HYDROGEOLOGY AND WATER RESOURCES
OF THE
AZTEC QUADRANGLE
SAN JUAN COUNTY, NEW MEXICO

by

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Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Science in Geology

New Mexico Institute of Mining and Technology

Socorro, New Mexico

May, 1976

Frontispiece. The Animas River Valley; view north towards San Juan Mountains, Colorado, from Mount Nebo, NW¼ Sec. 27, T.31N., R.10W; note irrigated floodplain.

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ABSTRACT

Groundwater must be further utilized in northwestern New Mexico in view of the impending shortage of surface waters. The purpose of this study was to examine the hydrogeology and water resources of the Aztec Quadrangle, San Juan County, in an attempt to evaluate the potential that groundwater holds for this area.

The quadrangle lies within the Central Basin of the San Juan Basin. Surface geologic units are the Quaternary deposits, and parts of the San Jose and Nacimiento Formations of Tertiary age; these were analysed by measurement and description of 8 stratigraphic sections, by detailed mapping of the Nacimiento-San Jose contact in the area, and by laboratory study of various units. Water wells and springs were inventoried and sampled, and chemical analyses were run.

The Quaternary valley-fill of the Animas and San Juan Rivers is presently the most important aquifer of the area. Numerous shallow wells yield moderate supplies of good quality water for various uses from this unit. These wells act to deplete river flow and irrigation return flow, however.

The predominantly sandy San Jose Formation has good potential as a bedrock source of potable water. The upper sandstones of the predominantly shaly Nacimiento Formation have some potential as aquifers, but both water quantity and quality are variable here. The lower sandstones of the Nacimiento Formation, and the Ojo Alamo Sandstone can be considered as potential sources of fresh, but not potable, water for the area. All deeper units hold variable quantities of brackish to very saline water.

INTRODUCTION

Problem and Purpose

The people of northern San Juan County have always relied heavily on surface waters provided by the San Juan, Animas, and La Plata Rivers. With increased industrialization and population of this area, however, the surface supplies are proving to be inadequate. Vast amounts of water have been appropriated for the production of coal and for gasification plants (Stone, 1976). The Navajo Indian Irrigation Project, which began operating in April, 1976, is expected to use 226,000 acre-feet of San Juan River water annually by the year 2000, according to the New Mexico Interstate Stream Commission and the New Mexico State Engineer Office (N.M.I.S.C. and N.M.S.E.O., 1975). The city of Farmington, which had a population of 3,000 only 25 years ago, has grown to 32,000 in 1975, and this population could double or triple within the next five years (Albuquerque Journal, June 2, 1975, p.1). From 25,000 to 33,100 acres of projected non-Indian irrigated land will have to be retired by the year 2020 in order to meet all the projected non-irrigation water requirements of San Juan County (N.M.I.S.C. and N.M.S.E.O., 1975, p.1).

The idea that prompted this study is that more groundwater can be utilized to supplement the surface water supplies and solve the problem of an imminent shortage in northwestern New Mexico. The purpose of this investigation was to examine the hydrogeology and water resources of the Aztec Quadrangle in an attempt to evaluate the potential that groundwater holds for this area.

The town of Aztec, the county seat of San Juan County, is an important population center with approximately 6,000 residents. Thousands of acres of rangeland and irrigated farmland, and the presence of hundreds of natural gas and oil wells make the Aztec Quadrangle important to both agriculture and industry. The present study should not only have importance for this area, but also for neighbouring areas where geologic conditions are similar.

Location

The Aztec Quadrangle is located in northeastern San Juan County, New Mexico and is bounded on the north by the Colorado border (fig. 1). It is a 15 minute quadrangle outlined by latitudes 36°45' and 37°N and longitudes 107°45' and 108°W, encompassing an area of approximately 240 square miles. The area includes the town of Aztec and the communities of Cedar Hill and Turley.

Structurally, the area lies in the San Juan Basin. The surface geology is composed of Quaternary deposits as well as parts of the San Jose and Nacimiento Formations of Tertiary age.

Previous Investigations

A great number of papers have been published on various aspects of the geology of the San Juan Basin. Works including the study of Tertiary and Quaternary geology, with which this report is particularly concerned, are also numerous. The early publications important to the stratigraphy and/or paleontology of the Tertiary and Quaternary systems of the eastern San Juan Basin are those of Cope (1875), Newberry (1876), Gardner (1910), Granger (1914), Sinclair and Granger (1914), and Reeside (1924). Two studies important to the study of Quaternary geology and geomorphology of the area are those of Atwood and Mather (1932) and Bandoian (1969). Later stratigraphic works are those of Dane (1946), Northrop and Wood (1946),

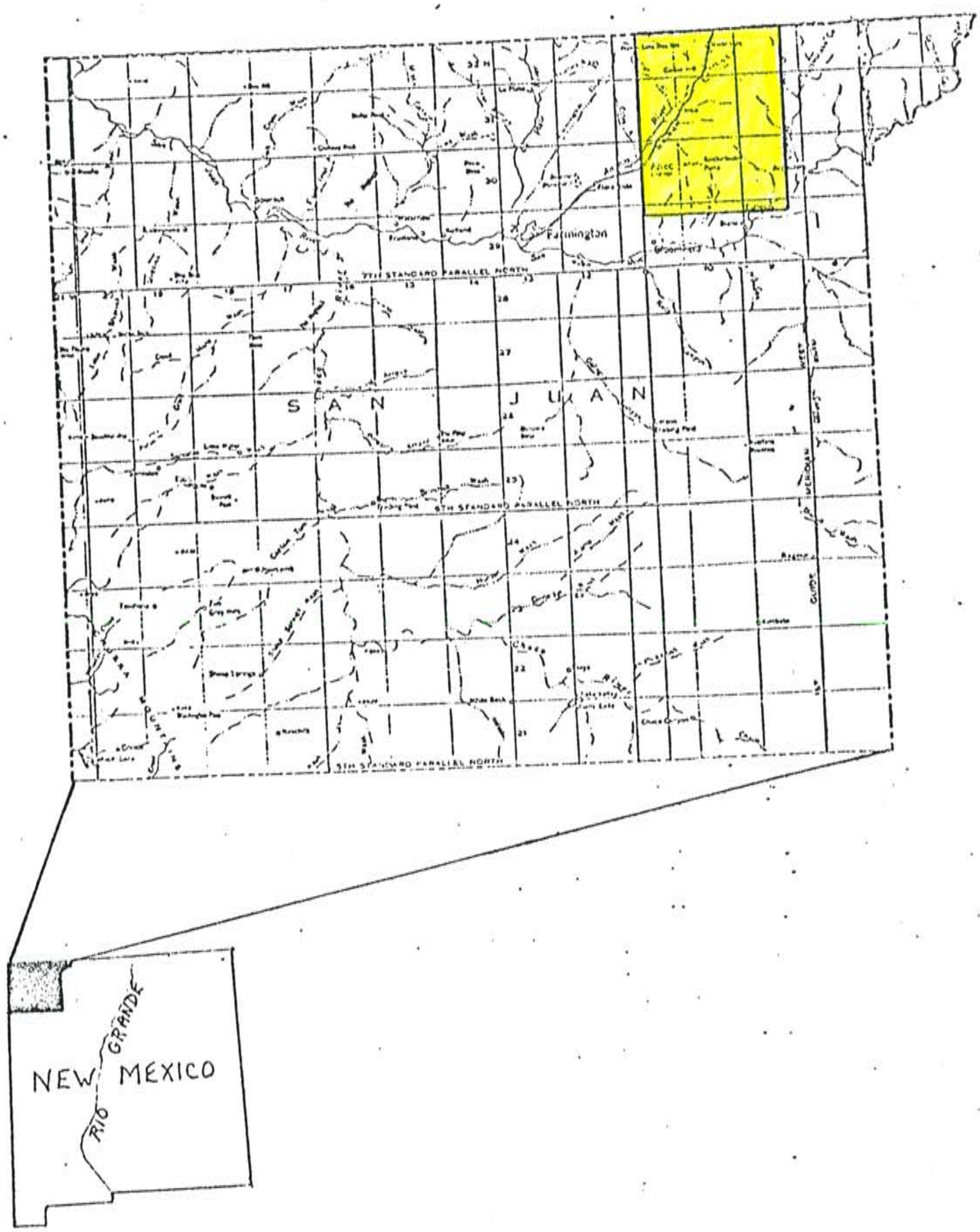


Figure 1. Location of Aztec Quadrangle within San Juan County and New Mexico (from U.S.G.S. Map of New Mexico).

Baltz (1967), McDonald (1972), and Powell (1973). Papers directly related to the hydrogeology and water resources of the area were written by Renick (1931), Rapp (1959), Berry (1959), Baltz and West (1967), and Brimhall (1973).

Approach and Methods

The hydrogeology and water resources of the study area were analysed through field work, laboratory analyses, and summary of available literature.

In the field, the hydrogeology was studied by detailed measurement and description of eight stratigraphic sections (Appendix A). Samples of various units were also collected for further study. Based on field and previously published work, the Nacimiento- San Jose contact was mapped in detail (Plate 1). Depths to bedrock in the Animas River Valley alluvium were tested by means of a portable hammer seismograph. Also in the field, the water resources of the area were studied primarily by inventorying wells and springs and collecting samples of these waters for laboratory study. Depth to water was measured in accessible wells.

In the laboratory, the surface rocks of the area were studied with a binocular microscope, in thin section with a petrographic microscope, and by staining of slabs (Appendix B). Electric logs were used to produce maps of the depth, thickness, and structure of particular units, and to construct stratigraphic cross sections of the quadrangle (Plates 4, 5). To study the water-conducting properties of a San Jose sandstone, several lab tests were run to determine values of hydraulic conductivity. Also in the lab, numerous water-well and spring samples were chemically analysed to evaluate water quality in various formations.

The available literature on the geology of surface and subsurface units was summarized. For subsurface units, only published information was reported. As stated above, the literature was also helpful in mapping the Nacimiento-San Jose contact. Also, much information was gleaned from the literature on the water-quality and water-bearing characteristics of surface and subsurface rocks. Many well inventories were obtained from the open files of the United States Geological Survey Water Resources Division. From the literature, summaries were made of the climate, soils and vegetation, land use and economy of the study area.

Acknowledgements

Sincere appreciation is extended to thesis committee chairman Dr. William Stone, who also suggested the study, and to Dr. John MacMillan and Dr. Lynn Gelhar, committee members, for their advice and supervision. I also extend thanks to the New Mexico Bureau of Mines and Mineral Resources (N.M.B.M.M.R.) and Director, Dr. Frank Kottlowski, for financial support of the study. Special thanks are due the following individuals: Mrs. Lynn Brandvold, N.M.B.M.M.R., for running the chemical analyses; Dr. Antonius Budding, New Mexico Institute of Mining and Technology (N.M.I.M.T.) for help with hydraulic conductivity tests; Dr. Allan Sanford, N.M.I.M.T., for advice on seismic refraction soundings; Mr. Robert Bieberman and Mr. Al Kendrick, N.M.B.M.M.R. and New Mexico Oil Conservation Commission, for assistance with geophysical logs; Mr. Forest Lyford and Mr. Peter Frenzel,

United States Geological Survey (U.S.G.S.) Water Resources Division, for water-well inventories and loan of equipment; Chief Brown and Mr. John Ahlm, El Paso Natural Gas Company (E.P.N.G.), for water well inventories.
I also wish to thank the landowners of the Aztec Quadrangle and the town of Aztec for their cooperation. I especially wish to thank my wife, Carolyn, for her patience and support during the study.

GEOGRAPHIC SETTING

Topography

The Aztec Quadrangle is located in the eastern half of the Navajo Section of the Colorado Plateau physiographic province (Fenneman, 1931). The topography is dominated by the flat-topped Mesa Mountains in the northern part of the map area, and by the extensively eroded divide between the Animas and San Juan Rivers.

The numerous arroyos of the area produce narrow, steep-walled canyons where they cut through interbedded sandstones and shales. The divides between these arroyos are often flat-topped and capped by sandstone (fig. 4). Several prominences do exist in the area, among them Slane Knob, Knickerbocker Peaks, Hart Mountain, Tank Mountain, Mount Nebo and Lone Tree Mountain. The maximum relief is over 1,600 feet; from elevation 5,600 feet in the river valleys to 7,216 feet at Tank Mountain in the northeastern part of the quadrangle. Local relief is greatest between the Animas River and the top of Mount Nebo, a rise of over 1,000 feet in less than one mile.

In the southern and western portions of the area, where shales of the Nacimiento Formation are predominant, a different landscape is present. Here, erosion has produced a "badlands" topography in which virtually all the land is in slope.

Drainage

The land of the Aztec Quadrangle is drained by two major perennial streams: the Animas and San Juan Rivers. Approximately 140 square miles, or a little over half the quadrangle, lie in the Animas River drainage basin. The river flows some 15 miles through the area in a southwesterly direction (fig. 3). The Animas is supplied with 40 percent of its flow by the melting snows of the San Juan Mountains of Colorado (Pastuszak, 1968, p. 16) and

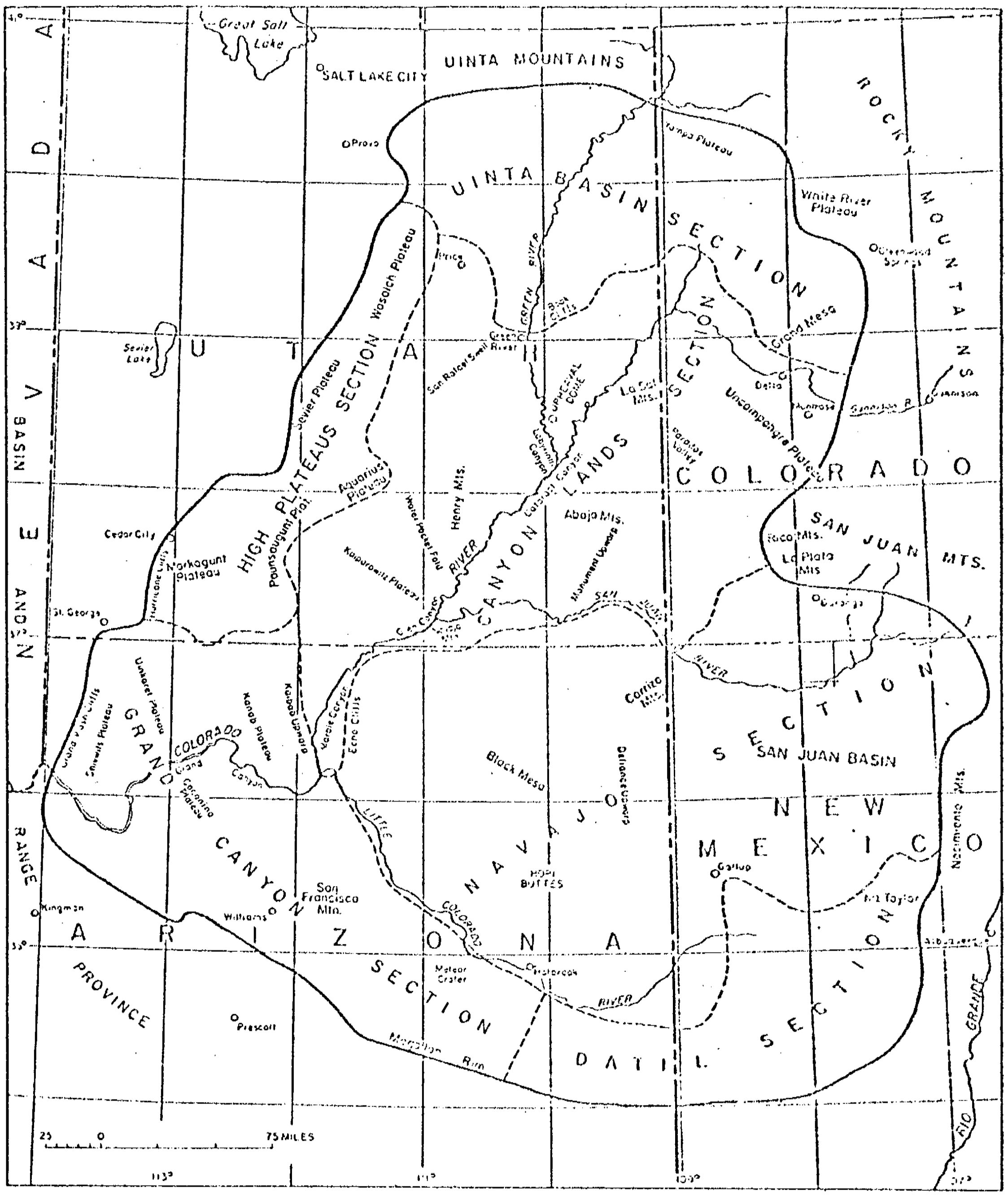


Figure 2. Physiography of the Colorado Plateau Region (Thornbury, 1965); Aztec Quadrangle is shaded.

is the main source of water for the cities of Aztec and Farmington. In the Aztec Quadrangle alone, approximately 3500 acres of farmland rely on the Animas River for irrigation water.

The headwaters of the Animas River are approximately 70 miles north of the study area in the San Juan Mountains. After a steep descent, the river crosses into New Mexico 4 miles north of Cedar Hill where it has incised a deep, narrow canyon in the Mesa Mountains (frontispiece). At Cedar Hill, however, the valley widens considerably and the Animas meanders on a flood plain that averages one mile in width. The average discharge of the Animas River is 814,200 acre-feet/year 4 miles north of Cedar Hill, and where it empties into the San Juan River near Farmington, it is 729,400 acre-feet/year (Cooper and Trauger, 1967).

The San Juan River flows westerly across the southeast corner of the quadrangle and drains approximately 100 miles of the study area. Below the Navajo Dam, which regulates its flow, the San Juan flows on a broad, irrigated flood plain. this river also rises in Colorado and drains a large area of both states. At Archuleta, New Mexico, the average discharge of the San Juan River is 943,300 acre-feet/year.

The drainage divide between the Animas and San Juan Rivers rises to an elevation of 6,000 to 7,000 feet and bisects the Aztec Quadrangle from northeast to southwest. In the study area the two streams are separated by approximately 12 miles of interbedded Tertiary sandstones and shales of the San Jose and Nacimiento Formations. In most of the quadrangle these formations are dissected by deep, steep-walled arroyos which generally form dendritic drainage systems (Bandoian, 1969, p. 11). The streams associated with these arroyos are ephemeral and flow only

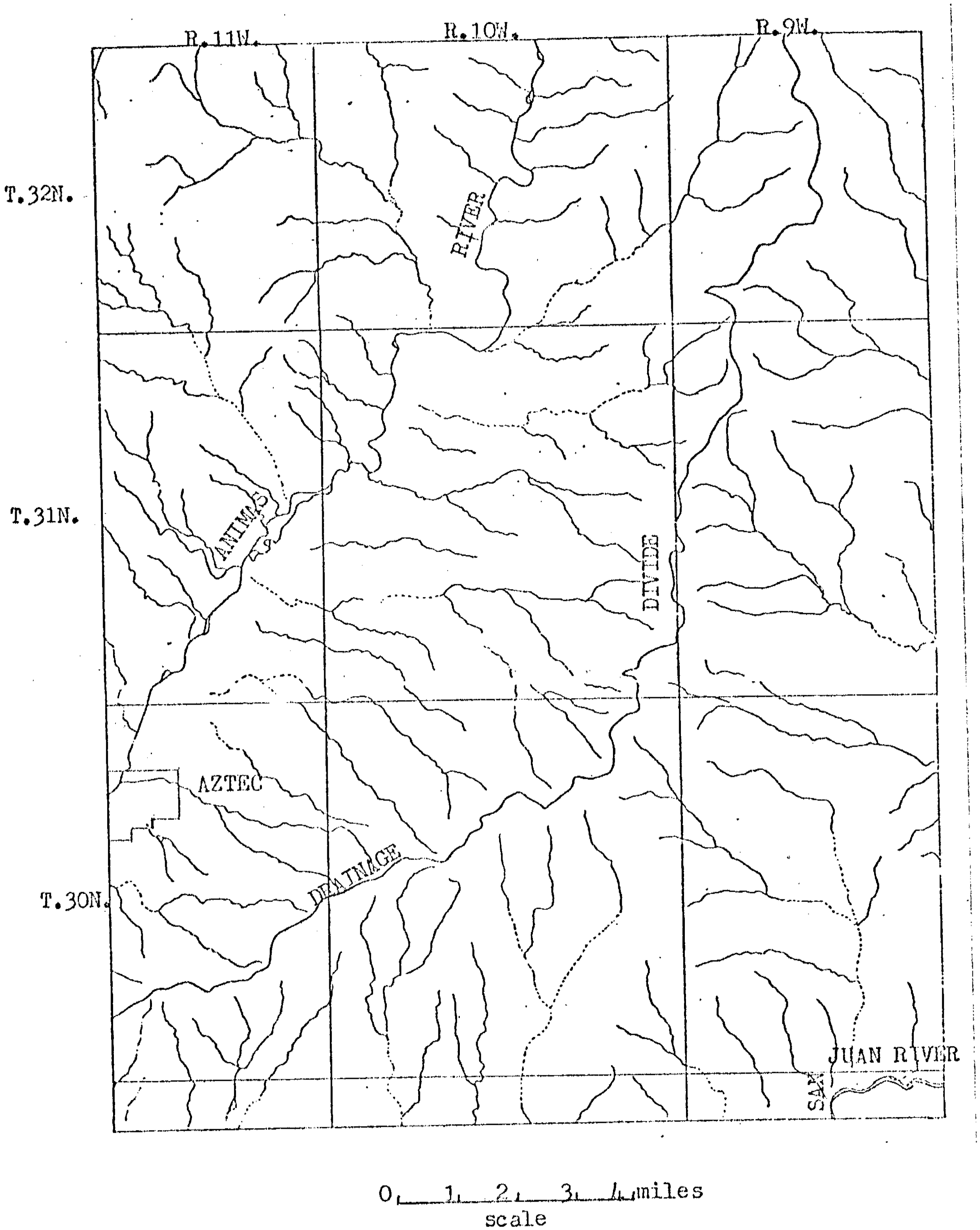


Figure 3. Drainage of the Aztec Quadrangle (from U.S.G.S. Topographic Map).

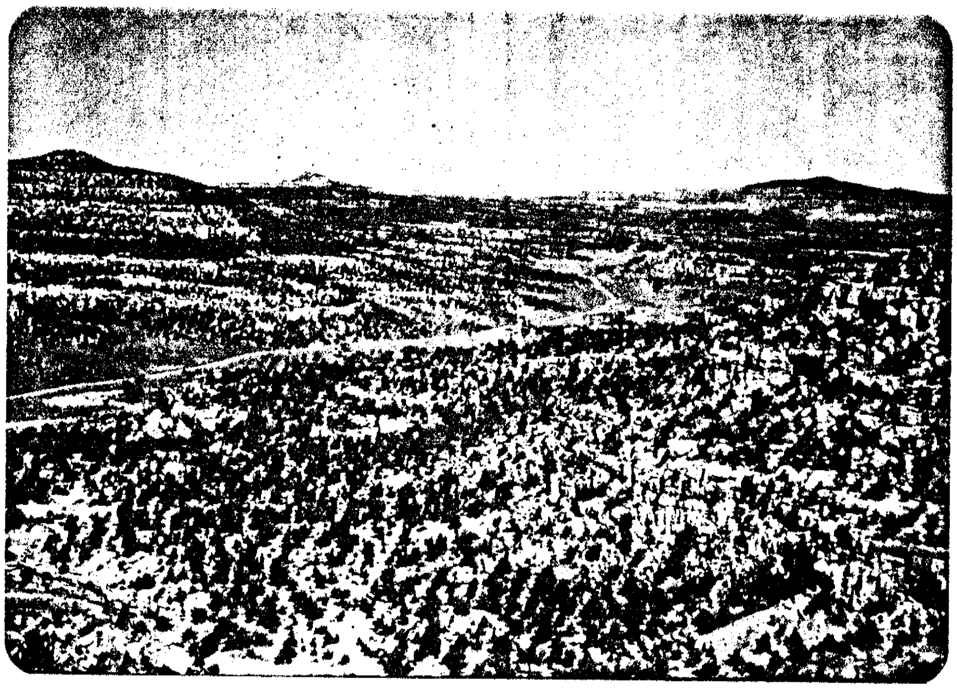


Figure 4. Cox Canyon, one of the larger drainages in the quadrangle; view north from NW¼ Sec. 20, T.32N., R.10W.; note cliff-forming sandstones of San Jose Formation.

during peak precipitation periods; transmission losses are often extensive in such streams due to their coarse bed materials (Stone and Brown, 1975). In the southern and western parts of the quadrangle, where shales dominate the surface rocks, more runoff occurs (Maker and others, 1971, p.14) and drainage densities increase (Bandoian, 1969, p. 12).

Climate

Maker, Keetch, and Anderson (1971) have summarized the climate of San Juan County and much of the following discussion is taken from their work. The Aztec Quadrangle is located in the Northwestern Plateau climatic subdivision of the U.S. National Weather Service. This subdivision is characterized by an arid to semi-arid climate having an average annual precipitation of 10.4 inches. Table I summarizes the mean monthly temperatures and precipitation at Aztec Ruins National Monument for the period 1931 through 1960. At this weather station, the average annual precipitation is 9.8 inches. The mean monthly temperature for July is 73.8°F and for January is 29°F; the mean annual temperature is 51.3°F. The average frost-free period (from May 20 to October 14) is 147 days.

The major factor influencing climatic variation in the study area is elevation. Shomaker and others (1971) estimated the vertical air temperature gradient to be 5°F per 1000 feet of elevation. This means that the temperatures near the Colorado border could be as much as 7°F cooler than at Aztec at any given time. Precipitation is also affected by this elevation change, as can be seen by the increased vegetation density in these higher areas. Nearly half (45.4 percent) of the annual precipitation in Aztec occurs in the months of July through October (Bandoian, 11969, p.14).

Table I. Monthly temperatures and precipitation, Aztec Ruins National Monument, San Juan County, New Mexico, 1931 to 1960, elevation 5640 feet (Maker, Keetch, and Anderson, 1971, table 2).

Item	Jan	Feb	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Temperature (F°)												
Average daily maximum	43	49	58	68	77	86	91	88	82	70	55	45
Average daily minimum	15	20	25	32	41	48	57	56	48	37	23	17
Daily mean	29	34	41	50	59	67	74	72	65	54	39	31
Extreme maximum	66	78	80	89	95	103	104	105	96	87	80	67
Extreme minimum	-22	-27	1	10	21	31	43	41	29	13	-7	-16
Precipitation												
Average (inches)	.74	.76	.79	.60	.67	.44	.94	1.32	1.12	1.09	.49	.86
Average days 0.10 inch or more (no.)	3	3	3	2	2	1	3	4	3	3	2	3
Average snowfall (inches)	6.7	4.8	2.0	0.5	T	T	0	0	T	0.1	1.8	5.7

T - Trace, amount too small to measure.

Most of this rain falls during intense, convective storms, so much is lost as runoff.

Skies are generally clear, sunshine abundant, and relative humidity low in this area, so evaporation from water surfaces is high (Shomaker and others, 1971, p. 6). Class A pan evaporation at nearby Farmington averages 49 inches in the period from May 1 through October 31. Average winds are from the southwest. Sources of wind and moisture for the area are the Gulf of Mexico, Gulf of California, and the Southern Pacific Ocean (Bandoian, 1969, p. 13).

Soils and Vegetation

Six general soil associations have been mapped by the U.S. Soil Conservation Service in the Aztec Quadrangle (fig. 5). As expected, these soils vary directly according to the lithology of the material upon which they lie. Detailed descriptions and general distribution of these soils in San Juan County are given by Maker, Keetch, and Anderson (1971). The following general descriptions of these soils and their corresponding vegetation are drawn from this source. Numbers in parentheses refer to map units shown on figure 5.

Persayo-Farb Association (I). These soils are predominantly calcareous and shallow, forming on material weathered from shale and sandstone on undulating to hilly areas where bedrock exposures are common. This association is used mostly for limited grazing as it supports a sparse cover of such grasses as galleta, Indian ricegrass, and blue grama. The more common shrubs and woody species are pinyon, juniper, serviceberry, bitterbrush, saltbrush, shadscale, and snakewood. Due to sparse

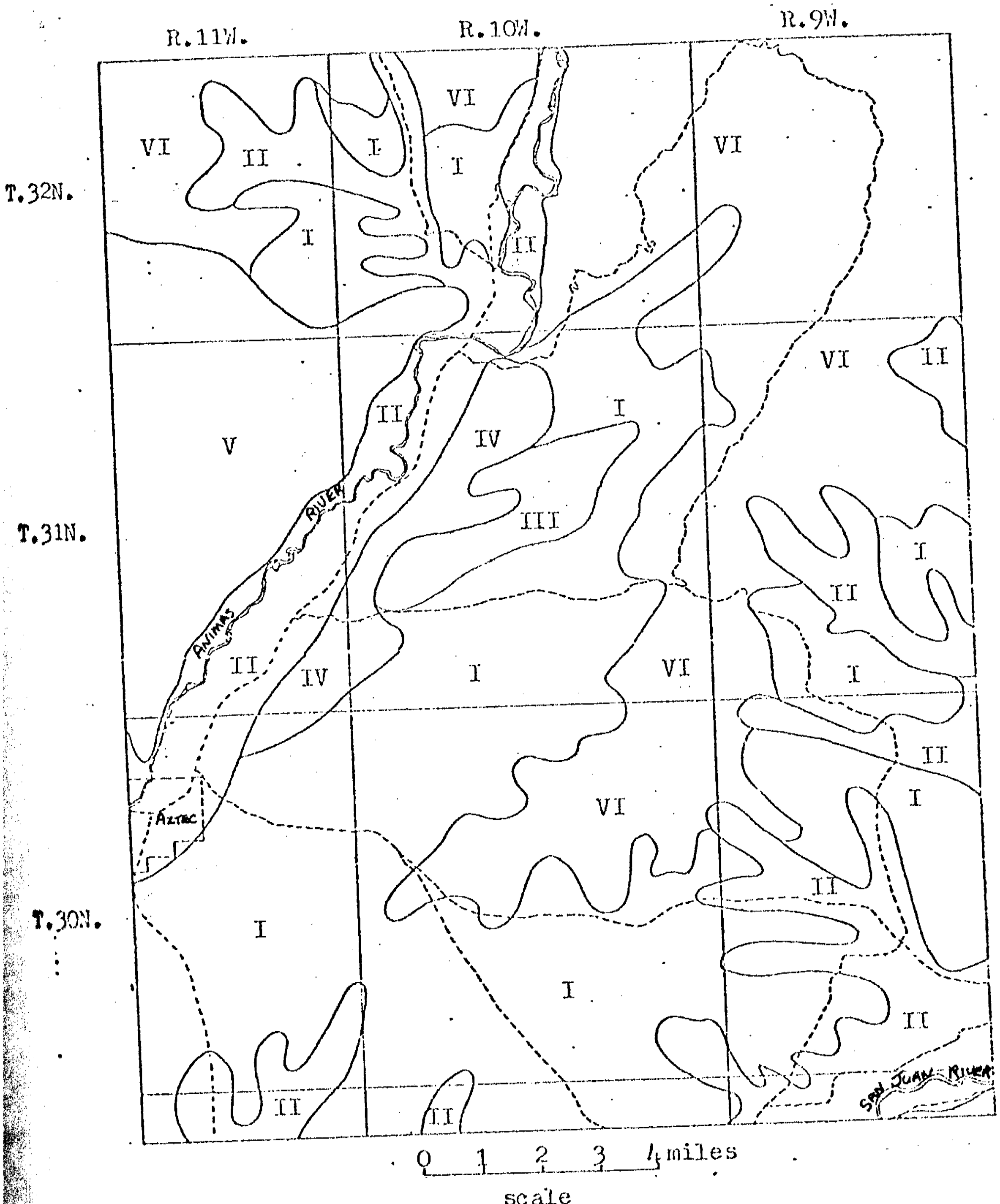


Figure 5. Generalized map of soil associations in the Aztec Quadrangle (after Maker, Keetch, and Anderson, 1971).

I	Persayo-Farb	IV	Hilly Gravelly Land
II	Werlow-Fruitland-Turley	V	Badland-Rock Land
III	Doak-Shiprock	VI	Travessilla-Rock Land

vegetation and low intake rates, runoff is high and erosion hazard moderate to severe. Irrigation potential is slight.

Werlow-Fruitland-Turley Association (II). These soils form on the level to gently sloping surfaces of the alluvium found in the Animas and San Juan River Valleys and their major tributaries. The association comprises essentially all of the irrigated acreage in the study area. Alfalfa and corn are the most extensively produced crops, but tree fruits, small grains, vegetables, and potatoes are also important. Native vegetation includes galleta, Indian ricegrass, sand dropseed, alkali sacaton, saltgrass, fourwing saltbrush, snakeweed, cottonwood, and salt cedar. The soils are sand, silt, and clay loams with generally high permeabilities and thus have high irrigation potential.

Doak-Shiprock Association (III). The soils of this association commonly form on the alluvial deposits of gently sloping ancient stream terraces or alluvial fans. These soils are used primarily for grazing as they can support fair yields of forage. Native vegetation indludes galleta, Indian ricegrass, blue grama, sagebrush, snakeweed, and some annuals. Soils of this association are well suited to irrigation as they have a moderate to high water-holding capacity and moderate permeability.

Hilly Gravelly Land Association (IV). These soils commonly form on the thin, gravelly alluvium covering the steep slopes of old river terraces such as those formed along the Animas River. These soils are generally loams, are shallow, and are used principally for grazing. Sparse native grasses found on these soils are galleta, blue grama, Indian ricegrass, sand dropseed, three-awn, ring muhly, and western wheat. Shrubs include sagebrush, snakeweed, rabbit brush, and juniper. Although permeability is moderate and gravels and cobbles help defend the soils against erosion, these soils are generally not suitable for irrigation due to the steep slopes of the terrain.

