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THE SAN ANDRES–GLORIETA AQUIFER IN WEST-CENTRAL NEW MEXICO

WILLIAM D. WHITE[1] and T. E. KELLY[2]
[1]Bureau of Indian Affairs, Albuquerque, New Mexico 87110; [2]Geohydrology Assoc., Inc., Albuquerque, New Mexico 87107

Abstract—The Glorieta Sandstone and overlying San Andres Limestone act as a single hydraulic unit which produces large quantities of water to wells in west-central New Mexico. The San Andres has been subjected to two periods of karstification which have locally reduced the thickness of the limestone and also created secondary permeability which enhances water production. The Zuni Mountains are the principal recharge area to the aquifer sequence; as much as 12,300 acre-feet of recharge occurs annually. Ground-water flow is radial from the mountains. Well production ranges from dry holes to several thousand gallons per minute. Chemical quality of the water is generally less than 1000 mg/l, but quality variations are significant in the Acoma sag.

INTRODUCTION

The principal source of potable ground water in west-central New Mexico is the San Andres-Glorieta aquifer system. Other formations are considered aquifers, but they are not as extensive, as productive or as good in water quality. For example, the Westwater Canyon Member of the Morrison Formation produces large quantities of water in the San Juan Basin (Kelly, 1977), but south of the basin the Westwater has been removed by erosion or pinches out. Several of the Cretaceous sandstones produce small to moderate quantities of ground water to wells. The gypsiferous Yeso Formation and older strata generally produce highly mineralized water. Only the Permian Glorieta Sandstone and overlying San Andres Limestone are capable of yielding moderate to large quantities of potable ground water.

The Glorieta Sandstone and San Andres Limestone with interbedded sandstone are hydraulically connected and act as a single hydrologic unit. This stratigraphic sequence is commonly referred to as the "San Andres-Glorieta aquifer system." Water production from this aquifer system ranges from zero for dry holes to several thousand gpm (gallons per minute). The water quality ranges from very good to highly mineralized. These variations in the quantity and quality of the water are a function of the stratigraphy and structure of the aquifer system.

STRATIGRAPHY OF THE AQUIFER SYSTEM

Glorieta Sandstone

The Glorieta Sandstone of New Mexico and the Coconino Sandstone of Arizona are correlative (Foster, 1957; Baars, 1962). While similar in lithologic character, the Glorieta is a marginal marine deposit, whereas the Coconino represents an eolian facies.

The Glorieta Sandstone is well exposed in the Zuni Mountains. In outcrop the sandstone is typically well-sorted, fine- to medium-grained, quartzose and uniformly bedded. Horizontal bedding predominates; where crossbedded, the bedding planes are relatively short and beveled at the top, suggesting a high energy, subaqueous mode of deposition. On the weathered exposures, the sandstone is typically yellowish brown to buff and gray. The unweathered samples from drill cuttings are characteristically pinkish white to pink. The degree and type of cementation vary throughout the areal extent of the sandstone units. In the Zuni Mountains the sandstone is typically cemented by calcium carbonate, and the degree ranges from very friable to hard.

Although McKee (1933) reported that silica is the principal cement of the Coconino Sandstone of Arizona, the type and degree of cementation of the Glorieta Sandstone is quite variable in New Mexico. Silica cement is common in the upper part of the unit in the Zuni Mountains (Gordon, 1961; Shomaker, 1971); carbonate cement predominates in areas drilled near Prewitt and Ramah (T. E. Kelly, unpubl. reports for Plains Electic Generation and Transmission Cooperative, 1981 and Bureau of Indian Affairs, 1988). As will be discussed in a later section, the degree and amount of cementation have a major bearing on the production of ground water from the Glorieta Sandstone.

In most of west-central New Mexico, the Glorieta Sandstone is conformable with the underlying Yeso Formation. Owing to the similarity of the upper Yeso with the basal Glorieta, the contact between the two units is not always distinct. In the subsurface the base of the Glorieta is usually identified as the bottom of the lowermost pink, well-sorted, quartzose sandstone. Using this criterion as the base of the Glorieta, the thickness of the sandstone ranges from a feather-edge on the north to as much as 100 m in the Zuni Mountains. There is a gradual thickening from north to south (Fig. 1). The northern boundary is erosional. There is an erosional remnant described as Glorieta in the Beautiful Mountain area of the Defiance uplift (Baars and Stevenson, 1977, p. 136).

