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Structure, Stratigraphy, and Hydrogeology of the Northern Roswell Artesian Basin, Chaves County, New Mexico

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Abstract

Structural and stratigraphic controls of the quantity and quality of waters within the northernmost part of the Roswell artesian basin were studied using outcrops, cores, samples, and electric logs.

Three structural zones are recognized: The Border Hill, Six Mile, and YO. A fourth near the town of Dexter is suggested, and a fifth in the vicinity of T. 14 S., R. 27 E. is considered because of the close dating of faulting (early Desmoines). Three structural blocks, Six Mile, Roswell, and Orchard Park, between the first four of these zones are delineated.

The strata in the Orchard Park block are most uniform and compare generally to the complete section preserved in the subsurface east of the artesian basin. The Glorieta, lower and upper units of the San Andres, and most of the Artesia Group are present. The artesian aquifer is developed in the top one third of the San Andres (all in the upper unit) and in the overlying Grayburg. The Queen forms the aquitard between the artesian and shallow aquifers. The latter comprises part of the Seven Rivers Formation and the overlying Tertiary–Quaternary alluvium.

Structural uplift and consequent deep, irregular erosion have stripped the Artesia Group and the upper unit of the San Andres from the Roswell block. Secondary porosity enlargement has been developed in the Slaughter zone of the lower San Andres and constitutes the principal porosity zone of the artesian aquifer. The Slaughter zone, a regionally porous and permeable unit, is the principal hydrocarbon-producing zone of the San Andres of the Northwest Shelf of southeast New Mexico and west Texas.

Reduced head, because of regional over-appropriation, and reduced pressure, caused by locally intensive pumping on the Roswell block, relieve the retarding hydrostatic pressure on the saline waters in the regionally porous Slaughter zone and permit saline water encroachment into the Roswell block. The positioning of the Queen aquitard on the downthrown side of the YO structural zone probably inhibits the movement of saline water from the Roswell to the Orchard Park block.

Erosion of the Roswell block has developed a collapse breccia and overlying terra rossalike residual clay, heretofore referred to the Artesia Group. This younger deposit forms the aquitard on the Roswell block. Physical differences of the Queen aquitard indicate that its leakage factor will be much higher than the Queen.

The Six Mile block is a grabenlike tilted fault block. A more complete San Andres comprises part of this block than the Roswell block. Remnants of the Artesia, previously reported, are not present in part of the block.

Considerations for control of saline encroachment include additional stratigraphic work to determine the areal extent of the base of the aquifer porosity and Slaughter porosity interface. Retardation might result from the employment of injection wells. Further investigations should include acquiring more electric logs, sample examination, continued study of the Glorieta, and adaptation of hydrologic methods to the geology.

Introduction

The exact limits of the Roswell artesian basin have not been hydrologically delineated. As administratively defined by the State Engineer, the Roswell artesian basin, in western Chaves and Eddy counties, New Mexico, has an irregular shape and extends from the state line southwest of Carlsbad to about 15 miles north of Roswell. The eastern edge of the declared basin lies immediately east of the Pecos River and its westernmost margin is the Chaves county line.

The hydrologic complex comprising the basin is essentially the crest of the Sacramento Mountains. The complimentary hydrologic complex resulting in the artesian basin near the Pecos Valley covers more than 3000 square miles. For practical purposes, the southern limit of the basin system is in the immediate vicinity of Major Johnson Springs, north of Carlsbad. The northern ground-water boundary is near Arroyo Macho, north of Roswell.

This investigation primarily concerns the vicinity of the City of Roswell in the northernmost part of the Roswell artesian basin. The effective extent of the area considered does not go beyond the limits of western Chaves County. The structure contouring (pls. 1 and 2) covers a larger area than that considered in dealing with the more detailed stratigraphy of the producing formations.

PURPOSE

For sixty years, the Roswell artesian basin has been the almost continuous subject of various hydrologic and geologic investigations. Fiedler and Nye's (1933) report on the area culminated a most complete geologic investigation. During the thirty years following their report, new geological and hydrological techniques have provided much additional information.

This investigation generally attempts to re-evaluate the structural and stratigraphic geology of the northern part of the Roswell artesian basin, to analyze the abundant hydrologic data available in the light of these geological controls, and to explain local conditions in various areas of the northernmost part of the basin. Specifically, this paper considers the stratigraphic and/or structural controls that influence the movement of ground water and control the quantity, quality, and distribution of saline water in the immediate Roswell area.

The writer hopes to propagate the criticism and dispute necessary to stimulate additional investigations and provide more alert investigators with a different approach to an old problem. If nothing else, this investigation may give some insight into the specific structural, stratigraphic, and hydrogeologic problems that need re-examining.

INVESTIGATIONS

Investigators have published hydrogeologic work on the Roswell artesian basin since the beginning of the century, most notably the reports by Fieldler and Nye (1933) and Mourant (1963).

Most of the many other reports on the area are local or limited in scope. Since 1933 (excepting Mourant), the rocks that carry and contain the waters of the Roswell artesian basin have received little attention. A selected bibliography follows the *References* at the end of this report.

The State Engineer's Office, the U.S. Geological Survey, the Roswell Geological Society, and various individuals are presently conducting geological and hydrological investigations. The New Mexico Institute of Mining and Technology, in conjunction with the New Mexico Water Resources Institute, has commenced a study of the Pecos Valley and the Roswell artesian basin system.

ACKNOWLEDGMENTS

I am indebted to many individuals and organizations for the data used and the assistance received in arriving at the interpretations presented herein.

The City of Roswell, the Pecos Valley Artesian Conservancy District, and the Hagerman Irrigation Company each expended many thousands of dollars to drill the test holes required to obtain the data used in this report. I cannot fully express my appreciation for the opportunity to use this information. The constituents and members of these groups should be proud of the councilmen and directors who have intelligently, aggressively, and prudently sought practical and scientifically sound solutions to large water problems, while constantly keeping in mind the well-being and rights of all other water users.

I thank my coworkers on the Stratigraphic Studies Committee of the Roswell Geological Society. In conjunction with the U.S. Geological Survey, these committeemen built a correlation network throughout the entire Roswell artesian basin. This work (in preparation) represents the first major regional geological reevaluation of the basin since Fiedler and Nye. I have freely used these regional control data and have attempted to utilize, for the sake of conformity, the same formational tops chosen by the Roswell Geological Society, which provide essentially the upper and lower boundaries for the stratigraphic discussions of this report; however, I accept all responsibility for the interpretations presented herein, as well as for formation tops indicated (or possibly omitted).

My sincere gratitude goes to the following fellow scientists for the individual help and constructive criticism they offered me: Jack R. Barnes, consulting hy-

drologist; S. E. Galloway, State Engineer's Office; Mervin L. Klug, ground-water consultant; George Maddox, U.S. Geological Survey; and Thomas Mann, Mann Engineering Co., consulting engineers. Many others have played major roles in obtaining data and helping to formulate the writer's concepts.

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MAJOR PROBLEMS

The major problems of the northern part of the Roswell artesian basin fall broadly into three interrelated groups:

(1) over-appropriation
(2) depletion of the flow of the Pecos River
(3) saline encroachment

OVER-APPROPRIATION

Storage data and accurate recharge measurements do not sufficiently delineate the annual over-appropriation from the entire Roswell artesian basin system, but the amount of withdrawal in excess of recharge amounts to about 250,000 acre feet a year (Hantush, 1965). Such large over-appropriation causes significant declines in the water levels of wells in the basin (State Engineer's Technical Reports, ground-water levels in New Mexico) and coincidentally changes the economics of pumping. Excessive withdrawals diminish the flow of the Pecos River and cause saline water encroachment.

PECOS RIVER FLOW

A major part of the Pecos River flow in the past has come from tributary streams flowing to the Pecos River across the artesian basin, ground-water flow from the shallow aquifer into the river, and spring flows emerging from the artesian aquifer and discharging into the Pecos River.

With increased appropriations from the artesian and shallow aquifers, the tributary stream flow has all but completely ceased, except for rare flooding. Decreased water levels in both the artesian and shallow aquifers have greatly reduced base flow to the Pecos River (Engineering Subcommittee, Pecos River Commission) and long ago caused cessation of spring flow from the large natural outlets of the artesian aquifer system, such as South Springs, North Springs, and Berrendo Springs.

Decreased flow in the Pecos River is of prime concern to the State Engineer, not only because he is charged with control and conservation of the waters of the State of New Mexico but also because of the Pecos River compact. Specific amounts of water originating in New Mexico are, by terms of the agreement with Texas, designated for downstream users. Diminution of river flow sources by drying of the tributary streams and spring flows places a much heavier burden on returns from irrigation as the primary sources to the Pecos River between Acme and the southern limits of the Roswell artesian basin.

Fiedler and Nye suggested that the 36,500-acre-foot (50-second-foot) gain of the Pecos River between Acme and Artesia during 1927 resulted from leakage from the artesian aquifer. During 1938, the net gain to the Pecos River over the same area was about 54,000 acre-feet, whereas in 1962 it was only 22,000 acre-feet. Discounting the abnormally high precipitation of 1941 and 1942, the intervening period shows a general decline in net ground-water discharge to the river. Continued overdraft will ultimately cause a significantly greater decrease in the flow of the Pecos River and reversal of the system. In 1964, the piezometric head on the artesian aquifer was insufficient throughout the irrigation season to force water through the leaky aquitard into the shallow aquifer. This further compounds the problem of depletion of the shallow aquifer below the point where it will contribute to the flow of the Pecos River and instead will eventually rob water from the river.

SALINE ENCROACHMENT

In and around Roswell, saline water has been moving into the artesian aquifer. The northernmost part of the basin, historically, has always had saline water in varying degrees. During the past few years, the problem has become one of movement of higher concentrations of chloride ions into areas of previously good water. The apparent direction of movement is generally from northeast of Roswell toward the southwest. Chloride ion concentrations currently range from about 40 ppm (parts per million) southwest of Roswell to 39,000 ppm northeast of the city. Hood, Mower, and Grogin (1960, p. 33) indicate encroachment at the rate of about 0.1 mile a year from August 1952 to September 1957.

ECONOMIC EFFECTS OF SALINITY ENCROACHMENT

While only the northernmost part of the basin is being significantly affected by salinity increases, the economic considerations are considerable. The effect on agriculture near Roswell has been severe in terms of crop productivity losses because of plant intolerability to chlorides and associated sodium. Some acreage has been completely lost because of the lack of sufficient low-salinity water for irrigation.

Supplemental irrigation waters obtained from the shallow aquifer cut the chloride content of waters from the artesian aquifer, but this provides only a temporary reprieve for many of the commercial irrigators. Evapotranspirative consumption still concentrates the salts into the shallow aquifer. In only a matter of time, the shallow waters will contain salt concentrations far in excess of the tolerability of osmotic plant processes.

The economic effects on Roswell are much more clearly evident. The U.S. Department of Public Health recommends that a municipal water supply not exceed a chloride ion concentration of 250 ppm chloride, 250 ppm sulfates, and 1000 ppm total dissolved solids. Many of the city's municipal supply wells have already exceeded these amounts (table 1).

The only solution at present is for Roswell to move its basic well supply field from within the city limits to an outside area. Such a plan is being implemented with a projected cost of several million dollars. Table 2 shows analyses of waters from the general area of the proposed new well field.

Roswell has expended many tens of thousands of dollars during the past three years in an effort to provide its 40,000 residents with the best quality of water available at the lowest possible cost. These moneys paid for drilling, testing, and evaluating numerous areas, both within and outside the Roswell artesian basin, which resulted in the selection of a new well field with water having about one half the total dissolved solids and one tenth the chlorides as its present water. The new water rates needed to pay for the proposed system will average about 24 cents a thousand gallons, a figure significantly lower than many cities.

The primary economic considerations for Roswell included chloride content, cost of acquisition, transmis-

TABLE 1. QUALITY OF WATERS, ROSWELL MUNICIPAL WELL FIELD (Samples collected September 1, 1966)

	CITY WELL NUMBER													
	2	4	5	6	7	8	10	11	12	13	14	15	16	17
ANALYSES BY WESTERN SOIL LABORATORY, ROSWELL, NEW MEXICO; CHEMICAL CONSTITUENTS IN PARTS PER ILLION (PPM)														
pH	7.9	8.0	8.0	8.0	7.95	8.0	8.1	8.05	8.0	7.9	7.95	7.85	8.0	7.85
Total dissolved solids evap. 179-181° C.	1648	1288	1232	1904	1768	1484	1172	1148	1264	1096	1788	1116	1136	1140
Sulfates	561	527	563	660	614	722	652	680	517	586	780	537	650	627
Chlorides	377	250	213	431	445	318	159	163	209	159	386	127	141	145
Carbonates as $CaCO_3$	20	0	0	0	0	0	0	0	0	0	0	0	0	0
Bicarbonates as $CaCO_3$	120	130	100	90	110	120	110	90	110	90	90	120	110	120
Calcium	180	157	142	202	173	168	145	142	148	137	192	155	150	143
Magnesium	75	74	68	75	67	70	77	73	67	69	86	68	73	55
Sodium	243	165	135	255	285	216	94	94	132	95	249	216	78	92
Potassium	2	2	2.5	3	3.5	3	2	2	2	1	2	2.5	2	2
Total hardness grains/gal.	44	41	37	47	41	41	40	38	38	37	52	39	40	34
ADDITIONAL ANALYSES FOR CHLORIDES BY MANN ENGINEERING COMPANY, ROSWELL, NEW MEXICO														
(samples collected June 1-2, 1966)														
Chlorides ppm	462	242	189	379	394	280	136	129	182	174	348	114	121	144
(samples collected October 1, 1966)														
Chlorides ppm	364	220	205	409	401	280	136	144	189	189	364	106	-	144
(samples collected November 1966)														
Chlorides ppm	326	235	197	394	447	326	144	159	295	182	364	121	144	152
(samples collected December 8, 1966)														
Chlorides ppm	356	235	189	409	432	318	152	159	197	197	364	129	129	152
(samples collected January 4, 1967)														
Chlorides ppm	303	235	205	409	417	311	136	152	197	182	356	121	129	129

TABLE 2. QUALITY OF WATERS, PROPOSED ROSWELL WELL FIELD

(Analyses by Western Soil Laboratory, Roswell, New Mexico; chemical constituents in parts per million (ppm))

	WILLIAMS & CHESSER			KERR	BIRDSLY	GRAY
	Sec. 24, T12S-R23E	Sec. 21, T12S-R23E		22-12S-24E	12-12S-24E	24-13S-24E
Date	11-28-66	11-28-66	11-28-66	6-17-66	6-17-66	10-21-66
pH	7.35	7.3	7.4	7.4	7.42	8.25
Total dissolved solids evap. 179-181° C.	572	656	604	668	660	496
Sulfates	257	267	271	288	284	273
Chlorides	50	54	36	62	62	27
Carbonates as $CaCO_3$	0	0	0	0	0	0
Bicarbonates as $CaCO_3$	220	232	196	218	208	210
Calcium	87	118	103	130	123	115
Magnesium	36	19	33	22	21	18
Sodium	29	26	18	43	49	62
Potassium	0.5	0.5	0.5	1	0.5	0.5
Total hardness grains/gal.	21	22	23	29	30	32

sion and distribution, well capacities, and longevity of supply.