Badland-Rock Land Association (V). These soils are characterized by barren or nearly barren outcrops of shale and sandstone on surfaces varying from narrow valley bottoms to steep slopes. Badland soils support little vegetation and are of little value. Rock Land soils support a sparse cover of native grasses, forbs, and brush and are used for grazing. Permeability is very low and flash floods follow heavy rains. This association has virtually no irrigation potential.

Travessilla-Rock Land Association (VI). This association is characterized by the rough, broken topography of the San Jose Formation. Outcrops of sandstone are a common feature of the upland areas, but thin deposits of silty, eolian materials or gravelly alluvium are also common. The area includes steep canyon walls and escarpments, as well as gently- to strongly-sloping fans and valley floors. The soils that form are generally loams. These soils are used mostly for grazing as they support blue grama, sideoats grama, Indian ricegrass, little bluestem, poverty three-awn, and sand dropseed grasses in variable densities. Common shrubs and woody species are pinyon, juniper, big sage, bitterbrush, serviceberry, snakeweed, rabbit brush, and cactus. Permeability is generally high, but because the soils are usually very thin and occur on rough, broken land, irrigation potential is very slight.

Land Use and Economy

Land use and economy in the Aztec Quadrangle are dominated by the petroleum industry and agriculture. The first natural gas discovery in the San Juan Basin was made one mile south of Aztec in 1920 (Barnes, 1950). Today approximately 400 wells have been drilled throughout the study area and the roads built to serve these wells provide good access to all parts (fig. 6). Because many services are necessary for oil and gas production, a large part of the area's economy is built around this industry.

Agriculture is also a major part of the economy and land use of the study area. Except for the populated areas, most of the quadrangle is used for the grazing of beef cattle. In the valleys of the Animas and San Juan Rivers, approximately 4,000 acres of land are irrigated for growing numerous crops.

Fishing and hunting bring many people to the area, but the only big tourist attraction is the Aztec Ruins National Monument in Aztec. Thousands of people visit these famous Indian ruins each year.

The town of Aztec, with a population of approximately 6,000, is the county seat of San Juan County. The total population of the study area is approximately 7,000. The town is a commercial center for the immediate area, as well as being home for many gas-field workers, public servants, and various service people. Many people also live along the Animas and San Juan Rivers and in the communities of Cedar Hill and Turley; very few live on the divides away from the valleys, however.

In the Aztec Quadrangle, an area of 240 square miles, land ownership is approximately as follows: 10 percent state, 18 percent private, and 72 percent federal

Figure 6. Drill rig constructing one of many natural gas wells in the study area; view northwest from $SE\frac{1}{4}$ Sec. 34, T.31N., R.10W.; note roughneck standing on rig at horizon.

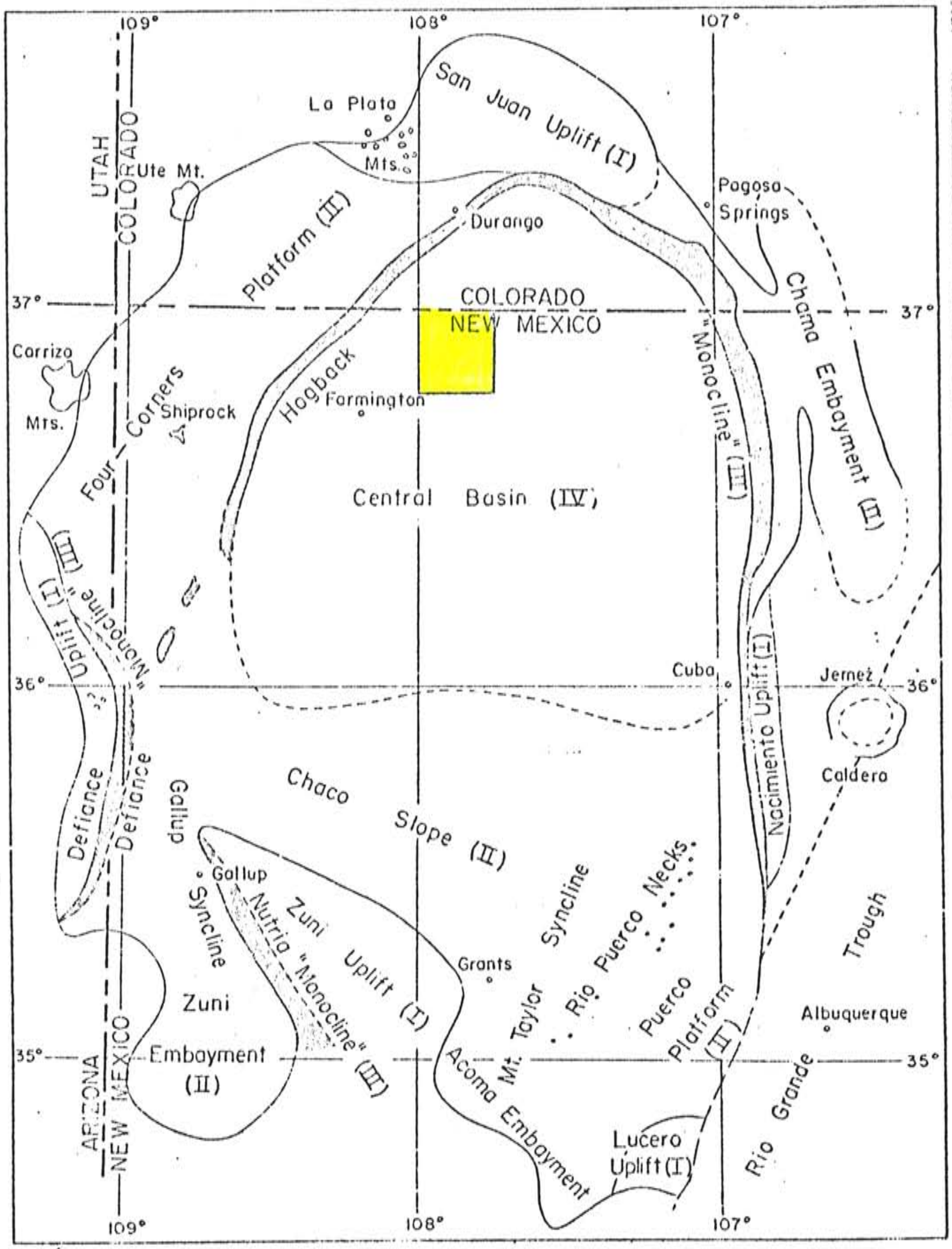
GEOLOGIC SETTING

Tectonic Framework

The Aztec Quadrangle lies near the deepest part of the San Juan Basin, a broad, structural depression which began to form in late Cretaceous time (Beaumont and Read, 1950) and contains a thick sequence of sedimentary rocks. The San Juan Basin trends northwest to southeast and is asymmetrical, with steeper dips on the northeast side. Kelly (1950) recognized several tectonic subdivisions within the San Juan Basin (fig. 7). The Aztec Quadrangle lies wholly within the Central Basin subdivision which is bounded by the Hogback Monocline on all sides but the south. In the southern part of the basin, strata dip gently toward the basin axis as there is no sharp structural boundary as on the other sides (Fasset and Hinds, 1971).

Stratigraphic Framework

Fassett and Hinds (1971, p.4) have summarized the stratigraphy of the San Juan Basin and much of the following discussion is from their work. Figure 8 illustrates the regional stratigraphic column through the Entrada Sandstone. The Morrison Formation, of Jurassic age, was deposited primarily in a continental fluviatile environment (Flesch, 1974, p. 191) as was part of the Dakota Sandstone (Owen, 1973). The upper Cretaceous section of marine shales and sandstones, however, represents repeated transgressions and regressions of shallow marine waters. The Pictured Cliffs Sandstone was deposited during the final regression of this Cretaceous sea from this area. All strata deposited after the Pictured Cliffs Sandstone represent continental sedimentation, consisting primarily of fluvial, lacustrine,



1 inch equals 30 miles

Figure 7. Structural elements of the San Juan Basin (Kelley, 1950); Aztec Quadrangle shaded.

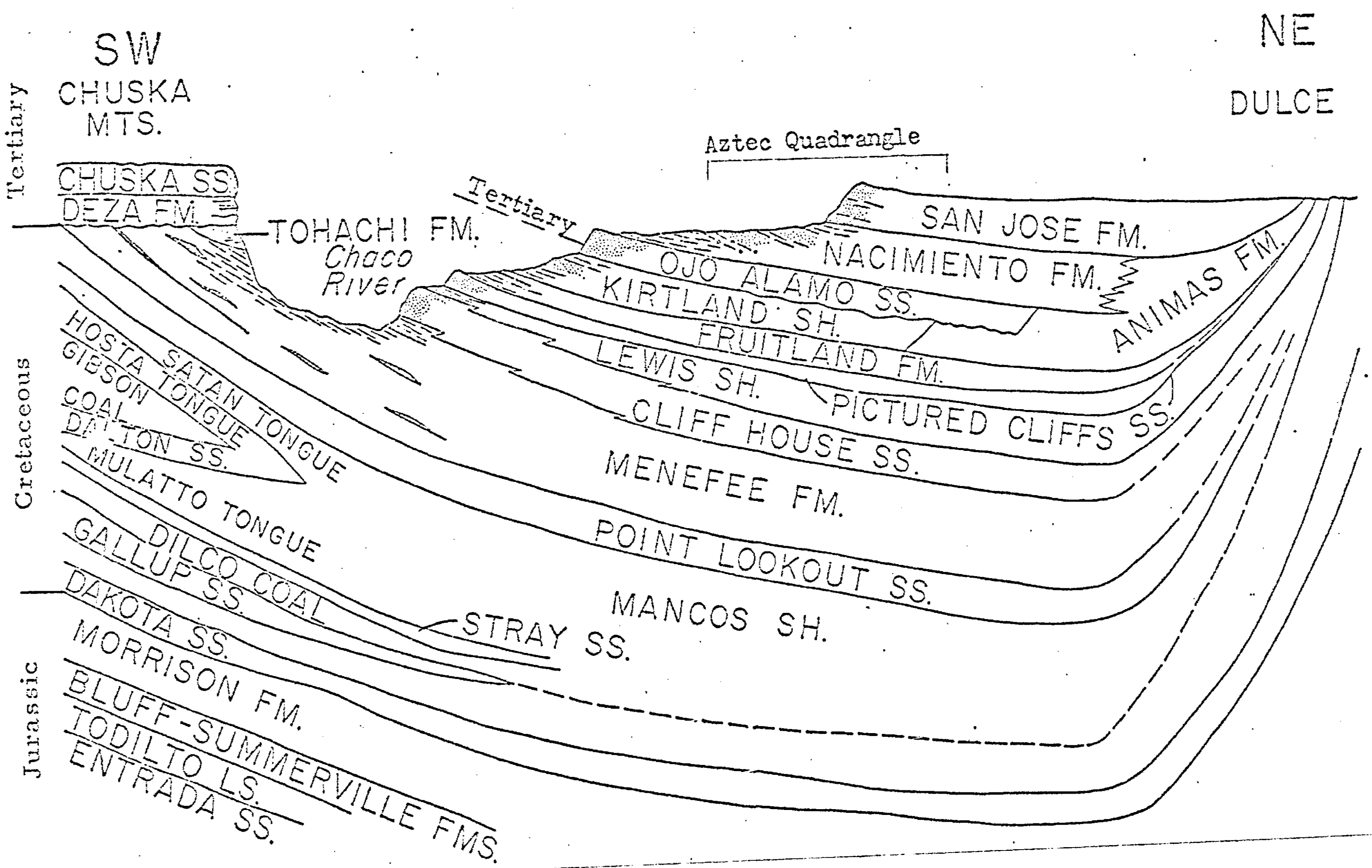


Figure 8. Generalized SW-NE cross-section, San Juan Basin (unpublished figure, W.J.Stone, New Mexico Bureau of Mines and Mineral Resources).

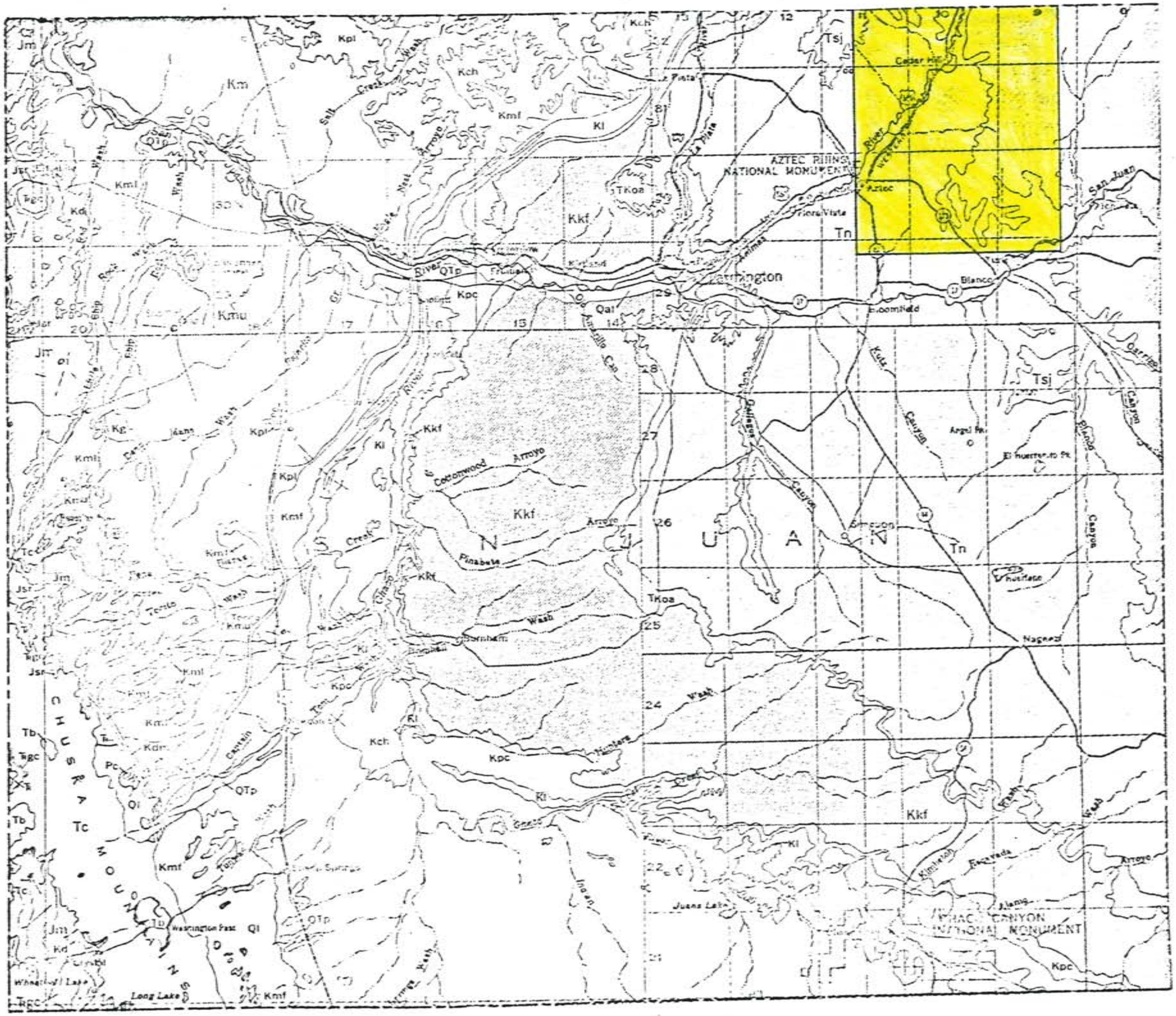


Figure 9. Geologic map of San Juan County (Dane and Bachman, 1965); Aztec Quadrangle shaded.

and paludal deposits.

According to Fassett and Hinds (1971), the section of Cambrian, Devonian, Mississippian, Pennsylvanian, Permian, Triassic, and Jurassic strata in the San Juan Basin reach a total thickness of up to 4,000 feet (fig. 8 and 9). Overlying these is the Cretaceous column which reaches 6,000 feet or more in thickness. Tertiary and Quaternary deposits in the basin reach a thickness of greater than 3,900 feet. All this combines to give a maximum total thickness of over 14,000 feet of sedimentary rock, a thickness proven by an E.P.N.G. well in Sec. 7, T.29N., R.5W.

HYDROGEOLOGY

General Statement

Hydrogeology of each unit will be discussed in descending order.

Surface Units

Quaternary Deposits

Alluvium

Lithologic Characteristics. In the Aztec Quadrangle, Quaternary deposits are of two major types: valley alluvium and terrace deposits (Plate 1). In the valleys of the Animas and San Juan Rivers and their major tributaries, alluvium consists of gravel, sand, silt, and clay. These materials have been deposited in Pleistocene and Recent time in each arroyo and valley but are now being eroded by streams. This process of "gullying" has been widespread throughout the southwestern United States since about 1880 and has been described by Bryan (1928) and others.

In the valley of the Animas River the alluvium consists predominantly of sand and gravel. Many driller's logs describe the alluvium as "boulders". According to Bandoian (1969), much of this material is outwash from Pleistocene glaciers in the San Juan Mountains to the north. Most driller's logs report the alluvium of the Animas Valley to be from 40 to 100 feet in thickness. The average thickness appears to be approximately 60 feet and generally coincides with the center of the valley.

Because some gas well logs report "surface sand and rocks" to a depth of up to 300 feet in the Animas Valley, several refraction seismic soundings were conducted at crucial localities. These were conducted using a Bison Signal Enhancement Seismograph and a 12 pound sledge hammer. Many problems were encountered with cultural seismic noise (traffic, pipelines, etc.) and the small velocity change from saturated alluvium to bedrock.

However, several good soundings were completed; results of two of these soundings are presented as time-distance plots in Appendix C.

In the northwest quarter of Sec. 24, T.31N., R.11W., the Aztec Oil and Gas Turner No. 1 well log records 69 feet of boulders to bedrock. In the southeast quarter of the same section and nearer the valley margin, the Primo Oil Ruple No. 1 well log records 170 feet to sand and shale. Appendix C presents the data obtained from a hammer-seismic sounding about half way between the two wells. The first break in the time-distance curve, presumed to represent the water table, gave a calculated depth of 13 feet. The second break, which represents the velocity change from alluvium to bedrock, gave a depth of 33 feet. The depth to water, however, was measured at 19.3 feet only 500 feet to the northeast, suggesting a possible error in depth calculations of up to 50 percent. This still results in a maximum calculated depth to bedrock of 50 feet. This value agrees well with the 69 feet reported, but strongly discounts the value of 170 feet near the edge of the valley.

The second time-distance plot in Appendix C is of a seismic sounding in the southwest quarter of Sec. 26, T.31N., R.11W. This sounding was conducted v.ry close to the Animas River, near the center of the valley. This location is less than a quarter mile southwest of the Southern Union Wilmuth No. 1 well for which 308 feet of "surface" materials were logged. The calculations show a depth to bedrock of 37.5 feet. Assuming again a maximum possible ereor of up to 50 percent, this suggests a maximum calculated alluvium thickness of less than 60 feet.

Drillers describe any soft, near-surface material, including weathered or poorly consolidated bedrock as "surface sand and rocks". Records of the Oil Conservation Commission reveal that many companies in the Aztec Area must drill through approximately 250 feet of such material before they can set their surface casing.

Water-Bearing Characteristics. The alluvial deposits of the Animas and San Juan River systems are presently the most important source of groundwater in the Aztec Quadrangle. In the two major river valleys especially, these deposits provide moderate supplies of generally good quality water to numerous shallow wells (Table V).

While no actual yield data are available, a driller familiar with the Aztec area reports that most domestic wells in the Animas River alluvium yield 10 to 20 gallons per minute (gpm). With proper completion and development, however, he suggests that these values might be increased by an order of magnitude (John Gilbert, personal communication). Rapp (1959, p.11) reported yields of up to 500 gpm from properly completed wells in 70 feet of similar saturated alluvium in another area.

The saturated thickness of the Animas River alluvium varies with the water table position and the thickness of the material itself. The water table does vary considerably throughout the year, its position depending on precipitation, amount of nearby irrigation, and Animas River flow, each of which act to recharge the alluvium. Because all of these factors are high in spring and summer, the water table appears to reach a peak in August. According to local residents, the water table reaches its low point during the month of March.

An example of the fluctuation of the water table position is that measured in the Bishop well in the southeast quarter of Sec. 24, T.31N., R.11W. (Table V). The depth to water was 7.9 feet on August 8, 1975, following a spring and summer of very high runoff in the Animas River. After a very dry winter, on February 26, 1976, the depth to water was 19.3 feet, a drop of 11.4 feet. Although the contrasting weather and runoff conditions suggest that this may be an extreme change, the owner reported that this was a typical fluctuation.

In the numerous tributary canyons and arroyos of the Animas and San Juan Rivers, five wells were located which are believed to be completed in alluvium. Four of these wells appear to have been abandoned. The probable reason is that they do not produce sufficient or reliable supplies due to the limited thickness of the alluvium here and the lack of recharge from streams during dry periods. Instead of using these wells, small surface reservoirs have been constructed to capture the surface runoff in these canyons and arroyos (fig. 10).

The quality of water from wells in the Animas alluvial aquifer is generally good. The average for the ten wells analyzed is 732 parts per million (ppm) total dissolved solids, with values ranging from 308 to 1923 ppm (Plate 2, Table II). The analyses show these waters to be highest in sulphate, sodium, and calcium.

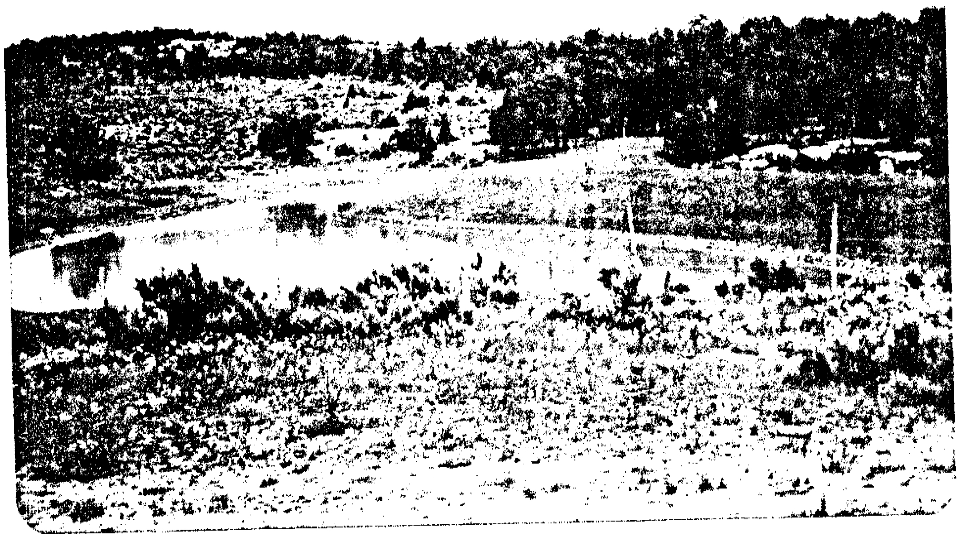


Figure 10. One of many surface reservoirs or stock tanks in the study area; view northeast, SW$\frac{1}{4}$ Sec. 22, T.31N., R.9W.

Terrace Deposits

Lithologic Characteristics. Ancient terraces have been formed by the Animas and San Juan Rivers as they cut down through bedrock over geologic time. These terraces are remnants of ancient flood plains formed by the meandering of these rivers. The coarse, rounded, fluvial gravels and sands typical of these deposits (Pastuszak, 1968) were deposited on the flood plains.

Bandoian (1969) has described the terrace deposits in the Animas River Valley and has mapped six separate terrace levels. The position of these terrace levels, not distinguished on Plate 1, varies from 70 to 470 feet above the present Animas River level. The gravel deposits vary in thickn ess from 6 to 18 feet but are eroded in many localities. Commonly these terraces are overlain by up to 12 feet of fine, red soil mantle determined by Bandoian to be eolian in origin.

In addition to six terrace levels, Bandoian described and maps remnants of two higher gravel surfaces in the area which, because of their shape and broad extent, were not considered river terrace deposits. The upper or Mesa Mountain Surface is partially preserved on both sides of the Animas River, just south of the Colorado border, at an elevation of 6800 to 7000 feet. Gravel deposits associated with this surface are 20 to 30 feet thick and consist of banded-quartzite, granite, and diorite cobbles and boulders, as well as pebbles of quartz, quartzite, and chert (Bandoian, 1969, p. 53). Atwood and Mather (1932) suggested that this surface is part of what they term the "San Juan Peneplain", formed in late Pliocene time by erosion of the late Tertiary volcanic plateau which occupies much of the San Juan region of Colorado.

The lower surface, the Ditch Canyon Surface of Bandoian (1969), may be an additional terrace. Gravel remnants occur between Hart and Ditch Canyons which Bandoian admits may have been washed down from a higher level. I agree with this interpretation but dispute the existence of the surface as mapped by Bandoian. Personal examination of this area, which has been recently burned and cleared, revealed gravel deposits on only a few small knobs. A few cobbles and boulders have been washed down onto a sandstone bench here, but most of the surface is covered by gray shale.

Water-Bearing Characteristics. Springs issuing from terrace gravels are used as a public water supply near the town of Cuba, New Mexico (Baltz and West, 1967, p. 32). No such springs, however, are known in the Aztec Quadrangle. Although the terrace deposits probably hold small quantities of water, they are relatively thin and most water probably evaporates of infiltrates into the bedrock below. Where the gravels are thicker and the water becomes temporarily perched on an impermeable substrate, small yields could be expected. These yields would be directly related to saturated thickness in magnitude. Chemical quality is likely to be best where precipitation has been the main source of recharge.

Tertiary Deposits

San Jose Formation

Lithologic Characteristics. The San Jose Formation of Eocene age covers approximately half the surface area of the Aztec Quadrangle (Plate 1). This formation, originally mapped as the Wasatch by Dane (1936) and by Wood and Northrop (1946), was renamed by Simpson (1948) because the name Wasatch had been previously used elsewhere. Simpson retained the three faunal subdivisions suggested by Gardner (1910): the Tiffany, Almagre, and Largo beds.

The San Jose Formation generally consists of coarse, yellow, resistant sandstones interbedded with olive green, gray, and purple shales and white non-resistant sandstones. The variable predominance of one lithologic facies over the others was used by Baltz and West (1967) to subdivide the San Jose Formation into four intergrading members: the Cuba Mesa, Regina, Llaves, and Tapacitos Members, in ascending order. This four-fold subdivision was used by Baltz and West in mapping the Jicarilla Apache Indian Reservation, but it does not appear to have application in the Aztec Quadrangle. Some general lithologic facies changes were noted, however, in the northern part of the area where part of the San Jose Formation is dominated by shales (Plate 3).

In the study area, the San Jose Formation consists predominantly of buff and yellow, conglomeratic, coarse to very coarse-grained, thick-bedded, arkosic sandstones. (Grain size, see Appendix D, measured-section and thin-section descriptions in Appendices A and B respectively). These sandstones are more abundant in the lower part of the formation, have a thickness of up to 116 meters (380 feet) per unit, and form steep cliffs in most places. In some localities, the thinner sandstones are lenticular, but most of the thicker units are quite continuous and can be followed for 2 to 3 miles.

The San Jose Formation has been interpreted by all previous workers to be fluvial in origin. Large-scale, low-angle, tangential, trough cross-bedding is common (fig. 11) and sandstone units occur as channels often cut into the shale units below. McDonald (1972) concluded that the primary sources of the San Jose sediments was the Brazos and San Luis-Sangre de Cristo Mountains area to the east and northeast and also the San Juan Mountains to the north.

The San Jose shales are, for the most part, silty to sandy in texture. The shale units are composed of interbedded, olive green, light to dark gray, and purple shales, claystones, and siltstones, and a few non-resistant gray-white sandstones.

The San Jose Formation was described by Reeside (1924) as lying "nearly horizontal:, but in T.32N., R.12W., he assigned it an easterly dip of 1 degree. While such a dip is hard to measure, the geologic map suggests that the San Jose strata do dip gently southeastward, toward the center of the San Juan Basin.

Water-Bearing Characteristics. Relatively few wells have been drilled or tested in the San Jose Formation of the San Juan Basin. Cooper and Trauger (1967) suggested, however, that the San Jose Formation, together with parts of the underlying Nacimiento Formation, "should be considered an important reservoir of large volume" in the eastern part of the San Juan Basin. These authors reported yields of up to 200 gpm and Baltz and West (1967) predicted yields of up to 1200 gpm from the

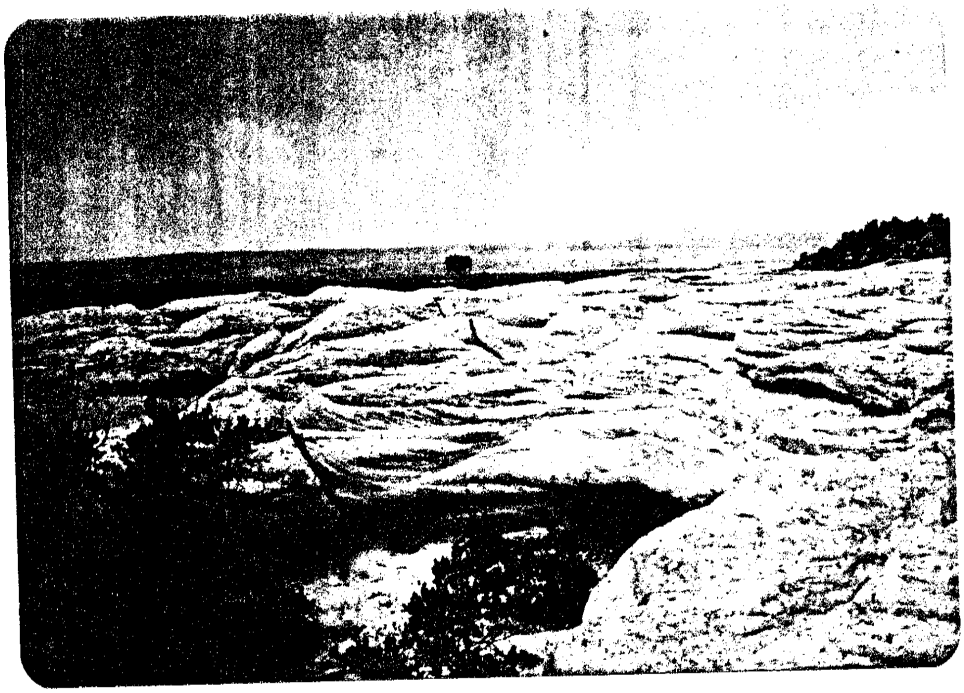


Figure 11. Trough cross-bedding exposed in a sandstone unit of the San Jose Formation above Arch Rock Spring; view northwest, SW$\frac{1}{4}$ Sec. 24, T.30N., R.10W.; tree in bottom left of photo is approximately 12 feet high.

San Jose aquifers. The average total depth of 43 wells reported by Baltz and West (1967, p. 28) to be in various members of the San Jose Formation on the Jicarilla Apache Indian Reservation, is 213 feet. Reported yields ranged from 0.2 to 60 gpm and specific capacities ranged from 0.07 to 1.04 gpm per foot of drawdown.

In the Aztec Quadrangle, eight water wells are known to be completed in the San Jose Formation (Table V). Most of these wells were drilled in the 1950's by the El Paso Natural Gas Company to obtain drilling water for nearby gas well construction. Most of the wells are plugged or inaccessible, but company records report yields from 6 to 40 gpm from individual sandstone units having thicknesses of 25 to 123 feet. Total depths range from 118 to 585 feet. No chemical analyses were recorded.

The San Jose sandstones appear to have the properties of good aquifers. Grains are generally well-sorted and thin-section analyses of surface samples reveal porosities of up to 25 percent (Appendix B).

At various localities and elevations, many springs issue from coarse sandstone strata of the San Jose Formation in the study area (figs. 12 and 13). These springs are estimated to have discharges of less than 2 gpm and are all of the contact type. That is, water percolated downward through a permeable sandstone unit until it reaches an impermeable shale along which it flows laterally to discharge where the contact is exposed. The springs, mapped on Plate 2, are generally marked by 1) an overhang of coarse sandstone above, due to undercutting and washing out of the shale below, and 2) by the presence of cottonwood trees or some other plant requiring more than average water. Most springs of the study area are fenced and developed with pipes, stock tanks, or concrete enclosures (figs. 11 and 12).

