic map of the overlying rocks.

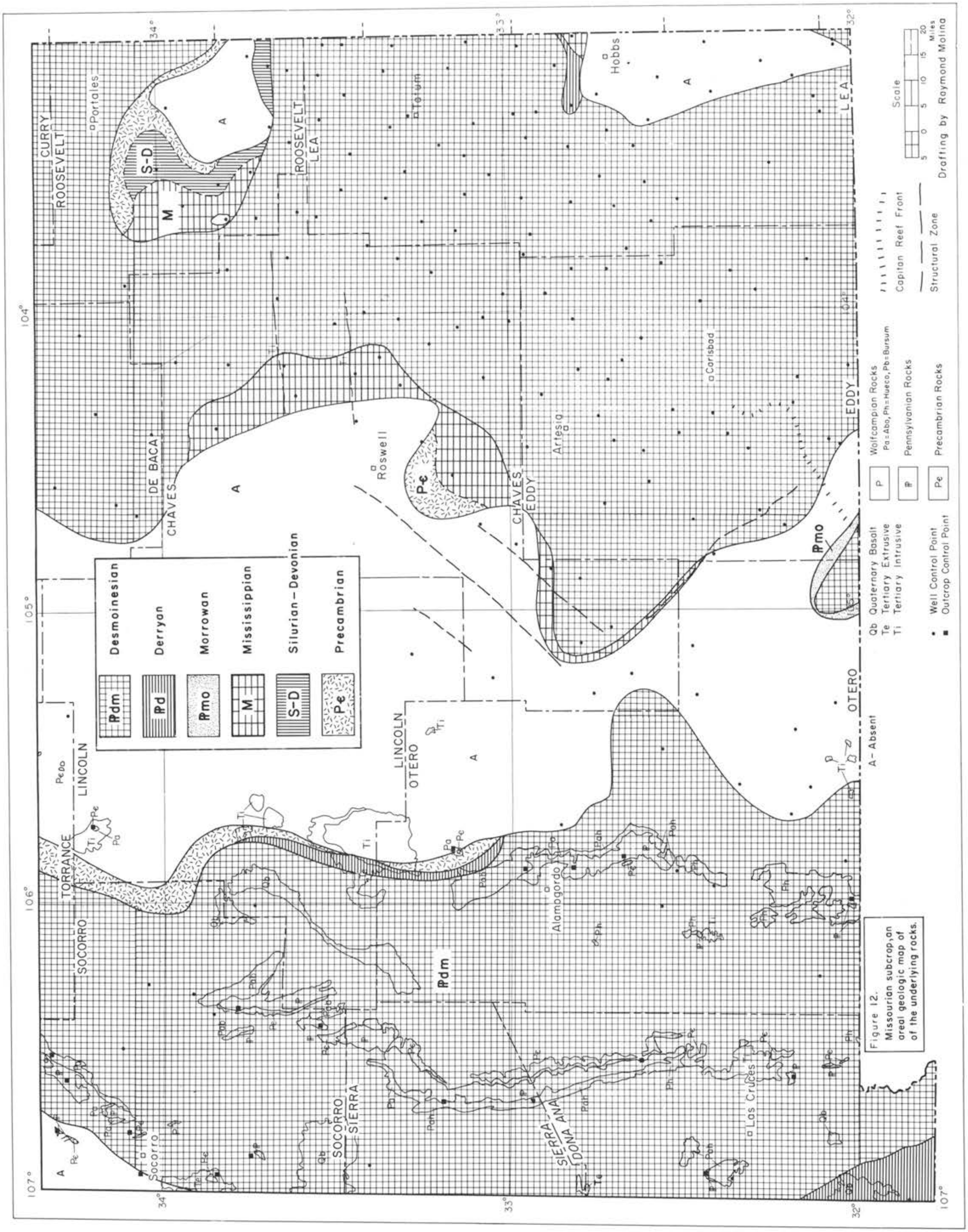


Figure 12. Missourian subcrop, an areal geologic map of the underlying rocks.

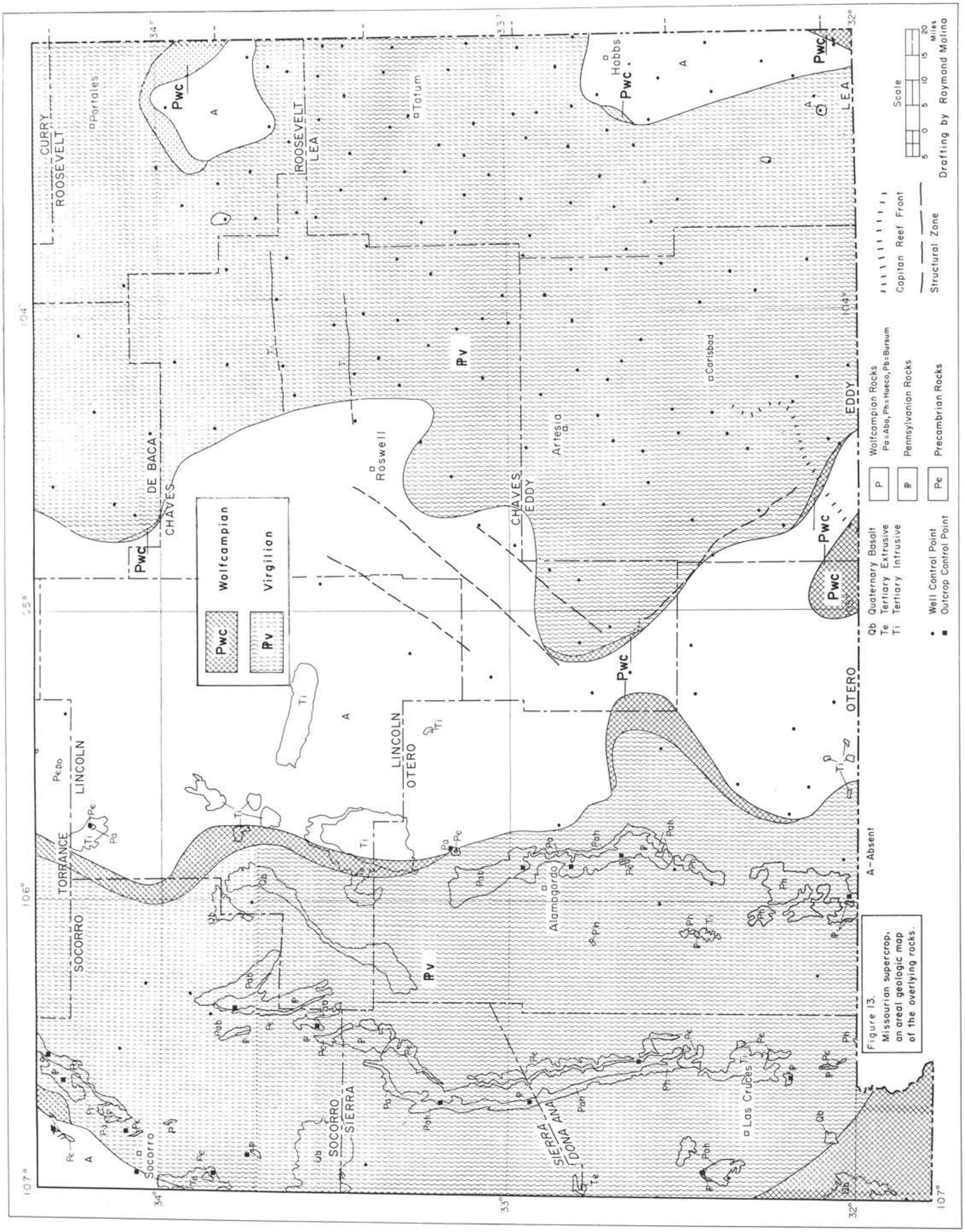


Figure 13. Missourian supercrop, an areal geologic map of the overlying rocks.

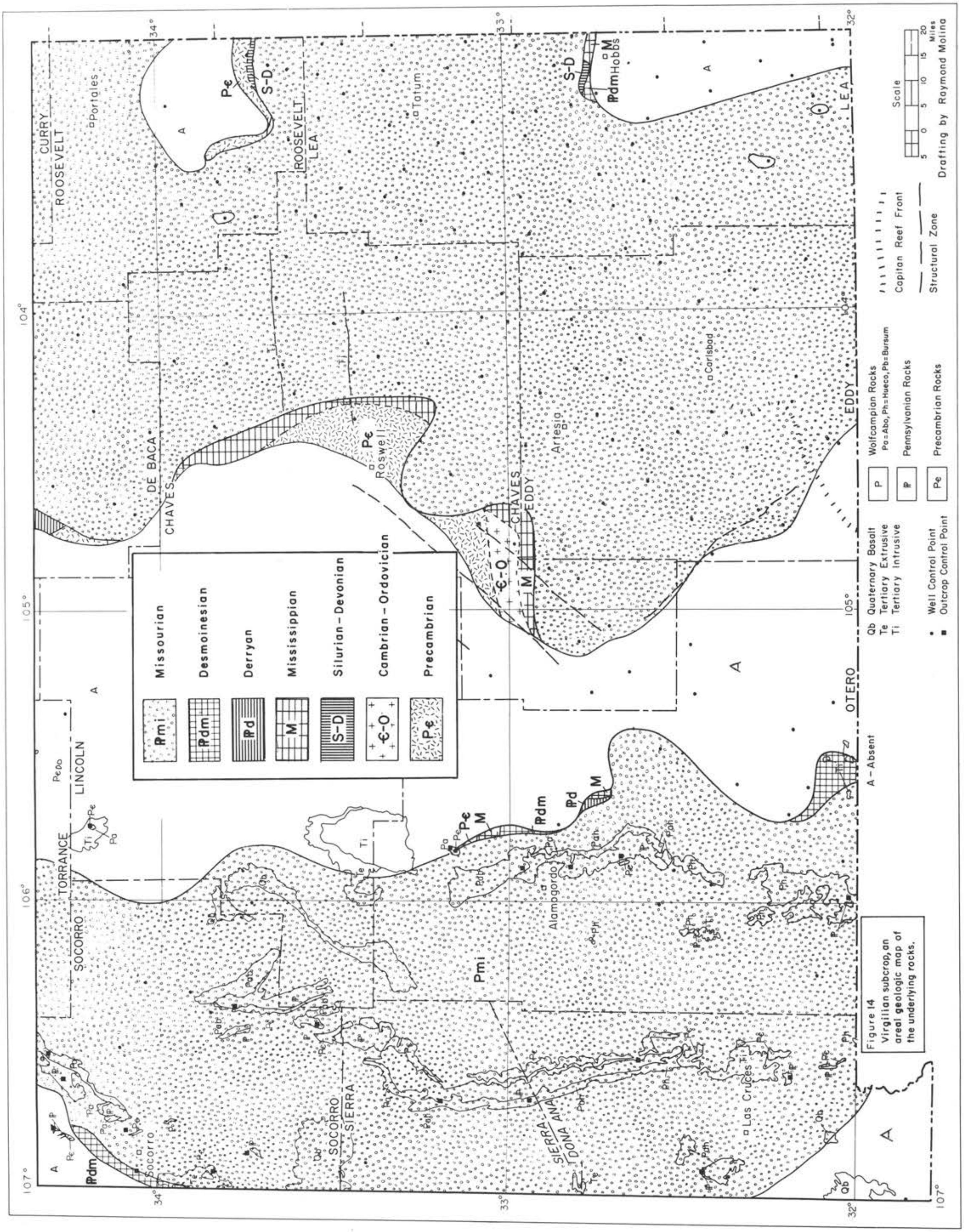


Figure 14
Virgilian subcrop, an areal geologic map of the underlying rocks.

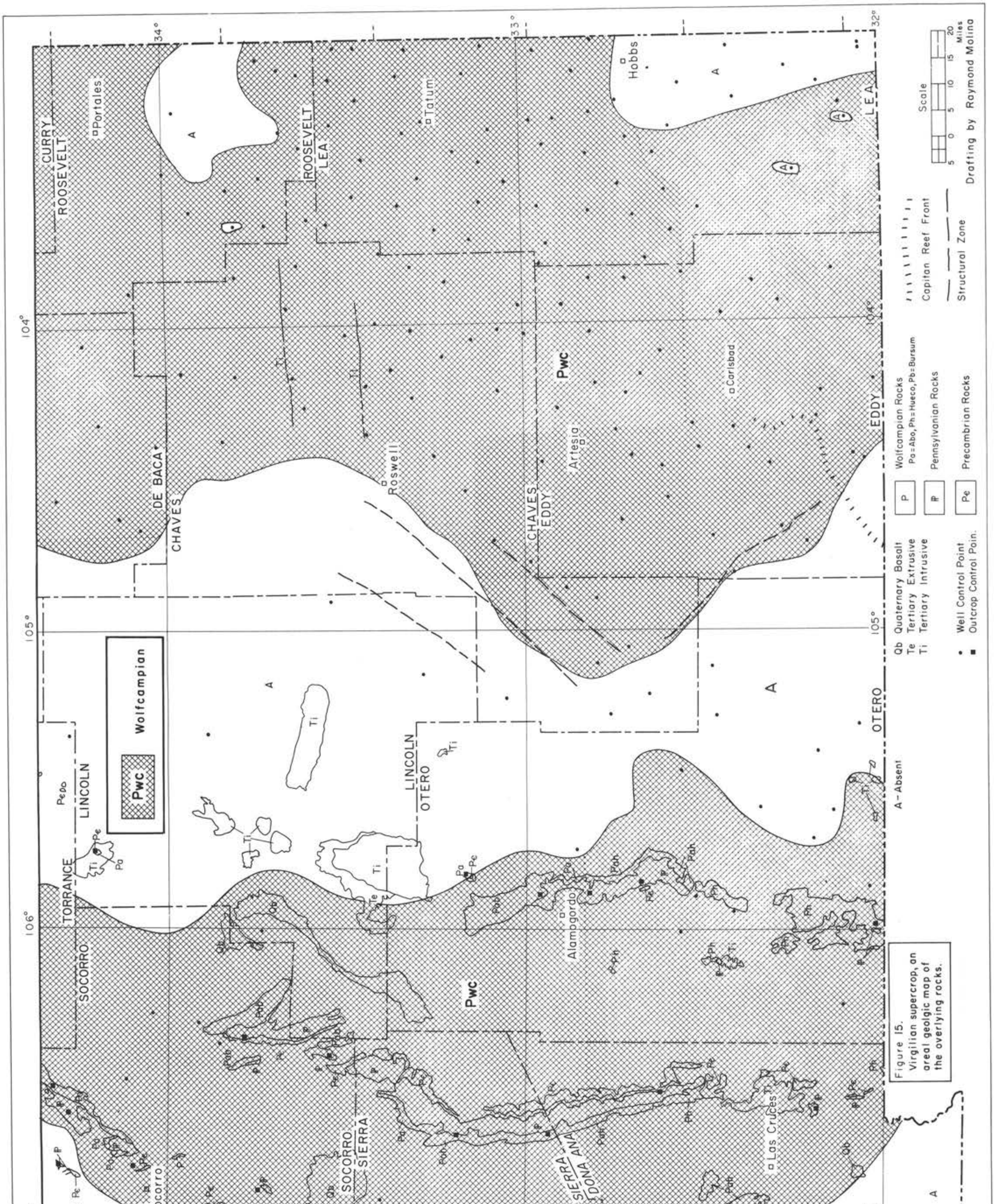


Figure 15. Virgilian supercrop, an areal geologic map of the overlying rocks.

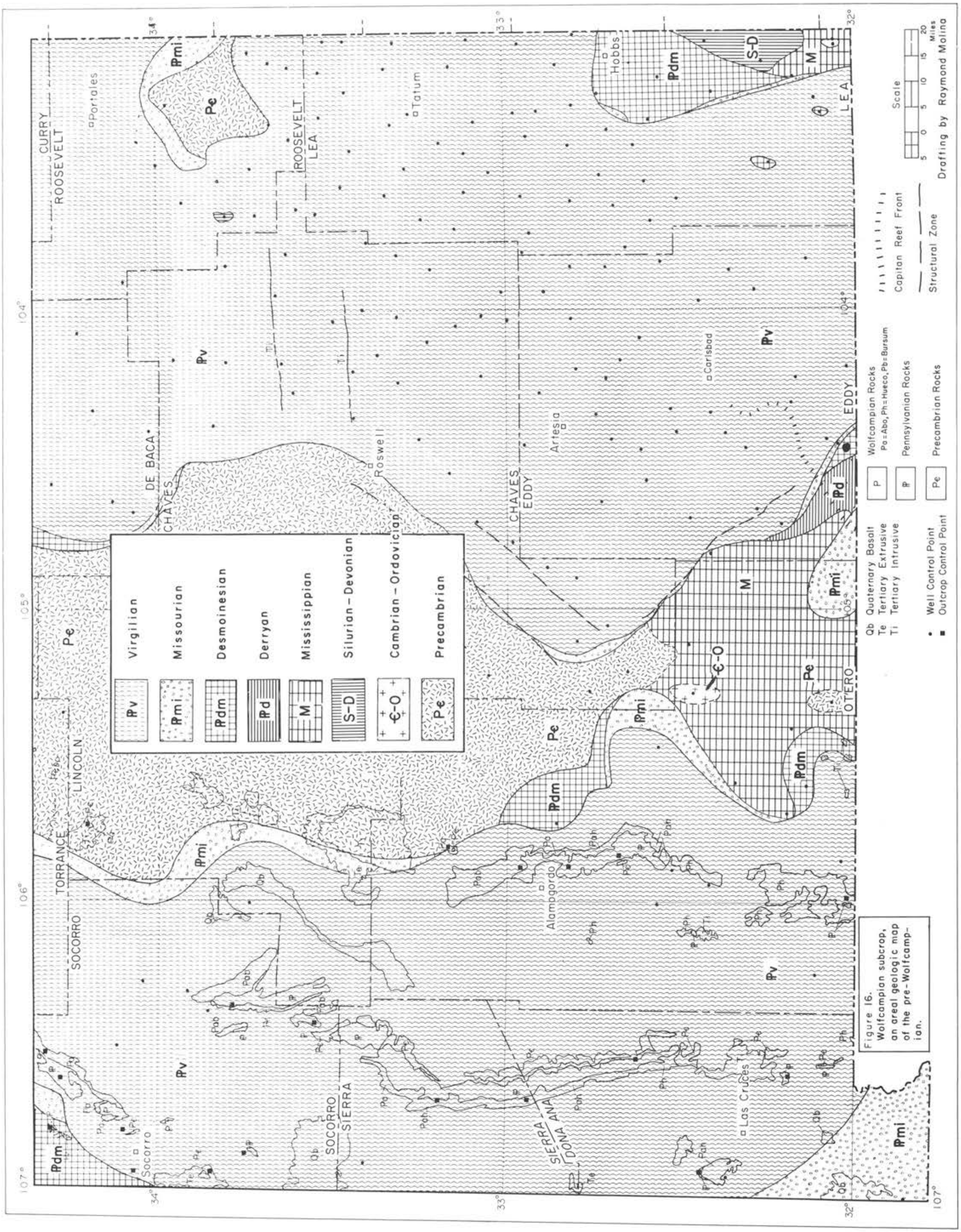


Figure 16. Wolfcampian subcrop, an areal geologic map of the pre-Wolfcampian.

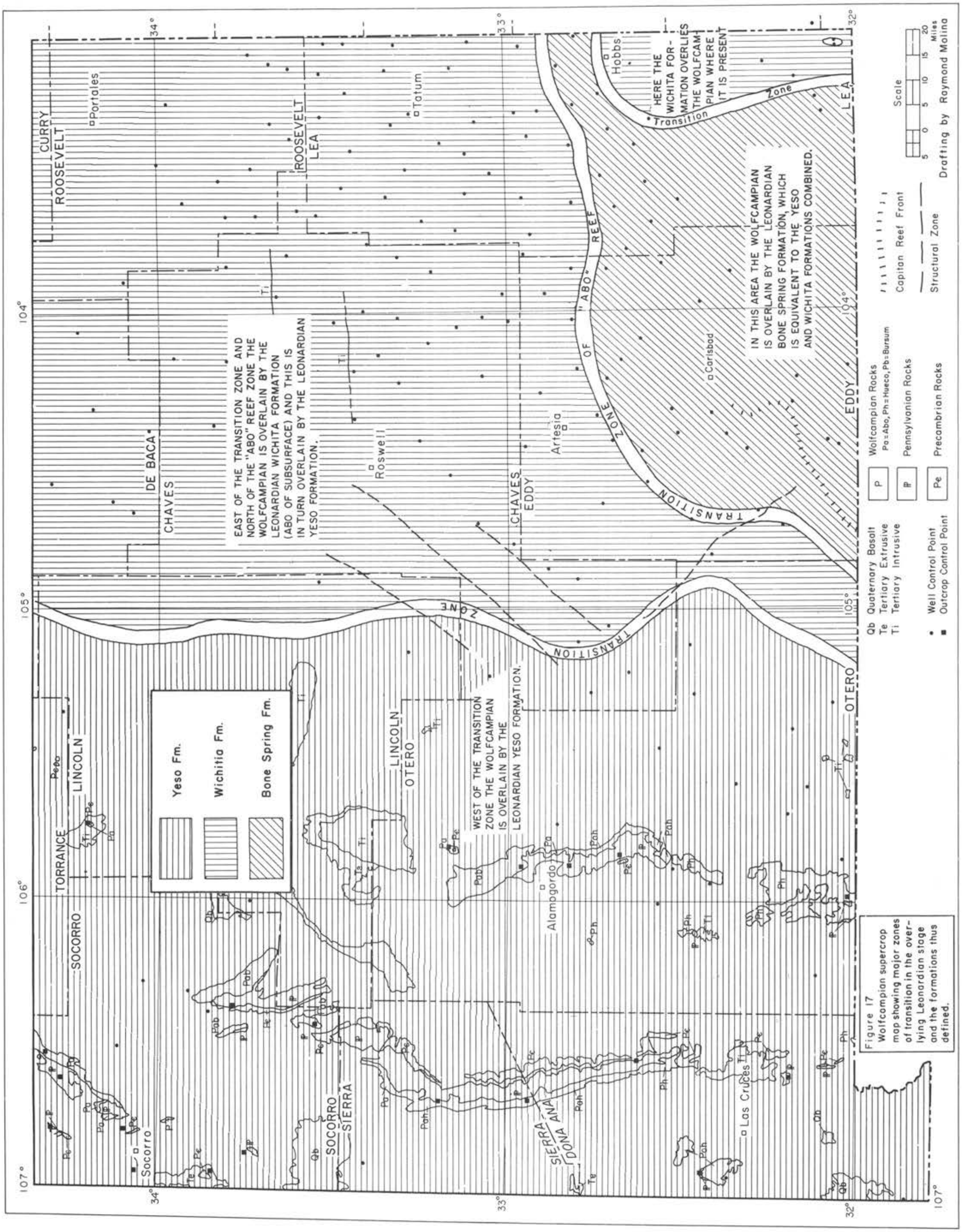


Figure 17 Wolfcampian supercrop map showing major zones of transition in the overlying Leonardian stage and the formations thus defined.

Stratigraphy

Stratigraphic nomenclature used in this memoir is summarized below:

- Permian System (Period)
  - Lower Permian Series (Epoch)
    - Leonardian Stage (Age)
    - Wolfcampian Stage (Age)
- Pennsylvanian System (Period)
  - Upper Pennsylvanian Series (Epoch)
    - Virgilian Stage (Age)
    - Missourian Stage (Age)
  - Middle Pennsylvanian Series (Epoch)
    - Desmoinesian Stage (Age)
    - Derryan Stage (Age)
  - Lower Pennsylvanian Series (Epoch)
    - Morrowan Stage (Age)
    - [Springeran Stage (Age)]

Series of the Pennsylvanian System correspond, in ascending order, to Ardian, Oklan, and Kawvian Series of Moore and Thompson (1949); the Derryan Stage is essentially correlative to their Atokan Stage. Subsurface geologists in west Texas commonly substitute Bend, Strawn, Canyon, and Cisco for Derryan, Desmoinesian, Missourian, and Virgilian, respectively. Strata of Springeran age are not identified in southeast New Mexico.

Series and stages are time-stratigraphic (chronostratigraphic) units and should not be misused for rock-stratigraphic (lithostratigraphic) units, in accordance with Articles 30 (d) and 31 (b) of the *Code of Stratigraphic Nomenclature* (American Commission on Stratigraphic Nomenclature, 1961). When reference is made to a series or stage, the allusion is to the aggregate of rocks deposited during that epoch or age.

The Pennsylvanian and Wolfcampian rocks of southeast New Mexico are characterized by numerous facies changes attributable to the crustal instability of those periods of time. As a result, individual lithic units can seldom be traced very far; this has led to a multiplicity of formation names in areas where the rocks crop out. On his nomenclature chart, Kottlowski (1960a) lists 27 formations and r 0 groups in the Pennsylvanian and three formations in the Wolfcampian; even this is an incomplete listing. It is convenient, therefore, to utilize biostratigraphic units for regional geologic analysis of Pennsylvanian and Wolfcampian events, which procedure is followed in this memoir.

At the present time, there is no published report dealing with rocks of Wolfcampian and Pennsylvanian ages for the region as a whole. The studies of Galley and of Adams et al. are concerned principally with the west Texas part of the Permian basin and serve as a useful adjunct; the summary of Pennsylvanian outcrop sections by Kottlowski (1960a) provides data for the western part of the area, and his studies of the Pennsylvanian of southwestern New Mexico (1962, 1963) are useful extensions to the west of this memoir.

In this area, known examples of graded bedding or repetitive stratification are quantitatively insignificant. Such examples as do occur are described in subsequent pages. While graded beds might signify eustatic changes in sea level, such changes might reasonably be expected to affect the entire region. This is not the case; therefore, the graded beds are interpreted as reflecting local structural movement. Relatively rapid uplift results in layers of coarse materials, while reduction of the uplifted area permits vertical gradation of layers to materials of progressively finer grain size.

Reference is also made in subsequent pages to organic reefs, the word *reef* carrying the meaning of definition 6 (American Geological Institute, 1957, p. 240-241):

> A rock structure, either moundlike or layered, built by sedentary organisms such as corals, etc., and usually enclosed in rock of a differing lithology. Moundlike reefs are referred to as bioherms and layered reefs as biostromes.

Both types of reefs are found in southeast New Mexico. Excellent examples of biohermal reefs are found in the Sacramento Mountains outcrops, whereas biostromes are not uncommon in the subsurface transition zone between the Northwest shelf and the Delaware basin.

Structural contour lines on the structural contour maps are lines of equal elevation above the sea level datum plane. Isopachs represent lines of equal thickness of the unit under consideration. Isolith lines represent lines of equal thickness of a specific lithology. On lithofacies maps, patterns (table 2) are shown that represent associations of lithologies; the patterns are bounded by the intersections of sandstone-shale ratio lines and elastic ratio lines taken from sandstone-shale ratio and elastic ratio maps, respectively, which are not included in the report. Limiting ratios used to establish boundaries of the patterns appear in the lithofacies triangles on each map. The shale color maps are prepared in similar fashion.

Nonelastic rocks of four types are considered. The most important of these is limestone, which constitutes an estimated 80 per cent of the bulk volume of the nonclastics in the area. Dolomite accounts for an additional 15 per cent, chert 4 per cent, and evaporites the remaining 1 per cent. The percentage of chert is indicated on the nonelastic isolith maps.

Sandstone isolith maps show, through two types of contour lines, the aggregate thickness of sandstone in the unit under consideration, as well as the percentage of the sandstone that is red in color.

The thickness of shale in each unit is shown by shale isolith maps and, in addition, the areal distribution of red, black, and variegated shales is presented by means of shale color-ratio maps.

Shale and sandstone color distributions are shown on the shale color-ratio and sandstone isolith maps by patterns and by percentage contour lines, respectively. Color of elastic sediments is helpful in interpreting environments of deposition and is probably the easiest of the attributes of sediments for which to gather data.

Quantitatively, not very much Morrowan or later Pennsylvanian sandstone is red in color. It will be evident from the several sandstone isolith maps that red sandstones are concentrated nearest the zero isolith lines; that is, adjacent to the uplifts. These deposits are usually pale red and arkosic; the quartz grains are coated with ferric oxide pigment; shale of any color is a minor constituent. The red beds are therefore interpreted as being tectonic red beds (Krynine, 1949; Dunbar and Rodgers, 1957; Folk, 1961) reflecting vertical movements of nearby uplifts.

The Precambrian rocks in southeast New Mexico have been mapped by Flawn (1956). They consist principally of granite and granodiorite of the Texas craton, with a smaller area, covering northern Lea County and southern Roosevelt County, of rhyolite of the Panhandle volcanic terrane. These Precambrian rocks were exposed more or less continuously throughout Pennsylvanian time in the Pedernal and Roosevelt uplifts and thus served as the source of clastic Pennsylvanian sediments. The arkosic sandstones are interpreted as indicating proximity to the strandline because fine-grained sediment was mostly winnowed out by wave action, leaving an arkosic beach sand; the same source areas must have supplied clastics throughout the basins, but offshore, fine-grained deposits accumulated, and transport of coarse grains resulted in comminution of the feldspar. Near the strandline, oxidizing conditions dominated and any ferric iron pigment present was preserved, whereas offshore, sufficient organic debris was admixed with the sediments to reduce the ferric iron.

Red shales occur throughout the Pennsylvanian sequence but, as with red sandstones, they are quantitatively insignificant and their occurrence is most frequent adjacent to uplifts. Where red shale beds extend a considerable distance from uplifts, they generally thicken landward and thin seaward.

The red beds of southeast New Mexico were derived from granitic terranes. Periods of uplift resulted in a supply of arkosic material to the sea. Some of this feldspathic sand was not transported beyond the strandline and accumulated there to become arkose. Wave action at the beach reduced most of the feldspar to clay-sized particles that were distributed in the sea as mud, while the quartz grains were distributed in the basins as quartzose sands.

Among the shales, those of gray color are most common. Other light-colored, nonred shales—yellow, brown, green, and purple—are included with the gray. The gray shales are widely distributed over the shelves and are considered indicative of well-aerated waters with unrestricted circulation. Microfossils are common in these shales, including large types of fusulinids.

Red shales are usually not significant quantitatively. Generally, they are closely associated with the uplifts and are interpreted as indicating periods of uplift and consequent heavy influx of red clay into the seas.

Black shales represent the accumulation of organic-rich sediments in places of restricted circulation. Here the organic material is not oxidized and destroyed. Black muds are common tidal flat deposits. They are also characteristic of the sea floor where circulation is restricted by thermal layering of the water or by physical barriers, such as the sills at the mouths of fjords. In southeast New Mexico, the black shale occurrences are within the basins, in a seaward direction from the light-colored shales and limestones of the shelves. The black shales are intercalated with black, dark-gray, and dark-brown limestones, and they are frequently matted with siliceous spicules, are commonly pyritiferous, and sometimes include unabraided fusulinds or other foraminifers. The fossils are most abundant in the limestones. For these reasons, the black shales are interpreted as deep-water deposits, the water depth being a consequence of regional subsidence of the basin floor relative to the shelf or else of local depression of a part of the basin floor. The latter would result in the shale color-ratio maps showing areally restricted patches of black shale.

PENNSYLVANIAN SYSTEM

LOWER PENNSYLVANIAN SERIES

Morrowan Stage

Lithology. Rocks of Morrowan age in the Orogrande basin consist of brown, massive, dense limestone and rare gray shale that grade eastward, on the Sacramento shelf (pl. 1), into well-sorted quartzose sandstone and gray and brown shales. East of the Pedernal uplift in the Delaware basin, along the same cross section, Morrowan strata are composed of beds of argillaceous, angular, fine- to coarse-grained quartzose sandstone, dark-gray shale, and dark-gray argillaceous oolitic limestone. The sandstones are commonly glauconitic. On the Central Basin platform, Morrowan black shale is preserved in the section penetrated by the Plymouth Federal—Lowe 1 well (L-38). Over the Northwest shelf (pls. a and 3), the Morrowan typically is comprised of interbedded gray shale and brown to tan, fine-grained, often cherty limestone in the upper part and gray shale with subordinate fine-to medium-grained quartzose sandstone in the lower part.

Thickness. Thicknesses of Morrowan rocks are more than 75o feet in the Orogrande basin and 1250 feet in the Permian basin (fig. i8). Locally absent on the Northwest shelf (L-5, L-44), the Morrowan is absent over most of the Central Basin platform. Morrowan strata are distributed as two tongues deposited in a sea that extended northward into the map area from the south and, on the Northwest shelf, from the east.

The wide and even spacing of the isopachs suggests that the zero lines around the Orogrande and Permian basins closely approximate original strandlines. The close spacing of the isopachs on the west side of the Delaware basin (between E-15 and E-24) and along the west margin of the Central Basin platform indicates that the sediments in these places were formerly more extensive, having been uplifted and eroded subsequent to deposition.

Lithofacies. The distribution of Morrowan lithofacies associations is shown in Figure 19. Interpretation of this map causes conflict, in places, with interpretations based upon the isopach map (fig. 18). In the Orogrande basin, where data points are sparse, limestone is present up to the margin of the unit. If, as indicated above, the zero isopach closely approximates the Morrowan strandline, clastic rocks might be expected at the basin margin; this is generally true in areas and at times of active uplift whereby clastic materials are supplied to adjacent seas. Inasmuch as such rocks are not apparent, it is presumed that an unknown amount of Morrowan rocks was eroded from the marginal areas subsequent to deposi-

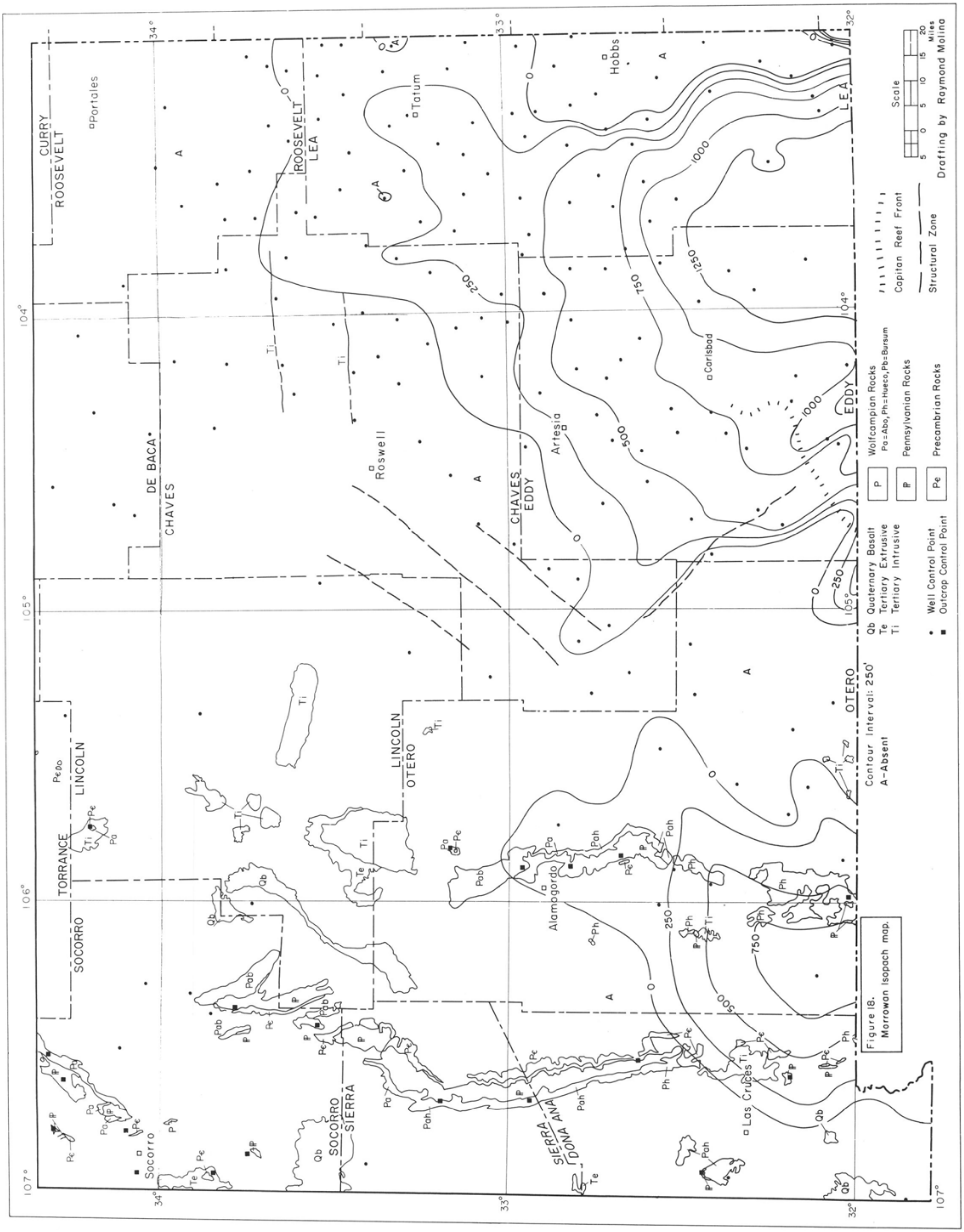


Figure 18. Morrowan Isopach map.

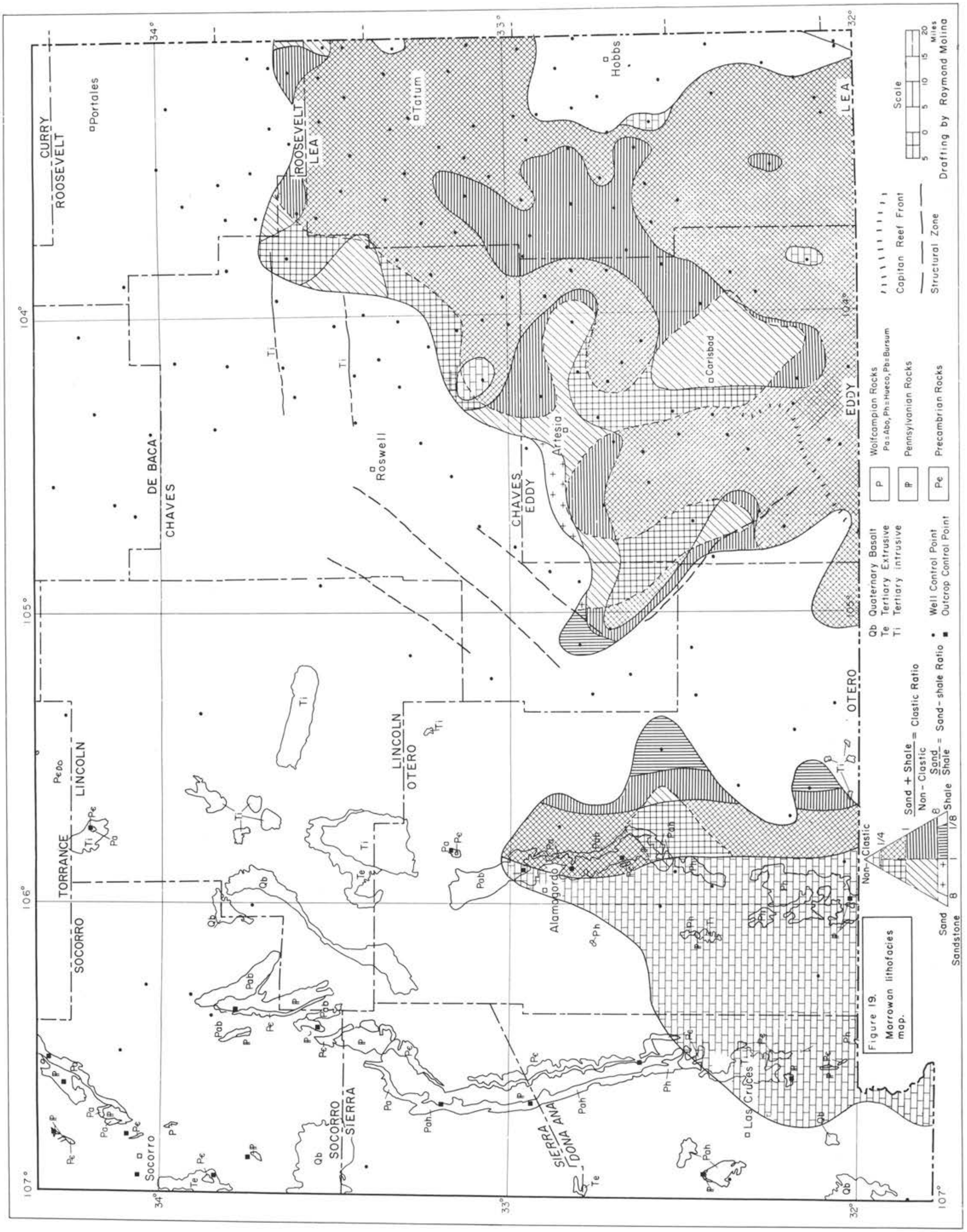


Figure 19. Morrowan lithofacies map.

tion. Over the Sacramento shelf, shale as well as shale- and sandstone-limestone associations are present, indicating a source of clastic rocks near this area. On the northwest side of the Permian basin, clastic rocks and clastic-nonclastic associations are present, indicating that here the zero isopach may be close to the depositional edge of Morrowan sediments. Along the west side of the Delaware basin, the limestone-shale association coincides with the zero isopach; it is inferred that sediments were originally deposited farther to the west, were perhaps contiguous with those of the Orogrande basin, and were later uplifted and eroded. A similar situation is believed to have existed over the Central Basin platform; it was probably first covered by Morrowan sediments that were later uplifted and eroded. The Permian basin is notable for its paucity of limestone (clastic ratios smaller than one quarter) and for its relative abundance of sandstone, compared with succeeding units.

Sandstone. The contour interval (I oo feet) of the sandstone isolith map (fig. 2o) is too great to reflect the fact that at least some sandstone occurs in the Morrowan Stage over essentially all of the Permian and Orogrande basins. In the Orogrande basin, aggregate thickness of sandstone is everywhere less than t oo feet, but it approaches this figure near the margin of the Pedernal uplift (0-6 and 0-12). Significant accumulations of sandstone are also found in the Permian basin. The isolith lines suggest that the Pedernal uplift was being subjected to subaerial erosion, with possibly a major river debouching into the Morrowan sea at a place along the northwest margin of the Northwest shelf.

Shale. Shale is up to too feet thick in the Orogrande basin (fig. 21). On the west side of the basin, it is virtually absent, as is sandstone (fig. 2o); this supports the view that the west margin of the basin is an erosional edge and is not coincident with the Morrowan shoreline. In the Permian basin, thickness of shale increases with distance from the featheredge of the unit. Distribution of shale color associations is indicated on the shale color-facies map (fig. 22). As with sandstone, red shale occurs on the Northwest shelf along the northwest margin of the unit. Most of the black shale is found on the west side of the Delaware basin. Because most black shales are rich in organic matter, which is easily oxidized, it is presumed that the water in this area was sufficiently deep and stagnant to permit reducing conditions to exist on the sea floor.

Nonelastic rocks. The thickness and distribution of nonclastic rocks in the Morrowan are shown in Figure 23. The strata are composed of two lithologies, limestone and chert. The percentage of chert is shown on this and succeeding nonclastic isolith maps by means of dashed contour lines for **I,** 25, and 5o per cent chert. The immediate source of most of the Pennsylvanian cherts evidently was siliceous sponge spicules, as was the case with the Permian rocks of southwest Montana (Cressman and Swanson, 1964). The dark shales of the Delaware basin are commonly spicule-bearing. The ultimate source of the silica is not known; volcanic ash, a commonly accepted source for silica, is not identified in Pennsylvanian strata in this area, although a few thin beds of "bentonite" are frequently used as markers on mechanical well logs. Cressman and Swanson calculated that organisms could extract enough silica from normal sea water to form chert.

At three places on the nonclastic isolith map (fig. 23), the isolith lines crowd the zero line: the west side of the Orogrande basin, the southwest side of the Delaware basin, and the west edge of the Central Basin platform. The condition in the Orogrande basin is further evidence that the Morrowan extended farther west but was removed by post-Morrowan upwarping and subsequent subaerial erosion. The abrupt pinch-out of Morrowan nonclastics on the west side of the Delaware basin and their reappearance in the Salt Flat embayment indicates that the Morrowan sea extended an unknown distance to the west and perhaps joined the sea in the Orogrande basin. If this is so, then the Morrowan clastic rocks of the Sacramento shelf may have been derived from islands of exposed granite or from pre-existing sediments being eroded from the Pedernal uplift. The closely spaced isolith lines adjacent to the Central Basin platform reflect the fault that borders that feature.

MIDDLE PENNSYLVANIAN SERIES

Derryan Stage

Lithology. On the Robledo shelf, the Derryan Stage is comprised of blackish silty limestone and green and gray shales (pl. 1). These rocks grade eastward into argillaceous, arenaceous, and cherty limestones and calcareous shales in the Orogrande basin. On the Sacramento shelf, Derryan rocks are made up of black argillaceous limestone and silty quartzose sandstone in the lower part, grading upward into tan to brown, dense limestone in the upper part. East of the Pedernal uplift, in the Delaware basin (pl.), Derryan beds consist of gray to brown to black, fine-grained to dense limestone, chert, and dark-gray **to black shales. On the Central** Basin platform, the Derryan (at L-38) consists of a lower unit of black shale similar to that of the underlying Morrowan and an upper unit of tan to brown, dense limestone with some interbedded gray shale. Northward, over the Joyita uplift (pl. 2), Derryan rocks are composed of quartzose conglomerate, gray and green quartz sandstone, dark-colored carbonaceous shale, and dark-gray arenaceous limestone. Where the Estancia and Orogrande basins join, including the Oscura uplift, the Derryan is characteristically of similar composition, differences being mainly in thicknesses. East of the Pedernal uplift, in the Tucumcari basin, Derryan strata consist of interbeds of pink, tan, and white fine-grained limestones, gray shale, and coarse-grained quartzose sandstone (pl. 4). Over the Northwest shelf, rocks of Derryan age are generally represented by two units. The lower unit consists of white, coarse- to very **coarse-grained, quartzose sandstone** and gray to black shale with minor tan to brown, fine-grained limestone; the upper one consists of tan to brown, very fine-grained limestone. Milky chert is common and gray shale is present in minor amounts.

Graded bedding. Graded bedding of Derryan age is described only from the southern Estancia basin (S-1; Stark and Dapples). The beds cannot usually be traced more than a quarter of a mile laterally but are vertically repetitive.

Ideally, a graded sequence consists, in ascending order, of coarse-grained, cross-bedded, micaceous sandstone; calcareous sandstone, olive-drab micaceous sandy shale; coarse-grained

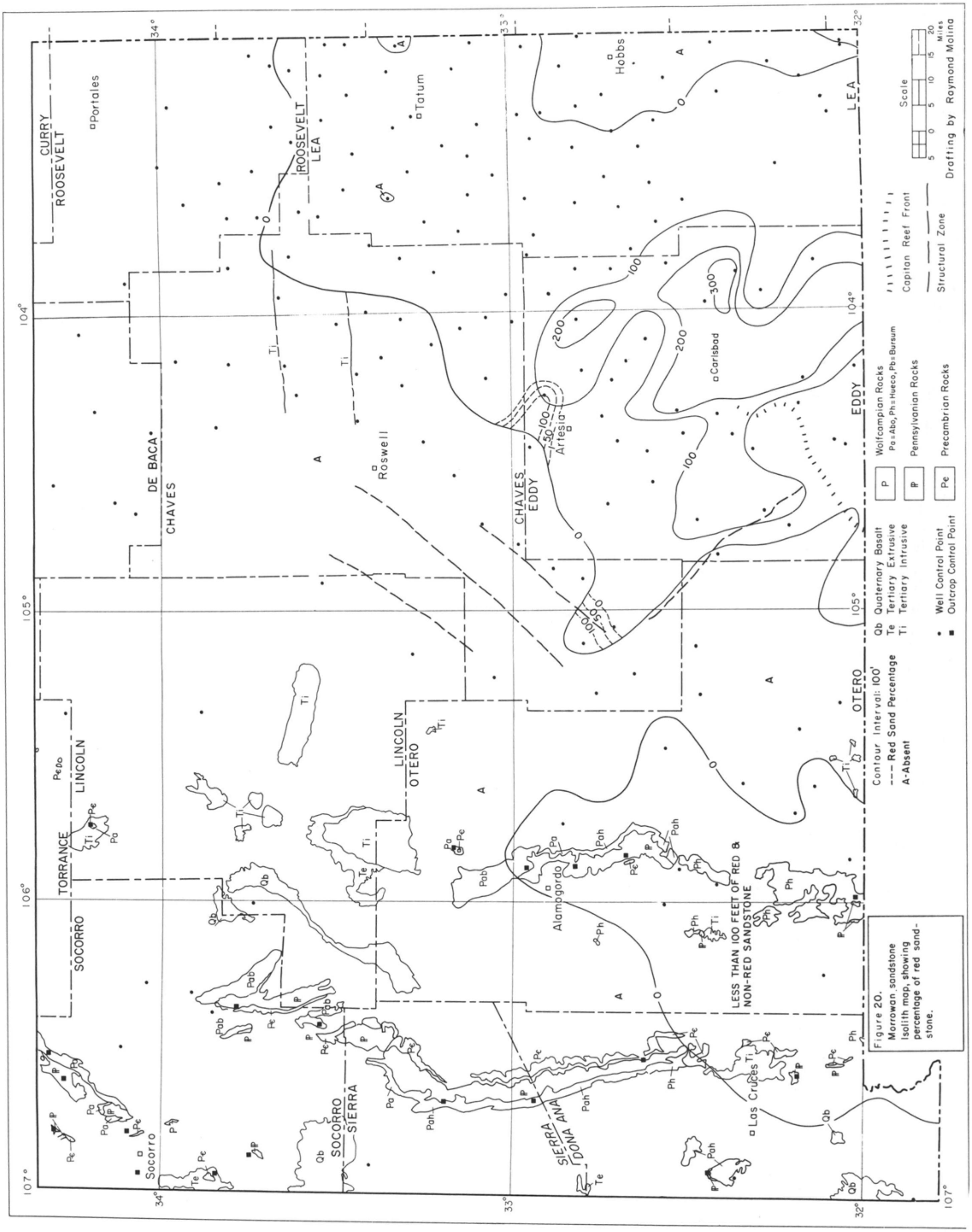


Figure 20. Morrowan sandstone Isolith map, showing percentage of red sandstone.

