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TRITIUM MIGRATION AT THE GASBUGGY SITE: EVALUATION OF POSSIBLE HYDROLOGIC PATHWAYS

Prepared by

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Evaluation of Possible Hydrologic Pathways

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submitted to

Nevada Operations Office
U.S. Department of Energy
Las Vegas, Nevada

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Marjory A. Jones, Desert Research Institute	Date

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ABSTRACT

An underground nuclear test named Gasbuggy was conducted in northwestern New Mexico in 1967. Subsequent groundwater monitoring in an overlying aquifer by the U.S. Environmental Protection Agency revealed increasing levels of tritium in a monitoring well located 132 m from the test, indicating migration of contaminants from the nuclear cavity. Two transport scenarios were evaluated with a travel time analysis. In one, transport occurs to the Ojo Alamo aquifer either up the emplacement hole or through fractures created by the blast, and then laterally through the aquifer to the monitoring well. In the other, lateral transport occurs through fractures in the underlying Pictured Cliffs detonation horizon and then migrates up the monitoring well through plugged casing connecting the two formations. The travel time analysis indicates that the hydraulic conductivity measured in the Ojo Alamo Formation during field tests is too low for lateral transport to account for the observed arrival of tritium at the monitoring well. This suggests transport either through fractures intersecting the Ojo Alamo close to Well 10–36, or through fractures in the Pictured Cliffs and up through the bottom plug in the well. However, if higher hydraulic conductivities measured on Ojo Alamo core samples are representative of the formation, lateral transport in the aquifer is a viable pathway. The two scenarios were investigated using hydrologic logging techniques and sampling at the monitoring well. No vertical movement of water was detected with a thermal flowmeter through the bottom cement plug and the water chemistry is consistent with the known characteristics of the Ojo Alamo, favoring transport of tritium through the aquifer rather than through the Pictured Cliffs and the bottom plug. Though relatively fresh formation water was present across from the perforations in the Ojo Alamo, the water did not contain measurable tritium at the time of sampling. This suggests that tritium was part of a transient pulse, perhaps driven by prompt injection or early–time vapor–phase transport, which was trapped in the tubing and repeatedly sampled during previous annual monitoring. This tritium was probably dispersed to non–detectable concentrations when the tubing was pulled prior to DRI's sampling. A layer of chemically distinct water, containing low levels of tritium, was found at the top of the water column and either enters the well through damaged casing or was introduced into the well from a surface impoundment.

INTRODUCTION

A nuclear detonation occurred on December 10, 1967, in northwestern New Mexico for the purpose of testing the effectiveness of such explosives for fracturing tight gas reservoirs to enhance production. This test, named Gasbuggy, was followed by production testing and pressure monitoring through 1976, and site cleanup activities concluding in 1978. Since that time, groundwater has been monitored in the Gasbuggy area by the U.S. Environmental Protection Agency as part of the Long-Term Hydrologic Monitoring Project. A pre-existing gas production well, EPNG 10-36, located 132 m from the test hole, was sealed with sand and cement prior to the nuclear test with the intention of reopening that well after the test to determine the effectiveness of the experiment. Drilling problems precluded reopening the well to its pretest total depth; however, the well was recompleted for the purpose of hydrologic monitoring, and added to the monitoring program. In 1984, tritium activities well above background began appearing in 10-36 (Figure 1). Though these activities are substantially below the drinking water standard for tritium, they indicate migration from the cavity and warrant further study. This report presents an analysis of the potential migration pathways and the results of a logging and sampling program designed to investigate the Gasbuggy site.

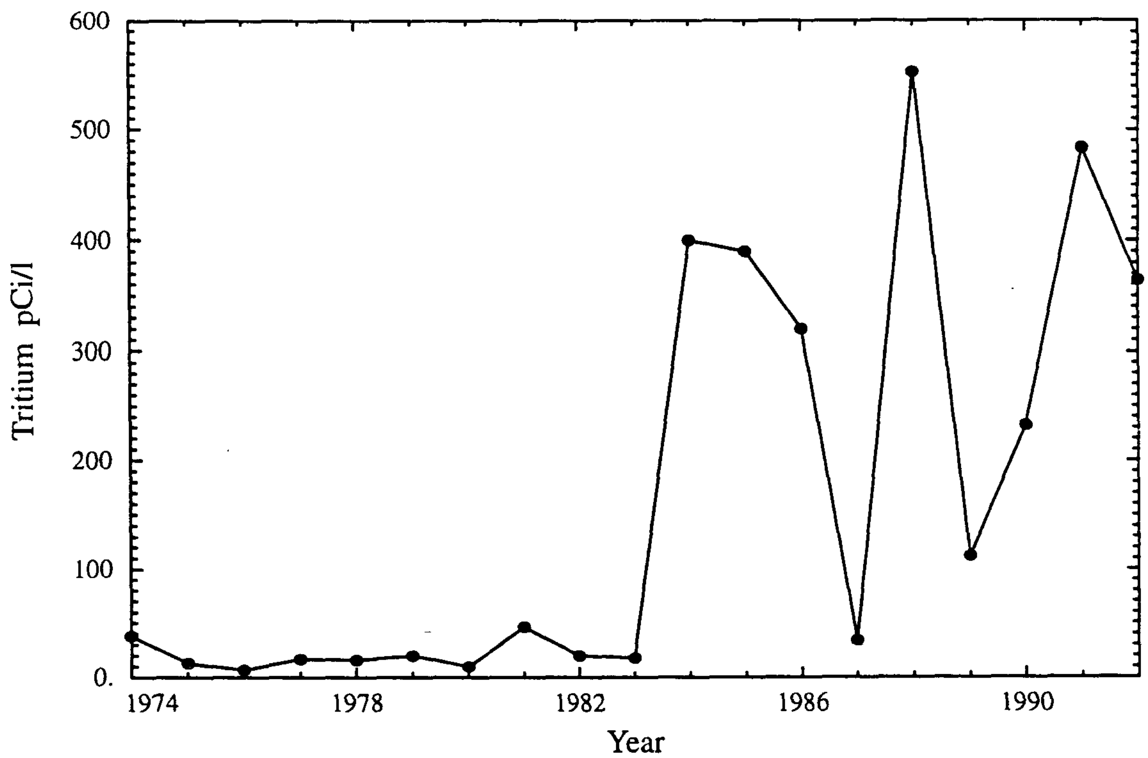

Figure 1. Tritium concentration for Well EPNG 10-36.

BACKGROUND INFORMATION

The Gasbuggy site is in the San Juan basin, a large structural basin containing about 3660 m of sedimentary rocks. Groundwater flow is believed to be to the west–northwest to discharge points along the San Juan River about 40 km away (Mercer, 1970) (Figure 2). At the site itself, hydraulic head values decrease with depth, indicating a potential for downward flow (Sokol, 1970). The gas producing horizon fractured by the shot is the Pictured Cliffs Formation, a tight sandstone between about 1189 to 1280 m below ground surface at the Gasbuggy site (Figure 3). The aquifer where the

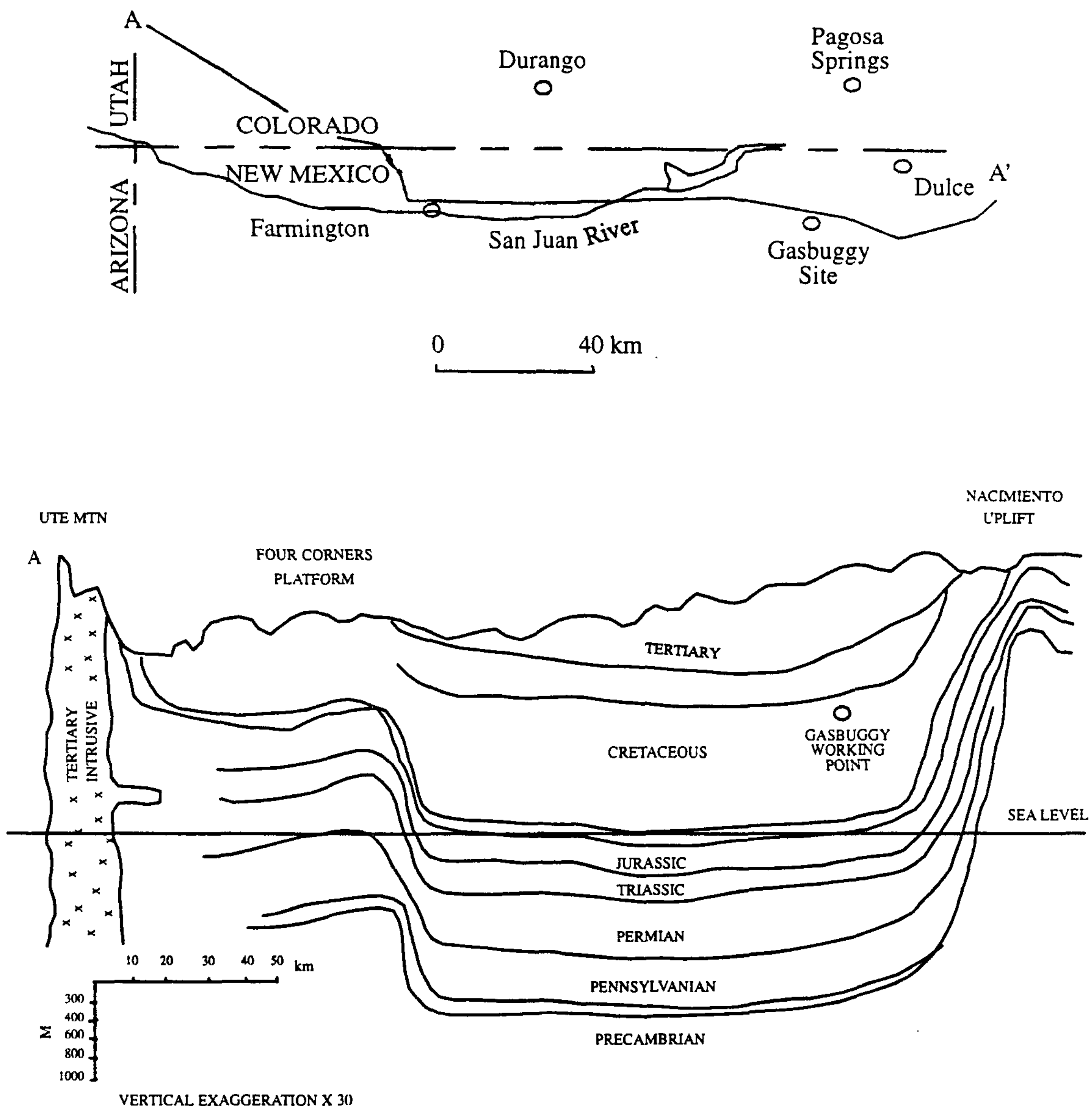

Figure 2. The upper portion of the figure shows the location of the Gasbuggy site in northwestern New Mexico and the location of the cross section shown in the lower portion. The cross section was modified by Sokol (1970) from that presented by Peterson et al. (1965).

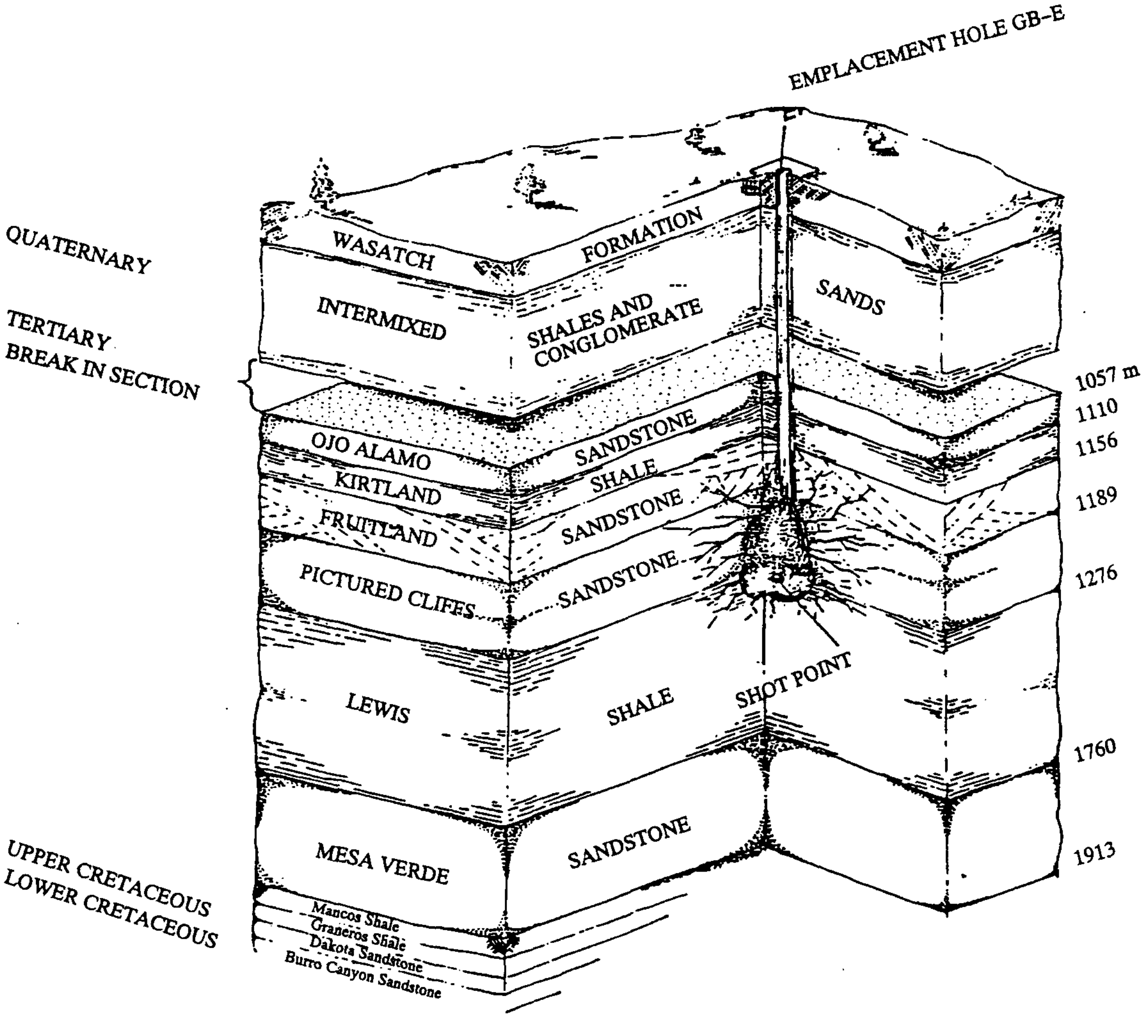

Figure 3. Generalized geologic cross section at the Gasbuggy emplacement hole. From U.S. DOE (1986).

tritium has been detected is the Ojo Alamo Sandstone, located between about 1057 and 1110 m below ground surface. The two sandstones are separated by over 60 m of shale and siltstone.