The economic considerations of saline encroachment, as well as over-appropriation, and the diminishing of the Pecos River affect a large part of New Mexico's population. The Roswell artesian basin is considered one of the world's outstanding examples of a rechargeable artesian aquifer system, but prolonged over-appropriation of water from the system could mean economic ruin for the Pecos Valley and a great loss to New Mexico. Conversely, stringent administration of the basin consistent with *all* available scientific data could save the present economic community.

The economy of the Pecos Valley might profit from pursuing fields of inquiry outside geology and hydrology. With water levels in many parts of the basin approaching the limits of profitability for agriculture, at least with present crops, less water-consumptive crops and transfer of water to industrial, municipal, and recreational applications should receive more attention.

PROCEDURE

The subsurface structural framework was developed by use of electric logs. The Roswell Geological Society established the original correlation network. Lithology determinations were made by sample examination, commercial sample logs, and drillers' logs available in the State Engineer's Office. The key subsurface control well for this study was the Pecos Valley Artesian Conservancy District No. 1 Stratigraphic Test in sec. 34, T. 10 S., R. 24 E., Chaves County. This well was cored almost continuously from the top of the artesian aquifer to the top of the Glorieta Sandstone, with relatively high core recovery, and a very complete electric log suite was run. This well was selected as a key control and reference point because no other well drilled in the Roswell artesian basin has nearly as much available information.

Surface data employed involved reconnaissance on the ground, examination of aerial photographs, and aerial inspection of observed structural trends. These surface trends were then projected into the subsurface by subsurface and geophysical controls.

Several petroleum exploration organizations and individuals provided geophysical data for the writer's inspection. He examined four separate sets of regional gravity and magnetic data and had aerial magnetic coverage of the area. Commercial gravity and magnetic maps can be purchased. The geophysical maps used by the writer are not for public use or examination.

All the electric logs employed in this survey can also be commercially obtained through normal electric log service companies.

Cores obtained from the Pecos Valley Artesian Conservancy District (PVACD) No. 1 Stratigraphic Test can be examined at the Roswell office. The writer has studied these cores (appendix A) twice, once immediately upon recovery and again some weeks later. Appendix B gives core analyses from this test. Of a total recovery of 594 feet of core, 201 samples were analyzed for porosity, horizontal permeability, and vertical permeability.

Samples examined, available at the State Engineer's Office in Roswell, came from wells drilled by the City of Roswell and the Hagerman Irrigation Company. Sample logs on many of the oil tests drilled through the artesian aquifer are commercially available, while the State Engineer's Office, Roswell, can provide drillers' logs.

Regional Sedimentation

The Roswell artesian basin is in the North basin, known locally as the Northwest Shelf, north of the western edge of the Guadalupian reef complex of the Permian basin. The following generalized summary of geological events places the present artesian basin in time and space.

At the close of Precambrian time and the beginning of Paleozoic, southeastern New Mexico was peneplaned, generally approaching base level. Some gentle topographic forms resisted the regional degradation. Along the present edge of the Northwest Shelf, a zone peripheral to the later Delaware basin and Guadalupian reef complex, some erosional remnants of Precambrian age persisted until late Permian time. Likewise, toward central New Mexico, the shelving Lower Pennsylvanian rocks suggest that the Precambrian surface had a regional slope toward the southeast, apparently away from the Transcontinental arch.

With the transgression of southeastern New Mexico by Cambro–Ordovician seas and again later by Siluro-Devonian seas came deposition throughout the area of the Ellen burger, Simpson, Montoya, Fusselman, and "Devonian" formations of subsurface terminology. Progressive onlap can be seen throughout much of the area, with a general thinning observable toward the ancient landmass of central New Mexico and toward the Milne-sand Dome area of southeastern Roosevelt County.

Some mild uplift occurred in post-Fusselman and pre-Woodford (Percha) time, because the highly carbonaceous Woodford Shale thins depositionally and becomes elastic along the northern margin of the present Northwest Shelf.

Renewed deposition during Mississippian time blanketed the Northwest Shelf with carbonate rock of Kinderhook, Osage, and Meramec ages. Massive, cherty, crinoidal limestones of the Osage–Meramec were then overlain by carbonaceous "Barnett-"type shales of the Chester. Facies changes in many parts of the area gave rise to limestones interbedded with the "Barnett-" type shales.

After close of Mississippian deposition, the southeast New Mexico basinal areas were folded and faulted. A strong north-south structural orientation developed along the present Central basin platform and throughout most of the Northwest Shelf area. Apparently some lesser movements developed along zones tangential to the margin of the Northwest Shelf, yielding an incipient framework that later developed into the present Delaware Basin and Northwest Shelf area.

There are only isolated indications of a subaerial type of regolith having developed on top of the Mississippian System. The marked absence of elastic and carbonate rocks of the Morrow throughout a large part of the Northwest Shelf, as compared to thick, relatively uniform blanket sandstones, interbedded marine shales, and glauconitic pebbly conglomerates locally filling structural lows, attests to the beginning of a major development later giving rise to the complex depositional environments characterizing southeastern New Mexico.

Throughout much of the Northwest Shelf, the Derryan (Atokan) lies directly upon the Mississippian. Rocks of Derryan age in the intrashelf Lovington basin thicken significantly on the downthrown side of north-south-trending post-Mississippian faults. Along the western edge of the Northwest Shelf, in part of the local area considered, the lack of evidence of difference in thickness of Derryan rocks across major faults indicates regional post-Mississippian uplift without faulting but apparently not necessarily exposure to active subaerial erosion.

Following Derryan deposition, active movement began along faults developed peripheral to the western side of the Northwest Shelf. Rocks of Cherokee age (Early Desmoinesian) exhibit significantly greater thickness on the downthrown side of post-Derryan normal faults. Actually, the thickening can be largely attributed to upper Cherokee deposition. In reality, south and east of the area covered by structure mapping in this report, the structural complexity becomes overshadowed by the stratigraphic complexities arising from reef formation of lower Cherokee through Wolfcampian and Leonardian through Guadalupian time.

In the east-central part of the map area (pl. 1), the Cherokee and older rocks became sharply up-tilted to the west. These units were all beveled along a narrow band about 3 to 4 miles wide. Immediately east of this truncated zone, Missourian carbonaceous shales unconformably overlie lower Desmoinesian rocks. Toward the west, the Missourian shales progressively overlap Derryan, Mississippian, all the pre-Mississippian, and finally the Precambrian basement.

The erosional truncation of the pre-Missourian rocks, commonly referred to the "pre-Pennsylvanian pinch-out" because of its economic hydrocarbon potential, was undoubtedly due to uplift in the Pedernal landmass and in turn was possibly associated with regional orogenic uplift of the ancestral Rocky Mountains.

Deposition throughout the western side of the Northwest Shelf was essentially continuous during Missourian, Virgilian, Wolfcampian, and Leonardian time. The characteristic feature of this sequence of sedimentation was the progressively more continental evaporitic aspect of the deposited rocks.

Guadalupian sedimentation behind the reef complex of the margin of the Delaware basin was typified by widespread carbonates, which progressively gave way to evaporite carbonates, evaporite shales, and evaporite fine-grained elastics. By Ochoan time, sedimentation was entirely evaporitic salt that now comprises the Salado Formation.

Late Virgilian faulting and/or folding recognized in the Milnesand Dome area of southern Roosevelt County and observed in the Sacramento Mountains has not yet been well demonstrated along the western edge of the Northwest Shelf.

Red beds and clastic rocks of the Triassic are regionally present and generally attributed to continental-deltaic deposition. Cretaceous rocks, probably thinly deposited in the area of the Pecos Valley, have subsequently been stripped by erosion. Tertiary–Quaternary alluvium and windblown deposits are widespread throughout the area.

Tertiary intrusive activity near the Sacramento Mountains, with basin and range faulting of the same area, caused the present regional dip observed in most of the southeast part of the state. The occurrence of El Camino del Diablo and Railroad Mountain dikes of Chaves and Roosevelt counties confirms intrusive activity in the form of east-northeast-trending dikes.

Structure of Northern Roswell Artesian Basin

The northern part of the Roswell artesian basin has an east-southeast regional dip of about 50 feet a mile. At least three major structural zones traverse the northern part (pl. 1) of the basin: the Border Hill, Six Mile, and YO. Each of the zones trends about northeast-southwest and has relative displacements giving rise to a horst and grabenlike effect but is in fact a tilted fault block. The writer suspects additional structure zones parallel to these, but the evidence is insufficient at present to delineate their positions.

The westernmost zones, the Border Hill and Six Mile, change strike from northeast-southwest to north-south in the northernmost section of the area. Considerably north of the subject area, geophysical data suggest that a continuation of the YO structural zone swings sharply to the east and strikes toward the fault zone that forms the southern boundary of the Milnesand Dome of southeast Roosevelt County. In that area it appears, as in this local area also, that the faulting cuts, or at least seriously deforms, the Guadalupian rocks.

At the southeast corner of the map area (pl. 1), in T. 14 S., R. 27 E., the faulting can be dated as commencing in lower Cherokee time and continuing episodically into at least Guadalupian time. In the same area, one cannot determine with any degree of clarity whether or not the Missourian through Leonardian rocks are actually faulted or if there is only a differential thickness on the downthrown side because of a greater accumulation of sediment.

Within and west of the Roswell area, insufficient deep well control prevents detailed dating of the structural events. From information obtainable in the outcrop, one can only conclude that the final rupturing of the Guadalupian is post late Guadalupian and pre late alluvium. It is reasonable to assume on geomorphic evidence that the faulting is pre-Pecos River and, from general alluvium distribution, entirely prealluvium. In my present opinion, the faulting developed in the Tertiary penecontemporaneously with strong uplift and intrusion in the Sacramento–Capitan mountains area.

The fault displacements appear essentially normal with apparent offsets of from 80 to 650 feet, as mapped on top of the eroded San Andres Limestone. Subsurface data suggest that as much as 1000 feet of stratigraphic throw may have occurred on the YO structural zone in the area south of Roswell, although structural contouring on top of the Glorieta Sandstone (pl. 2) does not indicate that much displacement. Some minor strike-slip movement is possible along the YO zone. Mourant (1963, p. 32) suggests some thrust fault displacement along the Border Hill zone.

A detailed structural analysis along the outcrop probably would yield beneficial data when integrated with other surface and subsurface information.

Stratigraphy and Hydrogeologic Characteristics

A basic understanding of the local stratigraphy is mandatory to appreciate the problems of the artesian aquifer system. To recognize the critical stratigraphic differences within the artesian aquifer system, the complete section adjacent to the basin will be examined, and then the stratigraphy of each of the structural blocks in the northern part of the basin will be discussed.

In this report, the "adjacent" stratigraphy means that found along the easternmost central edge of the map area (pl. 1). This specific area is selected because it represents the general stratigraphic section east of the eastern boundary of the Roswell artesian basin.

The Six Mile block is defined as the area between the Border Hill and Six Mile structure zones. The Roswell block, considered as lying between the Six Mile and YO structures, is the block upon which the city of Roswell rests. The Orchard Park block is the area southeast of the YO zone. The southeast limit of the Orchard Park block is not defined but is believed to lie along a line parallel to the YO zone, passing through approximately the NW¼ of sec. 4, T. 13 S., R. 26 E. This is another zone of structural displacement that detailed stratigraphic work might confirm (or refute). Irregular contouring patterns, changes in hydrologic characteristics, and geophysical data suggest this zone.

PRE-GUADALUPIAN

Pre-Pennsylvanian erosional truncation occurs in a northeast-southwest direction essentially parallel to the Orchard Park block. This structural-stratigraphic event is not involved directly in the artesian basin system. The lowest stratigraphic unit that appears active in the overall artesian system east of the Border Hill structural zone is the Glorieta Sandstone. Poorly defined and difficult to correlate reliably, the name *Glorieta Sandstone* is herein used advisedly and is consistent only with subsurface terminology to the east. I consider the Glorieta as the upper sandstone of the Yeso Formation and recognize that this classification conflicts with existing concepts. Detailed work now in progress by another geologist will, hopefully, adequately clarify this problem. The Glorieta Sandstone of this report about equals the Hondo Sandstone Member of Mourant (1963).

GUADALUPIAN

The Guadalupian Stage divides into the San Andres Limestone and the overlying Artesia Group.

SAN ANDRES LIMESTONE

The San Andres Limestone conformably overlies the Glorieta Sandstone. The San Andres is exceptionally widespread, with correlative units having been recognized throughout northeastern, central, and southern New Mexico, west Texas, and parts of eastern Arizona. The entire unit is very uniform laterally, with individual "marker beds," such as the Pi zone (an informal subsurface petroleum name) of eastern Chaves, Roosevelt, and northern Lea counties, being recognizable over several thousand square miles.

Throughout the Northwest Shelf, the San Andres readily divides into an upper and a lower half. The lower half contains the hydrocarbon-producing Slaughter zone of subsurface terminology. The Slaughter zone is responsible for oil and gas production in west Texas and in northern Lea, Roosevelt, Chaves, and Eddy counties, New Mexico.

ARTESIA GROUP

The Artesia Group comprises, in ascending order, the Grayburg Formation, Queen Formation, Seven Rivers Formation, Yates Formation, and Tansill Formation. Tait et al. (1962) discuss the regional distribution. Where present, the Queen Formation forms the aquitard between the shallow and the artesian aquifers.

OCHOAN

Rocks of this series form the Castile, Salado, and Rustler Formations, which, though not present within the artesian basin, occur to the east of the area of investigation.

POST-PERMIAN

Only the Tertiary—Quaternary alluvial deposits immediately overlying the Guadalpuian Stage are present within the area studied.

GLORIETA SANDSTONE

Because of the ill-defined limits of the Glorieta Sandstone, one cannot pinpoint it stratigraphically west of Roswell. The unit is generally gray to white, buff to yellow, fine-grained to very fine-grained, moderately well-cemented, well-sorted, clean quartz sandstone. It frequently has interbeds of limestone or dolomite. The Glorieta varies from 0 to 750 feet in thickness regionally but is 100 to 125 feet thick through the northern part of the basin.

