Hydrogeology of the San Augustin Plains, New Mexico

OF-51

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HYDROGEOLOGY OF THE SAN AUGUSTIN PLAINS, NEW MEXICO

An Independent Study Submitted
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science
in Geology

by

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and
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ABSTRACT

The San Augustin Plain is a topographically closed basin which has a water table that slopes toward the center of the basin. The water table beneath the central playas is several tens of feet deep, which indicates that evaporative discharge of groundwater is very small. A water-table contour map shows hydrologic conditions which suggest southward subsurface leakage, beneath the Continental Divide, from the southwestern portion of the basin. A hydrologic budget is used to estimate that the annual groundwater leakage is about 100,000 acre feet.

The absence of evaporite deposits in the Pleistocene lake sediment of the basin indicates that the dissolved solids in the lake water were flushed away in leaking groundwater before the water could become supersaturated by increased evaporation that accompanied climatic changes at the end of Pleistocene time.

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Fig. 1 ~~Index and location map~~

Maps in pocket

Map 1

Need

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Fig. 1 -- "Index map of New Mexico showing location of San Augustin Plains".

Sample map?
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p. 3 (bottom) need a reference to soil moisture studies that shows ~~the~~ sharply decreasing evaporation for ~~drying~~ dry soil (Dan, you have refs from class - mine are packed. Baker, Fisher, others also have them)

Plate 1 -- Redesignate as "Map 1" and give title.

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INTRODUCTION

The San A~~u~~gustin Plains are the floor of a closed basin in Socorro and Catron counties, west-central New Mexico. The Plains are nearly flat, and are at approximately 6,900 feet elevation. The basin, 1,965 square miles in area, lies within the Datil-Mogollon volcanic plateau and is surrounded by mountainous terrain that reaches altitudes of 8,000 to 10,000 feet. Thick sequences of Tertiary volcanic flows form the uplands that surround the basin floor. The climate is semiarid and the precipitation falls mostly as short, intense thundershowers during the late summer months. Vegetation is gramma grass along the basin bottom, piñon and juniper on the lower mountain slopes and Ponderosa pine and fir at the higher elevations.

Fig. 1 -- Index Map

No permanent streams of or surface-water bodies exist within the basin boundaries. Many of the alluviated arroyos and canyons which drain from the high mountains toward the basin center contain runoff during the more intense storms, but the runoff usually disappears quickly into alluvial fans at the foot of the mountains. Occasionally water bodies a few acres in extent exist in depressions in the basin floor until they evaporate and infiltrate, but the playas are normally dry.

Approximately 700 people live in the basin, the majority of whom reside in the communities of Datil and Horse Springs. The principal occupation is cattle ranching, and ranch headquarters can be found every few miles along the basin floor. Two paved highways, U. S. 60 and State Highway 12, run through the basin, and dirt roads provide access to most of the remainder of the area.

The basin topography is mapped on the U. S. Army Map Service Socorro, Tularosa, St. John's, and Clifton topographic maps at a scale of 1:250,000. A few U. S. Geological Survey 7½ minute topographic maps cover only the extreme southwestern part of the area. New Mexico County Highway Maps and the Army Map Service maps were used for location of wells, springs, and other features during the field work.

Previous Investigations

F. X. Bushman and C. P. Valentine (1954) tabulated all available water-level measurements and chemical analyses of water, but made no interpretation of the data. The geology has been described by Stearns (1962), who mapped the area and deduced the sequence of the stratigraphic units. Several surrounding quadrangles have been mapped in a reconnaissance style by Willard (1957a, 1957b) and Willard and Givens (1958). W. E. Powers (1939) wrote a report on the basin and described some of the shore features of extinct Lake San Augustin. Foreman, Clisby, and Sears (1959) described a 2,000-foot core drilled from the lowest spot in the basin. They reported sedimentary and pollen profiles, from which they interpreted past climates, erosional cycles, and structural events. In a State Engineer's report on New Mexico water resources, Cooper (1967) has given estimates of water use and possible future water needs.

Other reports on the area generally consist of brief comments.

Statement of the Hydrologic Question, and Purpose of the Study

Examination of preexisting hydrologic data revealed that the basin might contain a sizable ground-water leak. In a closed basin, a playa will exist in the lowest part of the basin, and the playa will be either perennially moist or dry, depending on hydrogeologic conditions. A moist playa in a non-leaky basin evaporates all of the groundwater which originated as precipitation within the basin. Soil evaporation rates where the soil surface is dry, probably always the case where the water table is deeper than 10 feet, are much too low for evaporative discharge to balance the total recharge in a large basin.(insert ref.) Hence, a dry playa can exist only where recharge in the basin is balanced by some other form of ground-water discharge. In a basin where extensive pumping occurs, this may provide the discharge. Phreatophytes can transpire water from a deep water table. Subsurface leakage of groundwater out of the basin can provide a natural discharge which will allow the water table to remain deep below the level of the playa surface.

The playa areas within the San Augustin Plains are dry, and the water table is several tens of feet deep. Groundwater pumpage is very small, and there are no extensive areas of phreatophytes. Therefore, the preliminary evidence pointed strongly to the existence of a subsurface ground-water leak.

A series of field trips were made by the junior author to the area ? to measure water levels and to collect water samples for analysis.

Tritium and chemical analyses have been used to delineate probable flow patterns and also to model reaction mechanisms between the groundwater and aquifer system. A hydrologic budget was constructed using precipitation, evaporation, and consumptive-water-use data. The paleohydrogeology was reconstructed using drill cores, geologic maps, the hydrologic budget, and present-day water chemistry.

Data Collection and Analyses

Wells are numbered in this report under a standard system for New Mexico that is used by the ~~State~~ New Mexico Bureau of Mines and Mineral Resources, the U. S. Geological Survey, and other agencies (see Bushman and Valentine, p. 2, 1954). Water levels in wells were measured, and the elevations of the well heads were either taken from the Bushman and Valentine report or were estimated in the field by interpolating from the 200-foot contour maps of the Army Map Service.

The pH and bicarbonate values for water samples were measured as soon as possible after returning the samples to the Chemical Lab. The pH was measured on a Sargent Model Dr pH meter and the bicarbonate was determined by titration with a 0.02 normal H_2SO_4 solution. Specific electrical conductance was measured in the lab with a conductivity meter and was corrected to 25° Centigrade. Chloride was determined by adding a potassium chromate indicator to the sample and titrating with a standard silver nitrate solution (Rainbow and Thatcher, p. 142, 1960). Sulfate was determined by adding a known excess of $BaCl_2$ to the sample and precipitating $SO_4^=$ as $BaSO_4$. A spectrophotometer then measured the amount of absorbance caused by the $BaSO_4$ and this value was compared to a standardization curve to yield the amount of $SO_4^{=}$ (Rainbow and Thatcher, p. 285, 1960). Calcium, magnesium, sodium, and potassium were determined by atomic absorption. Standard techniques, as outlined in the Perkin-Elmer working manual for their Model 303 atomic absorption instrument, were used.

Analytical tests to check the accuracy and precision of the chemical analyses were not run, and accuracy of better than ± 15 percent is not assumed. For the non-quantitative uses to which the chemical data are put, errors of this size will not alter the interpretations. For example, the analyses are plotted on a trilinear diagram and a 15% error in one constituent will cause only a few percent error in the plotting of the total constituents. The trilinear diagram is only used to show general water types. The analyses are also used to plot ratios of millimoles of each constituent to millimoles of bicarbonate, and the resulting graphs are visually compared to similar graphs for groundwaters of known lithologic association. The possible error does not prevent such visual correlation. Finally, the analyses are used to calculate relative percent of saturation with respect to the minerals calcite, dolomite, and gypsum. A 15% error in the analysis of a single constituent may produce an equal or perhaps greater error in the calculation of percent saturation for a mineral. Therefore, the calculations are used only to approximate mineral saturation values.

The results of the chemical analyses are listed in milliequivalent/liter in Table 5, and in parts per million (ppm) in Appendix A.

GEOLOGY

The report by Stearns (1962) on the geology of the north half of the Pelona Quadrangle is the only detailed geologic report on the San Augustin Plains area. All of the area surrounding the plains has been mapped only in a reconnaissance style, and very few strikes and dipss are shown on these maps. No attempt has been made to correlate the stratigraphic units between the mapped areas. No geologic cross sections were made, so that knowledge of the subsurface stratigraphy is rather limited.

Three test holes have been drilled into the basin alluvium. The southernmost hole was drilled for Oberlin College as a "Climatic Research" core hole. Located near the center of Sec. 28, T. 5 S., R. 13 W. (5·13·28·233), the hole was cored to 2,000 feet. It penetrated poorly consolidated water-deposited sediments through its entire depth. Foreman, Clisby, and Sears (1959) made detailed petrographic, textural, and pollen studies of the core to a depth of 645 feet.

The northernmost hole is an oil test hole drilled to a depth of 1,800 feet. Located near the center of Sec. 35, T. 2 S., R. 8 W. this hole (2·8·35·233) went through 710 feet of volcanically-derived gravels before striking welded rhyolite tuff.

The deepest hole was an oil-test hole drilled in Sec. 29, T. 3 S., R. 9 W., which penetrated 12,300 feet of sedimentary and volcanic rocks before striking Precambrian granite gneiss. Two hundred and thirty feet of alluvium were drilled before encountering volcanic flows.

A sequence of Tertiary volcanic flows over 6,000 feet thick was drilled above the Cretaceous Gallup Sandstone which was struck at 6,620 feet. Below this the sedimentary section above the Precambrian included Mancos Shale, Dakota Sandstone, Chinle Formation, San Andres Limestone, Glorieta Sandstone, Yeso Formation, Abo Formation and 1,800 feet of intrusive Tertiary sills encountered in the Paleozoic.

This deep oil-test hole appears to be located on a major north-south trending interbasin divide inasmuch as the valley-filling sediments thicken both to the northeast and southwest. The elevation of the contact between the base of the alluvial sediments and the welded rhyolite tuff is 6,826 feet. The maximum thickness of valley fill to the southwest exceeds the 2,000-foot test hole by an unknown amount.

Stearns (1962) reports the relative stratigraphic sequence for the volcanic flows and interbedded sediments of the southwestern San Augustin Plains area. The alluvial plain itself is considered to be a graben which formed after the extrusion of the last of the volcanics. Three to four thousand feet is the minimum amount of down dropping which has taken place. At least half of this structural relief has been reduced by accumulation of valley-filling sediment in the basin. The boundaries of the graben to the south and west are inferred to be at the contact between the gently sloping alluvial sediments and the steeply sloping volcanic rocks.

The predominantly volcanic Tertiary rocks of the San Augustin Plains are part of the Datil Formation, which has its type locality 30 miles to the northeast (Winchester, 1920). Within the study area, the Datil Formation has a maximum inferred thickness of 3,000 feet (Stearns, 1962, p. 7). Four facies are recognized: a rhyolite facies consisting of thick flows of rhyolite, tuff, and tuff-breccia; a latite facies of thick flows and flow-breccias; an andesite facies of andesite flows and breccias; and a sedimentary facies consisting of conglomerate, sandstone, siltstone, and mudstone. The sediments are of fluviatile, and locally eolian origin, and volcanic fragments comprise most of the detrital material.

(Need some logs or a cross section with liths.)
WJS

WATER LEVELS

Bushman and Valentine (1954) tabulated all known water-level measurements for the southwestern part of the San Augustin Plains. For topographic control on the basin floor, they used Powers' (1939) topographic maps, which has 10-foot contours. Elsewhere they used a U. S. Geological Survey topographic map of the Pelona Quadrangle with 100-foot contours which was published in 1918. Many of the wells which Bushman and Valentine measured were remeasured in the summer and fall of 1972 for this study. A comparison of the data shows that water levels have risen or fallen slightly in some locations and have remained static in others, but no overall pattern of change can be discerned. The water table has apparently been nearly stable. Water levels in wells, and the changes in water-level measurements in the same well between 1952 and 1972 are tabulated in Table 1.

A water-level contour map (Map 1) has been prepared using all available data. Where a well has been measured more than once, the more recent measurement was used. An important feature of the contours is the indication that only a gentle rise on the water table separates groundwater in the southwest basin from groundwater in the head of the Gila River drainge area to the south. The water table in the Gila drainage slopes southward at about 30 feet per mile. These conditions are quite consistent with the hypothesis of subsurface leakage. Water in a sloping water table will flow from the areas of higher potential toward the areas of lower potential. The evidence

Table 1 -- Water levels in wells.