The quality of water from springs in the San Jose Formation is generally quite good, averaging about 515 ppm total dissolved solids and varying from

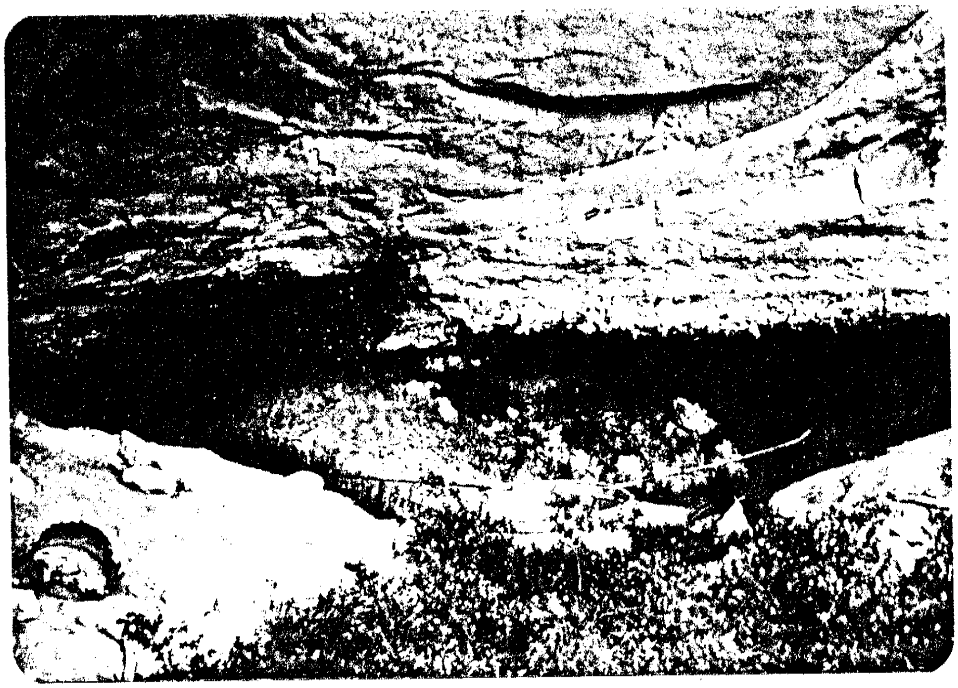


Figure 12. Jackson Spring, typical of most in the study area, issuing at a sandstone--shale contact, NE$\frac{1}{4}$ Sec. 14, T.30N., R.10W.; note pipes, stock tank, and wild rose bushes.

Figure 13. Garrison Spring, which produces clear, cool water from the contact between a shale and the sandstone in background; view east, NW$\frac{1}{4}$ Sec. 14, T.30N., R.10W.; note pipe leading to stock tank from spring.

110 to 1528 ppm. Table III lists the chemical analyses of 13 springs in the Aztec Quadrangle which are mapped on Plate 2. Last Chance and Garrison Springs, both of which have supported homesteads within the last 100 years (H. McWilliams, personal communication), have total dissolved solids concentrations of 110 and 136 ppm respectively. The broad, multi-story overhangs at Last Chance Spring are believed to have housed Pueblo Indians who roamed this area until about 650 years ago (Cooper and Trauger, 1967). Both Last Chance and Garrison Springs are used for watering stock today, as are most in the area. Hart Spring, however, is used domestically.

Nacimiento-San Jose Contact. The contact between the San Jose Formation and the underlying Nacimiento Formation has always posed a problem to workers in the northern part of the San Juan Basin. Because of the gradational nature of this contact, its location has differed by as much as 5 miles as mapped by Reeside (1924) and Dane and Bachman (1965).

In the southern part of the San Juan Basin, the San Jose Formation lies on the Nacimiento Formation with erosional, angular unconformity (Baltz and West, 1967). To the north, however, continuous deposition apparently took place in Paleocene and Eocene time (Reeside, 1924). Having followed this contact "in very rapid reconnaissance" to the divide between the Animas and San Juan Rivers, Reeside wrote of it (p. 41):

> "It is much less distinct toward the north owing to the appearance in the upper Torrejon [upper Nacimiento] of indurated, brown sandstones resembling the overlying formation, and in fact near the State boundary a separation is very difficult.
>
> ...[The evidence] strongly suggests that sedimentation in the northern part of the basin was continuous from

> Torrejon [late Paleocene] time into Wasatch [Eocene] time and that there is no such break in the series as is apparently present in the southern part of the basin."

Simpson (1948, p. 378), speaking of the northern part of the basin, stated the following:

> "Conditions here are strikingly different from those in other parts of the basin. ... Sedimentation was active here during or throughout the time represented by the Nacimiento-San Jose hiatus to the southeast and there was little pre-Wasatchian uplift and erosion directly in this area. ...In general there is a suggestion of nearly continuous deposition in the north."

The Nacimiento-San Jose contact was mapped as part of this study (Plate 1) using criteria similar to those of Reeside (1924, p. 46):

> "The Torrejon [upper Nacimiento] sandstones are thinner, shorter lenses and do not form as much of the bulk of the formation as those of the overlying beds. This hazy distinction has been used in mapping the base of the Wasatch [San Jose] Formation in northern San Juan County."

As Reeside's geologic map was generalized and the Nacimiento-San Jose contact dashed in most places, it was deemed necessary to remap it in detail in the study area. Generally, the contact was placed at the base of the first, thick, resistant, coarse-grained sandstone above which sandstones dominated and surpassed shales in thickness. In numerous places the contact was easily located by these criteria because a good portion of the Nacimiento shales and soft sandstones was exposed below (fig. 14). Examples of such localities are those in

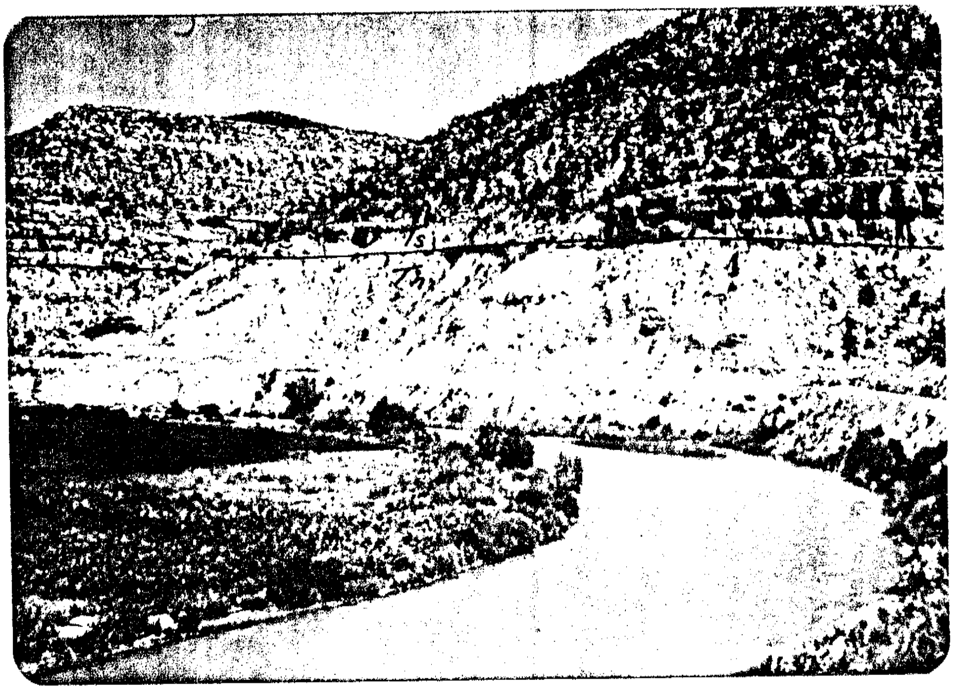


Figure 14. Nacimiento-San Jose contact (traced in ink) below Mount Nebo; view northeast, SE$\frac{1}{4}$ Sec. 22, T.32N., R.10W.; note Animas River, and car (lower left) for scale.

Sec. 27, T.32N., R.10W. on Mount Nebo, in Sec. 2, T.31N., R.10W. near the Flute Cave Section (Appendix A), and in Secs. 25, 35, and 36, T.30N., R.10W., north of Blanco. From these and other localities, the contact can be traced laterally with relative ease. In other areas, however, the contact is partially covered or the San Jose Formation is severely eroded. In such areas, as on the west side of Knickerbocker Peaks, T.30N., R.10W., the contact has been mapped by a dotted or dashed line respectively (Plate 1).

The Nacimiento-San Jose contact, as mapped on Plate 1, is noticeably irregular in elevation in the study area. The most significant irregularity is the low near the Animas River in T.32N., R.10W. where the contact drops from an elevation of over 6300 feet to less than 6200 feet. The very presence of the Animas River may be evidence of a structural anomaly here, but more work is needed to explain what has happened.

A major change in lithology of the lower part of the San Jose Formation was noted during field work. This is the much higher sandstone-shale ratio in the southeastern part of the study area. Basal sandstones in the northern part of the area seldom exceed 30 meters (93 feet) in thickness, whereas, to the southeast (measured section No. 8, for example) over 100 meters (330 feet) of sandstone were measured in the San Jose (Appendix A, Plate 3, and fig. 15).

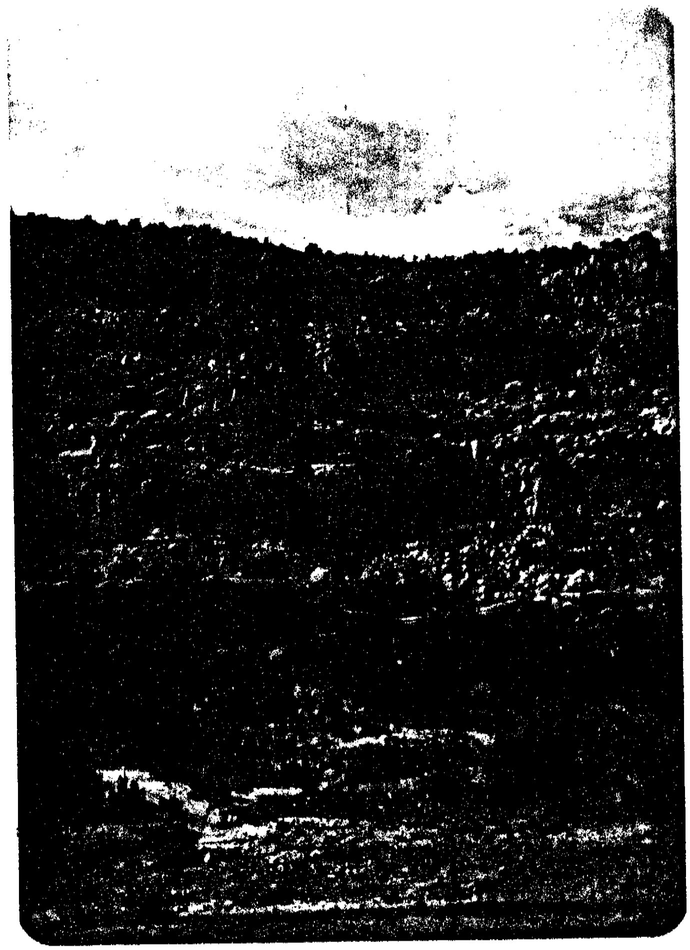


Figure 15. Nacimiento-San Jose contact (traced in ink) near Archuleta in measured section No. 8 (Appendix A); view north, SE$\frac{1}{4}$ Sec. 24, T.30N., R.9W.

Nacimiento Formation

Lithologic Characteristics. The Nacimiento Formation consists of gray, olive green, and purple shales, and gray-white to yellow, soft to resistant sandstones. Appendix A and B give detailed descriptions of the Nacimiento Formation in the Aztec Quadrangle.

The Nacimiento Formation of Paleocene age was named by Simpson (1948) following the suggestion of Gardner (1910). The formation had previously been subdivided, according to faunal assemblages, into the Puerco and Torrejon formations in ascending order (Sinclair and Granger, 1914). Simpson stated that the Puerco and Torrejon are not recognizable lithologic units so it is "simplest, most practical, and most logical" to consider them as a single formation and retain the names Puerco and Torrejon as faunal names only.

The Nacimiento Formation is considered fluvial in origin (McDonald, 1972), containing the discontinuous, coarse, channel sandstones and the floodplain silts and clays of the fluvial environment. The major source for these sediments is reported to be to the north and east of the study area in the Brazos, San Luis-Sangre de Cristo, and San Juan Mountains (McDonald, 1972). The fact that the formation thickens and becomes more sandy to the north supports this idea (Baltz and West, 1967).

In the study area, the Nacimiento Formation is approximately 2,000 feet thick. Electric logs show it to be silty or sandy throughout much of its vertical extent, but it is particularly so near its upper and lower boundaries, as both contacts are somewhat gradational and conformable. Baltz and West (1967) discussed the Ojo Alamo-Nacimiento contact and suggested that intertonguing of Nacimiento sandstones is responsible for the increased thickness of the Ojo Alamo Sandstone in the northern part of their study area. Such intertonguing was also pointed out by Powell (1973, p. 111) and has been observed in Head Canyon south of the San Juan River opposite Farmington.

In the Aztec Quadrangle the sandy nature of the upper part of the Nacimiento Formation is particularly noticeable near Cedar Hill in T.31N., R.10W. Here, thick, coarse-grained, arkosic sandstones are present which are indistinguishable from those of the Overlying San Jose Formation. These Nacimiento sandstones are also prominent in Measured Section No. 4 at Mount Nebo (Appendix A and Plate 3).

Water-Bearing Characteristics. Throughout most of its thickness, the Nacimiento Formation cannot be expected to yield large quantities of water to wells because of the discontinuous, silty nature of its sandstones (Brimhall, 1973). Quality is likely to be poor also, because of the amount of shale present in the formation. In its upper part, however, and where more extensive, coarse sandstones exist, the Nacimiento can provide valuable sources of good quality water (Cooper and Trauger, 1967). Baltz and West (1967) reported a yield of 42 gpm from a 20-foot-thick sandstone in the upper part of the Nacimiento Formation. Specific capacity of this sandstone, however, is only 0.07 gpm per foot of drawdown.

Brimhall (1973, p. 201) reported what may be a major aquifer of local importance, the Kaime Ranch Aquifer, in the Nacimiento of the west-central San Juan Basin. This predominantly sandstone aquifer is estimated to cover approximately 5 square miles and one water well here flows a full 8 inch stream from a perforated interval of 400 feet.

In the Aztec Quadrangle, 21 water wells are known to be completed in in the Nacimiento Formation. Nine of these are El Paso Natural Gas Company water wells with reported yields from 16 to 100 gpm. Several of these wells have been completed in two to four intervals to exploit total perforated intervals of 20 to 150 feet (Table V).

Three other non-domestic wells in the study area have been completed in the Nacimiento. These are the New Mexico Port of Entry well, the E.P.N.G. Knickerbocker Butte Water Well No.1, and the E.P.N.G. Atlantic State No.1 well which has been turned over to a rancher for use as a water well. The Port of Entry well is 750 feet deep and yields poor quality with a specific conductance of 12,700 mmhos/cm. The Knickerbocker Butte well is approximately 900 feet deep and is completed in four horizons to obtain water for drilling purposes. The Atlantic State No.1 well is 520 feet deep and is completed in three horizons for a total perforated thickness of 55 feet. Water from this well has a total dissolved solids concentration of 1,004 ppm.

Nine domestic wells in the area are drilled into the Nacimiento Formation and have an average depth of approximately 115 feet and average depth to water after completion of 24 feet (Table V). Because they are confined by overlying shales, many Nacimiento sandstone aquifers are under artesian pressure. The R. Valencia well, in Sec.35, T.30N., R.9W., was reported to flow with water rising 2 feet above ground level (Table V). The Kaime Ranch Aquifer of Brimhall is another example of artesian flow. The quality of water from these Nacimiento wells is relatively poor; six specific-conductance measurements averaged approximately 2000 micromhos per centimeter.

SUBSURFACE UNITS

Tertiary-Cretaceous Deposits

Ojo Alamo Sandstone

Lithologic Characteristics. The Ojo Alamo Sandstone has had a complicated nomenclatural history as summarized by Fassett (1973). The Ojo Alamo Sandstone was first named by Brown (1910) for a dinosaur-bearing shale unit and an overlying conglomerate bed. After 63 years and much controversy between stratigraphers and paleontologists, Powell (1973) has defined the Ojo Alamo Sandstone as consisting of two members: the lower or Nashoibito Member, a coarse-grained, cross-bedded, conglomeratic sandstone. By this definition, which is followed here, the Ojo Alamo Sandstone spans the Cretaceous-Tertiary boundary in age.

In cliffs east of the La Plata River near Farmington, in Measured Section No. 1, the Ojo Alamo Sandstone consists of 48 meters (158 feet) of thick-bedded, coarse-grained to very coarse-grained, very pale orange (10 YR 8/2) to dark yellowish orange (10 YR 6/6), cross-bedded, conglomeratic sandstone (figs. 16 and 17, and Appendix A).

The base of the Ojo Alamo Sandstone rests with regional disconformity on the Kirtland Shale and evidence of scouring and channelling is abundant (McDonald, 1972). The base is very irregular for this reason.

Powell (1973, p. 111) suggests an alluvial plain depositional model for the Kimbeto Member of the Ojo Alamo Sandstone and cites abundant paleocurrent data in evidence of a source area to the northwest of the San Juan Basin. A similar origin for the conglomeratic sandstone of the Nashoibito Member seems viable, whereas the shales between these conglomeratic sandstones may record a decreased sediment supply, a reduction of relative uplift of the source area, or a change in depositional facies. Powell (1973, p. 116) suggested that:

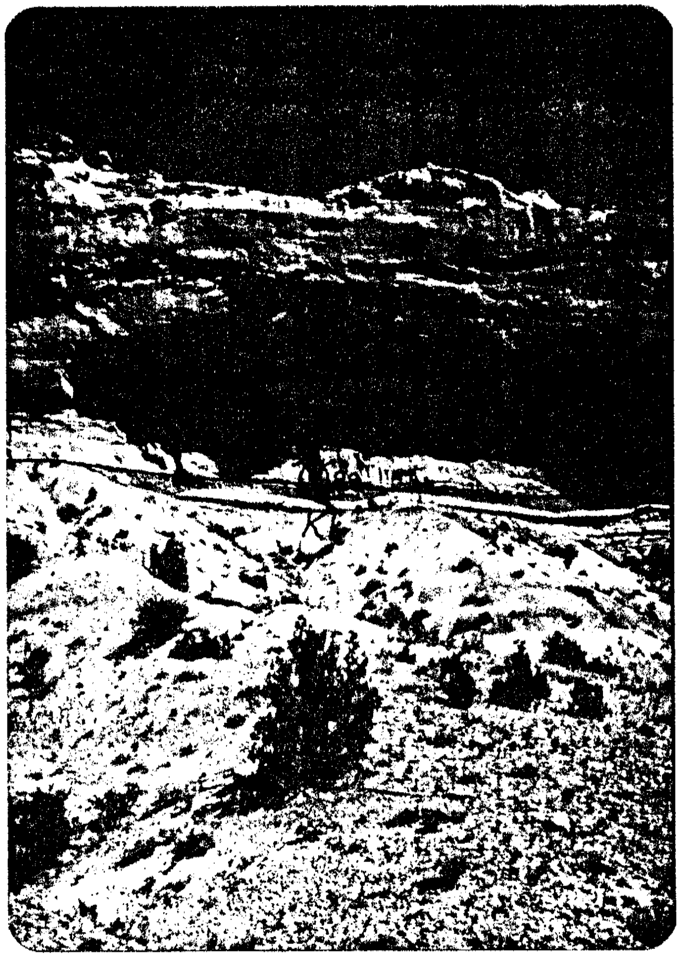


Figure 16. Kirtland-Ojo Alamo contact (traced in ink) at the La Plata River bluffs in measured section No. 1 (Appendix A); view east, SW$\frac{1}{4}$ Sec. 28, T.30N., R.13W.

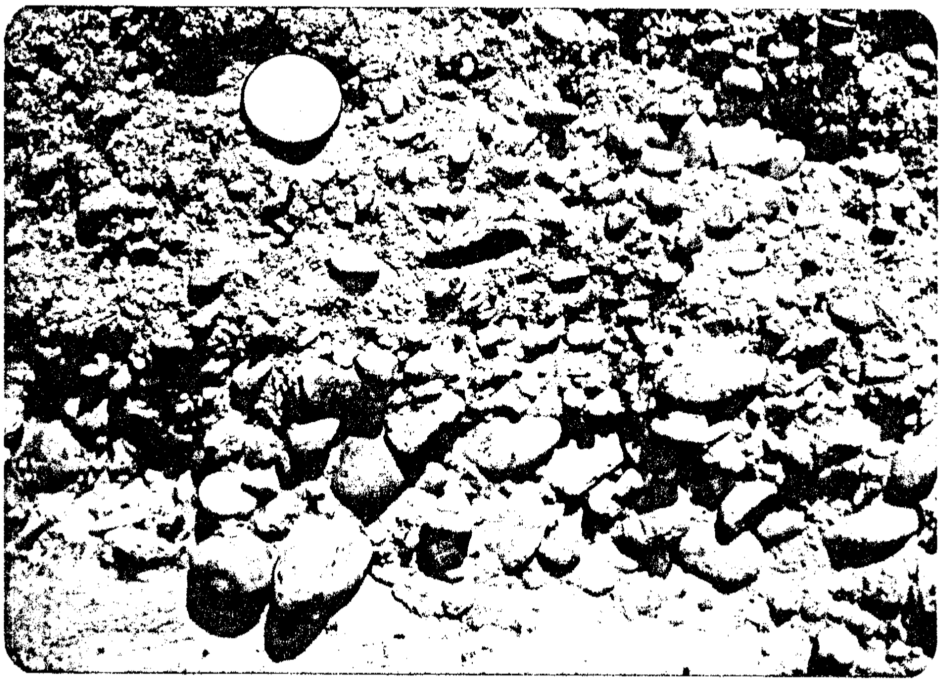


Figure 17. A conglomeratic unit of the Ojo Alamo Sandstone in bluffs south of San Juan River opposite Farmington.

> "The gradual change of depositional regime from alluvial plain to flood plain offers one explanation for the gradational and intertonguing nature of the contact between the Kimbeto Member (alluvial plain deposits) and the Nacimiento Formation (flood plain deposits)."

In the Aztec Quadrangle, the Ojo Alamo Sandstone lies at a depth averaging approximately 1500 feet (fig. 18) and it averages about 100 feet in thickness (fig. 19). The top of this unit is very irregular as mapped in figure 20, but part of this could be due to the gradational nature of the upper contact causing errors in the picking of the top on electric logs (Brimhall, 1973, p. 200).

Reeside (1924) stated that the Ojo Alamo Sandstone thins in outcrop and disappears 9 miles north of Farmington, New Mexico, perhaps by erosion. McDonald (1972), however, states that the Ojo Alamo becomes part of the Animas Formation near the Colorado border. The Animas Formation is characterized by andesitic and other volcanic detritus and was deposited in the northern end of of the San Juan Basin in latest Cretaceous and Paleocene time. The Animas, however, wedges out abruptly into the overlying Nacimiento Formation and loses its identity at the Colorado-New Mexico border (McDonald, 1972, p. 243). For this reason, the Animas Formation will not be considered further here.

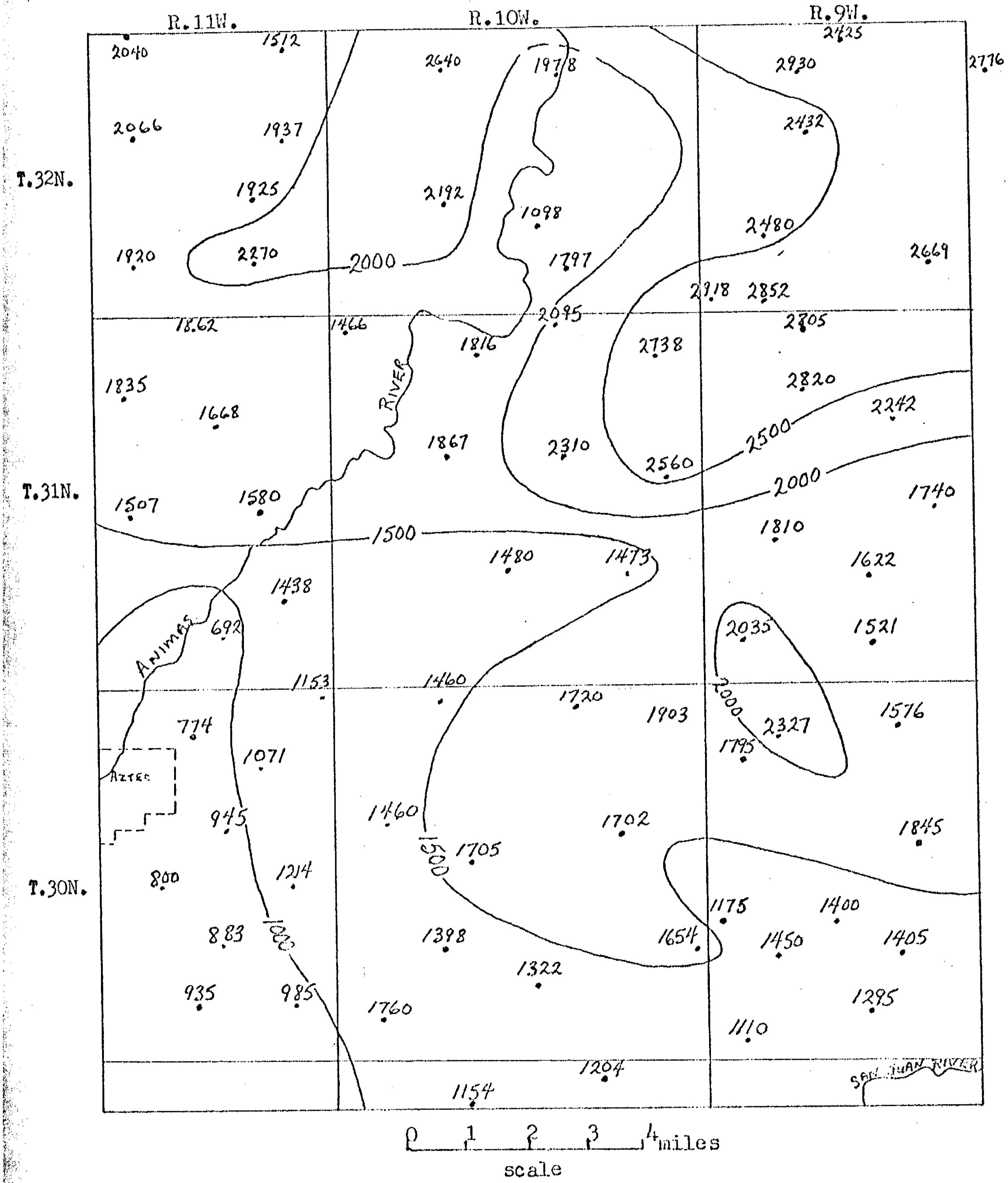


Figure 18. Depth to top of Ojo Alamo Sandstone in the Aztec Quadrangle; Contour interval 500 feet.

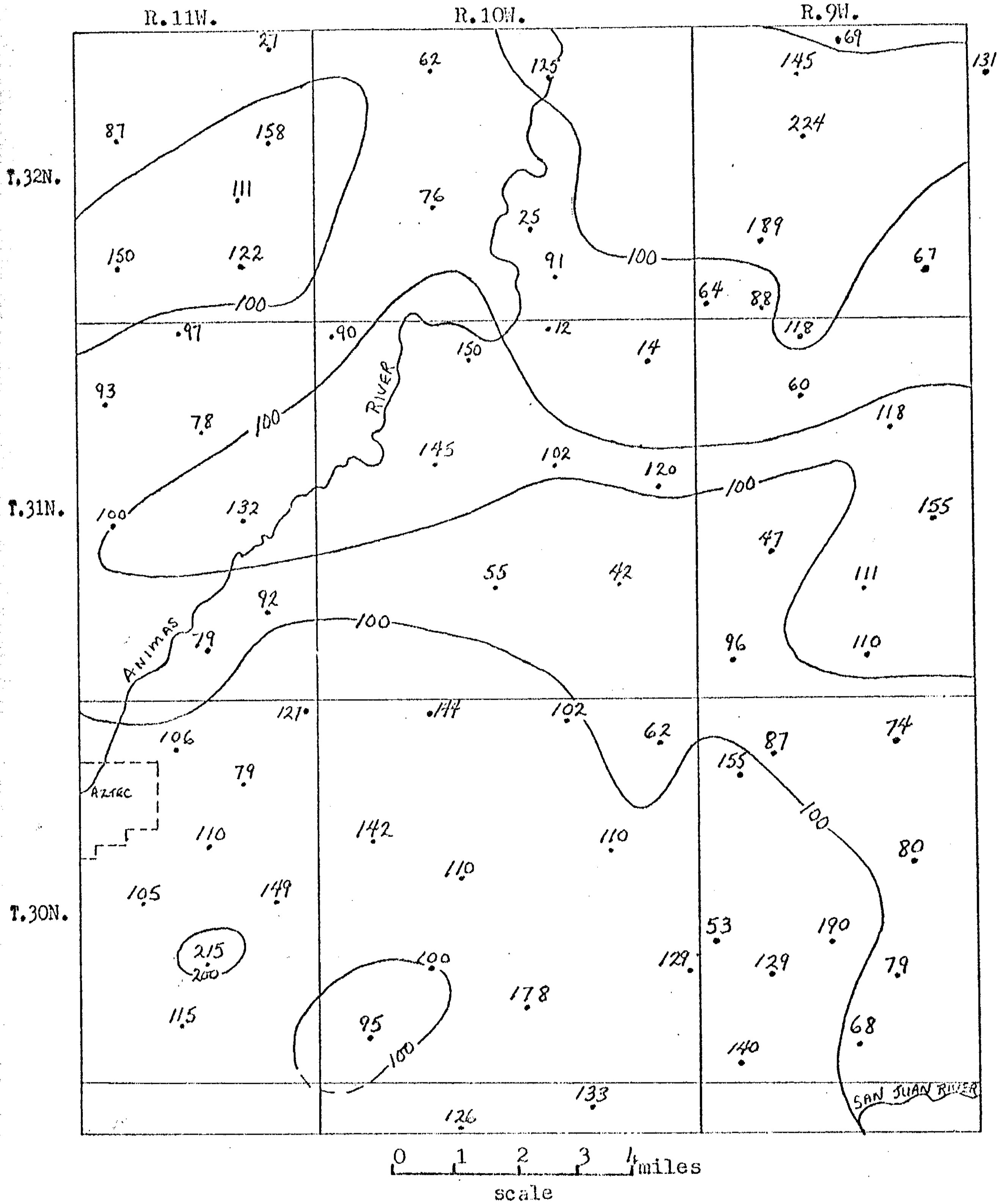


Figure 19. Isopach map of Ojo Alamo Sandstone in the Aztec Quadrangle; Contour interval 100 feet.

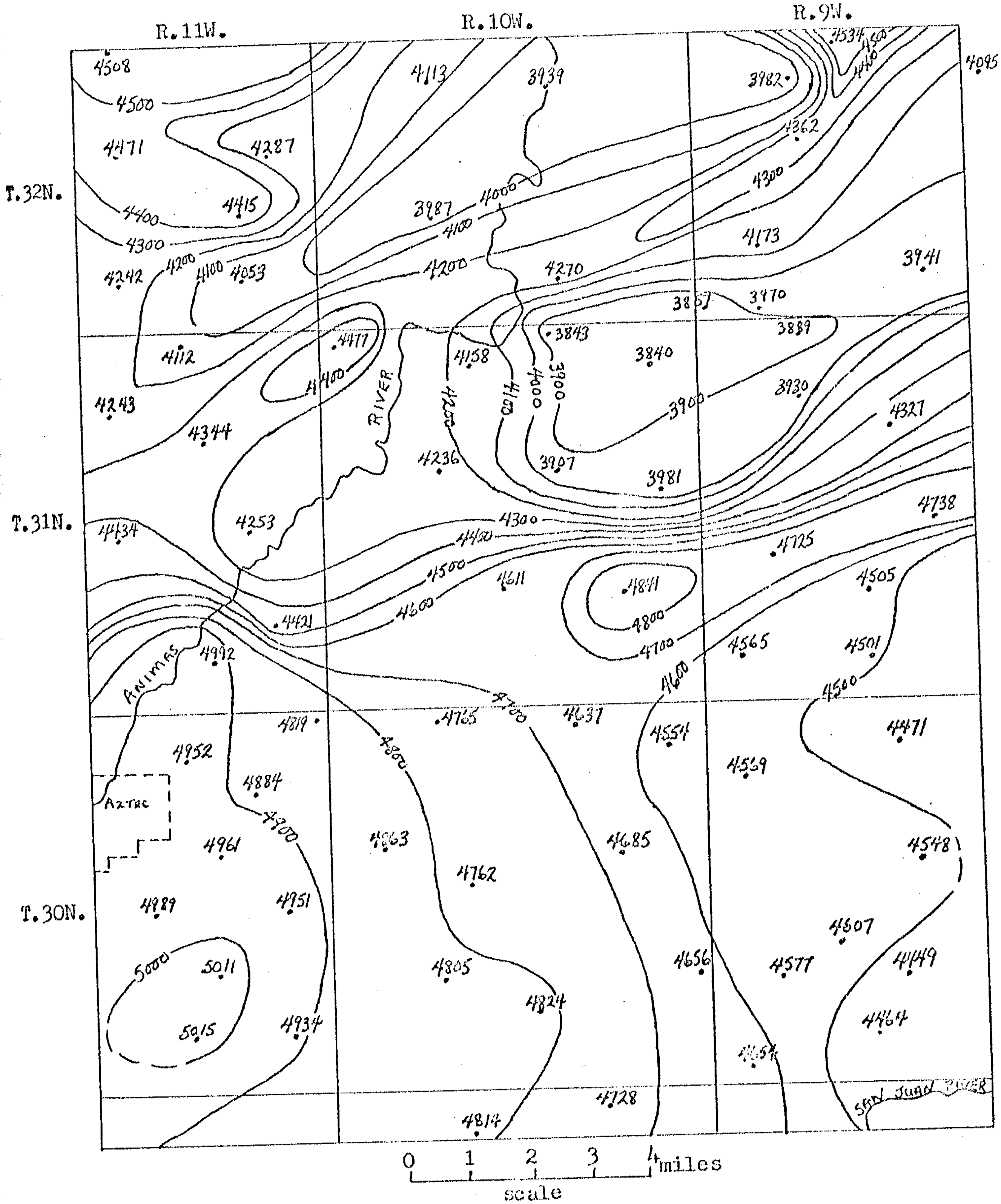


Figure 20. Structure contour map, top of Ojo Alamo Sandstone in the Aztec Quadrangle; contour interval 100 feet.