West of the Border Hill structural zone, the Glorieta is known to transmit water and to act as an unconfined aquifer. The sandstone typically provides low-yielding wells compared to the Roswell artesian aquifer. This has been questionably attributed to the fact that the water is in rapid transit and is not easily captured by the borehole, although lithologic and stratigraphic changes and characteristics do influence water distribution and production, as discussed by Mourant.

The Glorieta Sandstone has been considered as one of the primary transporting media for recharge to the confined limestone aquifer on the east (Bunte, 1960; Mourant, 1963). Three test wells were drilled by the City of Roswell on the western edge of the unconfined limestone aquifer in the Six Mile block. The westernmost test, the No. 1, found no significant productive capacity in the Glorieta; although the sandstone was extremely friable, it apparently lacked effective permeability. In the easternmost test, the No. 3, the Glorieta Sandstone yielded a small amount of water on initial testing, but the water was of poor quality. The chloride ion concentration in the highly friable, apparently low permeability sandstone was surprisingly high (table 3). This test also penetrated the top of the Yeso Formation. Table 3 compares these waters with those from the basal San Andres.

TABLE 3. QUALITY OF WATERS, GLORIETA—YESO AND BASAL SAN ANDRES, ROSWELL NO. 3 TEST (SE¼SE¼ sec. 19, T. 10 S., R. 23 E.)

ANALYSIS FOR	GLORIETA—	BASAL SAN
pH	7.25	7.55
Total dissolved solids		
evap. 179°-181° C	13,052	2628
Sulfates	2232	1115
Chlorides	5684	500
Carbonates as $CaCO_3$	0	24
Bicarbonates as $CaCO_3$	200	148
Sodium	4000	355
Calcium	952	376
Magnesium	190	106
Potassium	12	3
Specific conductance	13,212	2863

Sample collected August 1965, analysis by Western Soil Laboratory, Roswell. Chemical constituents in ppm. Top of Glorieta 822 feet (+3006 MSL), test interval 860 to 943 feet. Basal San Andres test interval 695 to 795 feet.

Farther east, on the western edge of the Roswell block, which is uplifted relative to the Six Mile block, the Glorieta Sandstone yields moderately high quantities of water with a chloride ion concentration on the order of 100 ppm.

If one assumes the lithologic and stratigraphic character of the Glorieta Sandstone to be homogeneous from the west side of the Border Hill structure zone, across the Six Mile block, and onto the Roswell block (which it undoubtedly is not), it is apparent that some condition exists between the saline water from the Glorieta in the easternmost test well in the Six Mile block and the good-quality water in the western edge of the Roswell block.

Conversely, if one assumes a nonhomogeneous lithologic and stratigraphic character for the Glorieta Sandstone, while still maintaining that the unit acts as the transmission medium for recharge water to the confined aquifer (which first occurs about parallel to the west edge of Roswell), it is then possible to explain the saline-fresh water anomalies by simple differential flushing, porosity, permeability, and so on. This, however, necessitates consideration of nonhomogeneity and differential flow patterns.

In the writer's opinion, neither of these situations alone provides the full answer. From the scanty well and electric log data available, it appears that the transmissive capability of the Glorieta Sandstone ends at about the point where the limestone aquifer saturation begins on the Six Mile block. Along the western edge of the Roswell block, the Glorieta lies in fault contact with the limestone aquifer on the west, and the sandstone again has developed transmissive capacity for some unknown distance to the east, probably to the edge of the confined aquifer. Toward the eastern edge of the Roswell block, in the Pecos Valley Artesian Conservancy No. 1 Stratigraphic Test, the Glorieta Sandstone again has lost significant transmissive capability and contains chloride-rich water measured at 95,496 ppm.

SAN ANDRES LIMESTONE

Regionally, the San Andres Limestone varies from about 1200 to 1400 feet in thickness. Immediately adjacent to the eastern edge of the Roswell artesian basin, the San Andres is 1200 to 1260 feet thick. In this area, the limestone divides into an upper and a lower unit. The upper unit is predominant limestone, nonporous dolomite, and anhydrite, with some thin shale, silt-stone, and halite beds. It varies from 550 to 600 feet thick in the easternmost part of the map area.

Two subunits comprise the lower unit of the San Andres Limestone. The upper subunit, the Slaughter zone of subsurface terminology, is a regionally porous and permeable, gray to brown, fine- to medium-crystalline dolomite containing some thin anhydrite beds. On the easternmost edge of the map area, the Slaughter is 225 to 275 feet thick. Oil production from this zone occurs immediately northeast of Roswell.

The lower subunit of the San Andres is composed partly of dark-brown to very dark-gray, medium-crystalline limestone. This dark limestone, called "black lime" by drillers, is thick-bedded and hard and generally contains no effective permeability. Part of the bottom half of the lower subunit usually contains a dark-brown porous dolomite overlying white to gray, medium- to coarse-crystalline, bedded anhydrite. The entire lower subunit is 375 to 400 feet thick in the easternmost edge of the map area.

On the Orchard Park block (pls. 3, 4), the over-all stratigraphic section encountered is generally similar to that just described. There is, however, a noticeable thinning of the upper unit of the San Andres toward the west, not unreasonable considering that only the lower half of the San Andres is present at the type locality in the San Andres Mountains (Kottlowski et al., 1956). On the Orchard Park block, the confined artesian aquifer is developed in the upper third of the San Andres, entirely in the upper unit of the formation, and in the overlying Grayburg.

The stratigraphic section (pl. 3) is constructed from the northeast, outside the artesian basin system, south through the eastern edge of wells drilled exploring for Slaughter oil production in the Bitter Lakes oil field, across the Pecos River into the East Grand Plains and Orchard Park farming communities, and westward into some of the most westerly irrigated lands on the Orchard Park block. Plate 4 shows a stratigraphic section constructed from beyond the eastern limits of the artesian basin system and westward into the Orchard Park area, ending with the same two wells as the previous section.

In both subsurface sections (pls. 3, 4), the stratigraphy is as would be anticipated from the easternmost wells. The San Andres Limestone yields copious amounts of water with low chloride content throughout most of the Orchard Park block.

On the Roswell block, a horstlike tilted fault block, the San Andres Limestone is deeply eroded. At the northeastern extremity of the Roswell block, outside the artesian basin system, the normal, complete San Andres section is present. Southwest of Roswell, where the Hondo River crosses the Six Mile structure, only the lower unit of the San Andres occurs. This indicates an erosional stripping of about 500+ feet of the upper San Andres. In addition, erosion appears to have removed about 400 feet of the section overlying the San Andres. In most of the Roswell block, where the aquifer is artesian, the Slaughter subunit forms the porous reservoir.

On the Roswell block, along a northeast-southwest direction, the base of the enlarged aquifer porosity directly contacts the regional porosity of the Slaughter zone. Plate 5 illustrates this contact. It should be reemphasized here, where fresh potable water is produced from the Slaughter zone beneath Roswell, that only a few miles to the northeast, hydrocarbons are produced from the Slaughter, with oil-field waters containing about 39,000 ppm chloride. Also, lest the significance be lost, the Slaughter zone is a continuous porosity horizon throughout the Northwest Shelf into West Texas.

The intrashelf Lovington basin is a north-south, elongate, structurally depressed, sedimentational basin with its axis lying about 20 miles west of the eastern boundary of the state in northern Lea County. It contains at least 3000 square miles on its western flank hydrologically connected with the artesian basin system. In the lower unit of the San Andres of this area, chlorides count more than 100,000 ppm.

On the east side of the Six Mile block, a grabenlike tilted fault block, the San Andres section is more complete than in the central or western parts of the Roswell block. Directly west of Roswell, on the north side of the highway, remnants of the Artesia Group reportedly rest on the San Andres Limestone (Mourant, 1963, p. 24 and pl. 2). Dane and Bachman (1958), on their preliminary geologic map of southeastern New Mexico, indicate the same area as San Andres exposures. Mr. Robert E. Murphy, Mobil Oil Company, suggested (personal communication, 1965) the possibility of the red- and pink-colored outcrops west of Six Mile hill being Artesia Group remnants.

Since drilling of the City of Roswell No. 3 test in the SE¼SE¼ sec. 19, T. 10 S., R. 23 E., on the edge of the Artesia Group reported by Mourant (pl. 2), the writer now believes that the outcrops are actually San Andres Limestone. The surface exposures, while poor, greatly resemble other outcrops of the San Andres throughout the area. The subsurface samples from the No. 3 well contain a greater amount of carbonate than would be expected were the Artesia Group present at this locality. In addition, the close correlativity of subsurface units by electric logs based upon sample data suggests to me the presence of San Andres (pl. 5).

In the No. 3 test, a 36-foot bed of clear to white crystalline gypsum occurred from 20 to 56 feet below the surface. The section from 56 to 150 feet deep comprised gray to dark-gray, dense to lithographic, anhydritic (gypsiferous) dolomites; pink, white, tan, dense, gypsiferous limestone; and brown, buff, and some pinkish shales. The section from 158 to 442 feet contained primarily buff and light-gray dense limestones and light to dark-gray, dense to very fine crystalline dolomites. At 442 feet, it changed sharply to dark-gray limestone, which dominated to 616 feet. From 616 to 800 feet, the samples changed to gray, brown, and black, dense to very fine crystalline dolomite. The top of the Glorieta was designated at 822 feet.

The interval from 442 to 822 feet in the No. 3 test, a net thickness of 380 feet, that directly overlies the Glorieta Sandstone quite closely resembles the lower subunit of the San Andres frequently seen to the east. Remember that the lower subunit ranges in thickness from 375 to 400 feet in the area adjacent to the east of the Roswell artesian basin. The section from 158 to 442 feet, a net thickness of 284 feet, would then correspond to the Slaughter zone. A close similarity of lithology between this interval and the Slaughter on the Roswell block exists. Remembering further, the Slaughter zone in the area adjacent to the east of the artesian basin ranges from 225 to 275 feet in thickness.

About 3 miles south of the No. 3 test and across the Six Mile structure, the Forsythe No. 1 Gibson penetrated 645 feet of San Andres section (Mourant, 1963, p. 76 and pl. 3), compared to 822 feet in the Roswell test. The San Andres to the west of the No. 3 test thins to 571 feet in the Roswell No. 1 test and to 480 feet in the PVACD observation well, sec. 16, T. 10 S., R. 21 E. Plate 2 illustrates the general structural conditions giving rise to the remaining thickness of San Andres on the Six Mile block.

In the City of Roswell No. 3 test, three major porosity and fluid zones were observed: 303 to 442 feet, 638 to 745 feet, and 805 to 889 feet (with most of both the porosity and fluid occurring in the interval from 878 to 889 feet). This latter zone lies in the Glorieta Sandstone. The water level of the first and second zones combined reached 317.32 feet, the upper zone alone reaching 316.90 feet. A 36-hour pump test of the first and second porosity zones showed a 0.13-foot drawdown at 200 gpm. Full recovery took 3 hours. A pump test of the upper zone alone showed a drawdown of 7.88 feet at 200 gpm. Recovery to within 0.03 foot of the original level occurred in 3 minutes. Complete recovery required 20 minutes. Tables 4 and 5 give analyses of water recovered.

TABLE 4. QUALITY OF WATER, ROSWELL NO. 3 TEST

ANALYSIS FOR	24-HOUR SAMPLE SEPTEMBER 1965	36-HOUR SAMPLE SEPTEMBER 1965
pH	7.45	7.45
Total dissolved solids		
evap. 179°-181° C	1594	1584
Sulfates	533	571
Chlorides	393	389
Carbonates as $CaCO_3$	8	12
Bicarbonates as $CaCO_3$	178	136
Calcium	168	163
Magnesium	39	34
Sodium	288	250
Potassium	3	3
Specific conductance	2103	2061

First and second porosity zones. Analyses by Western Soil Laboratory, Roswell. Chemical constituents in ppm.

TABLE 5. QUALITY OF WATER, ROSWELL NO. 3 TEST

ANALYSIS FOR	12-HR SPL. SEPT. 1965	24-HR SPL. SEPT. 1965	36-HR SPL. SEPT. 1965
pH	7.0		7.2
Total dissolved solids			
evap. 179°-181°C	1432		1388
Sulfates	557		654
Chlorides	306	291	291
Carbonates as $CaCO_3$	0		0
Bicarbonates as $CaCO_3$	204		204
Calcium	220		184
Magnesium	39		36
Sodium	213		201
Potassium	5		2
Specific conductance	1850	1788	1819

First porosity zone only. Analyses by Western Soil Laboratory, Roswell. Chemical constituents in ppm.

West of the Border Hill structural zone, the San Andres is thin and rests upon the Glorieta Sandstone. This investigation has not involved the stratigraphy of this area, which Mourant discussed.

ARTESIA GROUP

The lowermost unit of the Artesia Group, the Grayburg Formation, is comprised predominantly of dolomite and interbedded anhydrite, with some sandstone present, particularly in the lower half. The Grayburg Formation undergoes significant regional facies changes from its southern limits in the Guadalupian reef complex toward the north. The major change is from predominantly dolomite with anhydrite and sandstone interbeds on the south to anhydrite, shale, and sand-stone with some dolomite interbeds toward the north. On the Orchard Park block (pls. 3 and 4), the Gray-burg Formation is the principal completion zone for the artesian aquifer, although the enlarged aquifer porosity continues down into the upper third of the San Andres Limestone. Significantly, the porosity development in the Grayburg carbonates, as in the underlying upper third of the San Andres, developed through meteoric water leaching the carbonates and is directly related to the present position of the Pecos River. There is no regional porosity zone, such as the Slaughter, developed in the Grayburg Formation or in the upper third of the San Andres. Therefore, the artesian basin system effectively ends immediately east of the Pecos River. A deep well drilled in the SE¼NW¼ sec. 2, T. 15 S., R. 27 E. penetrated the entire Grayburg Formation and upper half of the San Andres Limestone, using compressed air, without encountering water or observable moisture.

On the Roswell block, the Grayburg Formation is interpreted herein as being absent because of erosion. Many reputable investigators consider this an almost heretical stand, I realize. One can, however, offer an alternate interpretation of the rocks present over the lower unit of the San Andres, so long considered Artesia Group equivalents, and can show the necessity of this alternate interpretation.

No question exists in my mind as to the correlatability of subsurface data in the eastern part (p1. 5). Assuming this a reasonably correct interpretation, one must account for the absence of the upper unit of the San Andres and the Artesia Group. At the same time, one must also place stratigraphically the Queenlike red beds that form the aquitard over the artesian aquifer.

