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DESERT RESEARCH INSTITUTE
UNIVERSITY OF NEVADA SYSTEM

EVALUATION OF GROUNDWATER MONITORING AT OFFSITE NUCLEAR TEST AREAS

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OVERALL PROGRAM FOR GROUNDWATER MONITORING AT OFFSITE NUCLEAR TEST AREAS

Introduction

Groundwater quality has been monitored at nuclear test sites distant from the Nevada Test Site as part of the Long-Term Hydrologic Monitoring Program (LTHMP) since 1972. Separate reports describing the monitoring programs recommended by the U.S. Department of Energy (DOE) Hydrologic Program Advisory Group were issued by the DOE for most of the offsite areas during the early 1980s, and the analytical results from the LTHMP have been regularly reported by the U.S. Environmental Protection Agency (EPA), but there has been little else published about the program. The LTHMP has continued to demonstrate the safety of drinking water supplies near the offsite areas and there have been very few modifications to the program initially mandated by the DOE in 1972. During this time, however, there have been many changes in the fields of hydrogeology and environmental monitoring. In 1988, the DOE requested the Desert Research Institute to perform a critical review of the LTHMP in light of the many technical and regulatory advances in groundwater monitoring in recent years. This report presents an evaluation of the offsite groundwater monitoring program and evaluations specific to the monitoring networks at each of the eight offsite test areas. Discussion of the overall program is presented first, followed by broad-based recommendations. Then, monitoring at individual sites is evaluated, followed by site-specific recommendations. References follow each section for the convenience of readers interested in particular sites.

Program Objectives

Groundwater quality can be monitored for a variety of reasons. Monitoring systems that achieve one objective may be inappropriate for meeting another type of objective. The purpose of the LTHMP at the offsite areas is thus central to evaluating the program.

The LTHMP was initiated in 1972 by the Nevada Operations Office of the U.S. Department of Energy (which at that time was part of the Atomic Energy Commission). Though offsite areas (meaning outside the boundaries of the Nevada Test Site) had been monitored prior to 1972 by the U.S. Geological Survey, Teledyne Isotopes, Inc., and the U.S. Public Health Service, the LTHMP has been solely conducted by the DOE and EPA through an Interagency Agreement. The LTHMP is incorporated in the overall offsite Radiological Safety Program, whose objective is "to measure levels and trends of radioactivity in the offsite environment surrounding testing areas to assure that the testing is in compliance with existing radiation protection standards" (U.S. EPA, 1974, p.i). Essentially the same objective can be found in the preface to the most recent EPA Offsite Monitoring Report, while the corresponding text states that the offsite Radiological Safety Program is conducted "to document compliance with standards, to identify trends, and to provide information to the public" (U.S. EPA, 1988, p.2).

Specific to the LTHMP itself, a 1972 letter from the Atomic Energy Commission (AEC) to the EPA initiating the program lists three items as the purpose of the program: 1) assure the public safety, 2) inform the public, the news media, and the scientific community, and 3) document compliance with existing federal, state, and local anticontamination requirements (R.E. Miller to M.W. Carter, 3 February 1972). The early EPA monitoring reports list the same three purposes, as do the site-specific LTHMP reports issued for some of the sites in the early 1980s. The program had a groundwater focus because there had been surface clean-up activities at the test sites and the AEC believed that the only remotely feasible way for contamination far below the land surface to be redistributed was through the action of groundwater. Thus, the AEC considered only hydrologic monitoring appropriate for a long-term monitoring program.

A 1985 draft report prepared by the EPA on the LTHMP states that the primary objective of the program is to determine whether or not any radioactivity produced by nuclear events is detectable in surface water or groundwater surrounding the test sites (Black and Bagley, in prep.). The latest description of the LTHMP states that water sampling points are monitored so that any migration of radioactivity from the test cavities to potable water sources can be detected by radioanalysis (U.S. EPA, 1988).

Using this background, the following objectives are singled out for evaluating the LTHMP at the offsite areas:

1) assuring public safety

2) documenting compliance with standards and regulations

3) detecting migration of radioactivity

4) disseminating information

The relative importance of these objectives to the DOE is not specified in the references examined, and there could be other purposes which have not been identified.

Objective 1: Assuring Public Safety

Public safety appears to have been a prime motivating factor in the selection of sampling sites for the LTHMP. Generally, any groundwater-use point (well or spring) in the vicinity of a nuclear test is in the monitoring program regardless of whether contaminant migration from the test to the use point is feasible or not. For example, some private wells are sampled even though they are hydrologically upgradient from an event. Though upgradient wells can be used to monitor background variations, the LTHMP does not distinguish between up- and downgradient wells and thus does not evaluate background concentrations. If the flow system and release scenarios are well understood and the data are not used for background monitoring, such sampling points serve no monitoring purpose other than reassuring nearby water users. However, there is always some level of uncertainty al possible contaminant transport from the offsite areas, and the LTHMP has demonstrated that supply wells have not been affected by nearby nuclear tests.

Annual monitoring of a downgradient private well may not always be the most effective way of assuring the water-user's safety. If a contaminant is detected in a private well, considerable migration from the test site will have already occurred, complicating or limiting remedial action alternatives. The sooner migration is identified, the easier and more effective any remedial action will be.

The adequacy of point-of-use monitoring varies from site to site depending on the hydrogeologic conditions and potential release pathways. For instance, monitoring closer to the Shoal site might improve the margin of safety for water users located several miles or more downgradient by increasing the chance for early detection of unanticipated contaminant migration. Close-in monitoring in the shallow aquifer at Rulison could also be useful, but monitoring the test horizon could actually have a detrimental effect if the monitoring wells themselves opened conduits between the shallow supply aquifer and the test zone located 8000 ft below land surface.

Objective 2: Documenting Compliance With Standards and Regulations

Results from the LTHMP are evaluated in the annual Offsite Environmental Monitoring Reports in relation to "Concentration Guides" based on the limits set in the Primary Drinking Water Standards, 40 CFR 141. As far as can be determined, this is the only regulatory evaluation performed. Two aspects of the current practice require study: the applicability of the Primary Drinking Water Standards, and the applicability of other regulations.

Primary Drinking Water Standards – Applicability and Requirements

The National Primary Drinking Water Regulations set maximum contaminant levels for ^{226}Ra, ^{228}Ra, and gross α particle radioactivity in Part 141.15. Levels for β particle and photon radioactivity from man-made radionuclides are set in Part 141.16. Both of these sections apply to community water systems, defined as a public water system that serves at least 15 connections used by year-round residents or regularly serves at least 25 year-round residents. The majority of LTHMP sampling points cannot be considered community water systems, though there are some exceptions (*e.g.*, city supplies at Purvis, Lumberton, and Columbia, Mississippi, near Tatum Dome).

Analytical results are probably compared to the Drinking Water Standards because the Standards provide an understandable frame of reference for the general public. However, it is not clear what action the DOE will take if a value exceeds the standard. Tritium concentrations higher than the standard have been consistently found in wells near the Gnome Site and Tatum Dome. The monitoring reports note that the results exceeded the the Drinking Water Standards and state that the wells are not accessible to the general public. If the DOE does not wish to apply the Drinking Water Standards to non-supply wells (and there is no regulatory requirement that they should), more appropriate bases of comparison could be established for these wells, such as natural background levels. The conditions under which remedial action would take place for a non-community water supply exceeding the Drinking Water Standards should be explicitly set by the DOE since the Drinking Water Standards themselves do not legally apply.

Application of Other Standards

The DOE has decided to treat underground nuclear test sites at the Nevada Test Site and the offsite areas as inactive hazardous waste sites under the Comprehensive Environmental Recovery and Compensation Liability Act (CERCLA). The regulatory requirements applying to CERCLA sites (40 CFR 300) describe a four-phase process of discovery or notification, site evaluation, remedial investigation/feasibility study (RI/FS), and remedial action. The first two phases have essentially been completed for the offsite nuclear test areas with a Preliminary Assessment report covering all of the areas submitted to the EPA in April 1988. To varying extents, some of the information required for a RI/FS may already exist in reports of pre- and post-shot investigations and roll-up activities.

The eventual remedial action to be taken at the former test sites has not been determined, but it is likely that groundwater monitoring will play a major role. Though the CERCLA requirements do not include monitoring systems, the Resource Conservation and Recovery Act (RCRA) does provide a detailed description of monitoring programs suitable for active hazardous waste disposal sites. The offsite test areas clearly are not active disposal sites and thus RCRA does not apply to them, but the RCRA monitoring requirements are the only ones published by the EPA in regulatory form and they probably reflect the general monitoring philosophy favored by the EPA. The comparison of current offsite monitoring to RCRA requirements presented below is for informational purposes only and is not an endorsement of that approach.

The current monitoring programs at the offsite areas are deficient in regard to RCRA requirements in several respects. The basic idea of the RCRA requirements is to monitor for groundwater contamination by statistically comparing wells hydrologically upgradient from a site with wells downgradient. The monitoring system must be able to immediately detect contamination migrating beyond the waste-management area boundary. Because most of the monitoring wells at the offsite areas are pre-existing local supply wells rather than wells designed and installed specifically for monitoring, the locations of the wells are often not adequate. For instance, at the Shoal site there is only one well that can reliably be considered downgradient, rather than the minimum of three required by RCRA. At the Central Nevada Test Area, several of the downgradient wells are too far from the test site to provide timely indications of contaminant migration.

In addition, the local supply wells tend to be drilled in the uppermost aquifers. While these aquifers may be the most important from a public safety standpoint, they may not be the ones most likely to exhibit contamination from a nuclear test thousands of feet below the surface. Thus, monitoring in zones below the uppermost aquifer may be required for some of the offsite areas.

Finally, the data obtained from the offsite areas by the LTHMP are apparently not analyzed using the statistical techniques required by RCRA. This process recognizes background data, upgradient data, and downgradient data and calls for a quantitative determination of differences between these populations using a t-test or similar approach. It may be that some or most of the data currently collected are not suitable for such an analysis.

Objective 3: Detecting Migration of Radioactivity

By virtue of careful site selection, underground nuclear tests have not been conducted in geologic units prone to allow rapid migration of radionuclides to underground sources of drinking water. Thus, by emphasizing existing supply wells in the LTHMP, there is little likelihood of detecting contaminant migration.

A detection-oriented sampling network must rely on optimally placed sampling points and a statistically sound basis for differentiating background values from contamination. Monitoring wells at the eight sites examined are often located far from the shot sites, are frequently not located on credible downgradient flow paths, and are often completed in zones relatively unconnected hydrologically to the shot horizon.

Problems with well locations in the LTHMP can be related to three main causes: 1) uncertainty in flow system characteristics, 2) uncertainty in potential release scenarios and thus in contaminant transport pathways, and 3) lack of use of hydrogeologic data to select monitoring locations. The development of sampling networks under conditions of hydrogeologic uncertainty is a topic at the forefront of research today. At some of the offsite test areas, more data may be needed to help define the flow system, while other sites may already have enough data to allow application of geostatistical techniques to optimize sampling locations. In either case, identifying and prioritizing potential release mechanisms is crucial to focusing monitoring efforts onto the critical pathways. Release-scenario development is particularly needed at the gas-stimulation sites where possible contaminant transport pathways are difficult to determine.

Though some offsite projects had extensive geohydrologic investigations, information from these studies does not seem to have been used by the DOE to choose sample locations in all cases. A good example is the monitoring system around the Shoal site. Shoal investigations located a groundwater divide to the west of the site, indicating that groundwater flow was most likely to the east from the detonation. Despite this interpretation, most of the LTHMP sampling points specified by the DOE are west of the divide. The method of replacing sampling locations in the program contributes to the problem. If a former location is unavailable, the EPA sampling team replaces it with another nearby point (S. Black, pers. comm., 1989). The primary criterion for selection of replacement sample points appears to be geographic proximity, with little evaluation of the hydrologic unit tapped or the position of the point in the groundwater flow system.

The EPA also samples additional wells upon request of a well owner. The policy of honoring such requests regardless of hydrologic considerations is probably sound. However, the program would benefit if requests for long-term monitoring of new wells were analyzed in a hydrogeologic context. The data could then be properly interpreted as providing either background or downgradient information.

The analytical procedures used by the EPA on the LTHMP samples are well documented in the annual offsite monitoring reports, as are the quality assurance procedures. However, the statistical methods used for the interpretation of the LTHMP data are not discussed. It is noted in the annual reports that tritium concentrations are consistent with the levels found in previous years, but the technique used to reach this conclusion is not presented. No distinction is apparently made in the data interpretation between upgradient and downgradient wells, with the exception of those on Amchitka. Additionally, background radiologic data collected prior to the nuclear tests and post-event data collected prior to the initiation of the LTHMP are apparently not considered in any analysis. In some cases, these relatively old data may not be comparable (if tritium analyses were not enriched in the past but are enriched in current LTHMP analyses). However, some sites had extensive, state-of-the-art for that time, background surveys performed and there is no replacement for pre-event data. In addition to a t-test, or similar approach, for differentiating between background, upgradient, and downgradient data populations, a statistical trend analysis could be useful for determining gradual increases in contaminant concentrations, as might be expected in the case of migration of radionuclides from a nuclear event.

Objective 4: Disseminating Information

The series of annual offsite Environmental Monitoring Reports published by the EPA provides a reliable means of regularly distributing data from the LTHMP. The reports contain maps of sampling locations, the analytical results obtained from the LTHMP samples, discussions of analytical methods and Quality Assurance/Quality Control (QA/QC) procedures, and a short discussion of the results. A draft report on the status of the LTHMP as of 1984 was prepared by the EPA in 1985 (Black and Bagley, in prep.). This report provided a more in-depth discussion of the data collected in the program and presented time-series plots of the data collected over the years. If the annual reports are trying to limit their length and technical discussions, periodic in-depth reports similar to Black and Bagley (in prep.) should be prepared and published.

In addition to the annual reports, the DOE supports an active public information program for the NTS area. This area essentially overlaps two of the offsite test areas (Central Nevada Test Area and the Shoal site), so citizens near those offsite areas have relatively easy access to public meetings and community monitoring information.

Recommendations

1. The DOE should reevaluate and prioritize the objectives of the LTHMP in light of changes in overall department objectives during the last 20 years. Affirmation of DOE objectives is necessary for planning any changes to the LTHMP.

2. Increase the use of hydrogeology in the program. This should involve a detailed analysis of the placement of wells within the hydrogeologic system around the test areas (a cursory evaluation is provided here), and development of release scenarios to identify probable contaminant transport pathways. This should lead to designation of monitoring wells as either up– or downgradient and near– or far–field, allowing for more meaningful data interpretation.

3. If a monitoring system equivalent to those at RCRA–licensed facilities is desirable at the offsite test areas, the work in recommendation #2 will have to be expanded to include determination of optimal placement of new groundwater monitoring wells. Analysis of uncertainties in the flow system will be necessary for locating optimum well sites and additional site characterization will also be needed at most test areas.

4. The purpose of comparing all LTHMP samples to the National Primary Drinking Water Standards should be determined. Comparison of only community water systems (as required in the regulations), or possibly any drinking water supply, to the standards should be considered. While evaluating the application of the drinking water standards, the plan of action for samples exceeding the standards should also be determined.

5. The current analytical suite for most of the monitoring wells consists of a γ–scan and a tritium analysis. As tritium is the most conservative (non–sorbing) radionuclide that could be released from a cavity, a tritium analysis should be a good indicator of contaminant transport. However, as the half–life of tritium is much shorter than that of many other shot–produced radionuclides, and non–radioactive contaminants may also be released from cavities, a change in the analytical suite may be desirable if sampling is to continue indefinitely.

6. All changes in sampling locations should be evaluated from a hydrogeologic perspective. Though it is recognized that available options may often be limited, the present method of deleting and adding sampling locations often results in replacement of one point with another that is hydrologically not equivalent.

7. The statistical techniques used for LTHMP data interpretation should be described in the offsite monitoring reports. Consideration should be given to applying the same sort of techniques recommended in the RCRA.

8. Pre–LTHMP monitoring data should be incorporated into the data interpretation whenever possible. This will require sorting the old data into those that are directly comparable with LTHMP data and those that are not (usually due to larger lower limits of detection). Efforts should be made to use pre–event data to calculate background concentrations of radionuclides.

Analysis of Monitoring Systems at Individual Offsite Areas

Analyses of the hydrologic monitoring programs at the eight underground nuclear test areas off the Nevada Test Site are presented below. The monitoring objectives, if documented, for a site are listed first. Then, hydrogeologic considerations in the monitoring program are described, such as the characteristics of the flow system and location of any contaminant sources within the system. A history of the sampling program is given, describing how the monitoring network was established and what changes have occurred. The current groundwater monitoring system is then evaluated in light of the hydrogeologic system and contaminant sources. Finally, recommendations for additional work to improve the monitoring system are presented.

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FALLON NUCLEAR TEST SITE - SHOAL EVENT

The Shoal site is in west-central Nevada in the Sand Springs Range, approximately 30 miles southeast of Fallon and several miles south of highway US-50. The Shoal event was part of Project Shade of the Vela Uniform Program, and was conducted to aid in the detection of nuclear detonations in active earthquake areas. The device had a yield of 12 kilotons and was detonated approximately 1200 ft below ground surface on October 26, 1963 (U.S. AEC, 1964). The working point was within the granite of the Sand Springs Range and no surface crater was formed by the event.

Hydrogeologic Considerations in Monitoring

The Shoal event was conducted within the granitic uplift of the Sand Springs Range. The highland area around ground zero is a regional groundwater recharge area, with regional discharge occurring both in the Fourmile and Eightmile Flats area to the west of the range and in the Humboldt Salt Marsh in the Dixie Valley to the northeast of the range (Figure 1). The University of Nevada (1965) analyzed hydrologic data in the Shoal area and concluded that a groundwater divide may exist northwest of the event and that the main component of lateral movement of groundwater near the shot point is southeast toward Fairview Valley. Cohen and Everett (1963) and Glancy and Katzer (1975) also identify a groundwater divide just to the west of the Shoal site, apparently based on a topographic divide. Once in Fairview Valley, groundwater will move north to the discharge areas in Dixie Valley. Though all indications are for groundwater flow to be toward the east from the Shoal site, the data from the granites are somewhat questionable due to testing difficulties and the possibility of westward groundwater flow cannot be completely ruled out.

Granitic bedrock is relatively near the surface beneath a veneer of alluvium to the west of the Sand Springs Range and hydrologic data are available for one well completed in bedrock in that area (well H-3). Farther to the west, and throughout Fairview Valley to the east of the range, bedrock is far below a thick layer of alluvium and is not penetrated by wells. Within Fairview Valley, groundwater occurs in at least 3 separate alluvial aquifers. The aquifers are separated by clay aquitards and no vertical gradients were detected between the units. The water apparently moves generally north toward the discharge areas in Dixie Valley. In the western valley containing Fourmile and Eightmile Flats, no aquitards were noted, but groundwater in the alluvial fill has increasing head with depth. The head distribution is believed to reflect upward movement of groundwater toward discharge zones in the playa of Fourmile Flat.

Calculations by Gardner and Nork (1970) suggested that it would take approximately 12 years for the Shoal rubble chimney to fill with groundwater. Migration of contaminated groundwater was not believed to be possible until the cavity had filled to pre-shot levels. Despite a large number of uncertainties, flow times through the granite were calculated to be very long, with tritium decaying to below the Concentration Guide level before the groundwater had traveled 3000 feet.

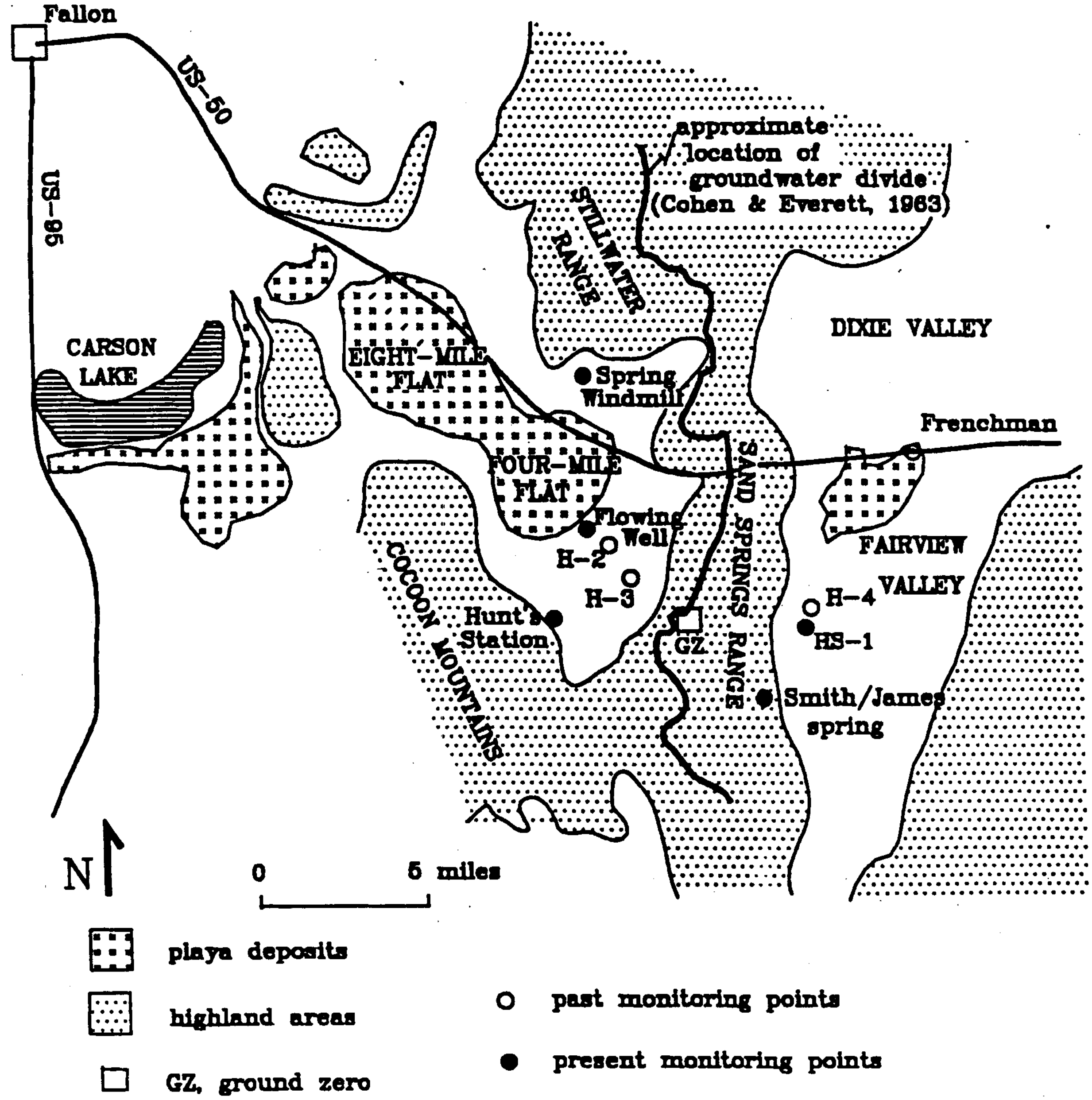

Figure 1. Geomorphic features and monitoring wells in the area around the Shoal Site. Modified from University of Nevada (1965) and Cohen and Everett (1963).

Past and Present Sampling

Pre-event groundwater sampling is poorly documented for the Shoal site. During hydrologic investigations of the site, samples were collected and analyzed radiologically by the U.S. Public Health Service (PHS), but the results were apparently not published (University of Nevada, 1965). The University of Nevada (1965) reports tritium values for four wells drilled during the site investigation. Post-detonation water levels were measured by the Desert Research Institute in wells within 25 miles of the test area and apparently samples were often collected for the PHS. Gardner and Nork (1970) report that the PHS analyses generally included ^{3}H, γ-scans, and gross β. Teledyne sampled 5 sites in 1968 for ^{3}H, gross α, and gross β. It is not known what sampling, if any, was done between 1968 and 1972.

A letter from the AEC to EPA on February 3, 1972 reported that the Hydrologic Program Advisory Group had chosen wells H-2, H-3, H-4, Frenchman Station Well and Hunt Station Well as the LTHMP Shoal sampling points. However, a 1984 report describing the LTHMP at Shoal lists the sampling points as HS-1, H-3, Flowing Well No. 2 (or simply, Flowing Well), Frenchman Station Well and Hunt Station Well. These points are the ones listed in the early EPA Offsite Environmental Monitoring Reports. These sample locations remained unchanged until 1980, though the analytical suite varied from well to well and year to year. All samples were analyzed for ^{3}H, and most also had γ-scans, and gross α and gross β analyses. In addition, many samples were also analyzed for ^{226}Ra, ^{89}Sr, ^{90}Sr, ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, and ^{239}Pu. The EPA report for sampling year 1978 discusses the relatively high gross β values found in previous years at the Flowing Well (U.S. EPA, 1979). The EPA says that a γ spectrometry analysis showed naturally occurring ^{40}K and ^{222}Rn daughters to be the sources.

In 1980, it was noted by EPA that the pump was inoperative in H-3. The well was sampled in 1983, 1985, and 1986 (it is not known if the pump worked or if the samples were bailed), but not in the other years. In the years that H-3 was not sampled, a sample was usually taken from the Spring Windmill. In 1987, Frenchman Station was not sampled and Smith/James Spring was added. Through this period, ^{3}H and γ-scans were the only analyses performed, though the Spring Windmill had some additional radioisotope analyses performed in 1985.

Analysis of the Current Monitoring System

Using the best estimate of the groundwater flow system in the Shoal area, the only monitoring point that could possibly intercept contaminant migration from the Shoal test is well HS-1. This well is east of Shoal in Fairview Valley and served as the water supply well for the project. The well is 699 ft deep and it was completed in two horizons, the upper and lower alluvial aquifers, which are separated by a low permeability clay. Literature review has not revealed where the pump is located or whether or not both zones are open to the well bore, though discussions of water chemistry in HS-1 (University of Nevada, 1965) suggest that both alluvial zones contribute water. No data are available as to which zone, if either, is the likely conduit for groundwater flow from the granites near ground zero. Though HS-1 is apparently downgradient from the test, it is also several miles away from the site, resulting in even greater uncertainty as to whether the well would intercept a contaminant plume.

The only other sampling point to the east of the Shoal site is Smith/James Spring. The location of this spring seems to coincide with either Water Point 29 or 30, identified during a well and spring inventory (University of Nevada, 1965). During this inventory, it was noted that those springs were the nearest granite-terrain points of natural discharge to the detonation site. However, they were believed to be upgradient from groundwater associated with the detonation and to be discharge from local, perched groundwater. If Smith/James Spring is one of these two springs, it would not be expected to monitor groundwater downgradient from the test.