Four holes were drilled as part of the Gasbuggy project (Figure 4). Hole GB-1 was the first exploratory hole, from which many cores were collected during drilling. These cores provide numerous porosity and permeability measurements in both the Ojo Alamo and Pictured Cliffs formations. Hole GB-2 was a second exploratory borehole. Hole GB-3 was drilled after the detonation, with the purpose of determining the effect of the blast on the underground environment, including the Ojo Alamo. Single-hole hydraulic tests were performed in each of the three holes. Hole GB-E/GB-ER was the event and reentry hole (this somewhat unusual configuration, drilling the reentry hole through the cement plug in the event hole, was performed to save costs by speeding drilling, eliminating a need to set casing, etc.). All of these holes have been plugged to the surface with cement and are therefore unavailable for additional measurements.

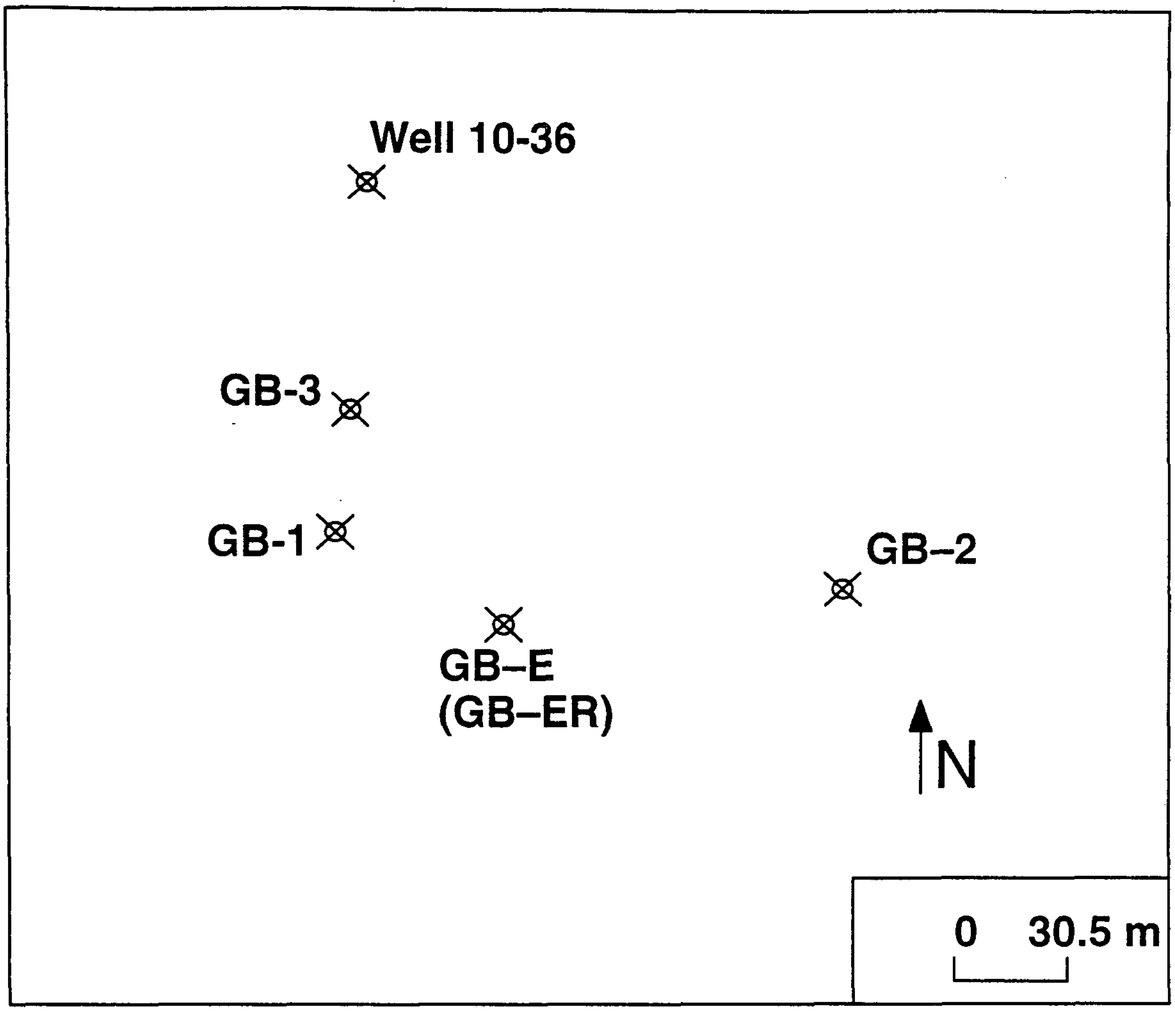

Figure 4. Locations of the boreholes drilled for the Gasbuggy Project and Well 10-36. The distance from GB-ER (the emplacement and reentry hole) to Well 10-36 is 433 ft.

The monitoring well, EPNG 10-36 (formerly known as well 29-4 no.10) was originally a gas production well, producing from the Pictured Cliffs Formation. To enhance production, hydraulic fracturing was performed at 10-36 at an unknown time in the past. The well had reportedly been producing for about ten years prior to the Gasbuggy test. The original plans had called to do postshot production testing at 10-36, so the perforated portion of the well opposite the Pictured Cliffs was filled with sand, then the remainder of the well plugged with cement prior to the nuclear test. Postshot drilling to clean out the cement encountered damaged casing near the bottom of the Ojo Alamo that prevented penetration to the Pictured Cliffs. The well was then completed in the Ojo Alamo by shot perforating the 14-cm casing and left for groundwater monitoring.

IMPORTANT OBSERVATIONS DURING GASBUGGY ACTIVITIES

There are a number of observations scattered throughout reports of Gasbuggy activities that are pertinent to the issue of contaminant transport to the Ojo Alamo. These observations are listed here for clarity and are discussed in the context of transport hypotheses in later sections.

- There was a pressure connection between GB-1 and Well 10-36 in the Pictured Cliffs, noted during testing in GB-1 prior to the Gasbuggy event.
- Water collected from the Ojo Alamo during reentry drilling of GB-ER contained tritium at twice background concentrations.
- Concentrations of tritium in cavity gas and water could not account for all the tritium produced by the shot.
- There was inflow of water from the Ojo Alamo to the cavity during production testing, presumably through a bad seal in GB-E.
- A pressure connection between the cavity and the Ojo Alamo at Well 10-36 was recorded during production testing of GB-ER.

CONTAMINANT TRANSPORT SCENARIOS

Vertical Transport from the Cavity to the Ojo Alamo

A fundamental problem with Gasbuggy release scenarios is that pressures measured in the Pictured Cliffs are apparently lower than those measured in the Ojo Alamo (Rawson and Korver, 1967; Power and Bowman, 1970). This means that if connected, water should be flowing downward from the Ojo Alamo into the cavity rather than vice versa. There are three ways of accounting for the known migration of tritium from the Pictured Cliffs to the Ojo Alamo: 1) the pressure measurements in the Pictured Cliffs are not representative of downhole conditions and the pre-shot estimate indicating a potential for upward flow is actually correct, 2) there was prompt injection of tritium at the time of the explosion, and 3) tritium migrated in the vapor phase.

The above-background tritium concentrations in the Ojo Alamo detected during reentry drilling are evidence that some migration occurred immediately after the shot at GB-ER ("prompt injection"). The source of the radioactivity was believed to be leakage of radioactive gas along the explosive arming and firing cable (Korver and Rawson, 1968). However, there was no direct injection of radioactivity to the Ojo Alamo at Well 10-36. The monitoring results show a 16 to 17 year lag from the time of the event to the detection of tritium. This means that some form of migration took place in addition to any prompt injection.

Rather than being driven into the Ojo Alamo by the force of the blast, tritium may have migrated to the Ojo Alamo in the vapor phase, sometime after the shot. The inflow of water from the Ojo Alamo to the cavity caused problems with gas production testing in GB-ER (Power and Bowman, 1970). Rawson and Korver (1967) note that "...if water can flow into the chimney from the Ojo Alamo, gas from the chimney will likely migrate into the Ojo Alamo, perhaps in significant quantities." Some of this gas, at least at early times, would be tritiated water vapor.

Both prompt injection and vapor phase migration would be less serious as contaminant transport sources because they would be short-term phenomena that would limit the amount of radioactivity released to the Ojo Alamo. However, given the difficulties of accurate downhole pressure measurements, it is just as likely that the head measurements for the two units are unreliable and that migration is continuing to occur from the cavity to the Ojo Alamo along fractures or through boreholes.

Lateral Transport from the Cavity to Well 10-36

Despite the uncertainty as to how migration occurred from the cavity in the Pictured Cliffs to the Ojo Alamo, it is clear that such transport did occur. Disregarding the apparent problem with the relative pressures in the two formations, there are two basic scenarios to consider for transport of tritium from the cavity to the Ojo Alamo at Well 10-36 (Figure 5). First, tritium reaches the Ojo Alamo either through fractures or the GB-ER borehole and it then migrates to 10-36 by lateral flow through the aquifer. Second, tritium migrates to 10-36 through the Pictured Cliffs and then moves up the stemmed borehole to the Ojo Alamo. The major difference between these pathways is in the length of transport in the Ojo Alamo. Each scenario also bears a different implication in terms of remediating the problem. In the second case, 10-36 is the only conduit allowing release of radioactivity to the overlying aquifer. Properly sealing off the Pictured Cliffs in 10-36 would solve the problem. The first case could be much more difficult to deal with, particularly if fractures are connecting the cavity and the Ojo Alamo.

There is evidence to support either basic scenario. The connection between the cavity and the Ojo Alamo through GB-ER has already been mentioned. Though final roll-up activities at the site included stemming GB-ER with cement to the surface, it is possible that the uncorrected pre-shot stemming problems that initially led to the leakage of water into the cavity persisted through the final stemming. The pressure connection between the cavity and the Ojo Alamo at Well 10-36, recorded during testing of GB-ER is also noteworthy. Power and Bowman (1970) show that the hydrostatic level in 10-36 responded to decreases in chimney pressure. Though their late-time data suggest a partial sealing of the leak by mid-April 1969, they note that "It now appears that the leak has been plugged by some obscure process although the permanency of this plug is not assured" (p.12). Though they assumed the connection was through GB-ER, there is no reason that it could not as well have been through fractures.

The second scenario (migration through the Pictured Cliffs) is supported by the good connection between GB-1 and 10-36 in the Pictured Cliffs, noted during pre-shot testing of GB-1. The connection was considered to be due to a combination of natural structural weaknesses and hydraulic fracturing in 10-36 (Rawson and Korver, 1967). Hydrocarbon stains along bedding plane partings at sandstone-shale contacts in GB-1 core were interpreted as indicating flow from the GB-1 area to 10-36 during the ten years of gas production from 10-36. Pre-shot studies led Rawson and Korver (1967, p. 41) to conclude that there would be "very probable communication between the explosion in GB-E and well 10-36." Migration from the Pictured Cliffs to the Ojo Alamo in 10-36 would be facilitated by the pre-shot stemming in 10-36, which included sand fill in the bottom 91.4 m, where perforations are open to the Pictured Cliffs. This somewhat unusual stemming was apparently done

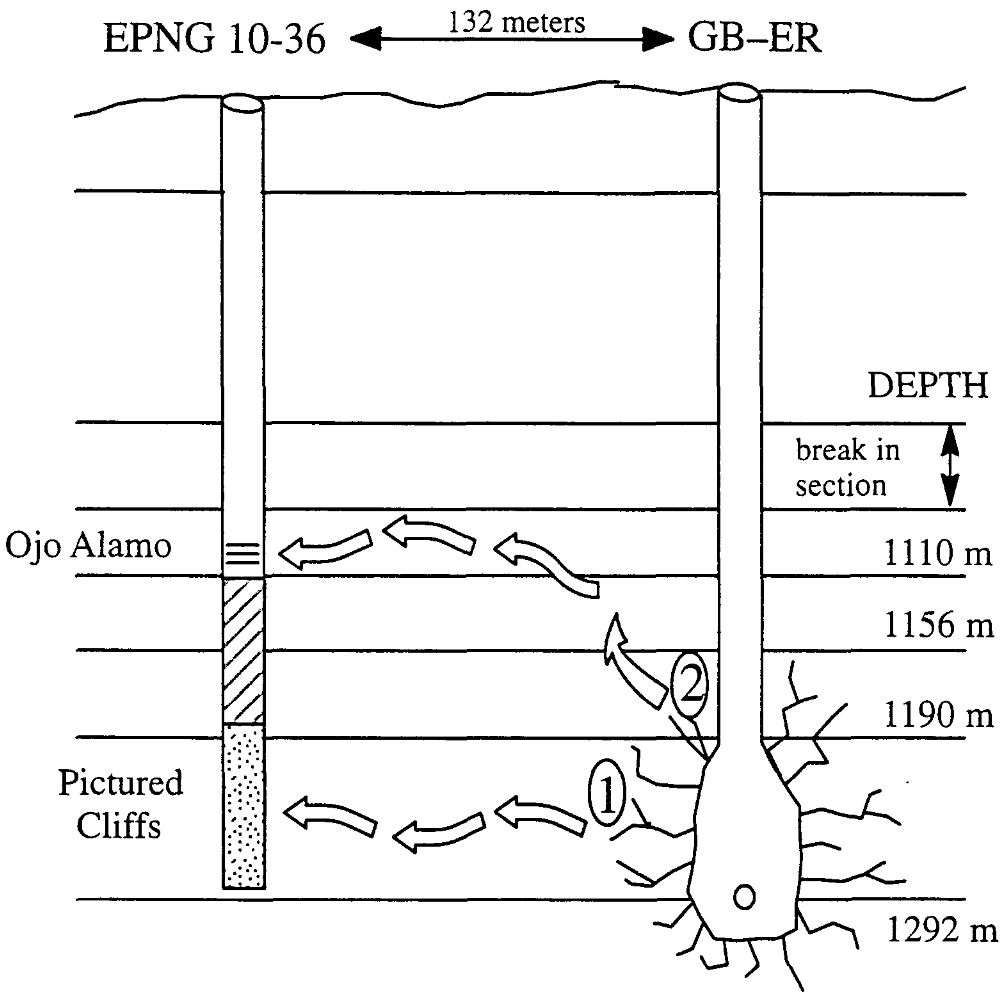

Figure 5. Two basic scenarios for the transport of tritium from the cavity at GB-ER to the monitoring well, EPNG 10-36. In case 1, transport occurs through fractures in the pictured Cliffs Formation, then up the 10-36 borehole. In case 2, transport is up the GB-ER borehole or through a fracture connecting the cavity and the Ojo Alamo, where in either situation, there is transport through the Ojo Alamo aquifer.

because the original plan was to clean out 10-36 postshot and test gas production, so they did not want to clog the perforations with cement. Though there are another almost 91 m of cement between the sand fill and the current bottom of the well at 1099 m below land surface, it is likely that the test compromised the plug's integrity. This is suggested by the damaged casing at 1101 m, caused by the nuclear explosion, which prevented postshot penetration to the Pictured Cliffs and led to establishing 10-36 as an Ojo Alamo monitoring well (Atkinson and Ward, 1969).