A pinkish, gypsiferous, shaly, limestone breccia immediately overlies the lower unit of the San Andres on much of the Roswell block. This unit, generally called *Artesia Group undifferentiated*, formerly Chalk Bluff (Tait et al.), underlies red shales similar in many aspects to those in the Queen Formation. Because the Queen forms the aquitard to the south and because the Grayburg Formation makes such a contribution to the artesian system, geologists have assumed that the formations continued onto what we recognize here as the Roswell block.

Recognition of the fact that the upper half of the San Andres Limestone has been removed by erosion suggests that the pinkish limestone breccia forming the top of the artesian aquifer is actually a solution collapse breccia derived from the upper San Andres. The red shales forming the thin aquitard are possible terra rossalike clays formed as the residual clay deposit from solution of limestones. In fact, an abundance of these red clays can be seen associated with San Andres outcrops on the Six Mile block.

Cores recovered in the PVACD No. 1 Stratigraphic Test clearly show, megascopically, the brecciated nature of the limestone (appendix A). The breccia is composed of angular fragments similar to the immediately underlying San Andres that intermix with red shale fragments. Both the limestone and red shale are surrounded and penetrated by anhydrite (gypsum) veinlets, which themselves show secondary solutional activity and an apparent second stage of drusylike anhydrite (gypsum) deposition. Even the red shale clasts appear to be undergoing solution, probably in the form of colloidal removal.

The hydrological importance of the stratigraphic differences in lithology, age, and mode of formation for the interval overlying the San Andres on either side of the YO structure is of prime concern in any regional consideration of the aquitard. Determination of a leakage factor for the aquitard on the Roswell block would not apply for the Orchard Park block and vice versa. I suspect that because of the thinner nature of the red shales on the Roswell block, plus considerably less overburden for a pertinent period of geological time, the aquitard would have measurably less effect than the Queen on the Orchard Park block. Observations confirm the truth of this (Hantush, 1955).

QUEEN FORMATION

The Queen Formation is primarily composed of very fine-grained red sandstones and siltstones, containing abundant frosted quartz grains, with red siltstone and gray anhydrite commonly interbedding with dark-red, hard, sandy, or silty shale. Some porous gray sandstones occur in the section.

The Queen Formation forms the aquitard on the Orchard Park block. It is absent throughout the Roswell block west of the Pecos River and also slightly east of the river and most of the Six Mile block.

The Queen has been locally developed as a water-producing horizon from porous gray sandstones and, occasionally, from dolomites. These zones would generally be expected to have hydrologic properties more similar to the shallow or alluvial aquifer because of the closer lithology.

Detailed subsurface mappings of the Queen Formation, not attempted during this investigation, would probably yield much valuable information directly applicable to the location, extent, and effectiveness of the aquitard. Obviously, more reliable hydrological calculations could be made if definitive hydrogeological information on the confining aquitard were available. Changes in the presence, lithology, thickness, and structure of the Queen would have direct bearing on the movement of ground water from or into the underlying confined aquifer and would thus be closely related to the base flow of the Pecos River.

SEVEN RIVERS FORMATION

Throughout the Orchard Park block, anhydrite, dolomite, and limestone interbedded with sandstone and red shale comprise the Seven Rivers Formation. In well cuttings, the section appears conglomeratic and is most difficult to distinguish from the overlying alluvial section. Although no stratigraphic work was even attempted in the course of this investigation, the Seven Rivers is presumed present where a top of the Queen can be readily recognized.

The Seven Rivers Formation appears to have hydrologic properties similar to the overlying alluvium and is considered as part of the shallow aquifer. This formation offers a challenge for detailed stratigraphic subsurface work, the potential value of which could not even be estimated at this time. It is absent from the artesian basin system on both the Roswell and Six Mile blocks.

YATES FORMATION

The Yates Formation is considered absent from the artesian basin system in the area of this investigation.

Structure and Related Hydrogeologic Characteristics

ORCHARD PARK BLOCK

The Orchard Park block (bounded on the northwest by the YO structural zone) is downthrown relative to the strata on the northwest side of the YO zone, is probably about 10 miles wide, and appears to be a step-like block bounded on the southeast by an undefined structural zone parallel to the YO. This undefined zone appears to trend northeast-southwest approximately through the NW¼ sec. 4, T. 13 S., R. 26 E.

The southeast boundary of the Orchard Park block is suggested by several features. The structure contours on top of the San Andres (pl. 1) show anomalous conditions southeast of the suggested zone. The strongest evidence is a geophysical anomaly along the described direction. It outlines the depressed Orchard Park block and indicates a structural change within the general area of the postulated zone that dies out to the northeast.

Also, the course of the Pecos River changes direction as it crosses off the Orchard Park block. The San Andres increases in thickness, from 976 feet in the Cities Service No. 1-A Stone, sec. 20, T. 12 S., R. 26 E., to 1315 feet thick in the Intex No. 1-26 Federal, sec. 26, T. 12 S., R. 26 E., an increase of 339 feet in about 4 miles.

Even less directly, but possibly more relevant, as several investigators have well noted (Fiedler and Nye; Hantush, 1955; Jack R. Barnes and Mervin L. Klug, personal communications), the hydrologic characteristics of the artesian aquifer change in the general area of the southeastern boundary of the Orchard Park block. Water level contours (George Maddox, unpublished map, 1966) on the Orchard Park block show a strong northeast-plunging (high) "nose" along the block. The southeast boundary of the "nose" almost parallels the suggested southeastern structural zone. The YO zone forms the northwest boundary of the "nose." The hydrologic interpretation of the significant change, or "nose," shown by water-level contours is a change in transmissibility to the southeast. The higher transmissibility is in the center of the Orchard Park block.

This transmissibility, in T. 12 S., R. 24 E., can be estimated on the basis of pump test data (Mervin L. Klug, personal communication, January 1967) at about 1,500,000 gallons a day a foot. Immediately southeast of the suggested possible structural zone, in the Dexter area, Hantush determined a transmissibility for the artesian aquifer of 75,000 gallons a day a foot. The stratigraphic section southeast of the Orchard Park block thus varies from the conditions on that block in a definite manner that has resulted in a lower permeability and porosity. This should be a geological phenomenon investigatable by present subsurface techniques. Comprehending the geology of the Dexter area may help answer questions regarding artesian storage, decline, drawdown, shallow storage and decline, effect upon the base flow of the Pecos River, how to cope with future problems of development, and changes in place or use of water rights.

The pre-Pennsylvanian erosional truncation may be related to the structural events and conditions affecting the Guadalupian Stage of the artesian basin system. Between the Franklin, Aston, and Fair No. 1 Orchard Park Test, sec. 1, T. 12 S., R. 25 E., the Cities Service No. 1-A Stone, and the Intex No. 1-26 Federal, the pre-Pennsylvanian section increases in thickness from 0 to 210 feet and more than 400 feet, respectively. Farther south, in T. 14 S., R. 27 E., there is evidence that much of the structural activity occurred in Cherokee (early Desmoinesian) time. Considering the effects in this latter area on the middle Permian as well as the pre-Pennsylvanian, and observing generally similar stratigraphic conditions across the possible structural zone in the Dexter area, it is reasonable to suppose an age relation of the original activity along these quasiparallel zones.

There appears to have been episodic movement along the zone in T. 14 S., R. 27 E., beginning in Cherokee time, but evidence for close dating is not available farther northwest. In the northwest, however, obvious strong rejuvenation of movement occurred along the YO zone, as the Guadalupian rocks are structurally deformed. Conversely, in T. 14 S., R. 27 E., evidence of post-Guadalupian movement is lacking or is at least not nearly so evident.

SIX MILE BLOCK

Examination of the structure contour map on top of the Glorieta Sandstone (pl. 2) and additional data from the three test wells drilled by the City of Roswell show the effect of structure on the hydrologic system.

Test No. 1, sec. 25, T. 10 S., R. 21 E., was drilled about 3 miles southeast of the PVACD observation well in which the water level is below the top of the Glorieta. This test encountered the Glorieta 318 feet structurally low to the PVACD well, but the water level was only 91 feet low.

Test No. 2, sec. 4, T. 11 S., R. 22 E., drilled about 3.5 miles southeast of No. 1, encountered the top of the Glorieta 89 feet structurally low to No. 1, but the water level was only 2 feet low.

Samples recovered in the No. 2 test between 690 and 720 feet were white, fine-grained, porous to tightly cemented sandstone. Also recovered were both fresh and altered diabasic igneous rock. Some of the sandstone showed well-developed metasomatic or hydro-thermal alteration. Although most of the sandstone was megascopically unaltered, some fragments (to 5 and 6 inches) were highly cemented and had developed large solution cavities with apparent high permeability. The igneous rock probably represented as much as 5 per cent of the recovered fragments, which in turn were a minimum of an estimated 2 cubic feet.

The electric logs indicated porosity and fluids from 418 to 580 feet and 638 to 658 feet (lowest logged depth), with some fracturing indicated between 580 and 658 feet by the microseismogram. Initial tests indicated high sulfate and chloride concentrations (466 to 497 ppm and 345 to 388 ppm, respectively).

The No. 2 test was plugged back to 500 feet for production testing. The static water level measured 428.30 feet, about 5 feet lower than the combined Glorieta and San Andres water level. A 7-hour pump test resulted in a 0.10-foot drawdown at 200 gpm. Complete recovery was almost instantaneous. Table 6 describes samples collected for analysis.

TABLE 6. QUALITY OF WATER, ROSWELL NO. 2 TEST

ANALYSIS FOR	45 MIN SPL. SEPT. 1965	3-HR SPL. SEPT. 1965	7-HR SPL. SEPT. 1965
'Total dissolved solids evap. 1 79°-181° C			1160
pH			7.5
Sulfates			447
Chlorides	219	240	240
Carbonates as CaCO3			0
Bicarbonates as CaCO3			184
Calcium			163
Magnesium			32
Sodium			150
Potassium			2
Specific conductance	1553	1553	1557

Analyses by Western Soil Laboratory, Roswell. Chemical constituents in ppm.

The writer believes that there is a structurally low area near the No. 1 test, as interpreted on Plate 2. The cause of this low may be, in part, related to the thin diabase found in the No. 2 test, combined with minor folding associated with movement along the Border Hill zone to the west. A marked difference occurs in water quality between the two tests and, surprisingly, in an area where only good-quality water is expected. This structure probably causes water to divert around the structure to some degree, occasioning a more southerly flow component locally.

A clean carbonate unit was encountered from 588 to 638 feet (*see* zone 5, pl. 6) in the No. 1 test and from about 720 to 780 feet in the No. 3 test. The corresponding zone in the No. 2 well was a shaly limestone. The clean zone is a principal water-bearing unit and therefore of more than passing interest. The "shaled-out" nature of zone 5 in the No. 2 test may be related to original structural controls on depositional environment.

ROSWELL BLOCK

In the Roswell block, the lower San Andres, Plate 5, is overlain by the Teritary–Quaternary alluvium. Deep irregular erosion has placed the Slaughter porosity zone in a position of intensive secondary porosity development beneath Roswell. Immediately east of the city, the secondary porosity development forming the artesian aquifer climbs stratigraphically until the base of the enlarged aquifer porosity is developed above the Slaughter zone.

Along an area about 3.75 miles wide (pl. 5), the *base* of the enlarged aquifer porosity is developed within the regionally porous Slaughter. Where the base of the aquifer is so developed, saline waters from the Slaughter zone to the east mix with fresh meteoric water to give rise to chloride ion concentrations greater than desirable for municipal or agricultural use. The upflow of mixed meteoric and saline formation water directly relates to pressure conditions across the interface. The pressure on the porosity interface is attributable to two primary factors: regional head exerted by the fresh waters and interference in regional head caused by local pumping in and adjacent to the interface zone.

The saline water, an integral part of the local artesian system, is confined to the Slaughter zone of the San Andres (lower unit). The Slaughter zone is, throughout southeastern New Mexico, a hydrodynamically responsive reservoir; that is, it will yield fluid in an artesian manner. For it to do this, the Slaughter zone must somewhere have head conditions created. It would seem most reasonable to associate the Roswell artesian basin with the head for the Slaughter zone east of the Pecos River.

In the winter months of low municipal, and particularly low agricultural, usage, the head of fresh water recovers sufficiently to permit some infiltration into the lower porosity section of the aquifer-Slaughter interface. This results in a decrease in chloride ion concentration by dilution. This condition should be particularly evident during the rare periods of excessive precipitation. During such periods, not only is the aquifer being recharged but the basin is subjected to greatly reduced withdrawals. Conversely, when head is lost because of over-appropriation or insufficient recharge on the Roswell block, formation pressures downdip exceed fresh water head, and the movement of saline water is permitted toward the west and southwest. This occurs during the irrigation season and during the summer months of peak demand by Roswell. The encroachment is caused by the change in pressure by high pump-age across the interface and reduction of over-all head. The former would appear to have the stronger effect. It may, in fact, be desirable to attempt to analyze by analog model, computer program, or manual equation the combined effects of pumping cone of depression and mounding across the interface because of the bottom-hole effects of pumpage, as combined with the reduction or gain in head, which causes differential movement across the interface. Although the interface is in fact a zone rather than a line and specific data are sparse, the results of such computations might tend to give credibility to various possible methods of controlling saline encroachment. The present plan by the City of Roswell to move part of its basic supply well field off the Roswell block should significantly deter additional saline encroachment. Wells presently planned for abandonment are high-yield wells directly in the interface zone.

Leakage in greater amounts across the aquitard on the Roswell block because of the differences in physical properties should be evaluated and compared to those in the Queen aquitard. Again, it should be noted that the aquitard on the Roswell block formed as a direct result of structural uplift and consequent erosion.

Transmissibility of the artesian aquifer on most of the Roswell block appears to be generally high and similar to that observed for several miles parallel to the YO structure on the Orchard Park block. The transmissibility averages about 1,400,000 gallons a day a foot. Hantush reported a transmissibility of 1,900,000. While the water levels are very closely comparable across the YO structure zone, a very significant fact should be observed regarding the structural position of the aquifer units across the YO zone. South of Roswell, in about sec. 13, T. 12 S., R. 23 E., it would be *ideally* expected that the artesian aquifer in the northwest corner of the section would be the lower unit of the San Andres under water-table conditions, with the "top" of the San Andres about 120 feet below land surface. In the southeast corner of the same section, the top of the Grayburg would be the top of the limestone aquifer and the top of the San Andres would be encountered at about 685 feet below land surface. The waters encountered in the southeast quarter of the section would be confined and artesian. An alluvial and Seven Rivers section would be present. The Queen aquitard would form the confining horizon over the artesian system.