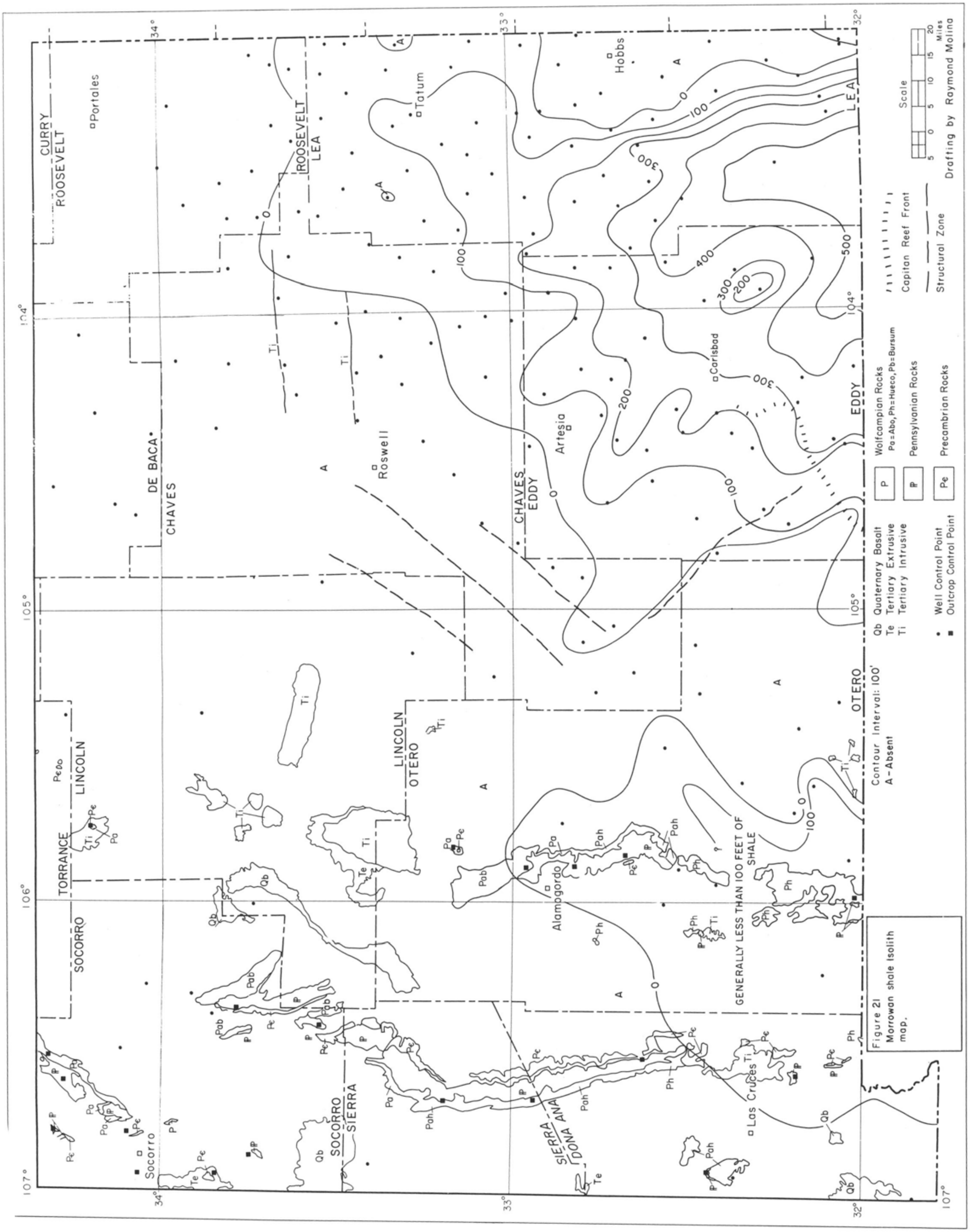


Figure 21
Morrowan shale isolith map.

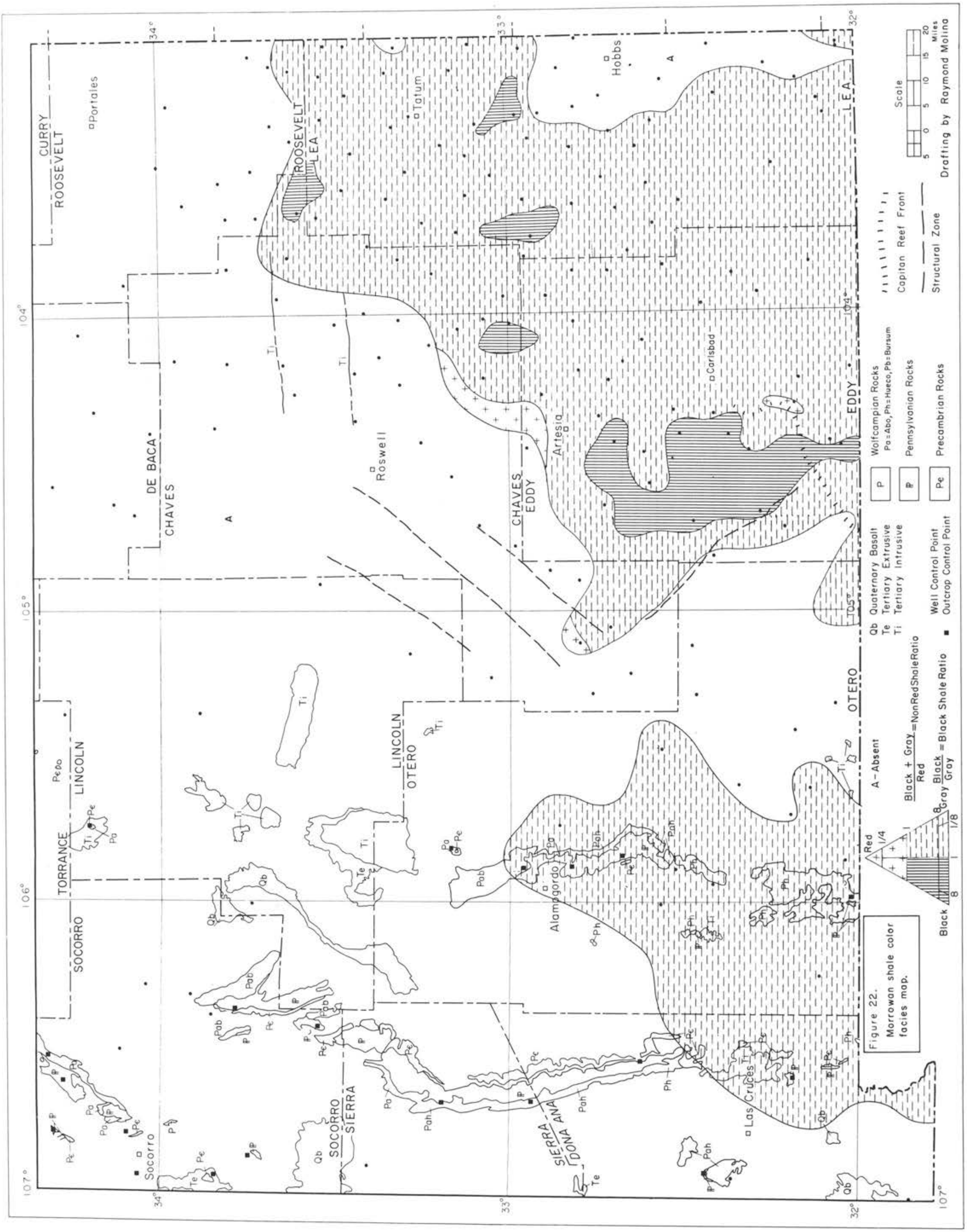


Figure 22. Morrowan shale color facies map.

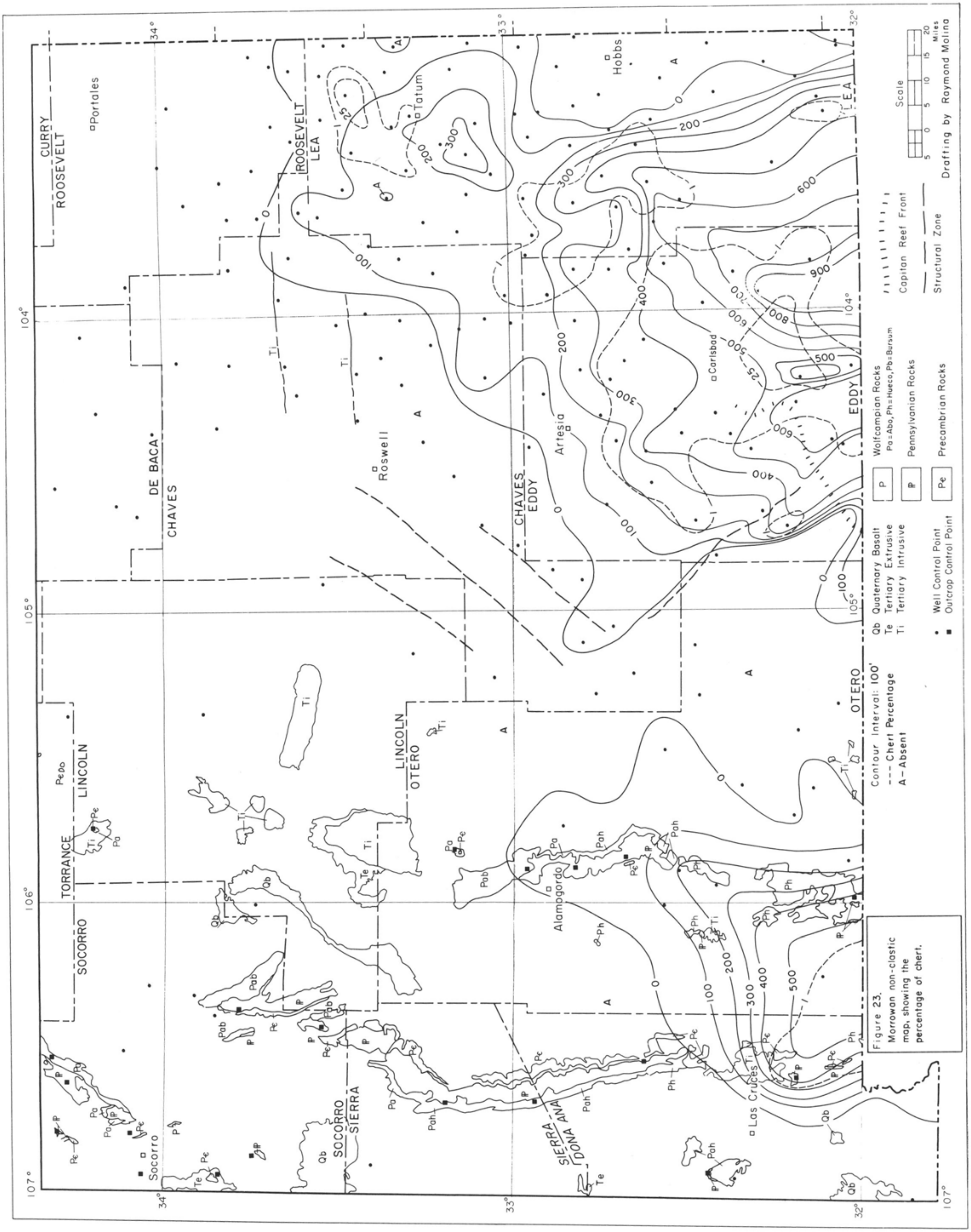


Figure 23. Morrowan non-clastic map, showing the percentage of chert.

fossiliferous limestone; and fine-grained to lithographic limestone. The graded beds occur in vertical sequences of 276 and 500 feet. The sandstones are 5 to 4o feet thick and constitute about 8o per cent of the section. The shale is usually in beds 20 feet thick, which make up about 5 per cent of the total section, whereas the limestones, generally in beds 5 feet thick, constitute as much as 15 per cent of the sequence.

Thickness. Distribution and thickness of Derryan strata are shown in Figure 24. West of the Pedernal uplift, the rocks appear to be as much as 275o feet thick. Maximum thickness (at O-11) is probably due to repetition of beds by reverse faulting, so that 1000 feet may represent more closely the regional maximum thickness. In the Tucumcari and Permian basins, the rocks attain a maximum thickness of about 75o feet. Derryan sediments are very thin at the side of the Robledo uplift (Y-3), and the broad Robledo shelf is evident along the west side of the Orogrande basin.

Where the isopachs become closely spaced very abruptly as the zero isopach is approached, it is probable that the unit is absent because of uplift and subsequent subaerial erosion.

Lithofacies. Lithofacies of Derryan strata are shown in Figure 25. The central part of the Orogrande basin is an area of sandstone- and shale-limestone associations; it is probable that the elastic rocks were derived from the Pedernal uplift. Carbonate rocks are most abundant over the Robledo and Sacramento shelves and at the site of the Oscura uplift. On each side of the south end of the Pedernal uplift, carbonate rocks are present as limestone and as limestone-shale associations. It is likely that these strata were deposited all the way across this part of the area and later removed. Farther north, however, along the west sides of the Permian and Tucumcari basins, there is strong evidence in the form of sandstone, shale, and predominantly clastic associations with carbonates that the present margins of the basins are near their depositional limits. The clastic rocks near the north end of the Central Basin platform are of interest in that they support the idea, emphasized in the section on the Desmoinesion Stage, that uplift and erosion of the platform took place in pre-Desmoinesian time, following deposition across the site of the uplift of Morrowan and Derryan rocks.

Sandstone. The distribution and thickness of sandstone in the Derryan sequence are shown in Figure 26. Some sandstone is present almost everywhere, but it is usually less than oo feet thick. The isolith lines in the northwestern part of the Orogrande basin indicate that the sediment source lay to the east in the area of the Pedernal uplift. Sandstone in the Tucumcari and Permian basins was evidently derived from the Pedernal uplift which, in Derryan time, was contiguous to the Roosevelt uplift. Some of the sandstone, along the western margins of these two basins, is red and arkosic, indicating exposure of the granite core of the Pedernal uplift as well as accumulation under conditions of oxidation. This may indicate proximity to the shoreline.

Shale. Thickness and distribution are shown on the shale isolith map (fig. 27) and the distribution of red, black, and gray shales on the shale color-facies map (fig. 28). The greatest thickness of shale is in the southern Orogrande basin, but part of this thickness may be a result of bed repetition due to reverse faulting. Relatively thick shale is found in the vicinity of the Joyita uplift, where anomalously thick sandstone also is present; however, the depth of water was apparently greatest southward, where a patch of black shale lies at the western edge of the map. Red shales border the northern margin of both the east and west sides of the Pedernal uplift, suggesting erosion of the granitic core of the uplift. The water was probably deepest in the southwest part of the Permian basin where a large patch of black shale is found; this occurrence coincides areally with that of Morrowan black shale (fig. 22).

Nonelastic rocks. Distribution and thickness of nonclastic Derryan rocks are shown in Figure 29. Strata are composed of limestone with variable amounts of chert, the chert being especially common in the Permian basin. These rocks are thickest over the north-central part of the Northwest shelf and in the Delaware basin at the southern margin of the map. In the Orogrande basin, the isolith lines are parallel to the west margin of the Pedernal uplift and are widely spaced along the west side of the basin, where clastic rocks are notably thick. Distribution of clastic and nonclastic rocks support the view that the principal source of elastics was from the west.

Desmoinesian Stage

Lithology. West of the Pedernal uplift (pl. 1), Desmoinesian strata on the Robledo shelf consist of a lower unit of calcareous shale and sandstone succeeded by an upper one of massive cherty limestone interbedded with nodular shaly limestone. Elsewhere in this area, the Desmoinesian is typically represented by tan to white to brown, massive-bedded, cherty dense limestone. This description pertains as well to the eastern part of the Sacramento shelf (0-6), but on the western part of the shelf near the edge of the Orogrande basin (0-2), the Desmoinesian is made up principally of gray, thick-bedded to massive, cherty calcilutite; this is the Bug Scuffle Limestone Member of the Gobbler Formation of Pray (1961). Along the Desmoinesian depositional strike, to the northwest and southeast, the calcilutite changes to shale, siltstone, and sandstone. In the upper part of the Desmoinesian in this area, silty quartzose sandstones are present, contrasting with the feldspathic sandstones of the overlying Missourian Stage. Northward (pl. z), near the Joyita uplift and the southern Estancia basin, the Demoinesian is made up mostly of medium- to dark-gray, massive- to thick-bedded, cherty limestone and subordinate green and gray shale, with a few beds of sandstone and conglomerate in the upper part. Clastic beds are essentially absent over the Oscura uplift (S-4), limestone predominating, but the sediments of the northern Orogrande basin are essentially the same as those of the southern Estancia basin. On the east side of the Pedernal uplift in the Delaware basin (pl. 1), Desmoinesian rocks are typically dark-brown, fine-grained, cherty limestone, although the lower part may contain interbeds of gray shale and gray to white, medium-grained, angular, quartzose sandstone. Northward, over the Northwest shelf (pl. 3), the Desmoinesian Stage is made up of white to light-brown to tan, commonly cherty, very fine-grained limestone with light-gray shale interbeds. In the Tucumcari basin (pl. 4), rocks of this age consist of interbedded, white to light tan, chalky limestone, red and gray shale, and minor white, medium-grained, quartzose sandstone. The red shales reflect

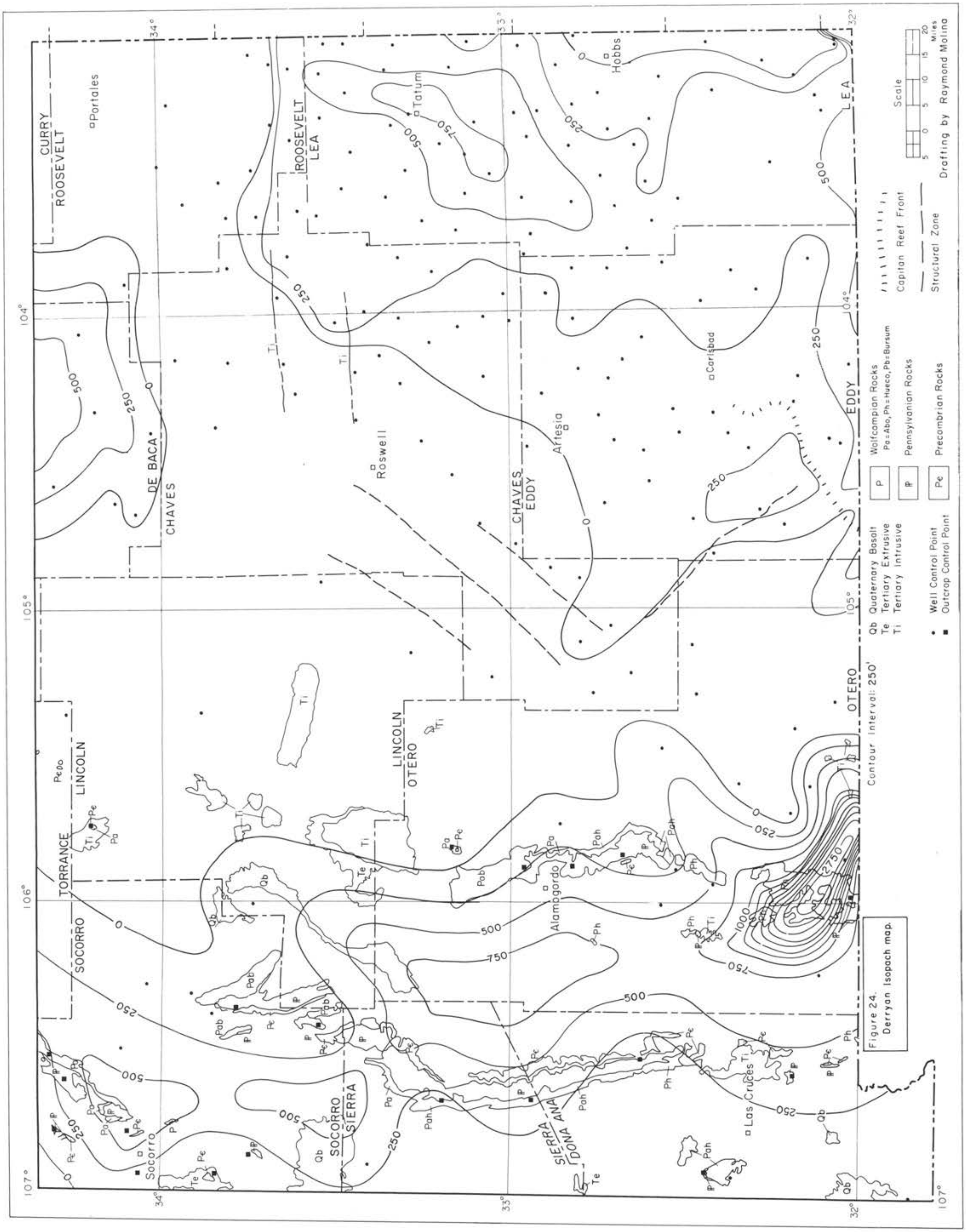


Figure 24. Derryan Isopach map.

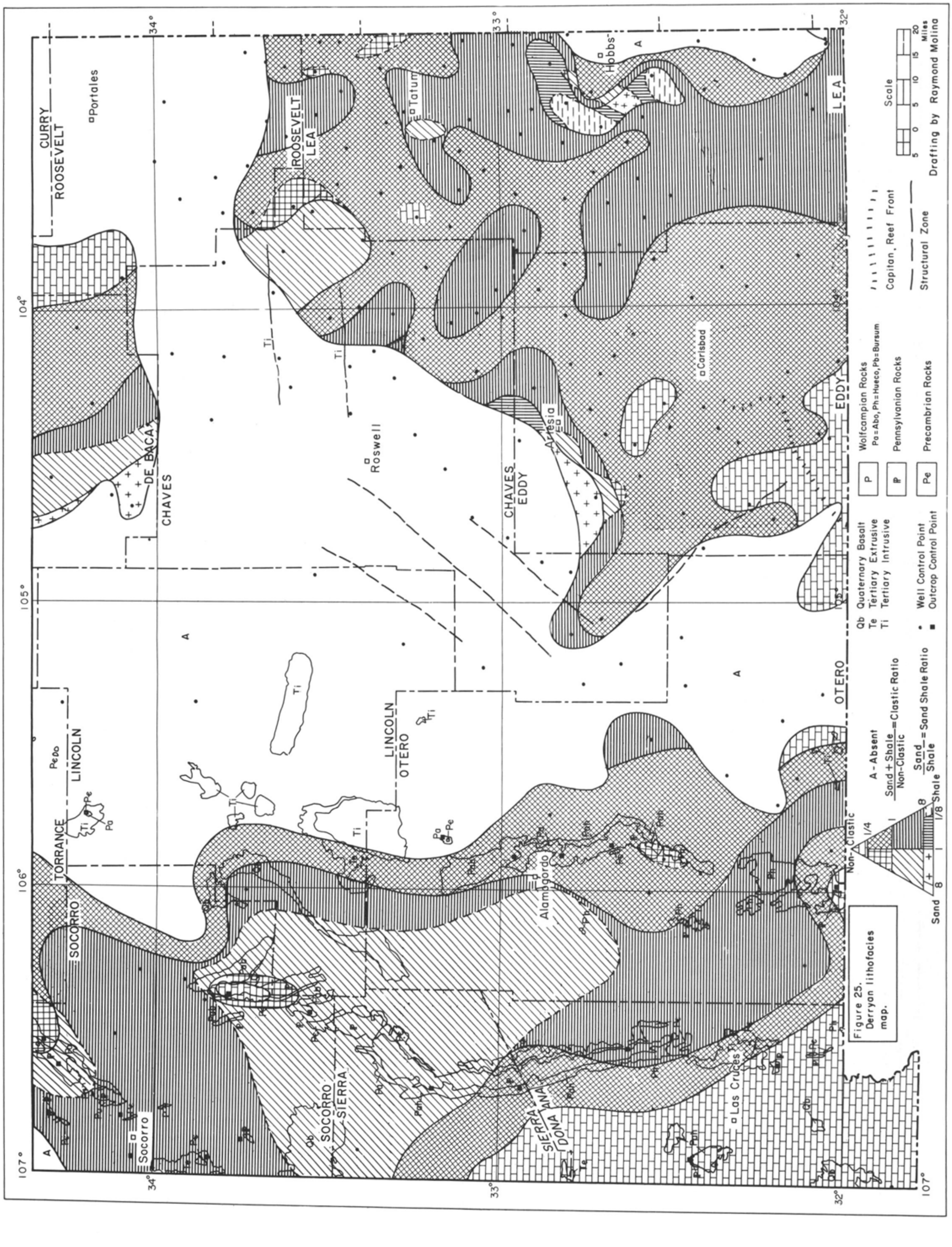


Figure 25. Derryan lithofacies map.

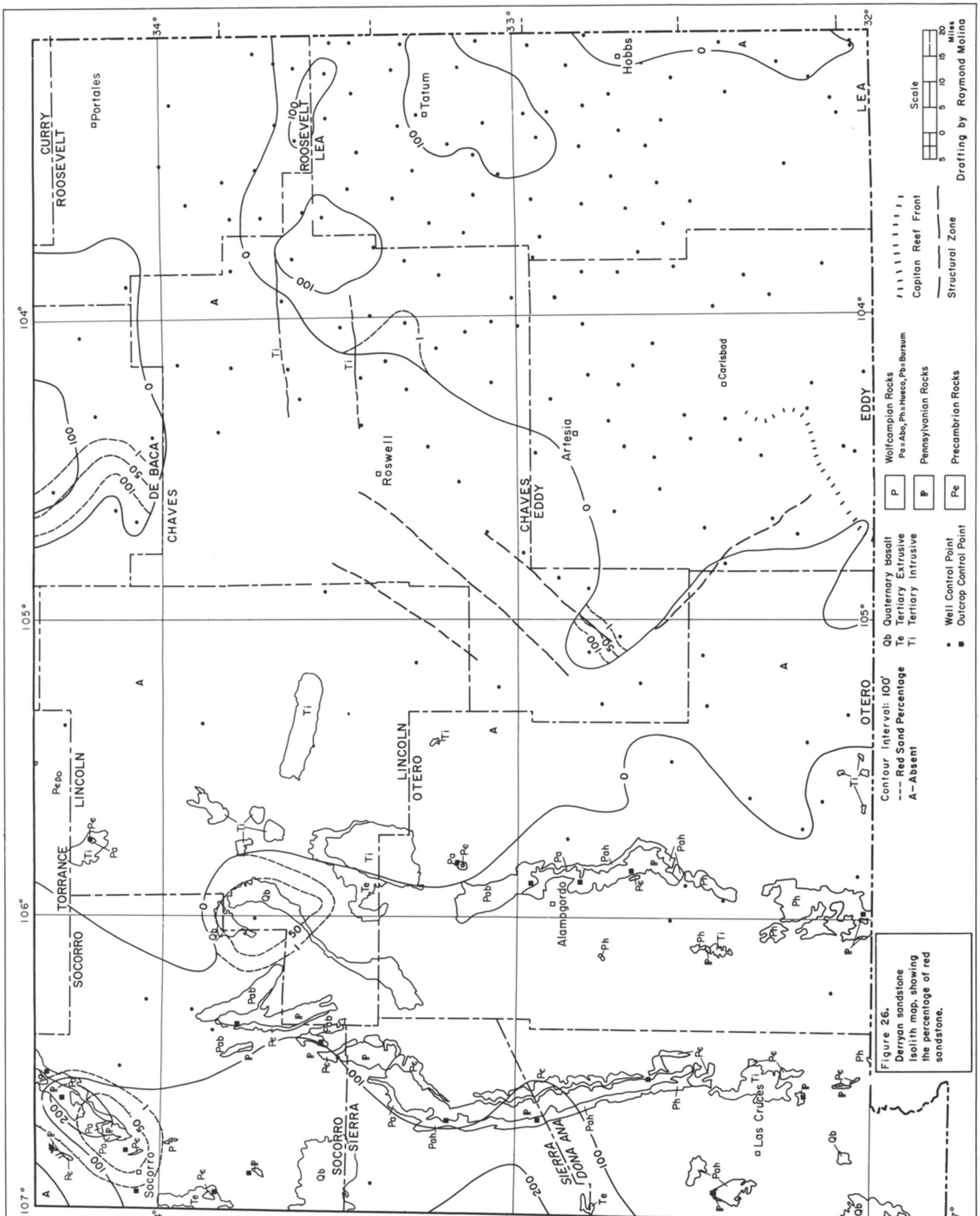


Figure 26.
Derryan sandstone isolith map, showing the percentage of red sandstone.

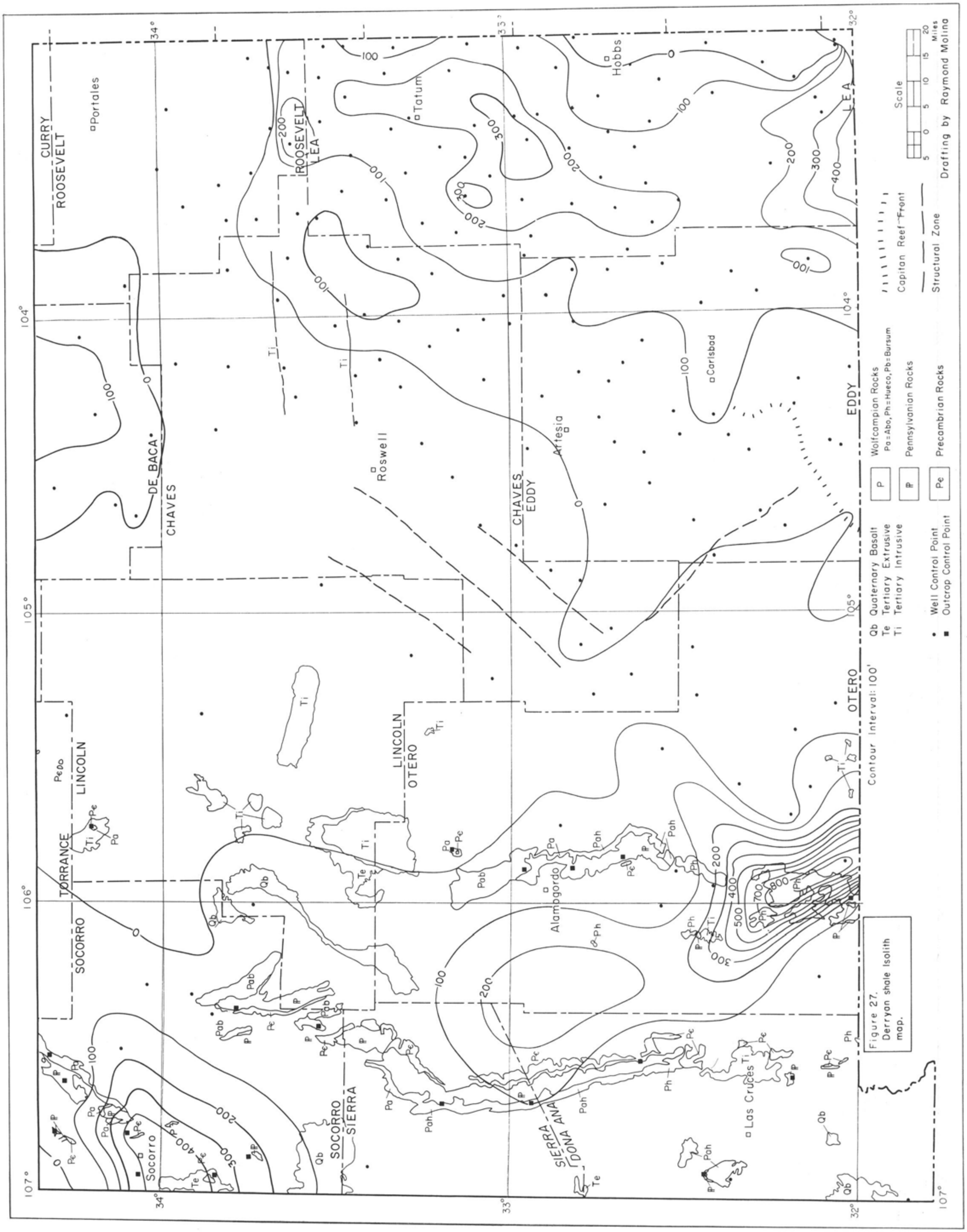


Figure 27. Derryan shale Isolith map.

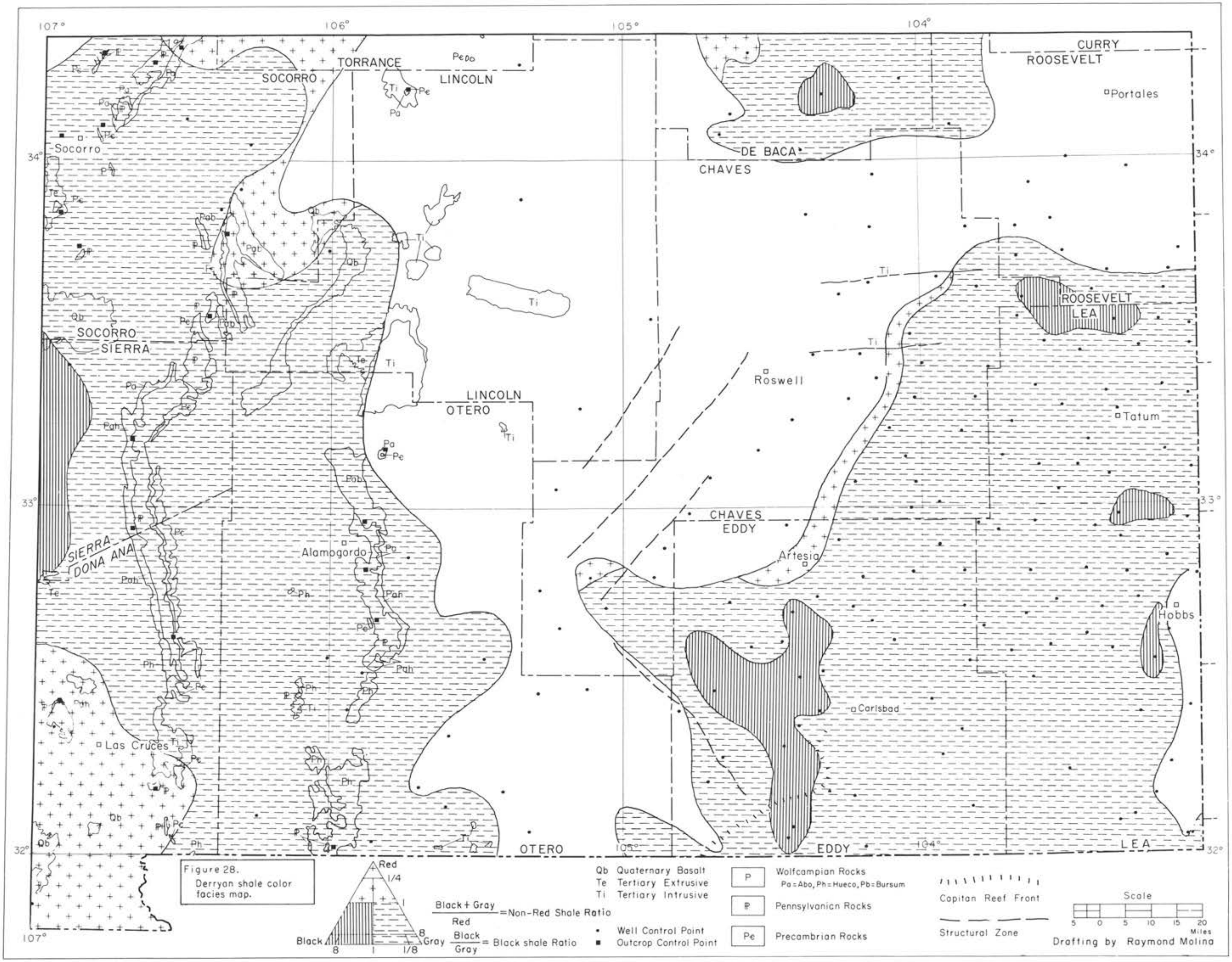


Figure 28.
Derryan shale color facies map.

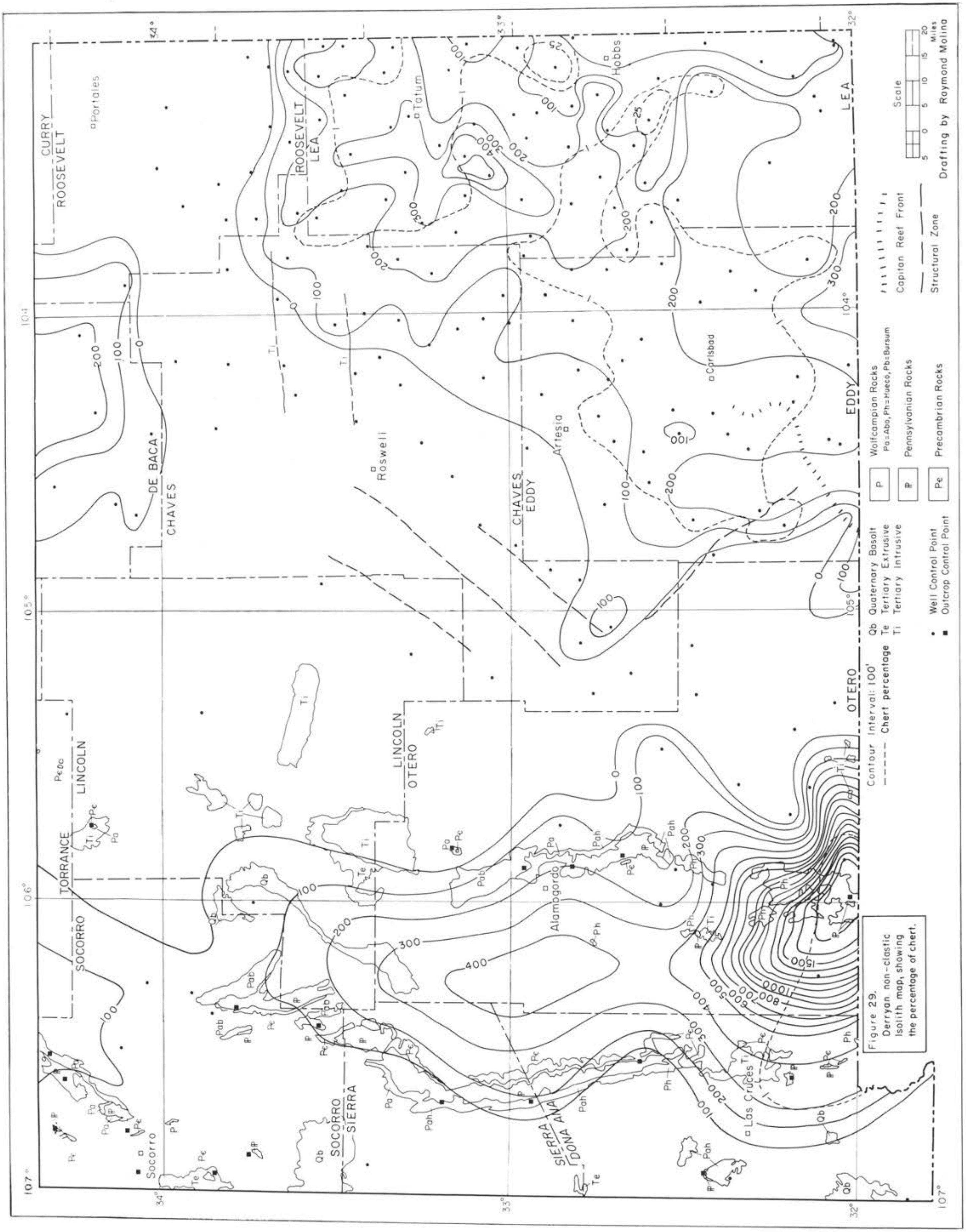


Figure 29. Derryan non-clastic isolith map, showing the percentage of chert.

temporary influxes of red mud probably derived from uplift a considerable distance to the north of this study area.

Reefs. Reefs occur in Desmoinesian strata along the western margin of the Orogrande basin at one locality (S-8), where they are found in the middle third of the sequence (Kottlowski et al., 1956) and consist of unsorted, nonlaminated fossil fragments. On the Sacramento shelf, a Desmoinesian reef, probably a biostrome, makes up the entire sequence in the Southern Production Cloudcroft Unit 1 well (0-3). The areal limits of this reef are indeterminate. In the Permian basin, biohermal reefs are found at two localities: the Lovington Penn East field, where oil is produced from a biohermal reservoir on the Northwest shelf at the margin of the Delaware basin, and the Cass field, where oil is produced from a reservoir in white, coarse-grained dolomite regarded as a dolomitized biostromal reef, although Tait (in Stipp et al., 1956) regards it simply as an anticline. The Cass field is located on the Central Basin platform near the margin of the Delaware basin (fig. 65).

Graded bedding. Graded bedding is described from this area only in the Los Pinos Mountains (S-1; Stark and Dapples). The rock sequences are of limited areal extent and the laminations consist, in ascending order, of nodular limestone, fine-grained silty limestone, and gray, micaceous, sandy shale. Graded beds in the Desmoinesian consist overwhelmingly of carbonate rocks in beds of variable thickness divided about equally between the two types; shale does not constitute more than 5 per cent of the sequence. The graded beds occur through sequences of as much as 480 feet.

Thickness. Distribution and thickness of Desmoinesian rocks (fig. 3o) are similar to those of the Derryan Stage (fig. 24). Thickness of the unit ranges from 0 to 1000 feet both on the west and on the east sides of the Pedernal uplift. The anomalous thickness along the west margin of the Central Basin platform (L-32) is attributed to repetition of strata in a reverse fault. The Tucumcari and Permian basins were joined in Desmoinesian time, and therefore the Roosevelt uplift appeared as a distinct paleogeographic feature for the first time.

Two large anomalies are evident in Figure 3o: A prominent nose is developed on the Sacramento shelf of the Orogrande basin, extending westward into the basin (O-2, O-4, O-5), and sediments in the Permian basin are thickest in two troughs that extend in a southwest-northeast direction. The southwestern trough lies along the margin of the Northwest shelf and Delaware basin, but that to the northeast simply cuts across the shelf. The northeast trough of thick sediments located on the Northwest shelf is informally referred to by some petroleum geologists as the *Lovington basin.*

Lithofacies. The Desmoinesian lithofacies map (fig. 31) shows that nonelastic rocks are the predominant lithologic type over almost the entire area. In the Orogrande basin, the areal distributions of the standstone- and shale-limestone associations give evidence of the deltaic deposits described by Pray and Graves (1954) in the outcrop. Along the west side of the Permian and Tucumcari basins, there is a suggestion that the edge of the subcrop is close to the depositional edge of the unit; the amount of elastics, and especially coarse elastics, is greatest adjacent to the uplift, as seen in the shale, shale-limestone, and sandstone-limestone associations. Farther south, on both sides of the Pedernal uplift, limestone and limestone-shale facies **abut the Pedernal uplift, suggesting that Desmoinesian strata covered the uplift and were mostly removed subsequent to deposition. Carbonate facies are present over most of the Permian and Tucumcari basins as well as** the Central Basin platform. During Desmoinesian time, the latter was the site of carbonate deposition which extended an unknown distance to the east; present distribution of Desmoinesion strata reflects later uplift and erosion.

Sandstone. The most notable feature of the Desmoinesian sandstone isolith map (fig. 32) is the small number of isolith lines, indicative of the very small amount of coarse elastics in the strata. Most of the sandstone is associated with the eastern margin of the Pedernal uplift, where it is predominantly of red color, and with the Joyita uplift, where it is similarly of red aspect. Adjacent source areas of elastic rocks appear to have been of small relief and were probably drained by sluggish streams incapable of transporting much coarse detritus. An exception is in an area on the west-central margin of the Pedernal uplift (near O-19) where the thick accumulation of sandstone probably indicates a delta similar to the one in Desmoinesian strata on the Sacramento shelf, described by Pray and Graves. This delta, and also that described by Pray (1961), consists of shale, siltstone, and quartzose sandstone that grades laterally into contemporaneous shelf limestones. Evidently, the detrital sediments were carried into the area by a major distributary whose headwaters lay in the Pedernal uplift to the east.

Shale. Thickness and distribution of fine-grained elastic rocks (fig. 33) and their color distribution (fig. 34) are not unlike those of Desmoinesian sandstones. The red shale distribution adjacent to the Pedernal uplift represents the distribution of red muds washed from the uplift; the muds accumulated in shallow sea water adjacent to the uplift. The presence of a delta (near O-19) on the western margin of the Pedernal uplift is supported by the roughly H-shaped configuration of the shale isolith lines. Elsewhere, water depth is indicated by the black shale pattern to have been greatest in the Delaware basin, along the margin of the Northwest shelf.

Nonelastic rocks. In Figure 35 is depicted the thickness and distribution of nonelastic Desmoinesian rocks, which are the thickest of the lithologic types of the stage. The chert percentage contour lines show the distribution and proportion of that material. Dolomite is estimated, from sample logs, to make up as much as 75 per cent of the rock over the Central Basin platform and is present locally on the Northwest shelf. Because nonclastics dominate, their thickness most strongly affects the isopachs of the total thickness map of the stage (fig. 3o).

In the Orogrande basin, the isolith lines of nonelastic rocks closely follow the configuration of the basin. Nonclastics are thin in the area of the delta on the Sacramento shelf and are of maximum thickness along the axis of the basin.

In the Permian basin, nonclastics are thin across the neck between the Tucumcari and Permian basins,_ west of the Roosevelt uplift, and progressively thicken southward over the Northwest shelf. The thickening terminates along a southwest-northeast axis that coincides with the trend of thick Desmoinesian sediments shown by the isopach map of the unit (fig. 3o). South of this axis in the Delaware basin, nonclastics are thin. An anomaly is associated with the Cen-

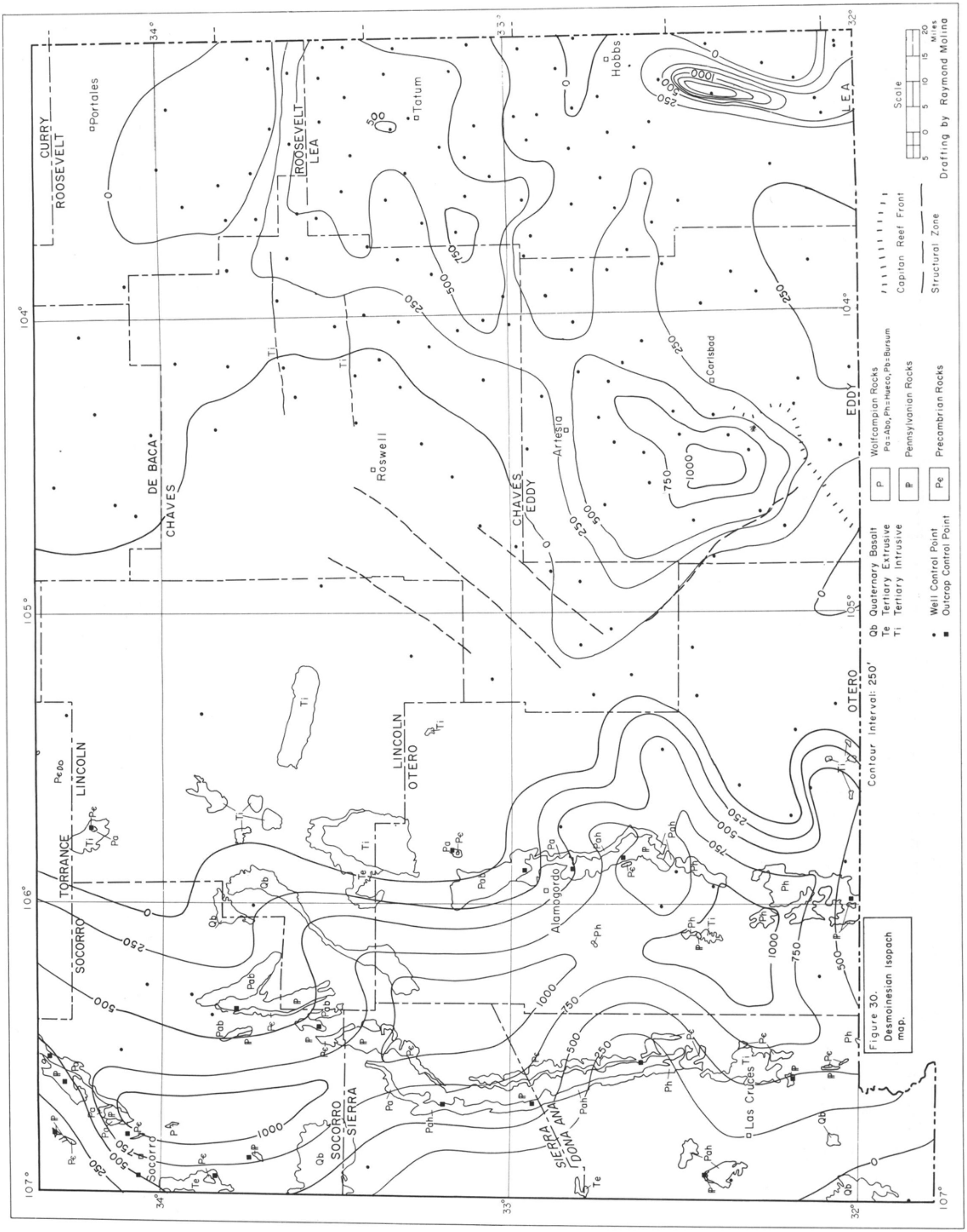


Figure 30.
Desmoinesian Isopach map.

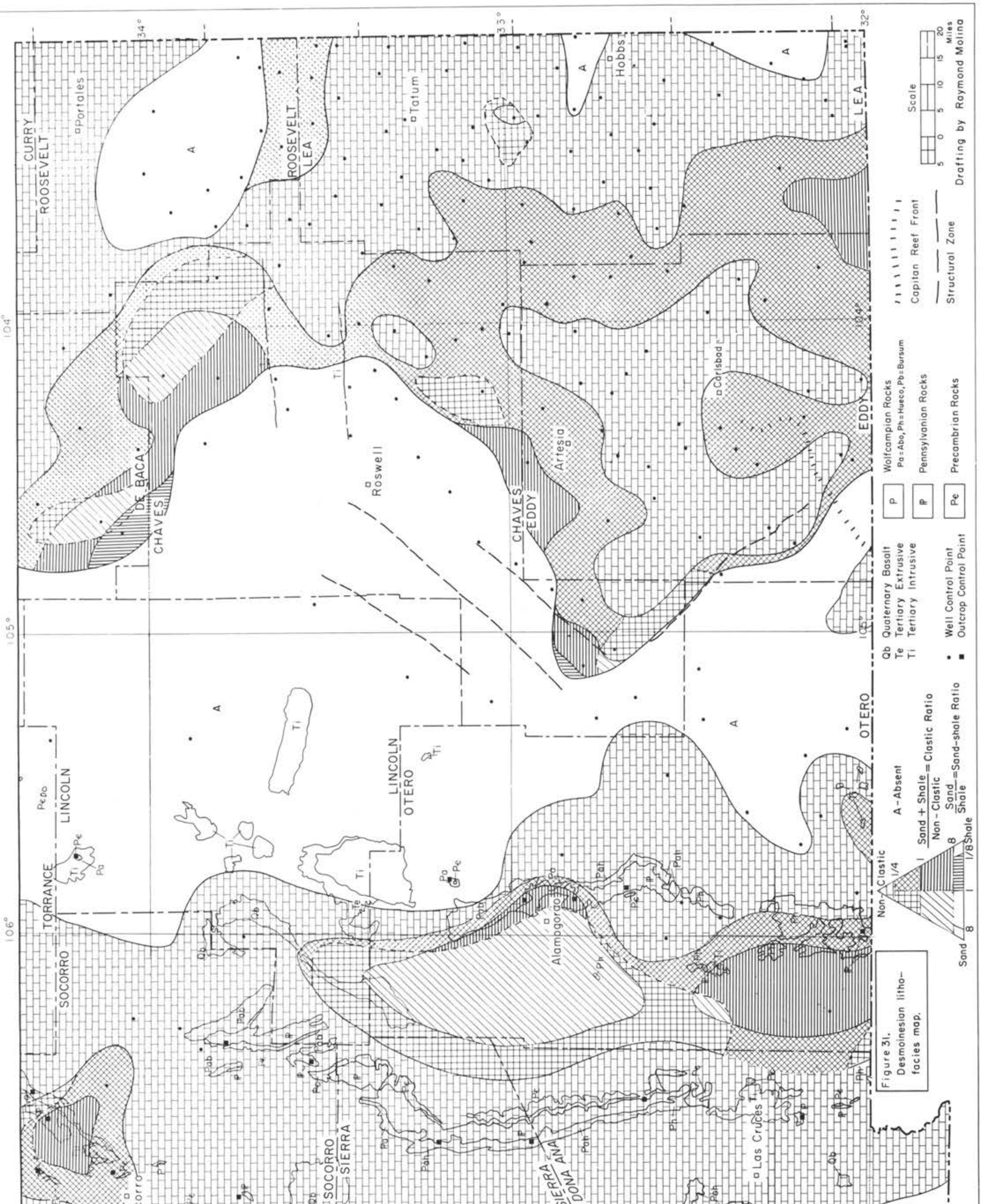


Figure 31. Desmoinesian lithofacies map.