TRAVEL TIME ANALYSIS

To evaluate the possible flowpath through the Ojo Alamo, a travel time analysis was performed. To derive the probability density function (pdf) of travel time, given available field information, is one of the most important issues of transport theory in porous media. However, very often the limited field data force the solution to be highly approximate. Sometimes the spatial structure of the hydraulic conductivity is unknown or available only through the results from similar geologic formations at different sites. In that case, the travel time analysis follows the simplest case of pure convective transport in a uniform flow field. If, in the other case, the spatial distribution of the flow field can be estimated using available data, this information should be considered in the calculation of the travel time distribution. The Gasbuggy case clearly belongs to the former case.

One possible attempt to analyze the pdf of travel time is to consider the simple kinematic motion neglecting the velocity spatial variation and the pore scale dispersion:

$$x(t) = Ut \tag{1}$$

where $x(t)$ denotes the mean displacement in direction of flow, U is a mean velocity, and t denotes time. This assumption implies that the transport process is only governed by the estimated mean velocity in the direction of the compliance surface. In general, the mean velocity is not measured in the field, but rather estimated indirectly using Darcy's law. Darcy's law is usually presented with the relation:

$$U = K_g \frac{J}{n} \tag{2}$$

where K_g is the geometric mean of the hydraulic conductivity, J is the mean hydraulic head gradient, and n is the effective porosity. Since these parameters are estimated from the scarce field data at the Gasbuggy site, they are subject to estimation errors which in turn produce the uncertainty in the mean velocity estimate. A detailed description of this probabilistic approach can be found in Andricevic et al. (1994), describing risk assessment for migration from the Nevada Test Site. The values used for the variables in (2) are discussed below.

Hydraulic Gradient

A gradient for the Ojo Alamo in the immediate site area could not be determined. Though five boreholes intersected the Ojo Alamo at and near the Gasbuggy site, a reliable static water level is only available from 10-36 and no precise ground elevation is available there. Head values in the GB holes were all collected during hydrologic testing, when expensive rig time precluded waiting for full recovery (static level was estimated by extrapolating from recovery curves). All indications are that there is little gradient between the closely spaced boreholes and very precise measurements of head would be necessary to accurately determine one. For the purposes of this analysis, a regional gradient is assumed, calculated from the Gasbuggy site to postulated discharge points on the San Juan River by Sokol (1970). There were three estimates: 0.036, 0.047, and 0.044. These lead to a mean = 0.041 and s.d. = 0.008.

Porosity

Porosity measurements were made on 57 core samples of the Ojo Alamo, collected from GB-1 (Rawson and Korver, 1967). The mean of these measurements was 0.128, with a standard deviation of 0.035. Though these measurements represent the vertical distribution of porosity rather than lateral, this parameter is probably the best known in the calculations.

Hydraulic Conductivity

There is a large discrepancy between permeability values obtained on cores from GB-1 (mean = 205 cm/yr, s.d. = 380 cm/yr, n = 57) and those calculated from transmissivities obtained from slug tests at the test holes, including GB-1 (mean = 31 cm/yr, s.d. = 16 cm/yr, n = 3). The discrepancy was noted by workers at the time and tentatively attributed to unloading of the cores and/or measurement techniques (Rawson and Korver, 1967). This uncertainty was treated by analyzing six cases: 1. Field data only; 2. Field data only, but increased variance (+1) to account for small scale variability; 3. Field data, plus the maximum and minimum values found in the core (n = 5) (this case was discarded part way through the analysis because the variance appeared unreasonable); 4. Field data plus the mean of the core data were treated as another data point (n = 4); 5. Same as #4, but the variance was increased as it was for case 2; and 6. Core data only.

Furthermore, we assume that the above parameters are lognormally distributed. The lognormality assumption has been shown to accurately describe the actual variability measured in the field (Hoeksema and Kitanidis, 1985) especially for those parameters which physically cannot assume a negative value (*e.g., K, n*).

If all parameters on the right-hand side of (2) are lognormally distributed, then so is U, such that the first two moments of the estimated mean velocity are

$$\mu_{lnU} = \mu_{lnK} + \mu_{lnJ} - \mu_{lnn} \tag{3}$$

$$\sigma^2_{lnU} = \sigma^2_{lnK} + \sigma^2_{lnJ} + \sigma^2_{lnn} \tag{4}$$

where m_{lnx} and s^2_{lnx} denote a log mean and log variance of any variable $\ln x$, respectively. The above equations give the necessary parameters for the construction of the pdf of the mean velocity estimate which takes the form of the lognormal distribution

$$p[U] = (\sqrt{2\pi}\,\sigma_{lnU}U)^{-1} \exp\left[-\frac{(lnU - \mu_{lnU})^2}{2\sigma^2_{lnU}}\right] \tag{5}$$

Due to the fact that only one observation well is currently available at the Gasbuggy site, the direction of the mean velocity is also subject to uncertainty which also results in the uncertainty in the distance, L.

Applying the inverse transformation of log values results in the following velocities for each case:

CASE	VELOCITY, cm/yr	σ
1	11	7.7
2	19	32
3	300	680
4	32	26
5	53	99
6	150	290

Length

The flowpath through the Ojo Alamo was assumed to be constrained to the distance between GB-ER and 10-36 (0 to 13,200 cm). This is not strictly true, as a fracture could have connected the two units in another direction, resulting in a longer flowpath. The spread of this range about the mean was assumed to be +3 s.d., resulting in lower probabilities of very short flow paths (transport directly up 10-36) and very long flow paths (transport directly up GB-ER). Calculations were also performed assuming a known path length with no uncertainty. Path lengths of 6600 cm (halfway from GB-ER to 10-36) and 13,200 cm (the entire length) were assumed.

RESULTS OF TRAVEL TIME ANALYSIS

The importance of knowing the hydraulic conductivity and its spatial variability in the Ojo Alamo Formation can be seen by comparing the pdf generated using the different case assumptions (Figure 6). Relying only on the field transmissivities (cases 1 and 2) yields high probabilities of velocities less than 20 cm/yr. The pdf for case 1 also has a short upper tail indicating little likelihood of high enough velocities to cause the observed tritium breakthrough. This is most easily seen on the cumulative distribution function which shows essentially no probability of arrival times to Well 10-36 less than 100 years when using the field values (Figure 7). Increasing the variance around the field values (case 2) results in a somewhat higher chance of shorter arrival times, indicating that evaluating small-scale variability in the conductivity distribution is important for evaluating the probability of rapid travel times.

Including the mean of the core permeability measurements in the analysis dramatically changes the shape of the pdf (see cases 4 and 5 in Figure 6). In effect, adding that one higher value greatly increases the chance of higher velocities and shorter travel times. Though there is still a higher probability of a groundwater velocity of 20 cm/yr or less (because there are three relatively low field values to the one mean core value included), the peak is much lower than in cases 1 and 2 and there is a much longer right-hand tail indicating an increased chance of faster velocities.

When only the core data are considered (case 6), not only is the mean conductivity higher, there is a greater variance because of the wide range of values measured. The resulting pdf is quite flat compared to the others, showing a more equal probability of a range of velocities. The effect on the

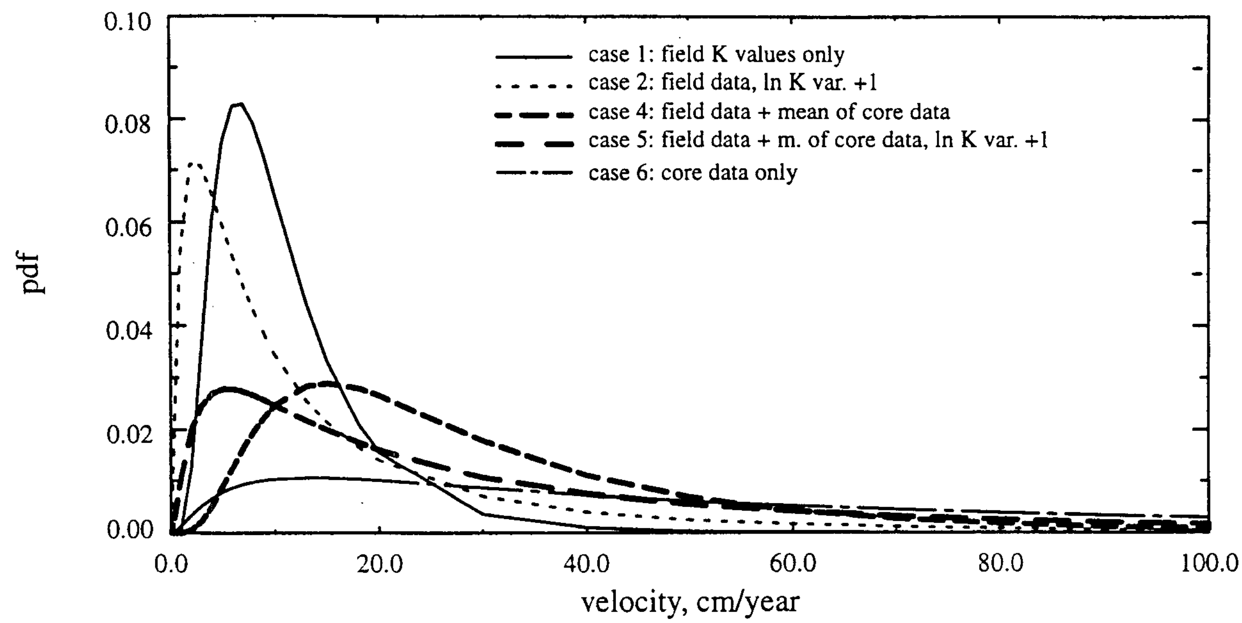

Figure 6. Probability density function for groundwater velocity in the Ojo Alamo Aquifer. Five different cases are presented, based on different assumptions of hydraulic conductivity (described in the text). The importance of the conductivity and its variance is clear in the different shapes for the pdfs.

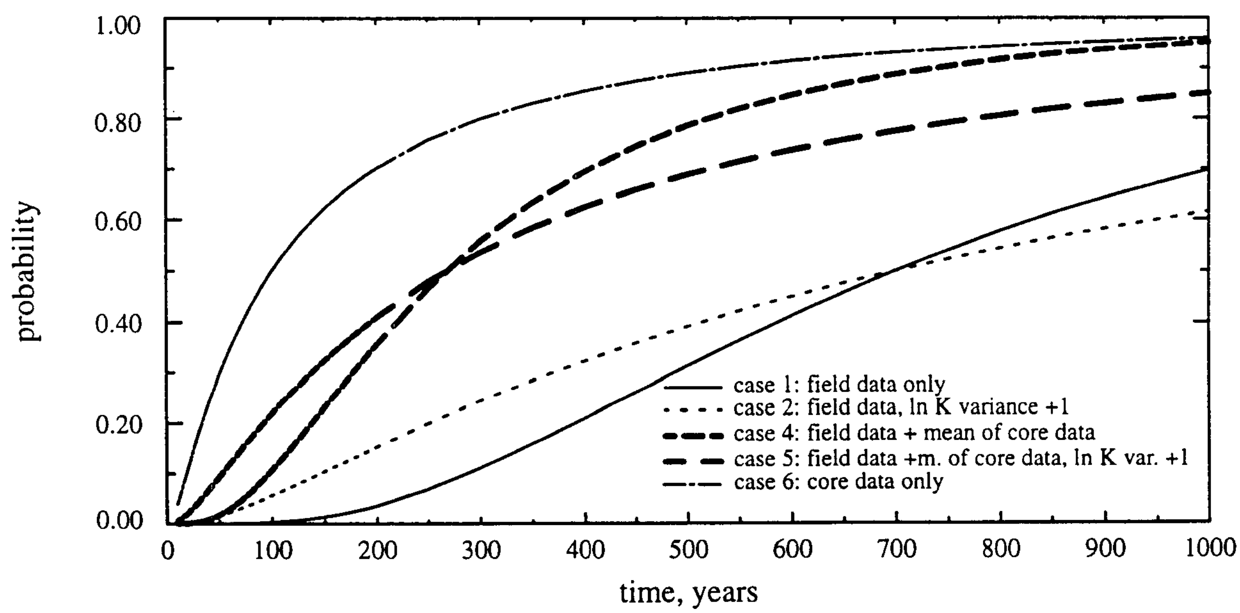

Figure 7. Cumulative distribution function for groundwater travel time in the Ojo Alamo Aquifer to Well 10-36. The travel path length is treated as an uncertain variable because the nature of the connection of GB-ER and the Ojo Alamo is unknown. The different hydraulic conductivities assumed for the cases tested result in widely different probabilities of time. For example, using the field data only (case 1) results in a 20% chance of travel to Well 10-36 in 400 years or less, while using the core data only (case 6) results in a 20% chance of travel in 33 years or less.

cumulative distribution function is to generate a steep curve, indicating a relatively high probability of rapid arrival times. Enlarging the time period of interest at Gasbuggy from Figure 7, Figure 8 shows a 10% chance that migration to Well 10-36 could occur in 20 years or less when using the core-only conductivities of case 6. Case 5 (using the mean of the core data and increasing the variance) is the only case using field data which also showed a reasonable chance of migration to 10-36 in the time frame observed.