The other three monitoring points are west of the Shoal site, on the other side of the probable hydrologic divide. There is enough uncertainty in the groundwater conditions in the Sand Springs Range that the location of the divide relative to the Shoal site is also uncertain, allowing for a remote possibility of westward flow. Of the three points in the Fourmile Flat area, the Flowing Well is in the best position to intercept possible groundwater flow from Shoal. The artesian conditions of the well, and its location next to the Fourmile Flat regional discharge area (Glancy and Katzer, 1975), indicate that the Flowing Well is in a groundwater discharge area. Neither the depth nor the zone of completion are known for this well.

The other two wells west of Shoal seem unlikely to be on potential flow paths from the event. Both the Spring Windmill and Hunt's Station wells are closer to other highlands (Stillwater Range and Cocoon Mountains, respectively) than to the Shoal area in the Sand Springs Range, and thus probably tap groundwater moving from those adjacent ranges toward Fourmile Flat. This is particularly true of Spring Windmill, which is located virtually on the opposite side of the alkali flat discharge area from Shoal.

Two former sample points had some favorable attributes. Well H-3 is the only monitoring well completed in granite bedrock (the ground zero was also in granite); however, it is on the other side of the probable groundwater divide. The groundwater chemistry of water from H-3 is the most similar to that in the immediate shot area (University of Nevada, 1965). Notes in the EPA Off-Site Monitoring Reports since 1980 have indicated difficulties with the pump in H-3, and that is probably the reason it is no longer sampled.

The well at Frenchman Station was sampled since the inception of the monitoring program, but was absent from the EPA report for 1987. No notes indicate why the well was not sampled, but the gas station/store at Frenchman closed during this period. The Frenchman Station well was the only point sampled in the expected downgradient direction that was used for water supply, but it was located over five miles from the Shoal area.

The current analytical suite consists of tritium and a γ-scan. Though this has been the suite since 1980, there are various other radiochemical results available for samples collected in earlier years.

Recommendations

There are a number of large uncertainties about groundwater flow in the Shoal area, despite the careful hydrogeologic investigations conducted in connection with the test. Most of the uncertainty is due to a lack of data on flow conditions in the fractured granite of the Sand Springs Range.

1. At a minimum, the location of the groundwater divide between Fairview Valley and Fourmile Flat should be confidently located in relation to the Shoal site. This may require additional field investigations, though the complete extent and quality of existing data have not been thoroughly reviewed. During this process, a potentiometric map should be constructed for each important aquifer in the region encompassing all monitoring wells (no existing map could be located).

2. The correlation of Smith/James Spring with either Water Point 29 or 30 in the University of Nevada study (1965) should be confirmed. If the spring is one of these points and its discharge elevation is above the potentiometric level of water at ground zero, the spring cannot be a downgradient monitoring point.

3. The elevations and hydrogeologic settings of the Spring Windmill and Hunt's Station well should be evaluated even if ground zero is west of the groundwater divide. Both of these wells are likely to be upgradient of any possible contaminant plume.

4. Well HS-1 is the most likely monitored well to be on a flow path from the test area. If there is any westward flow, then the Flowing Well would be downgradient. Continued monitoring data from both of these wells could thus be useful. A problem common to both HS-1 and the Flowing Well is their distance from ground zero (several miles). These distances and the lack of data result in large uncertainties as to whether or not the wells would intercept a contaminant plume, or if a plume would be at a detectable concentration at those points.

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CENTRAL NEVADA TEST AREA

The Central Nevada Test Area (CNTA) is in south central Nevada in the Hot Creek Valley. The area is in a remote desert region bordered on the southeast by U.S. Highway 6. The base camp is approximately 60 miles northeast of Tonopah and 110 miles southwest of Ely.

The only nuclear test conducted at the CNTA was Project Faultless on January 19, 1968. The purpose of the test was to determine the behavior of seismic waves generated by a nuclear detonation in the Hot Creek Valley and to evaluate the potential usefulness of the site for higher yield experiments. The device had a yield of less than one megaton and was detonated 3200 ft below land surface (Holmes and Narver, 1974). The explosion created an unusual collapse crater. Instead of the typical saucer-shaped depression, a large area subsided as an irregular block bounded by local faults.

Hydrogeologic Considerations in Monitoring

The hydrogeology of Hot Creek Valley is controlled in part by the basin-and-range topography. The valley is a long graben containing a thick sequence of Quaternary and Tertiary fill (up to 3600 ft) underlain by a thick section of Tertiary volcanic rocks. The bounding ranges on either side of the valley contain Paleozoic carbonates overlain by Tertiary age volcanics. The sequence penetrated by boreholes near the Faultless site generally included about 2000 ft of alluvium underlain by tuffaceous sediments and volcanics. The detonation occurred in the tuffaceous sediment section, but the resultant cavity extended into the overlying alluvium.

With the exception of information from a few holes drilled into the volcanics as part of the Faultless Project, there are no data on bedrock aquifers in the Hot Creek Valley. Within the alluvium, groundwater movement is believed to follow the general direction of surface flow. Recharge is believed to occur principally in the higher mountain ranges to the west (Hot Creek Range and Kawich Range), with groundwater flowing toward the east-central part of the valley (Figure 2). Discharge is by evapotranspiration in the area around Twin Springs Ranch, with a minor amount of water moving eastward through the alluvium beneath Hot Creek to Railroad Valley (Rush and Everett, 1966). Using the concentration distribution of constituents dissolved in groundwater, Fiero *et al.* (1974) also concluded that groundwater in the valley-fill generally moves from recharge areas in the highlands to discharge areas in the valley.

Dinwiddie and Schroder (1971) investigated the hydraulic head distribution and hydraulic properties in the northern part of the Hot Creek Valley, near the Faultless site. Head differences and corresponding chemical and temperature differences in water from the alluvial material and from the underlying volcanics suggest that the two are distinct water-bearing zones in the valley. Head values in the upper 1000 ft of the section indicate groundwater movement generally southward and southeastward. Head values measured in

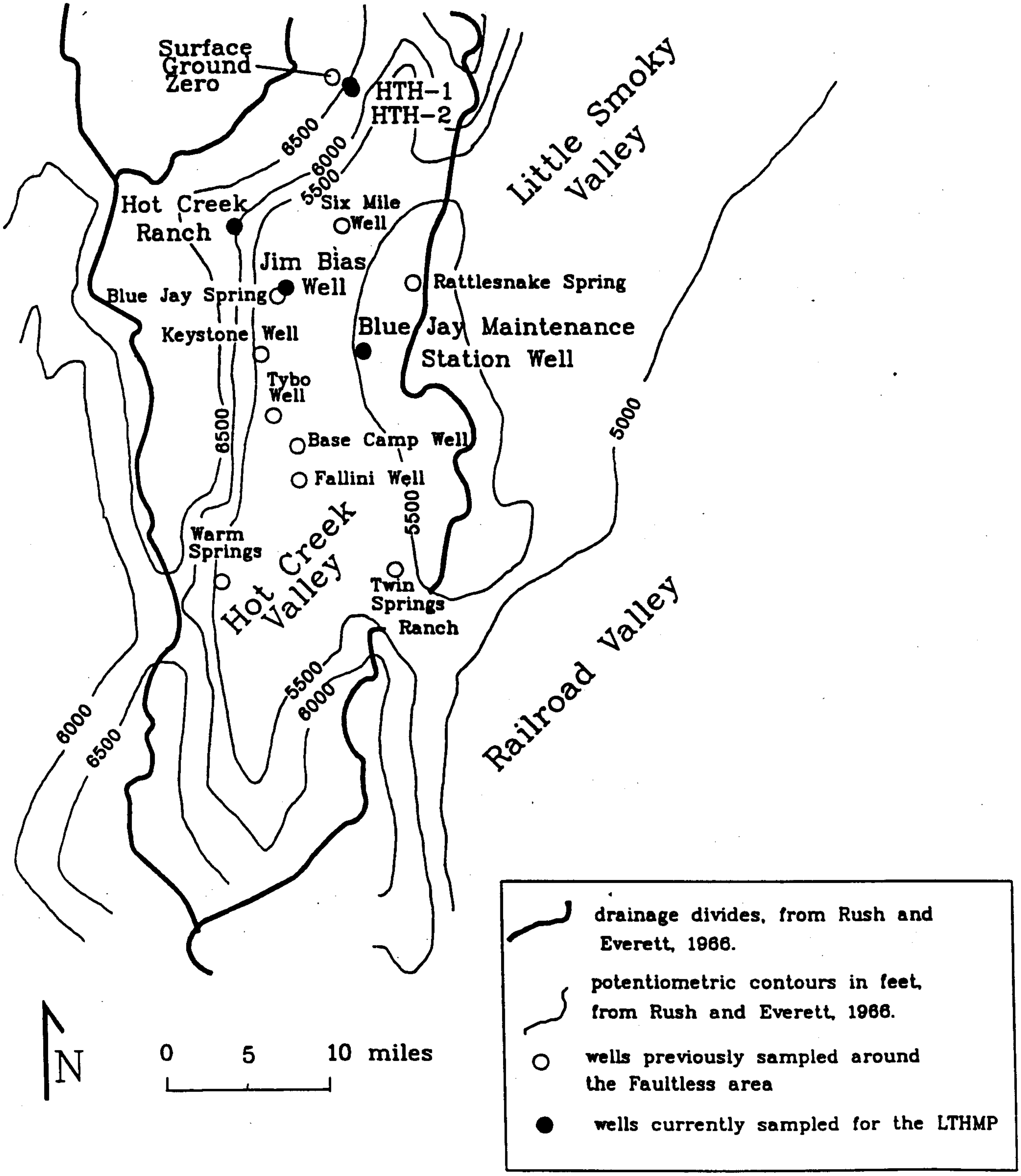

Figure 2. Potentiometric contour map for the uppermost water-bearing zone in Hot Creek Valley. Also shown are wells used for monitoring the CNTA. Modified from Nork et al. (1971) and Rush and Everett (1966).

units 5000 to 7000 ft below land surface reveal that the deep component of the flow system moves northeastward and eastward toward Railroad Valley. Evaluation of vertical head gradients showed a potential for downward flow in the north end of the valley (in the immediate test area), while an upward potential for flow existed over the southern part of their study area. However, Dinwiddie and Schroder (1971) conclude that vertical movement is very slow relative to lateral groundwater movement in the valley, based on anisotropy of hydraulic properties.

Thordarson (1987) described the hydrology around the Faultless explosion cavity. The rubble chimney created by the blast is believed to be contained within the alluvium and tuffaceous sediments. Water in these horizons is probably more at risk for contamination than water in the volcanic zones. A perched water table in the cavity was essentially static from 1968 to 1974. At the end of 1974, the water level began to rise to pre–test levels as the rubble chimney filled. By 1983, the water level had reached the top of the rubble chimney. Thordarson (1987) estimates that the pre–event water level will be reached between 1993 and 2018.

Though information on private wells in the area is limited, they are generally relatively shallow and thus believed to be completed in the upper part of the alluvial section. Some springs in the area have elevated temperatures and chemical characteristics that indicate they could be discharge points for deeper, regional flow systems. Figure 2 shows Faultless monitoring points superimposed on a hydraulic head map for alluvium in the area.

Past and Present Sampling

Monitoring at the CNTA was originally done by Teledyne Isotopes, Inc. There was an extensive pre–shot monitoring program to document background radioactivity levels in environmental waters and record natural fluctuations in those levels. The data were collected so the appearance of radioactivity produced by the underground nuclear explosion would not be masked by periodic fluctuations and cyclic variations in environmental radioactivity.

An initial 60–point well and spring network was established during the test–site selection process. This network was sampled between March and September of 1967 (most individual wells were sampled two to three times). As the selection process narrowed to a smaller region, the 60–point network was reduced to 30 points. These wells and springs were sampled from October 1967 to August 1968, with two wells also sampled in September 1970. When the Hot Creek Valley was chosen as the CNTA, the sampling network was further reduced to 8 points. Sampling continued from November 1967 through December 1970. In addition to these wells and springs, AEC holes for exploration, hydrologic testing, and reentry were sampled during 1967, 1968, and 1969. One AEC well was also sampled in 1970 and 1971. Water samples were analyzed for gross β–γ, gross α, K, and ^{3}H. Seven well samples were analyzed for ^{226}Ra, ^{210}Pb, ^{137}Cs, ^{90}Sr, and U one time. Nork *et al.* (1971) identify the wells, detail the sampling schedule, and present analytical results.

After the Faultless event, it was recommended that a series of sampling locations be monitored annually until a definitive description of groundwater flow direction and rate away from the Faultless site emerged. Periodic sampling of water from HTH-1, HTH-2, and UC-1-P-2SR was also recommended. The suggested analytical suite was gross β, gross γ, and low-level (20 TU) tritium (Nork *et al.*, 1971).

In 1972, groundwater monitoring of the CNTA was incorporated in the LTHMP. The planning document for the program directed EPA to collect samples from UC-1-P-2SR, HTH-1, HTH-2, Hot Creek Ranch Domestic Water supply, Six Mile Well, Blue Jay Spring, and Blue Jay Maintenance Station Well (February 3, 1972 letter from Miller (AEC) to Carter (EPA)). This included three of the eight points sampled by Teledyne, one new spring, and three AEC wells. One of the AEC wells, HTH-1, was sampled by Teledyne in 1967. The monitoring program described in a 1973 report (U.S. AEC, 1973) did not mention hole UC-1-P-2SR, though a 1974 report stated that samples were currently being collected from UC-1-P-2SR, as well as the other points. No analyses for UC-1-P-2SR are in the annual EPA reports, though some are reported in a U.S. Geological Survey report (Thordarson, 1985).

In 1977, both springs were dropped from the sample schedule and another private well was added. The new well (Jim Bias Well) is apparently close to Blue Jay Spring, but the reason for changing from sampling one to another is unknown. No samples were collected in 1979 and one well sample was lost in 1982. In 1984, one of the previously monitored springs was added back to the schedule and in 1985 one of the wells was dropped when its pump broke. From 1971 to 1976, the EPA reported ^{3}H, ^{89}Sr, ^{90}Sr, ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, ^{239}Pu, and occasionally ^{226}Ra. The monitoring reports state that gross α, gross β, and γ-scans were also done, but the results are not given. Starting in 1977, only ^{3}H, gross α, and gross β are reported, with γ-scans performed, but not reported. From 1980 on, only ^{3}H results are given, though γ-scans are still routinely done.

The EPA has not detected any increase in radioactivity at any of the sites monitored.

Analysis of Current Monitoring System

Of the five current sampling points, wells HTH-1 and HTH-2 are in the best position to detect the migration of contaminants from the Faultless test. These wells are close to the test site (within a mile), are completed in the hydrologic unit intercepted by the shot cavity, and are hydraulically downgradient from the event. The sampled unit, the alluvial aquifer, also provides the groundwater supply for the area.

Groundwater in alluvial units near the Faultless site apparently moves southeast to the valley axis and then travels in a more southerly direction toward the regional discharge area. The first supply well that could possibly be encountered along this flow path is the Jim Bias Well. The Six Mile Well is better positioned than the Jim Bias Well, but it is no longer sampled due to pump problems.

The spring at Hot Creek Ranch appears to be on a flowpath essentially parallel to those near the CNTA. Thus, there is little likelihood of groundwater from the test area ever discharging at the Hot Creek Ranch Spring. The usefulness of the Blue Jay Maintenance Station Well is more uncertain. Figure 2 shows the well located within the 5500 ft head contour for groundwater in the alluvium. If the head in that well is indeed higher than 5500 ft, groundwater moving from the test area down the valley cannot be intercepted by the well. However, the position of the well on the hydraulic head map is estimated, and the actual static water level in the well has not been identified during this study. In addition, the degree of drawdown due to pumping is unknown. The long period of record for this well (it was in the original Teledyne sampling network) makes it a valuable part of the monitoring program, if it is appropriately located in the flow system.

Recommendations

Recommendations for monitoring at the Central Nevada Test Area are as follows:

1. Continue sampling wells HTH-1 and HTH-2. As the water level in the cavity approaches the pre-shot level, the likelihood of lateral groundwater transport of contaminants increases. The Jim Bias Well is not optimally located downgradient from the Faultless event, but it is on a credible flow path and as the first location of groundwater withdrawal downgradient from the test area, there is value in continued sampling there.

2. Measure water levels in all available wells and boreholes in the valley to confirm existing potentiometric contour maps and locate monitoring wells precisely within the flow system.

3. Use the data from #2 to determine the water level in the Blue Jay Maintenance Station Well and its position in the alluvial aquifer flow system. If the well is located upgradient of lateral valley flow, then the reasons for sampling should be carefully reevaluated. The well has a very long record of annual samples and could be useful for providing background data, even if it is not on a possible flow path. A similar analysis should be made of Hot Creek Ranch Spring, including the spring's temperature and chemistry. The spring could be located on a parallel (non-downgradient) path, or could be a conduit for regional discharge.

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GASBUGGY

Project Gasbuggy was the first joint Government–industry experiment in the United States that utilized a nuclear explosive to stimulate a low productivity natural gas reservoir. The project included the detonation of a 29–kiloton nuclear device on December 10, 1967, at a depth of 4240 ft in the San Juan Basin of northwestern New Mexico, approximately 75 miles east of Farmington (Figure 3). Production testing was completed in late 1976 and site restoration was completed in July 1978 (U.S. DOE, 1983).

Hydrogeologic Considerations in Monitoring

Project Gasbuggy is located on the eastern side of the San Juan Basin. This structural feature is about 180 miles long and 135 miles wide. It covers the eastern part of the Navajo physiographic section of the Colorado Plateau Province. Rocks in and around the test site range in age from Precambrian to recent. Total thickness of sedimentary rocks in the Central Basin ranges from 10,000 to 15,000 ft. The formations penetrated by drilling at the Gasbuggy site are, in descending order: Surficial alluvium (recent), San Jose Formation, Nacimiento Formation, Ojo Alamo Sandstone, Kirtland Shale, Fruitland Formation, Pictured Cliffs Sandstone Formation, and Lewis Shale Formation, all of late Cretaceous age. The Pictured Cliffs Sandstone is of primary importance because it was within this unit that the Gasbuggy chimney was formed by the detonation in the underlying Lewis Shale (U.S. DOE, 1986). See Figures 4, 5, and 6 for stratigraphic section and geologic cross section.

Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone is predominantly a marine sandstone. At the Gasbuggy site, the Pictured Cliffs Sandstone is about 290 ft thick and is chiefly a light–gray, fine– to very fine–grained sandstone interbedded with dark, sandy shales. The formation is not known to yield substantial amounts of water and is not a water producer at the Gasbuggy site (U.S. DOE, 1986).

Fruitland Formation and Kirtland Shale

The Fruitland and the Kirtland Shale overlie the Pictured Cliffs Sandstone in ascending stratigraphic order. These formations comprise a 260–ft interval of gray to dark–green shale and siltstone interbedded with thin, very fine– to medium–grained sandstone. Abundant carbonaceous material and coal generally are associated with beds of shale. Coal stringers in the Fruitland Formation yield small amounts of water in some parts of the basin. The Kirtland Shale lacks aquifer characteristics and probably does not release water to wells in the Gasbuggy area (U.S. DOE, 1986).

Ojo Alamo Sandstone

The Ojo Alamo Sandstone overlies the Kirtland Shale, and is about 180 ft thick at the Gasbuggy site. The formation consists primarily of a light–gray, fine– to medium–grained,

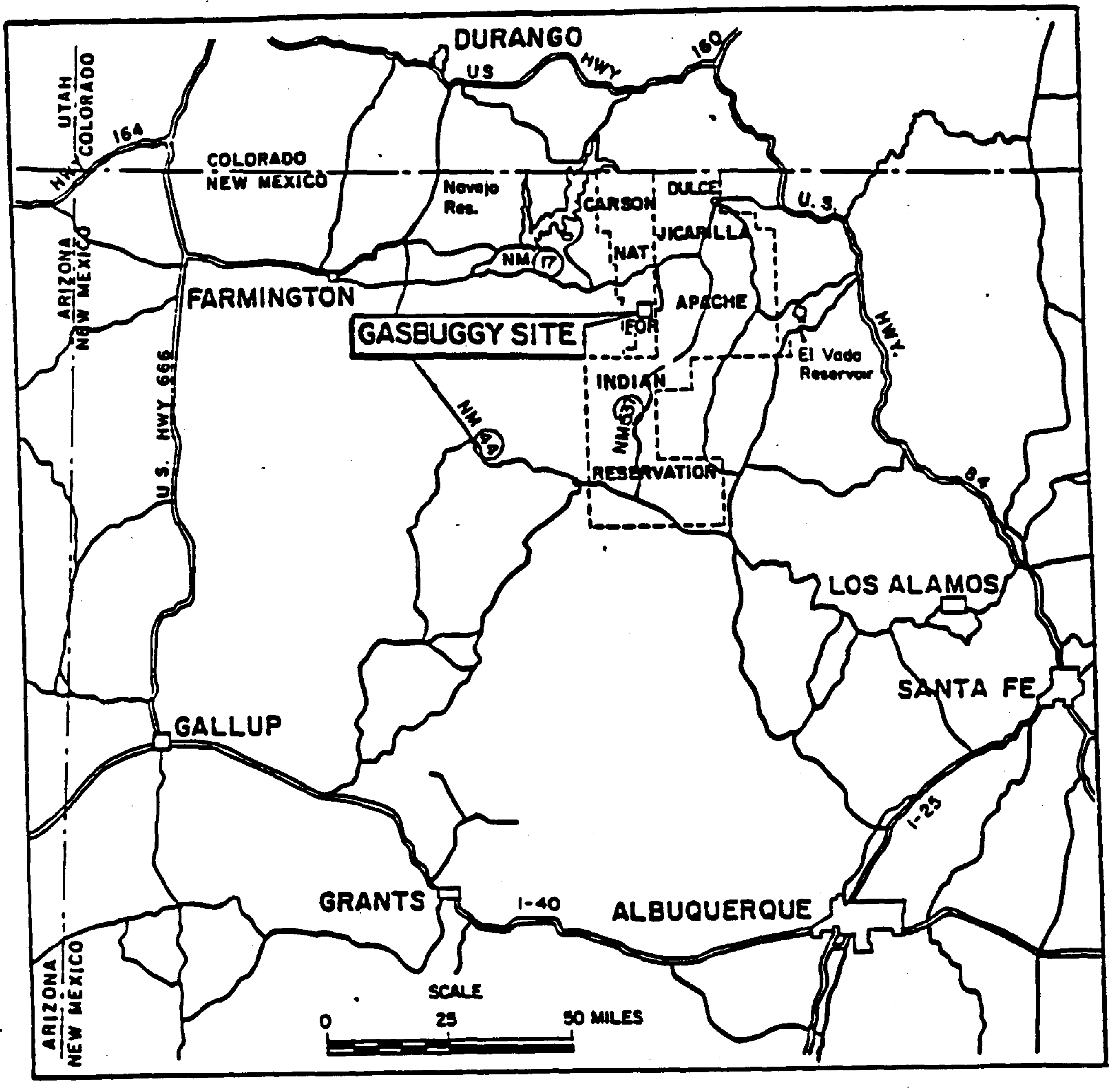

Figure 3. Location map for the Gasbuggy Site. From Eberline (1979).

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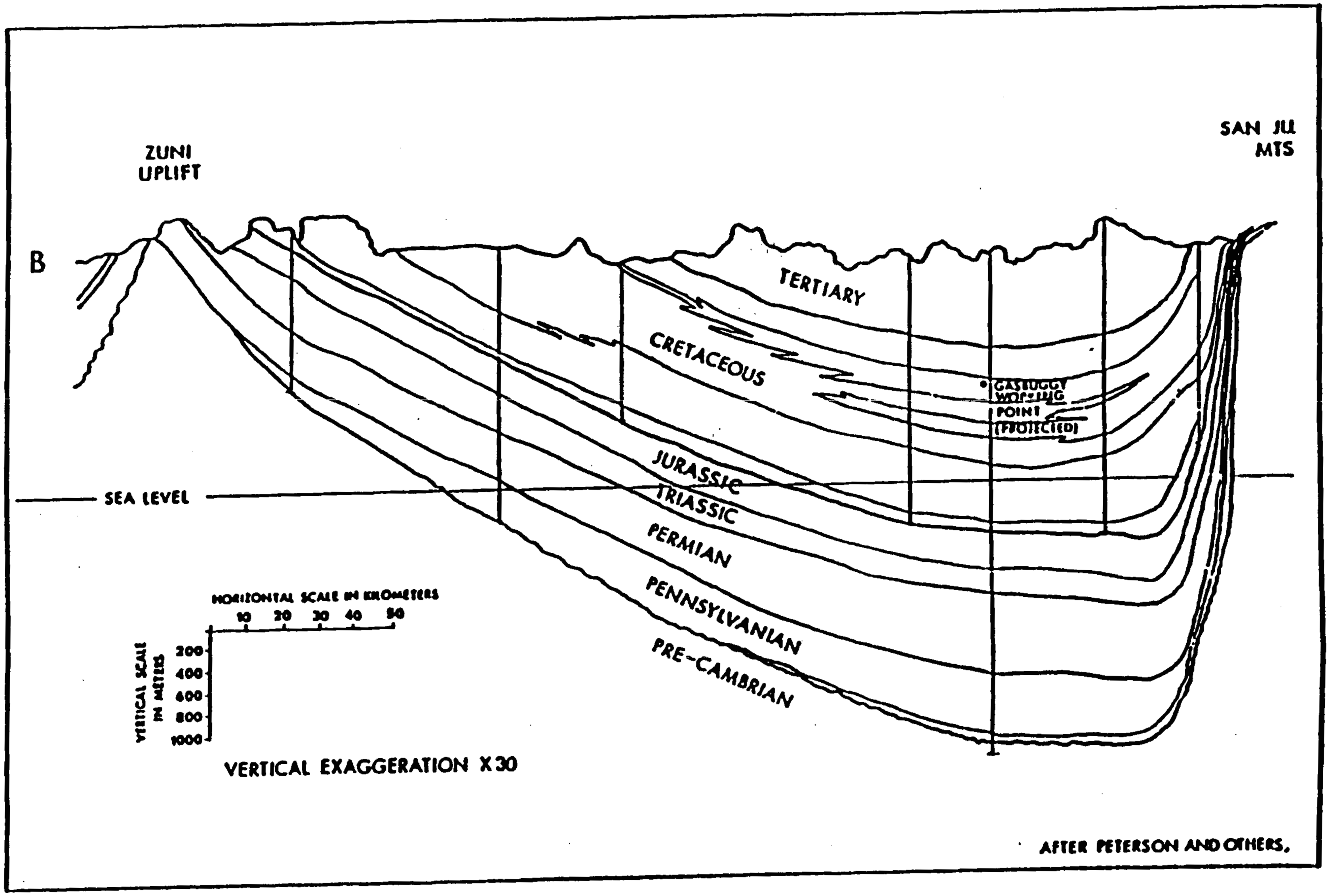

Figure 4. South–north geologic cross–section across the San Juan Basin. From Teledyne Isotopes (1970).