(Continued on next page)

Well Number (many inaccuracies)

~~Township & Range~~ ~~Locations~~* (T., R., Sec., plot)*	Well Elevation**	Depth to Water ~~Table~~***	Water Table Elevation	Date Measured	Change in Water Table
4. 8. 14. 320	7380	>380 m	<7000	11-4-72	-
4. 10. 34. 241	6900	183 m	6720	10-29-72	-
3. 7. 8. 213	7000	240 m	6760	11-4-72	-
3. 16. 35. 100	7700	400 r	7300	1972	-
4. 11. 34. 121	6800	140 m	6660	10-29-72	-
4. 13. 29. 331	6980	-	-	7-19-72	-
4. 15. 26. 331	7175	280 m	6895	7-11-72	-
4. 15. 32. 124	7125	320 m	6805	7-10-72	
—"—	—"—	290 r	6835	1952	+30 ft (?)
4. 16. 28. 211	7160	20 m	7140	7-10-72	-
4. 16. 35. 132	6950	135 m	6815	7-10-72	-
5. 9. 1. 111	6980	170 m	6810	11-4-72	-
5. 11. 1. 212	6775	98 m	6677	10-29-72	-
5. 12. 9. 434	6855	115 r	6740	1952	-

single space

* All Townships are South, all Ranges are West.

** Elevation in feet above mean sea level.

*** m - measured
r - reported.

Table 1

(Continued on next page)

	Well Number ~~Township & Range Locations~~ (T, R, Sec, Plot)	Well Elevation	Depth to Water ~~Table~~	Water Table Elevation	Date Measured	Change in Water Table
	5. 14. 9. 412	6866	Spring	6866	7-11-72	-
Single sp	5. 14. 30. 133	6800	80 m	6720	7-19-72	
	"	"	83 m	6717	12-3-52	-3 ft minus
	5. 15. 22. 314	7600	Spring	7600	7-11-72	-
	5. 16. 3. 133	6810	Spring	6810	7-10-72	-
	5. 17. 33. 141	6405	Stream	6405	7-10-72	-
	6. 9. 30. 224	7700	>350 m	<7350	10-29-72	-
	6. 13. 11. 244	6801	53 r	6748	1952	-
Single sp.	6. 14. 28. 314	6820	69 m	6751	7-19-72	
	"	"	66 m	6754	11-17-52	+3 ft
"	6. 14. 30. 433	6800	63 m	6737	7-19-72	
	"	"	63.5m	6736.5	1-27-53	-0.5 ft
"	6. 15. 13. 333	6923	180 m	6743	7-19-72	
	"	"	183 r	6740	1952	-3 ft (?)
	7. 8. 21. 000	6760	244 m	6516	11-4-72	-

Table 1 (cont'd)

Single space

Well Number ~~Township & Range Locations~~ (T, R, Sec, Plot)	Well Elevation	Depth to Water ~~Table~~	Water Table Elevation	Date Measured	Change in Water Table
7. 14. 3. 142	6855	107 m	6748	7-20-72	
"	"	198 r	6657	1952	—91 ft (?)
7. 14. 23. 112	7150	-	-	7-20-72	-
8. 11. 5. 242	7500	785 r	6775	1972 r	-
8. 12. 32. 211	7000	>325 m	<6675	10-29-72	-
8. 16. 2. 434	7480	>500 m	<6980	10-29-72	
"	"	570 r	6610	1952	?
9. 13. 16. 433	6900	455 m	6445	10-29-72	-

The small groundwater mound between the SW basin floor and the Gila River headwaters is probably a local system (see Tóth, 1963 pages 4805-11), underlain by regional flow to the south. (see also Freeze, R.A. and Witherspoon, P.A. "Theoretical Analysis of Regional Groundwater Flow, 1. Analytical and numerical solutions to the mathematical model" Water Resources Research, Vol 2, #4, 641-656, 1966.)

Tóth, J.; "A Theoretical Analysis of Groundwater Flow in Small Drainage Basins"; Jour. Geophysical Research; Vol. 68, No. 16, 1963, pp. 4795-4812 thus indicates leakage of the water which would otherwise have to be evaporated by a playa within the basin.

Numerous springs are situated in many places over the steep ground-water divides; but, along the part of the southern divide beneath which subsurface flow is inferred, no springs are known to occur. The water table beneath the divide in this mountainous area is inferred to be 1,000 feet deep or more, based upon the information from surrounding wells. The permeability of the volcanic rocks in the area must be high, otherwise recharge would have raised the water table to a much higher elevation.

A small topographic depression upon the basin floor is centered at T. 5 S. R. 11 W. Sec. 1. The lowest water table level within the basin is also situated in this locale but lack of data prohibits putting a definite boundary around the southeast and northeast sections of the depression. The subsurface flow entering this depression probably flows out to the southwest or to the southeast. The thickness of basin sediments, as indicated by the Oberlin College core hole, is definitely great enough ? to allow flow to the southwest. The lack of subsurface information to the southeast prohibits any definite answer as to whether flow can occur in this direction. In either case, subsurface flow will be flowing beneath a water-table divide.

A cross section illustrating topography, water-table configuration, and inferred flow patterns has been drawn (Figure 2). Due to the deep water table beneath the divide and to the fact that most of the runoff runs down mountain canyons until it reaches the alluvial fans, most of the recharge is inferred to occur in the area of Pleistocene lacustrine sediments. The tritium value for W 13 (6. 14. Sec. 30) is 250 ± 150 tritium units. Comparison with tritium values of New Mexico precipitation for the last several years (Rabinowitz, personal communication) indicates that this well water is one or two years old and is therefore fresh recharge water. The tritium value for water from the well located at 8. 12. Sec. 32 is 29 ± 2 tritium units. For the well at 7. 11. Sec. 26, the tritium value is 10 ± 2 tritium units. These very low values indicate that the water is probably a mixture composed predominantly of very old underflow (10 years) and of some old recharge water (5 years). The lesser depth to the water table for the well with the higher tritium value indicates that the water for that well is somewhat younger.

Figure ~~X~~ 2

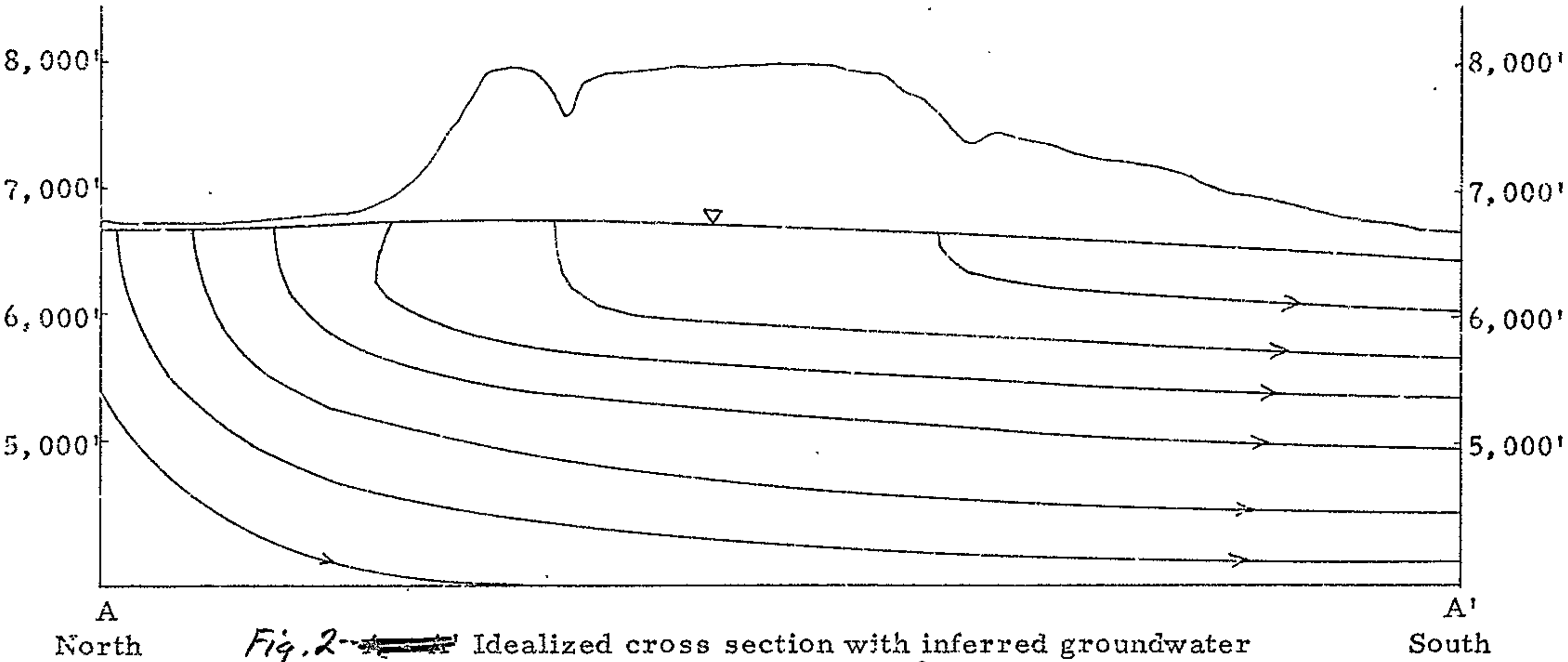

Fig. 2-- Idealized cross section with inferred groundwater flow paths (See Map 1 for location.)

HYDROLOGIC BUDGET

The hydrologic budget formulated below, based as it is on rather sparse data, provides only a quantitative approximation of the ground-water system. This budget in its simplest form is: Recharge = change in storage + subsurface outflow, but other factors are also considered in order to reasonably estimate variables in the equation. Precipitation data for the area are listed in Table 2. Note the absence of stations above 7,400 feet elevation. Figure 3 is a plot of annual precipitation versus station elevation.

Fig. 3 - Variation in annual precipitation with altitude

In Cooper's report on the water resources of the area (1967), he uses an average of 15 inches precipitation per year over the entire basin, and he estimates that half of the area lies above 7200 feet. Figure 3 implies, however, that precipitation at 7200 feet is 13.8 inches per year. For this report, a value of 14 inches per year average precipitation has been chosen. Multiplication of the total acreage by the average precipitation yields a total water input to the basin of about 1,500,000 acre-ft/year (See Appendix B).

Change in groundwater storage is an essential part of the hydrologic budget. Water levels in wells measured in 1952 and in 1972 are shown in Table 1. Inspection reveals that although both positive and negative changes have occurred since the earlier measurement,

Station Name, ~~Township & Range~~ Location	Altitude ~~Elevation~~	Average Annual ~~Yearly~~ Precipitation (in.)	Period of Record
Augustine T.2 S. R.8 W. Sec. 33,	6890'	10.56	1939 - 1952
Danley Ranch T.4 S. R.6 W. Sec. 8,	6800'	9.57	1939 - 1952
Datil T.2 S. R.10 W. Sec. 11,	7100'	13.06	1938 - 1951
Horse Springs T. ~~15~~ 4 S. R. ~~9~~ 13 W. Sec. 27,	7071'	11.79	1931 - 1939
Jewett Ranger Sta. T.4 S. R.17 W. Sec. 5,	7400'	15.37	1946 - 1952

Table 2 -- Precipitation data from U.S. Weather Bureau (19—)