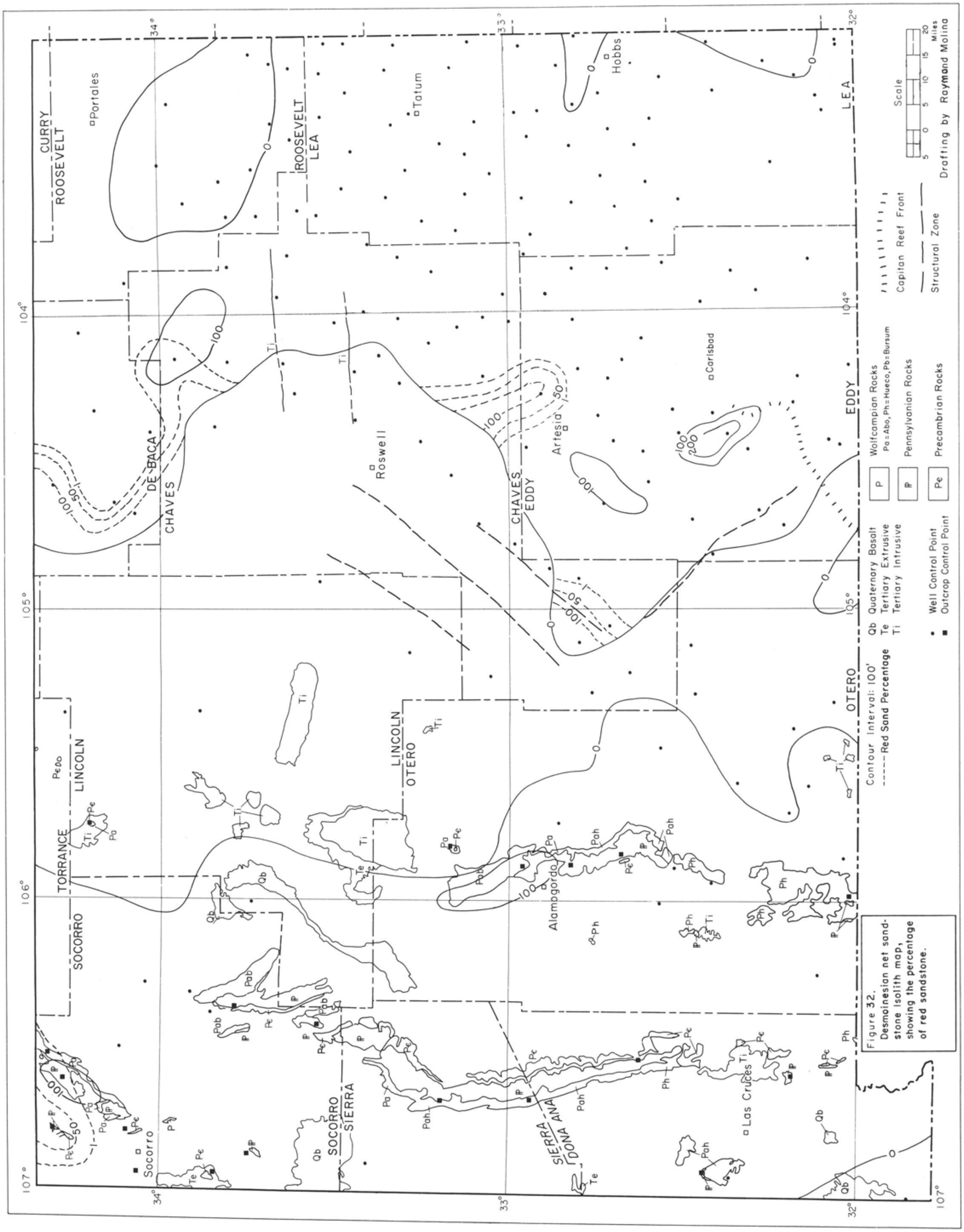


Figure 32. Desmoinesian net sandstone isolith map, showing the percentage of red sandstone.

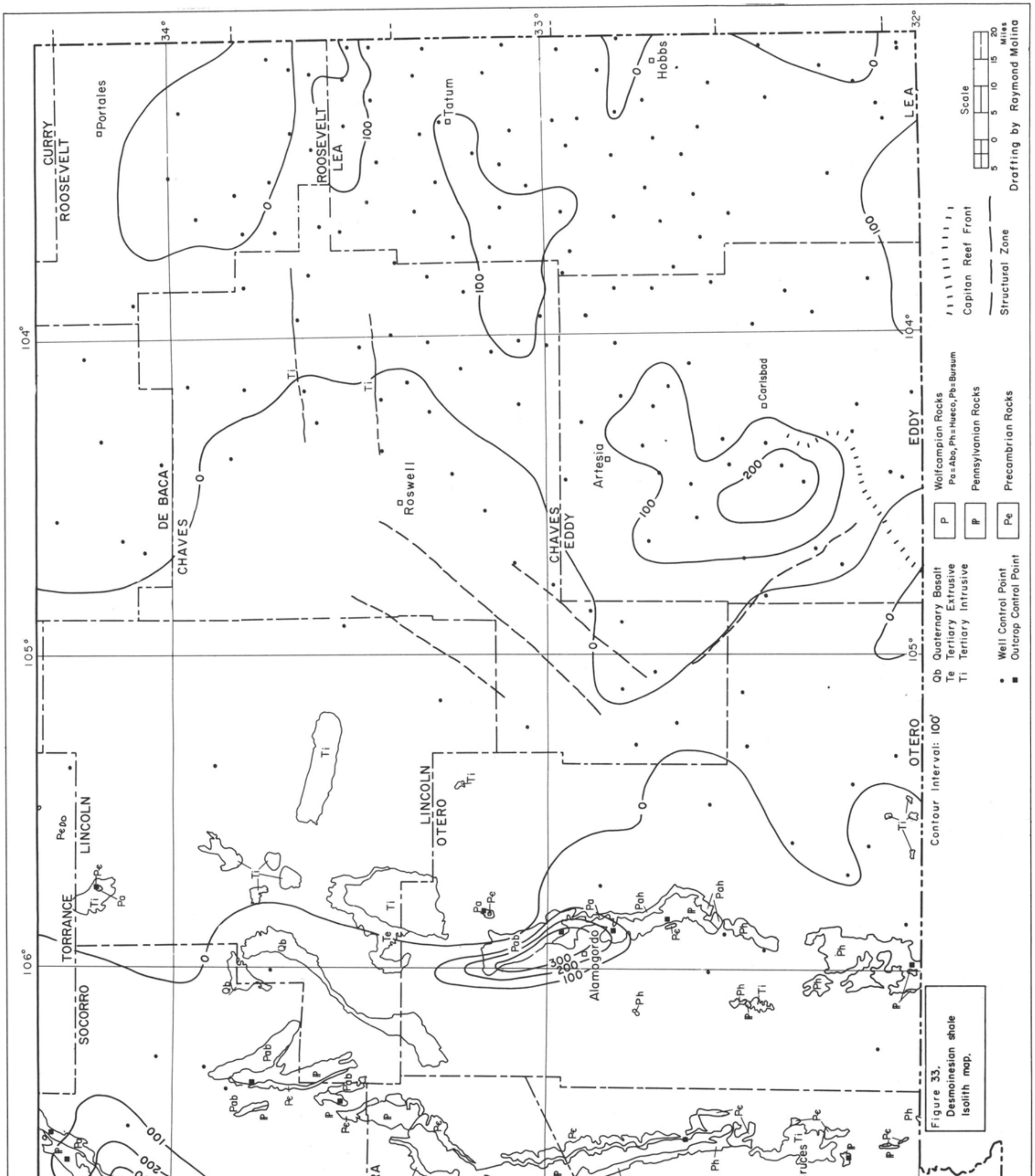


Figure 33.
Desmoinesian shale isolith map.

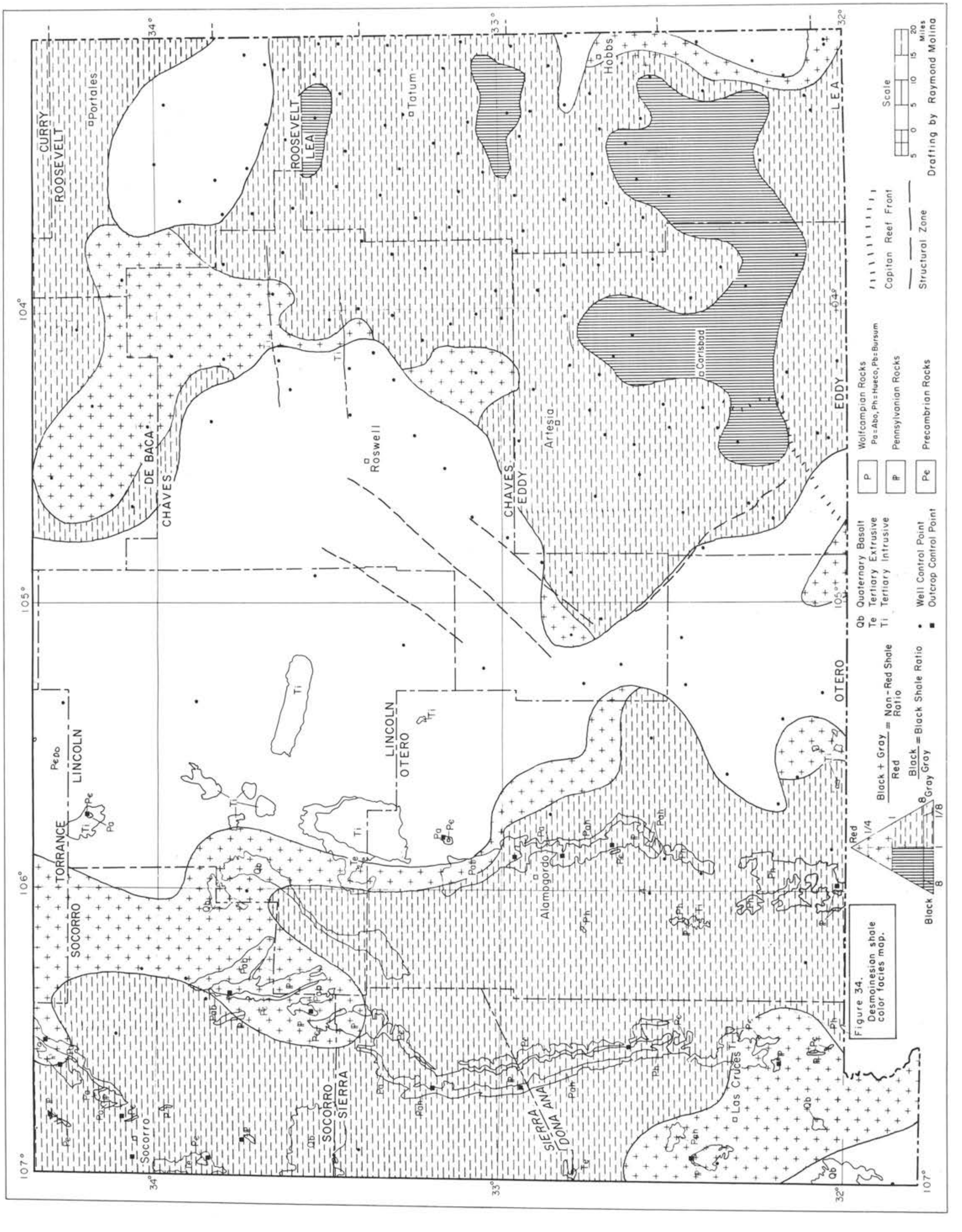


Figure 34. Desmoinesian shale color facies map.

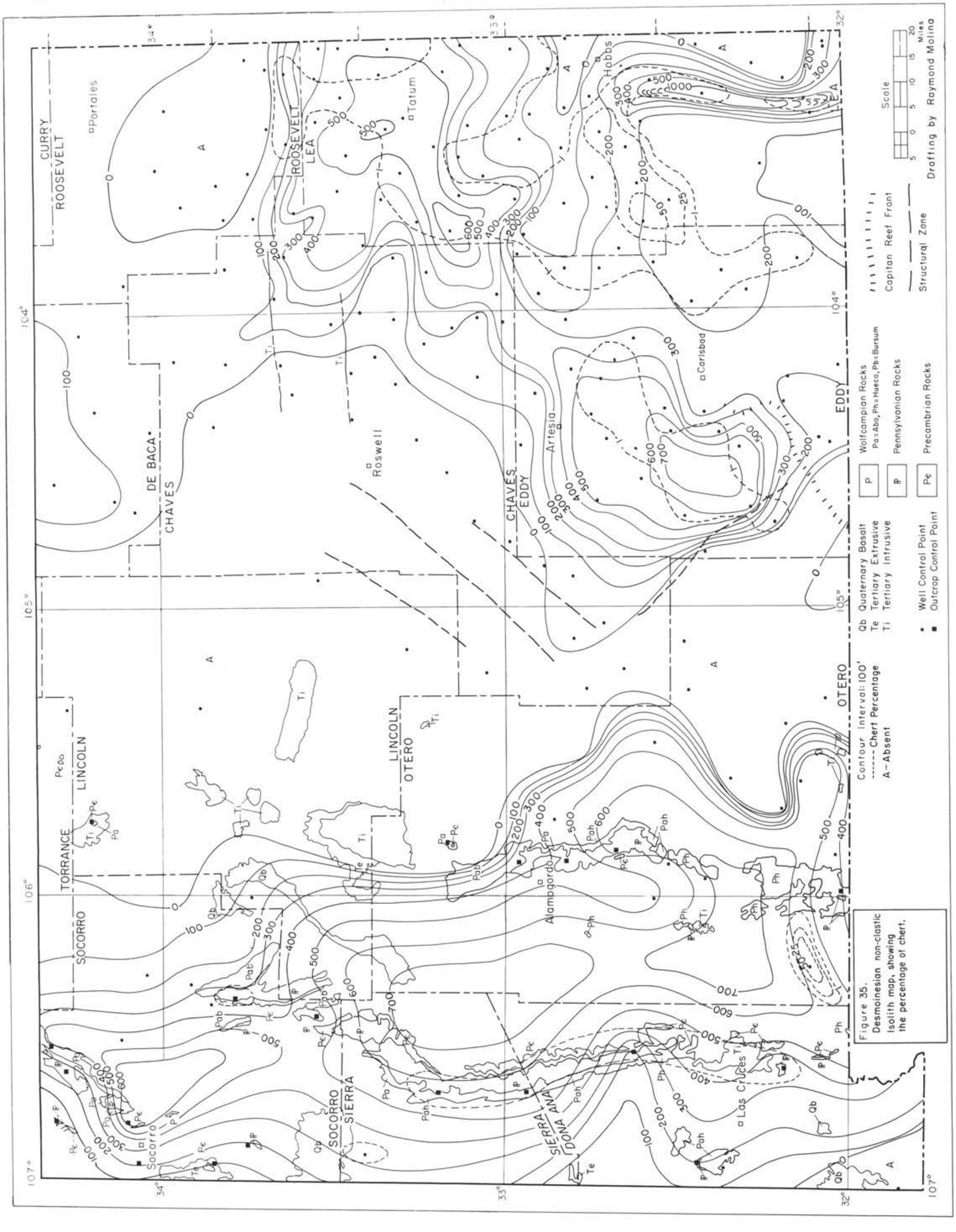


Figure 35.
Desmoinesian non-clastic isolith map, showing the percentage of chert.

tral Basin platform. The great thickness of the unit along the west side of that feature may be attributed to repetition of beds by faulting; of greater importance to structural interpretation is the fact that Desmoinesian strata are more extensive areally on the platform than are any of the older or younger Pennsylvanian rocks. This distribution of Desmoinesian rocks indicates pre-Desmoinesian uplift and erosion of the platform. It will be demonstrated later that uplift and erosion occurred again in Wolfcampian time.

UPPER PENNSYLVANIAN SERIES

Missourian Stage

Lithology. Over the Robledo shelf (pl. 1), Missourian strata consist of intercalated nodular limestone and gray to purple shale and are unconformable on underlying Desmoinesian rocks (Kottlowski, 1960a). In the Orogrande basin (O-4), the rocks consist of interbedded, brown, very fine-grained limestone, gray fine-grained dolomite, brown shale, and quartzose sandstone, the latter being most common toward the base of the unit. On the Sacramento shelf, near the basin margin (O-2), Missourian rocks are thin-bedded argillaceous limestone, calcareous shale, and greenish-gray feldspathic sandstone. Light-colored pure limestone occurs locally at O-2 (Pray 1961), while farther east near the edge of the Pedernal uplift (O-6), the rocks are almost entirely light-brown to tan, very fine-grained, dense limestone, with minor amounts of medium-grained quartzose sandstone. Northward (pl. 2), the Missourian over the Oscura uplift is dominantly calcareous, as is the underlying Desmoinesian Stage. In the southern Estancia basin, the Missourian is dominantly argillaceous and arenaceous, consisting of gray and red shales, green, brown, and gray quartzose sandstones, and feldspathic sandstones containing fresh pink feldspar. Southeastward, in the northern Orogrande basin (X-1), the Missourian Stage contains interbedded brown to tan, fine-grained limestone, red shale, feldspathic sandstone, and conglomeratic quartzose sandstone. In the Delaware basin, strata of this age include brown, gray, and black shale, some quartzose sandstone, chert, and brown and dark-gray to black, fine-grained, dense limestone, the entire section grading southward at PI (pl. 3) to black shale. Northward, over the Northwest shelf, the Missourian consists lithologically of white to tan to light-brown, fine-grained, chalky, fossiliferous limestone with gray and red shale interbeds. In the Tucumcari basin, the limestones are similar, but there is a strong admixture in the section of red shale, feldspathic sandstone, and white, medium-grained micaceous sandstone.

Graded bedding. Graded beds are described by Stark and Dapples from Missourian strata of the southern Estancia basin (S-1). In ascending order, the layers are micaceous cross-bedded sandstone, olive-drab micaceous sandy shale, dark-gray micaceous silty shale, nodular fossiliferous limestone, and dense limestone. Missourian graded beds occur in rocks 340 feet thick and are more diverse in character than graded beds of Derryan and Demoinesian ages from the same area. Of the total, about 25 per cent is sandstone, 3o per cent shale, and 25 per cent nodular limestone, the balance being dense, gray, massive limestone. The clastic beds often include plant fragments carried to the sea by streams draining adjacent uplifts.

Thickness. Rocks of Missourian age attain thicknesses of as much as I 000 feet both east and west of the Pedernal uplift (fig. 36). Sediments of this age are present over most of the area to the west; to the east, they are absent over the Central Basin platform, as well as locally (R-11, L-34, L-36).

Several features on the isopach map are notable. The Oscura uplift, which appeared on earlier maps as a southwest-trending nose, becomes on the Missourian isopach map a closed area of thin strata. The nose associated with the Sacramento shelf, first prominent on the Desmoinesian isopach map (fig. 30), persists on that of the Missourian. The southwest-northeast trend of thick sediments, first apparent from the Desmoinesian isopachs, is also a pronounced feature on the Missourian thickness map, the axis of the northeastern trough having shifted somewhat to the south. On this, as well as on all earlier thickness maps (figs. 18, 24, and 3o), the Salt Flat embayment of the Permian basin results in a bifurcation of the southeastern extremity of the Pedernal uplift; the contour lines in this area are drawn to conform to data points in the Trans—Pecos region of Texas south of the report area.

Lithofacies. Lithofacies of Missourian strata are shown in Figure 37. Nonclastic lithologic associations are mainly dominant west of the Pedernal uplift, except in the vicinity of the Joyita uplift and in the south-central part of the Orogrande basin. Limestone and limestone-sandstone facies occur over both the Robledo and the Sacramento shelves. The lithofacies patterns on either side of the Pedernal uplift are similar, supporting the belief that the sediments once extended much closer to the axis of the uplift and may, indeed, have covered it. Clastic rocks on the east side would presumably have been derived from restricted land areas not covered by the sea. (It should be noted at all times that the maps in this memoir represent stages and thus include rocks deposited through variable intervals of time; in addition, each map represents total amounts of sediment but does not describe the vertical distribution of the lithologic components of the sediment.) The concentration of clastic rocks near the Roosevelt uplift indicates erosion of that feature during Missourian time. The Central Basin platform was covered by Missourian rocks which were later removed; this is indicated by the Missourian rocks that were protected from erosion in the down-dropped fault block in the southeastern corner of the platform (0-37 and 0-38).

Sandstone. The amount of sandstone in the Missourian Stage is small (fig. 38); nowhere does it exceed 15o feet in thickness. There are, however, concentrations of red sandstone over the area of the northern Orogrande and Estancia basins and in two places on the eastern margin of the Pedernal uplift. The source of the sand which makes up these sandstones perhaps lay in nearby islands of Precambrian granite in the shallow Missourian sea. One such island may have been located in the vicinity of C-27 and C-29. To the north, it is possible that a larger area was emergent, furnishing coarse-grained red detritus to the Estancia basin.

Shale. Thickness and distribution of shale are shown in Figure 39 and the distribution of shale color facies in Figure 40. Shale makes up about one third of the Missourian unit thickness and, as may be seen from Plates I through 4, it is interbedded with other rock types, chiefly limestone. A large amount of red shale is present, especially near the margins of the basins adjacent to the Pedernal uplift. The paucity of sandstone, and of red sandstone in particular, together with the relatively large amount of red shale, indicates that the source area, the Pedernal uplift, was mostly of low relief and the sea occupying the Orogrande, Estancia, and Tucumcari basins and the Northwest shelf was shallow and well oxygenated, permitting preservation of ferric oxide in the elastic rocks. The pattern of black shale occurrences (fig. 40) is of interest in that it extends eastward along the north side of the Central Basin platform. The black shale probably joins with similar Missourian sediments of the Midland basin, many miles eastward in west Texas.

Nonelastic rocks. The map showing occurrences of nonclastic Missourian rocks (fig. 41) is similar in form to the isopach map of the unit (fig. 36). West of the Pedernal uplift, the nonclastic isolith lines conform very closely to the basin outline. In the Permian basin, adjacent to the area of black shale (fig. 40) and along its north side, is a southwest-northeast trend of thick Missourian nonclastic sediments. Along this axis, which closely follows that of Desmoinesian nonclastic rocks (fig. 35), dolomite is present in amounts up to 60 per cent. It is believed that this belt of thick carbonates represents reef growth that restricted circulation of the deeper water on its seaward side—that is, to the south—so that muds were deposited in an environment of restricted circulation (fig. 40). Relatively little of the nonclastic content of the Missourian Stage is chert; the percentage of chert is greatly reduced, compared with units already discussed, and is greatest in rocks of the Morrowan (fig. 23) and Derryan (fig. 29) stages, where dolomite is absent. In rocks of the Desmoinesian Stage (fig. 35), although chert is widespread in occurrence, it is absent in dolomite; dolomite first becomes common in Pennsylvanian rocks of Desmoinesian age. In Virgilian rocks, to be described next, dolomite reaches its maximum development for the Pennsylvanian of this area, and chert its minimum. There is, therefore, a direct relationship between the degree of silicification and the amount of dolomite, for reasons that are obscure. Chilingar (1956) made a study of chert in limestones and his conclusion (p. 15601561) may be applicable to the example described in this paragraph:

> Carbonate rocks with high concentrations of chert nodules, stringers, and beds usually have high Ca/Mg ratios, and similarly with increasing Ca/Mg ratios the percentage of chert stringers and nodules increases. Apparently the high pH and high temperature, which favor the deposition of dolomitic limestones, are not favorable for the precipitation of silica. This relationship holds true, however, only where the silica that forms chert nodules and stringers was deposited contemporaneously with the enclosing rocks (which is usually the case). In places, secondary dolomitization obscures the relationship.

Virgilian Stage

Lithology. On the Robledo shelf (pl. I; Kottlowski, 1960a), rocks of the Virgilian Stage are composed of a massive noncherty limestone underlain by calcareous shale and nodular limestone and overlain by intercalated massive noncherty limestone and nodular thin-bedded limestone. Eastward (Y-1), Virgilian strata increase greatly in thickness and are mapped on the surface as the Panther Seep Formation (Kottlowski et al., 1956). The rock sequence consists of brown silty shale, dark carbonaceous shale, dark-gray argillaceous limestone, silty calcareous quartzose sandstone, massive biostromal limestones, and, in the upper part, two thick beds of gypsum. In the Orogrande basin, the sediments consist of interbedded gray to brown, fine-grained limestone, gray and brown shale, and minor coarse-grained, partly feldspathic, quartzose sandstone. At the basin margin of the Sacramento shelf (O-2), Virgilian strata contain algal bioherms in the lower part, overlying rocks of the Missourian Stage and in turn being overlain by reddish shale, mudstone, marl, nodular limestone, and limestone conglomerate (Pray, 1961). Eastward, toward the Pedernal uplift, these rocks consist of brown, very fine-grained limestone with gray shale and gray, fine-grained, quartzose sandstone in the upper third. In the Estancia basin and on the Oscura uplift, rocks of this age are predominantly thin- to thick-bedded, light- to medium-gray limestone with minor red shale. In the Delaware basin, Virgilian strata are composed of variable amounts of brown to tan, fine-grained limestone, brown to black shale, and white, fine- to coarse-grained, subangular, quartzose sandstone. To the south, the strata (J-1, pl. 3) consist of black shale. Over the Northwest shelf, rocks of this age are comprised quite uniformly of light-colored, chalky, fossiliferous limestones interbedded with variegated shales; in the Tucumcari basin (pl. 4), they consist of very light-colored limestones, similar to those of the Northwest shelf, interbedded with green and red shales.

Reefs. West of Pedernal uplift, reefs of Virgilian age are found at several localities. King, King, and Knight described a reef made up of algae and silicified horn corals, from the base of Virgilian strata on the north end of the Diablo platform (fig. 2). Plumley and Graves (1953) described massive algal bioherms, from which colonial corals are absent, in basal Virgilian strata on the Sacramento shelf, along the margin of the Orogrande basin. These reefs are a few hundreds of feet to one mile in width and a maximum of z00 feet thick; the thickness diminishes rapidly outward from the centers of the reefs. Along the western margin of the Orogrande basin, on the Robledo shelf, biohermal reefs of early Virgilian age are found (Kottlowski et al., 1956); in size, these reefs are about half a mile across and up to 450 feet thick. In the Permian basin, a number of reefs of Virgilian age occur. The Kemnitz Wolfcamp oil field (Virgilian, fig. 65) is regarded by Oppel (in Sweeney et al., 1960) as producing oil from a reef reservoir. Thick, porous, coarse-grained Virgilian and, in places, Missourian dolomites (the strata penetrated in the Stanolind State AB I well (E-5)) appear to represent biohermal reefs. These dolomites are developed on the Northwest shelf marginal to the Delaware basin and now produce oil from reservoirs in a number of fields (fig. 69) along the west side of the basin.

Graded bedding. Graded beds are described by Kottlowski et al. (1956) from the middle part of Virgilian strata on the Robledo shelf marginal to the Orogrande basin (Y-x). Total thickness of graded deposits is 272 feet, with four or five kinds of layers; these ideally consist, in ascending order, of basal calcareous arkosic sandstone, greenish sandy shale, and silty carbonaceous micrites interbedded with dark calcareous to carbonaceous shales. On the east side of the Orogrande basin, along the Sacramento shelf (vicinity of 0-0,

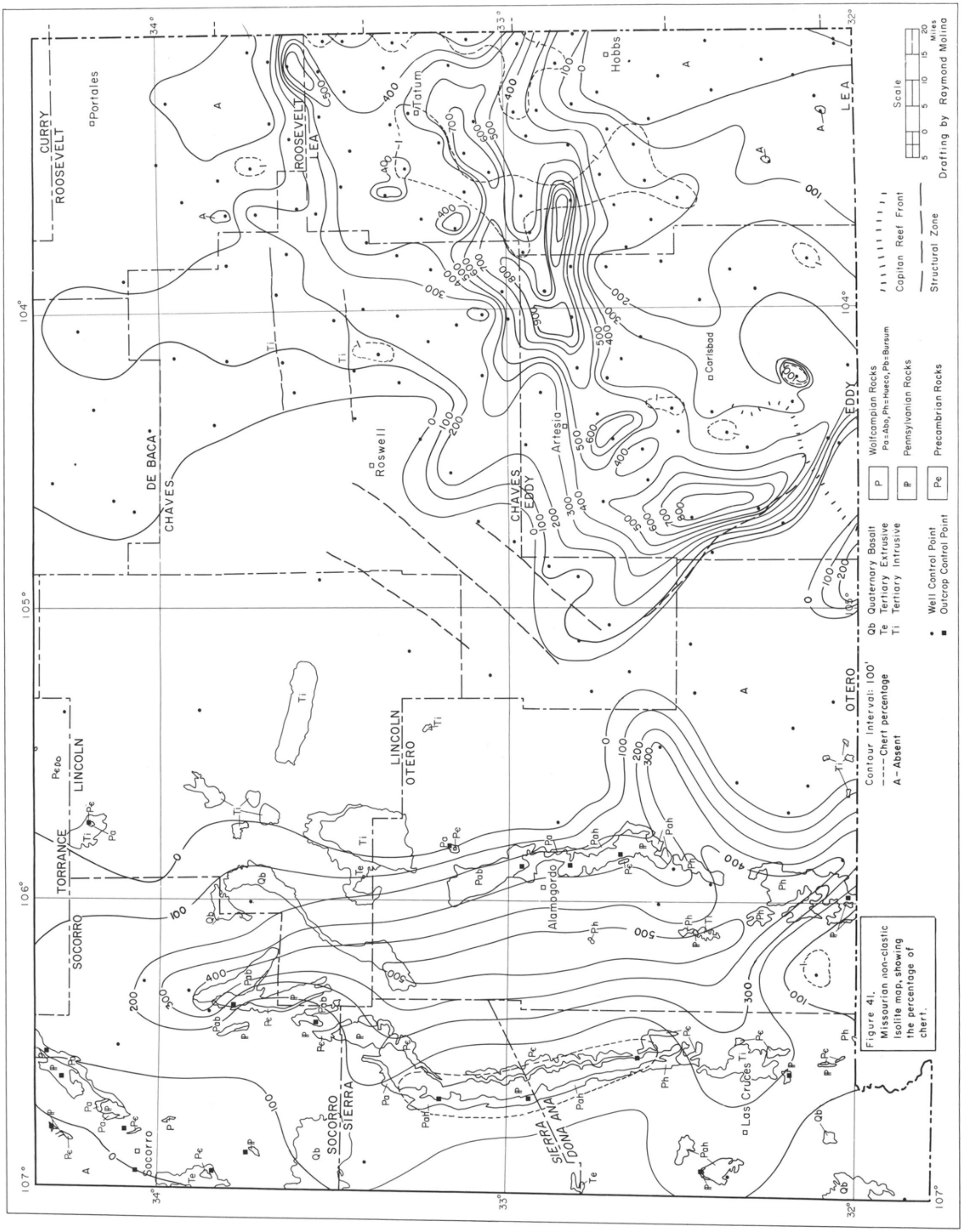


Figure 41. Missourian non-clastic isolite map, showing the percentage of chert.

Cline (1959) described graded bedding in upper Virgilian strata. These consist of alternations of limestone and shale that he believed accumulated in a lagoon between reefs along the basin margin on the west and the Pedernal uplift on the east. The deposits grade eastward, toward the uplift, into reddish brown and red shales; at the same time, the rock sequence becomes thinner and the number of limestone beds is sharply reduced.

Thickness. Distribution and thickness of Virgilian strata are shown on the isopach map (fig. 42). It is apparent that during this age the Orogrande basin was strongly negative, receiving at least 2500 feet of sediments, whereas little more than 1000 feet were deposited over the area east of the Pedernal uplift.

Regional features during Virgilian time were as follows: The Oscura uplift was diminished in areal extent but was still a distinct geologic feature, as was the southwest-extending nose of the Sacramento shelf. The axis of thick sediments across the middle part of the Permian basin persisted. Virgilian sediments over the Northwest shelf showed little variation in thickness. If the Salt Flat embayment existed during Virgilian time, it is not apparent on this or other maps of the Virgilian stage.

Lithofacies. Virgilian lithofacies are depicted in Figure 43. The shale-limestone association dominates over the central part of the Orogrande basin, whereas mostly calcareous rocks are present over the Robledo and Sacramento shelves. The small patch of rocks of sandstone-limestone facies on the southwest side of the Oscura uplift indicates influx of coarse elastics, possibly derived from that feature, during part of Virgilian time. Reefs, described before, are present on the shelves on the east-central, south, and west-central sides of the Orogrande basin. Evaporite deposits, not shown on the map, are present in Virgilian strata on the west-central side of the basin; evaporites are not of quantitative importance in earlier Pennsylvanian strata. Cross-bedded white sandstone is present in an outcropping of Virgilian(?) strata at O-19, and this is believed by Bachman (1960) to indicate proximity to the Virgilian strandline. Cline believed that graded beds occurring in the vicinity of O-2, on the Sacramento Shelf, were deposited in a lagoon whose shoreward limit was the Pedernal uplift. The observations of Bachman and of Cline strongly suggest the existence of a nearby shoreline not evident from the map (fig. 43). On the east side of the Pedernal uplift, data presented on the map are more suggestive that the western subcrops of the Virgilian are near the original depositional limits of the unit. The facies patterns show a predominance of coarse-grained elastic rocks that might be expected to accumulate near the strandline of an area of low relief. Eastward, except in the Delaware basin, the area was the site of mostly carbonate deposition, as shown by the widespread pattern of the limestone facies.

Sandstone. Distribution and thickness of sandstone in the Virgilian Stage are given in Figure 44. Quantitatively, the sandstone is small in amount but significant in occurrence. On the west side of the Pedernal uplift, it attains a thickness greater than 400 feet, about one sixth of the unit thickness of the Virgilian in the Orogrande basin. The percentage of the sandstone that is red in color increases to the west and to the north; it is therefore likely that the red sandstone was derived from a source to the west of the map area or from the north end of the Pedernal uplift. Nonred sandstone is present to the east, over the Sacramento shelf, and these elastic materials are most likely derived from a source in the Pedernal uplift. In the Permian and Tucumcari basins, all the sandstone in the Virgilian (up to one third of the unit thickness, where sandstone is present) is concentrated along the edge of the basins marginal to the Pedernal uplift. Northward, most of the coarse-grained elastic rocks present are red, indicating an oxidizing environment of deposition. Southward, the sandstone immediately adjacent to the uplift is red in color, but within a short distance basinward, where sandstone accumulation is at a maximum, this sediment is gray. Presumably, there was a sufficient amount of organic matter admixed with the red sand to effect a reduction of ferric iron to the ferrous state. No sandstone is associated with the Roosevelt uplift.

Shale. Shale makes up as much as one half of the gross thickness of Virgilian rocks in southeast New Mexico (fig. 45). Considered together with the shale color-facies map (fig. 46), the shale isolith map indicates conditions of deposition such as those shown in Figure 44. The source of red shale in the northern Orogrande and southern Estancia basins lay in the Pedernal uplift; east of that uplift, shale grades in color away from the basin margin, where it is red, to gray and variegated over the Northwest shelf and to black in the Delaware basin. The Roosevelt uplift was a feature of low relief, for it evidently contributed red shale but no sandstone (fig. 44) to surrounding areas.

Nonelastic rocks. Nonelastic rocks (fig. 47) make up about half the total thickness of Virgilian rocks, ranging in thickness up to m00 feet. West of the Pedernal uplift, the dominant lithology is limestone; however, much chert is present in the vicinity of the Diablo platform, and several hundred feet of gypsum occur near the axis of the basin, where nonelastic rocks are of maximum thickness. In the Permian basin, the region of maximum carbonate sedimentation coincides in location with similar ones of Missourian (fig. 41) and Desmoinesian (fig. 35) rocks. Chert is of no significance along this trend except by its absence; dolomite, however, locally makes up r 00 per cent of the carbonate and is quantitatively more significant than in any earlier stage of the Pennsylvanian. The axis of black shale accumulation (fig. 46) parallels that of the nonelastic rocks, lying basinward from it. The maximum accumulation of carbonate rocks developed principally through the vertical growth of reefs.

SUMMARY OF PENNSYLVANIAN ROCKS

Thickness. The map of the distribution and variation in thickness of the total Pennsylvanian section (fig. 48) reveals most of the structural elements of the area. The thickness of Pennsylvanian strata in the Orogrande basin may be as much as 4750 feet and in the Permian basin, 3000 feet. On the west, the Oscura uplift and a southeastward-extending nose of the Joyita uplift together mark the junction of the Estancia and Orogrande basins. On the east, Pennsylvanian sediments are absent over much of the Central Basin platform and over the Roosevelt uplift.

In Figure 48, the nose extending into the Orogrande basin from the Sacramento shelf, the Salt Flat embayment, and the southwest-northeast axis of thick sediment accumulation

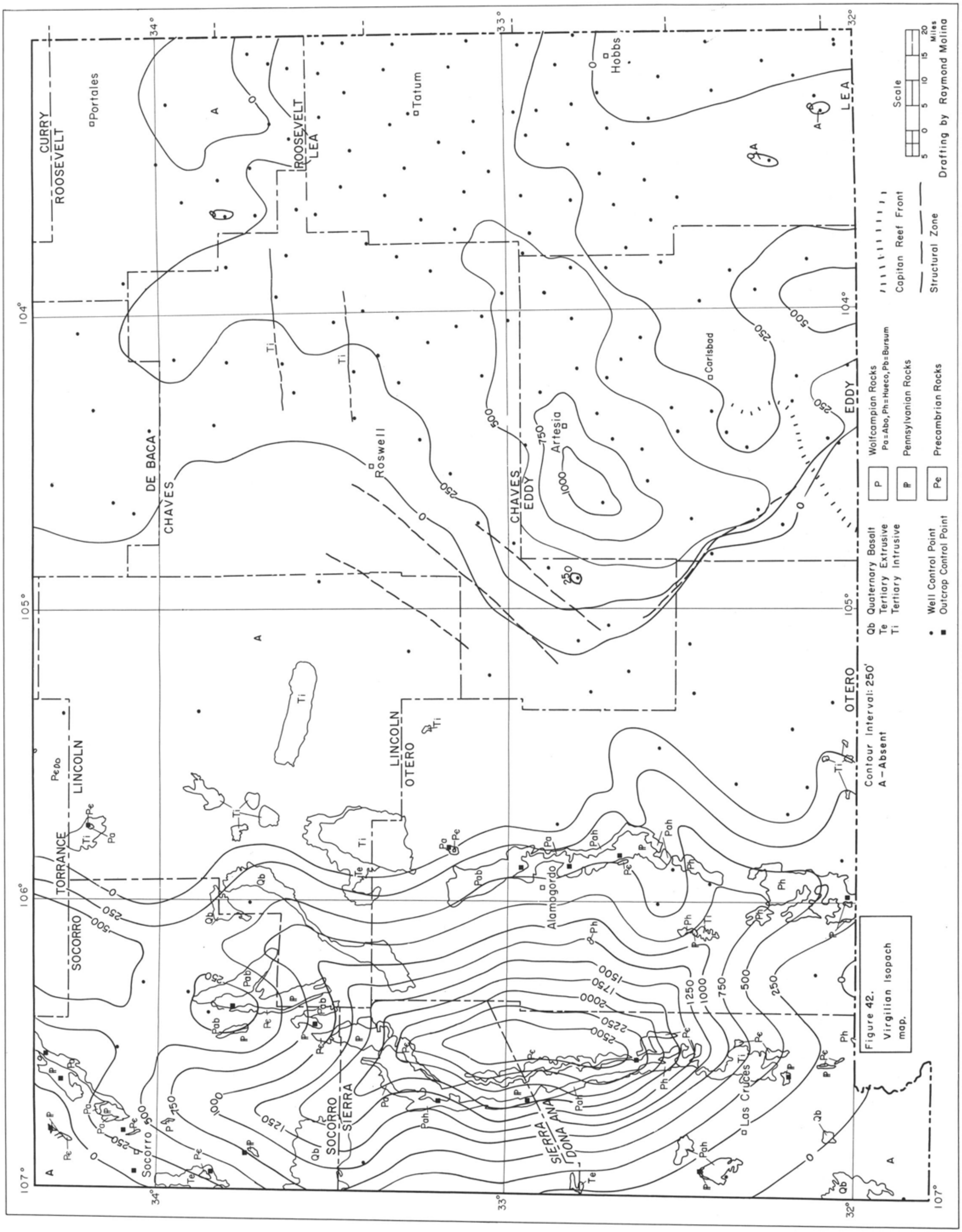


Figure 42.
Virgilian Isopach map.

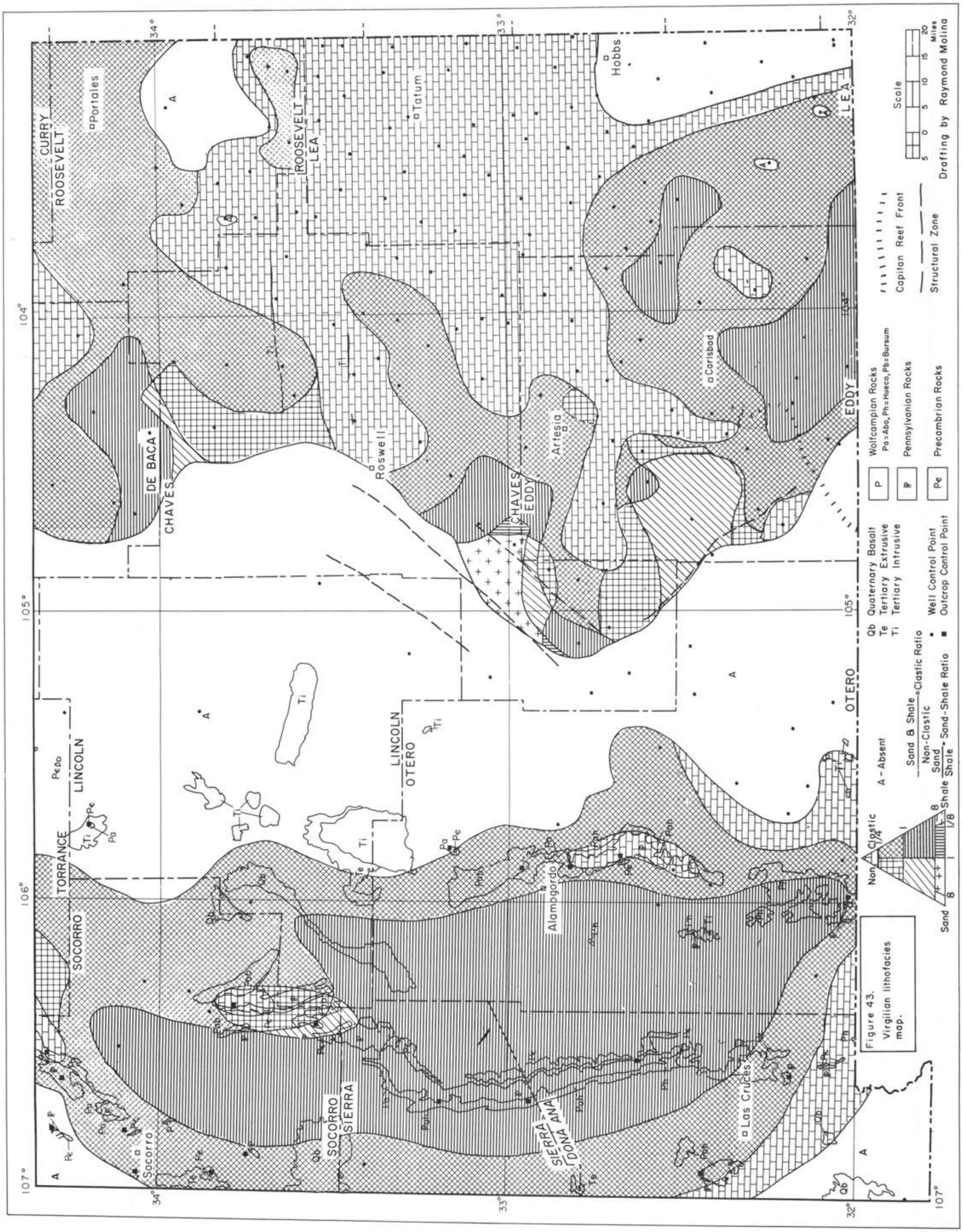


Figure 43. Virgilian lithofacies map.

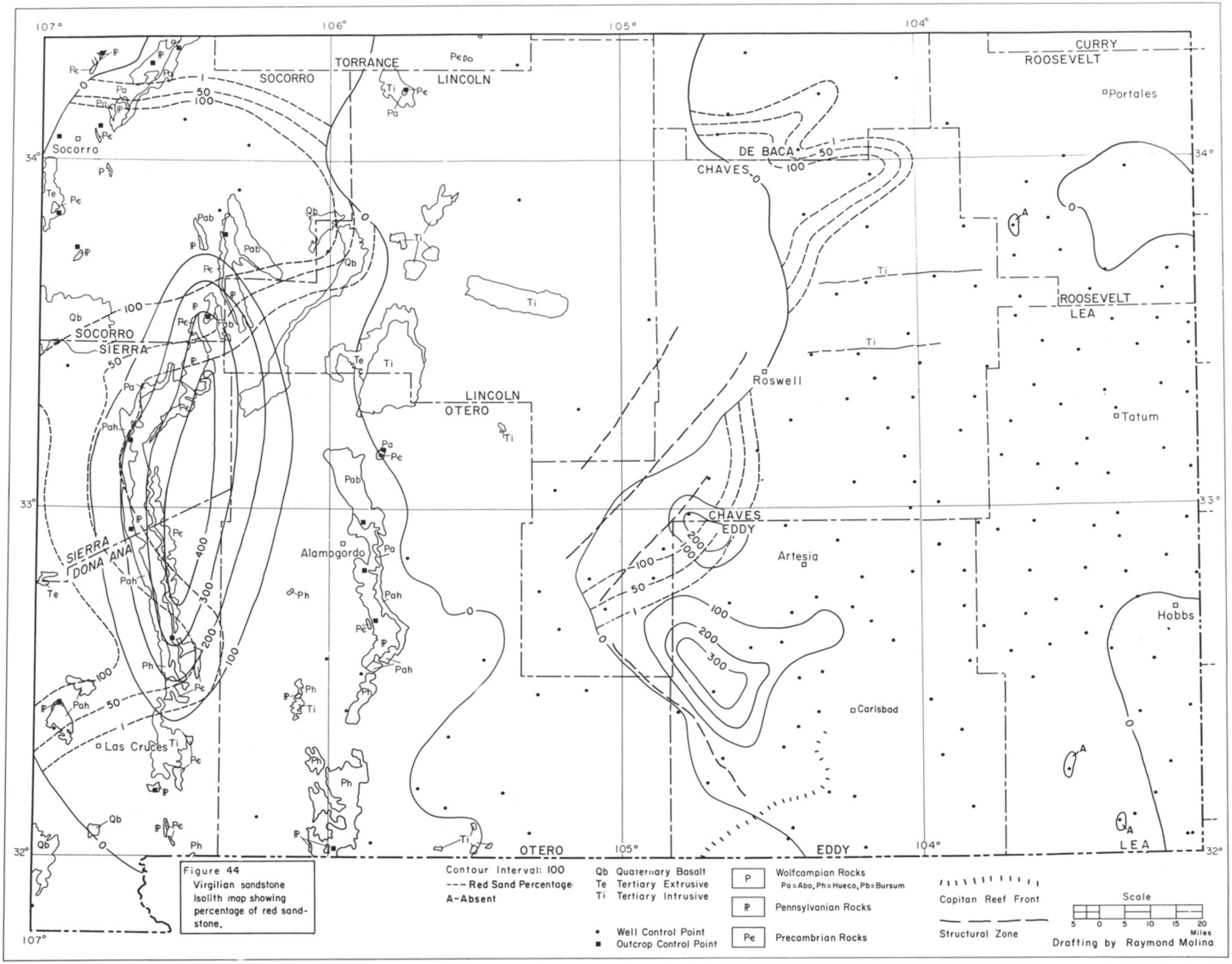


Figure 44
Virgilian sandstone isolith map showing percentage of red sandstone.

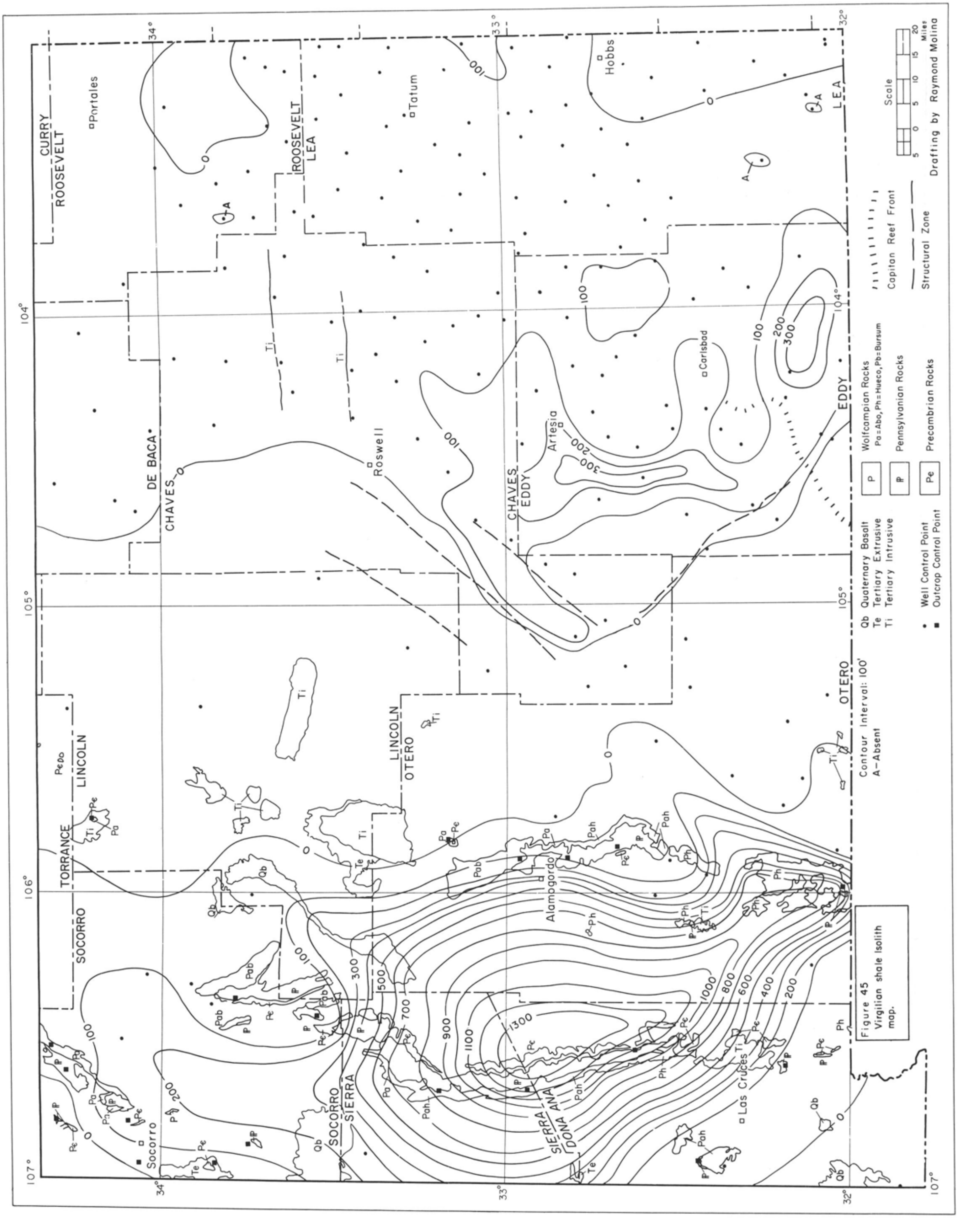


Figure 45
Virgilian shale isolith map.