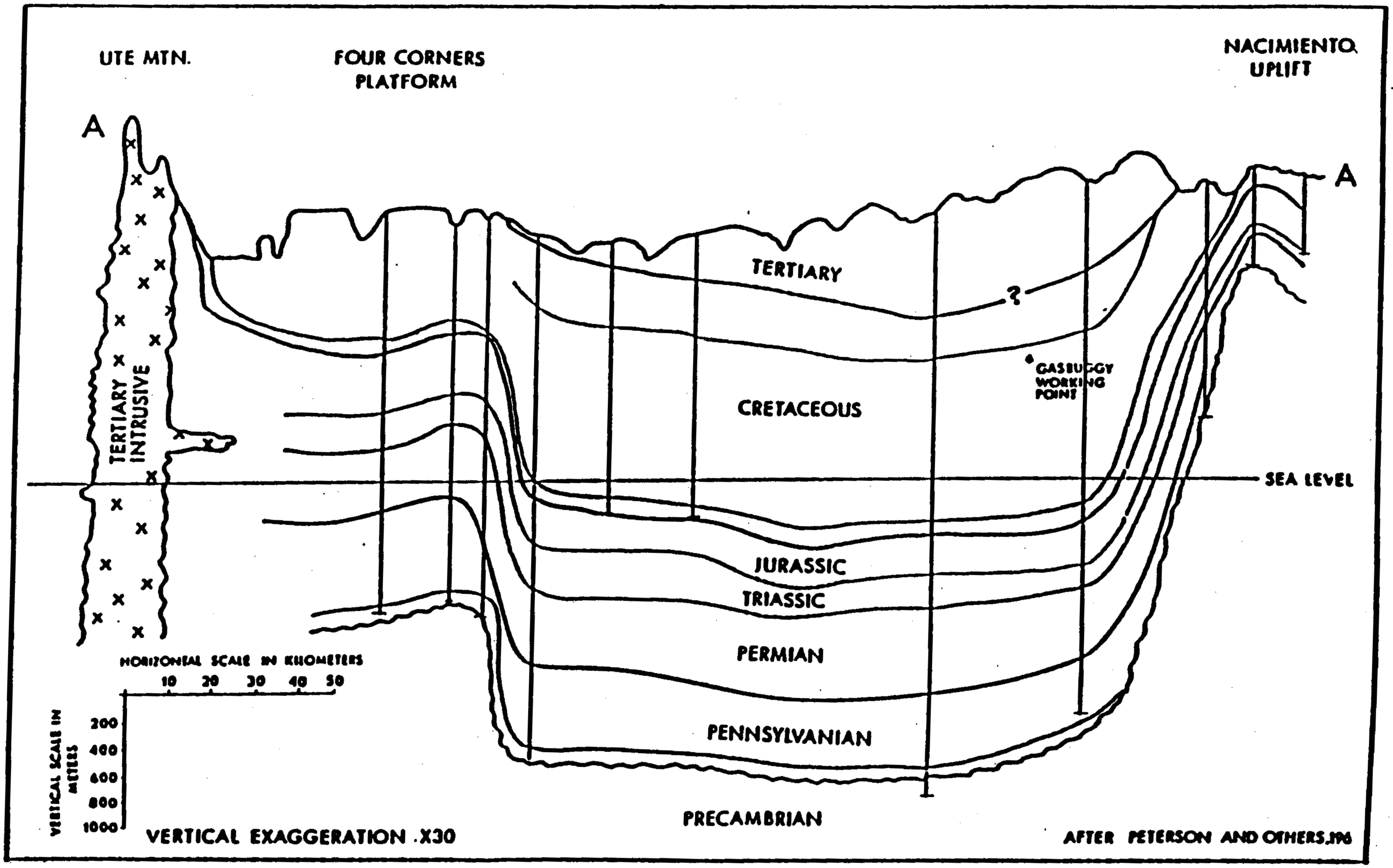

Figure 5. West–east geologic cross-section across the San Juan Basin. From Teledyne Isotopes (1970).

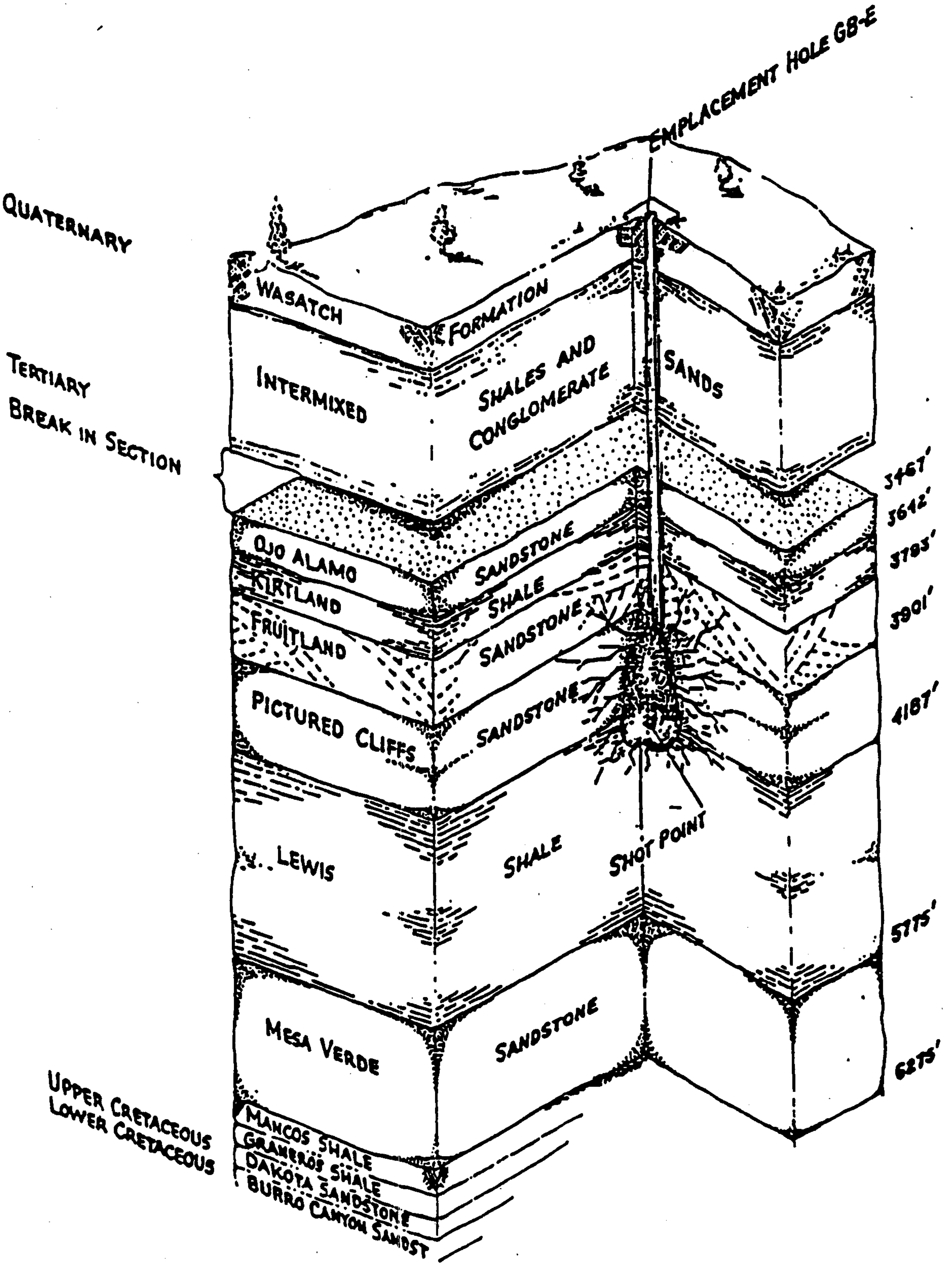

Figure 6. Project Gasbuggy generalized geologic cross-section. From U.S. DOE (1986).

clayey sandstone, but also contains a few minor beds of shale. The Ojo Alamo Sandstone generally is water bearing, and it yields water to domestic wells along the San Juan River 50 miles northwest of the test site where the formation is 1700 ft higher than it is at the Gasbuggy site. At the test site, the formation yields only minor amounts of water (U.S. DOE, 1986).

Nacimiento and San Jose Formations

The Nacimiento and San Jose Formations are continental flood–plain deposits and are the predominant surface formations in the Gasbuggy area. At the test site, they comprise a 3500–ft sequence of fine– to medium–grained, locally conglomeratic sandstone, interbedded with claystone and sandy, variegated shale. The beds of sandstone in the San Jose and Nacimiento Formations commonly contain water (U.S. DOE, 1986).

The surficial alluvium, the San Jose Formation, the Nacimiento Formation, and the Ojo Alamo Sandstone are the principal aquifers in the Gasbuggy area. The Ojo Alamo Sandstone was the only water–producing formation considered to be within the "unlikely but remotely possible" range of fracturing from the nuclear detonation. Hydrologic testing was, therefore, restricted to the Ojo Alamo Sandstone (U.S. DOE, 1986).

The direction of groundwater movement in the San Juan Basin is not well known. The major discharge point for water moving in the Ojo Alamo Sandstone probably is the San Juan River, 50 miles northwest of the test site. An estimate of the rate of groundwater movement is computed by using known or estimated values for permeability and porosity of the aquifer and for the hydraulic gradient (U.S. DOE, 1986). The coefficient of permeability of the Ojo Alamo Sandstone was determined to be about 0.017 gal/day/ft^2. This value was derived by using a coefficient of transmissibility of 3 gal/day/ft and an effective aquifer thickness of 180 ft, as determined from data collected from holes GB–1 and GB–2. A hydraulic gradient of 30 ft/mile across the Central Basin was assumed (U.S. DOE, 1986). An average porosity of 13 percent was determined from core samples analyzed by Core Laboratories, Inc. Calculations based upon these values indicate that the average rate of groundwater movement in the Ojo Alamo Sandstone across the basin is about 0.0001 ft/per day or 0.04 ft/year. However, due to very limited data to support hydraulic gradient estimates, travel time calculations should be viewed as very rough estimates. If fracturing reached this formation, the entry of water into the chimney would cause filling at an estimated rate of about 0.5 ft/day (U.S. DOE, 1986). A high TDS content makes water from this aquifer unsuitable for irrigation or domestic use.

The most likely mechanism of contaminant release from the Gasbuggy event is by radioactive gas seepage up the emplacement well into any one of several aquifers. Communication between the Ojo Alamo aquifer and the explosion cavity was clearly documented (Power and Bowman, 1970). The explanation for the communication is thought to be cement failure (Power and Bowman, 1970). Hydraulic gradients in the vicinity of the Gasbuggy test are downward, thus preventing any migration of contaminated water upward. However, upward migration of gas is plausible.

Past and Present Monitoring

Pre and post–event monitoring was conducted by the Southwestern Radiological Health Laboratory of the U.S. Public Health Service (SWRHL/PHS), Environmental Monitoring Systems Laboratory, U.S. Environmental Protection Agency, Las Vegas, Nevada (EMSL/EPA), the U.S. Geological Survey (USGS), Teledyne Isotopes (TI), and the Eberline Instrument Corporation (EIC). The primary objective of these monitoring programs was to determine if any local domestic water supplies were adversely affected by the Gasbuggy experiment.

The original hydrologic sampling network was established in 1967 by TI and the USGS to provide data for pre–event and post–event comparison of radionuclide concentrations in surface and groundwater in the area surrounding the event site (Teledyne Isotopes, 1970). Thirteen wells and 23 springs ranging in location from 1 mile to 150 miles from ground zero were inventoried to assist in appraising possible well damage claims and also to establish back ground radiation levels. Of these sites, 15 springs and 7 wells were found suitable for radiochemical sampling. Wells ranged in depth from 54 to 229 ft, with shallow wells producing from alluvium of ephemeral stream channels and deeper wells producing from the underlying sands of the San Jose Formation. The majority of springs are of the contact type discharging from the San Jose Formation. No wells or springs were found within 10 miles of ground zero that produce from any aquifers directly associated with the detonation horizon (Mercer, 1968).

A slightly modified network was sampled by TI personnel in June 1967 and again starting in January 1968. Samples were analyzed for tritium, gross β, γ emitters, and gross α. No increase in radionuclide concentrations was detected. Repeat samplings were made in March 1968 with similar results (Teledyne Isotopes, 1970).

Figure 7 shows the 34–station surface and groundwater monitoring network established by SWRHL. This network was sampled before and after the Gasbuggy event, and with increased sampling intensity immediately before and after gas flaring operations associated with production testing. No increase in radioactivity was detected as a result of the Gasbuggy event. The SWRLH sampling network represented a regional sampling network focusing on major domestic water supplies, in some cases as far from the test site as 120 miles. No sampling points discharge from hydrologic units near the test horizon.

In 1972, the EMSL/EPA under the cognizance of the DOE/NV, assumed responsibility for long term hydrologic monitoring at Gasbuggy. Initially, seven springs and four wells were monitored but two wells were discontinued due to pump failure. Figure 8 shows the monitoring network. Background radiation levels were determined for this monitoring effort by the sampling network established by the USGS and TI with the exception of EPNG well 10–36, which penetrates the deeper section affected by the detonation.

Depth to water, temperature, pH and electrical conductance are recorded at the time of collection. Prior to October 1, 1979, each sample was analyzed for γ emitters and tritium.

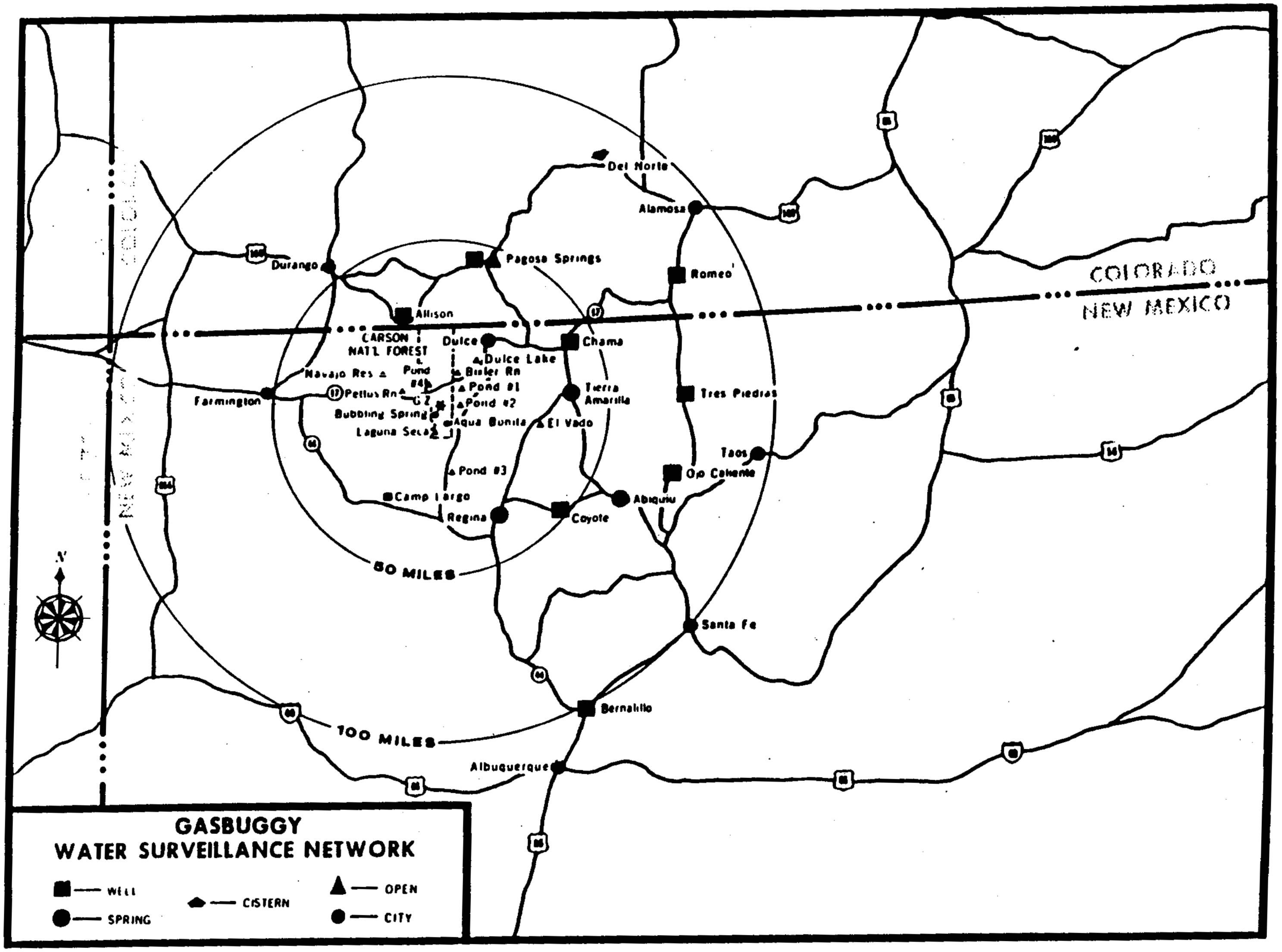

Figure 7. Gasbuggy water monitoring network established by the Public Health Service prior to the event. From Mercer (1968).

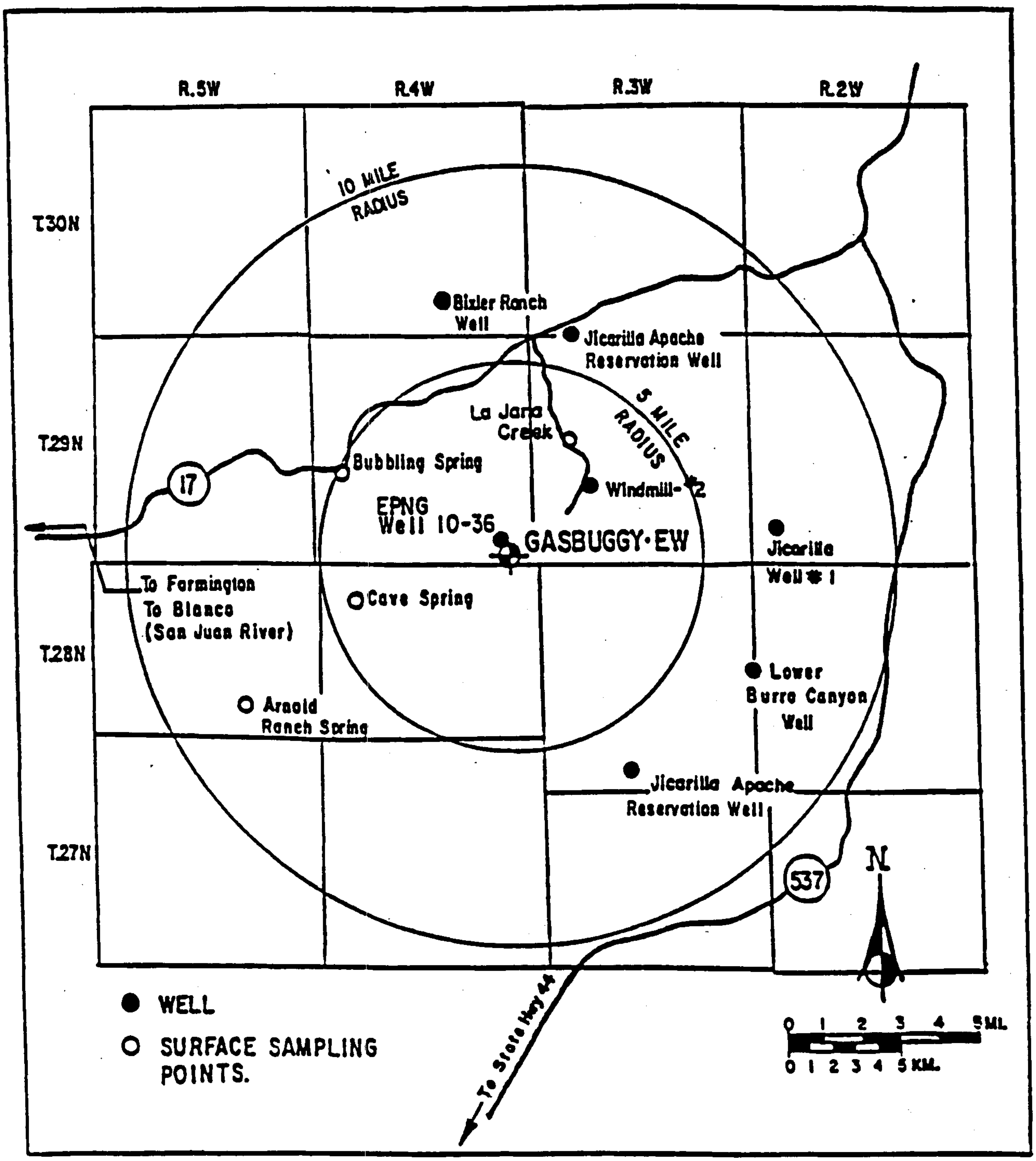

Figure 8. LTHMP sampling points for Project Gasbuggy.

Gross α and β radioactivity measurements were made on all samples collected. After October 1, 1979, these analyses were discontinued in favor of high-resolution gamma spectrometry using a GeLi detector. For each sample location, samples of raw water and filtered and acidified water are collected. The raw water samples are analyzed for tritium by the conventional method. Those samples with concentrations that are below the detection level for this method are then analyzed by the enrichment method. Portions of the filtered and acidified samples are analyzed for γ emitters.

Analysis of Current Monitoring System

The LTHMP sites chosen to monitor possible offsite migration of contaminants at the Gasbuggy site represent nearby domestic water supply sources. It is not evident that hydrologic data were considered in the selection of monitoring points. This sort of monitoring network cannot assure that contaminants are not migrating offsite, but only that certain water supplies have not yet been contaminated.

The groundwater flow system of the San Juan Basin has not been well defined; however, numerous references suggest that the groundwater flow direction in the Ojo Alamo aquifer is westward (U.S. DOE, 1986). Due to its stratigraphic proximity to the detonation horizon, this aquifer is considered the most likely zone to transport contaminants offsite (Weir, 1971). With this in mind, the present monitoring network is lacking in that only one well penetrates this unit and none are clearly downgradient.

With the exception of well EPGN 10-36, all sampling points discharge water from the San Jose Formation or surficial alluvium. In the hydrologic studies to assess Project Gasbuggy, it was assumed that the only affected aquifer would be the Ojo Alamo. As a result, the shallow groundwater flow systems were not defined. This makes evaluating LTHMP sites for their usefulness in detecting possible contaminant migration in the shallow groundwater system impossible.

Seven producing gas wells are located within 1.2 miles of ground zero. Little detailed information about these wells was uncovered for this report; however, it is likely that the majority of these wells penetrate the Ojo Alamo aquifer. Therefore, production of contaminated gas appears possible given the number of gas wells and their proximity to the Gasbuggy test. If these wells are still producing gas, the gas could also be periodically analyzed for radiation contamination.

Recommendations

1. Flow directions and hydraulic gradients for the Ojo Alamo aquifer have been estimated, but need to be more accurately determined. It is possible that these data may be obtainable from surrounding gas wells. Once groundwater flow direction has been determined, appropriate downgradient wells should be added to the monitoring network. It may be possible to recomplete old gas wells into groundwater monitoring wells.

2. Water level data collected during the USGS and TI well inventory should be carefully reexamined to better define the shallow regional groundwater flow system. After this is done, the usefulness of monitoring points should be reevaluated based upon hydrologic data.

3. Subsurface drilling is unrestricted at a distance of 600 ft away from the Gasbuggy emplacement well. This distance should probably be extended.

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PROJECT RULISON

Project Rulison was the second nuclear gas stimulation experiment, co-sponsored by the AEC and Austral Oil Company. The test was to determine the potential increase in gas production by using a nuclear explosive to stimulate and enhance natural gas recovery in the Mesa Verde Formation of the Rulison Field, Garfield County, Colorado (Figure 9) (U.S. AEC, 1970). Project Rulison is located in west central Colorado, 6 miles southeast of Grand Valley (population 340). The largest nearby city is Grand Junction (population 28,500), which is 40 miles to the southwest.

On September 10, 1969, a 43-kiloton fission type nuclear device was detonated at a depth of 8426 ft in an emplacement well (designated R–E) (Austral Oil Co., 1977). Reentry drilling operations through a separate reentry well (designated R–Ex) began in April and were completed in July of 1970. This reentry well was designed to production test the stimulated zone. Production testing took place over a seven month period and included four separate flow test periods. The well was shut in after the last test in April 1971 and left in a standby condition until a general cleanup was undertaken in 1972. The purpose of the cleanup was to decontaminate, if necessary, and remove from the site all equipment and materials not needed for possible future gas production.

Between September 1 and October 12, 1976, the R–E and R–EX wells were plugged and abandoned, and the equipment that remained after the 1972 general cleanup was decontaminated, if necessary, and removed from the site (Austral Oil Co., 1977).

Hydrogeologic Considerations in Monitoring

The rocks underlying the Rulison site range in age from Quaternary to Precambrian. Marine and nonmarine sedimentary rocks, approximately 18,000 ft thick, underlie the site. Figure 10 is a diagrammatic geologic cross-section through the study site, showing the major geologic formations.

The exploratory (R–EX) and emplacement (R–E) holes penetrated the following formations, in descending order: alluvium of Quaternary age, Green River and Wasatch Formations of Eocene age, an unnamed unit of Paleocene age, Ohio Creek Formation of Paleocene age, and Mesa Verde Group of late Cretaceous age. The Mesa Verde is of particular interest because the nuclear device was detonated within this group (Voegeli *et al.*, 1970).

The Quaternary deposits include mudflows, talus accumulations, fan and pediment gravel, slump blocks, and the alluvium of Battlement Creek and the Colorado River. These deposits generally range in thickness from 20 to 40 ft, but locally they may be more than 100 ft thick. The direction of groundwater flow in the alluvial deposits is expected to be northward, consistent with topographic slope. Rocks below the alluvium dip two degrees or less to the north and groundwater flow is expected to be northward also (Voegeli *et al.*, 1970).