Water-Bearing Characteristics. According to Brimhall (1973), the Ojo Alamo Sandstone is a major source of supply of groundwater in the San Juan Basin. He pointed out that the coarser, channel sandstones have the greatest potential for producing good supplies of water. Brimhall reported six wells completed in the Ojo Alamo Sandstone with yields ranging from 35 to 180 gpm, specific capacities ranging from .20 to 1.02 gpm /ft., transmissivities ranging from 425 to 1230 gpd/ft., and storage coefficients ranging from .0002 to .0067. The water qualities reported are generally good, ranging from 360 to 824 ppm total dissolved solids. These wells were up to 747 feet deep.

Rapp (1959) reported that wells tapping the Ojo Alamo Sandstone to the south and east of Farmington produce quantities sufficient for domestic and stock needs. Typically, however, the water exceeds 1000 ppm total dissolved solids and is high in sulphate.

In the Aztec Quadrangle, no wells are known to penetrate the Ojo Alamo Sandstone for water. Due to its potential as suggested by Brimhall (1973) and by Baltz and West (1967), however, its depth, thickness and structure were studied using geophysical and drillers logs (figs. 18, 19, and 20). While large quantities of water may be present in the Ojo Alamo Sandstone, electric logs indicate poor quality at depths of 1,000 to 2,000 feet in the study area (no negative SP responses were noted). If partial desalination became practical at some time, or if freshness was not a criterion for some particular use, the Ojo Alamo Sandstone would likely be a valuable source of water in the area.

Cretaceous Deposits

Kirtland Shale

Lithologic Characteristics. The Kirtland Shale is separated into an upper shale member, a middle sandstone (the Farmington Sandstone Member), and a lower shale member. The shales are predominantly gray, but some are blue or yellowish green in color. The shale members also contain beds of friable, white sandstone. The Farmington Sandstone Member is composed of interbedded, brown, resistant sandstones and shales as described above (Northrop, 1973).

In the study area, the total Kirtland Shale varies in thickness from 400 to 1,000 feet and the Farmington Sandstone Member ranges from 150 to 635 feet. The Kirtland Shale is conformable on and gradational with the Fruitland Formation. Fassett and Hinds (1971, p. 25) assign a river and flood plain depositional origin to the Kirtland Shale.

Water-Bearing Characteristics. The Kirtland Shale yields less than 10 gpm to most water wells between the the towns of Kirtland and Farmington. Rapp (1959) reported that these wells produce potable water where they are shallow, but implied that the quality deteriorates rapidly with depth. Since the Farmington Sandstone Member is at depth of 1500 to 2000 feet in the Aztec Quadrangle and is a potential source of hydrocarbons, the groundwaters of this unit should be expected to be brackish or very saline.

Fruitland Formation

Lithologic Characteristics. The Fruitland Formation is composed of discontinuous units of sandstone, siltstone, shale, carbonaceous shale, carbonaceous sandstone and siltstone, commercial coal, and in the lower part thin limestone beds (Fassett and Hinds, 1971). The general lithology of the Fruitland changes upward from limestone, sandstone, and thick coal beds to predominantly siltstone and shale beds in the upper part. Fassett and Hinds (1971, p. 19) assign coastal-swamp, river, flood-plain, and lacustrine depositional environments to the lower part of the formation and flood-plain and river environments to the upper part. Thickness of the Fruitland in the Aztec Quadrangle varies from 250 to 500 feet. This formation is conformable on and intertongues with the Pictured Cliffs Sandstone.

Water-Bearing Characteristics. The thin sandstone beds of the Fruitland Formation may yield small amounts of water to wells. Electric logs of gas wells, however, suggest that these beds are thin, of low porosity, and contain water of poor quality. Baltz and West (1967) reported that wells on the Jicarilla Apache Indian Reservation have yielded highly saline water from the Kirtland-Fruitland interval.

Pictured Cliffs Sandstone

Lithologic Characteristics. The Pictured Cliffs Sandstone is composed of an upper white, massive sandstone underlain by yellowish-brown to white sandstone (Northrop, 1973). Both contain shale beds. In the study area, the Pictured Cliffs varies in thickness from 65 to 180 feet. It has been assigned a shallow-water and beach origin of deposition by Fasset and Hinds (1971, p.9). The Pictured Cliffs Sandstone lies conformably on and is gradational with the Lewis Shale.

Water-Bearing Characteristics. West of the Aztec Quadrangle, and nearer its outcrop area, the Pictured Cliffs Sandstone is tapped by numerous water wells. In the study area, however, the formation is developed extensively as a natural gas reservoir. Rapp (1959, p.4) reported results of three chemical analyses of Pictured Cliffs formation waters which ranged in total dissolved solids from 29,800 to 37,800 ppm. These samples were collected from wells in T.29N., R.12W., at a distance of less than 10 miles from the Aztec Quadrangle. The depth and poor quality of its water make the Pictured Cliffs Sandstone an impractical source of water for the study area.

Lewis Shale

Lithologic Characteristics. The Lewis Shale is made up of dark gray to drab gray, sandy shales, clays, and sandstones with thin calcareous concretions and lenses of limestone. It also contains well-bedded calcareous shales and thin-bedded white to gray sandstone (Northrop, 1973). The Lewis is a thick, marine shale and varies in thickness from 1400 to 1600 feet in the study area. The Lewis Shale overlies the Mesaverde Group, the upper member of which is the Cliff House Sandstone.

Water-Bearing Characteristics. Positive SP log responses and relatively small resistivities from electrical logs suggest that the thin sandstone beds in the lower part of the Lewis Shale contain saline waters.

These beds are reported to be fine-grained and are probably of low permeability (Baltz and West, 1967). The Lewis Shale, therefore, offers little potential as a good source of water in the Aztec Quadrangle.

Cliff House Sandstone

Lithologic Characteristics. The Cliff House Sandstone is light gray, buff, and brown, thin-bedded to massive with shale partings (Northrop, 1973). In the Aztec area, it varies in thickness from 65 to 200 feet. The Cliff House is a transgressive marine sandstone (Pike, 1947, p. 97) which overlies and intertongues with the Menefee Formation.

Water-Bearing Characteristics. The Cliff House Sandstone has the properties of a good aquifer, with porosities varying from 13.7 to 28.3 percent (Renick, 1931). However, due to poor water quality and the presence of hydrocarbons at depth, the Cliff House is only tapped by water wells near its recharge area, 20 miles to the south and west of Aztec. Therefore, the Cliff House Sandstone would be a poor source of potable water in the study area.

Menefee Formation

Lithologic Characteristics. The Menefee Formation consists of interbedded gray-buff, massive to thin sandstones, gray shales, and coal seams (Northrop, 1973). It varies from 285 to 450 feet in thickness in the study area. Reeside (1924, p.14) stated that varied fossils indicate a fresh-water origin for some Menefee beds and a marine origin for others. The Menefee Formation lies conformably on the Point Lookout Sandstone or the Lower Gibson Coal Member of the Crevasse Canyon Formation.

Water-Bearing Characteristics. The sandstones of the Menefee Formation provide good supplies of potable water to numerous domestic and stock wells in western San Juan County, in and near the outcrop area. However, lying at depths of approximately 4500 feet in the Aztec Quadrangle, the Menefee Formation is too deep and probably too saline to be a good source of potable water.

Point Lookout Sandstone

Lithologic Characteristics. The Point Lookout Sandstone is composed of massive, light gray to yellow sandstone (Northrop, 1973). Baltz and West (1967) describe it as mainly medium-grained, but containing a few beds of fine-grained sandstone and some thin beds of shale. The Point Lookout Sandstone is a regressive beach deposit (Pike, 1947, p. 14) and it varies in thickness from 95 to 350 feet in the study area. It lies conformably on the Mancos Shale.

Water-Bearing Characteristics. The same properties that make the Point Lookout Sandstone a good aquifer, average porosity of 19 percent and hydraulic conductivity of 11.6×10^{-4} cm/sec (Charakulas, 1975), also make it a good hydrocarbon reservoir at depth. Lying at several thousand feet of depth in the Aztec Quadrangle, therefore, the Point Lookout can be expected to produce only saline waters. Berry (1959, Plate 26) mapped total concentration of Mesaverde formation waters ranging from 6,760 to 21,270 ppm in the Aztec area.

Mancos Shale

Lithologic Characteristics. The Mancos Shale is composed of light to dark gray, sandy shale containing sandstone lenses, fossiliferous calcareous shales, and thin limestone lenses (Northrop, 1973). It has been assigned a marine origin (Reeside, 1924, p. 9) and it is separated by the Gallup Sandstone (see below) into upper and lower shale members. The Mancos Shale overlies the Dakota Sandstone conformably or disconformably.

Water-Bearing Characteristics. The Mancos Shale is generally considered of poor potential as an aquifer in the San Juan Basin. Its sandstone lenses are likely to yield only small amounts of very poor quality water in the Aztec Quadrangle.

Gallup Sandstone

Lithologic Characteristics. The Gallup Sandstone consists of three persistent, massive, pink or light gray sandstones interbedded with gray shale and coal (Northrop, 1973). Molenaar (1973, p.85) assigns coastal barrier, paludal, and fluvial channel origins to the Gallup. In the San Juan Basin, the Gallup Sandstone varies from 0 to 450 feet in thickness and lies conformably on the lower Mancos Shale.

Water-Bearing Characteristics. The reservoir characteristics of the three Gallup Sandstone benches in the Bisti area have been studied by Reneau and Harris (1957). They describe the upper bench as a clean, permeable sandstone, whereas, the two lower benches are very silty and have low porosity and permeability.

The Gallup Sandstone is a fair to good aquifer and is tapped by many wells within approximately 20 miles of its outcrop area in western

San Juan County. Again, however, in the deeper parts of the Basin, including the study area, the Gallup Sandstone lies at impracitcal depths to be exploited as an aquifer. Also, the average salinity of 26 samples of Gallup saline waters (Central Basin) was 46,545 ppm (Berry, 1959, p. 108).

Dakota Sandstone

Lithologic Characteristics. The Dakota Sandstone is, at many localities, a yellow, buff, brown, red, and white sandstone interbedded with variegated clays, gray shales, and lignite. It can also be a massive, silica-cemented, quartz sandstone (Northrop, 1973). In the study area, the Dakota Sandstone varies in thickness from 65 to 180 feet. Owen (1973, p. 39) describes the Dakota as consisting of braided and meandering stream, coastal, and offshore deposits. The Dakota Sandstone unconformably overlies the Morrison Formation of Jurassic age or lower Cretaceous rocks.

Water-Bearing Characteristics. The Dakota Sandstone, with an average porosity of 11 percent and average permeability of 14 millidarcys (Reneau and Harris, 1957, p. 43), is a good reservoir for both water and hydrocarbons in different parts of the San Juan Basin. In western San Juan County, the Dakota is tapped by many water wells near its outcrop where the water is potable. In the study area, however, the Dakota Sandstone is at great depth, and has saline formation waters so is impractical as an aquifer.

Jurassic Deposits

Morrison Formation

Lithologic Characteristics. The Morrison Formation consists of variegated calcareous mudstone, siltstone, sandstone, shale, and conglomerate. It ranges in thickness from 0 to 1550 feet in the San Juan Basin and is disconformable on various formations of the San Rafael Group (Northrop, 1973). The Morrison Formation is variously composed of four members which are, in ascending order, the Salt Wash Sandstone, Recapture Shale, Westwater Canyon Sandstone, and Brushy Basin Shale Members. Other local names are used for these members in places (Smith, 1954). Not all members are present at all localities (Berry, 1959, p. 17). Flesch (1974) assigned a generally continental fluviatile origin to the members of the Morrison Formation.

Water-Bearing Characteristics. Near its outcrop area, especially in the southwestern portion of the San Juan Basin, the Westwater Canyon Sandstone Member of the Morrison Formation is a major aquifer. Hiss (1974) suggested that in places the Westwater Canyon Sandstone may be in hydraulic communication with the overlying Dakota Sandstone, so at depth would have waters similar in chemistry to those of that unit. At depths of 7,000 to 8,000 feet in the Aztec Quadrangle, it is most likely that any water from the Morrison Formation would be very saline.

REGIONAL GROUNDWATER FLOW

Recharge

The surface geologic units of the study area, the unnamed Quaternary deposits, San Jose Formation, and Nacimiento Formation, are recharged in various ways. Most recharge probably takes place directly from rain and snow which fall on this area. This averages only 9.8 inches annually at Aztec, but increases considerably with elevation towards the Colorado border. Most of this precipitation, however, does not percolate to the water table because it is lost by evaporation from the surface or the soil-moisture zone. Much of the total precipitation falls in intense, summer thunderstorms, so it is likely that much is also lost to runoff, particularly in areas underlain by the less permeable shales. Runoff, however, produces another method of recharge. The coarse bed materials of the many ephemeral streams cause transmission losses or percolation of runoff into these materials and then into subjacent units.

The alluvial aquifers of the major river valleys are recharged directly by their respective streams, but more importantly, by the abundant irrigation water which is spread over these aquifers each growing season. This can amount to approximately 2.5 feet of water per acre per year (N.M.I.S.C. and N.M.O.S.E., 1975) and the water table can be observed to rise with its application.

The subsurface units are each recharged in and near their respective outcrop areas by the methods described above. These areas for the San Juan County district are outlined on the geologic map (fig. 9).

Lastly, both surface and subsurface geologic units can be recharged by leakage or discharge from another unit. The simplest and probably most common example of this is percolation of water from coarse alluvium into bedrock. Because of their silty or sandy textures, many shales in the San Juan Basin do not stop the vertical movement of groundwater but only retard it. Water-bearing units can also communicate through fracture systems which are common in consolidated rocks.

Groundwater Movement

As stated by Darcy in 1856, groundwater flows in accordance with the hydraulic gradient which in turn is dependent upon gravity and pressure. For horizontal flow, groundwater moves from high to low pressure, but for inclined flow, the movement may even be in the direction of increasing pressure (Todd, 1959, p. 46). According to Darcy (1856), another factor affecting the rate of flow is the hydraulic conductivity, K, a property which varies both between and within most natural media.

In the surface units of the study area, groundwater is assumed to flow in response to a gravitational hydraulic gradient. That is, groundwater flow has a southeasterly component due to the regional dip of less than 1 degree. Near the surface, however, local topography can cause some flow towards topographic lows and away from highs. Groundwater should flow, for instance, away from the upland areas and divides and towards the deep canyons and river valleys of the area. The silty and sandy nature of the Tertiary shales should also allow some hydraulic communication between many sandstone aquifers.

In a study of hydrodynamics and geochemistry of groundwater in the San Juan Basin, Berry (1959, p. 157) suggested another mechanism for groundwater flow: osmotic pressure. Berry stated that shale units can act as semi-permeable membranes between sandstone units of different water quality. Fresher water tends to flow toward more saline water through the shale membrane with the exclusion of some ions. According to Berry (p. 81), this mechanism explains the depression of potentiometric surfaces in the Central Basin of the San Juan Basin. The strata involved are those of Jurassic and Cretaceous age overlying the Entrada Sandstone, which locally has very saline waters.

Berry concluded, therefore, that there are two major components of groundwater movement in the San Juan Basin: 1) flow due to gravity which causes movement mostly down dip from the flanks toward the center of the basin, and 2) flow due to osmotic influences which causes generally downward movement in the Central Basin.

In the Aztec Quadrangle, groundwater flow is believed to be generally southeasterly, toward the center of the basin. In the subsurface units of Cretaceous and Jurassic age, flow may also have a downward component as suggested by Berry (1959). Because of artesian pressures, it is likely that there is some local, upward movement also, made possible by leakage through zones of silty shale or fractures.

Discharge

Berry (1959) compiled potentiometric surface maps of the Jurassic and Cretaceous systems of the San Juan Basin. These maps indicate various points of gravitational discharge on the edges of the basin where outcrops lie at a lower elevation than potentiometric surfaces basinward. In the Central Basin, including the study area, however, Berry mapped a potentiometric low or sink due, he said, to flow of osmotic influence in these formations.

In the outcrop areas of all of the units considered here, some discharge can occur at seeps and springs where streams have cut canyons into the aquifers or where lithologic conditions allow artesian water to escape. In the Aztec Quadrangle, many springs have been mapped in the San Jose and upper part of the Nacimiento Formation (Plate 2). Near the surface, groundwater discharge can occur directly into a stream during times of low flow, or into the atmosphere by evaporation. As mentioned previously, some discharge or leakage can take place from one water-bearing unit to another. Artificial discharge, of course, consists mostly of pumpage from wells. In the study area, though, artificial discharge is important only in the Animas and San Juan River Valleys.

WATER QUALITY

General Statement

In the San Juan Basin as a whole, the major water problem is not one of quantity as much as it is one of quality. As fresh, meteroric waters percolate to the water table and begin to flow in response to the hydraulic gradient, they tend to dissolve mineral matter from the surrounding rock. Generally, the greater the time and distance travelled, the greater the dissolved solids content of the groundwater. Other factors, though, are are temperature and acidity (pH) of the water, and types of minerals present in the country rock. Todd (1959, p.178) stated that sodium and calcium are the common cations of groundwaters in sedimentary rocks; bicarbonate, and sulphate are the corresponding anions. Chloride and magnesium are generally limited constituents and nitrate is rare in most natural groundwaters.

Hem (1959) has thoroughly discussed the chemical constituents of natural groundwaters and much of the following discussion is taken from his work. Most groundwater in sedimentary rocks of semi-arid areas is high in sulphate because the soils are not fully leached. Major sources of sulphate are gypsum and anhydrite. Sodium, one of the most soluble constituents in the earth's crust, may be dissolved from salt beds laid down with sediments (halite, etc.) or from common minerals such as sodium feldspar (albite). Sodium content is increased in groundwater by the process of base exchange, in which sodium from a mineral is replaced by calcium or magnesium already in solution. Calcium is commonly a major constituent of groundwater both because of its abundance in various minerals and because it is easily dissolved. Calcium is generally dissolved from gypsum, anhydrite,

Table II. Chemical analyses of water wells in the Aztec Quadrangle (in equivalents per million).

OWNER OR WELL NAME	NUMBER	LOCATION	HCO_3	Cl	SO_4	Na	K	Mg	Ca	TDS (ppm)	Specific Conductance mmhos/cm	Date
B. Heizer	Q2	NW-15-32N-10W	2.25	0.48	2.54	1.61	0.00	1.85	2.01	308	550	8/75
N.M. Port of Entry	N4	SW-16-32N-10W	0.41	115.66	0.44	95.70	0.17	0.72	19.46	6,754	12,700	3/75
F. Clark	Q4	SE-21-32N-10W	3.75	2.56	4.58	9.35	0.04	0.58	1.39	687	1,120	9/75
A. Flaherty	Q6	SE-32-32N-10W	4.25	1.11	25.44	15.77	0.07	3.17	12.21	1,923	2,600	8/75
C. Lanier	Q7	NE-33-32N-10W	3.00	0.85	4.89	2.18	0.19	2.78	4.02	528	943	9/75
M. Bishop	Q9	SE-24-31N-11W	2.59	0.72	3.04	1.57	0.04	1.97	3.00	694	650	8/75
F. Randalmon	Q10	NW-26-31N-11W	4.61	0.73	3.04	1.52	—	0.56	5.09	484	777	8/59
A. Hill	Q11	SE-26-31N-11W	2.25	0.64	9.26	3.09	0.02	2.47	5.99	759	950	8/75
G. Foster	Q13	SW-34-31N-11W	2.75	0.31	2.39	1.07	0.11	0.82	3.73	317	610	8/75
L. Likes	Q14	SE-34-31N-11W	2.51	0.68	12.70	4.22	0.03	1.40	9.73	1,021	1,320	8/75
Pan Am Petroleum	Q17	5-31N-10W	6.00	1.61	7.77	5.83	—	2.23	7.34	1,104	—	4/59
J. Hollar	Q18	SE- 6-31N-10W	4.51	0.71	3.44	4.57	0.05	1.73	2.62	508	820	9/75
E. Flaherty	Q20	NW-18-31N-10W	4.25	0.41	5.20	2.14	0.49	1.87	5.39	576	780	9/75
Little Pump	S15	NW-21-31N- 9W	5.24	0.68	4.64	5.22	0.28	2.14	2.84	643	1,205	2/76
C. Van Dusen	Q22	9-30N-11W	4.95	1.07	51.22	26.27		—	—	—	4,320	7/54
Atlantic State #1	N14	NW- 2-30N-10W	1.75	0.34	11.26	2.00	0.07	1.86	9.46	1,004	1,523	11/75
EPNG Knickerbocker #1	N18	SE-23-30N-10W	0.20	0.60	75.00	65.00	—	1.10	8.80	5,204	—	3/72
" "		" "	2.00	1.00	54.00	46.00	—	1.00	10.00	1,921	—	10/74
C. Curule	Q26	NW- 4-29N- 9W	1.50	0.28	5.33	3.61	0.09	0.52	3.27	512	840	2/76

9-266d USGS-WRD, Nov. 1954

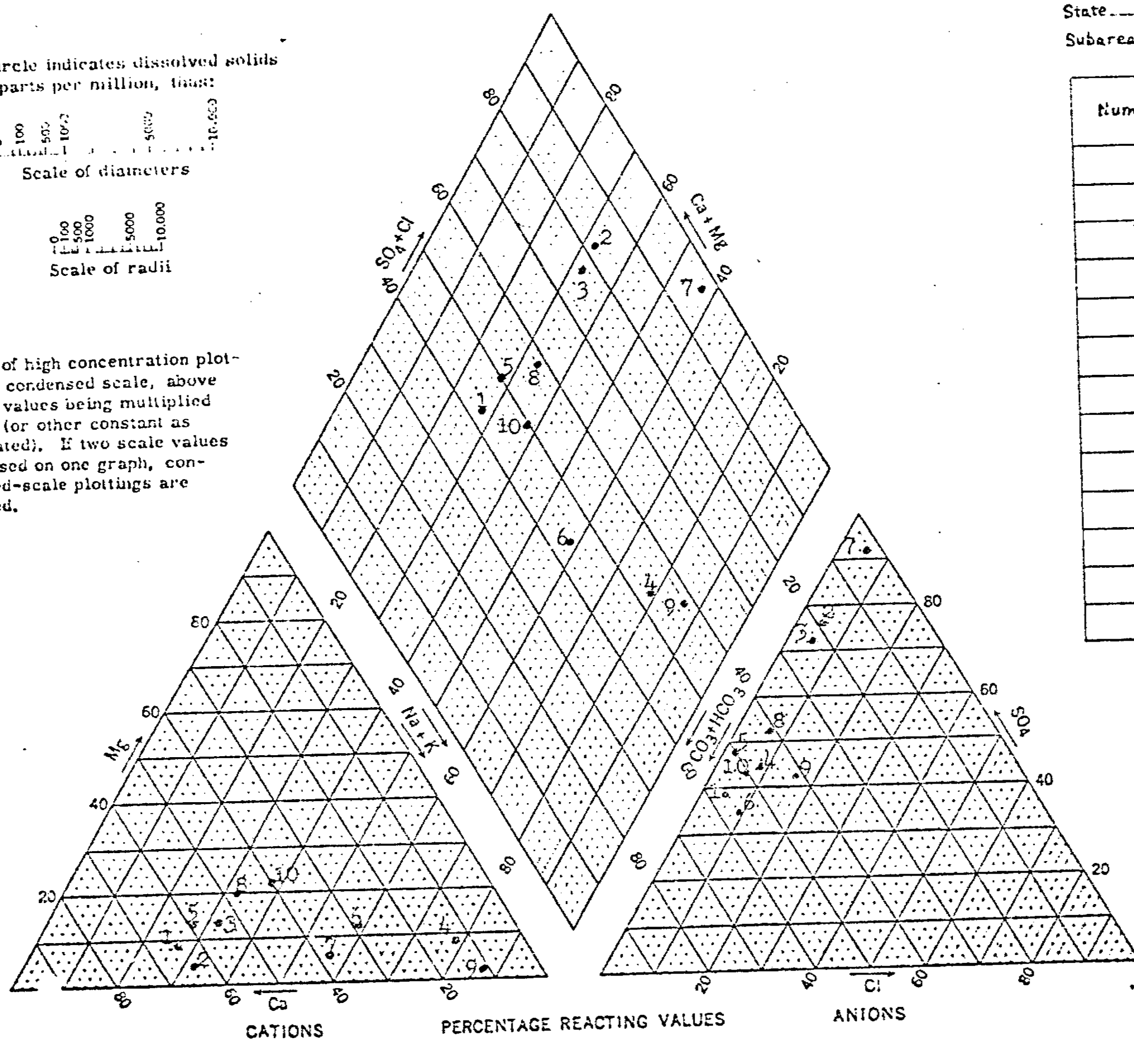
WATER-ANALYSIS DIAGRAM

Area of circle indicates dissolved solids in parts per million, thus:

Scale of diameters

Scale of radii

Waters of high concentration plotted at condensed scale, above scale values being multiplied by 10 (or other constant as indicated). If two scale values are used on one graph, condensed-scale plottings are shaded.



State New Mexico

Subarea Aztec Quadrangle

Number	Date	Dissolved Solids (ppm)	Aquifer
1	8/75	317	Qal
2	8/75	1,021	Qal
3	8/75	759	Qal
4	8/75	694	Qal
5	8/75	576	Qal
6	8/75	508	Qal
7	8/75	1,923	Qal
8	8/75	528	Qal
9	8/75	687	Qal
10	8/75	308	Qal

(67)

Plotted by D.R.B.

Checked by D.R.B.

Date 1976

Figure 21. Piper diagram for well samples from Animas River Valley alluvium.

Figure 22. Kiffen Canyon in the Nacimiento "badlands" area; view north, NE$\frac{1}{4}$ Sec. 11, T.31N., R.11W.; note the alkali dissolved out of the shales by groundwaters and precipitated onto streambed.

and calcite from limestones or cement in sandstone and shale. Carbonate and bicarbonate are common in most groundwaters because of the abundance of carbonate minerals in the earth's crust (calcite, aragonite, etc.) and the ready availability of carbon dioxide which enters into equilibria with them in solution.

In the Aztec Quadrangle, groundwaters of the Quaternary and Tertiary units are generally dominated by sulphate, sodium, calcium, and bicarbonate ions (Table II and fig. 21). Much of the sulphate is assumed to be dissolved out of the shales of the area because they are rich in gypsum (fig. 22). Sodium has been dissolved from various minerals present in the Tertiary sandstones and shales, although halite, for example is not present in any quantity. Because calcium content is also high in local groundwaters, base exchange may be partially responsible for their high sodium content. Gypsum is likely the main source of calcium in the area as limestones are not present and calcite cements are not abundant. In the Aztec Quadrangle, all the groundwaters tested were found to be of the bicarbonate type. Though not too common, calcite cements are probably the main source of this ion.

Surface Units

Alluvium. Analyses of 10 groundwater samples from the Animas River alluvium showed an average of 43 percent sulphate, 18 percent sodium, 15 percent bicarbonate, 14 percent calcium, 4.5 percent chloride, 4 percent magnesium, and 0.5 percent potassium (Table II). The average total dissolved solids content is 732 ppm and values range from 308 to 1923 ppm. The generally good quality of this water is due to two factors: 1) the sands and gravels from which the waters are pumped are relatively "clean" (low in matrix which contains readily soluble minerals) and 2) the aquifers are near the surface and are recharged from the relatively fresh waters of runoff, irrigation return flow, and direct precipitation.

San Jose Formation. The quality of water from aquifers of the San Jose Formation has been determined only for spring samples during this study (Table III). The average of analyses of 11 springs is as follows: 28 percent calcium, 27 percent sulphate, 20 percent bicarbonate, 14 percent sodium, 8 percent magnesium, 2 percent chloride, and 0.4 percent potassium. Total dissolved solids of the 11 springs averaged 515 ppm and ranged from 110 to 1528 ppm. The good quality here is likely due to the fact that groundwater has not travelled far from the recharge area and has travelled mainly through relatively clean sandstones. These waters can be expected to deteriorate in quality, however, as they travel along a shale-sandstone interface and as they lie on weathered shale. The poor quality of waters from Cave, Hidden, and Mud Springs may be related to the fact that cattle and wildlife have open access to these waters. This can add chloride and possibly sulphate, nitrate, and their cations to the water (Hall, 1963).

Nacimiento Formation. Because of its shaly nature, the Nacimiento Formation contains water of generally poor quality. Field values of specific conductance for water from six shallow wells in the Aztec Quadrangle averaged 2073 micromhos per centimeter (mmhos/cm.); the values ranged from 1120 to 4500 mmhos/cm. (Table II). Two other wells known to be completed in the Nacimiento Formation are not presently used and the owner of one reports that the water is not potable. The E.P.N.G. Atlantic State No. 1 water well, in NW$\frac{1}{4}$ Sec. 2, T.30N., R.10W., is also completed in the Nacimiento Formation. Chemical analysis of this water showed sulphate (43 percent) and calcium (36 percent) to be particularly important constituents (Table II). Total dissolved solids content of this water is 1004 ppm; a specific conductance of 1523 mmhos/cm. was reported.

Table III. Chemical analyses of springs in the Aztec Quadrangle (in equivalents per million).

SPRING NAME	NUMBER	LOCATION	HCO_3	Cl	SO_4	Na	K	Mg	Ca	TDS (ppm)	Specific Conductance mmhos/cm	Date
Cave	S1	SW-14-32N-11W	2.51	0.40	16.64	4.44	0.21	1.73	14.20	1,305	1,650	6/75
Cattail	S3	NE-13-32N-10W	3.75	0.40	5.04	6.05	0.22	1.40	1.60	567	820	6/75
High Hopes	S4	SE-17-32N-10W	2.00	0.17	1.46	0.42	0.05	0.62	2.60	208	350	8/75
Garrison	N9	NW-14-31N-10W	1.25	0.07	0.99	0.45	0.01	0.34	1.61	136	—	6/75
Arch Rock	S7	SW-24-31N-10W	2.25	0.17	1.97	1.34	0.00	0.86	2.26	256	390	6/75
Hart #1	S8	SW-25-31N-10W	1.25	0.07	1.25	0.77	0.00	1.44	1.31	150	295	6/75
Hart #2	S9	SE-26-31N-10W	3.25	0.65	3.89	1.50	0.05	1.32	4.61	454	700	6/75
Thurston	N12	NW-31-31N-10W	2.75	0.53	41.60	22.29	0.11	2.47	21.50	3,081	2,900	6/75
Last Chance	S10	SW- 5-31N- 9W	1.25	0.11	0.59	0.68	0.00	0.18	1.09	110	183	6/75
Hidden	S11a	NE- 6-31N- 9W	2.75	0.60	19.73	6.96	0.08	3.17	13.61	1,528	1,800	6/75
Cottonwood	S18	SE-31-31N- 9W	2.25	0.17	1.87	1.04	0.03	0.99	2.30	249	450	6/75
Mud	S19	NE- 2-30N-10W	2.00	0.12	8.95	1.70	0.09	1.89	7.37	709	1,000	9/75

Subsurface Units

General Statement. Relatively little information is available on the quality of groundwaters from the Ojo Alamo Sandstone, Kirtland Shale, and Fruitland Formation in the San Juan Basin. The geochemistry of deeper units of the Cretaceous and Jurassic systems were discussed in detail by Berry (1959) however. He reported chemical analyses and discussed the waters of the Pictured Cliffs Sandstone, Mesaverde Group, Gallup Sandstone, and Dakota Sandstone as well as other formations with which this study is not concerned. Because of the geochemical similarity of these four deeper units, they will be considered together in the discussion of water quality.

Ojo Alamo Sandstone. Rapp (1959) discussed the quality of waters from the Ojo Alamo Sandstone in the Farmington area. He noted that these groundwaters are typically of the sulphate type and have total dissolved solids contents in excess of 1000 ppm in and near the study area. Rapp (p. 4) gave a water analysis from a well in Sec. 26, T.29N., R.12W., in which sulphate composed 66 percent, sodium 23 percent, and calcium 8 percent of the total dissolved solids (5400 ppm). Baltz and West (1967) reported chemical analyses of five Ojo Alamo water samples which average 1554 ppm total dissolved solids, and ten samples which average 1492 mmhos/cm. specific conductance. The total dissolved solids varied from 1030 to 4010 ppm, and the specific conductances from 667 to 4490 mmhos/cm.

Ojo Alamo waters in the Aztec Quadrangle should be expected to be too high in dissolved solids to be potable, because the Ojo Alamo Sandstone is deeper and farther from the outcrop (recharge) area than where Rapp took samples.

Kirtland Shale. Shallow wells in the Farmington area generally produce potable water from sandstone lenses of the Kirtland Shale provided they are close to a source of infiltration recharge (Rapp, 1959, p. 6). Water analyses from four wells reported by Rapp, and believed to be in the Kirtland Shale, averaged 1686 ppm and varied from 686 to 2497 ppm total dissolved solids. These waters are generally high in sulphate and/or bicarbonate content. Rapp also recorced (1959, p. 4) analyses of four gas-well samples from the Farmington Sandstone Member of the Kirtland Shale. These are sodium chloride waters and average 53,750 ppm total dissolved solids, varying in content from 45,600 to 57,600 ppm. These samples were from wells in T.28 and 29N., R.12W.

In the Aztec Quadrangle, farther basinward, Kirtland Shale waters can be expected to be at least as saline as discussed above because the unit is deeper.