A travel time calculation was also performed for flow through the Pictured Cliffs (case 1 in Figure 5). In this case, fractures resulting from the detonation connect GB-ER and Well 10-36 at the shot horizon (the Pictured Cliffs Formation) so there is no lateral transport from the shot to the well in the Ojo Alamo. Though permeability measurements were made on core from the Pictured Cliffs, they represent unfractured values. Instead of those, the analysis used the published range of fractured-rock hydraulic conductivities (3.15×10^3 to 3.15×10^8 cm/yr, Freeze and Cherry, 1979). Measured porosities were not altered for the calculations ($m = 0.09$) and the flowpath length was assumed to be the total distance between the boreholes (13,200 cm).

Two cases were going to be analyzed: one assuming the regional gradient of the Ojo Alamo applied to the Pictured Cliffs, and the other assuming a much steeper gradient resulting from the detonation. However, using the regional gradient resulted in such rapid travel times (Figure 9) that the second case was not generated. The results make it clear that tritium could have moved from the cavity to 10-36 on the order of weeks after the detonation through fractures in the Pictured Cliffs. The subsequent delay in breakthrough at the Ojo Alamo would presumably be due to slower transport up the 10-36 borehole through the cement plug (assumed damaged by the shot).

The travel time calculations can be interpreted the following way: either the field hydraulic conductivities do not represent the aquifer or transport was not primarily through the Ojo Alamo. If the aquifer conductivity is actually represented by the core values, transport could have been through the Ojo Alamo. If the field-measured conductivities accurately represent the Ojo Alamo, then the tritium detected in 10-36 could not have traveled far through the aquifer. This means, transport had to be through a fracture intersecting the Ojo Alamo close to 10-36, or through the Pictured Cliffs and up the 10-36 borehole.

The implications of these two cases are very different. In the first case, transport of radionuclides from the nuclear event may occur rapidly, regardless of how the cavity and the Ojo Alamo are connected. The worst situation would be for there to be multiple connections between the cavity and the Ojo Alamo and for the core measurements to be representative. In the second case, transport of radionuclides from Gasbuggy to the accessible environment is unlikely. Material may migrate from the cavity to the Ojo Alamo, but will not travel far through the sandstone before radioactive decay reduces contaminant concentrations.

Resolving the discrepancy between the field and core hydraulic conductivity values will not be a trivial problem. Single well tests (drawdown by swabbing) were conducted at three different locations during Gasbuggy operations and yielded consistent results (Mercer, 1970; Weir, Jr., 1971). The final test was conducted after the detonation for the sole purpose of detecting increases in

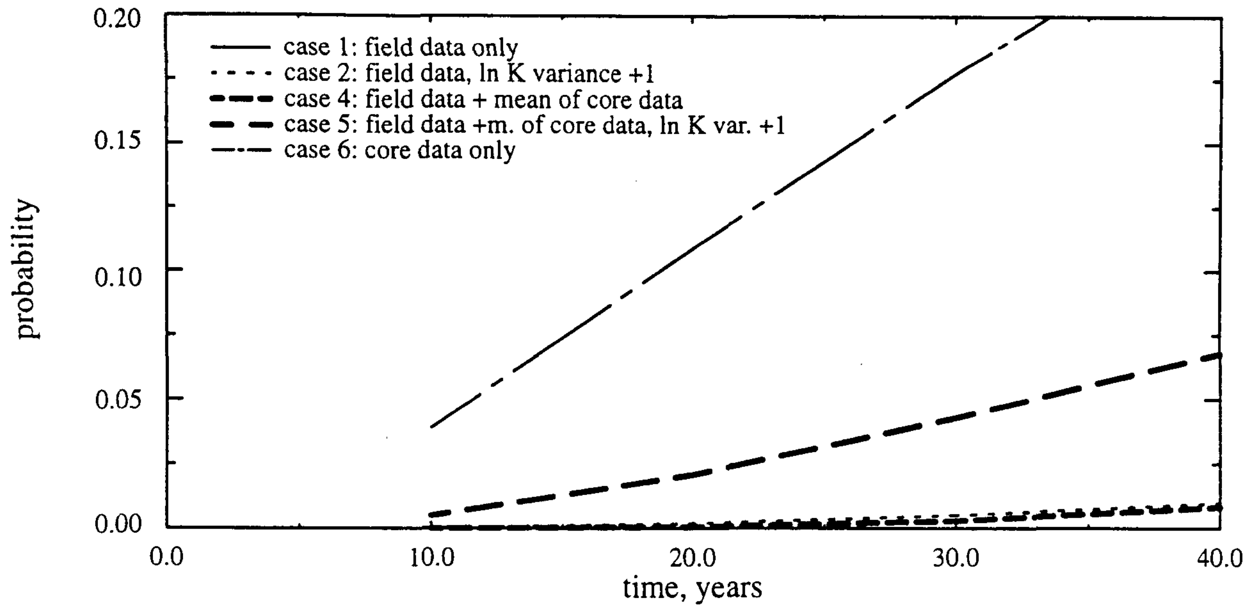

Figure 8. Zoomed view of the early-time portion of the cumulative distribution function shown in Figure 7. Only cases 5 and 6, using core data with a large variance, result in significant probabilities of transport to 10-36 in the time frame observed (16 to 17 years).

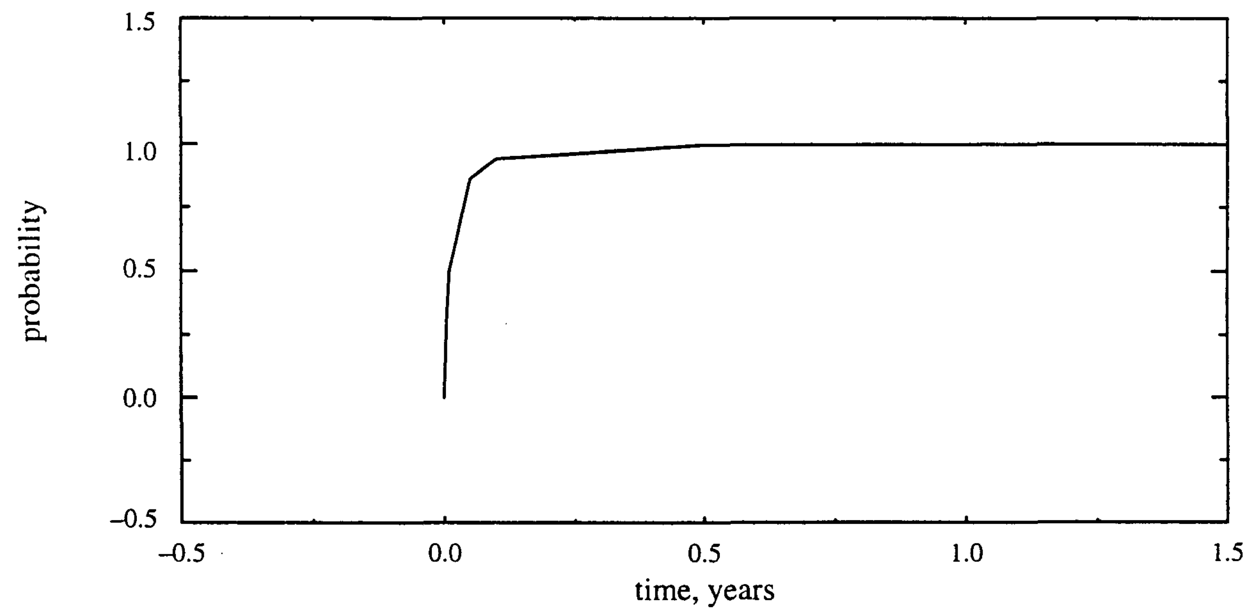

Figure 9. Cumulative distribution function of travel time to 10-36 through a fractured Pictured Cliffs Formation. In this scenario, the travel path length was assumed fixed at the total distance between GB-ER and 10-36, and the regional hydraulic gradient in the Ojo Alamo was assumed to apply to the Pictured Cliffs. Under the assumed conditions, travel is almost certain to occur within a few weeks.

conductivity due to the shot, and none were found (Weir, Jr., 1971). It is possible that the problem lies in inhomogeneity in the vertical distribution of permeability in the formation. The core results (Figure 10) indicate zones of higher permeability (up to 7.6 m thick) interspersed among low permeability horizons. Vertical variations in permeability were also identified during field testing, with the lower part of the formation found to be more transmissive than the upper section (Koopman and Ballance, 1968). However, the effective length of the formation contributing water still may have been greatly overestimated, yielding lower average transmissivities.

FIELD INVESTIGATION OF TRANSPORT SCENARIOS

A detailed hydrologic logging and sampling effort was designed by Desert Research Institute to test the transport hypotheses identified in the travel time analysis. The objectives were to determine if flow is moving up through the cement plug at the bottom of 10-36 and determine a profile of tritium in the water column to reveal where tritium is entering the well.

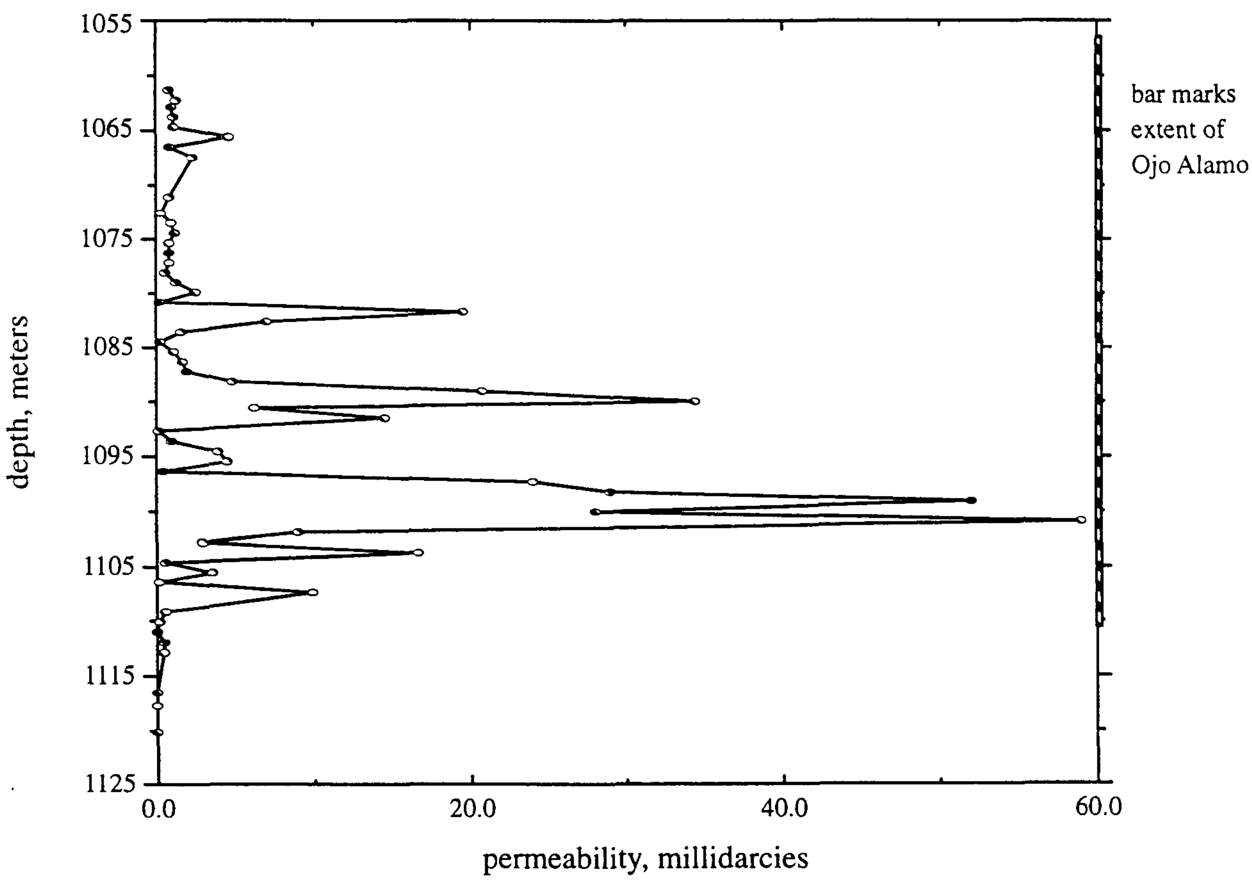

Figure 10. Vertical distribution of permeability measured in cores from GB-1. Data from Rawson and Korver (1967). Note the limited zones of higher permeability.

WELL CONSTRUCTION

Prior to the Gasbuggy nuclear test, sand was placed in Well 10-36 from the bottom of the well to above the perforated interval at 1189 m. The remainder of the well was filled with cement. After the test, the cement was drilled out to a depth of 1099.1 m. Drilling problems encountered precluded recompletion of the well to its original total depth (1283.2 m). The well was then shot perforated from 1085.4 m to 1090.3 m and from 1091.5 m to 1097.6 m so it could be used as a hydrologic monitoring well. Access tubing (0.05m) was placed in the well with perforations from 1093.6 m to 1099.1 m to be used as a sampling port (Figure 11).

FIELD ACTIVITIES

Field sampling and logging were conducted from May 27 through May 30, 1994. Prior to these activities, the Environmental Protection Agency measured the water level and collected their annual water sample for the Long-Term Hydrologic Monitoring Program on May 22. On May 23, IT Corporation and its contractor removed the 0.05-m tubing from Well 10-36 to allow access for large-diameter logging tools and to facilitate a casing integrity log requested by the U.S. Forest Service.

Water Sampling

Water samples were collected from the following depths: 932.9 m, 1083.8 m, 1092.7 m, and 1098.8 m. Samples were collected in order of increasing depth to decrease the potential of cross contamination of the samples through borehole mixing. These sample depths were chosen based on the borehole construction. The 1083.6 m, 1092.4 m, and 1098.5 m depths correspond to points above, between, and below the perforated sections of the borehole. The 932.7 m location was chosen because it is located adjacent to the portion of the borehole where the casing below it is cemented to the annulus and the portion above it is not, with the space between the borehole and the casing filled with drilling mud. All of these water samples were malodorous and had black suspended particles that became more prominent the deeper the sample was collected. Two additional water samples were collected, at 518.3 m and 640.2 m, based on the results from the chemical log. Although both samples had the bad odor associated with the samples collected deeper in the borehole, the shallower sample was clear in color while the sample from 640.2 m was aqua blue in color. Water samples were analyzed for anions, cations, oxygen and hydrogen stable isotope ratios, and enriched tritium. The results of these analyses are presented in Table 1.