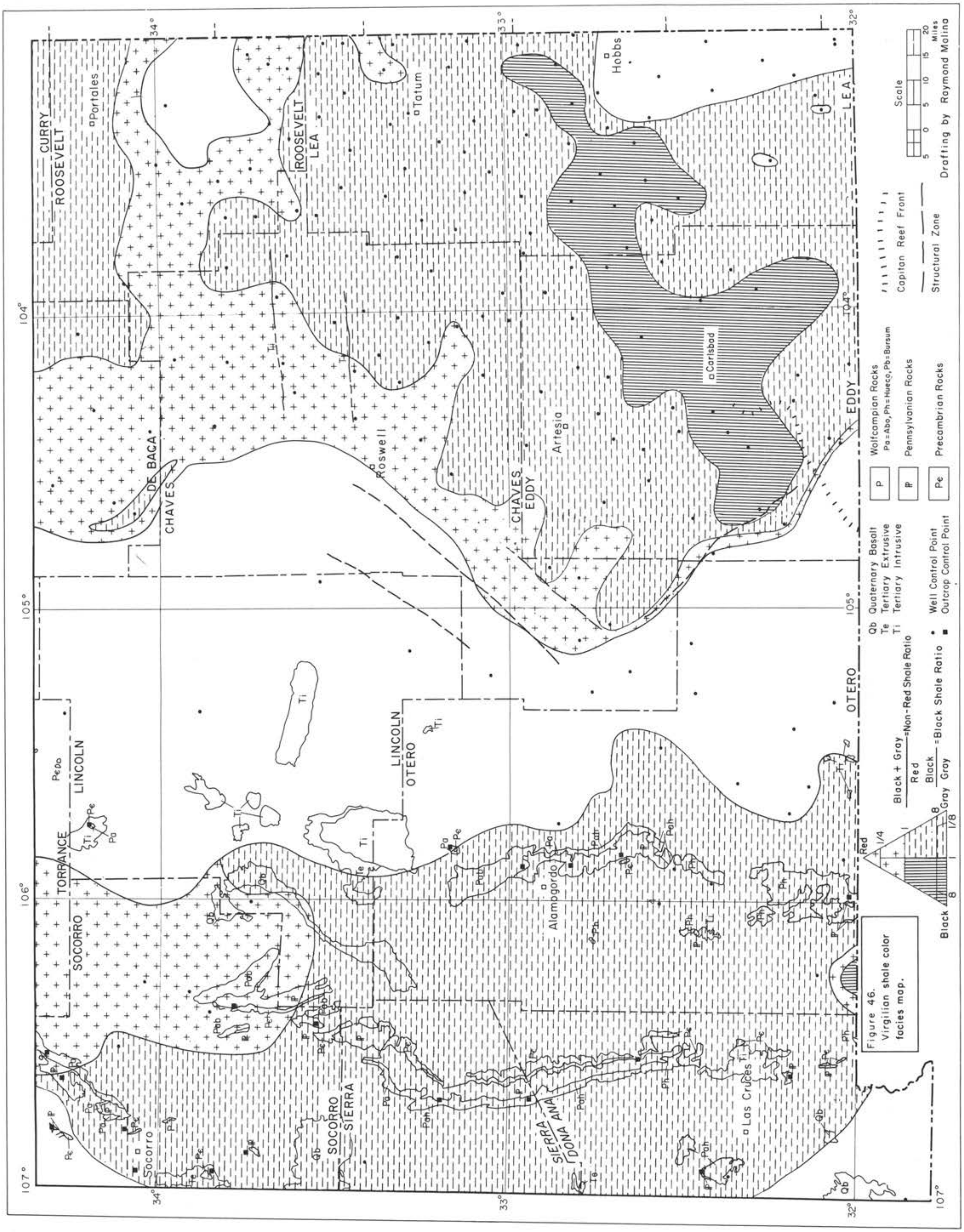


Figure 46. Virgilian shale color facies map.

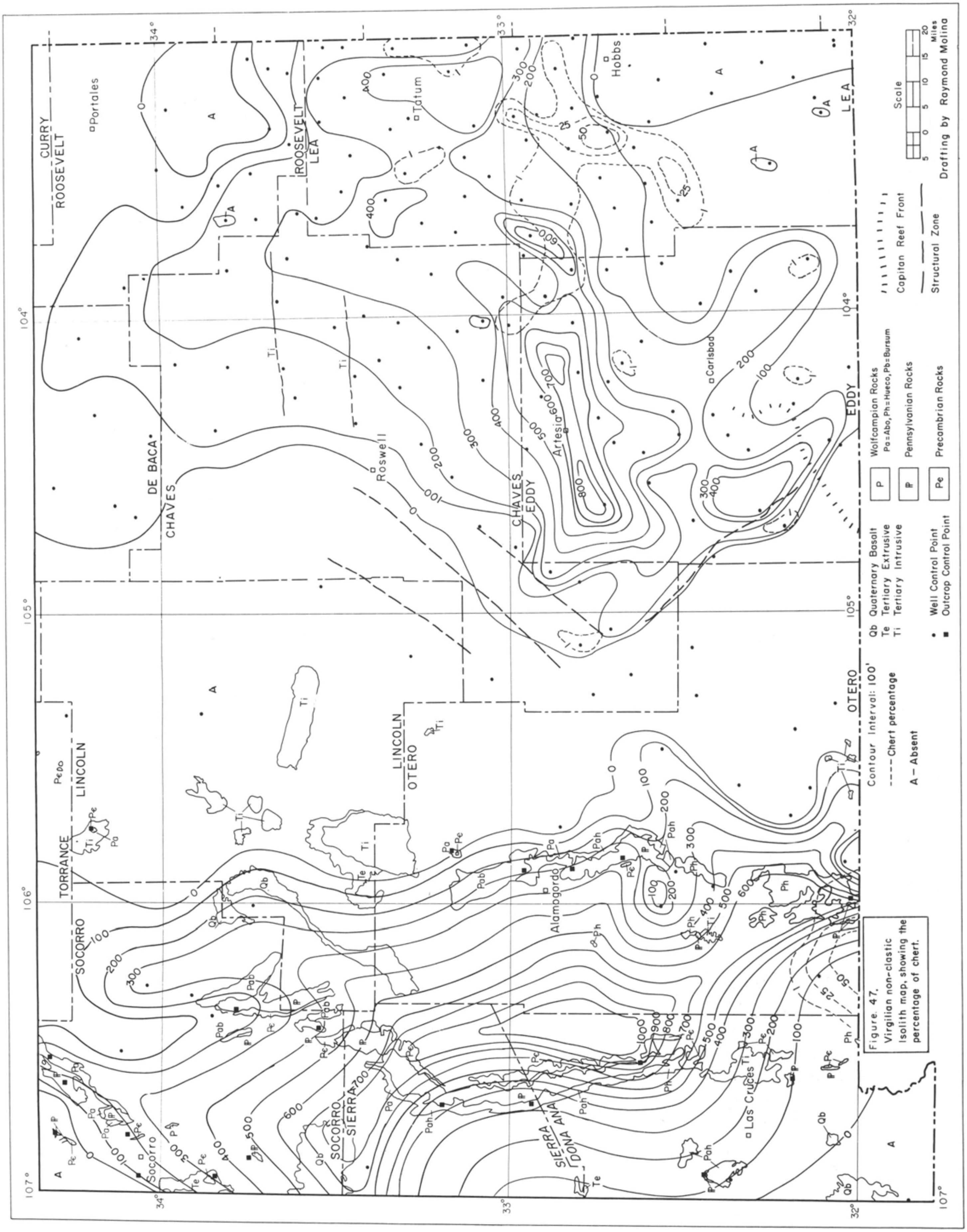


Figure. 47. Virgilian non-clastic Isolith map, showing the percentage of chert.

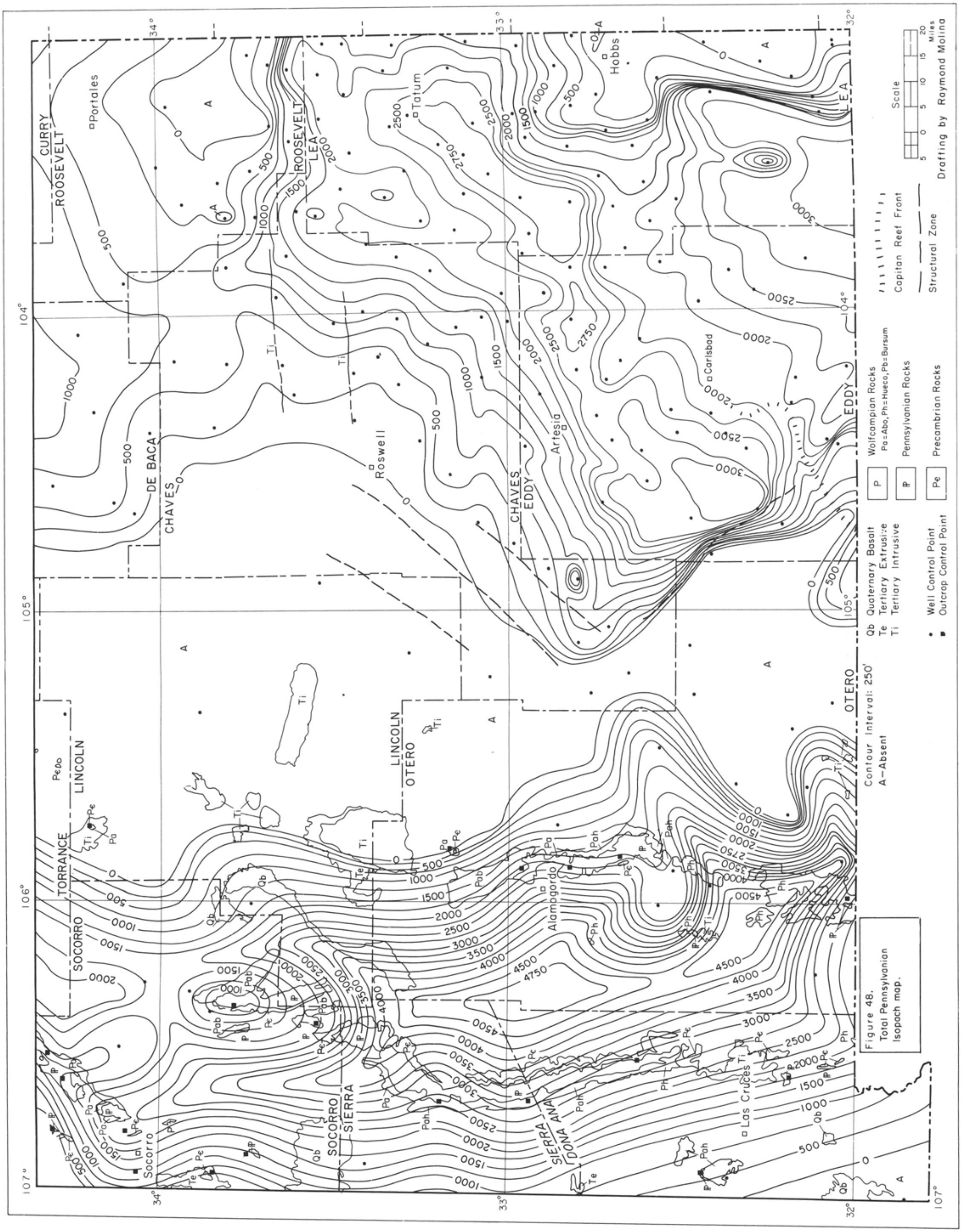


Figure 48. Total Pennsylvanian Isopach map.

across the Permian basin all are clearly evident. Pennsylvanian sediments do not progressively increase in thickness from the Northwest shelf into the Delaware basin, but rather they abruptly increase in thickness, then become thin, basinward, along a parallel axis. Finally, in the Delaware basin west of the Central Basin platform, the sediments again thicken; here they were deposited in a southward-plunging trough.

Lithofacies. Pennsylvanian lithofacies are shown on a map (fig. 49) that averages the five stages. The shelves and basins are sites in which predominantly carbonate rocks accumulated; principal lithologic associations are limestone, limestone-shale, and, less commonly, limestone-sandstone. Most of the uplifts appear on the map as areas of Precambrian granite or of older Paleozoic sediments; these areas are surrounded by Pennsylvanian rocks in which predominantly elastic lithofacies associations are adjacent to the uplifts. Wedging-out of the Pennsylvanian strata against the uplifts may be the result either of deposition followed by erosion or of non-deposition. In the latter instance, the strandline presumably lay nearby. Where the isopachs are evenly spaced across the shelves up to the zero isopach, at the margin of an uplift, and especially where this featheredge is accompanied by dominantly elastic lithofacies associations, a strandline is strongly suggested. This is generally true for the north half of the Pedernal uplift. Where the isopachs near the zero abruptly become closely spaced, and especially where this is accompanied by dominantly nonelastic lithofacies associations at the edge of the uplift, it strongly suggests that the wedge-out followed uplift and erosion, the strandline elastic sediments having thus been destroyed. Examples of this sort include the Central Basin platform, the southeast margin of the Pedernal uplift along the Huapache flexure, and the small, local area centered on R-11.

PERMIAN SYSTEM

LOWER PERMIAN SERIES

Wolfcampian Stage

Lithology. In the northwest part of the area, from the Joyita uplift across the Estancia basin to the Oscura uplift, the lower part of Wolfcampian strata consists of dark purplish-red and green shale, arkose, and gray nodular limestone. Overlying these beds is a sequence of dark red shale, dark red quartzose sandstone, and arkose which exhibits mud cracks, current ripple marks, cross-bedding, animal tracks, and plant impressions (pl. 2; Wilpolt et al.). To the southeast, approaching the Pedernal uplift (X-1), the lower purplish-red shale and nodular limestone unit is absent, the entire stratigraphic section being made up of red shale, conglomerate, and arkose, with minor amounts of limestone. To the south, along cross section A-A', the lower, purplish-red shale unit is present over the Robledo shelf, where the shale is succeeded by thin-bedded limestones and, near the top, by more red shales. Eastward, at the margin of the Orogrande basin (Y-1), the Wolfcampian contains a massive biostromal limestone at the base, succeeded by argillaceous limestones, cherty fossiliferous limestones, gray fossiliferous shales, and, at the top, red shale and arkose (Kottlowski et al., 1956). In the Orogrande basin, Wolfcampian strata are thick and consist of tan to brown, fine-grained limestone, gray and brown shale, and thin stringers of arkose. On the basin margin of the Sacramento shelf (O-2), Wolfcampian rocks are made up of a middle unit of thin-bedded limestones with thick beds of arkose and red shale at the base and at the top. This sequence continues eastward to the Pedernal uplift, across which only the upper red shales are present. In the Delaware basin, the Wolfcampian typically is composed of gray and brown, very fine-grained limestone, dark-gray to black shale, and lesser amounts of gray, fine-grained, quartzose sandstone; chert is common and at places predominant. Over the Northwest shelf, the sequence is light-brown to tan, fine-to medium-grained, fossiliferous limestones with variegated shale interbeds. In the Tucumcari basin (pl. 4), the limestones are similar to those of the Northwest shelf but are interbedded with red shale and arkose. Red shale is also predominant in the vicinity of the Roosevelt uplift (pl. 3).

Age relations. For the Pennsylvanian stages, time boundaries were chosen as closely as possible to the occurrences of the guide fossils. The units are essentially fusulinid assemblage zones; where biostratigraphic precision was not possible because of scantiness of fossil data, correlations were based on lithologic markers from the nearest data control points that were based upon fossil data.

For Wolfcampian strata, further remarks are pertinent concerning the basal and upper boundaries and the facies relations within the unit. The lowermost purplish-red shale and nodular limestone beds described from the Estancia basin area extend as far southward as the Robledo shelf and northern Sacramento shelf. This biostratigraphic unit is characterized by *Triticites creekensis* Thompson and has been mapped on the surface as the Bursum Formation (Wilpolt et al.), the Aqua Torres Formation (Stark and Dapples), the Bruton Formation (Thompson, 1942), and the Laborcita Formation (Otte, 1959a).

According to Ross, the Bursum Formation is distinctly older than the overlying Wolfcampian strata of the subject area, since it is considered by Ross to be older than the Neal Ranch Formation of the standard Wolfcampian Series of the Glass Mountains. The Neal Ranch Formation has no demonstrable time equivalent in strata west of the Pedernal uplift. The rocks overlying the Bursum are predominantly red beds to the north and marine carbonates to the south. The red beds are mapped on the surface as Abo Formation and the carbonate rocks as Hueco Limestone (Hueco Group of Williams, 1946); the surface exposures of the various units are indicated on the base maps utilized throughout this memoir. The Hueco Limestone is correlated with the Upper Wolfcampian Lenox Hills Formation of the standard Wolfcampian Series (Ross), but, in addition, the lowermost part of the Hueco may be as old as the upper part of the Middle Wolfcampian Neal Ranch Formation; the uppermost part of the Hueco is possibly of Leonardian age (Williams, 1963, 1964).

On the west side of the Pedernal uplift, over the Sacramento shelf, the marine carbonates from the Diablo platform area on the south intertongue with the red beds from the north. On the Diablo platform (fig. 3), a conglomerate at the base of the Hueco Limestone rests upon uplifted and trun-

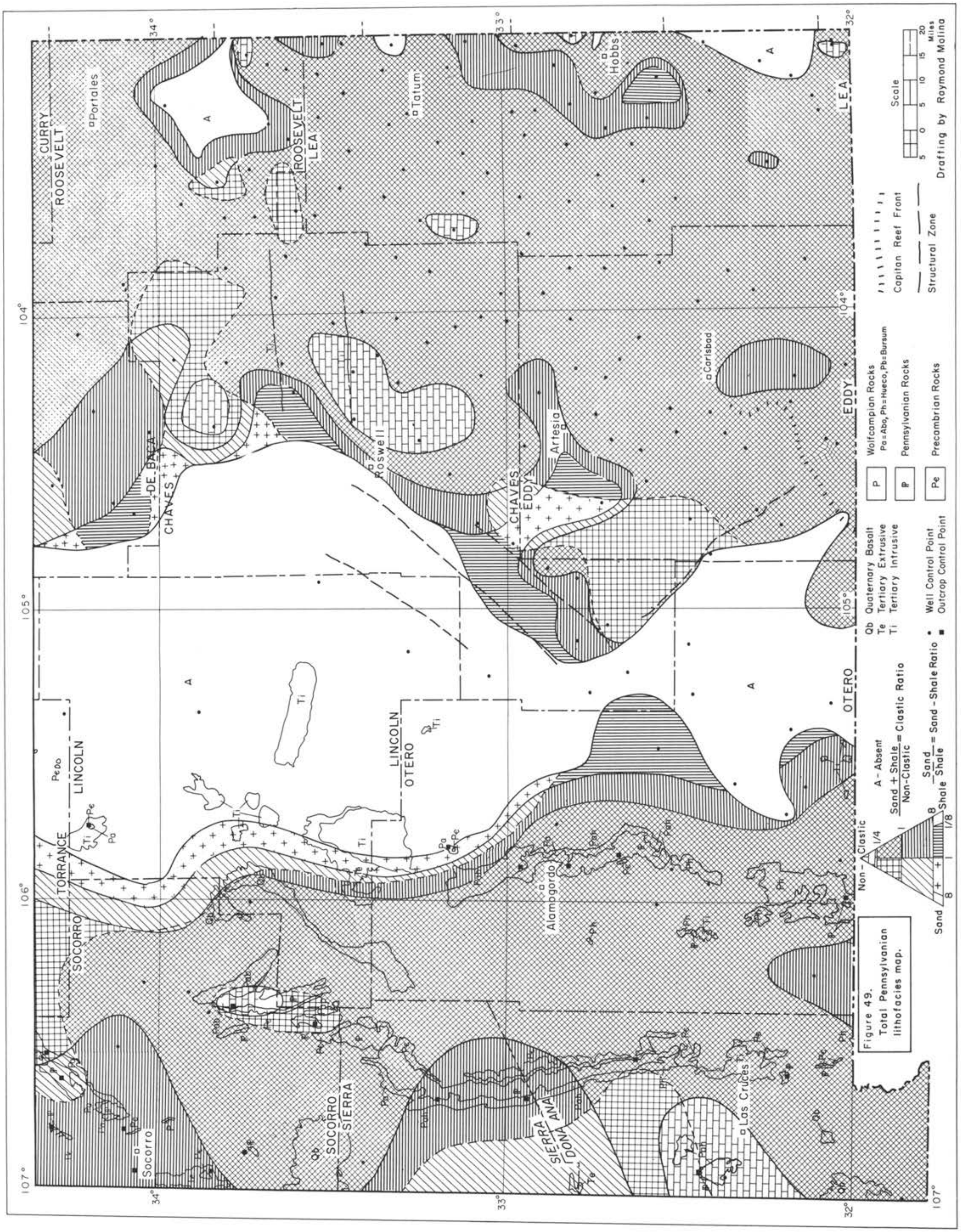


Figure 49. Total Pennsylvanian lithofacies map.

cated Pennsylvanian rocks (Williams, 1963). This conglomerate is correlated northward with the lowermost part of the red bed sequence (Pray and Otte, 1954). Similarly, a red shale near the top of the Hueco is correlated with an uppermost southward-extending tongue of the red beds; since Wolfcampian carbonate rocks of the Hueco Limestone overlie the upper red shale tongue, it is apparent that the main (Abo) red bed unit, of which the upper tongue is a part, is also of Wolfcampian age.

Over the Pedernal uplift, Wolfcampian red beds vary in thickness according to the amount of relief developed upon the underlying surface (pl. I, O-15 and E-15; pl. 2, X-3). East of the Pedernal uplift, these red beds grade into Wolfcampian carbonate rocks (pl. 1, E-15 to E-14; pl. 2, X-3 to C-9).

Overlying Wolfcampian strata west of the Pedernal uplift are the orange and red sandstones and evaporites of the Leonardian Yeso Formation. East of the Pedernal uplift, the Yeso Formation grades into the upper part of the Leonardian Bone Spring Formation in the Delaware basin (pl. 1, O-15 to E-25; pl. 4, E-4 to E-12), while the Yeso may be traced in the subsurface over the Northwest shelf (pls. 2, 3, and 4).

East of the Pedernal uplift, however, another unit of rocks of Leonardian age is present between Wolfcampian strata below and the Yeso Formation above. This unit consists of red beds and brown, fine-grained, anhydritic dolomite on the north (pl. 2; pl. 3, north of L-19; pl. 4, north of E-4). Southward and eastward, the red bed-brown dolomite sequence passes through a narrow zone of white, coarse-grained dolomite into the black siltstones and black massive limestones of the lower Bone Spring Formation. The Bone Spring Formation contains a Leonardian fusulinid fauna. Therefore, the white, coarse-grained dolomite, which is called by subsurface geologists the *Abo Reef* (LeMay in Sweeney et al.), and the red bed-dolomite sequence, which is called the *Abo Formation* of the subsurface, are Leonardian in age. The true Abo Formation of the outcrop area west of the Pedernal uplift is, as described above, of Wolfcampian age. It is recommended, therefore, that the Abo Formation of the subsurface be designated *Wichita Formation,* the Leonardian sequence of west Texas with which it is correlative and coeval. This designation is shown on the cross sections and was commonly used among subsurface geologists in New Mexico until about 1950; it is still the practice of west Texas geologists, as indicated in Herald (1957).

The areal distribution of the rock units described is shown on the supercrop map of the Wolfcampian (fig. 17). This discussion suggests a hiatus over the western part of, as well as west of, the Pedernal uplift for that period of early Leonardian time during which the Wichita Formation and its basin equivalent, the lower Bone Spring Formation, were deposited. It is likely that the uppermost Abo Formation of the outcrop is of Leonardian age (Bachman and Hayes, 1958), and, if so, there is a thin rock unit on the west representative in age of the Wichita Formation; the cross sections in this memoir do not show this possibility. An alternative interpretation of the red bed-brown dolomite sequence of the Permian basin has been advanced independently by Kottlowski (1963), who suggests equivalence of the Wichita sequence with the basal sandstone of the Yeso Formation.

Within the Wolfcampian Stage west of the Pedernal uplift, an unconformity exists between strata of Bursum age (Lower Wolfcampian) and strata of Hueco age (Upper Wolfcampian Lenox Hills), with age equivalents of the Neal Ranch Formation being absent. In the Permian basin, no evidence of significant time breaks in the Wolfcampian succession have been found, either lithologic or paleontologic. The fossils range in age from lower to upper Wolfcampian, including Neal Ranch types.

Reefs. Reefs of early Wolfcampian age are described by Otte (1954) from the northern part of the Sacramento shelf, adjacent to the Orogrande basin, in a zone one third of a mile in width and about three miles in length. The reefs are small and consist of fine-grained calcareous sediments trapped by filamentous algae. Wolfcampian reefs also occur on the west side of the Orogrande basin, in strata of upper Wolfcampian age (pl. 1, Y-1; Kottlowski et al., 1956).

Thickness. Wolfcampian rocks are distributed over essentially the entire area and range in thickness up to possibly 3500 feet (fig. 50). Over the Central Basin platform, Wolfcampian strata are commonly absent (L-37, for example); where present, they are thin. The straight, tightly spaced isopachs along the margins of the Delaware basin coincident with the Huapache flexure and Central Basin platform suggest normal or high-angle reverse faulting, following which the adjacent uplifted blocks were eroded. Wolfcampian rocks cover the Pedernal uplift, occurring as thick or thin accumulations depending upon the surface over which they were deposited. The pre-Wolfcampian surface was apparently folded prior to deposition of the Abo Sandstone, as were pre-Abo strata of the area of outcrop on the Sacramento shelf (Pray, 1949).

The Wolfcampian isopach map differs from that of the Pennsylvanian in the following respects: The sediments are distributed over the entire area, except locally on the Central Basin platform; the Oscura uplift and the nose extending southwestward from the Sacramento shelf have disappeared; the Roosevelt uplift is discernible; however, it is entirely covered by Wolfcampian sediments; the uplift of the Diablo platform is marked by a thinning of sediments at the south end of the Orogrande basin (as at O-10); the Robledo uplift is covered by a thick accumulation (Y-3), and a southwest-extending trough of thick sediments crosses the southern part of the Robledo shelf; and the southwest-northeast axis of thick Pennsylvanian accumulation of sediments has become the site of an axis of thin Wolfcampian accumulation of sediments. A belt of thick Wolfcampian rocks lies along the north margin of the thin accumulation; this belt of thick deposits extends eastward along the north side of the Central Basin platform and also southward along the west side of the Central Basin platform into the Delaware basin.

Lithofacies. Lithofacies of Wolfcampian rocks are depicted in Figure 51. Over the northwest quarter of the map, elastic lithologic associations are clearly dominant. These elastics are almost entirely red beds that interfinger, southward and eastward, with rocks of the marine carbonate facies. This interfingering appears on the map in the form of bands of shale- and sandstone-limestone associations which in turn give way seaward (eastward and southward) to bands of limestone-shale and limestone-sandstone associations, and finally to limestone. Southward, in the Delaware basin, the limestone is replaced by a limestone-shale association.

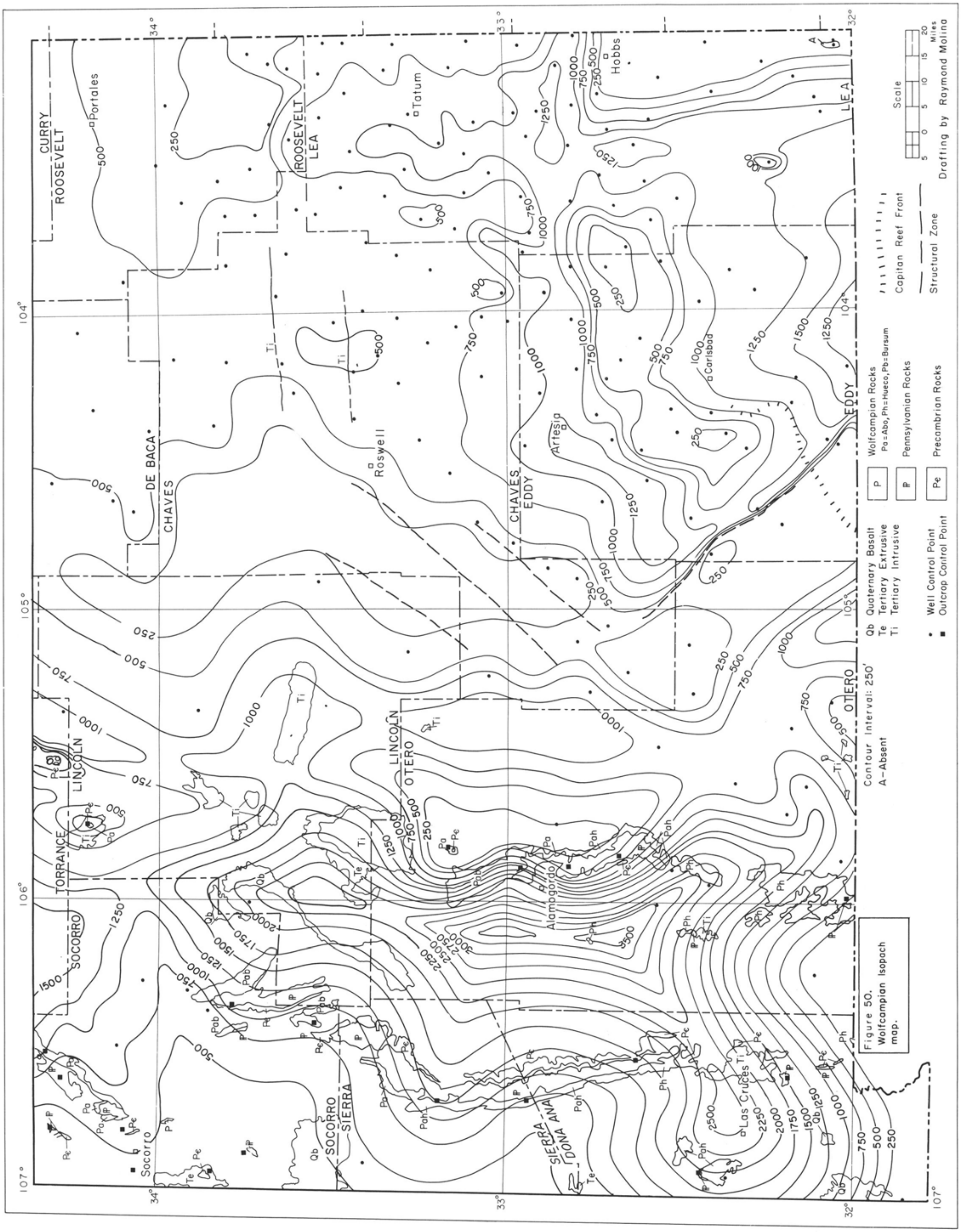


Figure 50. Wolfcampian Isopach map.

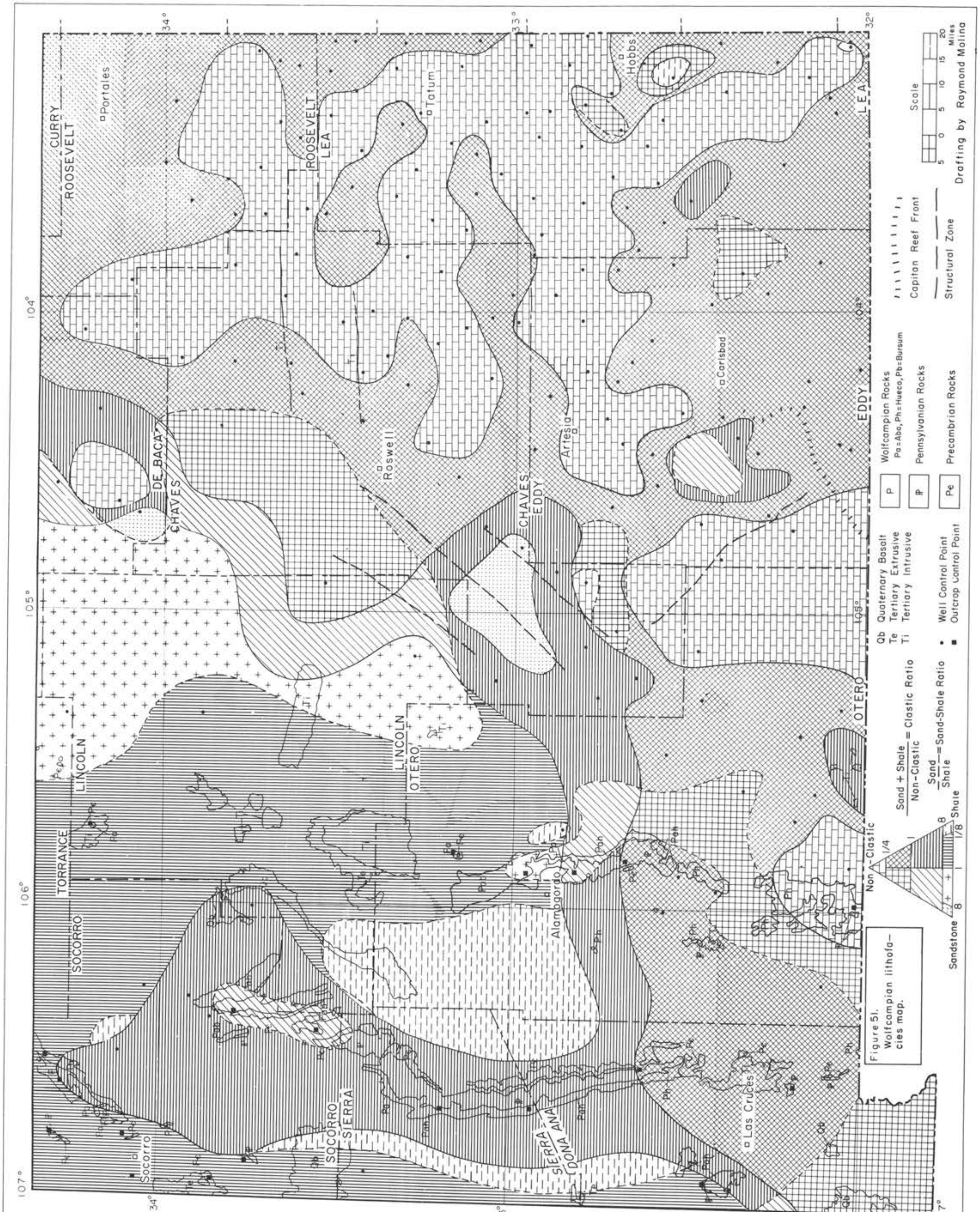


Figure 51. Wolfcampian lithofacies map.

Sandstone. The sandstone isolith map (fig. 52) shows very well that the source area lay to the north and west and that the detritus moved southeastward. Only small amounts of sandstone appear in the Wolfcampian southward and southeastward of the limits of red sandstone.

Shale. The shale isolith (fig. 53) and shale color-facies (fig. 54) maps demonstrate that well-defined environments of deposition existed during Wolfcampian time. Gray and variegated shales occur in the southern part of the Orogrande basin, and in the Permian basin, a narrow band of such shale separates the red beds on the north from the black shale of the Delaware basin on the south.

Nonelastic rocks. The occurrence of Wolfcampian marine nonelastic rocks is shown in Figure 55. The position of the zero isolith line, when compared with the sandstone (fig. 52) and shale (fig. 53) maps, shows that the strandline must have moved back and forth across a transition area, resulting in incursions of red sands and muds into the sea, interspersed at times of low elastic influx with deposition of marine limestones.

The band of variegated shale separating the red shale area from the black shale area of the Delaware basin (fig. 54) corresponds with the axis along which Wolfcampian carbonate rocks achieved maximum thickness in the Permian basin. It is also noteworthy that the principal axis of marine sedimentation in the Orogrande basin lies in an east-west direction, compared with its north-south direction during Pennsylvanian time.

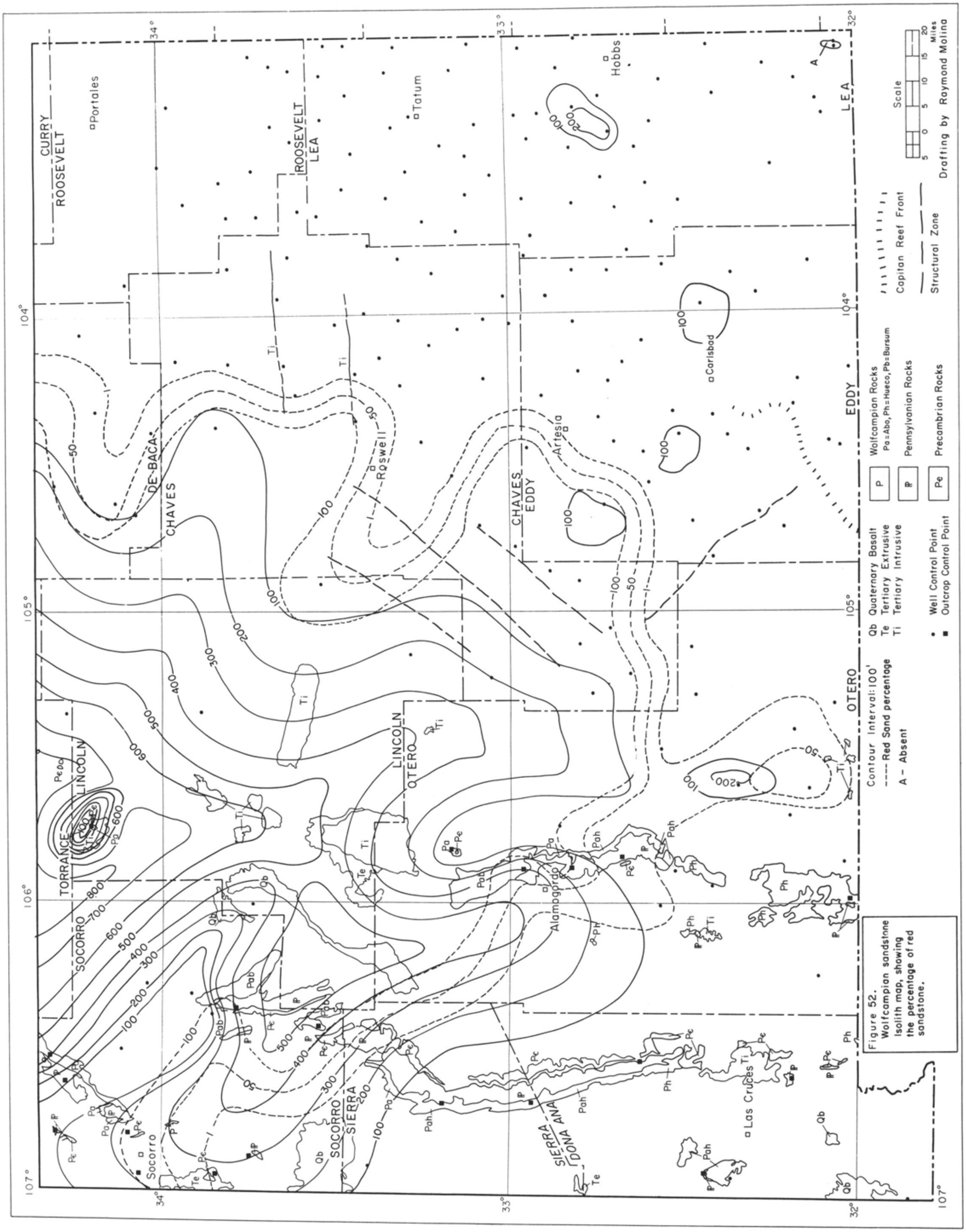


Figure 52.
Wolfcampian sandstone isolith map, showing the percentage of red sandstone.

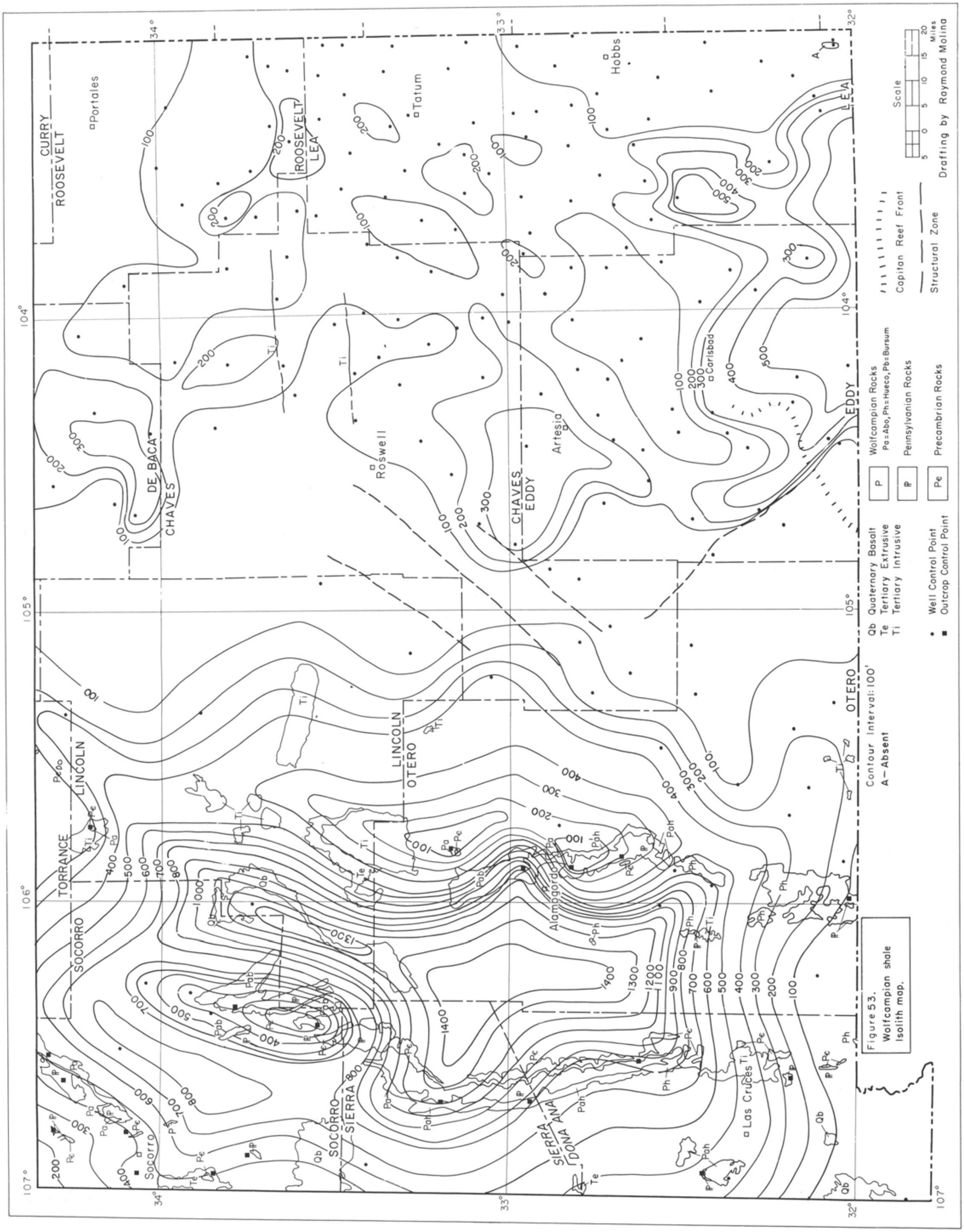


Figure 53.
Wolfcampian shale isolith map.

Contour Interval: 100'
A—Absent

Qb Quaternary Basalt
Te Tertiary Extrusive
Ti Tertiary Intrusive

• Well Control Point
■ Outcrop Control Point

P Wolfcampian Rocks
Pa=Abo, Ph=Hueco, Pb=Bursum

Pennsylvanian Rocks

Pe Precambrian Rocks

Capitan Reef Front

Structural Zone

Drafting by Raymond Molina

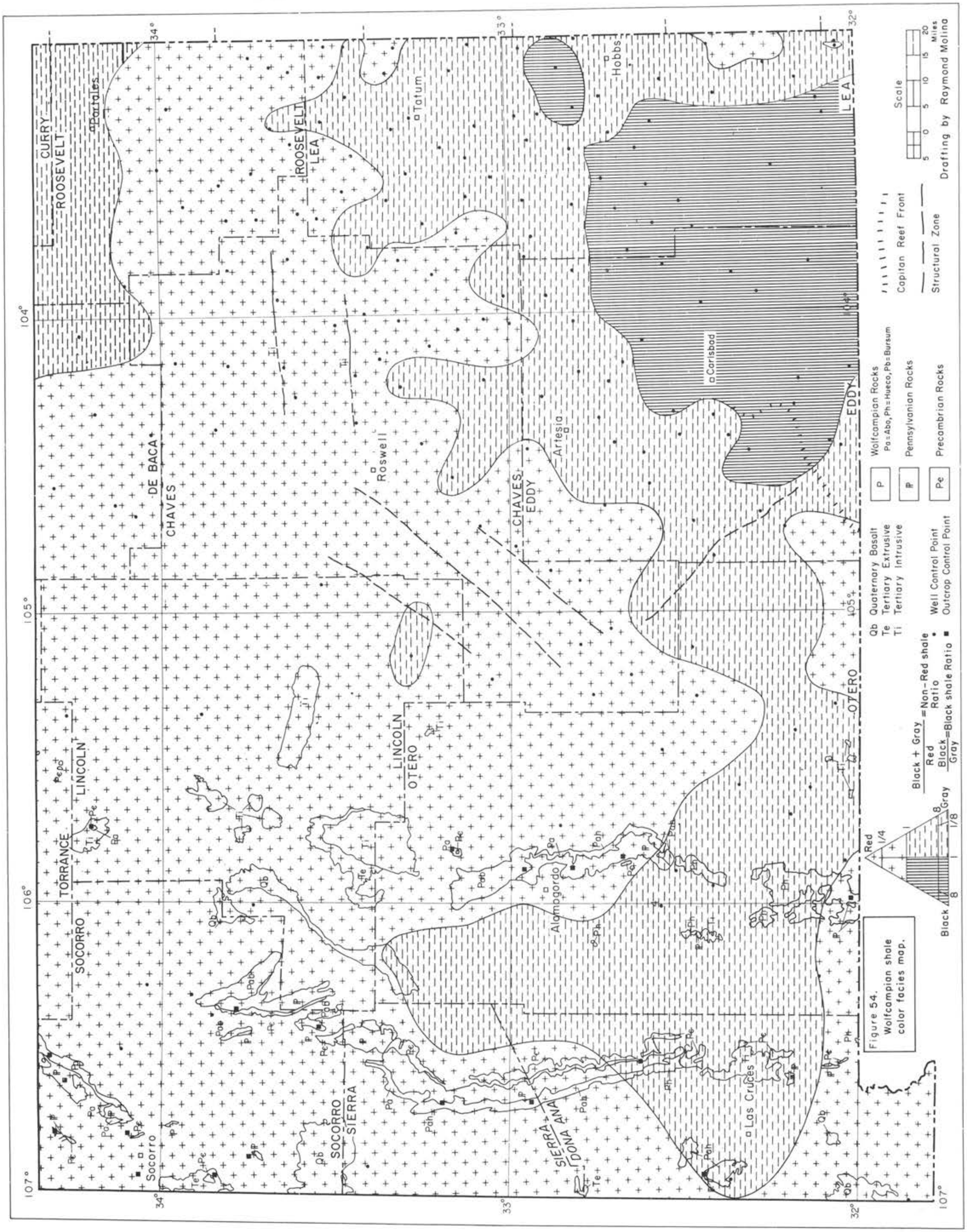


Figure 54. Wolfcampian shale color facies map.

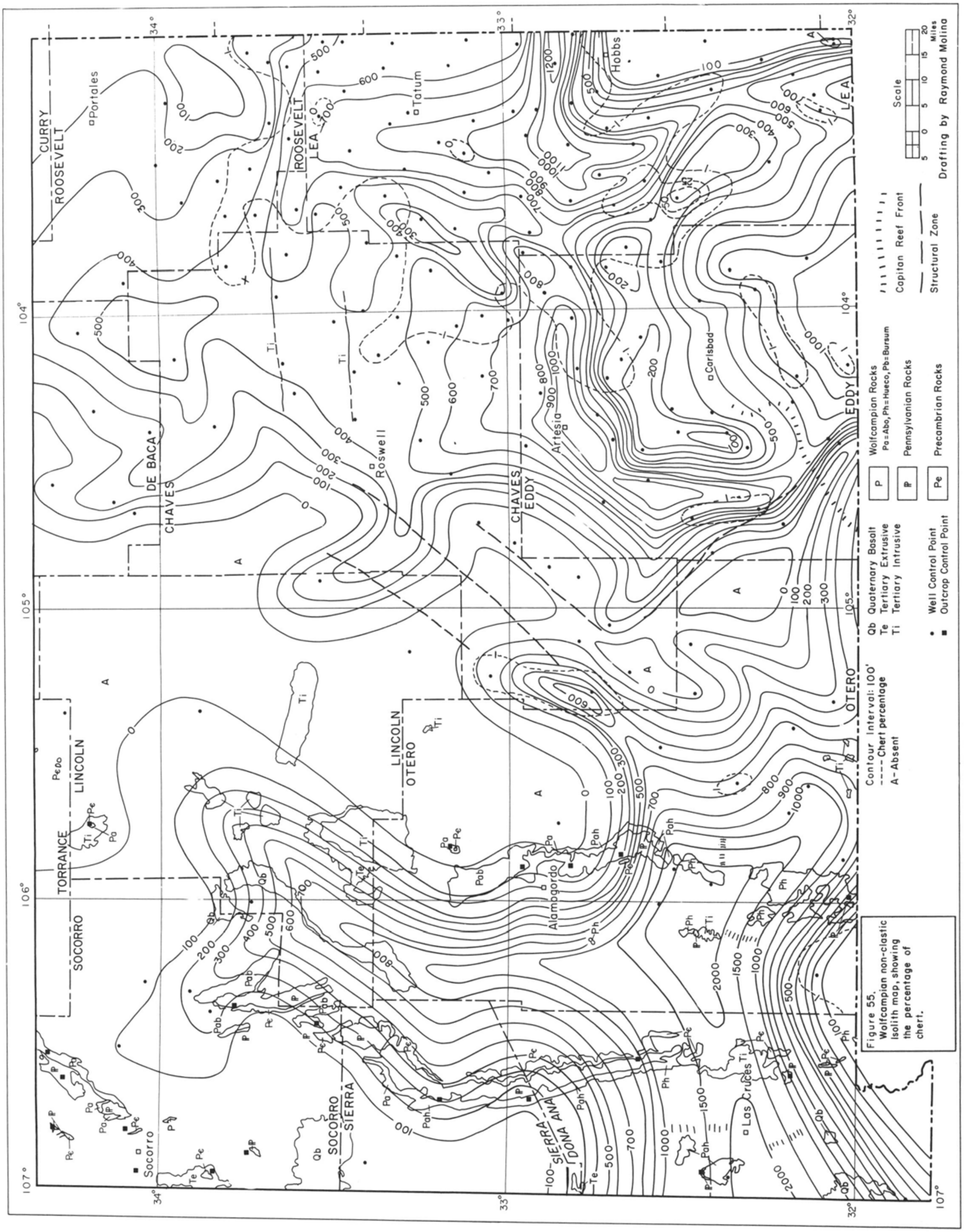


Figure 55. Wolfcampian non-clastic isolith map, showing the percentage of chert.

Structure

The two major structural features in the report area are the Pedernal uplift and the Central Basin platform. These two features represent the southeasternmost extension of the Colorado system of late Paleozoic uplifts (King, 1959), although King's map extends only as far south as the northern tip of the Pedernal uplift. King treated the Central Basin platform, as well as the Permian (West Texas) basin separately from and independently of other ancient structural elements. Although the Pedernal and Central Basin platform uplifts are not contiguous, they have followed similar modes and times of deformation. Both are faulted anticlinoria, with histories of compressional folding and uplift during Pennsylvanian time and normal or high-angle reverse faulting in Wolfcampian time; both uplifts were the sites of depositional shelves of pre-Pennsylvanian strata. The Pedernal uplift and Central Basin platform differ in these respects: that throughout virtually its entire extent, Upper Wolfcampian red beds rest on Precambrian rocks over the Pedernal uplift and only a relatively thin veneer of post-Wolfcampian strata is present; but over the Central Basin platform, thick Leonardian strata overlie rocks ranging in-age from Precambrian to Wolfcampian and are in turn overlain by great thicknesses of later Permian, Triassic, and Tertiary rocks; and in that the Pedernal uplift is, in present form, asymmetrically anticlinal with the steeper limb on the west, whereas the Central Basin platform is a tilted fault block dipping to the east.

