GROUND WATER HYDROLOGY OF TERTIARY ROCKS OF THE SAN JUAN BASIN, NEW MEXICO

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INTRODUCTION

The purpose of this paper is to present the known facts relating to Tertiary aquifers of the San Juan Basin in New Mexico. These facts are based on data collected from observations at outcrops, correlations of electric logs, data of pumping tests of water wells and chemical analyses of water samples. Some of these rocks have the basic characteristics of aquifers and are composed of clastic sediments that are porous, permeable and contain water. Not all tertiary clastics of the San Juan Basin are aquifers. Some beds are porous and permeable, but do not contain water. Whereas other beds are porous and contain water, but are not permeable. The rocks which cannot yield water in quantities and at rates sufficient for use are the silts, clays and sandy shales.

In the past, rivers have been the main source of supply of water for communities and industry of the San Juan Basin and they will continue to be the major source of supply for the future. Water from rivers, however, is for all practical purposes, either fully appropriated and committed to states other than New Mexico by compact_agreements or is otherwise committed for specific use in the future. Socioeconomic conditions of the Basin, including the plans for the gasification of coal, the generation of electrical power, agriculture, and increasing population have caused the surface waters to be almost fully appropriated (N.M. Inter. St. Str. Comm., 1972).

Since little surface water is now available for appropriation and use, and since demands for water will continue to increase, sources of supply of water must be developed and managed effectively, efficiently, and correctly. This will be particularly true for cattle ranching, the production of oil and natural gas, and the development of subdivisions. Municipalities may be required to augment existing sources of supply from aquifers — especially during times of peak demand. The value of aquifers as a source of supply of water will increase because of demand and competition for a resource in limited supply.

The rocks which were evaluated as aquifers are indicated in figure 1. These rocks include the Ojo Alamo Sandstone (To), the Nacimiento Formation (Tn), and the San Jose Formation (Tsj). The aquifer characteristics of the Animas Formation (Tka, Tau) were not evaluated. Figure 1 illustrates, in a generalized way, the areal distribution of rocks of Tertiary age within the San Juan Basin of New Mexico and Colorado.

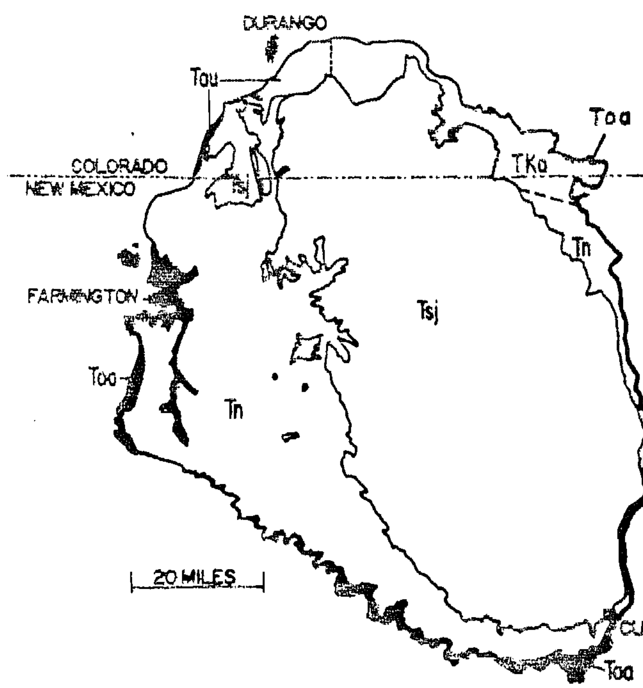

Fig. 1. Tertiary rocks of the San Juan Basin. Geology adapted from Fassett and Hinds (1971).

DISTRIBUTION OF AQUIFERS

One of the problems in evaluating the ground water potential of an area is determining the boundaries of rock facies that have aquifer characteristics. The contributions of other geologists, personal observations of the geology and hydrology, and correlations of electric logs were used to make this study. The distances between wells for which logs were correlated in this report varied from two to seven miles. Correlations were based on gross lithostratigraphic units and not individual beds of sandstone or clay and silt. A more detailed correlation and a resulting increase of accuracy in defining boundaries of aquifers could be made for small areas of the basin by using existing logs. A large amount of detail would be desirable for small areas; however, for this study enough unpublished data was analyzed to give an idea of the water potential of aquifers at selected locations. Almost all electric logs of wells drilled for hydrocarbons in the San Juan Basin have been released to the public.

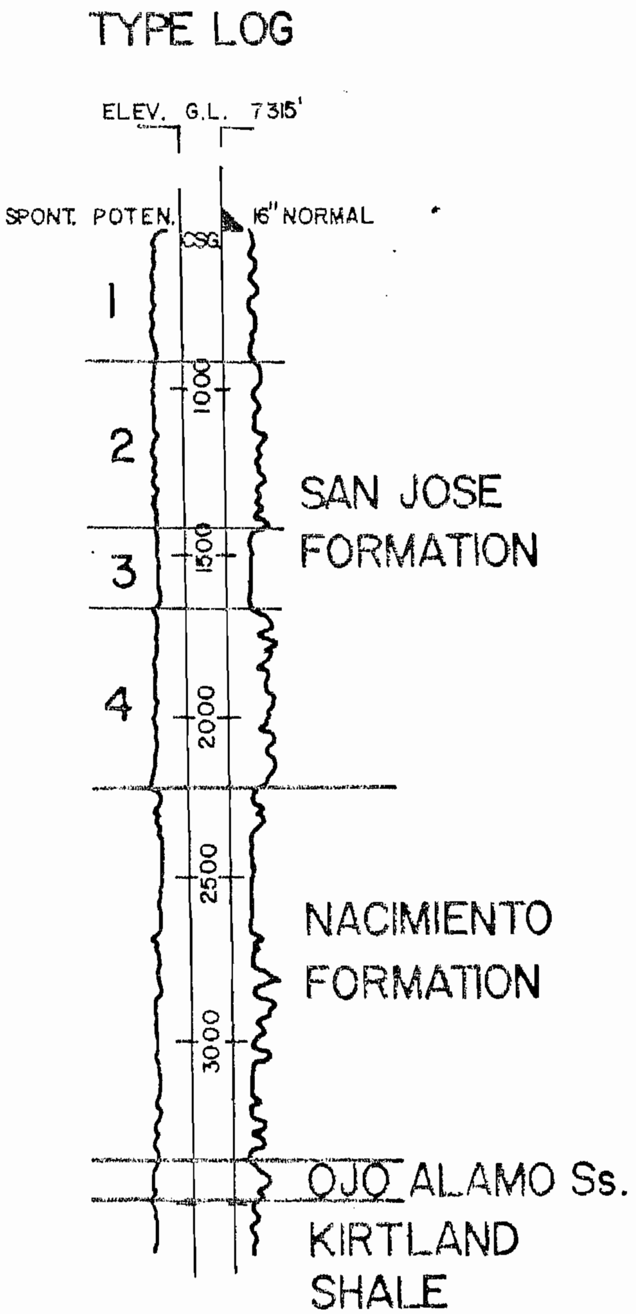

Fig. 2. Type log of rocks of Tertiary age, San Juan Basin, New Mexico. (Sunray DX Oil Company, #1 A Jicarilla Tribal, NW/4 NW/4, sec. 27, T. 28 N., R. 2W., Rio Arriba County, New Mexico.)