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Figure ~~2~~ 3

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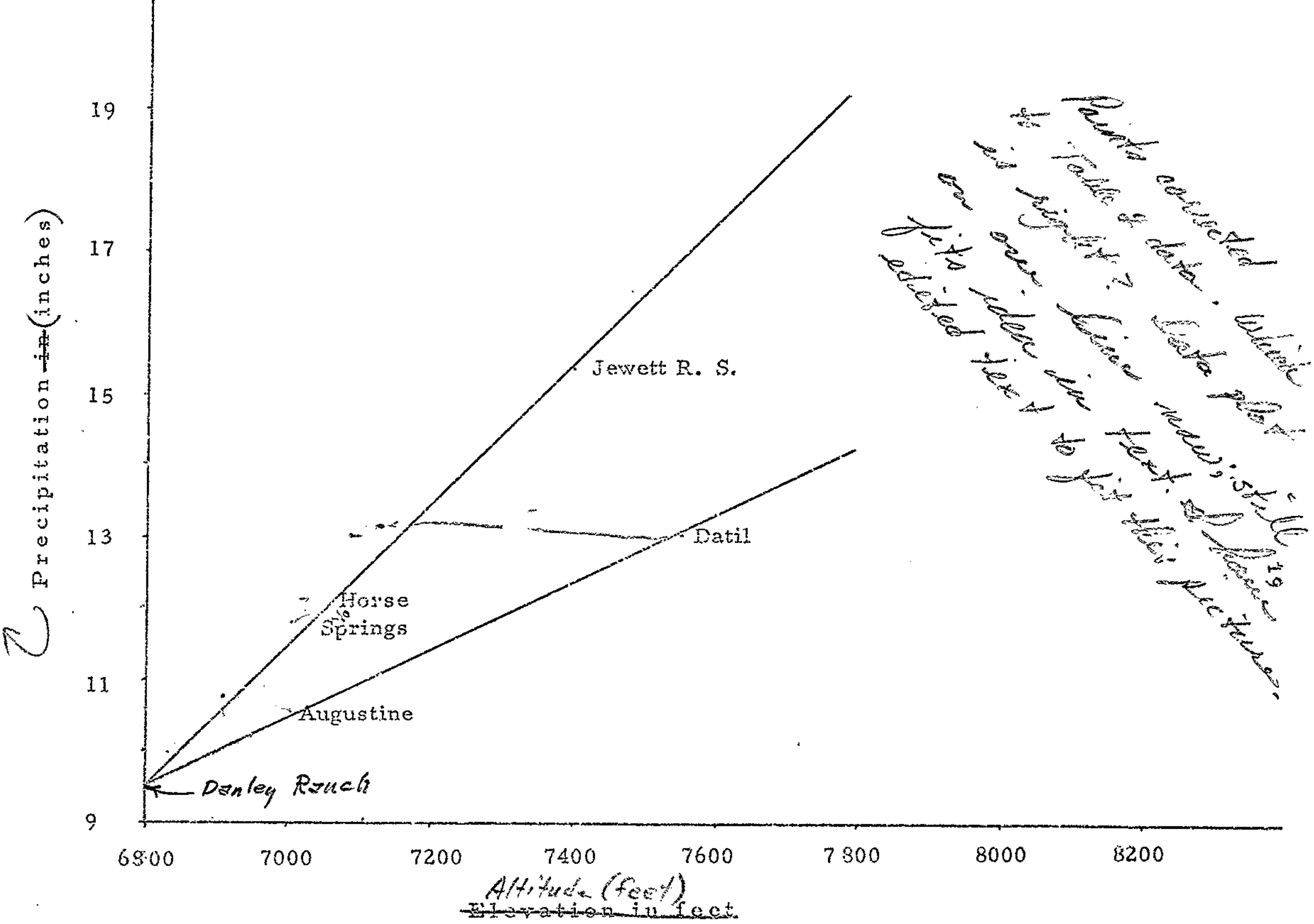

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Fig. 3:- Variation in annual precipitation with altitude

no overall pattern is apparent. The change in ground-water storage is therefore considered to be nil.

Use of groundwater by the populace and their livestock is considered by Cooper (1967). He estimates consumptive use of 10 acre-ft/year for domestic purposes, 130 acre-ft/year for livestock, and 90 acre-ft/year evaporated from stock ponds. No irrigation is known except for one very small plot which uses less than 10 acre-ft/year. The total water consumption by people and livestock therefore is less than 240 acre-ft/year.

Ground-water outflow from the basin is equal to recharge if there is no direct evapotranspiration from the deep water table within the basin and if the assumption of zero change in ground-water storage is true. A means of estimating ground-water outflow is to estimate recharge. Theis, in his 1937 paper, estimated recharge to the High Plains of Texas and New Mexico of one-half inch per year. This was for an area with 15 inches average annual precipitation, no permanent streams or large surface water bodies, average elevation of 4,000 feet, and a measured potential evapotranspiration of more than 70 inches per year.

The nearest weather station to the San Augustin Plains at which evaporation is measured, is in Reserve, New Mexico (T. 7 S. R. 19 W.) at an elevation of 5,700 feet. Here the average potential evapotranspiration for the five growing months (May - September) is approximately 50 inches per year.

Because the San Augustin Plains are 1,000 to 4,000 feet higher than the Reserve station, the figure for potential evapotranspiration should be significantly less than 50 inches per year. Comparing the values of evapotranspiration for the High Plains and the San Augustin Plains, the San Augustin figure is probably only half as large as the High Plains. Since the average precipitation for the two areas is very nearly the same, the amount of recharge to the San Augustin Plains must be significantly higher. A figure of one inch recharge per year for the San Augustin Plains will be used, realizing that the value could be higher or lower by a factor of two. The value obtained for recharge, hence subsurface outflow, is about 10^5 acre-ft/year (see calculation in Appendix B).

In the vicinity of Shaw Canyon south of the plains (T. 6 S. R. 11 W.), the Datil Formation dips to the south and southeast at 200 feet per mile. Included in the Datil in this area are two sedimentary units consisting of tuffaceous sandstone, eolian sandstone, and volcanic conglomerate with a sandy matrix. These units are usually soft and not well-lithified (Stearns, 1962). Just east of Sec. 25, T. 6 S., R. 14 W. Stearns has mapped a fault with a 1,000-foot downdrop to the west. This presumably juxtaposes these older sedimentary units against the basin-filling sediments of the San Augustin Plains. The southward dip is probably preserved. The thickness of these units is 2,100 feet at the oil-test hole located in Sec. 29, S. 3 S., R. 9 W. Stearns does not give measured sections for the units but he (?) identified outcrops of clastic sediment totaling at least 1,500 feet thick.

A subsurface leakage of 10^5 acre-feet per year is equivalant to about 0.9 x 10^8 gallons per day (Appendix B). A hydraulic gradient of eight feet per mile (measured from Fig. 2 water-table contours), and a cross-sectional of 1,500 feet by 13 miles can be used to calculate the permeability for the ineferred area of leakage. These values result in a calculated permeability of 5.7 x 10^2 gallons/day/ft^2 (See Appendix B for calculations). This value for the permeability falls within the normal range for clean sands (Todd, 1959, p. 53). The thickness and permeability of these beds, if they do indeed abut the basin sediments along the fault plane, seem adequate to discharge the groundwater that originates as recharge in the basin.

PALEOHYDROGEOLOGY

Examination of the evidence presented by Foreman, et al. (1959), reveals that the Pleistocene lake which disappeared at the end of the last major glacial epoch did not deposit any appreciable dissolved solids in an evaporite sequence. Their core, from a test hole started in the center of a large playa (Sec. 28, T. 2 S., 13 W.) was S analyzed for pollen species which would indicate climate at the time of deposition. From the bottom of the hole upward to the 950-foot depth, the pollen indicates a Tertiary temperate-climate forest. Pollen from the remainder of the core indicates slowly decreasing temperature up to a level 3.5 feet below present land surface, where a sharp palynological break indicates a sudden shift in the climate and disappearance of the lake. The change was from a cool, moist climate to our present-day semi-arid climate.

The time of lake disappearnce may be deduced approximately from a C^{14} date of 19,700 ± 1,600 years B.P. at a depth of 19 feet in the core and a second date of 29,000 ± 5,000 years B.P. at a depth of 28 feet (the latter of which Clisby and Sears (1956) thought to be of questionable accuracy. The upper 47 feet of core sediments consist exclusively of silty clays that are inferred to indicate slow and even deposition on the bottom of the lake. If in fact both dates are approximately correct then they indicate a sedimentation rate of about one foot per thousand years. The upper 19 feet has also accumulated at an average rate of about one foot per thousand years. On that basis, the lake disappeared three to four thousand years ago.

If estimates can be made of the relative rates, and the chemical compositions, of runoff and groundwater inflow, and of the precipitation and evaporation regime, then from this can be calculated the approximate chemical concentration of water contained in Lake San Augustin. In turn, this concentration could be used to deduce whether evaporites could have been deposited upon disappearance of the lake.

The chemical composition of groundwater inflow to the lake was probably the same as that of groundwater in the basin today. The groundwater samples that have been analyzed contain approximately 300 ppm dissolved solids with anionic proportions of 80% bicarbonate, 15% chloride, and 5% sulfate; and cationic proportions of 45% sodium plus potassium, 35% calcium, and 20% magnesium. All runoff within the basin today is ephemeral, and no data are available on its chemistry. Examination of the chemical data compiled by Livingston (1963) for stream flow in the western United States indicates that an average stream contains about 150 ppm total dissolved solids or less.

A hydrologic balance for extinct Lake Estancia 40 miles east of Albuquerque has been estimated by Leopold (1951), who used meridional profiles of the mean temperature of the free atmosphere to calculate snowline depression and annual mean air temperatures. A similar process will be used here to derive estimates of the precipitation and evaporation values that would be necessary to maintain the high water level in Lake San Augustin. Using the best estimates of four other authors, Leopold concluded that Pleistocene snowlines were 1,500 meters lower than those of today. To calculate from this the contemporaneous mean annual air temperature he used vertical profiles of the present-day mean temperature of the free atmosphere and showed that this amount of snowline depression would lower mean July surface temperatures by 16.2°. He argued that the temperature of each other month would be decreased by a constant percentage of the difference between the temperature of that month and the January temperature, in other words, that there would be an orderly reduction of the temperature of each month, with the maximum reduction occurring in July and none in January.

To apply this process to San Augustin basin a 15-year average mean temperature for each month at the Danley Ranch on the floor of the extinct lake (Sec. 8, T. 14 S. R. 6 W., elevation 6,800') is used. Table 3 lists the present average of mean monthly temperatures and the calculated pluvial reduction for each month. This technique suggests that the mean annual temperature during the pluvial stage was 41.8° F., or 7.6° F lower than that of today.

To estimate the potential evaporation in the basin, Class A land pan evaporation values for Santa Fe are used. The elevation and annual precipitation are the same for the two sites, and except for the months of December and January, the mean monthly temperatures are very similar. In Figure 4, mean monthly evaporation is plotted against mean monthly temperature. A coefficient of 0.7 was used to convert pan evaporation to evaporation from a free water surface, and application of this factor produced the dashed hysteresis loop. The figure indicates [illegible]

	Danley Ranch (T. 14 S. R. 6 W. Sec. 8) 15 Year Average Mean Monthly Temperatures (°F)	Calculated Pluvial ~~Reduced~~ Mean Monthly Temperatures (°F) (See text, page 26, for method)
January	32.5	32.5
February	35.6	34.2
March	39.3	36.2
April	47.4	40.7
May	54.8	44.8
June	63.1	49.3
July	68.7	52.5
August	66.9	51.4
September	61.7	48.6
October	51.0	42.7
November	39.2	36.2
December	33.2	32.9
Average Yearly Temperature	49.4~~5~~° F	41.8~~0~~° F

Table 3

Present mean-monthly and yearly temperatures, and calculated temperatures for ~~the~~ pluvial times.