Although the cross sections are stratigraphic in nature, drawn with the top of the Wolfcampian Stage as datum plane, they show most of the major pre-Wolfcampian structural elements clearly. Cross section A-A' crosses both the Pedernal uplift and the Central Basin platform and cross section B-B', the Pedernal uplift. The structural nature of these uplifts is also depicted on the structural contour maps (figs. 56-61). The Huapache fault, so-called because it underlies the surface geologic feature known as the Huapache monocline or flexure (fig. 2), is interpreted as a normal fault. Hayes (p. 40-42) considered it to be a thrust fault because the Humble Huapache Unit 1 well encountered a repeated stratigraphic section when drilled through the fault plane. The writer believes that, in the area where the Humble well was drilled, the nearly vertical normal fault has been overturned by post-Wolfcampian (probably Laramide) compression.

The scale of the maps in this memoir is such that minor folds cannot be shown because of their small amount of structural closure. Pennsylvanian strata are known to be folded into northwest-trending anticlines over the Sacramento shelf (Otte, 1959a; Pray, 1949); these folds are overlain by both Lower and Upper Wolfcampian strata that are not deformed. The irregularities in thicknesses of Wolfcampian strata apparent on the Wolfcampian isopach map (fig. 5o) are believed to be the result of deposition over the eroded remnants of pre-Wolfcampian folds on the Pedernal uplift. Deeply eroded anticlines, whose axes trend northwestward, underlie strata of the Leonardian and, in places, Wolfcampian Stages over the Central Basin platform. The Pennsylvanian and Wolfcampian oil and gas pools of the Northwest shelf (figs. 62-67) occur in reservoirs, many of which are associated with anticlines whose axes are most commonly oriented in a north-south direction (table 3). These anticlines formed during Early and early Middle Pennsylvanian time but are reflected in Late Pennsylvanian and Wolfcampian strata as supratenuous folds; these relationships are shown in a number of places on Plates r through 4.

The like orientation of the two major uplifts, as well as subsidiary folds both on their flanks and over the uplifts proper, indicates the folding to be compressional in nature. The folding was followed by essentially vertical uplift of the major structural elements, which was accompanied by normal faulting.

The Diablo platform (fig. 2), whose northern limit approximately coincides with the southern margin of the present map area, was the site of a shelf throughout Pennsylvanian time. It was uplifted, apparently as a tilted block, in Early Wolfcampian time, eroded, and then overlapped from south to north by Upper Wolfcampian strata.

The Joyita, Oscura, and Roosevelt uplifts were positive elements throughout much of Pennsylvanian time, finally disappearing with the advent of Wolfcampian deposition. They apparently represent vertical adjustments in the earth's crust, rather than compressional features.

On the base maps are shown three structural zones in addition to the Huapache flexure. These are prominent surface features, either tight folds or faults, that are not believed to involve Wolfcampian or Pennsylvanian strata; rather, they are believed to be decollement folds resulting from competent younger Permian strata slipping downdip over Leonardian gypsum beds.

The structural contour maps (fig. 56-61) are contoured only on the east side of the Pedernal uplift because of the sparseness of data on the west. Regional interpretation of the maps is based upon several assumptions. Where the structural contour lines terminate abruptly at a high angle to the margin of a stratigraphic unit, it is probable that uplift and erosion occurred subsequent to deposition. Where the structural contour lines remain evenly spaced as the featheredge of a unit is approached and are more or less parallel to that edge, then it is probable that the edge is depositional and is not far removed from the strandline. Where the contour lines are offset along either side of an almost straight line, then the line represents a fault; the displacement, in feet, equals the difference in value of contour lines which abut at the fault line.

The contour lines on the Morrowan structural contour map (fig. 56) indicate faulting along the Huapache flexure on the southeast edge of the Pedernal uplift and along the west and north sides of the Central Basin platform. It is suggested that the fault along the north end of the Central Basin platform was perhaps ten miles farther north than the apparent north end of the platform during later stages. The northeast margin of the Permian basin, near the site of the Roosevelt uplift, is erosional, Morrowan rocks having formerly extended farther northward. The present western limit of the Permian basin, in the area between the Huapache

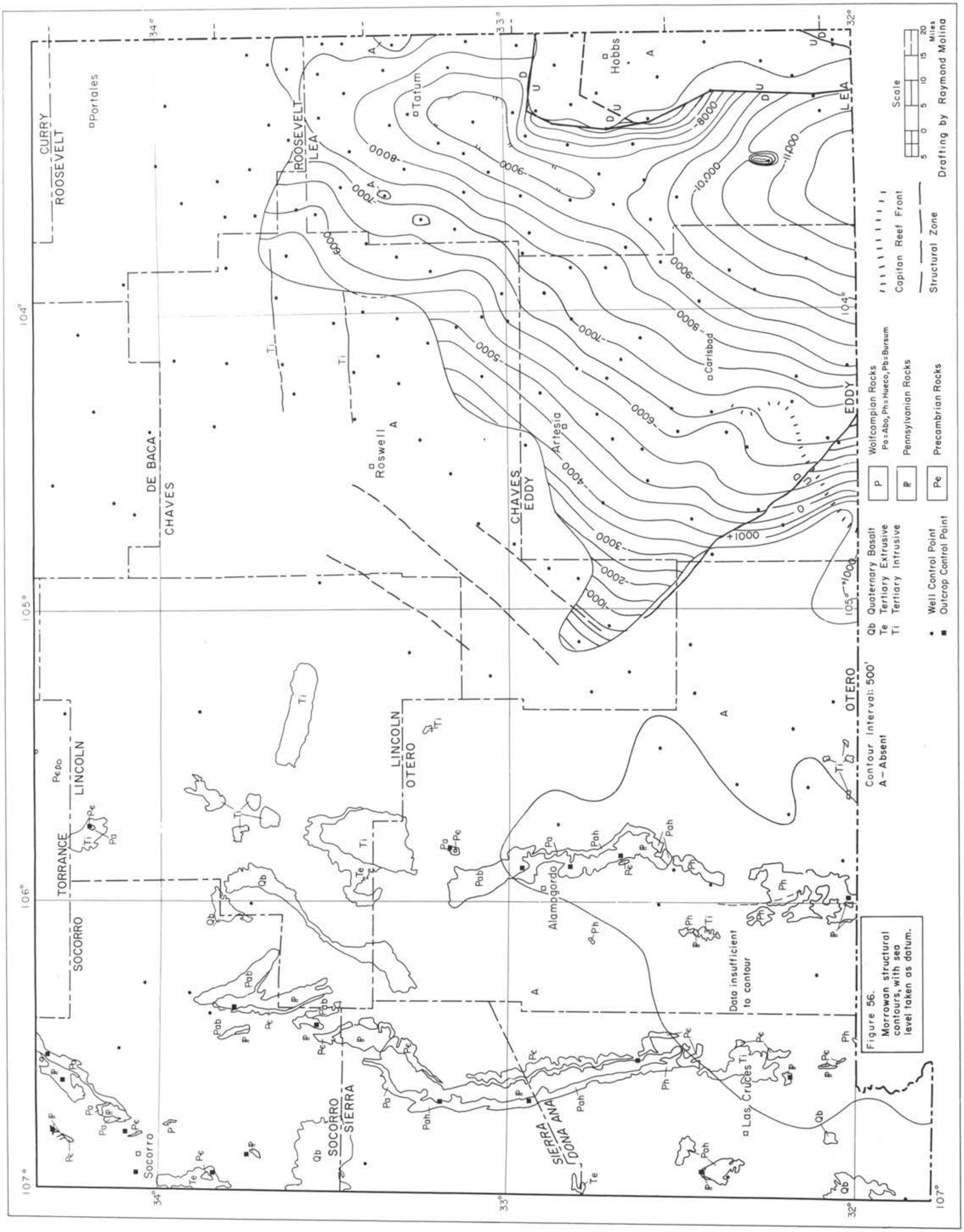


Figure 56. Morrowan structural contours, with sea level taken as datum.

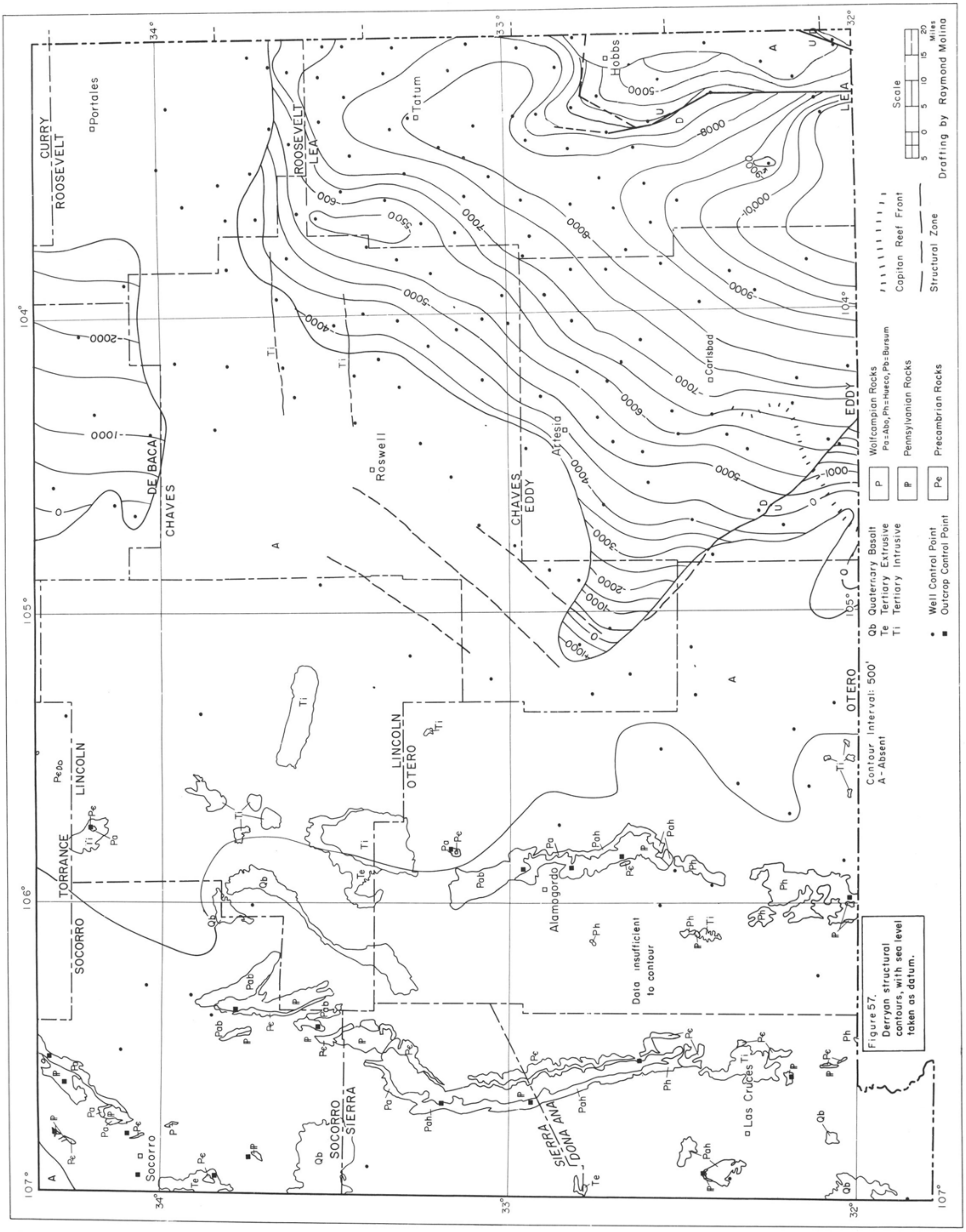


Figure 57. Derryan structural contours, with sea level taken as datum.

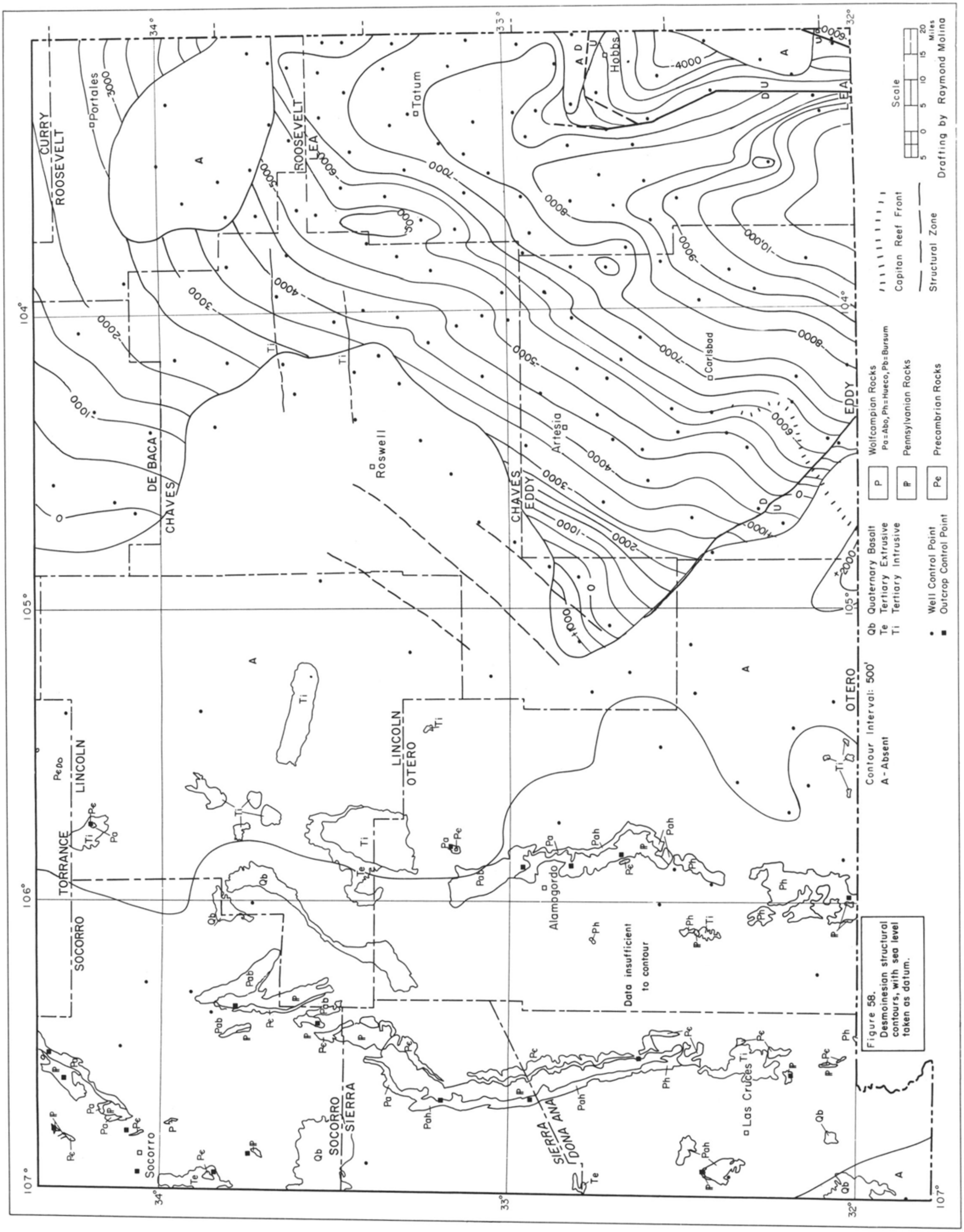


Figure 58. Desmoinesian structural contours, with sea level taken as datum.

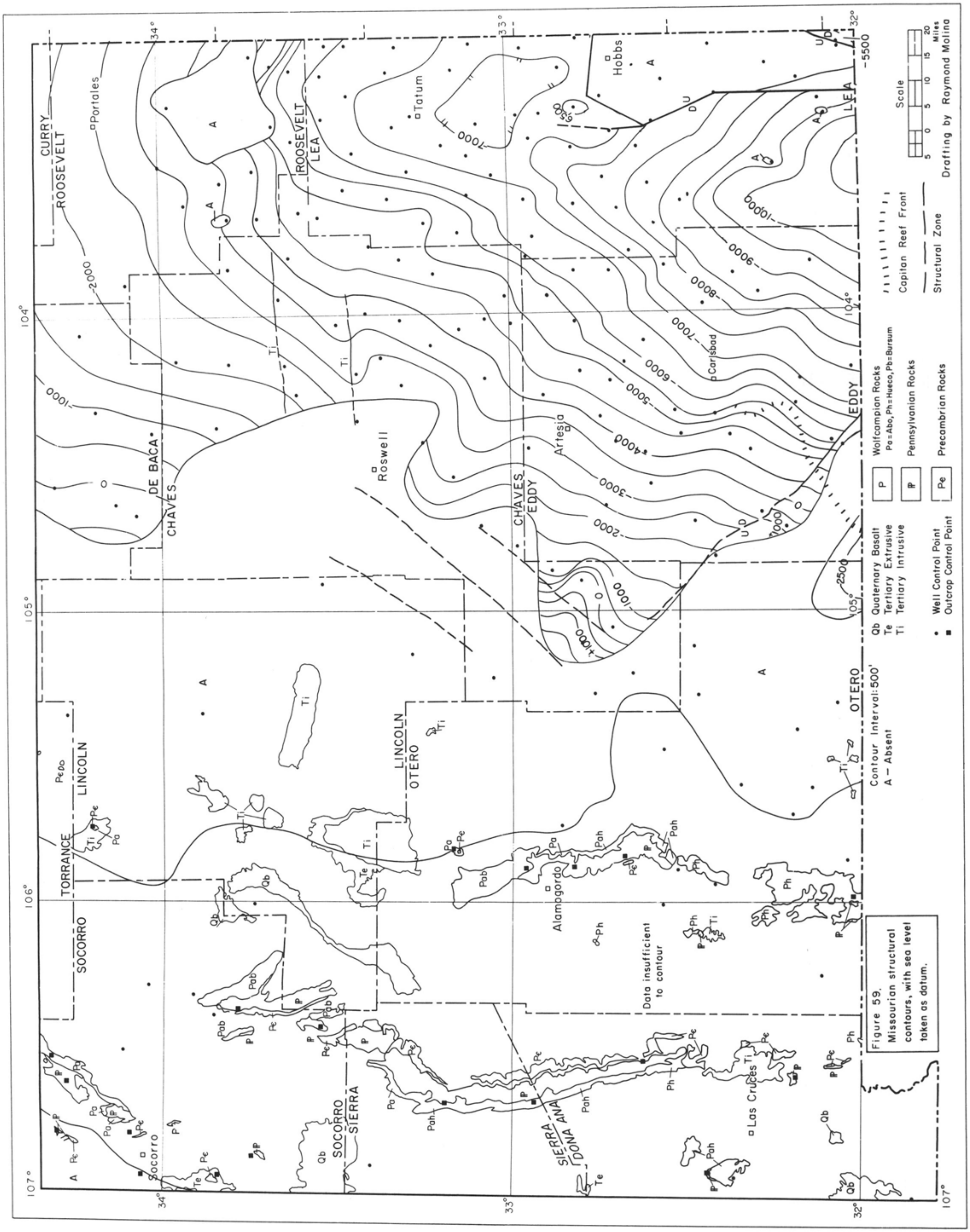


Figure 59. Missourian structural contours, with sea level taken as datum.

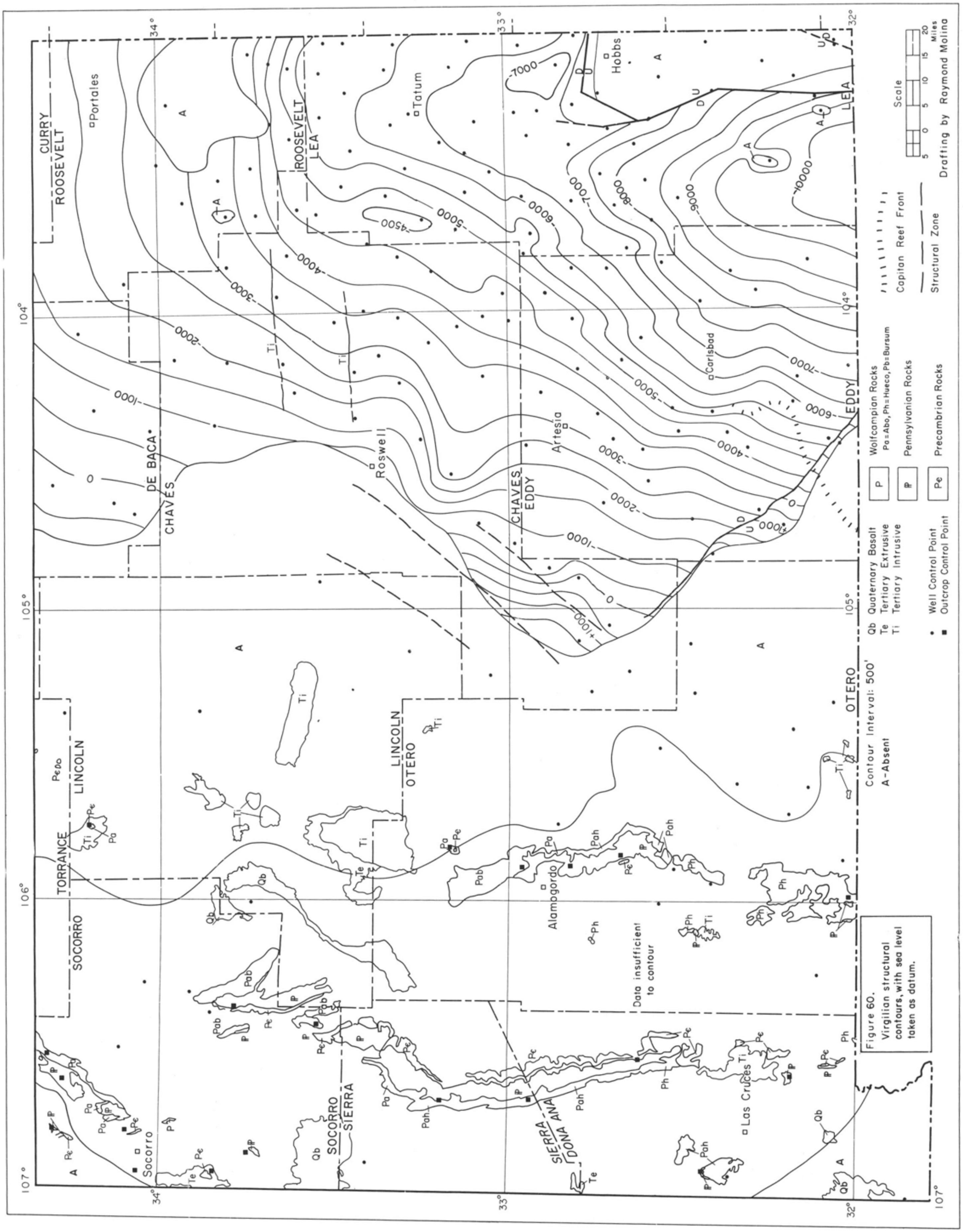


Figure 60. Virgilian structural contours, with sea level taken as datum.

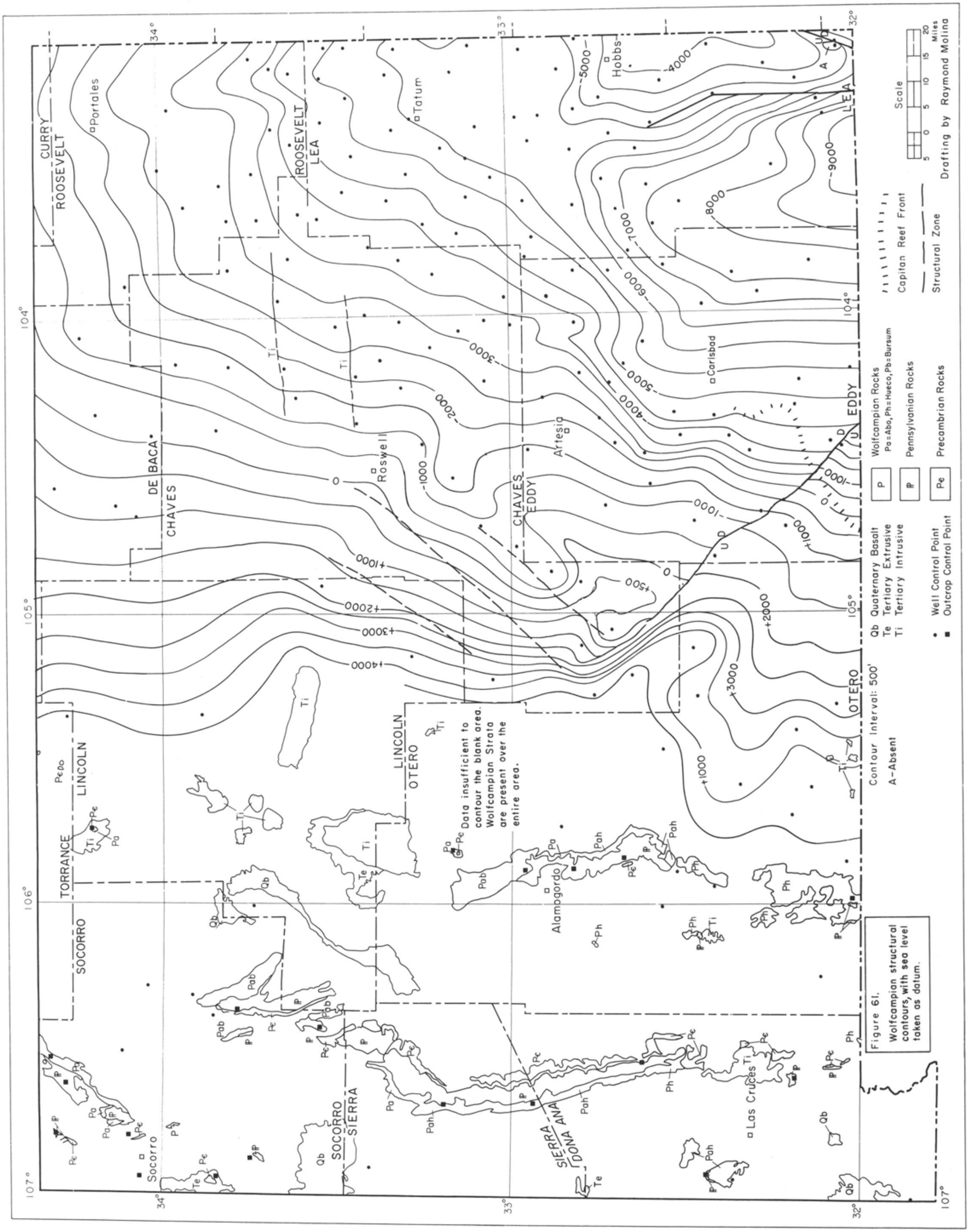


Figure 61. Wolfcampian structural contours, with sea level taken as datum.

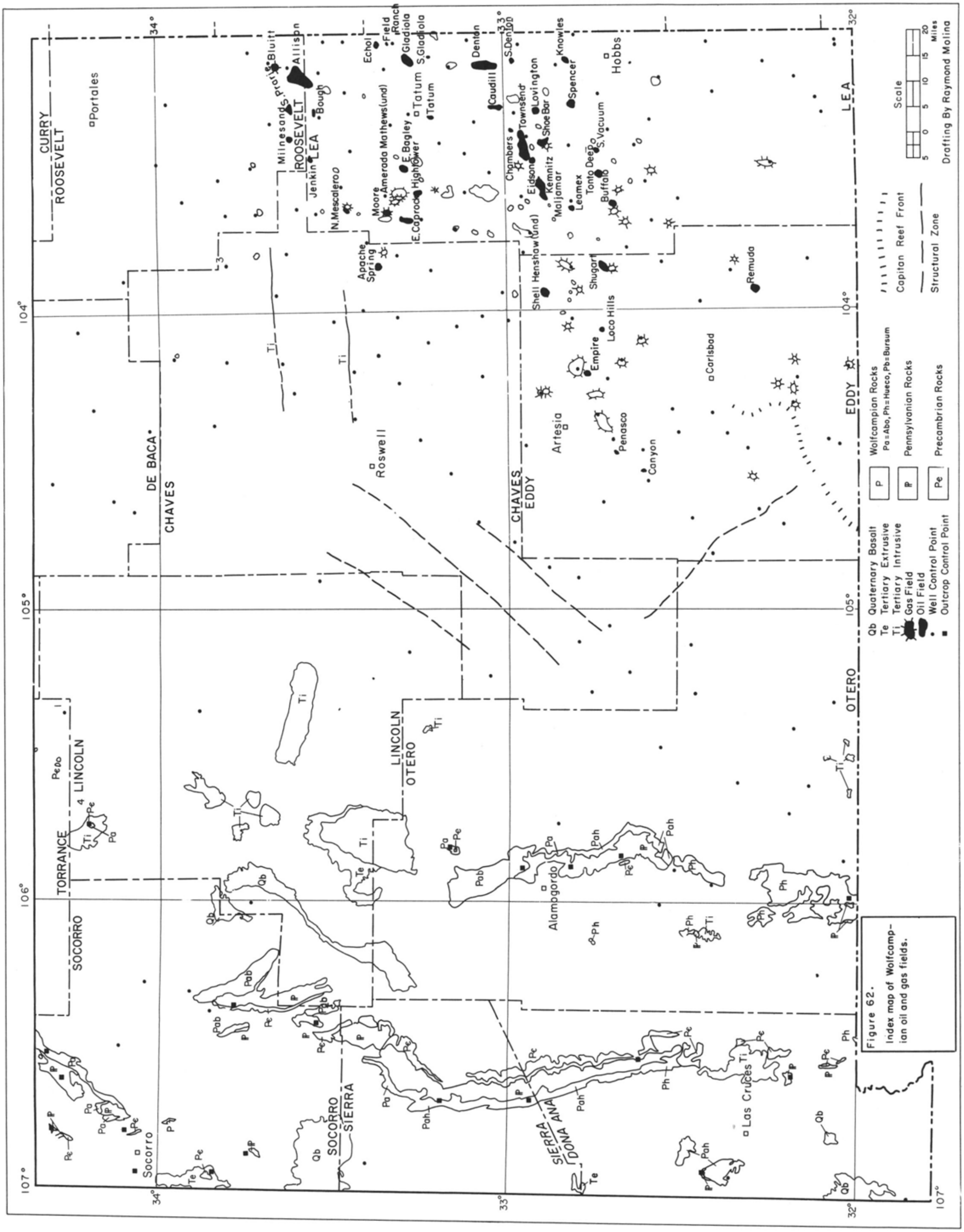


Figure 62. Index map of Wolfcampian oil and gas fields.

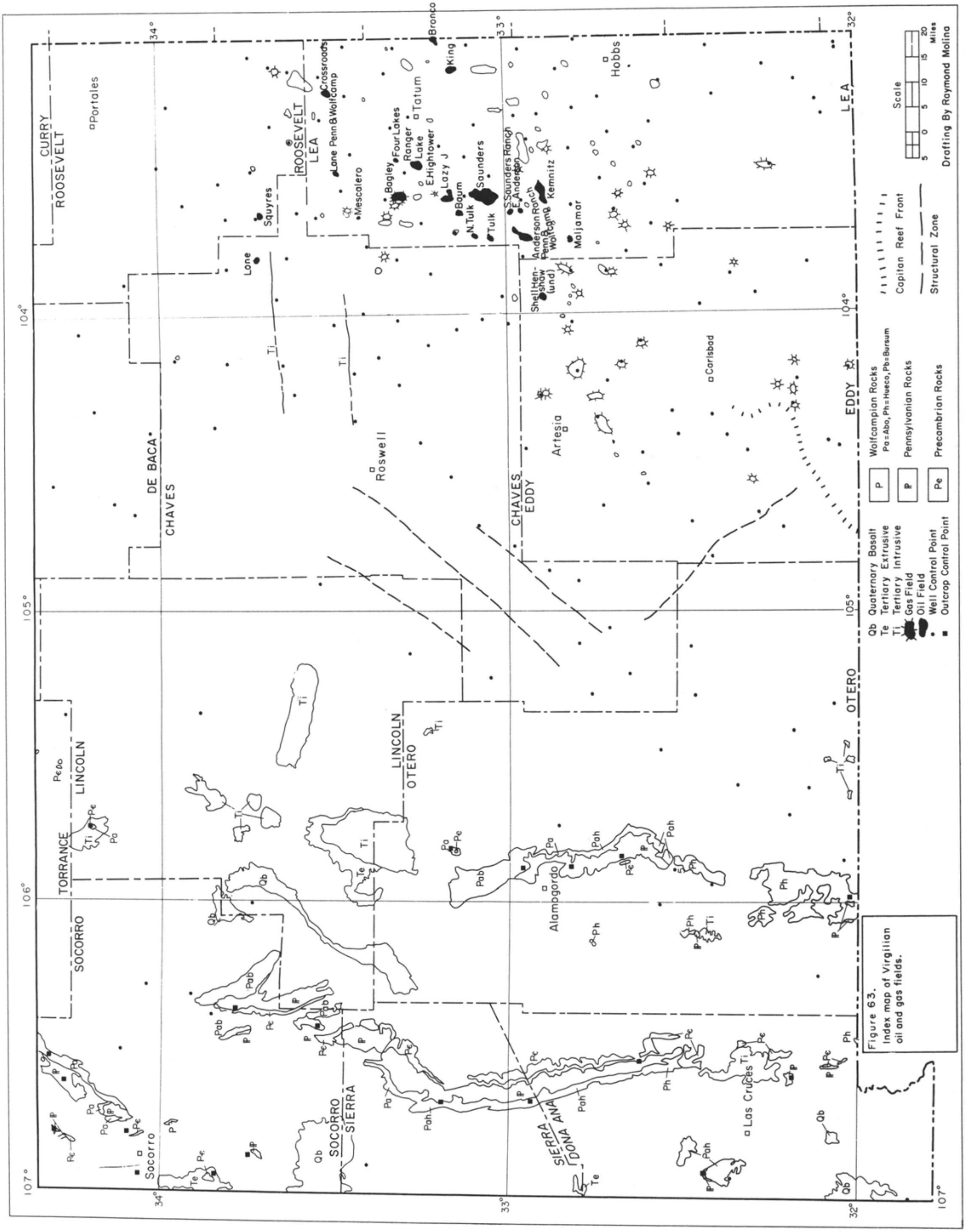


Figure 63. Index map of Virgilian oil and gas fields.

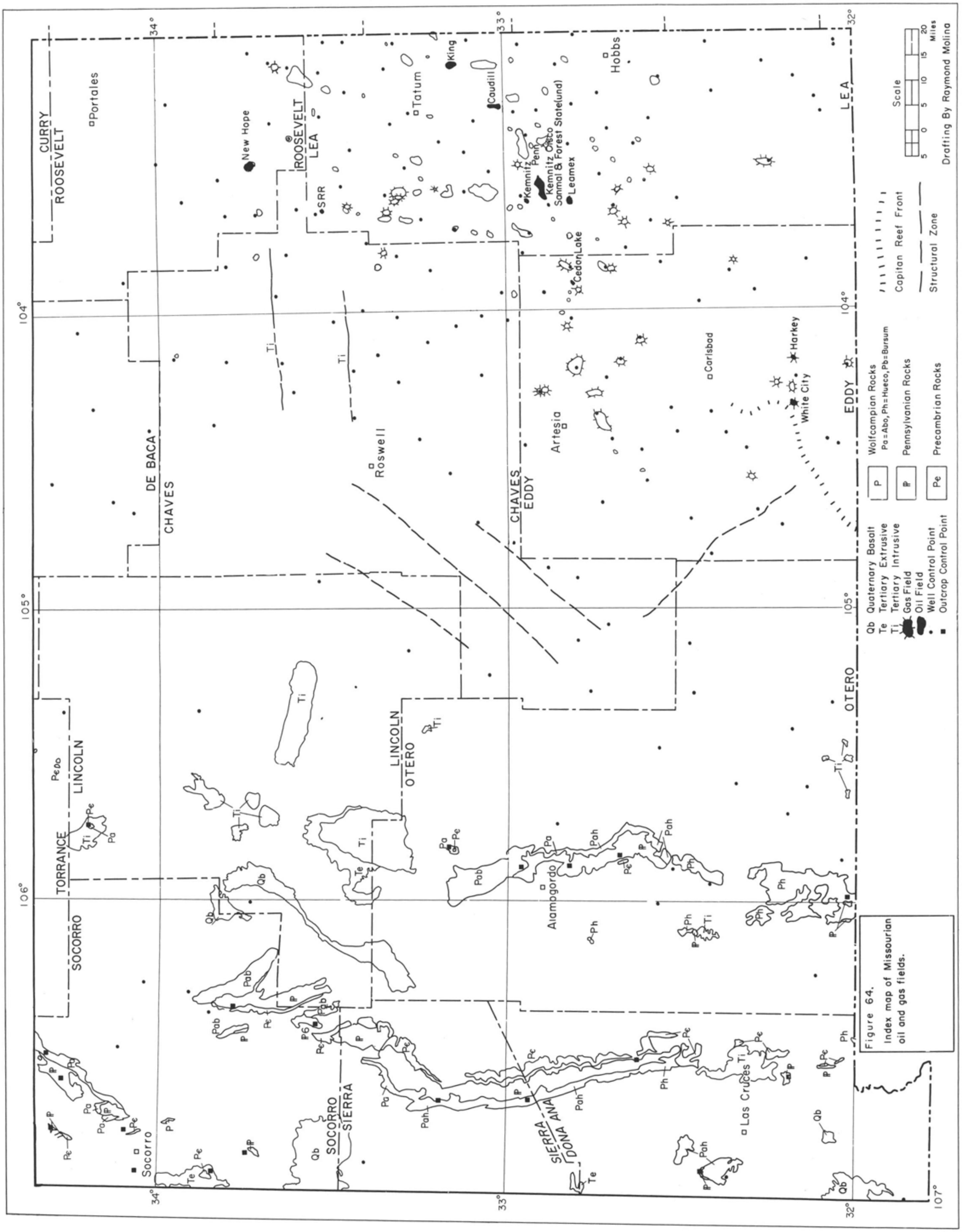


Figure 64. Index map of Missourian oil and gas fields.

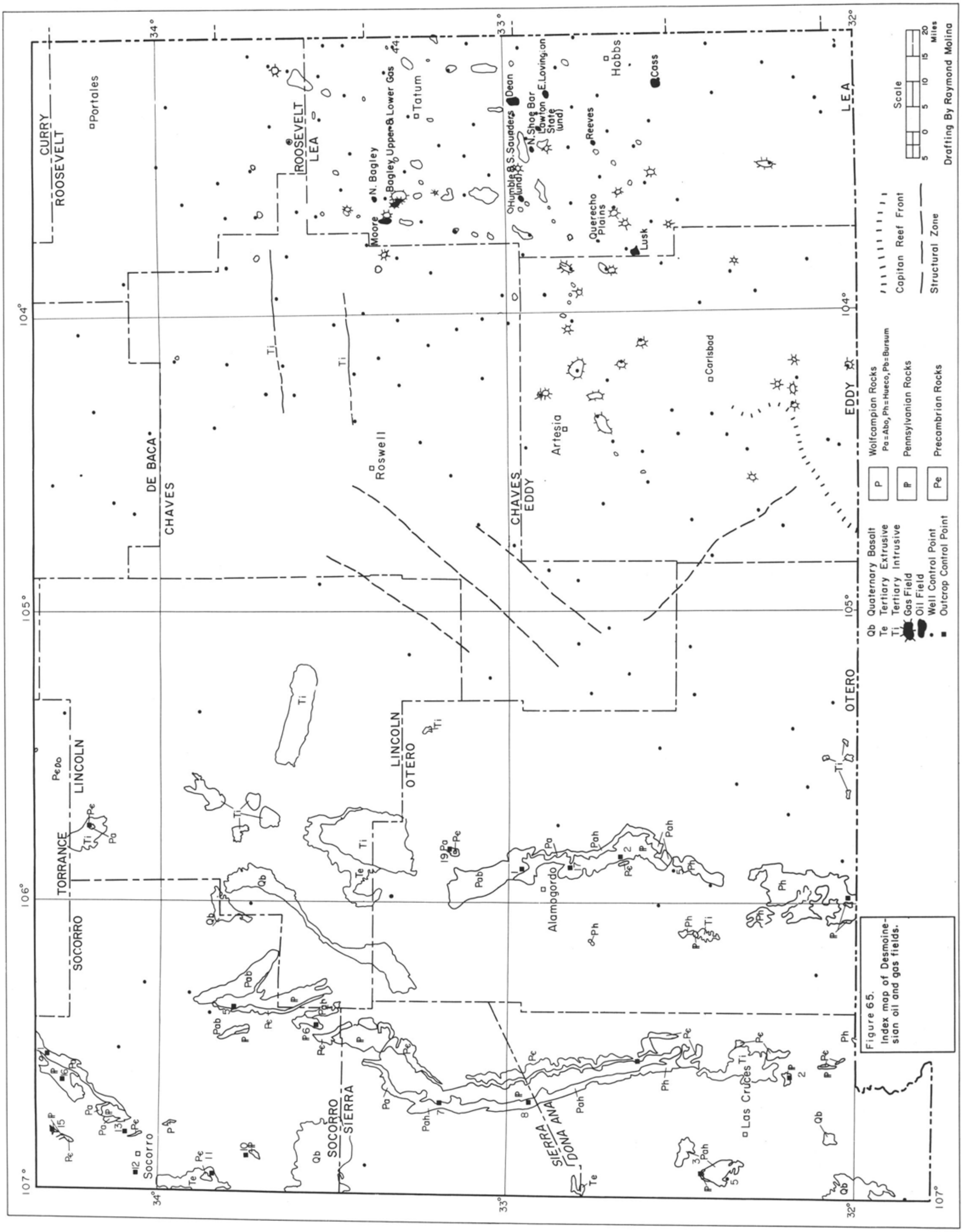


Figure 65. Index map of Desmoinesian oil and gas fields.

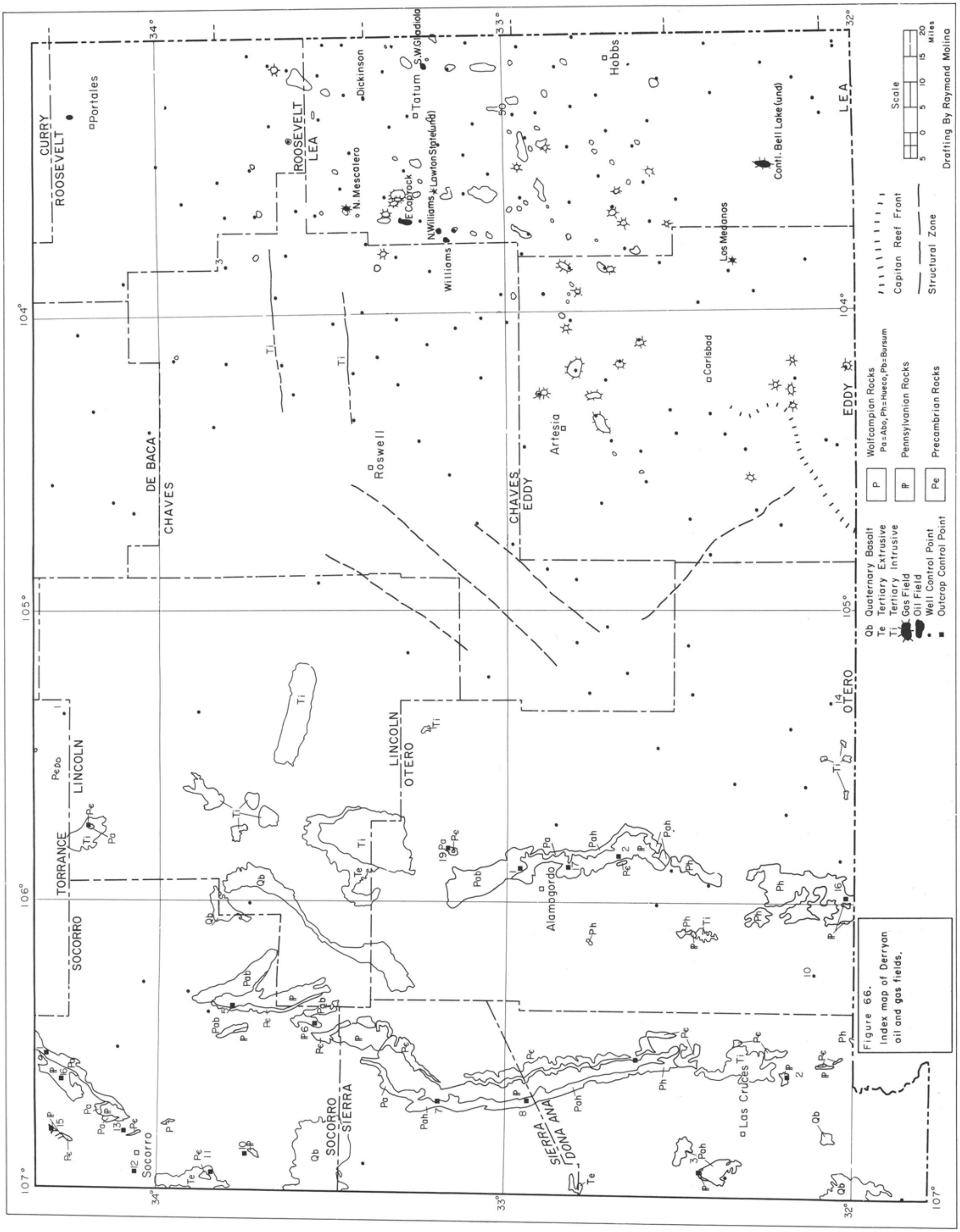


Figure 66. Index map of Derryan oil and gas fields.

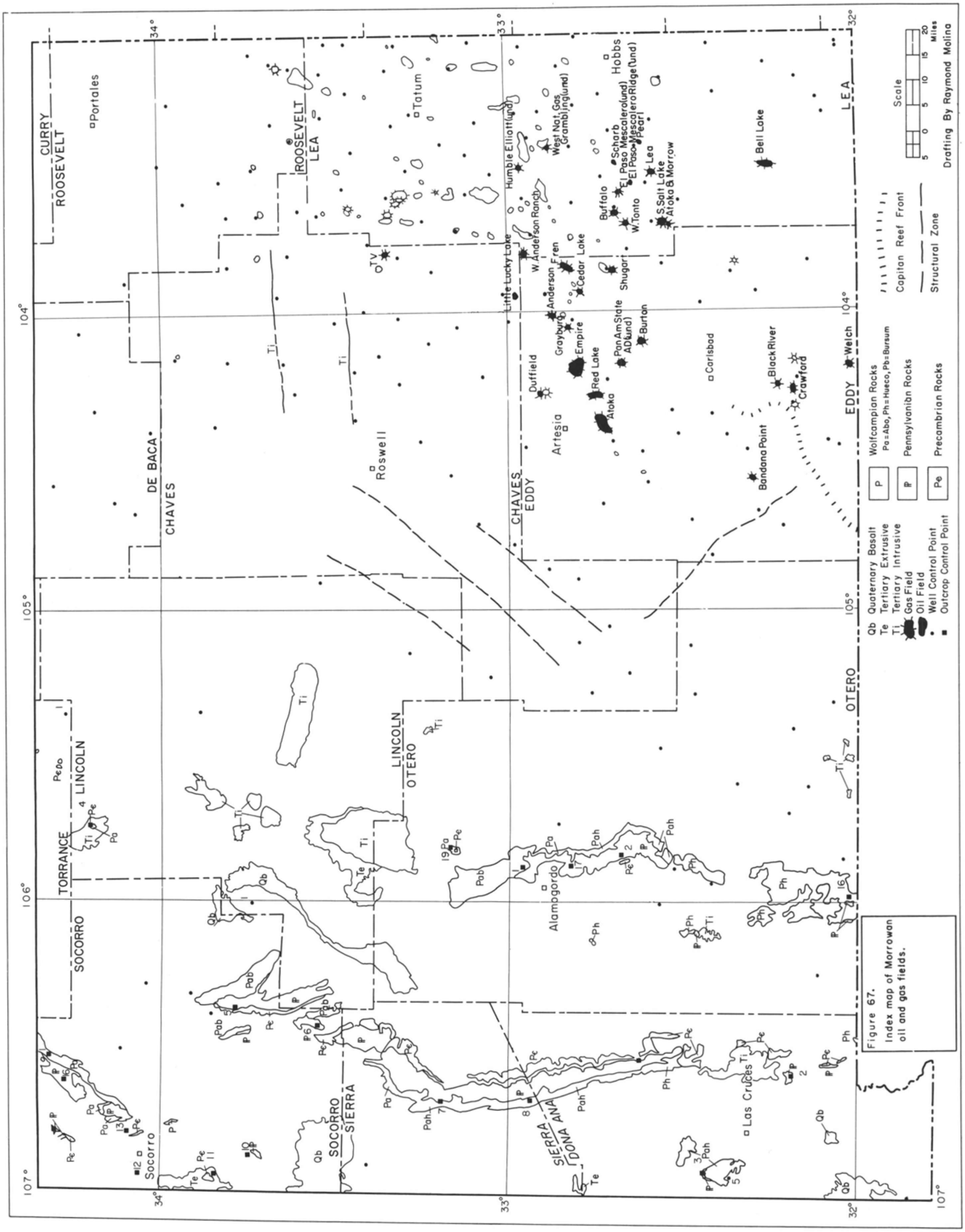


Figure 67.
Index map of Morrowan oil and gas fields.

TABLE 3. STRUCTURAL DATA ON ANTICLINES ASSOCIATED WITH SOME PERMIAN BASIN OIL AND GAS FIELDS

FIELD	UNIT OF WHICH UPPER SURFACE IS CONTOURED	MAXIMUM STRUCTURAL CLOSURE (feet)	MAXIMUM DIMENSIONS (miles)	DIRECTION OF LONGEST AXIS
Allison	Bough 'C' zone	250	6 x 1	NE-SW
Anderson Ranch Wolfcamp	lower Wolfcamp	65	1¾ x 1¼	N-S
Bagley Penn	a marker zone	200	2½ x 2	N-S
Baum Wolfcamp	lower Wolfcamp	nose	2 x ½	E-W
Bronco Wolfcamp	Wolfcamp	125	1¼ x 1¼	dome
Cass Penn	Strawn	30	6 x 3	NW-SE
Caudill Wolfcamp	Bursum	100	2 x 1	N-S
Crossroads	Bough 'C' zone	80 separate	2 x 2	dome
		41 closures	1 x ½	NW-SE
Dean	Cisco	100	2½ x 1¼	N-S
Denton Wolfcamp	Wolfcamp	400	4½ x 2	N-S
Gladiola	pay zone	100	1½ x 1	N-S
Hightower	Permo Penn	150	1½ x 1	NE-SW
King Penn	Penn	80	1½ x 1	N-S
Lazy J	lower Wolfcamp	nose	1½ x 1	E-W
Lovington East Penn	Pennsylvanian	250	3 x 2	E-W
Milnesand	lower Wolfcamp	64	2¼ x 1	E-W
Ranger Lake	pay zone	100	2 x 1½	N-S
Saunders	pay zone	100	5 x 2½	N-S
Townsend–Eidson	'R' datum (Wolfcamp)	nose	5 x 2	NE-SW
Tulk	lower Wolfcamp	35	1 x ¾	NW-SE

Data from Stipp et al., 1956; Sweeney et al., 1960.

flexure and the site of the Roosevelt uplift, appears to be parallel to the strandline but modified by uplift and erosion.

The general configuration of the Derryan structural map (fig. 57) is in most respects similar to that of the Morrowan (fig. 56). The Central Basin platform is somewhat reduced in length and the north end may be down-warped rather than faulted. The Tucumcari basin now exists, but the appearance of the structural contour lines suggests that its present-day limits were not its depositional limits. It seems evident that the Tucumcari and Permian basins were contiguous, strata having been deposited from the area of the Huapache structure northward and later having been removed by erosion.

Desmoinesian structural contours are shown in Figure 58. Fault relations along the two major uplifts are not unlike those shown on the preceding maps. The Roosevelt uplift is very much in evidence, but the intersection of the contour lines with the edge of the uplift indicates that some Desmoinesian strata were removed. The Permian and Tucumcari basins are definitely contiguous, the Desmoinesian probably having been deposited farther to the west than the present featheredge of the unit. The position of the strand-line is uncertain, but its direction was likely to have been northeast-southwest.