Fruitland Formation. Actual data regarding the quality of waters from the Fruitland Formation are scarce. Rapp (1959, p. 5) estimated the total dissolved solids content of these waters to be between that of the overlying Kirtland Shale (brine) and the underlying Pictured Cliffs Sandstone (very saline). This estimate would place the average total dissolved solids content of Fruitland waters between 30,000 and 60,000 ppm in the Farmington area. Therefore, at the greater depths encountered in the Aztec area, groundwaters of the Fruitland Formation are probably very saline.

Pictured Cliffs Sandstone, Mesaverde Group, Gallup Sandstone, and Dakota Sandstone. Berry (1959) has compiled and averaged numerous chemical analyses of the formation waters of each of these Cretaceos units. Berry's work indicated two systems in each of the above units: a fresh-water system and a saline-water system. The fresh-water system operates predominantly around the flanks of the San Juan Basin. Groundwater in this system flows in response to gravity, and ions in solution have been from the country rock during water movement. In the saline-water system of the Central Basin, both flow and the increased dissolved solids content of waters are predominantly a result of osmotic influences. According to Berry (1959), as the waters flow downward, the membrane effect of shale units tends to concentrate the ions in solution. The reader is referred to Berry (1959, p. 157) for a thorough discussion of this theory.

Table IV shows the concentrations of saline waters that exist at depth in the Central Basin. The Piper diagram (fig. 23) shows how similar these saline waters are in percentage of dissolved constituents. Typical of many petroleum fields, these waters are high in sodium chloride and average from 25,000 to 50,000 ppm total dissolved solids. Because the Aztec Quadrangle lies within the Central Basin, Berry's analyses are probably typical of the study area.

Morrison Formation. Because the Morrison Formation is believed to be in hydraulic communication with the Dakota Sandstone in places (Hiss, 1974), the geochemistry of these units is believed to be similar. High concentrations of sodium chloride in waters of the Central Basin are to be expected.

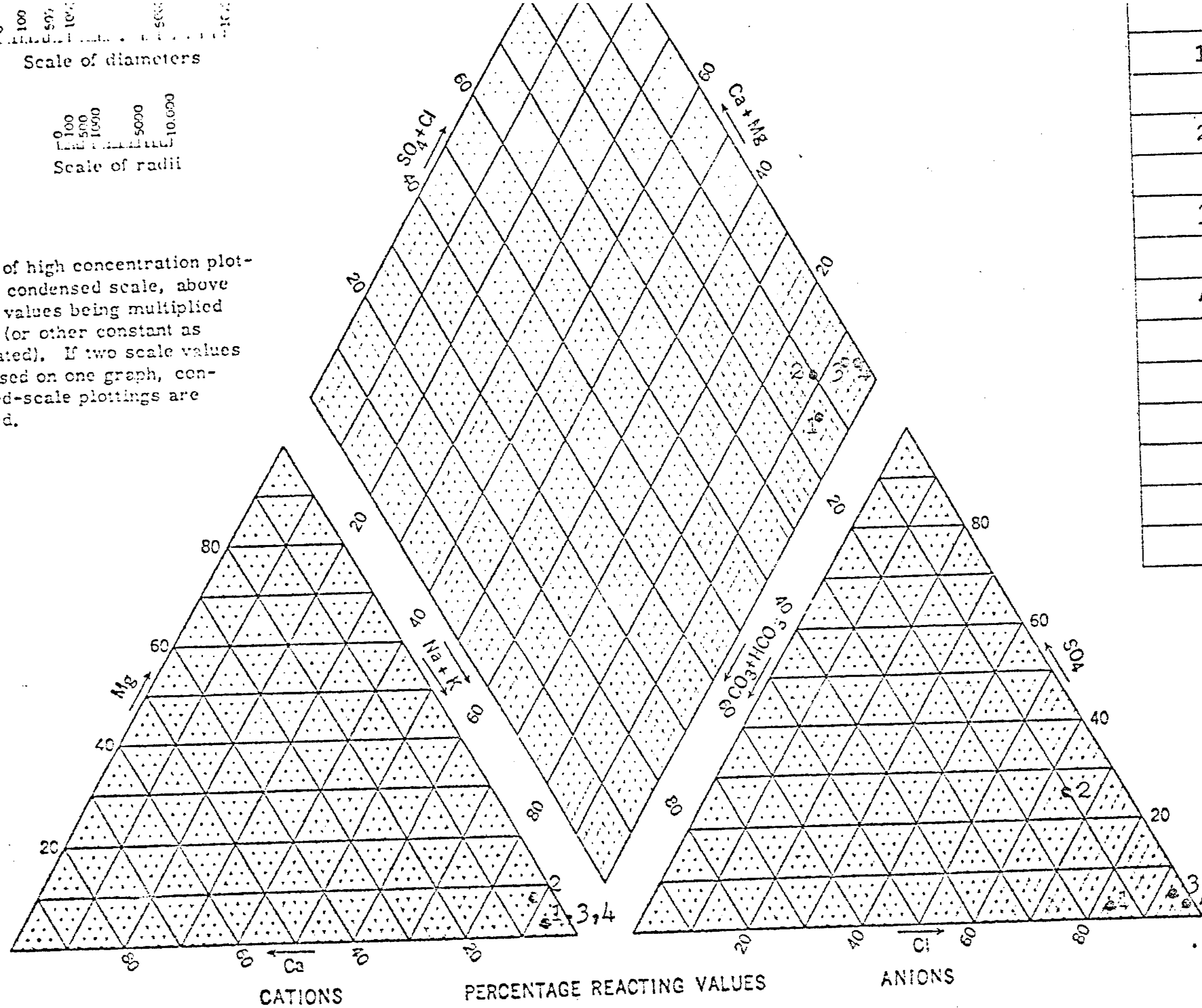
Table IV. Average chemical analyses (epm) for deep, saline, formation waters of the Central Basin (Berry, 1959).

Aquifer	HCO_3	Cl	SO_4	Na	K	Mg	Ca	TDS (ppm)	No. of samples
Pictured Cliffs Sandstone	60.09	341.86	7.38	382.66	1.12	6.18	19.37	25,447	49
Mesaverde Undivided	36.08	231.23	86.42	311.39	2.01	27.32	13.01	22,382	21
Gallup Sandstone	13.85	737.50	34.69	733.65	4.43	14.87	33.09	46,545	26
Dakota Sandstone (actual analysis)	0.83	452.00	18.20	437.90	1.40	5.00	26.70	27,670	1

Scale of diameters

Scale of radii

Waters of high concentration plotted at condensed scale, above scale values being multiplied by 10 (or other constant as indicated). If two scale values are used on one graph, condensed-scale plottings are shaded.



		(ppm)	
1		25,447	Kpc
2		22,382	Kmv
3		46,545	Kg
4		27,670	Kd

Plotted by D.R.B.
Checked by Berry (1959)
Date 1976

Figure 23. Piper diagram for deep formation waters of San Juan Basin; (data from Berry, 1959).

WATER USE AND SUPPLY

Urban

Present Sources

The town of Aztec diverts all of its water from the Animas River to a reservoir just north of the town (fig. 24). This reservoir, doubled in size in 1975, now has a storage capacity of approximately 7,000,000 gallons. The municipal water treatment plant is located at the reservoir and treats and distributes an average of 1,600,000 gpd. The Aztec municipal water supply has an average total dissolved solids content of 550 ppm (N.M.I.S.C. and N.M.O.S.E., 1975). In the treatment plant the river water is first treated with allum to settle out the sediment. It is also treated with copper sulphate to kill any algae and is then chlorinated. Animas River water contains enough natural fluoride to comply with fluoridation standards, so this process is not necessary.

The community of Turley, on the San Juan River, in the southeast part of the study area, obtains water for domestic use from a 32 foot deep well in the San Juan River Valley alluvium. The well has a capacity of 16,000 gpd but the system stores only 8,000 gallons (N.M.I.S.C. and N.M.O.S.E., 1975). Only five houses presently are tapped into the system. Quality of the water is quite good but it is treated (G. Lobato, personal communication).

The people of Cedar Hill, on the Animas River, obtain their water from individual wells, completed mostly in the valley alluvium.

Potential Sources

There are numerous wells in the Aztec area which tap the alluvium of the Animas River Valley. If it were deemed necessary at some future time, collector wells or a field of shallow wells could be constructed in the

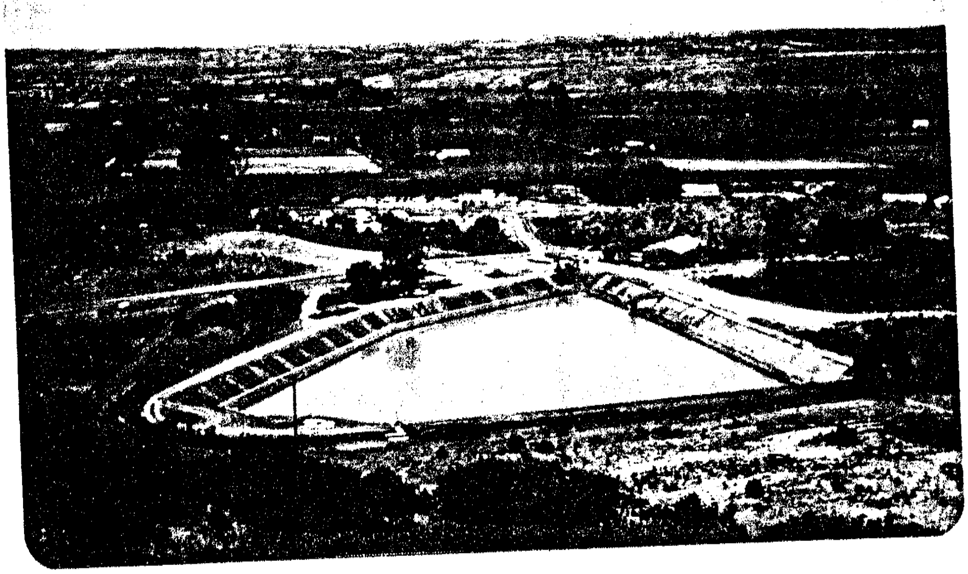


Figure 24. The Aztec municipal reservoir and treatment plant; view west, SE$\frac{1}{4}$ Sec. 3, T.30N. R.11W.; note construction in progress (July, 1975) to double reservoir capacity; note irrigated floodplain of Animas River.

valley to supplement the surface water supplies during times of peak consumption or low river discharge. A fact that must be considered, however, is that such an operation would also increase the depletion of the river supply by artificially inducing recharge in the area of the wells.

The only potential for water from a bedrock aquifer in the Aztec area lies in the sandstones of the Nacimiento Formation if these are well developed in the area. Test drilling would have to be conducted to determine the extent of these units and whether problems of quantity or quality existed here.

When increased water supply becomes necessary for the community of Turley, more wells or collectors could be constructed in the San Juan River alluvium. The same factor cited above concerning river water depletion will have to be considered, however. Diversion and treatment of San Juan River water is another alternative for this area. The nearby San Jose Formation is a second alternative. Withdrawing water from this source would likely prove more costly due to drilling and transportation expenses, but no direct depletion of San Juan River water would occur. Lastly, the sandstones of the upper Nacimiento Formation offer another possible source of water for this area if water quality and quantity are sufficient.

The community of Cedar Hill, on the Animas River, has essentially the same alternatives and factors to consider as does Turley, in evaluating a future water supply.

Industrial

Present Sources

The oil and gas companies in the study area use water primarily for drilling and developing their wells. In the 1950's much of this water was taken from wells in the Nacimiento and San Jose Formations. Now, however, only one such well, the Knickerbocker Butte Water Well No. 1 (Table V) is being used by El Paso Natural Gas Company. Most other water required is bought from ditch co-ops along the Animas and San Juan Rivers and trucked to the well sites. Good gravel roads make all corners of the quadrangle accessible to these tankers.

Potential Sources

Should river water become unavailable or too costly for the oil and gas companies, groundwater would have to be used again. Old water wells in the Nacimiento and San Jose Formations could be reopened and deepened where necessary, and new wells drilled. In the southern part of the area, where the Ojo Alamo Sandstone is only about 1,000 feet deep, this source could be tapped if very fresh water is not required.

Irrigation

Present Sources

Irrigated crop lands along the Animas and San Juan Rivers provide the biggest single use of water in the Aztec Quadrangle. Approximately 3500 acres of land are irrigated along the Animas River and several hundred acres along the small portion of the San Juan River in the area. All irrigation water is derived from these rivers; no groundwater is presently used. Based on the county average, the amount of surface water used for irrigation is approximately 9,000 acre-feet annually (N.M.I.S.C. and N.M.S.E.O., 1975).

Potential Sources

Surface waters are used for irrigation in San Juan County because they are readily available to the irrigable lands of the river valleys and are less costly to obtain than large supplies of groundwater. As previously stated, however, some irrigated lands will have to be retired in the foreseeable future to provide surface waters for the growing population and expanding industries if no other supplies are found.

One advantage of irrigation, however, is that waters need not be as fresh as waters used domestically or for industry in most cases. If leaching and drainage are adequate, water having 1,500 ppm total dissolved solids can be used on most plants and many moderately salt-tolerant crops can be irrigated with water of up to 2,000 ppm (National Academy of Science, 1974). For this reason, groundwater which might be considered unsuitable for domestic use may offer a solution to the coming shortage of irrigation water. An important factor to consider in using brackish irrigation waters, however, is that fresh surface waters or nearby groundwaters can be contaminated by their salts if care is not taken in their application and use.

In the Aztec Quadrangle, parts of the San Jose and Nacimiento Formations as well as the Ojo Alamo Sandstone probably hold water of sufficient quantity and quality to be used for irrigation. The San Jose Formation is likely to have the greatest potential. Smaller quantities are likely in the Nacimiento Formation and poorer quality waters in the Ojo Alamo Sandstone.

Rural

Present Sources

Several hundred farms and rural homes are located along the Animas and San Juan Rivers in the Aztec Quadrangle. Most of these homes have shallow water wells, usually less than 100 feet deep, dug or drilled into the alluvium of the river valleys. A few wells are drilled into bedrock of the Nacimiento Formation.

While no actual figures are available, it is estimated that up to 10 percent of these rural residents use river water, stored and treated in a cistern, for domestic use. In many cases, river water is used because local groundwater is of too poor a quality for domestic use.

As mentioned above, most wells used for stock water in the areas away from the major river valleys have been abandoned in favor of surface water supplies. This water is collected in surface reservoirs where arroyos have been dammed by earthen structures to trap runoff (fig. 10).

Potential Sources

In the northern part of the study area, near the Nacimiento-San Jose contact, the upper part of the Nacimiento Formation is very sandy and appears to have the properties of a good aquifer. In this area, the Nacimiento sandstones have some potential as sources of groundwater for rural homes and farms, however, water quality is quite variable (Table II).

In areas away from the river valleys, the San Jose Formation appears to have the best potential as a reservoir of groundwater. This is due to its overall coarse, sandy nature, broad extent, and apparently good water quality (Table II). Very few homes are located in this area, however.

Recreation

Present Sources

As mentioned above, the biggest tourist attraction within the quadrangle area is the Aztec Ruins National Monument. The monument is operated by the National Park Service and covers an area of 27 acres. It uses water for its public buildings, for several families of personnel who live on the grounds, and for irrigation of its grassed areas. River water is diverted for all these purposes.

Potential Sources

Because the Aztec Ruins National Monument is located partly on the Animas River Valley alluvium, one or two good wells in this aquifer would likely produce sufficient water of good quality to replace the surface water now used.

SUMMARY OF CONCLUSIONS

1) Groundwater must be further utilized in northwestern New Mexico in view of the impending shortage of surface waters.

2) The major water problem in both northwestern New Mexico in general and the Aztec Quadrangle in particular, is not one of quantity so much as it is one of quality. In the study area, most groundwaters of Quaternary and Tertiary aquifers are high in dissolved sulphate, sodium, calcium, and bicarbonate.

3) In the Aztec Quadrangle, the most important source of groundwater at present is the valley alluvium of the Animas and San Juan Rivers. These aquifers provide fair yields of generally good quality water to numerous wells, but better yields could be obtained by improved well construction and development practices. These sources could be used more extensively than at present, but depletion of river waters by artificially inducing recharge must be considered.

4) Ancient terrace gravels are fairly widespread along the Animas River, but these deposits are not believed to hold large supplies of groundwater. They would not be reliable producers of water because of their relative thinness and small lateral extent. No wells are known to take water from terrace deposits in the study area.

5) Sandstones of the San Jose Formation have the best potential as a source of bedrock groundwater in the study area. Numerous petroleum company wells have produced good supplies of groundwater from the San Jose in the past. A number of springs issue from this formation and some provide adequate supplies of fresh water for stock and domestic needs, although discharges are usually small.

6) The Nacimiento Formation is tapped by numerous industrial and domestic water wells in the study area, but both yields and quality are quite variable. Most wells produce water unsuitable for domestic use. The coarse sandstones of the upper part of the formation have the most potential as aquifers in this unit.

7) The Ojo Alamo Sandstone is apparently the only unit, of those which do not crop out in the Aztec Quadrangle, with any potential as a source of good quantities of relatively fresh groundwater for the area.

8) All formations below the Ojo Alamo Sandstone are believed to hold waters of too poor a quality for domestic, industrial, or agricultural use in the study area.

9) In the Aztec Quadrangle, aquifers are recharged by surface-water runoff, by irrigation return flow, by direct precipitation, and by leakage from adjacent units.

10) Groundwater flow is assumed to have a southeasterly component in the study area because the strata are largely confined and dip gently in that direction. Near the surface, some flow may occur in response to the topography. In some places, vertical movement may occur due to gravity or artesian pressure, through silty and sandy shales or through fracture systems in these units. Downward groundwater flow may also occur in the Central Basin due to the osmotic influences suggested by Berry (1959).

11) Discharge may occur around the edges of the basin where aquifers crop out at lower elevations than potentiometric surfaces basinward. In the Central Basin, however, most discharge is believed to be downward into older formations. Artificially-induced discharge through pumping wells generally accounts for a small part of the total and is only important in the valley-fill aquifers of the study area. Near the surface, some discharge takes place as seeps and springs in canyons, or directly into streams during low flow.

Table V. Records of water [illegible]

* = see Table II.

Aquifer: Qal=Quaternary alluvium; Tn=Nacimiento Formation; Tsj= San Jose Formation;)

OWNER OR WELL NAME	NUMBER	LOCATION	APPROXIMATE ELEVATION	TOTAL DEPTH ft	DEPTH TO WATER/DATE	TOTAL AQUIFER THICKNESS	PRINCIPAL AQUIFER	YEAR DRILLED	TYPE	USE	REPORTED YIELD gpm	PUMP	CHEMICAL ANALYSIS	REMARKS
Cox Canyon	Q1	NW-23-32N-11W	6400	—	53/9-75		Qal	—	drilled	S	—	windmill	—	plugged and abandoned
EPNG Barnes #2	S2	SW-23-32N-11W	6200	585	—	126?	Tsj	1953	drilled	I	—	—	—	
EPNG Barnes #1	N1	NE-24-32N-11W	6200	105	—	35	Tn	1953	drilled	I	—	—	—	
EPNG Horton #1	N2	SW-29-32N-11W	6400	588	—	55	Tn	1953	drilled	I	—	—	—	
EPNG Neal #6	N3	NE-33-32N-11W	6150	321	—	48	Tn	1953	drilled	I	—	—	—	
B. Heizer	Q2	NW-15-32N-10W	5945	35	—	35	Qal	—	dug	D,S	—	electric	*	use water softener
W. Head	Q3	NE-15-32N-10W	5920	30	15/9-74	30	Qal	—	dug	D	—	electric	—	24" steel casing
N.M. Port of Entry	N4	SW-16-32N-10W	5680	750	51/3-75	—	Tn	—	drilled	D	—	—	*	
F. Clark	Q4	SE-21-32N-10W	5920	104	24/9-74	—	Qal	1962	drilled	D,S	—	electric	*	3 sands: 45, 60, 97'
H. Knowlton	Q5	SE-28-32N-10W	5925	35	16/9-74	35?	Qal	1967	drilled	D,S	—	electric	—	S.C. = 1000 mmhos/cm
A. Flaherty	Q6	SE-32-32N-10W	5820	30	—	30?	Qal	—	dug	D	—	—	*	"not potable"
C. Lanier	Q7	NE-33-32N-10W	5870	55	45-55	55?	Qal	1950?	dug	D,S	—	—	*	"not potable"
G. Saller	Q8	SE-33-32N-10W	5920	64	36/9-74	64?	Qal	—	dug	D	—	electric	—	S.C. = 1025 mmhos/cm
M. Randalmon	N5	SW-24-31N-11W	5700	173	7/9-74	—	Tn?	—	drilled	—	—	—	—	"not potable"
M. Bishop	Q9	SE-24-31N-11W	5745	40	8/9-74	40?	Qal	—	dug	D,S	—	electric	*	use water softener
F. Randalmon	Q10	NW-26-31N-11W	5680	57	—	57?	Qal	—	drilled	—	—	—	*	S.C. = 777 mmhos/cm
A. Hill	Q11	SE-26-31N-11W	5720	39	23/8-75	39?	Qal	1961	drilled	D,S	—	electric	*	set in coarse gravel
L. Long	Q12	SE-26-31N-11W	5770	70	—	70?	Qal	—	drilled	I	—	electric	—	S.C. = 1120 mmhos/cm

Table V. (cont.) Records of water wells in the Aztec Quadrangle.

OWNER OR WELL NAME	NUMBER	LOCATION	APPROXIMATE ELEVATION	TOTAL DEPTH ft	DEPTH TO WATER/DATE	TOTAL AQUIFER THICKNESS	PRINCIPAL AQUIFER	YEAR DRILLED	TYPE	USE	REPORTED YIELD gpm	PUMP	CHEMICAL ANALYSIS	REMARKS
R. Pettijohn	N6	SW-34-31N-11W	5720	95	69/9-74	—	Tn	1960	drilled	D	—	electric	—	S.C. = 2250 mmhos/cm
G. Foster	Q13	SW-34-31N-11W	5670	60	7/8-75	60?	Qal	—	drilled	D	—	electric	*	"not potable"
L. Likes	Q14	SE-34-31N-11W	5680	47	20?	47?	Qal	1974	drilled	D	—	electric	*	
G. Saline	N7	SW-35-31N-11W	5720	—	8/9-74	—	Tn?	1952	drilled	D	—	electric	—	S.C. = 1575 mmhos/cm
A. Karlan	Q15	NE- 4-31N-10W	5760	—	14/9-74	—	Qal	—	dug	D	—	electric	—	S.C. = 780 mmhos/cm
unknown	Q16	NE- 5-31N-10W	5834	—	—	—	Qal	—	dug	D,S	—	electric	—	S.C. = 1100 mmhos/cm
Pan Am Petrol.	Q17	5-31N-10W	5810	27?	—	—	Qal	—	—	I?	—	—	*	
J. Hollar	Q18	SE- 6-31N-10W	5795	30	—	—	Qal	1950?	drilled	D	—	electric	*	strong odor, staining
C. Smith	Q19	NW- 8-31N-10W	5790	—	5/9-74	—	Qal	1952	dug	D	—	electric	—	S.C. = 760 mmhos/cm
EPNG Lucerne #1	N8	NE-10-31N-10W	6120	455	—	67	Tn	1955	drilled	I	25	—	—	
EPNG Kelly	N10	SW-14-31N-10W	6250	555	—	28	Tn	1954	drilled	I	—	—	—	plugged and abandoned
E. Flaherty	Q20	NW-18-31N-10W	5780	30	16/9-74	30?	Qal	1950	drilled	D,S	—	electric	*	taps a shallow spring
EPNG Schwertfeger #4	S11b	SW-10-31N- 9W	6520	462	—	100	Tsj	1952	drilled	I	—	—	—	plugged and abandoned
EPNG Riddle #1D	S12	SW-17-31N- 9W	6490	550	—	40	Tsj	1953	drilled	I	6	—	—	plugged and abandoned
EPNG Barret #1	S13	19-31N- 9W	6560	517	—	55	Tsj	1952	drilled	I	20	—	—	
EPNG Barret #2	S14	NE-20-31N- 9W	6260	202	—	30	Tsj		drilled	I	38	—	—	

Table V (cont.). Records of water wells in the Aztec Quadrangle.

OWNER OR WELL NAME	NUMBER	LOCATION	APPROXIMATE ELEVATION	TOTAL DEPTH ft	DEPTH TO WATER/DATE	TOTAL AQUIFER THICKNESS	PRINCIPAL AQUIFER	YEAR CONSTRUCTED	TYPE	USE	REPORTED YIELD gpm	PUMP	CHEMICAL ANALYSIS	REMARKS
EPNG Riddle #20	N11	SW-20-31N- 9W	6520	510	—	150?	Tn?	1953	drilled	I	50	—	—	
Little Pump	S15	NW-21-31N- 9W	6180	100+	51/2-76	—	Qal-Tsj		drilled	S	—	—	*	not presently used
EPNG Schwertfeger #1	S16	SW-27-31N- 9W	6080	120	—	25	Tsj		drilled	I	40	—	—	
EPNG Schwertfeger #2	S17	SE-27-31N- 9W	6080	118	—	34	Tsj	1952	drilled	I	20	—	—	
J. Boston	Q21	SE- 4-30N-11W	5640	50	35/9-74	35?	Qal	—	drilled	D,S	—	electric	—	S.C. = 890 mmhos/cm
C. Van Dusen	Q22	9-30N-11W	—	—	—	—	Qal?	—	—	—	—	—	*	S.C. = 4320 mmhos/cm
A. Moore	Q23	10-30N-11W	—	32	—	—	Qal	1958	augered	—	—	electric	—	
K. McCament	N13	NW-19-30N-11W	5575	143	24/9-74	—	Tn	1968	drilled	S	—	electric	—	S.C. = 1240 mmhos/cm
Brown Atlantic St.#1	N14	NW- 2-30N-10W	6360	520	—	55	Tn	1954	drilled	I	30	—	*	
B. Redding	N15	SE- 3-30N-10W	6400	320	—	—	Tn	1975	drilled	D	—	electric	—	50' to water
EPNG Turner #1	S20	13-30N-10W	6480	425	345	—	—		drilled	I	—	—	—	
Hartman	N16	SW-20-30N-1-W	6190	—	91	—	Tn?	—	drilled	S	—	windmill	—	
EPNG Riddle #1	N17	NE-23-30N-10W	6280	311	—	20	Tn	1952	drilled	I	20	—	—	
EPNG Knickerbocker #1	N18	SE-23-30N-10W	6219	886	—	—	Tn	1972	drilled	I	—	electric	*	
EPNG Florance #1	S22	NE-24-30N-10W	6280	293	—	—	Tsj	1953	drilled	I	20	—	—	

Table V (cont.). Records of water wells in the Aztec Quadrangle.

OWNER OR WELL NAME	NUMBER	LOCATION	APPROXIMATE ELEVATION	TOTAL DEPTH ft	DEPTH TO WATER/DATE	TOTAL AQUIFER THICKNESS	PRINCIPAL AQUIFER	YEAR DRILLED	TYPE	USE	REPORTED YIELD gpm	PUMP	CHEMICAL ANALYSIS	REMARKS
Slane Canyon	N19	NW-27-30N-10W	6180	—	53/9-75	—	Tn?	—	drilled	S	—	—	—	had a windmill
EPNG Quigley #1	N20	SW- 6-30N- 9W	6320	396	—	37	Tn?	1953	drilled	I	16	—	—	
EPNG Wood River #1	N21	NE- 8-30N- 9W	6200	258	—	123	Tn		drilled	I	25	—	—	
R. Valencia	N22	SW-35-30N- 9W	5620	30	+2/10-74	—	Tn	—	drilled	D,S	—	electric	—	S.C. = 4500 mmhos/cm
R. Chavez	Q24	NE- 3-29N- 9W	5612	16	6/10-74	—	Qal	1960	dug	D,S	—	electric	—	S.C. = 460 mmhos/cm
M. Jacquez	Q25	NW- 4-29N- 9W	5615	54	36/10-74	—	Qal	1958	drilled	D	—	electric	—	S.C. = 820 mmhos/cm
C. Gurule	Q26	NW- 4-29N- 9W	5610	45	—	45?	Qal	—	drilled	D	—	electric	*	
R. Gutierrez	Q27	SE- 4-29N- 9W	5575	20	9/10-74	—	Qal	1911	dug	D	—	none	—	S.C. = 595 mmhos/cm
C. Pacheco	N23	SW- 5-29N- 9W	5600	30	13/10-74	—	Tn?	1960	drilled	—	—	none	—	not presently used
F. Montoya	N24	SE- 6-29N- 9W	5630	48	22/10-74	—	Tn?	1962	drilled	D	—	electric	—	S.C. = 1750 mmhos/cm

APPENDIX A

MEASURED SECTIONS

MEASURED SECTION DESCRIPTIONS

General Statement

Eight stratigraphic sections were measured at major outcrops in the study area and at two locations (sections 1 and 8) outside the area. The following descriptions are presented in descending order. The unit numbers given in these descriptions are field numbers used to distinguish rock units and samples collected. Each unit, including covered intervals, was given a number. Where units were made up of several thin, similar strata, these were given sub-unit letters (a,b,c, etc.). Each unit is described as to general lithologic name (sandstone, siltstone, claystone, shale); bedding information; other sedimentary structures; color; grain size, sorting, and roundness; composition; fossil content; and character of lower contact.

Sections were measured in metric units using a 1.7 meter Jacob staff. The thicknesses reported are given to the nearest decimeter; numbers in parentheses are the corresponding values in feet given to the nearest half foot.

Plate 3 is a graphical representation of the measured sections and their position in the stratigraphic column using the Nacimiento-San Jose contact as datum.

Lithology. Sandstone refers to rock composed predominantly of sand-sized particles. Silty sandstone is one with a moderate amount of silt matrix. Siltstone refers to a rock in which silt-sized particles are the main constituent. Claystone is a rock composed mainly of clay-sized particles (Pettijohn, 1957, p.341) and is here restricted to non-fissile rocks. Modifiers such as silty may also by used to describe and name a claystone. Shale is here considered to be a fissile claystone or siltstone after the definition used by Pettijohn (1957, p.341). Silty is also used as a shale modifier.

Bedding. Descriptions of internal structure of beds follow the terminology of McKee and Weir (1953) who described laminae size as follows:

Very thick laminae	greater than 30 mm
Thick laminae	10 to 30 mm
Medium laminae	3 to 10 mm
Thin laminae	1 to 3 mm
Very thin laminae	less than 1 mm
Massive	no laminae distinguishable

The bedding uniformity definitions of Dunbar and Rodgers (1963) are used as follows:

Regular - beds do not vary in thickness laterally
Irregular - beds do vary in thickness laterally

Even - all beds in vertical succession similar in size
Uneven - vertically adjacent beds not similar in size

Bedding size definitions used are those of McKee and Weir (1953) as modified by Ingram (1954) as follows:

Very thick beds	greater than 100 cm
Thick beds	30 to 100 cm
Medium beds	10 to 30 cm
Thin beds	1 to 10 cm
Very thin beds	less than 1 cm

Cross-bedding descriptions are composed of the following properties as defined by the following workers:

Magnitude (Jacob, 1973):

Small scale	less than .05 m
Large scale	.05 to 5 m
Very large scale	greater than 5 m

Dip (Jacob, 1973):

Low angle	2 to 15°
High angle	greater than 15°

General shape (modified from McKee and Weir, 1953):

Planar

Tabular – sets bounded by parallel, planar surfaces

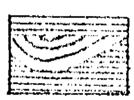
Wedge – sets bounded by converging, planar surfaces

Non-Planar

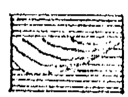
Trough – sets bounded by curved surfaces

Relation to lower bounding surface (Jacob, 1973):

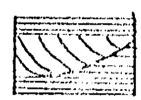
Concordant



Tangential



Discordant



Grouping (Allen, 1963):

Solitary – set bounded by other types of cross-strata or by strata that are not cross-stratified

Grouped – set is in contact with sets of same type

The types of bedding surface shapes used are modified from Campbell (1967) and are as follows:

Planar – continuous/discontinuous; parallel/non-parallel

Wavy – continuous/discontinuous; parallel/non-parallel

Curved – continuous/discontinuous; parallel/non-parallel

Color. The color names used in these descriptions and accompanied by number and letter codes are those given in the Rock-Color Chart prepared by Goddard and others (1951). The three codes in parentheses refer to hue, value, and chroma respectively, as given on this chart. Other color names are general and do not necessarily coincide with those of the chart.

Grain Character. Grain sizes given are those defined by Wentworth (1922); grain sizes were determined in the field with a millimeter scale or in the lab by visual comparison of grains with a Wentworth sand gage using binocular microscope. Sorting was estimated visually in the field using the terminology of Folk (1965, p. 103-105). Roundness was visually estimated following the whole-grain roundness chart of Powers (1953).

Lower Contact. Contacts were described by the terms gradational, abrupt and/or irregular. Gradational, as used here, implies the gradual change in character from the lithology of one unit to that of the next; this commonly is expressed as thin interbedding of sandstone and shale. Abrupt contacts are those at which lithologic character changes dramatically from one side of the contact to the other. If a contact is described as irregular, its position changes vertically, within perhaps 1 meter, along the contact. Irregularity may be the result of erosion between the deposition of one unit and the next.

SECTION 1, LA PLATA RIVER. West facing slope and bluff ¼ mile east of the La Plata River channel, and 2.5 miles north of the San Juan River; SW¼ sec. 28, T.30N., R.13W., San Juan County; section measured July 22, 1975 (fig. 17 and Plate 3).