~~Stan - are the months correct ??~~ Yes

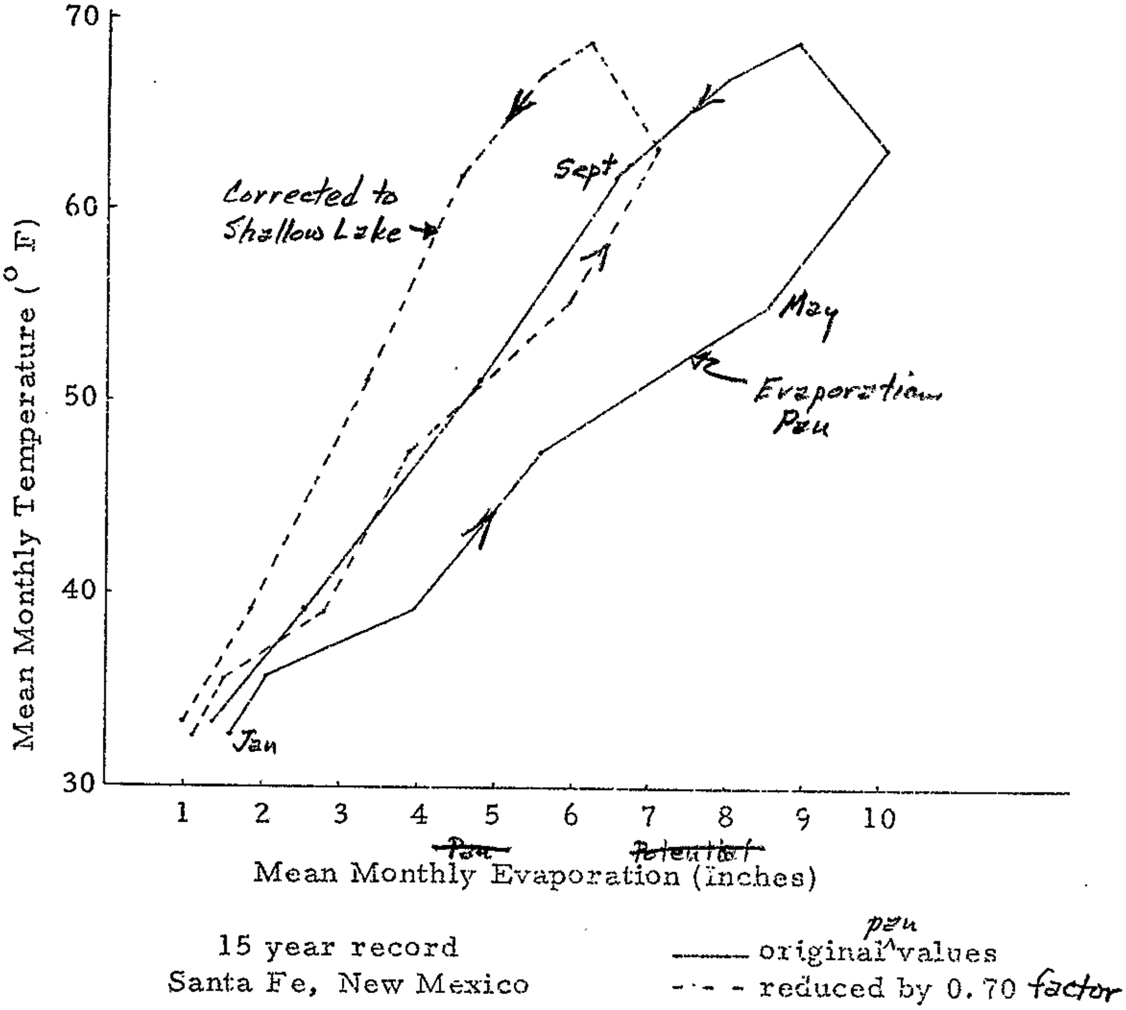
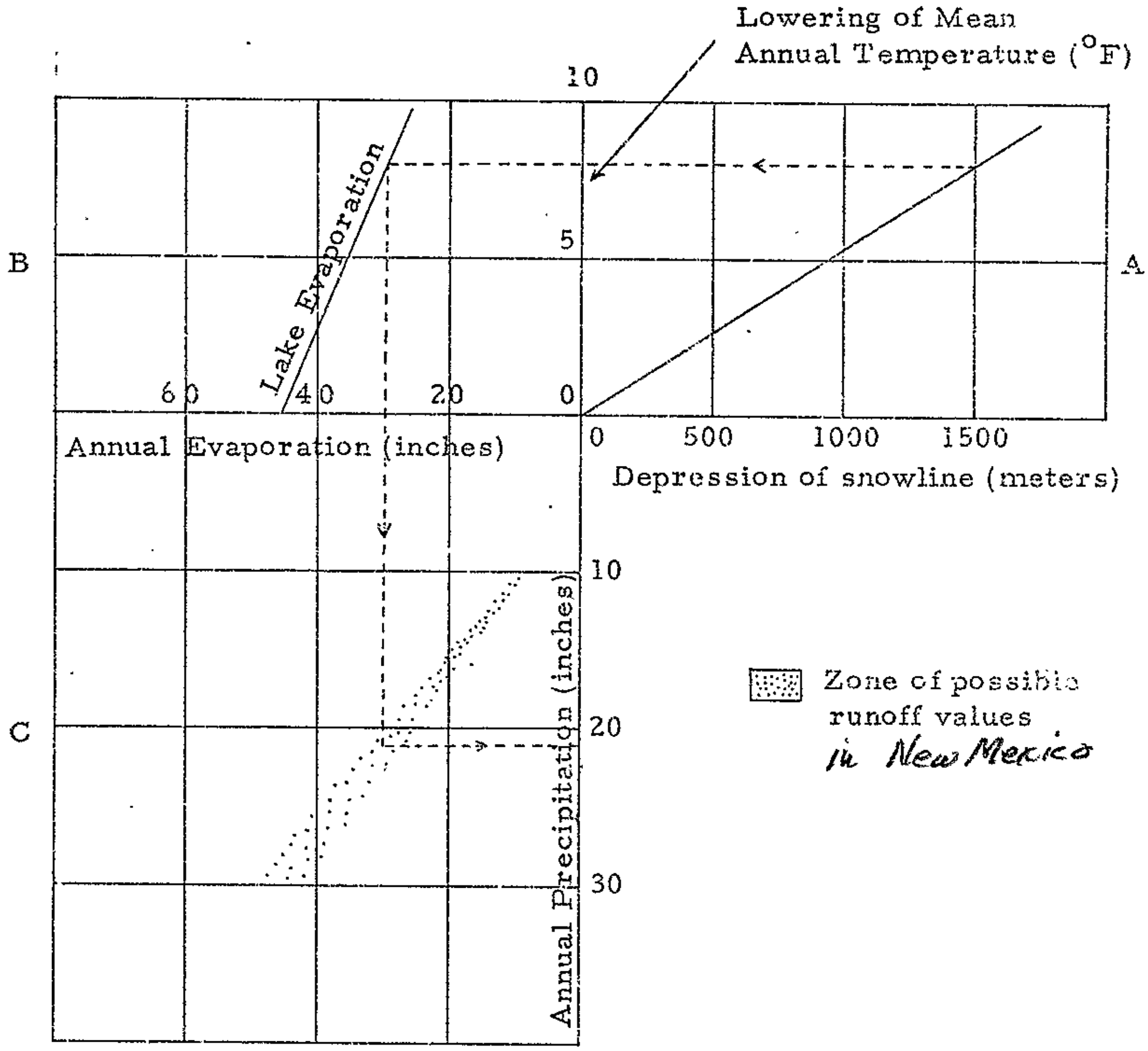


Figure ~~3~~4 Variation in evaporation potential with mean monthly temperature of this factor produced the dashed hysteresis loop. The figure indicates that modern lake evaporation from the San Augustin basin would be 45 inches annually.

The calculated mean monthly temperature values for pluvial time at the Danley Ranch location are applied to the adjusted evaporation values to yield a graph of lake evaporation versus lowering of mean annual temperature. Figure 5 is a composite diagram (after Leopold, 1951) of, A) depression of snowline vs. lowering of mean annual temperature, B) lake evaporation vs. lowering of mean annual temperature, and C) annual evaporation vs. annual precipitation. Part C of Figure 5 contains a stippled area which is the range of runoff values that can occur for any precipitation value for New Mexico (Langbein, 1949). Entering the diagram at a snowline depression of 1,500 meters produces a reduction in mean annual temperature of approximately 8°F; this means a lowering of annual lake evaporation potential from the present 45-inche to 29 inches. This in turn suggests, because existence of the lake was runoff dependent, that annual precipitation was in the range of 20 to 23 inches.

Using the values derived for evaporation and precipitation, an annual hydrologic budget can be established for the lake during its high level. In simplified form, the equation is: (lake evaporation) + (lake seepage loss) = (runoff) + (precipitation on the lake) + (groundwater inflow). Evaporation is taken as 29 inches over an area of 298 square miles. Groundwater inflow, which is inferred to leak [illegible] of the groundwater bas[illegible]

[illegible]



(After Leopold, 1951)

Figure 15

Nomogram relating: snowline depression, mean temperature, evaporation, and precipitation leakage out of the groundwater basin today, would have been greater due to the thicker saturated zone under a water table that was 200 feet higher than that of today (depth of lake plus depth to the modern water table). The minimum thickness of sediments through which groundwater inflow could occur today is 2,000 feet (from the Oberlin College core). Therefore, assuming a proportionate increase in transmissivity and no change in gradient, the pluvial groundwater inflow is assigned a value of 110,000 acre-ft, or 10% greater than the modern inflow. Solving the equation for runoff (using 100,000 acre-ft lake seepage to the aquifer, 110,000 acre-ft groundwater inflow, 460,000 acre-ft evaporation, and 350,000 acre-ft precipitation on the lake) gives a value of 100,000 acre-ft (all values rounded to the nearest ten thousand). This runoff is 5% of the total precipitation for the watershed, which agree closely with modern runoff values of western United States mountain watersheds covered with ponderosa pine forests (Love, 1960; Dortignac, 1960), as well as with measured runoff from the Walnut Gulch Experimental Watershed near Tucson, Arizona (Osborn and Laursen, 1973).

The values are now available to enable construction of a chemical balance for the steady-state lake at high stage. Precipitation and evaporation will be assumed neither to have added nor subtracted chemical constituents. Evaporation minus precipitation would have removed 1.1×10^5 acre-ft of water from the lake annually. Runoff would have added 1×10^5 acre-ft of water containing 150 ppm dissolved solids, and groundwater inflow would have added 1.1×10^5 acre-ft containing 300 ppm dissolved solids. Therefore, the average input water contained very nearly 230 ppm. Since about one-half the net input water was lost by evaporation and the other half by lake seepage which carried away all of the dissolved solids, a steady state lake would eventually have existed having a total dissolved solids content of 460 ppm. In other words, the lake seepage loss, which was one-half the input quantity, must have carried twice the concentration of dissolved solids for a steady state to exist. This means the lake water must have contained about twice the dissolved solids of the input waters.

Although there is no way of knowing how long the lake took to shrink from high stage to nothing, the assumption of an instantaneous½ climatic change enables a minimum time figure to be deduced. If the climate changed from 22 inches of annual precipitation to the present-day 12 inches (at the basin center) and if the evaporation increased from 29 inches to 45 inches per year, then shortly after the change the following conditions would obtain: seepage loss would be unchanged at 10^5 acre feet, runoff would be zero, groundwater inflow would reduce to 10^5 acre-ft, rainfall would be 1.9×10^5 acre-ft, and evaporation would be 7.2×10^5 acre-ft.

If the assumption is made that the effects of evaporation, lake seepage loss to the aquifer, groundwater inflow, and rainfall on the lake were all proportional to the lake area, an equation can be used to calculate incremental volumes of the shrinking lake, The equation is $V = V_o + T(R + I - L - E)A$ where:

where: V_o = previous lake volume

T = time increment (years)

R = annual rainfall on the lake (acre-ft)

I = annual groundwater inflow to lake (acre-ft)

L = annual seepage loss from lake to aquifer (acre-ft)

E = annual evaporation from lake (acre-ft)

A = factor equal to average of present and previous lake areas divided by initial lake area -

$$\frac{(A_1 + A_2)/2}{A_o}$$

Using a combination of the available topographic maps, a contour map of the lake basin was constructed. A planimeter was used to compute areas of the lake for its initial largest extent and for each 40-foot drop in lake level. Table 4A is a list of lake depths at the point of maximum depth, lake areas, and the proportionality factor used in the lake volume equation. The initial lake volume is calculated by multiplying the largest lake area by an average depth of 80 feet. The resultant volume is 181×10^5 acre-ft.

The groundwater inflow and the lake seepage loss cancel each other, regardless of the lake stage. The lake evaporation is 45 inches/year and the precipitation on the lake is 12 inches/year. A net lowering of the lake surface of 2.75 feet occurs each year. For a lake 165 feet deep at high stage, 60 years are required for the lake to disappear. This figure is minimal because evaporation rates actually decrease as the chemical concentration of the lake increases. This decrease in evaporation is ignored in the calculations here. For each 40-foot drop in lake level, 14.54 years are required. Table 4B is the result of solving the lake volume equation for V, using T = 14.54 (i.e., a 40-foot drop), and the initial values of R, E, I, and L, times the proportionality factor A from Table 4A. The factor A averages the changes in R, I, L, and E between one lake stage and the next.