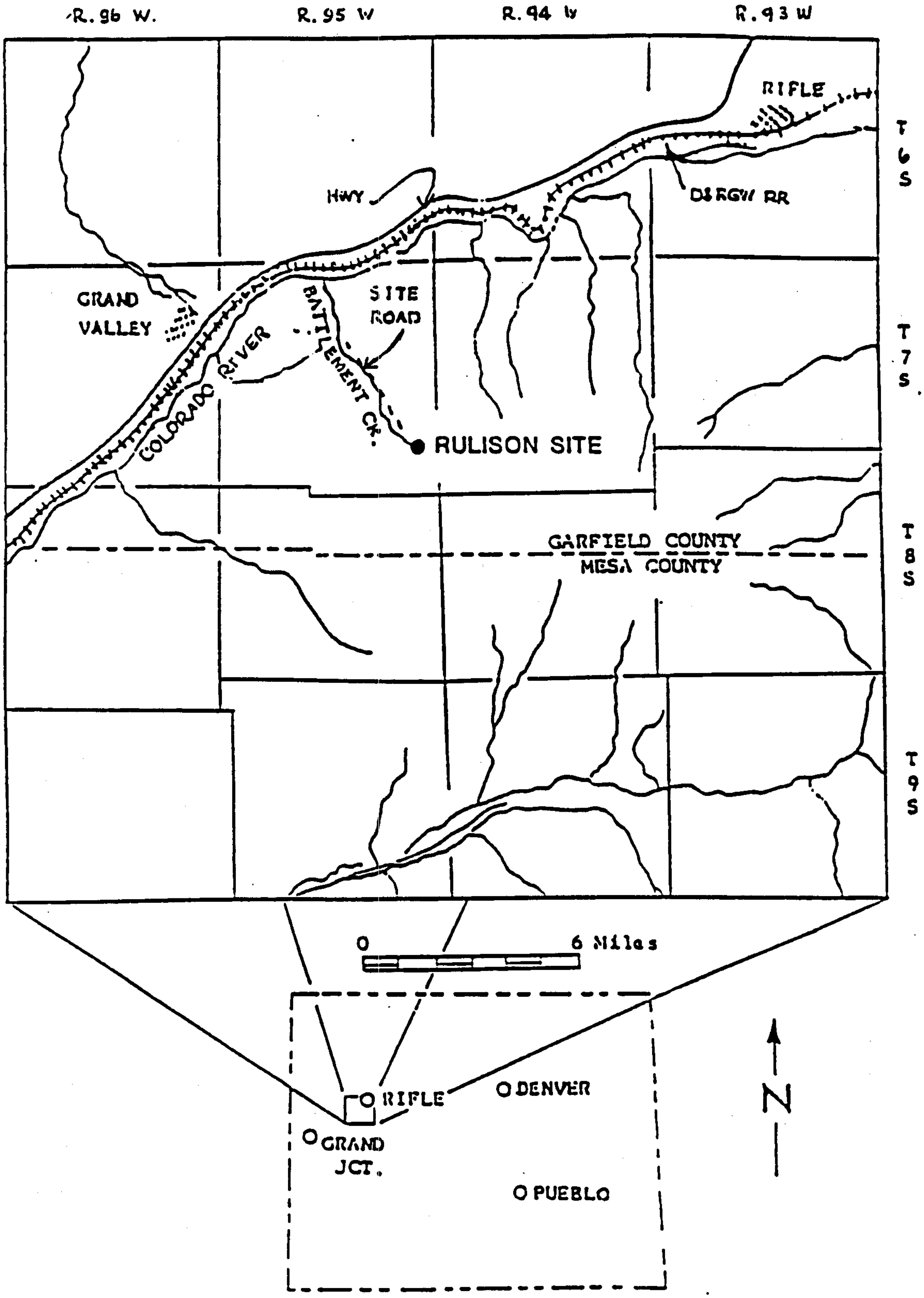

Figure 9. Location map for Project Rulison.
From DOE (1984).

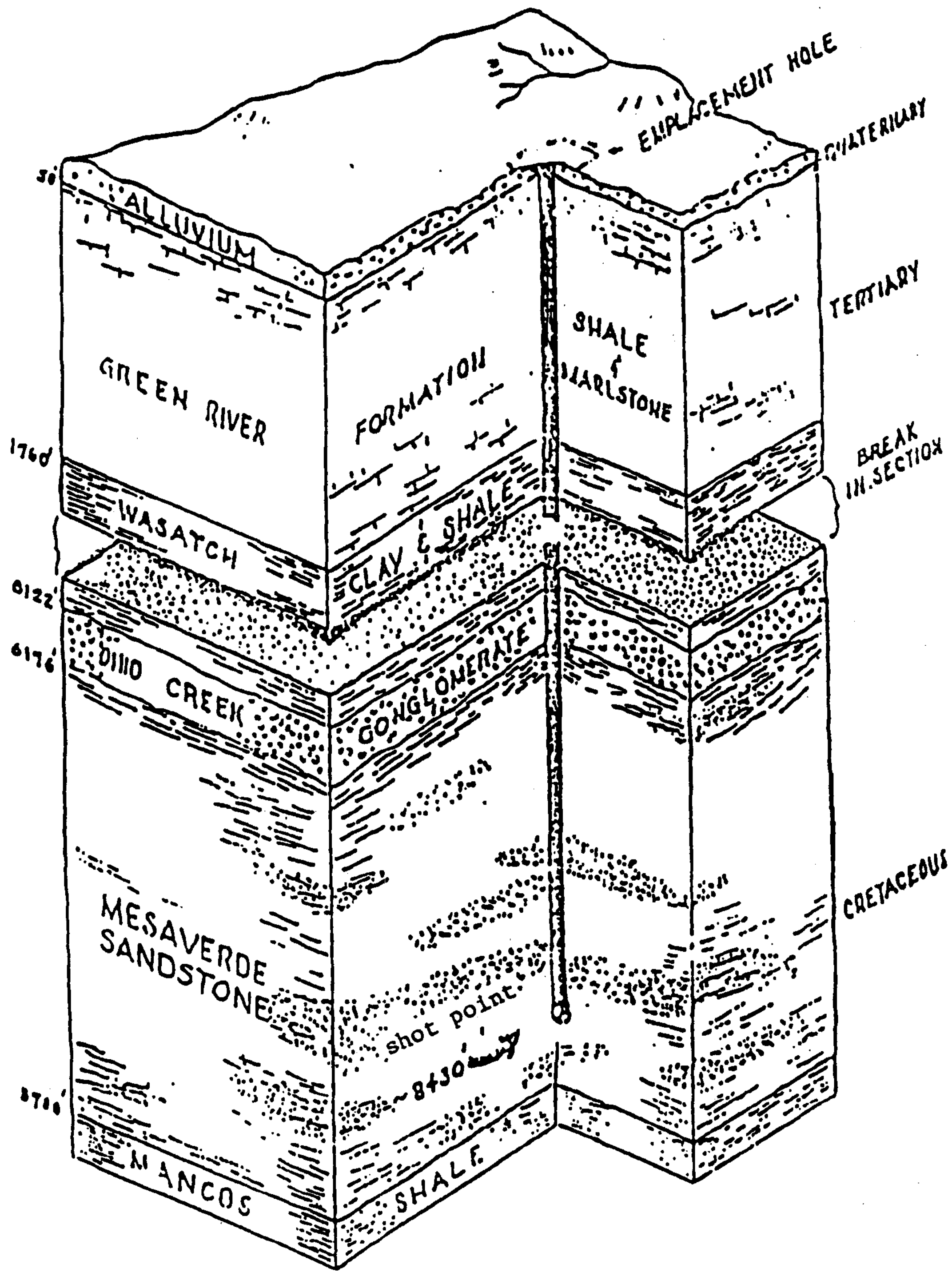

Figure 10. Genearlized geologic cross–section for the Rulison area.
From DOE (1984).

The Quaternary deposits are of particular importance since they provide most of the area's groundwater resources. These units are separated from the emplacement horizon by great thicknesses of low permeability formations, making transport of contaminants through the geologic medium unlikely. The most probable route of contamination is either up the annular space within the emplacement hole or the exploration hole. However, drill stem tests conducted by the USGS identified a low pressure zone between the emplacement horizon and a depth of about 7200 ft. This zone will prevent vertical flow into the higher pressure zones above, diverting contaminants to lateral flow along this hydrologic drain (Voegeli *et al.*, 1970).

The USGS tested all zones below the unnamed Paleocene unit that yielded water during drilling or that geophysical logs indicated as water bearing. Six zones were tested at the following depths: 6129–6149 ft; 6066–7080 ft; 7196–7198 ft; 7312–7320 ft; 7598–7604 ft; and 8014–8018 ft. Pressures recorded during the testing of water–bearing zones indicated little or no mobile water. However, USGS drill stem tests indicated steep pressure build–up curves as a function of time, but yielded low fluid recoveries. This could indicate fracture dominated permeability. The presence of linear features on the land surface supports this theory. If there is fracture flow, lateral flow rates could be much higher than those previously predicted. The most permeable interval tested was from 7196 to 7198 ft. The shut in pressure for this interval was 2875 psi, which is adequate to support a column of water 6630 ft high or within 566 ft of land surface (Voegeli *et al.*, 1970).

Decontamination of drilling equipment and radioactive fallout from gas flaring operations are also possible sources of shallow aquifer contamination. Extensive soil sampling at the site was done to assess surface contamination resulting from radioactive fallout during gas flaring. Contaminated soil was removed from the site and transported to a suitable disposal site (Eberline, 1977).

Past and Present Sampling

A pre–shot inventory of wells and springs in the Rulison area was conducted by the U.S. Geological Survey between March 20 and May 25, 1969. The purpose of the inventory was to document the condition of wells and springs (to determine later if the detonation physically damaged any of them) and to collect water samples for chemical and radiochemical analysis. All known wells within a 6–mile radius of the Rulison emplacement hole were inventoried. Selected wells and springs within a 10– to 20–mile radius were also inventoried (Voegeli *et al.*, 1970).

A total of 21 sample locations were selected for background radiochemical analyses. The 21–station hydrologic network was sampled 10 days after the Rulison event. Analysis confirmed that the event had not caused any increase in radioactivity in surface or groundwater supplies. The USGS also sampled springs, rivers, and wells before and after reentry drilling and after each of the three gas production tests (in which radioactive gas was flared) with the same negative results.

The sampling network for the LTHMP was established by the USGS and approved by the Hydrologic Program Advisory Group. The sampling points, as shown in Figure 11, are listed below:

a. Battlement Creek at the nearest accessible location downgradient from the test well;

b. Two private wells in alluvium on Morrisania Mesa, at the Lee Hayward and Glen Schwab Ranches;

c. Water supply springs for Grand Valley;

d. Two springs and two wells located close to surface ground zero. The wells are at the Albert Gardner and Felix Sefcovic Ranches and the springs are at the Bernklau and Potter Ranches.

e. The Austral Well.

The system was designed with a built-in flexibility to allow the addition of new monitoring points as they become available or to sample any water about which there is public concern (U.S. AEC, 1973). No significant changes in the monitoring network have occurred since inception of the monitoring program.

The established network is sampled yearly. Prior to October 1, 1979, samples were analyzed for γ emitters and tritium. Gross α and β radioactivity measurements were made on all samples collected. After October 1, 1979, these analyses were discontinued in favor of high-resolution gamma spectrometry using a GeLi detector. For each sample location, samples of raw water and filtered and acidified water are collected. The raw water samples are analyzed for tritium by the conventional method. Those samples with concentrations below the detection level for this method are then analyzed by the enrichment method. Portions of the filtered and acidified samples are analyzed for γ emitters.

Analysis of Current Monitoring System

It is not clear what release scenario or scenarios were considered in the selection of LTHMP sampling sites. No discussion was found in the monitoring reports to explain the relationship between the LTHMP sites and possible mechanisms for contaminant transport to the shallow monitoring wells from the shot point at a depth of over 8000 ft. The sampling program has clearly focused on local domestic supply waters. It appears that rather than drilling a network of monitoring wells based on hydrologic data, wells and springs already in place were selected for sampling.

Project Rulison reports unrelated to long-term monitoring conclude that the only remotely possible release scenario involves contaminant transport up the test holes. Even this scenario is considered virtually impossible due to the presence of a low-pressure horizon that is presumed to behave as a sump between the shot depth and near-surface aquifers. In

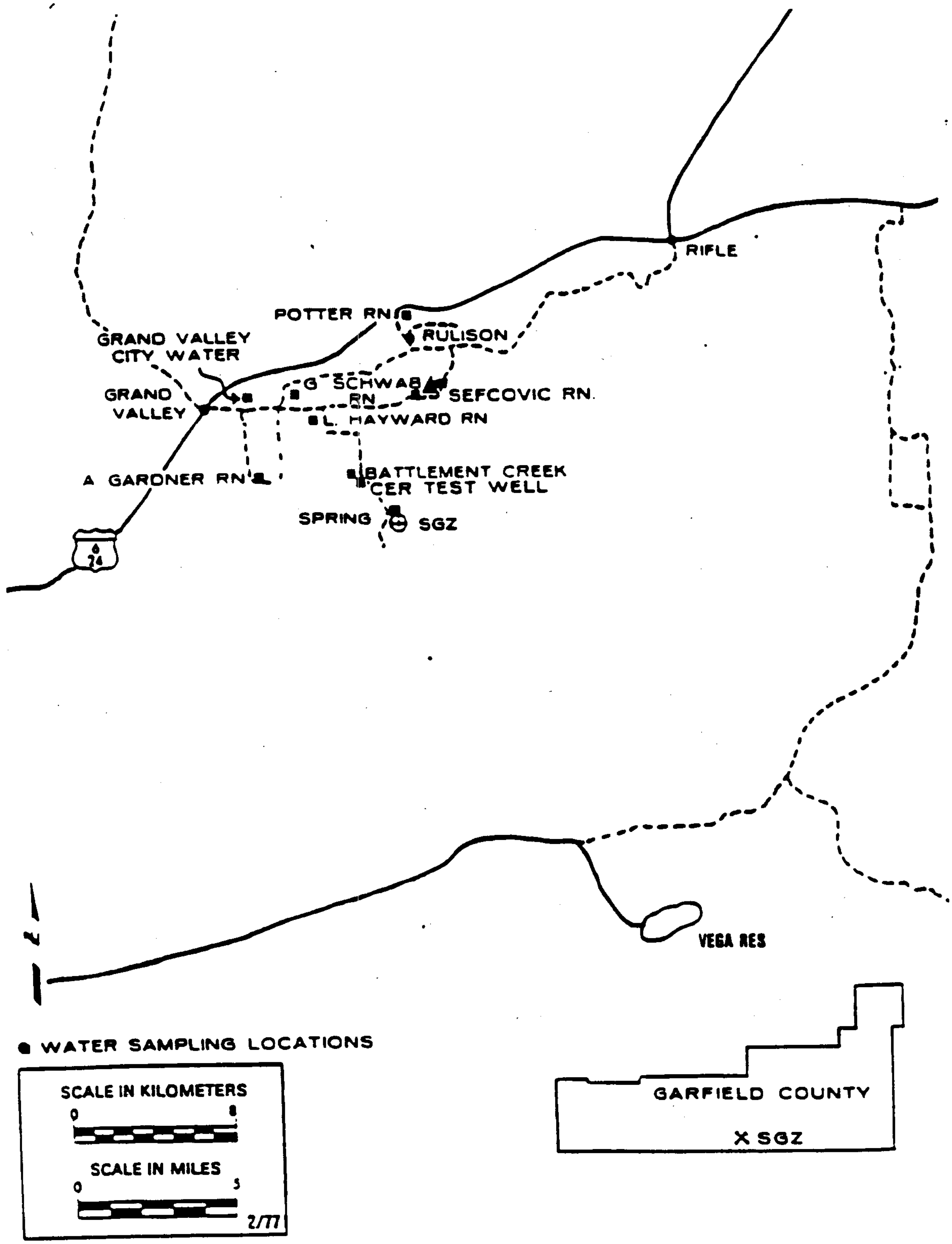

Figure 11. LTHMP monitoring locations for Project Rulison.
From DOE (1984).

addition, the boreholes were plugged. The possibility of surface contamination by fallout during gas flaring operations was addressed by monitoring during flaring and presumably no longer poses a threat.

It is beyond the scope of this report to evaluate the uncertainties and probabilities associated with the borehole release scenario. Clearly, if that scenario is verifiably impossible, there is no scientific reason to monitor the quality of the shallow aquifer. However, given that it is the only scenario proposed that could result in contamination of local supply aquifers, the LTHMP at Rulison is evaluated on the basis that contaminant transport is only possible through the boreholes drilled for the test. Given that scenario, the current monitoring system is lacking. Some of the sampling points are probably not optimally located with respect to the assumed hydraulic gradient (following topography), and most are too far from the potential source to allow the detection of anything other than large-scale migration.

Recommendations

If monitoring of near-surface units is considered necessary at the Rulison site, two improvements could be made to the program.

1. The hydrologic flow system in the local water-supply aquifer should be better defined and a potentiometric map created. This map can then be compared with sample locations to determine which wells are credibly downgradient of the shot location in the upper aquifer. Those wells that are not on possible flow paths should not be used for downgradient monitoring, but could provide information on variation in background values. The data needed to perform the flow analysis may exist, but were not located during this study. If no additional hydrologic data are found, measurement of water levels in area wells will be necessary.

2. Given the assumption that any release would be from one of the test holes, a system could be designed to monitor the integrity of the borehole plugs. For instance, shallow wells could be installed close to the Rulison test holes to allow early detection of any event-related contamination moving into the alluvial aquifer. Monitoring close to the source, combined with accurate knowledge of the flow system, might allow a reduction in the number of relatively distant sample locations.

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PROJECT RIO BLANCO

Project Rio Blanco is located in west central Colorado 52 miles northeast of Grand Junction (Figure 12). The immediate project area is sparsely populated, with most of the population living on scattered ranches. Project Rio Blanco was a joint government-industry experiment using nuclear explosives to stimulate the flow of natural gas from low permeability formations that could not economically produce gas through conventional methods. The project consisted of the simultaneous detonation of three nuclear explosives on May 17, 1973, in a 7000 ft well. The experiment was designed to fracture a 1300 ft section of the Fort Union and Mesa Verde gas sands. The explosives were located at depths of 5838, 6229, and 6689 ft and had a total explosive yield of approximately 90 kt (CER, 1975). Gas production testing and project evaluation continued through June 1976. Tritiated water produced during testing was injected at a depth of 5600 ft in a nearby gas well. Site clean–up and restoration activities were complete by November 1976.

Monitoring Objectives

General

Groundwater monitoring has been conducted at Rio Blanco by Eberline Instrument Corporation, CER Geonuclear Corporation, the Colorado Health Department, and most recently the EPA. Their objectives in some cases are overlapping. The primary objective of all of the monitoring has been to insure that local drinking water supplies have not been contaminated by the test; however, some of the sampling was specifically done during particular events when radiation releases were deemed most likely. Other monitoring programs concentrated on particular contamination transport mechanisms. The specific monitoring objectives of the EPA are described in detail in the introductory section of this report. The individual objectives of the other organizations are listed below.

CER Monitoring Objectives

1. Determine if the alluvial aquifer is contaminated by water with a high total dissolved solids (TDS) content from deeper aquifers as a result of increased communication along faults.

2. Determine the physical effects of the event on local springs and wells.

3. Detailed hydrologic monitoring associated with "higher risk" activities at the emplacement well site.

Eberline Instrument Corporation Monitoring Objectives

1. Establish background radiation levels in surface and shallow groundwater prior to the event.

2. Document seasonal variations that could be erroneously interpreted as radioactive releases from the nuclear detonations.

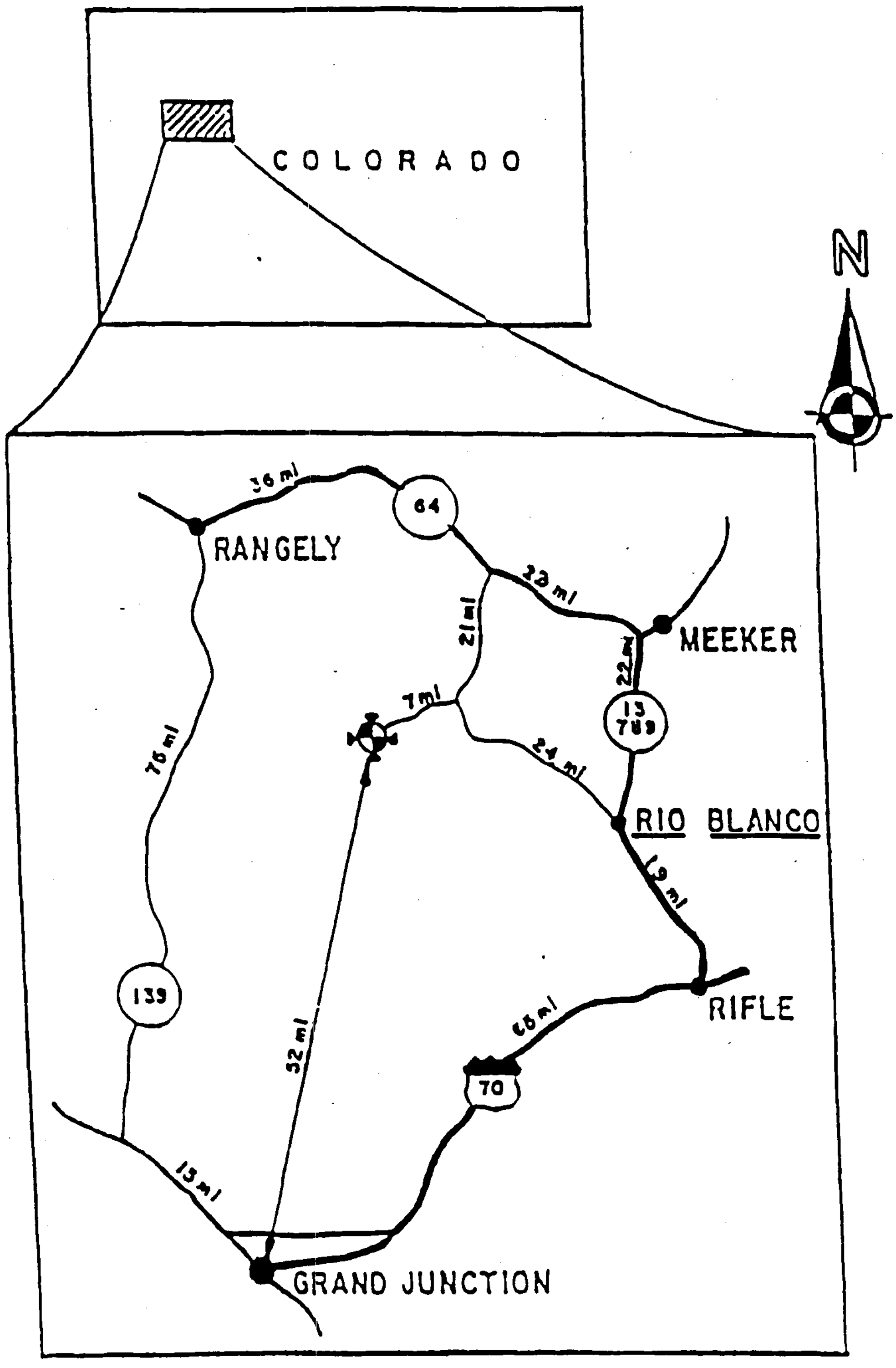

Figure 12. Project Rio Blanco location map.
From DOE (1986).

3. "Proof test" the environmental monitoring equipment and procedures.

Colorado Health Department Objectives

1. Establish background radioactivity levels in drinking water from the basin prior to the event.

2. Record variations in flow volume and salinity of streams.

3. Determine whether or not changes in radioactivity and salinity are caused by the nuclear detonations.

Hydrogeologic Considerations in Monitoring

Three aquifers comprise the majority of the Piceance Creek Basin groundwater resources: a shallow alluvial aquifer composed of Quaternary sediments and two Tertiary aquifers occurring below the surface alluvium. The upper, or "A", Tertiary aquifer contains potable water, while the lower, or "B", aquifer contains water which is highly saline. They are separated by an impervious layer called the Mahogany Oil Shale. Mixing of the "B" aquifer with the upper aquifers would result in increased salt content of wells and surface water in the basin (Colorado Dept. of Health, 1980).

The alluvial aquifer is the primary source of groundwater in the Piceance Creek Basin and can store and transmit more water per unit volume than any of the bedrock aquifers. The areal extent of the alluvial aquifer is limited to belts less than a mile wide along the major drainages. As a result, the total volume of water encountered in the alluvium is small compared to the underlying "A" and "B" aquifers. The alluvial aquifer is recharged by precipitation, applied surface water, streams, and leakage from the underlying aquifers. It discharges to streams, springs, wells, and to the atmosphere by evaporation. The thickness and cross-sectional area of the alluvium have been investigated by drilling at several sites on Piceance and Yellow Creeks. The alluvium thickness varies from 0 to 140 ft, and the saturated thickness reaches 100 ft. Water in the alluvium occurs under both water table and artesian conditions. Alluvial aquifers near the Rio Blanco site have a general northeasterly flow direction toward Piceance Creek (Figure 13). Flow velocities are thought to vary from 8.8 to 15.5 ft/day. These velocities represent maximum rates since it has been assumed that no stream recharge occurs, and that water volume into and out of the area are constant (CER Geonuclear, 1971). Dissolved solids concentration ranges from 250 mg/l to 25,000 mg/l, with better quality waters generally being in the upper reaches of the drainage basin.