Ideally, the situation diagrammed in Figure 1 might be expected to prevail. With comparable water levels on either side of the YO zone and closely comparable values of transmissibility in the "limestone" aquifer, a cursory examination would probably fail to indicate the potential presence of a geological control of the distribution of ground water. The interconnection of the San Andres and shallow aquifers across the YO, plus the Grayburg–San Andres on the south in contact with the Glorieta on the north, both being separated by semi-impervious rocks, may offer an explanation of conditions observed in the southwestern part of the Roswell block as related to the Glorieta Formation of the Six Mile block.

The original condition which drew the writer's attention to the possible controls of structure and stratigraphy for water quality and quantity in the northern part of the Roswell artesian basin was that situation existing in and around the East Grand Plains area. East Grand Plains lies on the Orchard Park block, immediately west of the Pecos River.

Pumpage data (Mower, 1959) for the East Grand Plains area show pumping at about 40 per cent greater by volume in 1958 than for the Roswell area in the same year. East Grand Plains has a markedly betterquality of water than Roswell and was considered to be downdip structurally and piezometrically from the city. With the initial inquiry into this problem, the structural aspects were considered in a cursory manner, and it was concluded that in "some" manner the YO structural zone inhibited the movement of saline water from the Roswell block into the East Grand Plains irrigated area on the Orchard Park block. At that time, insufficient electric log data were available to begin zonation of the San Andres stratigraphic section.

Examination of drillers' logs in T. 11 S., R. 24 E. revealed that a sharp change occurred across the YO zone and that the depth to the artesian limestone on the south side of the YO was markedly greater than on the north side. In addition, the writer's geological prejudice demanded the occurrence of the South Springs and geomorphologic consideration of the sharp changes in the direction of flow in the Hondo, South Springs, and Pecos River. Thus, in the writer's opinion, the YO structural zone became a controlling feature.

Although the conclusion was proposed that the YO in some manner inhibited the movement of saline water from the Roswell to the Orchard Park block, the problem of the lack of an apparent hydrologic boundary between the two suggested systems existed. Water levels on both sides were comparable, as well as apparent producing capacities and aquifer transmissibilities. The shallow aquifer was present on both sides and the artesian aquifer was developed in limestone on both sides. What kept the saline water of the Roswell block from moving into the more intensely pumped East Grand Plains area?

After much work by the Hagerman Irrigation Company and the City of Roswell, and the resultant substantial increase of subsurface data, it became apparent that strong stratigraphic differences existed between the Orchard Park and Roswell blocks. The accumulated data were then employed to develop the stratigraphy as depicted in the accompanying figures and plates.

It became apparent that the artesian aquifer developed in the upper San Andres and the Grayburg on the Orchard Park block, whereas it developed in the lower San Andres on the Roswell block. This led to the interpretation of the aquitard differences of the two blocks. The question then arose, could the Queen aquitard on the Orchard Park block lie in a position directly or partly opposite the Slaughter aquifer on the Roswell block?

Correlation of data approximately perpendicular to the YO zone and intergation of available subsurface data adjacent to the YO shows the feasibility of concluding that the Queen aquitard lies opposite the limestone aquifer along the YO zone in the vicinity of South Springs (fig. 2). This displacement then accounts for the inhibited movement of saline water. At the same time, a great similarity of gross hydrologic characteristics may be anticipated on either side of the zone.

While valid, such hydrologic characteristics are lacking in that they do not consider the geology of the sys tern. The transmissibility average of 1,400,000 gallons day a foot on either side of the YO zone does not reflect the fact that one measurement occurs in the Slaughter on the north side of the YO zone and the other in a different stratigraphic unit at a greater drilled depth across a structural zone. Similar considerations need be given to the determinations of water levels obtained from opposite sides of the YO zone.

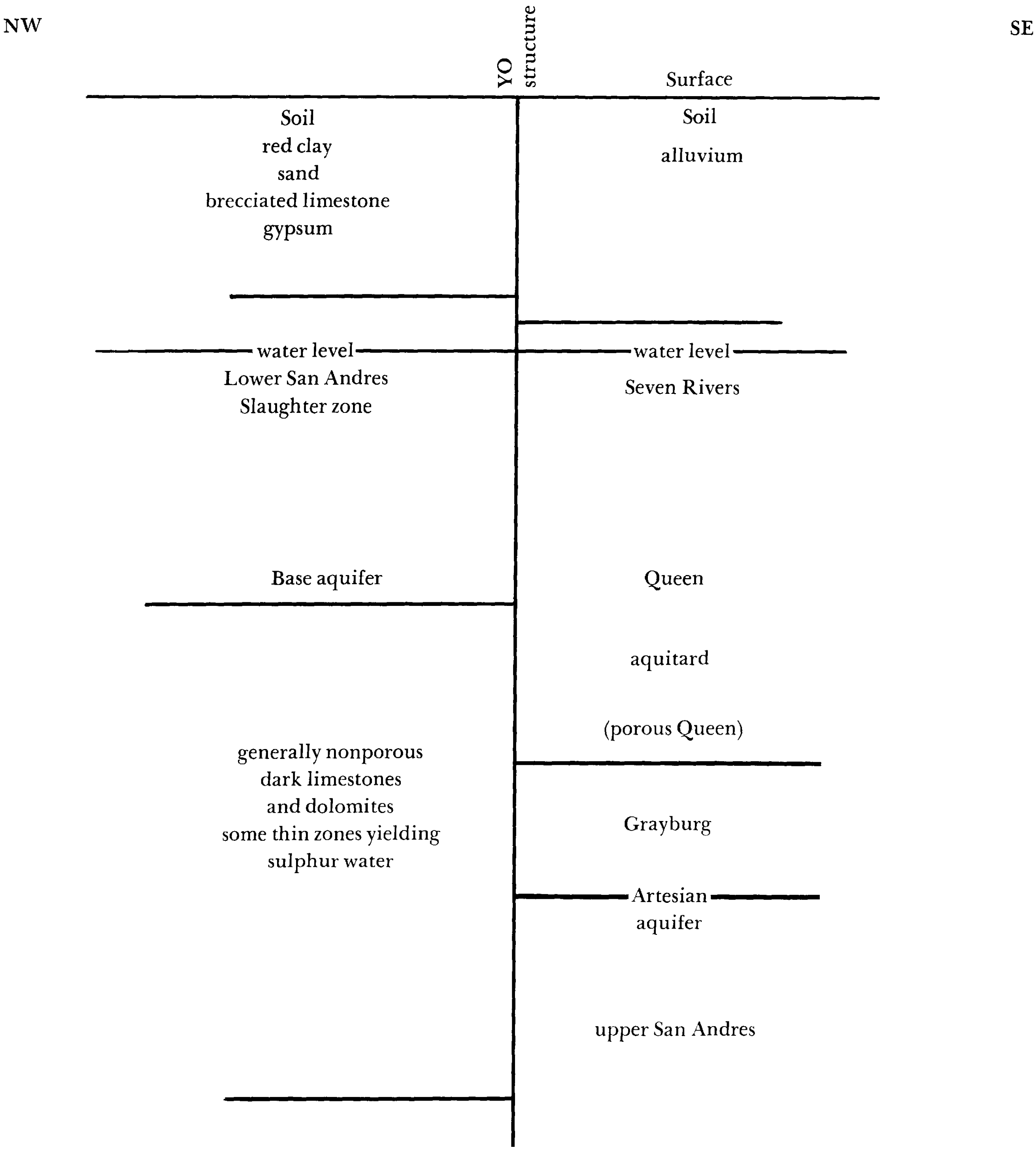

Figure 1

STRATIGRAPHIC SECTION ACROSS YO STRUCTURE ZONE, SOUTH OF ROSWELL

Idealized from projected data (see text). (Vertical scale: 1 inch = 100 feet)

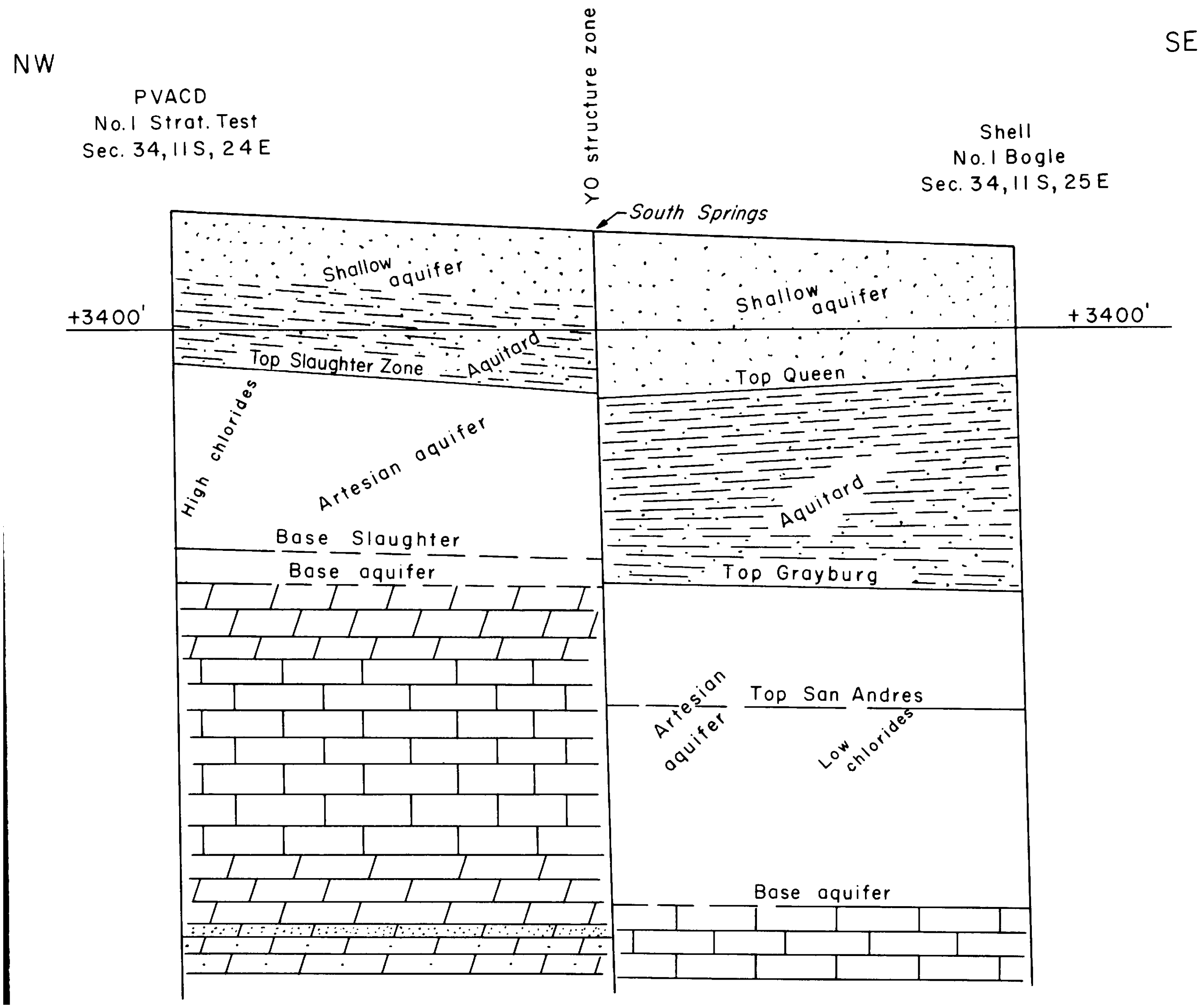

Figure 2

STRATIGRAPHIC SECTION ACROSS YO STRUCTURE ZONE, SOUTHEAST OF ROSWELL
Suggested lithologies highly generalized. (Vertical scale: 1 inch = 200 feet; no horizontal scale)

Recommendations

The following recommendations suggest items for further study that would add significantly to understanding of the geology and hydrology of the northern part of the Roswell artesian basin and the basin system as a whole. Their presentation does not follow any order of precedence.

1. Obtain more electric logs throughout the basin. The U.S. Geological Survey and the PVACD have logging units with which many data could be obtained as a part of their continuing studies under a coordinated, directed program. In addition, commercial logging services should be utilized to the utmost. It may not be out of order to require an electric log on each new well drilled.
2. Microscopically examine and describe samples in the State Engineer's Office from wells drilled and integrate the results with the electric logs. Samples provide the primary foundation of any stratigraphic study; the untapped reservoir of information contained in unexamined samples is tremendous.
3. Conduct more detailed regional stratigraphic and structural analyses of the Glorieta Sandstone to shed some light on the problems of recharge to the basin, as well as of potentially new horizons of limited amounts of otherwise unavailable water.
4. Re-evaluate hydrological data and accumulate new data in the stratigraphic and structural zones delineated in this paper to determine the effects of stratigraphic and structural controls on the amount and direction of recharge, leakage, quality, and transmissibility and the varying effects on the Pecos River.
5. Delineate the base of the aquifer and Slaughter zone interface on the Roswell block so that control of saline encroachment can best be investigated.
6. Determine by hydrogeologic analysis what steps, if any, can be taken to inhibit saline encroachment. Consideration might be given here to the possibility of establishing several injection wells in and around the interface of the base of the artesian aquifer and the Slaughter zone to pressurize the interface and deter encroachment from down-dip. Likewise, retirement of certain rights might increase the head on the Roswell block sufficiently to halt or reverse saline encroachment.
7. Conduct studies in the remainder of the Roswell artesian basin designed to zone the stratigraphy and delineate the structure to determine the hydrology of each geological unit.
8. Investigate the Slaughter and Glorieta in the southwest reaches of the Orchard Park block for possible untapped waters.

Summary

The Roswell artesian basin, and more particularly the northern part of the system, is one of the world's finest examples of a rechargeable artesian aquifer and is probably one of the more geologically complex basins. It is not composed of homogeneous units dipping uniformly from one side toward a river discharge point(s) on the other but is instead a hydrogeological complex composed of lithologically differing stratigraphic units that undergo frequent facies changes and structural interruptions.

The system is composed of parts of several thousand feet of stratigraphic units which within themselves have complex parts. Porosities and permeabilities vary horizontally and vertically, causing differential flow paths and rates. Formation waters intermingle with meteoric waters to yield varying qualities of water.

The data presented in this paper illustrate some of the problems to be solved before any long-range, meaningful, hydrological evaluation can be accepted. It cannot, and should not, be forgotten that it is the rocks into which and through which water moves. Obviously, any change in the nature of the rocks or their interrelationships affects the water contained in them.

The structural and stratigraphic relationships to the water discussed in this paper should, if nothing else, demonstrate the grossly inadequate state of our knowledge regarding the geology of the basin. It should further illustrate the availability of methods by which the necessary information might be obtained.