Distribution — The areal distribution of rocks of Tertiary age within the San Juan Basin of New Mexico and Colorado are shown in figure 1. These rocks are the Ojo Alamo Sandstone (Toa), the Nacimiento Formation (Tn), and the San Jose Formation (Tsj). The aquifer properties of the Animas Formation (Tka and tau) were not evaluated.

The vertical distribution of these rocks is illustrated in figure 2 which is the type log that was used as a standard to correlate other electric logs. Three lithostratigraphic units are shown on this log:-the Ojo Alamo Sandstone from 3475 feet to 3375 feet, the Nacimiento Formation from 3375 feet to 2230 feet, and the San Jose Formation from 2230 feet to the surface. Surface casing, as required by law, was set in this well at 542 feet; therefore, the interval from 542 to the surface could not be surveyed electrically. This is generally the case for oil and gas wells drilled in the San Juan Basin. Surface casing is set 200 to 600 feet in the well before electrical surveys are made, radioactivity surveys such as neutron and gamma ray, are not usually recorded at shallow depths. This makes correlations of rock units near the surface difficult if not impossible. (Producers of oil and natural gas are to be congratulated for obtaining some data on rocks that do not produce oil or gas — data of rocks at shallow depths. The reason for this, however, was to get their dollar's worth for the least expensive electrical survey and not for evaluations of aquifers.)

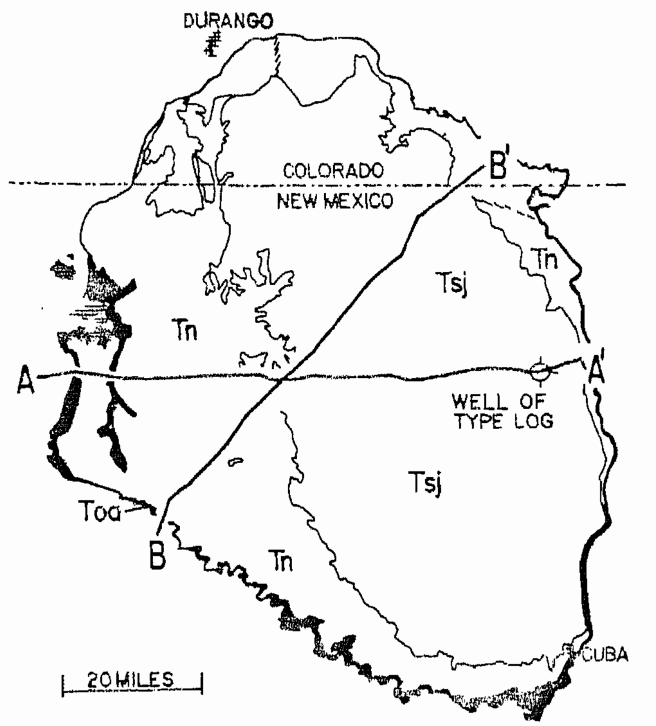

Fig. 3. Locations of cross sections A-A' (fig. 4) and B-B' (fig. 5) and the well of the type log (fig. 2).

Electrical logs were used to correlate rock units and to construct two cross sections. The locations of these cross sections, A-A' and B-B', are shown on figure 3. The location of the well is also shown. The two cross sections are shown on figures 4 and 5. Correlation lines do not necessarily represent the true position of the tops of formations except at the locations of wells. They do indicate that the thickness of the Ojo Alamo Sandstone is not uniform, that the Nacimiento Formation is more nearly uniform in thickness except at areas of erosion at the outcrops, and that only two members of the San Jose Formation are present throughout nearly the entire basin as it exists today. The four members are present only in the eastern part of the basin.

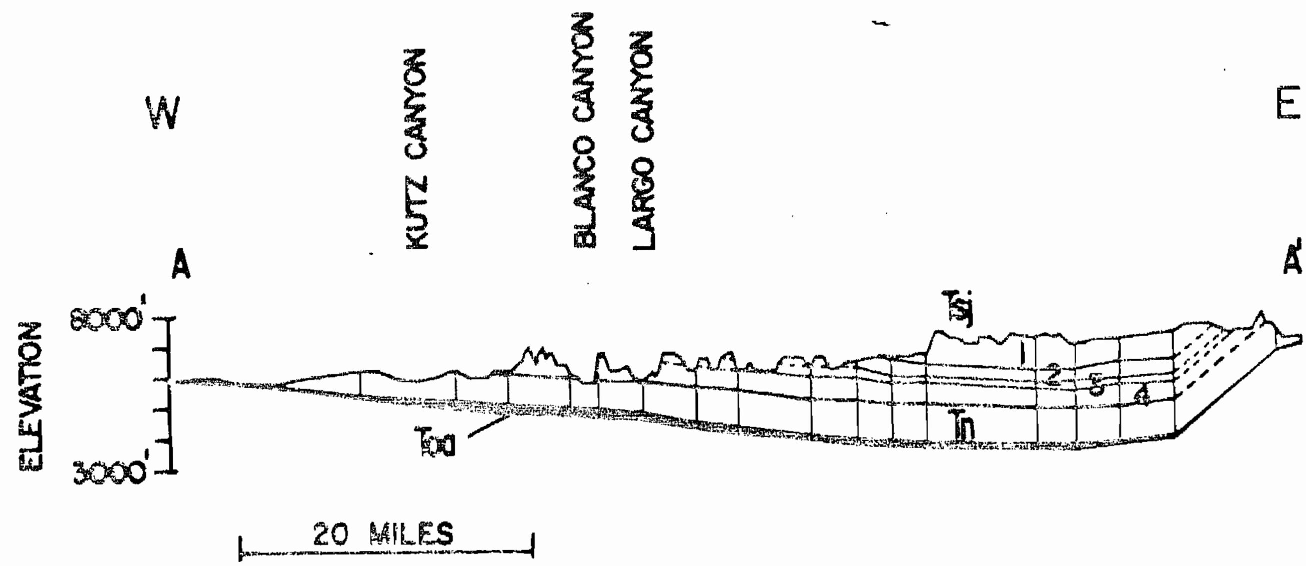

Fig. 4. Cross section A-A'. Vertical exaggeration is about 10X.