Because the alluvial aquifer is limited in areal extent, the "A" aquifer contains the majority of useable groundwater in the area. Permeability is controlled by an unevenly dispersed vertical fracture system. In general, fracture density seems to decrease as rock plasticity and thickness increase (CER Geonuclear, 1971). The TDS in water from springs fed by the "A" aquifer varies from 250 mg/l in the southern reaches of the valley to more than 1,800 mg/l in the central portion of the basin. Lower salinity waters are found near recharge

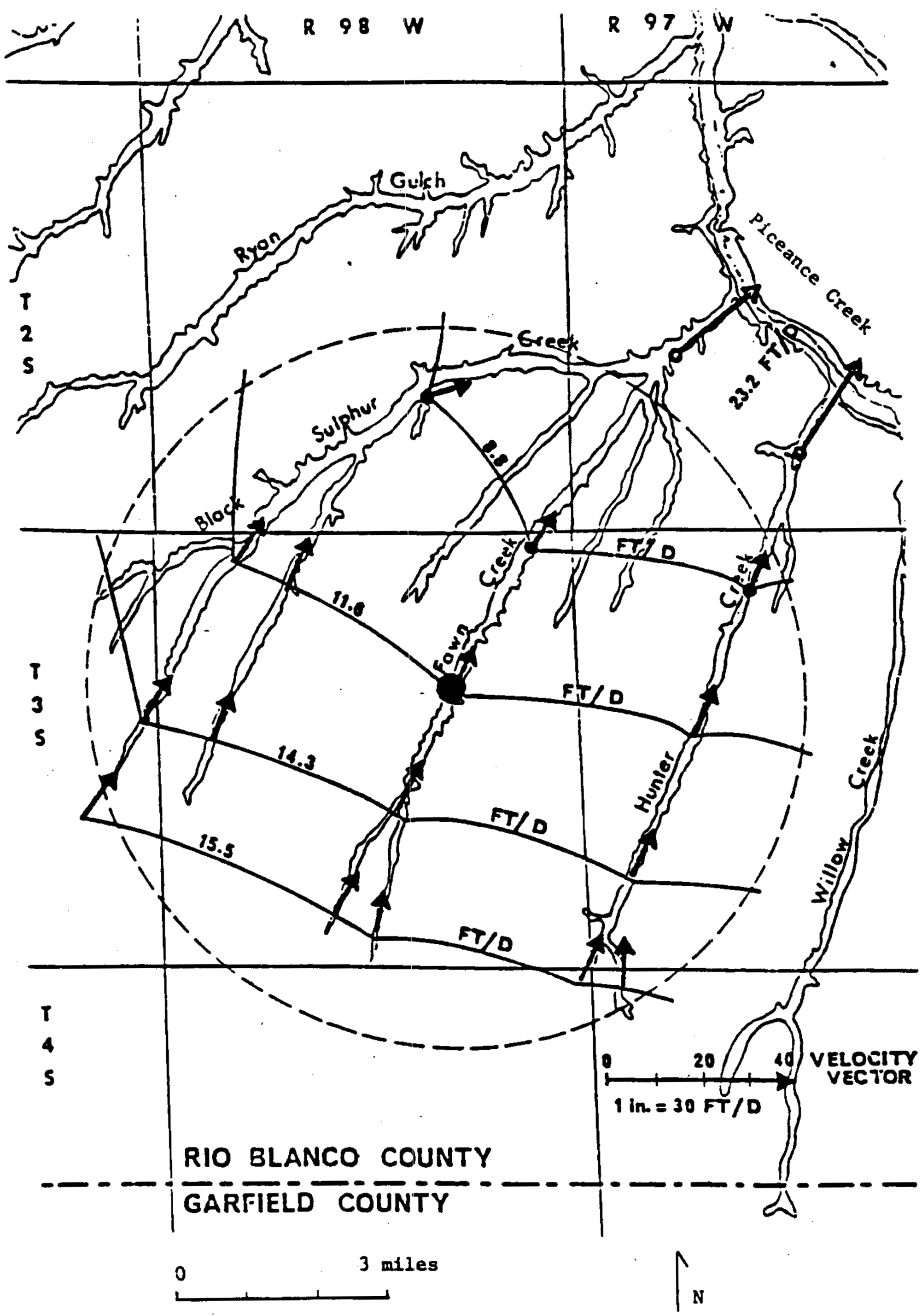

Figure 13. Flow directions and maximum flow velocities in the alluvial aquifers. From CER Geonuclear Corporation (1971).

areas and higher salinities are associated with areas of discharge. The transmissivity of the "A" aquifer was measured at 4,600 gal/day/ft during pre-detonation testing of well RB-D-01. As with the other primary aquifers, flow direction is NE toward Piceance Creek (Figure 14). Groundwater velocities are approximately 12 ft/day (Knutson, 1973).

The "B" aquifer is the principal confined groundwater zone in the Piceance Basin. Recharge occurs along the southern margin of the basin, where the fracture system provides limited communication through the Mahogany Aquitard. The "B" aquifer exhibits intermittent hydraulic continuity with the "A" aquifer via faults and poorly cemented wells. The variation in static water level in wells which tested both zones and chemical differences indicate only a tenuous connection between the "A" and "B" aquifers (CER Geonuclear, 1971). Testing of RB-D-01 (near the emplacement well) suggested that upward flow from the "B" aquifer to the "A" aquifer would occur given a break in the Mahogany Aquitard. Tests indicate that waters from the alluvial aquifer would flow downward into the "A" aquifer.

Transmissivity of the "B" aquifer was determined to be 200 gal/day/ft during pre-detonation aquifer testing of wells RB-D-01 and RB-S-03 (Knutson, 1975). Earlier calculations based on data from non-test wells predicted maximum velocities of from 2.4 ft/day in the northeast to 0.7 ft/day in the southwest portions of the basin. Flow direction is to the northeast in the "B" aquifer throughout the basin (Figure 15). Near-test water levels were measured at 40 ft below surface.

The most probable mechanism of contaminant release from the Rio Blanco event is by radioactive gas seepage up the emplacement well (Knutson, 1973). If such a leak occurs, it is thought that the "B" aquifer would take nearly all of the radioactive gas, allowing only 1% to migrate up to the "A" aquifer. Groundwater velocities in the "B" aquifer are slow enough to cause residence times of from 200 to over 1000 yrs. The only aquifers that would provide significant transport would be the "A" and the alluvial aquifers. "A" aquifer groundwater velocities are 10 times greater than those of the "B" aquifer. A minimum residence time of as little as eight years is possible within the "A" aquifer before surface discharge at Piceance Creek. An upward vertical hydraulic gradient was measured from the "B" aquifer to the "A" aquifer. Therefore, flow from the "B" aquifer to the "A" aquifer is likely in areas where communication between the two aquifers exists (Knutson, 1973).

Past and Present Sampling

One of the primary monitoring objectives was to determine if seismic activity from the Rio Blanco event would enhance flow up known fault planes and contaminate the shallow alluvial aquifer with lower quality (high TDS) water from the "B" aquifer. This issue was studied by CER Geonuclear under the Alluvial Water Quality Project as part of an agreement with the Colorado State Geologist. A series of wells was drilled through the alluvium up- and downgradient of known fault zones. Water quality measurements were made before and after the Rio Blanco event, with no detectable degradation of water quality (CER Geonuclear, 1973).

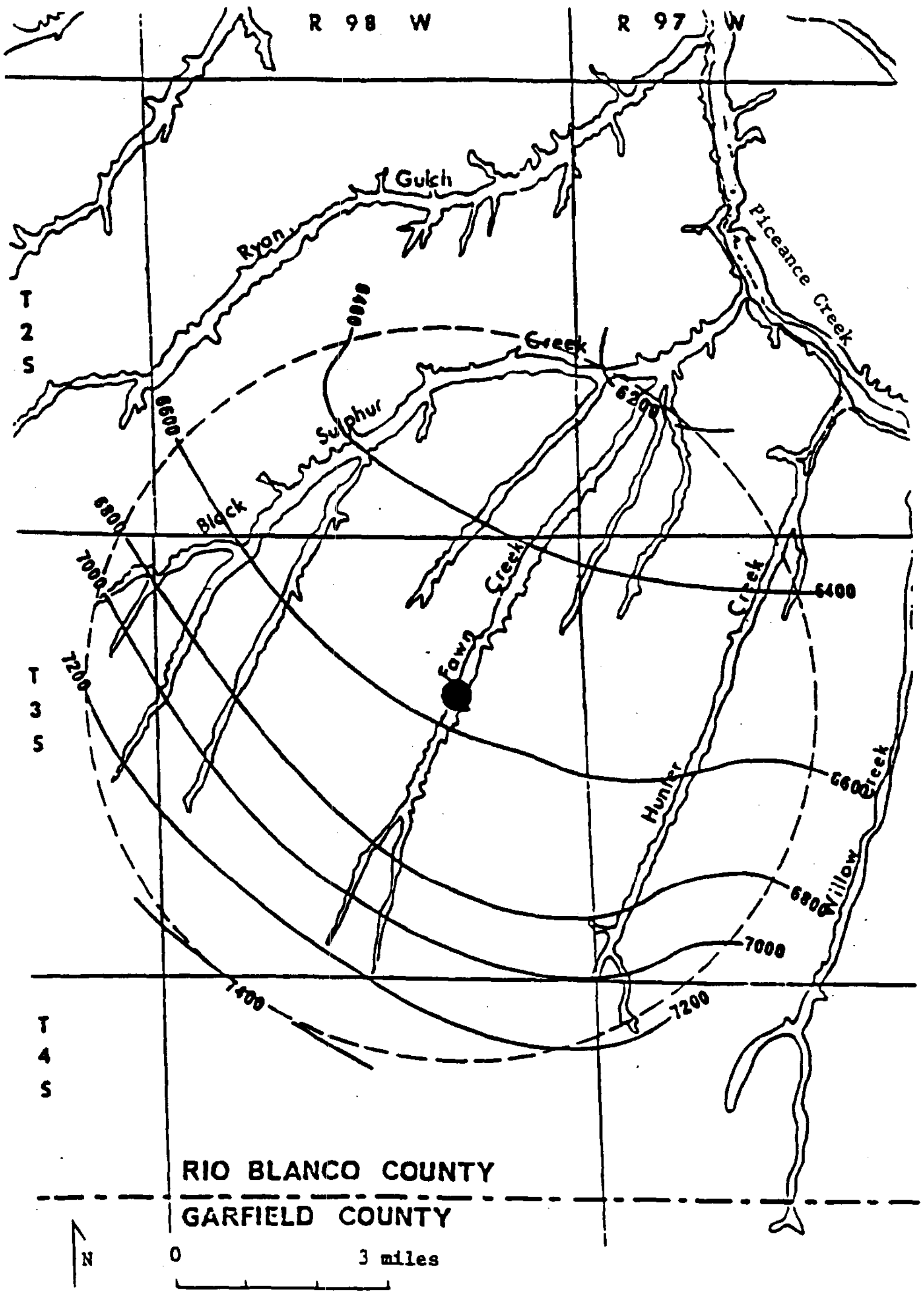

Figure 14. Potentiometric surface map for the "A" aquifer.
From CER Geonuclear Corporation (1971).

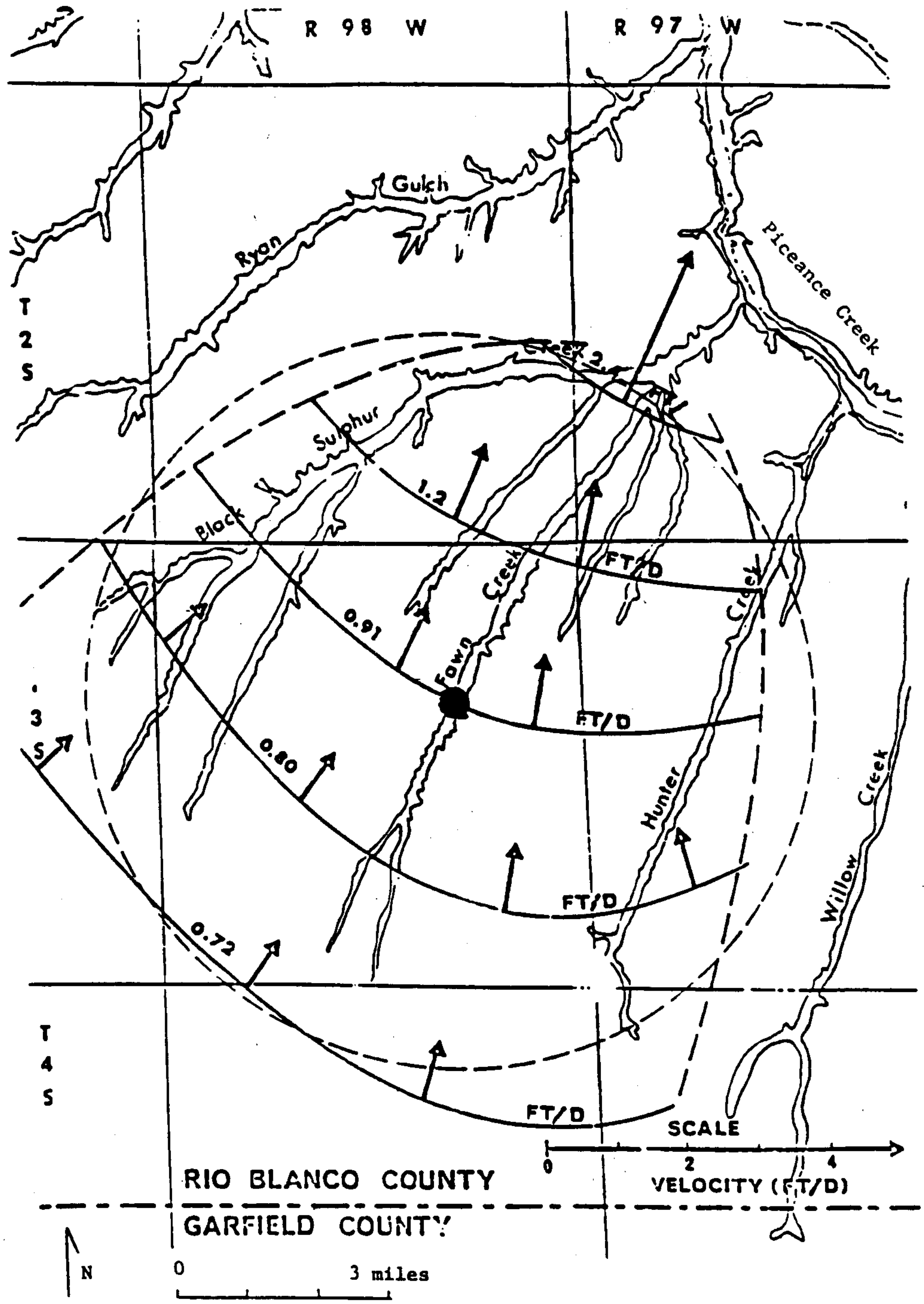

Figure 15. Flow directions and maximum flow velocities in the "B" aquifer. From CER Geonuclear Corporation (1971).

A second early objective of monitoring was to determine the physical effects of the event on local springs and wells. During May and August 1972, CER Geonuclear sampled all springs within 5 miles of the emplacement well and a select number from 5 to 10 miles away. In addition, flumes were installed in 26 springs within 10 miles of the emplacement well and flow rates were measured before and after detonation (CER Geonuclear, 1973). The general trend of spring flow versus time was an initial increase in flow rate with a gradual return to pre-detonation rates. In some cases, springs have dried up, and in others new springs were formed. The loss of springs seems to be a result of increased flow or new flow at other springs. New spring formation appears to be most common within 5 miles of the emplacement well (Knutson, 1975). Spring and well samples were analyzed for K, Na, Ca, Mg, Cl, SO_4, CO_3, HCO_3, and Fe. In addition TDS, electrical conductivity, and pH were measured. No significant change in water quality was apparent as a result of the Rio Blanco test (Knutson, 1975).

Eberline Instrument Corporation began radiological monitoring of surface and groundwater in October 1971 and continued until July 31, 1974. Monitoring was temporarily suspended from October 1972 until mid – February 1973 because adequate background data had been obtained and the detonation was many months away. Seventeen sites ranging in location from surface ground zero to as much as 50 miles away were monitored quarterly. The sites included:

(1) Two sites, up- and downstream in Fawn Creek near the test.

(2) RB-W-1, a shallow well near the test site, completed in alluvium to supply drinking water for on-site personnel.

(3) Water supplies from 4 nearby ranches.

(4) Drinking water from the 6 towns within 50 miles of the site.

(5) Six locations from surrounding streams and lakes.

Samples were analyzed for gross α, gross β, ^{90}Sr, ^{89}Sr, and tritium.

CER Geonuclear assumed responsibility for radiological monitoring after July 31, 1973. CER's monitoring concentrated around periods when radiological releases to the environment seemed most plausible, such as during production testing or during underground injections of tritiated water. This sampling continued until after all project wells associated with the nuclear testing were plugged and abandoned in 1976. The sampling network consisted of:

1. Three project wells drilled at the emplacement well site: RB-D-01 (completed in "B" aquifer), RB-W-01 (completed in the alluvial aquifer), and RB-S-03 (completed in "A" aquifer).

2. Fawn Creek at one mile downstream from the test.

3. The Berthelson Ranch water supply (probably alluvial aquifer).

4. The Brennan Ranch water supply (alluvial aquifer).

The Colorado Health Department had a water sampling network in existence prior to the Rio Blanco event. A concentrated sampling network was established in and around the test site, beginning in March 1973 and continuing through completion of Project Rio Blanco. The department collected and analyzed samples of drinking water from all the ranches in the basin and from principal streams of the area. The sampling effort detected no deterioration of water quality in the area as a result of the Rio Blanco nuclear detonations.

The EPA assumed responsibility for monitoring at Rio Blanco under the LTHMP in January 1977. Results of the analyses of the samples collected are published by EPA annually. The sampling network consists of (Figure 16):

1. Two upstream and two downstream samples from Fawn Creek.

2. One spring downstream and one spring upstream along Fawn Creek.

3. Three springs along Black Sulphur Creek.

4. The Brennan windmill.

5. The Johnson artesian well.

6. Project well RB-D-01.

Analysis of samples has not shown any increase in radioactivity in any of the sites monitored.

Analysis of Current Monitoring System

It is not clear which hydrologic units are being sampled at some of the Rio Blanco spring sites. It is assumed that these springs are fed either by the alluvial aquifer or the "A" aquifer. However, if they are part of small, local systems, their usefulness in a monitoring suite is questionable. Spring sites B-1 and CER-4 are not optimally positioned with respect to the hydraulic gradient.

Two upstream and two downstream locations are sampled in Fawn Creek. Given the downward hydraulic gradient from the alluvial to the "A" aquifer near the test site, a clear hydrologic mechanism does not appear to be present to transport contaminants to Fawn Creek.

Three wells are sampled at Rio Blanco: RB-D-01, the Brennan well, and the Johnson artesian well. RB-D-01 provides a good, close to source downgradient sample of the "B" aquifer. The other two wells are probably producing from the alluvium and are located too far from the source to be useful monitoring points with the exception of assuring the respective

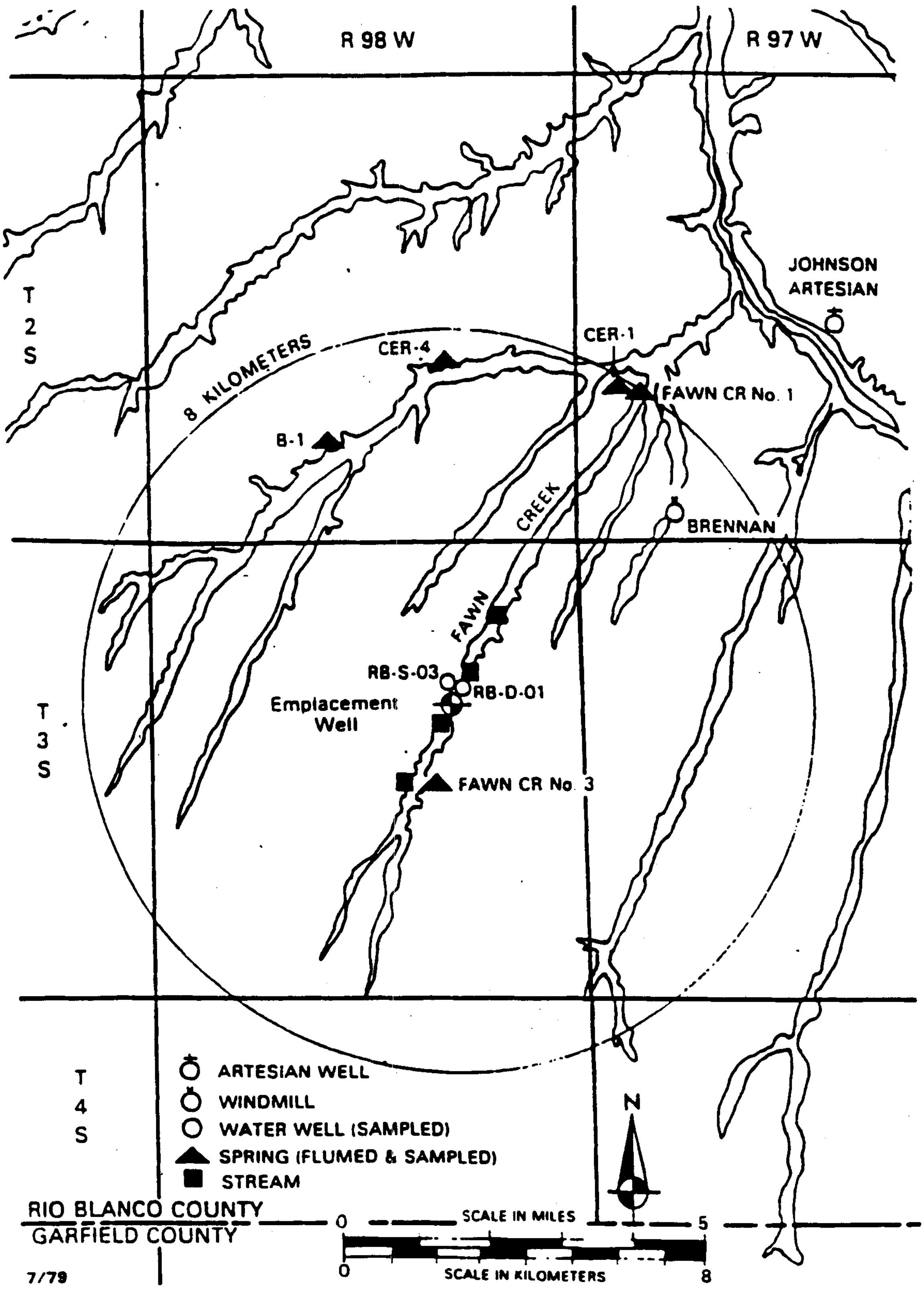

Figure 16. LTHMP monitoring locations for Project Rio Blanco.
From EPA (1988).

water users. Given that the "A" aquifer is the most likely aquifer to transport contaminants a significant distance offsite, it is unfortunate that no well samples are collected from this horizon near the site.

Recommendations

1. Discontinue collecting at spring locations B-1 and CER-4.

2. Determine what hydrologic units the remainder of the springs are fed by. If there is no "reasonable" release scenario to these aquifers, discontinue them as sampling locations.

3. Discontinue collection at the two most distant Fawn Creek surface water sampling points (6800 ft upstream and 8400 ft downstream).

4. If the wells are not plugged, add project-related wells RB-D-02 and RB-D-03 to the LTHMP. Both of these wells are 1000 ft downgradient from the test site. RB-D-02 is completed in the "A" aquifer and RB-D-03 is completed in the "B" aquifer. Including these wells in the LTHMP would increase the probability of early detection in the event of contaminant migration from the Rio Blanco site.

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AMCHITKA

Amchitka Island is the southernmost member of the Rat Island group of the Aleutian Chain, extending southwest from Alaska. Amchitka was the site of three underground nuclear tests: Long Shot was detonated at a depth of 2300 ft on October 29, 1965 and had a yield of 85 kilotons; Milrow was detonated at 3990 ft on October 2, 1969 with a yield slightly over 1 megaton; and Cannikin was detonated at 5875 ft on November 6, 1971 with a yield of less than 5 megatons (U.S. DOE, 1982).

Hydrogeologic Considerations in Monitoring

Consistent with its origin as part of an island-arc chain, Amchitka is composed of as much as 15,000 ft of Tertiary volcanics. The upper mantle of tundra, soil, peat, and fractured and weathered volcanic rocks (varying from a few feet to several hundred feet in thickness) is permeable and readily accepts recharge from the almost 38 inches of annual precipitation (Dudley *et al.*, 1977). There is a general decrease of transmissivity with depth, and fractures become the primary avenues for water movement at depth.

The groundwater system at Amchitka consists of a freshwater lens floating on seawater. To sustain this lens, there must be active freshwater circulation. This circulation can be generally characterized as recharge to the water table, a curving flow path with downward flow in the interior of the island and upward flow approaching the coast, with freshwater discharge to the ocean along the sea floor (Figure 17). Generally, the hydraulic gradient is from the axis of the island toward the coasts, though vertical components of flow are important.

Pre-test data were interpreted by Fenske (1972) as indicating that the seawater-freshwater interface was above the Cannikin cavity; but the same data were used by Dudley *et al.* (1977) to conclude that the interface was probably below the cavity. Apparently the hydraulic-head relationships suggested a maximum depth for the interface of about 3900 ft. The water salinity data, however, suggest circulation of groundwater to a depth of at least 5250 ft. Samples from that depth had salinities of only 4000 mg/L, with the results confirmed in two holes. Data from Milrow were also equivocal, indicating that the interface may have been close to, but probably above, the shot horizon. The Long Shot cavity is much shallower than the other two, and was calculated by Fenske (1972) to be over 1500 ft above the saline/freshwater interface. Thus, it is within the region of active freshwater circulation.

At Cannikin, Dudley *et al.* (1977) estimated groundwater travel times of 23 to 103 years from the cavity to the Bering Sea. A similar analysis of Milrow gave comparable results. For Cannikin, they conclude that "It seems likely that water carrying radionuclides, such as tritium, could begin to discharge on the floor of the Bering Sea within a century and possibly within a few decades." Fenske (1972) also analyzed velocities, but calculated longer transport times. The difference appears to be in the values of transmissivity assumed for the chimney.

The actively flowing groundwater system that must occur in the freshwater lens at Amchitka may eventually move contaminants from the three event cavities to discharge

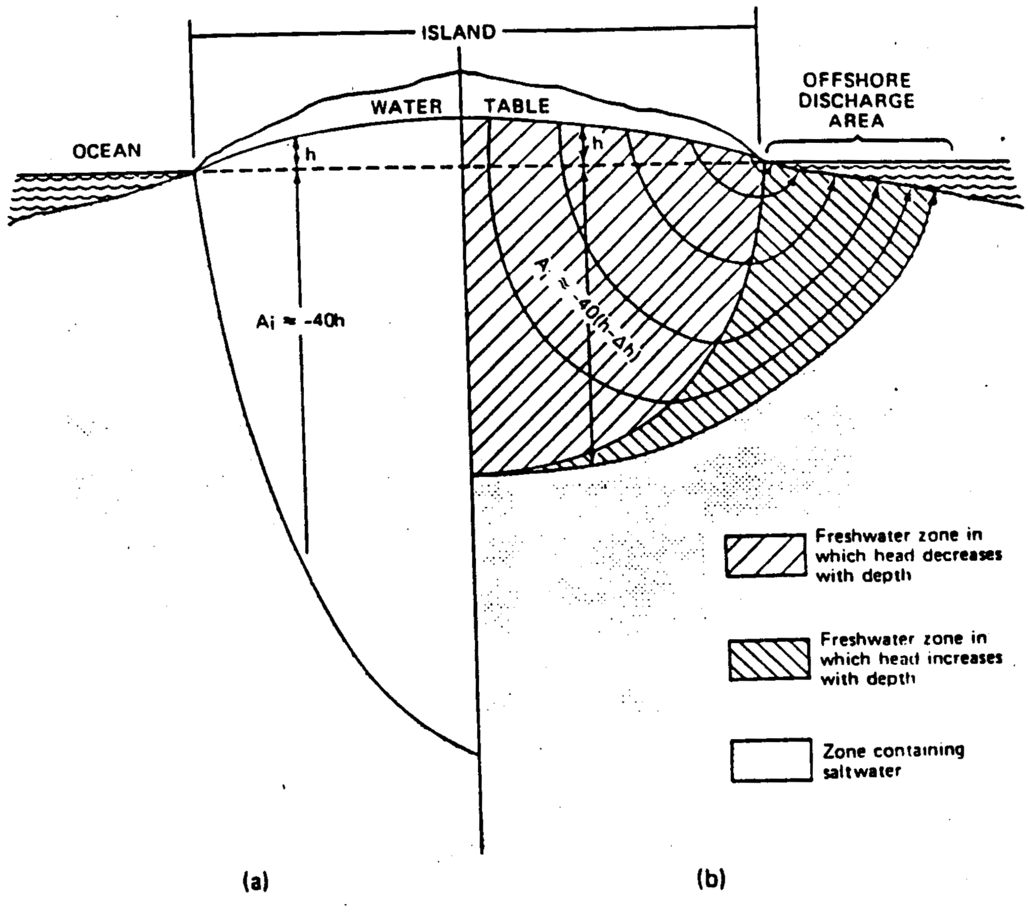

Figure 17. Idealized freshwater flow system beneath an island. Side (a) shows the depth of the freshwater lens in an idealized static system and (b) demonstrates a more realistic system accounting for flow and head changes with depth. From Dudley *et al.* (1977).

points on the ocean floor. In the case of Long Shot and Cannikin, this discharge will occur to the Bering Sea, while flow from Milrow will move to the Pacific Ocean.