Hydrologic Logging

Chemical Logging

Following water sampling, Well 10-36 was logged with the chemical logging tool (Figure 13). The depth to water measured with this tool was 316.6 m. However, prior to the removal of the 0.05-m tubing, EPA measured a depth to water of 286.1 m. The 30.5 m difference can be accounted for by the water that was displaced when the access tubing was in the well. When the tubing was removed, the water level dropped to a depth that was proportional to the volume of the tubing.

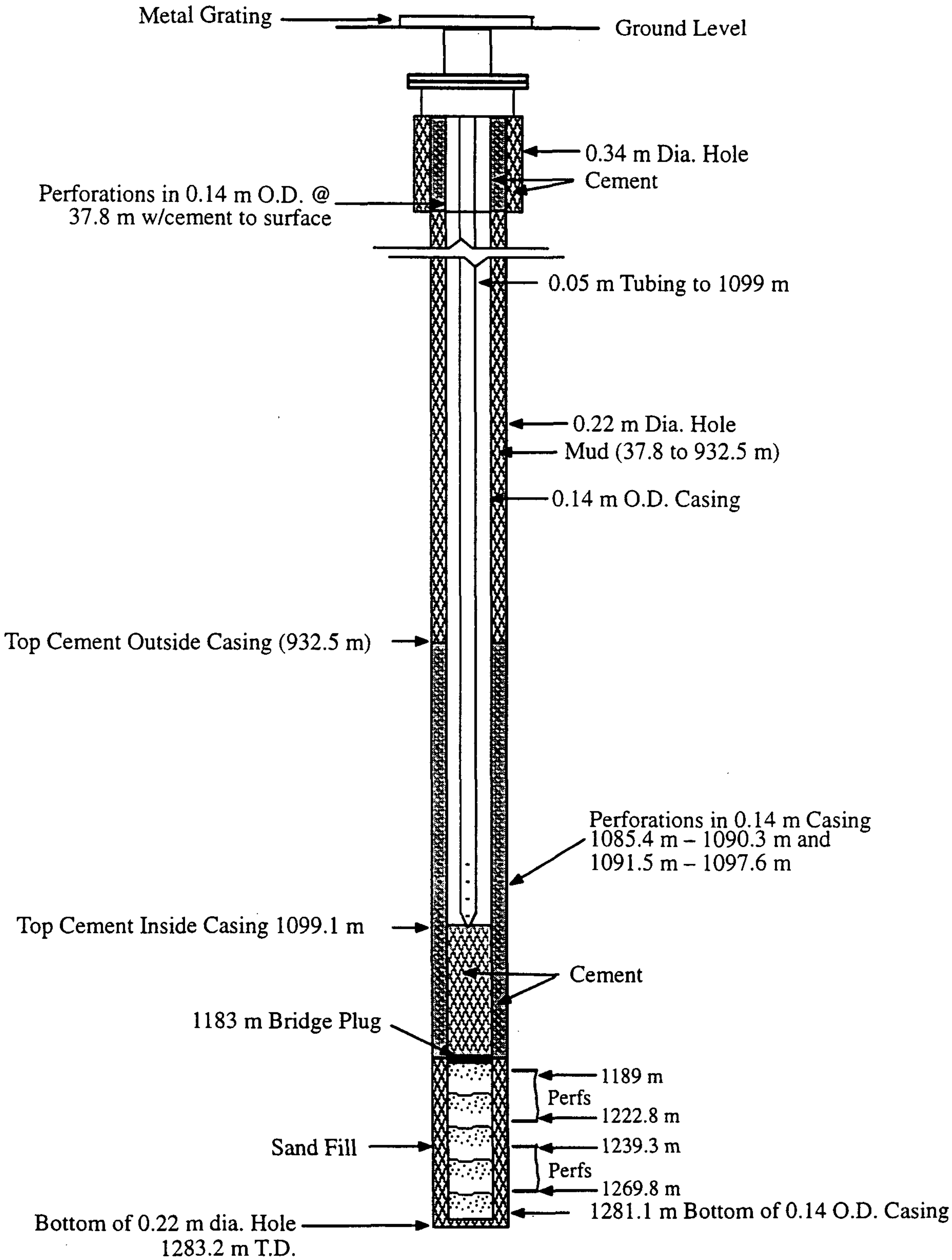

Figure 11. Status of Well 10-36, from Holmes and Narver (1983) prior to the 1994 field activity. The 5-cm tubing has been removed from the well.

Table 1. Chemical and Isotopic Analyses of Groundwater Samples from the Gasbuggy Site. All units are mg/l unless noted.

Well	Depth (m)	Date	pH	EC (μS/cm)	SiO_2	Ca	Mg	Na	K	Cl	SO_4	HCO_3	CO_3	OH	NO_3	$\delta^{18}O$	δD	^3H (pCi/L)
EPNG 10–36	518.3	30–May–94	12.1	4,670	4.0	69.5	< .1	520	154.0	66.5	670	0	54.7	215	0.18	–2.3	–32	*
EPNG 10–36	640.2	30–May–94	11.3	10,200	18.8	382	< .1	2,220	56.7	261	5,520	0	23.8	47.9	0.13	–9.9	–68	*
EPNG 10–36	932.9	27–May–94	11.2	10,200	18.6	382	< .1	2,240	54.7	263	5,460	0	25.1	34.2	0.13	–9.8	–69	*
EPNG 10–36	1083.8	27–May–94	10.1	9,760	18.5	406	.54	2,150	67.6	266	5,390	0	23.6	4.8	0.22	–9.9	–68	*
EPNG 10–36	1092.7	28–May–94	10.3	9,760	18.3	406	.99	2,180	69.0	263	5,380	0	24.2	7.0	0.18	–9.7	–68	*
EPNG 10–36	1098.8	28–May–94	10.2	9,830	22.7	414	1.78	2,170	80.7	263	5,430	0	25.4	6.0	0.13	–9.9	–68	*
GB–1	1071.0	23–Feb–67	7.7	8,210	8.0	218	14	2,160	14	272	4,060	223	0	0.0	0.0	N/A	N/A	
GB–1	1098.3	26–Feb–67	6.9	7,450	16.0	242	14	1,880	12	221	3,630	86	0	0.0	0.0	N/A	N/A	
GB–2	1056	17–Apr–67	7.2	9,350	10	251	12	2,220	1.6	282	4,440	306	0	NA	NA	NA	NA	
GB–2	1195	1–May–67								5320	480							
Indian E–1		5–May–67								3700								
Feasel #2		8–Feb–68								12,100								

N/A = not analyzed
* = not available

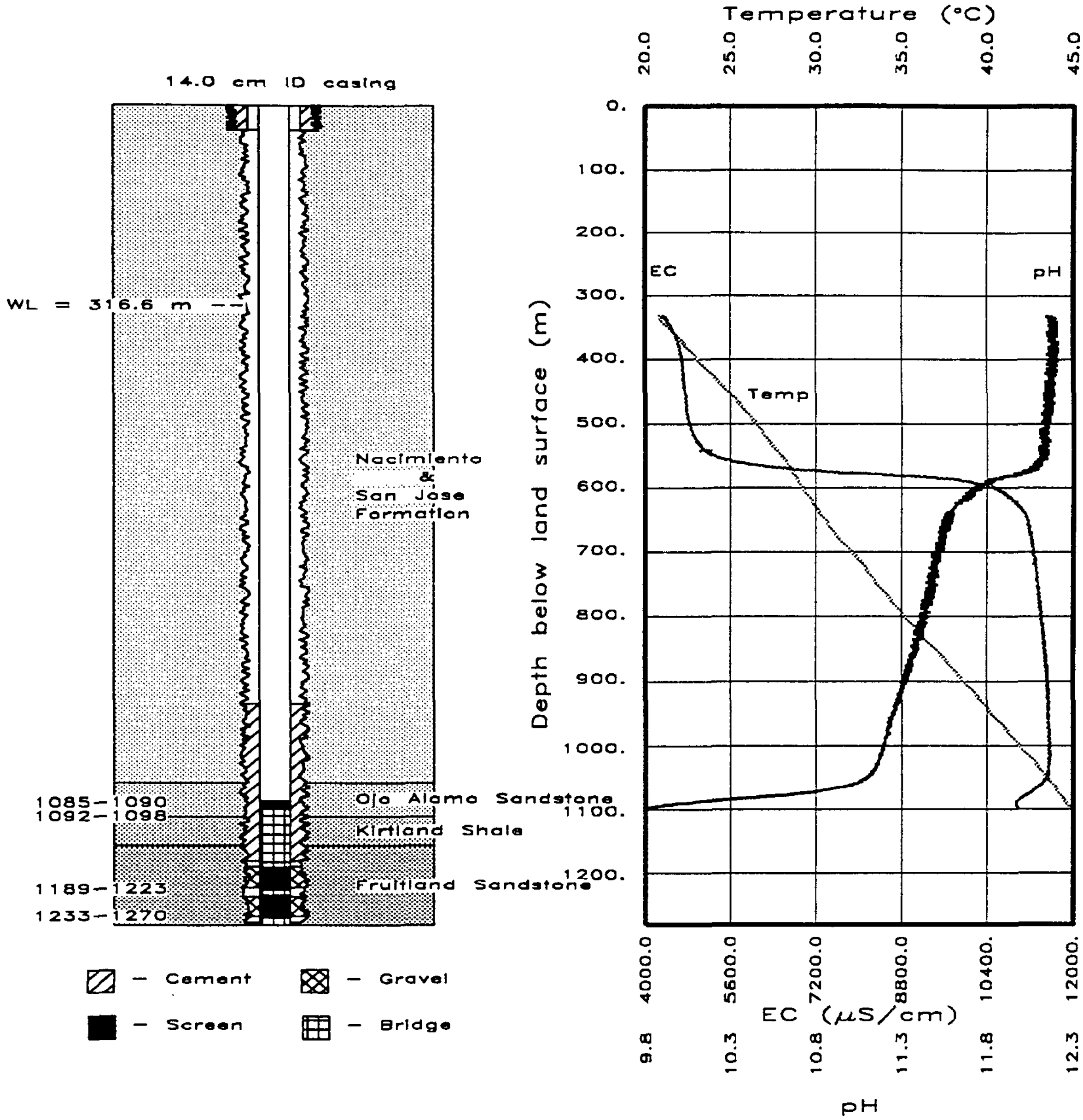

Figure 13. Temperature, EC and pH log of EPNG 10-36, May 29, 1994.

Although the well was recovering (water level rising), it was doing so very slowly. This recovery could be seen in subsequent water level tags that showed the depth to water decreasing with each successive measurement. The slow recovery indicates that the formation is not very productive or that the well does not have good communication with the formation. If the well is recovering only through the screened zone (i.e., if the casing integrity is good), the bottom water samples should be more representative of the formation water.

Temperature

The temperature log follows a relatively straight path along a geothermal gradient of 0.0315°C/m, although a few minor perturbations do occur. The first of these perturbations occurs from the top of the borehole to a depth of 490 m, where the gradient is slightly steeper than the average geothermal gradient. At this point, the gradient decreases and becomes less than the geothermal gradient to a depth of 685 m. From 685 m to 808 m, the gradient is equal to the geothermal gradient, although the temperature is slightly less than that predicted by the geothermal gradient. The remainder of the borehole can be described as having a gradient slightly greater than the average geothermal gradient.

Specific Conductance

The most notable feature on the specific conductance plot is the sharp increase of conductivity that begins at approximately 525 m. The conductivity at 525m is 4,900 μS/cm, which rapidly increases to 11,100 μS/cm at 640 m. This substantial increase is indicative of a dramatic change in water chemistry, and the chemical analysis from 518.2 m and 640.1 m confirms these different water chemistries. From 640 m to 1047 m, the conductivity slowly increases to 11,500 μS/cm but then decreases to 10,900 μS/cm at the bottom of the hole. This decrease in conductivity at the bottom of the borehole is likely the result of fresher formation water entering the borehole as the well was re-equilibrating from the removal of the casing.

pH

In the upper 1000 m of the borehole, the pH responded in a similar but inverse manner as compared to the specific conductance. The pH in the upper part of the borehole was 12.2, which began to rapidly decrease at approximately the same depth the specific conductance increased. At 640 m, the pH had decreased to 11.6 and continued to slowly decrease to 11.07 at 1047 m. From 1047 m to the bottom of the borehole the pH rapidly decreased to 9.8, again indicative of the inflow of fresher formation water. The high pH in this well is likely the result of the water reacting with the cement that was used to plug the well during the test.

Thermal Flow Logging

One of the main purposes of the well logging was to determine the source of the elevated tritium in Well 10-36. The thermal flow tool was used to determine vertical movement of water in the borehole. Measurements were made at each of the locations where water samples were collected. No vertical movement was detected with the thermal flow tool at all of the zones where measurements were made. Thus, if vertical transport from the cavity to the Ojo Alamo Sandstone through the plugged casing is occurring, it is at a rate below the sensitivity of the flowmeter (0.08 l/min).

Interpretation of Logging, Chemistry, and Radiochemistry Data

With the well recovering from the removal of the 0.05–m tubing, and given that the only perforations in the well are across from the Ojo Alamo at the bottom of the well, there should be upward flow occurring. Under conditions of no flow in a well, the TFM measures a flow response time of about 40 seconds (upward). This is due to the buoyancy effect of the heated sheet of water within the TFM flow tube. Response times greater than 40 seconds cannot be used to quantify flow rate or velocity, but can be used to measure flow direction. The measurements at eight different depths had flow response times ranging from 120 to 150 seconds. This suggests that there may actually be downward flow within the well, countering the buoyancy effect, which in turn requires some opening in the casing at ___ m or above.

The water samples collected all belong to the Na-K-SO_4 facies, but differences between the samples exist. The largest distinction is between the uppermost sample from 518.3 m and the deeper samples, with the top sample containing less calcium and sulfate than the deeper waters and more of a carbonate component. The unusually high pH values of all the samples results in most of the alkalinity being in the OH^- phase. In the pH range usually encountered in natural water, OH^- is a minor constituent, but at pH values above 10, it becomes important. The stable isotopic composition of the uppermost sample is also markedly different from the lower samples, with non-equilibrium enrichment of the heavy isotopes indicating evaporation (Figure 12). The chemistry of the samples collected close to the perforations does not vary significantly, though the pH is lower than the upper samples, confirming the logging results. The samples collected between the perforated zone and the upper sample appear to be transitional between the two water types in regard to their alkalinity and pH, but the rest of the ionic composition is similar to the deeper water.