Unit	Lithology	Thickness - meters (feet)
9	Covered slope: sand and gravel, well-rounded pebbles and cobbles of quartzite and various igneous rocks; trace of light gray (N7) shale in upper 2.0 m of slope.	7.5 (24.5)
OJO ALAMO SANDSTONE		
8	Sandstone: medium-laminated, irregular, uneven, thick to very thick beds with large scale, tangential, low to high angle, grouped, tabular and trough cross-bedding; bedding surfaces are planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) to dark grayish orange (10 YR 6/6) weathered, very pale orange (10 YR 8/2) to grayish orange fresh; grains coarse to granular, moderately to poorly sorted, sub-rounded, consisting mainly of quartz; scattered, well-rounded pebbles and cobbles consisting mainly of quartzite, chert, and various igneous rock types, and clay; trace of silt and clay matrix; cement mostly silica and iron oxide; lower contact irregular and abrupt.	48.2 (158.0)
KIRTLAND SHALE		
7	Silty claystone, sandstone, and claystone:	

d	Silty claystone: very thinly laminate, regular, uneven, thin beds with planar, continuous, parallel surfaces; pale greenish yellow (10 Y 8/2) to pale olive (10 Y 6/2) weathered and fresh; cement clay and silica; lower contact abrupt.	8.4	(27.5)
c	Sandstone: thinly laminated, irregular, uneven, medium beds with planar to curved, continuous, parallel surfaces; grayish orange (10 YR 7/4) weathered, very pale orange (10 YR 8/2) fresh; grains very fine, moderately sorted, consisting mainly of quartz, some mica; clay matrix; cement slightly calcareous, also clay and silica; lower contact abrupt.	0.7	(2.5)
b	Shale: fissile, regular, uneven, thin beds with planar, continuous, parallel surfaces; blackish red (5 R 2/2) weathered, grayish red (5 R 4/2) fresh; cement clay and silica; lower contact gradational.	0.8	(2.5)
a	Silty claystone: very thinly laminated, regular, uneven, thin beds with planar, continuous, parallel surfaces; grayish orange pink (5 YR 7/2) to dark yellowish orange (10 YR 6/6) weathered, pale greenish yellow (10 Y 8/2) fresh; cement silica and clay; lower contact abrupt.	4.2	(14.0)
6	Sandstone:		
b	Sandstone: thinly laminated, irregular, uneven, medium beds with planar, continuous, parallel surfaces; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) weathered and fresh; grains fine to medium, moderately sorted, sub-rounded, consisting mainly of quartz, trace feldspar and mica; 10 to 15 percent matrix of silt and clay;	4.0	(13.0)

cement clay, silica, and iron oxide; contains a few small iron concretions; lower contact gradational.

a Sandstone: thinly laminated, irregular, uneven, thin beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains fine, well-sorted, sub-rounded to sub-angular, consisting mainly of quartz, trace of feldspar; 10 to 15 percent matrix of silt and clay; silica, clay and iron oxide cement; lower contact abrupt. 1.7 (5.5)

5 Shale: fissile, regular, uneven, thin beds with planar, continuous, parallel surfaces; medium gray (N5) and grayish green (10 GY 5/2) weathered, brownish black (5 YR 2/1) and grayish green fresh; slight lustre mottling; clay and possibly silica cement; lower contact abrupt. 4.2 (14.0)

4 Sandstone, claystone and silty claystone, and silty sandstone, shale and silty shale:

d Sandstone: thinly laminated, irregular, uneven, thin beds with planar, continuous, parallel surfaces; very pale orange (10 YR 8/2) weathered and fresh; grains fine to medium, moderately to well-sorted, sub-rounded, consisting mainly of quartz; 5 to 10 percent silt and clay matrix; cement silica and clay; lower contact abrupt. 1.8 (6.0)

c Claystone and silty claystone: very thinly laminated, rarely fissile, regular, even, very thin to thin beds with planar, continuous, parallel surfaces; medium gray (N5), very pale orange (10 YR 8/2), 1.6 (5.0) and dusky yellow green (5 GY 5/2) weathered, brownish black (5 YR 2/1), very pale orange, and dusky yellow green fresh; consists mainly of clay and quartz grains; cement is clay and possibly silica; lower contact gradational.

b Silty sandstone: thinly laminated, regular, uneven, thin beds with planar, continuous, parallel surfaces; very pale orange (10 YR 8/2) weathered and fresh; grains very fine to silt, moderately to poorly sorted, sub-rounded, consisting mainly of quartz; approximately 10 percent silt and clay matrix; cement silica, iron oxide, and clay; few small iron concretions; lower contact gradational; 1.2 (4.0)

a Shale and silty shale: fissile, regular, uneven, very thin beds with planar, continuous, parallel surfaces; medium gray (N5) weathered, brownish black (5 YR 2/1) fresh; cement clay and possibly silica; lower contact gradational. 1.2 (4.0)

3 Sandstone: thinly laminated, irregular, uneven, thin beds with planar, continuous, parallel surfaces; very pale orange (10 YR 8/2) weathered and fresh; grains very fine to fine, moderately sorted, sub-rounded, consisting mainly of quartz, some feldspar and trace of mica; approximately 10 percent silt and clay matrix; contains a few small iron concretions; lower contact abrupt. 4.4 (14.5)

2 Siltstone and silty sandstone:

c Siltstone: very thinly laminated (?), regular, uneven, thin beds with planar, continuous, parallel surfaces; pale olive (10 Y 6/2) weathered, grayish olive (10 Y 4/2) fresh; mainly quartz silt with 1.0 (6.5) approximately 10 percent clay matrix and a trace of mica; silica and clay cement; lower contact abrupt.

b Silty sandstone: thinly laminated, regular, uneven, thin beds with planar, continuous, parallel surfaces; very pale orange (10 YR 8/2) weathered and fresh; grains very fine to silt, consisting mainly of quartz; some clay matrix; cement silica and clay; lower contact abrupt. 2.1 (6.5)

a Siltstone: very thinly laminated , regular, uneven, thin beds with planar, continuous, parallel surfaces; pale olive (10 Y 6/2) weathered, grayish olive (10 Y 4/2) fresh; consists mainly of quartz grains with clay matrix; cement clay and silica; lower contact gradational. 1.0 (3.5)

1 Covered slope: sand and gravel alluvium and colluvium; much probably weathered from Ojo Alamo Sandstone.

Total Thickness = 124.9 (409.5)

Measurement of section 1 was begun at the bed of the La Plata River, west of the bluffs capped by the Ojo Alamo Sandstone.

SECTION 2a, KIFFEN CANYON SOUTH. South-facing slopes and cliffs 1.2 miles north of the Animas River and approximately 800 feet east of the Kiffen Canyon road; SW¼ to NW¼ sec. 12, T.31N., R.11W.; section measured August 5, 1975 (Plates 1 and 3).

Unit	Lithology	Thickness - meters (feet)
NACIMIENTO FORMATION		
8	Sandstone: thinly to medium-laminated, irregular, uneven, thick to very thick beds with large scale, tangential, predominantly low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/2) weathered and fresh; grains coarse to very coarse, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; few scattered, well-rounded quartzite and chert pebbles; trace of silt and clay matrix; cement silica and iron oxide; few iron concretions; top eroded bare; lower contact abrupt.	21.7 (71.0)
7	Silty claystone and shale: very thinly laminated, some fissile, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; light brownish gray (5 YR 6/1) weathered, very dusky red (10 R 2/2) fresh; trace of mica; cement clay, possibly silica; few small iron concretions, lower contact abrupt.	10.2 (33.5)
6	Sandstone: thinly laminated to massive, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2)to grayish	7.2 (23.5)

orange (10 YR 7/2) weathered and fresh; grains medium to coarse, moderately sorted, sub-angular to sub-rounded, consisting mainly of quartz, some feldspar and mica; trace of silt and clay matrix; cement silica, iron oxide, and clay; few iron concretions; lower contact abrupt.

5 Sandstone: thinly to medium-laminated, irregular, uneven, thick beds with some large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very light gray (N8) to very pale orange (10 YR 8/2) weathered and fresh; grains coarse to very coarse, moderately sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar; trace of silt and clay matrix; cement silica, clay, and iron oxide; 1.8 m of grayish yellow green (5 GY 7/2) siltstone at bottom of unit; lower contact abrupt. 8.5 (28.0)

4 Sandstone: thinly to medium-laminated, irregular, uneven, thick to very thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) weathered and fresh; grains coarse to very coarse, well sorted, sub-rounded, consisting mainly of quartz and feldspar; few scattered, well-rounded chert and quartzite pebbles; approximately 5 percent silt matrix; cement silica, and iron oxide; lower contact abrupt. 6.6 (21.5)

3 Shale and silty claystone: very thinly laminated, predominantly fissile in lower part, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; pale olive (10 Y 6/2) weathered and fresh; 6.4 (21.0)

some quartz silt and micas apparent in upper half; cement clay and silica; abundant iron concretions, some petrified wood fragments; lower contact covered.

2	Sandstone: thinly laminated, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grains coarse to very coarse, well-sorted, sub-rounded, consisting mainly of quartz and feldspar; trace of silt and clay matrix; cement silica and iron oxide; few small iron concretions; lower contact abrupt.	2.8	(9.0)
1	Silty claystone and shale: very thinly laminated, predominantly fissile, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; pale olive (10 Y 6/2) weathered and fresh; cement clay and silica; abundant petrified wood fragments; lower contact covered.	5.3	(17.5)

Total Thickness = 68.7 (225.5)

Section 2a was measured from surface approximately 150 ft north of Aztec Oil and Gas Lawson No 1 gas well , SW$\frac{1}{4}$ sec 12, T.31N., R.11W.

SECTION 2B, KIFFEN CANYON NORTH. West- and south-facing slopes in north end of Kiffen Canyon, east fork, 3.0 miles south of Colorado-New Mexico border; SE$\frac{1}{4}$ sec. 28 to NW$\frac{1}{4}$ sec. 21, T.32N., R.11W.; section measured July 30 and August 14, 1976 (Plates 1 and 3)

Unit	Lithology	Thickness - meters	(feet)
17	Covered slope: sand and gravel; cobbles and boulders less than 30 cm, consisting of quartzite and various igneous rock types.	19.1	(62.5)
SAN JOSE FORMATION			
16	Sandstone: thinly to medium-laminated, regular, uneven, thick to very thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains coarse to granular, moderately sorted, sub-angular, consisting mainly of quartz and feldspar; some well-rounded pebbles consisting mainly of chert and quartzite; trace of silt matrix; cement silica and iron oxide, upper 1.0 m carbonate; lower contact covered.	6.1	(20.0)
15	Covered slope: sand and gravel; cobbles and boulders less than 30 cm, consisting mainly of quartzite and various igneous rock types.	6.8	(22.5)
14	Sandstone: thinly laminated, regular, uneven, medium to thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grains fine to medium, moderately sorted, angular, consisting	8.5	(28.0)

mainly of quartz, some feldspar and mica; trace of silt and clay matrix; cement silica and clay, possibly iron oxide; lower contact abrupt.

13 Covered slope and silty sandstone: sand and gravel; cobbles and boulders less than 30 cm, consisting mainly of quartzite and various igneous rock types; 3.5 m of silty sandstone 3.5 m from bottom of unit; very thinly to thinly laminated, regular, uneven, medium beds with planar, continuous, parallel surfaces; yellowish gray (5 Y 8/1) weathered, very light gray (N8) fresh; lower 1.2 m dusky yellow (5 Y 6/4) to yellowish gray (5 Y 7/2) weathered and fresh; grains very fine to fine, moderately to poorly sorted, sub-rounded, consisting mainly of quartz; approximately 10 percent silt and clay matrix; cement clay, silica, and iron oxide; lower contact covered. 14.6 (48.0)

12 Sandstone: thinly to medium-laminated, irregular, uneven, thick to very thick beds with large scale, tangential, low angle, grouped, tabular and trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) weathered and fresh; grains very coarse to granular, moderately to well-sorted, sub-rounded, consisting mainly of quartz and feldspar; trace of silt and clay matrix; cement silica and clay; few iron concretions; lower contact abrupt. 12.8 (42.0)

11 Shale and silty shale; very thinly laminated, predominantly fissile, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; grayish red (5 R 4/2), greenish gray (5 GY 6/1), and grayish yellow green (5 GY 7/2) weathered and fresh; cement clay and silica; lower contact abrupt. 12.7 (41.5)

10 Sandstone: thinly to medium-laminated, irregular, uneven thick to very thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) weathered and fresh; grains very coarse to granular, moderately to well-sorted, sub-rounded, consisting mainly of quartz and feldspar; trace of silt and clay matrix; cement silica, iron oxide, and clay; few small iron concretions; lower contact abrupt. 10.0 (33.0)

9 Shale and silty shale: very thinly laminated, predominantly fissile, regular, uneven, medium to thin beds with planar, continuous, parallel surfaces; greenish gray (5 GY 6/1) weathered, dark greenish gray (5 GY 4/1) fresh, grayish red (5 R 4/2) and grayish yellow green (5 GY 7/2) weathered and fresh; cement silica, clay, some carbonate; lower contact irregular, abrupt. 17.0 (56.0)

8 Sandstone: thinly to medium-laminated, irregular, even, thick to very thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) weathered and fresh; grains very coarse to granular, well-sorted, sub-rounded, consisting mainly of quartz and feldspar; trace of silt matrix; cement silica and iron oxide; few iron concretions; lower contact gradational. 10.2 (33.5)

7 Sandstone and shale: sandstone same as unit 8 above, but includes 3.8 m shale, 2.7 m from bottom of unit: fissile, regular, even, thin beds with planar, continuous, parallel surfaces; grayish yellow green (5 GY 7/2) weathered and fresh cement clay; lowet contact abrupt. 9.6 (31.5)

6	Shale: fissile, regular, uneven, thin beds with planar, continuous, parallel surfaces; greenish gray (5 GY 6/1) weathered, dark greenish gray (5 GY 4/1) fresh, and grayish yellow green (5 GY 7/2) weathered and fresh; some silt grains, trace of mica; cement clay and silica; lower contact abrupt.	3.4	(11.0)
5	Sandstone: thinly to medium-laminated, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) weathered and fresh; grains coarse to very coarse, moderately sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar; trace of silt and clay matrix; cement silica, iron oxide, and clay; lower contact abrupt.	7.5	(24.5)
4	Silty shale: very thinly laminated, predominantly fissile, regular, uneven, thin beds with planar, continuous, parallel surfaces; greenish gray (5 GY 6/1) weathered, dark greenish gray (5 GY 4/1) fresh, and grayish yellow green (5 GY 7/2) weathered and fresh; cement clay and silica; lower contact abrupt.	5.1	(16.5)
3	Sandstone: thinly to medium-laminated, regular to irregular, uneven, thick to very thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) weathered and fresh; grains coarse to granular, moderately sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar; trace of silt and clay matrix; cement silica and iron oxide; few small iron concretions; thin 0.9 m claystone 3.0 m from bottom of unit, grayish	24.3	(79.5)

yellow green (5 GY 7/2) weathered and fresh; lower contact slightly irregular and abrupt.

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2	Siltstone, claystone, silty claystone, and shale:		
d	Siltstone: thinly laminated, regular, uneven, thin beds with planar, continuous, parallel surfaces; grayish yellow green (5 GY 7/2) weathered and fresh; 5 to 10 percent clay matrix; cement clay and silica; lower contact gradational.	2.0	(6.5)
c	Shale, claystone, and silty claystone: very thinly laminated, some fissile, regular, uneven, thin beds with planar, continuous, parallel surfaces; grayish red (5 R 4/2), light olive gray (5 Y 6/1), greenish gray (5 GY 6/1), and grayish yellow green (5 GY 7/2) weathered and fresh; cement clay and silica; lower contact gradational.	26.9	(88.0)
b	Shale: fissile, regular, uneven, thin beds with planar, continuous, parallel surfaces; dark gray (N3) weathered, grayish black (N2) fresh; trace of organic matter; cement clay, some carbonate; lower contact abrupt.	1.0	(3.5)
a	Shale, claystone, and silty claystone: very thinly laminated, some fissile, regular, uneven, thin beds with planar, continuous, parallel surfaces; grayish red (5 R 4/2), light olive gray (5 Y 6/1), and grayish yellow green (5 GY 7/2) weathered and fresh; cement clay and silica; lower contact abrupt.	12.0	(39.5)
1	Sandstone and silty claystone: thinly laminated, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) weathered and fresh; grains coarse to very coarse, moderately sorted, sub-rounded, consisting	5.7	(18.5)

mainly of quartz and feldspar; trace of silt matrix; cement silica and iron oxide; few iron concretions; a 0.9 m grayish yellow green (5 GY 7/2) weathered and fresh, silty claystone exists 2.8 m from bottom of unit, separated from sandstones by abrupt contacts; lower contact covered.

Total Thickness = 207.8 (681.5)

Units above 2b measured from bottom of wash in SE$\frac{1}{4}$ sec. 28, T.32N., R.11W. Unit 2b and below measured from bottom of same wash in NE$\frac{1}{4}$ sec. 28, T.32N., R.11W.

SECTION 3, COX CANYON. Southeast-facing slopes and cliffs 3/4 mile south of Colorado-New Mexico border on the west side of Cox Canyon; NE$\frac{1}{4}$ sec. 18 to SW$\frac{1}{4}$ sec. 7, T.32N., R.10W., San Juan County; section measured August 6, 1975 (Plates 1 and 3).

Unit	Lithology	Thickness - meters (feet)
SAN JOSE FORMATION		
14	Sandstone: thinly laminated, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh, upper 2.0 m grayish brown (5 YR 3/2) weathered and fresh; grains medium to coarse, moderately sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar; approximately 5 percent silt and clay matrix; cement carbonate, clay, silica and iron oxide; lower contact abrupt.	4.9 (16.0)
13	Covered slope, shale, and sandstone:	
b	Covered slope: sand and sandstone boulders from units above; some medium gray (N5) fissile shale partially exposed.	6.2 (20.5)
a	Sandstone: thinly laminated, irregular, uneven, thick beds with some large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains coarse, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; trace of silt and clay matrix; cement silica and iron oxide; lower contact abrupt.	2.3 (7.5)

12 Covered slope: mostly sand, some boulders from sandstone units above; some light brownish gray (5 YR 6/1) claystone and grayish yellow green (5 GY 7/2) siltstone partially exposed. 13.2 (43.5)

11 Sandstone: thinly laminated, irregular, uneven, thick beds with large scale, tangential, low angle, grouped cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) weathered and fresh; grains medium to coarse, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; approximately 5 percent silt and clay matrix; cement silica, iron oxide, and clay; lower contact abrupt. 10.4 (34.0)

10 Siltstone and shale: very thinly laminated, some fissile, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; shales light brownish gray (5 YR 6/1) weathered and fresh, siltstones grayish yellow green (5 GY 7/2) weathered and fresh; cement clay and silica; lower contact slightly irregular, abrupt. 15.0 (49.0)

9 Sandstone: thin to medium-laminated, irregular, uneven, thick to very thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) weathered and fresh; grains very coarse to granular, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; some well-rounded pebbles of chert, quartzite, and various igneous rock types; trace of silt matrix; cement silica and iron oxide; few iron concretions; lower contact abrupt. 9.8 (32.0)

8	Covered slope: sand and some boulders from sandstone units above.	11.2	(36.5)
7	Sandstone: thin to medium laminated, irregular, uneven, thick to very thick beds with large scale, tangential, low to high angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) weathered and fresh; grains very coarse to granular, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; some well-rounded pebbles consisting mainly of chert, quartzite, and various igneous rock types; trace of silt matrix; cement silica and iron oxide; few iron concretions locally; lower contact irregular and abrupt.	24.1	(79.0)
6	Sandstone, siltstone, and shale: predominantly thinly laminated, irregular, uneven, thick sandstone beds with large scale, tangential, high angle, solitary, tabular cross-bedding; bedding surfaces predominantly planar, continuous, parallel; very pale orange (10 YR 8/2) weathered and fresh; grains medium to very coarse, poorly to moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; approximately 5 percent silt and clay matrix; cement silica, iron oxide, and clay; 2.0 m of pale olive (10 Y 6/2) siltstone and medium gray (N5) shale exist 6.0 m above the bottom of this unit; lower contact abrupt.	17.3	(56.5)
5	Sandstone: medium-laminated, irregular, uneven, thick to very thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) weathered and fresh; grains coarse to very coarse, moderately sorted, sub-rounded, consisting	13.1	(43.0)

mainly of quartz and feldspar; trace of silt matrix; cement silica and iron oxide; a few iron concretions; lower contact very irregular and abrupt.

4	Silty shale: very thinly laminated, predominantly fissile, regular, uneven, thin beds with planar, continuous, parallel surfaces; grayish yellow green (5 GY 7/2) weathered and fresh; cement clay, possibly silica; lower contact abrupt.	7.1	(23.5)
3	Sandstone: thinly to medium-laminated, irregular, uneven, thick to very thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) to very pale orange (10 YR 8/2) weathered and fresh; grains coarse to granular, moderately sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar; locally abundant and scattered, well-rounded pebbles of chert and quartzite; approximately 5 percent silt and clay matrix; cement silica and iron oxide; lower contact covered.	22.1	(72.5)

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2	Covered slope: sand and sandstone boulders from units above; approximately 2.0 m grayish yellow green (5 GY 7/2) silty shale partially exposed in middle of unit.	5.1	(16.5)
1	Sandstone:		
b	Sandstone: thinly to medium-laminated, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains coarse to very coarse, moderately sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar;	1.6	(5.0)

5 to 10 percent silt and clay matrix; cement silica, iron oxide, trace clay; lower contact gradational.

a	Sandstone: thinly laminated, irregular, uneven, medium beds with planar, continuous, parallel surfaces; very pale orange (10 YR 8/2) weathered and fresh; grains coarse, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; approximately 10 percent silt and clay matrix; cement silica, iron oxide, and clay; lower contact covered.	1.8	(6.0)

Total Thickness = 158.3 (519.0)

Measurement of section 3 was begun from the base of a 10 ft sandstone ledge 300 ft west of Cox Canyon road in NE$\frac{1}{4}$ sec. 18, T.32N., R.10 W.

SECTION 4, MOUNT NEBO. Southwest-facing slopes and cliffs, 0.5 to 1.5 miles northeast of Cedar Hill; NW$\frac{1}{4}$ sec. 34 to SE$\frac{1}{4}$ sec. 27, T.32N., R.10W.; section measured August 15, 1975 (Plates 1 and 3).

Unit	Lithology	Thickness - meters (feet)
28	Covered slope: sand and gravel; well-rounded pebbles, cobbles, and boulders less than 50 cm, consisting mainly of quartzite and various igneous rocks.	11.7 (38.5)
SAN JOSE FORMATION		
27	Sandstone: medium-laminated, irregular, uneven, thick to very thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains coarse to very coarse, moderately sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar; trace of silt matrix; cement is silica and iron oxide; lower contact abrupt.	10.2 (33.5)
26	Covered slope: mainly sand and gravel; a little gray shale is exposed near top of unit.	5.1 (16.5)
25	Sandstone: medium-laminated, irregular, uneven, thick beds with large scale, tangential, low to high angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange(10 YR 7/4) weathered and fresh; grains coarse, moderately sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar; trace of clay matrix; cement silica and iron oxide; lower contact abrupt.	3.9 (13.0)

24	Covered slope: sand and gravel, probably from unit 28.	5.1	(16.5)
23	Sandstone: medium-laminated, irregular, uneven, thick beds with large scale, tangential, low to high angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) to very pale orange (10 YR 8/2) weathered and fresh; grains predominantly coarse (upper 6.0 m medium), moderately sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar; upper 6.0 m has approximately 5 percent clay matrix; cement is silica, iron oxide, and clay; lower contact irregular and abrupt.	12.5	(41.0)
22	Claystone: thinly to very thinly laminated, regular, uneven, thin beds with planar, continuous, parallel surfaces; grayish yellow green (5 GY 7/2) weathered and fresh; clay, possibly silica cement; lower contact abrupt.	2.9	(9.5)
21	Sandstone: medium-laminated to massive, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains very coarse (upper 3.5 m medium), moderately sorted, sub-angular, consisting mainly of quartz and feldspar; cement silica and iron oxide; lower contact abrupt.	12.5	(41.0)
20	Silty claystone: thinly laminated, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; light gray (N7) weathered, medium light gray (N6) fresh; cement clay and silica; lower contact abrupt.	2.2	(7.0)

19 Sandstone: thinly to medium-laminated, locally massive, irregular, uneven, thick beds with some pred9minantly large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains very coarse, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; trace of silt and clay matrix; cement silica and iron oxide; lower contact abrupt. 2.2 (7.0)

18 Shale: very thinly laminated, predominantly fissile, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; light gray (N7) weathered, medium light gray (N6) fresh; lower 1.5 m silty, grayish yellow green (5 GY 7/2) weathered and fresh; cement clay and possibly silica; lower contact abrupt. 7.6 (25.0)

17 Sandstone: thinly laminated, irregular, uneven, thick beds with some large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains very coarse, moderately to poorly sorted, sub-rounded, consisting mainly of quartz and feldspar; trace of silt and clay matrix; cement silica and iron oxide; lower contact abrupt. 3.4 (11.0)

16 Shale: very thinly laminated, predominantly fissile, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; light gray (N7) weathered, medium light gray (N6) fresh; cement clay and possibly silica; 1.0 m thinly laminated, silty claystone 4.0 m from top of unit, pale red 15.5 (51.0)

(10 R 6/2) weathered, grayish red (10 R 4/2) fresh; cement is clay, possibly silica; lower contact abrupt.

15 Sandstone: thin to medium laminated, irregular, 6.8 (22.5) uneven, thick to very thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) to very pale orange (10 YR 8/2) weathered and fresh; grains coarse to very coarse, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; trace of silt and clay matrix; cement silica and iron oxide; lower contact abrupt.

14 Shale: fissile, regular, uneven, thin beds with 5.1 (16.5) planar, continuous, parallel surfaces; light gray (N7) weathered, medium light gray (N6) fresh; slightly silty; cement clay and possibly silica; lower contact abrupt.

13 Sandstone: thinly laminated to massive, irregular, 6.1 (20.0) uneven, medium to thick beds with planar, continuous, parallel surfaces; yellowish gray (5 Y 8/1) weathered and fresh; grains medium to fine, moderately to well-sorted, sub-rounded, consisting mainly of quartz, some feldspar; scattered, well-rounded quartzite pebbles in bottom 1.0 m; 5 to 10 percent silt and clay matrix; cement silica and clay; lower contact abrupt.

12 Shale: very thinly laminated, predominantly fissile, 15.4 (50.5) regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; pale olive (10 Y 6/2) weathered, medium gray (N5) fresh; cement clay and silica; 1.0 m silty shale 4.0 m from bottom of unit, pale red (10 R 6/2) weathered, grayish red (10 R 4/2) fresh; lower contact abrupt.

11	Sandstone, silty claystone, and siltstone:		
c	Sandstone: medium-laminated, irregular, uneven, thick beds with some large scale, tangential, predominantly low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered, very pale orange (10 YR 8/2) fresh; grains very coarse, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; trace of silt matrix; cement silica and iron oxide; lower contact abrupt.	10.9	(36.0)
b	Silty claystone: thinly to very thinly laminated, regular, uneven, thin beds with planar, continuous, parallel surfaces; pale olive (10 Y 6/2) weathered, grayish olive (10 Y 4/2) fresh; cement clay and silica; lower contact gradational.	3.0	(10.0)
a	Sandstone: thinly to medium-laminated, irregular, uneven, thick to very thick beds with abundant large scale, tangential, low to high angle, grouped, trough cross-bedding;bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) to very pale orange (10 YR 8/2) weathered and fresh; grains very coarse to granular, moderately to well-sorted, sub-rounded to rounded, and consist mainly of quartz and feldspar; scattered, well-rounded pebbles consisting mainly of chert and quartzite; trace of silt and clay matrix; 1.6 m very thinly laminated quartz siltstone 7.0 m from top of unit, pale olive (10 Y 6/2) weathered and fresh; cement silica and iron oxide; lower contact abrupt.	26.9	(88.0)

10 Silty claystone: thinly to very thinly laminated, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; upper 1.5 m and lower 1.6 m pale olive (10 Y 6/2) weathered and fresh, middle 2.8 m pale red (10 R 6/2) weathered, grayish red (10 R 4/2) fresh; cement clay and possibly silica; lower contact abrupt. 5.9 (19.5)

9 Sandstone: thinly laminated, irregular, uneven, thick to very thick beds with large scale, tangential, predominantly low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) to very pale orange (10 YR 8/2) weathered and fresh; grains medium to coarse, moderately to well-sorted, sub-angular, consisting mainly of quartz and feldspar; few well-rounded pebbles consisting mainly of chert and quartzite; trace of silt and clay matrix; cement silica and iron oxide; few iron concretions and petrified wood fragments less than 10 cm; lower contact abrupt. 18.3 (60.0)

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8 Sandstone and siltstone: thinly to very thinly laminated, regular, uneven, medium to thin beds with planar, continuous, parallel surfaces; light gray (N7) weathered and fresh, lower 2.0 m grayish yellow green (5 GY 7/2) siltstone weathered and fresh; grains medium to silt, moderately sorted, sub-rounded, consisting mainly of quartz, some feldspar; some silt and clay matrix; cement silica, some clay; lower contact abrupt. 6.8 (22.5)

7 Sandstone: thinly to medium-laminated, irregular, uneven, thick beds with large scale, tangential,

low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains coarse to very coarse, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; trace clay matrix; cement silica and iron oxide; few iron concretions; lower contact abrupt.

6 Shale: very thinly laminated, predominantly fissile, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; medium light gray (N6) weathered, medium gray (N5) fresh; 1.0 m silty shale near middle of unit pale red (10 R 6/2) weathered, grayish red (10 R 4/2) fresh; 2.0 m silty shale near top of unit grayish yellow green (5 GY 7/2) weathered and fresh; cement clay; lower contact abrupt. 15.3 (50.0)

5 Sandstone: thinly to medium-laminated, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) to very pale orange (10 YR 8/2) weathered and fresh; grains coarse to very coarse, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; trace of clay matrix; cement silica and iron oxide; few iron concretions; lower contact abrupt. 4.3 (14.0)

4 Shale: very thinly laminated, fissile, regular, uneven, thin beds with planar, continuous, parallel surfaces; light gray (N7) weathered, medium light gray (N6) fresh; clay cement; lower contact abrupt. 4.3 (14.0)

3 Sandstone: thinly to medium-laminated, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces

planar, to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains coarse to very coarse, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; scattered, well-rounded pebbles consisting mainly of chert and quartzite; trace of clay matrix; cement silica, iron oxide, and clay; lower contact abrupt.

2 Silty sandstone, silty shale, covered slope:

b Silty sandstone: very thinly laminated to massive, regular, uneven, medium beds with planar, continuous, parallel surfaces; pale olive (10 Y 6/2) weathered, grayish olive (10 Y 4/2) fresh; grains fine to very fine, moderately sorted, sub-rounded, consisting mainly of quartz, some feldspar and mica; 5 to 10 percent silt and clay matrix; cement silica and clay; lower contact abrupt. 5.0 (16.5)

a Covered slope, silty shale: most of unit covered by sand and boulders from units above; 2.0 m exposed near middle of unit, very thinly laminated, fissile, regular, uneven, medium beds with planar, continuous, parallel surfaces; pale red (10 R 6/2) weathered, grayish red (10 R 4/2) fresh; some silt grains; cement clay and possibly silica; lower contact covered. 11.8 (38.5)

1 Sandstone: thinly laminated, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) to very pale orange (10 YR 8/2) weathered and fresh; grains coarse to very coarse, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; little clay matrix; 28.9 (95.0)

cement silica and clay; very few small iron concretions; lower contact covered.

Total thickness = 284.3 (932.5)

Section 4 measured from surface of Animas River in NW$\frac{1}{4}$ sec. 34, T.31N., R.10 W.

SECTION 5, FLUTE CAVE. Southwest-facing slopes and cliffs 2.0 miles east of Cedar Hill, at east end of second arroyo south of Ditch Canyon; NE$\frac{1}{4}$ sec. 2, T.31N., R.10W., San Juan County; section measured September 19, 1975 (Plates 1 and 3).