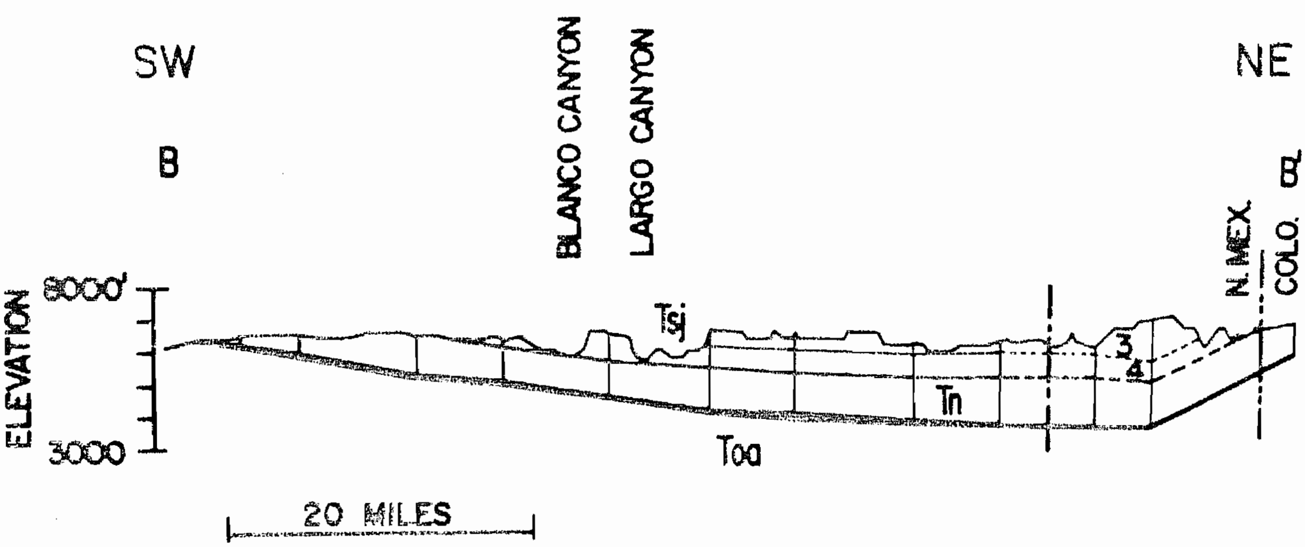

Fig. 5. Cross section B-B'. Vertical exaggeration is about 10X.

The dashed lines at the right end of each cross section indicate that the correlations are tenuous. At the right end of A-A', the outcrops were not mapped and were not correlated to the well nearest to the outcrop. At the right end of B-B', the rocks begin a gradational change of facies from the Nacimiento and San Jose Formations into Animas formation. The correlations are extremely difficult. The cross sections indicate that the tectonics of the San Juan Basin occurred after deposition of the Ojo Alamo Sandstone and continued nearly to the present.

DESCRIPTIONS OF AQUIFERS

Aquifers of the Ojo Alamo Sandstone — The Ojo Alamo Sandstone is a major source of supply of ground water in the San Juan Basin. It is a fluvial deposit of conglomeratic sandstone of Cretaceous and Paleocene age (Fassett, 1973). It consists of beds of sandstone that are interlayered with clays and silts. Both the interlayered beds of clays and silts and sandstone vary in thickness from a few inches to several tens of feet. The rocks at the outcrop appear to be inhomogeneous and anisotropic. The layers of sand are cross bedded and lenses of fluvial sandstone overlap one another. The sandstone is moderately consolidated and forms cliffs at most outcrops.

The Ojo Alamo aquifers correspond in part to the restricted Ojo Alamo Sandstone of Baltz, Ash, and Anderson (1966). Fassett (1973), O'Sullivan, et. al. (1972), Powell (1973), and Fassett and Hinds (1971, p. 28) have presented discussions of the history and defining and naming of the Ojo Alamo Sandstone. From the standpoint of ground water hydrology and development of resources of ground water, the name of a rock unit is not as important as the properties that make it an aquifer. Within the rock unit that is known as the Ojo Alamo Sandstone are sedimentary rocks that have the properties of aquifers. These rocks are given the name Ojo Alamo aquifers.

The electrical resistivity of the lower contact of the Ojo Alamo aquifer is generally greater than that of the underlying clays and silts; the Kirtland Shale. This contrast in resistivity makes the base of the Ojo Alamo aquifer easy to identify on electrical logs; however, the upper contact is not so easily identified. The top of the Ojo Alamo aquifer grades into the overlying silts and clays of the Nacimiento Formation. The progressive upward change in grain size and minerology from sand to clay and silt causes the electrical resistivity of the rock to gradually decrease — assuming the quantity of dissolved salts in the water does not increase. There is not a large contrast of resistivities at the top of the Ojo Alamo aquifer; therefore, the top is not easily determined.

There are two types of deposits of the Ojo Alamo Sandstone. Each is the result of different levels of energy of the environment of deposition. The first type is a flood plain deposit. These are broad units of sandstone that continue laterally for several miles. Examination of outcrops indicates that these deposits are composed of interlayered and overlapping lenses of sandstone. Channel deposits are the second type. These are usually much thicker than the flood plain deposits and are less than one mile wide. The channels in which these sands were deposited were cut into the underlying Kirtland Shale. The grain size of the channel deposits is larger than the grain size of the flood plain deposits. Channel deposits are medium to coarse grained sandstone. Flood plain deposits are fine to medium grained sandstone.

The best aquifers are located in channel deposits because their thickness and grain size are greater than in flood plain deposits. The best wells should be drilled in the channel sands and not in the thinner deposits of sand of the adjacent flood plains. Wells drilled into the flood plain deposits may produce water, but not in quantities as large as those wells in channel sands.

The two types of deposits of sand as described above are exposed at the outcrop of the Ojo Alamo Sandstone at Eagle Mesa in Sandoval County Southeast of Cuba, New Mexico. This area was mapped by Hinds (1966). Here the flood plain deposits are 20 feet to 40 feet thick. The sands deposited in fluvial channels are 80 to 150 feet thick.

Evidence of flood plain and fluvial channel deposits in the subsurface are shown in figure 6. This figure illustrates the correlation of logs of electrical surveys of four wells drilled into the Ojo Alamo aquifer north of Eagle Mesa. The locations of the four wells are shown in figure 10. An electric log was not recorded for the well labeled "BLM." The correlation of the top and bottom of the Ojo Alamo aquifer is marked by the horizontal lines. The bottom contact of the Ojo Alamo aquifer of each log was correlated on the horizontal line instead of correlating the tops. This distorts the geology but was done so the essential features of the rocks overlying and underlying the aquifer could be illustrated. The Ojo Alamo aquifer is thin in wells 1, 2 and 4. The upper and lower sand deposits of well 2 were screened for production. However, the upper sand (430 feet to 490 feet) does not contribute significant quantities of water to the well. During pumping tests, the level of water in well 2 dropped from 343 to 457 feet in 70 minutes of pumping at 35 gallons per minute. After 24 hours of pumping, the level of water in the well was at 521 feet. The static level of water before pumping was at 343 feet. The aquifer for well 2, for all practical purposes, is from 540 feet to 560 feet. This correlates with the aquifers of wells 1 and 4. The spontaneous potential curve and resistivity curve indicate that the upper sand contains silt and clay. Therefore, the transmissivity of the upper sand is much lower than that of the lower sand. Well 3 is drilled into the channel sands. The aquifer is 80 feet thick at this well.