San Andres Formation

The San Andres Formation is a highly variable lithologic unit in west-central New Mexico (Fig. 2). A lateral equivalent of the Kaibab Limestone of Arizona, the San Andres ranges from a cliff-forming limestone and dolomite in the Zuni Mountains to coarse-grained clastics of the Bernal Formation on the east, and an evaporite sequence southeast of the Zuni Mountains. From the standpoint of ground-water production, it is the presence of limestone that is critical to large well yields.

According to Baars (1962, p. 203), "the lithologic details are extremely variable throughout the range, representing numerous variations on a shallow carbonate shelf." In the Zuni Mountains there are three distinct units of the formation. The lower member contains thin- to

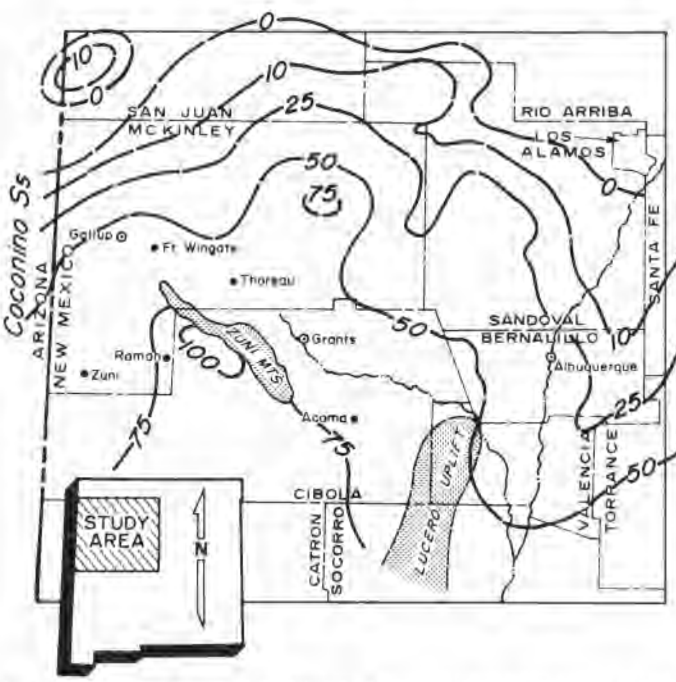

FIGURE 1. Isopach map of the Glorieta Sandstone showing thickness in ft; the sandstone is locally missing from the core of the Zuni uplift.

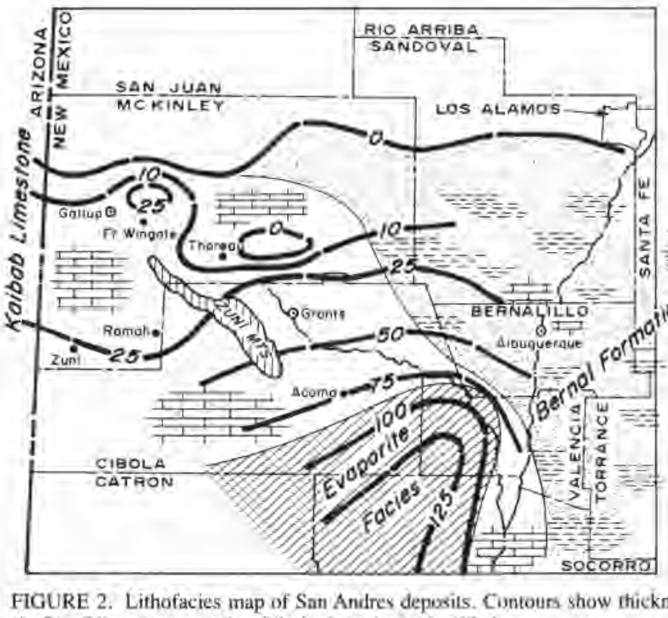

FIGURE 2. Lithofacies map of San Andres deposits. Contours show thickness (in ft) of limestone or other lithologies where identified.