No sources of contamination other than the cavities and chimneys are known at either Milrow or Cannikin. At Long Shot, however, tritium and krypton were found in water in mud pits and wells. Maximum tritium concentrations occurred in samples collected at depths between 200 and 300 ft and tritium decreased with distance from Long Shot ground zero. The source is believed to be gases that migrated to the top of the Long Shot chimney (which did not reach the surface). As the chimney filled with water, the gases are thought to have been pushed upward through the stemming material, out into the spall zone, then into solution in groundwater (Castagnola, 1969). The effects of such gas migration have not been noted at Cannikin or Milrow, presumably because their chimneys reached the surface, allowing gas to escape (Seymour and Nelson, 1977).

Past and Present Sampling

Groundwater quality data at Amchitka were collected by the USGS before and after the Long Shot event. Teledyne Isotopes joined the USGS for pre- and post-event monitoring of Milrow and pre-Cannikin monitoring. The USGS continued groundwater monitoring after Cannikin until 1974. The USGS results can be found in their series of "474-" reports, while Teledyne Isotopes' reports were published by NVO.

Groundwater monitoring at Amchitka resumed in 1977 when the Long Shot, Milrow, and Cannikin sites were added to the LTHMP. That year, many of the Amchitka water samples were analyzed for ^{89}Sr, ^{90}Sr, ^{226}Ra, ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, and ^{239}Pu. Several of the Amchitka samples had detectable levels of ^{90}Sr and ^{238}Pu, but the EPA concluded that the presence of these nuclides was related to atmospheric fallout (U.S. EPA, 1978). Elevated levels of ^{3}H were found in many of the Long Shot water samples, comparable to the results obtained in earlier USGS samples. The ^{3}H is believed to be due to migration of gases from the Long Shot cavity, as discussed in the previous section.

The original LTHMP sample locations included six sites at Cannikin, ten sites at Milrow, nine sites at Long Shot, and five background sites (most of which are located on the southeast end of the island near the airstrip) (Figures 18, 19 and 20). In 1978, four wells were added to the Milrow network (W-4, W-7, W-13, and W-18), and one added (Army No. 1) and two deleted (Mile 27 Stream and Base Camp Maintenance Building) from the background sites. Three more background locations were added in 1979 (Army No. 2, Army No. 3, and AEC 1) and another three in 1981 (Site D Hydrohole, Site E Hydrohole, and a rain sample). Army Well No. 4 was added in 1982 and Clevenger Lake in 1987. Well AEC 1 was dropped in 1982 and Army Well No. 3 was dropped in 1986.

The monitoring locations at Cannikin have remained fairly constant, with only the addition of DK-45 in 1983 and the Decon pond and Decon sump in 1987. The number of locations at Milrow increased in 1978, 1983, and 1984, with samples collected from additional

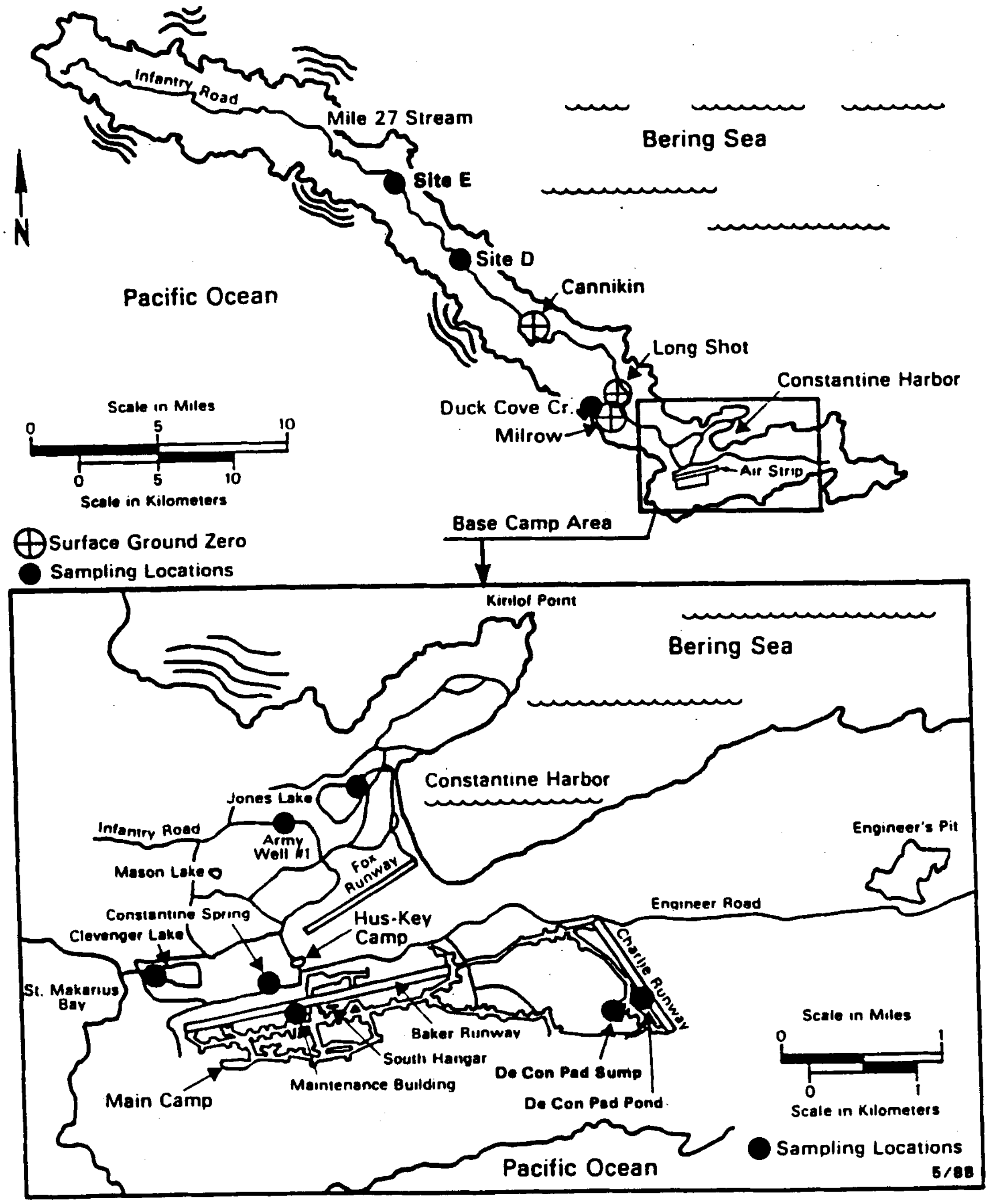

Figure 18. Amchitka Island and background sampling locations for the LTHMP.

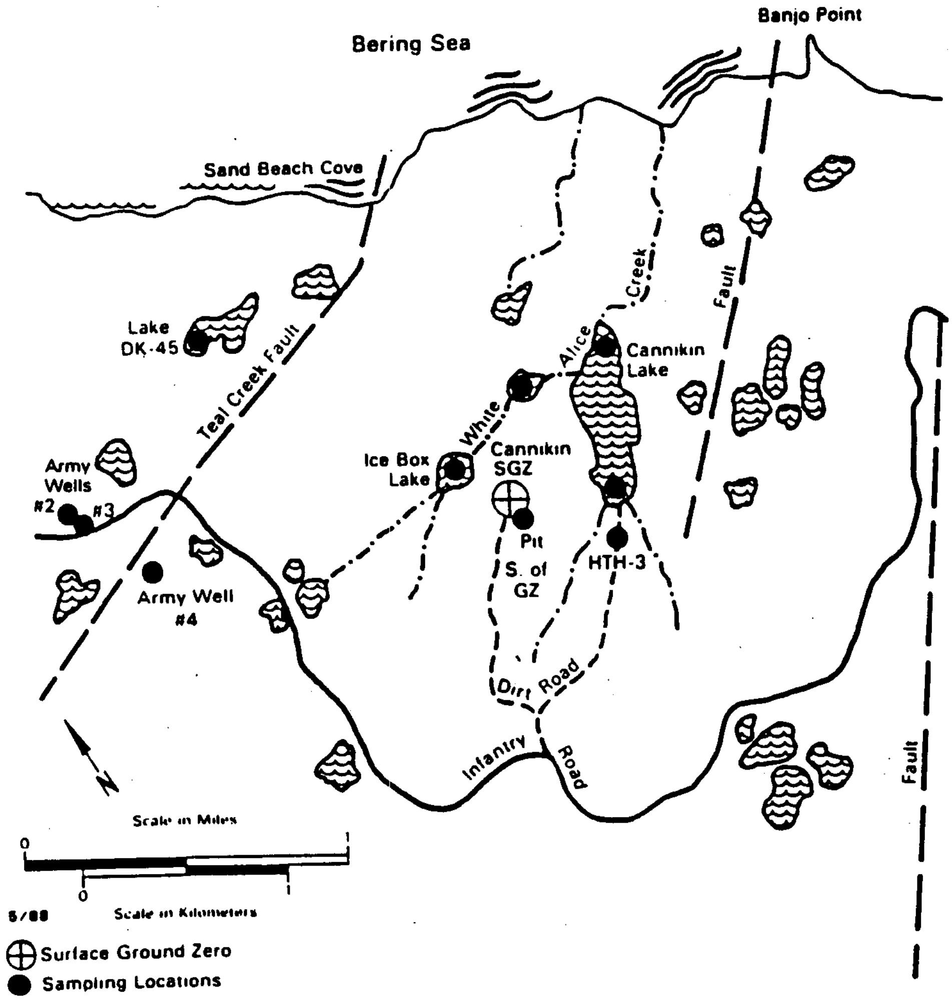

Figure 19. LTHMP sampling locations for Project Cannikin. From U.S. EPA (1988).

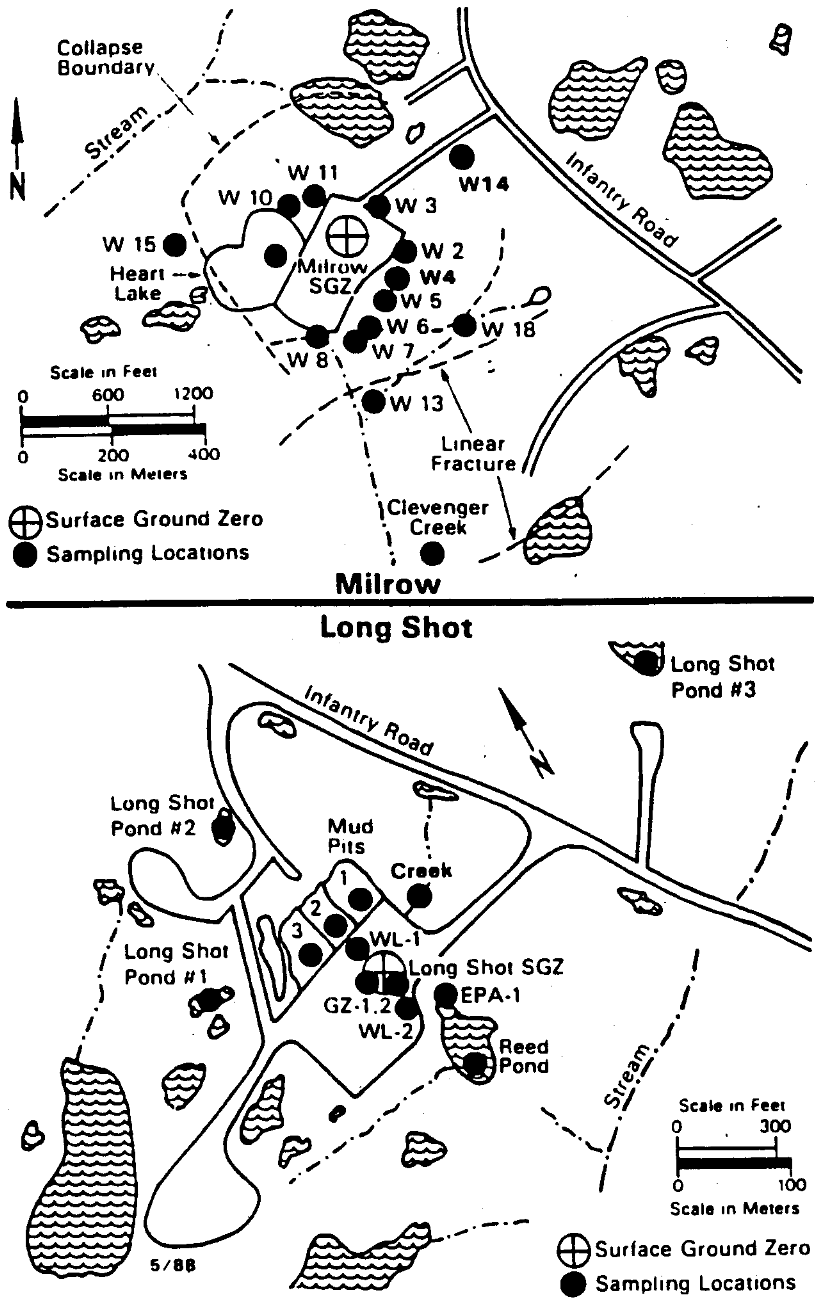

Figure 20. LTHMP sampling locations for Projects Milrow and Long Shot. From U.S. EPA (1988).

"W" wells. However, in 1987, seven of these wells were deleted from the sampling run. The locations at Long Shot have also undergone few changes, with Long Shot ponds 1, 2, and 3 added in 1982 and the stream east of Long Shot ground zero added in 1984.

Most samples have been given a gamma scan and analyzed for only ^{3}H. As mentioned previously, over half the samples were analyzed for a suite of other radionuclides when Amchitka was added to the LTHMP in 1977. The Long Shot Ponds and Army Well No. 4 were also given isotopic analyses (^{89}Sr, ^{90}Sr, ^{226}Ra, ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, and ^{239}Pu) when they were added to the LTHMP in 1982. In 1984, DK–45 and the stream east of Long Shot ground zero were analyzed for ^{238}Pu and ^{239}Pu.

Analysis of Current Monitoring System

The groundwater systems affected by the three underground nuclear tests are essentially unmonitored at Amchitka. Though there are a relatively large number of sample sites at each test location, all of the sites are too shallow to function as monitoring wells for potential migration from the cavities. One positive aspect of Amchitka monitoring is the recognition of a separate set of background sampling locations. Amchitka is the only offsite LTHMP area that has a defined background network.

The Cannikin monitoring network includes only one well location. Given that there are no known surface or near–surface releases associated with Cannikin, the preponderance of lake samples is puzzling. The most likely flow scenario involves movement of groundwater from the cavity toward discharge points in the Bering Sea, so it is unlikely that cavity–related contaminants would ever migrate to the surface sampling locations. The one monitoring well at Cannikin (HTH–3) is also too shallow (152 ft) and not located in the probable flow direction so that it serves little downgradient monitoring purpose. There are no monitoring wells between the Cannikin cavity and the Bering Sea.

The Milrow monitoring network includes a large number of wells (the "W" series), but all of these are very shallow. The deepest monitoring well for the Milrow event is 6.7 ft. As with Cannikin, no shallow contamination is known, so the reason for this network of shallow wells is unknown, but probably related to concerns raised by Long Shot.

In contrast to the other two sites, shallow monitoring at Long Shot is necessary because of the known presence of event–related radionuclides in the surface water and shallow groundwater. The source of the tritium is in the upper part of the Long Shot cavity and there are two possible pathways the contamination could follow: tritiated water could move downward through the chimney to join the bulk of the event–related contaminants on a groundwater pathway to the Bering Sea, or the tritiated water could discharge as base flow to streams and ponds then on to discharge to the Bering Sea as part of the surface water system.

The near–surface and surface water systems at Long Shot need to be better defined, but it appears that several of the surface water monitoring sites are located in downgradient positions. However, above–background tritium has already been detected at these sites and there are no monitoring locations beyond them. Thus, the extent of tritium migration in the shallow system is unknown and cannot be determined with the present monitoring locations. As with Cannikin and Milrow, migration of material from the Long Shot cavity in the deeper groundwater system is not monitored.

Recommendations

The dynamics of the island's freshwater/seawater hydrologic system control the monitoring of migration from the three event cavities. The vertical component of groundwater flow that is expected at all three sites could require very deep monitoring wells to track migration close to the cavities (in the case of Cannikin, the wells would be close to 6000 ft deep). Unlike other test horizons at great depth (*e.g.*, Rio Blanco), the hydrogeologic setting suggests a strong possibility of significant contaminant migration. However, the general direction of groundwater flow is well-known, so if the local flow paths toward the sea can be defined, shallower monitoring wells could be located closer to the discharge areas. Indeed, freshwater seeps exist in some areas along the coast. Several such seeps were sampled prior to the LTHMP (Essington *et al.*, 1971), though some were apparently located on cliff faces and thus were discharge from shallow systems.

1. Define flow paths between Milrow and the Pacific Ocean, and between Long Shot and Cannikin and the Bering Sea. This may require drilling new holes near each site.

2. Using the information gathered in #1, monitoring sites should be placed downgradient from each site. Though wells should be part of this network, natural groundwater discharge points (freshwater seeps along the coast) should also be used whenever available.

3. Install additional shallow monitoring wells and surface water sites between known Long Shot contamination and the Bering Sea to define the extent of migration.

4. Though background monitoring is important, some of the background sites could be deleted from the program. In particular, there is probably no need for so many sites near the airfield. In their place, some of the sites currently sampled at the individual test locations could be reclassified as background samples.

5. The number of shallow monitoring wells regularly sampled at Milrow by the LTHMP could be reduced.

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TATUM DOME

The Tatum Dome test site is in south-central Mississippi, approximately 20 miles southwest of Hattiesburg. As part of Project Dribble, Tatum Dome was the site of two nuclear detonations. The Salmon event was conducted on October 22, 1964 and had a yield of 5.3 kilotons. The Sterling event occurred on December 3, 1966 and had a 380 ton yield (DOE, 1975). The Miracle Play Program was also conducted at Tatum Dome and consisted of two high-explosive nonnuclear detonations. These explosions were named Diode Tube and Humid Water, and were conducted in 1969 and 1970. The original Salmon event occurred 2710 ft below ground surface, within the Tatum Salt Dome, and the three subsequent events were conducted in the cavity created by Salmon.

Hydrogeologic Considerations in Monitoring

The hydrogeologic system in the Tatum Dome area consists of Cenozoic-age units deposited during marine transgressions and regressions across the gulf coastal plain. Tatum Dome interrupts and deforms the lower units in the sequence. The salt dome itself has very low permeability, allowing little water movement, but the limestone and anhydrite caprock constitutes an aquifer by virtue of permeability along fractures and solution cavities.

There are seven recognized hydrologic units in the Tatum Dome area, exclusive of the dome and caprock. The deepest unit is Aquifer 5 in the Cook Mountain Limestone, which contains saline water. Aquifer 5 is used for injection of oil-field brines in the area. Aquifer 4 is in the Vicksburg Group and contains brackish water. Both Aquifers 4 and 5 are interrupted by the salt dome and thus do not occur immediately over the ground zero area. Aquifer 3 is in the Catahoula sandstone and Aquifers 2, 1, and the Local Aquifer are in the Pascagoula and Hattiesburg Formations. Within and between these units, low permeability clay beds behave as aquitards. The uppermost aquifer is the Surficial Aquifer in the sands and gravels of the Citronelle Formation and terrace and valley-fill deposits. Though the more permeable part of the Citronelle often occurs in sands near the base, the Surficial Aquifer is apparently continuous to the water table. The depositional environment of the permeable sands throughout the Miocene-age units (all aquifers above and including Aquifer 3) requires that the Cenozoic sediments be considered hydraulically as one flow system (Fenske and Humphrey, 1980). Though clay beds may create discrete aquifer zones in a local area, a significant amount of cross-aquifer flow must occur in the regional flow system.

The natural flow system has been disrupted by pumping from the upper aquifers and injection into Aquifer 5. As noted by Fenske and Humphrey (1980), there are also discrepancies in the groundwater flow directions reported by various studies of Tatum Dome hydrology. The transient conditions and lack of data result in uncertainties in groundwater flow directions. The following estimates are from Harvey and Chafin (1972). Groundwater in the Caprock Aquifer probably moves to the southwest. Flow in Aquifer 5 is believed to be to the north-northeast, driven by oil-field brine injection. Flow in Aquifers 1 and 4 is to the south-southwest, the original direction of flow in all area aquifers. Flow in Aquifers 2 and 3 is believed to be to the east–northeast, influenced by pumping withdrawals for municipal and industrial use. Fenske and Humphrey (1980) concluded that Aquifers 1, 2, and 3 behave regionally as one system, with flow in this combined system to the southeast. Flow in the Local Aquifer has been reported to both the southwest and northwest, and is probably generally westward toward the Pearl River in either case. Flow in the Surficial Aquifer is thought to follow land surface contours, interacting with local streams. In the immediate Tatum Dome area, the Surficial Aquifer discharges to or recharges from Half Moon Creek, depending on stream stage. Domestic and stock wells in the Tatum Dome area produce from the Surficial Aquifer (Harvey and Chafin, 1972; U.S. Geological Survey, 1972). Outside of the dome area, Aquifers 2 and 3 are used extensively for municipal and industrial use.

The activities at Tatum Dome have created three sources of potential contaminant transport: 1) the shot cavity itself with its residual radioactivity; 2) radioactive liquid waste disposed in Aquifer 5, which subsequently flowed through well HT–2m to the surface; and 3) drillback materials from the event cavity located in surface pits (U.S. DOE, 1975 and 1978). Each of these sources is described below.

Nuclear event cavity: Given the low permeability of salt and the fact that the detonations were fully contained, the most plausible scenario for migration of material from the cavity involves leakage up the emplacement or post–shot holes. Upward movement of water pressurized by salt creep occurred at Instrument Hole E–14. Based on the water's tritium concentration, it was concluded that the water had not been in contact with the nuclear event chamber. Studies of the seepage from E–14 also concluded that a similar movement of water from the cavity would not occur because of the careful sealing of the emplacement hole and the time required for salt creep to pressurize any water in the cavity (Fordham and Fenske, 1985).

Liquid Waste Injection: During 1965, 38 curies of beta and gamma activity and 3210 curies of tritium were injected into Aquifer 5 through well HT–2. The injection well was plugged in 1971 and a monitoring well, HT–2m, was drilled. The water level in HT–2m began rising, apparently due to production of some combustible gas in the aquifer (Fenske, 1973), and water containing tritium (34,000 pCi/L) was found at land surface in 1974. Some of this tritiated brine flowed along the road and into a swampy area during sampling activities. Well HT–2m was plugged in 1975. The completions of both HT–2 and HT–2m were designed to isolate Aquifer 5 from overlying aquifers.

Drillback Material in Surface Pits: During decommissioning activities at Tatum Dome from 1970 to 1971, cleanup criteria were relaxed for muddy areas around the Postshot No. 1 Slush Pit and Postshot No. 1 Mouse Hole. Analyses performed as part of the LTHMP discovered anomalous concentrations of tritium in the Half Moon Creek Overflow Pond and subsequent studies identified the source as incomplete cleanup of the old slush pits (U.S. DOE, 1978). Several areas of contaminated soil and shallow groundwater were identified and attributed to bulldozer contouring of the area around the pits and at a tank site where contaminated fluids were temporarily held. Water contaminated by tritium and salt is primarily limited to the unsaturated zone and the Surficial Aquifer, though some contamination was apparently introduced into the Local Aquifer during hydrologic testing (Fenske and Humphrey, 1980).

Groundwater contamination from the first possible source (leakage from the event cavity) could enter any of the hydrologic units via the emplacement or postshot holes. This possibility is not as likely as migration from the other two sources. The radioactive waste injected into Aquifer 5 is probably migrating to the north-northeast, driven by industrial brine injection. The events at HT-2m show that there is a potential for leakage from Aquifer 5 into the upper units. As with the event cavity, a probable scenario for such leakage would be through improperly plugged boreholes. Radionuclides from the source in the muckpiles have been documented to be entering the Surficial Aquifer, and are apparently moving toward Half Moon Creek. Some of this tritium has also entered the Local Aquifer, where it has the potential to move in a generally westward direction.

Past and Present Sampling

Pre-LTHMP groundwater monitoring is described in the report of LTHMP activities at Tatum Dome (U.S. DOE, 1975). According to that report, the PHS collected water samples near the Tatum Dome site prior to the Salmon event. The PHS, USGS, and Hazelton-Nuclear Science (later known as Teledyne Isotopes) all collected samples after the Salmon and Sterling events. The DOE (1975) reports that all analyses showed no detectable levels of radioactive contamination above background. No reports containing data from these monitoring activities were located during the present project.

The EPA began groundwater sampling around Tatum Dome under the LTHMP in 1972. Originally there were 18 sites, including test wells at Tatum Dome, municipal supply wells, domestic wells, and surface water occurrences. This list underwent only slight modifications until 1978, when 12 new wells at Tatum Dome were added. Included in this group were the shallow Hydrologic Monitoring Holes (HMH), drilled to provide an "early warning" if significant movement of tritium in the shallow groundwater takes place (U.S. DOE, 1978). Several new site wells were added in 1980 (the 6 "HM" wells), along with additional domestic supply wells. Though a few sample sites have been dropped from the program over the years (*e.g.*, when a well is plugged), overall the program has increased the number of monitoring sites to 48.