Unit	Lithology	Thickness - meters (feet)
SAN JOSE FORMATION		
16	Sandstone: medium-laminated to massive, irregular, uneven, thick to very thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains coarse to very coarse, poorly to moderately sorted, sub-angular to sub-rounded, consisting mainly of quartz and feldspar; less than 5 percent silt matrix; cement silica and iron oxide; lower contact abrupt.	10.8 (35.5)
15	Silty shale: very thinly laminated, fissile in places, regular, uneven, medium beds with planar, continuous, parallel surfaces; light gray (N7) weathered, medium light gray (N6) fresh; cement clay and possibly silica; lower contact abrupt.	12.3 (40.5)
14	Sandstone: medium-laminated, irregular, uneven, medium to thick beds with some large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains very coarse, moderately sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar; less than 5 percent silt and clay matrix, some gypsum; cement carbonate, silica, and iron oxide; lower contact abrupt.	1.0 (3.5)

13	Claystone and silty shale; very thinly to medium-laminated, some fissile, regular, uneven, medium beds with planar, continuous, parallel surfaces; light gray (N7) weathered, medium light gray (N6) fresh; cement clay and possibly silica; lower contact abrupt.	9.5	(31.0)
12	Sandstone: thinly to medium- laminated, irregular, uneven, medium to thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains very coarse, moderately to well-sorted, sub-rounded, consisting mainly of quartz and feldspar; trace of silt matrix; cement silica and iron oxide; lower contact abrupt.	1.5	(5.0)
11	Shale: very thinly laminated, predominantly fissile, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; medium light gray (N6) weathered, medium gray (N5) fresh; cement clay and possibly silica; lower contact abrupt.	7.0	(23.0)
10	Sandstone: thinly laminated to massive, regular, uneven, medium to thick beds with some large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) to very pale orange (10 YR 8/2) weathered and fresh; grains medium to coarse, well-sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar; trace of silt matrix; cement carbonate, silica, and iron oxide; lower contact abrupt.	2.3	(7.5)

9	Shale and sandstone: very thinly laminated, predominantly fissile, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; light gray (N7) weathered, medium light gray (N6) fresh; cement clay and possibly silica; 2.0 m fine-grained, poorly sorted, non-resistant, very pale orange (10 YR 8/2) weathered and fresh quartz sandstone, 2.7 m from bottom of unit;	17.7	(58.0)
8	Sandstone: medium-laminated, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains coarse to very coarse, well-sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar; trace of silt matrix; little gypsum; cement silica, gypsum, iron oxide; lower contact abrupt.	4.6	(15.0)
7	Shale: very thinly laminated, predominantly fissile, irregular, uneven, thin to medium beds with planar, continuous, parallel surfaces; light gray (N7) weathered, medium light gray (N6) fresh; cement clay; lower contact abrupt.	6.8	(22.3)
6	Sandstone: medium-laminated, irregular, uneven, thick to very thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) to very pale orange (10 YR 8/2) weathered and fresh; grains coarse to very coarse, very-well-sorted, sub-rounded, consisting mainly of quartz and feldspar; some scattered, well-rounded chert and quartzite pebbles; trace of silt matrix; cement silica and iron oxide; lower contact abrupt.	10.3	(34.0)

5 Claystone: very thinly to thinly laminated, irregular, uneven, thin to medium beds with planar, continuous, parallel surfaces; light gray (N7) weathered, medium light gray (N6) fresh; cement clay; lower contact abrupt. 3.5 (11.5)

4 Sandstone: thin to medium-laminated, locally massive, irregular, uneven, thick to very thick beds with abundant, large scale, tangential, predominantly low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains very coarse to granular, moderately to well-sorted, sub-rounded to rounded, consisting mainly ov quartz and feldspar; few well-rounded, chert, quartzite, and clay pebbles near base; approximately 5 percent silt matrix; cement silica and iron oxide; a few petrified wood fragments less than 10 cm; 1.5 m grayish yellow green (5 GY 7/2) silty shale 5.0 m from top of unit; lower contact irregular, gradational. 14.7 (48.0)

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3 Silty claystone: very thinly to thinly laminated, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; yellowish gray (5 Y 7/2) and pale olive (10 Y 6/2) weathered and fresh; more silt content near top of unit; cement clay and silica; small iron concretions near top of unit, lower contact abrupt. 10.2 (33.5)

2 Shale and silty shale: very thinly laminated, predominantly fissile, regular, uneven, thin to medium beds with planar, continuous, parallel 25.5 (83.5)

surfaces; yellowish gray (5 Y 7/2) and pale red purple (5 RP 6/2) weathered and fresh; lustre-mottled, small mica content; cement clay, possibly silica; few iron concretions; lower contact abrupt.

1 Sandstone: thinly laminated, regular, uneven, medium to thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very light gray (N8) weathered and fresh; grains predominantly fine, few lenses in upper part are coarse to very coarse, all moderately sorted, grains sub-rounded to sub-angular, consisting mainly of quartz, some feldspar; few well-rounded quartzite pebbles in upper lenses; 5 to 10 percent clay and silt matrix; cement silica, secondary (?) gypsum, iron oxide, and clay; flute cast on roof of small cave gives paleocurrent direction S. 5°E; lower contact abrupt. 13.5 (44.5)

Total Thickness = 151.2 (496.0)

Section 5 was measured from the bottom of the wash in NE¼ sec. 2, T.31N., R.10W.

SECTION 6, HART CANYON. South-facing slopes and cliffs 5.0 miles east of the Animas River on north side of Hart Canyon road; NW$\frac{1}{4}$ sec. 27 to SE$\frac{1}{4}$ sec. 22, T.31N., R.10W.; section measured August 28, 1975 (Plates 1 and 3, Appendix B).

Unit	Lithology	Thickness - meters	(feet)
SAN JOSE FORMATION			
7	Sandstone: medium-laminated to massive, irregular, uneven, thick to very thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) to very pale orange (10 YR 8/2) weathered and fresh; grains coarse to granular, moderately to well-sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar; well-rounded quartzite pebbles at base; trace of silt matrix; cement silica and iron oxide; large fragments of petrified wood and mold of 20 ft log near base; upper surface eroded bare or covered with less than 10 cm sand; lower contact irregular and abrupt.	22.1	(72.5)
NACIMIENTO FORMATION			
6	Shale: very thinly laminated, predominantly fissile, regular, uneven, medium beds with planar, continuous, parallel surfaces; pale olive (10 Y 6/2) weathered and fresh; trace of mica grains; cement clay; lower contact covered.	4.8	(15.5)
5	Sandstone: thinly to medium-laminated, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains	5.1	(16.5)

coarse to very coarse, moderately to well-sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar; approximately 5 percent silt and clay matrix; cement silica, carbonate, iron oxide; few iron concretions; lower contact abrupt.

4	Silty claystone: very thinly laminated, irregular, uneven, thin to medium beds with planar, continuous, parallel surfaces; pale olive (10 Y 6/2) weathered and fresh; cement clay, possibly silica; lower contact slightly irregular and abrupt.	1.8	(6.0)
3	Sandstone: thinly to medium-laminated, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains coarse to very coarse, moderately to well-sorted, sub-rounded to rounded, consisting mainly of quartz and feldspar; trace of silt matrix; cement silica and iron oxide; few small iron concretions; lower contact slightly irregular and abrupt.	6.1	(20.0)
2	Shale: very thinly laminated, predominantly fissile, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; pale olive (10 Y 6/2) weathered and fresh; cement clay; lower contact covered.	4.0	(13.0)
1	Covered slope: sand colluvium and alluvium.	6.4	(21.0)

Total Thickness = 50.3 (165.0)

Section 6 was measured from the level of Hart Canyon road in NW¼ sec. 27, T.31N., R.10W.

SECTION 7, SOUTH SLANE CANYON. West-facing cliffs exposed on the knob 1.0 mile north of intersection between Blanco road and Slane Canyon road; NW$\frac{1}{4}$ sec. 34 to SW$\frac{1}{4}$ sec. 27, T.30N., R.10W.; section measured August 22, 1975 (Plates 1 and 3).

Unit	Lithology	Thickness - meters (feet)
8	Covered interval: sand and gravel; cobbles and boulders less than 40 cm diameter, consisting mainly of quartzite and various igneous rocks.	7.1 (23.5)
SAN JOSE FORMATION		
7	Sandstone: thinly to medium-laminated, irregular, uneven, thick to very thick beds with abundant, large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; dark yellowish orange (10 YR 6/6) weathered, very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) fresh; grains coarse to very coarse, moderately sorted, sub-angular to sub-rounded, consisting mainly of quartz and feldspar; some scattered, well-rounded chert and quartzite pebbles; trace of silt and clay matrix; cement silica and iron oxide, some clay; few iron concretions; few scattered petrified wood fragments; lower contact irregular, gradational, with discontinuous shale partings.	39.6 (130.0)
NACIMIENTO FORMATION		
6	Sandstone: thinly laminated, irregular, uneven, thick beds with some large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4)	8.5 (28.0)

weathered and fresh; grains medium to coarse, moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; few scattered chert, quartzite, and clay pebbles; 5 to 10 percent silt and clay matrix, more in upper part; cement silica, clay, iron oxide; few fragments of petrified wood; lower contact irregular, abrupt.

5 Silty shale: very thinly bedded, some fissile, irregular, uneven, thin to medium beds with planar, continuous, parallel surfaces; pale olive (10 Y 6/2) weathered and fresh; cement clay, possibly silica; lower contact abrupt. 4.5 (15.0)

4 Shale: fissile, regular, uneven, thin beds with planar, continuous, parallel surfaces; pale red (5 R 6/2) weathered and fresh; cement clay; lower contact abrupt. 1.1 (3.5)

3 Silty claystone and shale: very thinly laminated, some fissile, regular, uneven, thin to medium beds with planar, continuous, parallel surfaces; pale olive (10 Y 6/2) and greenish gray (5 GY 6/1) weathered and fresh; cement clay and silica; lower contact abrupt. 4.7 (15.5)

2 Sandstone: thinly laminated, regular, even, medium beds with planar, continuous, parallel surfaces; grayish yellow (10 YR 7/4) weathered and fresh; grains medium to coarse, poorly to moderately sorted, sub-rounded, consisting mainly of quartz and feldspar; 5 to 10 percent silt and clay matrix; cement silica, carbonate, iron oxide, clay; lower contact abrupt. 4.8 (15.5)

1	Silty claystone: very thinly laminated, regular, even, thin to medium beds with planar, continuous, parallel surfaces; pale olive (10 Y 6/2) weathered and fresh; cement clay, possibly silica; lower contact covered with sand colluvium.	5.8	(19.0)

Total Thickness = 76.1 (249.5)

Section 7 was measured from the level of the first exposure of unit 1 approximately 250 feet east of the road in NE$\frac{1}{4}$ sec. 34, T.30N., R.10W.

SECTION 8, ARCHULETA. Southwest-facing slopes and cliffs on northwest side of San Juan River, $\frac{1}{4}$ mile south of Archuleta; SW$\frac{1}{4}$ sec. 19, T.30N., R.8W. to SE$\frac{1}{4}$ sec. 24, T.30N., R.9W.; section measured July 22, 1975 (Plates 1 and 3, fig. 14).

Unit	Lithology	Thickness = meters (feet)
SAN JOSE FORMATION		
6	Sandstone: thinly to medium-laminated, regular, uneven, thick to very thick beds with abundant large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) weathered and fresh; grains coarse to very coarse, moderately to well-sorted, sub-angular to sub-rounded, consisting mainly of quartz and feldspar; few scattered, well-rounded chert and quartzite pebbles; trace of silt and clay matrix; cement silica, iron oxide, clay; few iron concretions; few shale breaks observed laterally, but only thin benches where measured; top mostly bare, some thin sand and mainly quartzite gravel locally.	116.2 (381.0)
NACIMIENTO FORMATION		
5	Silty claystone and shale: very thinly to thinly laminated, some fissile, irregular, uneven, thin to medium beds with planar, continuous, parallel surfaces; grayish yellow green (5 GY 7/2), greenish gray (5 GY 6/1), light olive gray (5 Y 6/1), and grayish red (5 R 4/2) weathered and fresh; cement clay and silica; lower contact covered.	18.7 (61.5)
4	Covered slope: sand and boulder colluvium, probably from unit 6 above.	1.7 (5.5)

3 Sandstone: thinly laminated, irregular, uneven, thick beds with abundant large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; grayish orange (10 YR 7/4) weathered and fresh; grains coarse, moderately sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar, trace of mica; trace of silt and clay matrix; cement silica and iron oxide; lower contact covered. 2.3 (7.5)

2 Covered slope: sand and gravel; colluvium and alluvium, cobbles and boulders less than 30 cm consisting mainly of quartzite and various igneous rocks. 9.9 (32.5)

1 Sandstone: thinly laminated, irregular, uneven, thick beds with large scale, tangential, low angle, grouped, trough cross-bedding; bedding surfaces planar to curved, continuous, parallel to non-parallel; very pale orange (10 YR 8/2) weathered and fresh; grains medium to coarse, moderately sorted, sub-rounded to sub-angular, consisting mainly of quartz and feldspar, trace of mica; 5 to 10 percent silt and clay matrix; cement carbonate, silica, clay; few small iron concretions; lower contact covered. 10.4 (34.0)

Total Thickness = 159.2 (522.0)

Section 8 was measured from the San Juan River level in SW$\frac{1}{4}$ sec. 19, T.30N., R.8W.

APPENDIX B

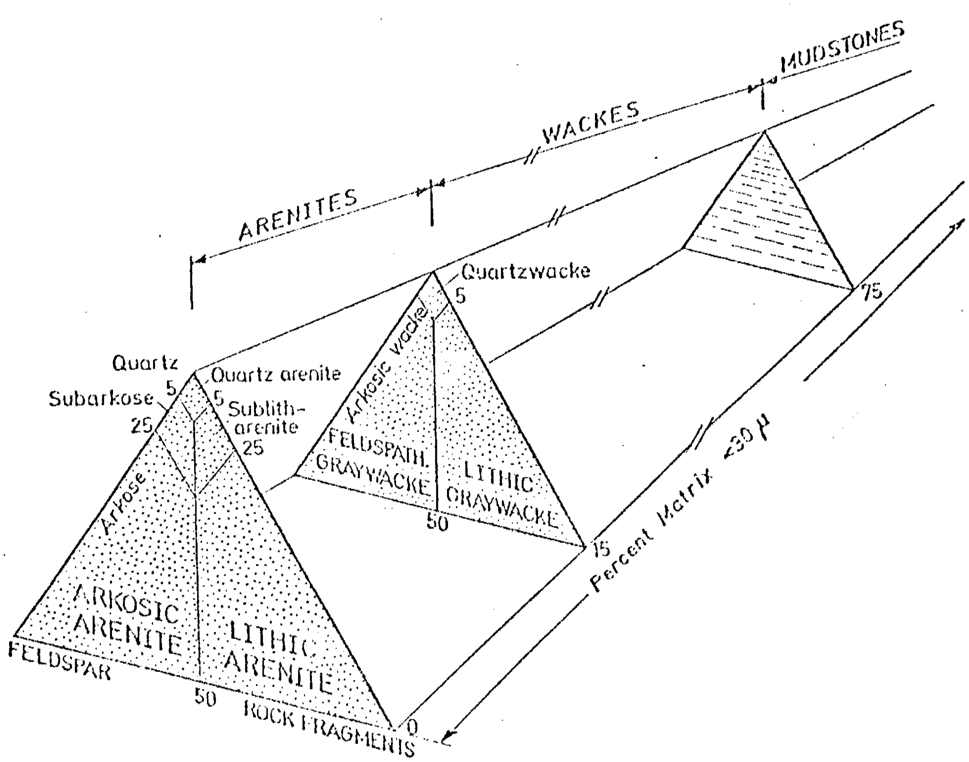
SEDIMENTARY PETROGRAPHY

THIN-SECTION DESCRIPTIONS

General Statement

Nine thin sections were made of various units of the Nacimiento and San Jose Formations in the study area. Thin sections were examined with a petrographic microscope to study mineralogical composition and texture of the grains, matrix, and cement of these rocks, as well as the amount and character of the porosity present. One hundred points were counted to determine the relative abundance of grains, matrix and cement, and porosity. Three hundred points were counted separately to determine the relative abundance of the different minerals making up the granular material.

Thin-section descriptions are given in the form of data sheets on following pages. Sample number, unit, location, and date are listed. Rock classification is that of Dott (1964), modified by Pettijohn, Potter, and Siever (1973, p. 158), and is reproduced below:



Granular material of the sandstones was considered to be that of the sand size defined by Wentworth (1922), that is, .0625 to 2.0 mm. Mineralogy was separated into monocrystalline quartz, polycrystalline quartz, potassium feldspar, plagioclase, and chert and rock fragments. Average grain size was visually estimated using the size of the field of view. Roundness and sphericity were estimated using the roundness-sphericity chart of Krumbein and Sloss (1955) which is reproduced below:

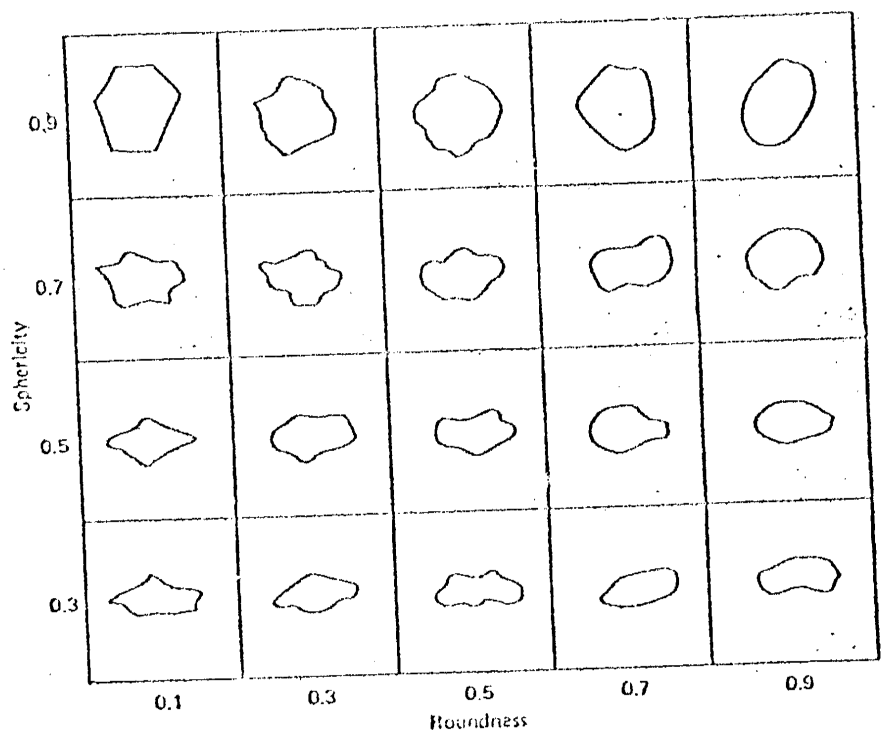


Chart for visual estimation of roundness and sphericity. (From Krumbein and Sloss, 1955)

Sorting terminology (moderately sorted, etc.) follows the definitions of Folk (1968, p. 105) and was visually estimated. Terms describing textural maturity are also from Folk (1968, p. 103) who used clay content, sorting, and roundness as determining factors. Grain to grain contacts were described as being either "line" or "concavo-convex" in character.

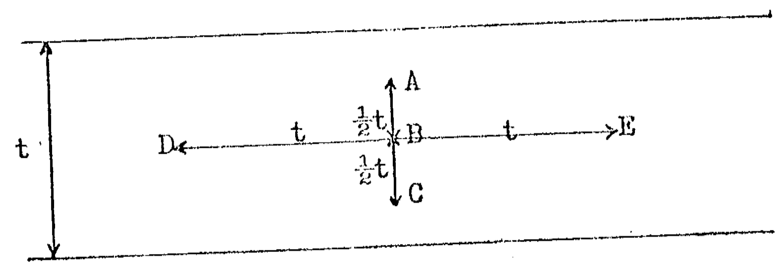
Matrix and cement were combined in point counts because chemical cements comprise less than 2 percent of most of these rocks and clay cement cannot be separated from the matrix. Matrix mineralogy was determined where possible and "texture" refers to general grain size of these materials.

Porosity was determined by point counting and these voids were described as being "interconnected" or "isolated" from each other. All porosity seen was primary, intergranular porosity, that is, voids that have remained between the grains since the rock was deposited.

One factor that must be considered in analyzing the results of these thin-section descriptions is that these rocks were sampled at the surface where they have been subjected to weathering for many years. Extensive alteration of feldspars has occurred which, in places, has caused the complete breakdown of these minerals. Matrix values may, therefore, be misleading as some of this material may be weathered feldspar grains. In the subsurface, therefore, it is possible that these arkoses have less matrix and more porosity than at the surface. The confining pressure of overlying rock must also be considered, however.

Arch Rock

Thin sections were studied of five samples collected from the sandstone above Arch Rock Spring. This sandstone is quite typical of most in the San Jose Formation in the study area. Samples were collected according to the diagram below:



t = unit thickness = 40 ft
A, B, C, D, E, = sampling positions

The results of the first 100 points counted on the Arch Rock thin sections is as follows:

CONSTITUENT	AR-A	AR-B	AR-C	AR-D	AR-E	AVERAGE
Grains	68%	67%	65%	70%	64%	67%
Matrix and cement	14%	15%	10%	11%	8%	12%
Porosity	18%	18%	25%	19%	19%	21%

Page 140 is a data sheet which describes thin section AR-B; all the Arch Rock samples are similar in composition and texture, so AR-B was chosen for the detailed 300 point count analysis.

<u>Hart Canyon</u>

Thin sections were studied from 4 units measured in section 6 at Hart Canyon. These 4 units, 3 sandstones and 1 silty claystone, span the Nacimiento-San Jose contact. Several minor textural changes were noted

THIN-SECTION DESCRIPTION

Sample No. AR-B Unit: San Jose Location: Arch Rock Spring Date: 5/76

Classification: Arkosic Arenite

Framework (% Grains): 71%

Mineralogy (%)	Average Grain Size (mm)	Roundness	Sphericity
1. Mono-quartz (53)	1.0	0.3	0.5
2. Poly-quartz (4)	1.4	0.5	0.7
3. K-feldspar (31)	1.0	0.4	0.6
4. Plagioclase (6)	1.0	0.5	0.5
5. Chert, Rock Frag. (9)	0.9	0.7	0.7

Sorting: poor to moderate Textural Maturity: sub-mature

Grain Contacts: lines, some concavo-convex

Matrix and Cement (% Intergranular material): 10%

Mineralogy: quartz and clay minerals

Texture: predominantly silt, some clay

Porosity (% voids): 19%

Type: interconnected

Other: cobaltinitrite staining shows approximately 25% K-feldspar

going from Nacimiento to San Jose sandstones. These were a slight reduction of matrix content and increase in porosity. No major mineralogical or textural variation has apparently taken place, however.

The following table summarizes the basic data from point counts of the Hart Canyon thin sections (section 6-4 is a siltstone):

CONSTITUENT	Tn 6-3	Tn 6-4	Tn 6-5	Tsj 6-7
Grains	70%	38.5%	76%	78%
Matrix and cement	18%	60%	9%	6%
Porosity	12%	1.5%	15%	16%

The following 4 pages are data sheets describing these thin sections in detail.

THIN-SECTION DESCRIPTION

Sample No. 6-3 Unit: Nacimiento Location: Hart Canyon Date: 5/76

Classification: Arkosic Arenite

Framework (% Grains): 70%

Mineralogy (%)	Average Grain Size (mm)	Roundness	Sphericity
1. Mono-quartz (39)	1.0	0.3	0.5
2. Poly-quartz (7)	1.5	0.5	0.7
3. K-feldspar (29)	1.0	0.4	0.6
4. Plagioclase (10)	1.0	0.5	0.5
5. Chert, Rock Frag. (15)	1.2	0.6	0.7

Sorting: moderate

Textural Maturity:

Grain Contacts: lines, some concavo-convex

Matrix and Cement (% Intergranular material): 18%

Mineralogy: quartz and clay minerals

Texture: predominantly silt, some clay

Porosity (% voids): 12%

Type: interconnected

Other: cobaltinitrite staining shows approximately 25% K-feldspar

THIN-SECTION DESCRIPTION

Sample No. 6-4 Unit: Nacimiento Location: Hart Canyon Date: 5/76

Classification: Arkosic Wacke

Framework (% Grains): 38.5%

Mineralogy (%)	Average Grain Size (mm)	Roundness	Sphericity
1. Mono-quartz (91)		0.4	0.5
2. Feldspar (6)		0.5	0.5
3. Rock Frag. (3)		0.5	0.5
4.			
5.			

Sorting: moderate

Textural Maturity: immature

Grain Contacts:

Matrix and Cement (% Intergranular material): 60%

Mineralogy: clay minerals

Texture:

Porosity (% voids): 1.5%

Type: isolated (may not be primary)

Other:

THIN-SECTION DESCRIPTION

Sample No. 6-5 Unit: Nacimiento Location: Hart Canyon Date: 5/76

Classification : Arkosic Arenite

Framework (% Grains): 76%

Mineralogy (%)	Average Grain Size (mm)	Roundness	Sphericity
1. Mono-quartz (48)	.75	0.4	0.6
2. Poly-quartz (7)	.90	0.5	0.6
3. K-feldspar (26)	.60	0.4	0.7
4. Plagioclase (6)	.75	0.5	0.7
5. Chert, Rock Frag. (13)	.75	0.7	0.8

Sorting: moderate to well Textural Maturity: sub-mature

Grain Contacts: lines, some concavo-convex

Matrix and Cement (% Intergranular material): 9%

Mineralogy: quartz and clay minerals

Texture: predominantly silt, some clay

Porosity (% voids): 15%

Type: interconnected

Other: cobaltinitrite staining shows 25 to 30% K-feldspar

THIN-SECTION DESCRIPTION

Sample No. 6-7   Unit: San Jose   Location: Hart Canyon   Date: 5/76

Classification: Arkosic Arenite

Framework (% Grains): 78%

Mineralogy (%)	Average Grain Size (mm)	Roundness	Sphericity
1. Mono-quartz (46)	1.0	0.3	0.6
2. Poly-quartz (15)	1.5	0.5	0.7
3. K-feldspar (30)	0.8	0.5	0.7
4. Plagioclase (2)	1.0	0.5	0.7
5. Chert, Rock Frag. (7)	.75	0.7	0.7

Sorting: moderate to well   Textural Maturity: sub-mature

Grain Contacts: lines, some concavo-convex

Matrix and Cement (% Intergranular material): 6%

Mineralogy: quartz and clay minerals

Texture: predominantly silt, some clay

Porosity (% voids): 16%

Type: interconnected

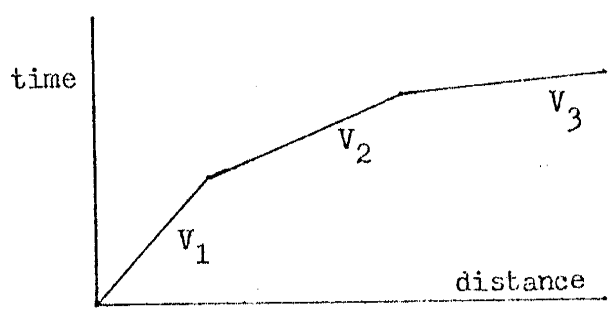
Other: cobaltinitrite staining shows approximately 30% K-feldspar

APPENDIX C

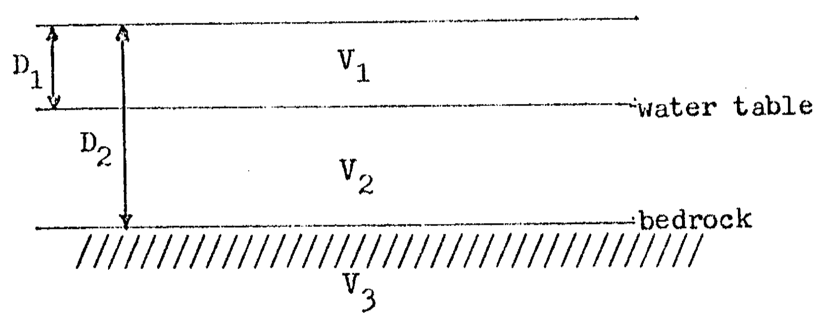
SEISMIC SOUNDINGS

SEISMIC SOUNDINGS

Seismic soundings were conducted to determine the alluvium thickness in the Animas River Valley. A Bison Signal Enhancement Seismograph was used and the refraction technique was employed (Dobrin, 1960). A 12 pound hammer was used as the energy source and it was struck on an alluminum plate placed at various distances along a line from the geophone. Travel time was read in milliseconds. The results of two soundings are illustrated as time-distance plots on the following pages. A generalized interpretation is shown below:

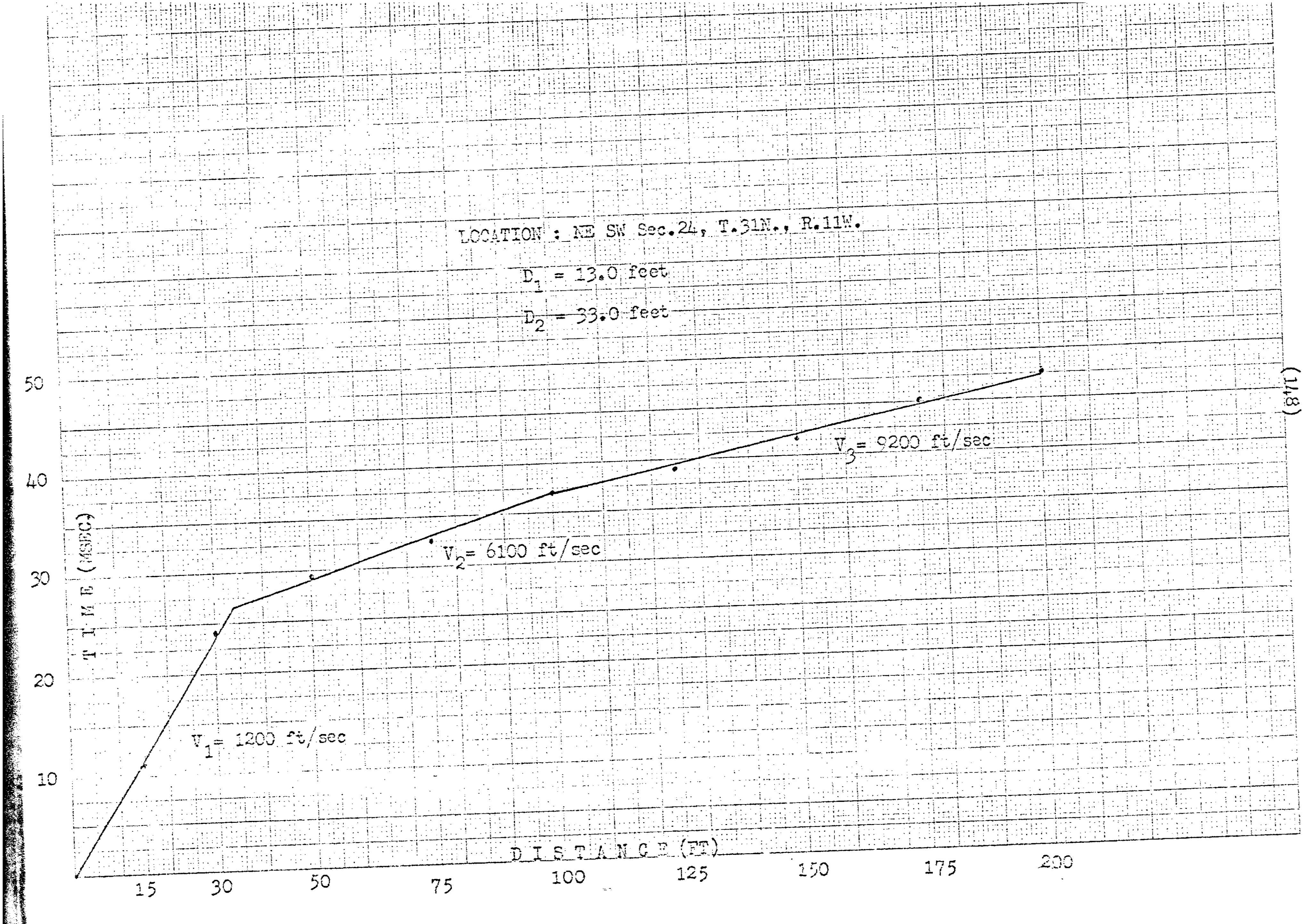


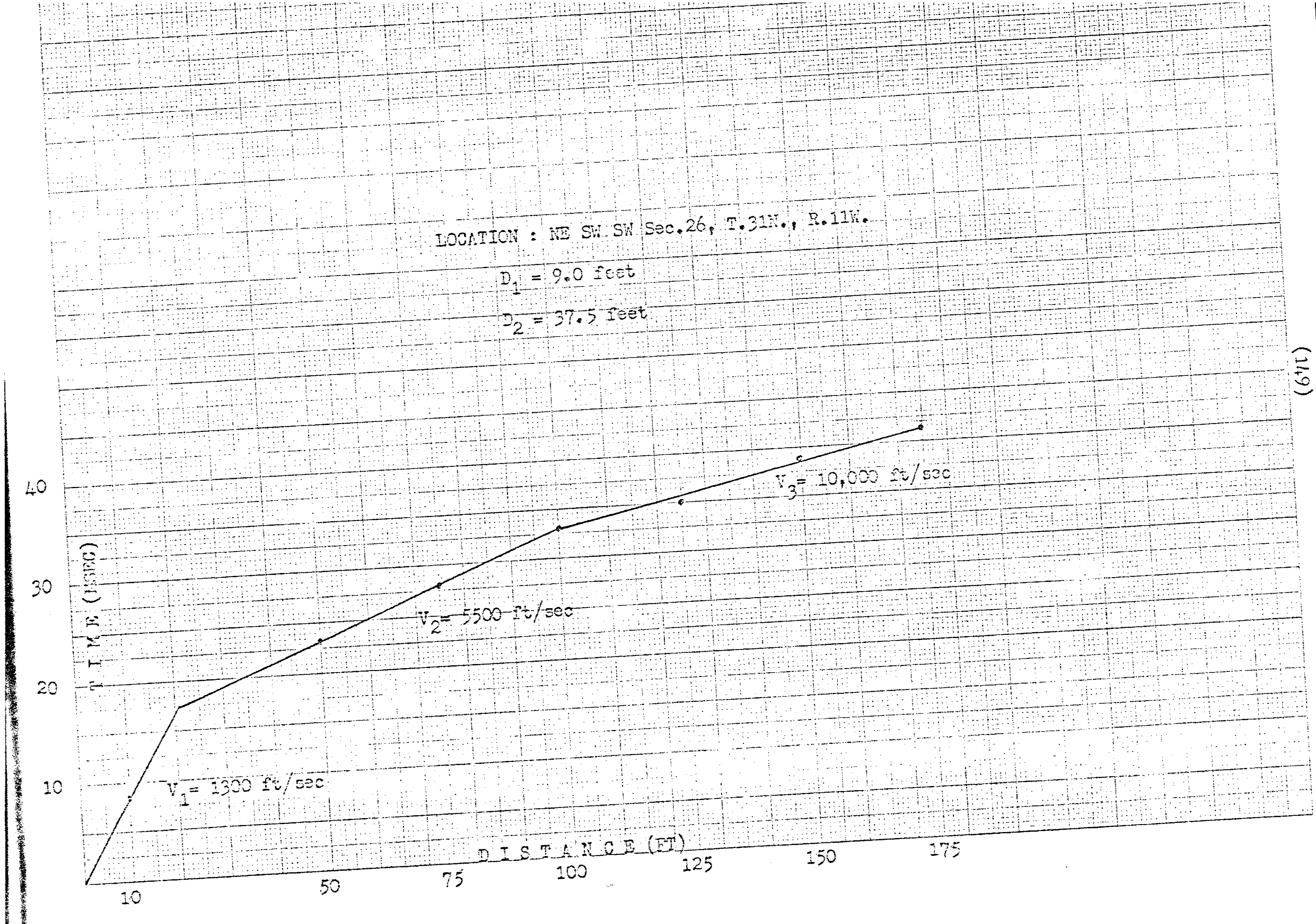
DATA PLOT



CROSS-SECTION

where: V = velocity
D = depth


LOCATION : NE SW Sec.24, T.31N., R.11W.
D_1 = 13.0 feet
D_2 = 33.0 feet
V_1 = 1200 ft/sec
V_2 = 6100 ft/sec
V_3 = 9200 ft/sec
T I M E (MSEC)
10
20
30
40
50
D I S T A N C E (FT)
15
30
50
75
100
125
150
175
200


LOCATION : NE SW SW Sec.26, T.31N., R.11W.
D1 = 9.0 feet
D2 = 37.5 feet
V1 = 1300 ft/sec
V2 = 5500 ft/sec
V3 = 10,000 ft/sec
TIME (MSEC)
10
20
30
40
DISTANCE (FT)
10
50
75
100
125
150
175

APPENDIX D

PARTICLE-SIZE ANALYSIS

PARTICLE-SIZE ANALYSIS

Method

Particle size analyses were conducted on four sandstone samples to accurately determine grain-size distribution. Two Nacimiento and two San Jose sandstones were analyzed.