Appendix A

GENERAL CORE DESCRIPTIONS

Pecos Valley Artesian Conservancy District No. 1
Stratigraphic Test
(SE¼SE¼SE¼ sec. 34, T. 10 S., R. 24 E.,
Chaves County, New Mexico

These descriptions were made on location prior to shipping cores to Hobbs, New Mexico, for analysis. All the descriptions are very general and megascopic. (*Note:* Wherever anhydrite is described, it may in fact be gypsum.)

Core no. 1, 263-289 feet Cut 26 feet and recovered 15 feet

FEET	
263-264	Brecciated limestone, red shale stringers, anhydrite, much vuggy porosity; high percentage of porosity developed along horizontal and vertical fractures; diagonal fractures show high degree of solutional activity
264-265	Limestone, tan to gray, fine crystalline to dense, much good porosity and obvious permeability
265-266	Top 0.5 foot as above; bottom 0.5 foot slightly more dolomitic or anhydritic as evidenced by acid reaction; porosity appears to increase within bottom 0.5 foot, probably related to dolomitic or anhydritic increase; drusy anhydrite lining on vugs
266-267	Limestone, dolomitic, anhydritic, large vuggy porosity; rectangular vug in top of foot is 1 inch by 0.75 inch and is obviously solution of a crystal; sizable fracture in center is lined with a nearly travertinelike coating
267-268	Limestone, as above; bottom 3 inches are dolomite with pinpoint porosity and vugs to 1 inch; few rectangular vugs, as above; a pronounced diagonal fracture is heavily lined, very fine crystalline, brown, drusy mineral (anhydrite?)
268-269	Dolomite, highly fractured, abundant pinpoint to small vuggy porosity; dolomite contact erratic and inclined; opposite side of core predominantly limestone, with the contact diagonally across core; probably a secondary relationship; some solution of fossils; red shale and anhydrite inclusions; suggestive of a lagoonal facies
269-270	Dolomite, very vuggy, rectangular solutional remnants; reddish cast to dolomite; one minor fracture through center of core; red shale and anhydrite inclusions
270-271	Dolomite, as above, slightly diagonal fracture in top 1 inch; much vuggy porosity, with rectangular vugs to 1 inch, lower 3 inches becoming denser with less vuggy porosity
271-272	Limestone, porous, lower 1.5 and top 3 inches more dolomitic with better porosity; pinpoint to small vuggy porosity throughout, best developed in dolomitic part; well fractured
272-273	Limestone, dolomitic (possibly anhydritic); top third with heavy vuggy porosity as seen in footage above; middle third fractured, stringers of red shale, generally less porous than above, but porosity still good; bottom third similar to top but slight increase in porosity.
273-274	Limestone, dolomitic, gray to brown, dense to very fine crystalline, very large vugs; fracture planes slightly oblique; strong solutional activity along fractures and considerable residual clay concentrations on fracture planes; many vugs have rectangular shape and are probably salt or anhydrite casts; heavy solutional activity has occurred along diagonal fractures, resulting in very good porosity
274-275	Limestone, as above, with less diagonal fracturing; large fracture plane in bottom part of foot has concentration of vugs ranging in size from slightly larger than pinpoint to more than 1 inch; upper part of foot has several rectangular vugs, whereas the vugs in the lower half of foot are more rounded and associated with fractures
275-276	Limestone, as above, upper 3 inches are dolomitic; lower 9 inches of foot more dolomitic with an increase in vug size to half an inch.
276-277	Limestone, as above, with much fracturing and solutional activity along fracture planes; fractures oblique to core at approximately 60 degrees; concentration of clays along the fracture planes; some travertinelike deposits along fracture planes
277-278	Limestone, as above, less fracturing; vugs to 1.5 inches
278-279	No recovery

Core no. 2, 289-301 feet Cut 11 feet and recovered 6 feet

289-290	Limestone, brown to gray, dense to very fine crystalline, shaly to clean in part; red and green shale inclusions abundant; appears trashy
290-291	Limestone, as above, very vuggy, large number of vugs developed along fracture planes; appears somewhat conglomeratic in texture; big vugs in top of foot seem to be formed by the removal of red shale; other parts of the foot show very large amounts of drusy anhydrite filling and lining; drusy anhydrite crystals tend to heal the fractures, and residual clay deposition along the floor of vugs denotes solution of some carbonate; much solution activity has removed large parts of the red shale inclusions; apparently from the central part of the inclusion outward
291-292	Limestone, as above. Lower 3 inches have very large fracture and vug system developed along fracture planes; very heavy drusy anhydrite lining vug; fracture is diagonal; clay concentration along floor of smaller vugs
292-294.5	Limestone, as above
294.5-295	Limestone, gray, dense, marked decrease in shale content, nearly a complete absence; vugs now oriented along fractures rather than solution and removal of shale, as above; vugs much more

FEET

penetrating than above; this foot marks a distinct lithologic change

295-300 No recovery

Core no. 3, 300-331 feet Cut 31 feet and recovered 7 feet

300-307 Limestone, gray, brown, dense to fine crystalline, very porous; vugs irregular in shape, some have flat bases because of development along fractures; porosity probably in excess of 25 per cent

307-331 No recovery

5-foot depth correction

Core no. 4, 336-386 feet Cut 50 feet and recovered 18 feet

336-337 Limestone, light brown, fine crystalline, much vuggy porosity along fractures; solution of (anhydrite?) inclusions

337-338 Limestone, as above; angular relation in lower 3 to 4 inches changes from gray cast to brown angular band; tight

338-339 Limestone, gray, brown, dense, fine crystalline, vuggy throughout; all porosity lined with drusy anhydrite, as is common to porosity above; lower 3 inches very vuggy

339-340 Limestone, brown to gray, very fine crystalline, scattered large vugs in top 0.5 foot, lower 0.5 foot vuggy; drusy vug lining

340-341 Limestone, gray to brown, dense to very fine crystalline, very vuggy, vugs to 1.5 inches.

341-342 Limestone, brown, gray, anhydrite inclusions, very fine crystalline to dense; porous in lower part; well fractured

342-343 Limestone, as above, pinpoint porosity to vugs 0.5 inch; middle part of foot nonporous

343-345 Dolomite, dense, gray, narrow zones of pinpoint porosity to some vuggy porosity; some fracturing

345-346 Dolomite, as above, small fracture in middle of foot; drusy dolomite crystals developed on fracture surface; some anhydrite

346-347 Dolomite, dense, tight, one solution vug (fossil?) and one diagonal fracture cutting through top half of foot

347-3-18 Dolomite, as above, slight increase in fracture porosity; some vuggy porosity

348-349 Dolomite, calcareous, gray, dense, some vugs in top 3 inches

349-350 Dolomite, dense, tight in upper 0.5 foot; lower 0.5 foot highly porous with vugs to 2 inches along high-angle fracture; some lithologic variation in this foot

350-351 Dolomite, as above, in top 0.5 foot; lower 0.5 foot has pronounced vertical vug 5 inches long; dolomite very calcareous, gray to tan, dense

351-354 Limestone, gray, tan, increased porosity over above but poorer quality; drusy lining still present in vugs and fractures; one healed high-angle fracture in bottom foot

354-386 No recovery

FEET

Core no. 5, 386-437 Cut 51 feet and recovered 3 feet

386-388.2 Dolomite, light gray, dense to lithographic, very little visible porosity; upper 5 inches show some minor unconnected porosity; one large vug with residual clay and heavy vug lining

388.2-389 Limestone, light gray, dense to very fine crystalline, abundant vuggy porosity, porosity ranges from pinpoint to 0.5 inch; limestone badly altered, thereby having slightly silty texture; crystal lining well developed

389-436 No recovery

Core no. 6, 437-503 feet Cut 66 feet and recovered 8 feet (bit dropped 16 feet after cutting 50 feet)

437-438 Limestone, dense to very fine crystalline, honey-combed with porosity in upper 3 inches; some vugs to 0.5 inch, drusy crystal lining over some of the vugs; the honycomb is itself a framework of drusy anhydrite developed along fractures, and the intervening limestone has been dissolved or altered; in all instances it appears that there is significant clay concentration because of solution and removal of the limestone; the middle 3 inches are tight; lower 6 inches are pinpoint to small vuggy porosity

438-439 Interval badly broken; top 2 inches limestone, gray to tan, some fine porosity, one vertical fracture through core is tight; middle of core is slightly dolomitic limestone, gray to brown, very fine to fine crystalline, diagonal shale parting, much vugular porosity, some drusy crystal lining in the bottom of vugs; bottom of foot has 1 inch dense, dark-gray dolomite partings; the fragments in this foot probably represent the hard streaks of many feet too porous to recover

439-440.5 Limestone, dolomitic, gray, dense, some minor fracturing filled with fine crystalline anhydrite; limestone vary badly altered by solution; honey-combed with drusy materal; vugs irregular in shape probably formed by network of intersecting fracture fillings and vug linings; the vugs are partly filled with altered limestone or residual clay

440.5-441.5 Dolomite, gray, dense, abundant pinpoint to 0.5 inch vugs

441.5-442.5 Dolomite, as above, more shaly, possible trace of chert

442.5-443.2 Limestone, gray, silty with thin intercalated hairline dark shale partings; has a silty texture; probably a micaeous siltstone in lower part of foot; next foot more granular, increase in grain size, some solution activity; minor solution activity by removal of calcite, with some deposition in the form of vug lining; the foot appears to be very shaly limestone that has undergone intense alteration by solution leaving high residual clay content

443.2-503 No recovery

FEET

Core no. 7, 503-517 feet Cut 14 feet and recovered 4 feet

503-506 Dolomite, calcareous, medium to dark gray, some light gray, dense to very fine crystalline; some scattered pinpoint to fine vuggy porosity; minor vugs to 0.25 inch, occasional vugs to 0.5 inch; dolomite is shaly with many hairline partings to irregular black shale planes; these shales appear to result from minor shale concentration and may be the incipient stages of stylolite development; the dolomite, calcareous, is stylolitic with amplitude to 0.75 inch, rarely more; rock is tight; sulphur odor on fresh break; at top of 504 feet, stylolite has an amplitude of approximately 1.5 inches and is sharp and ragged

506-517 No recovery

Core no. 8, 517-544 feet Cut 27 feet and recovered 20.5 feet

517-518.5 Dolomite, gray to dark brown, very fine crystalline, very shaly, much solution activity in top of foot, very stylolitic, vugs from pinpoint to 0.5 inch

518.5-523 Dolomite, dark brown to gray, very shaly, stylolitic, many hairline shale partings; vugs from pinpoint to 1 inch; vugs lined with drusy anhydrite

523-523.4 Shale, black, hard, dense

523.4-524.6 Dolomite, as above, some pinpoint porosity, and small vugs, slightly stylolitic

524.6-524.9 Shale, black, hard, dense

524.9-534 Dolomite, calcareous, brown to tan, dense to fine crystalline, shaly, pinpoint porosity 528 to 529 feet, moderately strong sulphur ordor on fresh break; pinpoint porosity 531.7 to 533.7, some small vugs; trace pinpoint porosity and scattered small vugs bottom of 533 and top of 534

534-537.5 Dolomite, as above, few scattered vugs, basically tight; 536.6 to 537.5 increased pinpoint porosity, generally bleeding waters; well-developed sulphur crystals line vug at 535 and below; sulphur crystals combine with anhydrite to form lining on some fracture surfaces

Core no. 9, 544-580 Cut 36 feet and recovered 34.5 feet

544-546 Dolomite, gray to medium dark gray, very fine to fine crystalline, abundant pinpoint porosity in top half of foot; 3 inch black shale from 544.5 to 544.8; lower part tight

546-548.5 Dolomite, calcareous, gray to medium gray, dense to very fine crystalline; isolated large vugs lined with drusy anhydrite, black sulphur stain, and some minor sulphur crystals

548.5-548.7 Limestone, dolomitic, dark gray, very fine crystalline

548.7-549.2 Shale, black

549.2-550 Dolomite, gray to medium gray, dense to very fine crystalline, very shaly, nonporous

550-550.5 Dolomite, as above, high frequency of hairline black shale partings

FEET

550.5-551.5 Dolomite, dark gray, fine crystalline, few scattered vugs lined with drusy anhydrite, trace of sulphur crystals

551.5-553.7 Dolomite, light to dark gray, very fine to fine crystalline, many black hairline shale partings, a few scattered vugs, tight

553.7-553.8 Shale, black

553.8-554.6 Dolomite, as above in top half of foot; large stylolite cuts diagonally across core, puts upper half in contact with light gray, calcareous dolomite

554.6-557.6 Dolomite, dark gray to medium gray, fine crystalline; the dark gray dolomite has some pinpoint porosity; lighter gray is slightly more calcareous

557.6-561 Dolomite, dark gray, fine crystalline, shaly, scattered vugs to 3 inches; large vugs lined with sharp anhydrite and sulphur crystals

561-562 Dolomite, dark gray, some incipient pinpoint porosity

562-573.5 Dolomite, gray to dark gray, dense to fine crystalline, shaly, some cleaner zones of lighter gray; pinpoint porosity in dark

573.5-578.4 Limestone, dolomitic, very shaly, few vugs, looks "ratty," very large vugs in lower 1.5 feet, developed along stylolites, black sulphur stain on pronounced drusy lining of anhydrite

Core no. 10, 580-609 feet Cut 29 feet and recovered 23 feet

580-582 Limestone, gray-brown, very fine crystalline, pinpoint and small vuggy porosity; anhydrite lining on vugs; limestone dense and tight, in lower 0.5 foot

582-586 Dolomite, calcareous, brown to dark gray, shaly to slightly shaly, slightly stylolitic, some hairline black shale partings; dolomite cleaner with small vugs and pinpoint porosity below the middle of 584

586-587 Dolomite, as above, more shaly, some vuggy porosity along horizontal fracture plane; many hairline black shale partings and inclusions; larger vugs to 3 inches becoming filled with anhydrite; the secondary anhydrite is showing effects of some solution by development of pinpoint porosity; lowermost large vug in bottom of foot lined with anhydrite and some sulphur crystals

587-588 Dolomite, calcareous, as above, very shaly, slightly styloli tic

588-589 Dolomite, as above, less shaly, small vugs have been completely filled with secondary anhydrite; minor pinpoint porosity

589-590 Dolomite, as above, brown to black, small diagonal fractures

590-591 Dolomite, fine crystalline, gray to dark gray, abundant pinpoint porosity, some filled with secondary anhydrite; many anhydrite veinlets resulting from filling of fractures by secondary anhydrite

591-592 Dolomite, calcareous, gray to dark gray, dense to very fine crystalline; stylolite in top of foot

FEET

lined with sulphur crystals; lower part of foot very shaly, minor pinpoint porosity