Data from the logs of figure 6, as well as logs of other wells, may be used to contour the base of the Ojo Alamo aquifer. The channel is clearly shown in figure 6 and well 3 is located in the approximate center of the channel.

Finding the channel sandstones of the Ojo Alamo aquifer is not easy. There is no evidence of their location at the surface. In some areas, the Ojo Alamo aquifer is covered by several hundred feet of younger sediments. Seismic techniques may be useful in exploring for ground water in the Ojo Alamo Sandstone — especially in areas where other subsurface data is not available.

The foregoing discussion suggests that Ojo Alamo aquifers are apparently not "homogeneous and isotropic"; however, this may not be true for a system of water moving to wells. This point will be discussed in the section in the water yielding properties of aquifers and wells.

Aquifers of the Nacimiento Formation — The "Nacimiento" was first described as a group by Gardner in 1910 (Reeside, 1924). The Nacimiento Group contained what was called the Puerco and the Torrejon Formation. The definition of the two formations was based on the vertebrate fossils they contained (Reeside, 1924). In a discussion of the Nacimiento Group, Simpson (1948, p. 272) made this statement:

> "The fact is that the Puerco — and the Torrejon are not recognizable lithogic units. No one has ever found it possible to draw a line between them in the field and they have never been mapped separately. As far as anyone has yet been able to establish, they are usable only as faunal names for distinctive fossil zones within what is, for field mapping purposes, a single formation. It would therefore seem simplest, most practical, and most logical to consider this part of the stratigraphic sequence as a single formation, not divisible into Puerco and Torrejon Formations but containing the markedly different Puerco and Torrejon Faunas."

A study of electric logs indicates that it is not possible to identify sedimentary facies that can be mapped as formations in the assembly of rocks that have been deposited between the Ojo Alamo Sandstone and the San Jose Formation. There are two rock types that can be identified: Sandstone and silty and sandy clays. These rock types were deposited in different environments of deposition. The environments of deposition

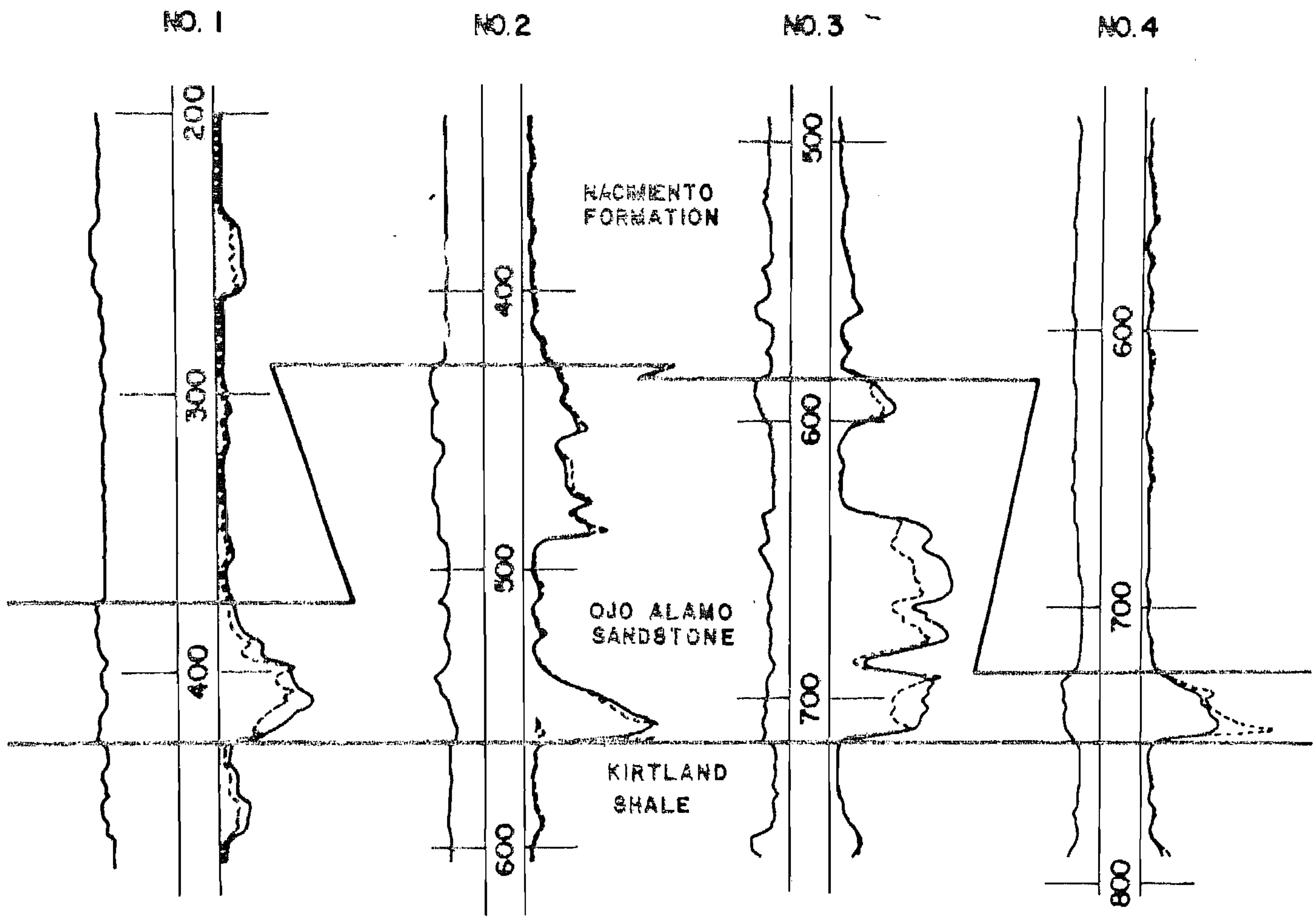

Fig. 6. Correlation of electric logs of wells in the Ojo Alamo aquifer near Eagle Mesa, Sandoval County, New Mexico.

of the sandstone were localized and did not cover large areas of the Basin. Most sandstones extend only a few thousand feet. This has been verified by observations at outcrops and studies of electric logs. Electric logs indicate that the Nacimiento Formation is composed mainly of beds of clays and silts. The most general environment of deposition was one of low mechanical energy; probably of the type found in still or slowly moving water. The results of correlations of electric logs support the argument of Simpson that the Nacimiento is a formation and not a group of two formations as Gardner contended.

Some sandstones in the Nacimiento Formation are aquifers and are given the name Nacimiento aquifers. The Nacimiento Formation is not, in its entirety, an aquifer. Nacimiento aquifers are neither generally continuous over large distances nor do they all crop out. The aquifers grade laterally into clays and silts. The sandstones that appear to have characteristics of aquifers overlay one another in much the same way as the sands of the Ojo Alamo aquifer. The sandstones are usually not well consolidated and will form moderately steep slopes. Fassett and Hinds (1971, p. 39) report that the Nacimiento Formation comformably overlies the Ojo Alamo Sandstone throughout most of the Basin. Correlations of electric logs support their conclusion.