Samples weighing approximately 50 grams were broken down and oven-dried. Wet sieving with a 4.0 phi screen was conducted to remove mud and silt from the sample. A 1.0 liter suspension of this material was mixed and 20 milliliters removed with a pipette. This sample was dried and the residue weighed. This weight times 50, plus that of any silt and clay obtained by sieving, gave the total mud weight. After mud was removed, each sample was sieved using 1.0 phi screen intervals. Each size fraction was then weighed.

Results of the four particle-size analyses are recorded on the following pages. For each analysis, a data sheet and cumulative curve are presented. On the data sheet, mode, median, mean, and sorting (Folk, 1968) are recorded for each sample, where possible. Classification is that of Folk (1968, p. 28) where S is sand, and mS is muddy sand.

COMPOSITE DATA SHEET FOR PARTICLE-SIZE ANALYSIS

e No. 2b-1 Analyzed By D.R.B. Date 5/76

iption of Sample Nacimiento sandstone from unit 1, meas. sect 2b

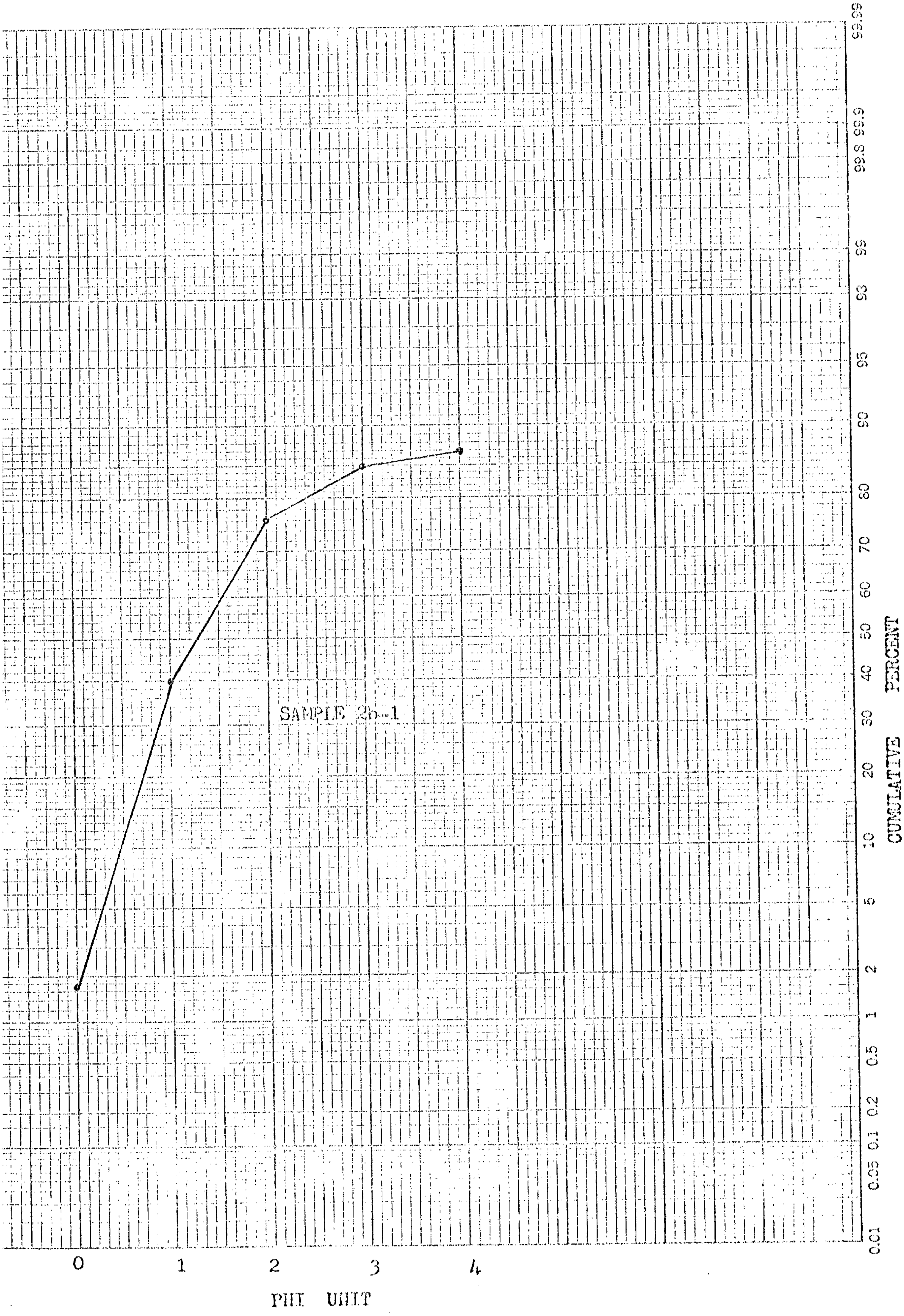
ks

ification (Folk) mS Initial Sample Weight 57.8144 g

1.0 Md 1.27 Mz 1.6 Si --

ss (mm)	Wentworth Class	Weight (g)	Percent	Cumulative Percent
0.0	very coarse	1.0180	1.76	1.76
1.0	coarse	22.3186	38.60	40.36
2.0	medium	20.7446	35.89	76.25
3.0	fine	5.0398	8.72	84.97
4.0	very fine	1.1725	2.03	87.00
mud	silt and clay	7.5131	13.00	100.00
	TOTAL	57.8066		

Totals


SAMPLE 2b-1
CUMULATIVE PERCENT
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
0
1
2
3
4
PHI UNIT

COMPOSITE DATA SHEET FOR PARTICLE-SIZE ANALYSIS

.e No. 8-1 Analyzed By D.R.B. Date 5/76

:iption of Sample Nacimiento sandstone from unit 1, meas. sect. 8

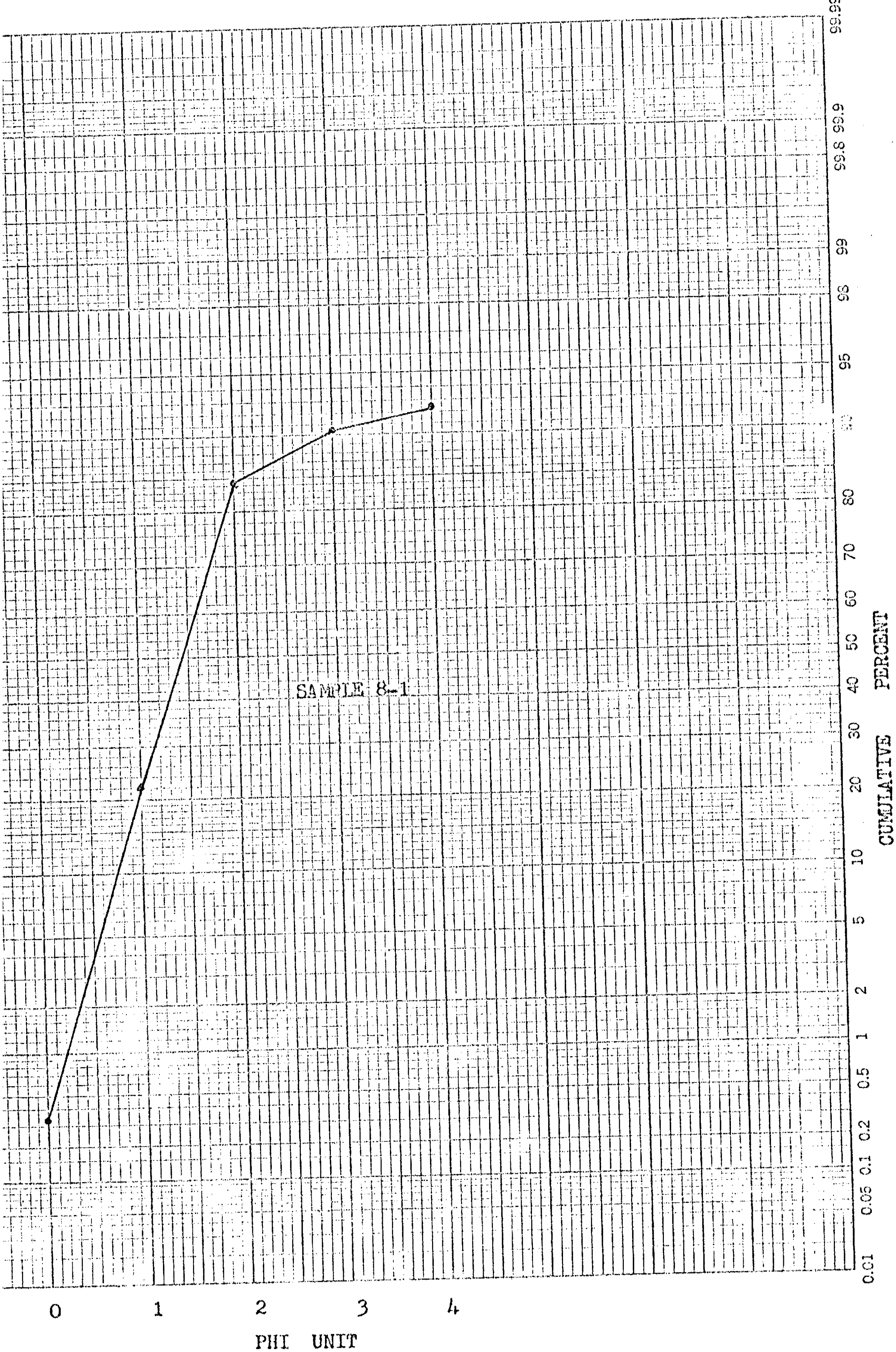
:ks

sification (Folk) S Initial Sample Weight 56.3075 g

2.0 Md 1.43 Mz 1.43 Si —

ass (mm)	Wentworth Class	Weight (g)	Percent	Cumulative Percent
0.0	very coarse	0.1372	0.24	0.24
1.0	coarse	12.5148	22.22	22.46
2.0	medium	34.9582	62.06	84.52
3.0	fine	3.4125	6.04	90.56
4.0	very fine	1.2137	2.15	92.71
mud	silt and clay	4.1032	7.28	99.99
	TOTAL	56.3396		

Totals


99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
CUMULATIVE PERCENT
SAMPLE 8-1
0
1
2
3
4
PHI UNIT

COMPOSITE DATA SHEET FOR PARTICLE-SIZE ANALYSIS

No. AR-B Analyzed By D.R.B. Date 5/76

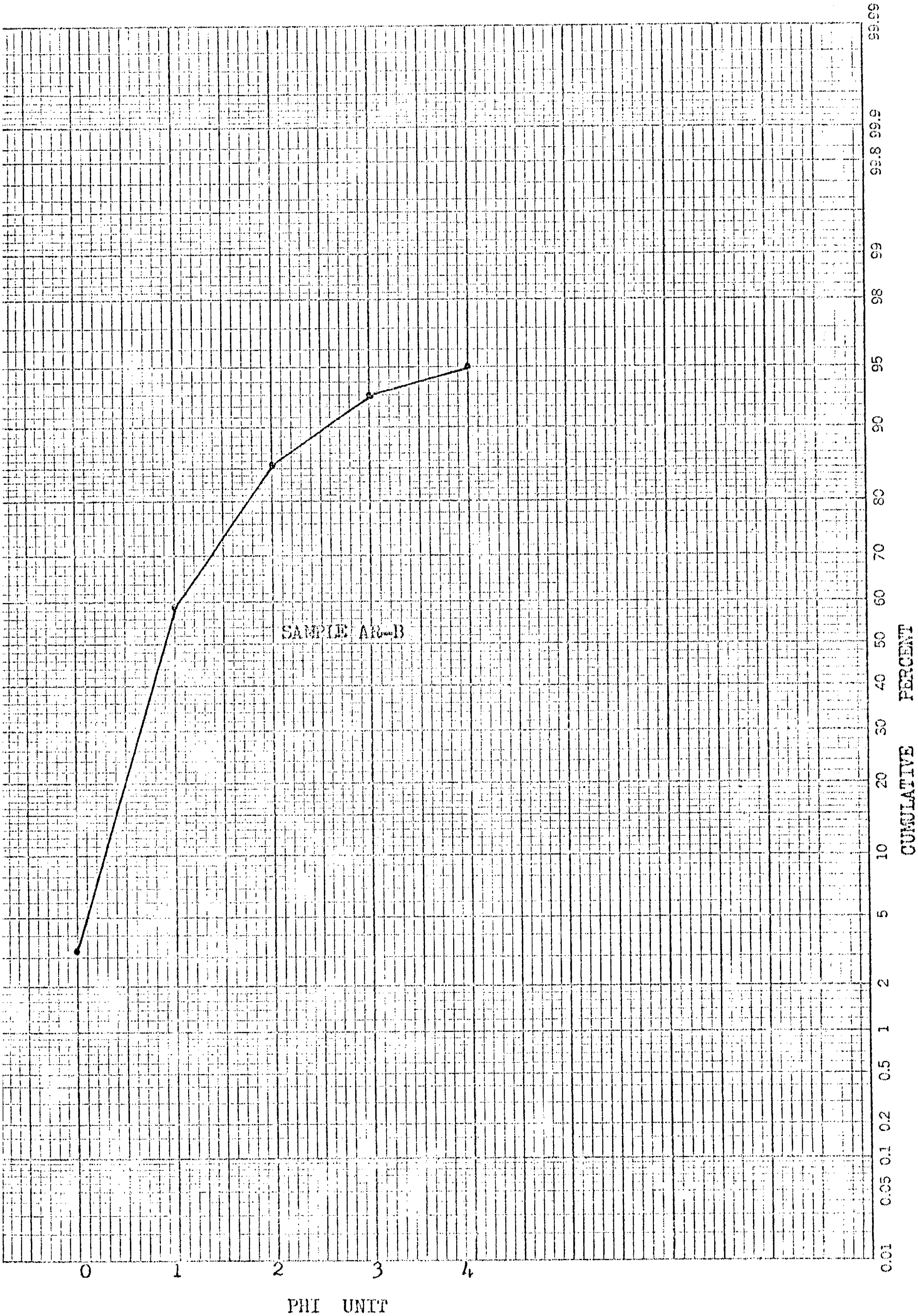
tion of Sample San Jose sandstone from unit above Arch Rock Spring.

ication (Folk) S Initial Sample Weight 59.2881 g

1.0 Md 0.88 Mz 1.07 Si 0.97

s m)	Wentworth Class	Weight (g)	Percent	Cumulative Percent
.0	very coarse	2.0041	3.40	3.40
.0	coarse	32.8242	55.69	59.09
.0	medium	15.7070	26.65	85.74
.0	fine	4.2886	7.28	93.02
.0	very fine	1.2217	2.07	95.09
ud	silt and clay	2.8927	4.90	99.99
	TOTAL	58.9383		

Totals


SAMPLE AR-B
0
1
2
3
4
PHI UNIT
CUMULATIVE PERCENT
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99

COMPOSITE DATA SHEET FOR PARTICLE-SIZE ANALYSIS

io. 2b-12 Analyzed By D.R.B. Date 5/76

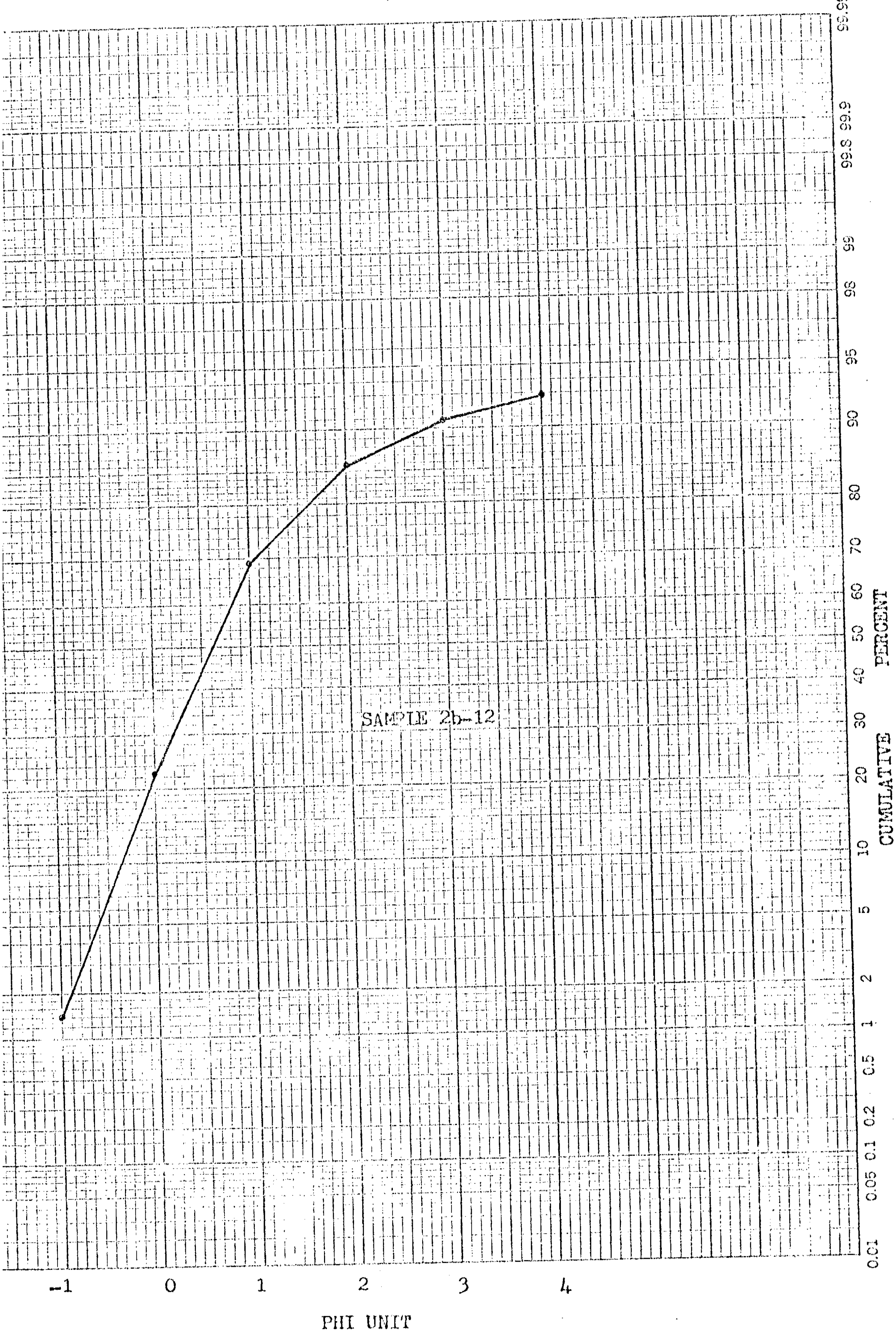
:ion of Sample San Jose sandstone from unit 12, meas. sect. 2b

ication (Folk) S Initial Sample Weight 66.8213 g

1.0 Md 0.61 Mz 0.77 Si —

m)	Wentworth Class	Weight (g)	Percent	Cumulative Percent
,0	pebbles	trace	trace	trace
.0	granules	0.9580	1.43	1.43
.0	very coarse	14.1335	21.24	22.67
.0	coarse	30.9562	46.52	69.19
.0	medium	11.1780	16.80	85.99
.0	fine	3.2150	4.83	90.82
.0	very fine	1.4096	2.11	92.93
ud	silt and clay	4.6890	7.05	99.98
	TOTAL	66.5393		

Totals


SAMPLE 2b-12
-1
0
1
2
3
4
PHI UNIT
CUMULATIVE PERCENT
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99

APPENDIX E

SOURCES OF SUBSURFACE DATA

SOURCES OF SUBSURFACE DATA FOR CROSS-SECTIONS

PLATES 4 AND 5

Well logs and electrical logs of the following oil and gas wells were used to define the tops of formations illustrated on Plates 4 and 5. In some cases, more than one well was used at a locality. All logs are on file at the New Mexico Bureau of Mines and Mineral Resources.

NW-SE Cross-Section

1. E.P.N.G., Barnes No.8, SW$\frac{1}{4}$ Sec. 26, T.32N., R.11W., elevation 6479, total depth 5908.

   Delhi Taylor, Barnes No.1, NE$\frac{1}{4}$ Sec. 26, T.32N., R.11W., elevation 6329, total depth 7785.

2. Delhi Oil, 4-A Atlantic A, SW$\frac{1}{4}$ Sec. 27, T.31N., R.10W., elevation 6337, total depth 7796.

3. Delhi Oil, Florance 1-13, NE$\frac{1}{4}$ Sec. 18, T.30N., R.9W., elevation 6160, total depth 7540.

4. Delhi-Taylor, Florance Fed. No.49, NE$\frac{1}{4}$ Sec. 22, T.30N, R.9W., elevation 5965, total depth 7711.

   Pan Am, Elliott B-8, SW$\frac{1}{4}$ Sec. 27, T.30N., R.9W., elevation 5815, total depth 7100.

5. Pan Am, Ulibarri No. 3, SW$\frac{1}{4}$ Sec. 35, T.30N., R.9W., elevation 5620, total depth 6866.

SW-NE Cross-Section

1. Beta, Federal No. 1F, SE$\frac{1}{4}$ Sec. 33, T.30N., R.11W., elevation 5894, total depth 6801.

2. International, Fogelson No. 1, SE$\frac{1}{4}$ Sec. 26, T.30N., R.11W., elevation 5899, total depth 7000.

3. E.P.N.G., Schumacher No. 11, SW$\frac{1}{4}$ Sec. 18, T.30N., R.10W., elevation 6282, total depth 7450.

   E.P.N.G., Schumacher No. 10, NE$\frac{1}{4}$ Sec. 18, T.30N., R.10W., elevation 6330, total depth 5221.

4. Delhi Oil, 4A Atlantic A, SW$\frac{1}{4}$ Sec. 27, T.31N., R.10W., elevation 6337, total depth 7796.

5. E.P.N.G., Barrett No. 3, SW$\frac{1}{4}$ Sec. 20, T.31N., R.9W., elevation 6658, total depth 5739.

   Delhi-Taylor, Barrett No. 1, SW$\frac{1}{4}$ Sec. 20, T.31N., R.9W., elevation 6676, total depth 8071.

6. E.P.N.G., San Juan Unit 32-9-70X, NE$\frac{1}{4}$ Sec. 21, T.32N., R.9W., elevation 6919, total depth 8596.

APPENDIX F

HYDRAULIC CONDUCTIVITY TESTS

HYDRAULIC CONDUCTIVITY TESTS

Method

An attempt was made to determine the hydraulic conductivity of various San Jose sandstones by means of a triaxial compression apparatus (figure following page). By this method both axial and lateral confining pressure are applied to a rock core to simulate natural conditions at depth. Water is then applied to one end of the core and the rate of flow is measured. Hydraulic conductivity is thus determined (Charukalas, 1975).

Results

Only one sandstone core from the San Jose Formation was successfully tested, due mainly to difficulty in obtaining core. Because only surface samples could be obtained, the coarse sandstones were weathered and tended to break up under the core drill. From more than twenty attempts, only two small cores were obtained. One core was contaminated by oil from the cell; the results of the one successful test are shown below:

Sample No. AR-A Location: SW$\frac{1}{4}$ Sec. 24, T.31N., R.10W.

Orientation: perpendicular to bedding

Discharge $Q = 0.84\ cm^3/sec$

Area of X-section $= 4.02\ cm^2$

Length of core $L = 4.04$ cm

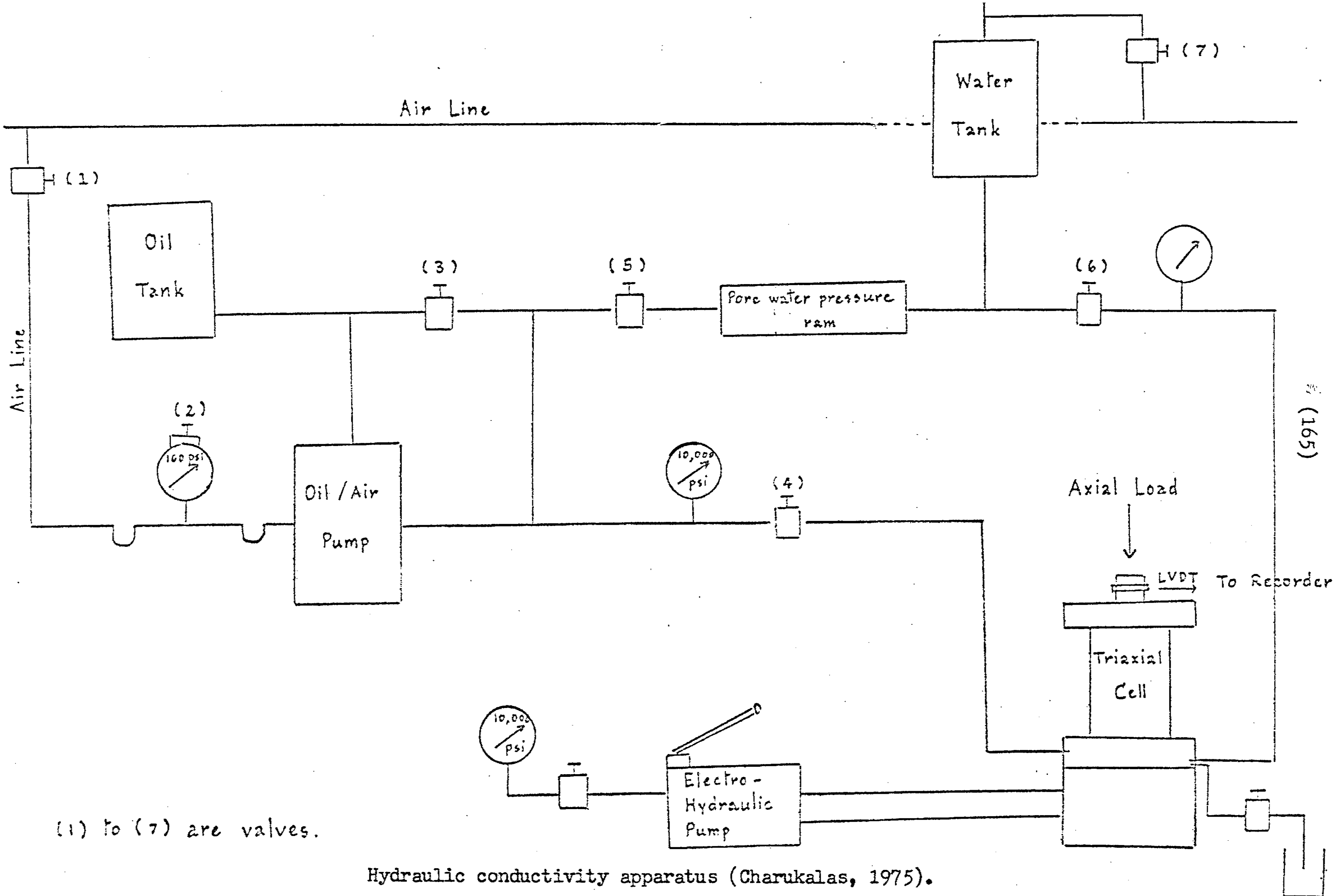
Pore Pressure $P = 200$ psi

Confining Pressure $= 600$ psi

Diff. in head $dh = 1408.18$ cm

Hydraulic conductivity $K = \frac{Q}{A} \times \frac{L}{dh}$ (Darcy's Law)

$$= 6.05 \times 10^{-4}\ cm/sec$$



(1) to (7) are valves.

Hydraulic conductivity apparatus (Charukalas, 1975).

APPENDIX G

GLOSSARY OF HYDROLOGIC TERMS

GLOSSARY OF HYDROLOGIC TERMS

neral Statement

The following terms are taken predominantly from Trauger (1972, . 115). Other sources are noted where appropriate. Only less commonly sed terms or terms about which there is some confusion are defined.

cre-foot - The amount of water (325,851 gal) that will cover one cre to a depth of one foot.

quifer - A rock formation, group of formations, or a part of a formation ontaining water that can be recovered through wells. An aquifer may be alled also a water-bearing bed, formation, or zone.

rtesian water - Ground water that rises above the level at which it is encountered by a well, but which does not necessarily rise to or above the surface of the ground - also called confined water.

Brackish water - Water with a total dissolved solids content of between 10,000 and 35,000 ppm.

Confined water - The same as artesian water.

Fresh water - Water with a total dissolved solids content of between 0 and 10,000 ppm.

Hydraulic conductivity - The flow of water in gallons per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 at a temperature of 60°F (Todd,1959). Other units, such as cm/sec can be used.

Hydraulic gradient - The gradient of the potentiometric surface or water table, in the direction of the steepest slope, generally expressed in feet per foot or feet per mile. May also be expressed as the change in static head per unit of distance in a given direction.

Potable water - Potable water is water which is suitable for domestic use and generally has less than 1,000 ppm total dissolved solids.

Saline water - Water with a total dissolved solids content of greater than 35,000 ppm.

Specific capacity - Yield of a well in gallons per minute per foot of drawdown after a specified period of pumping.

Specific conductance - The conductance of a water sample (here) measured in micromhos per centimeter (mmhos/cm).

Storage coefficient - The volume of water released or taken into storage in an aquifer per square foot of surface area per foot of vertical change in the head.

Transmissivity - Ability of a rock to transmit water under hydraulic head. The rate of flow of water at the prevailing temperature, through a vertical unit-wide strip of the aquifer, extending the full height of saturation, under unit hydraulic gradient.

Water table - Upper surface of the zone of saturation where that surface is not confined and is at atmospheric pressure. If water is confined in an aquifer, the term potentiometric surface is used, which is the surface which represents the static head. It is determined by the level to which water will rise in a tightly cased well.

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This thesis is accepted on behalf of the faculty of the Institute by the following committee:

William J. Stone

John R. MacMillan

Lynn W. Gelhar

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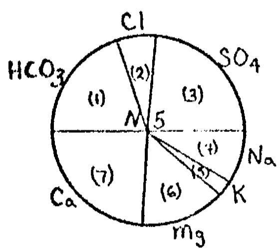
Date 17 May 1976

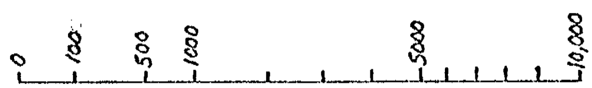
Water well, inventoried Table V.

Water well, not inventoried.

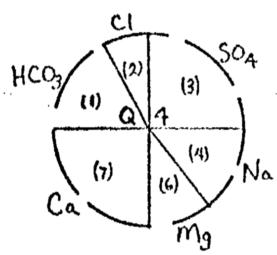
Spring, no chemical analysis.



Water well, chemical analysis in order shown.



Scale of radii for total dissolved solids (ppm).



Spring, chemical analysis in order shown,
potassium (K) content negligible.

Spring and well numbers refer to Table V:

Q = Quaternary alluvium

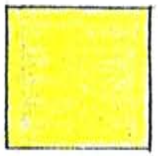
N = Nacimiento Formation

S = San Jose Formation

LEGEND FOR PLATE 2.

PLATE 1.

GEOLOGIC MAP OF AZTEC QUADRANGLE



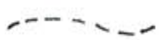
Quaternary alluvium, valley fill: gravel, sand, silt, and clay; predominantly coarse gravel.

Quaternary alluvium, terrace deposits: predominantly coarse gravel and sand (modified from Bandoian, 1969).

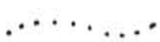
San Jose Formation (Tertiary): coarse, yellow, sandstones interbedded with green, gray, purple shales and white non-resistant sandstones.

Nacimiento Formation (Tertiary): gray, green, purple shales and gray to yellow, soft to resistant sandstones.

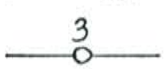
Geologic contact



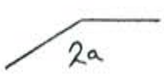
Geologic contact, upper unit eroded



Geologic contact, partially covered



Line of cross-section



Measured section

LEGEND FOR PLATE 1.