592-595.2 Dolomite, as above, sulphur crystals on fracture planes; much vertical fracturing; vugs filled with anhydrite and some sulphur crystals included; majority of porosity filled

595.2-596.8 Dolomite, calcareous, dark gray, hairline shale inclusions, dense, large stylolite in base of foot, 3 or 4 scattered vugs

596.8-599 Dolomite, calcareous, dark brown, dense to fine crystalline, hairline shale inclusions; some fracturing and vugs filled with secondary anhydrite

599-603 Dolomite, calcareous, dark gray, shaly, abundant black shale inclusions, dense to very fine crystalline; sulphur crystals in fracture planes, horizontal and vertical, and in shale creases; bottom 0.5 foot has slightly different color and texture: brown, fine crystalline

603-609 No recovery

Core no. 11, 609-639 feet Cut 30 feet and recovered 28 feet

609-613.5 Limestone, brown, dense to very fine crystalline, tight

613.5-619 Limestone, dark gray, dense to very fine crystalline, shaly in parts, slightly stylolitic, a few vugs, basically tight

619-623 Limestone, black, dense, shaly; stylolites with sulphur crystals

623-626.5 limestone, dark brown to dark gray-brown, dense to fine crystalline, lacking in porosity except lower 0.5 foot, pinpoint porosity in upper 0.5 foot; numerous stylolites with a sharp amplitude to 3 inches

626.5-630.5 Limestone, dense to very fine crystalline, shaly to very shaly; fair pinpoint porosity in middle of interval and in lower 1.5 feet; sulphur odor on fresh break; large vug at top 629 approximately 3 inches, heavily lined with sulphur crystals; tight vertical hairline fractures; traces of black shale concentrations in vertical planes appear to be along fracture planes, but also appear to be more like stylolite; lower 0.5 foot has increased porosity

630.5-632.5 Limestone, very dark brown to black, dense to very fine crystalline, some vertical fracturing, moderately good vug development, heavily lined with sulphur crystals

632.5-633.2 Limestone, dense, very fine crystalline, very large vug 1 inch diameter cuts nearly through core; heavily lined with sulphur crystals

633.2-637 Limestone, dark brown, dense to fine crystalline, hairline shale parting; several vugs 635 to 636 have two stages of anhydrite filling of vugs

637-639 No recovery

Core no. 12, 639-679 feet Cut 40 feet and recovered 41 feet

Limestone, dark gray to black, dense to fine crystalline; numerous hairline shale partings and inclusions; entire core shaly; some scattered zones of small vugs and pinpoint porosity; stylolitic; possible intraformational slump developed at 678

FEET

Core no. 13, 679-715 feet Cut 36 feet and recovered 34 feet

679-686 Limestone, dense to very fine crystalline, dark brown to black, shaly to very shaly, some scattered vugs to 1 inch, few scattered stylolites, many hairline shale partings; stylolites appear to have had some minor amounts of solutional activity; interval mostly nonporous

686-688.5 Shale, black, hard, some thin intercalated limestone

688.5-696 Limestone, dark gray, dense to fine crystalline, slightly shaly at top to many hairline shale partings and very shaly at bottom; stylolitic; few scattered vugs arc filled with anhydrite and some sulphur crystals

696-713 Limestone, shale, very shaly limestone, fossiliferous, fossils replaced with anhydrite; interval appears as highly shaly fossil hash, some cleaner limestone intercalated; drusy crystal lining of anhydrite and sulphur crystals; many vugs completely filled; stylolitic; few very thin, tight fractures

713-715 No recovery

Core no. 14, 715-762 feet Cut 47 feet and recovered 47 feet

715-726 Limestone, gray to dark gray, dense to fine crystalline, many shale partings; shaly fossiliferous hash, as described above

726-727.5 Limestone, dark brown to black, very fine to fine crystalline, fossiliferous, shaly, tight

727.5-727.8 Shale, black, calcareous

727.8-730 Limestone, dark brown to black, dense to fine crystalline, shaly; slightly cleaner in lower foot with some tight vertical fractures and some pinpoint to fine vuggy porosity

730-731 Limestone, black, fine crystalline, some small vugs in middle of foot; large vug in center lined with anhydrite and stained with sulphur

731-738.3 Limestone, shaly, fossiliferous hash, as described above; anhydrite replacement of fossils; lower 0.5 foot less shaly

738.3-748.5 Limestone, dark gray to black, shaly to very shaly, some intercalated fossiliferous hash zones, as described above; some minor vertical fracturing, tight; some large vug development filled with secondary anhydrite; few high amplitude stylolites; some minor pinpoint porosity

748.5-762 Limestone, as above, some brown; few large vugs filled with anhydrite; few stylolites; few tight fractures

Core no. 15, 762-804 feet Cut 42 feet and recovered 41 feet

762-803 Limestone, dark gray to black, dense to some very fine crystalline, hard, nonporous in general; a few small scattered vugs 762 to 765; several large vugs 773 to 776; some intercalated fossil hash, as in cores above, 786-790; trace of vertical fracturing; trace of stylolites

868.8-884 Dolomite, dark gray to brown, very fine crystalline, small vugs and pinpoint porosity scattered throughout; some large vugs do not appear in-

FEET

terconnected and are lined with calcite crystals; trace of sulphur staining in large vugs; slightly stylolite; parts of interval slightly shaly; dolomite is over-all more porous than limestone above

Core no. 18, 887-928 feet Cut 41 feet and recovered 27 feet

887-890 Limestone, dark brown, dense to very fine crystalline, shaly, many thin shale partings
890-890.7 Dolomite, dark brown, very shaly, tight
890.7-891 Dolomite, dark brown, pinpoint to vuggy porosity (zone where core was probably lost)
891-893.5 Dolomite, dark brown, dense, scattered small vugs to 0.25 inch
893.5-895 Dolomite, dark brown, dense to very fine crystalline, trace of pinpoint to vuggy porosity
895-895.6 Dolomite, as above, slightly shaly, vugs halfway through core; slightly fossiliferous; drusy lining on vugs
895.6-896.5 Dolomite, gray, shaly, soft, marllike
896.5-900 Dolomite, dark gray to black, dense to very fine crystalline, fair to good vuggy porosity; slightly shaly
900-901 Dolomite, dark gray to black, dense, shaly
901-904.6 Dolomite, gray-brown, shot through with anhydrite veinlets to 0.25 inch
904.6-905 Irregular contact with dolomite, as above, and anhydrite, clear, coarse crystalline
905-907.5 Anhydrite, clear, coarse crystalline, intercalated dolomite stringers and inclusions
907.5-914 Intercalated anhydrite, massive, and dolomite, dense, both with clear, coarse, anhydrite inclusions; some anhydrite exhibits flow structures; some of the anhydrite is very hard and dense, has appearance of dolomite, but will not respond to 10 per cent HCl
924-927.5 Anhydrite, gray, dense (recovered while circulating for DST)

Core no. 19, 928-979 feet Cut 51 feet and recovered 50 feet

928-968 Dolomite, dark brown, dense to very fine crystalline, shaly to very shaly, slightly stylolitic, many hairline shale inclusions and thin partings; scattered traces of pinpoint porosity to small vuggy porosity; majority of vugs filled with secondary anhydrite; scattered anhydrite veins to 0.25 inch, mostly in middle of 940; shaliness increases from 960 to 965.5
968-975.3 Dolomite, dark gray, dense, slightly shaly, tight
973.3-979 Anhydrite, gray, dense to fine crystalline, traces of medium crystalline; some indications of fracturing and minor movement of fluids as indicated by deposition of anhydrite vug fillings; fractures and stylolites randomly scattered to 966, in dolomite, above, do not continue into lower part of core

Core no. 20, 979-1012 feet Cut 33 feet and recovered 29.7 feet

979-981 "Anhydrite, gray, fine to medium crystalline, some dark brown, fractured, inclusions, tight

FEET

981-986.5 Anhydrite, gray to dark gray, fine to medium crystalline, some horizontal healed fractures; some inclusions of darker gray dense anhydrite in irregular shapes
986.5-990 Sandstone, very fine-grained well cemented, anhydritic to very anhydritic; well rounded, well sorted, nonporous
990-992 Sandstone, light gray, very fine-grained, friable, well sorted, well rounded, good porosity, sulphur staining throughout; this zone probably lost 3.5 feet of core
992-1007.3 Sandstone, very fine-grained, light gray, very anhydrite, thin wavy shale partings in minor amounts; very tight; places have greater percentage anhydrite than sand but still basically sand
1007.3-08.7 Anhydrite, gray, very fine crystalline, tight

Core no. 21, 1012-1050 feet Cut 38 feet and recovered 36 feet

1012-26 Dolomite, dark brown, dense to very fine crystalline, slightly fossiliferous, very sandy
1026-29 Anhydrite, gray, very fine to fine crystalline, sandy
1029-31 Sandstone, very light gray, very anhydritic, very fine-grained isolated spots of bleeding sulphur water in middle 1029
1031-33.5 Sandstone, as above, very slightly shaly, sulphur stain in some thin layers; tight
1033.5-45.5 Sandstone, gray, anhydritic, slightly dolomitic, very fine-grained, slightly friable, sulphur odor
1045.5-49 Anhydrite, very sandy, sulphur odor on fresh break; very tight
1049-50 Dolomite, dark gray to brown, sandy, dense to very fine crystalline, trace shale, very tight

Core no. 22, 1050-1077 feet Cut 27 feet and recovered 23.5 feet

1050-59.7 Dolomite, dark brown to gray, fine to medium crystalline, anhydrite, few hairline shale partings; trace stylolites; tight
1059.7-60.1 Dolomite, dark gray, dense to lithographic, tight
1060.1-64.4 Anhydrite, gray to clear, dense to coarse crystalline, -much dense gray dolomite included
1064.4-74.5 Dolomite, dark gray, dense, some anhydrite filling vugs to 1 inch; minor fractures, tight; very scattered, thin horizons of porosity, probably not interconnected; dolomite slightly siliceous, lighter in color in basal part; thin sandy zone in middle 1072

Core no. 23, 1077-1081 feet Cut 4 feet and recovered 4 feet

1077-77.5 Dolomite, gray, dense, tight
1077.5-81 Sandstone, gray, very fine-grained, anhydritic, dolomitic

Core no. 24, 1096-1102 feet Cut 6 feet and recovered 5 feet

1096-1102 Sandstone, gray, very fine-grained, very slightly friable, anhydrite, dolomite, speckled with sulphur stain

Appendix ***B***

Core analyses from Pecos Valley Artesian Conservancy District (PVACD) No. 1 Stratigraphic Test, SE1/4 SE1/4SE1/4 sec. 34, T. 10 S., R. 24 E., Chaves County, New Mexico. Well site geologist: Kay C. Havenor, assisted by Robert L. Borton, geologist, State Engineer's Office. Core analyses by RGM Core Analyses Ltd., Hobbs, New Mexico.

Data determined by full-diameter core (3-inch and 3.5-inch) analysis except where marked by an asterisk (*) to indicate conventional permeability because of badly broken core sample. Permeabilities greater than the number indicated are preceded by a plus (+) sign; permeabilities less than the number indeated are preceded by a minus (-) sign.

High "gypsum" content indicated by analyzer was done with the belief that the porosity and permeability were possibly induced by drilling fluid circulation during coring operations. These few values are therefore not considered reliable. The samples containing high or very high "gypsum" are in dicated by a dagger (t) .

SAMPLE	DEPTH OF	POROSITY	PERMEABILITY (millidarcys)	
NUMBER	SAMPLE	(%)	HORIZONTAL	VERTICAL
	FULL DIAMETER CORE ANALYSIS			
1	263.0-64.0	10.2	32.	26.
2	265.0-66.0	23.4	118.	86.
3	267.0-68.0	22.4	9.8	2.9
4	269.0-70.0	15.5	3480.	850.
5	271.0-72.0	14.3	15.	4.5
6	273.0-74.0	18.9	185.	90.
7	275.0-76.0	23.9	92.	75.
8	277.0-78.0	18.7	189.	75.
	278.0-89.0	Lost core		
9	289.0-90.0	15.5	197.	117.
10	291.0-92.0	10.2	123.	101.
11	292.0-93.0	13.0	+4500.	75.
12	294.0-95.0	7.3	71.	60.
	296.0-00.0	Lost core		
13	300.0-01.0	2.3	23.	8.2
14	302.0-03.0	26.5	56.	41.
15	304.0-05.0	25.7	75.	58.
16	306.0-07.0	18.1	118.	2.5
	307.0-31.0	Lost core		
	331.0-36.0	Depth correction		
17	336.0-37.0	11.5	4.7	3.8
18	338.0-39.0	5.2	4.2	3.6
19	340.0-41.0	22.6	4300.	3.6
20	342.0-43.0	7.3	1.3	0.6
21	344.0-45.0	7.7	15.	4.3
22	346.0-47.0	4.3	1.0	0.9
23	348.0-49.0	10.8	10.	5.2
24	350.0-51.0	14.2	11.	8.9
25	352.0-53.0	19.0	10.	8.7
	354.0-86.0	Lost core		
26	386.0-87.0	26.2	11.	5.8
27	388.0-89.0	9.0	0.6	0.4
	389.0-437.0	Lost core		
28	437.0-38.0	17.6	28.	25.
29	439.0-40.0	2.3	3.1	3.0
30	441.0-42.0	7.8	264.	243.
31	443.0-44.0	31.8	178.	136.
	445.0-503.0	Lost core		
32	503.0-04.0	10.4	4.1	2.0
33	505.0-06.0	9.3	14.	14.
	507.0-517.0	Lost core		
34	517.0-18.0	16.3	24.	11.
35	519.0-20.0	3.3	17.	13.
36	521.0-22.0	5.8	0.6	0.5
37	523.0-24.0	6.7	0.4	0.4
38	525.0-26.0	3.1	1.3	0.8
39	527.0-28.0	23.0	107.	71.
40	529.0-30.0	15.0	17.	15.
41	531.0-32.0	4.1	1.1	0.9
42	533.0-34.0	16.8	6.3	4.6
43	535.0-36.0	14.9	16.	11.
4	537.0-37.5	6.9	0.5	0.3
	537.5-44.0	Lost core		
45	544.0-45.0	5.0	0.2	0.2
46	45.0-46.0	3.8	0.3	0.3
47	46.0-47.0	6.3	0.7	0.4
48	47.0-48.0	6.9	2.0	1.7
49	48.0-49.0	4.2	1.4	1.3
50	551.0-52.0	6.2	0.7	0.3
51	554.0-55.0	4.3	1.5	1.4
52	55.0-56.0	4.2	3.5	2.5
53	56.0-57.0	4.8	2.5	2.4
54	559.0-60.0	18.0	1.2	0.5
55	562.0-63.0	5.3	3.6	2.3
56	63.0-64.0	6.1	1.4	1.0
57	64.0-65.0	5.6	2.1	1.2
58	65.0-66.0	6.1	2.1	1.5
59	66.0-67.0	8.2	1.3	1.0
60	67.0-68.0	6.5	1.7	1.5
61	68.0-69.0	6.7	1.1	0.9
62	69.0-70.0	5.2	1.6	1.5
63	70.0-71.0	4.4	1.2	0.9
64	71.0-72.0	5.7	1.0	0.9
65	72.0-73.0	5.6	0.6	0.6
66	73.0-74.0	6.8	1160.	1120.
67	74.0-75.0	5.2	5.9	5.9
68	75.0-76.0	9.6	32.	30.
69	76.0-77.0	17.3	350.	207.
70	77.0-78.0	14.6	18.	2.3
71	78.0-78.5	17.9	23.	4.4
	578.5-80.0	Lost core		
72	580.0-81.0	11.9	23.	3.8
73	81.0-82.0	12.5	39.	35.
74	82.0-83.0	9.5	15.	5.1
75	83.0-84.0	14.6	2.1	1.9
76	584.0-85.0	21.4	10.	10.
77	85.0-86.0	22.5	77.	70.
78	86.0-87.0	6.4	3.4	3.0
79	87.0-88.0	10.7	3.2	3.1
80	590.0-91.0	5.4	1.3	0.7
81	593.0-94.0	2.0	-0.1	-0.1
82	596.0-97.0	2.2	-0.1	-0.1
83	97.0-98.0	9.3	2.6	2.3
84	98.0-99.0	8.8	0.5	0.4
85	600.0-01.0	0.7	-0.1	-0.1