medium-bedded dolomites, variegated shales and siltstone and thin sandstone stringers similar to the underlying Glorieta deposits. The middle member is composed of white to pinkish, medium to coarse, massive sandstone. The upper unit is a cliff-forming massive, white to pink, locally fossiliferous, limestone. The middle clastic unit pinches out toward the west end of the Zuni Mountains. Kelley and Wood (1946) described the evaporite facies of the Lucero basin and distinguished these from the evaporites in the underlying Yeso Formation. Baldwin and Anderholm (in press) estimated that the San Andres consists of 55% gypsum, 35% limestone and 10% sandstone in outcrop on Lucero Mesa. The presence of these evaporites has a bearing on ground-water development because of the mineralization which they contribute to the water. It should also be noted that wells penetrating these strata have encountered igneous intrusives in the Acoma sag. Although the San Andres interfingers with the Bernal Formation along the Rio Grande trough, 7 m of limestone was penetrated by Shell's Santa Fe Pacific No. 1 which was drilled a few miles west of Bernalillo, New Mexico (Black and Hiss, 1974, table 2). Kelley and Northrop (1975, p. 52) described a thin sequence of limestone of San Andres age in the Sandia Mountains of Bernalillo County.

The northern extent of the San Andres Formation was established by gradual thinning of the formation toward the north followed by post-depositional erosion. The average thickness increases toward the south, with as much as 123 m being present in the Lucero basin (Baars, 1961, fig. 3) southeast of the Zuni Mountains. It should be noted that limestone is the distinguishing lithology of the San Andres Formation, particularly when examined in well cuttings. Thus, the absence of limestone might suggest the absence of the entire formation where a clastic facies is actually present.

The Permian-Triassic unconformity

The erosional cycle following Permian deposition was a critical event in the development of the San Andres-Glorieta aquifer system. The San Andres limestone is considered to be of lower Guadalupian age (Newell et al., 1953, p. 15). According to Cooley (1959, p. 66), the hiatus represented by the unconformity becomes progressively greater from west to east, and in the Zuni Mountains the upper Moenkopi(?) sediments are probably Upper Triassic in age.

Exposures in these mountains display a hill-and-valley erosional topography having a relief of about 12 m. However, there are local exposures of more significant erosion where dissection exceeded 31 m, and the San Andres Formation was completely removed exposing the Glorieta Sandstone. In the area between Ft. Wingate and Grants, Triassic sediments were deposited on a karst topography developed on the limestone (Smith, 1954). In one exposure south of Thoreau, a silty and sandy deposit containing petrified logs appears to have been a cave filling in the karst zone (Cooley, 1959). A well drilled by the Bureau of Indian Affairs south of Grants penetrated cavernous limestone within 8 km of the outcrop as did other exploratory wells on Acoma and Zuni Pueblo lands, as far as 60 km from the formation's outcrop.

This period of erosion and karstification greatly enhanced the porosity and permeability in the Glorieta and San Andres. Cementation of the well-sorted sandstone would have greatly reduced the primary porosity of the sands. However, the weathering of the sandstone added secondary porosity by removal of the calcium carbonate cement and a general breakdown of the lithification in the sandstones. The karst on the limestone is a form of secondary porosity. Not only were the joints opened, but karstification produces collapse of the overlying sediments and further adds to fracturing of the limestone.

Laramide deformation and erosion

The Chinle Formation blanketed the San Andres-Glorieta sequence and formed an effective seal which contains the ground water under artesian pressure. According to Hackman and Olson (1981), the Chinle Formation has a maximum thickness of about 460 m in the Gallup area; however, a well drilled by the Bureau of Indian Affairs near Ramah penetrated 595 m of Chinle (T. E. Kelly, unpubl. report for the Bureau of Indian Affairs, 1988). The Zuni uplift and associated structures are the result of Laramide deformation. Most of these structures have a northwest-southeast orientation; associated fault complexes have the same orientation in addition to a northeast-southwest trend (Kelley, 1967). As a result of this deformation, the Mesozoic rocks were stripped from the axis of the Zuni uplift, exposing the Paleozoic strata and the core of Precambrian rocks.