An equation to calculate the total quantity of dissolved solids is

$$S = S_o + T(XI - YL)A$$

where: S = total quantity of dissolved solids

S_o = previous total quantity of dissolved solids

T = years

X = input concentration of dissolved solids (tons/acre-ft)

I = groundwater inflow (acre-ft)

L = seepage from lake to groundwater (acre-ft)

Y = seepage concentration of dissolved solids (tons/acre-ft)

A = proportionality factor

The initial equilibrium lake concentration is 0.63 tons/acre-ft (460 ppm). For an initial lake volume of 181×10^5 acre-ft, a 0.63 tons/acre-ft concentration yields a total quantity of 114×10^5 tons of dissolved solids. T is again 14.54 years to correspond with a 40-foot drop in lake level. X is a constant 0.408 tons/acre-ft. A is the

A

Lake depth in feet (H)	165.0	125.0	85.0	45.0	5.0	0.0
Lake area in sq. miles	297.8	232.7	166.5	125.0	36.9	0.0
A -proportionality factor $(A_1 + A_2)/2A_o$	-	0.89	0.67	0.49	0.27	0.06

B

oK	H	165.0	125.0	85.0	45.0	5.0	0.0
oK	V	181 ~~153.0~~	113.8 ~~96.06~~	63.2 ~~53.2~~	25.9 ~~21.85~~	4.43 ~~4.58~~	0.0
oK	A	1.0	0.89	0.67	0.49	0.27	0.06
oK	A·R	1.9 ~~1.6~~	1.69 ~~1.42~~	1.27 ~~1.07~~	.93 ~~0.78~~	.51 ~~0.43~~	.11 ~~0.10~~
oK	A·I	1.0	0.89	0.67	0.49	0.27	0.06
oK	A·L	1.0	0.89	0.67	0.49	0.27	0.06
oK	A·E	7.2 ~~6.0~~	6.4 ~~5.34~~	4.8 ~~4.02~~	3.5 ~~2.94~~	1.9 ~~1.62~~	0.4 ~~0.36~~

R, I, L, E, V in units x 10^5 acre-ft

~~doesn't match p 3~~

C

A	1.0	0.89	0.67	0.49	0.27	0.06	oK
S	114 ~~93.64~~	111.44 ~~91.00~~	104.00 ~~89.01~~	91.00 ~~87.56~~	89.69 86.76	89.26 ~~86.58~~	oK
V	181 ~~153.0~~	113.8 ~~96.06~~	63.2 ~~53.20~~	25.9 ~~21.85~~	4.43 ~~4.53~~	0.0 0.0	oK
Y (ppm)	460 ~~450~~	718 ~~697~~	1215 ~~1250~~	2580 ~~2946~~	14,900 13,929	-	oK
Y (tons/ ac-ft)	0.63 ~~0.612~~	.978 ~~0.947~~	1.65 ~~1.673~~	3.51 ~~4.007~~	20.23 18.943	..	oK

Need correcting except first column of figures

S, V = units x 10^5 acre-ft. (ppm x 0.00136 = tons/acre-ft)
S = units x 10^5 tons

Done - D.B.

Table 4

proportionality factor designed to average the changes in I and L as the lake area shrinks. Table 4C lists the solution of the dissolved solids equation for lake concentration and the total quantity of dissolved solids.

If all the dissolved solids at year 58.16 are precipitated on a lake area of 36.9 square miles, a thickness of evaporites 1.15 inches deep will be deposited for a specific gravity of 2.6 gm/cc for the evaporite minerals. The calculations, while admittedly approximate, show without doubt that the maximum thickness of evaporites could not much exceed one inch. Since the disappearance of the lake, more than enough rainfall has fallen on the playa to flush away by way of infiltration all the evaporites which may have been precipitated.

WATER CHEMISTRY

Water samples from the study area were collected and analyzed in order to define the chemical characteristics of the groundwater and to delineate possible differences due to reaction along flow patterns. Table 5 is a tabulation of the results of the analyses.

Comparison of proportions of the cations and anions is the first step in attempting to differentiate water types. The Piper diagram (Hem, 1970) in Figure 6 includes all twenty chemical analyses. Immediately apparent from the anion triangle is the high percentage of bicarbonate ion in most of the samples. Only samples W 16 and W 11 are low in bicarbonate and high in chloride. Inspection of the cation triangle reveals that most analyses plot near the center. The majority of waters can thus be classified as mixed-cation, bicarbonate waters.

Relative percent of oversaturation or undersaturation for the minerals calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), and gypsum ($CaSO_4 \cdot 2H_2O$) was calculated from the chemical data. A computer program was used to calculate ionic strength (I) and, using the value of I, to calculate the activity coefficients of the ions by the Debye-Huckel equation (Garrels and Christ). The calculated ionic strengths were not over 0.01 so the Debye-Huckel equation is valid. An ion activity product was then calculated and compared to the solubility product for the mineral of interest.

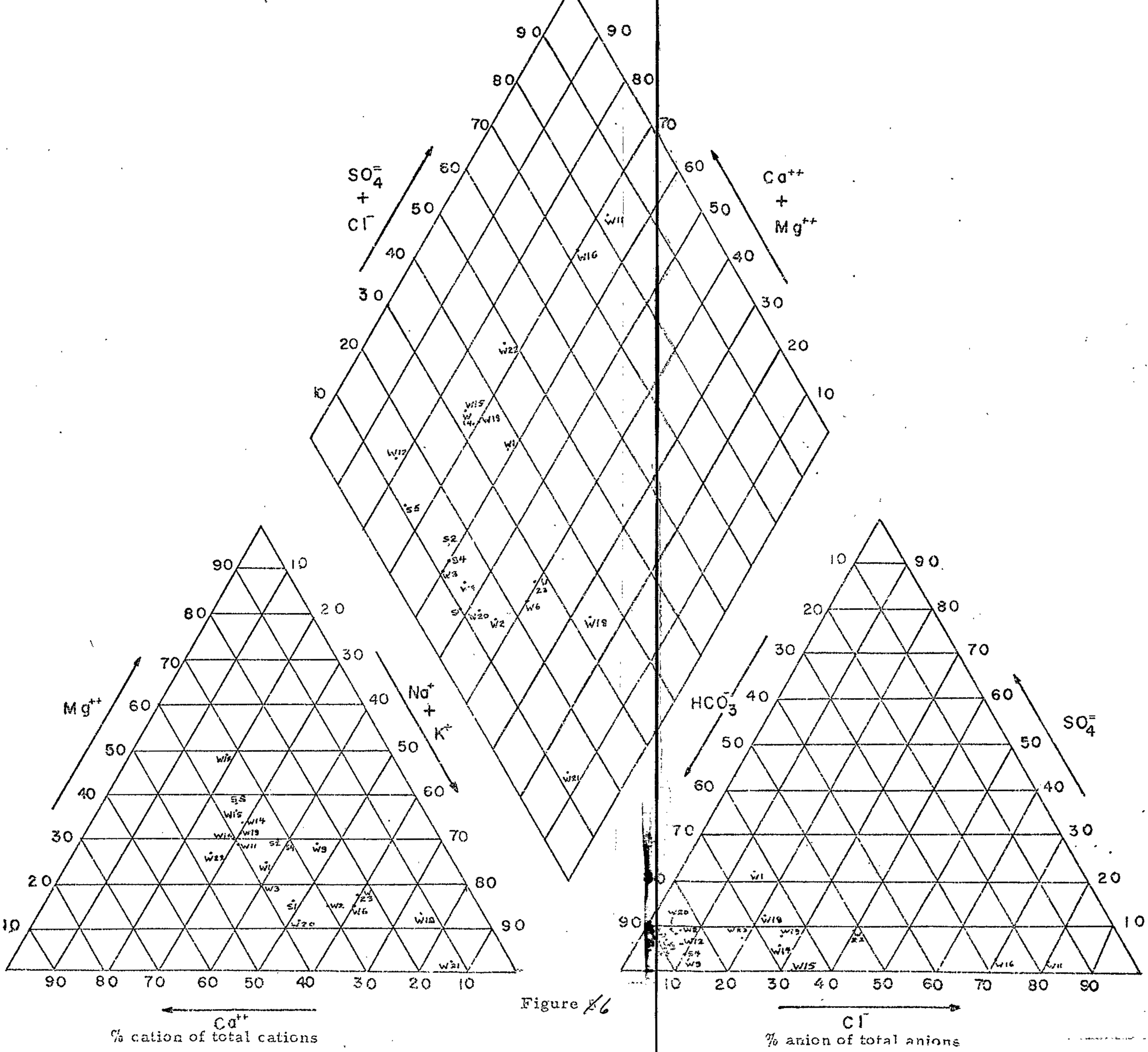
SO$_4^=$ + Cl$^-$
Ca^{++} + Mg^{++}
Mg^{++}
Na$^+$ + K$^+$
Ca^{++}
% cation of total cations
HCO$_3^-$
SO$_4^=$
Cl$^-$
% anion of total anions
10
20
30
40
50
60
70
80
90
W11
W16
W22
W15
W14
W13
W1
W12
S5
S2
S4
W3
W5
S1
W20
W2
W6
W23
W18
W21
W9

Figure 16

~~Place in order by location no., not sample no.~~

Sample Number, ~~Township & Range~~ Location Number	Ca^{++} meq/l*	Mg^{++} meq/l	Na^{+} meq/l	K^{+} meq/l	Cl^{-} meq/l	$SO_4^{=}$ meq/l	HCO_3^{-} meq/l	Total Cations / Anions	pH	Specific Conductivity**
S1 5. 16. 3. 133	1.05	0.494	1.26	0.20	0.11	0.20	2.90	3.00 / 3.21	7.84	332
S2 5. 17. 33. 141	1.21	1.14	1.23	0.18	0.20	0.25	2.56	3.75 / 3.01	6.80	415
S4 5. 14. 9. 412	0.67	0.675	0.70	0.17	0.23	0.10	2.00	2.22 / 2.33	7.70	250
S5 5. 15. 22. 314	0.90	0.979	0.53	0.17	0.17	0.15	2.53	2.58 / 2.85	8.03	300
W1 4. 16. 28. 211	0.90	0.59	0.67	0.31	0.34	0.54	1.56	2.47 / 2.44	6.77	247
W2 4. 16. 35. 132	0.70	0.35	0.91	0.36	0.17	0.22	2.04	2.32 / 2.43	7.69	216
W3 4. 15. 32. 124	1.30	0.66	0.96	0.33	0.17	0.19	2.88	3.25 / 3.22	7.64	370
W6 4. 15. 26. 331	0.61	0.43	1.33	0.20	0.34	0.34	2.21	2.57 / 2.89	8.08	284
W9 4. 13. 29. 331	1.07	0.90	1.57	0.11	0.42	0.12	3.16	3.65 / 3.70	7.68	374
W11 5. 14. 33. 133	7.73	5.93	5.22	0.28	17.55	0.39	4.02	19.16 / 21.96	7.57	2,533

(in mg/l in Appendix A)

Table 5 -- Chemical Analyses in milliequivalents per liter of Groundwater Samples

* millequivalents per liter

** micromhos per centimeter

Dan

1) Show mg/l too – this is what most people will look for, tho' you needed meq/l for calcs 3938

2) Title for table

3) Must show collection date or anal. date. either here or in Appendix

[collection date is same date as when water table was measured see Table 1 -DB.]

Sample Number, ~~Township & Range~~ Location Number	Ca^{++} meq/l	Mg^{++} meq/l	Na^{+} meq/l	K^{+} meq/l	Cl^{-} meq/l	$SO_4^{=}$ meq/l	HCO_3^{-} meq/l	Total $\frac{\text{Cations}}{\text{Anions}}$	pH	Specific Conductivity
W12 6. 15. 13. 333	0.85	1.28	0.35	0.14	0.20	0.12	2.00	$\frac{2.62}{2.32}$	7.35	212
W14 6. 14. 28. 314	0.91	0.82	0.54	0.18	0.56	0.12	1.40	$\frac{2.45}{2.08}$	7.69	242
W15 7. 14. 3. 142	0.88	0.90	0.50	0.15	0.65	0.00	1.40	$\frac{2.43}{2.05}$	7.92	235
W16 7. 14. 23. 112	2.40	1.80	1.65	0.18	4.36	0.21	1.64	$\frac{6.03}{6.21}$	7.85	726
W18 6. 13. 11. 244	0.55	0.66	3.10	0.18	1.01	0.58	3.08	$\frac{4.49}{4.67}$	7.89	546
W19 5. 12. 9. 434	1.55	1.28	1.04	0.18	1.07	0.33	2.68	$\frac{3.95}{4.08}$	7.67	424
W20 8. 12. 32. 211	0.912	0.304	1.30	0.28	1.97	0.26	2.56	$\frac{2.51}{3.02}$	7.17	205
W21 8. 11. 5. 242	0.404	0.082	2.82		0.197	0.21	2.84	$\frac{3.30}{3.25}$	7.88	258
W22 4. 11. 34. 121	3.44	1.97	1.87	0.47	2.31	0.51	2.96	$\frac{7.28}{5.78}$	7.11	726
W23 5. 11. 1. 212	1.72	1.30	4.35	0.47	1.24	0.51	4.80	$\frac{7.41}{6.55}$	7.20	716

Table 5 (Continued)

Table 6 is the list of relative percents of saturation for the three minerals. Because of the very low sulfate values, ion activity products for gypsum never exceeded 2% of the gypsum saturation value and mostly was less than 0.2%. Sample S5, from spring 5. 15. 22. 314, is 110% saturated with respect to dolomite. The water issues from a basalt caprock. Basalts typically have high Mg^{++} content (Clarke, 1924), and studies by Garrels (1967) and by others (Feth, et al., 1964; Garrels and MacKenzie, 1967) have shown that the ferromagnesian minerals, common in basalts, are highly susceptible to dissolution and leaching of Mg^{++} ions. This mechanism probably accounts for the supersaturation of dolomite in the sample.