What may become a major aquifer of local importance has been discovered in the Nacimiento Formation in the west central part of the Basin. A representation of an electric log through the rocks associated with this aquifer is shown in figure 7. The well in which this log was recorded is located in the SE/4 SE/4 NE/4 of sec. 6, T. 26 N., R. 7 W., Rio Arriba County, New Mexico. The elevation of ground level is 6019 feet. The log was measured from the derrick floor — 9 feet above ground level. At this location, the aquifer is 398 feet thick. An examination of the log suggests that the water between 955 feet and 1190 feet is of inferior quality to that between 515 feet and 913 feet, The main unit of the aquifer is from 515 feet to 645 feet. This unit will probably contribute the most water to a well drilled into the aquifer near this location.

A water well drilled at the ranch of Joe Kaime is completed in this aquifer. The well is reported to be 920 feet deep and produces water from an interval of aquifer of from 520 feet to 920 feet. The well will flow a full 8 inch stream of water without the aid of a pump. The potentiometric surface is 65 feet above ground level at the site of the well. This well is located at the ranch headquarters in the SW/4 sec. 5, T. 26 N.,

R. 7 W. The aquifer from which this well is producing is given the name of Kaime Ranch aquifer. The Kaime Ranch aquifer has not been mapped in detail at the time of the writing of this paper, but preliminary evidence suggests it may underlie at least 3200 acres of land.

Aquifers of the San Jose Formation — The sedimentary rocks that overlie the Nacimiento Formation were described and named the San Jose Formation by Simpson (1948, p. 280). Simpson's study enlarged and redefined the rock units that had been called Wasatch by previous workers. Simpson retained the division of the San Jose into three faunal zones as suggested by Granger (Simpson, 1948, p. 276).

Baltz (1962) studied the geology of the east central part of the San Juan Basin and concluded that the San Jose Formation was composed of four rock facies. He named these the Cuba Mesa, the Regina, the Llaves and the Tapicitos Members of the San Jose Formation.

Correlations of electric logs confirm that there are four mappable rock units in the San Jose Formation. These units are shown in figures 2, 4 and 5 and are numbered 1, 2, 3 and 4: Member 1 is primarily a sandstone facies, Member 2 is a clay and silt facies, Member 3 is a sandstone facies, Member 4 is a clay and silt facies. The correlations of logs have not been tied into outcrops; however, the numbered Members correspond to 1-Tapicitos: 2-Llaves, 3-Regina and 4-Cuba Mesa Members of Baltz (1962, pp. 143-163).

The sandstone facies of the San Jose Formation are known to be aquifers at some locations. The clay and silt members contain aquifers of sandstone that yield small quantities of water to wells (Baltz and West, 1967). However, the best aquifers in the San Jose Formation will be in the Cuba Mesa and in the Llaves Members.

The sandstone facies of the Cuba Mesa Member are moderately well consolidated. They form sheer cliffs at the outcrops but will crumble easily. As with the Ojo Alamo Sandstone, the sandstones appear inhomogeneous and non-isotropic. The lenses of sand are cross bedded and overlap one another. In the west central part of the Basin, the Cuba Mesa Member is 800 feet to 900 feet thick at the outcrops, but may thin to the east where it is overlain by the Regina Member. The Cuba Mesa Member contains beds of clay and silt up to approximately 200 feet thick.

Not much is known about the geohydrologic properties of aquifers of Members of the San Jose Formation because very few wells have been drilled or properly tested. The water yielding properties of 43 wells in the southern part of the reservation of the Jicarilla Apache Indians have been presented by Baltz and West (1967). One well is known to produce water from the Cuba Mesa Member in the west central part of the Basin. This well is located in the SE/4 SW/4 sec. 9, T. 29 N., R. 8 W., San Juan County, New Mexico. It was drilled to supply water for drilling and completing gas wells.

WATER YIELDING PROPERTIES OF AQUIFERS AND WELLS

Water Yielding Properties of Aquifers — The ability of aquifers to yield water to wells is related to the type of aquifer (artesian or water table), the amount of water in storage, and permeability of the rock. All aquifers observed in this study are artesian; the water is confined in the aquifers and is under

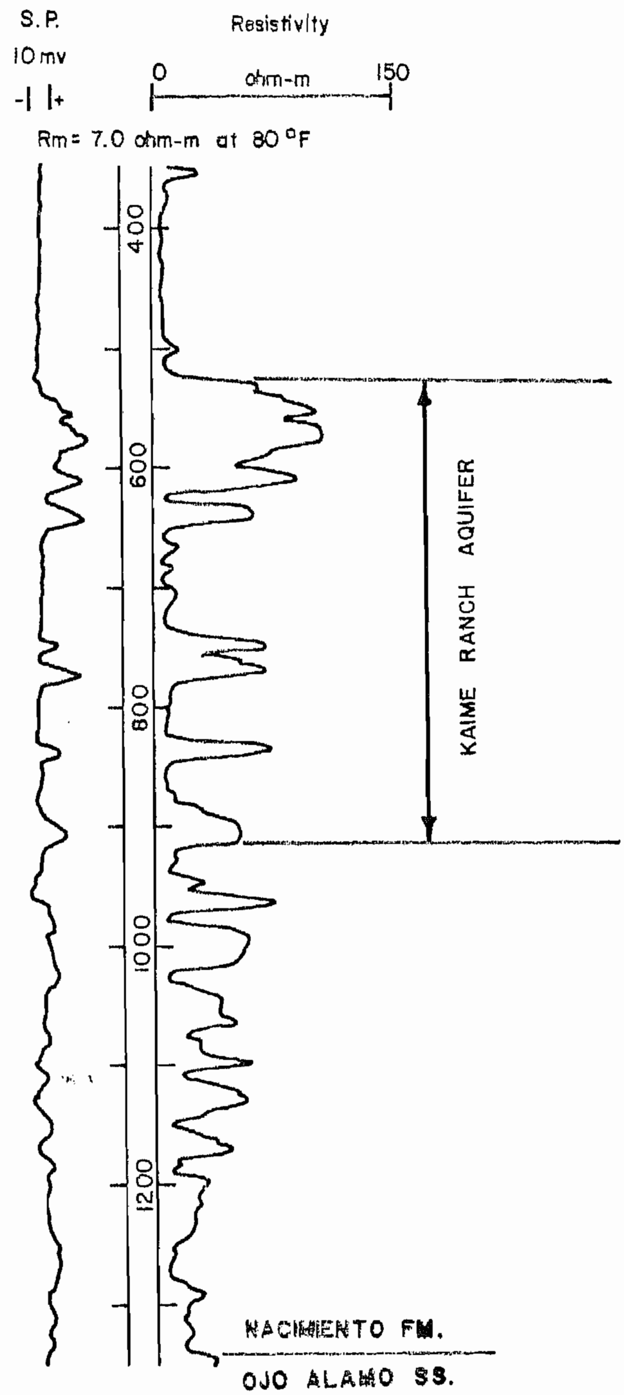

Fig. 7. Electric log of a well in the Kaime Ranch aquifer. (International Oil Corp., M.K.L. #5, SE/4 NW/4 NE/4 sec. 6, T. 26N., R. 7 W., Rio Arriba County, New Mexico.)

pressure. Water table conditions have been observed to exist in the alluvial deposits of arroyos and washes. Most of the wells are artesian. Water will rise in wells above the base of the upper confining layer of rock.