SAMPLE NUMBER	DEPTH OF SAMPLE	POROSITY (%)	PERMEABILITY (millidarcys) HORIZONTAL	VERTICAL	SAMPLE NUMBER	DEPTH OF SAMPLE	POROSITY (%)	PERMEABILITY (millidarcys) HORIZONTAL	VERTICAL
86	602.0-03.0	6.0	9.2	7.2	142	766.0-67.0	2.6	-0.1	-0.1
	603.0-09.0	Lost core			143	770.0-71.0	4.6	0.2	0.1
87	609.0-10.0	13.8	11.	8.4	144	773.0-74.0	7.4	0.8	0.7
88	613.0-14.0	1.1	-0.1	-0.1	145	74.0-75.0	6.8	0.3	0.2
89	617.0-18.0	1.7	0.5	0.3	146	75.0-76.0	6.4	-0.1	-0.1
90	621.0-22.0	2.7	0.2	-0.1	147	76.0-77.0	1.1	0.3	0.2
91	625.0-26.0	3.9	0.4	0.3	148	77.0-78.0	5.8	1.1	0.8
92	628.0-29.0	18.5	98.	2.5	149	78.0-79.0	3.8	1.0	0.3
93	29.0-30.0	15.7	1.7	1.4	150	79.0-80.0	7.3	2.0	1.5
94	633.0-34.0	10.5	1.0	0.7	151	80.0-81.0	7.6	2.0	0.5
95	636.0-37.0	1.1	0.7	0.5	152	81.0-82.0	5.7	0.9	0.4
	638.0-39.0	Lost core			153	82.0-83.0	5.1	7.2	0.2
96	639.0-40.0	1.4	0.3	-0.1	154	83.0-84.0	2.5	0.8	0.3
97	40.0-41.0	1.3	-0.1	-0.1	155	787.0-88.0	1.4	-0.1	-0.1
98	41.0-42.0	0.8	0.2	-0.1	156	791.0-92.0	1.6	-0.1	-0.1
99	645.0-46.0	1.8	1.2	-0.1	157	795.0-96.0	6.8	0.5	0.3
100	46.0-47.0	2.5	7.3	0.8	158	799.0-800.0	2.6	-0.1	-0.1
101	650.0-51.0	0.9	-0.1	-0.1		803.0-04.0	Lost core		
102	654.0-55.0	1.2	1.3	1.0	159	804.0-05.0	1.3	-0.1	-0.1
103	658.0-59.0	5.4	-0.1	-0.1	160	05.0-06.0	5.9	0.4	0.2
104	662.0-63.0	1.1	-0.1	-0.1	161	06.0-07.0	4.1	1.1	0.7
105	666.0-67.0	2.7	0.4	0.3	162	07.0-08.0	7.1	6.4	3.8
106	670.0-71.0	1.3	0.7	0.4	163	811.0-12.0	5.4	23.	0.7
107	675.0-76.0	1.3	-0.1	-0.1	164	12.0-13.0	4.4	1.3	1.1
108	679.0-80.0	1.0	-0.1	-0.1	165	13.0-14.0	12.8	2.8	2.2
109	683.0-84.0	0.8	-0.1	-0.1	166	817.0-18.0	1.4	16.	1.2
110	687.0-88.0	0.9	-0.1	-0.1	167	821.0-22.0	0.6	0.2	-0.1
111	691.0-92.0	L1	0.8	0.3	168	825.0-26.0	0.7	-0.1	-0.1
112	695.0-96.0	9.5	6.3	1.2	169	829.0-30.0	0.7	0.1	-0.1
113	699.0-700.0	4.8	381.	246.	170	833.0-34.0	2.1	0.4	0.2
114	703.0-04.0	1.0	1.8	0.2	171	837.0-38.0	0.6	-0.1	-0.1
115	04.0-05.0	5.7	1.3	0.8		838.0-39.0	Lost core		
116	05.0-06.0	5.3	11.	2.7	172	839.0-40.0	1.1	-0.1	-0.1
117	06.0-07.0	1.7	2.3	0.7	173	843.0-44.0	3.2	-0.1	-0.1
118	708.0-09.0	3.4	1.1	0.2	174	44.0-45.0	3.4	5.5	1.7
119	09.0-10.0	4.1	0.5	0.4	175	45.0-46.0	2.8	1.1	1.0
120	713.0-14.0	1.3	0.7	0.4	176	849.0-50.0	3.6	0.3	0.2
	714.0-15.0	Lost core			177	50.0-51.0	1.9	0.5	0.3
121	715.0-16.0	1.2	-0.1	-0.1	178	51.0-52.0	4.7	0.4	0.3
122	718.0-19.0	3.6	3.7	0.5	179	52.0-53.0	4.7	3.7	2.9
123	722.0-23.0	0.8	0.4	0.3	180	855.0-56.0	1.2	0.2	0.1
124	726.0-27.0	1.5	-0.1	-0.1	181	56.0-57.0	1.4	0.4	0.3
125	728.0-29.0	10.5	2.5	2.2	182	57.0-58.0	0.9	-0.1	-0.1
126	29.0-30.0	4.5	22.	1.5	183	861.0-62.0	0.7	-0.1	-0.1
127	30.0-31.0	0.8	2.4	0.5	184	865.0-66.0	0.8	0.3	0.2
128	734.0-35.0	0.6	1.2	0.8	185	868.0-69.0	3.0	0.3	0.2
129	738.0-39.0	1.6	1.8	0.8	186	69.0-70.0	11.7	8.3	6.2
130	742.0-43.0	1.4	0.8	0.3	187	70.0-71.0	8.4	0.9	0.5
131	746.0-47.0	0.6	-0.1	-0.1	188	71.0-72.0	8.5	0.7	0.6
132	750.0-51.0	1.7	20.	0.1	189	72.0-73.0	7.8	0.4	0.2
133	754.0-55.0	9.0	2.1	1.0	190	73.0-74.0	6.2	1.4	0.8
134	55.0-56.0	11.3	2.2	0.4	191	74.0-75.0	4.2	0.2	0.2
135	56.0-57.0	10.3	1.6	1.1	192	75.0-76.0	7.7	0.4	0.4
136	57.0-58.0	4.2	0.8	0.6	193	76.0-77.0	7.2	0.4	0.4
137	761.0-62.0	3.5	3.5	0.8	194	77.0-78.0	7.5	0.8	0.7
138	62.0-63.0	5.9	60.	3.6	195	78.0-79.0	6.8	1.4	0.5
139	63.0-64.0	4.7	0.5	0.3	196	79.0-80.0	10.4	1.2	0.6
140	64.0-65.0	4.4	0.1	-0.1	197	80.0-81.0	3.3	0.5	0.4
141	65.0-66.0	3.8	0.2	-0.1	198	81.0-82.0	1.8	1.1	0.4

SAMPLE NUMBER	DEPTH OF SAMPLE	POROSITY (%)	PERMEABILITY (millidarcys) HORIZONTAL	VERTICAL	SAMPLE NUMBER	DEPTH OF SAMPLE	POROSITY (%)	PERMEABILITY (millidarcys) HORIZONTAL	VERTICAL
199	882.0-83.0	1.7	0.7	0.5	246	1004.0-05.0	1.3	1.1	0.8
200	83.0-84.0	2.0	0.3	0.2	247	1007.0-08.0	1.0	1.7	0.5
	884.0-87.0	Lost core				1009.0-12.0	Lost core		
201	887.0-88.0	0.9	0.3	0.2	248	1012.0-13.0	2.1	1.1	0.7
202	890.0-91.0	3.9	1.4	0.6	249	1014.0-15.0	2.7	3.3	3.1
203	91.0-92.0	6.9	0.8	0.6	250	15.0-16.0	2.8	3.0	1.6
204	92.0-93.0	6.4	4.2	1.4	251	16.0-17.0	2.9	1.4	1.3
205	93.0-94.0	4.8	1.2	0.7	252	1018.0-19.0	1.5	1.6	1.4
206	94.0-95.0	3.0	0.5	0.3	253	1020.0-21.0	2.7	1.2	1.0
+207	95.0-06.0	11.1	+4500.	+4500.	254	1022.0-23.0	6.5	1.4	1.3
‡208	96.0-97.0	22.8	2.1	1.7	255	1024.0-25.0	6.9	1.6	1.5
‡209	899.0-900.0	20.3	5.5	4.6	256	1026.0-27.0	7.4	3.1	3.0
t210	900.0-01.0	13.1	182.	143.	257	1028.0-29.0	8.1	4.4	4.3
t211	01.0-02.0	24.7	391.	98.	258	1030.0-31.0	7.0	2.4	2.3
t212	02.0-03.0	12.7	149.	71.	259	1032.0-33.0	7.2	50.	47.
t213	03.0-04.0	17.0	235.	124.	260	1034.0-35.0	9.0	134.	121.
t214	906.0-07.0	38.7	4.9	4.9	261	1035.0-36.0	13.1	553.	553.
215	909.0-10.0	3.3	2.3	2.1	262	36.0-37.0	12.2	569.	562.
216	912.0-13.0	2.6	0.6	0.4	263	37.0-38.0	11.5	356.	351.
	914.0-24.0	Not sent to lab			264	38.0-39.0	10.3	243.	234.
217	925.0-26.0	1.1	0.7	0.6	265	39.0-40.0	10.7	280.	280.
218	928.0-29.0	3.3	1.3	1.1	266	40.0-41.0	12.0	437.	428.
219	931.0-32.0	2.5	1.6	1.5	267	41.0-42.0	11.0	263.	235.
220	934.0-35.0	7.0	0.7	0.4	268	42.0-43.0	10.3	55.	51.
221	937.0-38.0	5.9	1.0	0.8	269	43.0-44.0	11.5	71.	70.
222	940.0-41.0	8.3	2.0	1.5	270	44.0-45.0	9.9	5.4	5.4
223	943.0-44.0	5.4	5.4	4.3	271	45.0-46.0	12.0	36.	1.3
224	946.0-47.0	2.4	0.7	0.6	272	46.0-47.0	10.9	15.	14.
225	949.0-50.0	3.5	1.1	0.8	273	47.0-48.0	5.1	1.2	1.1
226	952.0-53.0	4.1	1.3	0.6	274	48.0-49.0	8.5	1.9	1.8
227	955.0-56.0	2.8	0.7	0.5	275	49.0-50.0	6.2	1.7	1.7
228	958.0-59.0	4.2	0.9	0.8	276	50.0-51.0	9.3	4.1	3.8
229	961.0-62.0	5.5	1.1	0.7	277	1053.0-54.0	5.4	3.3	3.2
230	964.0-65.0	6.6	0.7	0.7	278	1056.0-57.0	4.7	2.6	1.7
231	967.0-68.0	3.4	1.3	1.0	279	1059.0-60.0	7.3	2.0	1.9
232	970.0-71.0	4.8	1.6	1.0	280	1062.0-63.0	0.5	0.3	0.3
233	973.0-74.0	1.5	0.8	0.6	281	1065.0-66.0	3.4	1.5	1.1
234	976.0-77.0	1.4	0.7	0.5	282	1068.0-69.0	1.9	1.4	0.8
	978.0-79.0	Lost core			283	1071.0-72.0	6.9	2.0	1.4
235	979.0-80.0	1.1	1.1	1.0	284	1073.0-74.0	1.0	1.2	0.9
236	982.0-83.0	1.0	1.0	0.9		1075.0-77.0	Lost core		
237	984.0-85.0	1.2	0.9	0.5	285	1077.0-78.0	1.8	3.1	2.1
238	987.0-88.0	0.9	1.0	0.9	286	1080.0-81.0	12.2	75.	74.
239	989.0-90.0	9.6	2.4	1.9		1081.0-97.0	Drilled		
240	990.0-91.0	17.6	107.*		287	1097.0-98.0	13.8	25.	21.
241	91.0-92.0	17.3	221.*		288	98.0-99.0	5.5	2.3	2.0
242	92.0-93.0	10.6	4.5	4.2	289	99.0-1100.0	8.2	6.4	6.3
243	995.0-96.0	10.5	5.5	2.7	290	1100.0-01.0	7.2	2.2	2.1
244	998.0-99.0	12.9	7.3	4.7	291	01.0-02.0	12.2	9.2	8.0
245	1001.0-02.0	12.2	3.5	3.4		1102.0-55.0	Drilled		

Vuggy porosity

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YEAR OBSERVED	YEAR PUBLISHED	PAPER No.	PAGES
1925-1935	1936	777	109-114
1936	1937	817	195-197
1937	1938	840	252-254
1938	1939	845	279-300
1939	1940	886	376-422
1940	1941	911	151-174
1941	1943	941	184-212
1942	1944	949	258-293
1943	1945	991	205-244
1944	1947	1021	187-232
1945	1949	1028	203-240
1946	1949	1076	212-250
1947	1951	1101	190-234
1948	1951	1131	164-207
1949	1952	1161	161-204
1950	1953	1170	169-207
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1952	1955	1226	173-193
1953	1956	1270	181-205
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