Sample W11 from well 5. 14. 33. 133 is at 750% of saturation with respect to dolomite. This sample from the northwest edge of the plains floor is among all samples because it has by far the highest ionic concentration and the greatest degree of supersaturation with respect to both calcite and dolomite. Furthermore, the percentages of chloride among anions in this saline sample is very high and cannot be readily explained. Simple evaporative chemical concentration of surface runoff seems an unlikely explanation inasmuch as the chloride/ sulfate ratio for the sample is 45, whereas other water samples from the basin floor have ratios of about two. If the water had evaporated to concentrate the chloride ion, sulfate should still be present in approximately this ratio because gypsum solubility would not have been

Sample #	% saturation with respect to calcite	% saturation with respect to dolomite	% saturation with respect to gypsum
S1	95.0	34.0	0.12
S2	8.5	0.56	0.17
S4	31.0	7.6	0.042
S5	110.0	110.0	0.077
W1	2.5	0.031	0.30
W2	16.0	0.98	0.10
W3	52.0	11.0	0.14
W6	74.0	30.0	0.12
W9	71.0	35.0	0.075
W11	340.0	750.0	0.89
W12	17.0	3.5	0.063
W14	29.0	6.0	0.069
W15	48.0	19.0	0.0
W16	110.0	75.0	0.24
W18	56.0	31.0	0.17
W19	83.0	44.0	0.27
W20	38.0	1.5	0.33
W21	94.0	5.8	0.11
W22	120.0	25.0	1.7
W23	130.0	39.0	1.0

Title ?

Relative percentage of

Table 6 -- Mineral saturation in water samples ? ?

exceeded, therefore precipitation would not have occurred.

Another model that might account for the high chloride values in these two samples is one that cannot be readily substantiated. Local deposits of evaporite minerals may have been formed from the very dregs of Lake San Augustin as it was evaporating. Surface water infiltrating through such local deposits could dissolve the NaCl much more readily than the other evaporite minerals, thereby causing the high chloride.

Sample W 16 (7. 14. 23. 112) also has a chloride value that is approximately 10 times the average for water samples and a chloride/sulfate ratio that is anomalous. This well is not on the valley floor, but on the lower part of the slopes south of the southernmost San Augustin Plain.

Samples W22 and W23, from 4. 11. 34. 121 and 5. 11. 1. 212 respectively, are both supersaturated with respect to calcite. Since these two wells occur in a topographic and groundwater depression of local extent, evaporative concentration and subsequent infiltration of collected surface runoff may account for their supersaturation and relatively high specific conductivity.

Ion Ratios

Ion ratios have been used by several authors (Garrels, 1967; Feth, et al., 1964; Garrels and MacKenzie, 1967) to illustrate the relationship between lithology and chemical composition of groundwater.

The ratios of millimoles per liter of ion to millimoles per liter of HCO_3^- are graphed in Figures 7 and 8 for comparison with similar graphs for waters of known chemical composition and lithologic association. Figures 9 and 10 are taken from Garrels' (1967) paper on the origin of groundwaters. These are graphs of representative groundwater samples from known igneous terranes compiled by White, et al. (1963).

Sample S5, from spring 5. 15. 22. 314 is issuing from a basalt flow, has a graph very similar to the representative graphs for basalts, as does sample W12 (6. 15. 13. 333). The well from which W12 was collected receives its water from drainage over predominantly basaltic rocks on Long Canyon. Samples W1 (4. 16. 28. 211), W9 (4. 13. 29. 331), W14 (6. 14. 28. 314), W15 (7. 14. 23. 142), W18 (6. 13. 11. 244), W19 (5. 12. 9. 434), W20 (8. 12. 32. 211), S1 (5. 16. 3. 133), S2 (5. 17. 33. 141), and S4 (5. 14. 9. 412) all have graphs that are similar to rhyolites (only W1, W14, and W15 are showing, W14 and W15 being identical). The predominant rock type in the San Augustin drainage area is rhyolite.

Several samples contain Cl^-/HCO_3^- and $SO_4^=/HCO_3^-$ ratios so high that they do not compare with graphs for igneous drived groundwaters (W11, W16, W22 + W23). These waters are assumed to result from either evaporative concentration or possible leaching of soluble minerals from the lacustrine sediments.

The heights of the bars are proportional to the mole ratio of the constituents to HCO_3^-.

average of the 2?
or are graphs
identical?
explain in text

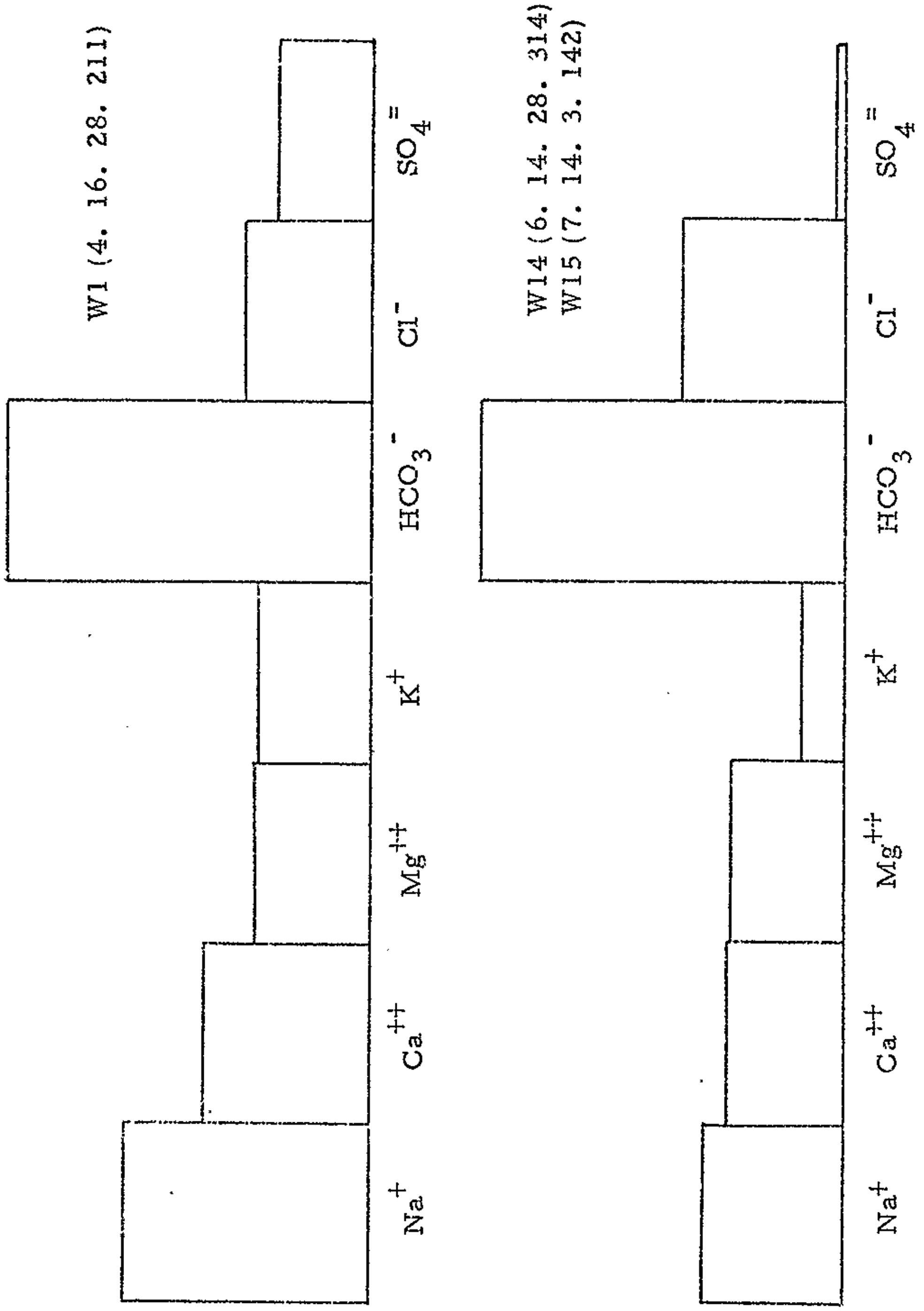


Figure 67

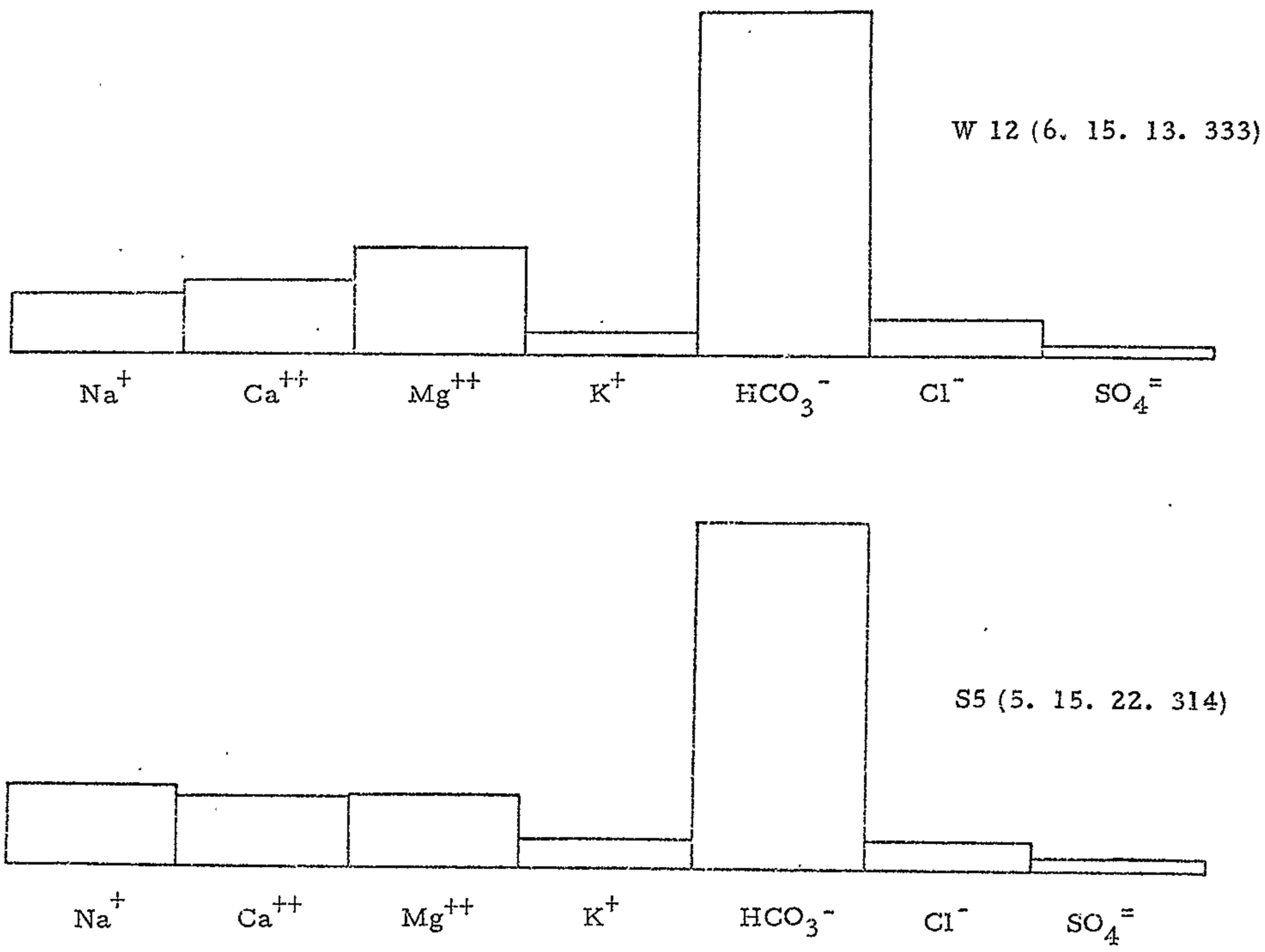


Figure 7/8

The heights of the bars are proportional to the mole ratio of the constituents to HCO_3^-.