The structural contour maps of the Missourian (fig. 59) and Virgilian (fig. 6o) depict the structural evolution of the area through Late Pennsylvanian time. On them, the structural relations of the Huapache flexure section of the Pedernal uplift, the Central Basin platform, and the Roosevlt uplift remain virtually unchanged. There are visible changes, however, on the western part of the Northwest shelf. A prominent re-entrant has developed across it, and the structural contour lines either intersect or are only subparallel to the knife-edge of the units. Deformation and subsequent erosion are indicated following each age.

On the Wolfcampian structural contour map (fig. 6i), the Pedernal uplift and the Central Basin platform are in evidence, structurally, but the Roosevelt uplift has disappeared. The re-entrant shown on the southern part of the Northwest shelf on the Missourian and Virgilian maps becomes longer, the axis of the feature bending in a southwestward direction. The contour lines are almost parallel and are evenly spaced as far to the west as they may be drawn with accuracy, showing that Wolfcampian strata have filled in the uneven surface of the Pedernal uplift, indicated by Figure 5o. The upper surface of the Wolfcampian is an almost flat surface dipping eastward.

Geologic History

During pre-Pennsylvanian time, southeast New Mexico was part of a shelf on which were deposited strata of Cambrian(?), Ordovician, Silurian, Devonian, and Mississippian ages. These rocks are dominantly carbonate in lithology, none shows evidence of nearshore facies within the map area, and all are in wedge-shaped deposits that are thickest on the south. From the present areal distribution of pre-Pennsylvanian strata (figs. 4 and r6), it appears that prior to and perhaps during the early part of the Pennsylvanian Period, these older rocks were tilted southward as a result of regional uplift in central New Mexico. Subsequent erosion resulted in their removal from the north part of the area; thus, Pennsylvanian deposits overlap progressively older strata northward.

Crustal instability is reflected in rocks of the Pennsylvanian System and Wolfcampian Stage; however, the instability extended back in time to at least the Chesteran Epoch. In the Permian basin of southeast New Mexico, Chesteran time is represented by as much as 1000 feet of massive limestones on the Northwest shelf. These grade southeastward within a lateral distance of a few miles into 30o feet or less of black shale (Barnett shale of local usage). Following Chesteran deposition, a hiatus that represents Springeran time occurred, for there is neither lithostratigraphic nor biostratigraphic evidence for the presence of rocks of Springeran age in the area.

The geologic history of southeast New Mexico during Pennsylvanian and Wolfcampian time began with the southward tilting and erosion of pre-Pennsylvanian strata. In Morrowan time, the Pedernal uplift came into being as a structural element. In the interval designated Springeran time, most of the report area was being subjected to subaerial erosion, the only exceptions possibly being the sites of the later Delaware basin and the Central Basin platform. During the balance of Pennsylvanian time, this land was progressively onlapped by strata deposited in seas entering the area from the south and, in Derryan time, from the north as well. The onlapping was not a steady progression but involved numerous fluctuations of the shoreline; the net effect, age by age, however, was to steadily diminish the land areas. The instability of the crust during Pennsylvanian time may be inferred from the examples of graded bedding and from the deltas and reefs.

The Pennsylvanian System as a whole is characterized by a maximum of elastic rocks, and especially coarse-grained elastics, in the Morrowan, progressively changing to carbonate rocks, with minor fine-grained elastics, through the Derryan and the Desmoinesian; by renewed amounts of coarse-and fine-grained elastics in the Missourian; and finally by dominantly carbonate rocks with subordinate, mostly fine-grained elastics, in the Virgilian. Thus, there is inferred a maximum uplift in Morrowan time, with reduction of relief in the Derryan, to a minimum of relief in Desmoinesian Age. In Missourian time, the uplifts were revived and were markedly unstable; however, they were not of so great relief as in Morrowan and perhaps Derryan times.

During the Virgilian Age, topographic relief was low in the east half of the area, and coarse-grained elastic rocks accumulated only near strandlines. In the area of the Orogrande basin, however, the crust of the earth was markedly unstable in Virgilian time. Accumulated Virgilian sediments there are much thicker than are accumulations of older rocks. Along the Sacramento shelf, bioherms grew, and in the lagoons between them and the Pedernal uplift, graded deposits accumulated. Graded deposits also formed on the Robledo shelf, on the west side of the basin.

In this area, active structural deformation of Appalachian age was concluded prior to Leonardian deposition; however, Wolfcampian structural events influenced Permian sedimentation throughout the Permian Period. The anticlines of the Permian basin developed in Morrowan and in early Derryan times and renewed deformation took place in Missourian time. The truncated folds of the Central Basin platform are of pre-Desmoinesian age.

In the west, faults and folds developed in pre-Wolfcampian that involve strata as young as Virigilian in age. These truncated faults and folds are overlain by strata of Early and Late Wolfcampian age, but such folds appear to have no counterparts on the east side of the area.

During Wolfcampian time, three major faults developed: on the north and probably west sides of the Diablo platform, on the southeast side of the Pedernal uplift, and along the west side of the Central Basin platform.

The Diablo platform was uplifted and tilted to the south prior to Late Wolfcampian time, permitting Upper Wolfcampian strata to be deposited across truncated Virgilian and older rocks. The platform is bounded on the north by a reverse fault whose effects were evident on Derryan maps (figs. 24, 27, and 29).

On the southeast side of the Central Basin platform, along the site of the Huapache flexure, a steep reverse or overturned normal fault is present (pl. 1; Hayes). Although this fault may have been active through much of Wolfcampian time, movement ceased prior to Leonardian time.

On the west side of the Central Basin platform, a bounding fault is apparent on the various maps. This fault must have been active through much of Wolfcampian time, for Wolfcampian strata are very thin or absent over the platform. No basal elastics were deposited in the Leonardian marls and dolomites that overlie Wolfcampian as well as older beds, so that vertical uplift presumably had ceased by the time Leonardian sedimentation began.

Wolfcampian sediments cover the area, except locally on the Central Basin platform. These sediments are of Early and Late Wolfcampian age on the west but may represent all of Wolfcampian time on the east. Therefore, the Appalachian Revolution in this area may be dated as post-Chesteran and pre-Leonardian.

Economic Geology

PETROLEUM DEPOSITS

Deposits of economic importance in Pennsylvanian and Wolfcampian reservoirs in southeast New Mexico consist solely of petroleum and natural gas. As of January 1, 1963, cumulative production amounted to 137,391,000 barrels of crude oil, 1,781,151 barrels of natural gas liquids (hereafter referred to as *condensate),* and 79,867,286 Mcf (thousand cubic feet) of dry natural gas as well as 179,308,000 Mcf of casinghead gas. The crude-oil production represents 8 per cent of the cumulative total of 1,640,777,817 barrels produced from all formations in the area. This percentage may be expected to increase somewhat as older, shallow Permian oil fields are depleted and new discoveries continue to be made in Pennsylvanian and Wolfcampian reservoirs. Reserves in the latter were estimated to be 78,218,383 barrels as of January 1, 1962; subsequent discoveries and field developments require this figure to be revised upward. Ninety-eight per cent of the crude oil is produced in Lea County, while 80 per cent of the gas, including both natural gas and that produced with oil, is derived from that county, 18 per cent from Eddy County, and most of the balance from Roosevelt County. Locations of petroleum deposits are indicated on the maps according to age (figs. 62-67). Basic reservoir data for the fields are given in Table 4 (in pocket).

Sources of data used throughout the text include Holland and Brice (1963), Mathews and Mayhew (1963), New Mexico Oil and Gas Engineering Committee (1963), Nicholas (1962), Stipp et al., and Sweeney et al.

In succeeding discussions in this section, the following generalizations apply: (1) Cumulative production and estimated ultimately recoverable oil data are computed as of January 1, 1962, and additional recovery by secondary methods is not considered; (2) estimated ultimately recoverable crude oil is computed according to the formula

$$7758Ahf \frac{(1-Sw_i)}{B_i} RF \quad ,$$

where 7758 is the number of 42-gallon API barrels an acre; A, the number of producing acres; h, the number of feet of net pay; f, the fractional porosity; Sw_1, the initial water saturation; B_1, the initial reservoir volume factor; and RF, the reservoir recovery factor. For the reservoirs under discussion, B1 averages 1.45 to 1.50 and RF is considered as 15 per cent for solution gas drive pools and 50 per cent for water drive pools; (3) a total of 93 crude oil and 36 natural gas fields was studied, but complete data are not available for all fields; and (4) field names (table 4) follow the nomenclature of the Oil and Gas Engineering Committee.

At the time of the review of oil and gas occurrences in New Mexico by Bates (1942), no petroleum had been discovered in reservoirs of either Pennsylvanian or Wolfcampian age. Only a small number of boreholes had penetrated pre-Leonardian strata. When Lloyd reviewed the pre-San Andres geology of the Permian basin part of the area, there were 11 known oil pools in Leonardian strata and 11 in pre-Leonardian strata, but of these, only one (Cass field) was in a Pennsylvanian reservoir and none was in Wolfcampian reservoirs. The initial Pennsylvanian crude oil discovery, in 1944, was made on the Central Basin platform.

Progress of discovery is listed chronologically (table 5) in terms of barrels of oil estimated to be ultimately recoverable. While the number of discoveries a year has tended to increase, the average size of the fields, in terms of estimated ultimate recovery, has decreased sharply. The figures for 1950 are large because of three discoveries in that year; two, the Denton Wolfcamp and Saunders Permo Penn, were the largest fields found to date.

Of the crude oil estimated to be ultimately recoverable from Pennsylvanian and Wolfcampian beds, 200,044,415 barrels, or 98 per cent, come from presently producing fields, while about 5,000,000 barrels, or 2 per cent, are accounted for by shut-in or abandoned fields. Numerically, however, the producing fields account for only 72 per cent of the total number of fields that have been discovered. Thus, more than a quarter of all discoveries has been abandoned and this one quarter accounted for only 2 per cent of the oil to be recovered. Wildcat wells are generally expected to be successful

TABLE 5. OIL FIELDS BY YEAR OF DISCOVERY AND ESTIMATED ULTIMATE PRODUCTION

YEAR	NUMBER OF DISCOVERIES	ESTIMATED ULTIMATE PRODUCTION (millions of barrels)	PER CENT OF TOTAL PRODUCTION (204.9 million barrels)	AVERAGE ESTIMATED PRODUCTION PER DISCOVERY (millions of barrels)
1944	1	3.9	2	3.9
1949	3	10.1	5	3.4
1950	3	69.7	34	23.2
1951	7	9.7	5	1.4
1952	7	29.0	14	4.1
1953	6	14.1	7	2.3
1954	5	27.9	14	5.6
1955	9	8.6	4	1.0
1956	11	26.9	13	2.4
1957	8	2.4	1	0.3
1958	3	0.3	<1	0.1
1959	3	0.2	<1	0.1
1960	15	1.6	<1	0.1
1961	10	0.5	<1	0.1
Total	91	204.9	100	3.4

one time out of nine. In the case of discoveries in rocks of the ages under discussion, one out of four of the successful tests will be abandoned after producing an average of only 20,000 barrels of crude oil.

Fifty different companies discovered the 93 crude oil and 36 natural gas deposits found in Pennsylvanian and Wolfcampian reservoirs. Of the 43 companies that discovered oil pools, 13 found 93 per cent of the estimated ultimately recoverable oil, the other 3o companies accounting for only 7 per cent. These figures indicate that discoveries are common, as reflected in the number of different companies that have drilled successful exploratory wells, but that relatively few of the discoveries lead to fields that are significant in terms of barrels of recoverable oil.

SIZE OF POOLS

The size distribution of crude oil pools (table 6) indicates that the chances of finding one with a significant amount of recoverable oil are small. Of 93 pools, 85 may be considered small (less than *5* million barrels of crude oil); these small pools account for 24 per cent of the oil. Eight pools, larger than those in the 5-million-barrel category, account for the remaining 76 per cent of the recoverable oil. Three large pools (in excess of 25 million barrels) are Allison Penn, Denton Wolfcamp, and Saunders Permo Penn; two moderately large pools (10 to 25 million barrels) are Kemnitz Wolf-camp and Townsend Wolfcamp; moderate-sized pools (5 to 10 million barrels) include Anderson Ranch Wolfcamp, Dean Permo Penn, Ranger Lake Penn, and possibly Bough Permo Penn.

DISCOVERY METHODS

On the basis of available data (table 7), seismic techniques have accounted for discovery of 65 per cent of the recoverable oil; subsurface geology, 1 per cent; combined seismic and subsurface geology, 3o per cent; random drilling, 1 per cent; and old wells worked over, 4 per cent. Much of the success with worked-over wells, however, is a result of subsurface geology. The part of the report area from which petroleum is now produced is located in the Great Plains physiographic province; flat-lying Tertiary deposits cover the area, masking subsurface structures, so that surface geology is ineffective. Reflection seismic methods have been ideal for exploration so far. Now, however, most of the Northwest shelf has been thoroughly explored by seismic methods, and it is unlikely that additional large structures will be located. As a result of past explorations, hundreds of oil and gas test wells have penetrated the Pennsylvanian section, and sufficient data have become available to make possible detailed investigations for stratigraphic traps. Currently, 47 per cent of the recoverable crude oil is produced from structural traps, 2I per cent from stratigraphic traps, and 32 per cent from combination traps. Many still-undiscovered stratigraphic traps are almost surely present in the area; it is the task of the geologist to locate them.

GEOLOGIC SETTING

The most logical place to look for Pennsylvanian and Wolfcampian petroleum is on the Northwest shelf; this subprovince of the Permian basin has accounted for 95 per cent of the crude oil and 78 per cent of the associated and nonassociated gas produced in southeast New Mexico (table 8). The Delaware basin has accounted for 1 per cent of the crude oil and I per cent of the total gas, the Central Basin platform 2 per cent of the crude oil and 1 per cent of the gas, and the transition zone between the Delaware basin and the Northwest shelf, marked in shallower Permian strata by the Abo, Goat Seep, and Capitan reefs, 3 per cent of the crude oil and 20 per cent of the total gas, mostly nonassociated. This distribution resulted mainly from the fact that during the 1950's, the principal objective in exploratory drilling was porous Si-

TABLE 6. SIZE OF OIL POOLS

SIZE (millions of barrels)	NUMBER OF POOLS	ESTIMATED ULTIMATE PRODUCTION (millions of barrels)	PFR CENT OF TOTAL PRODUCTION (205.1 million barrels)
Very small (up to 1)	70	49.3	24
Small (1-5)	15		
Moderate (5-10)	3	21.1	10
Moderately large (10-25)	2	38.6	19
Large (over 25)	3	96.1	47
Total	93	205.1	100

TABLE 7. OIL AND GAS ATTRIBUTABLE TO DIFFERENT EXPLORATION METHODS

METHOD	ESTIMATED ULTIMATE OIL PRODUCTION (millions of barrels)	PER CENT OF TOTAL OIL PRODUCTION (204.3 million barrels)	CUMULATIVE GAS PRODUCTION (billions of cubic feet)	PER CENT TOTAL GAS PRODUCTION (232.4 billion cubic feet)
Seismic	132.5	65	168.3	72
Subsurface	1.6	1	1.8	1
Combination of seismic and subsurface	61.8	30	43.4	19
Random drilling	0.1	<1	5.1	2
Reworked oil well	8.3	4	13.8	6
Total (to Jan. 1, 1962)	204.3	100	232.4	100

luro—Devonian dolomite, which is encountered at depths of 10,000 to 13,000 feet on the Northwest shelf. Local folds that form the petroleum traps are relatively easy to detect with the seismograph. Because the petroleum reserves contained in the Siluro—Devonian reservoirs were large, many test wells were drilled to this objective. Pennsylvanian and Wolfcampian reservoirs were found in the process of this deeper drilling. As development of such Pennsylvanian and Wolfcampian pools progressed, producers realized that such pools constituted an important objective in themselves. Exploration proceeded more slowly in the area of the transition zone, partly because early, deep test wells were unsuccessful and partly because there, as well as in the Delaware basin, Siluro—Devonian reservoirs occur at considerably greater depths than on the Northwest shelf, making exploration more costly. Since 1960, exploration of the transition zone and of the Delaware basin has proceeded at a more rapid pace.

AGE OF RESERVOIRS AND PETROLEUM

Reservoirs in rocks of Wolfcampian age account for 53 per cent of the recoverable oil, while Virgilian reservoirs account for another 25 per cent (table 9). Seven per cent of the balance comes from Desmoinesian strata. Virtually all this production is from carbonate rock. In contrast, nearly all the dry-gas deposits occur in sandstones of Morrowan age.

The geologic aspects of the origin of petroleum have been reviewed by Hedberg (1964). It is still unknown how original organic source materials, mainly marine plankton, are transformed to petroleum, and why crude oil is the transformation product in some instances and natural gas in others. It is reasonably certain that most source sediments are marine and that conditions favorable for preservation of the organic source material and the petroleum which evolves therefrom involve a reducing environment, the absence of destructive organisms, especially bacteria requiring hydrocarbons in their life cycles, active deposition of fine-grained sediment, and readily available reservoirs (Hedberg, p. 1770-1772). These conditions are met by the Pennsylvanian and Wolfcampian strata of the Permian basin, which provide both source rocks, the fine-grained black shales and limestones of the Delaware basin, and reservoir rocks, the laterally equivalent porous carbonates of the transition zone and Northwest shelf.

Apparently, the organic material accumulated together with fine-grained sediments in the relatively deep waters of the basin was transformed into petroleum and, as a result principally of compaction, the petroleum was expressed from the shales and micrites. In the form of droplets, or perhaps in solution in the water, the petroleum was free to migrate into porous beds, the reservoirs, in which it could accumulate. The structural contour maps (figs. 56-61) show the form of the Permian basin in southeast New Mexico to be trough-like, plunging to the south. Because its specific gravity is less than that of water, the oil moved updip through the water-saturated sediments to the shelf, where is was trapped in anticlines and in stratigraphic traps resulting from local reductions in the porosity of the reservoir rocks. It is also probable that a substantial part of upper Pennsylvanian and Wolfcampian reservoirs received some of their fluids from younger Permian rocks of the Delaware basin. These stratigraphically higher Permian beds, particularly the Bone Spring Formation, are now at nearly the same sea-level elevation as the older beds. Because no impervious bed, such as gypsum, separates the Bone Spring Formation from the stratigraphically lower porous Pennsylvanian carbonate rocks, there should have been no obstacle to the flow of fluids from the younger to the older beds. Analysis of crude oil and especially isotope studies might indicate whether such younger crude oil is present in the older formations.

The various maps in the report may be examined for evidence for the reasons underlying the localization of the petroleum deposits and the possible direction that presently known producing trends might be expected to take in the course of future exploration.

TABLE 8. OIL AND GAS PRODUCTION BY GEOLOGIC PROVINCE

GEOLOGIC PROVINCE	ESTIMATED ULTIMATE OIL PRODUCTION (millions of barrels)	PER CENT OF TOTAL OIL PRODUCTION (205.1 million barrels)	CUMULATIVE GAS PRODUCTION (billions of cubic feet)	PER CENT OF TOTAL GAS PRODUCTION (244.2 billion cubic feet)
Shelf	195.0	95	190.2	78
Basin	0.1	<1	3.0	1
Shelf-basin transition zone	6.1	3	49.3	20
Platform	3.9	2	1.7	1
Total (to Jan. 1, 1962)	205.1	100	244.2	100

TABLE 9. OIL AND GAS PRODUCTION ACCORDING TO GEOLOGIC AGE

GEOLOGIC AGE	NUMBER OF OIL POOLS	ESTIMATED ULTIMATE OIL PRODUCTION (millions of barrels)	PER CENT OF TOTAL OIL PRODUCTION (205.1 million barrels)	NUMBER OF GAS POOLS	CUMULATIVE GAS PRODUCTION (billions of cubic feet)	PER CENT OF TOTAL GAS PRODUCTION (65.1 billion cubic feet)
Wolfcampian	38	109.2	53	2	1.9	3
Virgilian	25	79.4	39	0	—	—
Missourian	10	1.5	1	2	0.2	<1
Desmoinesian	11	14.5	7	2	13.4	21
Derryan	5	0.4	<1	4	1.2	2
Morrowan	4	0.1	<1	26	48.4	74
Total (to Jan. 1, 1962)	93	205.1	100	36	65.1	100

PRODUCTION TRENDS

Morrowan Stage

The Morrowan oil and gas fields (fig. 67) show a strong east-west alignment or trend. That this trend is not structurally controlled is evident from the Morrowan structural map (fig. 56), which depicts very clearly the basin configuration. The fields along the main producing trend vary in elevation from minus 5000 to minus 9000 feet, the trend occurring nearly at right angles to the strike of the contour lines (an exception is Bell Lake field, which coincides with a very obvious reversal in the regional dip). It is evident that structure is not the principal control over the accumulations.

Most of the fields are found where the total thickness of the Morrowan (fig. 18) is between 500 and 750 feet. The lithofacies (fig. 19) and sandstone thickness (fig. 20) maps indicate that the deposits, principally natural gas, are not merely a product of variations in sandstone thickness or of lithofacies. Nearly all the production is derived from those areas where the sandstone-shale ratios are between one eighth and one; these are areas of few but thick sandstone lenses within thick shale sequences. Variable amounts of limestone occur along with clastic rocks but appear to have no bearing on the petroleum accumulations.

Derryan Stage

There are relatively few fields producing from rocks of Derryan age (fig. 66), and therefore only gross generalizations can be made concerning the habitat of the oil accumulations.

Most of the occurrences seem to be aligned along the strike of structural contour lines (fig. 57), indicating some structural control. In general, the fields fall between the 250- and 500-foot isopachs (fig. 24), between the 00- and 200-foot shale isolith lines (fig. 27), and between the 200- and 300-foot nonclastic isolith lines (fig. 29). The oil fields fall mainly in the area of shale-limestone lithofacies and the gas fields in that of limestone-shale lithofacies (fig. 25).

Most of the Derryan fields are in sandstone reservoirs, and again, the sandstones are thin, sandwiched between relatively thick units of shale. Since the number of fields is small, it is difficult to see any positive correlation between producing trends and the geology &rocks in which they occur.

Desmoinesian Stage

The structural contour map (fig. 58) indicates a trend of Desmoinesian reservoirs (fig. 65) that closely follows the minus-7500-foot contour line and therefore closely conforms to the basin configuration. The fields nowhere occur where the total thickness (fig. 30) of the Desmoinesian is greater than 500 feet, and they usually are found where the strata are less than 250 feet thick. All but two of the petroleum accumulations follow a north-south alignment within the limestone facies (fig. 31) and occur where the thickness of shale (fig. 33) is less than 100 and usually less than 50 feet. Desmoinesian reservoirs are found exclusively in carbonate rocks, most of which are considered to be biohermal reefs. The carbonate isolith map (fig. 35) shows that the petroleum deposits occur where the rock is from 80 to 500 feet thick; however, the trend of the oil pools does not follow bands of contour lines of equal thickness but, rather, cuts across them. The explanation may lie in the fact that the reefs from which the oil is produced grew to variable thickness (fig. 35), but all flourished under similar conditions of water depth and environment, as indicated by the structural contour map (fig. 58) and lithofacies map (fig. 31).

Missourian Stage

All present Missourian crude oil production (fig. 64) is from carbonate reservoirs. The now-abandoned New Hope pool produced from a basal conglomerate where Missourian strata overlie Mississippian rocks on the Roosevelt uplift (fig. 12). This occurrence appears to have been the only one associated with an unconformity thus far found in Pennsylvanian beds in southeast New Mexico.

In earlier parts of the memoir, a thick accumulation of sediments was described along the north margin of the Delaware basin (fig. 36). This trend is first evident in sediments as old as Derryan, but it did not affect petroleum accumulation until Missourian time. Reservoir rocks of Missourian age are closely related to the trend of thick sediments and, in addition, the reservoirs occur in the limestone-shale lithofacies (fig. 37). The carbonate isolith map (fig. 41) shows that the reservoirs occur where the total thickness of carbonate is at least 500 feet. Thus, ideal conditions for entrapment exist: thick, porous limestone beds intercalated with dark-colored shale beds of the basin. There is no relationship evident between the petroleum occurrences and the structural contour map (fig. 59), although there is a suggestion of a relationship with the minus-7000-foot contour line.

Virgilian Stage

All Virigilian production (fig. 63) is derived from carbonate reservoirs, predominantly limestone. The total thickness map (fig. 42) reveals that most of the reservoirs occur where the rocks are between 250 and 500 feet thick over a broad area in the east part of the Northwest shelf. The fields are aligned in a north-south direction; this alignment turns southwest as the transition zone with the Delaware basin is approached. All occurrences are within the limestone facies (fig. 43) where shale thicknesses (fig. 45) are small, from 30 to 50 feet, and carbonate thicknesses (fig. 47) range between 300 and 400 feet. In addition, the producing trend follows the structural configuration of the basin, in most instances occurring from 5000 to 6500 feet subsea. The porous Virgilian carbonate beds formed ready reservoirs for fluids which migrated from the Delaware basin.

Wolfcampian Stage

Production from Wolfcampian, as well as Middle and Upper Pennsylvanian rocks, is almost exclusively from carbonate reservoirs. Two distinct producing trends are apparent (fig. 62), an arcuate one across the northern Northwest shelf and a linear one extending in a northeast-southwest direction along the margin of the Delaware basin. The arcuate trend of the Northwest shelf follows the basin configuration, generally occurring between the minus-3500- and minus-4500-foot structural contour lines (fig. 61). This producing trend follows closely the 750-foot isopach (fig. 52), is mainly confined to limestone facies (fig. 51), and follows the 500-foot carbonate isolith line (fig. 55). Shale thickness along the trend is from l00 to 200 feet (fig. 53). The Virgilian and Wolfcampian oil field maps (figs. 63 and 62) are complementary in the sense that, taken together, they form an almost unbroken belt of production in a horseshoe-shaped pattern over the Northwest shelf.

The second Wolfcampian producing trend, which extends southwestward, is clearly controlled by the thick accumulation of sediments (fig. 50) along the margin of the Delaware basin. The thickness of these sediments is between 1000 and 1250 feet. Carbonate rocks are 700 to m00 feet in thickness (fig. 55), and the producing trend falls within limestone lithofacies (fig. 51). The structural contour map (fig. 61) reveals that the direction of the reservoir trend is at best only subparallel to the basin configuration. Therefore, the reservoirs are controlled largely by stratigraphic factors. Furthermore, this Wolfcampian producing trend shows a distinct alignment with production from the superjacent Abo reef (fig. 17); the thick accumulation of Wolfcampian appears to have been a controlling factor in the subsequent development of the Leonardian Abo reef reservoir. The Virgilian oil fields do not show a comparable relationship to the Abo reef.

The Wolfcampian, as well as the Middle and Upper Pennsylvanian reservoirs, represents porous beds occurring regionally updip from, and intertonguing with, fine-grained, richly organic source rocks. An unknown but probably negligible percentage of the petroleum is indigenous to the carbonate reservoir rocks. The reservoir rocks were deposited in a shallow-water, oxidizing environment of relatively high energy in which organic matter would have been exceedingly susceptible to destruction.

RESERVOIR STUDIES

For each of the 129 producing oil and gas fields being considered, certain basic statistical data were gathered (table 4). These data may be categorized as follows:

Geological: Depth of producing zone
Porosity of producing zone
Permeability of producing zone
Formation temperature
Thickness of producing zone
Initial pressure in producing zone
Fluid: Gravity of crude oil
Gas-oil ratio
Salinity of associated water
Production: Estimated ultimate oil production in barrels
Accumulative condensate production in barrels
Accumulative gas production in Mcf

The parameters make possible 66 data combinations. Data from all the 129 fields are not available for all parameters. The data were programmed for conversion to a form acceptable to a correlation coefficient program, omitting from consideration all pairs having a zero value for one of each pair. The results were run through the I.B.M. 1620 General Program Library Program 6.0.015 (40-40 correlation) to obtain a listing of 64 correlations of data pairs.

The resulting correlations were next compared with a t-value table (Huntsberger, 1961, p. 257) to determine whether the correlations were real or merely due to chance. In Table 10 are summarized the positive results; following each data pair, a number in parentheses indicates the number of pairs of values available for that particular correlation. Since the probabilities are based on degrees of freedom (numbers of values minus two) as well as correlation coefficients, a small number of values does not detract from the t-value. An x under the heading 0.10 (0 per cent) indicates that for a particular data pair—for example, thickness of producing zone-gas production—there is a 90 per cent chance (1 00 per cent-10 per cent) that the observed correlation is real rather than a chance variation in the sample of data that were collected. Similarly, an x under the heading 0.005 raises this certainty from 90 per cent to 99.5 per cent for a particular data pair.

Twenty-two meaningful correlations were derived from among the 64 possibilities, two pairs, salinity-condensate production and oil production-condensate production, being impossible.

Nine of the correlations are concerned with crude oil, condensate, and natural gas production; these are generally to be expected. Oil production is correlative with initial formation pressure, permeability, producing-zone thickness, porosity, and gas production; it does not correlate with formation temperature, crude oil gravity, producing-zone depth, gas-oil ratio, or formation water salinity. Condensate production correlates only with formation depth and gas production; condensate production must and does correlate with gas production, since the two are produced together. Gas production correlates with thickness of producing zone and porosity but is not correlative with gas-oil ratios, formation temperature, permeability, or initial formation pressure.

Besides the positive results derived from correlation with known production, some of the positive correlations would be expected for purely geologic reasons. Temperature gradients with depth have been established in most producing areas of the world; in this memoir area, the gradient is 1°F per 80 feet of depth throughout the Pennsylvanian—Wolfcampian stratigraphic interval, the temperature-depth correlation being excellent. Excellent correlation also exists between formation temperature and initial pressure, both parameters being a function of depth. Temperature correlates very well with the gravity of the crude oils; this suggests that, at least in this area, the oil underwent some cracking process as depth of burial increased. The correlation of temperature with gas-oil ratio is good, and plotting of the data shows that, in general, the higher temperatures are associated with higher gas-oil ratios. This data pair again is suggestive of a cracking process taking place at the higher temperatures accompanying increasing depth of burial.

The data pair of temperature and salinity yielded a 90 per cent meaningful correlation, a correlation sufficiently strong to be worthy of study for practical application. In formation tests taken in dry holes, the formation temperatures and formation water salinities are almost always recorded. If a graph were to be established with temperatures and salinities from producing reservoirs of a given formation as the ordinates, then similar data from dry holes could easily be compared;

dry-hole data plotted on the graph might indicate proximity to a petroleum deposit. There is no obvious reason why the temperature-salinity correlation exists, other than that temperatures increase with depth, and depth, as will be shown, may play a role in the diagenesis of fossil sea water.

The correlation of oil gravity with temperature has been discussed; there is also an excellent correlation of gravity with the gas-oil ratio and a good one with original shut-in pressure. Since the gas-oil ratios and the shut-in pressures increase with depth, as does oil gravity, the correlations are to be expected. In any formation test yielding hydrocarbon showings, these data are generally determined and may be used as another clue to the proximity of an economically valuable petroleum deposit.

An excellent correlation of depth with pressure was obtained as was a weak, but still meaningful, correlation of depth with gas-oil ratio. The excellent depth-temperature correlation was described above (gradient of 1 °F per 80 feet). The pressure gradient is 0.38 psi per foot, which is close to hydrostatic pressure.

In summary, a direct relationship exists among depth, temperature, and shut-in pressure, and to these may be added oil gravity, gas-oil ratio, and perhaps salinity. These data, again, lead to the conclusion that the higher API gravities (inverse of specific gravity) and gas-oil ratios result from a cracking of heavier oils with increasing depth of burial and hence increasing temperature and pressure.

In addition to correlating with temperature, the salinity of the oil field brines, in terms of parts per million (ppm), correlates well with thickness of pay zone and very well with formation pressure; the significance of these relationships is unknown. The relationship of salinity to hydrocarbons is not explicit, since no correlation was found between salinity and such parameters as oil gravity and petroleum production. Therefore, the meaningful salinity correlations must be related to the effects of physical factors of pressure and temperature upon the diagenesis of the brines. The fact of the existence of meaningful correlations is strong argument against these waters being of meteoric origin.

A weak correlation of permeability with thickness of producing zone and a fair correlation of porosity with thickness of producing zone are indicated. Such data would, of course, indirectly indicate a relationship between porosity and permeability. Such is not the case, since no meaningful correlation was found between porosity and permeability. The quantitative relation between the two is obscure and variable (Levorsen, 1954), but charts of reservoir sandstones generally show increasing permeability with increasing porosity (Levorsen, 1954). For the Pennsylvanian—Wolfcampian reservoirs, dominantly carbonate, fractures must be an important factor in effective porosity. If so, then increase in thickness of the producing zone could be expected to yield increased porosity values. Neither porosity nor permeability was affected by depth, as shown by negative correlations between these parameters; this indicates that overburden is not an important factor in increasing or reducing either one, at least at the depths involved in this study.

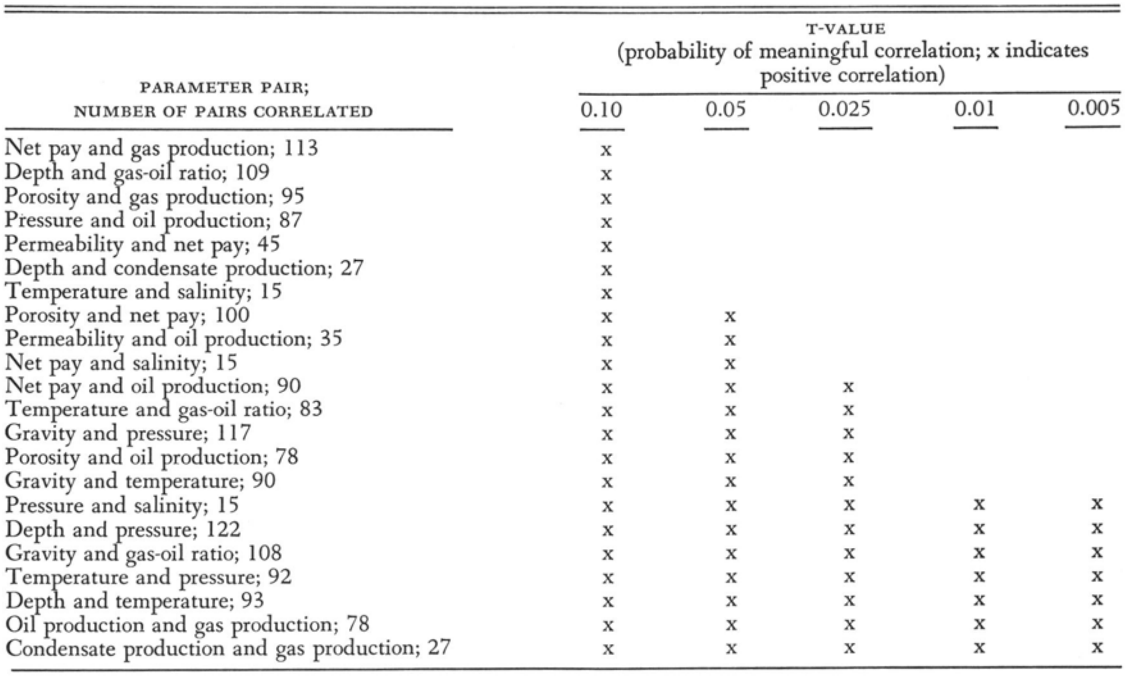
GEOCHEMISTRY OF FLUIDS

PRODUCING-ZONE WATER

The data presented in Table I c represent some Pennsylvanian and Wolfcampian producing-zone waters. It is assumed that the data represent chemical analyses rather than calculations based upon tables for the area.

Stiff (1951) proposed a method for plotting such analyses that involves converting the dissociated anions and cations to reaction equivalents to hydrogen per million (milligram equivalents per kilogram), or epm, as determined from conversi0n tables (Lange, 1956, p. 811; Hem, 1959, p. 32). Epm

TABLE 10. POSITIVE RESULTS OF RESERVOIR DATA CORRELATION COEFFICIENT PROGRAM



PARAMETER PAIR; NUMBER OF PAIRS CORRELATED	T-VALUE (probability of meaningful correlation; x indicates positive correlation)				
	0.10	0.05	0.025	0.01	0.005
Net pay and gas production; 113	x				
Depth and gas-oil ratio; 109	x				
Porosity and gas production; 95	x				
Pressure and oil production; 87	x				
Permeability and net pay; 45	x				
Depth and condensate production; 27	x				
Temperature and salinity; 15	x				
Porosity and net pay; 100	x	x			
Permeability and oil production; 35	x	x			
Net pay and salinity; 15	x	x			
Net pay and oil production; 90	x	x	x		
Temperature and gas-oil ratio; 83	x	x	x		
Gravity and pressure; 117	x	x	x		
Porosity and oil production; 78	x	x	x		
Gravity and temperature; 90	x	x	x		
Pressure and salinity; 15	x	x	x	x	x
Depth and pressure; 122	x	x	x	x	x
Gravity and gas-oil ratio; 108	x	x	x	x	x
Temperature and pressure; 92	x	x	x	x	x
Depth and temperature; 93	x	x	x	x	x
Oil production and gas production; 78	x	x	x	x	x
Condensate production and gas production; 27	x	x	x	x	x

or reacting value equals reacting weight times ppm of a cation or anion, reacting weight being the reciprocal of atomic weight divided by valence (Palmer, 1911). Patterns for waters from Table 11 appear in Figure 68, which includes the scale used; note that sodium and chlorine are increased by a factor of 1 0 over the others. Frequently such patterns show correlation between waters of the same age.

Among the plots shown (fig. 68), the most distinctive is that of natural sea water. Here calcium is less than magnesium is less than sodium. In the producing-zone waters, on the contrary, magnesium is less than calcium is less than sodium. On the anion side of the patterns, the producing-zone waters indicate CO_3--HCO_3<SO_4<C1, as is true of sea water. Plotted in this way, all producing zone waters differ significantly from sea water; the former have, therefore, been subject to alteration subsequent to entrapment. The producing-zone waters are sufficiently similar to each other to be characteristic of the geologic province. It is concluded that this method of plotting water analyses may be useful in distinguishing Pennsylvanian and Wolfcampian brines from brines of similar age in other provinces or from brines of substantially different age in the same province; the method apparently is not useful for distinguishing between pools occurring in Pennsylvanian and Wolfcampian reservoirs within the Permian basin province of southeast New Mexico.

Reasons for the lack of close correlation between Pennsylvanian and Wolfcampian pools may be that (1) the waters present in the rocks of each stage are not the waters originally trapped in those rocks or (2) the waters are the original waters (connate water) but have not been uniformly altered. If (1) is true, the waters may have been originally trapped in younger (or older) rocks and later migrated into their present reservoirs; an alternative interpretation is that the waters are derived, not from original sea water but from body fluids of plankton, in a way analogous to the formation of petroleum.

In regard to (2), it is not proposed that the analyses just described are very helpful in visualizing the composition of the water originally entrapped in the sediments; the problems involved in such speculation have been described by Revelle (1941, Rubey (1951), and Chave (1960, p. 357), who stated:

> If the nature and magnitude of these post-depositional changes (in entrapped sea water) can be evaluated, speculation on the chemistry of ancient sea water will be possible. At the present state of knowledge this cannot be done.

At the least, it seems clear that all the Pennsylvanian and Wolfcampian waters must originally have been of similar composition, whatever that was, and must have followed parallel paths of diagenesis after entrapment. This is reasonable, considering the relatively narrow range of absolute time involved and the similarity of the enclosing sediments (principally limestones and shales). The most dissimilar pattern, that of the Cass pool, is derived from water from a carbonate bed quite free of shale, and its anion pattern is remarkably close to that of sea water.

Assuming the producing-zone waters were originally sea water entrapped with sediments (not necessarily of the same age as the sediments in which the waters now are found), then the problem is to discover the mechanism through which alteration took place.

Brines less concentrated than sea water may result from dilution by fresh waters from the basin margin. No such examples of diluted brines appear in Table 11.

Brines more concentrated than sea water are generally attributed to some mechanism involving the adsorption of the chlorine anion and the calcium and magnesium cations by clays (Russell, 1933; De Sitter, 1947). Such a sieve action by fine-grained sediments would allow water molecules to pass while retarding salt ions. Contradictory evidence to this mechanism, resulting from a study of recent sediments ass0ciated with fjords, has been presented by Manheim (1963), who seemingly can demonstrate horizontal migration of saline waters for a distance of nearly a kilometer in fine-grained, apparently homogeneous clays without alteration of ionic concentration. If this is true, the sieve theory may require important modification.

The waters listed in Table II are substantially higher than sea water in terms of total parts per million with two

TABLE 11. COMPARATIVE ANALYSES OF SOME OIL FIELD WATERS AND SEA WATER
(parts per million)

WATER SAMPLE SOURCE	GEOLOGIC AGE	Na$^+$	Ca^{++}	Mg^{++}	Fe^{++}	SO$_4^{--}$	Cl$^-$	CO$_3^-$	HCO$_3^-$	TOTAL PPM
Sea water	Recent	11,000	420	1,300	—	2,690	19,350	150	—	34,910
Allison Penn	Wolfcampian	37,300	6,080	1,895	tr	675	73,120	377	—	119,447
Bagley Penn	Virgilian	22,300	2,600	724	—	365	40,600	—	509	67,098
Bough Permo Penn	Wolfcampian	34,000	6,200	1,300	26	900	67,000	194	—	109,594
Cass Penn	Desmoinesian	12,618	1,613	498	23	2,535	21,600	510	—	39,374
Denton Wolfcamp	Wolfcampian	35,630	3,234	890	—	2,568	60,968	—	415	103,705
Eidson Penn	Wolfcampian	29,865	4,283	628	—	607	54,780	—	396	90,559
Lazy J. Penn	Virgilian	33,728	5,520	1,118	tr	765	64,354	—	256	105,741
Lovington Wolfcamp	Wolfcampian	42,100	7,061	1,200	tr	962	80,160	—	61	131,544
Saunders Permo Penn	Virgilian	25,935	2,806	570	—	1,117	45,300	—	—	75,728
Townsend Wolfcamp	Wolfcampian	37,002	5,529	1,354	—	352	70,400	—	214	114,851
Atoka Penn Gas	Morrowan	18,900	1,860	210	100	350	32,400	—	915	54,635
Crossroads Penn	Virgilian	36,376	7,105	1,907	4	629	73,622	—	270	119,909
Kemnitz Wolfcamp	Virgilian	24,700	5,500	90	—	737	49,500	—	855	81,382
King Wolfcamp	Virgilian	35,148	5,074	1,007	tr	3,395	63,653	—	133	108,410
King Penn	Missourian	37,884	7,685	138	tr	994	71,609	—	211	118,521
N. Shoe Bar Penn	Desmoinesian	8,439	2,400	447	—	1,428	17,197	—	573	30,484

Analyses from Stipp et al., 1956; Sweeney et al., 1960; tr, trace.

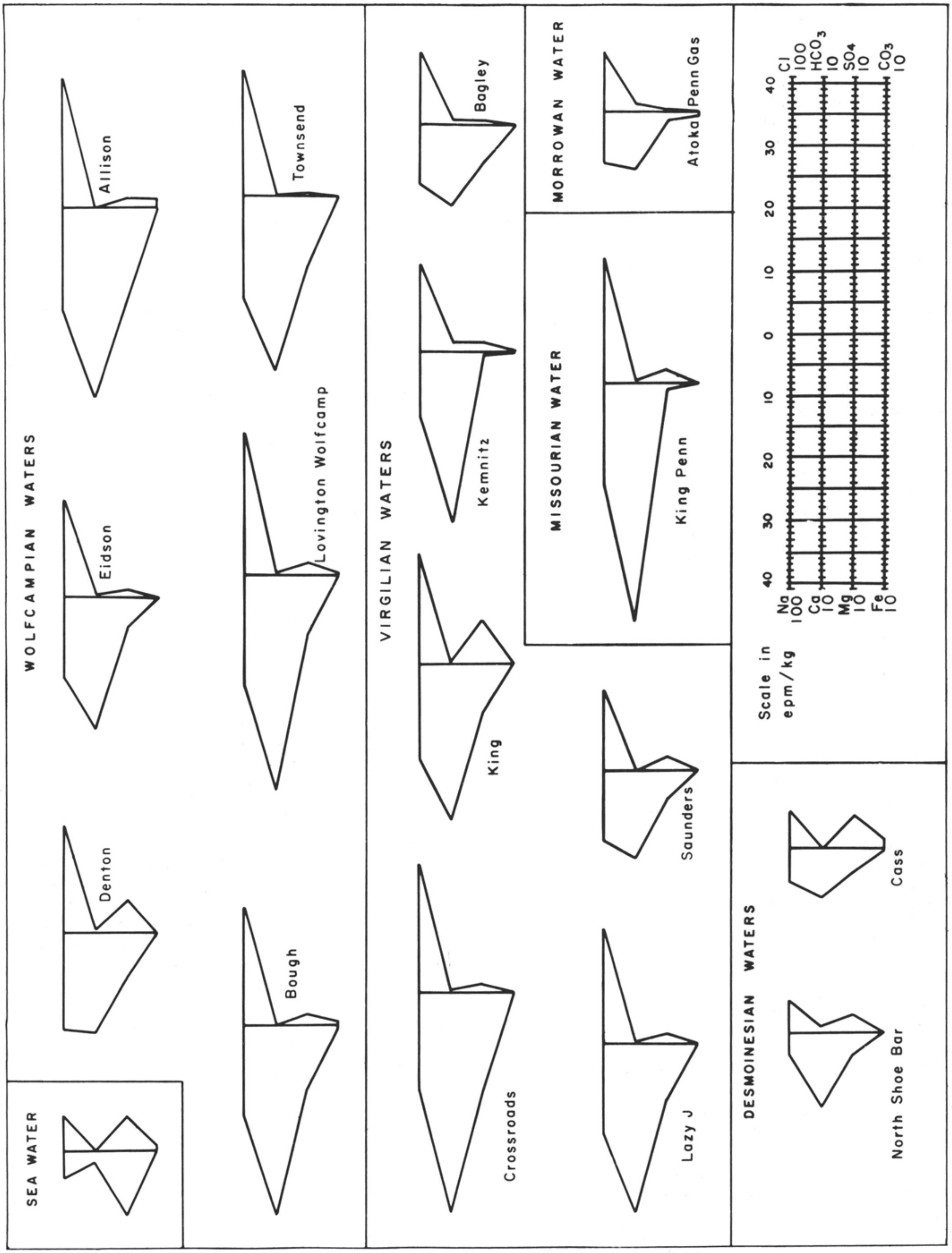


Figure 68

Typical Pennsylvanian and Wolfcampian producing zone water analyses by patterns based on equivalents per million exceptions, both in Desmoinesian reservoirs. North Shoe Bar water is less concentrated than sea water and Cass water is only slightly more so; these conditions must in some manner be the result of dilution; their epm patterns (fig. 68), which eliminate dilution effects, differ in several respects from sea water. In particular, the positions of Ca++ and Mg++ are reversed with respect to epm.

The iron cation is not quantitatively important either in sea water or in the oil field waters. However, iron occasionally is of the order of magnitude of 1000 ppm in brines (White, 1957).

In sea water, magnesium dominates over calcium by a ratio of 3: (White). In the waters under consideration, calcium is clearly dominant; in fact, it is in this component that the waters have most obviously undergone diagenesis. In the area of this report, the cause of this magnesium-calcium reversal is probably related to the postdepositional uptake of magnesium by argillaceous sediments, and the growth of chlorite or illite or muscovite, without a compensating addition of calcium to the waters, as suggested by Chave.

The sodium cation is readily soluble and tends to remain in solution. It would not likely decrease in concentration in water which has been trapped. Chave indicated that in terms of parts per million, sodium is usually calculated, not analyzed, and hence is subject to invalidating errors. It is Hem's belief that most of the increased concentration in sodium results from natural contamination, a likely circumstance in this area, where the beds under study are overlain by massive salt deposits.

Whatever the reason, the chloride anion is much less abundant in sea water than in formation water (table 1; fig. 68). As with sodium, the excessively high readings in parts per million may be attributed largely to contamination from overlying beds.

The SO_4 anion remains substantially equal in concentration to that of sea water, or else it is significantly reduced in formation water (table ; fig. 68). In the former case, it is assumed to have been little affected during alteration of the original water, although it is possible that the sulfate ion was reduced by an unknown amount and later replenished by contamination from overlying anhydrite beds. Where the concentration of the SO_4 is much reduced, a condition also obtaining in the interstitial waters of many recent marine and estuarine sediments, the cause may be found in the following reaction (Revelle): $3Na_2SO_4$ C6H12O6 bacteria $3H_2S$ that Chloride brines result from alteration of circulating

Little can be said with confidence in regard to the CO_3 and HCO_3 anion concentrations because insufficient data are available on pH values or CO_2 concentrations; therefore, the parts per million values given may be invalid. The sulfate reduction indicated in the preceding paragraph perhaps accounts for the anomalous HCO_3 concentrations in a number of the brines in Table I 1.

Not all geologists share belief in the "fossil" nature of subsurface formation waters. Chebotarev (1955, p. 210-21I) proposed a cycle of alteration of circulating ground waters to account for subsurface waters. In particular, he believed that chloride brines result from alteration of circulating meteoric waters, especially when they stagnate in closed structures near oil deposits. Clayton et al. (1964), in a study of the origin of the brines of the Illinois and Michigan basins, found a positive correlation of oxygen isotope composition with total dissolved solids and with dissolved (Ca + Mg) in 60 brines. Extrapolation to zero salinity yielded oxygen isotope values for local meteoric water. Furthermore, they found that the deuterium concentration of the brines varied little from the local meteoric water and concluded, therefore, that the brines were of fresh-water origin, the original sea water having been lost through compaction and later flushing. It is difficult to see how such a mechanism could function in this memoir area, where meteoric water has extremely limited access to the subsurface formations in a lateral direction and virtually no access in a vertical direction through thousands of feet of shales and evaporites.

The preceding discussion does not consider that the fluids in sediments comprise a hydrodynamic, not a static, system. Thus, any tilting of the strata results in a downdip movement of water, which, when it comes to rest, must again achieve equilibrium with its new environment through ion exchange. Some of the ways this may take place were just described.

Because the area being considered underwent many episodes of folding and tilting throughout Pennsylvanian and Permian time, and because the geologic history of the area is unclear during Mesozoic and Paleogene time, the actual age of the brines now contained in reservoirs of Pennsylvanian and Wolfcampian ages is unknown.

CRUDE PETROLEUM

Analyses of crude oils are available for only seven Pennsylvanian and Wolfcampian reservoirs in southeast New Mexico (U.S. Bureau of Mines Bartlesville Laboratory, Okla.; McKinney and Garton, 1957, p. 139, 142, 146). Of these, three (Bagley, Kemnitz, and Saunders) are in Virgilian and four (East Caprock, Denton, Gladiola, and Townsend) in Wolfcampian strata. The seven reservoirs may be considered representative of those occurring in strata under study because Virgilian and Wolfcampian pools account for 92 per cent of Pennsylvanian and Wolfcampian petroleum; the seven pools include all the large ones except Allison Penn; and they are widely distributed areally (figs. 62 and 63).

General characteristics of the crude oils are presented in Table 12. These characteristics indicate that the oils are of excellent quality. They are of low specific gravity and, hence, high API gravity. All but one (Kemnitz) have pour points below 5°F, and all possess Saybolt Universal viscosities of about 34 seconds (at 00°F), indicating that the oils may easily be stored and transported by pipeline at ordinary surface temperatures. The weight per cent of sulfur is very low, well below the 0.5 per cent usually considered excessive from the refiner's point of view. Weight per cent of nitrogen and asphalt, which are generally in correspondence, is similarly low. The percent of asphalt was calculated as 4.9 times the per cent of carbon residue of crude oil listed in the analyses.