Development of joint systems accompanied the Laramide and later deformation. These joint systems provide secondary permeability to the rocks, they facilitate weathering, and they control the development of surface drainage systems. Orr (1987, p. 8) noted that there is a well-developed joint system paralleling the axis of the Piñon Springs anticline near Zuni Pueblo, and much of the surface drainage in that area is controlled by jointing. A second phase of karst development occurred with the exposure of the San Andres Limestone on the Zuni uplift. Gordon (1961) noted that the amount of karst development increased toward the Zuni Mountains in the Grants-Bluewater area. In the Acoma area, Baldwin and Anderholm (in press) suggested that dissolution occurred along a southeastward extension of the Zuni uplift. In both of these cases the increase in permeability would be associated with the Laramide deformation rather than the earlier, pre-Chinle erosion cycle.

HYDROLOGIC CONDITIONS

Recharge and ground-water movement

With uplift of the Zuni Mountains, a classic example of an artesian system was produced in the San Andres-Glorieta aquifer. More than 596 km^2 of the aquifer are exposed in an arcuate outcrop belt which completely encircles the core of the Zuni uplift. The elevation of the outcrop belt ranges from 2150 to 2550 m where it receives a minimum of about 0.36 m of precipitation. Shomaker (1971, p. 55) assumed that about 0.02 m of precipitation infiltrated to the aquifer as recharge while the remainder was lost from the outcrop by surface runoff and by evapotranspiration. Nevertheless, 20,000 m^3 of precipitation equals 16.2 acre-feet of recharge per km^2 per year, or a total of 12,300 acre-feet per year (4×10^9 gallons) to the aquifer system.

Recharge to the system moves down-dip within the aquifer. The overlying Chinle shale acts as a confining bed to water within the aquifer, and an artesian pressure is developed in the subsurface. Water in wells will rise above the top of the aquifer.

The level to which the water rises in a well is called the potentiometric surface. The configuration of this surface produced in the San Andres-Glorieta aquifer is shown in Figure 3. This map shows that ground water migrates radially away from the Zuni Mountains. The lowest

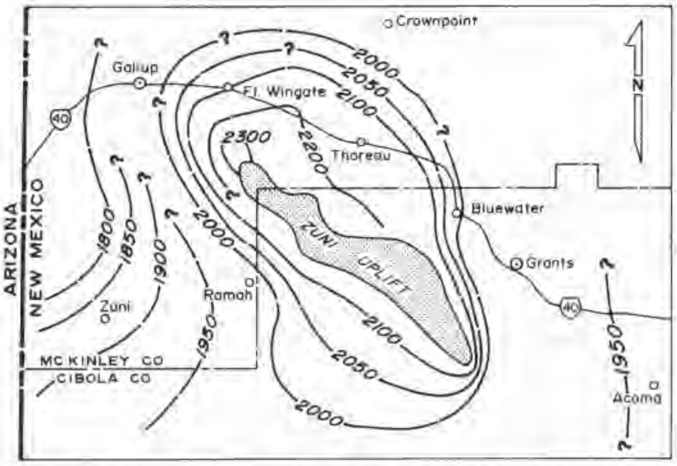

FIGURE 3. Potentiometric surface map of the San Andres-Glorieta aquifer system. Shaded area indicates the core of the Zuni uplift. Contours in meters above sea level; contour interval variable.

elevations on the potentiometric surface have been measured at 1850 m above sea level in the vicinity of Zuni and about 1950 m near Acoma. In those areas where erosion has lowered the land surface below the top of the potentiometric surface, all wells tapping the aquifer will flow at the land surface. Flowing wells are common on the north flanks of the Zuni Mountains between Thoreau and Ft. Wingate, and in the vicinity of Acoma and San Rafael at the east end of the uplift.