The heights of the bars are proportional to the mole ratio of the constituents to HCO_3^-.

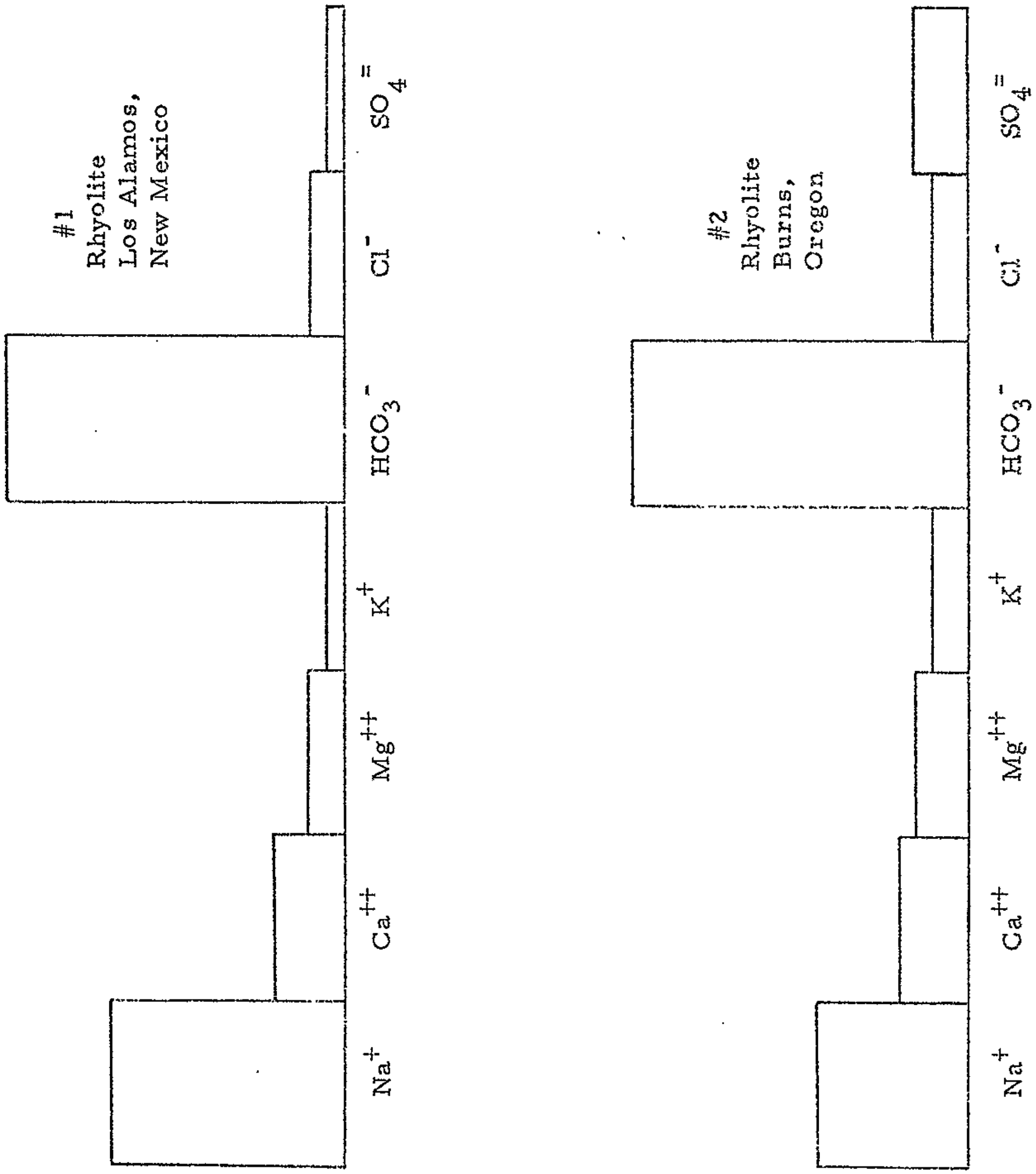


Figure ~~8~~ 9

The heights of the bars are proportional to the mole ratio of the constituents to HCO_3^-.

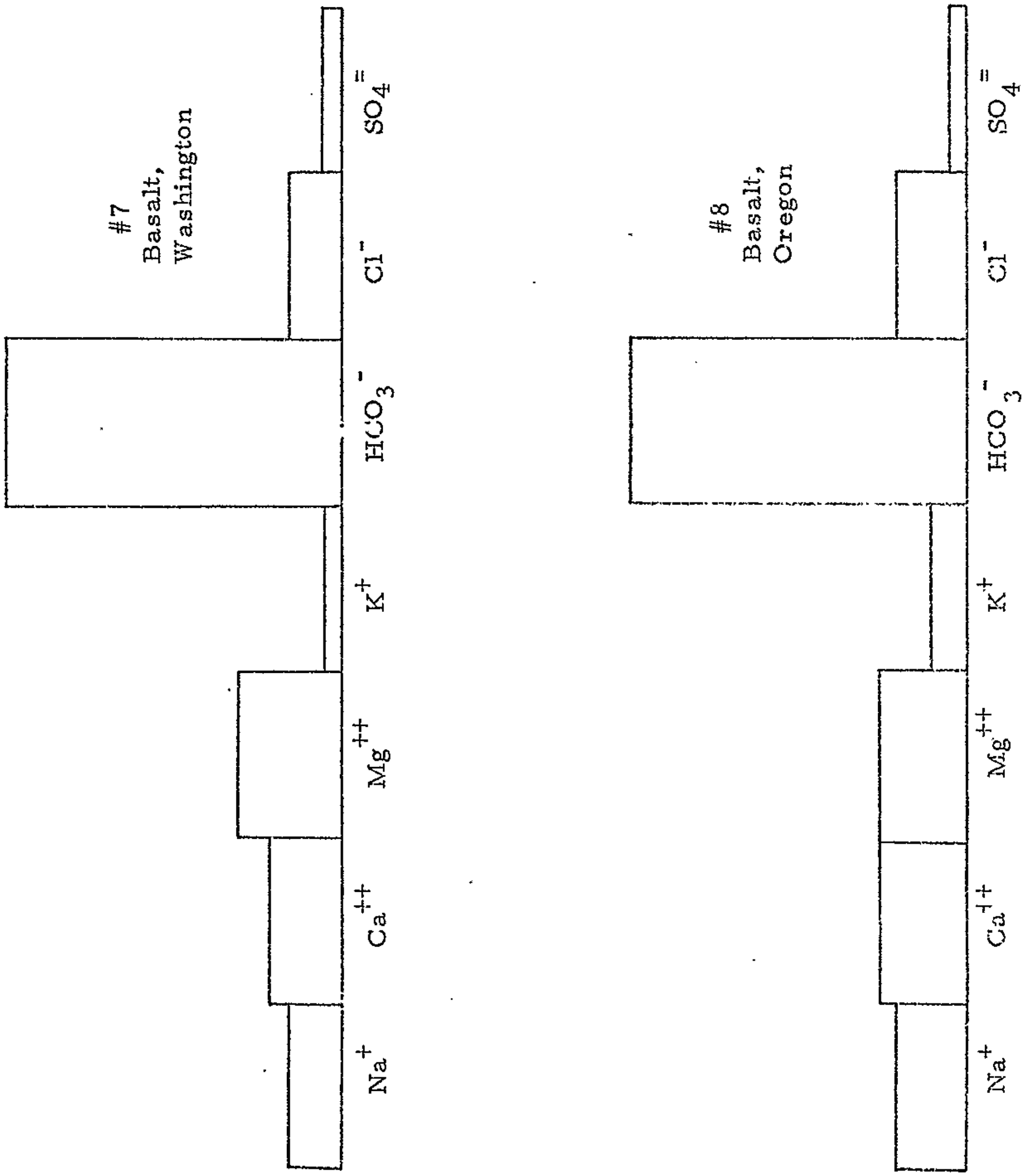


Figure ~~9~~ 10

SUMMARY

The San Augustin Plains, a closed basin in west-central New Mexico, was the site of an extinct Pleistocene lake. Reconstruction of the past hydrologic regime shows that little if any evaporites were deposited by the disappearing lake. Three deep drill cores substantiate the lack of evaporites.

The topographic basin is in a graben with 3, 000 to 4, 000 feet of downthrow. Surrounding the graben are thick sequences of predominantly rhyolitic lava flows. Chemically analyzed water samples are mostly of the mixed-cation bicarbonate type. Comparison of these analyses with water analyses from known lithologic associations suggest that the water chemistry results from contact with rhyolitic rocks.

Water levels throughout the basin were measured and compared to levels measured twenty years ago. No apparent change in overall water levels was noted. A water table contour map was constructed from the water levels. The contours suggest an area of substantial subsurface leakage at the south end of the basin. A hydrologic budget is used to estimate the amount of subsurface leakage. Using the inferred area of leakage and the water table contours at the south end of the basin, the permeability of the sediments through which leakage probably occurs was calculated to be $\underline{5.7 \times 10^2 \text{ gpd/ft}^2}$.

ACKNOWLEDGMENTS

We wish to thank Mary Osmer for substantial help. We especially thank well owners who allowed access to their wells and who provided much useful information based on their experience with "practical" hydrology.

APPENDIX A

Chemical Analyses in ~~Parts per Million~~ milligrams per liter

Sample #	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Cl^{-}	$SO_4^{=}$	HCO_3^{-}	Total
S1	21.0	6.0	29.0	8.0	4.0	9.6	177	254.6
S2	24.3	13.8	28.3	7.0	7.0	12.0	156	248.4
S4	13.5	8.2	16.2	6.5	8.0	4.8	122	179.2
S5	18.0	6.5	6.5	12.2	6.0	7.0	154	215.6
W1	18.1	7.2	15.5	12.0	12.0	26.0	61	151.8
W2	14.0	4.2	21.0	14.0	6.0	10.8	60	130.0
W3	26.0	8.0	22.0	13.0	6.0	9.0	124	208.0
W6	12.2	5.2	30.5	8.0	12.0	16.5	135	219.4
W9	21.5	11.0	36.0	4.4	14.8	6.0	158	251.7
W11	750.0	72.0	120.0	11.0	634.0	19.0	211	1817.0
W12	17.0	15.0	8.0	5.6	7.0	6.0	100	158.6
W14	18.2	10.0	12.4	7.0	20.0	6.0	70	143.6
W15	17.6	11.0	11.6	6.0	23.2	0.0	70	139.4
W16	48.0	22.0	38.0	7.0	154.8	10.0	82	361.8
W18	11.0	8.0	71.4	7.0	36.0	28.0	154	315.4
W19	31.0	15.0	24.0	7.0	38.0	16.0	134	265.0
W20	45.7	3.7	30.0	1.1	7.0	12.5	156	256.0
W21	20.3	1.0	118.0	-	7.0	10.0	173	329.3
W22	172.6	24.0	43.0	1.7	72.0	24.5	164	501.8
W23	86.3	15.8	160.0	1.8	44.0	24.5	293	625.4

APPENDIX B

Calculations

Page 20 1965 square miles x 640 acres/ square mile = 1,257,600 acres

$\frac{14}{12}\ \frac{\text{feet precipitation}}{\text{year}} \times 1{,}257{,}600 \text{ acres} = 1{,}467{,}200 \text{ ac-ft/yr}$

Page 22 $1{,}467{,}200 \text{ acre-ft/year} \cdot \frac{1}{14}\ \frac{\text{inch recharge}}{\text{inch precipitation}} =$