The LTHMP sites can be considered in three groups according to their proximity to ground zero. Sample locations within approximately 600 ft of surface ground zero (SGZ) include the shallow wells monitoring the Surficial Aquifer in the "HMH" series, all but one of the "HM"wells that are completed in aquifers above the Cook Mountain Limestone (the Surficial and Local Aquifers, and Aquifers 1, 2a, 2b, and 3), and the surface water sampling site at the Half Moon Creek Overflow (Figures 21 and 22). Located over the salt dome area,

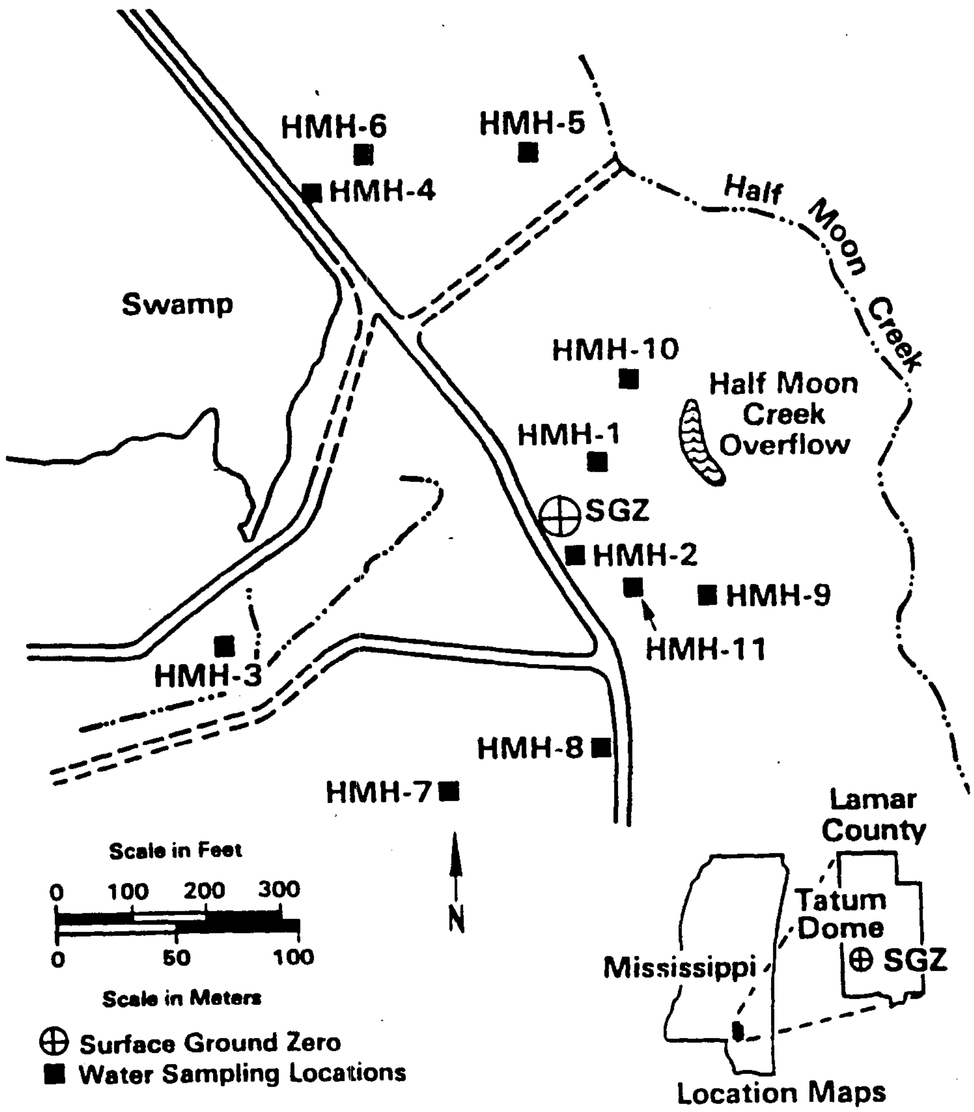

Figure 21. LTHMP sampling locations for Project Dribble – near ground zero. From U.S. EPA (1988).

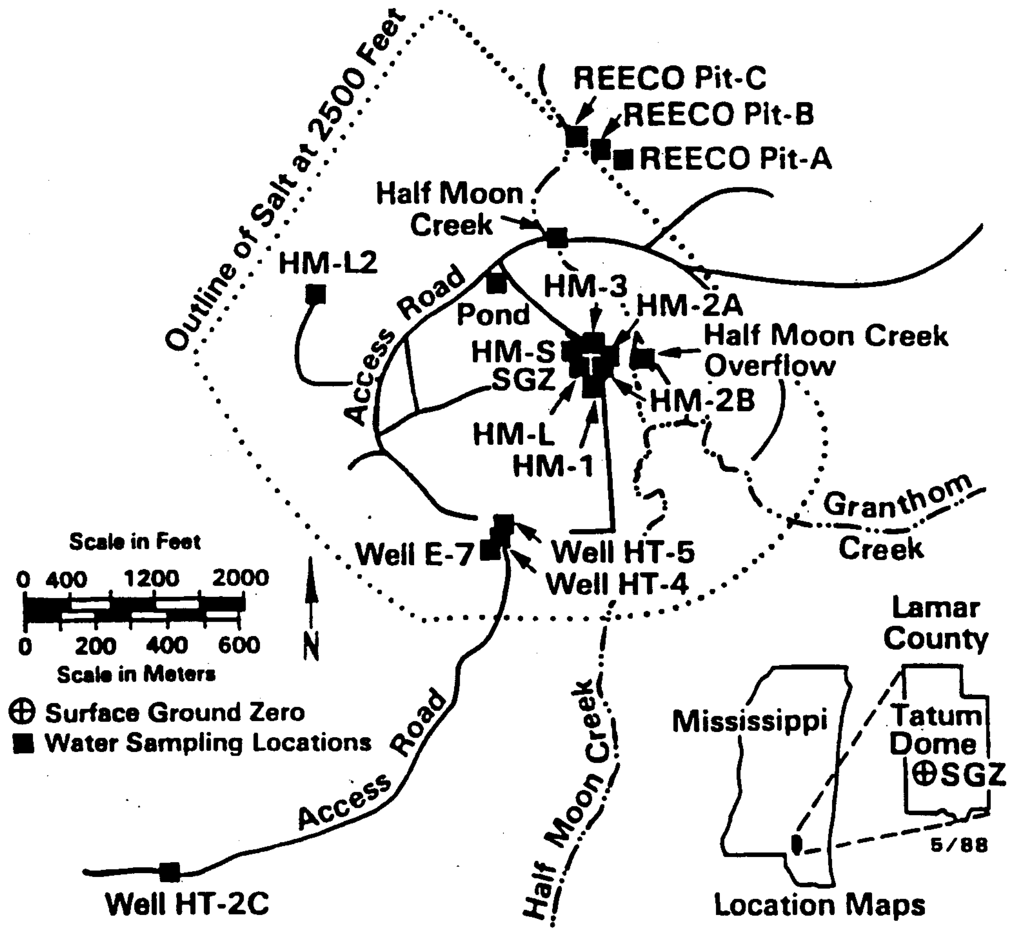

Figure 22. LTHMP sampling locations over the salt dome at Project Dribble. From U.S. EPA (1988).

but farther from ground zero are wells HT–5 (Aquifer 2a), HT–4 (Aquifer 1), E–7 (Caprock Aquifer), and HM–L2 (unknown, but probably the Local Aquifer), and several surface water sampling sites (Half Moon Creek, the pond west of ground zero, and REECo Pits A, B, and C) (Figure 22). Outside of the dome area are one DOE well (HT–2c, completed in the Local Aquifer), the domestic and municipal supply wells, and Lower Little Creek (Figure 23).

Completion data are not available for most of the non–DOE wells sampled by the LTHMP. Studies report that domestic and stock wells around Tatum Dome produce water from the Surficial Aquifer (Fenske and Humphrey, 1980), a conclusion that is consistent with most reported well depths. A few of the deeper domestic wells may produce water from the Local Aquifer (*e.g.*, Chambliss, A.C. Mills, and Kelly). The deeper aquifers (2a, 2b, and 3) are the sources of municipal and industrial supplies in the region, but it is not known which, if any, of the LTHMP wells produce from those units exclusive of four of the DOE wells.

In most years, the Tatum Dome samples for the LTHMP have only been analyzed for tritium concentrations. In 1972, as well as 1977 through 1979, gross α and β analyses were also performed. In 1975 and 1976, a broader range of radioanalyses was done, including ^{89}Sr, ^{90}Sr, ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, and ^{239}Pu. A few of these additional analyses have also been performed on selected samples in other years.

Analysis of Current Monitoring System

Monitoring Leakage From the Nuclear Cavity

If there was migration of radioactivity from the Salmon cavity past failed borehole seals, the contamination could enter any of the aquifers overlying Tatum Dome. The LTHMP collects samples from at least one well in each of the aquifers over the dome. No samples are collected from Aquifers 4 and 5, but these units are interrupted by the dome (*i.e.*, they do not occur over the dome and thus are not over the ground zero area). Even if the regional flow directions were well known (which they are not), actual flow paths across a small area can be highly uncertain. Therefore, it is difficult to determine if a well 15 to 20 ft away from ground zero is truly downgradient. With the rough information available, it appears that most of the dome–area wells are located in, or close to, the suspected downgradient direction for each aquifer relative to SGZ. Possible exceptions to this are the wells monitoring Aquifers 2b and 3. In addition to having good locations relative to SGZ, the HM wells are also located very close to the emplacement hole. The proximity of the HM wells to SGZ offers the possibility of early detection of seepage of water up the emplacement hole, as well as the opportunity for a well to intercept diffusion of a contaminant even if the well is not directly down a flow path. Though refinement of flow directions is desirable, monitoring for leakage up the boreholes in the SGZ area appears adequate.

Monitoring of Injected Liquid Waste

The liquid waste injected in HT–2 is essentially unmonitored by the LTHMP. No LTHMP wells are completed in either Aquifer 4 or 5. Thus, the fate of the injected radioactive

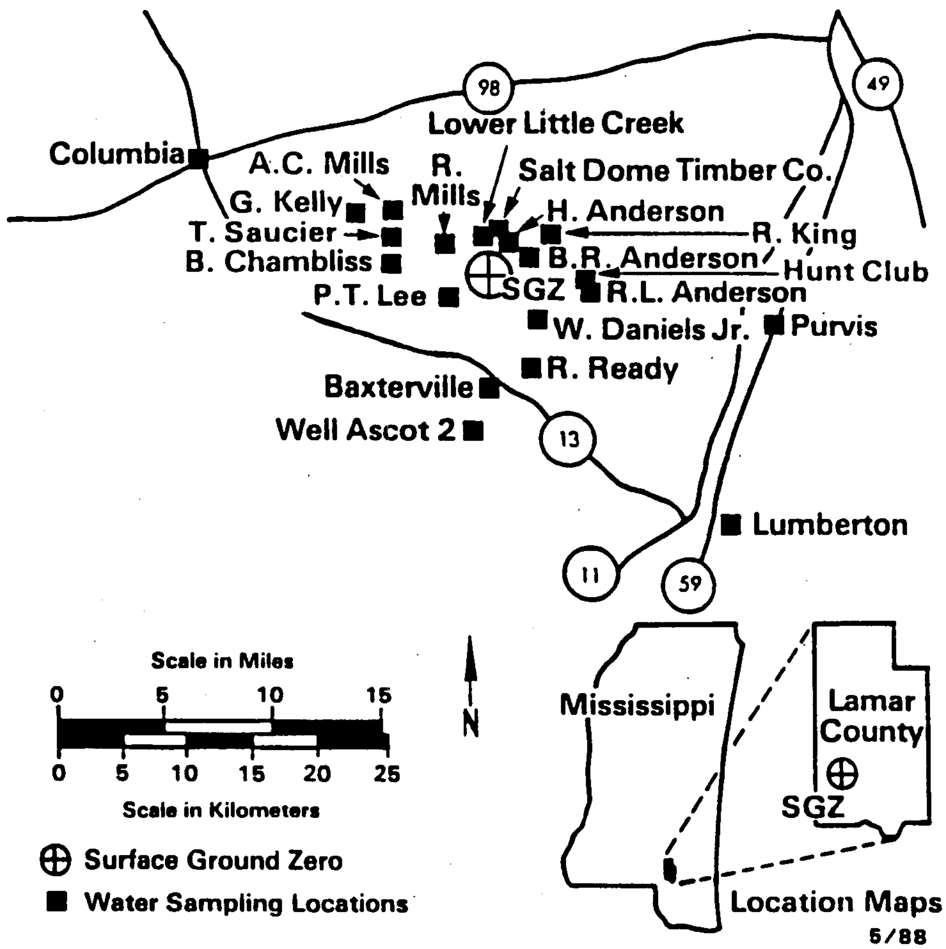

Figure 23. LTHMP sampling locations at towns and residences around Tatum Dome. From U.S. EPA (1988).

waste has not been assessed since HT–2m was plugged in 1975. The risk presented by the injected slug has been thought to be small. Fenske (1973) analyzed the HT–2 injection and predicted a maximum movement of above–background tritium of 1200 ft. In addition, neither Aquifer 4 nor 5 is used for water supply in the Tatum Dome area. However, the high pressure conditions in Aquifer 5 create the potential for migration of waste into the upper aquifers through any improperly plugged boreholes. The situation is further complicated by the brine injection at the Baxterville Oil Field. At the time of the last studies in Aquifer 5, the oil–field injections had created a gradient for flow in Aquifer 5 to the north–northeast. If this gradient was maintained, flow induced in Aquifer 5 will eventually approach the area where the Cook Mountain Limestone is truncated by the salt dome. Given the pressure gradients, the water in Aquifer 5 could move upward into overlying aquifers through structural features along the side of the dome. Another possibility is lateral flow around the dome.

Whether through borehole leakage or cross–formational flow, any migration of contamination from Aquifer 5 to the upper aquifers would most likely occur between the injection well, HT–2, and the edge of the salt dome, southwest of well E–7. Given the estimated flow directions in the upper aquifers, the wells monitoring Aquifers 2a, 2b, and 3 are downgradient of the possible source area. Because of the southwest–to–westerly flow directions in Aquifer 1 and the Caprock and Local Aquifers, wells monitoring those units cannot be expected to monitor potential leakage of contaminants from the HT–2 area.

Monitoring of Slush Pit Contamination

Events regarding the near–surface contamination at Tatum Dome demonstrate both the value and shortcomings of the LTHMP. Analytical results early in the program revealed above–background tritium concentrations in the Half Moon Creek Overflow Pond. This triggered an extensive site investigation in 1977 and 1978 that methodically determined the area of contamination and isolated the most probable cause as incomplete cleanup of the old slush pits (U.S. DOE, 1978). During the 1978 investigation, eleven monitoring wells were installed to function as an early warning system for contaminant migration in the shallow aquifer.

Unfortunately, the hydrogeology of the Surficial Aquifer was not adequately factored into the placement of the new monitoring wells. Despite the careful survey of the location of contamination, there is no record of any measurements of water level elevations so that flow directions in the shallow system could be accurately determined. The working hypothesis was that flow followed surface elevation contours and was generally toward Half Moon Creek (east of SGZ), though the analytical results suggested that migration from the SGZ area had been predominantly to the north and south (Figure 24). The HMH wells were located apparently without regard to these possible downgradient directions, with the locations chosen to "surround the contaminated area" (U.S. DOE, 1978). Though the approach of surrounding the contaminated area has value from the standpoint of providing background data and acting as insurance for uncertainty in flow directions, it is not a substitute for placing

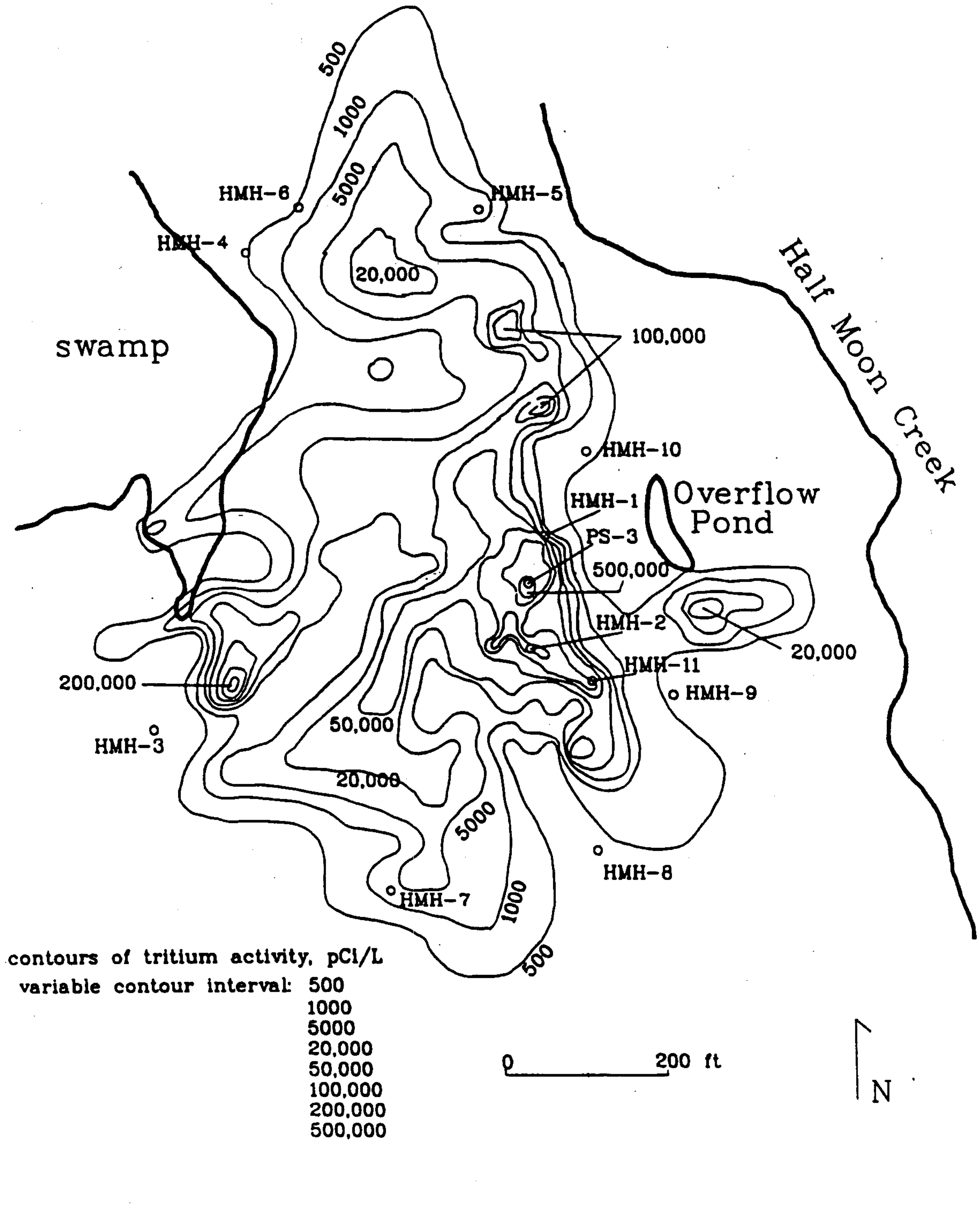

Figure 24. Location of near-surface contamination at Tatum Dome and the HMH wells. Adapted from DOE (1978).

monitoring wells in the most likely areas for migration. For example, the concentration contours around the contaminated area south of the overflow pond suggest migration toward Half Moon Creek, approximately 200 ft to the east. No wells are located between this area and the creek, and the monitoring station on the creek is located downstream.

Monitoring the migration is further complicated by the possibility of vertical flow. The results from the PS-3 borehole (U.S. DOE, 1978) and well HM-S (Fenske and Humphrey, 1980) strongly suggest that there is downward migration through the Citronelle Formation, possibly by means of interconnected sand stringers. The near-surface hydrogeologic environment at the site merits additional description in this respect. The Surficial Aquifer is the shallow water-table aquifer in the sands and gravels of the Citronelle Formation, terrace deposits, and valley alluvium. By virtue of its fluvial/alluvial origin, this aquifer is heterogeneous in lateral and vertical directions. In the SGZ area, the water table occurs between 1 and 10 ft below land surface. The upper 20 ft are described as brown, orange, and red clays (U.S. DOE, 1978). From 20 to 30 ft is a fine-grained white to grey sand with unconsolidated gravel in the bottom 2 ft. This entire 10-ft section in PS-3 was described as a water producer. In HM-S, this permeable sand occurred between 20 and 35 ft deep and was considered the producing section for the Surficial Aquifer (Fordham and Fenske, 1985). The sand also crops out along Half Moon Creek. Below the permeable bed is a green clay with a lower permeability, based on its rate of water production in PS-3. Fordham and Fenske (1985) postulate that the sandy zone below 20 ft functions as a zone of lateral transport (principally toward streams). They also suggest that the amount of lateral transport in this zone may be greater in the SGZ area than elsewhere because the pad area has been stripped of vegetation, allowing more infiltration.

Given this setting, it seems likely that water movement between the surface and the first vertically extensive sand lens is predominantly vertical, toward the high permeability layer. Once in the sand, lateral movement can occur toward surface water discharge points and toward other permeable sand lenses leading deeper below the surface. The results from the PS-3 borehole (U.S. DOE, 1978) and well HM-S (Fenske and Humphrey, 1980) strongly support the concept of downward migration through the Surficial Aquifer. All of the HMH wells are less than 12 ft deep. In all probability, the HMH wells are monitoring locations dominated by vertical flow, with well HM-S the only LTHMP well completed in the more permeable sand likely to permit lateral flow. Thus, lateral migration of tritium from the slush-pit contamination is unlikely to be intercepted by the "early warning" system established by the HMH wells.

Despite the shortcomings of the HMH wells, the analytical results from them have continued to demonstrate the existence and migration of tritium in near-surface groundwater at Tatum Dome. The migration is evidenced by the continued presence of above-background tritium concentrations in the overflow pond and concentrations in some wells declining at rates above that of radioactive decay (suggesting transport and dilution). Despite this evidence, monitoring of the slush-pit contamination has remained essentially unchanged since the HMH wells were installed in 1978.

Water Supply Monitoring

Compared to most of the other offsite test areas, there are a relatively large number of domestic and municipal supply wells close to Tatum Dome. As a result, there is a relatively large number of supply wells in the LTHMP Tatum Dome network. Most of the domestic wells are believed to be completed in the Surficial Aquifer. Those wells to the south and east on the opposite side of Half Moon Creek from the site are reasonably assured to be upgradient of the contamination in the Surficial Aquifer. Those in the downstream direction (north and northwest) are potentially downgradient. Any domestic wells completed in the Local Aquifer to the west of the site may also be downgradient. Unfortunately, accurate maps of well locations and topography could not be located during this study to determine precisely which wells fall into each category.

It is not known what aquifers are tapped by the municipal wells in the LTHMP. Given Fenske and Humphrey's (1980) conclusion that most of the flow in the Miocene aquifers is to the east-northeast, the well at Purvis is the only municipal well that can be considered downgradient from the test site. All of the municipal wells are at least 10 miles from Tatum Dome and therefore detection of any contaminant migration (even in the downgradient well) is highly unlikely.

Discussion of Recommendations

Monitoring for leakage of radioactive material from the event cavity is reasonably adequate at Tatum Dome. Monitoring wells are located close to the SGZ area and are completed in all of the potable aquifers nearby. Considering that the probability of cavity leakage is low and that additional wells around SGZ could afford the opportunity for cross-contamination from near-surface sources to deeper aquifers, no additional action in regard to cavity monitoring is recommended.

Monitoring of the fate of the radioactive waste injected into Aquifer 5 is essentially non-existent. Given the problems that developed in the well that originally monitored Aquifer 5 (*i.e.*, the leakage of waste to the surface through HT-2m), the lack of subsequent efforts to monitor Aquifer 5 is understandable, though perhaps not prudent. Some follow-up to the analysis performed by Fenske (1973) should be performed to determine if the northeast gradient caused by injection activities at the Baxterville Oil Field is still operative in Aquifer 5. Underground injection activities have come under increasing regulation during the last decade and studies of the integrity of Aquifer 5 for brine injection may have been performed by local oil and gas producers or regulating agencies. Other hydrologic data for the region may also now be available and information on flow systems near domes was generated during studies of domes for nuclear waste disposal. These data, along with previous Tatum Dome work, should be evaluated in the framework of the Underground Injection Control regulations of the State of Mississippi to determine what, if any, action should be taken. As the injection site is located southwest of the SGZ area, the slush pit contamination would not pose a problem for any investigative drilling, though contamination of the overlying aquifers by Aquifer 5 is a concern.

Migration of the slush pit contamination through the Surficial Aquifer and surface water system near Tatum Dome is known to be occurring, and this should be the issue of greatest concern to the LTHMP. The current "early warning" system provided by the HMH wells is inadequate for monitoring tritium migration from the slush pit material. Though the source term was well-defined during the 1978 studies, the vertical and horizontal components of flow were not, and have not, been determined. Given the probable complexity of the Surficial Aquifer hydrostratigraphy (*i.e.*, interbedded permeable and impermeable materials) and changing relationships between the aquifer and surface water (depending on rainfall and stream stage), a reliable steady-state model of transport in the aquifer may not be possible without enormous effort. A large first step could be made if surface elevations are available for the 171 holes augered for the 1978 investigation. Depths to water and tritium distributions are available for these holes and a three-dimensional picture of the water table and contamination could be constructed for one point in time. Improving the monitoring system will probably require installing deeper monitoring wells in transmissive sections of the Surficial Aquifer and collecting samples at several times of the year, depending on rainfall conditions.

Despite the suggestions given above, recommendations for monitoring the near surface at Tatum Dome cannot be made without better definition of DOE's objectives for the area. The DOE is already aware of the contamination in the Surficial Aquifer and the migration of that contamination both laterally and vertically. If no action will be taken to mitigate the site under any circumstances, there is no purpose in improving the monitoring program. Any investigation of the slush-pit contamination should be accompanied by development of action levels so that monitoring results have a meaningful role at Tatum Dome.

Specific Recommendations

Recommendations for monitoring at the Tatum Dome site can be summarized as follows:

1. DOE objectives in regard to the slush-pit contamination must be formulated. This should include the development of action levels, the contaminant concentrations that would trigger specific actions by the DOE (*e.g.*, remediation).

2. Depending on the objectives chosen in recommendation #1, the monitoring of the slush pit contamination can be improved by installing monitoring wells in the permeable horizon between 20 and 35 ft below land surface. The geographic locations of such wells should be determined based on hydraulic gradients, accounting for impacts of variable stream stage. Such optimum well placement will necessarily require additional characterization of

the Surficial Aquifer to determine the lateral and vertical components of flow. Maximum use of data collected by previous studies should be made (if details of surface elevations, etc. can be located) as several "snapshots" through time may reveal the interaction of the shallow groundwater system with surface water and rainfall.

3. Predictions of the fate of the radioactive waste injected in Aquifer 5 should be revised using information on brine injection at the Baxterville Oil Field during the last 15 years. These revised estimates should then be evaluated in the context of State of Mississippi Underground Injection Control regulations to determine if any action is prudent.

4. Continue monitoring all of the DOE wells that are currently part of the LTHMP. In particular, the HM-series wells are the best positioned wells at any offsite test location to detect leakage from an event cavity. The HMH wells, though not located to detect lateral migration in the most likely horizon, provide important data on leaching of the slush-pit contamination into the saturated zone.

5. Sampling horizons (*i.e.*, aquifers) and locations relative to hydrogeologic features are needed for all non-DOE wells in the LTHMP. Recommendations on additions or deletions to this set of wells could not be made with available data, however, some of the current wells are undoubtedly upgradient of Tatum Dome contaminant sources. Additions of more supply wells to the LTHMP should be evaluated within the hydrogeologic context so that only wells on reasonable downgradient flow paths are permanently added to the program.