Ground-water production

The pumping rate of wells tapping the San Andres-Glorieta aquifer is quite variable, not only on a regional basis but within relatively short distances (Table 1). This variability is due to: (1) the presence or absence of limestone and (2) the degree of secondary permeability that has developed within the aquifer deposits. In selecting a well location, it is possible to estimate the amount of limestone that is likely to be present by consulting nearby well logs or maps, such as those shown in Figure 2; although this map shows that the limestone is thin to absent in areas where carbonates were expected to be present. The amount of secondary permeability at any given site is a matter of blind luck.

Under ideal conditions, a well should be drilled completely through the aquifer sequence, and the entire water-bearing zone should be screened. The transmissivity (ft^2/day) is the amount of water produced from a vertical strip of the aquifer one ft wide per unit head of gradient. (Transmissivity is roughly equivalent to the hydraulic conductivity times the thickness of the aquifer.) In many cases it is economically prohibitive to drill and screen the entire thickness. Therefore, only the most productive section of the aquifer will be screened. In the case of the San Andres-Glorieta aquifer, this is always the top of the aquifer sequence where the secondary permeability of both the limestone and sandstone is most likely to be greatest. Where only a portion of the aquifer is tested, it is appropriate to divide the calculated value of transmissivity by the screened interval to determine the hydraulic conductivity (ft/day). The hydraulic conductivity is roughly equivalent to the average permeability of the screened portion of the aquifer. Since the upper part of the San Andres-Glorieta aquifer is usually tested, it is possible to compare values of hydraulic conductivity in order to determine the possible production capacity of the aquifer in any given area.

A considerable number of aquifer tests have been conducted in the San Andres-Glorieta system; unfortunately, many of the tests were conducted on wells with unknown histories. In these cases, the perforated interval frequently is unknown, and it is not possible to calculate the hydraulic conductivity. Also, a number of wells in the Grants area have shown phenomenally high values for hydraulic conductivity (Gordon, 1961, table 8); however, most of these were multiple completions in both the San Andres-Glorieta aquifer and the overlying unconsolidated alluvium of the Rio San Jose. Consequently these values are somewhat misleading.

Values for hydraulic conductivity from wells known to be completed in the aquifer system do range from a phenomenal high of 1040 ft/day in the vicinity of Acoma Pueblo (Baldwin and Anderholm, in press) to less than 0.01 ft/day in other locations (Fig. 4). The hydraulic conductivity on the north slope of the Zuni uplift is generally less than 1.0 ft/day west of the Grants irrigation area (Shomaker, 1971, table 1; T. E. Kelly, unpubl. report for Plains Electric Generation and Transmission Coop., 1982). Perhaps the most noteworthy characteristic of these values is the variability within relatively short distances. Near Zuni Pueblo, the hydraulic conductivity in well Zuni F-5 was 26.4 ft/day and in well Black Rock 3 was 1.2 ft/day; these wells are approximately 4.83 km apart (Orr, 1987, p. 12). Crouch (in press) details a multiple well aquifer test near Zuni Pueblo's south boundary, with hydraulic conductivity values ranging from 2 to 62 ft/day within a 300 m radius. The wide range is attributed to completions in the cavernous system and intersecting fractures. Near Ramah the Bureau of Indian Affairs exploratory well No. 87-21 had a hydraulic conductivity of only 0.0046 ft/day. This well is approximately 30 km east of those at Zuni.

TABLE 1. Hydraulic characteristics of selected wells tapping the San Andres-Glorieta aquifer.

Well No. or Name	Location	Transmissivity ft^2/day	Hydraulic Conductivity ft/day
La Mosca	5. 8.35.123	cavernous	——
North Pasture	6.10. 7.141	70*	0.16
Sand Canyon	8. 6.20.333	108*	0.17
Sky City (Canyon)	8. 8.25.423	25	0.07
Zuni ZS-12	8.19.29.331	6,000	2.3
Zuni ZS-1	8.19.30.442	16,000	62.5
Casa Blanca	9. 6.16.111	542	1.2
Acoma N. 1	9. 9.28.1344	——	1530
Anzac	10. 9.25.3241	200,000	1040
Black Rock #3	10.19.24.122b	300	1.2
Zuni #F-5	10.19.27.112	1400	26.4
BIA 87-21	10.15.11.231	0.66	0.0046
Plains Electric #2	14.14.28.111	55	0.27
Prewitt Ranch New Well	14.15.17.412	110	0.27
BIA PM-7	14.16. 9.1222	520	2.97
Plains Electric #1	15.15.26.322	2936	14.7
Plains Electric #2	15.15.36.144	170	0.85
El Paso Natural Gas #6	15.16.20.2443	200	0.82