Comparison of the 1994 10-36 sample analyses with published chemical analyses of water (Table 1) from the Ojo Alamo and the Pictured Cliffs formations strongly suggests that the water present in 10-36 originates in the Ojo Alamo. With the exception of the pH and alkalinity, the 1994 samples bear a strong resemblance to the samples collected from the Ojo Alamo in well GB-1 as part of the Gasbuggy Project (Mercer, 1970). In contrast, the incomplete Pictured Cliffs analyses reported by Power and Bowman (1970) reveal a chloride rather than sulfate dominated water in the

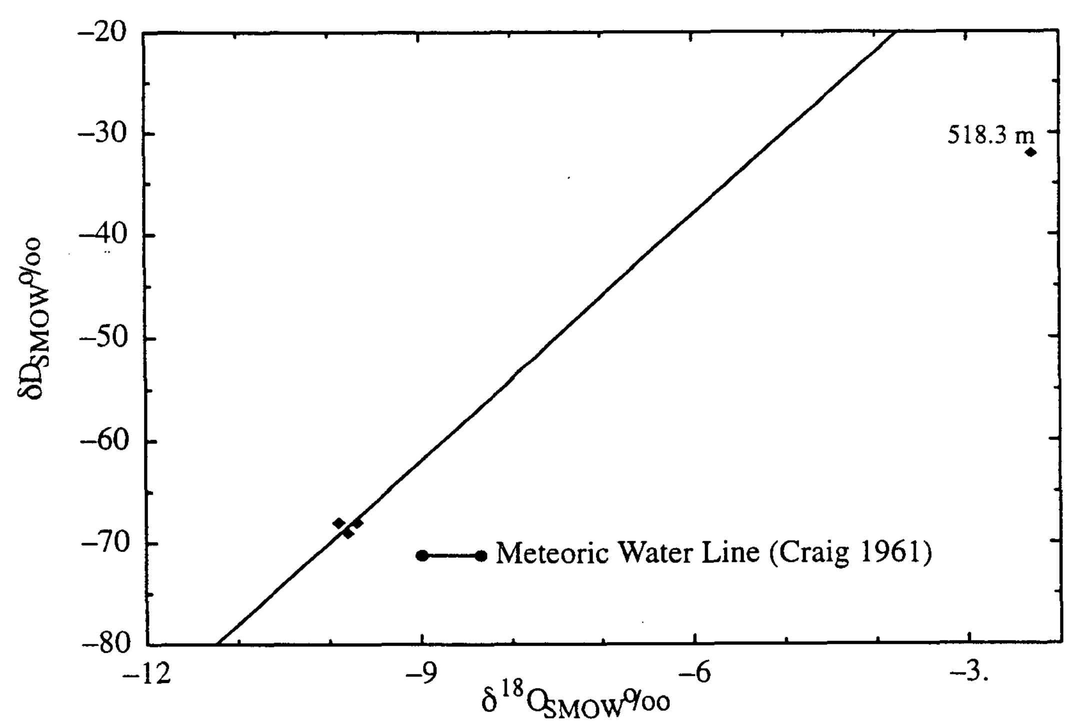

Figure 12. Stable isotopic composition of samples from EPNG 10-36. The sample collected at a depth of 518.3 m exhibits nonequilibrium enrichment suggestive of evaporation.

Pictured Cliffs. This distinction is large, an order of magnitude less sulfate and an order of magnitude more chloride in the Pictured Cliffs, and was used by Power and Bowman to determine the source of water infilling the Gasbuggy cavity.

The unusual pH and difference between earlier Ojo Alamo analyses and the current samples indicate that the water in 10-36 is no longer representative of natural conditions and has been altered by some process, most likely the cementing of the well prior to the shot. Residual cement has clearly raised the pH, changed the distribution of alkalinity species, and resulted in carbonate precipitation. The water in the upper zone has also been affected by these processes, but has a chemical and isotopic signature suggestive of a water source other than the Ojo Alamo.

The tritium concentration decreased with increasing depth in the well (Table 1). Measureable tritium was found in the upper two samples (121 ± 8 pCi/l at 518 m and 12 ± 9 pCi/l at 640 m), and tritium was below the detection limit (<10 pCi/l) in the bottom sample from 1099 m. The three samples inbetween (933, 1084, and 1093 m) may contain tritium close to the detection limit value. This distribution of tritium in the well is surprising based on the EPA monitoring results (Figure 1), though differences between the EPA and DRI results can be expected because the well conditions were radically changed by the removal of the tubing.

The DRI results indicate that tritium was not entering the well at the Ojo Alamo perforations at the time of sampling. The lower pH value at the Ojo Alamo perforations suggests that relatively fresh formation water was entering the well in response to removal of the tubing (though at a low rate of flow according to the flowmeter results), yet none of the three samples collected near the perforations contained measureable tritium. If the tritium measured by EPA had the Ojo Alamo as its source, then it appears that the tritium was part of a transient pulse which has passed. Such a pulse could have been generated by either the prompt injection or vapor–phase migration scenarios. These short–term phenomena would release a limited amount of radioactivity to the Ojo Alamo. Once in the tubing, the tritium may have been effectively trapped there and resampled by EPA year after year. Pulling the tubing prior to DRI's sampling may have dispersed the tritium throughout some length of the well, diluting it beyond detection.

The tritium located higher in the well is associated with water having an origin other than the Ojo Alamo, based on the chemical and isotopic results. The enriched isotopic composition suggests water that has been exposed to evaporation, which in turn suggests surface exposure. It is possible that the water's chemical and isotopic signature evolved when it was recharged and that the tritium represents the residual impacts of atmospheric nuclear testing on global precipitation and surface water. This water would have to enter the well through a breach in the casing because the only perforations are at the Ojo Alamo, and such entry would be consistent with the thermal flowmeter measurements suggesting slight downward flow in the well. Another possibility, however, is that this water was introduced as part of Gasbuggy close–out activities. For example, the lower salinity and enrichment in heavy isotopes are all consistent with a temporary surface water pond on site, with the tritium content related to gas flaring activities. The unusual aqua blue color of one of the upper water samples may be related to some sort of drilling additive in the pond. If such a pond water was introduced into 10–36, it would remain at the top of the water column because of density differences.

CONCLUSIONS

Two scenarios have been identified that could explain the transport of tritium from the Gasbuggy test to Well EPNG 10-36: vertical transport from the shot horizon in the Pictured Cliffs Formation through the plugged casing in the well, or lateral transport from the shot chimney through the Ojo Alamo Formation sampled by the well. Analysis of hydraulic data generated during field tests at the time of the Gasbuggy project suggests that the hydraulic conductivity of the Ojo Alamo is too low for lateral transport over the timeframe of interest. This means that transport was through either a fracture intersecting the Ojo Alamo close to Well 10-36, or through fractures in the Pictured Cliffs and up through the bottom plug in the well. However, if the conductivity of the Ojo Alamo is better represented by values obtained from core samples, lateral transport could be a pathway.

Results from logging and sampling at Well EPNG 10-36 favor the scenario of transient transport of tritium through the Ojo Alamo. Flow logging did not detect any vertical movement up through the bottom plug, within the sensitivity of the measurements (0.08 l/min). Hydrochemical logging and sample results are consistent through most of the well with the known characteristics of groundwater in the Ojo Alamo, with the exception of altered pH and alkalinity conditions presumably caused by cementing operations. At the time of sampling, no measurable tritium was entering the well at the Ojo Alamo perforations, suggesting that the tritium measured previously by the EPA was part of a transient pulse, perhaps related to prompt injection or early–time vapor–phase transport. A zone of water of unknown origin occurs at the top of the well, marked by lower water salinity, an isotopic signature indicative of evaporation, and measurable tritium. These characteristics suggest surface exposure, perhaps in a project–related pond that was subsequently injected in the well.

The tritium distribution in the well, both in space and time, needs to be monitored to determine if other short– or long–term transient pulses occur. The steady state conditions in the well should also be determined with hydrologic logging after the well has recovered from the removal of the tubing. The origin of the upper water layer could be investigated by additional chemical (both organic and inorganic) and isotopic analysis. Future work can address refining estimates of the hydraulic conductivity and its spatial variability in the Ojo Alamo and obtaining chemical and isotopic samples representative of *in situ* conditions. Both of these objectives will probably require drilling new wells near the site, though it is possible that development of 10-36 could purge the effects of the cement contamination. Included in any new data collection should be hydraulic conductivity measurements in the Ojo Alamo, precise head measurements in both the Ojo Alamo and Pictured Cliffs formations, major ion analyses of water from both zones, and isotopic analyses of deuterium, oxygen-18 and tritium.

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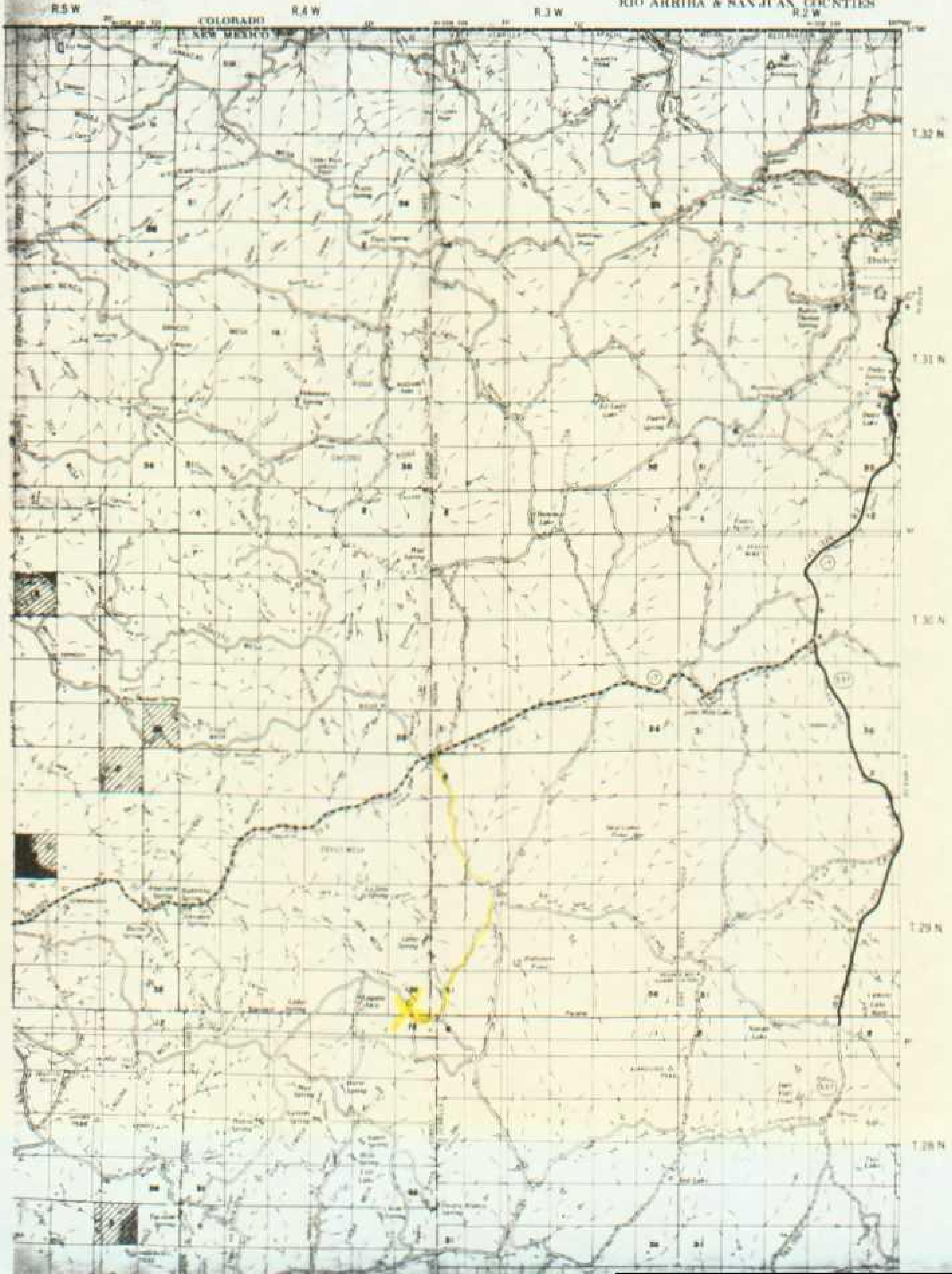