The amount of water in storage is described by the coefficient of storage, S. The coefficient of storage indicates the volume of water that can be produced from or injected into a column of aquifer of unit cross sectional area because of a change of head of one unit (Jacob, 1950). A formula for the coefficient of storage is given as $S=S_s b$. Ss is the specific storage and is the volume of water that can be produced from or injected into a unit volume of aquifer because of a unit change of head. The specific storage is a function of the specific weight (γ) and compressibility (α) of the water, and the compressibility of the rock (β) and the porosity (η) of the aquifer. Bear (1972, p. 204) gave a formula for the specific storage as $[\beta\eta+\alpha(1-\eta)]$. It can be seen from these two formulas, that the greater the thickness of the aquifer and the greater the coefficient of storage, the greater will be the volume of water in storage. The coefficient of storage is dimensionless.

The volume of water that can move through a section of aquifer of unit width under a unit gradient of head is called the coefficient of transmissivity, T. A formula for the coefficient of transmissivity is $T=Kb$ (Jacob, 1950). Where K is the hydraulic conductivity and b is the thickness of the aquifer. K is directly proportional to the size of the grains of the rock and the specific weight of the water and is inversly proportional to the viscosity of the water at the temperature of the aquifer. The units of the coefficient of transmissivity are gallons per day per foot. For a constant hydraulic conductivity, the coefficient of transmissivity is greater for the thickest aquifer.

The value of T and S is in their importance in determining estimates of how much water may be produced from an aquifer for how long a time period at a specified rate of withdrawal. In the absence of other relevant data, the best method of estimating T and S for an aquifer is from an analyses of data of pumping tests. The values determined represent averages for the volume of aquifer surrounding the well that is within the zone of influence of the test. The values of T and S determined from tests of wells may or may not be representative of the whole aquifer.

Water Yielding Properties of Wells — The ability of wells to yield water is related to the type of aquifer, the properties of the aquifer (T and S), the type and power of the pump, the type of completion (open hole, or cased and perforated, or screened, etc.), and the effectiveness of well development to improve the permeability characteristics of the aquifer near the well bore. The "specific capacity" is used to compare the ability of wells to produce water. Specific capacity is the ratio of production to the amount of drawdown at a specified time after pumping of the well commenced (Jacob, 1946). Determinations of specific capacity require the measurement of a constant rate of discharge, the static level of water before pumping, and the drawdown as a function of time.

The theory of well hydraulics indicates that a semilog graph of drawdown as a function of time should plot on a straight line if certain conditions exist. These conditions are:

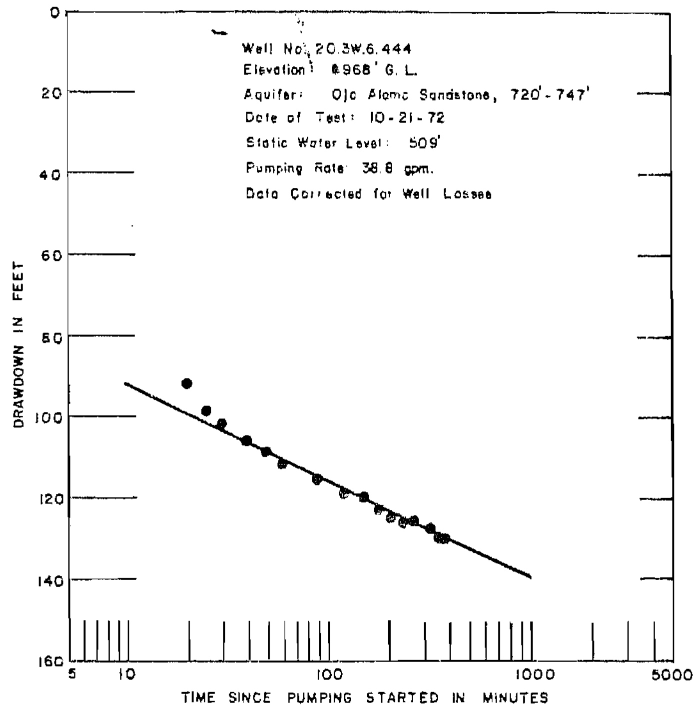

Fig. 8. Data of drawdown of a pumping test. Well number 20.3W.6.444.

the flow is radial, the rate of discharge is constant, the aquifer is artesian, nonleaky, of constant thickness, and homogeneous and isotropic, and the coefficients of storage and transmissivity are constant. Drawdown, for purposes of evaluating aquifers, may be measured in the pumping well or in a nearby observation well. Theories relating to the movement of ground water and analyses of pumping tests are discussed in Hantush (1964), Todd (1966, p.p. 89-114), and Walton (1970). Figure 8 illustrates data of a pumping test of well number 20.3W.6.444. (Note: well numbers are after the method of the U.S. Geological Survey. The scheme is illustrated in figure 9.) These data have been corrected for well losses because drawdown was measured in the pumping well and match a radial flow model after 25 minutes of pumping. Only part of the data from the entire test are presented. Drawdowns were measured for rates of discharge other than 38.8 gallons per minute as shown. These data suggest that the conditions cited above existed during the test. The data plot on a straight line on the semilog graph after 25 minutes of pumping. However, this does not prove that the aquifer is homogeneous and isotropic, but it does suggest that the radial flow model of a nonleaky artesian aquifer can be used to estimate properties of flow and storage of aquifers of the Ojo Alamo Sandstone. The stimulus of drawdown in a well causes a response in the associated ground water system. The responses may match a model of idealized conditions. These idealized conditions may include homogeneity and isotropy. However, the human systems that identify a rock as being nonhomogeneous and anisotropic should not be equated with a ground water system.

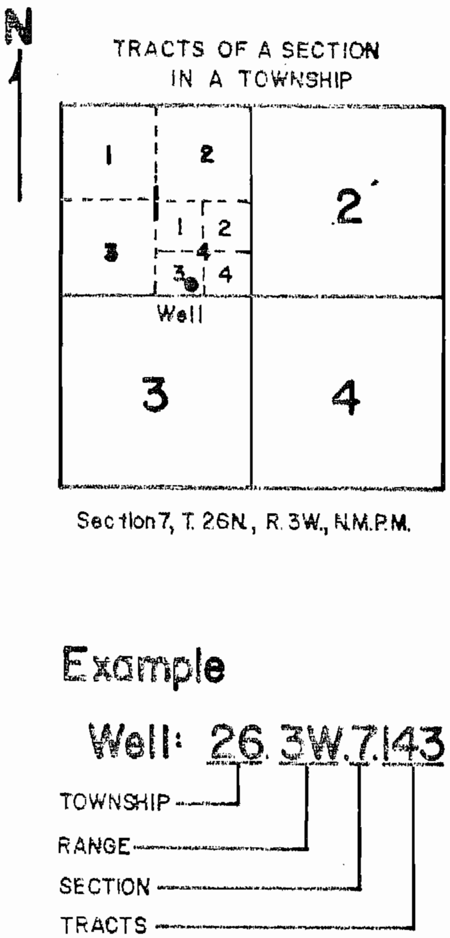

Fig. 9. System used to number water wells.