*open to other horizons also

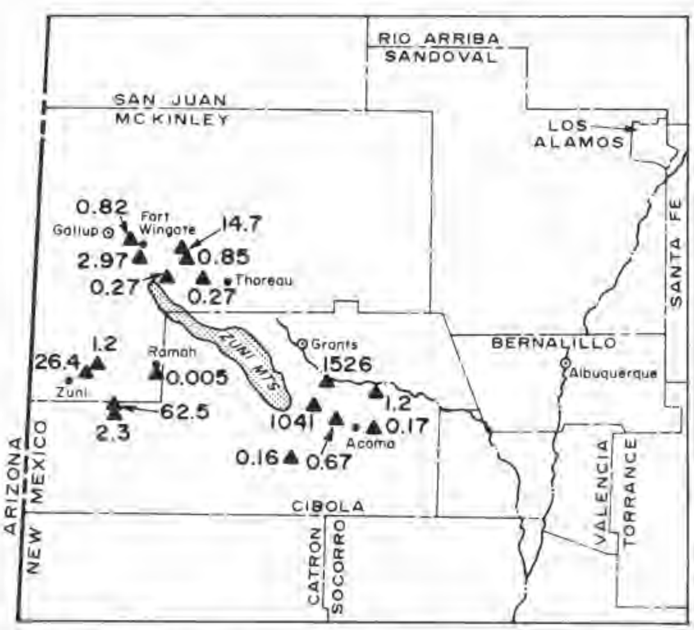

FIGURE 4. Map showing values of hydraulic conductivity for the San Andres-Glorieta aquifer sequence in west-central New Mexico.

Similarly, two wells drilled by Plains Electric Generation and Transmission Cooperative only 2460 m apart have hydraulic conductivities of 14.7 and 0.85 ft/day (Table 1). Values for hydraulic conductivity in the Acoma area range from the phenomenally high 1041 ft/day to a low of 0.07 ft/day. Of nine wells completed in the San Andres-Glorieta of the Acoma sag, four encountered cavernous zones as far as 60 km from the formation outcrop.

CHEMICAL QUALITY OF WATER

Potable water is obtained from most wells tapping the San Andres-Glorieta aquifer in west-central New Mexico. This water generally has less than 1000 mg/l (milligrams per liter) dissolved solids, which is quite good in comparison with many rural New Mexico areas. The water from the aquifer is locally used for small-scale irrigation; it provides the municipal supply for the Village of Thoreau, and the aquifer is tapped by wells which supply the Escalante Power Plant near Prewitt. Municipal wells at Grants and Milan also tap the aquifer, but most of these wells also are completed in the overlying alluvial deposits of the Rio San Jose. Therefore, samples from these wells are not necessarily representative of the chemical quality of the San Andres-Glorieta aquifer itself.

There is some variation in anions and cations within the aquifer (Fig. 5). Near Grants the water is a calcium bicarbonate type water, whereas calcium sulfate ions predominate in the Ft. Wingate area. East of the Zuni Mountains in the Acoma sag, the water chemistry is widely disparate, ranging from a calcium bicarbonate type to a calcium sulfate type.

The anomalous hydraulic conductivity value cited earlier for the Acoma sag is also the location of an anomalous geochemical and geothermal association. The exploratory well completed in sec. 28, T9N, R9W yields water with a comparatively low total dissolved solids (TDS) value and moderate temperature value, while a well (sec. 25, T10N, R9W) approximately 13 km distant yielded water with a high TDS value and high temperature (Table 2). While the second well was allowed to flow, a drawdown response was recorded at the first, suggesting a transmissivity value of 200,000 ft²/day (Baldwin and Anderholm, in press).