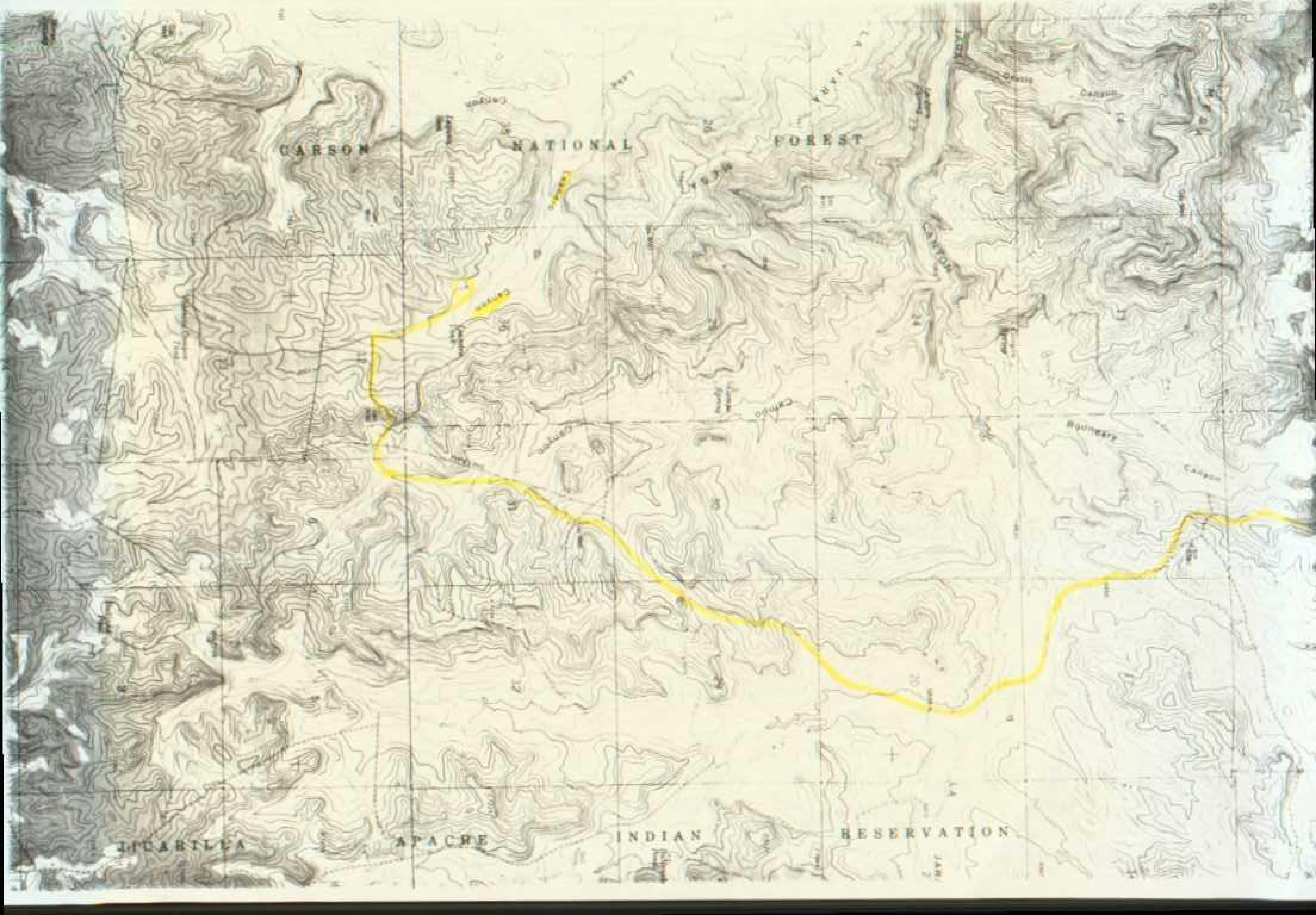
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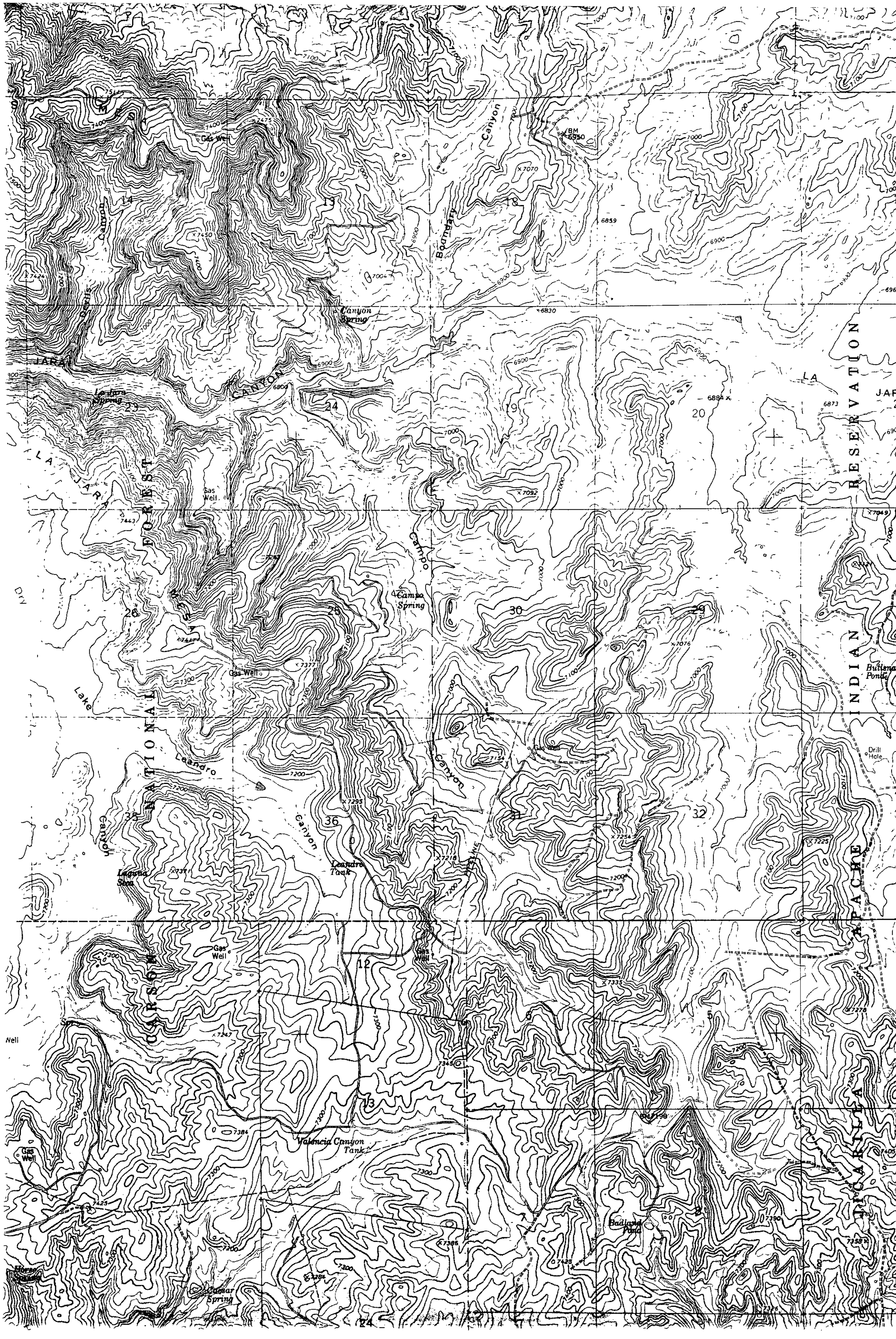

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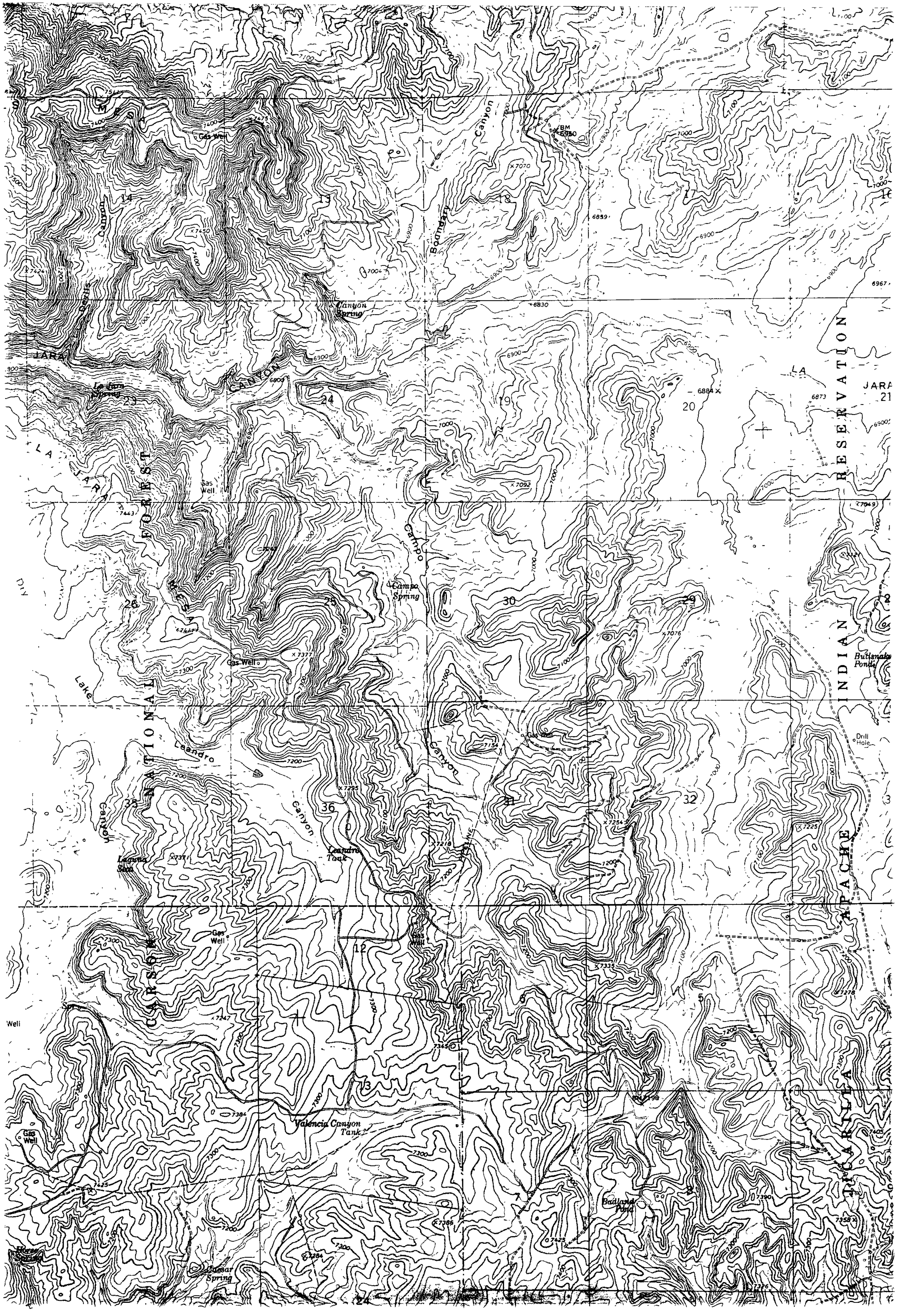

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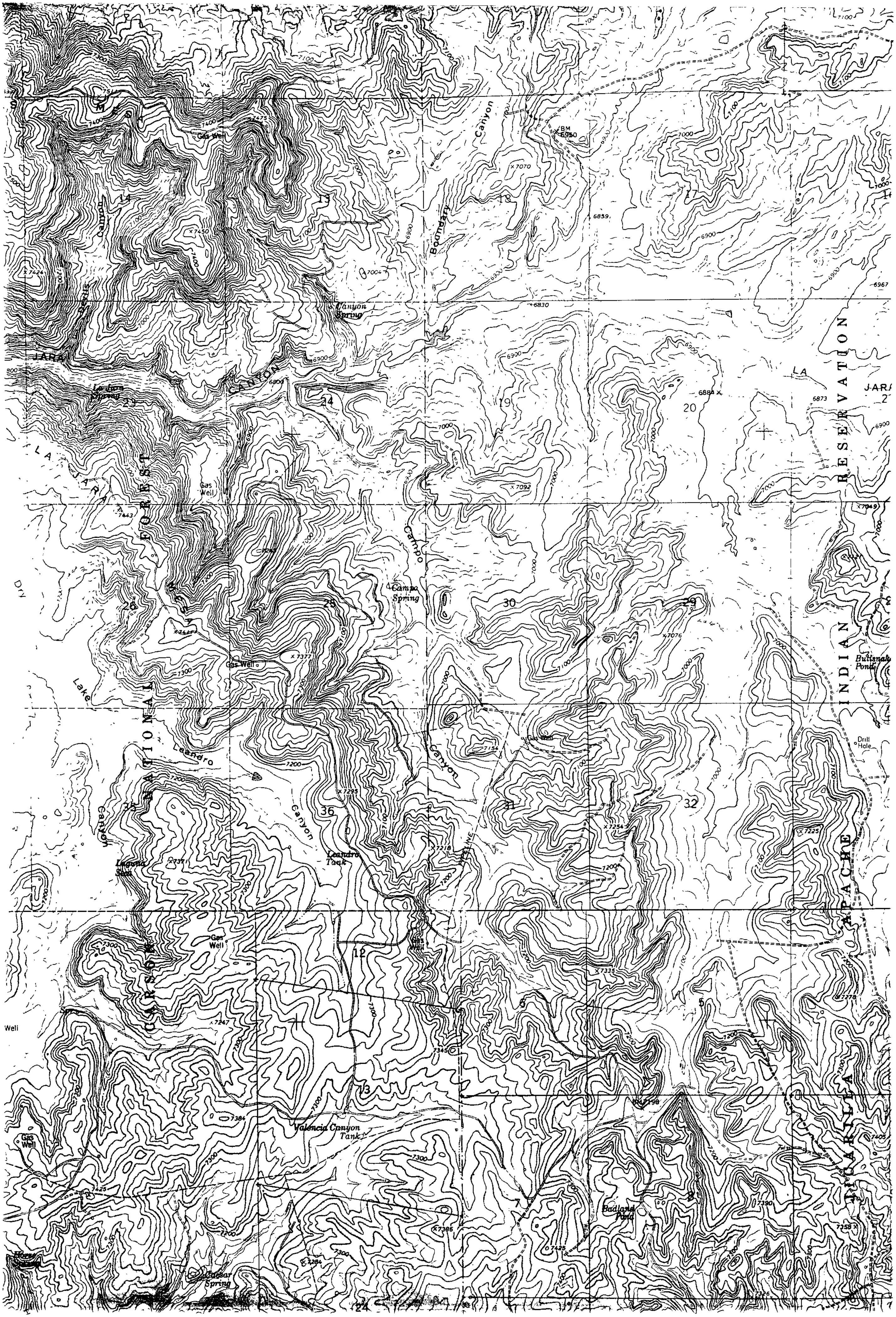