The technique of matching field data of pumping tests to type curves was used. Both techniques indicate the same things — the Ojo Alamo aquifers are artesian, nonleaky, etc., and both techniques are useful in estimating characteristics of flow and storage.

A summary of specific capacities of well, coefficients of storage, and transmissivity of aquifers is given in table 1. Aquifers are identified by Toa for aquifers of the Ojo Alamo Sandstone and Tscm for the Cuba Mesa Member of the San Jose Formation. The pumping rates shown are not necessarily the maximum possible rates of the wells. The symbol HNBD indicates that the property has not been determined because the data necessary for such determinations have not been observed and recorded. The values of the coefficients of transmissivity and storage were determined from analyses of data of pumping tests of six wells.

Depths to static levels of water in wells and depths of corresponding aquifers are summarized in Table 2. The symbol Tn is used to identify aquifers of the Nacimiento Formation. The levels of static water are given as positive if they are below ground level and negative if above. (Note: Well 20.3W.6.444 was equipped with 2 inch tubing for the discharge of water and a string of 1 inch tubing for a probe line. A 20 horsepower pump was used to lower the head in the well and to discharge water. The tubing with pump and the probe line were installed in 8 inch casing. An 8 inch stainless steel screen was installed at the aquifer. The casing was cemented in place from the top of the well screen to the surface of the ground. The diameter of the bit used to drill the well was 12¼ inches. The well was not gravel packed, but it was developed by jetting the screen and by pumping before tests were made. During the tests, drawdown was measured by lowering an electric water level indicator inside the probe line.)

QUALITY OF GROUND WATER AND ITS USAGE

The quality of resources of ground water is a relative measure of its use value. Quality is related to the quantity of dissolved salts in the water. Water that is of poor quality for purposes of human consumption may be of good quality for purposes of industry and agriculture. Water that is considered suitable for human consumption at one area or time may be considered unsuitable for the same use elsewhere. These conditions exist for the use of ground water from aquifers of Tertiary rocks of the San Juan Basin. This water is used for drilling and completing gas wells, processing natural gas, watering livestock and some irrigation, and for consumption by humans. The community of Cuba, New Mexico used water from the Ojo Alamo aquifer (R. Valarde, personal communication, 1972). A well field is being developed to supply water to the community of Navajo Indians in the area of Torreon, New Mexico. The Ojo Alamo aquifer is the source of supply.

Partial chemical analyses of samples of water from wells in aquifers of Tertiary rocks are summarized in table 3. Concentrations of cations, anions, and total dissolved solids are in units of parts per million. Specific conductance is in units of micromhos per centimeter at 77°F. The purposes for which the water is being used, or may be used, are indicated by the symbol *A* (agriculture), *D* (domestic), and *I* (industrial — oil and gas).

RECHARGE TO AQUIFERS

The rate of recharge of Tertiary rocks has not been studied in detail. Hydrologic budgets were not determined. However, recharge may occur from one or more sources; percolation and seepage of precipitation at the outcrops, ground water recharge from washes and arroyos where they cross over outcrops, and leakage from confining rocks of clay and silt. Leakage from confining rocks would indicate that they are not totally impermeable. Fractures where they exist at errosional surfaces may or may not be significant in contributing to recharge.

Evidence related to the recharge of an aquifer is illustrated in Figure 10. The solid lines represent contours of elevation of static head (the potentiometric surface) for 5 wells and the dashed lines represent the direction of natural ground water flow from the sources of recharge. The aquifer is in the Ojo Alamo Sandstone and the wash is San Isidro Wash. The direction of natural flow of ground water is away from the area where the wash passes over and through the outcrop and from the general area of the outcrops to the southwest. The gradient of the wash is toward the south. These data indicate that the greatest rate, and consequently, the greatest amount of recharge is from the wash. Recharge from percolation and seepage is coming from the area of the outcrop in the southwest. The rate of natural flow through the aquifer between C and C′ is approximately 40 gallons per minute. The distance from C to C′ is 1 mile and the average thickness of the aquifer is estimated to be 35 feet.

ECONOMICS OF GROUND WATER DEVELOPMENT

The development of resources of ground water will become more significant in the future. Competition for surface cources of supply will increase. The least expensive source may be from aquifers at or near the location of intended use — especially if costs of transportation by tanker truck or pipeline are excessively high. However, the drilling, completions, and development of water wells will not be inexpensive. The estimated cost to drill, develop, and equip a well that will yield 50 gallons per minute from 800 feet is summarized below. Equipment and materials are assumed to be new.

Drill well (12¼″ bit)	$ 6,400.
Casing (8″, 750′ at $4.37 per ft.)	3,500.
Well screen (8″, stainless, 50′ @ $56.00 per ft.)	2,800.
Cement	800.
Tubing and probe line	400.
Pump, cable, control panel, etc.	5,500.
Phase converter	1,800.
Electric logs	600.
Development	300.
Drilling water and miscellaneous expenses	300.
Total cost	$22,400.

$22,400.00 is not a cheap price to pay for a water well, but expenditures of this order of magnitude may be necessary for the development of the resource. The cost of installation and maintenance of energy to power the pump is not included. This may be a major expense in areas remote from electrical service. However, portable generators may be used.

John Love, Governor of Colorado is quoted as saying: *"Water runs in the direction of money"* (Denver Post, June 6, 1972). This statement is given the name Love's Law. It most certainly is applicable to resources of water of Tertiary rocks of the San Juan Basin. If the resource is needed, hen the cost of development must be paid. Hopefully, through wise management and use, the benefits will exceed the overall costs. Overall costs may include effects on future generations.

CONCLUSIONS

Correlations of electric logs are useful in mapping rock facies of Tertiary age in the San Juan Basin.

The Ojo Alamo Sandstone (Toa) is a major source of supply of ground water. The aquifer is artesian and wells may yield water at the rate of 35 gallons per minute to 180 gallons per minute. The coefficients of transmissivity have been determined to vary from 425 gallons per day per foot to 1230 gallons per day per foot. The coefficients of storage vary from 0.0002 to 0.0067. Specific capacity of wells vary from 0.26 gallons per minute per foot to 1.02 gallons per minute per foot. Total dissolved solids vary from 360 ppm to 824 ppm.