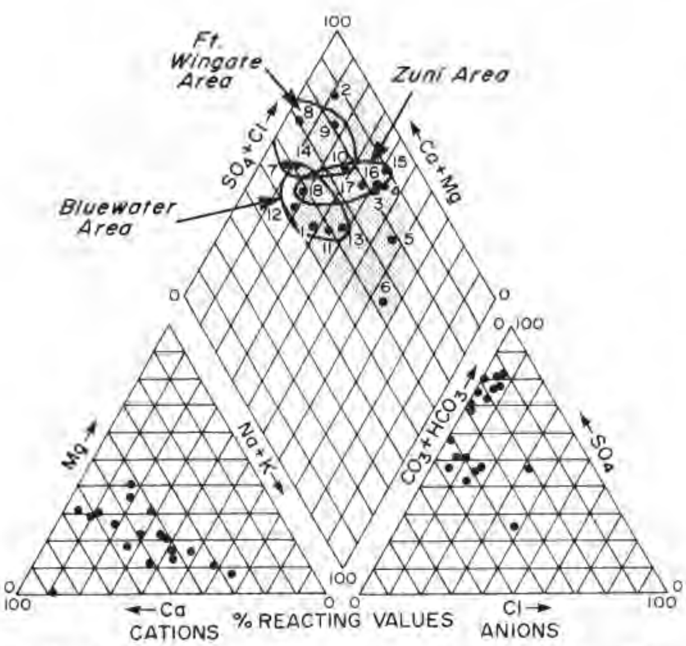

FIGURE 5. Trilinear diagram of water types found in the San Andres-Glorieta aquifer system of west-central New Mexico. Some grouping of water types is noted for small regions on the north and west flanks of the Zuni uplift, whereas the waters of the Acoma sag are widely disparate (shaded area). Sample numbers are listed in Table 2.

TABLE 2. Chemical quality and temperature data for water sources tapping the San Andres-Glorieta aquifer. Numbers correspond with samples plotted on Figure 5.

Plot No.	Location	Depth(m)	TDS(mg/l)	Sp. Cond.	Temp.(°C)	Source
			Acoma Area			
1.	9. 9.28.134	753.8	855	1100	35	USGS
2.	8. 8.25.423	707.7	3284	3390	36.5	BIA
3.	8. 6.20.333	673	5299	5080	40*	BIA
4.	9. 6.16.111	769	3515[a]	5100	56.8*	BIA
5.	10. 9.25.324	897	4160	8160	—	BIA
6.	6.10. 7.141	723	6199	8000	34	USGS
	5. 8.35.123	—	—	2800	—	USGS
			Ft. Wingate Area			
7.	13.13. 1.222	223	615	889	—	USGS
8.	15.15.18.3313	495	876	1190	—	USGS
9.	15.16.21.3231	401	971	1310	—	USGS
10.	15.17.13.1142	158	958	1330	—	USGS
			Bluewater Area			
11.	10.10. 3.423	Spr.	920	1410	17	USGS
12.	11.10. 8.111	41	512	805	—	USGS
13.	11.10.26.321	75	1350	1880	23	USGS
14.	12.10.23.233	266	2170	3040	—	USGS
			Zuni Area			
15.	10.19.13.444	367	889	1150	21	USGS
16.	10.19.24.122	326	1068	1470	26	USGS
17.	10.19.27.112	341	884	1190	26	USGS
18.	8.19.29.330	210	770	1010	27	BIA

[a]Calculated value
*Bottom hole temperature log

SUMMARY

The San Andres-Glorieta stratigraphic sequence forms an aquifer system of major importance in west-central New Mexico. Although there is very little natural porosity in these units, there have been two periods of erosion which have induced secondary permeability through weathering and dissolution of the aquifer.

This is a classic artesian aquifer system which receives recharge along the axis of the Zuni uplift, and the ground water migrates radially away from the mountains. Well production ranges significantly as a result of the variation in secondary permeability. The values for hydraulic conductivity range from 1040 ft/day in the vicinity of Acoma to less than 0.01 ft/day at various locations. Water in the San Andres-Glorieta aquifer is generally less mineralized than most of the other water-producing formations in that part of the state, but some locations are highly mineralized. Some variation in anions and cations has been noted. Some local grouping of water types has been noted.