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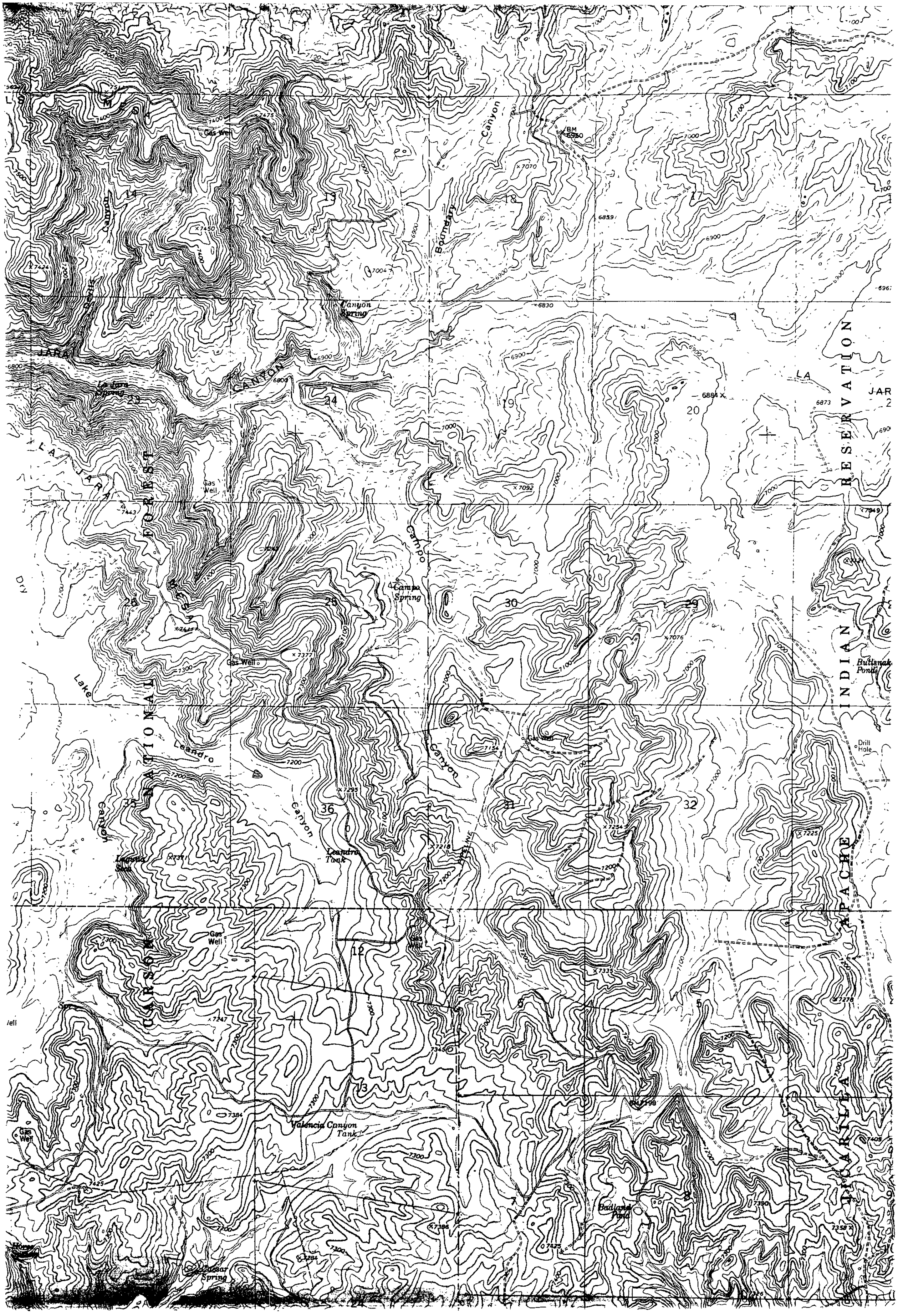

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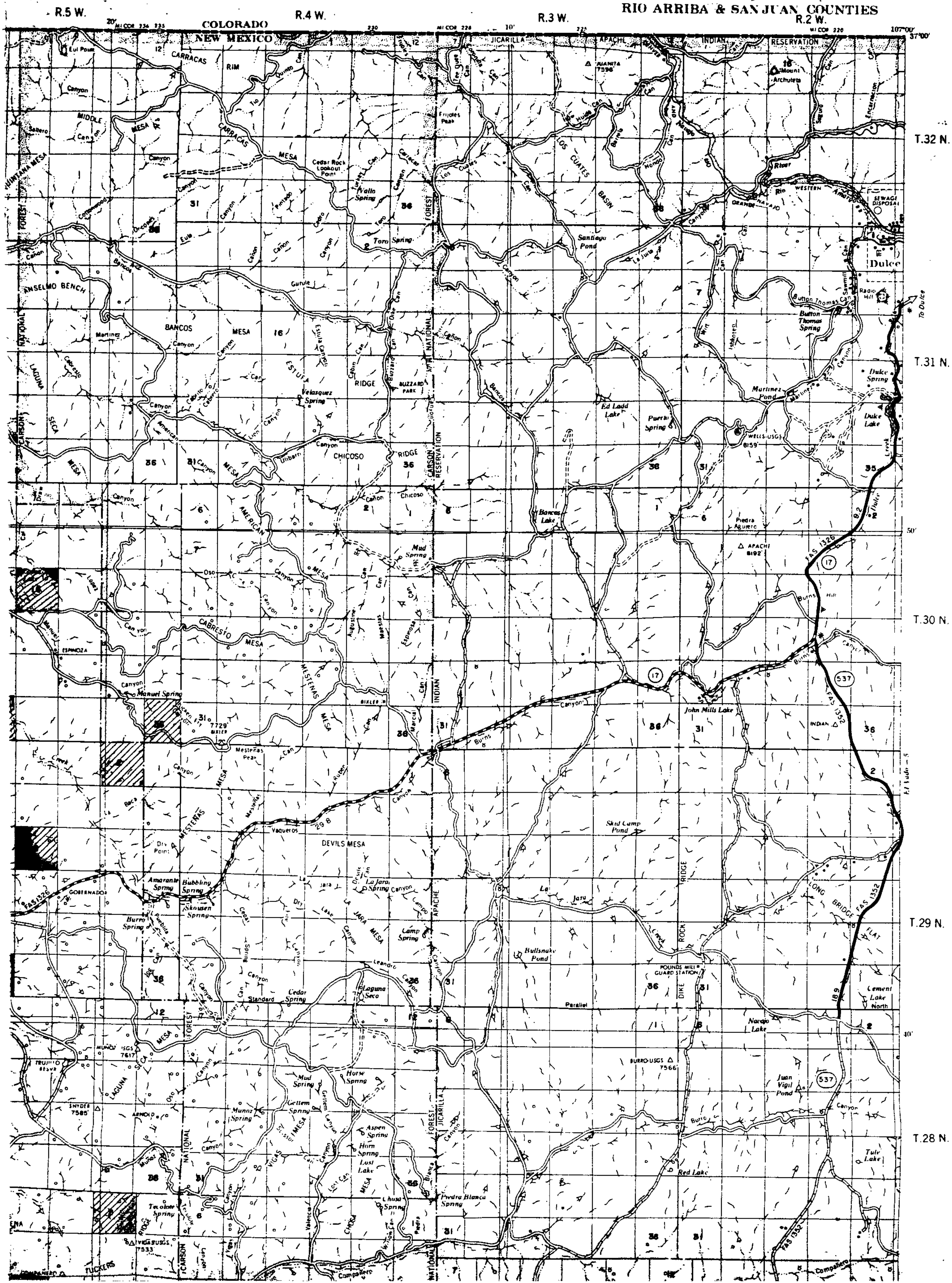

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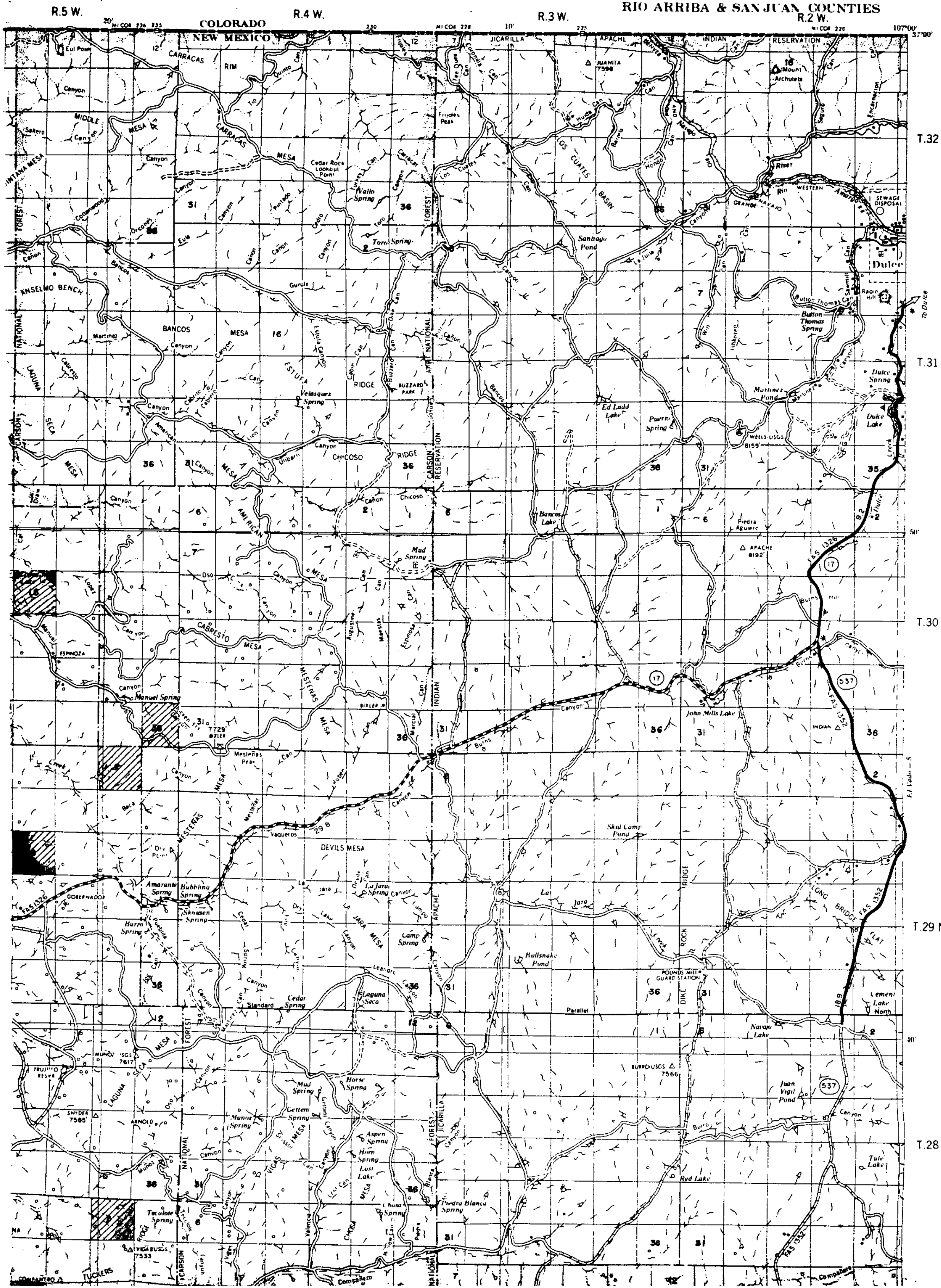

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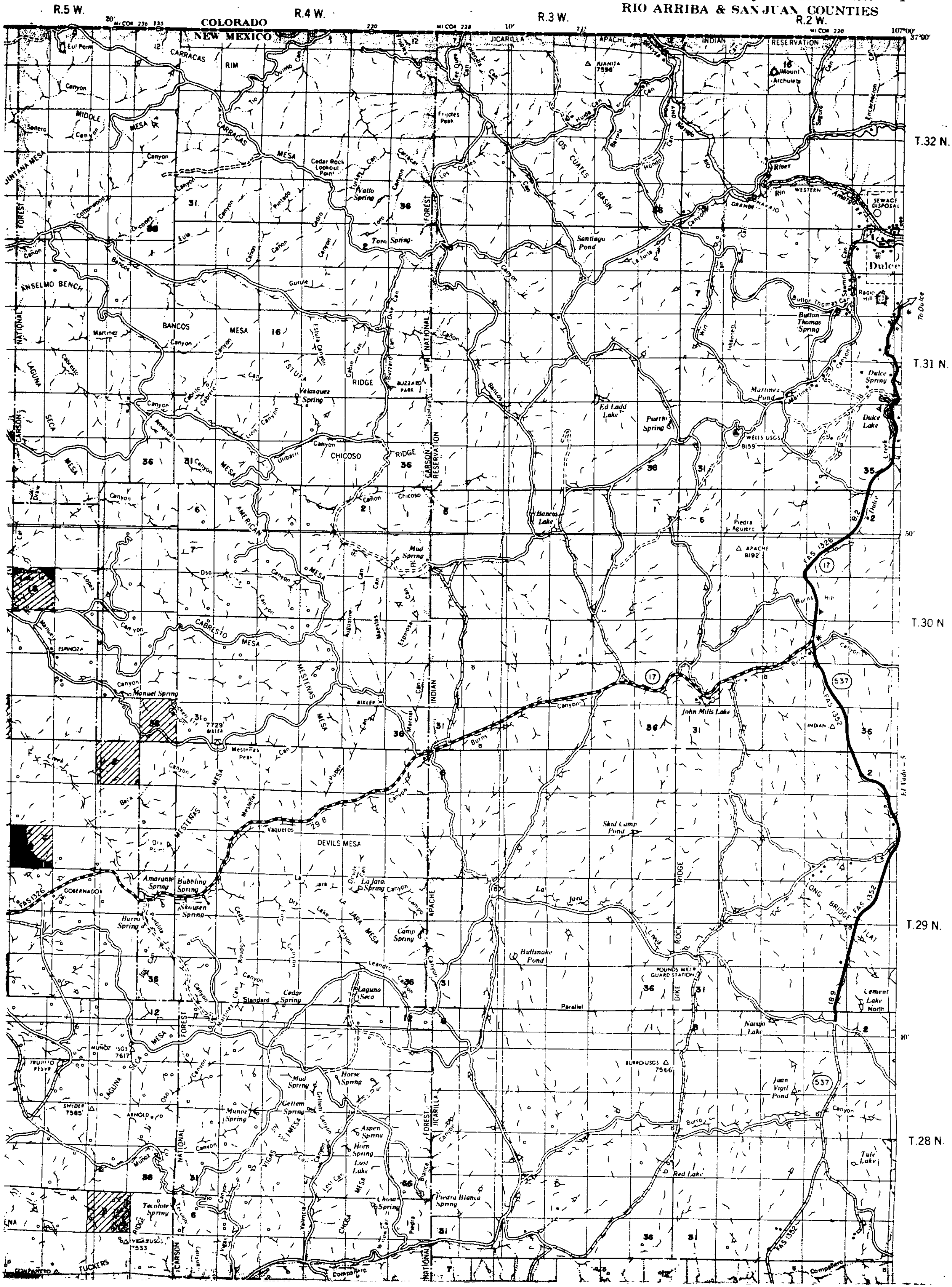

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