6. Given the possibility of contaminants in addition to tritium, periodic analysis of a larger analytical suite should be considered. In particular, the nature of the 38 curies of beta and gamma activity injected in HT-2 should be determined and analyses for those radionuclides periodically performed. As leaks from tanks of "radiologically contaminated fluids" at the site were described in DOE (1978), radionuclides in addition to tritium could conceivably be in the Surficial Aquifer as well. Long-term monitoring of the injection and/or cavity leakage should include a shift away from solely tritium to include longer-lived radionuclides.

7. Given the location of Tatum Dome within the oil and gas producing area along the Gulf of Mexico and the use of salt domes for gas storage and brine production, there is a possibility for inadvertent human intrusion through the test cavity or the waste injection horizon in the future. Passive and active institutional barriers are particularly important to safeguard against such intrusion. The adequacy of the monument at Tatum Dome and the drilling restrictions should be assessed in light of recent developments in passive barriers by nuclear waste programs.

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GNOME

The Gnome Site is in southeastern New Mexico, about 30 miles southeast of the town of Carlsbad. Gnome was the first nuclear detonation designed for peaceful purposes and the first underground event in the Plowshare Program to take place outside the Nevada Test Site boundary. The event was detonated on December 10, 1961, at a depth of 1216 ft in the Salado salt formation. The yield was slightly over 3 kilotons and the event resulted in unexpected venting of radioactive gases to the atmosphere (U.S. DOE, 1982). A second experiment, Project Coach, was cancelled for the Gnome Site, though excavations were begun for it.

Hydrogeologic Considerations in Monitoring

The Gnome site is located in the northern part of the Permian-age Delaware Basin (Cooper and Glanzman, 1971). The basin is bounded by the horseshoe-shaped Capitan Reef and contains sedimentary rocks deposited in a Permian sea, including a thick section of evaporites. The Gnome ground zero was located within these evaporites, in bedded halite of the Salado Formation. Below the Salado is another evaporite formation, the Castile, followed by basin-facies clastics and carbonates. The units below ground zero are important in that they include major oil and gas producing horizons, but no potable aquifers occur in them.

Above ground zero is approximately 500 ft of Salado halite, conformably overlain by the Rustler Formation. The Rustler is predominantly composed of anhydrite and gypsum, but contains two laterally continuous dolomite beds. Above the Rustler are the Dewey Lake Redbeds, which in turn are overlain by Quaternary alluvial deposits. Triassic sandstones and Tertiary alluvium (*e.g.*, Ogallala Formation) occur in the geologic section to the east and north but are not present at the Gnome site. The geologic section and hydrogeologic properties are affected by salt dissolution in the basin. Dissolution is progressing from west to east and has created a large dissolution basin, Nash Draw, west and north of Gnome.

The Rustler Formation contains three water-bearing zones: a layer of permeable dissolution residue at the base of the Rustler and top of the Salado, the Culebra Dolomite, and the Magenta Dolomite. The dissolution residue has variable hydraulic properties, generally increasing in transmissivity in the direction of dissolution (to the west). The unit is a recognized brine aquifer in Nash Draw and is known to discharge brine to the Pecos River at Malaga Bend. The Culebra Dolomite is the most regionally extensive aquifer in the Gnome area. It is a vuggy, fractured dolomite, ranging from 25 to 30 ft thick. Water quality is increasingly saline to the east, but is suitable for domestic and stock use in the Gnome area. Groundwater in the Culebra moves generally westward and southwestward to the Pecos River (Figure 24). The Culebra was used for a radioactive tracer experiment at the Gnome Site. The upper Rustler dolomite, the Magenta, is generally above the zone of saturation in the Gnome area. Above the Rustler, the Dewey Lake Redbeds are not known to produce significant amounts of water in the area. Localized perched groundwater is known to occur in the Quaternary units, particularly in the gravels of the Gatuna, but the lateral extent of such zones is probably small.

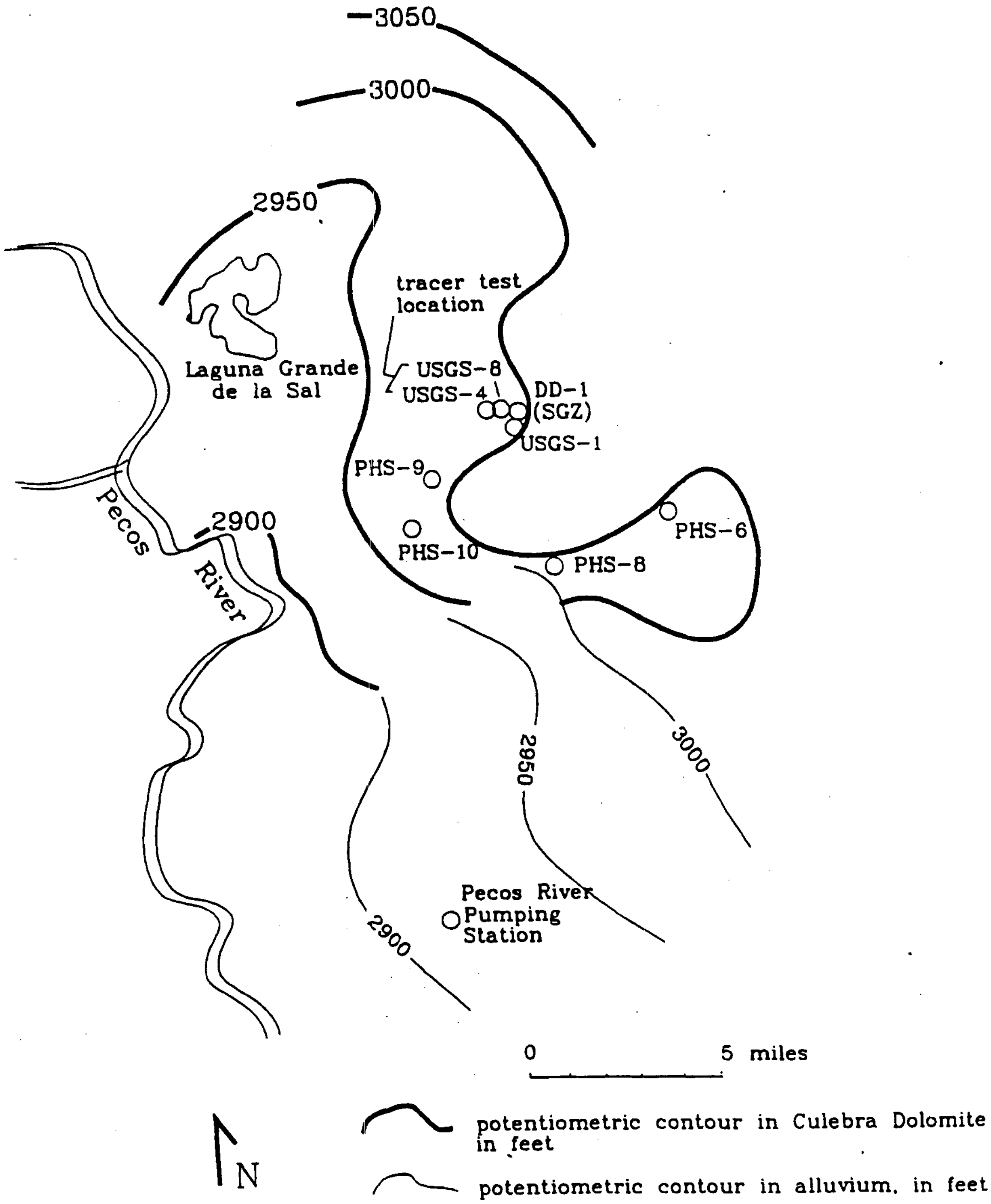

Figure 25. Potentiometric contours in the Gnome area.
Modified from Cooper and Glanzman (1971).

Potential Sources of Contamination

There are four potential sources of groundwater contamination related to the Gnome Project. Two of these are near-surface sources: fallout from the venting of the shot and surface contamination from site activities (*i.e.*, drillback operations). The other two are sources at depth: radioactive material in the event cavity and drifts, and the radioactive tracer injected into the Culebra Dolomite.

The potential impact of the near-surface sources on water quality in the area is minor compared to the possible impact of the subsurface sources. The venting was a one-time event that was dispersed through the atmosphere. Surface contamination at the site was successfully reduced to below established decontamination criteria during two decontamination projects, leading to unrestricted use of the land surface (REECo, 1981). Radionuclides remaining from either of these sources would have a long travel path through the unsaturated zone before reaching the water table, or down intermittent streambeds to surface water bodies.

Of the two subsurface sources, the tracer in the Culebra Dolomite is of paramount concern. The 1963 injection included 20 Ci of ^{3}H, 10 Ci of ^{137}Cs, 10 Ci of ^{90}Sr, and 4 Ci of ^{131}I. These radionuclides were placed directly in the most transmissive aquifer at the site and have been free to migrate downgradient for 27 years. Given estimates of groundwater velocity of 0.5 ft/day, the tritium plume could have moved almost a mile west of the site. These velocity estimates could be unconservative (*i.e.*, too low) because they do not take into account channelizing of flow along fractures. Though the other radionuclides can be expected to be retarded, the degree of retardation may be lower than that found in laboratory studies due to the salinity of the water and fracture flow.

The radioactive material in the cavity and underground workings is also a matter of concern. During the initial cleanup in 1968 and 1969, the Gnome shaft was filled with radioactively contaminated material to within seven feet of the surface. Additional contaminated material was slurried into the cavity and drifts during the final cleanup operations in 1979. Though reference is made to secure plugging of holes penetrating the underground workings (except monitoring holes), the integrity of shaft sealing must be held suspect due to the manner of filling. The shaft had a concrete liner to a depth of 720 ft and grout was injected into the Culebra behind the liner to reduce seepage. However, cracks in the liner and grout will occur as the shaft deforms in response to natural stresses. It is reasonable to expect that there could be interconnected porosity between the cavity, drift, and shaft. As the salt around the drifts and cavity deforms and compresses the material inside, a driving force will be created to push contamination upward. The slurrying method insures that water is available as a medium of transport (indeed, concerns that the cavity would fill with water prior to disposal of a major part of the radioactive material prompted a switch to a recirculating fluid system (REECo, 1981)). If contamination moves up the shaft, the most likely connecting pathway would be to exit at the Culebra Dolomite, and then flow westward in the downgradient direction. Another possibility is to exit through the Rustler–Salado dissolution residue. This zone was apparently not productive in the Gnome shaft and thus this pathway is considered less important than the Culebra, but the horizon is saturated in at least one Gnome-related hole (USGS No. 5), and discharges to the Pecos River.

Past and Present Sampling

Pre-event water sampling was conducted by both the PHS and USGS. DOE (1982) reports that the PHS collected pre- and post-shot groundwater samples from 14 wells within a 30 mile radius of ground zero. The analysis for gross radioactivity revealed no appreciable increase. The USGS reported radiochemical analyses of water collected from 22 wells in the Gnome area (Cooper and Glanzman, 1971) and two of the USGS Gnome test wells, No. 1 and No.2 (Cooper, 1962a). All of the samples were collected prior to the Gnome event and were analyzed for gross α, gross β, uranium, ^{226}Ra, and ^{90}Sr. Though the DOE (1982) reports that the USGS collected post-event samples from wells in 1967 and 1969, results of the analyses have not been located in the present study. Pre-shot analyses for test wells No. 4 and 5 have also not been found, though they were reportedly performed.

The letter initiating the LTHMP (Miller to Carter) specified the following Gnome site LTHMP wells: USGS wells No. 1, 4, and 8, PHS wells No. 6, 7, 9, and 10, and public water supplies at Malaga, Loving, and Carlsbad (Figure 25). PHS No.7 was never sampled by the LTHMP, with PHS No. 8 apparently taking its place. In addition, samples have been regularly collected from Pecos River Pumping Station Well No. 1, owned by El Paso Natural Gas. Malaga tap water was only sampled in 1975 and 1976, presumably because it is piped from Loving. The only other change in this relatively constant list of sampling locations was the addition of wells LRL-7 and DD-1 in 1981. Though listed as an LTHMP sample point in the report describing the program at Gnome (U.S. DOE, 1982), well DD-1 has not been sampled since 1983.

From 1973 to 1976, a fairly extensive analytical suite was run on the groundwater samples. In several years this included ^{89}Sr, ^{90}Sr, ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, and ^{239}Pu in addition to ^{3}H. This has tapered off through the years to usually only a ^{3}H analysis for non-contaminated wells. However, wells USGS No. 8 and LRL-7 have consistently had a ^{137}Cs analysis, and in some years USGS 4 and 8 and LRL-7 have been analyzed for strontium and plutonium isotopes (most recently in 1986).

Analysis of Current Monitoring System

The current monitoring system is inadequate for detecting contaminant leakage from the Gnome cavity or shaft, or for monitoring the migration of the radionuclides injected into the Culebra at USGS well 8. No monitoring wells are located downgradient of the tracer test location. Though the wells involved in that test (USGS 4 and 8) were located to be "downgradient from the shot point, in the direction of water movement" (Cooper, 1962b), they are already contaminated with ^{3}H, ^{137}Cs, and ^{90}Sr, and thus are compromised as monitor wells for cavity leakage.

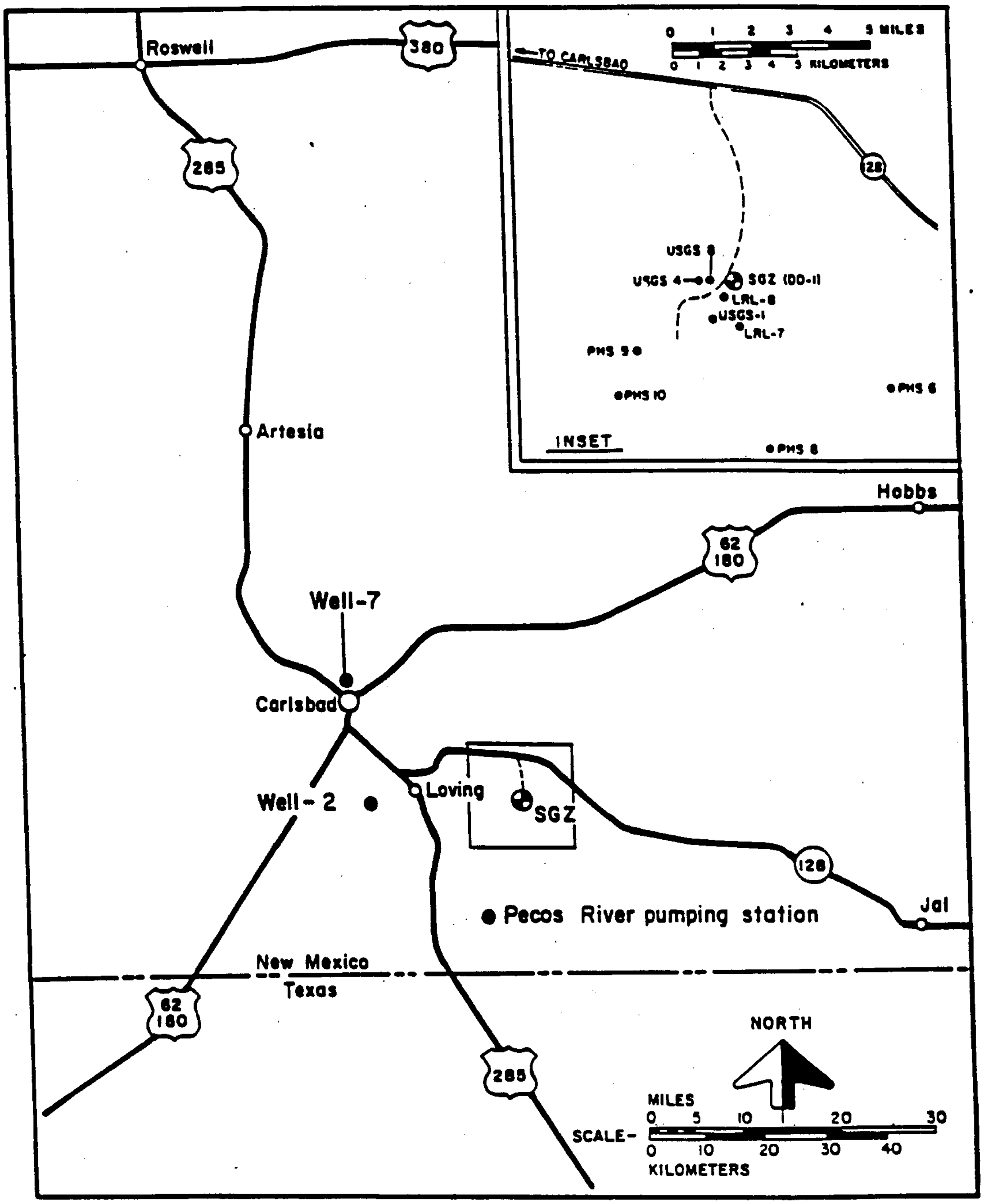

Figure 26. LTHMP monitoring network around Project Gnome.
From U.S. DOE (1982).

While migration is not monitored, the LTHMP does collect samples from the sources: USGS 4, 8 and LRL-7 (completed in the Coach drift). Samples from all three locations consistently reveal high levels of radionuclides, not surprising given the injected tracer and drift contents. It is not clear what use the LTHMP makes of these source data, as the only interpretation in the monitoring reports is an explanation of the cause of the high activities. However, a comparison of the 1972 through 1987 data reveals a decrease in tritium activities at a rate higher than that of radioactive decay in both USGS 4 and 8 (the period of record is shorter for LRL-7, but the same trend is evident) (Figure 26). This strongly suggests migration of tritium through the Culebra Aquifer, away from the tracer test location. The data for ^{90}Sr in USGS-8 also reveal a decline more rapid than radioactive decay. In the case of ^{90}Sr, most of the drop occurred between 1979 and 1980, so the possibility of a procedural change should be investigated. In any case, the LTHMP data indicate the migration of at least tritium from the Gnome Site, though the extent of that migration cannot be determined with the current monitoring network.

The only other DOE well that is part of the LTHMP is USGS No.1. This well is slightly south of ground zero and the access shaft and therefore is probably not directly downgradient. However, with conditions of fracture flow in the Culebra, local flow directions could be at angles to the regional gradient. In addition, USGS No. 1 is very close to the site activities and is completed in the primary zone of interest, the Culebra Dolomite, and thus is a reasonable choice for a monitoring well.

The rest of the wells in the Gnome LTHMP are probably of little use for monitoring migration of groundwater contaminants from Gnome. Though fairly good records are available of the depth of the LTHMP wells and the hydrogeologic units the wells are sampling, correlating the location of the PHS wells with the well inventory in Cooper and Glanzman (1971) proved difficult. The difficulty is attributed to an inaccurate map in the Off-Site Environmental Monitoring Report (Fontana *et al.*, 1988). According to that map, PHS wells 6, 8, 9, and 10 are all well beyond a five-mile radius of the site, but all indications are that these wells are actually within that radius. If the identifications given in Table 1 are correct, none of the PHS wells are downgradient of Gnome. In addition, they are over two miles away from ground zero and the tracer test.

Table 1. Identification of PHS Wells.

PHS Well Number	Location No.	Name
6	24.31.17.111	Ranch Headquarters Well - Snyder
7	24.30.12.430	Poker Well
8	24.30.23.312	New Well
9	24.30.8.113	Ranch Headquarters Well - Eaton
10	24.30.18.231	Two Mile Mill

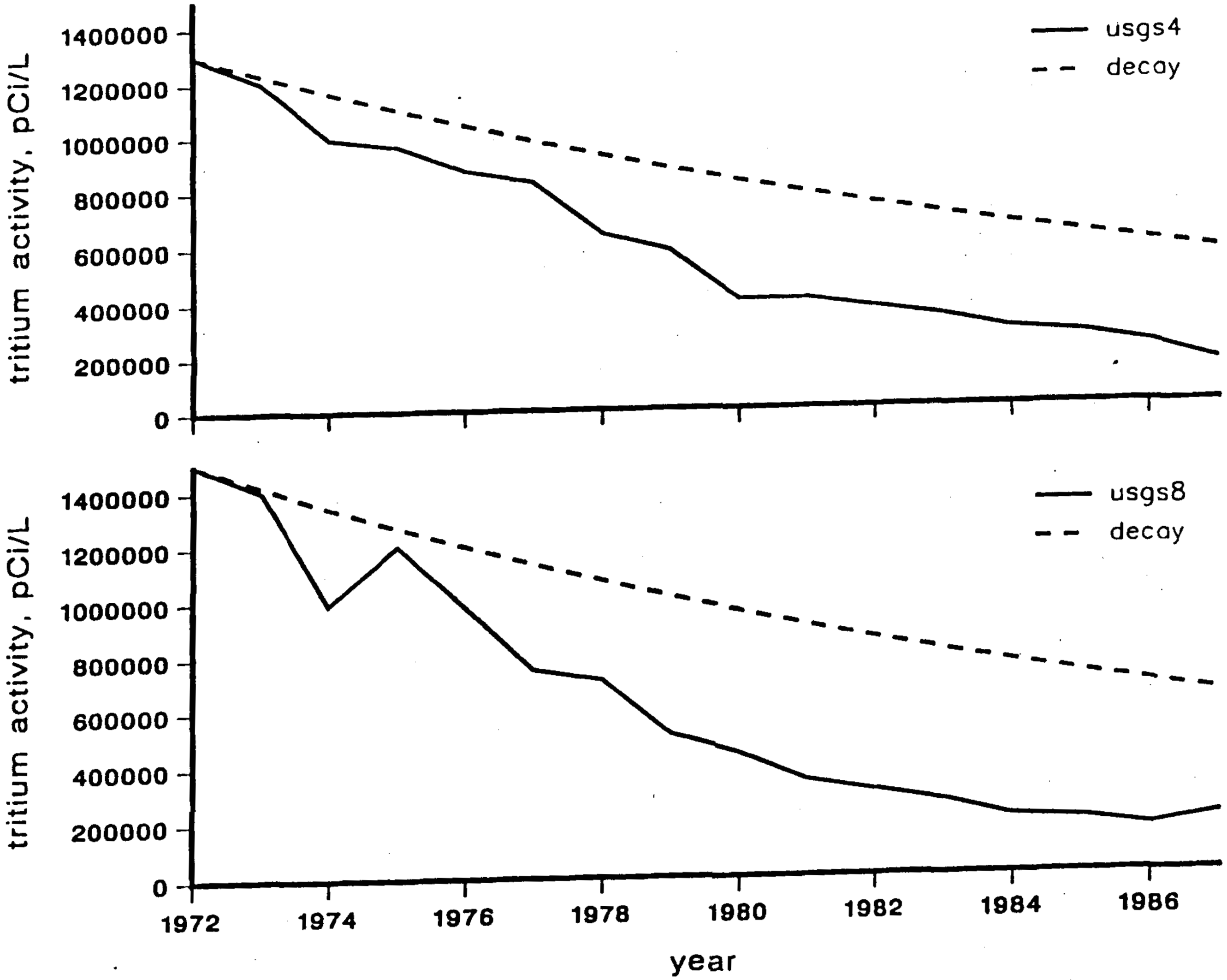

Figure 27. Tritium activities through time in wells USGS-4 and USGS-8.

Both of the municipal supply wells sampled by the LTHMP are located on the west side of the Pecos River. There is no possibility for a groundwater contaminant transport pathway to connect these wells to the Gnome site. This is particularly true for the Carlsbad well, which is completed in the Capitan Reef and contains water recharged in the Guadalupe Mountains. The Loving well is reportedly completed in alluvium (DOE, 1982), which probably takes water from the Pecos River and local rainfall. However, the well is up-river from points along the Pecos where groundwater moving across the Gnome site could discharge, and is across the river from the site. Contamination from the atmospheric fallout caused by the venting is the only possible pathway that could impact these municipal supplies.

No explanation could be found for the inclusion of the Pecos River Pumping Station Well #1 in the LTHMP program. It is located over ten miles from the site, with several other wells between it and Gnome. The well is completed in a thick alluvial section that is not present at Gnome and thus there is essentially no possibility of detecting Gnome-related contaminants in the samples.

Recommendations

1. New wells are needed in the Culebra Dolomite downgradient of USGS No. 4. The primary objective should be to determine the extent of migration of the radioactive tracers. Once the plume is identified, a decision can be made as to whether to place monitoring wells downgradient or perform remediation.

2. During investigation of contaminant migration from USGS wells 4 and 8, efforts should be made to understand the contaminant transport behavior of ^{3}H, ^{90}Sr, and ^{137}Cs. Many large uncertainties remain as to the sorption characteristics of radionuclides in aquifer environments, and yet field tracer studies are essentially prohibited by environmental concerns. The Gnome tracer experiment provides the DOE with a unique opportunity to evaluate transport behavior over the span of decades. The information gained will not only benefit the Gnome Site, but could be of great use to other DOE contaminant transport concerns (*e.g.*, the Waste Isolation Pilot Plant (WIPP) Site).

3. Monitoring wells should be placed in the Culebra and in the Rustler/Salado dissolution residuum downgradient of the Gnome shaft, and downgradient of any boreholes that penetrate the cavity and may be improperly plugged (the condition of DD-1 is of particular concern, but no information could be found on its status). These wells should be located close enough to the shaft that they are not downgradient of USGS No. 4 and 8. The shaft, in particular, is a potential conduit for contaminant transport and is not monitored by the current system. Consideration should be given to investigating conditions within the shaft as well.

4. A new well survey should be conducted to update the plate prepared by Cooper and Glanzman (1971). Any new wells in credible downgradient locations from Gnome should be added to the LTHMP, possibly replacing PHS No. 6, 8 or Pecos River Pumping Station Well

No. 1. Wells PHS No. 6 and 8, and Pecos River Pumping Station Well No. 1 are not located within the hydrogeologic system such that they serve any downgradient monitoring purpose. The same may also be true for PHS wells No. 9 and 10, but they are closer to the area of concern.

5. Monitoring of Carlsbad City Well No. 7 and Loving City Well No. 2 could be left to personnel from the WIPP Site. Neither of these wells has any credible hydrogeologic connection to the Gnome Site, so their place in the LTHMP is probably related simply to their being the closest municipal supply wells. These wells are monitored as part of the WIPP environmental program and presumably the analytical results could be shared with the LTHMP.

6. Monitoring of regional groundwater discharge to the Pecos River in the vicinity of Malaga Bend would be prudent even though the area is about 7 miles from the Gnome site. Again, this site may be monitored by WIPP personnel and thus the LTHMP could inquire about sharing their data.

7. Long-term protection of the cavity from inadvertent human intrusion is a matter of concern at Gnome. The Delaware Basin is an actively explored oil and gas area, heightening the risk of such intrusion. As with Tatum Dome, advances in passive safeguards should be investigated for use at Gnome.

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