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REFERENCES

Baars, D. L., 1961, Permian strata of central New Mexico: New Mexico Geological Society, Guidebook 12, p. 113–120.

Baars, D. L., 1962, Permian system of Colorado Plateau: American Association of Petroleum Geologists Bulletin, v. 46, p. 149–218.

Baars, D. L. and Stevenson, G. M., 1977, Permian rocks of the San Juan Basin, New Mexico and Colorado: New Mexico Geological Society, Guidebook 28, p. 133–138.

Baldwin, J. A. and Anderholm, S. K., in press, Geohydrology of the San Andres-Glorieta aquifer in the Acoma embayment and eastern Zuni uplift, west-central New Mexico: U.S. Geological Survey, Water Resources Investigation Report (prepared in cooperation with the New Mexico State Engineer Office, Pueblo of Acoma, Pueblo of Laguna and Bureau of Indian Affairs).

Black, B. A. and Hiss, W. L., 1974, Structure and stratigraphy in the vicinity of the Shell Oil Co. Santa Fe Pacific No. 1 test well, southern Sandoval County: New Mexico Geological Society, Guidebook 25, p. 365–370.

Cooley, M. E., 1959, Triassic stratigraphy in the state line region of west-central New Mexico and east-central Arizona: New Mexico Geological Society, Guidebook 10, p. 66–73.

Crouch, T. M., in press, Evaluation of the Bidahochi and San Andres-Glorieta aquifers on parts of the Zuni Indian Reservation, McKinley and Cibola Counties, New Mexico: U.S. Geological Survey, Water Resources Investigation Report (prepared in cooperation with the Pueblo of Zuni).

Foster, R. W., 1957, Stratigraphy of west-central New Mexico: Four Corners Geological Society, Guidebook 2, p. 62–72.

Gordon, E. D., 1961, Geology and ground-water resources of the Grants-Bluewater area, Valencia County, New Mexico: New Mexico State Engineer, Technical Report 20, 109 p.

Hackman, R. J. and Olson, A. B., 1981, Geology, structure, and uranium deposits of the Gallup 1° × 2° quadrangle, New Mexico and Arizona: U.S. Geological Survey, Miscellaneous Investigation Map I-981.

Kelley, V. C. and Wood, G. H., 1946, Lucero uplift, Valencia, Socorro and Bernalillo counties, New Mexico: U.S. Geological Survey, Oil and Gas Investigation Series, Preliminary Map 47.

Kelley, V. C., 1967, Tectonics of the Zuni-Defiance region, New Mexico and Arizona: New Mexico Geological Society, Guidebook 18, p. 28–31.

Kelley, V. C. and Northrop, S. A., 1975, Geology of Sandia Mountains and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 29, 136 p.

Kelly, T. E., 1977, Geohydrology of the Westwater Canyon Member, Morrison Formation, of the southern San Juan Basin, New Mexico: New Mexico Geological Society, Guidebook 28, p. 285–290.

McKee, E. D., 1933, The Coconino Sandstone—its history and origin: Carnegie Institute of Washington Publication, no. 440, p. 77–115.

Newell, N. D., Rigby, J. K., Fischer, A. G., Whiteman, A. J., Hickox, J. E. and Bradley, J. S., 1953, The Permian reef complex of the Guadalupe Mountains region, Texas and New Mexico. San Francisco, W. H. Freeman and Co.

Orr, B. R., 1987, Water resources of the Zuni tribal lands, McKinley and Cibola counties, New Mexico: U.S. Geological Survey, Water-Supply Paper 2227, 76 p.

Shomaker, J. W., 1971, Water resources of Fort Wingate Army Depot and adjacent areas, McKinley County, New Mexico: U.S. Geological Survey, Open-file Report, 276 p.

Smith, C. T., 1954, Geology of Thoreau Quadrangle, McKinley and Valencia counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 31.

Enchanted Mesa near Acoma Pueblo (photo courtesy of Mark Nohl, New Mexico Economic Development and Tourism Department).