U.S. Bureau of Mines routine crude oil analyses are conducted in two stages and 15 cuts at temperature increments of 25°C. The ten cuts or fractions of stage I are made at atmospheric pressure and the five cuts of stage 2 at reduced pressure (40 mm mercury) to prevent thermal decomposition of the petroleum. Each succeeding fraction is heavier, and has a higher boiling point, than its predecessor (Smith et al.,

TABLE 12. GENERAL CHARACTERISTICS OF CRUDE OILS FROM SEVEN RESERVOIRS IN VIRGILIAN AND WOLFCAMPIAN STRATA

FIELD NAME	BAGLEY	E. CAPROCK	DENTON	GLADIOLA	KEMNITZ	SAUNDERS	TOWNSEND
Gravity, °API	46.5	43.2	42.6	42.1	36.4	41.7	38.2
Specific gravity	0.795	0.810	0.813	0.815	0.834	0.817	0.834
Pour point, °F	below 5	below 5	below 5	below 5	20	below 5	below 5
Viscosity, Saybolt universal, secs. at 100°F	33	35	35	35	35	34	34
Sulfur, weight per cent	0.14	0.17	0.35	0.10	0.12	0.11	0.12
Asphalt, weight per cent	0.98	1.37	2.15	2.15	4.41	2.15	1.96
Nitrogen, weight per cent	0.025	0.034	0.04	0.053	0.06	0.052	0.027
Approximate summary, per cent							
Total gasoline and naphtha	48.7	46.0	45.6	46.6	44.8	46.9	48.6
Kerosene distillate	11.7	12.2	5.4	5.7	4.9	5.2	—
Gas oil	15.6	17.3	19.8	21.3	19.9	19.8	21.3
Nonviscous lubricating distillate	8.5	9.2	9.0	8.8	7.7	8.4	7.8
Medium lubricating distillate	2.4	3.2	5.0	4.0	4.4	4.4	5.1
Viscous lubricating distillate	—	—	—	—	4.2	—	0.7
Residuum	9.6	11.7	14.1	12.4	13.1	13.6	11.9
Distillation loss	3.5	0.4	1.1	1.2	1.0	1.7	4.6

Source of data: U.S. Bureau of Mines Bartlesville Laboratory, Okla.; McKinney and Garton, 1957.

1951); this is a reflection of the increasing weight and complexity of the hydrocarbon molecules.

The approximate summary section of Table 12 indicates the yield of the crude oils in terms of commercial products. The per cent yield of light products is very high, whereas that of lubricating distillate, especially viscous distillate, is very low. The small amount of residuum and the low distillation loss also are indicative of the high yield of light fractions and the nonasphaltic character of the petroleum.

In Table 13 (in pocket) are listed certain physical attributes of the distillate fractions of the petroleums. In the left-hand column are the distillate fractions and their temperatures and pressures. The following data are derived directly from U.S. Bureau of Mines routine analysis data sheets (Holliman et al., 1950): volume per cent, specific gravity of fraction, refractive index, specific dispersion, correlation index of fraction, cloud test, and viscosity. The specific gravity on a theoretically aromatic-free basis was calculated from the equation of McKinney and Garton (p. 30). Molecular weights of average molecules of the fractions were determined from a chart (Mills, Hirschler, and Kurtz, 1946, fig. 3, p. 443), and from a chart prepared from data tabulated by those authors (table X, p. 447). Correlation indexes of the crude oils on an aromatic-free basis, that is, of the paraffin-naphthene components, were computed in the same manner as correlation indexes of the fractions (Smith, 1940, 1964, p. 18-29). The volume per cent of aromatic hydrocarbon (Thorne et al., 1945) was derived according to the equation of Smith (1964, p. 30); this parameter may also be read from a chart (McKinney and Garton, fig. 1, p. 28) with somewhat less accuracy. Volume per cent aromatics may be converted easily to weight per cent by a simple equation (Gooding, Adams, and Rall, 1946). Weight per cent of naphthene rings is most easily read from a chart (McKinney and Garton, fig. 2, p. 29) but may also be calculated (Lipkin, Martin, and Kurtz, 1946); a random check showed that results achieved by the two methods fell within a few percentage points of each other, differences being greatest in the higher fractions. The weight per cent of paraffin hydrocarbons plus paraffin side chains on rings is derived by simple subtraction (1 0o minus naphthenes plus aromatics).

Molecular weights of some petroleum products are gasoline, 1 00; light naphthenic lubricating oil, 150; heavy naphthenic or light paraffinic lubricating oil, 600. On this basis, it is evident that the crude oils under study would not yield heavy or viscous lubricants; this is borne out by the approximate summary (table I 2). The increase in average molecular weight from about 80 to 355 through successive fractions is suggestive of increasing numbers of carbon atoms per molecule, as well as increasing complexity of structural groups from simple paraffinic chains through naphthene rings to aromatic rings with long paraffin side chains.

The correlation index was devised by Smith (1940) to compare crude oils by means of curves. This index, a function of specific gravity and the reciprocal of absolute boiling point, may be plotted against distillation fraction numbers to form a profile. Fractions 1 0 and I 1 are not plotted because the distillation method used would cause a misleading discontinuity in the profile at these points (Smith, 1964, p. 20). Correlation index profiles are useful, not only to compare petroleums but also to derive an approximation of their composition; this depends upon the fact that the larger, more complex molecules have higher molecular weights and therefore higher densities.

In formulating the index profile, the n-paraffins were assigned an index of zero and benzene, 100. Because no crude oil is a pure hydrocarbon, the indexes of crude oils fall between zero and about 120. A plot of various oils (Smith, 1964) shows that an index of less than 15 indicates a predominantly paraffinic crude oil, whereas an index greater than 50 suggests a predominantly aromatic one. The predominantly naphthenic oils fall mostly between 15 and 50. Smith, Smith, and McKinney (1950, p. 613) found that if a crude oil exhibits a high value (at least 30) on the profile at fractions four and five and then decreases between fractions five and seven, the oil contains useful quantities of the aromatic, toluene. Such a reversal on the profile has been termed an *aromatic* hump.

Correlation index profiles for the seven Virgilian—Wolfcampian crude oils under discussion appear in Figure 69. Three of these, Kemnitz, Saunders, and Townsend, display aromatic humps, indicating that in the eight fractions they are decidedly aromatic; this is borne out by consideration of the aromatic hydrocarbon profiles (fig. 70). The Townsend and Kemnitz crude oils, especially, contain pronounced percentages of aromatic hydrocarbons. In the higher fractions, of course, aromatics tend to increase in all the samples. The predominantly naphthenic character of the crude oils, particularly fractions three to eight and eleven, is shown in Figure 71; these naphthene profiles are constructed in the same way as correlation index profiles, but on a theoretically aromatic-free basis, by recomputing the specific gravity to eliminate the aromatic contribution to each fraction. Only the East Caprock crude oil remains predominantly paraffinic throughout the first eleven fractions.

Examination of Figures 69 and 70 discloses that four of the crude oils, Bagley, East Caprock, Denton, and Gladiola, are very similar, and one, Saunders, differs from them only in that it is more aromatic in the first six fractions. Two of the oils, Kemnitz and Townsend, differ significantly from the others because of high aromatic hydrocarbon contents in fractions three to eight. In addition, both Kemnitz and Townsend oils have distinctly higher specific gravities of crude oil, higher specific gravities of distillation residuum, and higher molecular weights in each fraction (table 13). The Kemnitz sample contains a much higher percentage of asphalt and of nitrogen than the other six and is the only one to possess a pour point above 5°F (table 12).

Clearly, such variations in composition of crude oils must carry geological implications. The seven reservoirs occur in limestones through a narrow vertical range. The crude oils fall in two groups, one relatively low in aromatics, one relatively high, and each group contains at least one crude oil in a Virgilian reservoir and one in a reservoir of Wolfcampian age. All the reservoirs are located on the Northwest shelf with two, Kemnitz and Townsend, being close to the margin of the Delaware basin. Geographic locations of the fields are shown in Figures 62 and 63.

It is concluded that the differing compositions of the crude oils are not a function of age or reservoir lithology. There is an implication that geologic setting plays a part in determining composition, because the two crude oils distinctly high in am-

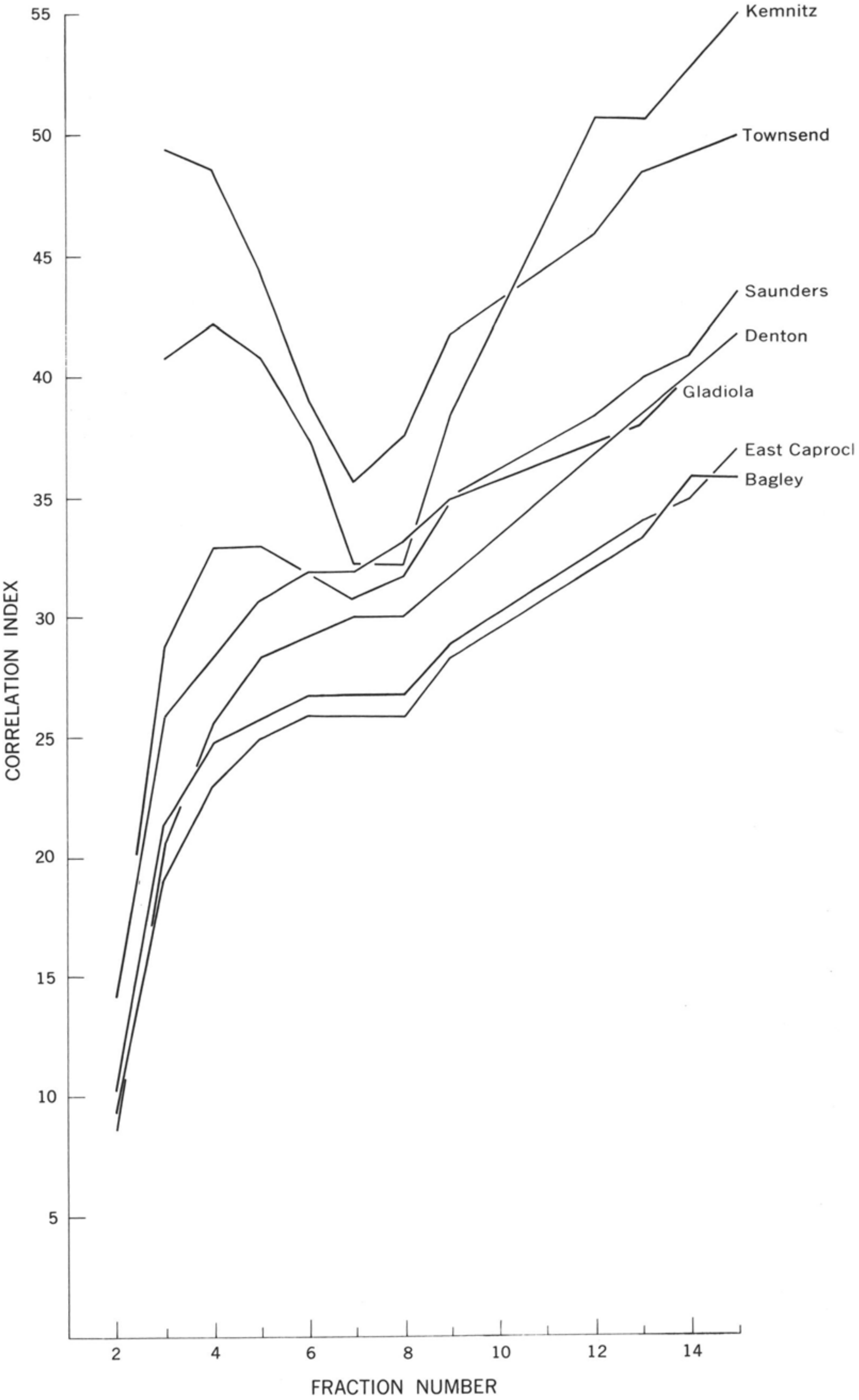


Figure 69

Correlation index profiles for crude oils from seven reservoirs in Virgilian and Wolfcampian strata

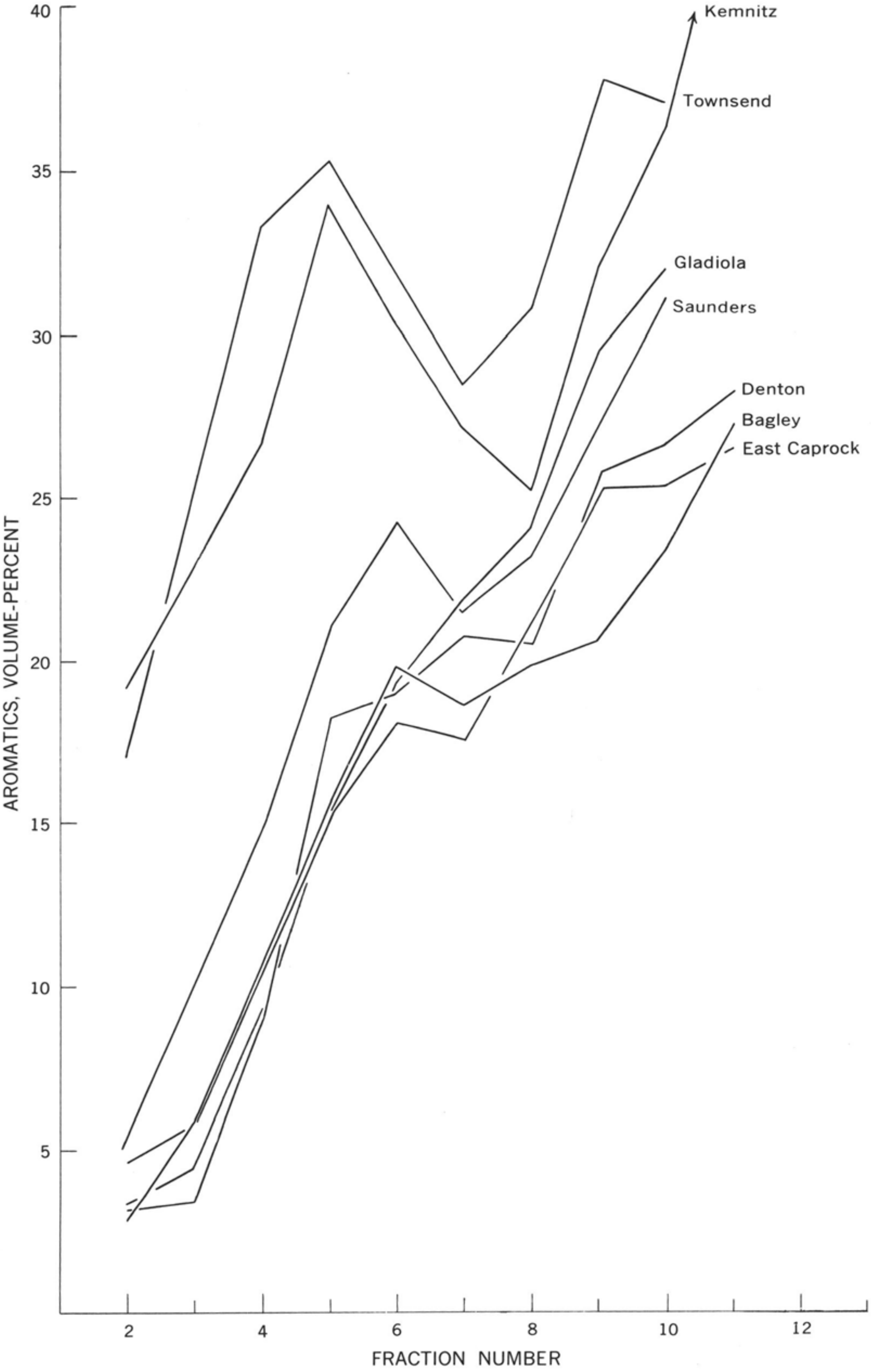


Figure 70

AROMATICS PROFILES FOR CRUDE OILS FROM SEVEN RESERVOIRS IN VIRGILIAN AND WOLFCAMPIAN STRATA

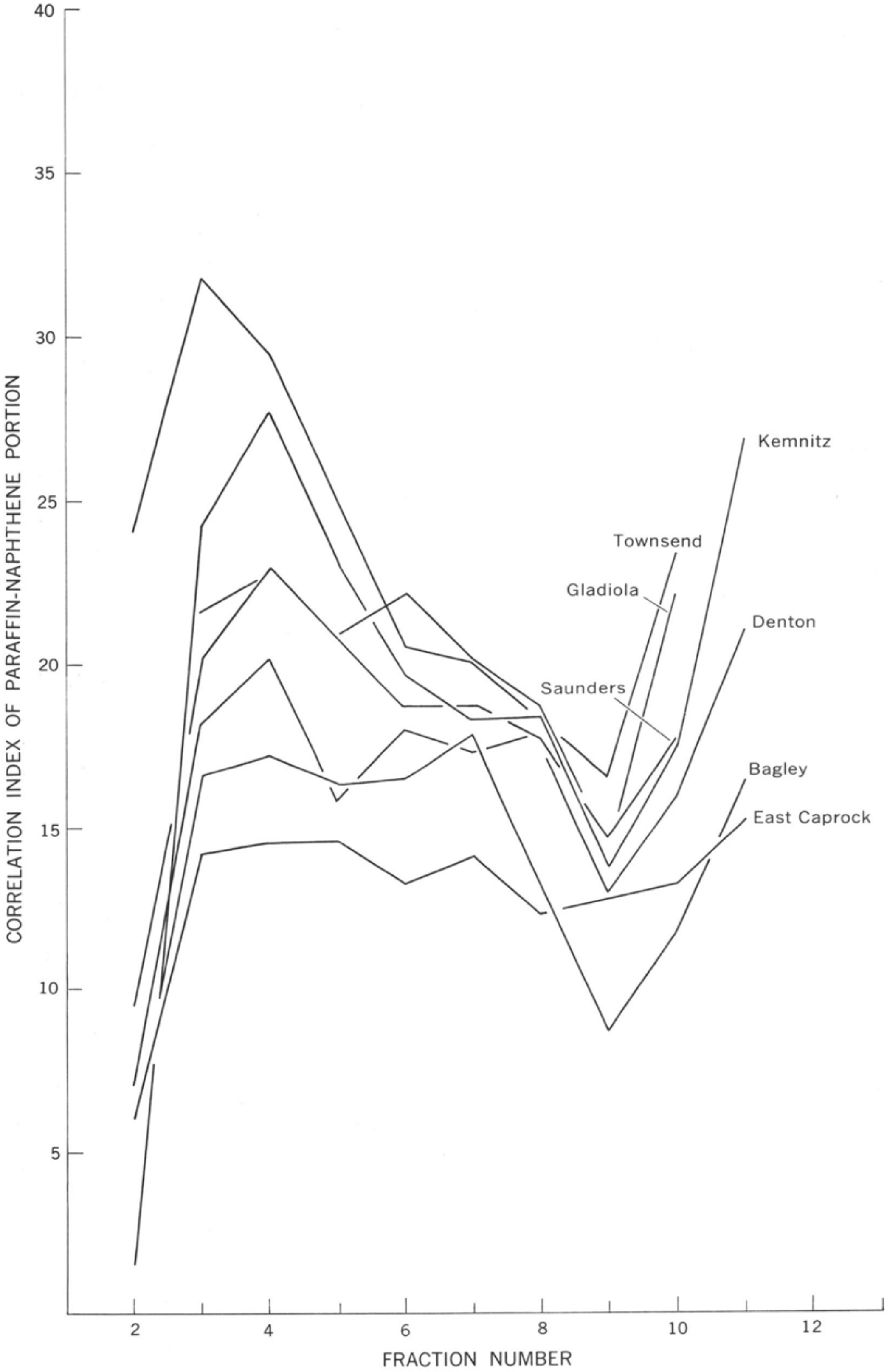


Figure 71

Naphthene profiles for crude oils from seven reservoirs in Virgilian and Wolfcampian strata matics, Kemnitz and Townsend, lie closest to the basin margin. Assuming that all the petroleum originally was generated in the basin and not on the shelf, two possibilities exist. All the crude oils may originally have been similar and five of them, which migrated farthest, somehow lost a considerable percentage of their aromatic hydrocarbons; this process would most likely involve catalytic cracking through the agency of such metals as chromium, vanadium, and nickel contained in the sediments. On the other hand, the crude oils may reflect different source materials or different environments of sedimentation of similar source materials. The geographic area involved is not large and conditions of sedimentation at a given time must have been rather uniform throughout, judging from the geologic analysis presented earlier in this paper. Furthermore, the crude oils do not vary greatly in terms of viscosity, distillation yields, or contents of sulfur, nitrogen, or asphalt; the significant variations are confined to the hydrocarbons. It is concluded, therefore, that the oils were derived from essentially identical source materials but were altered in the direction of simplification of hydrocarbon structure through the process of catalytic cracking and subsequent reforming during migration.

A suggestion of source materials may be gained by comparing the correlation index profiles of the seven Virgilian-Wolfcampian crude oils with those of some oils of different ages. The profiles were prepared from data in McKinney and Garton. Three of the oils from reservoirs of Siluro—Devonian age on the Northwest shelf are nearly identical, whereas one, Denton, differs in that it is considerably more naphthenic than the others (fig. 72). The profile for the Denton Wolfcampian petroleum (fig. 69) is very much like that from the Siluro—Devonian reservoir, except that it is more naphthenic throughout all fractions. The other Siluro—Devonian crude oils do not resemble those of Virgilian—Wolfcampian age, being much more paraffinic. It does appear, however, that the two Denton samples may have been derived from similar or identical source materials, the uniformly higher paraffin content of the Siluro—Devonian sample being attributable to cracking due to higher temperatures involved with greater depth of burial.

Of the three crude oils from Ordovician reservoirs (fig. 73), all of which are located on the Central Basin platform, only that from the Brunson pool resembles the Virgilian—Wolfcampian oils. The other two are much more paraffinic.

Correlation index profiles for six Upper Permian crude oils from reservoirs on the Central Basin platform (fig. 74) differ from those for oils of Virgilian—Wolfcampian age. Only the petroleum from the Drinkard pool resembles the Virgilian-Wolfcampian oils. On the other hand, petroleum from four Upper Permian reservoirs located in the transition zone between the Delaware basin and the Northwest shelf (fig. 75) shows close similarity to that of the Virgilian—Wolfcampian reservoirs. This suggests that the petroleum in reservoirs of Virgilian—Wolfcampian and Upper Permian ages evolved from similar source materials deposited under similar conditions. Whether all the oil is of Upper Permian age or whether the oil in Virgilian—Wolfcampian reservoirs is of Virgilian—Wolfcampian age is indeterminant. In its general characteristics, the crude oil in Upper Permian reservoirs differs from that in older reservoirs in its higher specific gravity, darker color, much higher sulfur content (average of 1.5 per cent), considerably higher viscosity, and much higher asphalt content (Lane, 1942, table 3, p. 5). The similarity of hydrocarbons and dissimilarity of nonhydrocarbons indicate the probability that the crude oils were derived from similar source materials deposited in different environments.

NATURAL GAS

In Table 14 are listed natural gas analyses for 15 reservoirs of Pennsylvanian and Wolfcampian ages in southeast New Mexico. All determinations were made by the U.S. Bureau of Mines as a part of its helium survey program. Analytical methods involve a special apparatus for helium and a mass spectrometer for other components (Boone, 1958, p. 8-9, I-15). Heating values are calculated in terms of gross BTU per cubic foot, dry, at 60°F and 30 inches of mercury; the values are based upon heats of combustion of individual components, adjusted to percentage composition (Boone). Of the 15 samples, 5 (Allison, Hightower, Lusk, Saunders, and Scharb) represent casing-head gas; that is, gas associated with crude oil deposits.

Aside from hydrocarbons, certain other gases are frequent components of natural gas. The natural gases herein described contain extremely small quantities of helium, hydrogen sulfide, hydrogen, argon, and oxygen, up to three per cent of carbon dioxide, and generally small amounts of nitrogen. The natural gas from Los Medanos field is 18.9 per cent nitrogen. The nitrogen, oxygen, and argon appear most likely to represent remaining amounts of air trapped with the organic source materials and largely utilized in oxidation processes (Levorsen, 1954; Rankama and Sahama, 1950). Hydrogen and helium probably derive from alpha-particle irradiation of hydrocarbons, with most of the resultant hydrogen becoming involved in hydrogenation processes and only a little remaining as atomic hydrogen (Whitehead and Breger, 1963). The hydrogen sulfide is most readily accounted for by bacterial reduction of sulfates to sulfides (ZoBell, 1963). The small amounts of carbon dioxide present in the natural gases of this area probably originated from destruction of hydrocarbons by anaerobic bacteria or by the oxidation of hydrocarbons by mineralized subsurface waters (Levorsen, 1954).

Of the hydrocarbons in the natural gases, methane (CH4) is most abundant, structurally simplest, and thermodynamically most stable. Next most abundant is ethane (C_2H_6), followed by propane (C_3H_8), n-butane, and isobutane (C4H10)• These hydrocarbons have low boiling points and are present as gases. Succeeding, higher boiling hydrocarbons, n-pentane and isopentane, cyclopentane, and the hexanes plus higher molecular weight hydrocarbons are present as vapors.

Table 14 shows that there is little to distinguish the associated from the nonassociated natural gases on the basis of nonhydrocarbon content; this is not true of the hydrocarbon content of the mixtures, however. The nonassociated gases are almost invariably of high methane content and are drier; that is, they contain considerably lower proportions of liquid hydrocarbons. Gas from the Los Medanos field, nonassociated, has an anomalously low methane content, but the variation is accounted for by the abnormally high nitrogen content, not by a high content of heavier hydrocarbons.

In terms of heating value, all the gases are high, with the exception, of course, of that from Los Medaños field. The highest heat values are from gases from the Allison, Saunders, and Scharb fields, all being associated occurrences enriched in higher molecular weight components, especially propane (bottled gas) and n-butane.

VALUE OF PETROLEUM PRODUCED

The average barrel value of crude petroleum produced in 1962. and 1963 in southeast New Mexico was $2.90 (Kirby and Moore, 1964). On this basis, the total value at wells for cumulative production of crude oil to January 1, 1964, from

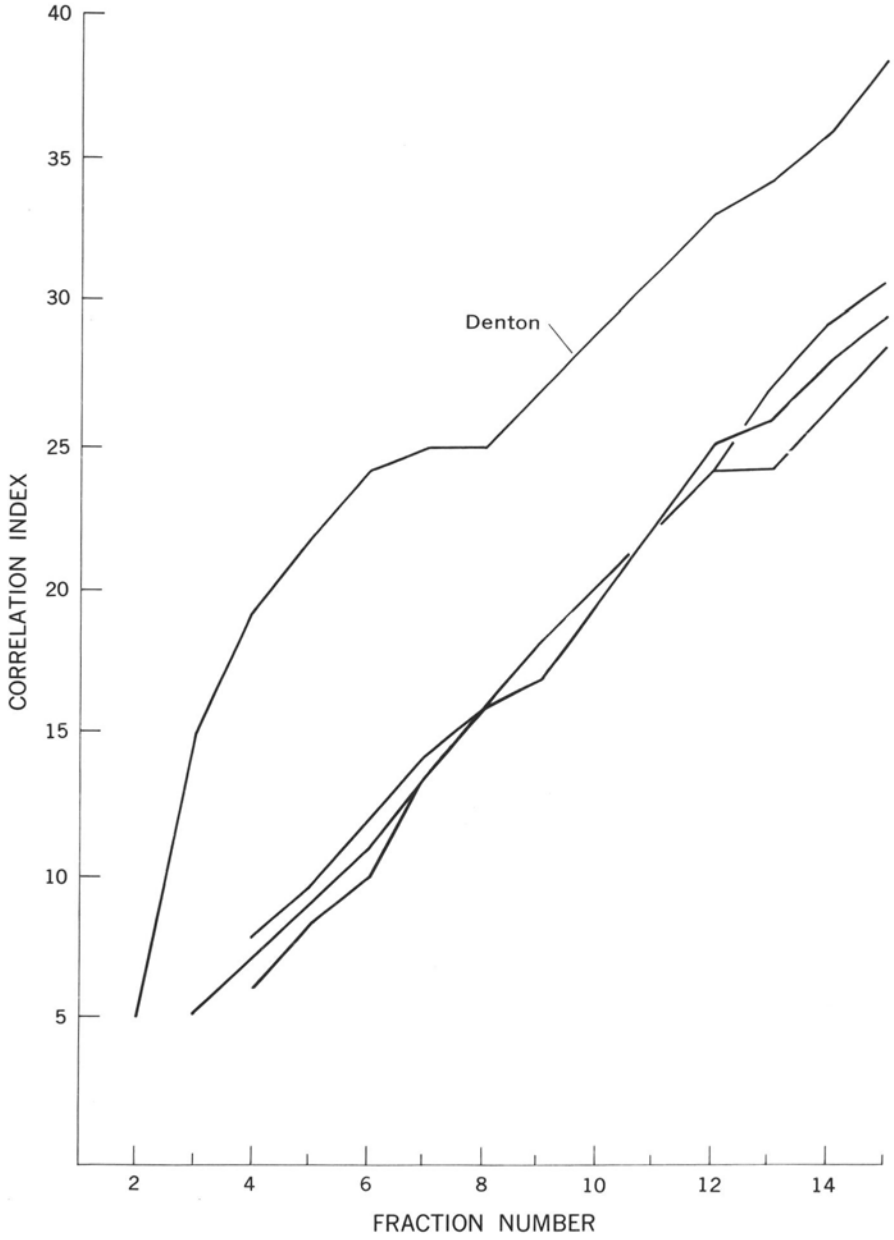


Figure 72

CORRELATION INDEX PROFILES FOR CRUDE OILS FROM FOUR RESERVOIRS IN SILURO–DEVONIAN STRATA ON THE NORTHWEST SHELF

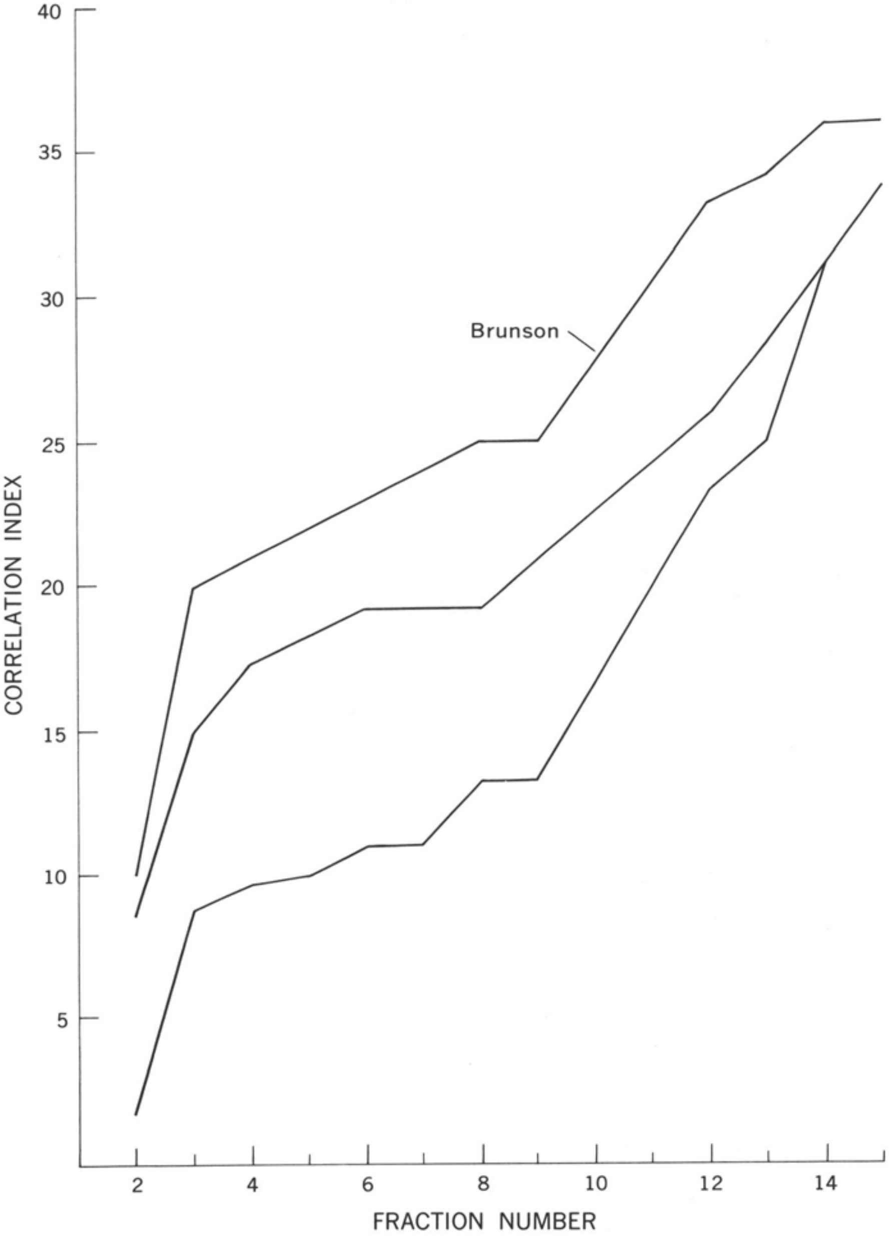


Figure 73
Correlation index profiles for crude oils from three reservoirs in Ordovician strata on the Central Basin

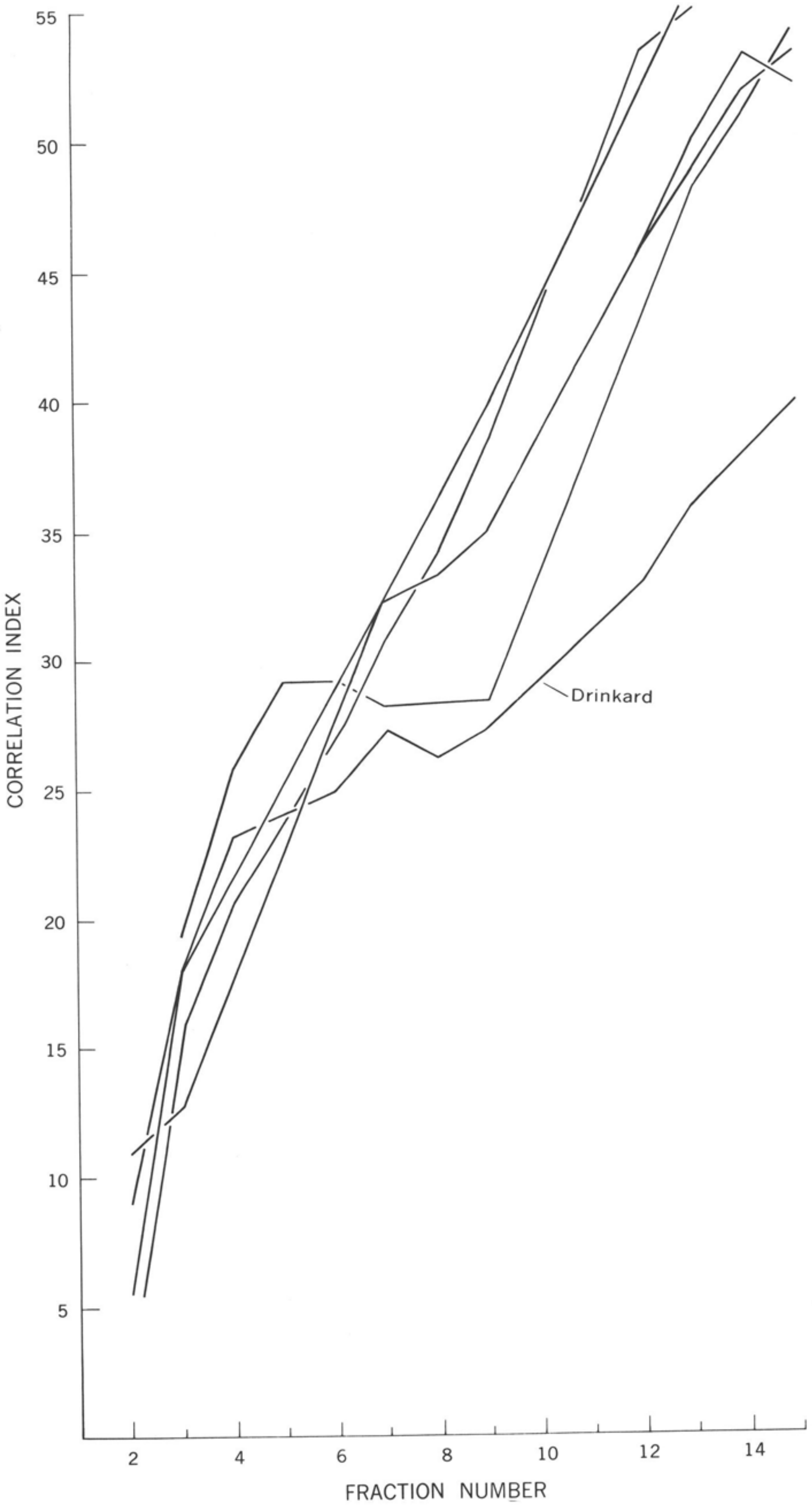


Figure 74

Correlaton index profiles for crude oils from six reservoirs in Upper Permian strata on the Central Basin platform

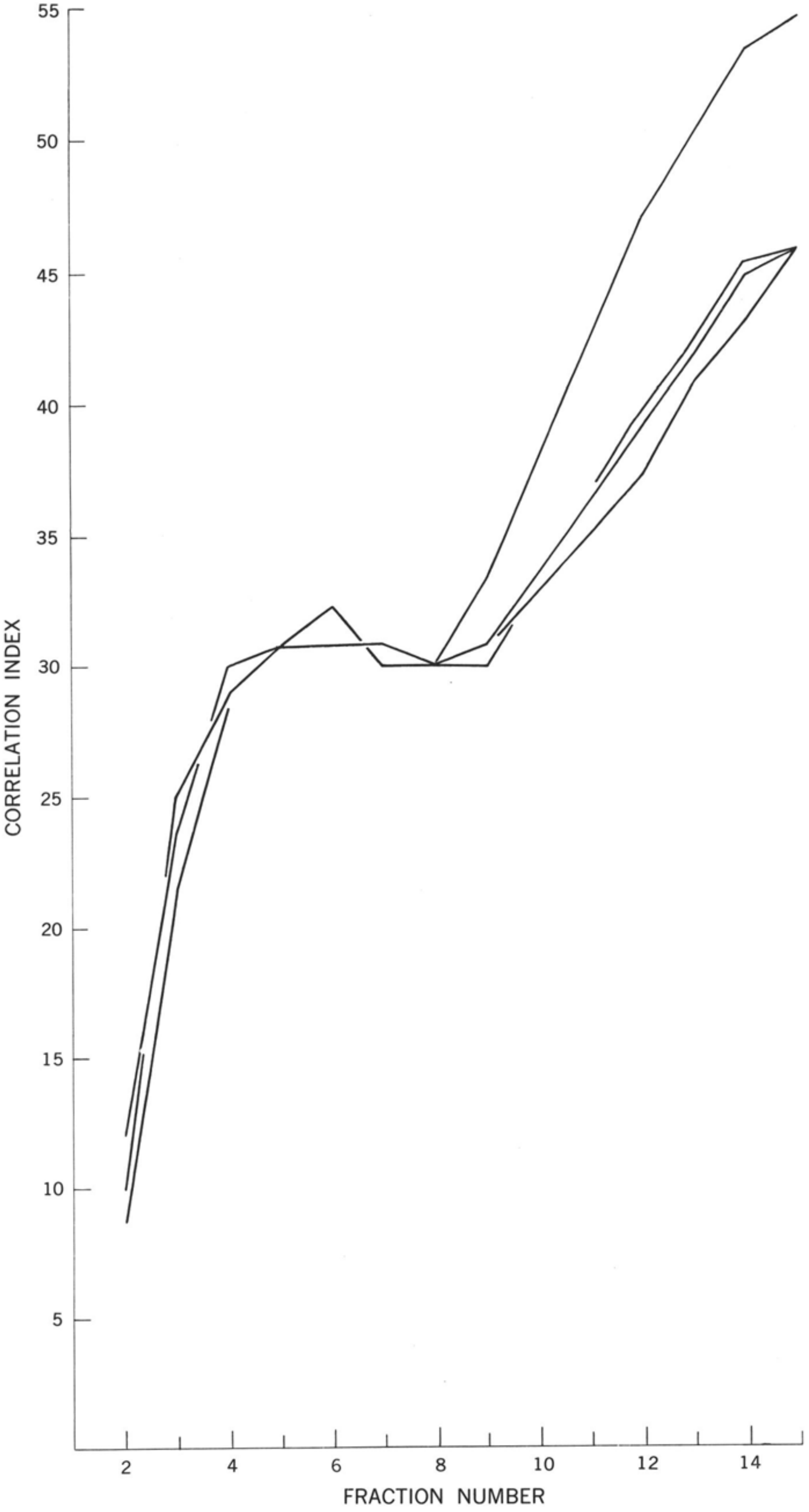


Figure 75

Correlation index profiles for crude oils from four reservoirs in Upper Permian strata in the transition zone

TABLE 14. COMPOSITION OF NATURAL GAS FROM CERTAIN RESERVOIRS IN PENNSYLVANIAN AND WOLFCAMPIAN STRATA

FIELD NAME	ALLISON	ATOKA	BLACK RIVER	BUFFALO	CRAW-FORD	DUF-FIELD	EMPIRE	HIGH-TOWER	LOS MEDAÑOS	LUSK	SAUNDERS	SCHARB	TV	WELCH	CONT'L. 2 BELL LAKE
Analysis, mole per cent															
Methane	66.5	89.9	97.0	90.9	93.8	89.7	90.0	81.9	70.9	73.4	64.7	78.3	83.4	97.7	83.6
Ethane	11.7	5.5	1.1	4.6	.4	5.5	6.8	7.8	3.3	16.4	13.6	9.6	8.5	.5	9.6
Propane	8.4	1.7	.1	1.9	.1	2.0	2.0	3.9	1.4	5.7	9.8	5.4	3.5	.0	3.2
n-Butane	4.2	0.5	tr	0.5	tr	.5	.3	1.2	.2	1.2	3.6	2.0	1.1	.0	.5
Isobutane	1.9	0.5	tr	0.3	tr	.3	.1	.5	.1	0.5	1.4	.9	0.9	.0	.5
n-Pentane	1.2	0.1	.0	0.1	.0	tr	.1	.4	tr	0.1	.9	.3	0.5	.0	.1
Isopentane	1.1	0.1	tr	0.2	tr	.2	.0	.1	.1	0.3	.7	1.3	.0	.1	.2
Cyclopentane	.2	0.2	tr	tr	tr	tr	.0	tr	tr	0.1	.1	.3	.1	.0	tr
Hexanes plus	1.0	0.4	.1	0.1	tr	.1	.1	.3	.1	0.1	.5	.7	.5	.0	.2
Nitrogen	3.3	0.5	.8	0.8	4.1	1.3	.2	3.2	18.9	1.6	1.4	.7	.8	.3	1.5
Oxygen	.1	tr	tr	0.1	.4	.1	tr	.1	4.4	tr	.2	tr	tr	.0	.2
Argon	.0	.0	.0	.0	tr	tr	.0	tr	.2	.0	.0	.0	.0	.0	tr
Hydrogen	.0	.0	tr	.0	tr	.0	.1	tr	.0	.3	—	.0	.0	.2	.1
Carbon dioxide	.4	.0	.8	.4	1.1	.3	.3	.4	.3	.0	3.2	.4	.6	1.2	.2
Hydrogen sulfide	.0	.5	.0	.0	.0	—	.0	—	.0	.2	—	.0	.0	.0	.0
Helium	tr	tr	tr	tr	tr	tr	tr	.1	tr	tr	tr	tr	tr	tr	tr
Heating value, Btu per cu ft	1573.	1124.	1010.	1097.	960.	1100.	1109.	1165.	833.	1270.	1420.	1319.	1206.	1004.	1159.
Mode of occurrence, associated (A) or nonassociated (NA)	A	NA	NA	NA	NA	NA	NA	A	NA	A	A	A	NA	NA	NA

Source of data: Boone, 1958; Miller and Norrell, 1964a,b; Munnerlyn and Miller, 1963.

Pennsylvanian and Wolfcampian reservoirs is $398,433,900. As of the same date, the ultimate producible crude oil from the same reservoirs was estimated to be 205,041,000 barrels, with an ultimate value of $594,618,900.

In 1963, the average value for all natural gas liquids at plants was $1.97 a barrel (Avery, 1964a). On this basis, the value of cumulative production of natural gas liquids to January 1, 1963, from Pennsylvanian and Wolfcampian reservoirs in southeast New Mexico was $2,968,896.

The average value of natural gas at the well head in 1963 was 15.8 cents a thousand cubic feet (Avery, 1964b). This figure would permit an estimation of $38,617,570 for cumulative natural gas production from Pennsylvanian and Wolfcampian reservoirs in the subject area to January 1, 1963.

TABLE 15. NEW FIELDS DISCOVERED DURING 1962 AND 1963 AND CHANGES IN STATUS OF SOME OLD FIELDS

OIL FIELDS

Allison Penn Lea
Allison Penn Roosevelt } fields created from Allison Penn field
Allison Penn West; new field
Anderson Ranch Wolfcamp
Anderson Ranch Wolfcamp North } fields created from Anderson Ranch Wolfcamp field
Anderson Ranch Wolfcamp South; new field
Bagley Upper Penn North; new field
Bagley Wolfcamp North; new field
Baish Wolfcamp; new field
Baish Wolfcamp North; new field
Bough Penn South; new field
Caudill Permo Penn; includes Caudill Wolfcamp
Cedar Lake Cisco; formerly Cedar Lake Atoka (abandoned)
Estacado Penn; new field
Flying M Penn; abandoned
Greenwood Strawn; new field
Henshaw Wolfcamp; field created from Shell Henshaw 1, 2, and 3 undesignated wells
High Plains Penn; new field
Inbe Penn; new field
Inbe Wolfcamp; new field
Kemnitz Lower Wolfcamp West; new field
Lane Penn Middle; new field
Lane Penn South; new field
Lovington Penn; new field
Lusk Strawn Eddy
Lusk Strawn Lea } fields created from Lusk Strawn field
Maljamar Penn; new field
Saunders Permo Penn East; new field
Tonto Wolfcamp; abandoned
Tulk Wolfcamp South; new field
Vacuum Penn; new field
Vacuum Wolfcamp; new field
Forest No. 1 State 'A' undesignated well; dropped from annual report
Pan American No. 2 Big Eddy Unit undesignated well; new field
Pan American No. 7 Greenwood Unit undesignated well; new field
Sohio No. 1 Collier et al. undesignated well; new field

GAS FIELDS

Big Eddy Wolfcamp; new field
Buffalo Valley Penn; new field
Hope Strawn; new field
Indian Basin Morrow; new field
Indian Basin Upper Penn; new field
Indian Hills Upper Penn; new field
Lake Arthur Penn; new field
Lusk Morrow; new field
Lynch Penn; new field
Mescalero North Penn; field now designated Sunray Mid-Continent New Mexico State K 1 undesignated oil well
Quail Ridge Morrow; field formerly El Paso Mescalero Ridge Unit 1 undesignated well
Quail Ridge Morrow North (abandoned); field formerly El Paso Mescalero Unit 1 undesignated well
Seven Rivers Hills Morrow; new field
Shoe Bar Penn; field formerly Western Natural Gas Grambling–State 1 undesignated well
Gulf Hackberry Hills 1 undesignated well; new field
Humble Federal–Elliott 1 undesignated well; dropped from annual report
Pan American Buffalo Unit 5 undesignated well; new field (Buffalo Penn East)
Shell Antelope Ridge Unit 1 undesignated well; new field (Antelope Ridge Morrow Penn)
Skelly West Jal Unit 1 undesignated well; new field
Southern New Mexico Oil Lusk Deep Unit 2, 3, and 5 undesignated wells; includes wells formerly designated El Paso Lusk Deep Unit 2 and 3 undesignated wells

DEVELOPMENTS IN 1962 AND 1963

Preceding parts of this report have been concerned with data available as of January 1, 1962. Petroleum activity for the years 1962 and 1963 is briefly reviewed herewith. New fields discovered during those years are shown in Table 15 and their locations are indicated in Figure 76; no attempt has been made to classify the reservoirs according to age. Table 15 also shows changes in designation of the fields used in this report (table 4), according to the Annual Report for 1963 of the New Mexico Oil and Gas Engineering Committee.

By the end of 1964, these fields had been under development for a sufficiently long period of time to allow evaluations. Six of the oil fields had recorded significant development, as tabulated below:

PRODUCTION FROM OIL FIELDS DISCOVERED IN 1962 AND 1963

FIELD	NUMBER PRODUCING WELLS	CUMULATIVE PRODUCTION (barrels)
Bagley Upper Penn North	7	294,740
Inbe Penn	10	345,516
Lane Penn South	22	1,300,701
Saunders Permo Penn East	4	674,228
Vacuum Penn	10	485,331
Vacuum Wolfcamp	27	916,359
15 other fields listed	20	565,737

Gas fields are more difficult to evaluate on the basis of production figures because of the frequent shortage of gas-gathering facilities. The tabulation below lists production to January 1, 1965:

PRODUCTION FROM GAS FIELDS DISCOVERED IN 1962 AND 1963

FIELD	NUMBER PRODUCING WELLS	CUMULATIVE GAS (Mcf)	PRODUCTION CONDENSATE (barrels)
Antelope Ridge Morrow Penn	1	2,138,667	13,781
Buffalo Penn East	1	378,085	17,559
Buffalo Valley Penn	1	719,369	6,009
Indian Basin Morrow	4	178,376	0
Indian Basin Upper Penn	6	32,148	212
Lake Arthur Penn	1	279,889	1,510
Lusk Morrow	3	1,037,310	26,257
Skelly 1 West Jal Unit	1	1,361,683	28,673
51 other fields listed	2	19,734	0

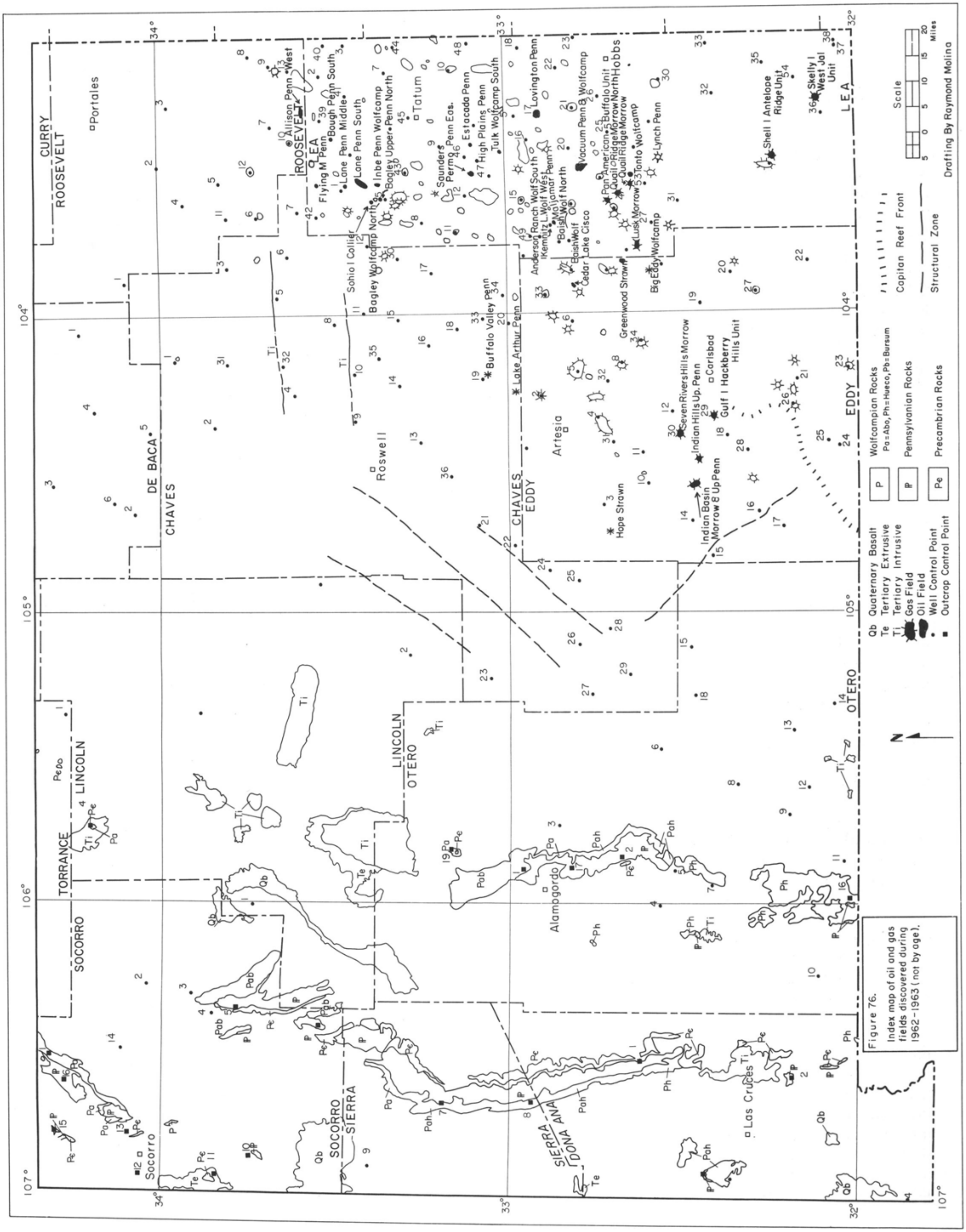


Figure 76. Index map of oil and gas fields discovered during 1962–1963 (not by age).