104,800 acre-ft/year

Page 22 100,000 acre-ft/year x 325,851 = 3.25851×10^{10} gal/year

325.851×10^8 gal/yr ÷ 365 days/yr = 0.892×10^8 gal/day

$0.892 \times 10^8 \text{ gal/day} \cdot 1 \text{ ft/1 mile} \cdot (1 \text{ mi.} \times 1 \text{ ft.}) \cdot \frac{1}{13} \cdot$

$$\frac{1}{1500} \cdot \frac{1}{8} = \text{gallons/day/ft}^2$$

$\frac{0.892 \times 10^8}{0.156 \times 10^6} = 5.71 \times 10^2 \text{ gallons/day/ft}^2$

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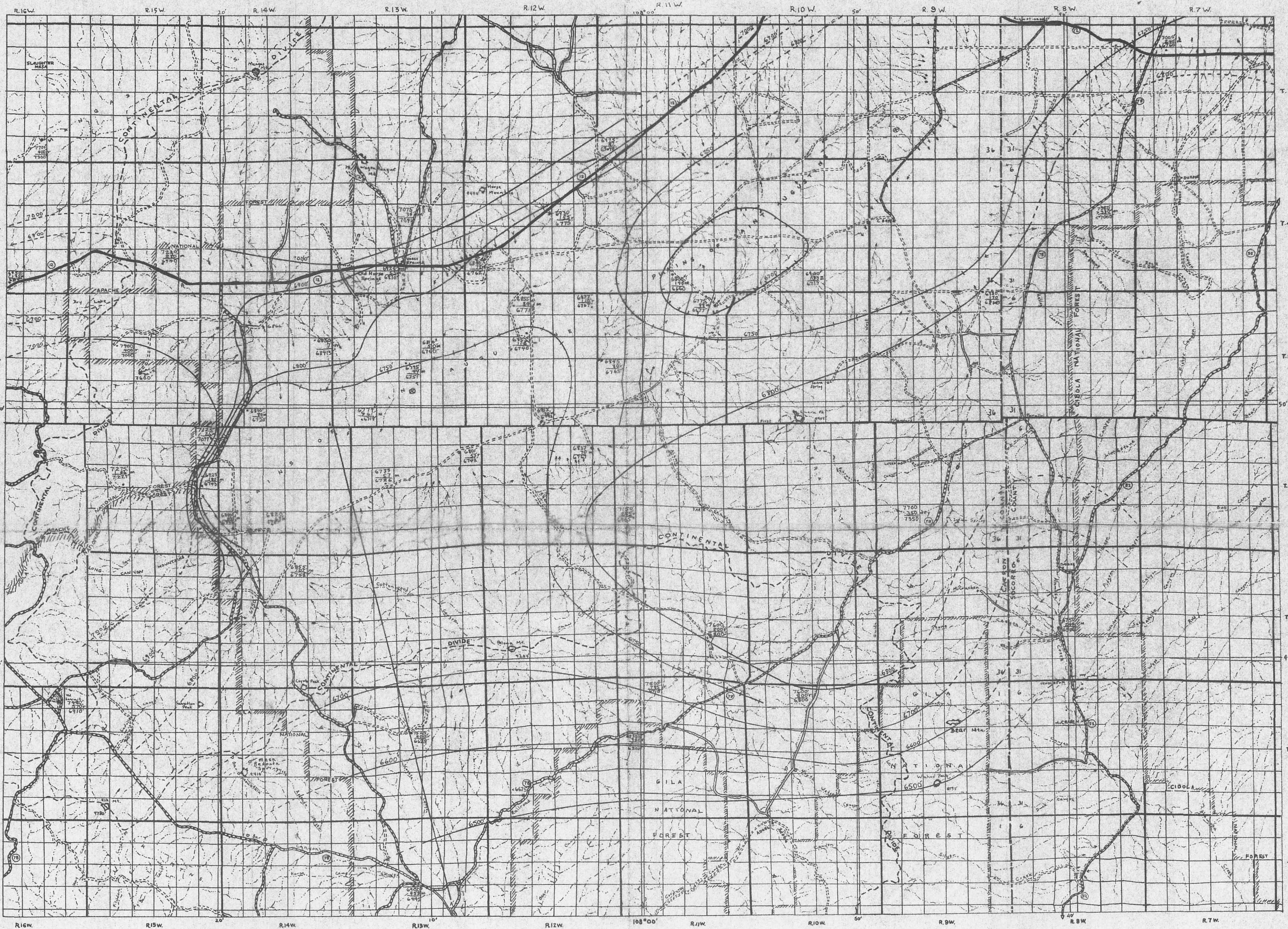


Scale 1/1?,000 or 1 Inch = 3 Miles

Plate 1

Index Map of New Mexico showing
location of San Augustin Plains

• - well
- spring

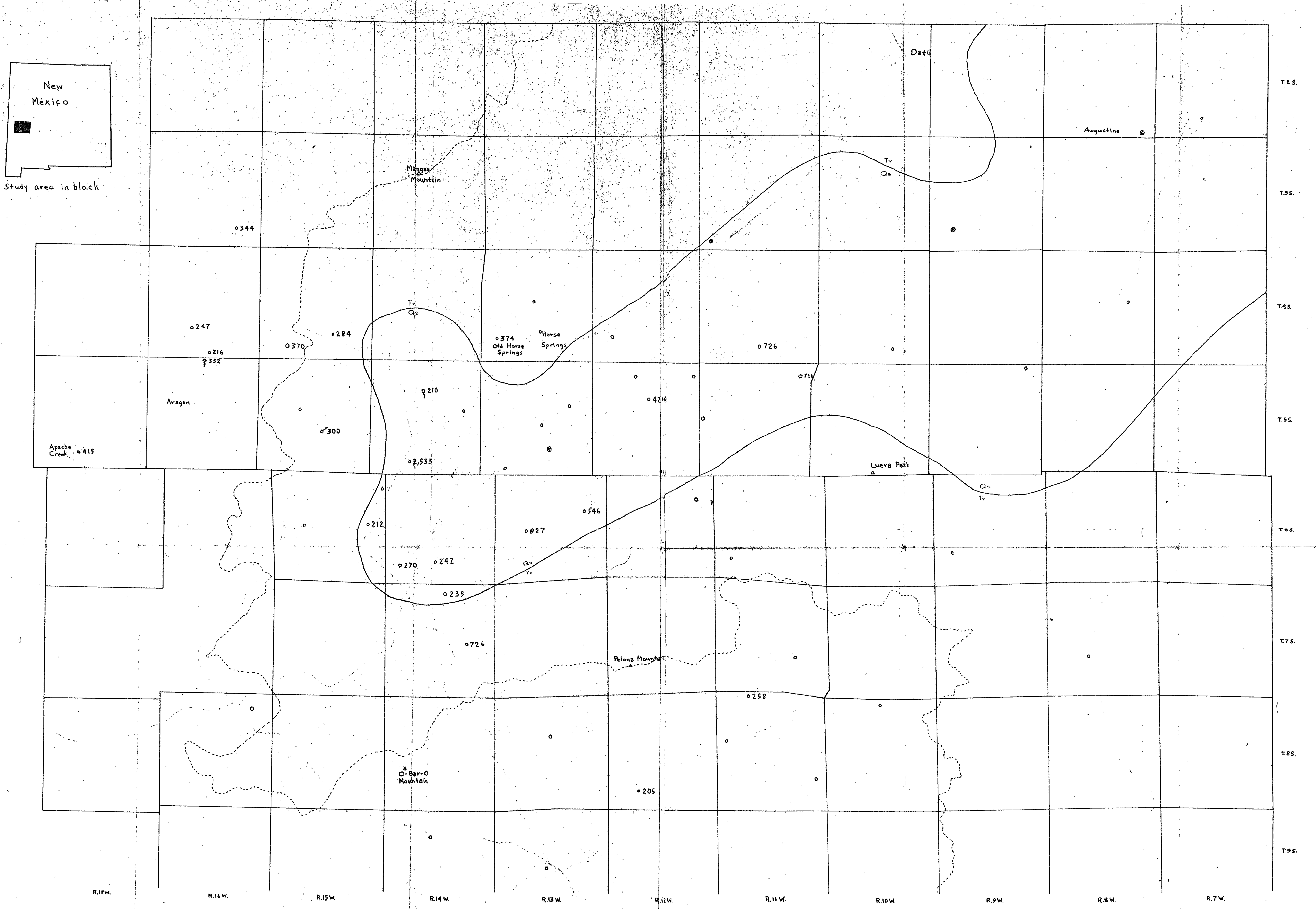
7325' well elevation
350' depth to water { r-reported
6975 water table elevation { m-measured

6700' 100 foot water table contours dashed where inferred

6750' 50 foot supplementary contours

A——A' Cross Section - Figure 1 in text

⊗ Deep Test Holes



Map Source:
New Mexico County Highway
Department Quadrangle Maps

Plate 2

Township and Range Locations
of
Wells and Springs

Key:

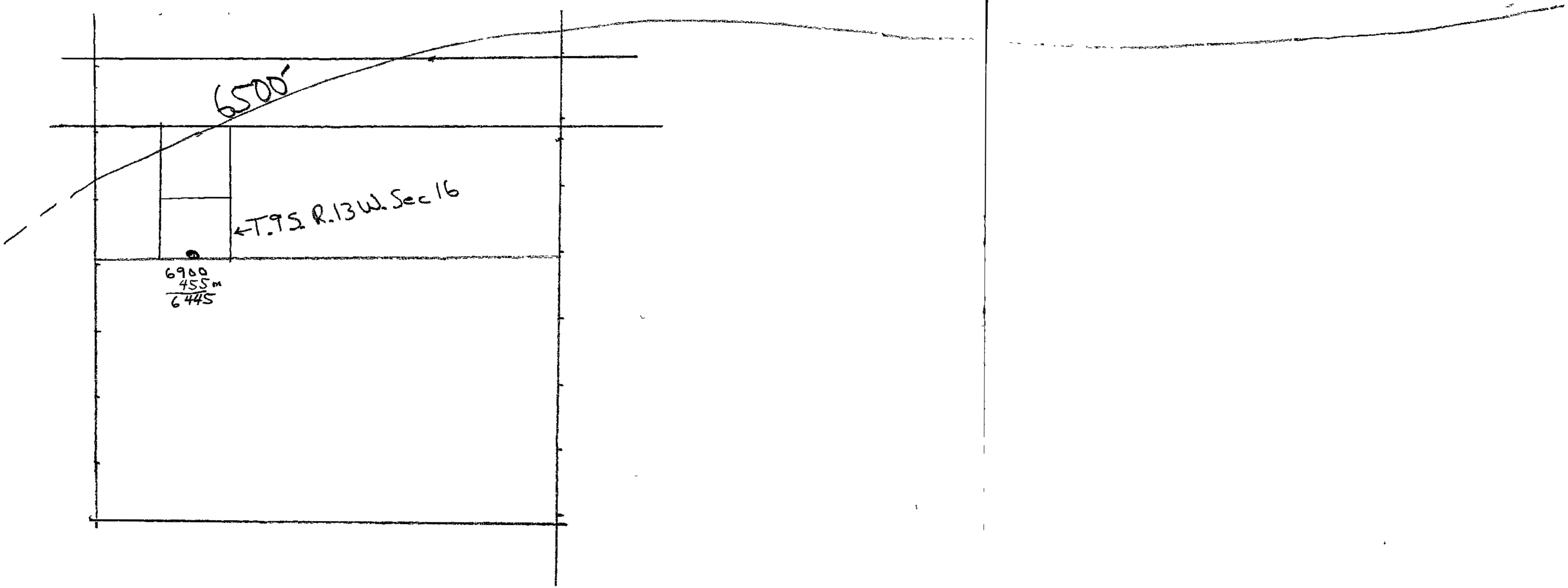
- —— - Roads
- ------ - Continental Divide
- o - Wells
- o~ - Springs
- 526 - Specific Conductance of Well or Spring Water
- —— - Boundary Between Basin Sediments (Qs) and Volcanic Flows (Tv)
- ⊗ - Deep Test Holes

By:
D. D. Blodgett
1972

WATER TABLE CONTOUR MAP

Note: a – elevations largely inaccurate

OK
8/8/73


6500'
←T.9S. R.13W. Sec 16
6900
455m
6445