The Nacimiento Formation (Tn) cannot be mapped as two formations. The clay and silt facies contain sandstones that are artesian aquifers of limited size. Wells may yield from

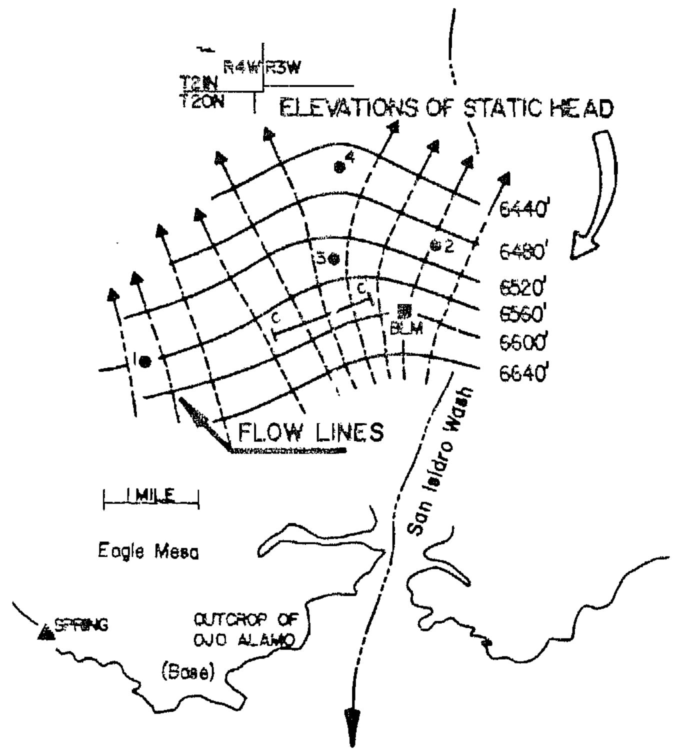

Fig. 10. Elevations of static head and direction of natural ground water flow, Eagle Mesa, Sandoval County, New Mexico.

35 gallons per minute to well over 200 gallons per minute. Wells may flow naturally. Samples of water indicate that water from Nacimiento aquifers may contain from 700 parts per million to 14,000 parts per million of total dissolved solids.

The San Jose Formation (Tsj) may be mapped as four rock units — two sandstone facies and two clay and silt facies. The Cuba Mesa Member is a sandstone facies that is an aquifer. Wells may yield from 30 gallons per minute to 60 gallons per minute. The specific capacity of one well (29.8W.9.343) is 0.23 gallons per minute per foot of drawdown at 1 hour of pumping. T and S have not been determined.

Data of pumping tests are useful for estimating coefficients of storage and transmissivity of aquifers of the Ojo Alamo Sandstone. Data of tests match radial flow models of a homogeneous and isotropic aquifer.

Water suitable for domestic, livestock and industrial use may be produced from aquifers of the Ojo Alamo Sandstone and the Nacimiento Formation. The Cuba Mesa aquifer of the San Jose Formation will yield water suitable for livestock and industrial use. The Aquifers of Tertiary rocks yield water that is characteristically high in ions of sodium and sulfate. The removal of iron may be required.

Percolation and seepage of precipitation, and ground water from washes and arroyos contribute to the recharge of aquifers. The present demands for resources of ground water are exceeding rates of recharge.

The cost of drilling and equipping a well to yield 50 gallons of water per minute may cost as much as $28.00 per foot of well depth.

TABLE 1. Pumping rates and specific capacities of wells and coefficients of transmissivity and storage of aquifers at well locations.

Well Number	Aquifer	Pumping Rate gpm	Spec. Cap. gpm/ft.	Pump. Time hours	T gpd/ft	S
20 .3W .6.444	Toa	39.0	0.28	7	430	0.0005
20 .3W .7.444	Toa *	80.0	0.93	6	1,230	0.0067
20 .3W .8.424	Toa	35.4	0.27	12	425	0.0002
25 .9W.19.114	Toa	80.0	0.68	12	800	0.0030
27.12W.13.142	Toa	180.0	1.02	12	1,160	0.0009
27.12W.13.222	Toa	40.0	0.2	12	660	0.0007
29 .8W .9.343	Tscm	38.0	0.23	1	HNBD	HNBD

TABLE 2. Depths to static levels of water in wells and depths to corresponding aquifers. Depths are measured from ground level.

Well Number	Symbol	Aquifer Top ft.	Base ft.	Static Level of Water ft.	Elevation of G.L. ft.
20 .3W .6.444	Toa	720	747	509	6968
20 .3W .7.444	Toa	633	715	339	6876
20 .3W .8.424	Toa	540	560	343	6819
20 .4W.14.444	Toa	375	420	367	6925 Est.
25 .9W.19.114	Toa	1,022	1,100	548	6740
26 .7W 5.333	Tn	520	920	-65	6035 Est.
27.23W.13.142	Toa	550	629	408	6070
27.12W.13.333	Toa	635	705	302	6110
29 .8W .9.343	Tscm	588	774	569	6492

TABLE 3. Partial chemical analyses of water from wells in aquifers of tertiary rocks of the San Juan Basin, New Mexico. Concentrations of ions and total dissolved solids are in parts per million. Wells marked by an asterisk are gas wells that flow water when the bradenhead valve is opened. "X" means iron is present, but the concentrations were not determined.

Well Number	Date	Aquifer	Use	Na	Ca	Mg	Fe	C1	HCO_3	SO_4	CO_3	TDS	Spec. Cond.
520 .3W .6.444	10-22-72	Toa	D	—	8	18	0.08	—	—	340	—	360	1,200
20 .3W .7.444	8-10-72	Toa	D	115	32	10	0.10	0.8	0	0.4	6.4	403	900
20 .3W .8.424	7-18-72	Toa	D	110	16	15	—	3.2	0	0.8	3.2	402	1,724
25 .6W .3.414	5-10-72	Tn	I	—	—	—	—	26.	—	565	—	704	—
26 .7W 5.333	9-14-72	Tn	DA	360	0	0	X	16.	220	510	29.	785	1,485
26.10W.25.41	8-18-72	Toa	I	345	4.8	0	X	8.	240	475	0	732	1,100
27 .5W .3.214	5-2-67	Tn	I	445	125.	7	X	40.	160	1,080	0	1,680	2,180
27.12W.13.222	2-22-71	Toa	I	—	—	—	—	12.	—	447	—	824	1,100
* 28 .8W.26.141	1-12-72	Tn	I	2,070	385.	30	X	z40	65	5,420	14.	8,030	10,000
* 28 .8W.33.414	1-13-72	Tn	I	1,725	265.	11	X	25	0	4,330	12.	6,308	5,950
29 .6W.28.342	2-4-70	Tn	I	480	235.	22	X	145	105	1,400	0	2,164	2,240
29 .8W 9.343	10-5-72	Tscm	I	140	365.	15	0.8	18	180	1,060	0	1,824	2,160
* 29 .9W.22.123	6-12-72	Tn	I	2,415	300.	50	X	85	100	5,455	25	14,150	15,600

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