Summary and Conclusions

Pennsylvanian and Wolfcampian strata of southeast New Mexico may be divided into chronostratigraphic units, series and stages, by the use of fusulinids for aiding in the establishment of isochronous boundaries. Such boundaries are objective over shelf areas, where fossils are common; they become in large measure subjective adjacent to uplifts, where the strata consist largely of elastic rocks and fossils are uncommon.

Projection of unit boundaries from areas where fossils are numerous into areas where fossils are scarce may be accomplished with considerable accuracy, provided a large number of stratigraphic cross sections are constructed. Cross sections should use as a datum plane a surface as close as possible to the part of the stratigraphic section under study in order to reduce difficulties resulting from structural deformation.

There is no evidence in southeast New Mexico for rocks of earliest Pennsylvanian (Springeran) age. As a general rule, Upper Mississippian Chesteran strata are succeeded by Lower Pennsylvanian Morrowan or lower Middle Pennsylvanian Derryan rocks.

Morrowan rocks are the most restricted, geographically, of the strata under study, being confined to the southern part of the area, whereas Wolfcampian rocks are the most widely distributed. Pennsylvanian rocks represent a major transgressive cycle that begins with the deposition of predominantly elastic rocks during Morrowan time. The sea encroached upon the land from south to north; therefore, the coarsely elastic rocks deposited in it are mostly Early Morrowan in age to the south but are essentially Derryan in age in northern New Mexico, as represented by the Sandia Formation. The Desmoinesian strata of both the southeast and the north (lower Gray Limestone Member of Madera Formation) are mostly limestone. A moderate regression in Missourian time is indicated by the elastic nature of much of the rock sequence of both the southeast and the north (lower part of the upper Arkosic Limestone Member of the Madera Formation). Finally, the Virgilian rocks of the southeast as well as the north (upper part of the upper Arkosic Limestone) are predominantly carbonate. During Wolfcampian time, carbonate deposition continued in the Permian and southern Orogrande basins, but uplift to the north and west provided source areas for vast quantities of arkose and red mud; these sediments were carried southeastward by streams and deposited on mud flats and deltas over the slowly subsiding Pedernal uplift and in the adjacent Wolfcampian sea.

Structurally, the area was dominated during this period of time by the Pedernal uplift. The uplift physically separated the negative areas on the east (Permian basin) and on the west (Orogrande basin) during essentially all of the Pennsylvanian Period. Smaller uplifts were present in the map area at various times, the largest and best known of these being the Roosevelt uplift.

The structural evolution of the Central Basin platform cannot be detailed from the small part of that feature present within the limits of this report. Certain facts relating to that evolution are apparent. Thick sequences of Morrowan and Derryan rocks were deposited over the site of the platform and were subsequently folded, uplifted, and eroded. Desmoinesian strata now truncate folds involving pre-Pennsylvanian rocks on the platform. Upper Pennsylvanian and Wolfcampian rocks were next deposited at this place and were eroded when the platform was uplifted as a fault block during late Wolfcampian time. A Wolfcampian fault, on the west side of the Delaware basin, is now expressed at the surface as the Huapache monocline.

Numerous anticlines involving Pennsylvanian and Wolfcampian strata occur on the Northwest shelf. These structures are generally aligned north to south and are most intensely folded at depth. The folds appear to have originated in early Pennsylvanian time as a result of lateral compression, the folding of the younger Pennsylvanian and Wolfcampian rocks being supratenuous.

The fluids contained within rocks are basic constituents of the rock bodies and should be so considered, whether of economic significance or not. The fluids here involved include water, crude oil, and natural gas.

Diagrams of selected oil field brines, constructed to eliminate dilution effects, may be used to correlate waters between reservoirs. Such diagrams are also a helpful means of studying the degree to which the waters are altered from sea water. The waters in the rocks under study are apparently ancient, having been trapped with sediments. What cannot be determined is whether the waters are indigenous to the rocks in which they now occur or whether they are exotic, having migrated into their present reservoirs from elsewhere. In a hydrodynamic system, water moves downdip from inlet to outlet. During Pennsylvanian time, inlets were provided at various times along the margins of uplifts; it is therefore highly unlikely that the present waters are those originally in the sediments.

In the same hydrodynamic system, on the other hand, petroleum and natural gas move updip until trapped in a suitable reservoir. The hydrocarbons in a given reservoir may therefore have been generated in the containing rocks or may have evolved in either older or younger rocks that were subsequently depressed to lower structural elevation than the reservoirs. Because any earth movement will affect the hydrodynamic equilibrium of an area, and consequently the entrapment of petroleum and natural gas, the sum of all movements subsequent to reservoir bed development must be considered in the search for new deposits. Thus, in evaluating prospects for new areas or re-evaluating prospects for old ones, it is helpful to reconstruct the fluid systems as they may have existed at the time the rocks being studied were deposited, as well as the probable changes that have since occurred.

Studies of oil and gas composition are necessary for determining potential value of the hydrocarbons at the refinery; in particular, gravity, viscosity, wax content, and impurities. Composition studies have a further utility in establishing correlations between reservoirs; the correlation index and the aromatics profiles are especially useful. The petroleum aspect of petroleum geology has largely been disregarded, to the not inconsiderable detriment of exploration.

Studies involving the correlation of various reservoir parameters may also have an important bearing on exploration. If certain parameters correlate positively in the producing reservoirs of a given area, then the same parameters should be exploited in the evaluation of exploratory wells. This will require routine analysis of water and crude oil samples from all wells.

This memoir involves a variety of studies based upon variable amounts of supporting data. The validity of such studies is, of course, a function of the quantity and quality of the data available, as well as the degree to which the data are representative of the subject.

In regard to the maps of this report, data points were sufficient to permit an accurate interpretation of the geology. Data points are abundant in the Permian basin area, common to sparse elsewhere. Least precision was attained in the northeast and southwest corners of the maps and along the north half of the west side of the Pedernal uplift. An accurate portrayal of the geology is possible if each succeeding map is related to its predecessors and is not drawn as a unique item and if care is exercised that all zero lines of a given sequence match.

Correlation studies of reservoir parameters involved sufficient data to be meaningful for the Pennsylvanian and Wolfcampian reservoirs of this area. Whether the same correlations would be meaningful under other conditions will have to be demonstrated. There appears to be no inherent weakness in the technique, assuming that the published data are reliable.

The studies of oil field brines involved only about 17 per cent of the petroleum reservoirs; however, the data quality is believed to have been good and the chosen reservoirs to have been representative. It is thought, therefore, that such fluid studies, taken together with data from unsuccessful test wells, will materially aid exploration.

Crude oil and natural gas analyses were available for only a limited number of reservoirs. The reservoirs chosen, however, were representative for the area and the techniques used should be applicable elsewhere. In drawing conclusions from petroleum composition studies concerning source beds and the origin of petroleum, it must be noted that fluids migrate readily, and only rarely, if ever, would they remain unaltered at their places of origin throughout geologic time.

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CROSS SECTION A-A'

West-East Correlation Section from Dona Ana County to Lea County, New Mexico

Datum: Top of Wolfcampian Stage

Line of cross section is shown on figure 2

N.B.
In well O-4 the patterned beds are andesitic sills of Tertiary (?) age.

Geology: Richard F. Meyer
Drafting: Raymond Molina

LEGEND

Explanation of Formation Test Symbols

- ◇ Dry Well
- ● Oil producing zone
- ☼ Gas producing zone
- ✹ Oil and gas producing zone
- ☼ Gas show
- ◆ Oil show
- ◆ Oil and gas show
- M Drilling mud
- SW Salt water
- Sul W Sulfur water
- W Water

Explanation of Mechanical Logging Curves

- G Gamma ray
- R Resistivity
- SP Spontaneous potential
- N Neutron

LEGEND

Explanation of Formation Test Symbols

- ⌖ Dry Well
- ● Oil producing zone
- ☼ Gas producing zone
- ✹ Oil and gas producing zone
- ☼ Gas show
- ◆ Oil show
- ✦ Oil and gas show
- M Drilling mud
- SW Salt water
- Sul W Sulfur water
- W Water

Explanation of Mechanical Logging Curves

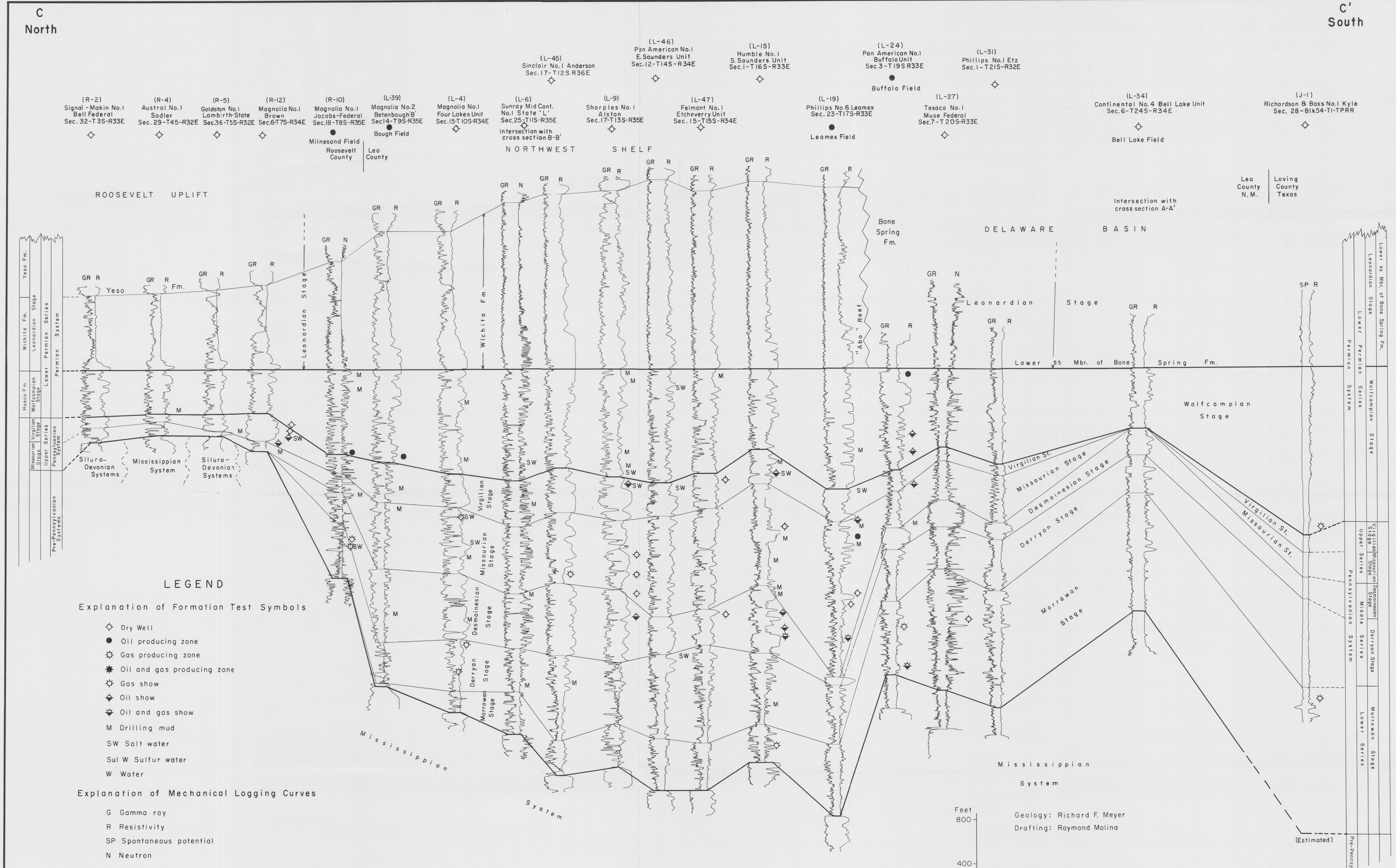
- G Gamma ray
- R Resistivity
- SP Spontaneous potential
- N Neutron

Geology: Richard F. Meyer
Drafting: Raymond Molina

CROSS SECTION B-B'
West-East Correlation Section from
Socorro County to Lea County, New Mexico

Datum: Top of Wolfcampian Stage

Line of cross section is shown on figure 2



CROSS SECTION C-C'

North – South Correlation Section from Roosevelt County, New Mexico to Loving County, Texas

Datum: Top of Wolfcampian Stage

Line of cross section is shown on figure 2

Feet 800 400 0

0 6 12 Miles

Vertical Exaggeration: 80 x

Geology: Richard F. Meyer
Drafting: Raymond Molina

Vertical Exaggeration: 80 x

Geology: Richard F. Meyer
Drafting: Raymond Molina

LEGEND

Explanation of Formation Test Symbols

- ⌖ Dry Well
- ● Oil producing zone
- ☼ Gas producing zone
- ✹ Oil and gas producing zone
- ☼ Gas show
- ◆ Oil show
- ✹ Oil and gas show
- M Drilling mud
- SW Salt water
- Sul W Sulfur water
- W Water

Explanation of Mechanical Logging Curves

- G Gamma ray
- R Resistivity
- SP Spontaneous potential
- N Neutron

CROSS SECTION D-D'

North-South Correlation Section from
De Baca County to Eddy County, New Mexico
Datum: Top of Wolfcampian Stage

Line of cross section is shown on figure 2

TABLE 4. SELECTED RESERVOIR DATA ON OIL AND NATURAL GAS FIELDS OF PENNSYLVANIA AND WOLFCAMPIAN AGES IN SOUTHEAST NEW MEXICO

			DISCOVERY																PRODUCTION			
																			ESTIMATED ULTIMATE AS OF 1962	CUMULATIVE AS OF 1963	CUMULATIVE AS OF 1962	
FIELD NAME	AGE	COUNTY	YEAR	METHOD[1]	PROVINCE	LITHOLOGY	TRAP TYPE	PRODUCING STATUS	DRIVE TYPE	DEPTH TO TOP (feet)	NET THICKNESS (feet)	POROSITY (per cent)	PERMEABILITY (md)	GRAVITY OF LIQUID (°API)	TEMPERATURE (°F)	INITIAL PRESSURE (psi)	GAS OIL RATIO	BRINE SALINITY (ppm)[2]	CRUDE OIL (thousand barrels)	CRUDE OIL (thousand barrels)	CONDENSATE (thousand barrels)	NATURAL GAS (million cu ft)
GAS FIELDS																						
Anderson	Morrowan	Eddy	1954	SUS	transition	sandstone	stratigraphic	producing	gas expansion	11039	18	—	1	48	—	5000	24390	0			160	6893
Anderson Ranch West Penn	Morrowan	Lea	1955	SEI	shelf	sandstone	stratigraphic	abandoned	gas expansion	12512	26	—	1	56	—	2990	—	—			9	101
Atoka Penn	Morrowan	Eddy	1957	SUS	transition	sandstone	stratigraphic	producing	gas expansion	9079	31	10	51	56	158	3700	90840	54635			62	5666
Bagley Lower Penn	Desmoinesian	Lea	1951	—	shelf	limestone	structural	producing	gas cap	9805	20	6	1	56	163	3254	0	—			383	8349
Bagley Upper Penn	Desmoinesian	Lea	1955	RAN	shelf	limestone	structural	producing	gas cap	8600	15	6	—	63	150	2930	28390	0			79	5068
Bandana Point Penn	Morrowan	Eddy	1959	SEI	basin	sandstone	combination	producing	gas expansion	9782	14	8	—	—	125	3200	0	—			0	24
Bell Lake Penn	Morrowan	Lea	1958	SUS	basin	sandstone	structural	producing	gas expansion	14417	28	5	—	—	187	6603	0	—			0	434
Black River Penn	Morrowan	Eddy	1958	SUB	basin	sandstone	stratigraphic	producing	gas expansion	11566	32	—	—	—	—	—	—	—			0	134
Bluitt Wolfcamp	Wolfcampian	Roosevelt	1959	SEI	shelf	limestone	structural	producing	solution gas	8022	50	8	5	72	135	3020	27000	—			1	24
Buffalo Penn	Morrowan	Lea	1958	SUS	transition	sandstone	stratigraphic	producing	gas expansion	13270	35	7	—	54	170	6330	12500	—			74	1463
Burton Penn North	Morrowan	Eddy	1960	SEI	transition	sandstone	stratigraphic	producing	gas expansion	10886	19	7	—	52	165	5625	14000	—			0	62
Cedar Lake Morrow	Morrowan	Eddy	1961	—	transition	—	—	producing	gas expansion	11357	26	—	—	59	—	2100	22324	—			2	84
Crawford Penn	Morrowan	Eddy	1957	SUS	basin	sandstone	stratigraphic	producing	gas expansion	11060	39	—	—	42	194	4850	108000	—			0	736
Duffield Penn	Morrowan	Eddy	1952	SEI	transition	sandstone	stratigraphic	producing	gas expansion	8616	56	9	—	54	—	3065	—	—			16	4003
Empire Penn	Morrowan	Eddy	1953	SEI	transition	sandstone	stratigraphic	producing	gas expansion	10102	25	12	—	60	156	3014	44607	—			144	8920
Fren Penn	Morrowan	Eddy	1954	SEI	transition	sandstone	stratigraphic	producing	solution gas	11962	15	9	125	51	160	4970	1180	—			132	4836
Grayburg Atoka Gas	Morrowan	Eddy	1957	—	transition	sandstone	—	producing	gas expansion	10680	80	—	—	56	—	3252	28300	—			95	2765
Harkey Penn	Missourian	Eddy	1958	SUS	basin	limestone	combination	producing	gas expansion	10917	93	—	—	—	160	4000	—	—			0	79
Lea Penn	Morrowan	Lea	1961	SEI	transition	sandstone	structural	producing	gas expansion	13034	23	11	—	55	177	6691	10682	—			4	70
Los Medaños Atoka	Derryan	Eddy	1958	SUS	basin	sandstone	stratigraphic	producing	gas expansion	12920	9	6	—	56	196	8371	86012	—			8	734
Mescalero Penn North	Derryan	Lea	1956	SEI	shelf	sandstone	stratigraphic	producing	gas expansion	10180	11	—	—	50	165	2258	—	0			4	238
Moore Wolfcamp	Wolfcampian	Lea	1952	SEI	shelf	limestone	structural	producing	gas cap	8198	45	8	—	60	—	2850	17050	—			63	1827
Red Lake Penn	Morrowan	Eddy	1956	SEI	transition	sandstone	stratigraphic	producing	gas expansion	9443	22	8	2	53	153	1450	209000	—			16	4505
Salt Lake Atoka South	Morrowan	Lea	1958	SUS	transition	sandstone	stratigraphic	producing	gas expansion	12909	7	7	—	48	—	1681	37175	0			29	1048
Salt Lake Morrow South	Morrowan	Lea	1960	SEI	transition	sandstone	stratigraphic	producing	gas expansion	13242	39	10	50	53	195	500	30930	0			19	561
Shugart Penn	Morrowan	Eddy	1958	OWO	transition	sandstone	stratigraphic	producing	gas expansion	10912	49	9	3	60	143	4855	22300	—			142	3774
Tonto Penn West	Morrowan	Lea	1960	SEI	transition	sandstone	structural	producing	gas expansion	13325	53	10	—	—	—	640	60000	—			2	113
TV	Morrowan	Chaves	1960	OWO	shelf	sandstone	stratigraphic	producing	gas expansion	12860	33	9	15	51	190	4800	15000	—			24	437
Welch Penn	Morrowan	Eddy	1956	SEI	basin	limestone	stratigraphic	producing	solution gas	12502	6	8	—	58	180	3551	—	—			0	769
White City Penn	Missourian	Eddy	1960	SEI	basin	limestone	combination	producing	gas expansion	9806	10	7	—	58	148	4384	—	—			0	151
Continental Bell Lake Unit 2	Derryan	Lea	1954	SEI	basin	—	combination	shut-in	gas expansion	12690	—	6	—	50	178	6092	—	—			15	164
El Paso Mescalero Unit 1	Morrowan	Lea	1961	SEI	transition	—	—	abandoned	gas expansion	13160	37	—	—	—	—	4052	7224	—			1	56
Humble Elliott Federal 1	Morrowan	Lea	1952	SEI	shelf	sandstone	structural	abandoned	gas expansion	12880	30	—	—	51	—	400	17686	—			0	83
Lawton State 2	Derryan	Lea	1952	SEI	shelf	sandstone	structural	abandoned	gas expansion	11342	40	—	—	53	150	1600	11700	—			3	38
Pan American State AD 1	Morrowan	Eddy	1954	SEI	transition	sandstone	structural	abandoned	gas expansion	11060	24	—	—	48	—	4380	—	—			1	140
Western Natural Gas Grambling State 1	Morrowan	Lea	1954	SEI	shelf	sandstone	combination	producing	gas expansion	12310	40	—	—	58	160	6792	20000	—			16	758
																					1504	65107
OIL FIELDS																						
Allison Penn	Wolfcampian	Lea	1954	SEI	shelf	limestone	combination	producing	solution gas	9673	17	9	200	48	155	3363	1346	119447	27349	16031		9923
Anderson Ranch Penn	Virgilian	Lea	1954	OWO	shelf	dolomite	structural	abandoned	water	12362	10	—	—	38	—	—	0	—	0	0		0
Anderson Ranch Wolfcamp	Virgilian	Lea	1953	SEI	shelf	limestone	structural	producing	solution gas	9664	50	10	114	42	140	3731	313	—	8881	4405		4541
Anderson Ranch Penn East	Virgilian	Lea	1957	SUS	shelf	limestone	structural	abandoned	solution gas	10960	24	4	1	40	152	60	1732	—	10	20		17
Apache Springs Wolfcamp	Wolfcampian	Chaves	1955	SUS	shelf	limestone	stratigraphic	abandoned	water	7929	7	8	1	42	134	1900	1094	—	5	5		0
Bagley Penn	Virgilian	Lea	1949	SEI	shelf	limestone	combination	producing	solution gas	9001	45	7	1	47	148	3290	2700	67098	3334	3238		9598
Bagley Lower Penn North	Desmoinesian	Lea	1957	SUS	shelf	limestone	stratigraphic	producing	solution gas	10058	20	6	—	53	145	3775	3091	—	175	120		313
Bagley East Wolfcamp	Wolfcampian	Lea	1955	SEI	shelf	limestone	combination	abandoned	solution gas	9994	17	8	1	43	129	3680	1200	—	19	19		11
Baum Wolfcamp	Virgilian	Lea	1955	SUB	shelf	limestone	combination	producing	solution gas	9940	20	8	—	43	150	150	1141	—	181	116		128
Bough Permo Penn	Wolfcampian	Lea	1949	SEI	shelf	limestone	combination	shut-in	solution gas	9615	20	13	30	44	160	3588	1604	109594	4500	4505		6340
Bronco Wolfcamp	Virgilian	Lea	1953	SEI	shelf	limestone	combination	producing	solution gas	9600	25	13	45	41	138	3640	1037	—	1795	742		421
Buffalo Wolfcamp	Wolfcampian	Lea	1954	SEI	transition	limestone	structural	producing	solution gas	10597	28	8	—	38	155	3700	1052	—	103	48		37
Canyon Wolfcamp	Wolfcampian	Eddy	1959	SEI	transition	dolomite	stratigraphic	producing	water	5741	12	9	—	45	—	300	—	—	42	23		0
Caprock Wolfcamp East	Wolfcampian	Lea	1953	SUB	shelf	limestone	combination	producing	solution gas	8400	13	10	—	44	127	2895	1190	—	630	263		396
Caprock East Penn	Derryan	Lea	1952	SUB	shelf	limestone	combination	abandoned	water	10000	9	8	—	48	154	1099	5060	—	23	23		0
Cass Penn	Desmoinesian	Lea	1944	SUS	platform	limestone	structural	producing	solution gas	7700	35	11	—	40	145	3146	196	39374	3855	1931		1657
Caudill Penn	Missourian	Lea	1951	SEI	shelf	limestone	structural	abandoned	water	11440	25	8	—	45	—	40	930	—	2	0		0
Caudill Wolfcamp	Wolfcampian	Lea	1956	OWO	shelf	limestone	structural	producing	solution gas	10292	22	8	1	42	155	3020	930	—	1627	1309		854
Cedar Lake Atoka	Missourian	Eddy	1961	—	transition	dolomite	—	producing	solution gas	10919	8	7	—	42	—	—	1894	—	41	12		18
Chambers Wolfcamp	Wolfcampian	Lea	1955	SEI	shelf	limestone	structural	producing	solution gas	10581	34	6	36	44	178	3827	1195	—	327	157		235
Crossroads Penn	Virgilian	Lea	1949	SEI	shelf	limestone	combination	producing	solution gas	9750	12	7	—	49	164	—	1663	119909	2298	2006		2489
Dean Permo Penn	Desmoinesian	Lea	1955	OWO	shelf	limestone	combination	producing	solution gas	11560	38	5	3	44	169	4134	1655	—	6366	4654		8512
Denton Wolfcamp	Wolfcampian	Lea	1950	SUS	shelf	limestone	structural	producing	solution gas	9395	53	10	13	45	154	3820	164	103705	38461	22815		8768
Denton Wolfcamp South	Wolfcampian	Lea	1960	SUB	shelf	limestone	—	producing	solution gas	10000	8	9	—	44	147	80	655	—	58	92		12
Dickinson Penn	Derryan	Lea	1957	SUS	shelf	limestone	combination	abandoned	solution gas	11504	40	7	—	43	161	75	2509	—	88	27		69
Echol Wolfcamp	Wolfcampian	Lea	1960	OWO	shelf	limestone	structural	producing	solution gas	9446	10	9	—	42	145	2560	584	—	33	11		4
Eidson Penn	Wolfcampian	Lea	1953	SEI	shelf	limestone	stratigraphic	producing	solution gas	10705	35	9	20	41	158	4064	1892	90559	2592	2219		3777
Empire Wolfcamp	Wolfcampian	Eddy	1954	SEI	transition	limestone	stratigraphic	abandoned	solution gas	7390	17	8	—	41	118	2435	432	—	46	46		53
Field Ranch Wolfcamp	Wolfcampian	Lea	1956	SEI	shelf	limestone	combination	producing	solution gas	9466	14	7	—	42	—	3200	310	—	82	65		15
Four Lakes Penn	Virgilian	Lea	1956	SUS	shelf	limestone	structural	producing	solution gas	10277	16	10	60	43	163	3803	2386	—	1051	1372		1048
Gladiola Wolfcamp	Wolfcampian	Lea	1951	SEI	shelf	limestone	combination	producing	solution gas	9555	35	8	—	42	—	3672	1600	—	4354	3094		2935
Gladiola Wolfcamp South	Wolfcampian	Lea	1955	SEI	shelf	dolomite	combination	producing	solution gas	9688	26	8	—	38	155	2982	800	—	163	122		50
Gladiola Penn South West	Derryan	Lea	1961	OWO	shelf	sandstone	structural	producing	solution gas	11119	5	7	—	54	163	525	1975	—	123	147		148
Hightower Permo Penn	Wolfcampian	Lea	1950	SEI	shelf	limestone	structural	producing	solution gas	8660	30	10	—	70	144	3130	875	—	960	468		4036
Hightower Penn East	Virgilian	Lea	1959	SUS	shelf	dolomite	stratigraphic	producing	solution gas	10218	26	7	—	41	—	3140	477	—	136	69		53
Jenkins Wolfcamp	Wolfcampian	Lea	1960	SEI	shelf	limestone	structural	producing	solution gas	9604	15	7	20	48	180	525	1214	—	184	194		149
Kemnitz Wolfcamp	Virgilian	Lea	1956	SUS	shelf	limestone	stratigraphic	producing	solution gas	10742	32	9	9	39	158	3788	1623	81382	15076	10012		13103
Kemnitz Cisco	Missourian	Lea	1957	SUB	shelf	dolomite	stratigraphic	producing	solution gas	11446	30	8	16	43	163	6911	1140	—	502	325		572
Kemnitz Penn	Missourian	Lea	1956	SEI	shelf	dolomite	—	producing	solution gas	11219	50	8	—	44	—	1100	932	—	305	135		376
King Wolfcamp	Virgilian	Lea	1951	SEI	shelf	limestone	combination	producing	solution gas	10125	7	8	—	36	158	3948	734	108410	625	488		563
King Penn	Missourian	Lea	1960	SUB	shelf	limestone	combination	producing	solution gas	10708	25	4	38	37	152	3713	870	118521	28	12		18
Knowles Wolfcamp South	Wolfcampian	Lea	1961	SEI	basin	—	—	abandoned	—	10001	99	—	—	39	—	4055	848	—	2	2		2
Lane Penn	Virgilian	Lea	1956	SEI	shelf	limestone	structural	producing	solution gas	9802	18	3	9	50	162	3537	1980	—	612	451		597
Lane Wolfcamp	Virgilian	Lea	1955	SEI	shelf	limestone	structural	producing	solution gas	9648	13	11	100	50	162	3516	2000	—	1450	1028		1541
Lazy J Penn	Virgilian	Lea	1952	SEI	shelf	limestone	structural	producing	solution gas	9580	20	6	8	43	146	3546	1200	105741	4155	3326		4702
Leamex Wolfcamp	Wolfcampian	Lea	1958	SEI	transition	limestone	combination	producing	solution gas	10622	54	7	—	37	133	4048	1003	—	261	93		27
Leamex Penn	Missourian	Lea	1956	SEI	transition	limestone	combination	producing	solution gas	11316	36	7	—	37	136	150	1061	—	525	76		486
Little Lucky Lake Penn	Morrowan	Chaves	1959	—	shelf	—	—	abandoned	—	10252	30	—	—	48	—	4820	3200	—	1	1		0
Loco Hills Wolfcamp	Wolfcampian	Eddy	1960	SUS	transition	—	—	abandoned	water	9685	—	—	—	42	—	300	—	—	1	1		0
Lone Wolfcamp	Virgilian	Chaves	1953	SEI	shelf	limestone	stratigraphic	producing	solution gas	7774	19	11	—	42	129	3068	1220	—	168	115		180
Lovington Wolfcamp	Wolfcampian	Lea	1952	SUB	transition	limestone	combination	abandoned	solution gas	10148	5	9	—	40	150	3727	719	131544	81	81		159
Lovington Penn East	Desmoinesian	Lea	1951	SEI	transition	limestone	combination	producing	solution gas	11080	30	7	2	43	168	3327	1092	—	2484	1543		1780
Lusk Strawn	Desmoinesian	Lea	1960	SEI	transition	—	—	producing	water	11168	38	7	17	48	161	5810	3084	—	262	1763		0
Maljamar Wolfcamp	Wolfcampian	Lea	1961	SUS	transition	limestone	stratigraphic	producing	solution gas	10390	10	9	—	42	152	2638	927	—	83	94		20
Maljamar Strawn	Virgilian	Lea	1960	RAN	transition	limestone	combination	abandoned	solution gas	11616	10	7	—	51	226	6210	1022	—	51	36		32
Mescalero Permo Penn	Virgilian	Lea	1952	SUS	shelf	limestone	structural	producing	solution gas	8390	16	8	18	46	163	325	432	—	1134	682		877
Mescalero Wolfcamp North	Wolfcampian	Lea	1960	SUS	shelf	limestone	combination	producing	water	8350	15	9	13	43	142	3011	1074	—	97	54		0
Milnesand Penn	Wolfcampian	Roosevelt	1956	SEI	shelf	limestone	combination	producing	solution gas	9202	14	4	10	47	134	3320	1570	—	936	844		1076
Moore Penn	Desmoinesian	Lea	1952	SUB	shelf	limestone	structural	producing	solution gas	9654	8	7	—	48	164	3411	2454	—	66	29		363
New Hope Penn	Missourian	Roosevelt	1951	SEI	shelf	limestone	stratigraphic	abandoned	solution gas	8131	11	5	—	48	150	2590	1615	—	7	7		14
Pearl Penn	Morrowan	Lea	1959	SEI	transition	sandstone	stratigraphic	producing	solution gas	12640	24	7	—	43	164	325	4700	—	71	42		98
Penasco Wolfcamp	Wolfcampian	Eddy	1960	SEI	transition	limestone	stratigraphic	producing	solution gas	5740	10	6	—	45	105	700	1345	—	25	13		24
Prarie Penn South	Wolfcampian	Roosevelt	1960	—	shelf	limestone	—	producing	solution gas	9653	7	4	194	42	—	—	1600	—	729	1558		751
Querecho Plains Penn	Desmoinesian	Lea	1957	SEI	transition	limestone	combination	producing	solution gas	11595	50	7	25	42	171	50	1621	—	339	304		441
Ranger Lake Penn	Virgilian	Lea	1956	SEI	shelf	limestone	combination	producing	solution gas	10312	33	10	28	41	162	3620	796	—	5854	3093		2334
Reeves Penn	Desmoinesian	Lea	1956	SEI	transition	sandstone	structural	producing	solution gas	10945	10	10	—	45	171	4650	1432	—	882	753		766
Remuda Wolfcamp	Wolfcampian	Eddy	1960	SEI	basin	limestone	structural	producing	solution gas	11111	43	9	—	47	140	100	—	—	26	8		18
Sanmal Penn	Missourian	Lea	1957	—	transition	limestone	—	shut-in	solution gas	11708	14	7	—	42	—	500	1036	—	10	10		35
Saunders Permo Penn	Virgilian	Lea	1950	SEI	shelf	limestone	structural	producing	solution gas	9908	30	10	—	43	146	3523	1400	75728	30286	22536		32955
Saunders Permo Penn South	Virgilian	Lea	1951	SUS	shelf	limestone	combination	producing	solution gas	10587	22	8	1	36	150	2600	820	—	377	134		95
Scharb Penn	Morrowan	Lea	1960	SEI	transition	sandstone	stratigraphic	abandoned	solution gas	13033	23	—	—	54	244	6640	—	—	4	4		49
Shoe Bar Penn	Wolfcampian	Lea	1954	SEI	transition	limestone	stratigraphic	producing	solution gas	10440	55	10	—	44	—	1000	879	—	423	205		47
Shoe Bar Penn North	Desmoinesian	Lea	1958	OWO	transition	limestone	stratigraphic	producing	solution gas	10954	26	7	—	43	—	1100	1227	30484	69	30		54
Shugart Wolfcamp	Wolfcampian	Eddy	1961	SEI	transition	limestone	structural	producing	water	9615	10	9	—	42	142	3690	1894	—	60	12		18
Spencer Penn	Wolfcampian	Lea	1961	SUB	transition	limestone	combination	abandoned	solution gas	9698	60	—	—	44	166	3825	700	—	1	1		0
Squyres Penn	Virgilian	Roosevelt	1961	SUB	shelf	limestone	combination	producing	solution gas	8380	10	7	—	45	—	3388	163	—	20	6		4
SRR Penn	Missourian	Lea	1955	SEI	shelf	limestone	structural	abandoned	solution gas	9208	10	—	—	49	162	3185	3160	—	37	37		164
Tatum Wolfcamp	Wolfcampian	Lea	1957	SUS	shelf	limestone	structural	producing	solution gas	10285	19	10	12	43	—	3930	2100	—	1235	372		367
Tento Deep Wolfcamp	Wolfcampian	Lea	1960	SEI	transition	limestone	stratigraphic	abandoned	solution gas	11394	29	—	—	40	—	20	41	—	2	2		1
Townsand Wolfcamp	Wolfcampian	Lea	1952	SEI	shelf	limestone	stratigraphic	producing	solution gas	10410	36	8	38	40	156	3950	2003	—	23493	14927		45597
Tulk Wolfcamp	Virgilian	Lea	1951	SEI	shelf	limestone	combination	producing	solution gas	9700	25	8	—	42	161	3470	1178	—	1825	1276		1955
Tulk North Wolfcamp	Virgilian	Lea	1952	SUS	shelf	limestone	structural	abandoned	water	9564	10	—	—	41	144	3025	1500	—	5	5		0
Vacuum South Wolfcamp	Wolfcampian	Lea	1960	OWO	transition	limestone	combination	producing	solution gas	10011	16	9	—	38	—	—	—	—	69	63		23
Williams Penn	Derryan	Lea	1955	SEI	shelf	sandstone	stratigraphic	abandoned	water	11097	17	—	—	48	161	4187	3089	—	82	55		0
Williams Penn North	Derryan	Lea	1961	SEI	shelf	limestone	structural	producing	—	11050	10	—	—	48	—	4186	5640	—	51	4		8
Amerada Mathers B 1	Wolfcampian	Lea	1957	SEI	shelf	limestone	structural	producing	solution gas	8641	16	9	—	46	—	675	2819	—	84	50		264
El Paso Mescalero Ridge Unit 1	Morrowan	Lea	1961	SEI	transition	—	—	abandoned	—	13328	12	—	—	—	—	6545	—	—	11	11		5
Forest State A 1	Missourian	Lea	1958	—	shelf	—	—	abandoned	water	11450	73	—	—	42	—	750	1349	—	3	3		0
Humble S Saunders Unit 1	Desmoinesian	Lea	1956	SUB	shelf	limestone	structural	abandoned	water	—	34	—	—	39	—	—	—	—	0	0		0
Lawton State L 1	Desmoinesian	Lea	1953	SEI	transition	limestone	stratigraphic	abandoned	water	11438	34	—	—	42	155	1100	1243	—	4	4		0
Shell Henshaw 1	Wolfcampian	Eddy	1960	SEI	transition	limestone	combination	producing	solution gas	8500	10	6	17	43	126	3410	1377	—	51	143		97
Shell Henshaw 2	Virgilian	Eddy	1961	SEI	transition	limestone	combination	producing	solution gas	9124	18	7	20	42	126	3390	595	—	54	130		27
Shell Henshaw 3	Virgilian	Eddy	1961	SEI	transition	limestone	combination	producing	solution gas	8711	30	7	2	41	126	3390	1501	—	53	34		16
																			205041	137391		179308

Sources of data: New Mexico Oil & Gas Engineering Committee, Annual Reports; Stipp et al., 1956; Sweeney et al., 1960; American Association of Petroleum Geologists Bulletin, annual exploration issues; International Oil Scouts, annual production reviews; various oil companies.

[1] SEI, seismic; SUB, subsurface geology; SUS, seismic plus subsurface geology; RAN, random drilling; OWO, oil well worked over.

[2] 0, no water in reservoir.

TABLE 13. CERTAIN CHARACTERISTICS OF DISTILLATE FRACTIONS OF CRUDE OILS FROM SEVEN RESERVOIRS IN VIRGILIAN AND WOLFCAMPIAN STRATA

FRACTION NUMBER AND FIELD (Distillation temp.; 1-10 at 740 mm Hg, 11-15 at 40 mm Hg)	VOLUME PER CENT		SPECIFIC GRAVITY (60/60°F)		REFRACTIVE INDEX (n_d at 20°C)	SPECIFIC DISPERSION	MOLECULAR WEIGHT	CORRELATION INDEX		AROMATICS		NAPHTHENES (weight per cent)	PARAFFINS (weight per cent)	CLOUD TEST (°F)	VISCOSITY S.U. SECS (100°F)
	FRACTION	SUM	FRACTION	AROMATIC FREE				FRACTION	AROMATIC FREE	VOLUME PER CENT	WEIGHT PER CENT				
1 (50°C, 122°F)															
Bagley	3.3	3.3	0.642												
Caprock, East	1.5	1.5	.643												
Denton	4.1	4.1	.641		1.37247	129.9									
Gladiola	3.5	3.5	.645		.36836	134.1									
Kemnitz															
Saunders	2.8	2.8	.639		.36484	112.1									
Townsend															
2 (75°C, 167°F)															
Bagley	5.3	8.6	.673	0.667	.37855	126.9	79	9	6	2.8	2	5	93		
Caprock, East	2.6	4.1	.676	.665	.37430	130.0	83	10	5	4.7	4	5	91		
Denton	4.1	8.2	.673	.667	.37876	122.0	83	8	6	3.3	3	6	91		
Gladiola	4.1	7.6	.683	.667	.38343	127.3	83	14	6	3.0	2	15	83		
Kemnitz	2.7	2.7	.698	.655	.41407	152.5	82	—		19.1	15	0	85		
Saunders	4.1	6.9	.684	.673	.38386	129.9	83	14	9	4.7	4	13	83		
Townsend	4.0	4.0	.735	.704	.41041	147.7	79	—	24	16.9	13	43	44		
3 (100°C, 212°F)															
Bagley	8.2	16.8	.716	.705	.40041	130.8	84	19	14	5.7	5	23	72		
Caprock, East	7.3	11.4	.721	.710	.40140	130.8	93	22	17	5.7	5	7	88		
Denton	8.7	16.9	.720	.713	.40113	127.7	93	21	18	3.6	3	50	47		
Gladiola	9.8	17.4	.729	.721	.40527	129.1	92	26	22	4.6	4	36	60		
Kemnitz	10.7	13.4	.761	.727	.42432	154.7	89	41	25	23.3	19	43	38		
Saunders	10.2	17.1	.735	.718	.40927	136.3	90	28	20	9.7	8	33	59		
Townsend	15.9	19.9	.778	.742	.43264	157.2	85	49	32	25.7	21	54	25		
4 (125°C, 257°F)															
Bagley	11.0	27.8	.742	.725	.41483	137.8	105	23	15	11.0	9	23	68		
Caprock, East	10.7	22.1	.746	.730	.41527	137.1	105	25	17	10.5	9	27	64		
Denton	9.3	26.2	.749	.737	.41673	134.4	105	26	20	8.6	7	35	58		
Gladiola	11.0	28.4	.754	.742	.41940	135.1	104	28	23	9.2	8	41	51		
Kemnitz	13.7	27.1	.785	.753	.43737	158.4	100	43	28	27.1	23	49	28		
Saunders	11.0	28.1	.763	.743	.42381	142.4	103	33	23	14.6	12	39	49		
Townsend	11.8	31.7	.795	.756	.44274	166.2	99	48	29	33.4	28	51	21		
5 (150°C, 302°F)															
Bagley	8.8	36.6	.763	.741	.42636	143.2	118	25	15	16.4	14	23	63		
Caprock, East	9.5	31.6	.765	.741	.42636	142.0	118	26	16	15.5	14	26	60		
Denton	7.3	33.5	.769	.745	.42916	144.9	117	28	17	17.9	16	27	57		
Gladiola	6.6	35.0	.775	.755	.43092	141.8	117	31	21	15.5	14	36	50		
Kemnitz	7.4	34.5	.797	.758	.44478	163.4	113	41	23	33.8	34	38	28		
Saunders	7.7	35.8	.779	.754	.43436	148.9	115	33	21	21.3	19	36	45		
Townsend	7.4	39.1	.803	.763	.44834	165.3	113	44	25	35.6	31	42	27		
6 (175°C, 347°F)															
Bagley	6.9	43.5	.779	.753	.43551	146.2	130	26	14	19.8	17	23	60		
Caprock, East	7.5	39.1	.782	.759	.43560	143.8	129	27	16	17.9	16	28	56		
Denton	7.3	40.8	.785	.762	.43884	145.3	128	29	18	19.2	17	31	52		
Gladiola	6.1	41.1	.792	.771	.44083	144.9	128	32	22	19.0	17	39	44		
Kemnitz	6.1	40.6	.802	.766	.44809	158.1	126	37	20	30.6	31	34	35		
Saunders	6.1	41.9	.792	.764	.44147	150.5	128	32	19	23.8	21	33	46		
Townsend	4.9	44.0	.805	.768	.44936	159.8	125	38	21	32.1	28	37	35		
7 (200°C, 392°F)															
Bagley	5.2	48.7	.792	.767	.44234	144.2	146	26	14	18.2	16	24	60		
Caprock, East	6.9	46.0	.794	.773	.44248	143.2	146	27	17	17.4	15	32	53		
Denton	4.8	45.6	.800	.774	.44553	147.3	145	30	17	20.9	19	31	50		
Gladiola	5.5	46.6	.806	.780	.44870	147.3	144	32	20	21.9	19	36	45		
Kemnitz	4.2	44.8	.808	.776	.45057	154.0	144	33	18	26.8	27	32	41		
Saunders	5.0	46.9	.802	.777	.44716	147.7	144	31	19	21.3	19	34	47		
Townsend	4.6	48.6	.813	.780	.45266	155.9	142	36	20	28.6	25	36	39		
8 (225°C, 437°F)															
Bagley	6.0	54.7	.804	.775	.44938	146.5	165	26	12	20.0	17	23	60		
Caprock, East	6.2	52.2	.807	.778	.44960	147.9	164	27	14	21.1	19	24	57		
Denton	5.4	51.0	.813	.787	.45253	146.9	164	30	18	20.4	18	32	50		
Gladiola	5.7	52.3	.820	.789	.45695	150.7	162	33	19	23.8	21	34	45		
Kemnitz	4.9	49.7	.820	.788	.45682	152.3	162	33	18	25.2	25	33	42		
Saunders	5.2	52.1	.816	.787	.45452	150.1	162	32	18	23.2	20	33	47		
Townsend	4.2	52.8	.828	.788	.46115	159.0	160	37	18	31.1	27	34	39		
9 (250°C, 482°F)															
Bagley	5.7	60.4	.819	.787	.45757	149.7	180	28	13	20.8	18	23	59		
Caprock, East	6.0	58.2	.821	.779	.45730	154.9	180	29	9	25.5	22	16	62		
Denton	5.7	56.7	.828	.788	.46128	154.6	180	32	13	25.5	22	24	54		
Gladiola	5.8	58.1	.835	.791	.46654	159.3	178	35	14	29.4	26	26	48		
Kemnitz	5.9	55.6	.841	.792	.46902	162.8	178	38	14	32.5	28	30	42		
Saunders	5.6	57.7	.834	.792	.46469	157.0	178	35	15	27.6	24	30	46		
Townsend	5.8	58.6	.850	.796	.47428	169.4	175	42	17	38.2	33	32	35		
10 (275°C, 527°F)															
Bagley	6.1	66.5	.834	.798	.46551	157.2	200	30	13	23.5	21	25	54		
Caprock, East	6.8	65.0	.834	.795	.46548	160.0	199	30	12	25.4	22	22	56		
Denton	6.2	62.9	.842	.804	.47007	161.3	199	34	16	26.5	23	31	46		
Gladiola	6.3	64.4	.849	.818	.47533	168.6	198	37	23	31.8	28	41	31		
Kemnitz	6.0	61.6	.858	.807	.48029	174.6	194	41	17	36.3	32	32	36		
Saunders	6.3	64.0	.850	.808	.47440	166.5	198	38	18	30.4	27	34	39		
Townsend	5.5	64.1	.867	.820	.48429	174.7	192	46	23	36.7	32	42	26		
11 (200°C, 392°F)															
Bagley	2.9	69.4	.849	.811	.47279	160.5	221	33	15	26.9	24	30	46	—	—
Caprock, East	4.3	69.3	.849	.814	.47307	159.8	220	33	17	26.4	24	33	43	15	39
Denton	2.4	65.3	.858	.823	.47652	161.5	216	37	21	27.8	25	39	36	—	—
Gladiola	3.0	67.4	.860	.836	—	—	216	38	—	—	—	—	—	15	39
Kemnitz	5.8	67.4	.884	—	.49091	181.6	210	50	27	43.4	39	47	14	20	41
Saunders	2.8	66.8	.862	—	—	—	215	39	—	—	—	—	—	10	40
Townsend	2.1	66.2	.874	—	.49117	—	222	45	—	—	—	—	—	14	41
12 (225°C, 437°F)															
Bagley	5.3	74.7	.855	—	.47582	160.8	244	32	—	—	—	—	—	—	—
Caprock, East	6.5	75.8	.857	—	.47701	169.0	242	33	—	—	—	—	—	44	40
Denton	5.4	70.7	.864	—	.47910	160.1	238	37	—	—	—	—	—	—	—
Gladiola	5.4	72.8	.865	—	—	—	240	37	—	—	—	—	—	30	42
Kemnitz	5.3	72.7	.894	—	.49766	189.2	234	51	—	—	—	—	—	40	51
Saunders	4.8	71.6	.868	—	—	—	240	38	—	—	—	—	—	35	44
Townsend	4.6	70.8	.883	—	.49360	—	236	46	—	—	—	—	—	30	46
13 (250°C, 482°F)															
Bagley	4.5	79.2	.864		.48159	164.9	268	33	—	—	—	—	—	—	52
Caprock, East	4.2	80.0	.866		.48248	157.0	268	34	—	—	—	—	—	55	55
Denton	5.1	75.8	.875		.48469	168.3	265	38	—	—	—	—	—	—	56
Gladiola	4.9	77.7	.874		—	—	265	38	—	—	—	—	—	45	54
Kemnitz	4.3	77.0	.901		.50377	189.1	260	51	—	—	—	—	—	60	70
Saunders	4.8	76.4	.878		—	—	265	40	—	—	—	—	—	50	55
Townsend	4.3	75.1	.896		.49951	—	236	48	—	—	—	—	—	50	59
14 (275°C, 527°F)															
Bagley	3.7	82.9	.877		—	—	295	36	—	—	—	—	—	—	—
Caprock, East	3.5	83.5	.874		—	—	295	35	—	—	—	—	—	70	72
Denton	4.4	80.2	.885		—	—	292	40	—	—	—	—	—	—	77
Gladiola	4.2	81.9	.885		—	—	291	40	—	—	—	—	—	65	73
Kemnitz	4.6	81.6	.912		—	—	285	53	—	—	—	—	—	80	125
Saunders	3.5	79.9	.888		—	—	290	41	—	—	—	—	—	65	74
Townsend	3.8	78.9	.905		—	—	286	49	—	—	—	—	—	64	87
15 (300°C, 572°F)															
Bagley	4.0	86.9	.883				330	36	—	—	—	—	—		103
Caprock, East	4.4	87.9	.885		—	—	335	37	—	—	—	—	—	85	110
Denton	4.6	84.8	.895		—	—	345	42	—	—	—	—	—	—	135
Gladiola	4.5	86.4	.895		—	—	335	42	—	—	—	—	—	85	120
Kemnitz	4.3	85.9	.922				355	55	—	—	—	—	—	90	265
Saunders	4.8	84.7	.897		—	—	330	43	—	—	—	—	—	80	125
Townsend	4.6	83.5	.912		—	—	340	50	—	—	—	—	—	80	170
Residuum															
Bagley	9.6	96.5	.925												
Caprock, East	11.7	99.6	.926												
Denton	14.1	98.9	.935												
Gladiola	12.4	98.8	.946												
Kemnitz	13.1	99.0	.959												
Saunders	13.6	98.3	.943												
Townsend	11.9	95.4	.949												

Source of data: U.S. Bureau of Mines Bartlesville Laboratory, Okla., McKinney and Garton, 1957.